Higgs sector CP violation in $t\bar{t}$ production at the LHC

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- W. B., A. Brandenburg, M. Flesch, Phys. Rev. **D 56** (1997) 90; W.B., A.B., M.F., hep-ph/9812387.
- W. B., M. Flesch, P. Haberl, Phys. Rev.**D 58** (1998) 114031.
- W. B., T. Leineweber, Z.G. Si, unpublished
- for $\gamma\gamma \to t\bar{t}$, see: Phys. Rev. D **52** (1995) 3803

Higgs sector of SM extensions
like 2 Higgs doublet extensions, MSSM, NMSSM, ...
(effective) Higgs potential may be CP-noninvariant
$\Rightarrow$ neutral spin 0 mass eigenstates φ have no definite CP parity,
CP-violating Yukawa interactions,
e.g., for t quarks

$$\mathcal{L}_Y = -(\sqrt{2}G_F)^{1/2} m_t (a_t \bar{t}t + b_t \bar{t} i\gamma_5 t)\,\varphi$$

top quarks/ τ leptons good probe of CP properties of heavy/ light Higgs bosons

measure of CP violation: $\gamma_{CP} = -a_f b_f$

Consider

- for $m_\varphi \sim$ 350 – 500 GeV, s-channel production

$$\mathsf{pp} \to \varphi \mathsf{X} \to \mathsf{t\bar{t}X} \to \begin{cases} 2\ell + \mathsf{jets} \\ \ell + \mathsf{jets} \end{cases}$$

- for light φ, associated production

$$\mathsf{pp} \to \varphi\ \mathsf{t\bar{t}} \to \begin{cases} \varphi + 2\ell + \mathsf{jets} \\ \varphi + \ell + \mathsf{jets} \end{cases}$$

Determination of CP properites of φ
with $\tau/$ t spin correlations

consider $\varphi \to \mathrm{f\bar{f}}$, $\mathrm{f} = \mathrm{t}, \tau$

• if φ scalar, $J^{PC} = 0^{++}$
$\Rightarrow$ $\mathrm{f\bar{f}}$ in $^3P_0$ state
$\Rightarrow < \mathbf{s}_\mathrm{f} \cdot \mathbf{s}_{\bar{\mathrm{f}}} >= 1/4$

• if φ pseudoscalar, $J^{PC} = 0^{-+}$
$\Rightarrow$ $\mathrm{f\bar{f}}$ in $^1S_0$ state
$\Rightarrow < \mathbf{s}_\mathrm{f} \cdot \mathbf{s}_{\bar{\mathrm{f}}} >= -3/4$

• if φ with $\gamma_{CP} \neq 0$
then CPV spin correlation at tree level
$< \hat{\mathbf{k}}_\mathrm{f} \cdot (\mathbf{s}_\mathrm{f} \times \mathbf{s}_{\bar{\mathrm{f}}}) >= \gamma_{CP}\, \beta_\mathrm{f}/(b_\mathrm{f}^2 + a_\mathrm{f}^2 \beta_\mathrm{f}^2)$

and in the presence of absorptive parts
$< \hat{\mathbf{k}}_\mathrm{f} \cdot (\mathbf{s}_\mathrm{f} - \mathbf{s}_{\bar{\mathrm{f}}}) > \neq 0$

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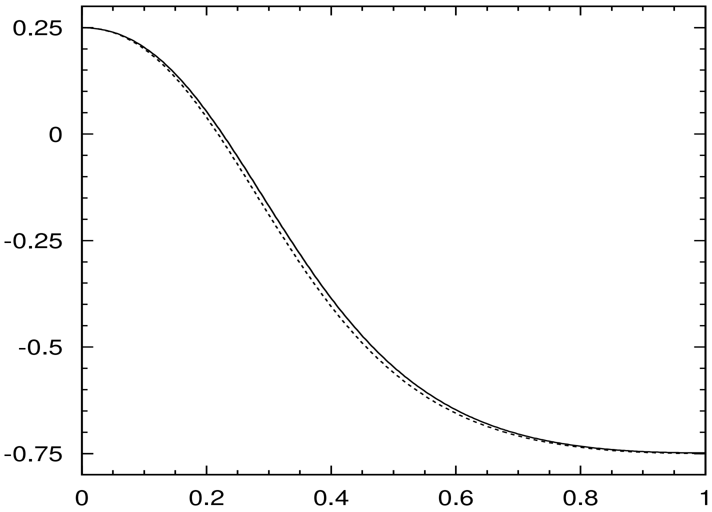
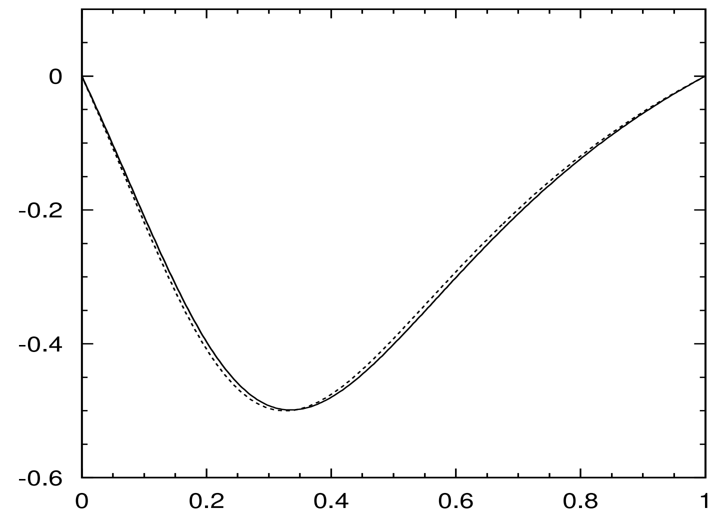
Expectation values of $< \mathbf{s}_\mathrm{f} \cdot \mathbf{s}_{\bar{\mathrm{f}}} >$ and $< \hat{\mathbf{k}}_\mathrm{f} \cdot (\mathbf{s}_\mathrm{f} \times \mathbf{s}_{\bar{\mathrm{f}}}) >$, resp., as functions of $b_t/(a_t + b_t)$ for $m_\varphi = 400$ GeV

(Phys. Rev. **D 56** (1997) 90)





Scenario: heavy φ ($m_\varphi \sim$ 350 – 500 GeV) which predominantly couples to top quarks and with $\Gamma_\varphi < \Gamma_{SM-Higgs}$

for instance, if φ pseudoscalar, then no couplings to W^+W^-, ZZ at tree level

At LHC, in the channel

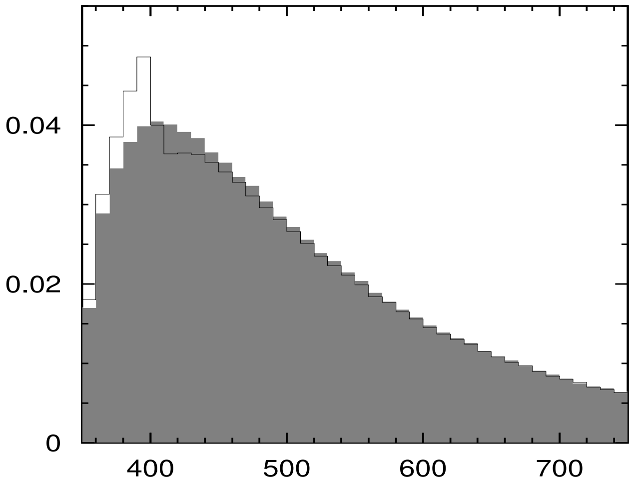
$$gg \to \varphi \to t\bar{t}$$

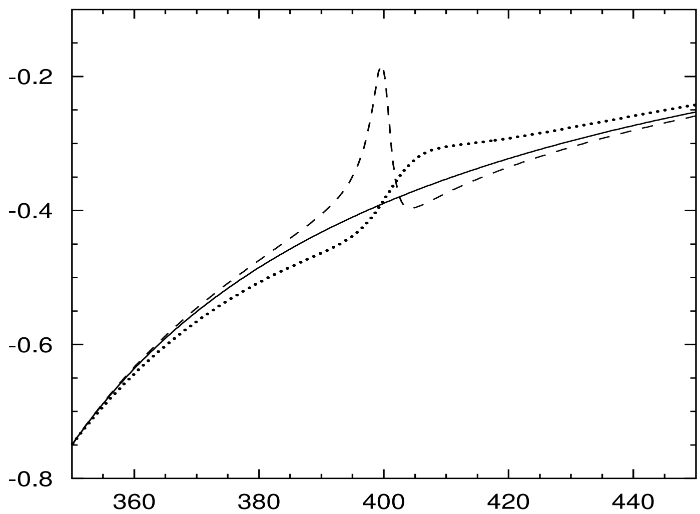
interference with non-resonant background amplitudes

$$gg \to t\bar{t}$$

produces peak-dip structure in differential cross section and in other observables

Example: $m_\varphi = 400$ GeV
$pp \to \varphi \to t\bar{t}X \to \ell +$ jets
(Phys. Rev. **D 58** (1998) 114031)





scalar $\leftrightarrow$ pseudoscalar in the reaction

$$\mathrm{pp} \rightarrow \varphi \mathrm{X} \rightarrow \mathrm{t\bar{t}X} \rightarrow \begin{cases} 2\ell + \mathrm{jets} \\ \ell + \mathrm{jets} \end{cases}$$

$$< \mathbf{s}_t \cdot \mathbf{s}_{\bar{t}} > \qquad \rightarrow \qquad \mathcal{O}_S = \hat{\ell}_+ \cdot \hat{\ell}_- = \cos\theta_{+-}$$

useful observables

$$\sigma^{-1} \frac{d\sigma}{d\cos\theta_{+-}} \qquad \text{or} \qquad \frac{d < \mathcal{O}_S >}{dM_{tt}^2}$$

in dilepton and, likewise, in lepton + jets channels

Evaluation of $\mathcal{O}_S$ in t, $\bar{t}$ rest frames
and in $t\bar{t}$ invariant mass bins $[m_\varphi - 30GeV, m_\varphi]$

In dilepton channels with $N \sim 2 \times 10^5$ events
discrimination of scalar (a=1,b=0) vs. pseudoscalar (a=0,b=1) possible
with $> 5\sigma$ in mass range 350 GeV - 450 GeV

If φ exchange is CP-violating, $\gamma_{CP} \neq 0$

$\Longrightarrow$ these couplings induce, at the level of $t\bar{t}$, the following CP-odd terms in $|\mathcal{M}|^2$:

$$\hat{\mathbf{k}}_t \cdot (\mathbf{s}_t \times \mathbf{s}_{\bar{t}}) \ , \qquad \hat{\mathbf{k}}_t \cdot (\mathbf{s}_t - \mathbf{s}_{\bar{t}})$$

These CP observables $\rightarrow$ obs. involving the final state varibales

Consider, e.g., the ℓ + jets channels

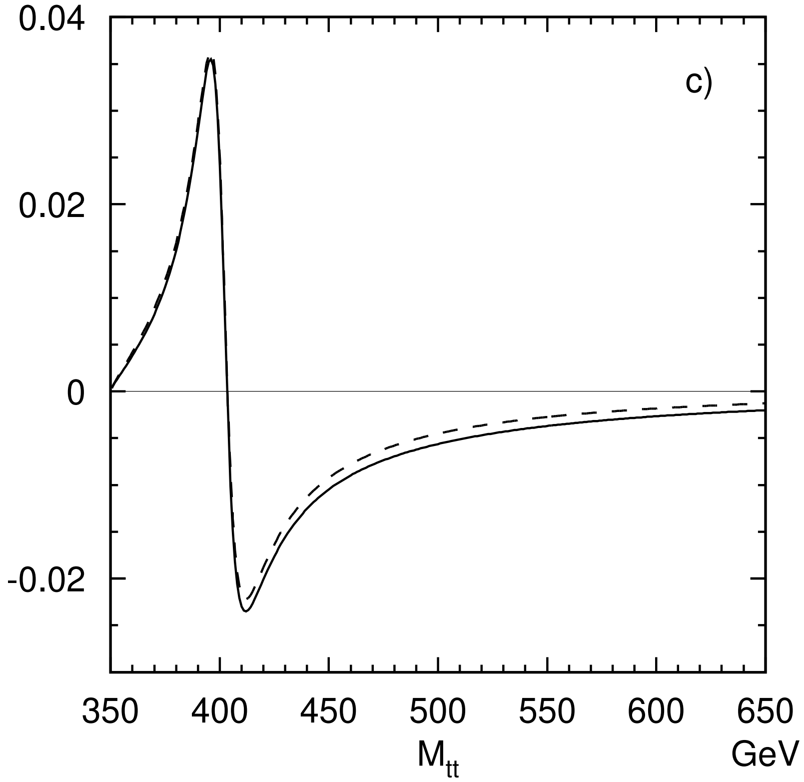
$$\mathrm{pp} \rightarrow \varphi \mathrm{X} \rightarrow \mathrm{t\bar{t}X} \rightarrow \begin{cases} \ell^+ + \text{jets} \\ \ell^- + \text{jets} \end{cases}$$

then, e.g.,

$$\hat{\mathbf{k}}_t \cdot (\mathbf{s}_t - \mathbf{s}_{\bar{t}}) \quad \rightarrow \quad \mathcal{O} = \cos\theta_+ \ - \ \cos\theta_-$$

where $\theta_+ = \angle(t, \ell^+)$, $\theta_- = \angle(\bar{t}, \ell^-)$

$< \mathcal{O} >$ as function of $t\bar{t}$ invariant mass for $m_\varphi = 400$ GeV and $\gamma_{CP} = 1$ (hep-ph/9812387)



Use also asymmetries which may be more robust experimentally

e.g., for dilepton channels

$t\bar{t} \to \ell^+\ell'^- \ + \ ....$
e.g. , observable

$\mathcal{O} = \cos\theta_+ \ - \ \cos\theta_-$

corresponding asymmetry

$$A \ = \ \frac{N_{\ell\ell}(\mathcal{O} > 0) - N_{\ell\ell}(\mathcal{O} < 0)}{N_{\ell\ell}}$$

Result of analysis at level of partonic final states:
For couplings such that $|\gamma_{CP}| = |a_t b_t| > 0.2$
and m_φ in the range 300 - 500 GeV
effects statistically significant

CP properties of light φ in associated production

$$\mathrm{pp} \rightarrow \varphi\, \mathrm{t\bar{t}} \rightarrow \begin{cases} \varphi + 2\ell + \text{jets} \\ \varphi + \ell + \text{jets} \end{cases}$$

Strategy: use $t, \bar{t}$ spin observables,
respectively, their translation into correlations among final state particles in above channels
for analyzing whether φ is scalar/pseudoscalar or has indefinite CP

scalar $\leftrightarrow$ pseudoscalar with
$\mathbf{s}_t \cdot \mathbf{s}_{\bar{t}}$, $\quad (\hat{\mathbf{k}}_t \cdot \mathbf{s}_t)(\hat{\mathbf{k}}_{\bar{t}} \cdot \mathbf{s}_{\bar{t}})$
Search for $\gamma_{CP} \neq 0$ with
$(\hat{\mathbf{k}}_t - \hat{\mathbf{k}}_{\bar{t}}) \cdot (\mathbf{s}_t \times \mathbf{s}_{\bar{t}})$

Results at level of partonic final states, assuming 100 fb^{-1}:
For light φ with $m_\varphi < 150$ GeV
- scalar (a=1) $\leftrightarrow$ pseudoscalar (b=1) with $\sim 3\sigma$,
- for $|\gamma_{CP}| = 1$ stat. significance $\sim 3\sigma$.

(W.B., T. Leineweber, Z.G. Si)