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Rescuing VBF Higgs Invisible Events with Novel Vertex Selection

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ABSTRACT

ATLAS has developed a new approach for primary vertex selection in events containing an invisible Higgs boson decay in vector-boson fusion (VBF) under current LHC as well as HL-LHC conditions, integrating calorimeter and tracking information to mitigate the impact of pileup vertex merging. A new way to handle forward jets outside the current tracking acceptance is also introduced using the concept of vertex confidence. The new algorithm is insensitive to pileup density and improves the average vertex selection efficiency from 80% to 88% in current LHC conditions, and from 88% to 97% in HL-LHC conditions, under tight VBF Higgs event selection cuts.

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1 Introduction

The event reconstruction in the ATLAS experiment [1] requires the identification and selection of a hard-scatter (HS) primary vertex among the multiple interaction vertices reconstructed in each event. Currently the HS vertex candidate is selected based on the largest sum of squared transverse momenta (p_{T}) over the associated tracks.* While this method works very well in events containing hard physics objects within the tracker acceptance, it suffers from low efficiency in final states containing forward and/or low p_{T} jets, such as in the case of events containing an invisible Higgs boson decay (e.g. $H \to ZZ^* \to 4\nu$, see Appendix A) in vector-boson fusion (VBF), later referred to as VBF Higgs invisible events, where the correct primary vertex is chosen correctly only 80% of the time.

In order to overcome this challenge and improve the signal acceptance for VBF Higgs invisible events, we introduce two novel ideas. First, we propose a new vertex selection algorithm that combines tracking with calorimeter jet information to overcome the challenge of events with low p_{T} jets. This new algorithm improves the vertex selection efficiency by 10%. Second, to address the case of events containing forward jets outside the tracking acceptance, we introduce the concept of vertex confidence. We classify events as high/low confidence based on the amount of track p_{T} associated to hard jets. Events in which the majority of the total jet p_{T} is outside the (pseudorapidity) η acceptance of the tracker ($|\eta| > 2.5$) are classified as low vertex confidence events and no vertex is chosen for this category. For VBF Higgs invisible events, we find that the new algorithm selects the correct primary vertex 97% of the time for the high confidence events. The remaining events are classified as low confidence VBF events, for which no attempt is made to assign a HS vertex even though there is still a VBF jet signature.

In LHC Run 4, where the upgraded ATLAS Inner Tracker (ITk) [2] provides an extended acceptance of $|\eta| < 4$, the new vertex selection algorithm improves upon the current selection technique by 10% under the busier HL-LHC conditions in terms of pileup (PU).

2 Datasets and Event Selection

Samples of simulated $H \to ZZ^* \to 4\nu$ events in ATLAS Run 3 (Run 4) conditions, with a center-of-mass energy of 13 (14) TeV and a mean number of proton-proton interactions μ of 60 (200) per bunch crossing are used, assuming the ATLAS ITk geometry layout and reconstruction performance for Run 4, as described in Ref. [2].

Physics event selections ensure that every event has a vertex of interest, setting the theoretical maximum vertex selection efficiency at 100%. A key challenge in studying primary vertex identification is the fact that physics event selections depend on the choice of the primary vertex. For example, in order to suppress background PU interactions, jets are required to have a large fraction of their track p_{T} pointing to the selected HS primary vertex. This is typically achieved by requiring jet $R_{p_{\mathrm{T}}} > 0.1$, where $R_{p_{\mathrm{T}}}$ [3] is defined as:

$$R_{p_{\mathrm{T}}} = \sum_{\text{tracks}} \frac{p_{\mathrm{T(track)}}}{p_{\mathrm{T(jet)}}} \mathbb{1}(\Delta R < 0.4). \tag{1}$$

Here we sum over tracks attached to the selected HS primary vertex, $\mathbb{1}$ is the indicator function, and ΔR is the distance between the track and jet in the $\eta - \phi$ space. Since the $R_{p_{\mathrm{T}}}$ condition requires the definition of an HS vertex, it biases the measurement of the vertex selection efficiency. This is because VBF Higgs events in which the selected vertex is not the true HS primary vertex do not pass the jet selection due to low $R_{p_{\mathrm{T}}}$ with respect to the incorrect vertex, and are not considered in the calculation of the efficiency, leading to an overestimation of the vertex selection efficiency.

To overcome this, a new event selection is defined that is unbiased with respect to the choice of the vertex. The idea is to ensure that every event has a VBF Higgs invisible vertex that is identifiable under typical VBF jet criteria. To achieve this, truth level information from the simulation is used to impose the VBF jet criteria on reconstructed jets that come from the VBF Higgs invisible HS interaction. This ensures

*There exist specialized vertex selection algorithms that use photons to identify the HS vertex as in the case of H$\to \gamma\gamma$ [4]. These will not be discussed in this report as the vertex selection algorithms under consideration do not utilize detector objects beyond tracks and calorimeter jets, and are hence in principle generally applicable.

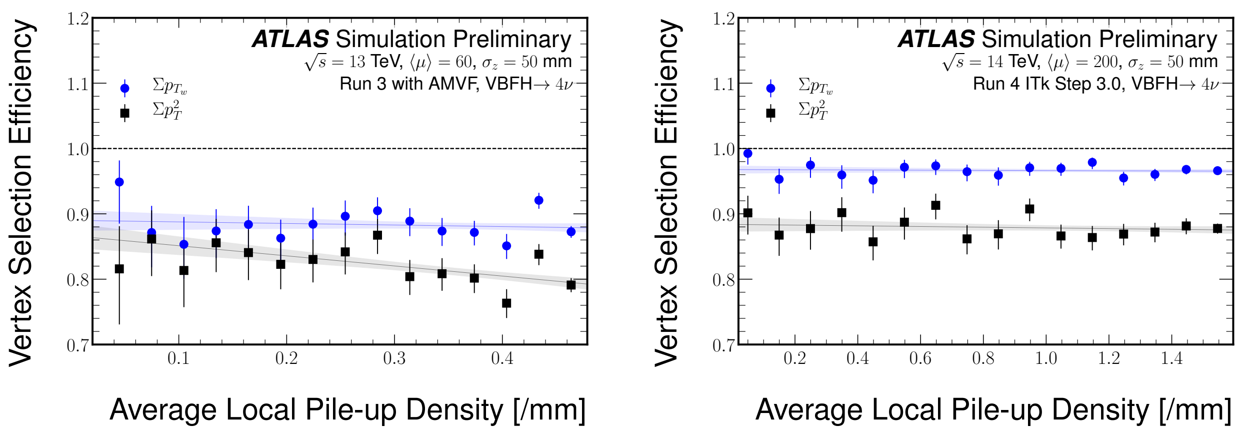
that all identifiable VBF Higgs events are considered for the calculation of the vertex selection efficiency regardless of the choice of vertex, leading to a vertex-unbiased event selection.

3 Current Approach and its Limitations

The current approach to find the HS vertex in an event is to identify the vertex with the largest scalar summed squared track transverse momentum,

$$\text{sumPT} = \sum_{\text{tracks}} p_{\text{T}}^2. \tag{2}$$

One limitation of this method is that it becomes vulnerable to selecting high p_{T} vertices resulting from the merging of nearby PU vertices, which occurs when the typical distance between such vertices is comparable to or smaller than the vertex resolution. This effect is illustrated in Figure 1(a), where the sumPT vertex selection efficiency shows a downward trend with increasing average local PU vertex density. This consequence of merged PU vertices is exacerbated for VBF Higgs invisible events due to low visible p_{T} because of the invisible particles in the final state. This is related to the general limitation of the method when applied to low visible p_{T} interactions, as events often contain PU interactions that have sumPT larger than the HS interaction, even without the effect of PU vertex merging. This is highlighted in Figure 1(b) where sumPT gives an efficiency of 88% despite PU vertex merging being addressed by ATLAS in HL-LHC conditions thanks to improved tracking resolution and vertex reconstruction [2].



(a) (b)

Figure 1: Vertex selection efficiency as a function of the PU density, defined as the local density of vertices at the primary vertex in the event. The default sumPT selection method (square) is compared with the proposed sumPTw selection (circle). Error bars are statistical errors. Best fit linear functions are drawn through the sets of points with 1-sigma error bands to visualize the slopes with respect to the PU density. (a) LHC Run 3 conditions, (b) HL-LHC Run 4 conditions. Note that the efficiencies are larger for Run 4 than for Run 3 as the increased tracking acceptance at the HL-LHC [2] allows for tracks inside forward HS VBF jets. From Ref. [5].

4 New Technique

A new vertex selection technique is developed to tackle the two limitations discussed above. To handle merged PU vertices, one can exploit angular correlations between the tracks from the HS vertex and the high p_{T} HS jets in the event. The tracks from merged PU vertices are not strongly correlated in angles with each other, or with these jets, because they originate from independent close-by interactions. Therefore one can resolve the substructure associated with vertices and groom the tracks attached to the vertices such that tracks correlated to HS processes are selected preferentially. To address the problem of low visible p_{T} HS interactions, one can leverage the fact that, in general, VBF jets have higher p_{T} than PU jets; the high HS jet p_{T} can be used to preferentially weigh the sum over track p_{T} for the HS vertex.

Based on these insights, we propose a new algorithm for vertex selection in VBF Higgs invisible events that makes use of the track-jet correlations within each vertex, based on maximizing an augmented version of the standard sumPT algorithm that projects tracks onto hard jets,

$$\mathrm{sumPTw} = \sum_{\mathrm{tracks}} p_{\mathrm{T}_w} = \sum_{\mathrm{tracks}} p^2_{\mathrm{T(track)}}\, p^2_{\mathrm{T(closest\ jet)}} \frac{1}{\Delta R} \mathbb{1}(\Delta R < 0.4) \mathbb{1}(p_{\mathrm{T(jet)}} > p_{\mathrm{T(threshold)}}). \tag{3}$$

Here $\mathbb{1}$ is the indicator function, $p_{\mathrm{T(threshold)}} = 30$ GeV is used, and ΔR is the distance between a track and the closest jet with sufficient p_{T} in the $\eta - \phi$ space. This projects tracks onto jets and adds the weighted p_{T_w} as defined above. Thus sumPTw is a bolstered measure of the total vertex sumPT in jets. Since merged PU vertices are made of two or more independent interactions, their tracks are not correlated in the $\eta - \phi$ space with the HS interaction. Therefore by projecting their tracks onto hard jet axis directions, their large sumPT is significantly reduced. Additionally the use of the $p_{\mathrm{T(closest\ jet)}}$ term adds a weight that is larger for the HS interaction.

Figure 1 shows the new sumPTw algorithm performance versus the standard sumPT algorithm. The former flattens the PU vertex density dependence of the vertex selection efficiency in Figure 1(a). This demonstrates the robustness of sumPTw against merged PU vertices. The new algorithm also improves the average vertex selection efficiency from 80% to 88% in Figure 1(a), and from 88% to 97% in Figure 1(b), which is an approximately 10% improvement in each case compared to the current approach. The improvements in the average efficiencies, particularly in the case of Figure 1(b), can be attributed to the jet p_{T} weight term that helps the otherwise low visible p_{T} of the HS vertex.

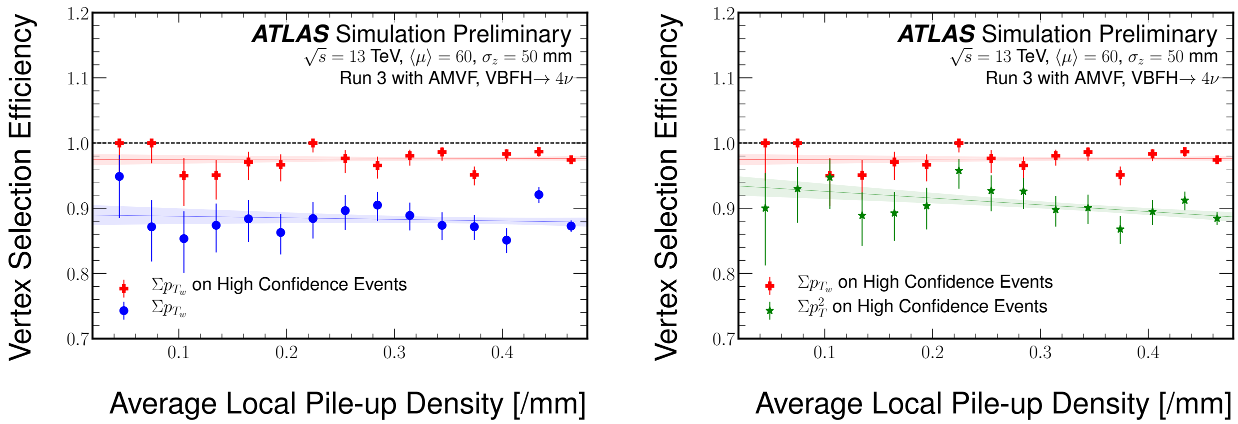
5 Experimental Challenges and Future Improvements

The sumPTw algorithm mitigates the effects of PU vertex merging and low visible p_{T} that limits the performance of vertex selection in VBF Higgs invisible events. However, the new method applied in Run 3 conditions underperforms when compared to HL-LHC conditions. This is due to the expanded η acceptance of the tracker in ATLAS at HL-LHC [2].

To address the reduced tracking coverage in Run 3, an event category is defined which captures events where the majority of the total jet p_{T} is outside the η acceptance of the tracker. These events contain HS vertices that have very few tracks inside the tracker, and thus have low sumPT or sumPTw. Referred to as low confidence events, they are defined by the presence of more than one jet in the $|\eta| > 2.1$ region of the detector that has $p_{\mathrm{T}} > 30$ GeV and $R_{p_{\mathrm{T}}} < 0.1$ with respect to all the vertices in the event (20% of the events used). All other events, referred to as high confidence events, by definition have high p_{T} jets within the tracker η acceptance, and thus the HS vertex has all of its tracks within the tracker (80% of the events used).

The performance of sumPTw on high confidence events as compared to all the events in Run 3 is shown in Figure 2(a). It can be seen that the performance of sumPTw on high confidence events in Run 3 has parity with the performance of sumPTw on all the events with the expanded tracker of the ATLAS detector at the HL-LHC from Figure 2(b). This is due to events in both cases having a HS vertex that has all its tracks within the tracker. One can also compare the performance of sumPT and sumPTw on high confidence events and note the improvement in average efficiency from 88% to 97%, as seen in Figure 2(b).

This justifies the idea that the efficiency for sumPTw seen in Figure 1(a) is limited by events with HS p_{T} outside the tracker η acceptance. By defining the high/low confidence events one can address the effect of the limited tracking η acceptance in Run 3. For the high confidence events one can identify the HS vertex with 97% efficiency, whereas for the low confidence events no attempt is made to assign a HS vertex even though there is still a VBF event signature.



(a) (b)

Figure 2: Vertex selection efficiency as a function of the PU density, defined as the local density of vertices at the primary vertex in the event. (a) The sumPTw selection on all events (circle) is compared with the sumPTw selection on high confidence events (cross). (b) The default sumPT selection (star) is compared with the proposed sumPTw selection (cross) on high confidence events. Error bars are statistical errors. Best fit linear functions are drawn through the sets of points with 1-sigma error bands to visualize the slopes with respect to the PU density. From Ref. [5].

Finally, the challenge of PU interactions with high p_{T} jets, referred to as hard QCD PU interactions, prevents the sumPTw performance from reaching 100% efficiency in both Figure 1(b) and Figure 2. When the event has hard QCD PU interactions, the PU vertices have tracks pointing along hard PU jets and thus get selected by sumPTw. This final limitation is a shortcoming of topology-agnostic vertex selection algorithms; they can't distinguish between different topologies. For this reason sumPTw can pick a hard QCD PU vertex instead of the VBF Higgs HS vertex. This paves the way for a more sophisticated vertex selection algorithm which extends the innovations presented here and combines them with topology discriminating properties. Such an algorithm would then be able to distinguish hard QCD PU from HS vertices, despite competing summed scalar transverse momenta, etc.

6 Conclusions

ATLAS has developed a new approach for primary vertex selection that integrates calorimeter and tracking information to mitigate the impact of pileup vertex merging and handle hard-scatter interactions with low visible p_{T}. The new algorithm is insensitive to pileup density and improves the average vertex selection efficiency for events containing an invisible Higgs boson decay in vector-boson fusion inclusively from 80% to 88% in LHC Run 3 conditions and from 88% to 97% in the HL-LHC Run 4 conditions. A possible avenue for improvement upon the new algorithm proposed here involves developing an algorithm that exploits topological information and can handle pileup interactions with high p_{T} jets.

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[5] ATLAS Collaboration, "Rescuing VBF Higgs Invisible Events with Novel Vertex Selection", Public Plots IDTR-2020-002, https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/IDTR-2020-002/.

A Appendix: Feynman Diagram for VBF $H \to ZZ^* \to 4\nu$

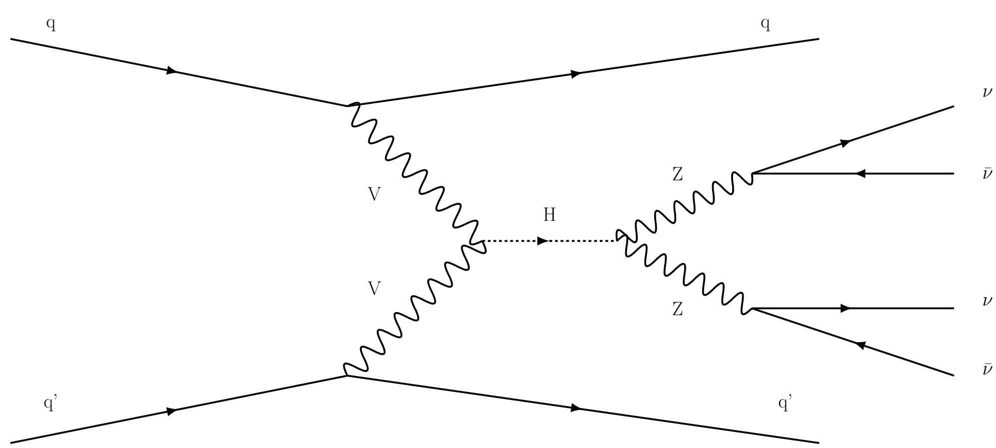

Figure 3: Feynman diagram for VBF $H \to ZZ^* \to 4\nu$. The quarks that radiate the vector bosons form the two forward jets that make up the distinct VBF jet signature. In the invisible final state, it becomes crucial to capture the tracks inside the two VBF jets for identify the hard scatter primary vertex.