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Asymmetry Observables for Measuring Spin Correlations in Top-Quark Pair Production

Kai MA (马凯) arXiv:1706.01492; PRD **(R)**, **96**, 071501(2017).

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Motivations

- 1. Top-quark is a natural probe of new physics.
 - heaviest mass in SM
 - short decay width
- 2. Spin correlations between top-quark and anti-top-quark in pair production are sensitive to physics beyond the standard model.
- 3. How to avoid the momenta reconstruction for top-quarks in measuring of the spin correlation.
- 4. Spin correlations have been observed by both ATLAS and CMS by measuring the observable which is defined as the azimuthal angle difference between the two charged leptons in the laboratory frame.

Motivations



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Spin density matrix

No matter what is the dynamics in the top-quark pair production, by employing the narrow width approximation, the helicity amplitude can be written as a product of the production term and the decay term,

$$\mathcal{M} = \sum_{s_1, s_2 = \pm 1/2} \mathcal{M}_P(s_1, s_2) \mathcal{M}_D(s_1, s_2) \,. \tag{1}$$

Correspondingly, the amplitude squared can also be factorized into production and decay density matrices,

$$\overline{|\mathcal{M}|^2} = \sum_{s_1, s_2; s_1', s_2'} \mathcal{P}_{s_1', s_2'}^{s_1, s_2} \mathcal{D}_{s_1', s_2'}^{s_1, s_2}.$$
 (2)

However, in a chosen reference frame *R*, the top-quark pair and the lepton pair can be treated as two single systems whose spin can be either 0 or 1. The helicity of these two systems along the direction \vec{Q} are equal, and can have values $\lambda_f = s, 0, \pm 1$. After spin projection, the amplitude squared $\overline{|\mathcal{M}|^2}$ can be decomposed as,

$$\overline{|\mathcal{M}|^2} = \sum_{\lambda_f, \lambda_f' = s, 0, \pm 1} \widetilde{\mathcal{P}}_{\lambda_f'}^{\lambda_f} \widetilde{\mathcal{D}}_{\lambda_f'}^{\lambda_f},$$
(3)

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The decay helicity amplitude $\mathcal{M}_D(s_1, s_2)$ can be written at leading order as a product of helicity amplitudes $\mathcal{M}_{D_1}(s_1)$ and $\mathcal{M}_{D_2}(s_s)$ for top-quark and anti-top-quark decays, respectively, which can be obtained directly according to the Feynman rules of the SM,

$$\mathcal{M}_{D_1}(s_1) = \frac{g_W^2}{2D_{W_1}} \left\{ \overline{u_{\nu_\ell}} \gamma_\mu P_L v_{\bar{\ell}} \right\} \left\{ \overline{u_b} \gamma^\mu P_L u_t(s_1) \right\}, \tag{4}$$

$$\mathcal{M}_{D_2}(s_2) = \frac{g_W^2}{2D_{W_2}} \left\{ \overline{u_\ell} \gamma_\nu P_L v_{\bar{\nu}_\ell} \right\} \left\{ \overline{v_{\bar{\ell}}(s_2)} \gamma^\nu P_L v_{\bar{b}} \right\}.$$
(5)

Spin correlations between the anti-lepton (lepton) and the top-quark (anti-top-quark) can be clearly observed by applying Fierz transformations after replacing wave functions of the anti-lepton (lepton) and the top-quark (anti-top-quark) by the ones of their anti-particles,

$$\mathcal{M}_D(s_1) = -g_W^2 D_{W_1}^{-1} \left\{ \overline{u_{\bar{\ell}}} P_L u_t(s_1) \right\} \left\{ \overline{u_b} P_R v_{\nu_{\ell}} \right\}, \tag{6}$$

$$\mathcal{M}_D(s_2) = -g_W^2 D_{W_2}^{-1} \{ \overline{\nu_t}(s_2) P_R \nu_\ell \} \{ \overline{u_{\overline{\nu_\ell}}} P_L \nu_{\overline{b}} \}.$$
(7)

Factorization of the lepton pair system from top-quark pair system can be realized by simply applying the Fierz transformation one more step. Then we find,

$$\mathcal{M}(s_1, s_2) = \mathcal{H}^{\mu}(s_1, s_2) \,\mathcal{K}_{\mu} \,\mathcal{X} \,\overline{\mathcal{X}} \,, \tag{8}$$

where

$$\mathcal{H}^{\mu}(s_1, s_2) = \overline{\nu_t}(s_2) \gamma^{\mu} P_L u_t(s_1), \qquad (9)$$

$$\mathcal{K}_{\mu} = -\frac{1}{2} \overline{u_{\bar{\ell}}} \gamma_{\mu} P_{R} v_{\ell} = \frac{1}{2} \overline{u_{\ell}} \gamma_{\mu} P_{L} v_{\bar{\ell}} , \qquad (10)$$

$$\mathcal{X} = g_W^2 D_{W_2}^{-1} \left[\overline{u_b} P_R v_{\nu_\ell} \right], \qquad (11)$$

$$\overline{\mathcal{X}} = g_W^2 D_{W_1}^{-1} \left[\overline{u_{\overline{\nu}_\ell}} P_L v_{\overline{b}} \right].$$
(12)

Spin projection along chosen direction \vec{Q} in a reference frame *R* can be easily obtained by inserting a complete projection relation,

$$g_{\mu\nu} = \sum_{\lambda_f = s, 0, \pm} \eta_{\lambda_f} \epsilon^*_{\mu}(\vec{Q}, \lambda_f) \epsilon_{\nu}(\vec{Q}, \lambda_f) \,. \tag{13}$$

Then we find,

$$\mathcal{M}(s_1, s_2) = \sum_{\lambda_f = s, 0, \pm} \widetilde{\mathcal{H}}_{\lambda_f}(s_1, s_2) \, \widetilde{\mathcal{K}}_{\lambda_f} \,, \tag{14}$$

where the scalar functions $\widetilde{\mathcal{H}}_{\lambda_f}(s_1,s_2)$ and $\widetilde{\mathcal{K}}_{\lambda_f}$ are defined as

$$\widetilde{\mathcal{H}}_{\lambda_f}(s_1, s_2) = \sqrt{E_1 E_2} \, \mathcal{X} \, \overline{\mathcal{X}} \, \mathcal{H}^{\mu}(s_1, s_2) \, \epsilon^*_{\mu}(\vec{Q}, \lambda_f) \,, \tag{15}$$

$$\widetilde{\mathcal{K}}_{\lambda_f} = \frac{1}{\sqrt{E_1 E_2}} \eta_{\lambda_f} \mathcal{K}^{\nu} \epsilon_{\nu}(\vec{Q}, \lambda_f), \qquad (16)$$

with E_1 and E_2 are energy of the anti-lepton and lepton in *R*, respectively. The spin-projected decay density matrix is simply given as

$$\widetilde{\mathcal{D}}_{\lambda_{f}^{\prime}}^{\lambda_{f}} = \widetilde{\mathcal{K}}_{\lambda_{f}} \widetilde{\mathcal{K}}_{\lambda_{f}^{\prime}}^{\dagger} \,. \tag{17}$$

And the spin-projected production density matrix can be obtained by summing up the helicity s_1 and s_2 ,

$$\widetilde{\mathcal{P}}_{\lambda_{f}^{\prime}}^{\lambda_{f}} = \sum_{s_{1}, s_{2}; s_{1}^{\prime}, s_{2}^{\prime}} \mathcal{P}_{s_{1}^{\prime}, s_{2}^{\prime}}^{s_{1}, s_{2}} \widetilde{\mathcal{H}}_{\lambda_{f}}(s_{1}, s_{2}) \widetilde{\mathcal{H}}_{\lambda_{f}^{\prime}}^{\dagger}(s_{1}^{\prime}, s_{2}^{\prime}).$$

$$(18)$$

Explicit expressions of $\widetilde{\mathcal{D}}_{\lambda'_{f}}^{\lambda_{f}}$ can be obtained in a straightforward way once *R* and \vec{Q} are given. Without loss of generality, we can set $\vec{Q} = (0,0,1)$, *i.e.*, it is the unite vector along the *z* direction in *R*, then we find

$$\widetilde{\mathcal{K}}_{\lambda_{f}} = \begin{cases}
-\sqrt{2} c_{1}s_{2}e^{i\phi_{+}} & \lambda_{f} = +1 \\
\sqrt{2} s_{1}c_{2}e^{-i\phi_{+}} & \lambda_{f} = -1 \\
c_{1}c_{2}e^{i\phi_{-}} - s_{1}s_{2}e^{-i\phi_{-}} & \lambda_{f} = 0 \\
c_{1}c_{2}e^{i\phi_{-}} + s_{1}s_{2}e^{-i\phi_{-}} & \lambda_{f} = s
\end{cases}$$
(19)

where θ_1 (ϕ_1) and θ_2 (ϕ_2) are the polar (azimuthal) angles of the antilepton and lepton in the reference frame *R*, respectively; and $c_i = \cos(\theta_i/2)$, $s_i = \sin(\theta_i/2)$, and the phases $\phi_{\pm} = (\phi_1 \pm \phi_2)/2$. Spin correlations between the lepton and top-quark systems are encoded in the following density matrix,

$$\rho_{\lambda_{f}}^{\lambda_{f}} = \widetilde{\mathcal{P}}_{\lambda_{f}'}^{\lambda_{f}} \widetilde{\mathcal{D}}_{\lambda_{f}'}^{\lambda_{f}}, \qquad (20)$$

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The diagonal elements are

$$\begin{split} \rho_{+}^{+} &= \frac{1}{2} \widetilde{\mathcal{P}}_{+}^{+} (1 + \cos \theta_{1}) (1 - \cos \theta_{2}) \,, \\ \rho_{-}^{-} &= \frac{1}{2} \widetilde{\mathcal{P}}_{-}^{-} (1 - \cos \theta_{1}) (1 + \cos \theta_{2}) \,, \\ \rho_{0}^{0} &= \frac{1}{2} \widetilde{\mathcal{P}}_{0}^{0} (1 + \cos \theta_{1} \cos \theta_{2} - \sin \theta_{1} \sin \theta_{2} \cos(2\phi_{-})) \,, \\ \rho_{s}^{s} &= \frac{1}{2} \widetilde{\mathcal{P}}_{s}^{s} (1 + \cos \theta_{1} \cos \theta_{2} + \sin \theta_{1} \sin \theta_{2} \cos(2\phi_{-})) \,, \end{split}$$

 $\frac{d^2\sigma}{d\cos\theta_1^*d\cos\theta_2^*} \propto 1 + B_1\cos\theta_1^* + B_2\cos\theta_2^* - C\cos\theta_1^*\cos\theta_2^*$

W. Bernreuther, D. Heisler, Z.-G. Si, JHEP, 12, 026(2015).

The off-diagonal elements are

$$\begin{aligned} &\operatorname{Re}[\rho_{-}^{+}] &= -\frac{1}{2}|\widetilde{\mathcal{P}}_{-}^{+}|\sin\theta_{1}\sin\theta_{2}\cos(2\phi_{+}+\delta_{-}^{+})\,,\\ &\operatorname{Re}[\rho_{0}^{+}] &= \frac{1}{2\sqrt{2}}|\widetilde{\mathcal{P}}_{0}^{+}|\left\{(1-\cos\theta_{2})\sin\theta_{1}\cos(\phi_{1}+\delta_{0}^{+})-(1+\cos\theta_{1})\sin\theta_{2}\cos(\phi_{2}+\delta_{0}^{+})\right\}\\ &\operatorname{Re}[\rho_{s}^{+}] &= \frac{-1}{2\sqrt{2}}|\widetilde{\mathcal{P}}_{s}^{+}|\left\{(1-\cos\theta_{2})\sin\theta_{1}\cos(\phi_{1}+\delta_{s}^{+})+(1+\cos\theta_{1})\sin\theta_{2}\cos(\phi_{2}+\delta_{s}^{+})\right\}\\ &\operatorname{Re}[\rho_{0}^{-}] &= \frac{1}{2\sqrt{2}}|\widetilde{\mathcal{P}}_{0}^{-}|\left\{(1+\cos\theta_{2})\sin\theta_{1}\cos(\phi_{1}-\delta_{0}^{-})-(1-\cos\theta_{1})\sin\theta_{2}\cos(\phi_{2}-\delta_{0}^{-})\right\}\\ &\operatorname{Re}[\rho_{s}^{-}] &= \frac{1}{2\sqrt{2}}|\widetilde{\mathcal{P}}_{s}^{-}|\left\{(1+\cos\theta_{2})\sin\theta_{1}\cos(\phi_{1}-\delta_{0}^{-})+(1-\cos\theta_{1})\sin\theta_{2}\cos(\phi_{2}-\delta_{0}^{-})\right\}\\ &\operatorname{Re}[\rho_{s}^{0}] &= \frac{1}{2}|\widetilde{\mathcal{P}}_{s}^{0}|\left\{(\cos\theta_{1}+\cos\theta_{2})\cos(\delta_{s}^{0})-\sin\theta_{1}\sin\theta_{2}\sin(2\phi_{-})\sin(\delta_{s}^{0})\right\},\end{aligned}$$

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Asymmetry Observables

Apart from the spin-independent total cross section,

$$\sigma = \frac{1}{2} \left(\overline{\widetilde{\mathcal{P}}_{s}^{s}} + \overline{\widetilde{\mathcal{P}}_{0}^{0}} + \overline{\widetilde{\mathcal{P}}_{+}^{+}} + \overline{\widetilde{\mathcal{P}}_{-}^{-}} \right),$$
(21)

where the over line "-" means summing up PDFs of the initial state and integrating over phase space apart from the following region,

$$d\Phi_2 = \frac{1}{16\pi^2} \int_{-1}^{1} d\cos\theta_1 \int_{0}^{2\pi} d\phi_1 \int_{-1}^{1} d\cos\theta_2 \int_{0}^{2\pi} d\phi_2 \,.$$
 (22)

Our approach can provide 15 independent observables, and can be classified into two kinds of asymmetries:

$$\mathcal{A}[f(\varsigma)] = \frac{\sigma[g_+(\varsigma) > 0] - \sigma[g_+(\varsigma) < 0]}{\sigma[g_+(\varsigma) > 0] + \sigma[g_+(\varsigma) < 0]},$$
(23)

and

$$\mathcal{C}[f(\varsigma)] = \frac{\sigma[g_{-}(\varsigma) > 0] - \sigma[g_{-}(\varsigma) < 0]}{\sigma[g_{-}(\varsigma) > 0] + \sigma[g_{-}(\varsigma) < 0]},$$
(24)

where $g_{\pm}(\varsigma) = f(\varsigma) \pm f(-\varsigma)$ with $f(\varsigma)$ a function of angular variables.

Even Asymmetry Observables

The simplest observables are $A_{\theta_i} = A[\cos \theta_i]$ for the single side distributions, which measure the polarizations of top-quarks inclusively,

$$\mathcal{A}_{\theta_i} = \frac{1}{4\sigma} \left\{ Q_i \left(\overline{\mathcal{P}_-^-} - \overline{\mathcal{P}_+^+} \right) + 2 \overline{\mathcal{P}_s^0 \cos \delta_s^0} \right\},\tag{25}$$

where $Q_{i=1,2}$ are electric charges of the anti-lepton and lepton, respectively, in unite of |e|. There are also single side even asymmetries for the azimuthal angles, $\mathcal{A}_{\phi_i} = \mathcal{A}[\cos \phi_i]$ having following explicit expressions,

$$\mathcal{A}_{\phi_i} = \frac{-1}{2\sqrt{2}\sigma} \sum_{\lambda=\pm 1} \left\{ \lambda \overline{\mathcal{P}_s^\lambda \cos \delta_s^\lambda} + Q_i \overline{\mathcal{P}_0^\lambda \cos \delta_0^\lambda} \right\}.$$
 (26)

 $A_{\theta_1\theta_2} = A[\cos \theta_1 \cos \theta_2]$ is the simplest double side even asymmetry, and measures helicity correlation,

$$\mathcal{A}_{\theta_1\theta_2} = \frac{1}{8\sigma} \left\{ \overline{\mathcal{P}_s^s} + \overline{\mathcal{P}_0^0} - \overline{\mathcal{P}_+^+} - \overline{\mathcal{P}_-^-} \right\}.$$
 (27)

Even Asymmetry Observables

Furthermore, linear combinations of the azimuthal angles can also be used to define double side asymmetries as $\mathcal{A}_{\phi\pm} = \mathcal{A}[\cos(2\phi_{\pm})]$. And the explicit expressions are,

$$\mathcal{A}_{\phi_{+}} = \frac{\pi}{4\sigma} \overline{\mathcal{P}_{-}^{+} \cos \delta_{-}^{+}}, \qquad (28)$$

$$\mathcal{A}_{\phi_{-}} = \frac{\pi}{8\sigma} \left\{ \overline{\mathcal{P}_{0}^{0}} - \overline{\mathcal{P}_{s}^{s}} \right\}.$$
(29)

There are also double side even asymmetries involving polar and azimuthal angles of oppositely charged leptons, $\mathcal{A}_{\theta_i \phi_{i'}} = \mathcal{A}[\cos(\theta_i) \cos(\phi_{i'})]$ with $i \neq i'$,

$$\mathcal{A}_{\theta_i \phi_{i'}} = \frac{1}{4\sqrt{2}\sigma} \sum_{\lambda = \pm 1} \left\{ \mathcal{Q}_i \overline{\mathcal{P}_s^\lambda \cos \delta_s^\lambda} - \lambda \overline{\mathcal{P}_0^\lambda \cos \delta_0^\lambda} \right\}.$$
(30)

Odd Asymmetry Observables

The simplest single side odd asymmetries are $C_{\phi_i} = C[\sin \phi_i]$,

$$C_{\phi_i} = \frac{1}{2\sqrt{2}\sigma} \sum_{\lambda=\pm 1} \left\{ \overline{\mathcal{P}_s^{\lambda} \sin \delta_s^{\lambda}} + Q_i \lambda \, \overline{\mathcal{P}_0^{\lambda} \sin \delta_0^{\lambda}} \right\}.$$
 (31)

In contrast, there are no single side odd asymmetry for polar angles. On the other hand, linearly combinations of the azimuthal angles can give two double side asymmetries $C_{\phi_+} = C[\sin(2\phi_+)]$ and $C_{\phi_-} = C[\sin(2\phi_-)]$ as follows,

$$\mathcal{C}_{\phi_+} = -\frac{\pi}{8\sigma} \overline{\mathcal{P}_-^+ \sin \delta_-^+}, \qquad (32)$$

$$\mathcal{C}_{\phi_{-}} = \frac{\pi}{8\sigma} \overline{\mathcal{P}_{s}^{0} \sin \delta_{s}^{0}} \,. \tag{33}$$

In addition, there are two more double side odd asymmetries involving azimuthal and polar angles of oppositely charged particles, $C_{\theta_i\phi_{i'}} = C[\cos(\theta_i)\sin(\phi_{i'})]$ with $i \neq i'$,

$$\mathcal{C}_{\theta_i\phi_{i'}} = \frac{1}{4\sqrt{2}\sigma} \sum_{\lambda=\pm 1} \left\{ \overline{\mathcal{P}_0^{\lambda} \sin \delta_0^{\lambda}} - Q_i \lambda \overline{\mathcal{P}_s^{\lambda} \sin \delta_s^{\lambda}} \right\}.$$
 (34)

Correlations Among Density Matrix Elements

However, the 15 matrix elements (16 before normalization) may not be independent in general. If the top-quark pair are generated in pure quantum state, the production density matrix can be obtained by using transition amplitude, $\widetilde{P}_{\lambda_t'}^{\lambda_t} = \widetilde{\mathcal{M}}_P(\lambda_t)\widetilde{\mathcal{M}}_P^{\dagger}(\lambda_t')$. Then there are only 4 independent magnitudes $|\mathcal{M}_P(\lambda_t)|$, and following relations have to be hold exactly,

$$\left|\widetilde{\mathcal{P}}_{\lambda_{t}^{\prime}}^{\lambda_{t}}\right| = \sqrt{\widetilde{\mathcal{P}}_{\lambda_{t}}^{\lambda_{t}} \, \widetilde{\mathcal{P}}_{\lambda_{t}^{\prime}}^{\lambda_{t}^{\prime}}} \,. \tag{35}$$

Note that this number reduce to 3 after normalization. Furthermore, the number of independent phases is reduced to 3 (after an overall phase is removed), and following relations are also exact,

$$\delta_{\lambda_t'}^{\lambda_t} = \delta(\lambda_t) - \delta(\lambda_t') = \delta_{\lambda_t'}^{\lambda_t} - \delta_{\lambda_t'}^{\lambda_t''},$$
(36)

where $\delta(\lambda_t)$ are phases of the production helicity amplitudes $\mathcal{M}_P(\lambda_t)$. At hadron collider, the colliding protons are mixed states, and the mixture are described by the PDFs. As a result the top-quark pair are not in pure state, and hence the relations (35) and (36) can be violated. However, if only one kind of the subprocess dominates the transition under considering, then the relations should be hold approximately. CP observables: $e^-e^+ \rightarrow h t \bar{t}$ @500GeV

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K. Hagiwara, K. Ma, H. Yokoya, JHEP, 06, 048(2016).

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SM predictions?

Anomalous interactions in decay of top-quarks?

New physics ...?