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Spin effects in the process of associative production of the Higgs boson and $W^{\pm}$ boson

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In this paper, we study the angular features of the signal and background processes of the associated production of the Higgs boson with W boson. Signal and background processes are generated using the CompHEP generator. Monte Carlo data is processed in ROOT software. In the course of studying the basic kinematic properties it was found that the shape of the distributions of the angular variables differs for the signal and background processes. The presence of the spin effect makes it possible to consider the difference between the distributions of angular variables. The observed deviations can potentially reduce the background relative to the signal.

Keywords: Higgs, W boson, spin, CompHEP, associative production.

Introduction

One of the important production mechanisms for the Higgs bosons in the Standard Model is the associated production of the Higgs boson and $W^{\pm}$ boson, $q\bar{q} \rightarrow WH$, where W decays into leptons, H decays into a $b\bar{b}$ pairs. The main difficulty in observing this decay channel is the large background. The study of its properties is also difficult. A partial decrease of the background contribution and an increase of the signal to background ratio, which is the main goal of this work, we expect to achieve by using the angular variables. The relevance of this work is determined by the fact that observing the decay of the Higgs boson into a pair of $b\bar{b}$ quarks is a very important discovery for particle astrophysics, and the study of fundamental interactions. The $H \to b\bar{b}$ channel was observed in the ATLAS and CMS experiments in 2018, after a combination of all production channels [1, 2].

The angular variables were found to be very useful for this analysis. The Z and $W^{\pm}$ bosons do not differ in magnitude of the spin. The spin of the Higgs boson is equal to S=0, but S=1 for the Z boson. The difference in the spin should influence the angular distribution of the decay particles. We can try to reduce the background using this effect.

This work was done by using CompHEP [3], which is designed to calculate the total cross sections and provide kinematic distributions for processes with several particles in the final state. The program starts with the Feynman rules for the Lagrangian gauge model and calculates the matrix element for any process defined by the user. We analyzed the Monte Carlo data obtained using the CompHEP generator by means of the ROOT [4] program.

Calculations of the signal and background processes

In this paper, we considered the signal process $pp \to WH \to l + \nu + b + \bar{b}$ ($l = e^{\pm}$ or $\mu^{\pm}$), and two main background processes $pp \to WZ \to l + \nu + b + \bar{b}$ and $\to Wb\bar{b} \to l + \nu + b + \bar{b}$. At the beginning the model "SM Feynman gauge" was chosen in the CompHEP generator. Energies of the 1st and 2nd beam (protons) were set to 6500 GeV. For the structure function of proton (PDF) the CTEQ6l1 set was taken, which is a popular PDF used in LHC generators. We have generated all possible diagrams for signal and main background processes shown in Figures 1 (a, b, c).

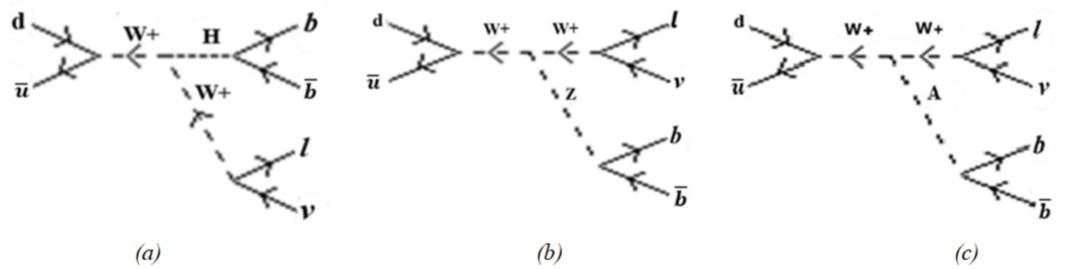

Figure 1. Feynman diagram for the signal subprocess: $d\bar{u} \to WH \to l, \nu, b, \bar{b}(a)$ for the first background subprocess: $d\bar{u} \to WZ \to l, \nu, b, \bar{b}(b)$ and for the second background subprocess: $d\bar{u} \to Wb\bar{b} \to l, \nu, b, \bar{b}(c)$.

It should be noted that all diagrams for these subprocesses were obtained after entering the process $pp \to l, \bar{\nu}, b, \bar{b}$ into the CompHEP generator program. We deal only with 8 subprocesses (depending on colliding quarks and antiquarks: $u\bar{d}$, $d\bar{u}$, $u\bar{s}$, $s\bar{u}$, $d\bar{c}$, $c\bar{d}$, $s\bar{c}$, $c\bar{s}$) for further processing. Each subprocess has a different number of diagrams. Two diagrams from the signal process are not associative production; in the background WZ process, we have five diagrams in the first subprocess, but due to their small contribution, two of them were excluded.

We performed symbolic calculations after obtaining the diagrams. Then, the functions "Write Results" and "Code C" were used to save the results of calculations.

In the "Model Parameters" section, you can set the Higgs boson mass m_H =125 GeV. The "Kinematics" menu of the CompHEP provides selection of the decay particles and allows one to choose optimal phase space parameterization, which is important for effective Monte Carlo integration. Then "Regularization" section should be filled. This function allows you to automatically smooth sharp peaks for a matrix element squared.

In the "Numerical Session", the following values were taken as parameters:

- "the number of iterations" is 50 (for the accuracy increase high value is given);
- "the number of integrand evaluations per iteration" is 7776000;

In the section "Set distribution", we defined the histograms that should be filled during the subsequent Monte Carlo integration.

Then we have started integration process and obtained cross section values for signal and background processes.

Data analysis

In Table 1 we compare the cross section values obtained for signal and background processes with those taken from relevant references. Generator uncertainty (CompHEP) and approximate uncertainties for theoretical prediction (Theory) are given in parentheses.

Table 1.
Cross sections of signal and background processes.

Process	Cross section, [pb] (uncertainties)	
	CompHEP	Theory
Signal process WH→l+ν+ b+$\bar{b}$	0.216 (±0.5%)	0.175 (±2%) [5]
Background process WZ→l+ν+ b+$\bar{b}$	0.815 (±0.1%)	0.841 (±5%) [6]
Background process Wb$\bar{b}$ →l+ν+ b+$\bar{b}$	71.305 (±0.01%)	81.850 (±15%) [7, 8]

Considering the level of uncertainties and the cross sections in the next to leading order can differ from the cross sections in the leading order up to 30%, the obtained results can be considered acceptable. Signal and background processes contain all subprocesses, and we have ROOT file for each subprocess. For further data processing, we use some scripts where all files are combined into two separate ROOT files for signal and background processes.

The search for signal events is complicated by the background processes occurring with large cross-section values. Finding kinematic variable that can help is extremely important in the selection of signal events. We will show how the angle between the lepton and the W boson (Figure 2) gives the opportunity to reduce the background for the process of the WH production.

For the background process (WZ) we calculated the angle of the lepton in W rest frame relative to the W direction in WZ center of mass system. The same parameters were calculated for signal WH and for $Wb\bar{b}$. To do this, we have to boost all momenta from laboratory system to the WH center of mass system. Then we rotate the direction of the W boson so that it moves in the z direction.

Finally, we boost along the z axis to rest frame of W boson. A similar approach was used in the past for polarization analyses at LEP [9] and recently in the ATLAS experiment [10].

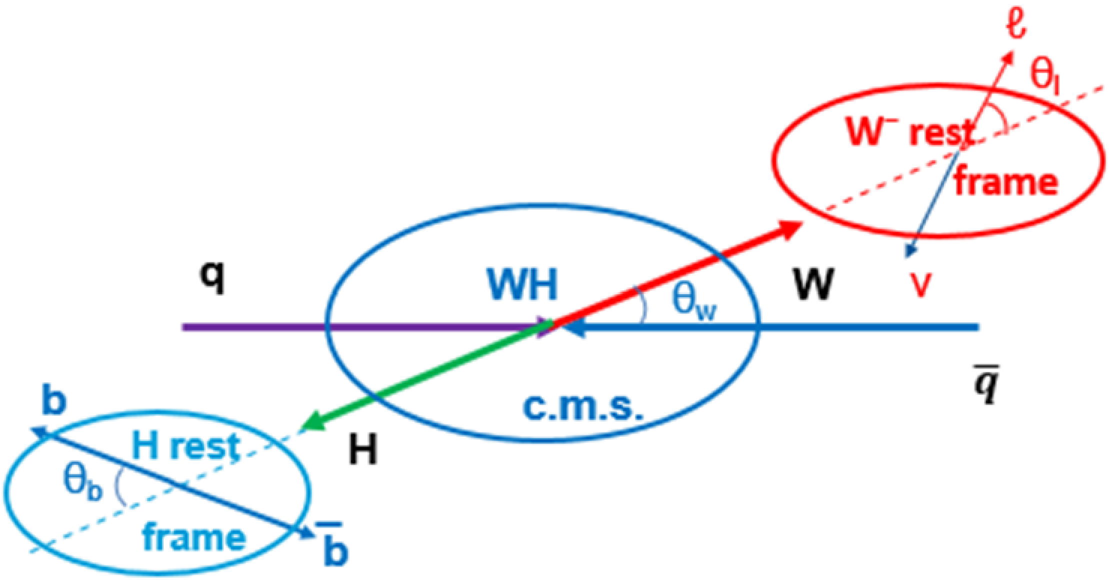

Figure 2. Angular correlations for *WH*.

Results

Figures 3-7 below show the distributions on the cosine of some angular variables. Figures 3-5 give information about the distribution of the cosine of W boson emission angle in the center-of-mass system (c.m.s) of $q\bar{q}$ with no selection of P_T^W (Figure 3) and for two P_T^W intervals: 150 GeV< P_T^W <250 GeV (Figure 4) and P_T^W >250 GeV (Figure 5). In Figure 6 (Figure 7) we show distributions of the cosine angle between the direction of $W(H)$ in the center-of-mass system of $q\bar{q}$ and the direction of decay particles, lepton (b-quark) in the $W(H)$ rest frame. In all figures the solid red line indicates the signal process $WH \to l, \nu, b, \bar{b}$, and the dotted blue and dashed green lines represent the background processes $WZ \to l, \nu, b, \bar{b}$ and $Wb\bar{b} \to l, \nu, b, \bar{b}$, correspondingly. It is clear that the shapes of distributions for signal and background processes are different.

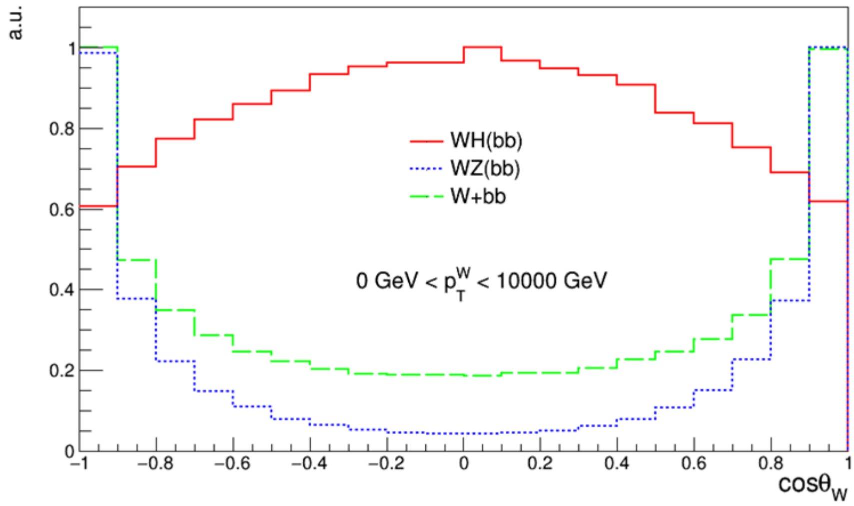

Figure 3. Distribution of the $W^{\pm}$ boson emission angle in the center-of-mass system of $q\bar{q}$: with no selection of P_T^W .

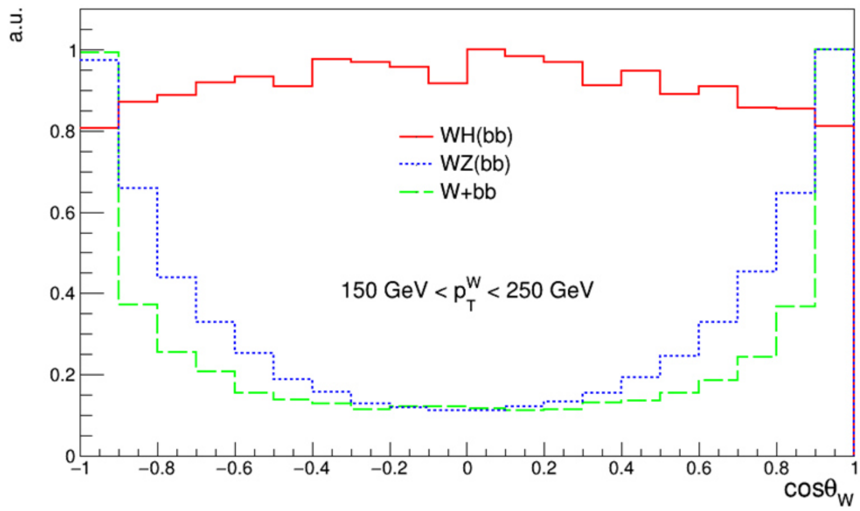

Figure 4. Distribution of the $W^{\pm}$ boson emission angle in the center-of-mass system of $q\bar{q}$: for two P_T^W intervals: 150 GeV< P_T^W <250 GeV.

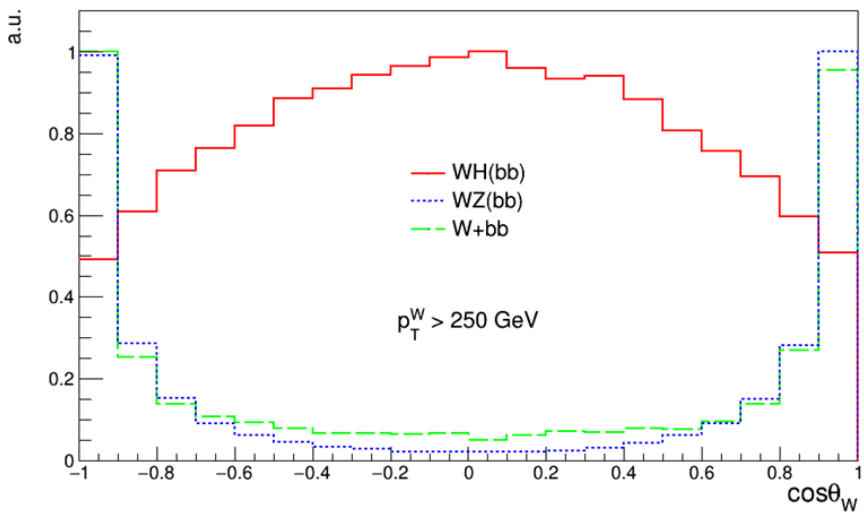

Figure 5. Distribution of the $W^{\pm}$ boson emission angle in the center-of-mass system of $q\bar{q}$: P_T^W >250 GeV.

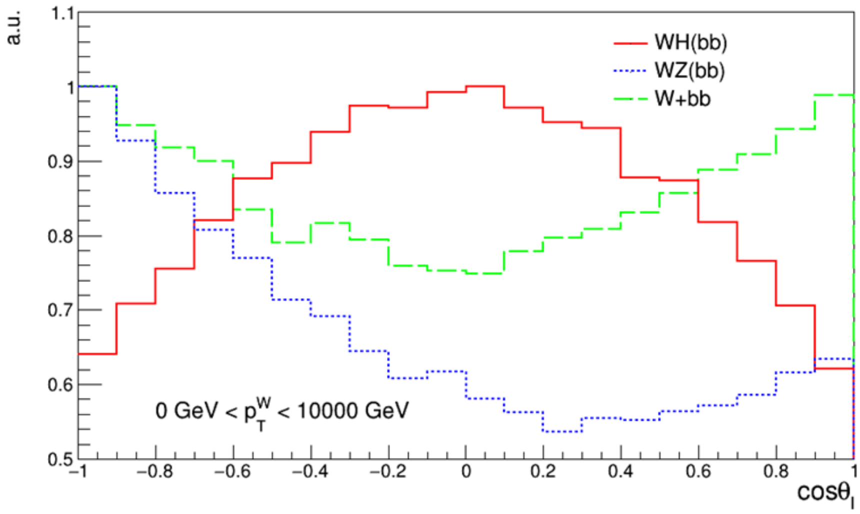

Figure 6. Cosine angle distribution between the direction of the charged lepton in the $W^{\pm}$ rest frame and the direction of the $W^{\pm}$ boson in the $q\bar{q}$ c.m.s.

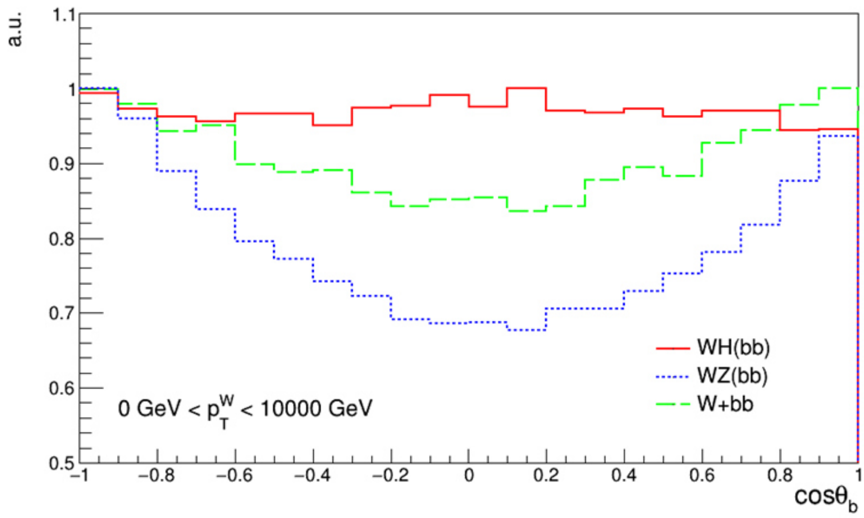

Figure 7. Distribution of the cosine angle between direction of the $\bar{b}$-quark in the rest frame of the H and direction of the Higgs boson in c.m.s. of $q\bar{q}$.

One can see that in the signal process, the events mainly fill the central part of the histograms with the cosine value close to 0. While in background reactions events are emitted in directions when the cosine is close to ± 1. This feature of the signal process can be used to suppress the contribution of background reactions. It should be noted that the calculations were performed in the lowest order of perturbation theory. It is necessary to take into account other important mechanisms which could change the shapes of the distributions, like hadronization of partons and final state interactions. We also expect that spin effects will be more visible in the events with higher transverse momenta of the decay particles.

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