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# Performance of Jet Vertex Tagger in suppression of pileup jets and $E_T^{miss}$ in ATLAS detector

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**Abstract.** The Intermediate missing transverse analysis group are investigating the production of Higgs with missing transverse energy. This analysis is based on missing transverse momentum ( $E_T^{miss}$ ) in ATLAS detector and Jets are important objects in reconstruction of missing transverse momentum in ATLAS experiment. In run I, the Jet  $E_T^{miss}$  group used the jet vertex fraction method to discriminate pileup jet from hard-scatter. Due to increase in collision energy in the ATLAS run II a new method called the Jet vertex tagger has been developed. This document presents the performance of Jet Vertex Tagger (JVT) working points using ATLAS simulated Monte Carlo samples. Comparing the fraction and efficiency of jets passing JVT cuts or run I and run II, we see about 20% difference in run II and run I.

## 1. Introduction

The Large Hadron Collider (LHC) is an hadronic collider used to collide proton beams. The LHC was designed for search for physics in support of the Standard Model (SM) and new physics for the theories Beyond the Standard Model (BSM). Collisions of proton bunches in LHC result in hard-scatter (HS) interaction know as signal and an addition collision called the pile-up (PU) collision. The presence of these simultaneous interactions (PU) dilute the signal in LHC. Simulations show that the number of PU interactions will increase in the LHC Run 2 to about  $\sim 40$  as compared to  $\sim 25$  in Run 1 and more after upgrade to High Luminosity LHC [1]. The LHC experiment is handling this challenge by: improving the basic event reconstructions, removal of pile-up before event final state and improving the physics interpretation tools like b-tagging and jet-suppression techniques to be more effective against pile-up. This document presents the performance of jet using the improved jets vertex tagger algorithm.

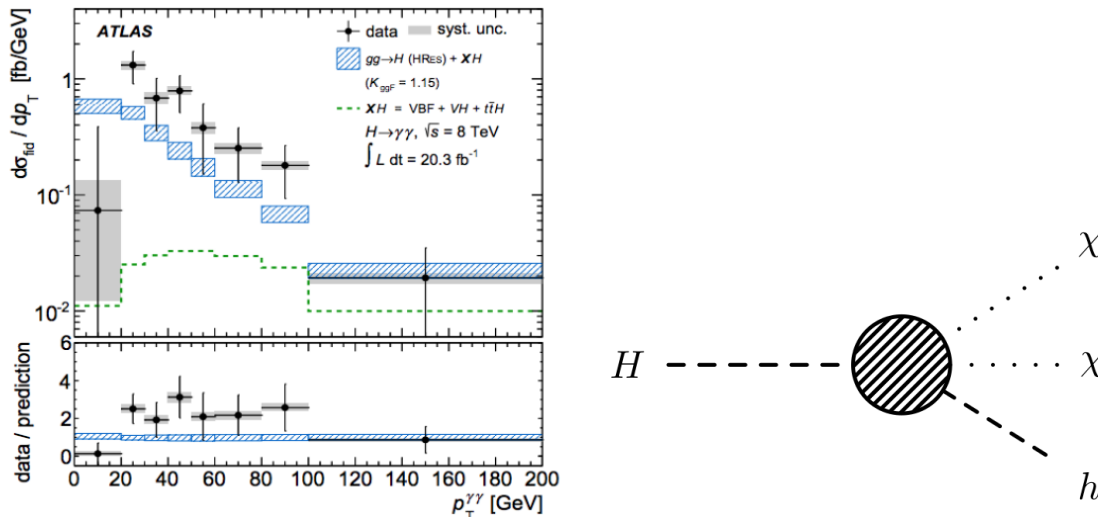
## 2. ATLAS Detector

The LHC has different detectors at different positions along the ring. These detectors and the experiments associated with them are called ATLAS (A Toroidal LHC Apparatus), CMS (Compact Muon Solenoid), ALICE (A Large Ion Collider Experiment), LHCb (Large Hadron Collider Beauty), TOTEM, LHCf and MoEDAL. Each experiments has unique setup and sizes. The ATLAS detector is a general purpose detector that is used to investigate different range of physics. The detector has sub-system like the inner detector ( $|\eta| < 2.5$ ) used mainly for vertex reconstruction, electromagnetic and hadronic sampling calorimeters used to reconstruct energy in the detector and muon system. The ATLAS detector covers pseudorapidity range of  $|\eta| < 4.9$ .



The detector has special trigger system used for event selection. A detailed description can be found in Ref. [2]

### 3. Motivation



**Figure 1.** Left: Higgs  $p_T$  spectrum Run 1 [3]. Right: Decay of a Heavy scalar particle [4]

Figure 1 Left shows the transverse momentum ( $p_T$ ) data for Higgs production at center of mass energy of 8 TeV, the shaded regions depict the theoretical prediction and the dots represent the experimental data. The plots shows a difference in the  $p_T$  spectrum of observation and SM prediction.

Among all the possible explanations of Higgs boson  $p_T$  behavior, is the production of Higgs in associated with invisible particles such as Dark Matter (DM) candidate. Figure 1 Right shows one of the predicted decay mode of an Heavy scalar particle decaying to the SM Higgs and DM candidates. The DM candidate are inferred by the presence of  $E_T^{miss}$  in the detector. The dominant decay modes are  $b\bar{b}$ ,  $WW^*$ ,  $ZZ^*$ ,  $\tau\tau$ ,  $\gamma\gamma$  in decreasing order of branching ratio. None of these channels predicted the Higgs boson  $p_T$  distribution like the one observed in ATLAS, this could be because of  $E_T^{miss}$  from particle not observable by the detector.

### 4. $E_T^{miss}$ and $E_T^{miss}$ Reconstruction

The missing transverse energy ( $E_T^{miss}$ ) is an imbalance in the sum of energy of all particles traveling transverse to the beam axis. This value is the negative vector sum of the momenta of all particle detected in the proton-proton collisions.  $E_T^{miss}$  reconstruction is performed by ATLAS using the energy deposited in the calorimeter and the Muon spectrometer [5]. The  $E_T^{miss}$  components are calculated by:

$$E_{x(y)}^{miss} = E_{x(y)}^{miss,calo} + E_{x(y)}^{miss,\mu} \quad (1)$$

The calorimeter term in Equation 1 is calculated based on reconstructed physics objects (electrons, photons, taus, jets and muons) associated with cells, cells which are not associated with physics objects are tagged  $E_{x(y)}^{miss,CellOut}$ . The  $E_{x(y)}^{miss,calo}$  term is given by:

$$E_{x(y)}^{miss,calo} = E_{x(y)}^{miss,calo,e} + E_{x(y)}^{miss,calo,\gamma} + E_{x(y)}^{miss,calo,\tau} + E_{x(y)}^{miss,calo,jets} + E_{x(y)}^{miss,calo,\mu} + E_{x(y)}^{miss,CellOut} \quad (2)$$

each term in Equation 2 is calculated from the negative sum of the calibrated cell energies corresponding to objects as follows:

$$E_x^{miss,term} = - \sum_{i=1}^{N_{cell}} E_i \sin\theta_i \cos\phi_i, \quad E_y^{miss,term} = - \sum_{i=1}^{N_{cell}} E_i \sin\theta_i \cos\phi_i \quad (3)$$

The muon term in Equation 1 is calculated from the momenta of muon reconstructed with  $|\eta| < 2.7$  as follows:

$$E_{x(y)}^{miss,\mu} = - \sum_{muons} P_{x(y)}^\mu \quad (4)$$

$E_T^{miss}$  and its angle  $\phi^{miss}$  are calculated by:

$$E_T^{miss} = \sqrt{(E_x^{miss})^2 + (E_y^{miss})^2}, \quad \phi^{miss} = \arctan(E_y^{miss}, E_x^{miss}) \quad (5)$$

A good  $E_T^{miss}$  performance is gotten when using  $E_T^{miss}$  calibration with the following configuration:

- $E_T^{miss,e}$  term is calculated using medium electron with  $p_T > 10$  GeV [6].
- $E_T^{miss,\gamma}$  term is calculated from "tight" photon with  $P_T > 10$  GeV.
- $E_T^{miss,\tau}$  term is calculated from "tight" taus [7] with  $P_T > 10$  GeV and with the LCW calibration
- $E_T^{miss,soft}$  term is calculated from jets with  $7 < |P_T| < 20$  GeV (reconstructed using the anti-kt algorithm with  $R=0.6$ ) calibrated with the LCW calibration
- $E_T^{miss,jets}$  term is calculated from jets with  $P_T > 20$  GeV (reconstructed using the anti-kt algorithm with  $R=0.6$ ) calibrated with the LCW calibration and the jet energy scale factor (JES) [8].

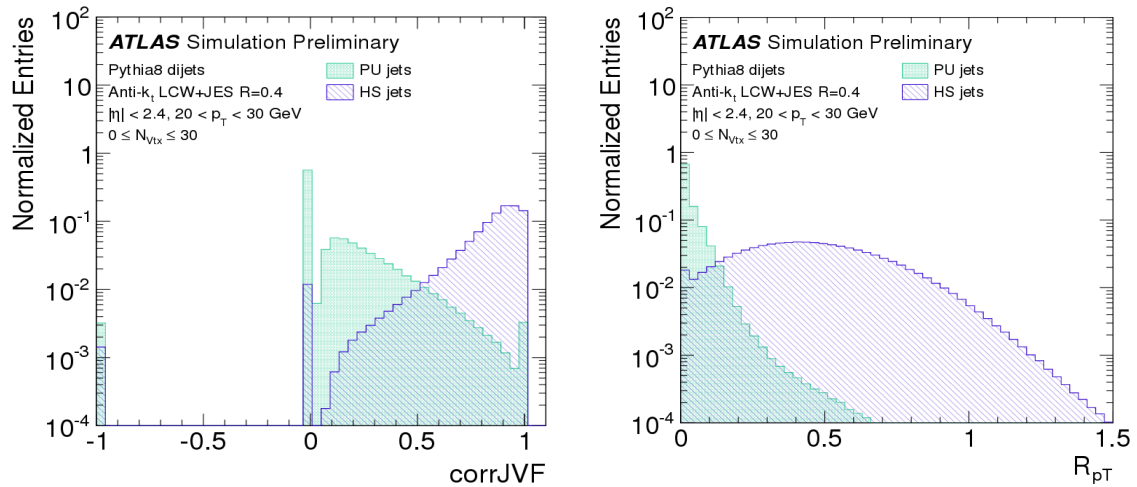
The  $E_T^{miss,soft}$  is the energy sum of all energy clusters or tracks that are not associated with any of the identified physics objects, this makes the  $E_T^{miss,soft}$  most sensitive to pile-up which is corrected by implementation of JVT.

## 5. Jet tagger

The ATLAS experiment uses Jet-Vertex-Tagger (JVT) variables to identify and suppress PU jets coming. The JVT is a replacement for the old discriminate: jet vertex fraction (JVF) Equ. 6 variable used Run I. The JVT variable is a 2-dimensional likelihood variable, it is estimated based on the  $k$ -nearest-neighbour algorithm whose inputs are corrected-JVF (corrJVF) Equ. 7 and  $R_{pT}$  Equation 8 [1].

$$JVF = \frac{\sum_k P_T^{trk_k}(PV_0)}{\sum_k P_T^{trk_l}(PV_0) + \sum_{n \geq 1} \sum_l P_T^{trk_k}(PV_n)} \quad (6)$$

$$corrJVF = \frac{\sum_k P_T^{trk_k}(PV_0)}{\sum_k P_T^{trk_l}(PV_0) + \frac{\sum_{n \geq 1} \sum_l P_T^{trk_k}(PV_n)}{(k.n_{trk}^{PU})}} \quad (7)$$



**Figure 2.** Left: corrJVF distribution for pileup and hard-scatter jet in simulated dijet events. corrJVF = -1 for jets with no associated tracks. Right:  $R_{pT}$  distributions for PU and HS jets from Ref. [1]

$$R_{pT} = \frac{\sum_k p_T^{trk_k}(PV_0)}{P_T^{jet}}. \quad (8)$$

From Figure 2, showing the distribution of corJVF and  $R_{pT}$  in simulated sample, we see HS jets are characterized by large corJVF and large  $R_{pT}$  and PU jets are concentrated at low  $R_{pT}$  and low corJVF values. The jet  $E_T^{miss}$  recommendation defines three JVT working point (JVT WP), which are JVT cut 0.14, JVT cut 0.64 (default) and JVT cut 0.92

## 6. Performance of the new jet tagger

Using the fraction (the proportion of all hard-scatter divided by the pileup jet in all jet passing a given JVT cut) and efficiency (the proportion of hard-scatter/pileup jet passing given JVT cut) distributions to study the performance of JVT.

### 6.1. Fraction

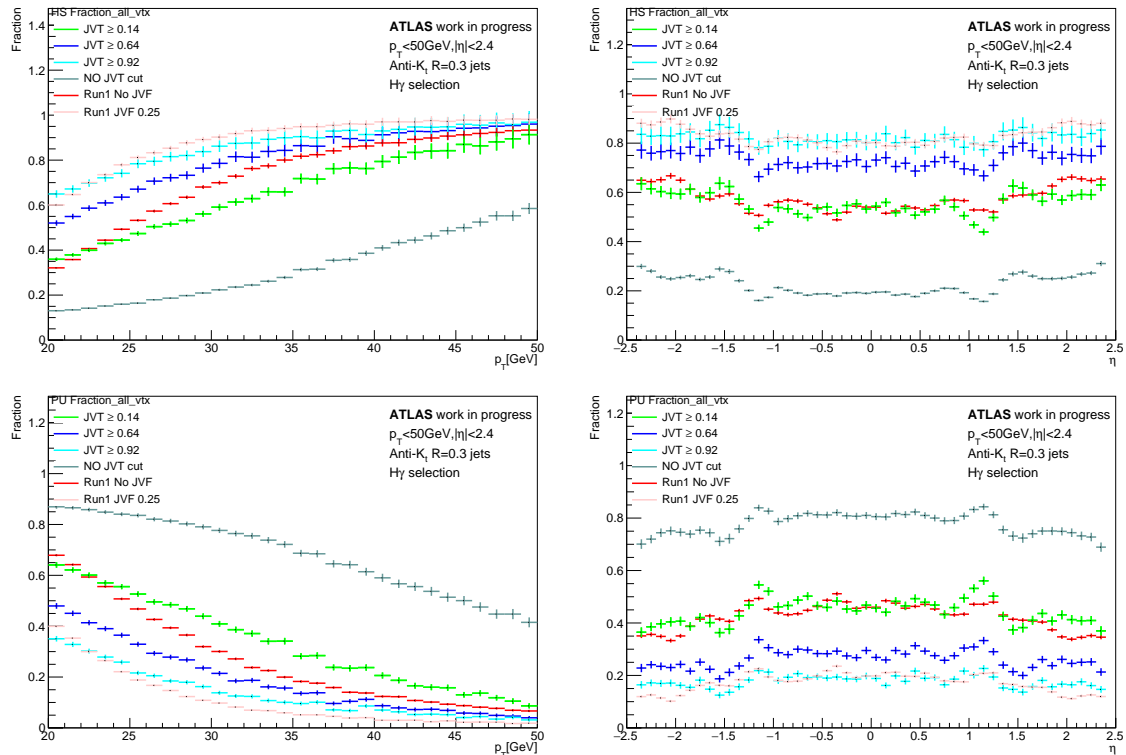
The Hard-scatter and Pileup jet fraction is defined as:

$$F_{HS} = \frac{N_{HS}}{N_{HS} + N_{PU}}, \quad F_{PU} = \frac{N_{PU}}{N_{HS} + N_{PU}}, \quad (9)$$

where  $F_{HS/PU}$  represents the fraction of hard-scatter/pileup jet,  $N_{HS/PU}$  is the number of hard-scattered or pileup jet.

### 6.2. JVT Performance

Figures 3 and 4 show fraction jet distribution for gluon-gluon fusion sample at center of mass energy of 13 TeV comparing with Run 1 JVF 8 TeV sample. Figure 3 shows the fraction of jet before events are corrected for number of primary vertex. The Run 2 jet distributions without JVT cut differ from the Run1 by about 20% in both PU and HS and the default JVT WP ranges between 50 - 65% in the HS fraction, 10 - 50% for PU fraction. Figure 4 shows the fraction of



**Figure 3.** Distributions of hard-scatter (top row) and pileup (bottom row) jet fraction in JVT region as a function of (left)  $p_T$  and (right)  $\eta$  from the gluon-gluon fusion Higgs production mode when all vertices are considered.

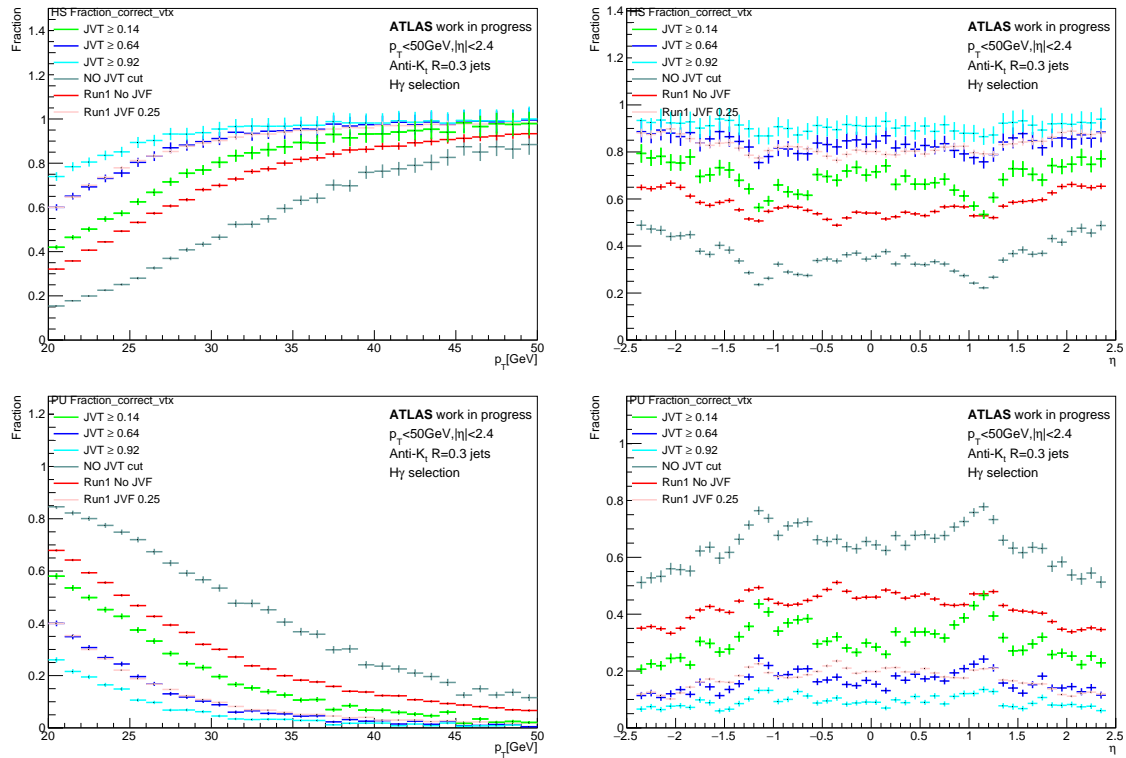
jet after events are corrected for number of primary vertex by rejecting event outside  $z < 0.3mm$  of the detector. The Run 2 distribution without JVT cut improves as compared with the Run1 by about 10% in both PU and HS, There is good agreement between jet performance for JVT 0.64 (Run II) and JVF 0.25 JVF (Run I). Purity of jets passing the JVT 0.64 (default JVT WP) cut ranges from 60% to 85% VS  $P_T$  in the HS and 40% to 15% VS  $P_T$  in the PU.

## 7. Conclusions

A search for an Heavy scalar particle which decays to Higgs with associated Dark Matter particle which are inferred by the presence of intermediate  $E_T^{miss}$  in the detector.

The search is heavily influenced by  $E_T^{miss}$ , and  $E_T^{miss}$  is in turn sensitive to the jet going into its reconstruction algorithm. A new jet-vertex tagging method, JVT, has been developed to mitigate the effect of pile-up jets. The JVT algorithm is the improved version of the previous JVF algorithm used in ATLAS. The JVT algorithm is based on two new pileup-insensitive variables: corrJVF and  $R_{pT}$  in 2-dimension likelihood.

the selection of events with correct vertex improves the distribution of fraction of jets for all the JVT working point. Purity of jets passing the JVT 0.64 cut ranges from 60% to 85% VS  $P_T$ . There is good agreement between jet performance for JVT 0.64 (Run II) and JVF 0.25 JVF (Run I). Significant amount of Pileup jets in the detector's forward region ( $0.5 \leq |\eta| \leq 1.5$ ) were observed as shown by the purity vs  $\eta$  plots.



**Figure 4.** Distributions of hard-scatter (top row) and pileup (bottom row) jet fraction in JVT region as a function of (left)  $p_T$  and (right)  $\eta$  from the gluon-gluon fusion Higgs production mode when all vertices are considered.

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