Identifying VBF Higgs boson production using the *jet pull vector* observable

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Introduction

The ATLAS experiment is a particle physics experiment conducted at CERN using the Large Hadron Collider (LHC). In the LHC, protons are accelerated to more than 99.9999% of the speed of light, before colliding in the middle of the ATLAS detector (Fig. 1). Under impact, protons break into smaller particles, and sometimes, a Higgs boson is produced.

The Higgs boson is a particle predicted by the Standard Model of particle physics that constitutes evidence for electroweak symmetry breaking, which "gives mass" to other fundamental particles. It has various production and decay modes with probabilities also predicted by the Standard Model. If these ratios are not respected, our theory might be wrong!

We need to precisely measure each Higgs boson production rate to test the Standard Model.

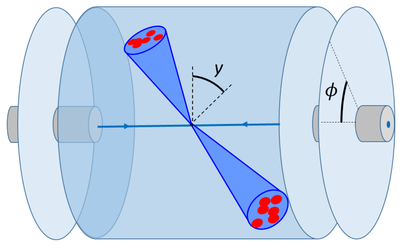

Figure 1 : Detector outline with two jets (blue) and their constituents (red) produced in a proton-proton collision in the middle of the detector.

Issue

VBF and ggF are two Higgs boson production modes (Fig. 2). VBF production is characterized by the formation of two jets with large angular separation in rapidity (y). Unfortunately, ggF production can have the same characteristics! Other discriminants are thus needed to properly identify VBF Higgs boson production. An observable that was never used before in Higgs boson analyses is the *jet pull vector*.

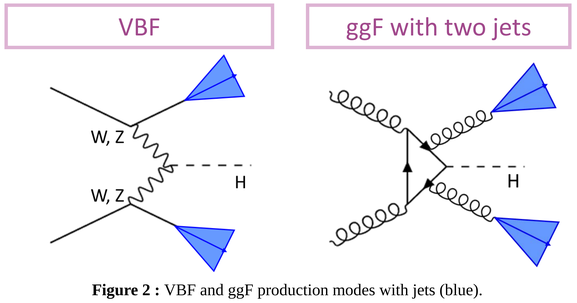

Figure 2 : VBF and ggF production modes with jets (blue).

Can we use the *Jet pull vector* observable to discriminate VBF events?

Theory

Color flow in jets

Jets are groups of particles (called hadrons) produced when a quark or a gluon is knocked out of a proton that collides in the LHC. The jets used for the results shown here are formed by grouping hadrons from Monte Carlo simulated data samples. Jets used in data measurements are formed from calorimeter energy clusters.

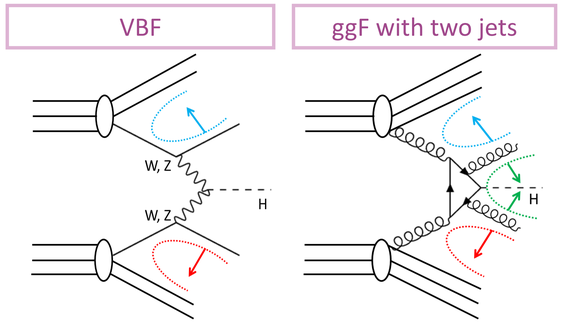

Figure 3 : VBF and ggF production modes with jets color flow.

For VBF production, we expect the jets to be color connected to the beam. Jet constituents will then tend to follow the beam, leading to tails of particles pointing **toward forward rapidity**. For ggF production, jets are both color connected to the beam and each other. We don't expect jets constituents to point as much toward forward rapidity. They could even point toward each other, because of their color connection.

Jet pull vector : a jet substructure observable to quantify color flow

The ***jet pull vector*** $\vec{v}_p^J$ is calculated using

$$\vec{v}_p^J = \sum_{i \in J} \frac{p_T^i |\vec{r}_i|}{p_T^J} \vec{r}_i \,,$$

where the sum is over jet constituents and

$\vec{r}_i = (y_i - y_J, \phi_i - \phi_J)$,
p_T: transverse momentum,
y : rapidity (Fig. 1),
ϕ : polar angle (Fig. 1).

The **pull vector angle** is defined as the smallest angle between the pull vector and the forward beam.
What we expect :

- pull vector angle close to π for VBF **backward jet**,
- pull vector angle close to **0** for VBF **forward jet**.

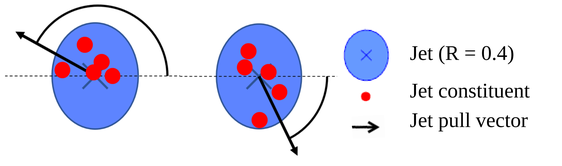

Figure 4 : Backward (left) and forward (right) jets with their expected pull vector angles.

Results

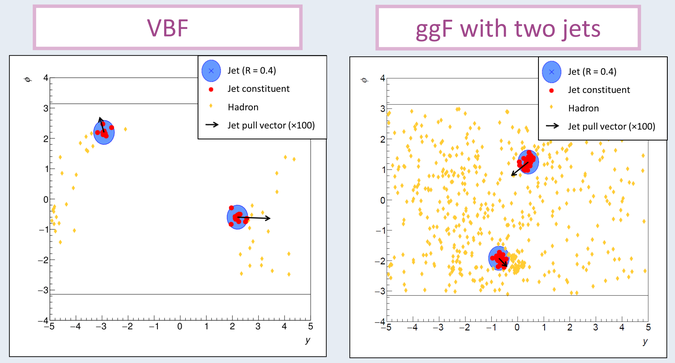

Figure 5 : VBF looking as expected and typical ggF event displays at truth level.

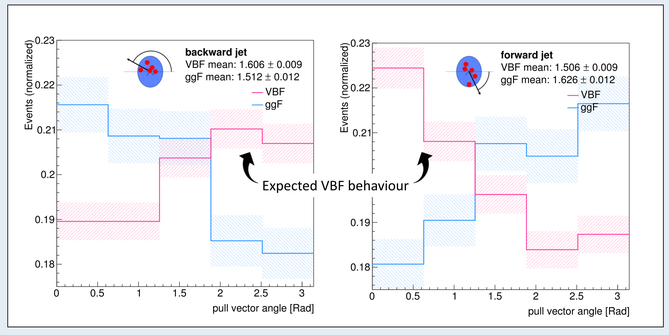

Figure 6 : Backward and forward jets pull vector angle distributions at truth level.

Results are obtained using Monte Carlo simulated $H \to \gamma\gamma$ VBF and ggF events from the ATLAS HGam group. Objet selection is also the default selection from the ATLAS HGam group [3]. Backward and forward jets are those with highest transverse momentum. Analysis is done at **truth level**.

Events display

A simple graphic tool was build to produce event displays. Using this tool, some noticeable differences between a typical ggF event and a VBF event looking as expected are observed (Fig. 5). The two jets have **larger separation** in rapidity for VBF than for ggF. There is **fewer hadrons** produced in VBF, and they make tails of particles pointing outward. VBF *jet pull vectors* are also pointing **toward forward rapidity**. Unfortunately, not all VBF events look like this.

Pull vector angle distribution

A small increase in the number of events having a pull vector angle close to π for VBF backward jets and having a pull vector angle close to 0 for VBF forward jets is observed (Fig. 6). For ggF pull vector angles, we observe the opposite tendency, with most *jet pull vectors* pointing inward. This is **consistent with the theory**. However, the difference of proportion of events that have these behaviours is quite **small**.

Conclusion

We would expect VBF *jet pull vectors* to be oriented mostly toward forward rapidity, while ggF *jet pull vectors* should not. We observed a **small but significant** tendency of the above using truth jets constituents to calculate *jet pull vectors*.

Based on truth Monte Carlo studies using VBF quark decay products, we have some indications that improved results could be obtained by

- increasing the radius of jets,
- calculating *jet pull vectors* in the jets center of mass referential frame.

Also, full analysis still needs to be conducted at reconstructed level.

***The Jet pull vector* observable might not be a golden bullet, but might prove valuable in VBF multivariate analyses.**

References

[1] Gallicchio, Jason et al., *Seeing in Color: Jet Superstructure*, Phys.Rev.Lett. 105 (2010) 022001 arXiv:1001.5027 [hep-ph].

[2] Joshi, Kiran Daniel et al., *Measurement of colour flow with the jet pull angle in $t\bar{t}$ events using the ATLAS detector at $\sqrt{s}$ = 8 TeV*, ATL-COM-PHYS-2015-136 (2015), URL: https://cds.cern.ch/record/1994254/.

[3] Lenzi, Bruno et al., *Supporting note: Selection and performance for the $H\to\gamma\gamma$ and $H\to Z\gamma$ analyses*, ATL-COM-PHYS-2015-1326 (2015), URL: https://cds.cern.ch/record/2062580/.

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