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## Reconstruction, Analysis of the Process ggH Decay to llvv Monte Carlo with MH=125 GeV and Introduction of the Physical Background

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# Reconstruction, Analysis of the Process $ggH$ Decay to $ll\nu\nu$ Monte Carlo with $M_H=125$ GeV and Introduction of the Physical Background

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**Abstract:** This paper outlines analysis the process  $gg \rightarrow H \rightarrow WW \rightarrow ll\nu\nu$  Monte Carlo, collision events with  $M_H=125$  GeV. The discovery of the Higgs boson perfected the standard model and proposed more processes of the production, decay of the Higgs and the Higgs Mechanism. In this analysis,  $ggH$  process is reconstructed. Analyzed and calculated the probability of decay  $WW$  pairs as productions of decay process. Simulated Monte Carlo signal samples and background are compared to data from Atlas.

## 1. Introduction

### 1.1. Summary of The Standard Model

The standard model is a theory that describes the fundamental forces (strong, weak, electromagnetic) between elementary particles and the elementary particles of matter. This model belongs to the category of quantum field theory. At the same time, the Standard Model is also satisfied with relativity (SR) and quantum mechanics. The standard model is not the final answer, it is not perfect yet. So far, the standard model cannot describe gravity. However, experiments on strong, weak, and electromagnetic forces have verified the correctness of the standard model. Each of the three columns on the left constitutes a generation of matter. The next column on the right is the gauge boson, and the rightmost particle is the Higgs boson.

In 1954, Yang and Mills proposed the theory of non-Abelian field gauge groups, which initiated the progress of particle physics across the age. Then Steven Weinberg established the unified theory of weak electricity based on the Young Mills field. The strong interaction was verified afterwards. After adding the Higgs mechanism, the standard model becomes complete. Now, the Standard Model is a necessary theory for studying high-energy physics, particle physics, and nuclear physics.

In the study of the Standard Model, up to 61 common elementary particles are included. These particles are divided into fermions and bosons. The most significant difference between fermions and bosons is the difference in spin. Fermions are semi-odd spins and obey the Pauli exclusion principle.



On the other hand, bosons are just the opposite, their spins are integers and they do not obey the Pauli exclusion principle. In terms of function, fermions are the basic particles that make up matter, while bosons are responsible for transmitting force [1]. The corresponding relationship between each boson and the force is as follows:

Gluons - strong interaction spin = 1. There are 8 known gluons.

Photon - electromagnetic interaction spin = 1.

W, Z bosons - weak interaction spin = 1. There are 3 kinds known.

Higgs - the source of the mass of particles (matter), Higgs is not the gauge boson. The Higgs boson will be discussed in depth in section 3,4.

In particle physics that has emerged, strong interactions are described by quantum chromodynamics (QCD), while weak interactions and electromagnetic interactions are described by the unified theory of electroweakness [2]. The above theory is included in gauge field theory. In short, these theories connect fermions with bosons very well. Since bosons are responsible for transmitting force, the Lagrangian function and gauge transformation related to bosons in each group of particles are the same. Here bosons are also called gauge bosons. The Lagrangian function in QCD is as follows:

$$\mathcal{L}_{QCD} = \sum_{\psi} \bar{\psi}_i \left( i\gamma^{\mu} (\partial_{\mu} \delta_{ij} - ig_s G_{\mu}^a T_{ij}^a) \right) \psi_j - \frac{1}{4} G_{\mu\nu}^a G_a^{\mu\nu} \quad (1)$$

Use theory group to define and describe the standard model: SU(3)SU(2)U(1). This is described using the gauge group, SU(3) is the gauge group describing the strong interaction, and SU(2)U(1) describes the electroweak interaction. It is worth noting that gravity is not described in the standard model. In fact, the concept of 'gravitons' has been proposed, but there is no experiment to prove the existence of 'gravitons'. This is where the standard model is not perfect. The following content will introduce the particles of interest in the Standard Model [3, 4].

*Quark* is a kind of elementary particles. There are 6 flavors in the standard model, namely up, down, strange, charm, top, and bottom. In addition to electric charge, quarks also possess color charges. It can be imagined that quarks have three color charges, red, green and blue, and their corresponding antiquarks also have corresponding color charges, which are anti-red, anti-green and anti-blue. Color charge does not really mean that quarks and gluons "have colors." In fact, the color charge theory is related to strong interaction, that is, color charge is part of QCD. Due to the mathematical complexity of QCD, we will not discuss the specific principles here.

Quark is the basic unit of matter, and different quarks are combined into hadrons. The protons and neutrons we know all belong to hadrons and are the most stable of hadrons. Quark has a very interesting phenomenon, quark confinement. This makes it difficult to observe quarks. Most of our current understanding of quarks is based on hadron collision experiments. Due to the existence of weak interaction, elementary particles have a phenomenon called decay, and so does quark. The larger mass quarks will eventually decay into smaller masses u and d.

Unlike quarks, *neutrinos* are leptons and common elementary particles. There are currently three kinds of neutrinos, all of them have 1/2 spin, and they are all light and uncharged. The symbol for neutrinos is  $\nu$ . Neutrinos can be produced in weak interactions between arbitrary particles. Because it is not charged, and its mass and volume are relatively small, it is difficult to find. It was not until 2013 that high-energy neutrinos were first discovered [5].

Neutrinos also have a special phenomenon - neutrino oscillation. We mentioned that there are three kinds of neutrinos, namely electron neutrinos, mu neutrinos, and tau neutrinos. The phenomenon of neutrino oscillation means that the taste of neutrinos will change continuously, that is, the three kinds of neutrinos will switch to each other. This phenomenon is very interesting, and it is also inconsistent with the standard model, because neutrinos have a non-zero static mass. At present, we cannot give the ultimate cause of neutrino oscillation.

### 1.2. Relativity and Collider Physics

In 1905, Einstein proposed his famous statements about the fast-moving objects. Against the traditional absolute reference system, where the velocity can be simply accumulated or subtracted

when transformation occurs, the special relativity enlightens people with a constant speed invariant for all transformation of reference system -- the light speed  $c$ .

$$c = 299792458 \text{ m/s} = \text{constant} \quad (2)$$

This postulate of a constant drastically changes the transformation of two reference system. The transformation of two coordinate system,  $(x, y, z, t)$  and  $(x', y', z', t')$ , having a relative velocity  $v$  along  $x$  axis is

$$x' = \frac{x-vt}{\sqrt{1-\frac{v^2}{c^2}}} \quad (3)$$

$$y' = y \quad (4)$$

$$z' = z \quad (5)$$

$$t' = \frac{t-\frac{v}{c^2}x}{\sqrt{1-\frac{v^2}{c^2}}} \quad (6)$$

instead of simple addition of the velocity component in  $x$  axis according to Galileo transformation. This form can be further contract into a more compact form, introducing the definition of four-vector

$$a_\mu = (a_0, -a_1, -a_2, -a_3) \quad (7)$$

which is called a *covariant form* of four-vector. For the disposition coordinate mentioned above, the four vector is

$$x_\mu = (t, -x, -y, -z) \quad (8)$$

$$x'_\mu = (t', -x', -y', -z') \quad (9)$$

and a transformation matrix can be attached to the equation array as a concise form

$$\Lambda_\nu^\mu = \begin{pmatrix} \gamma & 0 & 0 & -\gamma\beta \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -\gamma\beta & 0 & 0 & \gamma \end{pmatrix} \quad (10)$$

where the parameter  $\gamma$  and  $\beta$  are defined by  $\beta = \frac{v}{c}$ ,  $\gamma = \frac{1}{\sqrt{1-\beta^2}}$ . This matrix is called *Lorentz transformation matrix*, which serves as  $x'_\mu = \Lambda_\nu^\mu x_\nu$ .

Therefore, the displacement vector in four dimension and its transformation between different frames is shown above. Moreover, the four-momentum can be similarly created and performed by the Lorentz Transformation.

$$p_\mu = \left( \frac{E}{c}, -p_x, -p_y, -p_z \right) \quad (11)$$

$$p'_\nu = \Lambda_\nu^\mu p_\mu \quad (12)$$

where the vector is composed of the energy and momentum vector in the Cartesian space.

The applications of Special relativity and Lorentz transformation are of vital importance in the theoretical prediction and authentic detection for particle and high energy physics, as a result of extreme high velocity and transformation between laboratory frame and center of mass (COM) frame. In a typical accelerator, the particles are pumped through the beam pipe, where the detectors are surrounding the pipe; when the collision happens, the particles will be scattered into all directions, going through the detectors and leave information about their velocity. By applying the Lorentz transformation, we can calculate the momentum and energy of the particle just after the collision in COM frame, reconstructing the event.

### 1.3. LHC and Atlas

The Large Hadron Collider [6, 7], often referred to LHC, is a powerful particle accelerator located in Geneva, Switzerland where the European Center of Nuclear Research lies in. It is composed of a 27-kilometers ring of superconducting electromagnets with a great many of accelerating structures that accelerate hadrons such as protons and ions to approach the speed of light. In the very long and narrow pipe, we assume particles from two high-energy beams, which travel in opposite directions, are made to collide at four sites around the machine. There are four detectors lying in these four sites, respectively named ATLAS, CMS, ALICE, and LHCb.

A Toroidal LHC Apparatus [8], often referred to ATLAS, is the largest-volume collider detector at present which covers the widest possible range of physics at the LHC. It is designed to precisely measure the properties of Higgs Boson and search for new physics beyond the Standard Model. It is made up of an inner tracking detector, electromagnetic, muon spectrometer, and a hadron calorimeter.

### 1.4. Monte Carlo Simulation

In the field of particle physics, the Monte Carlo [9] method is often used to model the processes taking place at colliders. Monte Carlo simulations use random sampling and statistical distributions to evaluate the behavior of complex systems [10]. Many simulations are carried out according to this scheme: first, we simulate the processes and obtain the probability density function for the characteristics of the final particles. Further, the statistics necessary for modeling the measurements of the required parameters of the theory are collected. During the simulation, the response of the detector and reconstruction programs are simulated to create a set of events like data recovery [11, 12].

## 2. Higgs Mechanism

The Higgs Mechanism [13] now provides a convincing demonstration for the mass generation of the bosons, especially the massiveness observed for the particles  $W^\pm$ ,  $Z$ , which play a part in the weak interaction. This process is now included into the Standard Model (SM) as so-called Electroweak Symmetry Breaking (EWSB) [14].

The original derivation from Higgs comes from the modification of Goldstone's Lagrangian [15] into a gauge-invariant form, containing two Hermitian scalar fields  $\phi_1(x), \phi_2(x)$ , having a dimension of mass, and one more vector field  $A_\mu(x)$ .

By maintaining the zero bare mass, which help to maintain the Lagrangian invariant in transformation, the vacuum expectation value for the scalar fields, when choosing a specific gauge [16]

$$\langle 0 | \phi_1(0) | 0 \rangle = 0 \quad (13)$$

$$\langle 0 | \phi_2(0) | 0 \rangle = \eta \quad (14)$$

where the  $|0\rangle$  stands for the vacuum state. The  $\phi_2(x)$  obviously harvests a non-zero mass  $\eta$ , and the  $\phi_1(x)$  can further combined with the vector field  $A_\mu(x)$  as

$$B_\mu(x) = A_\mu(x) - \frac{1}{e_0 \eta} \frac{\partial}{\partial x^\mu} \phi_1(x) \quad (15)$$

which corresponds to a new vector field with mass  $e_0$ . This mass induction mechanism, further accomplished by later scientists, is called *Higgs Mechanism*. And the scalar fields in the generation process is called *Higgs Field*. A more intuitive form of Higgs field is in the electroweak dynamics [2], where the scalar fields are contracted into a more concise form of a complex vector

$$\Phi = \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} \quad (16)$$

and the Higgs potential has the form

$$[\mathcal{V}(\Phi^\dagger \Phi) = \lambda(\Phi^\dagger \Phi)^2 - \mu^2(\Phi^\dagger \Phi)] \quad (17)$$

This form, with  $\lambda, \mu^2 > 0$ , is a quadratic function with a minimum at  $\Phi^\dagger \Phi > 0$ , having a plot shown in the section 4, from which the  $\Phi^\dagger \Phi = 0$  is an unstable local maximum.

### 3. Reconstructing the $gg \rightarrow H \rightarrow WW \rightarrow ll\nu\nu$ Decay

ATLAS and CMS collaboration studied the use of data sets 7 and 8 TeV Higgs boson decay into a pair of W bosons in the final state leptons are explored [17-19].

In 2015, LHC restarted high luminosity pp collision at  $\sqrt{s} = 13$  TeV. The new data is used to further restrict the nature of the Higgs boson: the SM prediction of any significant deviation would be a clear sign of new physics [20]. In the pp collision with  $\sqrt{s} = 13$  TeV, the Higgs with 125 GeV is the main production method of gluon fusion (ggH), process is shown in Fig. 1. The branching fraction of the large Higgs boson to the W boson pair makes this channel suitable for accurate measurement of the Higgs boson production cross-section, and allows the study of secondary main production channels, such as through vector boson fusion (VBF) and related Higgs bosons are produced with vector bosons (VH) [20].

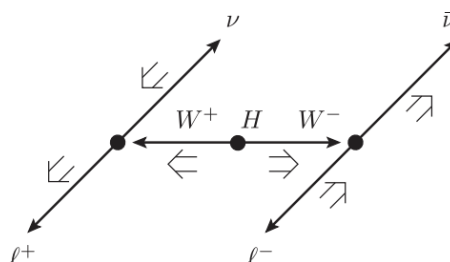
#### 3.1. The Decay of $gg \rightarrow H \rightarrow WW \rightarrow ll\nu\nu$

Lepton decay of the W boson is a very clean process, in the final state  $W \rightarrow l\nu$ , where  $l$  is an electron or a meson. Select electron or meson pairs with neutrinos as the analysis event. It is also worked to choose two pairs of leptons. The relevant background is shown in Figure 1.

Name	Process	Feature(s)
WW	WW	Irreducible
Top quarks		
$t\bar{t}$	$t\bar{t} \rightarrow WbW\bar{b}$	Unidentified $b$ -quarks
$t$	$\begin{cases} tW \\ t\bar{b}, tq\bar{b} \end{cases}$	Unidentified $b$ -quark $q$ or $b$ misidentified as $\ell$ ; unidentified $b$ -quarks
Misidentified leptons (Misid)		
$Wj$	$W + \text{jet(s)}$	$j$ misidentified as $\ell$
$jj$	Multijet production	$jj$ misidentified as $\ell\ell$ ; misidentified neutrinos
Other dibosons		
$VV$	$\begin{cases} W\gamma \\ W\gamma^*, WZ, ZZ \rightarrow \ell\ell\ell\ell \\ ZZ \rightarrow \ell\ell\nu\nu \\ Z\gamma \end{cases}$	$\gamma$ misidentified as $e$ Unidentified lepton(s) Irreducible $\gamma$ misidentified as $e$ ; unidentified lepton
Drell-Yan (DY)		
$ee/\mu\mu$	$Z/\gamma^* \rightarrow ee, \mu\mu$	Misidentified neutrinos
$\tau\tau$	$Z/\gamma^* \rightarrow \tau\tau \rightarrow \ell\nu\ell\nu$	Irreducible

**Figure 1.** The relevant background to  $H \rightarrow WW$  [17]

Since there is a large Drell-Yan and top quark background in the event of the same flavor of leptons or



**Figure 2.** Decay process of  $H \rightarrow WW$  [17]

ejections, the most sensitive signal area is in the final state of  $e\mu$  zero ejection. The main background of this category is the production of WW, which effectively suppresses the production of WW by using the decay characteristics of the W boson and the spin-0 property of the Higgs boson, process is shown in the Figure 2. The next section will process the data provided by Atlas and discuss the details of the decay products, and we will get intuitive conclusions.

### 3.2. Details of $WW$ Decay

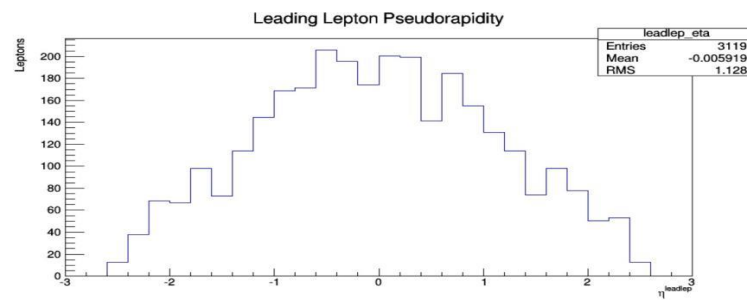
There are many kinds of decay products of  $W$  bosons, usually fermion pairs.  $W$  bosons can decay to a lepton and anti-lepton or a quark and anti-quark (for example  $u, \bar{d}$  and  $c, \bar{s}$ ). Decay channel of  $W$  boson is shown in Table 1. The data in the table is obtained in Ref. [21], and the table is rebuilt. It can be calculated that the probability of decay  $WW \rightarrow ll\nu\nu$  is 32.57%.

**Table 1:** Decay channels of  $W$  bosons [21]

Decay channel	Probability of Decay
$W^+ \rightarrow e^+ + \nu$	10.75%
$W^+ \rightarrow \mu^+ + \nu$	10.57%
$W^+ \rightarrow \tau^+ + \nu$	11.25%
Hadron	67.60%

### 4. Data analysis for gluon-gluon Higgs fusion process

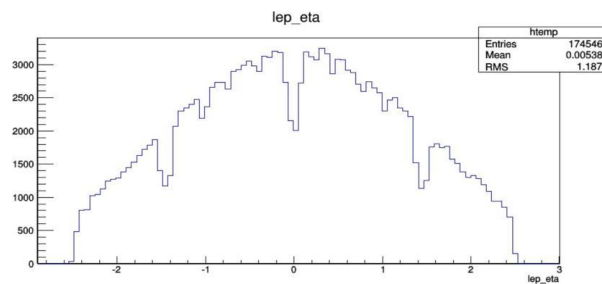
As a practice, the gluon-gluon Higgs fusion  $gg \rightarrow H \rightarrow WW \rightarrow ll\nu\nu$  with  $M_H = 125\text{GeV}$  data from the ATLAS open datasets [22] is selected as an example to analyze. The whole process is carried out in Oracle Virtual Machine and Ubuntu OS, which is modified by CERN to optimize the data processing environment, with Python the primary programming language and assistance of ROOT software.



**Figure 3.** A statistics of the leading leptons falling in the corresponding  $\eta$  area, with the resolution 0.2.

The data package is generated from MC method, which includes  $N = 10^5$  events. With such a large data flow, several criteria need to be emphasized in order to locate the Higgs decay process filtering the background noise, which should be appearing in the codes. As we have discussed in the Decay section 4, the characteristic features for the gluon-gluon fusion and double  $W$  boson decay will generate 2 leptons visible to the detector, as well as two hardly detectable neutrinos (Fig. 3).

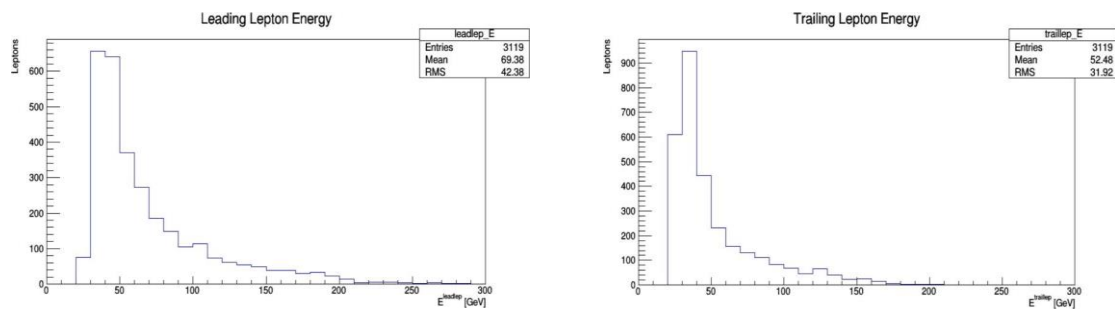
For distinction, the two leptons will be named *leading lepton* and *trailing lepton* separately according to their momentum difference. Once the two spontaneous-generated leptons are detected, or satisfying the criteria in our simulations, the physical properties will be recorded. After a full traverse of data, the statistical module as well as the plotting function goes in, classifying the leptons and generating diagrams, which are available in ROOT file type. A typical statistical diagram is shown in Fig. 3.



**Figure 4.** The authentic data for lepton  $\eta$ , noticing the data quantity is nearly 500 times larger than the simulation

In this diagram, the average pseudo-rapidity  $\eta = -0.005919 \pm 1.128$ , which is indicated in Fig.6. as most the leptons nearly symmetrically distributed at either side of  $\eta = 0$ . This result is just in correspondence with our intuition, as the leptons should be scattered to all direction equally. The referred authentic data [22] is given in Fig.4. Though rough and inaccurate, the simulated data correctly reflect the shape and average of the realistic ones.

Moreover, from the very same diagram the total events for such Higgs generation and annihilation are counted as  $n = 3119$ . Therefore, the probability for getting such a pattern would be about 3%.



**Figure 5.** The energy statistics of leading (a, left) and trailing lepton (b, right).

Nevertheless, the pseudo rapidity of the leptons is only one part of its physical features, and the differences are illustrated between leading lepton and trailing lepton since the latter one will generate its own diagram. A discreet comparison of their energy is shown in Fig. 5, showing the leading lepton with  $\overline{E_{lead}} = 69.38 \pm 42.38\text{GeV}$  and trailing lepton  $\overline{E_{trail}} = 52.48 \pm 31.92\text{GeV}$ , which satisfies our classification that the leading lepton possesses larger momentum, therefore inheriting higher energy. Additionally, the cut-off energy as Fig. 5 shows is about 25GeV, which corresponds to the selection of the events including the Higgs decay pattern.

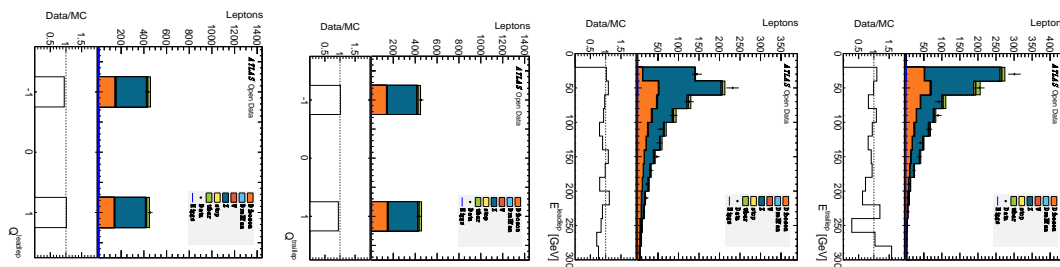
Finally, the diagrams are converted to *.pdf* type, combining with more information and particles involved in the reaction.

A well-developed, colored diagram considering all the channels are listed in Fig. 6, where the thoroughly predetermined and measured data are inherited in the outputs. Such as in the (a)-1 and (c)-1, the charge of both leptons is separately listed, which is just intuitively correct -- the charge is  $\pm 1$ . Other distribution along x axis is just as we have predicted and plotted in ROOT -- the energy of the leading one has a climax in about 70GeV, while for the trailing one the number reduced to about 50, as shown in Fig. 6. (a)-3 and (c)-3. At the same time, our prerequisites -- the energy limit for choosing a lepton pair must surmount 25GeV -- is also indicated in the plots, as we have discussed in the context. For all other properties exhibited in Fig. 6, the two series behave nearly the same, since they are just the outcomes from the very same collision.

The overall features and generated plots are listed in Appendix, which are the collisions occurring alongside our main reaction, but have relatively less connection with our discussion. However, the



leptons collected in these data can still have a interference with the Higgs Mechanism, thus making further data excavation necessary.



**Figure 6.** The colored data for leading[(a)-1, (c)-1] and trailing[(a)-3, 3] lepton parameters. The order is from left to right.

## 5. Conclusions

This article focuses on introducing some physical backgrounds about the  $gg \rightarrow H \rightarrow WW \rightarrow ll\nu\nu$  decay process. The Monte Carlo method is used to simulate the decay event and compare it with the given data of the Atlas Open Data.

In the research of high energy physics, it is necessary to make theoretical predictions of differential cross sections and compare them with experimental results. In the theoretical and experimental fields of high energy physics, the Monte Carlo method has been widely applied and developed. Monte Carlo is a very important numerical calculation method guided by probability and statistics theory. Refers to the use of random numbers (or more commonly pseudo-random numbers) to solve many computational problems.

$H \rightarrow WW$  is the cleanest from of Higgs decay because of the productions (leptons and  $\nu$ ). Compared the energy statistics of leading and trailing lepton, which satisfies classification that the leading lepton possesses larger momentum, therefore inheriting higher energy and Higgs decay pattern. Some interesting data analysis results are shown in Appendix A.

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## Appendix A. The thorough analyzing plots from the Higgs data package

