Detecting FIPs at a Future Higgs Factory

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Abstract

The dark matter problem has various different theorie and approaches to solve it, but in this project a theory including the dark sector is investigated. The dark sector consists of a dark photon and a dark Higgs which both mix with the standard model particles feebly. The analysis takes place on the basis of the International Linear Collider, a future Higgs factory. The dark photon is supposed to be reconstructed because of its long lifetime due to the small interaction and therefore, characteristic decay signature into two charged particles within the tracker, called V_0. As a goal, the efficiency of this dark photon reconstruction is studied.

Contents

1 Introduction

The standard model of particle physics offers broad explanation for lots of phenomena in physics. But still, there short comings in observed behaviour or properties that are not covered by the standard model. One of these includes astrophysical observation which hint to the existence of dark matter with the assumption that currently accepted theories of gravity are right. This form of matter is called dark because it does not interact with the electromagnetic field and is unseen.

One approach to solve this problem are weakly interacting particles (WIPs) which interact with the standard model particles in a weak way. Up until now, they have not been observed but they are also not excluded, but possible masses for those particles increase. As another possible explanation, not weakly but feebly interacting particles (FIPs) are introduced which interact even weaker and are not too massive. To observe those particles, a precise measurement in future Higgs factory is neccesary which will be investigated in this project.

2 Theory

To explain phenomena like dark matter, an extension of the standard model might be needed. A suitable candidate for such an extension is the hidden sector introducing new, dark particles. Because of similar symmetry properties, they should interact with the SM particles, but since they have not yet been observed, the interaction is small. These dark particles interact via gravitation, which makes them dark matter candidates but this interaction is too weak to detect them.

There a many different theories on how to introduce dark particles, but in this project is based on [1]. There, a spontaneously broken $U(1)_D$ gauge symmetry is introduced. The mediator of this symmetry is the dark photon Z_D, a vector boson, which interacts with the SM particles through kinetic mixing with the Z boson. If the $U(1)_D$ gauge symmetry is spontaneously broken via a dark Higgs mechanism, the resulting dark Higgs will mix with the SM Higgs. Therefore, interaction between the hidden sector and the SM can happen either through the *hypercharge portal* which is characterised by the kinetic mixing or the *Higgs portal* which describes the Higgs mixing. The mixing parameters of the dark photon are as already mentioned small, that is why it is classified as a FIMP - a feebly interacting massive particle. Because of the small interaction strength, the dark photon lives long and decays within the detector which can be used to identify the particle. The coupling strength for the kinetic mixing is called ϵ and influences the deacy length of the dark photon. The Higgs mixing is described by the parameter κ, from which the new parameter

$$\kappa' = \kappa \frac{m_H^2}{|m_H^2 - m_{H_D}^2|^2} \tag{1}$$

is deduced which depends on the SM Higgs mass m_H and the dark Higgs mass m_{H_D} and is used for calculating the branching ratio for the decay of the Higgs to two dark photons. This branching ratio has to be small, because otherwise this process would have already been observed. But assuming that the branching ratio of the dark Higgs decay to two dark photons is 1 since there are no other decay options, the cross section is proportional to κ'^2. For $\kappa'^2 \sim 10^{-3}$, the resulting cross section is about 85 ab.

In this model, the dark Higgs and the dark photon are the only dark particles and if there are no hidden sector particles with a mass below the Z_D mass, the dark photon will decay to SM particles including leptons, if $m_{Z_D} > 2m_e \sim 1\,\mathrm{MeV}$. Consequently, the model can not provide a complete answer to the dark matter question because stable particles making up the dark matter are missing, but the dark Higgs and dark photon can still be a hint to the hidden sector which might need to be extended afterwards. In this project, the focus will be on a dark photon which is massive enough to decay into muons.

Special parameters of interests are the mass of the SM Higgs and the dark Higgs which the model predicts. The mass of the SM Higgs has to agree with the current measurement results and the mass of the dark Higgs is expected to be near that mass as well. The masses are described by

$$m^2_{H,H_D} = v^2\lambda + v_D^2\lambda_D \pm \mathrm{Sign}(v^2\lambda - v_D^2\lambda_D)\sqrt{v^4\lambda^2 + v_D^4\lambda_D^2 + v^2v_D^2(\kappa^2 - 2\lambda\lambda_D)}, \qquad (2)$$

with v and v_D being the vacuum expectation values and λ and λ_D being the self coupling for the SM Higgs or the dark Higgs respectively.

In Fig. 1, the Feynman diagram for the whole process analysed in this project is shown. Here, the Higgs portal is investigated because the e^+e^- pair initially creates a Z boson which radiates a Higgs boson. This Higgs boson mixes via the Higgs portal and decays into two dark photons which then decay into muons. The muon channel is selected because it provides the best precision. In this process, the production and the decay of the dark phon are decoupled because the production happens through the Higgs portal and the decay through the hypercharge portal. The remaining Z boson decays hadronically to make it easier to differentiate.

Another possible process, which is not analysed in this project, is the production of an Z boson directly out of the e^+e^- collision which does not radiate a Higgs boson but mixes with the dark photon which then decays to two muons, as displayed in Fig. 2. In this process, the cross section and the decay width are not decoupled but given by the same kinetic mixing parameter.

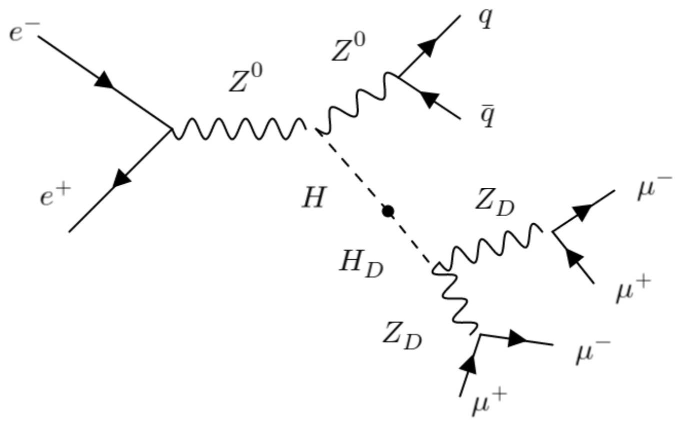


Figure 1: Feynmann diagram of the process analysed. The e^+e^- collision creates a Z boson which radiates a Higgs boson. The Higgs boson then mixes with the dark Higgs which then decays into two dark photons.

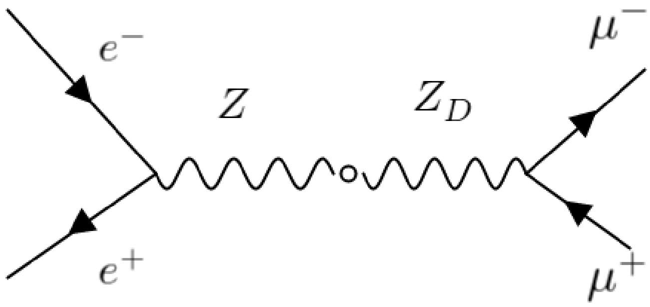


Figure 2: The e^+e^- collision creates a Z boson which mixed with the dark photon. The dark photon then decays to two muons.

3 The Experiment

3.1 The ILC

The ILC (International Linear Collider) is a planned linear particle accelerator where electrons and positrons should collide [2]. The approach considered in this report is the one with a centre of mass energies of 250 GeV which makes it a Higgs factory. To achieve this, a length of about 20 km would be necessary. The ILC is currently under political consideration in Japan.

In Fig. 3 an overview about the structure of the ILC can be seen. The electrons are created by a photocathode and and a laser via the photoelectric effect and then accelerated. In this production, the electrons are polarised to 80 %. The high energy electrons pass through a helical undulator and emit synchrotron radiation which will produce electron-positron pairs on a target. The resulting positrons are collected and accelerated separately. The positron bunches are only to 30 % polarised because of the production mechanism. Before being accelerated, the particle bunches are reduced in size in the damping rings. As the last step, they finally collide in one of the two experiments. With the polarisation of the particles, the likelihood of processes with the weak interaction can directly be influenced.

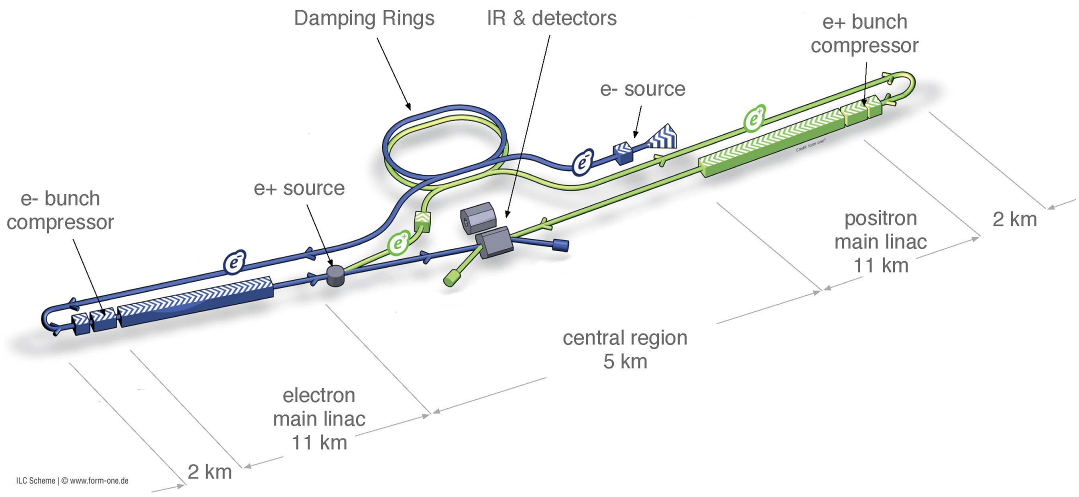


Figure 3: Graphic overview of the ILC [2].

The purpose of building the ILC is the discovery of physics beyond the Standard Model such as light super symmetric particles or weakly interacting massive particles.

3.2 The ILD

The ILD (International Large Detector) is the detector used at the ILC. In Fig. 4, a schematic overview of the detector is shown next to a close up of the time projection chamber. The ILD is optimised for particle flow, of which the time projection chamber is a part. The time projection chamber is an important part of the detector for the search of the dark photons because of the continuous tracking of the characteristic V_0 structure. Here, the θ angle as shown in Fig. 4 is important because particles with a $|\cos\theta|$ close to 1 fly in the direction of the beampipe and cannot be detected and therefore should not be considered for an evaluation of the efficiency.

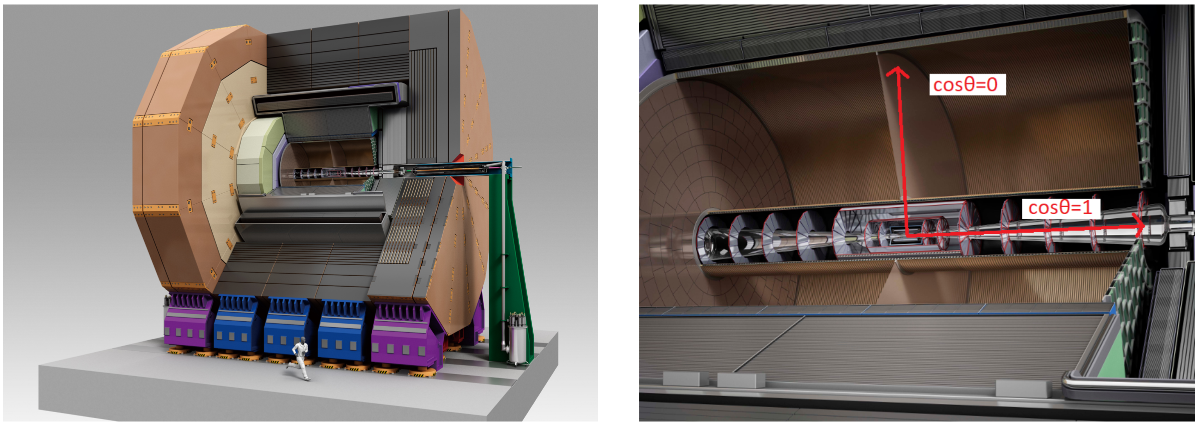


Figure 4: Scheme of the ILD and the TPC [2].

4 Simulation

The event generation is done with WHIZARD and PYTHIA as Monte Carlo generators, where WHIZARD simulates the matrix element and the process until the dark photon and PYTHIA simulates the decay of the dark photon and the parton shower.
One of the challenges of this project was to find a suitable parameter set with a right SM Higgs mass as an output. For this matter, different parameters were investigated:

- kinetic mixing of Z and Z_D: ϵ
- mixing of SM H and dark H: κ
- SM Higgs self coupling: λ
- dark Higgs self coupling: λ_D
- dark Higgs vacuum expectation value: v_D
- mass of dark photon: M_{Z_D}
- decay width of dark photon: W_{Z_D}

The Higgs mass and the dark Higgs mass, generated by WHIZARD, are described by Eq. eq:mass. Another result is the lifetime of the dark photon which needs to be reasonably high since the dark photon is supposed to be a long lived particle. Therefore, the parameters describing the mixing have to be small.

After the simulation of the event, the interaction between the particles and the material in the detector is simulated with GEANT4. The resulting detector response is then reconstructed with MarlinReco. Besides a standard reconstruction procedure, especially the V_0 finder is used to identify the dark photons. In general, a V_0 is defined as a neutral particle that decays into two charged particles of opposite charge with a displaced vertex. In Fig. 5, a scheme of a V_0 candidate is shown. Possible particles to find with the V_0 finder are Λ^0, K_S^0 and photons. The V_0 finder identifies particles by searching for vertices and testing mass hypotheses for the different possible particles. If a particle shows a V_0 structure and the mass lays within the predefined mass range of the dark photon, it is identified as a Z_D.

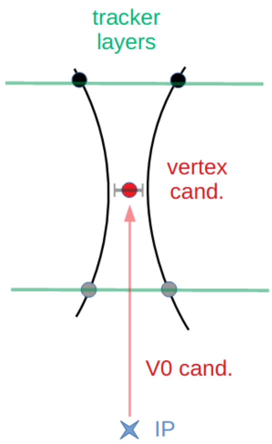


Figure 5: Scheme of a V_0 candidate. The V_0 particle has to be neutral and decay into two charged tracks in the detector.

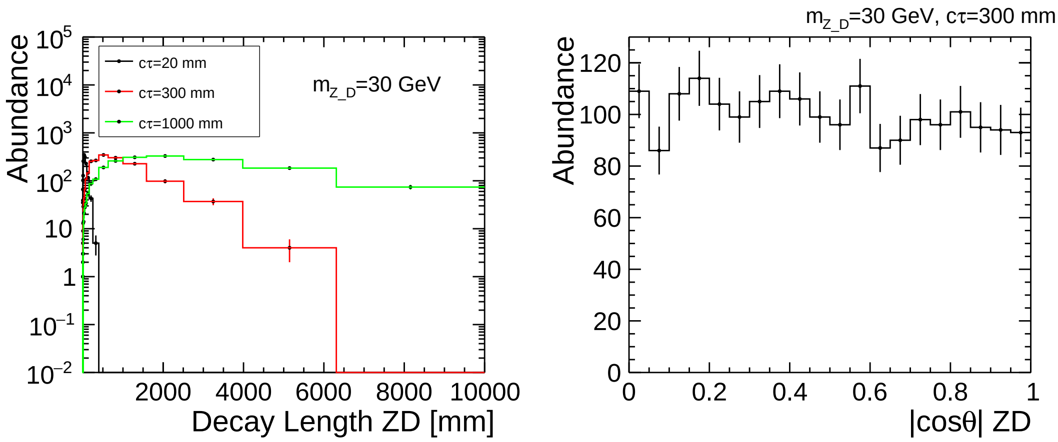


Figure 6: The decay width and the angular distribution of the Z_D for one mass or one sample respectively. The other plots can be seen in the appendix.

5 Results

Different parameters sets were analysed to cover a range of possible properties of the dark photon. The resulting Higgs mass has always been set to 125 GeV and the dark Higgs mass to 126 GeV. The nine different parameter sets produced have a dark photon mass of $m_{H_D} = \{10, 30, 60\}$ GeV and a decay length of $c\tau = \{20, 300, 1000\}$ mm.

5.1 The Truth Dark Photons

As can be seen in Fig. 6, the decay width of the dark photons agree with the preset $c\tau$ and the Z_Ds are radiated flat in $|\cos\theta|$.

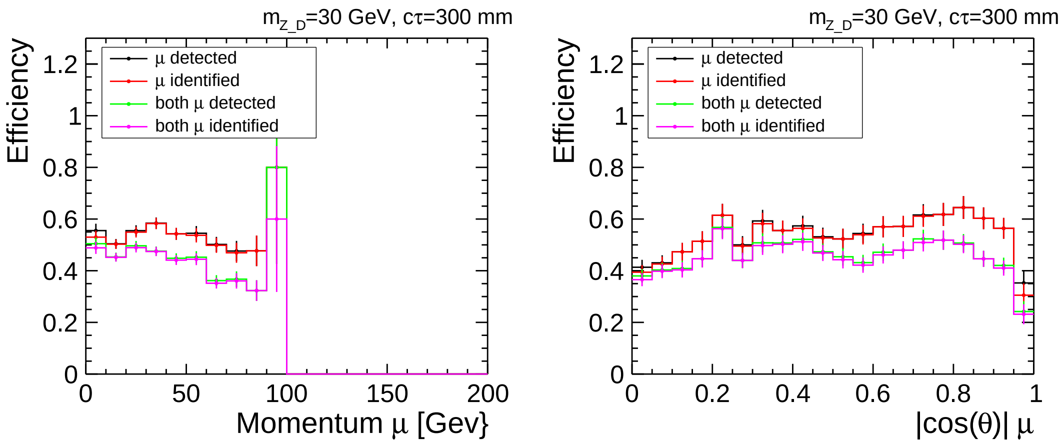


Figure 7: Muon efficiencies for detection and identification of one or both muons from the dark photon for one sample. The other plots can be seen in the appendix.

5.2 Muon Reconstruction Efficiency

As a prerequisite for the V_0 finder to work properly, the muons coming from the Z_D have to be detected in first place and in the best case identified as muons. Therefore, the efficiencies of the muon reconstruction have been investigated. Here, the efficiency is defined as

$$\text{efficiency} = \frac{\text{found (correctly reconstructed) particles}}{\text{truth particles}} \,. \tag{3}$$

The particle is considered correctly reconstructed if the reconstructed particle can be linked to a truth particle.
In Fig. 7, the efficiencies for one sample can be seen and it can be observed that the efficiency is unusually low because muons are usually very well detectable. This also influences the efficiencies of the V_0 finder. Many muons might not be detectable because the Z_Ds do not decay within the tracker because the decay length is too long, especially for high $c\tau$ and low m_{Z_D}. A more detailed overview over the decay length is shown in Fig. 12.

5.3 Z_D Total Efficiency

For evaluating the performance of the V_0 finder, the overall efficiency of finding dark photons is evaluated. The efficiency here is defined as all the Z_Ds found by the V_0 finder divided by the total truth Z_Ds. For comparison, it has to be considered that not every particle can potentially be detected because of the direction of flight. If the

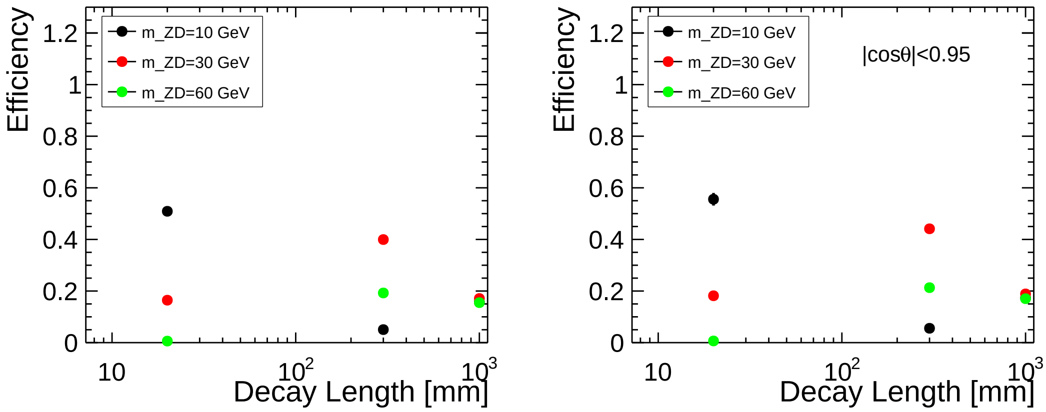


Figure 8: Total Z_D efficiency with and without cutting on $|\cos\theta|$.

particle has a $|\cos\theta|$ of 1, meaning it goes in beam direction, it cannot be detected as already described in Ch. 3.2, so a second efficiency where those particles were left out was calculated. In Fig. 8, the results can be seen and again, the efficiency is rather low and also the cut does not change a lot. To check, whether this is due to the low muon detection, all the possibly findable Z_D are investigated in the next step.

5.4 V_0 Efficiency

To check whether the low efficiency originates from the problem in the muon detection or is a problem of the V_0 finder, all the particles potentially findable by the V_0 finder were investigated. For this, it was checked how many truth muons have a track which passes all the cuts by the V_0 finder. As a new efficiency, the truth muons with tracks that pass all the cuts divided by the truth muons with tracks is defined and shown in Fig. 9. This V_0 efficiency is higher compared to the total Z_D efficiency.

5.5 V_0 Finder Efficiency

As a last thing to combine the two previous steps, the Z_Ds found by the V_0 were divided by the potentially by the V_0 finder findable particles to define the V_0 finder efficiency. This is displayed versus the Z_D momentum and $|\cos\theta|$ in Fig. 10. This efficiency is significantly higher which indicates that the V_0 itself is not the problem but rather the muons.

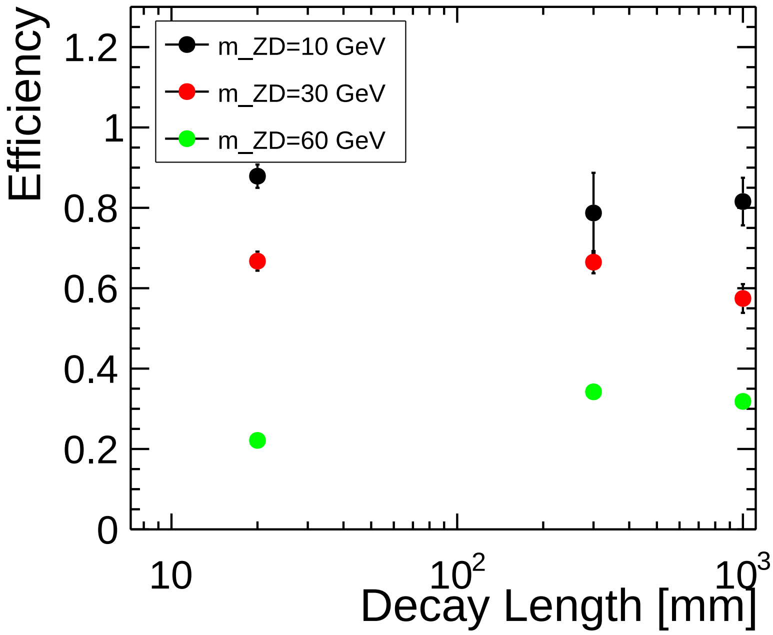


Figure 9: $V0$ efficiency.

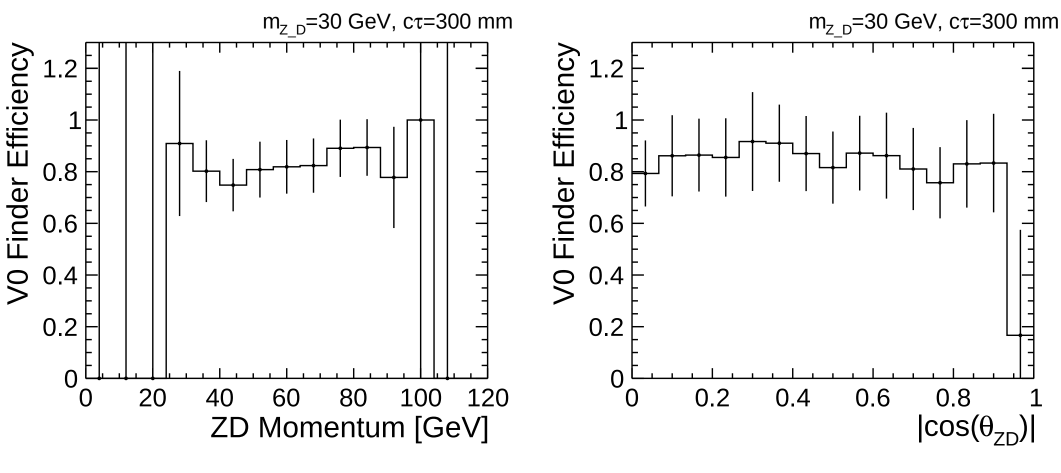
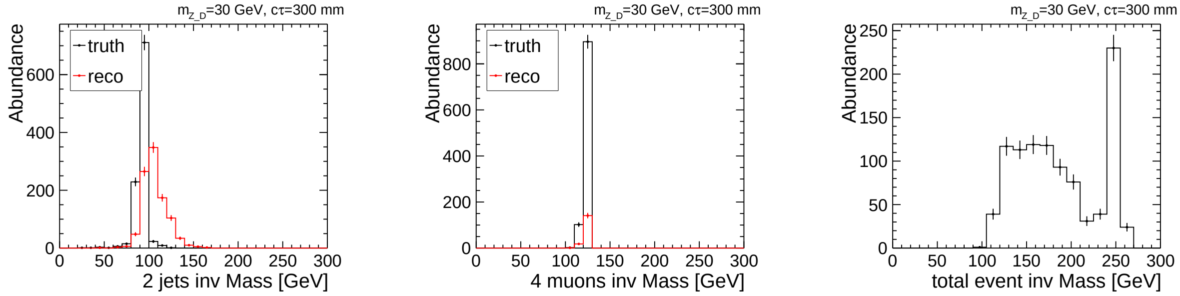


Figure 10: Efficiency of the V_0 finder versus the Z_D momentum and $|\cos\theta|$.



(a) Two jets total invariant mass.

(b) Four muons total invariant mass.

(c) Total event invariant mass.

Figure 11: Cross checks for one sample. The other plots are in the appendix.

5.6 Cross Checks

To validate that the right process with the right physics behaviour has been simulated, some cross checks are done. As one example, the invariant mass of the two jets has been plotted for the different parameter sets and it can be seen in Fig. 11a that it peaks at the Z mass but is a broader than the truth distribution. For the four muons invariant mass, the reconstructed distribution peaks exactly at the truth Higgs mass, but the statistics is lower due to the fact that both of the Z_Ds were not reconstructed very often, as can be seen in Fig. 11b. Another observable is the total event invariant mass which should equal the centre of mass energy of 250 GeV, but as seen in Fig. 11c, there are cases where the total event invariant mass is below that. This might be the influence of the missing muons which shows.

5.7 Background

To estimate a possible observation of the dark photon, the signal and background yields are investigated. For this, a luminosity of 2 ab^{-1} was assumed, a signal cross section of 85 ab and the highest total efficiency for the different masses was cosidered. The leading background processes consisting of 2f_ee_leptonic, 4f_ZZ_leptonic, 4f_WW_leptonic and 4f_singleZee_leptonic were analysed and the results of that are displayed in Fig. 1. For a dark photon mass of 10 GeV, there is background whereas for 30 GeV and 60 GeV there is none. Overall, the significance of 6 to 8 shows that the analysis is already sensitive to the dark photons.

m_{Z_D}	10 GeV	30 GeV	60 GeV
Cross Section [ab]	85	85	85
highest total eff	0.55	0.44	0.21
Signal	94	75	35
Background	130	0	0
Significance	6	8	6

Table 1: Signal and background yields for the analysis.

6 Conclusion

To summarise it all, the dark photon could be found with this approach! It can be seen that the V_0 finder clearly works for finding the dark photons. There still is a problem with the detection of the muons which might be due to the fact that the decay length of the dark photons is too long. In further analyses, this muon detection and identification is an important topic which needs to be further studied.

Moreover, more parameter points could be scanned to cover more possibilities for the dark photon and test the V_0 finder.

7 Acknowledgement

It was a very nice experience being part of the DESY summer school. Thanks to all the organisers but especially Olaf!

I also want to thank my supervisors Uli and Mikael for offering the project, supervising and helping me! I felt very welcome in the FTX group.

Most importantly, I want to thank the Ice Cream Van for providing me with ice cream on a daily basis. To fulfil my promise, here is the official ranking of the ice cream flavours:

1. Haselnut
2. Greek Joghurt
3. Chocolate
4. Mango
5. Strawberry
6. Straciatella
7. Vanilla
8. Snickers
9. Waldmeister
10. Egg nog
11. Bubblegum
12. Lemon
13. Kinderriegel

8 Appendix

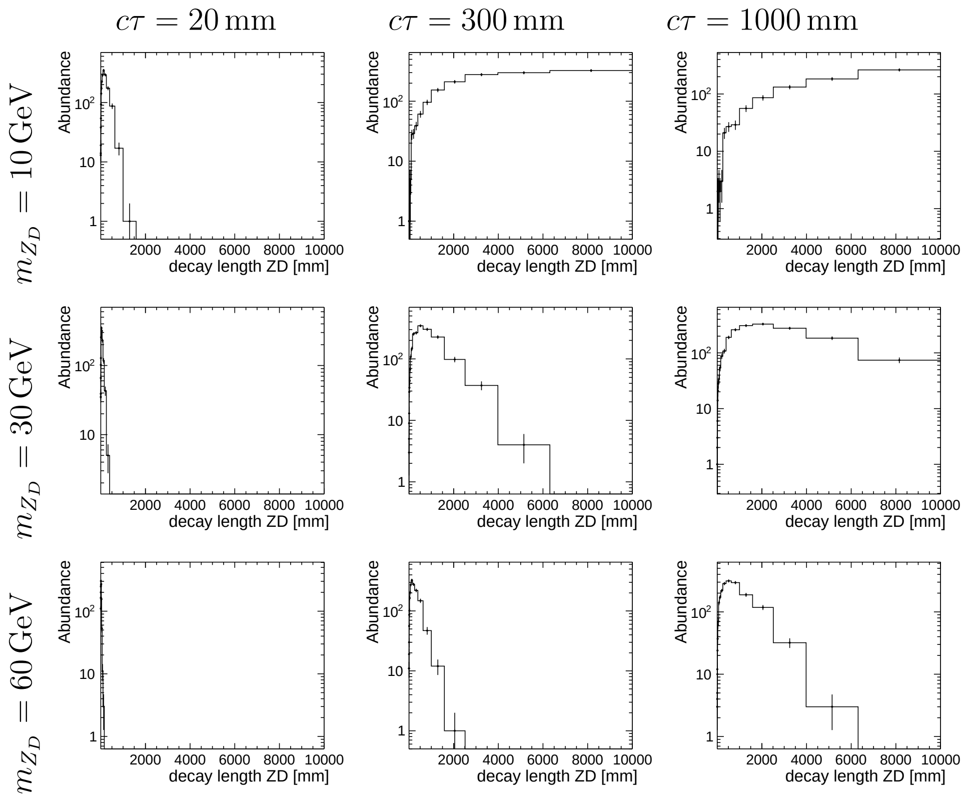


Figure 12: Z_D decay length.

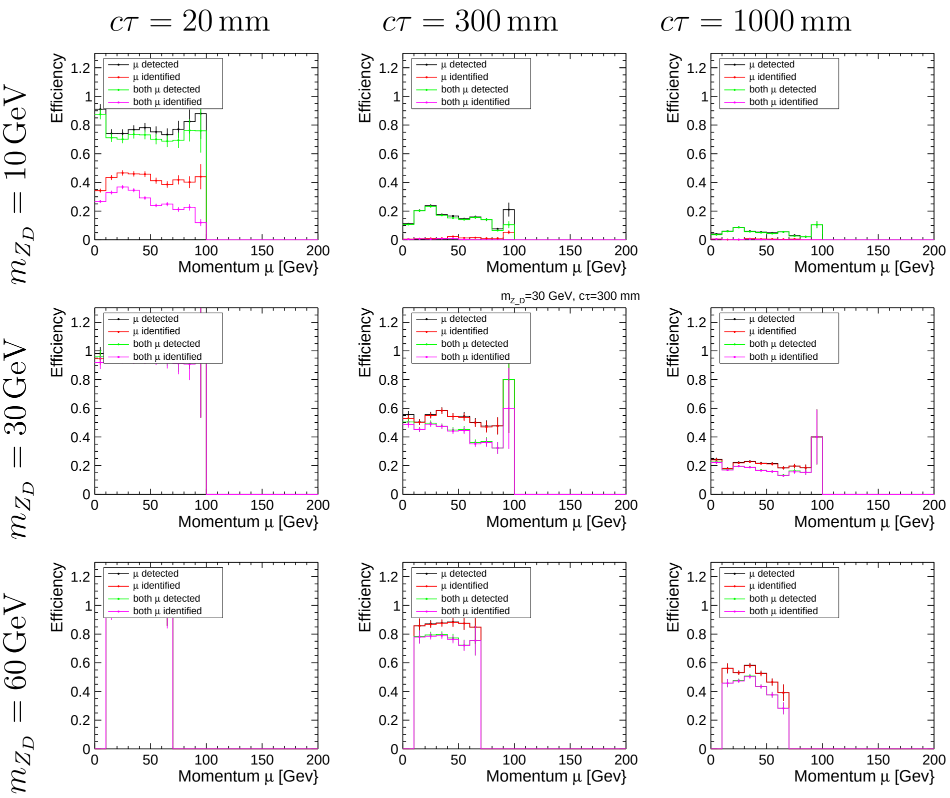


Figure 13: Muon efficiency.

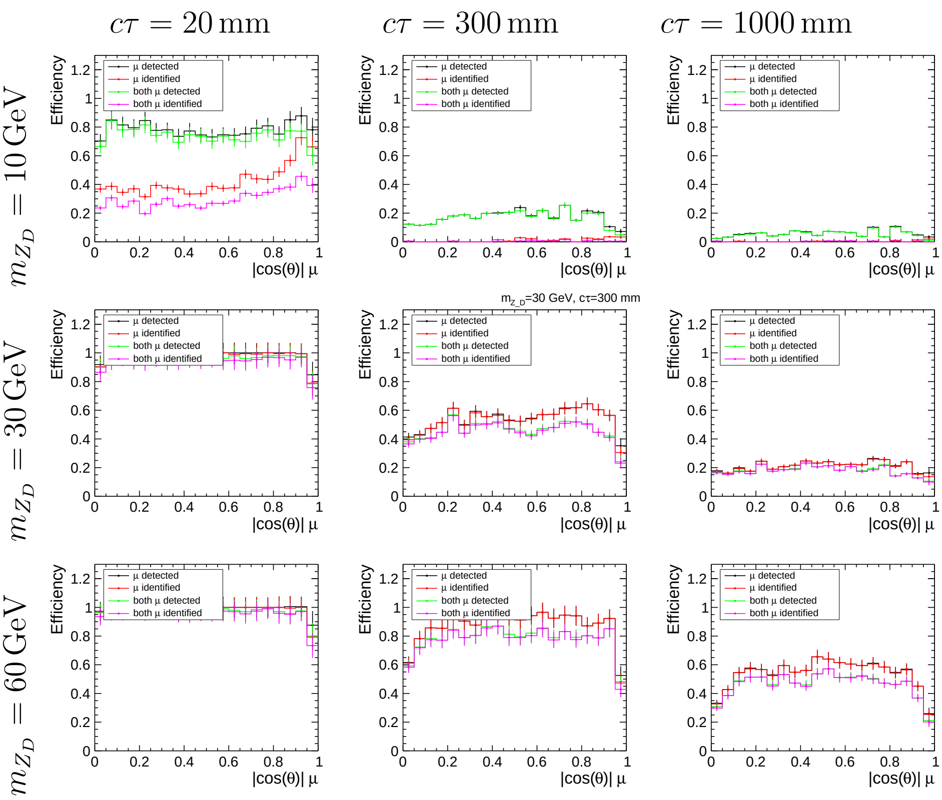


Figure 14: Muon efficiency.

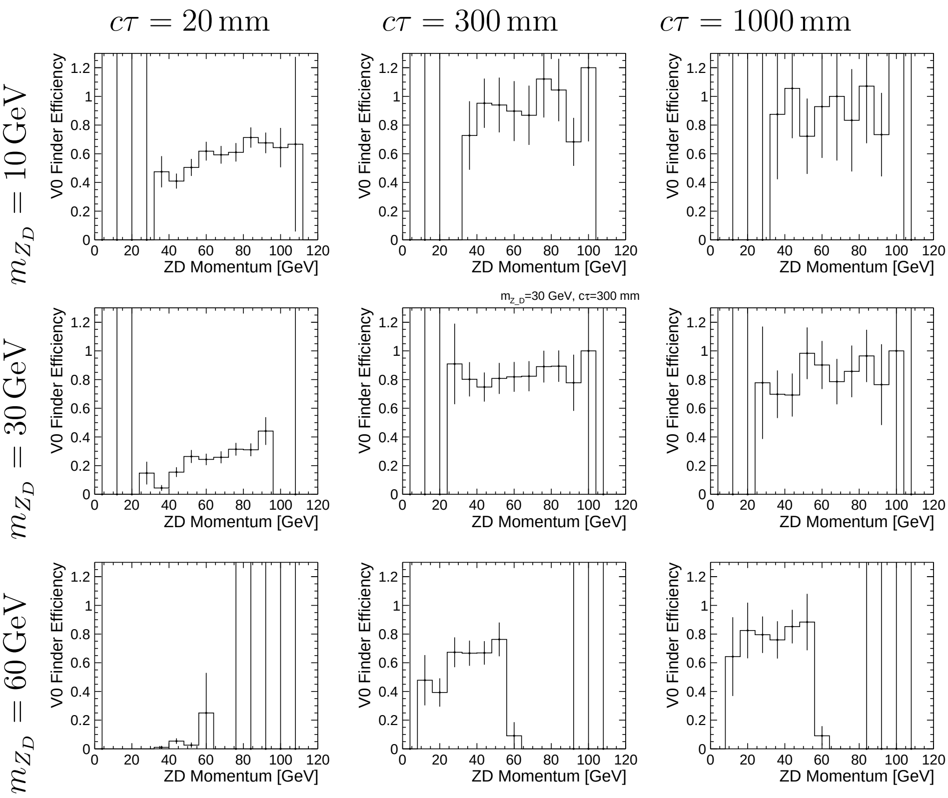


Figure 15: V_0 finder efficiency.

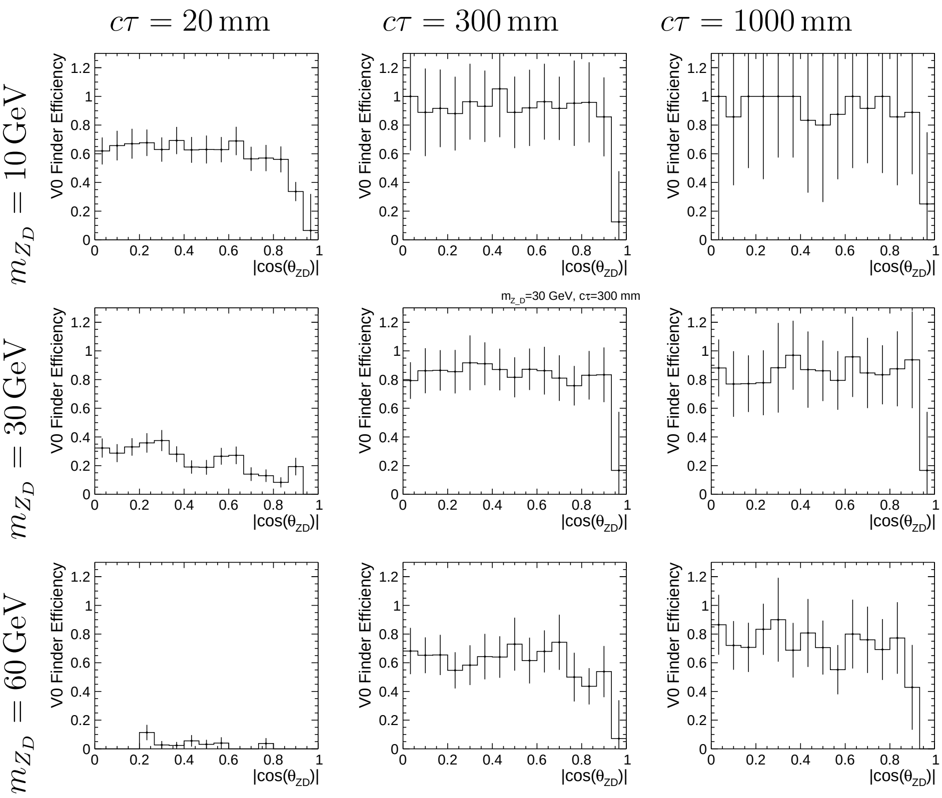


Figure 16: V_0 finder efficiency.

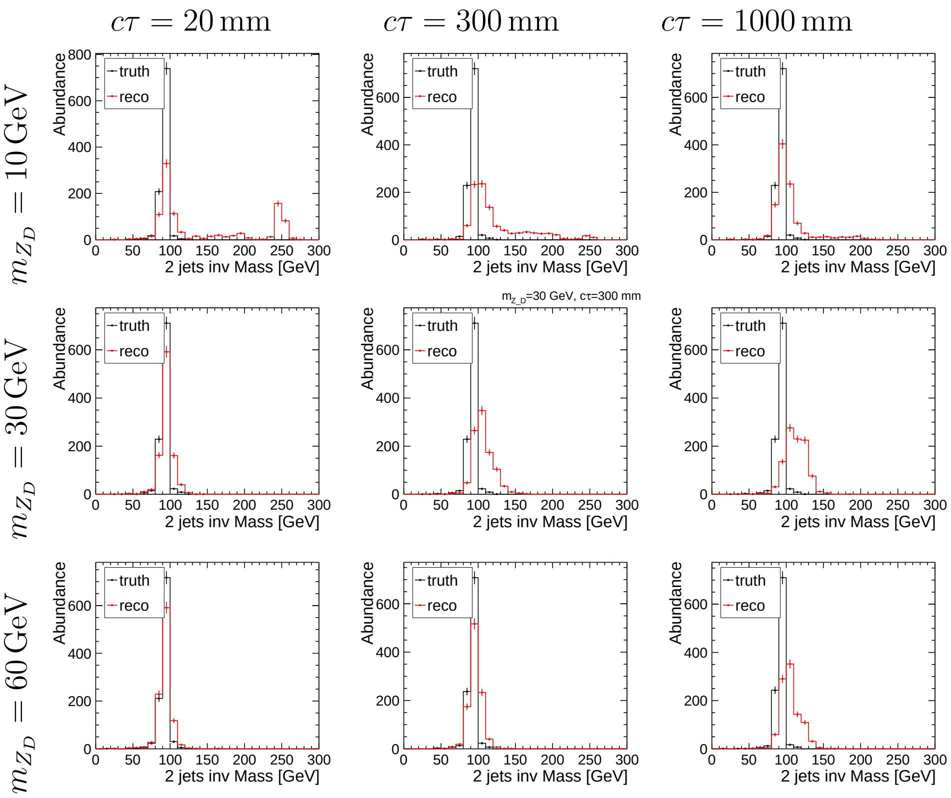


Figure 17: 2 jets invariant mass.

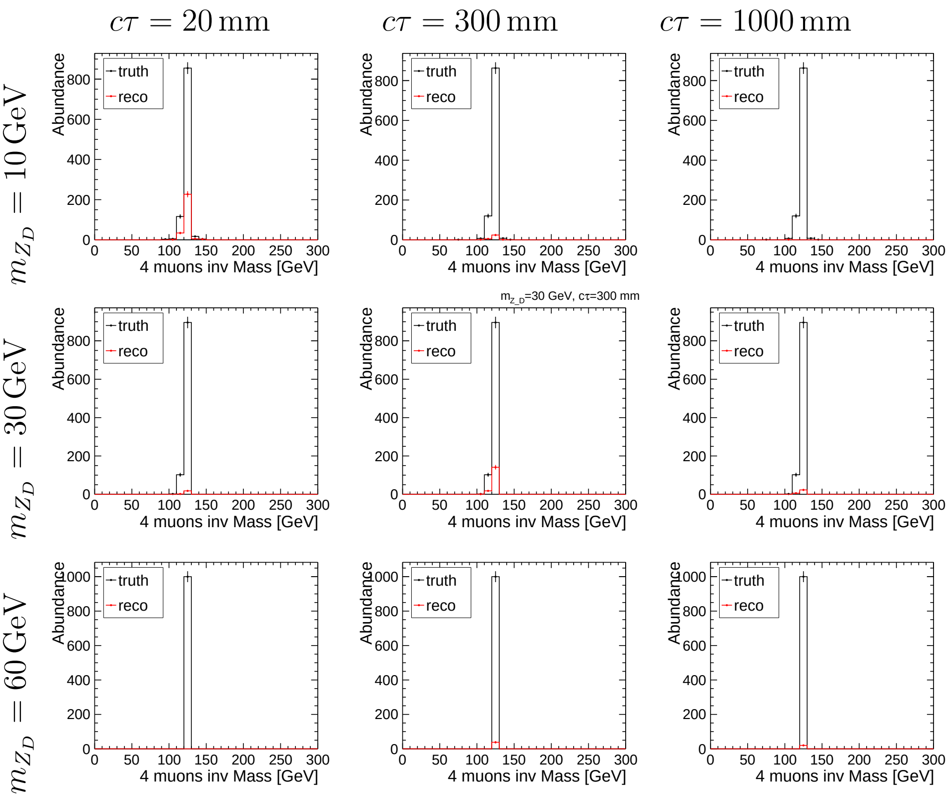


Figure 18: 4 muons invariant mass.

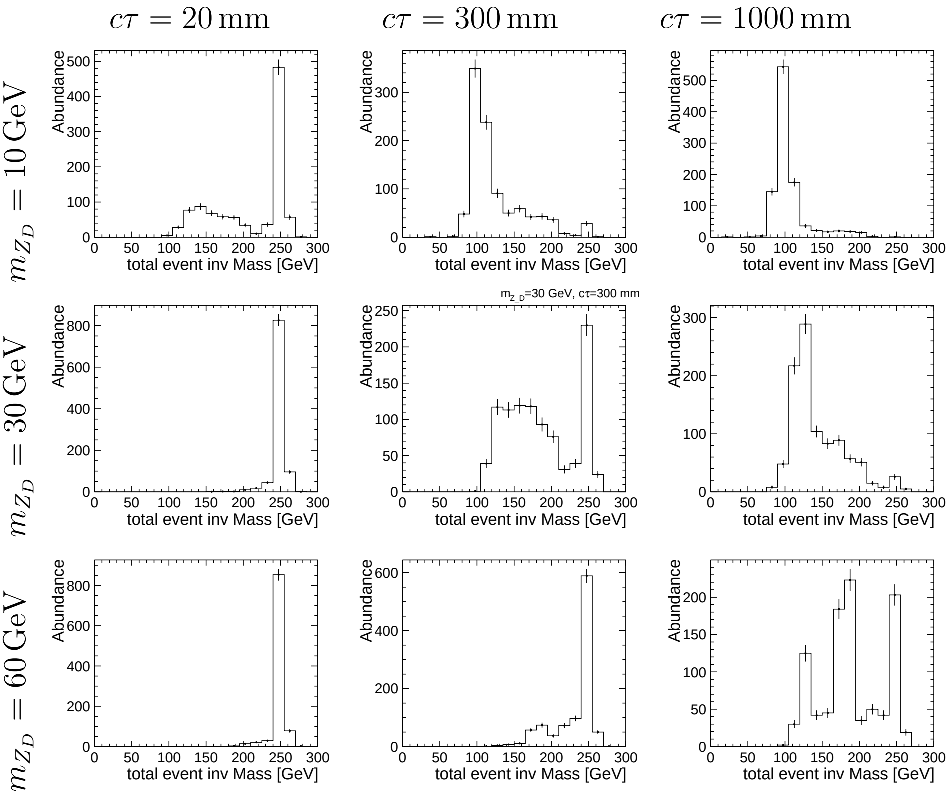


Figure 19: Total event invariant mass.

References

[1] Illuminating Dark Photons with High-Energy Colliders *David Curtis et al.* **JHEP**, 2014.

[2] International Large Detector: Interim Design Report *The ILC Collaboration*, 2020.