Measurement of the Higgs Boson Transverse Momentum and its Sensitivity to New Physics Beyond the Standard Model

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Abstract. When simulations based on the Standard Model (SM) of particle physics are compared to actual data obtained by the ATLAS and CMS experiments at the CERN Large Hadron Collider (LHC). It is seen that there is an excess in the transverse momentum cross-sectional data above what is predicted by the simulations. In order to make predictions for higher centre of mass energies at the LHC, simulations of processes resulting in the production of Higgs bosons were done for different centre of mass energies. At the energy scales seen at the LHC, the SM predicts that the main production mechanism for Higgs bosons is gluon fusion. The production of a Higgs boson in this manner must be accompanied by the production of one or more other particles in order for the Higgs boson to acquire transverse momentum ($P_T$). This is because there is no transvers momentum coming into the collision and so conservation of momentum requires two or more particles with opposite $P_T$ to be produced in order for them to have non-zero $P_T$. If a heavy scalar boson is produced in this interaction which decays into a Higgs boson and some other particle, the emission of this other particle would give the Higgs boson extra transverse momentum above what is predicted by the SM.

1. Theoretical background

1.1. The Standard Model of particle physics

The standard model of particle physics (SM) is a theory that stems from quantum field theory (QFT) and explains three of the four fundamental forces as interactions between the fundamental particles. These forces are the electromagnetic, the weak nuclear and the strong nuclear forces. In the fundamental particles of SM there are 12 matter particles separated into three generations and further separated into 6 quarks and 6 leptons, as well as 4 gauge bosons and a scalar boson (the Higgs). (Figure 1)
The three generations of matter particles are called fermions and all have a spin of 1/2. The gauge bosons on the other hand, have a spin of 1 and the Higgs boson has zero spin. The gauge bosons are considered the force carriers and although this is a foreign concept the forces mentioned above are understood to be experienced by the transfer of virtual gauge bosons. The gluon is responsible for the strong nuclear force and only interacts with quarks and itself. The photon is responsible for the electromagnetic force and only interacts with charged particles, and the W and Z bosons are responsible for the weak force and interact with all matter particles. The Higgs is responsible for giving mass to the massive particles, the quarks, leptons and W and Z bosons. [2]

1.1.1. Gauge invariance. In gauge theory the redundant degrees of freedom in a Lagrangian are referred to as gauges. A symmetry group (such as SU(3) in QCD) then defines the transformations between these gauges. Associated with the symmetry group are group generators for which there necessarily arise vector fields or gauge fields for each group generator, which must be added to the Lagrangian in order to ensure its gauge invariance. The quantization of these vector fields result in what are gauge bosons. For example SU(3) has 8 group generators which result in the 8 gluons in QCD. Now a form of the SM Lagrangian which obeys SU(2)×U(1) gauge invariance can be written down in which all the particles have no mass which is a problem because there is a vast amount of experimental data saying fermions and W and Z bosons have mass and furthermore if we simply give these particles mass the gauge invariance of SU(2)×U(1) is violated. Thus, a mechanism that gives mass without violating gauge invariance is needed. This mechanism in spontaneous electroweak symmetry breaking.

1.1.2. Spontaneous electroweak symmetry breaking. In order to reconcile SU(2)×U(1) symmetries another interaction must be introduced, which turns out to be the Higgs mechanism. This is done by introducing a potential \( V(\phi) \) dependent on a scalar field \( \phi \) that is required to be symmetric about \( \phi \rightarrow -\phi \):
\[ V(\varphi) = \mu^2 \varphi^\dagger \varphi - \lambda (\varphi^\dagger \varphi)^2 \]  

(2)

By requiring \( \lambda > 0 \) and \( \mu^2 < 0 \), \( V(\varphi) \) will have two minima at \( \varphi = \pm v = \pm \sqrt{-\mu^2/\lambda} \). The minima are removed from \( \varphi = 0 \) and thus the system will spontaneously break symmetry when it moves into a ground state. The Lagrangian for this potential is:

\[ \mathcal{L}_\varphi = (D_\mu \varphi)^\dagger (D_\mu \varphi) - V(\varphi) = (D_\mu \varphi)^\dagger (D_\mu \varphi) - \frac{1}{2} \mu^2 \varphi^2 - \frac{1}{4} \lambda \varphi^4 \]  

(1)

Where \( D_\mu \) is the covariant derivative and \( \mathcal{L}_\varphi \) forms the scalar component of the SM Lagrangian Now in order to give the \( W^\pm \) and \( Z \) bosons mass while leaving the photon massless the scalar field \( \varphi \) is defined as a complex doublet:

\[ \varphi = \begin{pmatrix} \varphi^+ \\ \varphi^- \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \varphi_1 - i \varphi_2 \\ \varphi_3 - i \varphi_4 \end{pmatrix} \]  

(2)

\[ \Rightarrow V(\varphi) = \mu^2 \varphi^\dagger \varphi - \lambda (\varphi^\dagger \varphi)^2 \]  

(3)

If it is chosen that \( \varphi_1 = \varphi_2 = \varphi_4 = 0 \) and \( \varphi_3 = \frac{1}{\sqrt{2}} \left(-\frac{\mu^2}{\lambda}\right)^{1/2} \) then it can be shown that:

\[ \varphi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \sqrt{v} + h \end{pmatrix} \]  

(4)

Where \( h \) is the real component of the neutral scalar field \( \varphi \). These corrections as well as the necessary Yukawa terms then make up the SU(2)×U(1) Lagrangian which can be used to calculate the strength of Higgs to other particle couplings.

1.1.3. Quantum field theory and the SM. The mathematics of the SM comes from quantum field theory (QFT) in which the partials of the SM are considered fields that permeate space-time and the interactions between the fields are understood by Lagrangian mechanics. The internal symmetries of the system are usually defined, and then the most general renormalizable Lagrangian that obeys these symmetries can be defined. There are three fundamental interactions; the strong, the weak and the electromagnetic. The electromagnetic and weak interactions can however be combined into one interaction called the electroweak interaction. The gauge symmetry of SM is SU(3)×SU(2)×U(1) where each of the factors are said to give rise to the three interactions. [2] SU(3) for Quantum Chromo Dynamics (QCD), the strong interaction, SU(2) for the weak interaction and U(1) for the electromagnetic interaction. The SM Lagrangian for these symmetries can be written in terms of the QCD sector and the EW sector:

\[ \mathcal{L}_{SM} = \mathcal{L}_{SU(3)} + \mathcal{L}_{SU(2) \times U(1)} \]  

(1)

1.2. Higgs production at the LHC

At the CERN Large Hadron Collider (LHC) protons are accelerated to speeds close to the speed of light in opposite directions and then smashed together. [3] This process is energy intensive enough to cause the protons to split up into its constituents. These constituents then interact in interesting ways
that reveal the nature of the forces governing these interactions. One such interaction is Higgs production through gluon fusion via an intermediate top quark loop (\(gg \rightarrow H\)): [4]

![Feynman diagram for Higgs production via gluon-gluon fusion](image)

**Figure 2:** Higgs production via gluon-gluon fusion [5]

This is in fact the leading production mechanism of the many partonic processes producing the Higgs at the LHC. [4] The problem with this interaction is that the Higgs must have transvers momentum (\(P_T\)) in order to be observed. So one needs to look at the case where one or more other particles are produced as well as the Higgs. These particles decay into hadronic jets and because the net \(P_T\) must be zero the Higgs will have the same \(P_T\) in the opposite direction as the net \(P_T\) of the jets. One such example is (\(gg \rightarrow gH\)): [4]

![Feynman diagram for partonic process \(gg \rightarrow gH\)](image)

**Figure 3:** Feynman diagram for partonic process \(gg \rightarrow gH\) [5]

2. **Higgs transvers momentum data obtained from the LHC**

The transvers momentum data for Higgs production obtained from the LHC for the center of mass energy of 8TeV is shown in figure 4, 5 and 6. The shaded regions depict what theory predicts and the dots represent the actual data obtained. Figure 4 and 5 was obtained from the ATLAS experiment and figure 6 was obtained from the CMS experiment.
The data collected at ATLAS as well as at CMS show a structure that does not correlate with theory from around 40 to 100 GeV. One can see the data has got higher cross-sections than predicted over this range. This discrepancy could be the result of a statistical fluctuation (i.e. we got lucky) and it doesn’t truly represent what happens, an error in the model (i.e. QCD is not properly understood for this process) or it could indicate new physics. The same structure is however observed at both ATLAS and CMS and since they use different physical mechanisms for detection, this makes a statistical fluctuation less likely. Further more the theory so well predicts Z boson production at ATLAS as the theory and the data correlate quite well particularly for the region where we see discrepancies for the Higgs. Which compels us to believe that our model for Higgs production could not be as far off as it is. Thus this structure may indicate new physics.
3. Investigation into the transvers momentum of Higgs production at the LHC

In order to investigate the $P_T$ data for Higgs production and how it will change when the LHC runs at the higher centre of mass energy of 13TeV I ran simulations using MadGraph [10] for Higgs production at the LHC for different centre of mass energies from 8TeV to 14TeV in 1TeV steps. I did this for proton collisions resulting in a Higgs and a jet ($p p \rightarrow h j$) as well as two jets ($p p \rightarrow h j j$). I then compared the $P_T$ cross-sectional data, from these simulations, for each energy step to each other. I plotted the $P_T$ cross-sectional data for the respective energies. I also plotted the ratios of this data (figure 8,9), the integrated cross-sectional data and the ratios of the integrated cross-sectional data (figure 10,11). What these plots show is that the cross-section is expected to increase as the energy increase and that the increase will be faster at higher $P_T$ values. These plots are useful in that they give predictions that can be compared to actual data and in this case highlight areas of disagreement with theory and data.

Figure 7: $P_T$ for Z boson production at ATLAS [9]

Figure 8: Ratios of $P_T$ cross-sectional data for $p p \rightarrow h j$

Figure 9: Ratios of $P_T$ cross-sectional data for $p p \rightarrow h j j$
As discussed above there may be a structure that is not predicted by the SM presenting itself and so it would be useful to investigate models that resolve this discrepancy and investigate how this would influence $P_T$ cross-sectional data for Higgs production and how it may change as the energy changes. A heavy -scalar boson hypothesis mentioned below offers a reasonable rationalisation.

3.1. Heavy scalar boson hypothesis

In a few beyond standard model models (BSM) a heavy -scalar boson ($A$) is predicted which would decay into a SM like Higgs plus another particle. The emission of this other particle would thus give the Higgs more $P_T$ than predicted by the SM and so explain the different structure seen in the $P_T$ data. In order to roughly approximate how this might change the $P_T$ cross-sectional data simulations were done at 8TeV and 13TeV for the process in which protons collide and produce a Higgs ($p p \rightarrow h$) where the Higgs is now thought of as an $A$. Then by varying the mass of the Higgs ($A$) the ratios of the total cross-sections at 13TeV to 8TeV as a function of the mass of the $A$ was obtained (figure 12). What this plot indicates is that as the mass of $A$ increases the ratio of the total cross-section at 13TeV to 8TeV increases meaning that if there is an $A$ being produced that is decaying into a SM like Higgs and something else, the expectation would be that the amount of Higgs seen at 13TeV would be greater than predicted by the SM.
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