

Improvement of the Invariant Mass Reconstruction for the Double Higgs Production Measurement at CLIC

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SUMMER STUDENT PROJECT REPORT

Compact Linear Collider CLiC

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1 Introduction

The Compact Linear Collider (CLiC) is one of the proposed projects for the future of CERN. It is designed to collide e^- and e^+ and it is currently being developed and optimized.

These studies focus on the measurement of double Higgs production. Figure 1 shows the three Feynman's diagrams which contribute to the signal. In the decay channel selected for the studies, each of the two Higgs bosons decays into a bottom quark pair ($b\bar{b}$). These b and $\bar{b}$ hadronize into jets, hereafter called b-jets. The neutrinos are not detected.

This channel is very promising at CLiC, due to the high branching ratio of $H \rightarrow b\bar{b}$ and the clean environment at CLiC. As CLiC is a lepton collider, jet and b-tagging reconstruction are very precise. The challenges of this decay channel are the low cross section of the double Higgs production with a high level of Standard Model (SM) background. Additionally, the b-jets have to be reconstructed in all detector regions.

The studies in this report are concerned with the optimization of the Higgs mass resolution, a crucial variable in the double Higgs analysis. Section 2 explores the dependency of the Higgs mass resolution on detector regions. In Section 3, different methods for combining four b-jets into two Higgs bosons are compared and improved. Their influence on the Higgs mass resolution is evaluated. Section 4 describes the efforts that have been made to determine the b-jet charge in order to find out if the b-jet resulted from a b or $\bar{b}$. A conclusion can be found in Section 5.

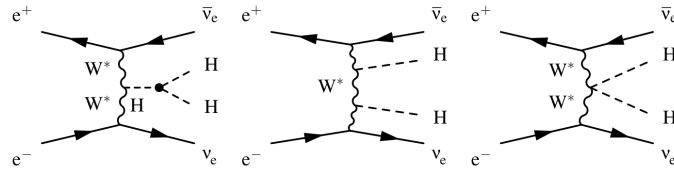


Figure 1: Double Higgs production: These three processes result in two Higgs bosons and an electron neutrino and antineutrino pair.

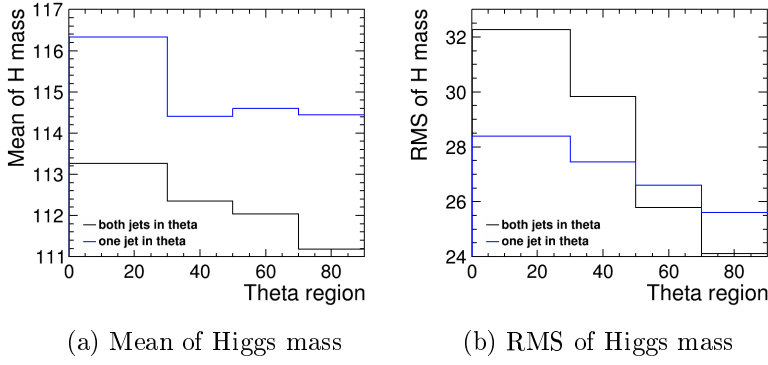


Figure 2: Mean (left) and RMS (right) of the Higgs mass as a function of θ (in degrees): The RMS is equivalent to the resolution. A low value indicates a good resolution. As expected, the mass resolution is improved in the barrel region. The χ^2 combination method was used.

2 Higgs Mass Resolution Depending on Detector Regions

The CLiC detector is designed in a cylindrical symmetry with a barrel region and a forward (or end-cap) region. A cylindrical coordinate system is used, with the origin located in the centre of the detector and the z-axis parallel to the beam. The polar angle, θ , to the z-axis has a range of $0 < \theta < \pi$ and the azimuthal angle, ϕ , in the plane orthogonal to the z-axis has a range of $0 < \phi < 2\pi$.

Because of the detector symmetry, measurements of any physical quantity should not depend on ϕ . In contrast, depending on θ , particles pass through different detector regions. Therefore, the dependence of the Higgs mass m_H on θ has been studied.

However, the Higgs is not measured directly. It decays into two b-jets. The Higgs mass resolution therefore depends on the jet measurements. To understand how the Higgs mass resolution depends on θ , it is not sufficient to look at the dependency on θ_{Higgs} , because the two jets are generally detected in other θ regions.

Figure 2 shows the mean of the Higgs mass and the resolution (quantified by the RMS) depending on θ regions with a distinction if one or two of the jets have been measured in that region. Because of the detector symmetry, events with $\theta > 90^\circ$ have been rescaled to a polar angle of $180^\circ - \theta$.

As can be observed from Figure 2b, the resolution is improving with θ for both scenarios (one or both b-jets in θ region). This is to be expected because jet reconstruction in the forward region is more challenging. In particular the energy of the jet can be mismeasured due to the limited detector acceptance.

Another interesting effect in Figure 2b is the change at $\theta = 50^\circ$. For lower θ , the mass resolution is better for only one b-jet in the region. For higher θ , the resolution is improved when both b-jets are in the region. This is a logical effect: In a region with a potentially good resolution (barrel region) it has a good influence on the resolution if

both b-jets are in that region.

For Figure 2, the b-jets have been combined using the χ^2 method. For more information on the b-jet combination methods, see Chapter 3.

3 Combination Methods and Truth Matching

In the channel under study, $HH\nu\nu \rightarrow b\bar{b}b\bar{b}\nu\nu$, four b-jets are produced which result from two Higgs. To reconstruct the Higgs bosons, the b-jets have to be grouped correctly into pairs, with one pair resulting from the same Higgs. However, there are three possible combinations and a method has to be defined to distinguish the correct combination.

Three methods to determine the jet-to-Higgs pairing have been studied. Each method focuses on a parameter and selects the combination for which the parameter is minimal.

The χ^2 method minimizes the difference of each Higgs masses to the true Higgs mass. From all possible b-jet combinations, the combination with the smallest

$$\chi^2 = (m_{H1} - 126 \text{ GeV})^2 + (m_{H2} - 126 \text{ GeV})^2 \quad (1)$$

is selected. In the generated Monte Carlo samples, the Higgs mass is 126 GeV.

The opt method selects the combination that results in two similar Higgs masses. The difference between the masses

$$\Delta m_{\text{opt}} = |m_{H1} - m_{H2}| \quad (2)$$

is minimized.

The jangle method is based on the assumption that two b-jets are more likely to come from the same Higgs boson when they are closer together. The minimized quantity is

$$\alpha_{\text{jangle}} = |\beta_{H1}| + |\beta_{H2}|, \quad (3)$$

where β_{Hi} is the 3D angle between the two b-jets of Higgs number i . Figure 3 clearly shows that the assumption is true only for the polar angle θ and not for ϕ . Therefore, the definition of the jangle method was optimized to

$$\alpha_{\text{jangle}} = \Delta\theta_{H1} + \Delta\theta_{H2}, \quad (4)$$

where $\Delta\theta_{Hi} = |\theta_{\text{jet}i1} - \theta_{\text{jet}i2}|$, and $\text{jet}ij$ is the b-jet number j from Higgs number i .

In order to compare the quality of the three jet-to-Higgs pairing methods, it has to be determined how often each method selected the right pairing.

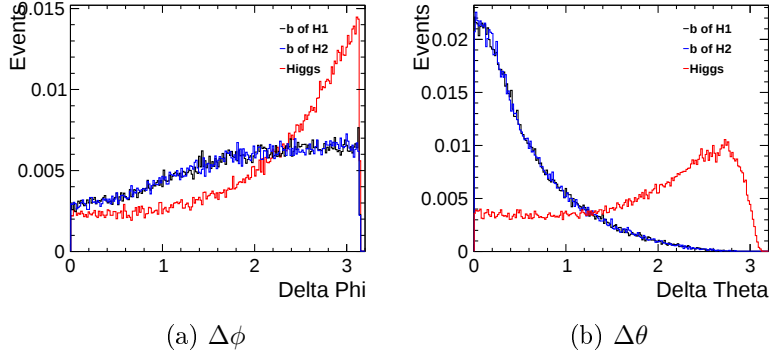


Figure 3: $\Delta\phi$ and $\Delta\theta$ between the b quarks of the first and second Higgs (black and blue) and between both Higgs bosons (red).

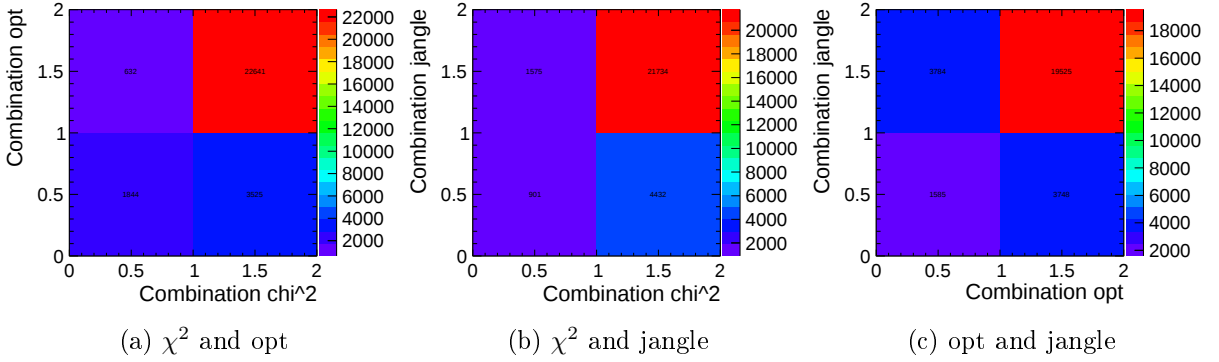


Figure 4: Comparison of jet-to-Higgs combination methods: A value of zero indicates a wrong, a value of one indicates a true combination for the specified method.

Truth matching is a process to find the jet (on reconstruction level) which resulted from b quark (on particle level). From the 24 possible ways of matching four bs to four jets, the combination with the smallest sum of angles between the matched b-jet-pairs is chosen.

With this information, the quality of the methods can be compared, as shown in Figure 4. The χ^2 method is correct in 91.36 % of events, the opt method in 81.25 % and the jangle method in 81.38 %.

As there are multiple events where at least one method is correct, it would be advantageous to combine all the methods. To achieve this, a new method was developed.

The all method aims at combining the advantages of all the previous methods. Therefore, the value that gets minimized A_{all} has to be a combination of all previous parameters. Also, they have to be weighted. For the weighting, χ^2 and Δm_{opt} are divided by their root mean square (rms). For $\Delta\theta$, the mean of the function has to be subtracted first, before determining the rms of this distribution. The rms and mean values are

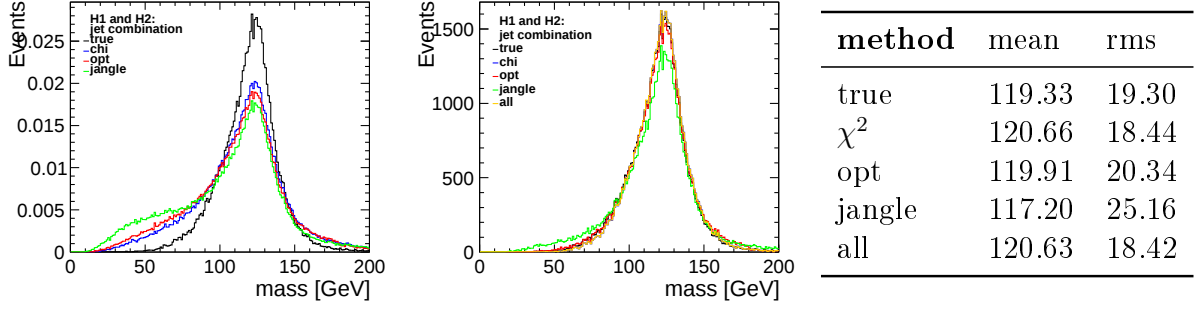


Figure 5: Comparison of Higgs mass using different jet-to-Higgs combination methods. All events (left), only for successful truthmatching (right). Mean and RMS are for right graph, values in GeV.

obtained using the true combination of the b-jets. This results in

$$A_{\text{all}} = \frac{\chi^2}{\chi_{\text{rms}}} + \frac{\Delta m_{\text{opt}}}{\Delta m_{\text{rms}}} + \frac{|\Delta\theta_{\text{H1}} - \Delta\theta_{\text{mean}}| + |\Delta\theta_{\text{H2}} - \Delta\theta_{\text{mean}}|}{\Delta\theta_{\text{rms}}}, \quad (5)$$

where $\chi_{\text{rms}} = 22.05$, $\Delta m_{\text{rms}} = 23.05$, $\Delta\theta_{\text{rms}} = 0.67$, $\Delta\theta_{\text{mean}} = 0.00$.

This method chooses the right combination in 91.52%, which is not a significant improvement to the χ^2 method for the signal sample. With more time, the methods could have been tested on the most relevant background samples. Figure 5 shows a comparison of the mass distributions obtained by using different jet-to-Higgs combination methods.

4 Jet Charge

The jet charge, q_{jet} , has been computed in order to distinguish between b and $\bar{b}$. Summing over all jet charged particles and weighting them with their momentum, $\vec{p}_i$ and the normalized jet direction $\vec{j}$, the jet charge is

$$q_{\text{jet}} = \frac{\sum_i q_i |\vec{j} \cdot \vec{p}_i|^\kappa}{\sum_i |\vec{j} \cdot \vec{p}_i|^\kappa}, \quad (6)$$

where κ can be adjusted to achieve the best effect. The method has been tried for $\kappa = 1$. For the jets with the true jet combination, there is a certain degree of separation between b and $\bar{b}$, see Figure 6.

5 Summary and Conclusion

The θ -dependency of the Higgs mass resolution has been found as expected. The all combination method has been developed and is expected to be a larger advantage when used on background and not only signal events.

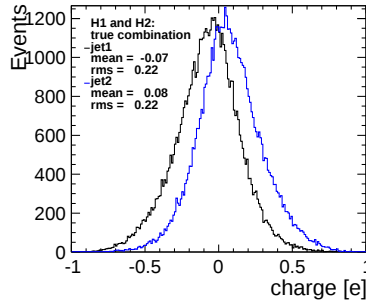


Figure 6: Jet charge: The b and $\bar{b}$ can be distinguished, the mean value of each distribution is not at $q_b = \pm e/3$. The method only aims at distinction, not at precise values.