

# ***CP*-properties of the Higgs-boson couplings from $H +$ dijets through gluon fusion**

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At lowest order in perturbation theory, the production of a Higgs boson in association with dijets displays a strong correlation in the azimuthal angle between the dijets, induced by the *CP*-properties of the Higgs Boson coupling. However, the phase space cuts necessary for a clean extraction of the *CP*-properties in the gluon fusion channel simultaneously induce large corrections from emissions of hard radiation and thus formation of additional jets. This contribution discusses how the *CP*-properties of the Higgs boson coupling can be cleanly extracted from events with more than two jets, based on a technique developed from insight into the high energy limit of hard scattering matrix elements.

## **1 Introduction**

One of the primary goals of experiments at the CERN Large Hadron Collider (LHC) is the search for the Higgs boson(s) which, within the Standard Model (SM) and many of its extensions, provide direct access to the dynamics of electroweak symmetry breaking. Once discovered, the focus of Higgs physics will turn to the study of Higgs boson properties, like its mass, spin, *CP* parity and the strength and structure of Higgs boson couplings to heavy fermions and gauge bosons.

Among the various Higgs channels at the LHC, the production of a Higgs boson in association with two energetic jets has emerged as particularly promising in providing information on the dynamics of the Higgs sector. This is true in particular for the gluon fusion channel, where the *CP*-properties of the Higgs boson couplings to the fermions in the loop-induced coupling can be extracted<sup>1</sup>: Tree-level considerations lead to the expectations of a strong azimuthal correlation between the two jets, with a phase depending on the relative weight of a *CP*-even (SM-like) and *CP*-odd coupling. The azimuthal angle modulations get particularly pronounced when the two jets are widely separated in rapidity. Equivalent effects are expected in vector boson fusion and have been discussed in Ref.<sup>2,3</sup> for the idealised situation of parton level events at leading order.

The extraction of the *CP*-properties of the Higgs boson couplings in gluon fusion will require some cut on the rapidity separation between the two hard (e.g.  $p_{\perp} > 40\text{GeV}$ ) jets; typically, they are required to be at least 3 units apart in rapidity<sup>1</sup>, or alternatively<sup>4</sup> the Higgs boson is required to be produced between the dijets in rapidity, with a minimum distance of .5-1 units of rapidity between the Higgs boson and the hard jets.

## **2 Hard Radiative Corrections**

The tree-level observations leading to the expectation of the azimuthal correlation are jeopardised by the requirement of a size-able rapidity separation between the jets. For the gluon fusion channel, this requirement increases the hard radiative corrections leading to the formation of additional jets; and therefore one must address the problem of how to extract the *CP*-properties of the Higgs boson couplings from events with strictly more than two jets, where one might think it is not so clear how to generalise the azimuthal angle studied for events of pure Higgs-boson plus dijet. It is clear that the study of just the azimuthal angle between any two jets (e.g. the two hardest) will necessarily be less correlated once real radiative corrections are taken into account. This contribution discusses how to form an observable, so that the extraction of the *CP*-properties is stable against radiative corrections<sup>4</sup>.

First, we will briefly discuss the reason for the increasing weight of real, hard radiative corrections as the rapidity span between the dijets is increased. This is caused by two effects.

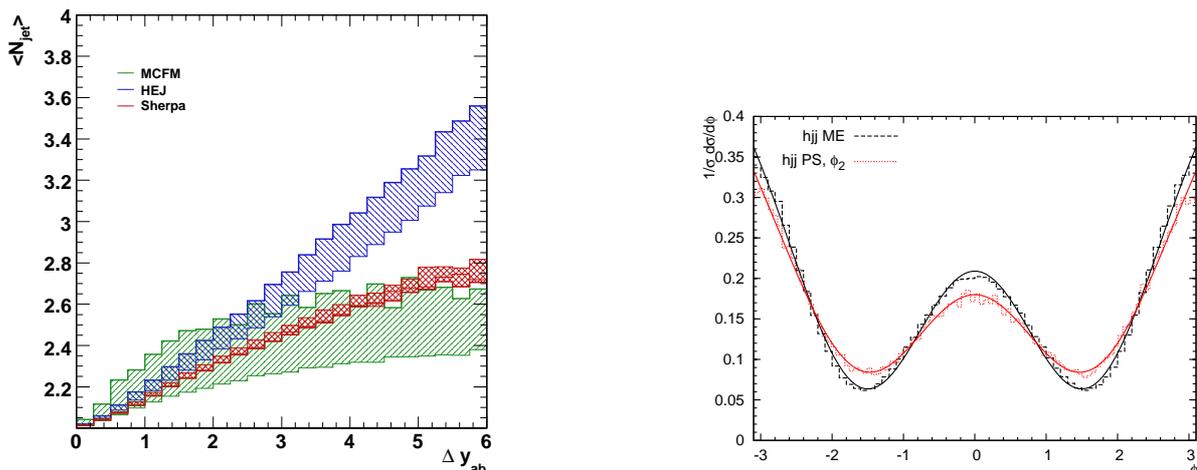


Figure 1: Left: The average number of hard jets ( $p_{\perp} > 40\text{GeV}$ ) in Higgs-boson production in association with dijets as a function of the rapidity difference between the most forward and most backward hard jet. Figure taken from Ref.<sup>6</sup> Right: The differential cross section on the azimuthal angle discussed in the text for the tree-level calculation (black) and for showered and hadronised events (red). Figure taken from Ref.<sup>6</sup>

First, two widely separated (in rapidity) jets will dominate the contribution to the light-cone momentum fraction of the partons extracted from the proton, so the relative impact of extracting a little extra energy from the proton in order to form an additional central jet is small (the details will obviously depend on just how steeply the parton density functions are falling with increasing  $x$ ). Secondly, the phase space for the emission of additional radiation increases as the rapidity span between the most forward and most backward jet is increased. These kinematic considerations are shared of course by all processes, and by all models for the these (e.g. shower MC, fixed order perturbation theory). The amount of hard radiation generated obviously differs between different processes (e.g. Higgs boson+dijets through weak boson fusion or gluon fusion<sup>5</sup>), and between different models of a given process (e.g. shower MC, NLO, resummation). To illustrate this last effect, Figure 1 (taken from Ref.<sup>6</sup>) displays the average number of jets in events (at a  $pp$ -machine with  $\sqrt{s} = 10\text{TeV}$ ) with a Higgs-boson in association with at least two hard jets (of transverse momentum greater than  $40\text{GeV}$ ) as a function of the rapidity span between the most forward and most backward hard jet, as calculated at fixed next-to-leading order<sup>7</sup> (green), **Sherpa**<sup>8</sup> with tree-level matching up to Higgs-boson plus four partons using **Comix**<sup>9</sup> (red), and finally an all-order sum of the leading radiative corrections for widely separated emissions<sup>10,11,12,13</sup> (blue). The width of the bands indicate the scale variation, but the initial choice is different and the range of variation is smaller in **Sherpa** than in the two other models. We see that all models for this process predicts a strong correlation between the rapidity span between the most forward and most backward hard jet, and the average number of hard jets (all above  $40\text{GeV}$  in transverse momentum) in the event. In fact, the increasing relevance of the high-multiplicity states with growing rapidity span is a central motivation for the BFKL<sup>14,15</sup> resummation programme for hard processes. Indeed, the strong correlation between the rapidity span of the event and the average number of hard jets were observed in variants<sup>16,17</sup> on the BFKL formalism also for pure jets<sup>18</sup> and  $W$ +dijets<sup>19</sup>. While the BFKL formalism reproduces the limit of the full QCD amplitudes for infinite rapidity separation between all (hard) particles, the formalism developed in Ref.<sup>10,11,12,13</sup> obeys also other constraints (e.g. gauge-invariance) in all of phase space (i.e. also for sub-leading kinematics).

Figure 1 also indicates that for the rapidity spans of interest for the extraction of the  $CP$ -properties, the average number of jets is significantly larger than 2. For the NLO calculation,

the exclusive 2-jet and 3-jet rates have to be equal, in order to get an average number of hard jets of 2.5. It is clear that understanding the pattern of multi-jet radiation will be important for a stable extraction of the  $CP$ -properties of the Higgs-boson couplings.

### 3 Lessons From The High Energy Limit

In order to generalise the lowest order study of the azimuthal angle between the dijets to the case of multiple hard jets we start by studying the (colour and helicity summed and averaged) square of the matrix element for  $gg \rightarrow g \cdots ghg \cdots g$  in the limit of infinite rapidity separation between each produced particle (the so-called multi-Regge-kinematic (MRK) limit):

$$|\overline{\mathcal{M}}_{gg \rightarrow g \cdots ghg \cdots g}|^2 \rightarrow \frac{4\hat{s}^2}{N_C^2 - 1} \left( \prod_{i=1}^j \frac{C_A g_s^2}{\mathbf{p}_{i\perp}^2} \right) \frac{|C^H(\mathbf{q}_{a\perp}, \mathbf{q}_{b\perp})|^2}{\mathbf{q}_{a\perp}^2 \mathbf{q}_{b\perp}^2} \left( \prod_{i=j+1}^n \frac{C_A g_s^2}{\mathbf{p}_{i\perp}^2} \right), \quad (1)$$

where  $\mathbf{q}_{a\perp} = -\sum_{i=1}^j \mathbf{p}_{i\perp}$ , where  $j$  is the number of gluons with rapidity smaller than that of the Higgs boson, and  $\mathbf{q}_{b\perp} = \mathbf{q}_{a\perp} - \mathbf{p}_{h\perp}$ . In this limit, the contribution from quark-initiated processes is found by just a change of one colour factor  $C_A \rightarrow C_F$  for each incoming gluon replaced by a quark. The effective vertex for the coupling of a SM Higgs boson to two off-shell gluons through a top loop is in the combined large- $m_t$  and MRK limit<sup>20</sup>

$$C^H(\mathbf{q}_{a\perp}, \mathbf{q}_{b\perp}) = i \frac{A}{2} (|\mathbf{p}_{h\perp}|^2 - |\mathbf{q}_{a\perp}|^2 - |\mathbf{q}_{b\perp}|^2) = -iA \mathbf{q}_{a\perp} \cdot \mathbf{q}_{b\perp}, \quad (2)$$

$$A = \frac{\alpha_s}{3\pi v}, \quad v = 246 \text{ GeV}.$$

In the simple case of  $hjj$  at tree level in the SM we recover from Eq. (2) a cosine modulation in the azimuthal angle between the two jets, which is indeed the correct limiting behaviour seen in the full tree-level matrix element. A CP-odd contribution to the coupling would introduce a sinus-component, and a phase-shift in the angular distributions discussed later. However, Eq. (2) also hints how to recover this azimuthal modulation in events with more than two jets<sup>4</sup>: simply divide the jets into two sets according to whether their rapidities are smaller or greater than that of the Higgs boson; then calculate the azimuthal angle between the transverse sum of vectors from each set. This angle will in the MRK limit display the same behaviour as that of the azimuthal angle between the two partons in the lowest order analysis.

## 4 Results

In Ref.<sup>4</sup> we checked the stability of the angle as defined above against several corrections beyond the tree-level description, and will here present just a few of the findings. The first thing one could worry about is the stability against the effects, both perturbative and non-perturbative, included in a general-purpose Monte Carlo generator. In Fig. 1 (right) we compare the azimuthal modulation using the definition discussed in the previous section found at tree-level with that found after showering and hadronisation of these states with HERWIG++<sup>21</sup>. We see that the azimuthal modulation survives the effects of hadronisation etc., and also that the real emission from the shower, which does not end up in hard jets (and is thus not included in the construction of the azimuthal angle), does not spoil the positions of the peaks and troughs of the distribution.

While the shower-formalism correctly resums the soft- and collinear radiation from the tree-level  $hjj$ -configuration, the pure shower-formalism underestimates the amount of hard radiation, which can lead to further decorrelation. In order to check the stability of the azimuthal distribution, against such radiation, we analyse the constructed azimuthal observable on a set of  $hjj$ -events generated in the all-order formalism discussed earlier<sup>10,11,12,13</sup>. In Fig. 2 we show on

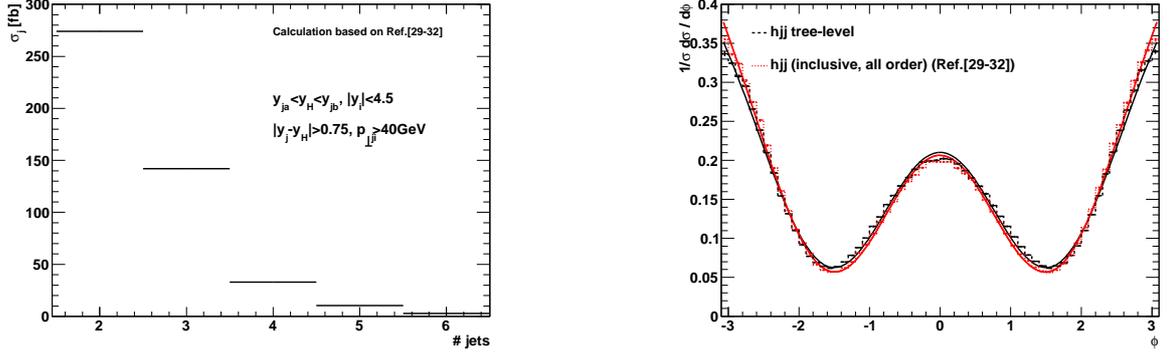


Figure 2: Left: The jet rates in the inclusive all-order sample generated with the method discussed in Ref.<sup>10,11,12,13</sup>. The exclusive 2-jet rate accounts for only roughly 60% of the inclusive 2-jet sample. Right: The distribution on the azimuthal angle discussed in the text as calculated at tree-level (black) and in the all-order sample. Figure taken from Ref.<sup>4</sup>

the left the distribution of the number of hard jets in the event sample within the cuts mentioned in the figure. The exclusive 2-jet rate accounts for around 60% of the inclusive two-jet rate, so it is clearly necessary with a strategy for a stable extraction of the  $CP$ -properties of the Higgs boson couplings for events with strictly more than two jets. In Fig. 2 (right) we have used the same event sample as used for the plot on the left, and show the differential distribution on the azimuthal angle constructed as discussed. Furthermore, we compare this to the result obtained at lowest order.

In conclusion, the constructed azimuthal observable is clearly very stable against higher order perturbative corrections, allowing for a stable extraction of the  $CP$ -properties of the Higgs boson couplings in gluon fusion.

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