Probing the pseudoscalar top-Higgs coupling through CP-odd observables

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Outline

- Introduction and motivations.
- Theoretical framework: differential xs for $t\bar{t}H$ production and triple products.
- CP-odd observables:
  - Asymmetry and Angular distributions: definitions and results.
  - Observables not depending on t and $\bar{t}$ spin vectors.
  - Observables that do not require full reconstruction of p_t and $p_{\bar{t}}$.
- Comments on the experimental feasibility.
- Summary and concluding remarks.

Introduction & Motivations

- Precise characterization of the Higgs boson very important. In particular, Higgs couplings to fermions: CP-transformation properties and consistency with the SM prediction.
- **top-Higgs coupling**, phenomenological and theoretical motivations:
  - Governs ggF production mechanism and contributes to the decay to $\gamma\gamma$.
  - Particular features of top quark: most massive fermion (SM t-H coupling $\mathcal{O}(1)$), decays before it can hadronize (spin information preserved in the decay products).
  - Involved in the scalar-field naturalness problem (leading dependence on Λ in corrections to m_H).
  - Possible important role in the mechanism for EWSB.
- Indirect constraints $\rightarrow$ no NP particles in loops and/or rest of Higgs couplings standard:
  - Higgs boson production and decay rates (diphoton, digluon channels).
  - Electric dipole moments.
- Direct constraints $\rightarrow$ processes with smaller cross sections ($H \rightarrow t\bar{t}$ kinematically forbidden): tH ($\bar{t}H$) and $t\bar{t}H$ productions
  - tH ($\bar{t}H$) involves a diagram with H emitted from the intermediate W $\rightarrow$ dependent on κ_W (useful for determining the relative sign between κ_t and κ_W).
  - We focus on $t\bar{t}H$ production with $t\bar{t}$ decaying dileptonically.
- Several **CP-even observables** sensitive to $\kappa_t, \tilde{\kappa}_t$: invariant mass distributions, p_T^H, $\Delta\phi(t, \bar{t})$, etc $\rightarrow$ **not sensitive to the relative sign**.
- **CP-odd observables** are required to disentangle the sign of $\kappa_t/\tilde{\kappa}_t$.
- **Goal**: Propose and test such observables, establish a hierarchy in sensitivity.

Theoretical Framework

- Consider the process $pp \to t\ (\to b\ell^+\nu_\ell)\ \bar{t}\ (\to \bar{b}\ell^-\bar{\nu}_l)\ H$. Parametrization of the effective lagrangian for tH coupling:

$$\mathcal{L}_{t\bar{t}H} = -\frac{m_t}{v}(\kappa_t \bar{t}t + i\tilde{\kappa}_t \bar{t}\gamma_5 t)H$$

$\Rightarrow$ SM ($\kappa_t = 1, \tilde{\kappa}_t = 0$), CP-odd ($\kappa_t = 0, \tilde{\kappa}_t = 1$), CP-mixed ($\kappa_t \neq 0$ and $\tilde{\kappa}_t \neq 0$)

- "Factorized" tree-level expression for the differential xs (dominant contribution gg fusion):

$$d\sigma = \sum_{\substack{bl^+\nu_l \\ \text{spins}}} \sum_{\substack{\bar{b}l^-\bar{\nu}_l \\ \text{spins}}} \left(\frac{2}{\Gamma_t}\right)^2 d\sigma(gg \to t(n_t)\bar{t}(n_{\bar{t}})H)\, d\Gamma(t \to bl^+\nu_l)\, d\Gamma(\bar{t} \to \bar{b}l^-\bar{\nu}_l)$$

  - The spin four-vectors n_t and $n_{\bar{t}}$ are not arbitrary

$$n_t = -\frac{p_t}{m_t} + \frac{m_t}{(p_t \cdot p_{l^+})} p_{l^+}$$

$$n_{\bar{t}} = \frac{p_{\bar{t}}}{m_t} - \frac{m_t}{(p_{\bar{t}} \cdot p_{l^-})} p_{l^-}$$

  - Production and decay contributions linked by final-state kinematical variables in the spin four-vectors.
  - Similar expression also valid for $q\bar{q}$-initiated production.

Theoretical Framework

- In terms of $Q \equiv \frac{q_1 + q_2}{2}$, $q \equiv \frac{q_1 - q_2}{2}$, t, $\bar{t}$, n_t and $n_{\bar{t}}$ $\rightarrow$ 15 TPs $\boldsymbol{\epsilon_n = \epsilon_{\alpha\beta\gamma\delta} p_i^\alpha p_j^\beta p_k^\gamma p_l^\delta}$ (not linearly independent):

$$d\sigma(gg \rightarrow t(n_t)\bar{t}(n_{\bar{t}})H) = \underset{\text{P-even}}{\underset{\uparrow}{\kappa_t^2\, f_1(p_i \cdot p_j)}} + \underset{\text{P-even}}{\underset{\uparrow}{\tilde{\kappa}_t^2\, f_2(p_i \cdot p_j)}} + \underset{\text{P-odd}}{\underset{\uparrow}{\kappa_t \tilde{\kappa}_t \sum_{n=1}^{15} g_n(p_i \cdot p_j)\, \epsilon_n}},$$

$d\Gamma(t \rightarrow b l^+ \nu_l)$ and $d\Gamma(\bar{t} \rightarrow \bar{b} l^- \bar{\nu}_l)$ are functions of $p_i \cdot p_j$ (P-even)

  - P-even terms contribute to the total xs, no sensitivity to the relative sign ($\propto \kappa_t^2, \tilde{\kappa}_t^2$).
  - P-odd terms do not contribute to the xs, but are sensitive to the relative sign ($\propto \kappa_t \tilde{\kappa}_t$)

- From the 15 TPs, focus on $\epsilon_1 \equiv \epsilon(t, \bar{t}, n_t, n_{\bar{t}})$, $\epsilon_2 \equiv \epsilon(Q, \bar{t}, n_t, n_{\bar{t}})$ and $\epsilon_3 \equiv \epsilon(Q, t, n_t, n_{\bar{t}})$
  - No dependence on q (cannot be expressed in terms of the momenta of final state particles).
  - Include information on the decay products of both t and $\bar{t}$ (via n_t and $n_{\bar{t}}$).

CP-odd observables

- We set $\kappa_t = 1$ and vary $\tilde{\kappa}_t = 0, \pm 0.25, \pm 0.5, \pm 0.75, \pm 1$. In particular, concentrate in **benchmark scenarios**: CP-even ($\kappa_t = 1, \tilde{\kappa}_t = 0$) and two CP-mixed cases ($\kappa_t = 1, \tilde{\kappa}_t = \pm 1$).
- 10^5 events simulated with MadGraph5_aMC@NLO at parton level (different integrated luminosities for each $\tilde{\kappa}_t$).

Asymmetry:

- Asymmetry associated to a given TP ϵ:

$$\mathcal{A}(\epsilon) = \frac{N(\epsilon > 0) - N(\epsilon < 0)}{N(\epsilon > 0) + N(\epsilon > 0)}$$

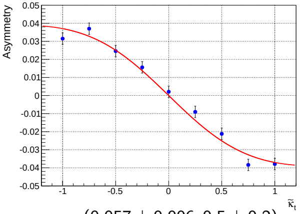
- Results for $\epsilon_1 = \epsilon(t, \bar{t}, n_t, n_{\bar{t}})$, $\epsilon_2 = \epsilon(Q, \bar{t}, n_t, n_{\bar{t}})$ and $\epsilon_3 = \epsilon(Q, t, n_t, n_{\bar{t}})$:

κ_t	$\tilde{\kappa}_t$	$\mathcal{A}(\epsilon_1)$	$\mathcal{A}(\epsilon_1)/\sigma_{\mathcal{A}}$	$\mathcal{A}(\epsilon_2)$	$\mathcal{A}(\epsilon_2)/\sigma_{\mathcal{A}}$	$\mathcal{A}(\epsilon_3)$	$\mathcal{A}(\epsilon_3)/\sigma_{\mathcal{A}}$
1	-1	0.0315	10.0	0.0332	10.5	-0.0307	-9.7
1	0	-0.0021	-0.7	0.0009	0.3	-0.0011	-0.3
1	1	-0.0379	-12.0	-0.0411	-13.0	0.0378	12.0

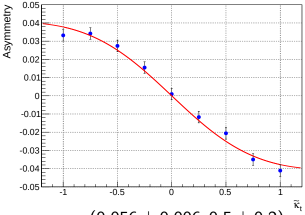
  - Asymmetries provide clear separation between SM and CP-mixed cases, tipically of order 10σ.
  - SM consistent with zero as expected.
  - Three asymmetries allow to determine the sign of $\tilde{\kappa}_t$, cases $\tilde{\kappa}_t = \pm 1$ effectively separated by more than 20σ.
  - Sensitivity of $\mathcal{A}$ quite similar for the three TPs.
  - Asymmetry not useful for discriminating between SM and pure pseudoscalar hypotheses ($\mathcal{A} \propto \kappa_t \tilde{\kappa}_t$).

CP-odd observables

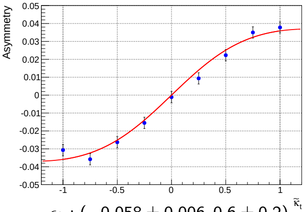
- Asymmetry scan $\kappa_t = 1, \tilde{\kappa}_t = 0, \pm 0.25, \pm 0.5, \pm 0.75, \pm 1$. Fitting function: $a\tilde{\kappa}_t/(1 + b\tilde{\kappa}_t^2)$ (a quantifies the sensitivity to $\tilde{\kappa}_t$, b the deviation from linear behaviour)



$\epsilon_1 : (0.057 \pm 0.006, 0.5 \pm 0.2)$



$\epsilon_2 : (0.056 \pm 0.006, 0.5 \pm 0.2)$



$\epsilon_3 : (-0.058 \pm 0.006, 0.6 \pm 0.2)$

- Linear combinations of ϵ_1, ϵ_2 and ϵ_3. Discriminating power increased $\sim 2.8\sigma$ for

$$\epsilon_4 \equiv \epsilon_3 - \epsilon_2 = \epsilon(Q, t - \bar{t}, n_t, n_{\bar{t}})$$

In Q rest frame $\Rightarrow \epsilon_4 = Q^0(\vec{t} - \vec{\bar{t}}) \cdot (\vec{n}_t \times \vec{n}_{\bar{t}})$

CP-odd observables

Angular distributions

- It is possible to associate angular distirbutions to the TPs. Example: $\epsilon_1 = \epsilon(t, \bar{t}, n_t, n_{\bar{t}})$
  In the system $t + \bar{t} = 0$ with $\vec{\bar{t}} \parallel +\hat{z}$:

  $$\epsilon(t+\bar{t}, \bar{t}, n_t, n_{\bar{t}}) = M_{t\bar{t}}\,|\vec{\bar{t}}|\,(\vec{n}_t \times \vec{n}_{\bar{t}})_z = M_{t\bar{t}}\,|\vec{\bar{t}}||\vec{n}_t||\vec{n}_{\bar{t}}|\sin\theta_{n_t}\sin\theta_{n_{\bar{t}}}\sin\Delta\phi(n_t, n_{\bar{t}})$$

  Sign of the TP determined by the sign of the angle $\Delta\phi(n_t, n_{\bar{t}})$ (defined in the range $[-\pi, \pi]$)

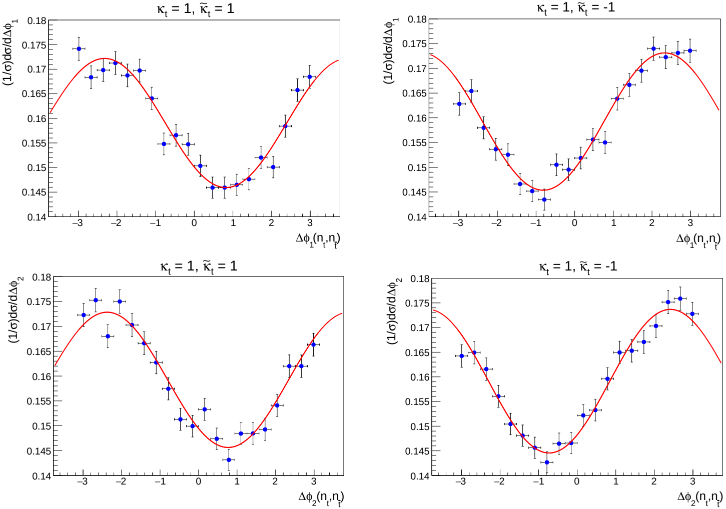
  $\Rightarrow$ distribution $dN/d\Delta\phi(n_t, n_{\bar{t}})$ is related to $\mathcal{A}(\epsilon_1)$:

  $$\mathcal{A} = 1 - 2\frac{N(\epsilon < 0)}{N} \quad \text{and} \quad \frac{N(\epsilon < 0)}{N} = \int_{-\pi \le \Delta\phi \le 0} \frac{1}{N}\frac{dN}{d\Delta\phi} d\Delta\phi.$$

- Angular distributions associated to the TPs:
  1. $\boldsymbol{\epsilon_1 = \epsilon(t, \bar{t}, n_t, n_{\bar{t}})}$. $d\sigma/d\Delta\phi_1(n_t, n_{\bar{t}})$ in $t\bar{t}$ rest frame with $\vec{\bar{t}} \parallel +\hat{z}$. $\Delta\phi_1(n_t, n_{\bar{t}}) \equiv$ angular diference between the projections of n_t and $n_{\bar{t}}$ onto the plane $\perp$ to $\vec{\bar{t}}$ (JHEP04(2014)004).
  2. $\boldsymbol{\epsilon_2 = \epsilon(Q, \bar{t}, n_t, n_{\bar{t}})}$. $d\sigma/d\Delta\phi_2(n_t, n_{\bar{t}})$ in Q rest frame with $\vec{\bar{t}} \parallel +\hat{z}$. $\Delta\phi_2(n_t, n_{\bar{t}}) \equiv$ angular diference between the projections of n_t and $n_{\bar{t}}$ onto the plane $\perp$ to $\vec{\bar{t}}$.
  3. $\boldsymbol{\epsilon_3 = \epsilon(Q, t, n_t, n_{\bar{t}})}$. $d\sigma/d\Delta\phi_3(n_t, n_{\bar{t}})$ in Q rest frame with $\vec{t} \parallel +\hat{z}$. $\Delta\phi_3(n_t, n_{\bar{t}}) \equiv$ angular diference between the projections of n_t and $n_{\bar{t}}$ onto the plane $\perp$ to $\vec{t}$.

- Similar behaviour, can be fitted with the function $c_1 + c_2\cos(\Delta\phi + \delta) \Rightarrow \mathcal{A} = -4c_2\sin\delta$.
  For $\delta = 0, \pi$, $\mathcal{A} = 0$ but the distributions are clearly different $\rightarrow$ allow to distinguish the SM from the pure CP-odd case.

CP-odd observables



- Fit using the function $c_1 + c_2 \cos(\Delta\phi + \delta)$.
- Phase shift δ sensitive to the value and sign of $\tilde{\kappa}_t$.
- Phase shift δ between 0.7 and 0.8 (-0.8 and -0.7) for $\kappa_t = -\tilde{\kappa}_t = 1$ ($\kappa_t = \tilde{\kappa}_t = 1$). Slightly higher sensitivity in $\Delta\phi_1$ distribution.

CP-odd observables not depending on n_t and $n_{\bar{t}}$

- Other possibilities for constructing CP-odd observables. The TPs considered so far can be written in terms of five TPs that involve $t, \bar{t}, H, \ell^+$ and ℓ^-:

$$\epsilon(t,\bar{t},n_t,n_{\bar{t}}) = \frac{m_t^2}{(t\cdot\ell^+)(\bar{t}\cdot\ell^-)}\,\epsilon(t,\bar{t},\ell^-,\ell^+),$$
$$\epsilon(Q,\bar{t},n_t,n_{\bar{t}}) = \frac{m_t^2}{(t\cdot\ell^+)(\bar{t}\cdot\ell^-)}\left(\epsilon(t,\bar{t},\ell^-,\ell^+) + \epsilon(H,\bar{t},\ell^-,\ell^+) + \frac{(t\cdot\ell^+)}{m_t^2}\epsilon(H,\bar{t},t,\ell^-)\right)$$
$$\epsilon(Q,t,n_t,n_{\bar{t}}) = \frac{m_t^2}{(t\cdot\ell^+)(\bar{t}\cdot\ell^-)}\left(-\epsilon(t,\bar{t},\ell^-,\ell^+) + \epsilon(H,t,\ell^-,\ell^+) + \frac{(\bar{t}\cdot\ell^-)}{m_t^2}\epsilon(H,\bar{t},t,\ell^+)\right).$$

- $\epsilon(H,\bar{t},t,\ell^-)$ and $\epsilon(H,\bar{t},t,\ell^+)$ negligible sensitivity $\Rightarrow$ focus on $\epsilon_5 \equiv \epsilon(t,\bar{t},\ell^-,\ell^+)$, $\epsilon_6 \equiv \epsilon(H,\bar{t},\ell^-,\ell^+)$ and $\epsilon_7 \equiv \epsilon(H,t,\ell^-,\ell^+)$

κ_t	$\tilde{\kappa}_t$	$\mathcal{A}(\epsilon_5)$	$\mathcal{A}(\epsilon_5)/\sigma_{\mathcal{A}}$	$\mathcal{A}(\epsilon_6)$	$\mathcal{A}(\epsilon_6)/\sigma_{\mathcal{A}}$	$\mathcal{A}(\epsilon_7)$	$\mathcal{A}(\epsilon_7)/\sigma_{\mathcal{A}}$
1	−1	0.0315	10.0	−0.0134	−4.2	0.0111	3.5
1	0	−0.0021	−0.7	−0.0011	−0.3	0.0009	0.3
1	1	−0.0379	−12.0	0.0143	4.5	−0.0137	−4.3

  - The sensitivity of $\mathcal{A}(\epsilon_5)$ clearly higher than $\mathcal{A}(\epsilon_6)$ and $\mathcal{A}(\epsilon_7)$.
  - As expected $\mathcal{A}(\epsilon_5) = \mathcal{A}(\epsilon_1)$

- Test of linear combinations of ϵ_5, ϵ_6 and ϵ_7, sensitivity enhanced for

$$\epsilon_8 = 2\epsilon_5 - \epsilon_6 + \epsilon_7 = \epsilon(t+\bar{t}+H, t-\bar{t}, \ell^+, \ell^-) \text{ in } t\bar{t}H \text{ rest frame } M_{t\bar{t}H}(\vec{t}-\vec{\bar{t}})\cdot(\vec{\ell^+}\times\vec{\ell^-})$$

$\Rightarrow$ Only difference with combination ϵ_4: $n_t, n_{\bar{t}} \leftrightarrow \ell^-, \ell^+$.

  - Higher sensitivity with respect to ϵ_1-ϵ_3 and ϵ_5-ϵ_7, but smaller with respect to $\mathcal{A}(\epsilon_4)$ (due to the replacement of spin vectors by leptons momenta).

CP-odd observables not depending on t and $\bar{t}$

- All the above observables require the full reconstruction of t and $\bar{t}$. Challenging due to the presence of two neutrinos in the final state. Possibilities:
  - Apply a kinematic reconstruction algorithm (kinematical equations from conservation of transverse momentum and from m_W and m_t constraints).
  - Define additional observables that make use of b and $\bar{b}$ instead of t and $\bar{t}$. Modify the most sensitive TPs: $\epsilon_4 = \epsilon(Q, t - \bar{t}, n_t, n_{\bar{t}})$ and $\epsilon_8 = \epsilon(t + \bar{t} + H, t - \bar{t}, \ell^+, \ell^-)$.

- Replacement $t, \bar{t} \leftrightarrow b, \bar{b}$ in ϵ_8:

$$\epsilon_9 = \epsilon(b + \bar{b} + H, b - \bar{b}, \ell^+, \ell^-)$$

  - In the $b\bar{b}H$ rest system the sign of ϵ_9 is determined by $(\vec{b} - \vec{\bar{b}}) \cdot (\ell^+ \times \ell^-)$ (similar observable in Phys. Rev. D (2015) 015019).

κ_t	$\tilde{\kappa}_t$	$\mathcal{A}(\epsilon_9)$	$\mathcal{A}(\epsilon_9)/\sigma_{\mathcal{A}}$
1	-1	0.0171	5.4
1	0	0.0010	0.3
1	1	-0.0247	-7.8

  - Sensitivity decreases $\sim 5\sigma$, but the observable may still discriminate the hypotheses.

- Proceed in similar manner with ϵ_4. By using the definition of the spin vectors:

$$\epsilon_4 \to \epsilon(Q, t - \bar{t}, \ell^-, \ell^+) + \frac{(\bar{t} \cdot \ell^-)}{m_t^2} \epsilon(Q, t, \ell^+, \bar{t}) - \frac{(t \cdot \ell^+)}{m_t^2} \epsilon(Q, \bar{t}, t, \ell^-)$$

CP-odd observables not depending on t and $\bar{t}$

Replace t and $\bar{t}$ by their visible parts $b + \ell^+$ and $\bar{b} + \ell^-$,

$$\epsilon_{10} = \epsilon(\tilde{Q}, c_{b\bar{b}}, \ell^-, \ell^+) - w_1\, \epsilon(\tilde{Q}, b, \bar{b}, \ell^+) + w_2\, \epsilon(\tilde{Q}, b, \bar{b}, \ell^-)$$

$\tilde{Q} \equiv (b + \ell^+ + \bar{b} + \ell^- + H)/2$ (visible part of Q), $c_{b\bar{b}} \equiv (1 - w_1)\, b - (1 - w_2)\, \bar{b}$,
$w_1 \equiv (\bar{b} \cdot \ell^-)/m_t^2$ and $w_2 \equiv (b \cdot \ell^+)/m_t^2$. Note that $\epsilon_{10} = \epsilon_9/2$ for $w_1 = w_2 = 0$.

Results for the asymmetry:

κ_t	$\tilde{\kappa}_t$	$\mathcal{A}(\epsilon_{10})$	$\mathcal{A}(\epsilon_{10})/\sigma_{\mathcal{A}}$
1	−1	−0.0213	−6.7
1	0	0.0031	1.0
1	1	0.0300	9.5

- Again sensitivity decreases with respect to ϵ_1-ϵ_5, but CP-mixed scenarios may be disentangled.
- Effective separation between the CP-mixed cases increases by about 3σ with respect to $\mathcal{A}(\epsilon_9)$

  -ϵ_{10} contains information on the spin vectors (in ϵ_9 the leptons momenta are used).

  -To obtain ϵ_{10} the visible parts of t and $\bar{t}$ have been used (b and $\bar{b}$ in the case of ϵ_9).

Experimental feasibility

- Number of events considered (10^5) relatively large $\Rightarrow$ reexamine most promising observables using sample sizes more attainable in the near future.
- Rough estimate for the HL-LHC: xs for $pp \to t\ (\to b\ell^+\nu_\ell)\ \bar{t}\ (\to \bar{b}\ell^-\bar{\nu}_l)\ H\ (\ell = e, \mu)$ at $\sqrt{s} = 14$ TeV ~ 15.3 fb $\to N_{ev} \sim 15.3$ fb $\times 3000$ fb$^{-1} = 4.59 \times 10^4$ (larger if $\tilde{\kappa}_t \neq 0$ assuming $\kappa_t = 1$).
- Since selection cuts as well as efficiency related to momentum reconstruction reduce N_{ev}, we consider $N_{ev} = 5 \times 10^4, 1 \times 10^4$ and 5×10^3.
- Results for $\mathcal{A}(\epsilon_4)$:

κ_t	$\tilde{\kappa}_t$	$N_{\rm ev} = 5 \times 10^4$		$N_{\rm ev} = 1 \times 10^4$		$N_{\rm ev} = 5 \times 10^3$	
		$\mathcal{A}(\epsilon_4)$	$\mathcal{A}(\epsilon_4)/\sigma_{\mathcal{A}}$	$\mathcal{A}(\epsilon_4)$	$\mathcal{A}(\epsilon_4)/\sigma_{\mathcal{A}}$	$\mathcal{A}(\epsilon_4)$	$\mathcal{A}(\epsilon_4)/\sigma_{\mathcal{A}}$
1	−1	−0.0405	−9.1	−0.0426	−4.3	−0.0496	−3.5
1	0	0.0004	0.1	−0.0084	−0.8	−0.0004	−0.03
1	1	0.0443	9.9	0.0434	4.2	0.0420	3.0

  - For 5×10^4 events (close to the HL-LHC estimate) CP-mixed scenarios effectively separated by 19σ.
  - Even with 5×10^3 the separation is 6.5σ.

Experimental feasibility

- Although t and $\bar{t}$ would not need to be reconstructed to measure $\mathcal{A}(\epsilon_{10})$, still interesting to consider more conservative N_{ev}.
- Results for $\mathcal{A}(\epsilon_{10})$:

κ_t	$\tilde{\kappa}_t$	$N_{\rm ev} = 5 \times 10^4$		$N_{\rm ev} = 1 \times 10^4$	
		$\mathcal{A}(\epsilon_{10})$	$\mathcal{A}(\epsilon_{10})/\sigma_{\mathcal{A}}$	$\mathcal{A}(\epsilon_{10})$	$\mathcal{A}(\epsilon_{10})/\sigma_{\mathcal{A}}$
1	−1	−0.0270	−6.0	−0.0184	−1.8
1	0	0.0022	0.5	−0.0086	−0.9
1	1	0.0313	7.0	0.0380	3.8

  - Even with 10^4 events, the observable is able to distinguish the CP-mixed cases by 5.6σ.
- To be fully conclusive is necessary to include the effects of hadronization, detector resolution and reconstruction efficiencies as well as the study of the impact of the backgrounds.
- Nevertheless, this initial analysis shows that the proposed observables might be probed with luminosities of order 300-600 fb^{-1} (depending on the value of $\tilde{\kappa}_t$).

Summary and conclusions

- Collection of CP-odd observables useful for disentangling the relative sign between κ_t and $\tilde{\kappa}_t$. Test of the sensitivity using different observables (asymmetries, angular distributions).
- From the expression for the differential xs $\Rightarrow$ $\epsilon_1 \equiv \epsilon(t, \bar{t}, n_t, n_{\bar{t}})$, $\epsilon_2 \equiv \epsilon(Q, \bar{t}, n_t, n_{\bar{t}})$ and $\epsilon_3 \equiv \epsilon(Q, t, n_t, n_{\bar{t}})$.
  - By using $\mathcal{A}$, CP-mixed scenarios separated by more than $\sim 20\sigma$.
  - Angular distributions, phase shift varies according to the values of κ_t and $\tilde{\kappa}_t$.
  - TPs that incorporate H and the momenta of leptons less sensitive.
- Combination $\epsilon_4 \equiv \epsilon_3 - \epsilon_2$, sensitivity increases by at least 2.8σ w.r.t ϵ_1-ϵ_3.
- If the momenta of the leptons are used intead of spin vectors (ϵ_8), the asymmetry decreases.
- Two observables that avoid the difficulty of fully reconstructing t and $\bar{t}$:
  ϵ_9, where $t, \bar{t}$ are replaced by $b, \bar{b}$.
  ϵ_{10}, where $t, \bar{t}$ are replaced by their visible parts.
  - ϵ_{10} more sensitive leading to a separation of $\sim 16\sigma$.
- With 5×10^3 and 1×10^4 events, $\mathcal{A}(\epsilon_4)$ and $\mathcal{A}(\epsilon_{10})$ respectively are still useful for testing the CP-mixed hypotheses. Separations of order $\sim 6\sigma$ for luminosities between 300-600 fb^{-1}.
- Necessary to further study the most promising observables by performing a complete simulation (hadronization and detector effects) for the signal and backgrounds and applying kinematic reconstruction method.