CP violation in top physics

CP violation from *new physics* in top-quark pair production and decay with T-odd correlations
one of my first papers with John

At future high-energy accelerators, the traditional methods of studying $CP$ nonconservation will no longer be useful. We present potential new ways to find $CP$ nonconservation at high-energy $e^+e^-$ and $p\bar{p}$ colliders which use jet variables in inclusive or semi-inclusive processes. These make use of asymmetries formed with beam and jet momenta. Signals are estimated in the standard model and appear to be small, but the tests could be sensitive to $CP$ nonconservation in new interactions which become visible at higher energies.

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net $b$ helicity could remain. The choice of $t$-quark decay was motivated by this problem, as in the case of $T$ mesons the spin-one $T^*$ is expected\(^3\) to decay \textit{weakly}, not by electromagnetic or strong processes. This occurs for quite simple reasons. First, the weak decay rate grows by the fifth power of the quark mass and rapidly becomes sizable. Second, the $T^*-T$ mass splitting decreases as an inverse power of the quark mass, so that the $P$-wave phase space in $T^* \rightarrow T + \gamma$ rapidly suppresses this mode. For our purposes, the existence of an almost stable $T^*$ implies that the $t$ quark can maintain its helicity around one half of the time.
T-odd observables

• simple kinematic correlations of the form
  \[ \vec{p}_1 \cdot (\vec{p}_2 \times \vec{p}_3) \]

• T-odd: change sign under `naive’-T but no interchange of initial/final states

• These correlations can be:
  - CP-odd if involve particle anti-particle pairs
  - CP-even but not at tree-level as they require a phase -- small and distinguishable `background’

• The can be that of a composite object (jet) sums over processes
T-odd correlations-2

- triple product correlations appear in invariant matrix elements in the form

\[ \epsilon(p_t, p_{\bar{t}}, p_\ell^+, p_\ell^-) \equiv \epsilon_{\mu\nu\alpha\beta} p_\mu^t p_\nu^{\bar{t}} p_\alpha^\ell p_\beta^{-\ell} \]

- 4 independent four-vectors needed, so unless one has an effective theory with vertices involving 5 particles at least, they originate from spin correlations*

- top pair production is ideal `lab' to look for them
Examples for LHC, Tevatron

- **Heavy (bsm) Higgs with CP violation**
  - large intrinsic asymmetry
  - hard to extract (if such a Higgs exists!)
- **Anomalous top-quark couplings**
  - exhibits the correlations in the general case (including those between initial and final state momenta)
  - contains examples that are truly CP odd and others that are not
  - small asymmetries (by assumption ...)

G. Valencia (Iowa State), DGHfest, Amherst Oct. 22, 2010
kinematics

or $q\bar{q}$

or jets

new physics with CP violation

sum over final states such that CP conjugate pairs appear with equal probability

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T-odd Spin correlations

- The underlying T-odd correlations are spin correlations, different observables correspond to different spin analyzers.

\[ \varepsilon(p_t,p^-_t,s_t,s^-_t) \]

CP violation in the production vertex

\[ \varepsilon(p_t,p^-_b,p^-_l,s^-_t) \]

CP violation in the decay vertex

- Want the lab frame, not the top-rest frame.
CP Violation via Neutral Higgs

- A neutral Higgs has the general coupling:
  \[ -\frac{m_t}{v} H \bar{t} (A + iB\gamma_5) t \]

- which violates CP if both \( A \) and \( B \) are non-zero at the same time (multi-Higgs models)

- Weinberg showed that
  \[ |AB| \leq \frac{1}{\sqrt{2}} \]

- under some assumptions
  - lightest neutral mass eigenstate is dominant
  - different vevs have comparable sizes
  - use upper bound for numerics

with Yili Wang
Case of H decay

• For a sufficiently heavy H, it decays to top pairs. The decay chain, for example,

\[ H \rightarrow t\bar{t} \rightarrow b\bar{b}W^+W^- \]

• picks a CP odd correlation

\[ \mathcal{O}_1 = \epsilon(p_t, p_{\bar{t}}, p_b, p_{\bar{b}}) H_{C.M.} \propto \vec{p}_t \cdot (\vec{p}_b \times \vec{p}_{\bar{b}}) \]

\[ CP \rightarrow -\vec{p}_t \cdot (-\vec{p}_b \times -\vec{p}_{\bar{b}}) = -\vec{p}_t \cdot (\vec{p}_b \times \vec{p}_{\bar{b}}) \]

• which can be measured with a counting asymmetry such as

\[ A_{CP} \equiv \frac{N_{\text{events}}(\vec{p}_b \cdot (\vec{p}_b \times \vec{p}_t) > 0) - N_{\text{events}}(\vec{p}_b \cdot (\vec{p}_b \times \vec{p}_t) < 0)}{N_{\text{events}}(\vec{p}_b \cdot (\vec{p}_b \times \vec{p}_t) > 0) + N_{\text{events}}(\vec{p}_b \cdot (\vec{p}_b \times \vec{p}_t) < 0)} \]
Can be easily computed

\[ A_{\text{CP}} = \frac{\pi}{4} \sqrt{1 - \frac{4m_t^2}{M_H^2} |A|^2 |B|^2} \left( \frac{1 - \frac{2M_w^2}{m_t^2}}{1 + \frac{2M_w^2}{m_t^2}} \right) \left( \frac{1}{1 - \frac{2m_t^2}{M_H^2} - 2 \frac{|A|^2 - |B|^2}{|A|^2 + |B|^2} \frac{m_t^2}{M_H^2}} \right) \]

There is a large intrinsic asymmetry: near 7% for A=B and maximum CP violation.
But need to isolate the sample with the asymmetry...

top pair production at LHC (14 TeV)

Higgs: top pairs from Higgs are swamped by others

gluon fusion

q q annihilation
How did we get a CP test?

\[ p \ p \rightarrow H \rightarrow t \ \bar{t} \rightarrow (bW^+) (\bar{b}W^-) \rightarrow (b\mu^+\nu_\mu)(\bar{b}\mu^-\bar{\nu}_\mu) \]

- **p p initial state is not a CP eigenstate**
  - get good CP properties from final state: view LHC as a Higgs (or more generally a t \bar{t}) factory
  - this works for g g or q \bar{q} initial states after we sum over spin and color
  - won’t work for q q initial state, need to reject it.
  - pick final states such that this is a small contamination
• electric dipole moments indicate T violation (and thus CP violation)
• experimental limits on electron edm and neutron edm; for example $d_n < 2.9 \times 10^{-26}$ e- cm
• one contribution to neutron edm is the light quark edm and also its cedm:

$$\mathcal{H} \sim \frac{1}{2} e d_q \bar{q} \sigma_{\mu\nu} \gamma_5 q F_{\mu\nu} + \frac{1}{2} g_s \tilde{d}_q \bar{q} \sigma_{\mu\nu} \gamma_5 t_a q G_{\mu\nu}^a$$

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quark edm (cedm)

• beyond the SM these can be induced at one-loop
• for example models with scalars generate contributions such as

\[ d_q, \tilde{d}_q \sim m_q^3 \]

• perhaps heavy quarks can have large (c)edms?
• measure at a top-quark factory, LHC?
**CP violating top-quark couplings**

- For CP violation in the production process: a (chromo)-edm of the top-quark:

\[
\mathcal{L}_{cedm} = -i g_s \frac{d}{2} \bar{t} \sigma_{\mu\nu} \gamma_5 t G^{\mu\nu}
\]

- It modifies the \( t \bar{t} g \) coupling and introduces a ``seagull'' term

with Oleg Antipin

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\[ gg \text{ or } q\bar{q} \rightarrow t\bar{t} \rightarrow (b\mu^+\nu_\mu)(\bar{b}\mu^-\bar{\nu}_\mu) \]

- The differential cross section now contains the following CP-odd correlations:

\[
\begin{align*}
\mathcal{O}_1 &= \epsilon(p_t, p_\bar{t}, p_{\mu^+}, p_{\mu^-}) \\
\mathcal{O}_2 &= (t - u) \epsilon(p_{\mu^+}, p_{\mu^-}, P, q) \\
\mathcal{O}_3 &= (t - u) \left( P \cdot p_{\mu^+} \epsilon(p_{\mu^-}, p_t, p_\bar{t}, q) + P \cdot p_{\mu^-} \epsilon(p_{\mu^+}, p_t, p_\bar{t}, q) \right)
\end{align*}
\]

- where the sum and difference of parton momenta are denoted by \( P \) and \( q \).
  - for \( W \) as one jet: lepton \( \leftrightarrow \) b-jet momenta
  - for more jets: lepton \( \leftrightarrow \) d-jet momenta

- Notice that they are quadratic in \( q \)

\[ (t - u) = q \cdot (p_\bar{t} - p_t) \]
CP violation in the decay vertex

- For anomalous $tbW$ couplings, there is only one that interferes with the SM amplitude in the limit of massless $b$ quark:

\[
\Gamma_{Wtb}^\mu = -\frac{g}{\sqrt{2}} V_{tb}^* \bar{u}(p_b) \left[ \gamma_\mu (f_1^L P_L + f_1^R P_R) - i\sigma^{\mu\nu}(p_t - p_b)_{\nu} (f_2^L P_L + f_2^R P_R) \right] u(p_t),
\]

\[
\bar{\Gamma}_{Wtb}^\mu = -\frac{g}{\sqrt{2}} V_{tb} \bar{v}(p_t) \left[ \gamma_\mu (\bar{f}_1^L P_L + \bar{f}_1^R P_R) - i\sigma^{\mu\nu}(p_t - p_b)_{\nu} (\bar{f}_2^L P_L + \bar{f}_2^R P_R) \right] v(p_b),
\]

- include absorptive phases also and take:

\[
f_1^L = \bar{f}_1^L = 1, \quad f_2^R = f e^{i(\phi_f + \delta_f)}, \quad \bar{f}_2^L = f e^{i(-\phi_f + \delta_f)}.
\]

- no seagulls (with a gluon) are present
T-odd correlations

- this time they appear in the differential cross section as:

\[ |\mathcal{M}|^2_T = f \sin(\phi_f + \delta_f) \epsilon(p_t, p_b, p_{\ell+}, Q_t) + f \sin(\phi_f - \delta_f) \epsilon(p_t, p_{\bar{b}}, p_{\ell-}, Q_{\bar{t}}). \]

- \( Q \) is a four momentum (spin analyzer), it is a linear combination of other momenta in the process
- the correlations are NOT CP odd, they can be also signal absorptive phases
- true CP odd observables can be constructed by comparing the top and anti-top decays

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Observables

• We have the `theoretical' correlations. Need some that only involve observable momenta.
  - for LHC we use the di-lepton (muon) channel, for Tevatron the lepton (muon) + jets, and multijet channels:

\[ p_{\mu^+}, \; p_{\mu^-} \]
\[ p_b, \; p_{\bar{b}}, \; \text{some observables require distinguishing them} \]
\[ \tilde{q} \equiv P_1 - P_2, = \text{difference of proton momenta} \]
\[ p_{j_1}, \; p_{j_2} \cdots \; \text{non} - b \; \text{jets ordered by } \; p_T \]

- any CP-blind ordering of the jets should work
Some Correlations

- **Di-muon channel**
  - basic one
    \[ \tilde{O}_1 = \epsilon(p_b, p_b, p_\mu^+, p_\mu^-) \xrightarrow{bb \; CM} \propto \vec{p}_b \cdot (\vec{p}_\mu^+ \times \vec{p}_\mu^-) \]
  - no need to distinguish b jets:
    \[ \tilde{O}_2 = \tilde{q} \cdot (p_\mu^+ - p_\mu^-) \epsilon(p_\mu^+, p_\mu^-, p_b + p_b, \tilde{q}) \]

- **Lepton plus jets**
  - hardest non-b jet
    \[ O = \epsilon(P, p_b + p_b, p_\ell, p_{j1}) \xrightarrow{lab} \propto (\vec{p}_b + \vec{p}_b) \cdot (\vec{p}_\ell \times \vec{p}_{j1}) \]

- **Multijet channels**
  \[ O_6 = \epsilon(p_b, p_b, p_{j1} + p_{j2}, p_{j1}' + p_{j2}') \xrightarrow{t\bar{t} \; CM} \propto (\vec{p}_{j1} + \vec{p}_{j2}) \cdot (\vec{p}_b \times \vec{p}_b) \]

- **Many others including CP even tests ...**
\( \tilde{d} = 0 \) (SM)

\( \tilde{d} = 5 \times 10^{-4} \text{ GeV}^{-1} \)
### Numbers in Perspective

<table>
<thead>
<tr>
<th>coupling</th>
<th>$\tilde{d} \left[ \frac{1}{m_r} \right]$</th>
<th>$f \left[ \frac{1}{m_r} \right]$</th>
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<tbody>
<tr>
<td>Theory Estimate</td>
<td>$&lt;10^{-13}$ SM*</td>
<td>$0.03$ QCD&amp;</td>
</tr>
<tr>
<td></td>
<td>$\sim 10^{-6}$ H**</td>
<td>(CP conserving and no phase)</td>
</tr>
<tr>
<td></td>
<td>$\sim 10^{-3}$ SUSY*</td>
<td></td>
</tr>
<tr>
<td>with 10fb$^{-1}$ at 5$\sigma$</td>
<td>0.05</td>
<td>$\sim 0.10$ (both CP and/or str.)</td>
</tr>
</tbody>
</table>

**units**

$$3.0 \times 10^{-4} \text{ GeV}^{-1} = \frac{0.05}{m_t} \leftrightarrow 5 \times 10^{-18} g_s \cdot \text{cm}$$


Conclusions

• We have studied several T-odd correlations that illustrate the different possibilities in searching for CP violation in top physics.

• We have estimated the asymmetries for the simple cases of anomalous top-quark couplings in both top production and decay, and a multi-Higgs model.

• With these examples we have estimated the statistical sensitivity of the LHC and the Tevatron to the CP violating top-quark couplings.

• The time is ripe for experimental studies of CP violation in top physics: any observation would signal new physics.

• We have D0 and Atlas students looking into this ...