HIGGS PLUS SINGLE TOP PRODUCTION AT THE LHC*

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We study the th production at the LHC in the presence of a CP violating top Yukawa coupling. The helicity amplitudes for the $ub \to dth(d\bar{b} \to u\bar{t}h)$ processes provide information on the kinematical distributions. Observables such as the azimuthal asymmetry between the forward jet and the top (antitop) quark, and the top (antitop) quark polarization asymmetry can be used to probe CP violation.

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The top-quark Yukawa coupling has been measured by ATLAS and CMS [1, 2] to be consistent with the SM prediction in $t\bar{t}h$ and $th(\bar{t}h)$ production processes at the LHC. We study the possible consequences of CP violation in the top Yukawa coupling by using the effective Lagrangian

$$\mathcal{L}_{tth} = -gh\bar{t}(\cos\xi + i\gamma_5 \sin\xi)t\,, \tag{1}$$

with real and positive coupling g, and the CP phase ξ ($-\pi < \xi < \pi$). When $g = g_{\mathrm{SM}} = \frac{m_t}{v}$ and $\xi = 0$, the Lagrangian reduces to the SM. For the Higgs plus single top production at the LHC $pp \to thj$, the cross section at $\sqrt{s} = 13$ TeV is shown for $g = g_{\mathrm{SM}}$ in figure 1. The ξ dependence of the $t\bar{t}h$ production is also shown as a comparison. The latter is symmetric about $|\xi| = \frac{\pi}{2}$, whereas the $th + \bar{t}h$ production cross section grows monotonically with $|\xi|$, reaching 13 times the SM prediction at $|\xi| = \pi$ when the sign of the Yukawa coupling is reversed. In figure 2, diagram (a) has the hWW coupling and diagram (b) has the htt coupling. By comparing the cross section at $\xi = 0$ (SM) and $\xi = \pi$, we can tell that there is a strong destructive interference between the two diagrams.

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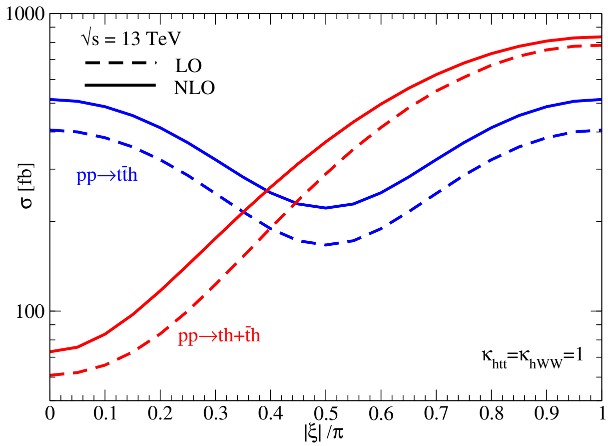

Fig. 1. CP phase dependence of the cross section for $pp \to thj$ and its comparison with $pp \to t\bar{t}h$ production at LO and NLO at $\sqrt{s} = 13$ TeV with $|\xi|$ from 0 to π. $\xi = 0$ gives the SM, and $|\xi| = \pi$ reverses the sign of the top Yukawa coupling.

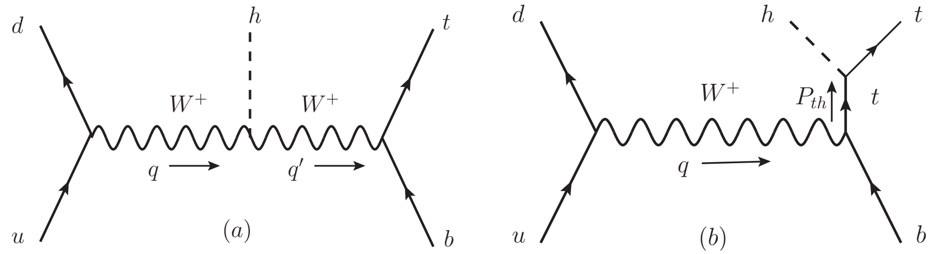

Fig. 2. Feynman diagram for the $ub \to thd$ process (a) with hWW coupling and (b) with htt coupling.

The helicity amplitude for the $ub \to dth$ process can be expressed as

$$\mathcal{M}_\sigma = \sum_{\lambda=\pm1,0} j\left(u \to dW^+_\lambda\right) \hat{\mathcal{M}}\left(W^+_\lambda b \to t_\sigma h\right) \;, \tag{2}$$

as a summation over the initial W helicites ($\lambda = \pm1, 0$) in the rest frame of the $W^+b \to th$ for the top helicity of $\sigma/2$. By choosing the virtual W^+ momentum along the positive z-axis, we find the amplitudes [3, 4]

$$\begin{aligned}
\mathcal{M}_{+} &= \frac{1-\tilde{c}}{2}\,\mathrm{e}^{i\phi}\sin\frac{\theta^*}{2}\left[\frac{1+\cos\theta^*}{4}\bar{\beta}A\right] \\
&\quad+\frac{1+\tilde{c}}{2}\,\mathrm{e}^{-i\phi}\sin\frac{\theta^*}{2}\left[\left(\frac{1+\cos\theta^*}{4}\bar{\beta}+\epsilon\delta\delta'\right)A-\left(\mathrm{e}^{-i\xi}+\delta\delta'\,\mathrm{e}^{i\xi}\right)B\right] \\
&\quad+\frac{\tilde{s}}{2}\frac{\mathtt{W}}{\mathtt{Q}}\cos\frac{\theta^*}{2}\left[\left(\frac{q^*E_h^*+q^{0*}p^*\cos\theta^*}{\mathtt{W}^2}+\epsilon\delta\delta'\right)A-\left(\mathrm{e}^{-i\xi}+\delta\delta'\,\mathrm{e}^{i\xi}\right)B\right],
\end{aligned} \tag{3a}$$

$$\begin{aligned}
\mathcal{M}_{-} &= -\frac{1-\tilde{c}}{2}\,\mathrm{e}^{i\phi}\cos\frac{\theta^*}{2}\left[\frac{1-\cos\theta^*}{4}\bar{\beta}A\right]\delta \\
&\quad-\frac{1+\tilde{c}}{2}\,\mathrm{e}^{-i\phi}\cos\frac{\theta^*}{2}\left[\left(\frac{1-\cos\theta^*}{4}\bar{\beta}-\epsilon\frac{\delta'}{\delta}\right)A+\left(\mathrm{e}^{-i\xi}+\frac{\delta'}{\delta}\,\mathrm{e}^{i\xi}\right)B\right]\delta \\
&\quad-\frac{\tilde{s}}{2}\frac{\mathtt{W}}{\mathtt{Q}}\sin\frac{\theta^*}{2}\left[\left(\frac{q^*E_h^*+q^{0*}p^*\cos\theta^*}{\mathtt{W}^2}+\epsilon\frac{\delta'}{\delta}\right)A-\left(\mathrm{e}^{-i\xi}+\frac{\delta'}{\delta}\,\mathrm{e}^{i\xi}\right)B\right]\delta,
\end{aligned} \tag{3b}$$

where $\mathtt{Q}=\sqrt{-q^2}$ is the invariant momentum transfer of the vitral W^+ and $\mathtt{W}=\sqrt{P_{th}^2}=m_{th}$ gives the invariant mass of the th system. The factors A and B are proportional to the hWW and the htt coupling, respectively,

$$A = 2g^2 g_{hWW}\frac{m\,m_{th}}{m_W^2}D_W(q)D_W(q')\tilde{\omega}\sqrt{2q^*(E^*+p^*)}\,, \tag{4a}$$

$$B = -2g^2 g_{htt}m_{th}D_W(q)D_t(P)\tilde{\omega}\sqrt{2q^*(E^*+p^*)}\,, \tag{4b}$$

and are chosen such that they are positive definite. $\tilde{c}=\cos\tilde{\theta}$, $\tilde{s}=\sin\tilde{\theta}$, and $2\tilde{\omega}=\mathtt{Q}/\cos\tilde{\theta}$ give the $u\to dW^+$ splitting amplitudes in the Breit frame, where the azimuthal angle ϕ measures the opening angle between the $u\to dW^+$ and the $W^+b\to th$ phases. The ϵ, δ, and δ' factors are $\epsilon=m_W^2/m^2$, $\delta=m/(E^*+p^*)$, and $\delta'=m/\mathtt{W}$. At high energy, high $\mathtt{W}$ ($\mathtt{W}=m_{th}\gg m_t,m_h,m_W$), we have $\delta\sim\delta'\ll 1$. The third lines of $\mathcal{M}_+$ and $\mathcal{M}_-$ are the helicity $\lambda=0\,(W_{\mathrm{L}})$ contributions, which are proportional to $\frac{\mathtt{W}}{\mathtt{Q}}$. We can confirm with numerical evaluation that W_{L} is dominant at low $\mathtt{Q}$ ($\mathtt{Q}<100$) GeV and large $\mathtt{W}$ ($\mathtt{W}>400$ GeV), where top polarization asymmetry is most optimal. On the other hand, $W_{\mathrm{T}}\,(\lambda=\pm1)$ is significant at large $\mathtt{Q}$ ($\mathtt{Q}>100$ GeV) and small $\mathtt{W}$ ($\mathtt{W}<400$) GeV, where significant azimuthal asymmetry effects are anticipated, because the azimuthal angle phase factors $\mathrm{e}^{\pm i\phi}$ appear only in the $\lambda=\pm1$ amplitudes. These would be helpful in selecting the relevant kinematical regions.

In figure 3, we show the azimuthal asymmetry,

$$A_\phi(\mathtt{W}) = \frac{\int_{-\pi}^{\pi} \mathrm{d}\phi\, \mathrm{sgn}(\phi) \mathrm{d}\sigma/\mathrm{d}\mathtt{W}/\mathrm{d}\phi}{\mathrm{d}\sigma/\mathrm{d}\mathtt{W}} . \tag{5}$$

As expected, the asymmetry is large at small $\mathtt{W}$ and large $\mathtt{Q}$, where longitudinal and transverse W^+ are comparable. This is beneficial because the full event reconstruction with a tagged jet is possible when $\mathtt{Q}$ is large.

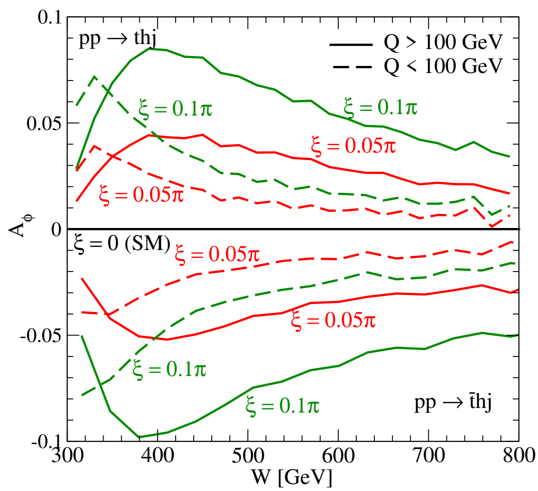

Fig. 3. The asymmetry A_ϕ *versus* $\mathtt{W} = m_{th}$ for $pp \to thj$ and $\bar{t}hj$. The azimuthal angle ϕ is the opening angle between the $u \to dW^+$ plane and the $W^+b \to th$ planes.

The top-quark polarization is obtained from the density matrix

$$\rho_{\sigma\sigma'} = \frac{\mathrm{d}\sigma_{\sigma\sigma'}}{\mathrm{d}\sigma_{++} + \mathrm{d}\sigma_{--}} = \frac{1}{2}\left(\delta_{\sigma\sigma'} + \sum_{k=1}^{3} P_k \sigma^k_{\sigma\sigma'}\right) , \tag{6}$$

where $\mathrm{d}\sigma_{\sigma\sigma'}$ gives the complex distribution of $\mathcal{M}_\sigma \mathcal{M}^*_{\sigma'}$, such that $\mathrm{d}\sigma_{++} + \mathrm{d}\sigma_{--}$ is the differential cross section in the th rest frame. Note that σ^k with $k = 1, 2, 3$ are the Pauli matrices. The 3-vector $P = (P_1, P_2, P_3)$ gives the general polarization of the top quark. The magnitude $P = |\vec{P}|$ gives the degree of polarization. Specifically, $P = 1$ for 100% polarization, and $P = 0$ for no polarization. The orientation gives the direction of the top-quark spin in the top rest frame. We find that $\vec{P}$ lies in the $W^+b \to th$ scattering plane in the SM ($\xi = 0$). The component

$$P_2 = \frac{-2\,\mathrm{Im}\left(\mathcal{M}_+ \mathcal{M}^*_-\right)}{|\mathcal{M}_+|^2 + |\mathcal{M}_-|^2} \tag{7}$$

gives the top polarization orthogonal to the $W^+b \to th$ production plane, which appears for nonzero ξ. The sign of P_2 determines the sign of ξ. The integration of P_2 for the backward top (antitop) quarks ($\cos\theta^* \sim \vec{p}_t^{\,*} \cdot \vec{p}_{W^+} < 0$) is shown in figure 4. Since the polarization asymmetry P_2 is proportional to $\mathrm{Im}(\mathcal{M}_+\mathcal{M}_-^*)$, and the amplitudes are large at small Q and large W, we expect that it can be measured in large $\mathtt{W} = m_{th}$ events without forward jet tagging. Possible direct tests of CP violation, at the LHC, by comparing asymmetries in th and $\bar{t}h$ events, are thoroughly studied in Ref. [4].

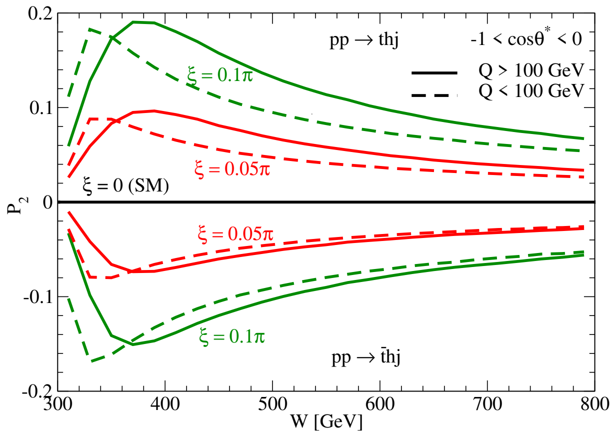

Fig. 4. Top polarization P_2 *versus* W distribution for $pp \to thj$ and $\bar{t}hj$. P_2 is the top-quark polarization along the direction perpendicular to the production plane in the th rest frame.

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