ENERGY CORRELATION OF BOTTOM QUARKS FROM DECAYS OF TOP QUARKS IN ELECTRON-POSITRON ANNIHILATION AT HIGH ENERGY

Ivan Truten[1] Alexandr Korchin[1,2]

[1]Akhiezer Institute for theoretical physics
NSC Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine

[2]V. N. Karazin Kharkiv National University, Kharkiv, Ukraine

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Motivation

- The study of top-quark properties is a significant area of interest in particle physics, particularly in our quest to uncover effects that go beyond the Standard Model (SM). One of the key properties we focus on is polarization. Polarization allows us to gain more detailed insights into the top quark and potential influences of what we call new physics.
- It is believed that more precise measurements of top-quark properties at e^+e^- colliders will be sensitive to physics beyond the SM.
- In this context our work is focused on the future electron-positron collider, The Compact Linear Collider (CLIC). During its first cycle of experiments, CLIC is expected to achieve a center-of-mass energy of 380 GeV.

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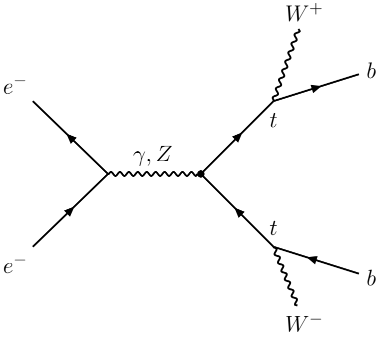
Let us consider the process of electron-positron annihilation into a pair of quarks

$$e^+e^- \to t\bar{t} \to b\bar{b}W^+W^-$$

At the tree level, this process is described by two Feynman diagrams involving the exchange of a photon and Z boson:



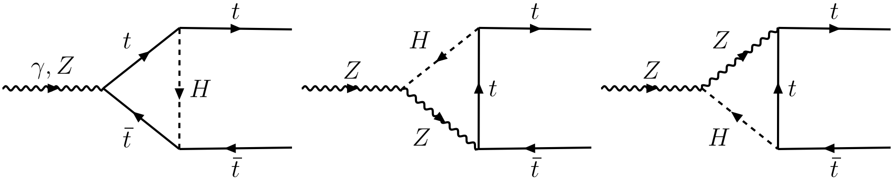
The vertex of the interaction between γtt and Ztt

We assume that the Lagrangian describing the interaction of the photon and Z boson with quarks consists of Standard model (SM) contributions and terms beyond the SM (BSM).
The corresponding γtt and Ztt vertices are written as

$$\Gamma^{\mu}_{t\bar{t}V} = -ie\bar{t}\left(\underbrace{\gamma^{\mu}(v_t^V - a_t^V\gamma_5)}_{SM} + \underbrace{\frac{1}{2m_t}\sigma^{\mu\nu}q_{\nu}(\overbrace{i\kappa^V(s)}^{CP\ \text{even}} - \overbrace{\tilde{\kappa}^V(s)\,\gamma_5}^{CP\ odd})}_{BSM}\right)t$$

where $V = \gamma,\ Z$.
The terms proportional to the coupling κ^V are CP-even, while the terms $\tilde{\kappa}^V$ are responsible for the CP violation.

One-loop corrections to the vertices γtt and Ztt



(a) (b) (c)

To generate *CP* violation effects, the interaction of the Higgs boson with the top quarks is chosen in the form

$$\mathcal{L}_{htt} = -\frac{m_t}{v}\, h\,\bar{t}\,(\alpha + i\,\beta\gamma_5)\,t$$

which includes scalar and pseudoscalar parts. The values $\alpha = 1$, $\beta = 0$ correspond to the Lagrangian in the SM.

Using the Cutkosky rules (cut of the Feynman diagram) for the diagram with vertex γtt (“a”)

$$\mathrm{Im}\,\tilde{\kappa}(s) = \alpha\beta \frac{Q_t m_t^4}{8\pi E_t p_t v^2} \left(1 - \frac{m_h^2}{4p_t^2} \log \frac{m_h^2 + 4p_t^2}{m_h^2}\right) \theta(s - 4m_t^2).$$

For vertex Ztt (“a”) similarly

$$\mathrm{Im}\,\tilde{\kappa}_Z(s)_a = \frac{v_t}{Q_t} \mathrm{Im}\,\tilde{\kappa}(s).$$

Knowing the expressions for the imaginary parts of $\tilde{\kappa}(s)$ and $\tilde{\kappa}_Z(s)$ the real parts of the form factors can be calculated using the dispersion relations:

$$\begin{aligned} \mathrm{Re}\,\tilde{\kappa}(s) &= \frac{1}{\pi}\mathrm{PV}\int_{s_0}^{\infty} \frac{\mathrm{Im}\,\tilde{\kappa}(s')}{s'-s} ds', \\ \mathrm{Re}\,\tilde{\kappa}_Z(s) &= \frac{1}{\pi}\mathrm{PV}\int_{s_1}^{\infty} \frac{\mathrm{Im}\,\tilde{\kappa}_Z(s')}{s'-s} ds' \end{aligned}$$

PV denotes the integral in the sense of the principal value.

The numerical values of the *CP*-violating form-factors with $\sqrt(s) = 380$ GeV for arbitrary values of α and β are as follows:

$$\begin{aligned}
\tilde{\kappa} &= \alpha\beta\,(0.0068 + i\,0.0104), \\
\tilde{\kappa}_Z &= \alpha\beta\,(0.0019 + i\,0.0030) - \beta\,(0.0004 + i\,0.0007).
\end{aligned}$$

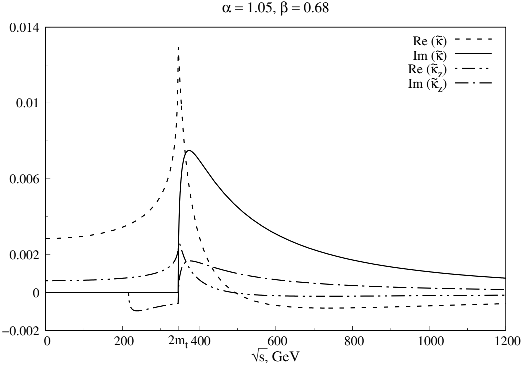


Figure: The form-factor real and imaginary parts as function of the invariant energy $\sqrt{s}$

Constraints on anomalous *Htt* couplings are obtained by CMS analysis through the combination of the *Hgg* results with measurements of the *ttH* and *tH* processes in the $H \to 4l$ and $H \to \gamma\gamma$ channels.

Channels	Coupling	Observed	Expected
tH & t$\bar{t}$H & ggH	α	$1.05^{+0.25}_{-0.20}$	$1.00^{+0.34}_{-0.26}$
	β	$-0.01^{+0.69}_{-0.67}$	$0.00^{+0.71}_{-0.71}$

Table: Summary of constraints on the *Htt*, *Hgg*, and *HVV* coupling parameters in the Higgs basis of SMEFT. CMS Analysis: HIG-19-009

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Differential cross section of the process

The evaluation of the cross section of two-step processes is based on the formalism that the b-quark and $\bar{b}$-quark are produced by decays of top-quarks on the mass surface.

$$d\sigma_{e^+ e^- \to b\,\bar{b}\,W^+\,W^-} = 4 \int \frac{d\sigma_{e^+ e^- \to t\,\bar{t}}\,(n^\mu,\ n'^\mu)}{d\Omega_t}\ \frac{d\Gamma^0_{t\to b\,W^+}}{\Gamma_t}\ \frac{d\Gamma^0_{\bar{t}\to \bar{b}\,W^-}}{\Gamma_t}\ d\Omega_t,$$

$$\frac{d^2\sigma_{e^+ e^- \to b\,\bar{b}\,W^+\,W^-}}{dE_b\,dE_{\bar{b}}} = 4 \left(\frac{m_t}{4\pi p_t p_b^0}\right)^2 \int \frac{d\sigma_{e^+ e^- \to t\,\bar{t}}\,(n^\mu,\ n'^\mu)}{d\Omega_t}\ d\Omega_t\, d\phi_b\, d\phi_{\bar{b}}$$

The 4-polarization vectors of the top-quark and antitop-quark n^μ and n'^μ are defined in the following way

$$n^\mu = \alpha_b \left(-\frac{p_t^\mu}{m_t} + \frac{m_t p_b^\mu}{p_t \cdot p_b}\right), \qquad n'^\mu = \alpha_{\bar{b}} \left(-\frac{p_t'^\mu}{m_t} + \frac{m_t p_{\bar{b}}^\mu}{p_t' \cdot p_{\bar{b}}}\right),$$

$\alpha_b = -\alpha_{\bar{b}}$ is the asymmetry parameters in the decays of the top-quark.

Energy distribution

To investigate the effects of *CP* violating, let us analyze the cross section of the combined process.

$$W(E_b,\ E_{\bar{b}}) = \frac{1}{\sigma_0}\,\frac{d^2\sigma_{e^+e^-\to b\,\bar{b}\,W^+\,W^-}}{dE_b\,dE_{\bar{b}}}$$

where $\sigma_0 \equiv \sigma_{e^+e^-\to t\,\bar{t}}$ is the total unpolarized cross section of the process $e^+e^- \to t\,\bar{t}$. For convenience, let us re-designate the energies $\varepsilon \equiv E_b$ and $\bar{\varepsilon} \equiv E_{\bar{b}}$.
The overall structure of the energy distribution looks like this

$$\begin{aligned} W(\varepsilon,\,\bar{\varepsilon}) &= S(\varepsilon,\,\bar{\varepsilon}) + (\varepsilon - \bar{\varepsilon})\,T(s), \\ T(s) &= \left[a(s)\,\mathrm{Im}\,\tilde{\kappa}(s) + b(s)\,\mathrm{Im}\,\tilde{\kappa}_z(s) + c(s)\mathrm{Re}\,\tilde{\kappa}(s) + d(s)\mathrm{Re}\,\tilde{\kappa}_z(s)\right], \end{aligned}$$

where $S(\varepsilon,\,\bar{\varepsilon})$ is the symmetric term of the energies ε and $\bar{\varepsilon}$.

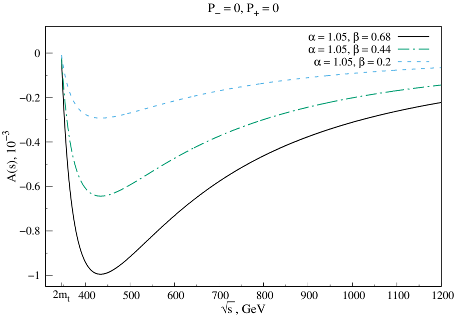
Asymmetry

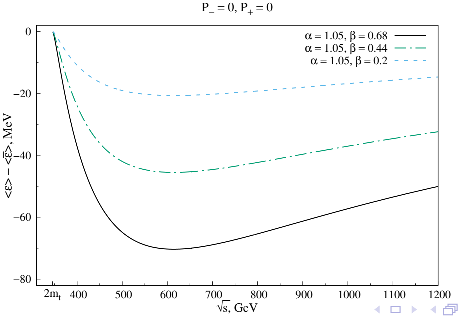
We introduce a dimensionless quantity, the asymmetry of the energy distribution of b and $\bar{b}$ quarks:

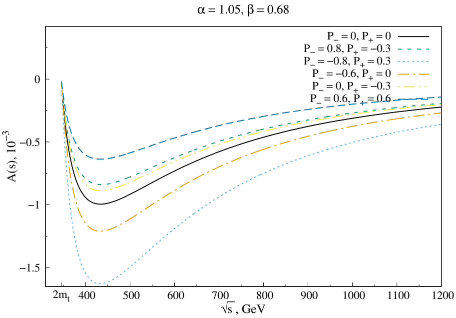
$$A(s) \equiv \int_{E_-}^{E_+} \int_{E_-}^{E_+} W(\varepsilon,\, \bar{\varepsilon}) \left[\theta(\varepsilon - \bar{\varepsilon}) - \theta(\bar{\varepsilon} - \varepsilon)\right] d\varepsilon\, d\bar{\varepsilon} = \frac{1}{3}(E_+ - E_-)^3\, T(s)$$

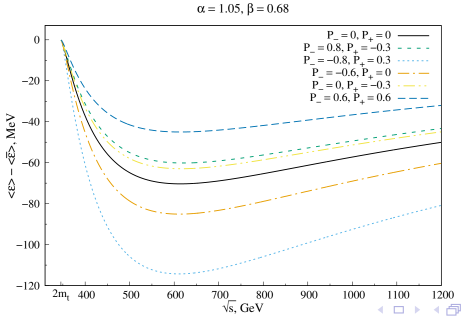
$A(s)$ corresponds to the experimentally measured quantity in terms of the number of events $(N_{E_b > E_{\bar{b}}} - N_{E_{\bar{b}} > E_b})/N_{tot}$.
Another observable quantity carrying information about the form factors of $\tilde{\kappa}$ and $\tilde{\kappa}_Z$ is the difference in the mean energies of b and $\bar{b}$ quarks:

$$\langle\varepsilon\rangle - \langle\bar{\varepsilon}\rangle \equiv \int_{E_-}^{E_+} \int_{E_-}^{E_+} W(\varepsilon,\, \bar{\varepsilon})\, (\varepsilon - \bar{\varepsilon})\, d\varepsilon\, d\bar{\varepsilon} = \frac{1}{6}(E_+ - E_-)^4\, T(s).$$


P_ = 0, P+ = 0
α = 1.05, β = 0.68
α = 1.05, β = 0.44
α = 1.05, β = 0.2
A(s), 10^−3
0
−0.2
−0.4
−0.6
−0.8
−1
2mt
400
500
600
700
800
900
1000
1100
1200
√s , GeV


P_ = 0, P+ = 0
α = 1.05, β = 0.68
α = 1.05, β = 0.44
α = 1.05, β = 0.2
<ε> − <ε̄>, MeV
0
−20
−40
−60
−80
2mt
400
500
600
700
800
900
1000
1100
1200
√s, GeV


α = 1.05, β = 0.68
P_ = 0, P+ = 0
P_ = 0.8, P+ = −0.3
P_ = −0.8, P+ = 0.3
P_ = −0.6, P+ = 0
P_ = 0, P+ = −0.3
P_ = 0.6, P+ = 0.6
A(s), 10^−3
0
−0.5
−1
−1.5
2mt 400 500 600 700 800 900 1000 1100 1200
√s , GeV


α = 1.05, β = 0.68
P_ = 0, P+ = 0
P_ = 0.8, P+ = −0.3
P_ = −0.8, P+ = 0.3
P_ = −0.6, P+ = 0
P_ = 0, P+ = −0.3
P_ = 0.6, P+ = 0.6
<ε> − <ε̄>, MeV
0
−20
−40
−60
−80
−100
−120
2mt 400 500 600 700 800 900 1000 1100 1200
√s, GeV

Conclusions

- The process of electron-positron annihilation into a pair of decaying top quarks in the conditions of the future e^+e^- collider is considered.
- Observables corresponding to the effects of *CP* invariance violation are proposed.
- The dependence of the observables on the β parameter is studied.
- I.V. Truten, A.Yu. Korchin. Energy correlation of bottom quarks from decays of top quarks in electron–positron annihilation. J. Phys. G 49 (2022) 4, 045003. arXiv:2109.10693

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Thanks for your attention!