UNIVERSIDAD SAN FRANCISCO DE QUITO USFQ

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Feasibility study for the measurement of acausal particles with wrong displaced vertices at the LHC

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RESUMEN

En Física de Partículas, se han propuesto varias extensiones al Mínimo Modelo Estándar para resolver el problema de la jerarquía. Muchas de estas teorías suponen la existencia de nuevas partículas que podrían ser detectadas en el LHC en su corrida 2 a $\sqrt{s}$ =13 TeV. Una de ellas es el Modelo Estándar de Lee Wick, el cual busca estabilizar la masa del Higgs contra términos divergentes al introducir la presencia de partículas acausales en la escala microscópica. Se propone la definición de un nuevo parámetro llamado pseudo parámetro de impacto, el cual será utilizado para la detección de estas partículas acausales hipotéticas en el LHC. Para esto, se realizan simulaciones de Monte-Carlo para los estados finales con partículas acausales y sus procesos de fondo para una luminosidad integrada de 100 fb^{-1}. Se estudia la masa invariante para los dos jets más fuertes de cada evento aplicando cortes estándar de análisis de datos previos en Física de Partícula, e implementando un nuevo corte desarrollado para partículas acausales, utilizando el pseudo parámetro de impacto.

Palabras clave: Modelo Estándar, problema de la jerarquía, Modelo Estándar de Lee Wick, partícula acausal, masa invariante, pseudo parámetro de impacto.

ABSTRACT

In Particle Physics, many extensions to the Minimal Standard Model have been proposed trying to solve the hierarchy problem. Most of those theories imply the existence of new particles that could be detected in the LHC Run 2 at $\sqrt{s}$ =13 TeV. One of them is the Lee Wick Standard Model, which aims to stabilize the Higgs mass against divergent terms by introducing the presence of acausal particles at the microscopic scale. We propose the definition of a new parameter called the pseudo impact parameter, which will be used for the detection of these hypothetical acausal particles at the LHC. For this, Monte-Carlo simulations of final states with acausal particles and its causal backgrounds are performed for an integrated luminosity of 100 fb^{-1}. We study the invariant mass for the two hardest jets of each event applying standard cuts from previous data analysis in Particle Physics, and implement a new cut developed for acuasal particles, using the pseudo impact parameter.

Key words: Standard Model, hierarchy problem, Lee Wick Standard Model, acausal particle, invariant mass, pseudo impact parameter.

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A los físicos que han trabajado en el desarrollo de la teoría del Modelo Estándar de Lee Wick, en especial a T.D. Lee y G.C. Wick, ya que sin sus ideas y aportes, este proyecto no hubiese podido ser realizado.

Contents

1 Introduction

The Standard Model (SM) describes the fundamental particles and their interactions governed by the four fundamental forces. Even though the SM has had great phenomenological success, it still cannot solve the hierarchy problem. Due to the hierarchy problem, many extensions to the minimal SM have been proposed. For instance: supersymmetry, extra-dimensions, little Higgs, etc. However, until now, the LHC has not been able to find evidence of the validity of any of those theories.

Among the extensions to the minimal Standard Model that have been proposed, there is a theory that was developed by Lee and Wick in the 70's [1] [2]. One of the facts that gives rise to the hierarchy problem is the extreme fine-tuning that the Higgs mass requires in order to be kept small compared to the Planck scale. Therefore, the Lee Wick (LW) theory proposes a modification to the SM which stabilizes the Higgs mass against quadratically divergent radiative corrections[1].

As a consequence of the modification made by Lee and Wick, acausal particles appear in the theory, each of these particles is a partner of the fundamental particles in the minimal SM, and share all the SM particles properties except their mass. The mass of the LW particles is greater than the mass of the SM particles so that the LW particles will decay fast enough to make the acausality effect happen in a very small time scale, not affecting the macroscopic causality property. In [4] it is suggested that the range of the LW particles mass should be $M_l \leq 450$ GeV so that the acausal vertex displacements can be detected in the LCH era.

In order to prove the existence of these LW particles, it is necessary to determine a way to detect them. Since the acausal effect takes place in a microscopic scale, it might be possible to propose an observable that shows a different behaviour for SM particles and LW particles as a result of the microscopic violation of causality, such as the transversal momentum, the invariant mass or the impact parameter. For this,

[1]This model suffers from unsettled issues such as quantum instability of the vacuum due to gravitational interaction. However, it still attracts a lot of attention in the literature for several phenomenological reasons[3].

a simulation is developed to show how the LW particles would be seen in the Large Hadron Collider (LHC) in the Compact Muon Solenoid (CMS) detector. The LW signal obtained is compared to three different backgrounds. The invariant mass for the simulated processes is analysed, and a new variable is defined, the pseudo impact parameter, which will be a tool to determine a cut to identify acausal particles.

2 The Standard Model and its limitations

The SM describes the fundamental particles that matter is made of, and how they interact. The main pillars of matter are fermions, and the force carriers are bosons. The difference between fermions and bosons is their spins; fermions carry half-integer spins, and bosons carry integer spins. Fermions are divided into two families, leptons and quarks, each of which have 6 members with spin $\frac{1}{2}$ (see Figure 1).

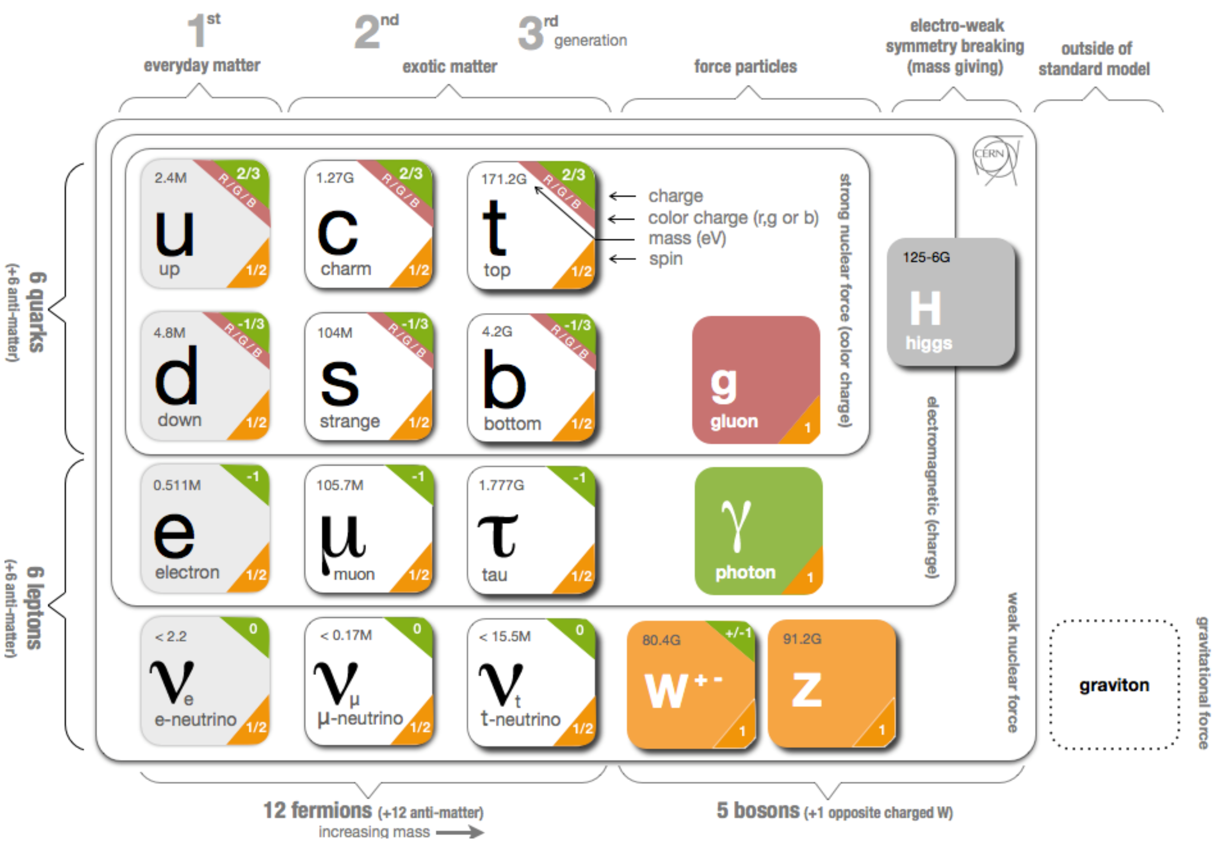


Figure 1: The fundamental particles in the Standard Model [5].

These building blocks of matter interact with each other through the four fundamental forces. Each force has one or more carriers:

Table 1: Fundamental forces in nature known so far.

Force	Strength	Theory	Mediator
Strong	10	Chromodynamics	Gluon
Electromagnetic	10^{-2}	Electrodynamics	Photon
Weak	10^{-13}	Flavordynamics	W and Z bosons
Gravitational	10^{-42}	Geometrodynamics	Graviton

The SM is simple and powerful. There are complex mathematical expressions that corroborate the validity of this model and allow theorists to make predictions with great precision. Over the past five decades, thanks to development of new technology, almost every theoretically predicted quantity has been successfully measured in particle physics laboratories. However, the model have some limitations at higher energies. One of the major problems that the SM faces is that it does not include gravity, which is one of the four fundamental forces. Also, the SM cannot explain why gravity is much weaker than the other 3 fundamental forces. Another problem is the wide range in mass for the elementary particles, e.g., the electron is about 200 times lighter than the muon and 3500 times lighter than the tau. The same thing happens for quarks. So, how is it possible to have such a wide spectrum of masses among the building blocks of matter? Many theorists believe this is unnatural.

Furthermore, the equations of the SM establish relations between the fundamental particles. For instance, the Higgs boson has a basic mass to which theorists add a correction for each particle that interact with it, as a result, the heavier the particle, the larger the correction. Therefore, theorists wonder how the measured Higgs boson mass can be as small as it was found. In order to solve this riddle, theorists predict that there might be other yet undiscovered particles that can change this picture, so that the corrections made to the Higgs mass can be cancelled out by some other hypothetical particle and lead to the low Higgs boson mass that has been measured.

Moreover, the SM only describes visible matter, which is a very small part of what the Universe is made of. There is ample evidence showing that the Universe is mostly made of dark energy and dark matter. Dark matter is completely different from the ordinary matter that the SM model describes, so the SM cannot give a complete picture of what the Universe is made of. Many of these limitations give rise to the already-mentioned hierarchy problem, which has inspired the proposal of new theories in Physics Beyond the Standard Model such as: Supersymmetry, Little Higgs, Lee Wick Standard Model, etc.

3 Lee-Wick Toy Model in QED

Lee and Wick basically studied the possibility that a propagator[2] corresponds to a physical degree of freedom[3]. In order to briefly illustrate how the Lee-Wick (LW) theory works, a toy model for a finite theory of Quantum Electrodynamics can be described considering a one self-interacting scalar field $\widehat{\Phi}$ with a higher derivative term [6], so that its Lagrangian density is[4]:

$$\mathcal{L}_{hd} = \frac{1}{2}\partial_\mu \widehat{\Phi}\partial^\mu \widehat{\Phi} - \frac{1}{2M^2}(\partial^2 \widehat{\Phi})^2 - \frac{1}{2}m^2 \widehat{\Phi}^2 - \frac{1}{3!}g\widehat{\Phi}^3 \; , \tag{1}$$

the propagator of $\widehat{\Phi}$ is:

$$\widehat{D}(p) = \frac{i}{p^2 - p^4/M^2 - m^2} \; . \tag{2}$$

The higher derivative propagator has two poles, one corresponding to the massless photon, and the other corresponding to a massive LW-photon. For $M \gg m$, this propagator has poles at $p^2 \simeq m^2$ and also at $p^2 \simeq M^2$, hence the propagator describes more than one degree of freedom. In order to make these new degrees of freedom

[2] A propagator gives the amplitude for a particle to travel between two spacetime points.

[3] In the LWSM, every field in the minimal SM has a higher derivative kinetic term that introduces a corresponding massive LW resonance, which are additional free parameters in the theory and must be high enough to evade current experimental constraints

[4] In equation 1, m is the mass of a photon in QED, M is the mass of a LW-photon, and p is the four-vector momentum of the propagator. The Lagrangian density shown in equation 1 can be explained as: the first term is the kinetic term; the second term shows the interaction of the particle with itself; the third term is the potential term; and the fourth is also and interaction term, which shows that a particle comes in and two particles go out.

evident in the theory, an auxiliary scalar field[5] $\tilde{\Phi}$ is introduced, so that the theory is:

$$\mathcal{L} = \frac{1}{2}\partial_\mu \widehat{\Phi}\partial^\mu \widehat{\Phi} - \frac{1}{2}m^2\widehat{\Phi}^2 - \tilde{\Phi}\partial^2\widehat{\Phi} + \frac{1}{2}M^2\tilde{\Phi}^2 - \frac{1}{3!}g\widehat{\Phi}^3 \; . \tag{3}$$

Computing the equation of motion of $\tilde{\Phi}$, one gets:

$$\frac{\partial \mathcal{L}}{\partial \tilde{\Phi}} \; - \; \partial_\mu \, \frac{\partial \mathcal{L}}{\partial(\partial_\mu \tilde{\Phi})} \; = \; 0$$

$$\frac{\partial \mathcal{L}}{\partial \tilde{\Phi}} \; = \; -\partial^2\widehat{\Phi} \; + \; M^2\tilde{\Phi}$$

$$\frac{\partial \mathcal{L}}{\partial(\partial_\mu \tilde{\Phi})} \; = \; 0$$

$$\Rightarrow \;\; -\partial^2\widehat{\Phi} \; + \; M^2\tilde{\Phi} \; = \; 0$$

$$\tilde{\Phi} \; = \; \frac{\partial^2\widehat{\Phi}}{M^2} \; ,$$

so by replacing $\tilde{\Phi}$ in equation 3, $\mathcal{L}_{hd}$ is obtained.

By defining $\Phi = \widehat{\Phi} + \tilde{\Phi}$, there are two fields, a normal scalar field Φ which corresponds to our SM toy theory, and a new field $\tilde{\Phi}$, which will be the LW field. As a result, the Lagrangian is:

$$\mathcal{L} = \frac{1}{2}\partial_\mu \Phi \partial^\mu \Phi - \frac{1}{2}\partial_\mu \tilde{\Phi}\partial^\mu \tilde{\Phi} + \frac{1}{2}M^2\tilde{\Phi}^2 - \frac{1}{2}m^2(\Phi - \tilde{\Phi})^2 - \frac{1}{3!}g(\Phi - \tilde{\Phi})^3 \tag{4}$$

For simplicity, the mass m is neglected[6], so that the propagator of $\tilde{\Phi}$ is given by:

$$\tilde{D}(p) = \frac{-i}{p^2 - M^2} \; . \tag{5}$$

[5] The auxiliary LW fields will reproduce the higher derivative terms when integrated out[6].

[6] In the LWSM, the mass M of LW particles must be heavier than the mass m of SM particles, so $m \ll M$.

The LW field is associated with a nonpositive definite norm on the Hilbert space, as seen in $\tilde{D}(p)$. Hence, if this state were to be stable, unitarity of the S matrix [7] would be violated. However, with a further analysis and by modifying the usual integration contour in Feynman calculus as was proposed by Lee and Wick, it can be seen that the width of the LW field differs in sign from the widths of usual particles, and as a consequence, the unitarity of the theory is maintained. Thus the unusual sign of the propagator is compensated by the unusual sign of the decay width [6].

This LW prescription is equivalent to imposing the boundary condition that there are no outgoing exponentially growing modes. Therefore, these conditions cause violations of causality. As it was previously mentioned, it is believed that the acausal effects in the LW theory occur only on microscopic scales, and show up as a peculiar time ordering of events [6], i.e., the decay products of a LW particle appear at times before the LW particle itself is created; this means that a wrong vertex displacement is obtained.

After a proton-proton collision, as part of the products of the collision, there are long-lived particles, which will decay after travelling a certain distance. The proton-proton interaction point in space is known as the primary vertex (PV), and the point in space where the long-lived particles decay, is the secondary vertex (SV). A wrong vertex displacement is a vertex displacement in which the decay products coming from the secondary vertex have a total momentum that points from the secondary to the primary vertex [4]. On the other hand, in the case of the usual causal effect, i.e., SM particles, for long-lived particles, the vertex displacement shows a behaviour where the total momentum points from the secondary vertex but away from the primary vertex. Additionally, short-lived causal particles have their decay products momentum coming from the primary vertex.

[7] The S matrix is defined as the matrix element of the transition from one asymptotic set of states to another. By taking the square of the S matrix, we can calculate the transition probabilities.

4 The LHC and the CMS Detector

The Large Hadron Collider (LHC) at CERN is the largest and the most energetic hadron accelerator in the world. It lies at about 175 m underground in a tunnel with a ring of superconducting magnets of 27 km in circumference, located beneath the France-Switzerland border near Geneva, Switzerland. The collider tunnel contains two adjacent parallel beam pipes that intersect at four points, each containing a beam, which travel in opposite directions around the ring. In these intersection points, seven detectors have been constructed. The main experiments at LHC are ATLAS, CMS, ALICE and LHCb [7]. For our purpose we work with simulations of events in the CMS detector.

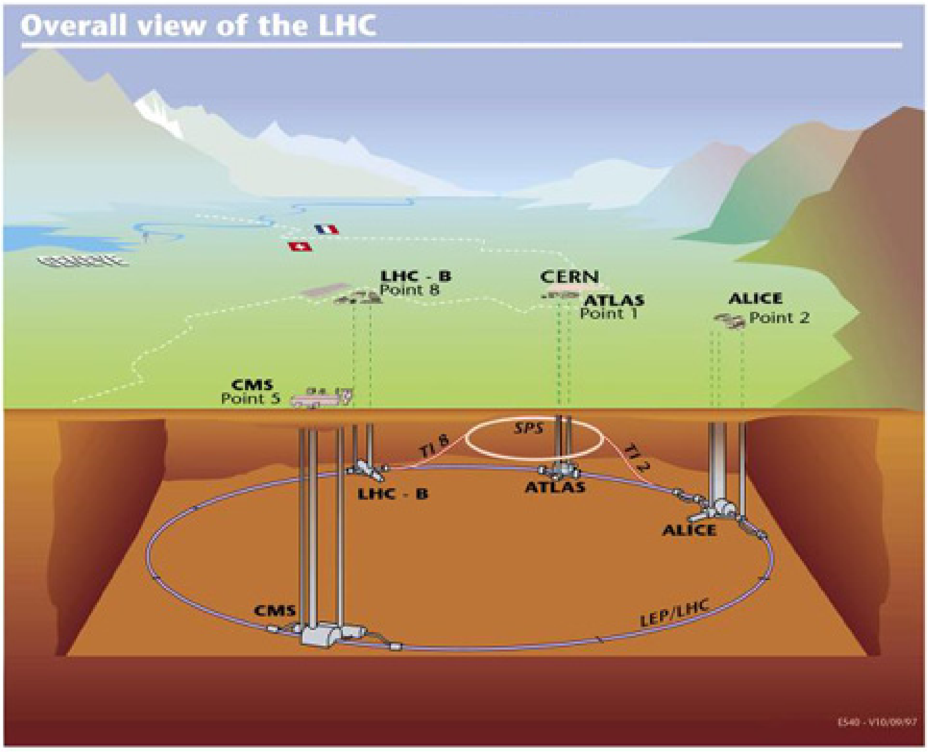


Figure 2: Overview of the LHC[8].

The LHC smashes groups of protons together at a speed close to the speed of light with an energy of 13TeV (6.5 TeV per beam)[8]. Part of the collision energy will be turned into mass, which can decay into lower mass states with momentum, so that short-lived particles fly out and into the detector. These short-lived particles might

[8]The energy of collisions in the Run 2 of LHC in 2015 is ∼13 TeV, higher than 8 TeV in 2012.

be previously undetected particles, and thus new particles could be observed in the Compact Muon Solenoid (CMS) particle detector. The new particles that are detected could give clues about how nature behaves at fundamental level and, as a result, many theoretical predictions can be confirmed.

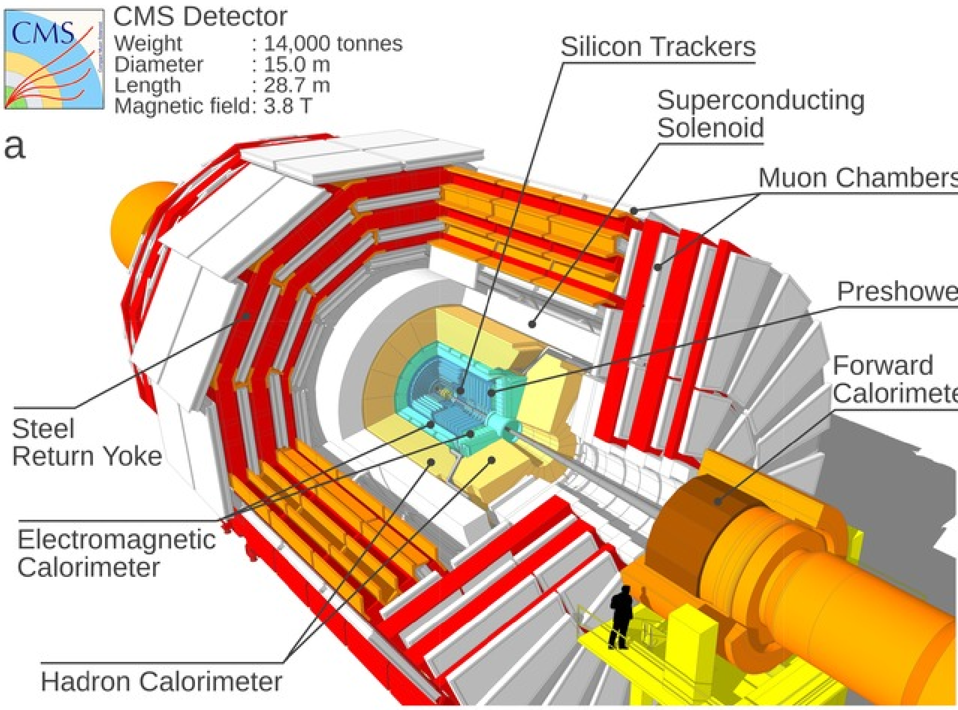


Figure 3: General design of the CMS detector [9].

The CMS detector is a particle detector that aims to see a wide range of particles and phenomena produced in high-energy collisions in the LHC. It is designed like a cylindrical onion that is built around a huge solenoid magnet (Figure 3). The detector has different layers of material that exploit most of the properties of the interactions of particles with matter to catch, and measure the energy and momentum of each one[9]. CMS uses this fact as a tool to build up a picture of events at the heart of the collision.

In experimental Particle Physics, due to the geometry of the detectors, spherical coordinates are used. In the case of the CMS detector, see Figure 4, the direction of the beams of protons is taken as the z-axis ($\theta = 0°$). Perpendicular to this, are the x axis (which points to the center of the accelerator) and the y axis points upwards. The

[9]For a more detailed explanation of the CMS detector design, see [10].

azimuthal angle, ϕ, lies in the transverse plane xy. The polar angle θ is replaced by a quantity known as the pseudorapidity, η, which is defined as:

$$\eta = -\ln\left(\tan\frac{\theta}{2}\right).$$

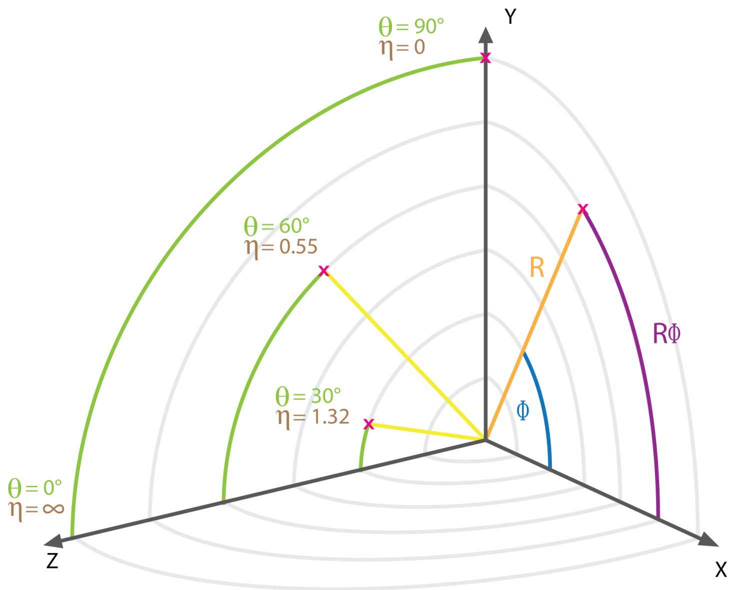


Figure 4: Coordinate system used in the CMS detector [11]. The $z-$axis is the direction of the beams.

Our analysis is based on the characteristics of the LHC in the Run 2. In the Run 2, the LHC collides protons at $\sqrt{s} = 13 \sim 14$ TeV [10], with an instantaneous luminosity $L \sim 1 \cdot 10^{34}$ cm^{-2}s^{-1}, and bunch spacing of mostly 25 ns, so that the integrated luminosity $\int L\, dt$ is at $\sim$75$-$100 fb^{-1}[12].

5 Events generation and selection

For the LW and background events generation, hadronization and detection simulations, MadGraph [13], Pythia 6.420 [14] and Delphes 3.2.0 [15] are used respectively. For the LW and background events simulation, the run card of MadGraph is modified so that only events with $|\eta| < 2.4$ are generated[11]. This condition is set in order to

[10] s is a Mandelstam variable that encodes the energy, momentum, and angles of particles in a scattering process and is generally used in Particle Physics since it is Lorentz-invariant.

[11] As seen in section 4, due to the design of the CMS detector, particles coming as products of proton-proton collisions will be localized mainly at the center of the detector, i.e., the particles with

ensure that the reconstructed jets come from hard collisions in CMS.

For the hadronization process held in Pythia, no modifications are made to the default run card. Furthermore, effects like pile-up are not considered. The interaction of decay products with the material in the CMS detector (Run 2) is simulated in Delphes. In MadGraph, the default run card works with the CMS detector parameters for Delphes, and no special conditions are needed for the hadronization process in Pythia. Hence, Delphes and Pythia are run along with MadGraph instead of standalone, so that the events[12] are generated for each process with LHC collisions at 13 TeV.

5.1 Lee Wick Events Generation

At first, the process that was intended to be generated is[13]:

$$q\overline{q} \to A, Z, \tilde{B}, \tilde{W}^3 \to \overline{\tilde{l}^e_e}\tilde{l}^e_e \ ,$$

where, in turn,

$$\overline{\tilde{l}^e_e}\tilde{l}^e_e \to Ze^+Ze^- \to e^+e^-jjjj \ . \tag{6}$$

However, this process requires to create a new model in MadGraph.

A model for the LWSM in MadGraph was created in [4]. In this model, the mass term is changed in the range of $M_l \leq 450$ GeV. Nevertheless, the events generated with this model only show the LW particles invariant mass[14] resonance and not the acausal behaviour of the LW particles. Additionally, in [4], the simulations made did not include the whole simulation chain, i.e., no simulations at the detector level were made. Thus, it is not be possible to use this model for simulations and to compare

harder transverse momentum will be located at $\sim |\eta| < 2.4$. Particles out of that area are neglected from the analysis since they could be part of pile-up events.

[12] The normalized events in each process depend on the cross section obtained with MadGraph for each process.

[13] Where q is a quark and $\overline{q}$ is an antiquark; A, Z, $\tilde{B}$, $\tilde{W}^3$ are gauge bosons; and $\tilde{l}^e_e$ and $\overline{\tilde{l}^e_e}$ are LW leptons and antileptons respectively.

[14] See section 6.2.

them with real data obtained from CMS.

Since the only parameter that changes in the LW partners of each SM particle is the mass, an analogue process to the one shown above was simulated:

$$q\bar{q} \to Z\,Z \to jjjj\;. \tag{7}$$

If the electron and positron from equation (6) were included as part of the decay products in our process in equation (7), they will enhance the available handles for detection, i.e., the process in equation (7) is harder to analyse than the one in equation (6) would be.

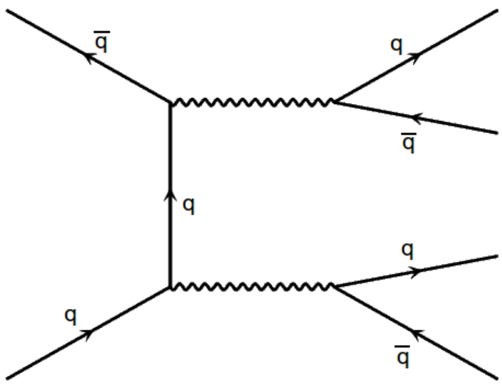
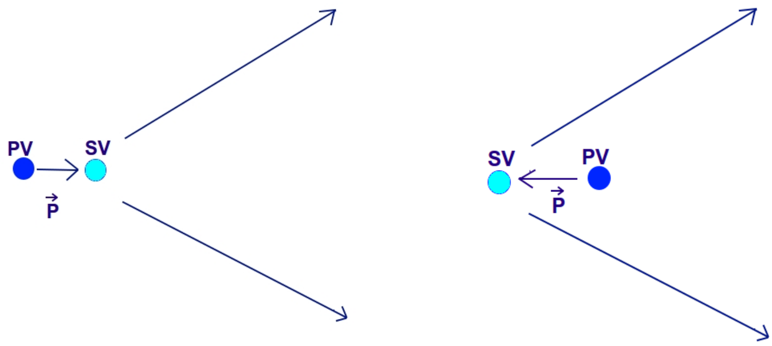


Figure 5: Feynman diagram for a LW process with LW-leptons simulated in MadGraph. The process generated was the one shown in equation (7) but with a mass of 300 GeV.

The process shown in equation (7), Figure 5, is chosen since it is similar to the process we are intending to simulate in equation (6). In the LWSM theory, the LW particles decay into SM particles so fast that it is not possible to observe them, but their effects could be detected in the CMS detector. As a result, simulating a SM process with heavier gauge bosons, 300 GeV, that decay into 4 jets, would give us LW events as long as the vertex displacement and momentum is also modified to reproduce the acausal effect.

Hence, for the generated events, the original primary vertices were modified to create the acausal behaviour that LWSM requires. Figures 6(a) and 6(b) show how a SM particle will differ from a LW particle. In the SM theory, a long-lived particle will come from its primary vertex, and in its secondary vertex it will decay, so that its secondary



(a) (b)

Figure 6: Vertex displacements and total momentum for causal and acausal particles. Primary (PV) and secondary (SV) vertices are shown for a (a) SM particle and a (b) LW particle.

vertex and the center of mass of its products have a total momentum with the same direction as the total momentum of the particle in its primary vertex. On the other hand, a LW particle will have a secondary vertex and its products with a center of mass total momentum in opposite direction to the total momentum of the particle in its primary vertex.

For the process shown in equation (7), 20000 events[15] with an energy of 13TeV were generated. In order to obtain a better approximation for the LW process, the Z boson mass was modified in the parameters card of MadGraph, so that the new mass is 300 GeV with a total cross section[16] of 66.7 fb [4].

Figure 7 shows a 3D view of a SM event in the CMS detector generated in MadGraph with equation (7), and Figures 8 and 9 show a ϕ- and longitudinal-view, respectively, of the same SM event in the detector before the modification to have a wrong vertex displacement is made. To get both plots, the Event Display option of Delphes was used, which is an Event Visualization Environment of the ROOT[16] package. In Figure 7, it is seen that the number of jets obtained, depicted by the yellow cones, is greater

[15]The LW events generated had a total cross section of 66.7 fb, and the integrated luminosity that we will work with is 100 fb^{-1}. As a result, 20000 were generated in order to have a significant normalised signal to work with compared to the others, as it will be seen in the Events Analysis section.

[16]In [4], three LW-leptons are analysed, with 3 different masses: 300, 400 and 500 GeV. The LW-leptons that were chosen for the present analysis are the ones with mass of 300 GeV because their total cross section is the largest among those three cases.

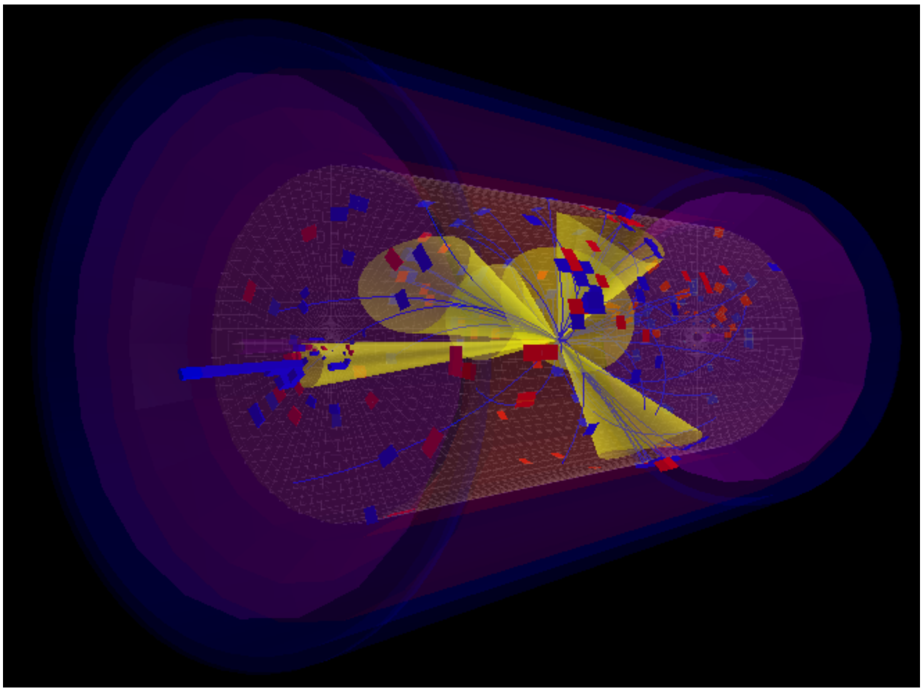


Figure 7: 3D view of an acausal event in the parametrized CMS detector for the LW process in equation (7) without modifications to get the acausal behaviour. The yellow cones represent the reconstructed jets, the blue lines are the particles tracks, and the blue and red rectangles are deposits of energy in the calorimeters.

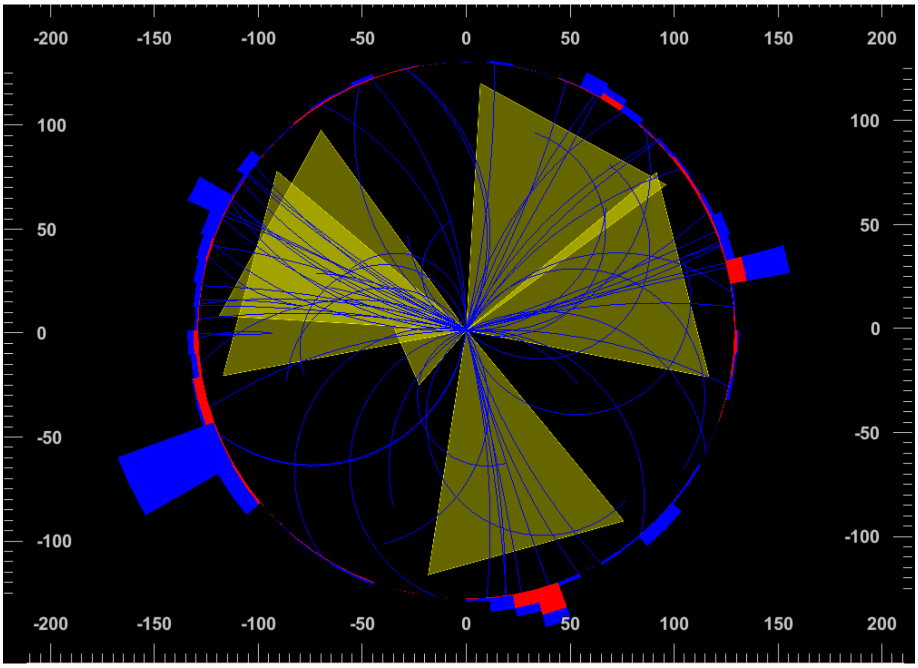


Figure 8: $\phi-$view of an acausal event in the parametrized CMS detector for the LW process in equation (7) without modifications to get the acausal behaviour. The yellow triangles represent the reconstructed jets, the blue lines are the particles tracks, and the blue and red rectangles are deposits of energy in the calorimeters.

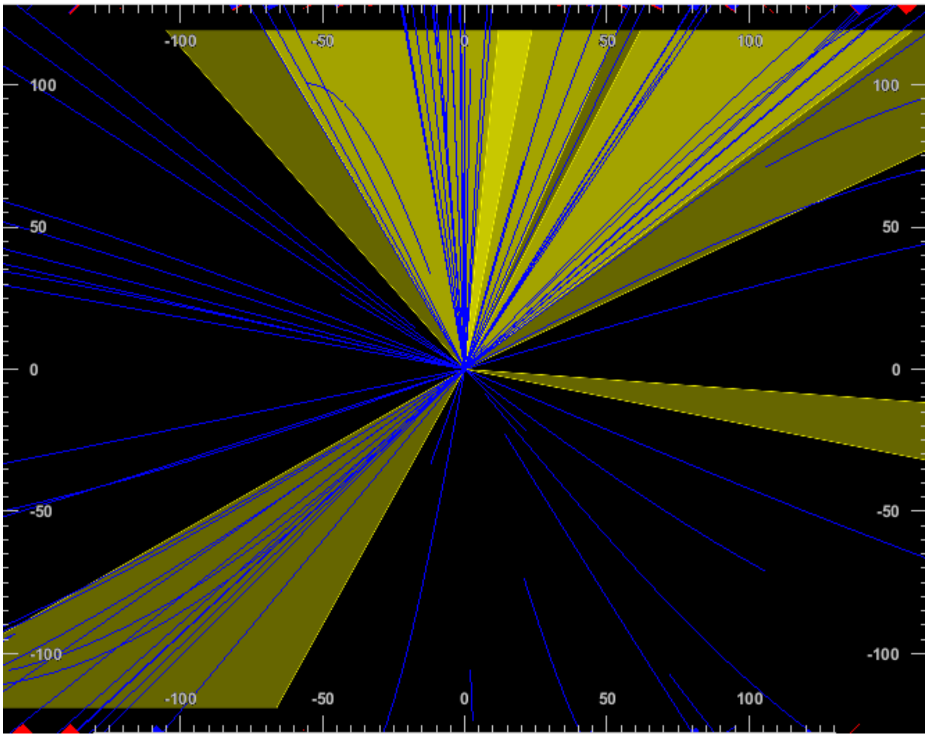


Figure 9: Longitudinal view of an acausal event in the parametrized CMS detector for the LW process in equation (7) without modifications to get the acausal behaviour.The yellow triangles represent the reconstructed jets and the blue lines are the particles tracks.

than the one that was initially generated with the run card at MadGraph. Also, in Figures 7 and 8, one notices that there are 4 jets that form two pairs since they are not too spatially apart from each other, and that the other 2 jets do not seem to be spatially connected to each other or to the other jets. As a result, it can be said that those 2 jets might have been generated from the underlying event[17], or are not energetic enough to be part of the main decay products of the process shown in equation (7).

The events obtained had as many as 11 jets, so in order to displace the primary vertices, it was necessary to first identify the 4 jets that came from the LW particles (Z bosons in the simulation). To find those 4 jets the following procedure was pursued:

- Since the simulation is made for the CMS detector, only jets with $|\eta| < 2.4$ are considered to come from a LW particle.
- In the detector level simulation, the position coordinates of the jets and LW

[17]The underlying event is everything except the 4 outgoing hard scattered jets[17]. In real life, this effect will be enhanced due to pile up interactions.

particles, are zero or near zero, so it is necessary to modify them negligibly in order to obtain the shortest distance from the LW particle primary vertex to each jet trajectory. The position coordinates of the jets and LW particles are slightly modified with a Gaussian distribution[18].

- The 4 jets that are considered for the analysis are chosen as the ones that have the largest transversal momentum in each event. Later, those 4 jets are matched as a pair that come from the same particle mother by comparing their invariant mass with the mass of the hypothetical LW particle.

- In order to find the origin of the jets, the center of mass between the pair of jets that were previously selected is computed with:

$$\overrightarrow{P}_{CM} = \frac{\overrightarrow{P_1}\, P_1 + \overrightarrow{P_2}\, P_2}{P_1 + P_2}$$

$$P_{T_{CM}} = \sqrt{P^2_{X_{CM}} + P^2_{Y_{CM}}}$$

$$\cos\phi_{CM} = \frac{P_{X_{CM}}}{P_{T_{CM}}} \tag{8}$$

$$\sinh\eta_{CM} = \frac{P_{Z_{CM}}}{P_{T_{CM}}}\,. \tag{9}$$

The directions of the center of mass of the jets (in ϕ and η) are compared to

[18]Delphes, by default, does not work with primary and secondary vertices. In Delphes, most of the collisions occur at the center of the detector, so, mainly all the initial particles are located in the origin. Also, since the particles that we work with decay really fast, the secondary vertex where the jets originate, are not separated from the particle that originated it. For instance, the Z boson with a half-life of the order of 10^{-25} s would make a displacement of $\sim 10^{-18}$ m. Since this displacement is too small, the data is automatically set to zero instead of a value of the order of 10^{-18} m. In order to compute the pseudo impact parameter (see section 6.1), it is necessary to have the jets separated from the particle primary vertex, so that the pseudo impact parameter is not zero. The scale taken is a value taken from the half-life of the particle and the CMS detector efficiency. This value is used to give a smearing to the PV and a point in the jet track. The same principle is used for displacing the primary vertices and the jets positions in the backgrounds.

those of each LW particle with:

$$\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}\,, \tag{10}$$

the smallest ΔR is used to designate which LW particle produced the pair of jets.

- The LW particle is displaced in the direction of the center of mass of the two jets that come from it. The displacement is made with a Gaussian distribution so that it varies between 20 and 50 μm. This displacement was taken since in [4] the wrong vertex displacements considered for the analysis are greater than $\Delta x = 20\mu$m, which is consistent with the resolution of the CMS pixel tracker detector.

- For the analysis, the new total momentum of the displaced LW particle is determined by computing the total momentum of the center of mass between the 2 jets that originated from that LW particle. The direction of the new total momentum is changed to be opposite to the original direction.

After this process[19], a wrong displaced vertex is obtained for each LW particle, which will be used for a further analysis.

5.2 Background Events Generation

For our analysis of the LW process, only three backgrounds are considered: 4 jets production from ZZ, 4 jets production from ZZ with causal displacements, and $t\bar{t}$ production. For a more accurate and complete analysis, more backgrounds are needed, but for simplicity, only three backgrounds are considered; these are representative of the causal particle that can be encountered in the CMS.

5.2.1 Jets production from ZZ

The first background is the same process as the one done for the LW process in equation (7), the only difference in the events generation is that the Z boson mass is

[19] Appendix I shows the script lwevents.C which was used to create a LW process by using the ZZ process.

not modified in the run card of MadGraph.

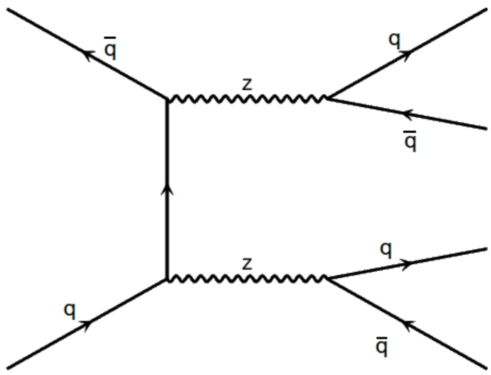


Figure 10: Feynman diagram for the SM production of ZZ pairs going to 4 jets. The process generated was the one shown in equation (7).

In this process, 200000 events[20] are generated at 13 TeV. Figure 10 shows the Feynman diagram for ZZ to 4 jets. The total cross section for this process is 1.556 ± 0.049 pb. There are as many as 9 jets in each event. As a result, an analogue procedure[21] as the one done for LW events is followed to determine the 4 jets that originated from the Z bosons:

- Only jets with $|\eta| < 2.4$ are considered to come from a Z boson.
- The 4 jets that are considered for the analysis are the ones which have the largest transversal momentum in each event. These 4 jets are matched as a pair by comparing their invariant mass with the Z boson mass.
- The jets positions and the Z bosons vertices are slightly modified with a Gaussian distribution[22] to simulate real conditions.
- In order to identify the Z boson that produced the jets, the center of mass between the pair of jets that were previously selected is computed. The directions of the center of mass of the jets (ϕ and η) are compared to those of each Z boson with (10), and the smallest ΔR is used to designate which Z boson originated the pair of jets.

[20] The number of events generated depend on the cross section and integrated luminosity, see footnote 15.

[21] Appendix II shows the script smevents.C which modifies the ZZ process without primary vertex causal displacements.

[22] See footnote 18.

- The total momentum of the displaced Z boson is determined by the total momentum of the center of mass of the pair jets that were originated from it.

5.2.2 Jets production from ZZ with causal displacements

This background is simulated in order to show an hypothetical case representing any causal process with long-lived particles. For simplicity, the process shown in equation 7 is simulated as in section 5.2.1, with the same number of events and total cross section. For selecting the jets that we work with in this background, the same procedure as the one shown in section 5.2.1 is followed. After that, the causal displacement is simulated with a Gaussian distribution so that the secondary vertex displacement varies between 20 and 50 μm[23]. This displacement is taken to show the difference between the pseudo impact parameter of a causal particle, and an acausal particle. The same displacement as for the LW particles is taken but the direction of the momentum is preserved to obtain a causal scenario.

5.2.3 $t\bar{t}$ Production Events Generation

The general $t\bar{t}$ production[24] process considered is,

$$q\overline{q} \to t\,\bar{t} \to b\,W^{+}\,\bar{b}\,W^{-}\ .$$

However, depending on the decay modes of the $W^{\pm}$ bosons, 2, 4 or 6 jets can be obtained. Thus, 4 different processes for $t\bar{t}$ production are generated at 13 TeV. Figure 11 shows the Feynman diagrams for the different decays of the $W^{\pm}$ bosons. Table 2 shows the processes that were simulated, and the number of events generated for each process.

The number of events produced for each process was determined depending on the branching ratio of the process. In total, 10000 events were generated for $t\bar{t}$ production.

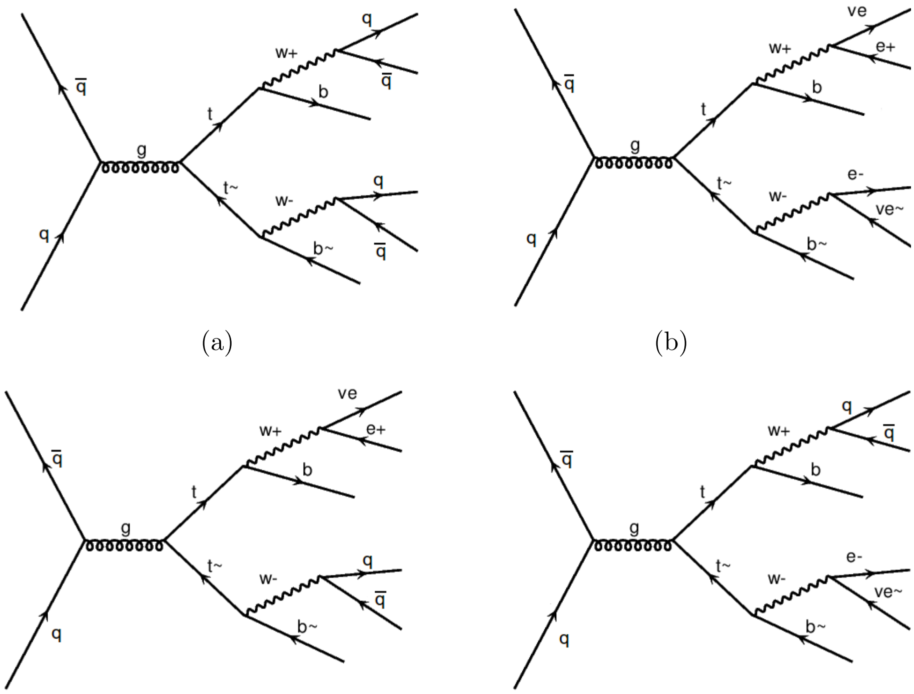
After the events generation, it is seen that more jets than the expected are obtained,

[23]Appendix II shows the script smevents.C which modifies the ZZ process with primary vertex causal displacements.

[24]The $t\bar{t}$ production was considered as a background since it has been already widely studied, so their behaviour is predictable.

Table 2: Events generated for $t\bar{t}$ production

$W^{\pm}$ Bosons Decay Modes	Number of Events	Min. Number of Jets	Total σ [pb]
$W^+ > q\ q\ ,\ W^- > q\ q$	6500	6	111.06 ± 0.536
$W^+ > l^+\ \nu_l\ ,\ W^- > l^-\ \overline{\nu}_l$	500	2	17.27 ± 0.212
$W^+ > q\ q\ ,\ W^- > l^-\ \overline{\nu}_l$	1500	4	44.353 ± 0.561
$W^+ > l^+\ \nu_l,\ W^- > q\ q$	1500	4	44.371 ± 0.419



(a) (b) (c) (d)

Figure 11: Feynman diagrams for $t\bar{t}$ production with different decays for the $W^{\pm}$ bosons: (a) both W bosons with hadronic decays; (b) both W bosons with dilepton decays; (c) W^+ with dilepton decay and W^- with hadronic decay; (d) W^+ with hadronic decay and W^- with dilepton decay.

e.g., for the first process shown in Table 2, as many as 13 jets are seen by the detector where only 6 are the ones that result from $t\bar{t}$ production. Consequently, it is necessary to determine the jets that come from t or $\bar{t}$ quarks. An analogue procedure[25] to the one for LW and ZZ processes is followed:

- Only events with at least 2, 4 or 6 jets, depending on the process, are accepted.
- Only jets with $|\eta| < 2.4$ are considered for the analysis.

[25] Appendices III, IV and V show the scripts dileptons.C, hadronic.C, and wplus.C, wminus.C respectively. These scripts modify the $t\bar{t}$ processes for the different decays of the W bosons.

- The 2, 4 or 6 jets (depending on the process) with hardest transversal momentum are selected. In order to determine the origin of each of the jets, ΔR is used in comparison with the t and $\bar{t}$ quarks.

- The jets position coordinates, t and $\bar{t}$ quarks vertices are modified infinitesimally with Gaussian distributions[26].

- The coordinates and momentum of the t and $\bar{t}$ quarks are determined with the center of mass of the jets that come from them.

6 Events Analysis

After the events selection process, the number of jets, which are used for computing the invariant mass[27] between the two hardest jets and the pseudo impact parameter[28] is reduced. For the analysis, an integrated luminosity[29] of 100 fb^{-1} was considered.

Since each process had a different cross section and number of events, it is necessary to normalize the data generated. Table 3 shows the weight factor[30] computed for each process with:

$$W_f = \frac{\sigma}{N} \int L \, dt \,, \tag{11}$$

where σ is the cross section, L is the integrated luminosity, and N is the number of events that were originally simulated.

Aiming to develop a realistic simulation of what can be obtained from CMS, for our study, the data is the sum of the normalized LW signal and the three backgrounds. Figure 12 shows the transversal momentum[31] of the jets that were finally selected for each process. For the LW events, it is seen that most of the jets have a transversal

[26] See footnote 18.

[27] See section 6.2.

[28] See section 6.1.

[29] See section 4.

[30] The same weight factor is taken for ZZ to 4 jets events with and without causal vertices displacements.

[31] Appendix V shows the script plotpt.C which was created to plot the transversal momentum of all the selected jets of all the events of each process.

Table 3: Weight factor used in the normalization for each process.

Simulated Process	Weight
LW events (acausal events)	0.333
ZZ to 4 jets events	0.782
$t\bar{t}$ (both W with dileptonic decay)	3.454
$t\bar{t}$ (both W with hadronic decay)	1.708
$t\bar{t}$ (W^+ with dileptonic decay)	2.958
$t\bar{t}$ (W^- with dileptonic decay)	2.956

momentum greater than 50 GeV, and the same for the background events. Therefore, in order to get cleaner signals, the analysis of the invariant mass and the impact parameter will take into account this condition. Conditions like the jets having a transversal momentum in a certain range, are the usual cuts that are done when studying causal events.

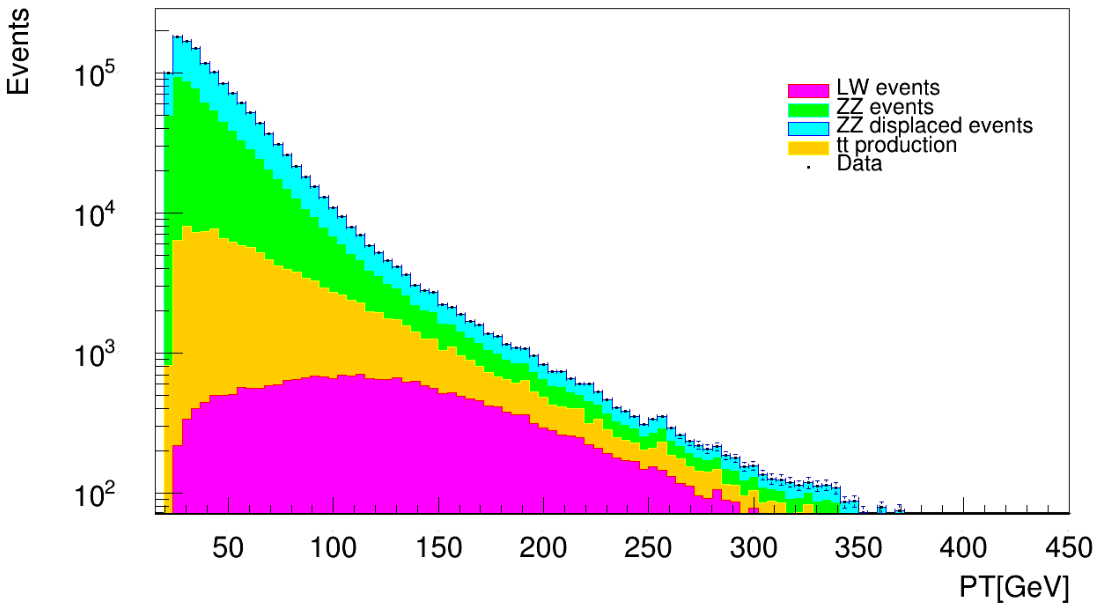


Figure 12: PT plot for LW events, its backgrounds events and data events.

Also, the process that was simulated for LW events, required to have 4 jets as products. Hence, another cut is made by neglecting events that only have 2 jets. As a result, from $t\bar{t}$ production, the process where both W bosons decay into dileptons is deleted from the analysis. The rest of the analysis is done with standard cuts defined by the following conditions[32]

- The jets must have $|\eta| < 2.4$.

[32]In Table 4, the event yield with standard cuts applied can be found.

- Each event must have at least 4 jets.
- The jets transversal momentum must be greater than 50 GeV.

6.1 Pseudo Impact Parameter

In order to show the acausal behaviour of the LW events, a new variable, the pseudo impact parameter, is computed. The impact parameter is defined as the distance of closest approach of a track to the interaction point [18]. However, in this case, we define a pseudo impact parameter which will be considered as the dot product between the momentum of the particle mother that originated the jets $\overrightarrow{P}_{CM}$, and the vector position of the point at which one gets the shortest distance from this particle mother primary vertex to the track of each jet $\overrightarrow{D}$. The pseudo impact parameter was defined in that way so that it allows one to notice the effect that the wrong vertex displacement have in the signal, especially because of the direction of the total linear momentum.

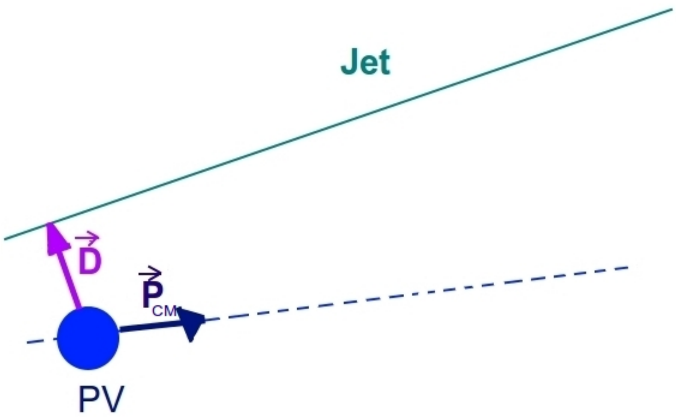


Figure 13: Vector of the shortest distance **D** from the primary vertex PV to the jets trajectory

The same analysis procedure is used for the LW and background events. For simplicity, it is assumed that the trajectory followed by the jets is linear. The directions of the jet η and ϕ, and the modified jet position coordinates are used in order to determine the linear equation of the jet trajectory. After that, the vector of the shortest distance between the primary vertex of the particle that produced the jets, and the jet trajectory is found (Figure 13)[33].

[33] Appendix V shows an analogue structure of the script that was created to plot the pseudo impact

It is expected to see a significant change in the pseudo impact parameter $\vec{D} \cdot \vec{P}_{CM}$ computed for the LW events and the background events. This is because for the LW events, the primary vertices were displaced with a greater width than in the backgrounds, and also, the PV was modified to be a wrong displaced vertex.

Figures 14, 15, 16 and 17 show the pseudo impact parameters for each process. Clearly, it can be seen that for three backgrounds, ZZ to 4 jets and $t\bar{t}$ production, which are SM processes, the behaviour of the pseudo impact parameter is symmetrical. On the other hand for the LW process and the ZZ to 4 jets but with causal vertex displacement, the histograms show an asymmetrical behaviour. Figure 18 shows the three process together. For these events only the standard cuts have been made.

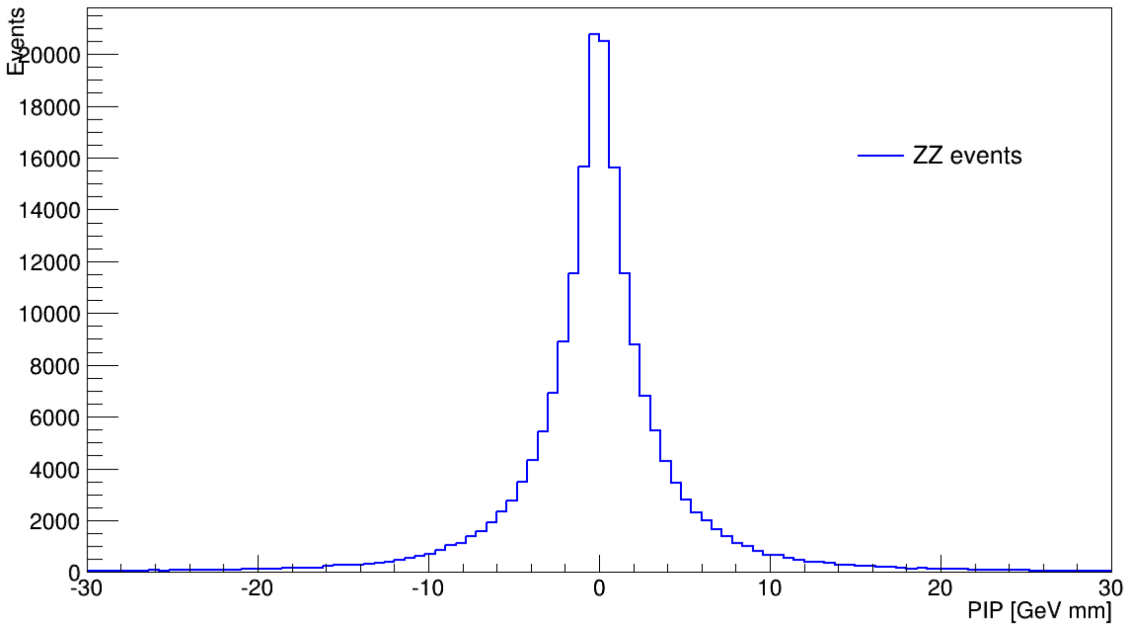


Figure 14: Pseudo impact parameter for events where ZZ pairs decay into 4 jets without primary vertex displacement. The standard cuts mentioned before are already set.

By analysing the plots, one can infer the fact that due to the asymmetrical behaviour and the wrong vertex displacement for LW events, there is a region where the LW signal predominates. The cut chosen is for $\vec{D} \cdot \vec{P}_{CM}$ <-10 GeV·mm [34]. This cut in

parameter of the different signals that was computed with appendices I, II and III.

[34]The script used for the cut in the pseudo impact parameter, is similar to the one shown in Appendix V.

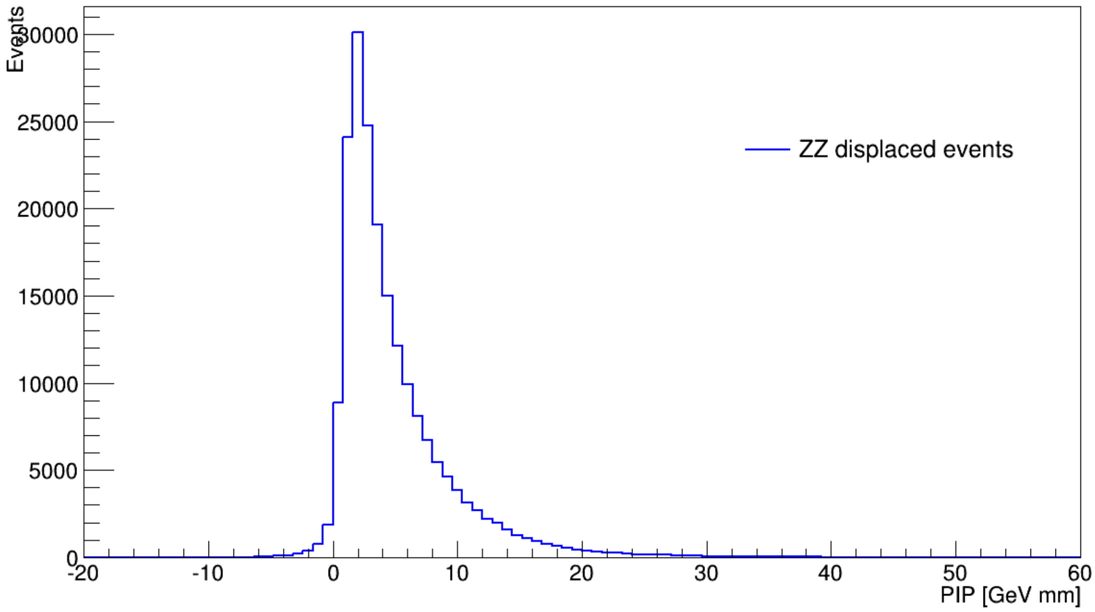


Figure 15: Pseudo impact parameter for events where ZZ pairs decay into 4 jets with causal primary vertex displacement. The standard cuts mentioned before are already set.

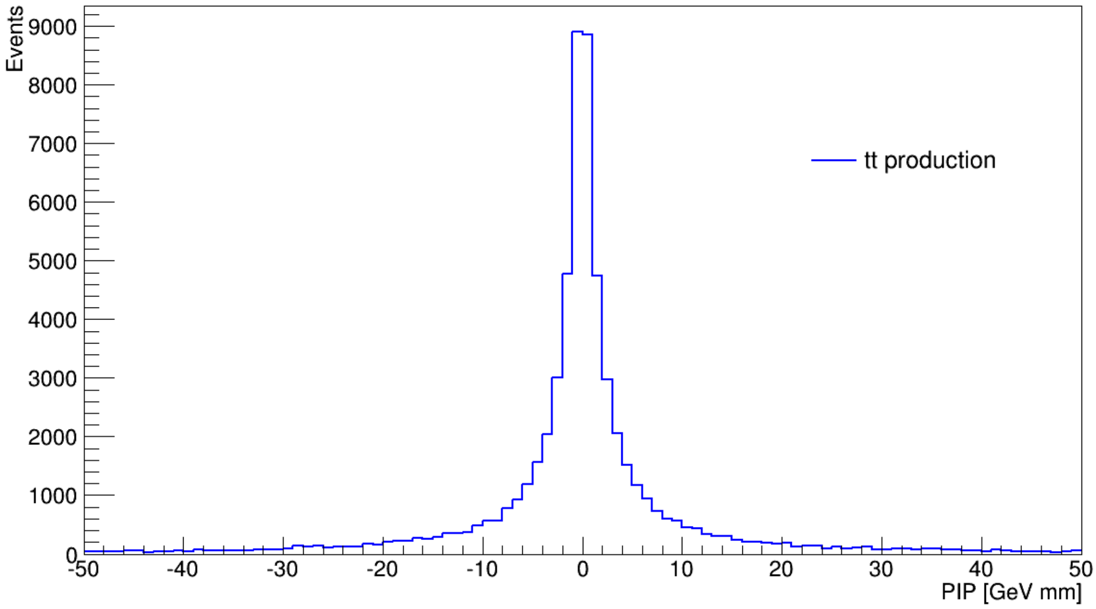


Figure 16: Pseudo impact parameter for $t\bar{t}$ events. The standard cuts mentioned before are already set.

our new variable, the pseudo impact parameter, has never been implemented before, so it represents a powerful tool to get rid of causal events, and keep only acasual events, which in this case correspond to LW events.

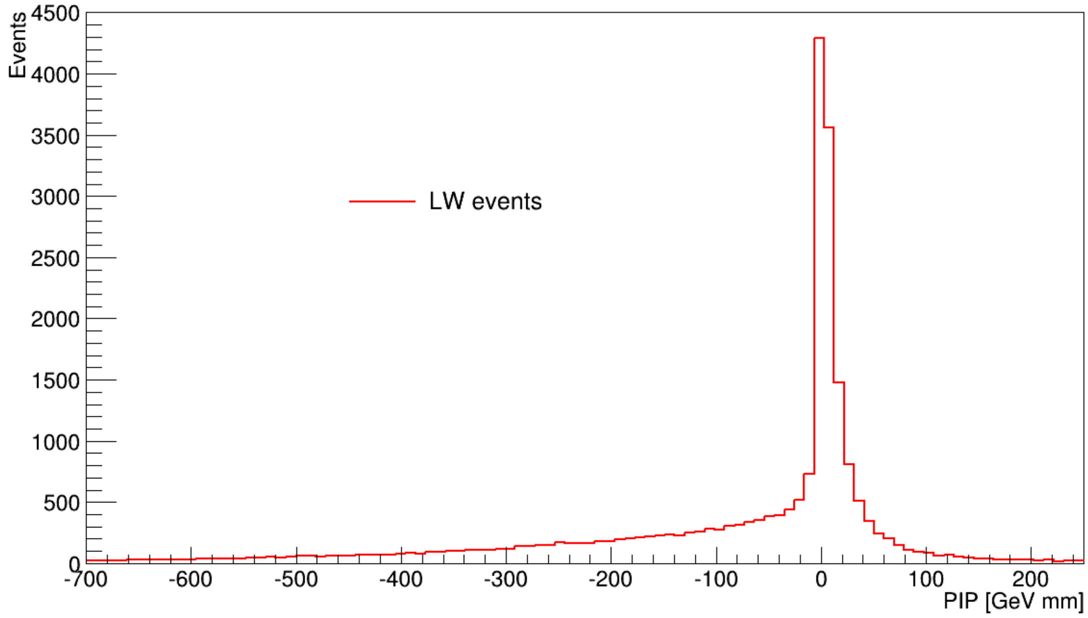


Figure 17: Pseudo impact parameter for LW events. The standard cuts mentioned before are already set.

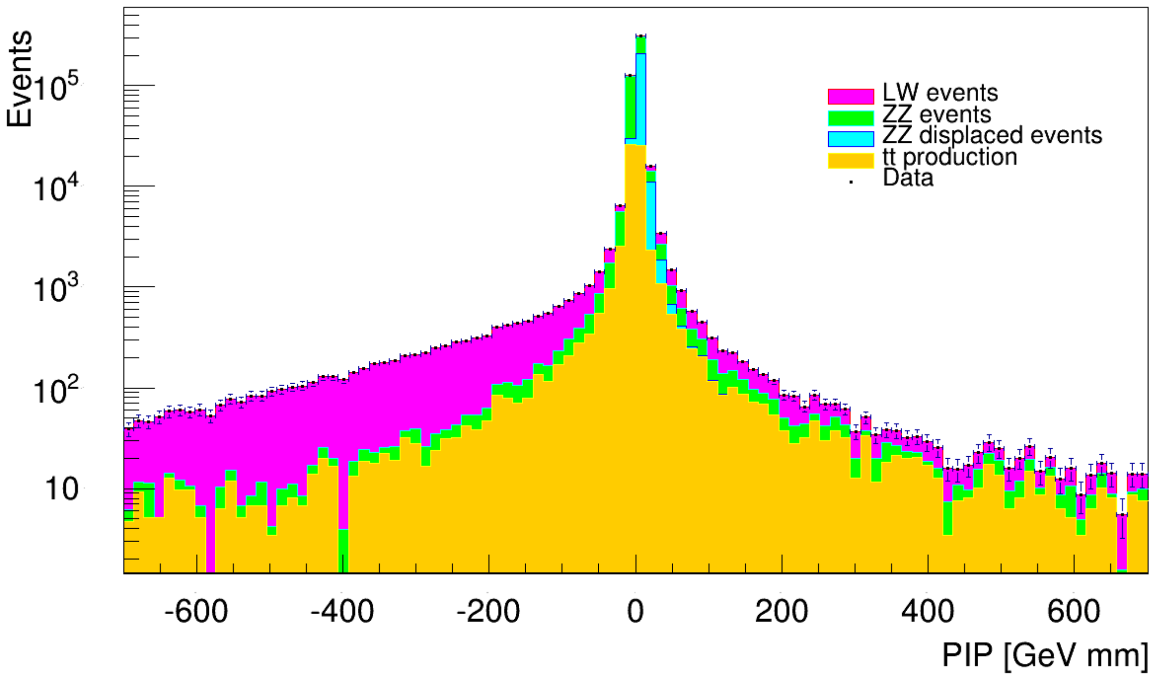


Figure 18: Pseudo impact parameter for LW events and three backgrounds. The standard cuts mentioned before are already set.

Figure 19 shows the pseudo impact parameter after applying the cut. With the data obtained, it is clear that the cut at < -10 GeV·mm gives a very clean signal since few background events were seen in the rest of the data. Hence, using the pseudo impact parameter as a possible observable to identify LW particles is more accurate than studying the invariant mass. Also, it is important to notice that this pseudo impact parameter, like the invariant mass, only requires to know the energy, total linear momentum, and position of the particles and jets that were analysed. Therefore, by computing the pseudo impact parameter for real data, one expect to have a total symmetrical behaviour if there are no LW particles present, or to have a great amount of data in the area where the cut was made, and determine if the events observed can be or not a candidate to be a LW particle.

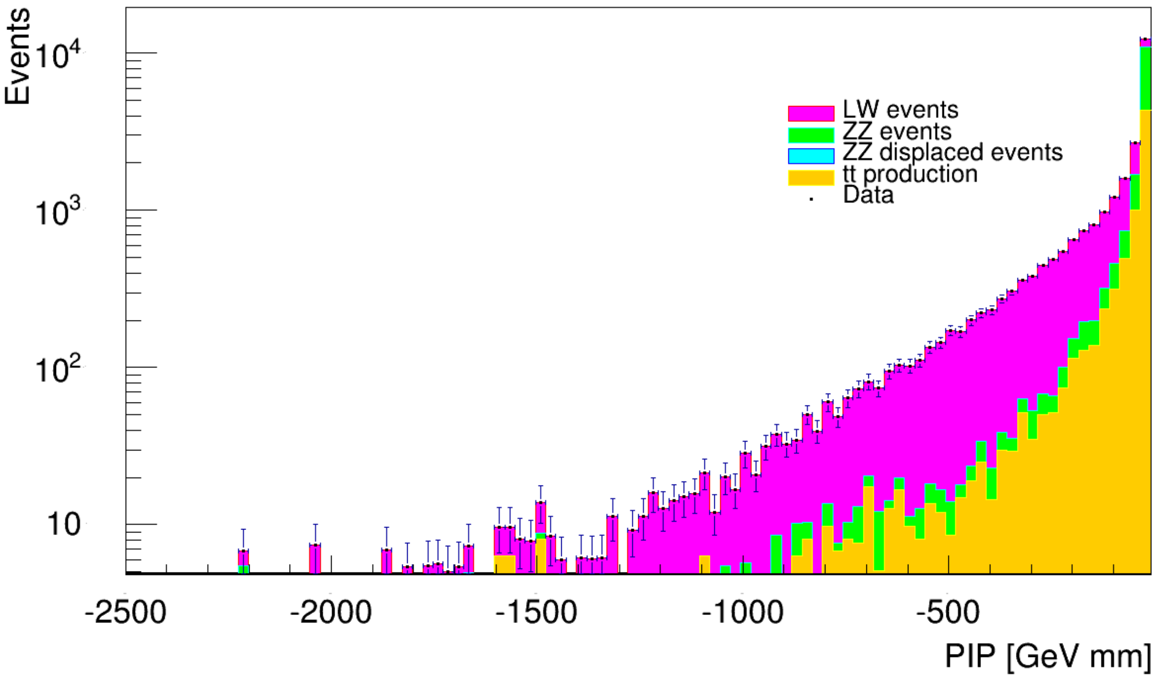


Figure 19: Pseudo impact parameter for LW events and three backgrounds with a cut applied at -10 GeV·mm in addition to the standard cuts.

6.2 Invariant Mass

If the LW particles show up as resonances (see section 3) then the invariant mass of the two hardest jets of an event is a good observable. Also, the invariant mass is a quantity that depends only on the particle or jet energy and linear momentum, and not on the system of reference that is taken, as shown in (12).

$$M_{inv} = \sqrt{(E_1 + E_2)^2 - (\overrightarrow{P_1} + \overrightarrow{P_2})^2} \tag{12}$$

Figure 20 shows the invariant mass distribution for the two hardest jets in the LW signal and the backgrounds events[35]. Table 4 shows the event yield with the standard cuts made for the signal and the backgrounds events.

In Figure 20 it can be seen that there is a resonance for LW events invariant mass in a range greater than 100 GeV/c^2 which is the range of LW particles mass. If when analysing real data a peak of resonance is found in that range, then that resonance can represent the existence of new particles that belong to Physics Beyond the Standard Model theories, hopefully to the LWSM theory. However, in Figure 20, the LW signal is insignificant in comparison to the backgrounds, so by analysing the real data, no resonance peak in the LW mass range would be spotted by only applying the standard cuts.

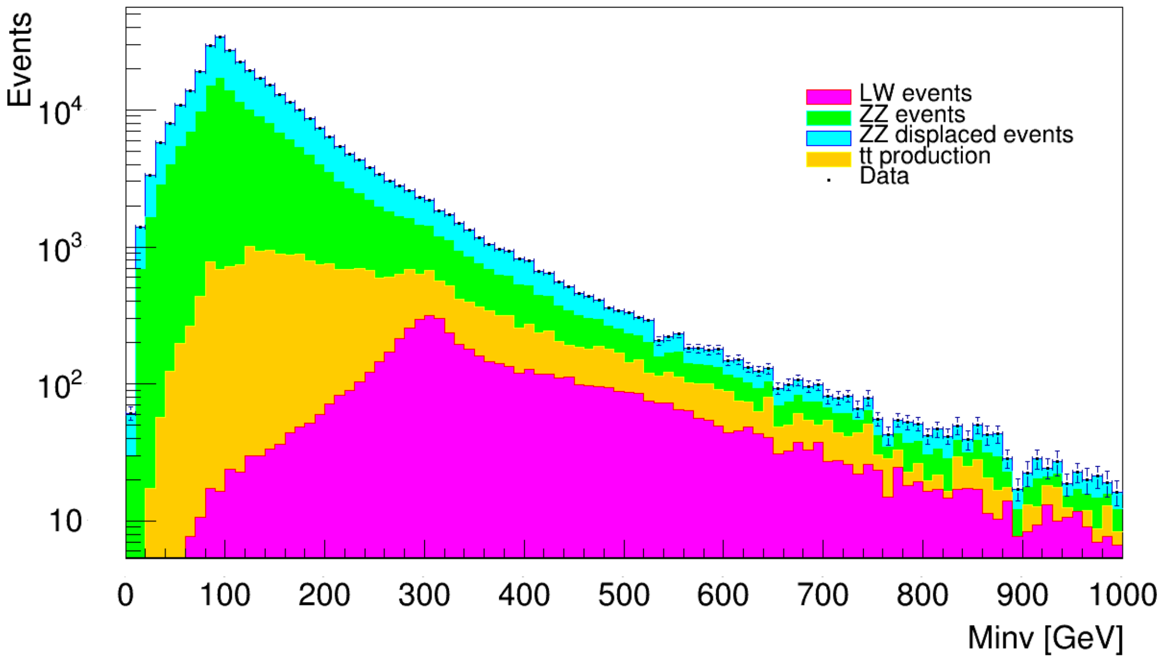


Figure 20: Invariant mass computed for the two hardest jets of each process after the events selection was made.

As it was seen in section 6.1, acausal events show a particular asymmetrical behaviour for the PIP, where most of these events belong to PIP< -10 GeV·mm. Therefore, by applying this cut to get rid of the background events[36], we are able to find the

[35] Appendix V shows an analogue script to the one that was created to plot the invariant mass of the two hardest jets of each event for all the processes.

[36] The cut made with PIP is made so that the two hardest jet must have PIP< -10 GeV mm.

Table 4: Event yield with standard cuts, and with the PIP cut.

Generated Process	Events with $\lvert\eta\rvert < 2.4$	Events with at least 4 jets	Events with PT>50 GeV	Events with PIP<-10 Gev·mm
LW events	53598	53598	6670	2150
ZZ events	222208	222208	156417	91
ZZ displaced events	222208	222208	156417	0
tt events	21376	21250	19975	16
Total Backgrounds	465792	465666	332809	107
Data	519390	519264	339436	2257

peak of resonance in the LW mass range as shown in figure 21.

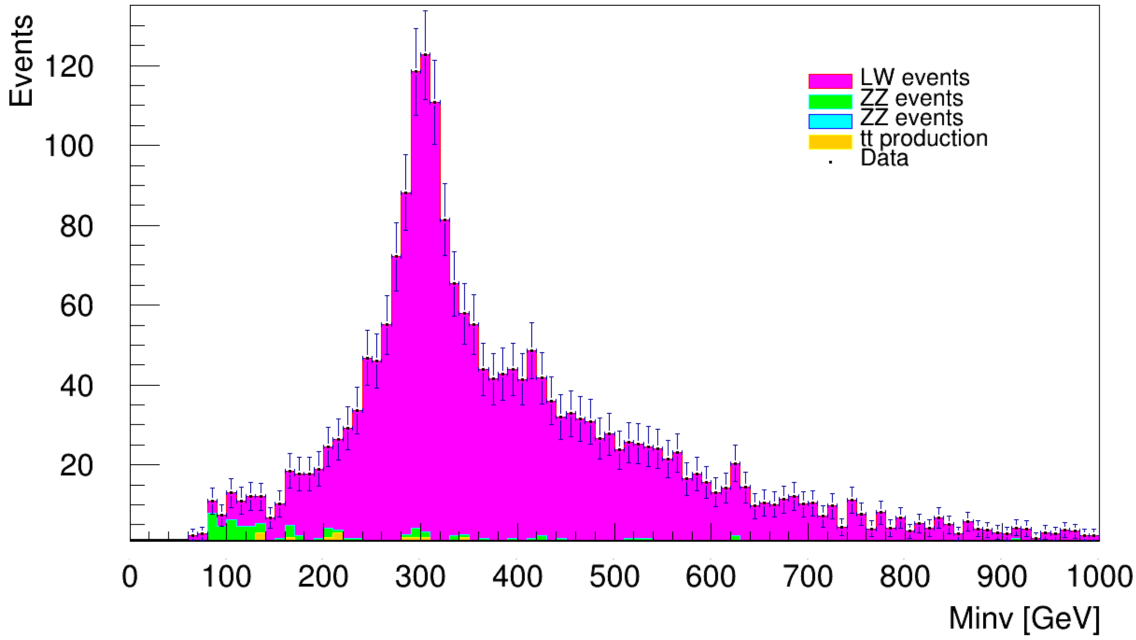


Figure 21: Invariant mass computed for the two hardest jets of each event, with the standard cuts and the PIP< -10 GeV·mm cut.

From Figure 21 and Table 4[37] it is seen that by applying a cut in PIP we can indeed identify acausal events from causal ones. So we can use this as a tool to look for the existence of acausal particles in the data from CMS detector working at LHC Run 2.

Appendix V shows an analogue structure for the script used to make the standard cuts and the PIP cut in the invariant mass.

[37] The event yield shown is the sequence of the cuts from left to right, i.e., the second column show the event yield for events with jets that have $|\eta| < 2.4$; and the third column show the event yield for events with jets that have $|\eta| < 2.4$ and events with at least 4 jets, and so on.

7 Conclusions

The Lee Wick Standard Model proposes a partial solution to the hierarchy problem[38]. The main feature of the LWSM is the possibility of acausal behaviour for LW particles. As a result, it was intended to use this feature as a tool to determine a cut in the data for certain observables such as invariant mass, and a pseudo impact parameter, which was defined in order to emphasize the wrong vertex displacement produced from LW particles.

The results show that for the pseudo impact parameter, the difference between SM particles and LW particles is determinant. For the two SM backgrounds without causal vertices displacements that were used, it was seen that the pseudo impact parameter that was computed gives a symmetrical histogram; and in the case of the background with causal vertices displacements an asymmetrical histogram was obtained with most of the events at PIP> -10 GeV mm. However, for acausal particles, the pseudo impact parameter gives an asymmetrical histogram, and most of the data are focused on negative values, PIP< -10 GeV mm. Therefore, a cut was determined at -10 GeV·m and thus most of the events that remained belong to the LW signal. The PIP behaviour that was found is crucial property for the LW process since it shows a relevant cut that can be used for a further analysis of data coming from the LHC in the Run 2.

Furthermore, the analysis of the invariant mass of the two hardest jets in each event showed that by only applying the standard cuts it was hard to spot new mass resonances in the LW mass range, so it would not be feasible to find these acausal particles with those conditions. Nevertheless, by implementing a new cut that focus on the acausal behaviour, PIP< -10 GeV mm, we can get rid of background events, and a resonance in invariant mass could be found in an easier way within the LW mass range. Hence, the pseudo impact parameter is an important tool to identify acausal particles at the LHC in the new era.

[38]The LWSM only leads with quadratic terms produced by the Higgs mass. For instance, it still have limitations at the gravitational force problem.

8 Future Work

In order to get a more realistic result, it is suggested to add more backgrounds to the events simulations, for example, QCD. Also, other effects like pile-up and trigger need to be taken into account in the events selection procedure. However, due to the high discrimination power of the new cut given by the pseudo impact parameter, an analyis of real data from the CMS experiment at LHC in the Run 2 can take advantage of this new cut and look for data that can be identified as acausal particles in the real world, which could belong to LWSM theory.

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9 Appendices

From the events generation, 6 .root files were obtained, 4 for $t\bar{t}$ events, 1 for LW events and 1 for ZZ events. In order to do the events selection, the data stored in each TTree was analysed by using the MakeClass option from ROOT [16]. MakeClass generates an .h and a .C files from the .root file. For each TTree, the .h file was only modified by adding some new functions in the constructor. On the other hand, the .C file has the all the information about the vertices' changes, selected transversal momentum, invariant mass, and pseudo impact parameter. So only the .C files are shown in appendices I to V.

In appendices VI to IX, there are scripts for the plotting of the LW signal and the backgrounds. These scripts are based on the data obtained from the files mentioned above.

9.1 Appendix I: Script for analysing LW acausal particles signal events.

The following script, lwevents.C, works for LW events. It generates the wrong vertex displacements, and computes the invariant mass and pseudo impact parameter. For the pseudo impact parameter it is already considered the fact that only jets with PT>50 GeV will be analysed.

```
//Author: Raquel Quishpe

#define lwevents_cxx
#include "lwevents.h"
#include <TH2.h>
#include <TStyle.h>
#include <TCanvas.h>
#include <TRandom.h>
#include "TMath.h"
#include <iostream>
#include <fstream>
using TMath::ASinH;
using namespace TMath;
```

```
void lwevents::data()
{
//The data() function will filter some data, and then displace
//the vertices of the mother particles and the positions of the
//jets that come from it. Since this is a LW process, the mother
//particle's vertices are wrongly displaced. The invariant mass
//for the hardest jets is computed. The pseudo impact parameter
//is computed. A cleaner invariant mass is computed.

   if (fChain == 0) return;
   Long64_t nentries = fChain->GetEntriesFast();
   Long64_t nbytes = 0, nb = 0;

   ofstream myfile1;
   ofstream myfile2;
   ofstream myfile3;
   ofstream myfile4;
   ofstream myfile5;
   myfile1.open("ip_lw.dat");
   myfile2.open("pt_lw.dat");
   myfile3.open("im_lw.dat");
   myfile4.open("cim_lw.dat");
   myfile5.open("cut_ip_lw.dat");

//variables to count the number of jets after every filter
        int                count4jets=0;
        int                countip=0;
        int                countjets=0;
//variables to find the hardest jets and compute the
//invariant mass
        float              hardpt;
        int                ID[4];
        int                Jet_ID[4];
        float              invmass[6];
        float              Jet_E[4];
        float              dminv[6];
//LW particle's mass in GeV
```

```
        float              lw_mass = 300;
//variables for the PV and jets position and momentum
        int                Z_ID[4]; //0 from first Z, 1 from second Z
        Float_t            Z_PT[2];
        Float_t            Z_Phi[2];
        Float_t            Z_Eta[2];
        Float_t            Z_X[2];
        Float_t            Z_Y[2];
        Float_t            Z_Z[2];
        Float_t            LW_X[2];
        Float_t            LW_Y[2];
        Float_t            LW_Z[2];
//variables to change and exchange the vertex of the Z
        Float_t d_sigma=30e-3; //20um
        Float_t sigma=9e-3; //9um
        Float_t z_sigma=9e-5;
        Float_t Jet_X[4];
        Float_t Jet_Y[4];
        Float_t Jet_Z[4];
        Float_t Small_X[4];
        Float_t Small_Y[4];
        Float_t Small_Z[4];
        Float_t Small_LW_X[4];
        Float_t Small_LW_Y[4];
        Float_t Small_LW_Z[4];
        Float_t fPx[2];
        Float_t fPy[2];
        Float_t fPz[2];
//variable to determine the impact parameter
        Float_t LW_IP[4];
   for (Long64_t jentry=0; jentry<nentries;jentry++) {
      Long64_t ientry = LoadTree(jentry);
      if (ientry < 0) break;
      nb = fChain->GetEntry(jentry);   nbytes += nb;
      // if (Cut(ientry) < 0) continue;
        for (int ijjet=0 ; ijjet<kMaxJet ; ijjet++ ){
        if (Jet_PT[ijjet]==0) continue;
        countjets++;
```

```
}
if (Jet_PT[3]==0) continue;
for (int jjjet=0 ; jjjet<kMaxJet ; jjjet++ ){
if (Jet_PT[jjjet]==0) continue;
count4jets++;
}
//let's find the 4 hardest jets
hardpt = 0;
for (int ijet0=0 ; ijet0<kMaxJet ; ijet0++ ){
if ( fabs(Jet_Eta[ijet0])>2.4 ) continue;
if(Jet_PT[ijet0]>=hardpt){
hardpt = Jet_PT[ijet0];
ID[0] = ijet0;
}
}
hardpt = 0;
for (int ijet1=0 ; ijet1<kMaxJet ; ijet1++ ){
if ( fabs(Jet_Eta[ijet1])>2.4 ) continue;
if (ijet1 == ID[0]) continue;
if(Jet_PT[ijet1]>=hardpt){
hardpt = Jet_PT[ijet1];
ID[1] = ijet1;
}
}
hardpt = 0;
for (int ijet2=0 ; ijet2<kMaxJet ; ijet2++ ){
if ( fabs(Jet_Eta[ijet2])>2.4 ) continue;
if ( ijet2==ID[0] || ijet2==ID[1] ) continue;
if(Jet_PT[ijet2]>=hardpt){
hardpt = Jet_PT[ijet2];
ID[2] = ijet2;
}
}
hardpt = 0;
for (int ijet3=0 ; ijet3<kMaxJet ; ijet3++ ){
if ( fabs(Jet_Eta[ijet3])>2.4 ) continue;
if ( ijet3==ID[0] || ijet3==ID[1] || ijet3==ID[2]) continue;
if(Jet_PT[ijet3]>=hardpt){
```

```
        hardpt = Jet_PT[ijet3];
        ID[3] = ijet3;
        }
        }
//let's compute the invariant mass for every combination between the 4
    jets
        for(int ijet=0; ijet<4; ijet++){
        Jet_E[ijet]=Jet_PT[ID[ijet]]*Jet_PT[ID[ijet]]*cosh(Jet_Eta[ID[
            ijet]])*cosh(Jet_Eta[ID[ijet]]) + Jet_Mass[ID[ijet]]*
            Jet_Mass[ID[ijet]];
        Jet_E[ijet]=sqrt(Jet_E[ijet]);
        }
        for(int k0=1; k0<4; k0++){
        invmass[k0-1] = pow( ( Jet_PT[ID[0]]*cos(Jet_Phi[ID[0]]) +
            Jet_PT[ID[k0]]*cos(Jet_Phi[ID[k0]]) ) , 2 ) + pow( (
            Jet_PT[ID[0]]*sin(Jet_Phi[ID[0]]) + Jet_PT[ID[k0]]*sin(
            Jet_Phi[ID[k0]]) ) , 2 ) + pow( ( Jet_PT[ID[0]]*sinh(
            Jet_Eta[ID[0]]) + Jet_PT[ID[k0]]*sinh(Jet_Eta[ID[k0]]) ) ,
             2 );
        invmass[k0-1] = pow( (Jet_E[0]+Jet_E[k0]) , 2 ) - invmass[k0
            -1];
        invmass[k0-1] = sqrt(invmass[k0-1]);
        dminv[k0-1] = fabs(invmass[k0-1]-lw_mass);
        }
        for(int k1=2; k1<4; k1++){
        invmass[k1+1] = pow( ( Jet_PT[ID[1]]*cos(Jet_Phi[ID[1]]) +
            Jet_PT[ID[k1]]*cos(Jet_Phi[ID[k1]]) ) , 2 ) + pow( (
            Jet_PT[ID[1]]*sin(Jet_Phi[ID[1]]) + Jet_PT[ID[k1]]*sin(
            Jet_Phi[ID[k1]]) ) , 2 ) + pow( ( Jet_PT[ID[1]]*sinh(
            Jet_Eta[ID[1]]) + Jet_PT[ID[k1]]*sinh(Jet_Eta[ID[k1]]) ) ,
             2 );
        invmass[k1+1] = pow( (Jet_E[1]+Jet_E[k1]) , 2 ) - invmass[k1
            +1];
        invmass[k1+1] = sqrt(invmass[k1+1]);
        dminv[k1+1] = fabs(invmass[k1+1]-lw_mass);
        }
        invmass[5] = pow( ( Jet_PT[ID[2]]*cos(Jet_Phi[ID[2]]) + Jet_PT
            [ID[3]]*cos(Jet_Phi[ID[3]]) ) , 2 ) + pow( ( Jet_PT[ID
```

```
    [2]]*sin(Jet_Phi[ID[2]]) + Jet_PT[ID[3]]*sin(Jet_Phi[ID
    [3]]) ) , 2 ) + pow( ( Jet_PT[ID[2]]*sinh(Jet_Eta[ID[2]])
    + Jet_PT[ID[3]]*sinh(Jet_Eta[ID[3]]) ) , 2 );
  invmass[5] = pow( (Jet_E[2]+Jet_E[3]) , 2 ) - invmass[5];
  invmass[5] = sqrt(invmass[5]);
  dminv[5] = fabs(invmass[5]-lw_mass);
//now let's look for the smallest difference btw the invariant mass
//and the LW particle's mass
  float s_dm=dminv[0];
  int i_dm_1=0;
  for(int im=0; im<6; im++){
  if(dminv[im]<=s_dm){
  s_dm=dminv[im];
  i_dm_1=im;
  }
  }
  if(i_dm_1==0)   { //
  Jet_ID[0]=ID[0] ;
  Jet_ID[1]=ID[1] ;
  Jet_ID[2]=ID[2] ;
  Jet_ID[3]=ID[3] ;
  }//


  if(i_dm_1==1)   { //
  Jet_ID[0]=ID[0] ;
  Jet_ID[1]=ID[2] ;
  Jet_ID[2]=ID[1] ;
  Jet_ID[3]=ID[3] ;
  }//
  if(i_dm_1==2)   { //
  Jet_ID[0]=ID[0] ;
  Jet_ID[1]=ID[3] ;
  Jet_ID[2]=ID[1] ;
  Jet_ID[3]=ID[2] ;
  }//
  if(i_dm_1==3)   { //
  Jet_ID[0]=ID[1] ;
```

```
        Jet_ID[1]=ID[2] ;
        Jet_ID[2]=ID[0] ;
        Jet_ID[3]=ID[3] ;
        }//
        if(i_dm_1==4)   { //
        Jet_ID[0]=ID[1] ;
        Jet_ID[1]=ID[3] ;
        Jet_ID[2]=ID[0] ;
        Jet_ID[3]=ID[2] ;
        }//
        if(i_dm_1==5)   { //
        Jet_ID[0]=ID[2] ;
        Jet_ID[1]=ID[3] ;
        Jet_ID[2]=ID[1] ;
        Jet_ID[3]=ID[0] ;
        }//
//let's select the direction of the Z bosons based on the jets center
    of mass
float px, py, pz;
//for the first Z
        px = Jet_PT[Jet_ID[0]]*cos(Jet_Phi[Jet_ID[0]]) + Jet_PT[Jet_ID
            [1]]*cos(Jet_Phi[Jet_ID[1]]);
        py = Jet_PT[Jet_ID[0]]*sin(Jet_Phi[Jet_ID[0]]) + Jet_PT[Jet_ID
            [1]]*sin(Jet_Phi[Jet_ID[1]]);
        pz = Jet_PT[Jet_ID[0]]*sinh(Jet_Eta[Jet_ID[0]]) + Jet_PT[
            Jet_ID[1]]*sinh(Jet_Eta[Jet_ID[1]]);
        Z_PT[0]  = sqrt( pow(px,2) + pow(py,2));
        Z_Phi[0] = acos (px/Z_PT[0]);
        Z_Eta[0] = ASinH (pz/Z_PT[0]);
//for the second Z
        px = Jet_PT[Jet_ID[2]]*cos(Jet_Phi[Jet_ID[2]]) + Jet_PT[Jet_ID
            [3]]*cos(Jet_Phi[Jet_ID[3]]);
        py = Jet_PT[Jet_ID[2]]*sin(Jet_Phi[Jet_ID[2]]) + Jet_PT[Jet_ID
            [3]]*sin(Jet_Phi[Jet_ID[3]]);
        pz = Jet_PT[Jet_ID[2]]*sinh(Jet_Eta[Jet_ID[2]]) + Jet_PT[
            Jet_ID[3]]*sinh(Jet_Eta[Jet_ID[3]]);
        Z_PT[1]  = sqrt( pow(px,2) + pow(py,2));
        Z_Phi[1] = acos (px/Z_PT[1]);
```

```
        Z_Eta[1] = ASinH (pz/Z_PT[1]);
//let's change the jets origin
        for(int jeti=0; jeti<4; jeti++){//******
        Jet_X[jeti] = gRandom -> Gaus(0,sigma);
        Jet_Y[jeti] = gRandom -> Gaus(0,sigma);
        Jet_Z[jeti] = gRandom -> Gaus(0,sigma);
        }//end of jeti
//let's change a little the vertex for the original model
        for(int iz=0; iz<2; iz++){
float SMR;
SMR = gRandom -> Gaus(0,z_sigma);
        Z_X[iz] = SMR*cos(Pi()-Z_Phi[iz])*sin(2*atan(exp(-(Pi()-Z_Eta[
           iz]))));
        Z_Y[iz] = SMR*sin(Pi()-Z_Phi[iz])*sin(2*atan(exp(-(Pi()-Z_Eta[
           iz]))));
        Z_Z[iz] = SMR*cos(2*atan(exp(-(Pi()-Z_Eta[iz]))));
        }
//let's get the acausal vertex
float d;
float theta;
int aux_mj;
        while (d<20e-3){
        d = gRandom -> Gaus(0,d_sigma);
        }
        for(int ia=0; ia<2; ia++){//****
        fPx[ia] = d*cos(Z_Phi[ia])*sin(2*atan(exp(-Z_Eta[ia])));
        fPy[ia] = d*sin(Z_Phi[ia])*sin(2*atan(exp(-Z_Eta[ia])));
        fPz[ia] = d*cos(2*atan(exp(-Z_Eta[ia])));
        LW_X[ia]=Z_X[ia]+fPx[ia];
        LW_Y[ia]=Z_Y[ia]+fPy[ia];
        LW_Z[ia]=Z_Z[ia]+fPz[ia];
        }
        for(int lwj=0; lwj<4; lwj++){//*****
        LW_IP[lwj]=0;
        if(Jet_PT[Jet_ID[lwj]]<50) continue;//comment for no cut
        if(lwj==0 || lwj==1) aux_mj=0;
        if(lwj==2 || lwj==3) aux_mj=1;
        theta = 2*atan(exp(-Jet_Eta[Jet_ID[lwj]]));
```

```
        Small_LW_X[lwj] = pow( LW_X[aux_mj] , 2) + pow( LW_Y[aux_mj] ,
             2) + pow( LW_Z[aux_mj], 2 ) + LW_Y[aux_mj]*(Jet_X[lwj]*
            tan(Jet_Phi[Jet_ID[lwj]])-Jet_Y[lwj]) + LW_Z[aux_mj]*(
            Jet_X[lwj]/(cos(Jet_Phi[Jet_ID[lwj]])*tan(theta))-Jet_Y[
            lwj]);
        Small_LW_X[lwj] = Small_LW_X[lwj]/(LW_X[aux_mj]+LW_Y[aux_mj]*
            tan(Jet_Phi[Jet_ID[lwj]])+LW_Z[aux_mj]/(cos(Jet_Phi[Jet_ID
            [lwj]])*tan(theta)));
        Small_LW_Y[lwj] = Jet_Y[lwj] + (Small_LW_X[lwj] - Jet_X[lwj])*
            tan(Jet_Phi[Jet_ID[lwj]]);
        Small_LW_Z[lwj] = Jet_Z[lwj] + (Small_LW_X[lwj] - Jet_X[lwj])
            /(cos(Jet_Phi[Jet_ID[lwj]])*tan(theta));
        LW_IP[lwj] = Small_LW_X[lwj]*(Z_PT[aux_mj])*cos(Pi()-Z_Phi[
            aux_mj]) + Small_LW_Y[lwj]*(Z_PT[aux_mj])*sin(Pi()-Z_Phi[
            aux_mj]) +Small_LW_Z[lwj]*(Z_PT[aux_mj])*sinh(Pi()-Z_Eta[
            aux_mj]);
        myfile1<<LW_IP[lwj]<<endl;
        countip++;
        }
//applying some cuts and storing some information in .dat
        for(int pti=0; pti<4; pti++){
        myfile2<<Jet_PT[Jet_ID[pti]]<<endl;
        }
        myfile3<<invmass[0]<<endl;
        if(Jet_PT[Jet_ID[0]]>50 && Jet_PT[Jet_ID[1]]>50){
        myfile4<<invmass[0]<<endl;
        if(LW_IP[0]<=-10 && LW_IP[1]<=-10){
        myfile5<<invmass[0]<<endl;
        }
        }
    }//end of jentry
myfile1.close();
myfile2.close();
myfile3.close();
myfile4.close();
myfile5.close();
cout<<"original: "<<countjets<<endl;
cout<<"at least 4 jets: "<<count4jets<<endl;
```

```
cout<<"after ip: "<<countip<<endl;
}
```

9.2 Appendix II: Scripts for analysing background events of ZZ to 4 jet with and without primary vertex displacements.

The following script, smevents.C, works for the ZZ to 4 jets process in the SM. It computes the invariant mass and impact parameter. For the impact parameter it is already considered the fact that only jets with PT>50 GeV will be analysed. It also reproduce the causal vertex displacement that is used for the second background.

```
//Author: Raquel Quishpe
#define smevents_cxx
#include "smevents.h"
#include <TH2.h>
#include <TStyle.h>
#include <TCanvas.h>
#include <TRandom.h>
#include "TMath.h"
#include <iostream>
#include <fstream>
using TMath::ASinH;
using namespace TMath;

void smevents::data()
{
//The data() function will filter some data, and then smear
//the vertices of the mother particles and the positions of the
//jets that come from it.
//The invariant mass for the hardest jets is computed. The pseudo
//impact parameter is computed. A cleaner invariant mass is computed.

   if (fChain == 0) return;
   Long64_t nentries = fChain->GetEntriesFast();
   Long64_t nbytes = 0, nb = 0;
   ofstream myfile1;
```

```
  ofstream myfile2;
  ofstream myfile3;
  ofstream myfile4;
  ofstream myfile5;
  myfile1.open("ip_sm.dat");
  myfile2.open("pt_sm.dat");
  myfile3.open("im_sm.dat");
  myfile4.open("cim_sm.dat");
  myfile5.open("cut_ip_sm.dat");
//variables to count the number of jets after every filter
        int              count4jets=0;
        int              countip=0;
        int              countjets=0;
//variables to find the hardest jets and compute the
//invariant mass
        float            hardpt;
        int              ID[4];
        int              Jet_ID[4];
        float            invmass[6];
        float            Jet_E[4];
        float            dminv[6];
//Z boson mass in GeV
        float            Z_mass = 91.1876;
        int              Z_ID[4]; //0 from first Z, 1 from second Z
        Float_t          Z_PT[2];
        Float_t          Z_Phi[2];
        Float_t          Z_Eta[2];
        Float_t          Z_X[2];
        Float_t          Z_Y[2];
        Float_t          Z_Z[2];
//variables to change and exchange the vertex of the Z
        Float_t d_sigma=30e-3; //20um
        Float_t sigma=9e-3; //9um
        Float_t z_sigma=9e-5;
        Float_t Jet_X[4];
        Float_t Jet_Y[4];
        Float_t Jet_Z[4];
        Float_t Small_X[4];
```

```
        Float_t Small_Y[4];
        Float_t Small_Z[4];
//variables to determine the impact parameter
        Float_t SM_IP[4];
   for (Long64_t jentry=0; jentry<nentries;jentry++) {
      Long64_t ientry = LoadTree(jentry);
      if (ientry < 0) break;
      nb = fChain->GetEntry(jentry);   nbytes += nb;
      // if (Cut(ientry) < 0) continue;
        for (int ijjet=0 ; ijjet<kMaxJet ; ijjet++ ){
        if (Jet_PT[ijjet]==0) continue;
        countjets++;
        }
        if (Jet_PT[3]==0) continue;
        for (int jjjet=0 ; jjjet<kMaxJet ; jjjet++ ){
        if (Jet_PT[jjjet]==0) continue;
        count4jets++;
        }
//let's find the 4 hardest jets
        hardpt = 0;
        for (int ijet0=0 ; ijet0<kMaxJet ; ijet0++ ){
        if ( fabs(Jet_Eta[ijet0])>2.4 ) continue;
        if(Jet_PT[ijet0]>=hardpt){
        hardpt = Jet_PT[ijet0];
        ID[0] = ijet0;
        }
        }
        hardpt = 0;
        for (int ijet1=0 ; ijet1<kMaxJet ; ijet1++ ){
        if ( fabs(Jet_Eta[ijet1])>2.4 ) continue;
        if (ijet1 == ID[0]) continue;
        if(Jet_PT[ijet1]>=hardpt){
        hardpt = Jet_PT[ijet1];
        ID[1] = ijet1;
        }
        }
        hardpt = 0;
        for (int ijet2=0 ; ijet2<kMaxJet ; ijet2++ ){
```

```
if ( fabs(Jet_Eta[ijet2])>2.4 ) continue;
if ( ijet2==ID[0] || ijet2==ID[1] ) continue;
if(Jet_PT[ijet2]>=hardpt){
hardpt = Jet_PT[ijet2];
ID[2] = ijet2;
}
}
hardpt = 0;
for (int ijet3=0 ; ijet3<kMaxJet ; ijet3++ ){
if ( fabs(Jet_Eta[ijet3])>2.4 ) continue;
if ( ijet3==ID[0] || ijet3==ID[1] || ijet3==ID[2]) continue;
if(Jet_PT[ijet3]>=hardpt){
hardpt = Jet_PT[ijet3];
ID[3] = ijet3;
}
}
for(int ijet=0; ijet<4; ijet++){
Jet_E[ijet]=Jet_PT[ID[ijet]]*Jet_PT[ID[ijet]]*cosh(Jet_Eta[ID[
    ijet]])*cosh(Jet_Eta[ID[ijet]]) + Jet_Mass[ID[ijet]]*
    Jet_Mass[ID[ijet]];
Jet_E[ijet]=sqrt(Jet_E[ijet]);
}//end of ijet
for(int k0=1; k0<4; k0++){
invmass[k0-1] = pow( ( Jet_PT[ID[0]]*cos(Jet_Phi[ID[0]]) +
    Jet_PT[ID[k0]]*cos(Jet_Phi[ID[k0]]) ) , 2 ) + pow( (
    Jet_PT[ID[0]]*sin(Jet_Phi[ID[0]]) + Jet_PT[ID[k0]]*sin(
    Jet_Phi[ID[k0]]) ) , 2 ) + pow( ( Jet_PT[ID[0]]*sinh(
    Jet_Eta[ID[0]]) + Jet_PT[ID[k0]]*sinh(Jet_Eta[ID[k0]]) ) ,
     2 );
invmass[k0-1] = pow( (Jet_E[0]+Jet_E[k0]) , 2 ) - invmass[k0
    -1];
invmass[k0-1] = sqrt(invmass[k0-1]);
dminv[k0-1] = fabs(invmass[k0-1]-Z_mass);
}
for(int k1=2; k1<4; k1++){
invmass[k1+1] = pow( ( Jet_PT[ID[1]]*cos(Jet_Phi[ID[1]]) +
    Jet_PT[ID[k1]]*cos(Jet_Phi[ID[k1]]) ) , 2 ) + pow( (
    Jet_PT[ID[1]]*sin(Jet_Phi[ID[1]]) + Jet_PT[ID[k1]]*sin(
```

```
      Jet_Phi[ID[k1]]) ) , 2 ) + pow( ( Jet_PT[ID[1]]*sinh(
      Jet_Eta[ID[1]]) + Jet_PT[ID[k1]]*sinh(Jet_Eta[ID[k1]]) ) ,
       2 );
    invmass[k1+1] = pow( (Jet_E[1]+Jet_E[k1]) , 2 ) - invmass[k1
      +1];
    invmass[k1+1] = sqrt(invmass[k1+1]);
    dminv[k1+1] = fabs(invmass[k1+1]-Z_mass);
    }
    invmass[5] = pow( ( Jet_PT[ID[2]]*cos(Jet_Phi[ID[2]]) + Jet_PT
      [ID[3]]*cos(Jet_Phi[ID[3]]) ) , 2 ) + pow( ( Jet_PT[ID
      [2]]*sin(Jet_Phi[ID[2]]) + Jet_PT[ID[3]]*sin(Jet_Phi[ID
      [3]]) ) , 2 ) + pow( ( Jet_PT[ID[2]]*sinh(Jet_Eta[ID[2]])
      + Jet_PT[ID[3]]*sinh(Jet_Eta[ID[3]]) ) , 2 );
    invmass[5] = pow( (Jet_E[2]+Jet_E[3]) , 2 ) - invmass[5];
    invmass[5] = sqrt(invmass[5]);
    dminv[5] = fabs(invmass[5]-Z_mass);
//now let's look for the smallest one
    float s_dm=dminv[0];
    int i_dm_1=0;
    for(int im=0; im<6; im++){
    if(dminv[im]<=s_dm){
    s_dm=dminv[im];
    i_dm_1=im;
    }
    }
    if(i_dm_1==0)   { //
    Jet_ID[0]=ID[0] ;
    Jet_ID[1]=ID[1] ;
    Jet_ID[2]=ID[2] ;
    Jet_ID[3]=ID[3] ;
    }//
    if(i_dm_1==1)   { //
    Jet_ID[0]=ID[0] ;
    Jet_ID[1]=ID[2] ;
    Jet_ID[2]=ID[1] ;
    Jet_ID[3]=ID[3] ;
    }//
    if(i_dm_1==2)   { //
```

```
        Jet_ID[0]=ID[0] ;
        Jet_ID[1]=ID[3] ;
        Jet_ID[2]=ID[1] ;
        Jet_ID[3]=ID[2] ;
        }//
        if(i_dm_1==3)   { //
        Jet_ID[0]=ID[1] ;
        Jet_ID[1]=ID[2] ;
        Jet_ID[2]=ID[0] ;
        Jet_ID[3]=ID[3] ;
        }//
        if(i_dm_1==4)   { //
        Jet_ID[0]=ID[1] ;
        Jet_ID[1]=ID[3] ;
        Jet_ID[2]=ID[0] ;
        Jet_ID[3]=ID[2] ;
        }//
        if(i_dm_1==5)   { //
        Jet_ID[0]=ID[2] ;
        Jet_ID[1]=ID[3] ;
        Jet_ID[2]=ID[1] ;
        Jet_ID[3]=ID[0] ;
        }//
//let's select the direction of the Z bosons based on the jets center
    of mass
float px, py, pz;
//for the first Z
        px = Jet_PT[Jet_ID[0]]*cos(Jet_Phi[Jet_ID[0]]) + Jet_PT[Jet_ID
            [1]]*cos(Jet_Phi[Jet_ID[1]]);
        py = Jet_PT[Jet_ID[0]]*sin(Jet_Phi[Jet_ID[0]]) + Jet_PT[Jet_ID
            [1]]*sin(Jet_Phi[Jet_ID[1]]);
        pz = Jet_PT[Jet_ID[0]]*sinh(Jet_Eta[Jet_ID[0]]) + Jet_PT[
            Jet_ID[1]]*sinh(Jet_Eta[Jet_ID[1]]);
        Z_PT[0] = sqrt( pow(px,2) + pow(py,2));
        Z_Phi[0] = acos (px/Z_PT[0]);
        Z_Eta[0] = ASinH (pz/Z_PT[0]);
//for the second Z
```

```
        px = Jet_PT[Jet_ID[2]]*cos(Jet_Phi[Jet_ID[2]]) + Jet_PT[Jet_ID
           [3]]*cos(Jet_Phi[Jet_ID[3]]);
        py = Jet_PT[Jet_ID[2]]*sin(Jet_Phi[Jet_ID[2]]) + Jet_PT[Jet_ID
           [3]]*sin(Jet_Phi[Jet_ID[3]]);
        pz = Jet_PT[Jet_ID[2]]*sinh(Jet_Eta[Jet_ID[2]]) + Jet_PT[
           Jet_ID[3]]*sinh(Jet_Eta[Jet_ID[3]]);
        Z_PT[1] = sqrt( pow(px,2) + pow(py,2));
        Z_Phi[1] = acos (px/Z_PT[1]);
        Z_Eta[1] = ASinH (pz/Z_PT[1]);
//let's change the jets origin
        for(int jeti=0; jeti<4; jeti++){//******
        Jet_X[jeti] = gRandom -> Gaus(0,sigma);
        Jet_Y[jeti] = gRandom -> Gaus(0,sigma);
        Jet_Z[jeti] = gRandom -> Gaus(0,sigma);
        }//end of jeti
//let's change a little the vertex for the original model
        for(int iz=0; iz<2; iz++){
float SMR;
SMR = gRandom -> Gaus(0,z_sigma);
        Z_X[iz] = SMR*cos(Pi()-Z_Phi[iz])*sin(2*atan(exp(-(Pi()-Z_Eta[
           iz]))));
        Z_Y[iz] = SMR*sin(Pi()-Z_Phi[iz])*sin(2*atan(exp(-(Pi()-Z_Eta[
           iz]))));
        Z_Z[iz] = SMR*cos(2*atan(exp(-(Pi()-Z_Eta[iz]))));
        }
//let's find the vector for the shortest distance and IP in the
   original model SM
float theta;
int aux_mj;
        for(int mj=0; mj<4; mj++){
        SM_IP[mj]=0;
        if(mj==0 || mj==1) aux_mj=0;
        if(mj==2 || mj==3) aux_mj=1;
        if(Jet_PT[Jet_ID[mj]]<50) continue;//comment for no cut
        theta = 2*atan(exp(-Jet_Eta[Jet_ID[mj]]));
        Small_X[mj] = pow( Z_X[aux_mj] , 2) + pow( Z_Y[aux_mj] , 2) +
           pow( Z_Z[aux_mj], 2 ) + Z_Y[aux_mj]*(Jet_X[mj]*tan(Jet_Phi
           [Jet_ID[mj]])-Jet_Y[mj]) + Z_Z[aux_mj]*(Jet_X[mj]/(cos(
```

```
        Jet_Phi[Jet_ID[mj]])*tan(theta))-Jet_Y[mj]);
    Small_X[mj] = Small_X[mj]/(Z_X[aux_mj]+Z_Y[aux_mj]*tan(Jet_Phi
        [Jet_ID[mj]])+Z_Z[aux_mj]/(cos(Jet_Phi[Jet_ID[mj]])*tan(
        theta)));
    Small_Y[mj] = Jet_Y[mj] + (Small_X[mj] - Jet_X[mj])*tan(
        Jet_Phi[Jet_ID[mj]]);
    Small_Z[mj] = Jet_Z[mj] + (Small_X[mj] - Jet_X[mj])/(cos(
        Jet_Phi[Jet_ID[mj]])*tan(theta));
    SM_IP[mj] = Small_X[mj]*Z_PT[aux_mj]*cos(Z_Phi[aux_mj]) +
        Small_Y[mj]*Z_PT[aux_mj]*sin(Z_Phi[aux_mj]) +Small_Z[mj]*
        Z_PT[aux_mj]*sinh(Z_Eta[aux_mj]);
    myfile1<<SM_IP[mj]<<endl;
    countip++;
    }
//applying some cuts and storing some information in .dat
    for(int pti=0; pti<4; pti++){
    myfile2<<Jet_PT[Jet_ID[pti]]<<endl;
    }
    myfile3<<invmass[0]<<endl;
    if(Jet_PT[Jet_ID[0]]>50 && Jet_PT[Jet_ID[1]]>50){
    myfile4<<invmass[0]<<endl;
    if(SM_IP[0]<=-10 && SM_IP[1]<=-10){
    myfile5<<invmass[0]<<endl;
    }
    }
  }//end of jentry
myfile1.close();
myfile2.close();
myfile3.close();
myfile4.close();
myfile5.close();
cout<<"original: "<<countjets<<endl;
cout<<"at least 4 jets: "<<count4jets<<endl;
cout<<"after ip: "<<countip<<endl;
}
/*************************************************************/

void smevents::causal()
```

```
{
//The causal() function will filter some data, and then
//give the mother particles vertices a causal displace displacement
//after giving smearing the vertices of the mother particles and
//the positions of the jets that come from it.
//The invariant mass for the hardest jets is computed. The pseudo
//impact parameter is computed. A cleaner invariant mass is computed.

   if (fChain == 0) return;
   Long64_t nentries = fChain->GetEntriesFast();
   Long64_t nbytes = 0, nb = 0;
   ofstream myfile1;
   ofstream myfile2;
   ofstream myfile3;
   ofstream myfile4;
   ofstream myfile5;
   myfile1.open("ip_causal.dat");
   myfile2.open("pt_causal.dat");
   myfile3.open("im_causal.dat");
   myfile4.open("cim_causal.dat");
   myfile5.open("cut_ip_causal.dat");
//variables to count the number of jets after every filter
        int             count4jets=0;
        int             countip=0;
        int             countjets=0;
//variables to find the hardest jets and compute the
//invariant mass
        float           hardpt;
        int             ID[4];
        int             Jet_ID[4];
        float           invmass[6];
        float           Jet_E[4];
        float           dminv[6];
//Z boson mass in GeV
        float           Z_mass = 91.1876;
        int             Z_ID[4]; //0 from first Z, 1 from second Z
        Float_t         Z_PT[2];
        Float_t         Z_Phi[2];
```

```
        Float_t          Z_Eta[2];
        Float_t          Z_X[2];
        Float_t          Z_Y[2];
        Float_t          Z_Z[2];
        Float_t fPx[2];
        Float_t fPy[2];
        Float_t fPz[2];
//variables to change and exchange the vertex of the Z
        Float_t d_sigma=30e-3; //20um
        Float_t sigma=9e-3; //9um
        Float_t z_sigma=9e-5;
        Float_t Jet_X[4];
        Float_t Jet_Y[4];
        Float_t Jet_Z[4];
        Float_t Small_X[4];
        Float_t Small_Y[4];
        Float_t Small_Z[4];
//variables to determine the impact parameter
        Float_t SM_IP[4];
   for (Long64_t jentry=0; jentry<nentries;jentry++) {
      Long64_t ientry = LoadTree(jentry);
      if (ientry < 0) break;
      nb = fChain->GetEntry(jentry);   nbytes += nb;
      // if (Cut(ientry) < 0) continue;
        for (int ijjet=0 ; ijjet<kMaxJet ; ijjet++ ){
        if (Jet_PT[ijjet]==0) continue;
        countjets++;
        }
        if (Jet_PT[3]==0) continue;
        for (int jjjet=0 ; jjjet<kMaxJet ; jjjet++ ){
        if (Jet_PT[jjjet]==0) continue;
        count4jets++;
        }
//let's find the 4 hardest jets
        hardpt = 0;
        for (int ijet0=0 ; ijet0<kMaxJet ; ijet0++ ){
        if ( fabs(Jet_Eta[ijet0])>2.4 ) continue;
        if(Jet_PT[ijet0]>=hardpt){
```

```
hardpt = Jet_PT[ijet0];
ID[0] = ijet0;
}
}
hardpt = 0;
for (int ijet1=0 ; ijet1<kMaxJet ; ijet1++ ){
if ( fabs(Jet_Eta[ijet1])>2.4 ) continue;
if (ijet1 == ID[0]) continue;
if(Jet_PT[ijet1]>=hardpt){
hardpt = Jet_PT[ijet1];
ID[1] = ijet1;
}
}
hardpt = 0;
for (int ijet2=0 ; ijet2<kMaxJet ; ijet2++ ){
if ( fabs(Jet_Eta[ijet2])>2.4 ) continue;
if ( ijet2==ID[0] || ijet2==ID[1] ) continue;
if(Jet_PT[ijet2]>=hardpt){
hardpt = Jet_PT[ijet2];
ID[2] = ijet2;
}
}
hardpt = 0;
for (int ijet3=0 ; ijet3<kMaxJet ; ijet3++ ){
if ( fabs(Jet_Eta[ijet3])>2.4 ) continue;
if ( ijet3==ID[0] || ijet3==ID[1] || ijet3==ID[2]) continue;
if(Jet_PT[ijet3]>=hardpt){
hardpt = Jet_PT[ijet3];
ID[3] = ijet3;
}
}
for(int ijet=0; ijet<4; ijet++){
Jet_E[ijet]=Jet_PT[ID[ijet]]*Jet_PT[ID[ijet]]*cosh(Jet_Eta[ID[
    ijet]])*cosh(Jet_Eta[ID[ijet]]) + Jet_Mass[ID[ijet]]*
    Jet_Mass[ID[ijet]];
Jet_E[ijet]=sqrt(Jet_E[ijet]);
}//end of ijet
for(int k0=1; k0<4; k0++){
```

```
        invmass[k0-1] = pow( ( Jet_PT[ID[0]]*cos(Jet_Phi[ID[0]]) +
           Jet_PT[ID[k0]]*cos(Jet_Phi[ID[k0]]) ) , 2 ) + pow( (
           Jet_PT[ID[0]]*sin(Jet_Phi[ID[0]]) + Jet_PT[ID[k0]]*sin(
           Jet_Phi[ID[k0]]) ) , 2 ) + pow( ( Jet_PT[ID[0]]*sinh(
           Jet_Eta[ID[0]]) + Jet_PT[ID[k0]]*sinh(Jet_Eta[ID[k0]]) ) ,
            2 );
        invmass[k0-1] = pow( (Jet_E[0]+Jet_E[k0]) , 2 ) - invmass[k0
           -1];
        invmass[k0-1] = sqrt(invmass[k0-1]);
        dminv[k0-1] = fabs(invmass[k0-1]-Z_mass);
        }
        for(int k1=2; k1<4; k1++){
        invmass[k1+1] = pow( ( Jet_PT[ID[1]]*cos(Jet_Phi[ID[1]]) +
           Jet_PT[ID[k1]]*cos(Jet_Phi[ID[k1]]) ) , 2 ) + pow( (
           Jet_PT[ID[1]]*sin(Jet_Phi[ID[1]]) + Jet_PT[ID[k1]]*sin(
           Jet_Phi[ID[k1]]) ) , 2 ) + pow( ( Jet_PT[ID[1]]*sinh(
           Jet_Eta[ID[1]]) + Jet_PT[ID[k1]]*sinh(Jet_Eta[ID[k1]]) ) ,
            2 );
        invmass[k1+1] = pow( (Jet_E[1]+Jet_E[k1]) , 2 ) - invmass[k1
           +1];
        invmass[k1+1] = sqrt(invmass[k1+1]);
        dminv[k1+1] = fabs(invmass[k1+1]-Z_mass);
        }
        invmass[5] = pow( ( Jet_PT[ID[2]]*cos(Jet_Phi[ID[2]]) + Jet_PT
           [ID[3]]*cos(Jet_Phi[ID[3]]) ) , 2 ) + pow( ( Jet_PT[ID
           [2]]*sin(Jet_Phi[ID[2]]) + Jet_PT[ID[3]]*sin(Jet_Phi[ID
           [3]]) ) , 2 ) + pow( ( Jet_PT[ID[2]]*sinh(Jet_Eta[ID[2]])
           + Jet_PT[ID[3]]*sinh(Jet_Eta[ID[3]]) ) , 2 );
        invmass[5] = pow( (Jet_E[2]+Jet_E[3]) , 2 ) - invmass[5];
        invmass[5] = sqrt(invmass[5]);
        dminv[5] = fabs(invmass[5]-Z_mass);
//now let's look for the smallest one
        float s_dm=dminv[0];
        int i_dm_1=0;
        for(int im=0; im<6; im++){
        if(dminv[im]<=s_dm){
        s_dm=dminv[im];
        i_dm_1=im;
```

```
}
}
if(i_dm_1==0)   { //
Jet_ID[0]=ID[0] ;
Jet_ID[1]=ID[1] ;
Jet_ID[2]=ID[2] ;
Jet_ID[3]=ID[3] ;
}//
if(i_dm_1==1)   { //
Jet_ID[0]=ID[0] ;
Jet_ID[1]=ID[2] ;
Jet_ID[2]=ID[1] ;
Jet_ID[3]=ID[3] ;
}//
if(i_dm_1==2)   { //
Jet_ID[0]=ID[0] ;
Jet_ID[1]=ID[3] ;
Jet_ID[2]=ID[1] ;
Jet_ID[3]=ID[2] ;
}//
if(i_dm_1==3)   { //
Jet_ID[0]=ID[1] ;
Jet_ID[1]=ID[2] ;
Jet_ID[2]=ID[0] ;
Jet_ID[3]=ID[3] ;
}//
if(i_dm_1==4)   { //
Jet_ID[0]=ID[1] ;
Jet_ID[1]=ID[3] ;
Jet_ID[2]=ID[0] ;
Jet_ID[3]=ID[2] ;
}//
if(i_dm_1==5)   { //
Jet_ID[0]=ID[2] ;
Jet_ID[1]=ID[3] ;
Jet_ID[2]=ID[1] ;
Jet_ID[3]=ID[0] ;
}//
```

```
//let's select the direction of the Z bosons based on the jets center
    of mass
float px, py, pz;
//for the first Z
        px = Jet_PT[Jet_ID[0]]*cos(Jet_Phi[Jet_ID[0]]) + Jet_PT[Jet_ID
           [1]]*cos(Jet_Phi[Jet_ID[1]]);
        py = Jet_PT[Jet_ID[0]]*sin(Jet_Phi[Jet_ID[0]]) + Jet_PT[Jet_ID
           [1]]*sin(Jet_Phi[Jet_ID[1]]);
        pz = Jet_PT[Jet_ID[0]]*sinh(Jet_Eta[Jet_ID[0]]) + Jet_PT[
           Jet_ID[1]]*sinh(Jet_Eta[Jet_ID[1]]);
        Z_PT[0] = sqrt( pow(px,2) + pow(py,2));
        Z_Phi[0] = acos (px/Z_PT[0]);
        Z_Eta[0] = ASinH (pz/Z_PT[0]);
//for the second Z
        px = Jet_PT[Jet_ID[2]]*cos(Jet_Phi[Jet_ID[2]]) + Jet_PT[Jet_ID
           [3]]*cos(Jet_Phi[Jet_ID[3]]);
        py = Jet_PT[Jet_ID[2]]*sin(Jet_Phi[Jet_ID[2]]) + Jet_PT[Jet_ID
           [3]]*sin(Jet_Phi[Jet_ID[3]]);
        pz = Jet_PT[Jet_ID[2]]*sinh(Jet_Eta[Jet_ID[2]]) + Jet_PT[
           Jet_ID[3]]*sinh(Jet_Eta[Jet_ID[3]]);
        Z_PT[1] = sqrt( pow(px,2) + pow(py,2));
        Z_Phi[1] = acos (px/Z_PT[1]);
        Z_Eta[1] = ASinH (pz/Z_PT[1]);
//let's change the jets origin
        for(int jeti=0; jeti<4; jeti++){//******
        Jet_X[jeti] = gRandom -> Gaus(0,sigma);
        Jet_Y[jeti] = gRandom -> Gaus(0,sigma);
        Jet_Z[jeti] = gRandom -> Gaus(0,sigma);
        }//end of jeti
//let's change a little the vertex for the original model
        for(int iz=0; iz<2; iz++){
float SMR;
SMR = gRandom -> Gaus(0,z_sigma);
        Z_X[iz] = SMR*cos(Pi()-Z_Phi[iz])*sin(2*atan(exp(-(Pi()-Z_Eta[
           iz]))));
        Z_Y[iz] = SMR*sin(Pi()-Z_Phi[iz])*sin(2*atan(exp(-(Pi()-Z_Eta[
           iz]))));
        Z_Z[iz] = SMR*cos(2*atan(exp(-(Pi()-Z_Eta[iz]))));
```

```
        }
//let's find the vector for the shortest distance and IP in the
    original model SM
float theta;
int aux_mj;
float d;
        while (d<20e-3){
        d = gRandom -> Gaus(0,d_sigma);
        }
        for(int ia=0; ia<2; ia++){//****
        fPx[ia] = d*cos(Z_Phi[ia])*sin(2*atan(exp(-Z_Eta[ia])));
        fPy[ia] = d*sin(Z_Phi[ia])*sin(2*atan(exp(-Z_Eta[ia])));
        fPz[ia] = d*cos(2*atan(exp(-Z_Eta[ia])));
        Z_X[ia]=Z_X[ia]+fPx[ia];
        Z_Y[ia]=Z_Y[ia]+fPy[ia];
        Z_Z[ia]=Z_Z[ia]+fPz[ia];
        }
        for(int mj=0; mj<4; mj++){
        SM_IP[mj]=0;
        if(mj==0 || mj==1) aux_mj=0;
        if(mj==2 || mj==3) aux_mj=1;
        if(Jet_PT[Jet_ID[mj]]<50) continue;//comment for no cut
        theta = 2*atan(exp(-Jet_Eta[Jet_ID[mj]]));
        Small_X[mj] = pow( Z_X[aux_mj] , 2) + pow( Z_Y[aux_mj] , 2) +
            pow( Z_Z[aux_mj], 2 ) + Z_Y[aux_mj]*(Jet_X[mj]*tan(Jet_Phi
            [Jet_ID[mj]])-Jet_Y[mj]) + Z_Z[aux_mj]*(Jet_X[mj]/(cos(
            Jet_Phi[Jet_ID[mj]])*tan(theta))-Jet_Y[mj]);
        Small_X[mj] = Small_X[mj]/(Z_X[aux_mj]+Z_Y[aux_mj]*tan(Jet_Phi
            [Jet_ID[mj]])+Z_Z[aux_mj]/(cos(Jet_Phi[Jet_ID[mj]])*tan(
            theta)));
        Small_Y[mj] = Jet_Y[mj] + (Small_X[mj] - Jet_X[mj])*tan(
            Jet_Phi[Jet_ID[mj]]);
        Small_Z[mj] = Jet_Z[mj] + (Small_X[mj] - Jet_X[mj])/(cos(
            Jet_Phi[Jet_ID[mj]])*tan(theta));
        SM_IP[mj] = Small_X[mj]*Z_PT[aux_mj]*cos(Z_Phi[aux_mj]) +
            Small_Y[mj]*Z_PT[aux_mj]*sin(Z_Phi[aux_mj]) +Small_Z[mj]*
            Z_PT[aux_mj]*sinh(Z_Eta[aux_mj]);
        myfile1<<SM_IP[mj]<<endl;
```

```
        countip++;
        }
        for(int pti=0; pti<4; pti++){
        myfile2<<Jet_PT[Jet_ID[pti]]<<endl;
        }
        myfile3<<invmass[0]<<endl;
        if(Jet_PT[Jet_ID[0]]>50 && Jet_PT[Jet_ID[1]]>50){
        myfile4<<invmass[0]<<endl;
        if(SM_IP[0]<=-10 && SM_IP[1]<=-10){
        myfile5<<invmass[0]<<endl;
        }
        }
   }//end of jentry
myfile1.close();
myfile2.close();
myfile3.close();
myfile4.close();
myfile5.close();
cout<<"original: "<<countjets<<endl;
cout<<"at least 4 jets: "<<count4jets<<endl;
cout<<"after ip: "<<countip<<endl;
}
```

9.3 Appendix III: Scripts for analysing $t\bar{t}$ production background events.

The following script, dileptons.C, works for $t\bar{t}$ events where the W bosons from the process only decay to dileptons.

```
//Author: Raquel Quishpe
#define dileptons_cxx
#include "dileptons.h"
#include <TH2.h>
#include <TStyle.h>
#include <TCanvas.h>
#include <TRandom.h>
#include <iostream>
#include <fstream>
```

```
#include "TMath.h"
using TMath::ASinH;
using namespace TMath;
using namespace std;

void dileptons::pt()
{
   if (fChain == 0) return;
   Long64_t nentries = fChain->GetEntriesFast();
   Long64_t nbytes = 0, nb = 0;
   float hardpt=0;
   Int_t ID[2];
ofstream myfile1;
ofstream myfile2;
ofstream myfile3;
myfile1.open("pt_dileptons.dat");
myfile2.open("im_dileptons.dat");
myfile3.open("cim_dileptons.dat");
   for (Long64_t jentry=0; jentry<nentries;jentry++) {
      Long64_t ientry = LoadTree(jentry);
      if (ientry < 0) break;
      nb = fChain->GetEntry(jentry);   nbytes += nb;
      // if (Cut(ientry) < 0) continue;
//only accept events that have at least 2 jets
        if(Jet_PT[1]==0) continue;
//finding the 2 hardest jets
        hardpt=0;
        for(int j0=0; j0<kMaxJet; j0++){
        if (Jet_PT[j0]==0) continue;
        if (fabs(Jet_Eta[j0])>2.4) continue;
        if (fabs(Jet_PT[j0])>=hardpt){
        hardpt  = fabs(Jet_PT[j0]);
        ID[0]   = j0;
        }
        }
        hardpt=0;
        for(int j1=0; j1<kMaxJet; j1++){
        if (j1==ID[0]) continue;
```

```
        if (Jet_PT[j1]==0) continue;
        if (fabs(Jet_Eta[j1])>2.4) continue;
        if (fabs(Jet_PT[j1])>=hardpt){
        hardpt  = fabs(Jet_PT[j1]);
        ID[1]   = j1;
        }
        }
        for(int k=0; k<2; k++){
        myfile1<<Jet_PT[ID[k]]<<endl;
        }
float hardinvm;
float jete1, jete2;
   jete1 = sqrt( pow( Jet_Mass[ID[0]] ,2 ) + pow( Jet_PT[ID[0]]*cosh(
      Jet_Eta[ID[0]]) ,2 ) );
   jete2 = sqrt( pow( Jet_Mass[ID[1]] ,2 ) + pow( Jet_PT[ID[1]]*cosh(
      Jet_Eta[ID[1]]) ,2 ) );
   hardinvm = sqrt( pow( jete1+jete2 ,2 ) - pow((Jet_PT[ID[0]]*cos(
      Jet_Phi[ID[0]])+Jet_PT[ID[1]]*cos(Jet_Phi[ID[1]])),2) - pow((
      Jet_PT[ID[0]]*sin(Jet_Phi[ID[0]])+Jet_PT[ID[1]]*sin(Jet_Phi[ID
      [1]])),2 ) - pow((Jet_PT[ID[0]]*sinh(Jet_Eta[ID[0]])+Jet_PT[ID
      [1]]*sinh(Jet_Eta[ID[1]])),2) );
        myfile2<<hardinvm<<endl;
        if(Jet_PT[ID[0]]>50 || Jet_PT[ID[1]]>50){
        myfile3<<hardinvm<<endl;
        }
   }//end of nentries
myfile1.close();
myfile2.close();
myfile3.close();
}// end of pt()
//*****************************************************

void dileptons::iparameter()
{
   if (fChain == 0) return;
   Long64_t nentries = fChain->GetEntriesFast();
   Long64_t nbytes = 0, nb = 0;
        float hardpt=0;
```

```
        Int_t ID[2];
        int countip=0;
        int countjet=0;
        int count2j=0;
        float drt[4];
        float aux_drt;
        int aux_id;
        int id[2];
        float sx,sy,sz,ip,theta;
        float x,y,z;
        float vx,vy,vz;
        Float_t j_sigma=9e-3; //9um for the jet component
        Float_t t_sigma=9e-5;//for the t vertex
ofstream myfile;
myfile.open("ip_dileptons.dat");
   for (Long64_t jentry=0; jentry<nentries;jentry++) {
      Long64_t ientry = LoadTree(jentry);
      if (ientry < 0) break;
      nb = fChain->GetEntry(jentry);   nbytes += nb;
      // if (Cut(ientry) < 0) continue;
        for(int a=0; a<kMaxJet; a++){
        countjet++;
        }
//only accept events that have at least 2 jets
        if(Jet_PT[1]==0) continue;
        for(int b=0; b<kMaxJet; b++){
        count2j++;
        }
//finding the 2 hardest jets
        hardpt=0;
        for(int j0=0; j0<kMaxJet; j0++){
        if (Jet_PT[j0]==0) continue;
        if (fabs(Jet_Eta[j0])>2.4) continue;
        if (fabs(Jet_PT[j0])>=hardpt){
        hardpt   = fabs(Jet_PT[j0]);
        ID[0]    = j0;
        }
        }
```

```
        hardpt=0;
        for(int j1=0; j1<kMaxJet; j1++){
        if (j1==ID[0]) continue;
        if (Jet_PT[j1]==0) continue;
        if (fabs(Jet_Eta[j1])>2.4) continue;
        if (fabs(Jet_PT[j1])>=hardpt){
        hardpt   = fabs(Jet_PT[j1]);
        ID[1]    = j1;
        }
        }
//setting the mother particle
        for(int kj=0; kj<2; kj++){
        drt[kj]   = sqrt ( pow( (Jet_Phi[ID[kj]]-Particle_Phi[6]) , 2
           ) + pow( (Jet_Eta[ID[kj]]-Particle_Eta[6]) , 2 ) );
        drt[kj+2] = sqrt ( pow( (Jet_Phi[ID[kj]]-Particle_Phi[7]) , 2
           ) + pow( (Jet_Eta[ID[kj]]-Particle_Eta[7]) , 2 ) );
        }
aux_drt = drt[0];
        for(int kn=0; kn<2; kn++){
        if(drt[kn]<=aux_drt){
        aux_drt = drt[kn];
        aux_id = kn;
        }
        }
        if ( aux_id==0 || aux_id==3 ){
        id[0]=6;
        id[1]=7;
        }
        if ( aux_id==1 || aux_id==2 ){
        id[0]=7;
        id[1]=6;
        }
//displacing the vertices and computing ip
        for(int k=0; k<2; k++){
        x = gRandom->Gaus(0,j_sigma);
        y = gRandom->Gaus(0,j_sigma);
        z = gRandom->Gaus(0,j_sigma);
        vx = gRandom->Gaus(0,t_sigma);
```

```
        vy = gRandom->Gaus(0,t_sigma);
        vz = gRandom->Gaus(0,t_sigma);
        theta = 2*atan(exp(-Jet_Eta[ID[k]]));
        sx = (vx*vx + vy*vy + vz*vz + vy*(x*tan(Jet_Phi[ID[k]])-y) +
           vz*(x/(cos(Jet_Phi[ID[k]])*tan(theta))-z))/(vx + vy*tan(
           theta) + vz/(cos(Jet_Phi[ID[k]])*tan(theta)));
        sy = y + (sx-x)*tan(Jet_Phi[ID[k]]);
        sz = z + (sx-x)/(cos(Jet_Phi[ID[k]])*tan(theta));
        ip = sx*Particle_PT[id[k]]*cos(Particle_Phi[id[k]]) + sy*
           Particle_PT[id[k]]*sin(Particle_PT[id[k]]) + sz*
           Particle_PT[id[k]]*sinh(Particle_Eta[id[k]]);
myfile<<ip<<endl;
        countip++;
        }
   }//end of nentries
myfile.close();
cout<<"original: "<<countjet<<endl;
cout<<"after at least 2 jets: "<<count2j<<endl;
cout<<"after ip: "<<countip<<endl;
}// end of iparameter()


void dileptons::borrar()
{

   if (fChain == 0) return;
   Long64_t nentries = fChain->GetEntriesFast();
   Long64_t nbytes = 0, nb = 0;

//variables to count the number of jets after every filter
        int countsm=0;

   for (Long64_t jentry=0; jentry<nentries;jentry++) {
      Long64_t ientry = LoadTree(jentry);
      if (ientry < 0) break;
      nb = fChain->GetEntry(jentry);   nbytes += nb;
      // if (Cut(ientry) < 0) continue;
        int aux=0;
```

```
        if (Jet_PT[3]==0 && Jet_PT[4]==0) continue;
        for (int i=0 ; i<kMaxJet; i++){
        if ( fabs(Jet_Eta[i]) < 2.4) continue;
        aux=aux+1;
        }
        if (aux>0) countsm++;
    }//end of jentry

cout<<endl<<countsm<<endl;
}
```

For the rest of the processes in $t\bar{t}$ events, an analogue script is used.

9.4 Appendix IV: Weight factors.

For the scripts mentioned in Appendix V, the library constants.h is needed. It stores the weight for each process generated so that the histograms that are plotted can be normalized. The weights were computed with the number of events, cross section and integrated luminosity of each event.

```
//Author: Raquel Quishpe
#define wsm             0.782
#define wdileptons      3.454
#define whadronic       1.7086
#define wwplus          2.958066667
#define wwminus         2.956866667
#define wlw             0.3335
```

9.5 Appendix V: Scripts used for plotting.

The plotpt.C script, plots the transversal momentum for the jets that were selected from each signal. The entries for the histograms are normalized with the total cross section of each process, the number of events generated, and an integrated luminosity of 100 fb^{-1}. For the cuts made in section 6, only jets with PT>50 GeV were plotted, and since more than 4 jets are required, the dileptons events will be neglected.

```
//Author: Raquel Quishpe
#include <TH2.h>
```

```
#include <TStyle.h>
#include <TCanvas.h>
#include <constants.h>
#include <THStack.h>

void plotpt()
{

//constructors for the plots
   TCanvas *c1  = new TCanvas("c1","c1",600,400);
   TH1F *h_data  =   new TH1F("h_data","h_data",100, 15, 450);
   TH1F *h_SM_pt = new TH1F("h_SM_pt","h_SM_pt",100, 15, 450);
   TH1F *h_LW_pt = new TH1F("h_LW_pt","h_LW_pt",100, 15, 450);
   TH1F *h_tt_pt = new TH1F("h_tt_pt","h_tt_pt",100, 15, 450);
   TH1F *h_causal_pt = new TH1F("h_causal_pt","h_causal_pt",100, 15,
      450);
   THStack *hs = new THStack("hs"," ");
   h_data->Sumw2();
//for ttbar events
//for dileptons
TFile *f1dil = new TFile("dileptons_events.root","RECREATE");
TTree *diltree = new TTree("dileptons_events","ptpact parameter data
   for ttbar dileptons");
Long64_t dillines = diltree->ReadFile("pt_dileptons.dat","ptdileptons"
   );
Float_t ptdileptons;
diltree->SetBranchAddress("ptdileptons",&ptdileptons);
Int_t dilentries = diltree->GetEntriesFast();
for(Int_t dilentry=0; dilentry<dilentries; dilentry++){
diltree->GetEntry(dilentry);
if (ptdileptons==0) continue;
h_data->Fill(ptdileptons,wdileptons);
h_tt_pt->Fill(ptdileptons,wdileptons);
}
//for hadronic decay
TFile *f1had = new TFile("hadronic_events.root","RECREATE");
TTree *hadtree = new TTree("hadronic_events","ptpact parameter data
   for ttbar hadronic");
```

```
Long64_t hadlines = hadtree->ReadFile("pt_hadronic.dat","pthadronic");
Float_t pthadronic;
hadtree->SetBranchAddress("pthadronic",&pthadronic);
Int_t hadentries = hadtree->GetEntriesFast();
for(Int_t hadentry=0; hadentry<hadentries; hadentry++){
hadtree->GetEntry(hadentry);
if(pthadronic==0) continue;
h_data->Fill(pthadronic,whadronic);
h_tt_pt->Fill(pthadronic,whadronic);
}
//for wplus to leptons
TFile *f1wplus = new TFile("wplus_events.root","RECREATE");
TTree *wplustree = new TTree("wplus_events","ptpact parameter data for
    ttbar wplus");
Long64_t wpluslines = wplustree->ReadFile("pt_wplus.dat","ptwplus");
Float_t ptwplus;
wplustree->SetBranchAddress("ptwplus",&ptwplus);
Int_t wplusentries = wplustree->GetEntriesFast();
for(Int_t wplusentry=0; wplusentry<wplusentries; wplusentry++){
wplustree->GetEntry(wplusentry);
h_data->Fill(ptwplus,wwplus);
h_tt_pt->Fill(ptwplus,wwplus);
}
//for wminus to leptons
TFile *f1wminus = new TFile("wminus_events.root","RECREATE");
TTree *wminustree = new TTree("wminus_events","ptpact parameter data
   for ttbar wminus");
Long64_t wminuslines = wminustree->ReadFile("pt_wminus.dat","ptwminus"
   );
Float_t ptwminus;
wminustree->SetBranchAddress("ptwminus",&ptwminus);
Int_t wminusentries = wminustree->GetEntriesFast();
for(Int_t wminusentry=0; wminusentry<wminusentries; wminusentry++){
wminustree->GetEntry(wminusentry);
if (ptwminus==0) continue;
h_data->Fill(ptwminus,wwminus);
h_tt_pt->Fill(ptwminus,wwminus);
}
```

```
//************************************
//for SM
TFile *f2 = new TFile("sm_events.root","RECREATE");
TTree *smtree = new TTree("sm_events","ptpact parameter data for SM");
Long64_t mlines = smtree->ReadFile("pt_sm.dat","ptsm");
Float_t ptsm;
smtree->SetBranchAddress("ptsm",&ptsm);
Int_t smentries = smtree->GetEntriesFast();
for(Int_t smentry=0; smentry<smentries; smentry++){
smtree->GetEntry(smentry);
if (ptsm==0) continue;
h_data->Fill(ptsm,wsm);
h_SM_pt->Fill(ptsm,wsm);
}
//for SM causal
TFile *f2 = new TFile("causal_events.root","RECREATE");
TTree *causaltree = new TTree("causal_events","ptpact parameter data
   for casual");
Long64_t mlines = causaltree->ReadFile("pt_causal.dat","ptcausal");
Float_t ptcausal;
causaltree->SetBranchAddress("ptcausal",&ptcausal);
Int_t causalentries = causaltree->GetEntriesFast();
for(Int_t causalentry=0; causalentry<causalentries; causalentry++){
causaltree->GetEntry(causalentry);
if (ptcausal==0) continue;
h_data->Fill(ptcausal,wsm);
h_causal_pt->Fill(ptcausal,wsm);
}
//for LW
TFile *f3 = new TFile("lw_events.root","RECREATE");
TTree *lwtree = new TTree("lw_events","ptpact parameter data for LW");
Long64_t wlines = lwtree->ReadFile("pt_lw.dat","ptlw");
Float_t ptlw;
lwtree->SetBranchAddress("ptlw",&ptlw);
Int_t lwentries = lwtree->GetEntriesFast();
for(Int_t lwentry=0; lwentry<lwentries; lwentry++){
lwtree->GetEntry(lwentry);
if (ptlw==0)continue;
```

```
h_data->Fill(ptlw,wlw);
h_LW_pt->Fill(ptlw,wlw);
}
        TStyle *MyStyle = new TStyle("MyStyle","My Root Styles");
        MyStyle->SetStatColor(0);
        MyStyle->SetCanvasColor(0);
        MyStyle->SetPadColor(0);
        MyStyle->SetPadBorderMode(0);
        MyStyle->SetCanvasBorderMode(0);
        MyStyle->SetFrameBorderMode(0);
        MyStyle->SetOptStat(0);
        MyStyle->SetStatBorderSize(2);
        MyStyle->SetOptTitle(0);
        MyStyle->SetPadTickX(1);
        MyStyle->SetPadTickY(1);
        MyStyle->SetPadBorderSize(2);
        MyStyle->SetPalette(51, 0);
        MyStyle->SetPadBottomMargin(0.15);
        MyStyle->SetPadTopMargin(0.05);
        MyStyle->SetPadLeftMargin(0.15);
        MyStyle->SetPadRightMargin(0.25);
        MyStyle->SetTitleColor(1);
        MyStyle->SetTitleFillColor(0);
        MyStyle->SetTitleFontSize(0.05);
        MyStyle->SetTitleBorderSize(0);
        MyStyle->SetLineWidth(1);
        MyStyle->SetHistLineWidth(3);
        MyStyle->SetLegendBorderSize(0);
        MyStyle->SetNdivisions(502, "x");
        MyStyle->SetMarkerSize(0.8);
        MyStyle->SetTickLength(0.03);
        MyStyle->SetTitleOffset(1.5, "x");
        MyStyle->SetTitleOffset(1.5, "y");
        MyStyle->SetTitleOffset(1.0, "z");
        MyStyle->SetLabelSize(0.05, "x");
        MyStyle->SetLabelSize(0.05, "y");
        MyStyle->SetLabelSize(0.05, "z");
        MyStyle->SetLabelOffset(0.03, "x");
```

```
        MyStyle->SetLabelOffset(0.03, "y");
        MyStyle->SetLabelOffset(0.03, "z");
        MyStyle->SetTitleSize(0.05, "x");
        MyStyle->SetTitleSize(0.05, "y");
        MyStyle->SetTitleSize(0.05, "z");
        gROOT->SetStyle("MyStyle");
h_LW_pt->SetLineColor(kRed);
h_LW_pt->SetFillColor(kMagenta);
h_LW_pt->SetLineWidth(1);
h_LW_pt->SetTitle();
h_SM_pt->SetLineColor(kCyan);
h_SM_pt->SetFillColor(kGreen);
h_SM_pt->SetLineWidth(1);
h_SM_pt->SetTitle();
h_tt_pt->SetLineColor(kYellow);
h_tt_pt->SetFillColor(kOrange);
h_tt_pt->SetLineWidth(1);
h_tt_pt->SetTitle();
h_causal_pt->SetLineColor(kBlue);
h_causal_pt->SetFillColor(kCyan);
h_causal_pt->SetLineWidth(1);
h_causal_pt->SetTitle();
h_data->SetMarkerColor(kBlack);
h_data->SetMarkerStyle(7);
h_data->SetTitle();
h_data->GetYaxis()->SetTitle("Events");
h_data->GetXaxis()->SetTitle("PT [GeV]");
hs->Add(h_LW_pt,"sames");
hs->Add(h_tt_pt,"sames");
hs->Add(h_SM_pt,"sames");
hs->Add(h_causal_pt,"sames");
c1->cd();
hs->Draw();
hs->GetXaxis()->SetTitle("PT[GeV]");
hs->GetYaxis()->SetTitle("Events");
hs->GetXaxis()->SetNdivisions(510);
c1->Modify();
h_data->Draw("E1 sames P");
```

```
c1->Update();
gPad->SetLogy();
      leg = new TLegend(0.9,0.7,0.7,0.85);
      leg->SetFillStyle(1001);
      leg->SetFillColor(kWhite);
      leg->SetLineColor(kWhite);
      leg->SetLineWidth(2);
      leg->SetTextFont(42);
      leg->SetTextSize(0.038);
leg->AddEntry("h_LW_pt","LW events","f");
leg->AddEntry("h_SM_pt","ZZ events","f");
leg->AddEntry("h_causal_pt","ZZ displaced events","f");
leg->AddEntry("h_tt_pt","tt production","f");
leg->AddEntry("h_data","Data","*P");
leg->Draw("sames");
c1->Print("jetsPT.png");

cout<<"ttbar:"<<h_tt_pt->Integral(0,10000)<<endl;
cout<<"LW:"<<h_LW_pt->Integral(0,10000)<<endl;
cout<<"SM:"<<h_SM_pt->Integral(0,10000)<<endl;
cout<<"causal:"<<h_causal_pt->Integral(0,10000)<<endl;
cout<<"data:"<<h_data->Integral(0,10000)<<endl;
}//end of plotpt()
```

For the rest of the plots, i.e., invariant mass and pseudo impact parameter, a similar script was used.