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QCD corrections to jet correlations in weak boson fusion

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Abstract

Higgs boson production via weak boson fusion is sensitive to the tensor structure of the HVV $(V = W, Z)$ couplings, which distinguishes loop induced vertices from SM expectations. At the CERN large hadron collider this information shows up most clearly in the azimuthal angle correlations of the two forward and backward quark jets which are typical for weak boson fusion. We calculate the next-to-leading order QCD corrections to this process, in the presence of anomalous HVV couplings. Gluon emission does not significantly change the azimuthal jet correlations.

1. Introduction

The production of Higgs bosons in the weak boson fusion (WBF) process will provide a direct and highly sensitive probe of HWW and HZZ couplings at the CERN Large Hadron Collider (LHC) [1–5]. The determination both of the strength and of the tensor structure of these couplings is crucial for the identification of the produced boson as a remnant of the spontaneous symmetry breaking process which is responsible for W and Z mass generation.

Within spontaneously broken, renormalizable gauge theories like the standard model (SM), this coupling originates from the kinetic energy term, $(D_\mu \Phi)^\dagger (D^\mu \Phi)$, of a scalar Higgs field, Φ, whose neutral component obtains a vacuum expectation value (vev), $\Phi^0 \to (v + H)/\sqrt{2}$. This replacement then leads to a characteristic coupling in the interaction Lagrangian, of the form $HV_\mu V^\mu$ $(V = W, Z)$. The existence of the vev is necessary to produce a trilinear HVV coupling at tree level: with $v = 0$ all couplings to the gauge fields V contain two scalar fields, i.e., only HHV and $HHVV$ couplings would be generated. A trilinear HVV coupling may also be loop-induced, however. The SM $H\gamma\gamma$ and Hgg effective couplings are an example: they are induced by W-boson and/or top quark loops. Gauge invariance dictates a different tensor structure of these loop-induced couplings: the corresponding effective Lagrangian contains the square of the field strength, i.e., the lowest order loop-induced terms are of the form $HV_{\mu\nu}V^{\mu\nu}$ or $HV_{\mu\nu}\tilde{V}^{\mu\nu}$, where $\tilde{V}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\rho\sigma}V_{\rho\sigma}$ denotes the dual field strength of the gauge field.

The task of future Higgs experiments is, then, twofold: (i) to measure the overall strength of the HVV coupling, and (ii) to identify its tensor structure.

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One would expect a loop-induced coupling to be much smaller than the expected SM HVV coupling strength. However, the measurement of WBF rates alone will not be sufficient to establish H as being related to spontaneous symmetry breaking: to give just two examples, the loop-induced couplings might be substantially enhanced by additional non-SM particles in the loop or by the existence of multiplets of large weak isospin which couple strongly to H. Or a particular LHC signature may be strongly enhanced by a much larger H decay branching ratio than in the SM. A confirmation that the HVV coupling has tree level strength is, thus, ambiguous: a clear identification of the Higgs boson also requires the identification of the tensor structure of the HVV vertex.

It was pointed out some time ago that the azimuthal angle correlations of the two quark jets in the weak boson fusion process $qQ \to qQH$ provide tell-tale signatures for the tensor structure of the HVV couplings [6]: the SM expectation is for a flat distribution, while the loop-induced couplings lead to a pronounced dip at azimuthal separations ϕ_{jj} of the two tagging jets of 90 degrees for a $HV_{\mu\nu}V^{\mu\nu}$ coupling and at 0 and 180 degrees for the CP violating $HV_{\mu\nu}\tilde{V}^{\mu\nu}$ vertex. Observation of the tagging jets is crucial for isolating the WBF process from backgrounds and, therefore, their distributions will be available for all WBF samples. Also, signal to background ratios for WBF processes are expected to be very good within the SM, exceeding the 1:1 level for wide ranges of the Higgs boson mass [1–5].

The analysis of Ref. [6] was performed at leading order (LO) in QCD. This means that additional gluon emission, which might lead to a de-correlation of the tagging jets, was ignored in the analysis. Subsequently it was argued [7] that such de-correlation effects play an important role in a related process, $gg \to Hgg$, when the two tagging jets are widely separated in rapidity, which is a typical requirement for WBF studies. In this Letter we analyze this question, by calculating the tagging jet distributions in next-to-leading order (NLO) QCD, for the production of a scalar H via WBF with an arbitrary tensor structure of the HVV vertex. If de-correlation is important, it should show up in the form of large radiative corrections at NLO. We use the term “Higgs boson” as a generic name for the produced scalar in the following.

2. The NLO calculation

Our calculation is an extension of the NLO QCD corrections for the SM WBF processes $qQ \to qQH$ (and crossing related ones) [8–10]. For the total cross section these corrections have been known for over a decade [8]. Recently, we have recalculated them by developing a NLO parton level Monte Carlo program [9] which provides the flexibility to calculate arbitrary distributions at NLO, such as the azimuthal angle correlations that we are interested in here.

The calculation of Ref. [9] uses a SM vertex function, $T^{\mu\nu}(q_1,q_2) = \frac{2m_V^2}{v} g^{\mu\nu}$ for the HVV vertex in Fig. 1. Here we need to generalize this vertex to the most general structure compatible with Lorentz invariance. Taking into account that the quark currents in Fig. 1 and for the corresponding gluon emission processes are conserved, all terms proportional to q_1^μ or q_2^ν may be dropped, and the most general HVV vertex may be written as

$$T^{\mu\nu}(q_1,q_2) = a_1(q_1,q_2)g^{\mu\nu} + a_2(q_1,q_2)\left[q_1\cdot q_2 g^{\mu\nu} - q_2^\mu q_1^\nu\right] + a_3(q_1,q_2)\varepsilon^{\mu\nu\rho\sigma} q_{1\rho} q_{2\sigma}. \quad (1)$$

Here q_1 and q_2 are the four-momenta of the two weak bosons, and the $a_i(q_1,q_2)$ are Lorentz-invariant form factors, which might, for example, represent scalar loop integrals in a perturbative calculation. It is straightforward to implement the general vertex of Eq. (1) into our NLO QCD Monte Carlo: the virtual amplitude of Fig. 1 is proportional to the Born amplitude, $\mathcal{M}_{\rm Born}$, irrespective of the structure of the HVV vertex. Thus, all amplitudes reduce to a simple contraction of quark (or quark–gluon) currents with the vertex function of Eq. (1). These currents, and their contractions, are evaluated numerically, using the

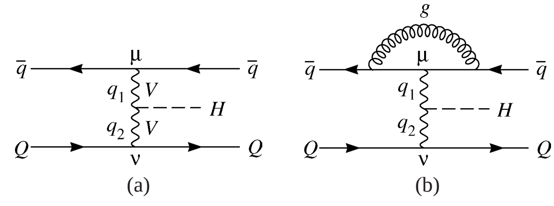

Fig. 1. Feynman graphs contributing to $\bar{q}Q \to \bar{q}QH$ at (a) tree level and (b) including virtual corrections to the upper quark line. The momentum labels and Lorentz indices for the internal weak bosons correspond to the vertex function of Eq. (1).

amplitude formalism of Ref. [11]. All other aspects of the present NLO calculation are handled as in Ref. [9], except that we do not simulate any Higgs boson decays in the following. Factorization and renormalization scales are fixed to $\mu_F = \mu_R = Q_i$ for QCD corrections to the first or second quark line in Fig. 1. Here Q_1 and Q_2 are the virtualities of the exchanged weak bosons. We use CTEQ6M parton distributions [12] with $\alpha_s(M_Z) = 0.118$ for all NLO results and CTEQ6L1 parton distributions for all leading order cross sections.

3. Anomalous couplings and form factors

While the $g^{\mu\nu}$-term in the vertex function (1) corresponds to a SM Higgs coupling, the anomalous coupling terms a_2 and a_3 can be related to higher-dimensional operators in an effective Lagrangian. They first appear at the dimension 5 level[1] and may be written as

$$\mathcal{L}_5 = \frac{g_{5e}^{HWW}}{\Lambda_{5e}} H W_{\mu\nu}^{+} W^{-\mu\nu} + \frac{g_{5o}^{HWW}}{\Lambda_{5o}} H \tilde{W}_{\mu\nu}^{+} W^{-\mu\nu} + \frac{g_{5e}^{HZZ}}{2\Lambda_{5e}} H Z_{\mu\nu} Z^{\mu\nu} + \frac{g_{5o}^{HZZ}}{2\Lambda_{5o}} H \tilde{Z}_{\mu\nu} Z^{\mu\nu}, \qquad (2)$$

where the subscript e or o refers to the CP even or odd nature of the individual operators. In our discussion we will neglect possible contributions from $H\gamma\gamma$ and $H\gamma Z$ couplings which can appear in $SU(2) \times U(1)$ invariant formulations [13,14]. The precise mix of HWW, HZZ, $HZ\gamma$ and $H\gamma\gamma$ contributions is quite irrelevant for the observable azimuthal angle distributions, as long as we do not consider interference effects between SM and anomalous vertices, and it will not affect our conclusions about the size of NLO corrections. For simplicity we therefore set $a_1 = 0$ for the anomalous coupling case and choose relative contributions from WW and ZZ fusion as in the SM, by taking $g_{5o}^{HWW} = g_{5e}^{HWW} = 1$, $g_{5e}^{HZZ} = g_{5o}^{HZZ} = 1/\cos^2\theta_W$, and by using either $\Lambda_{5e} \simeq 480$ GeV, $\Lambda_{5o} = \infty$ for the CP even case or $\Lambda_{5o} \simeq 480$ GeV, $\Lambda_{5e} = \infty$ for the CP odd case, which roughly reproduces SM rates for a scalar mass of $m_H = 120$ GeV.

The effective Lagrangian of Eq. (2) produces couplings

$$a_2(q_1, q_2) = -\frac{2}{\Lambda_{5e}} g_{5e}^{HWW}, \qquad a_3(q_1, q_2) = \frac{2}{\Lambda_{5o}} g_{5o}^{HWW} \qquad (3)$$

for the HWW vertex, and

$$a_2(q_1, q_2) = -\frac{2}{\Lambda_{5e}} g_{5e}^{HZZ}, \qquad a_3(q_1, q_2) = \frac{2}{\Lambda_{5o}} g_{5o}^{HZZ} \qquad (4)$$

for the HZZ vertex. In general, the a_i are form factors which are expected to be suppressed once the momentum transfer, $\sqrt{-q_i^2}$, carried by the virtual gauge boson reaches the typical mass scale, M, of the new physics which is responsible for these anomalous couplings. Below we use the simple ansatz

$$a_i(q_1, q_2) = a_i(0, 0) \frac{M^2}{q_1^2 - M^2} \frac{M^2}{q_2^2 - M^2} \qquad (5)$$

for discussing the consequences of such form factor effects.

4. Results

The typical signature of a weak boson fusion event at the LHC consists of the two quark jets (tagging jets) and the Higgs decay products. The tagging jets tend to be widely separated in rapidity, with one quite forward (typical pseudorapidity of 3 to 4) and the second one backward, but frequently still located in the central detector (pseudorapidity below 2.5). Various Higgs decay modes have been considered in the literature for WBF, $H \to WW$ [1], $H \to \tau\tau$ [2], and $H \to \gamma\gamma$ [3] being the most promising ones. While optimized event selection varies, in particular for the decay products, the cuts on the tagging jets are fairly similar in all analyses. Since here we are interested in the QCD features of WBF events, which do not depend on the Higgs decay mode, we perform our NLO analysis without simulating Higgs decays, and we only impose typical WBF cuts on the tagging jets.

[1] The dimension 5 language is appropriate for, e.g., an isosinglet scalar resonance H. For a Higgs doublet Φ with a vev, the leading operators appear at dimension 6 level [13,14] and the couplings in Eq. (2) are suppressed by an additional factor $g_5^{HVV} \sim v/\Lambda$.

In order to reconstruct jets from the final-state partons, the k_T-algorithm [15] as described in Ref. [16] is used, with resolution parameter $D = 0.8$. In a given event, the tagging jets are then defined as the two jets with the highest transverse momentum, p_{Tj}, with

$$p_{Tj} \geqslant 20\ \text{GeV}, \qquad |y_j| \leqslant 4.5. \tag{6}$$

Here y_j denotes the rapidity of the (massive) jet momentum which is reconstructed as the four-vector sum of massless partons of pseudorapidity $|\eta| < 5$. Backgrounds to weak-boson fusion are significantly suppressed by requiring a large rapidity separation of the two tagging jets. This motivates the final cut

$$\Delta y_{jj} = |y_{j_1} - y_{j_2}| > 4, \qquad y_{j_1} \cdot y_{j_2} < 0, \tag{7}$$

which includes the requirement that the two tagging jets reside in opposite detector hemispheres.

The structure of the HVV coupling affects the production dynamics of H and we can expect significant deviations in jet observables if, instead of the SM, anomalous couplings describe the vertex of Eq. (1). One example is shown in Fig. 2, where transverse momentum distributions, $d\sigma/dp_{Tj}(\max)$, are compared between the SM (solid line) and the CP even coupling $a_2(q_1, q_2)$, with different form factor scales M in Eq. (5). Here, $p_{Tj}(\max)$ is the maximum p_T of the two tagging jets. Only the shape of the distribution is considered, since the rate can always be adjusted by multiplying the anomalous couplings by a constant factor. Also, we should note that a CP odd coupling leads to very similar curves for a given form factor scale. In all cases we show the LO expectations (dashed lines) together with the NLO results: QCD corrections are of order 10%, typically, and well under control.

One finds that anomalous HVV couplings generally lead to harder p_T spectra of the two tagging jets. Since the anomalous Lagrangian in Eq. (2) couples the Higgs boson to weak boson field strengths, transverse polarizations of the incident VV pairs dominate the anomalous case, while longitudinal VV fusion is responsible for SM Higgs production. A telltale sign of transverse vector boson fusion is the more central

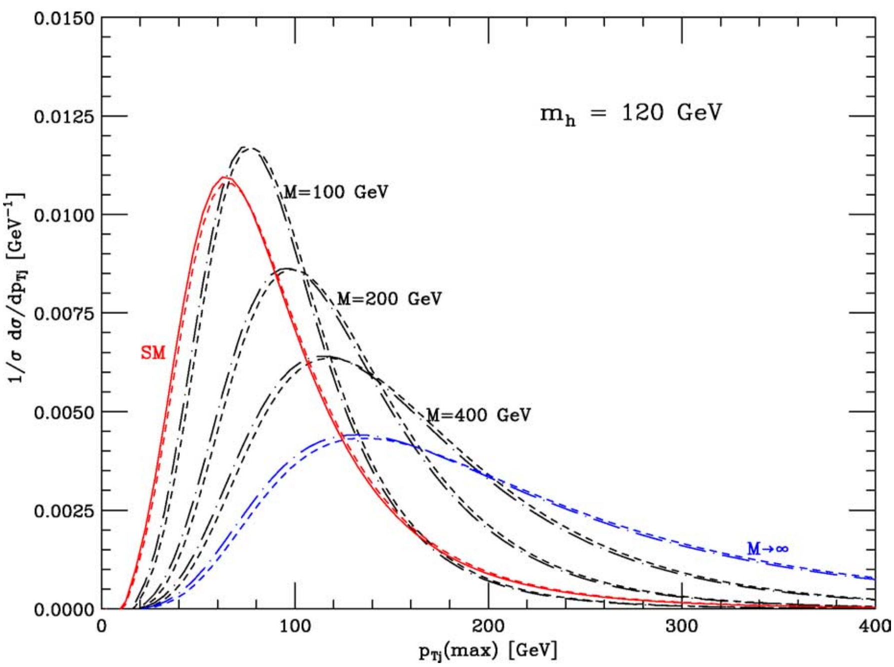

Fig. 2. Normalized transverse momentum distribution of the hardest jet for the SM Higgs boson (light grey (solid red line in the web version)) and a scalar H of mass $m_H = 120$ GeV with CP even anomalous coupling $a_2(q_1, q_2)$. The dash-dotted curves correspond to different form factor scales $M = 100$, 200, 400 GeV in Eq. (5) and $a_2 = \text{const}$ (grey (blue curves in the web version)) at NLO. LO curves are shown by the dashed lines and differ very little from the NLO results.

and, hence, higher p_T production of the tagging jets. This effect is enhanced by the momentum factors in the HVV anomalous vertices.

While the changed transverse momentum distributions in Fig. 2 could be used to rule out the SM, the reverse is not readily possible: a jet transverse momentum distribution compatible with SM expectations might be faked by anomalous couplings and a judiciously chosen form factor behavior of the coefficient functions a_2 or a_3 in Eq. (5). The different scale choices in Fig. 2 demonstrate this effect: a low form factor scale of $M = 100$ GeV or slightly lower would be difficult to distinguish from the SM expectation and one can certainly find a functional form of the form factors which reproduces the SM within experimental errors.

A much better observable for distinguishing the different tensor structures of the HVV vertex is the azimuthal angle correlation of the two tagging jets, $d\sigma/d\phi_{jj}$ [6]. Here ϕ_{jj} is the azimuthal angle between the two tagging jets. The corresponding distributions are shown in Fig. 3 for the SM (solid line) and for the same choices of form factors as before. The dip at $\phi_{jj} = 90$ degrees for the CP even coupling and the suppression at 0 and 180 degrees for the CP odd coupling are clean signatures which only depend on the tensor structure of the couplings and not on the precise dynamics which is responsible for the form factors. The remaining form factor dependence is very small and can be explained by kinematic effects related to the higher average jet transverse momentum for big form factor scales, M: at small ϕ_{jj} two high p_T jets recoil against the H scalar, resulting in an increased invariant mass of the event compared to the situation with two back-to-back jets. This leads to a more asymmetric ϕ_{jj} distribution for high form factor scales.

The pronounced dip at 90 degrees, which is characteristic of the CP even coupling, is also found in Hjj production via gluon fusion [17], at LO. This is not surprising because, in the large top mass limit, the Hgg vertex can be described by an effective Lagrangian proportional to $HG^a_{\mu\nu}G^{a\mu\nu}$, which exhibits the same field strength squared behavior and hence the same tensor structure as the CP even HVV coupling in Eqs. (1), (2). Since the two tagging jets are far apart from each other, separated by a large rapidity gap of 4 units of rapidity or more, this LO behavior may be significantly reduced by gluon radiation when higher order QCD corrections are taken into account. Such decorrelation effects have been studied for dijet events at the Tevatron [18]. For Hjj production via gluon fusion, Odagiri [7] has argued that the dip structure is largely washed out by additional gluon emission between the two tagging jets.

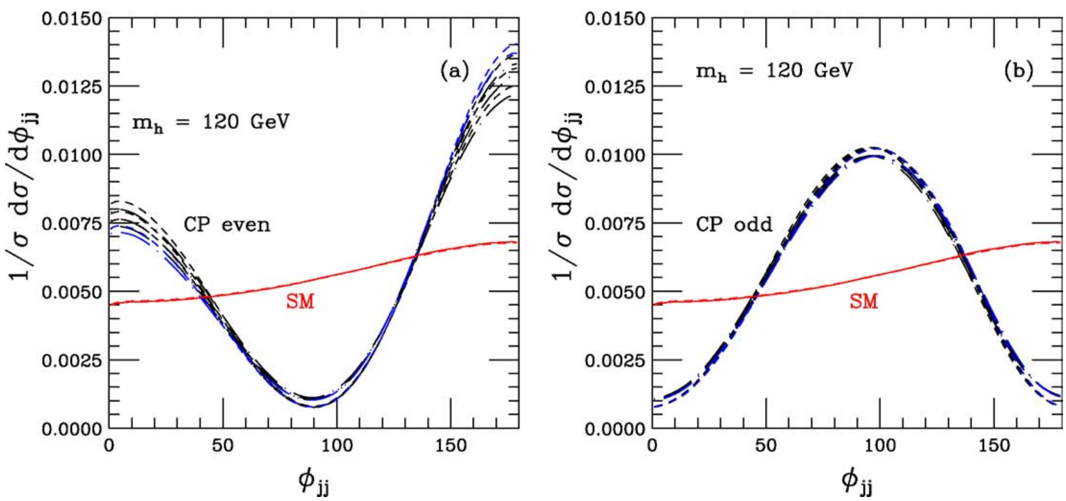

Fig. 3. Normalized azimuthal angle distribution, $1/\sigma\, d\sigma/d\phi_{jj}$ where ϕ_{jj} is the azimuthal angle separation of the two tagging jets. NLO (solid and dot-dashed) and LO results (dashed lines) are shown for $m_H = 120$ GeV in the SM (light grey (red curves in the web version)) and (a) for a CP even anomalous coupling $a_2(q_1, q_2)$, (b) for a CP odd anomalous coupling $a_3(q_1, q_2)$ with form factor scales $M = 100$, 200, 400 GeV and (grey (blue curves in the web version)) $M = \infty$.

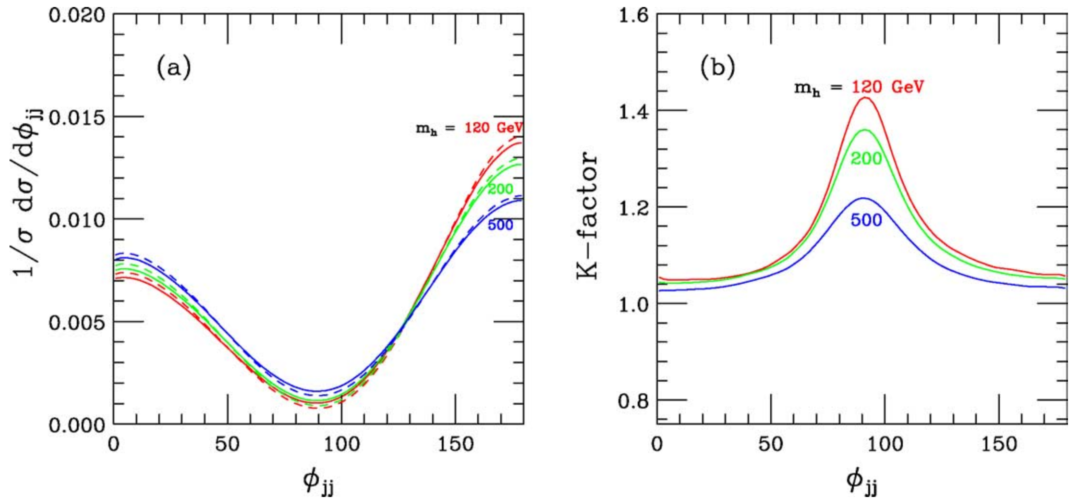

Fig. 4. Higgs mass dependence of the azimuthal angle separation ϕ_{jj} of the two tagging jets. In (a) the normalized azimuthal angle distributions are shown at LO (dashed lines) and NLO (solid lines) for Higgs masses of $m_H = 120$, 200, 500 GeV and a constant CP even anomalous coupling a_2. Corresponding K-factors are shown in (b).

Our NLO calculations show that such de-correlation effects are irrelevant for weak boson fusion, where t-channel color singlet exchange severely suppresses gluon radiation in the central region. The LO and the NLO curves in Fig. 3 are virtually indistinguishable. In order to better exhibit the size of NLO QCD effects for the WBF case, we show, in Fig. 4(a) the azimuthal angle correlations for a pure CP even anomalous coupling for three different Higgs masses, $m_H = 120$, 200 and 500 GeV. Only small changes are visible when going from LO (dashed lines) to NLO (solid lines). The differences between LO and NLO are smaller than kinematical effects that can be induced by cuts on the Higgs decay products or by variations of the Higgs boson mass.

The small to modest size of the QCD corrections is quantified in Fig. 4(b) where the K-factor for the distribution is shown, which is defined as

$$K(\phi_{jj}) = \frac{d\sigma^{\mathrm{NLO}}/d\phi_{jj}}{d\sigma^{\mathrm{LO}}/d\phi_{jj}}. \qquad (8)$$

The K-factor is below ≈ 1.4 even in the dip region, where the cross section is severely suppressed. Virtually identical results hold for the CP-odd case. Clearly, the characteristic azimuthal angle distributions of the jets in WBF are not affected in any significant way by NLO QCD corrections.

5. Conclusions

We have performed a first calculation of the NLO QCD corrections to Higgs boson production via WBF in the presence of arbitrary anomalous HVV ($V = W, Z$) couplings. Anomalous couplings lead to characteristic changes in the azimuthal angle correlation of the two tagging jets in weak boson fusion events at the LHC, which provides for a very sensitive test of the tensor structure of the HVV couplings of the Higgs boson or of any other scalar with sufficiently large production cross section in WBF [6]. We have shown by explicit calculation that these azimuthal correlations are not washed out by gluon emission, at NLO QCD, even though the tagging jets are widely separated in rapidity. This behavior can be understood as a consequence of t-channel color singlet exchange in WBF which severely suppresses the central gluon radiation which might cause tagging jet de-correlation.

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