CP violating anomalous top couplings at the LHC

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Preliminary

- We know that the current best upper limit on the neutron EDM (nEDM) amount to

$$|d_n| < 2.9 \times 10^{-26}\ e\ .\ cm$$

- A finite nEDM can be explained by the processes that violate CP symmetry.
- Possible contributions to nEDM include the light quark EDM and also its CEDM.

$$\mathcal{L} \sim \frac{e}{2}\ d_q\ \bar{q}\sigma_{\mu\nu}\gamma_5 q\ F^{\mu\nu} + \frac{g_s}{2}\ \tilde{d}_q\ \bar{q}\sigma_{\mu\nu}\gamma_5 t_a q\ G_a^{\mu\nu}$$

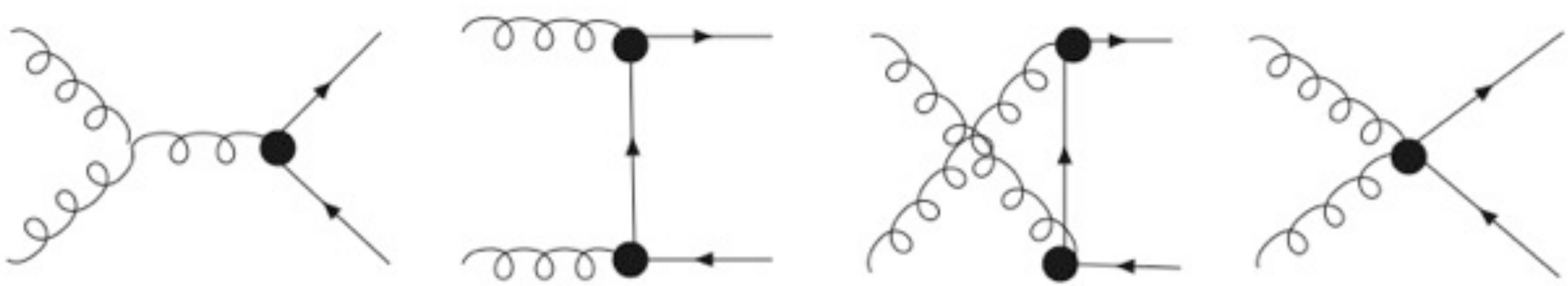
contd...

- A direct type of CP violation can be tested in the top sector as it is short-lived and doesn't hadronize.
- At the LHC we will have $\sim 10^7$ top-pairs/year which is mostly (> 90%) due to gluon fusion.
- We study CP violating effects in the top pair production arising due to anomalous couplings at the production as well as the decay level.

Top Pair Production@LHC

- The $t\bar{t}$ production process is modified relative to the SM interaction by the interaction

$$\mathcal{L}_{cdm} = -ig_s \frac{\tilde{d}}{2} \bar{t}\, \sigma_{\mu\nu} \gamma_5\, G^{\mu\nu}\, t$$



Top Decay Vertex

- The most general $t \to b\, W^+$ decay vertex can take the following form

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

$$f_1^L = \bar{f}_1^L = 1, \quad \longleftarrow \text{SM}$$

$$f_2^R = f e^{i(\phi_f + \delta_f)}, \qquad \bar{f}_2^L = f e^{i(-\phi_f + \delta_f)}.$$

- which include absorptive phases as well.

The Final Process

- We concentrate on W decaying into muons:

$$pp \to t\bar{t} \to (bW^+)(\bar{b}W^-) \to (b\mu^+\nu)(\bar{b}\mu^-\bar{\nu})$$

- The spin and colored averaged matrix element that contain CP violating correlations is given by (O Antipin, G Valencia, PRD 79, 013013 (2009) [arxiv:0807.1295])

$$|\mathcal{M}|^2_{CP} = C_1(s,t,u)\,\mathcal{O}_1 + C_2(s,t,u)\,\mathcal{O}_2 + C_3(s,t,u)\,\mathcal{O}_3$$

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

- These observables are different spin correlations in the process.
- The corresponding counting asymmetries can be defined as

$$A_i \equiv \frac{N_{events}(\mathcal{O}_i > 0) - N_{events}(\mathcal{O}_i < 0)}{N_{events}(\mathcal{O}_i > 0) + N_{events}(\mathcal{O}_i < 0)}$$

- As not all the momenta $(P,\ q,\ p_t,\ p_{\bar{t}})$ can be reconstructed fully at the LHC, we need to modify them with the substitutions

$$p_t \to p_b + p_{\mu^+} \quad p_{\bar{t}} \to p_{\bar{b}} + p_{\mu^-}$$
$$P \to p_b + p_{\mu^+} + p_{\bar{b}} + p_{\mu^-} \quad q \to \tilde{q} \equiv P_1 - P_2$$

- Modified correlations thus take the form

$$\begin{aligned}
\tilde{\mathcal{O}}_1 &= \epsilon(p_b, p_{\bar{b}}, p_{\mu^+}, p_{\mu^-}) \\
\tilde{\mathcal{O}}_2 &= \tilde{q} \cdot (p_{\mu^+} - p_{\mu^-})\, \epsilon(p_{\mu^+}, p_{\mu^-}, p_b + p_{\bar{b}}, \tilde{q}) \\
\tilde{\mathcal{O}}_3 &= \tilde{q} \cdot (p_{\mu^+} - p_{\mu^-})\, \epsilon(p_b, p_{\bar{b}}, p_{\mu^+} + p_{\mu^-}, \tilde{q})
\end{aligned}$$

- In case of CP violation in decay vertex, the color and spin matrix element square takes the following form

(O Antipin, G Valencia, PRD 79, 013013 (2009) [arxiv:0807.1295])

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

  - with δ_f and ϕ_f as absorptive and CP-violating phases respectively.
  - This contains terms with 3 four momenta from one of the decay vertices, we find additional correlations

$$\begin{aligned}
\mathcal{O}_4 &= \epsilon(P, p_b - p_{\bar{b}}, p_{\mu^+}, p_{\mu^-}) \\
\mathcal{O}_5 &= \epsilon(p_t, p_{\bar{t}}, p_b + p_{\bar{b}}, p_{\mu^+} - p_{\mu^-}) \\
\mathcal{O}_6 &= (t-u)\,\epsilon(P, p_b + p_{\bar{b}}, p_{\mu^+} - p_{\mu^-}, q)
\end{aligned}$$

Numerical Analysis

- We replaced SM matrix-element square with the new (CPV) one in MADGRAPH.
- The major background for the process is due to $gg \to b\bar{b}\mu^+\mu^- X$ with minimal acceptance cuts the cross-sections at the LHC are 4.3 pb and 24 pb for S and B respectively.

After applying (10)

$$\begin{array}{ll} p_T(\mu^\pm) > 20 \text{ GeV} & p_T(b, \bar{b}) > 25 \text{ GeV} \\ |\eta(b, \bar{b}, \mu^\pm)| < 2.5 & \Delta R(b\bar{b}) > 0.4. \end{array} \tag{10}$$

these numbers become: 2.6 pb and 1.2 pb

and after (11):

$$\not{E}_T > 30 \text{ GeV}. \tag{11}$$

2.3 pb and 0 pb respectively

Results

5×10^{-4} GeV^{-1}

	A_1	A_2	A_3	A_4	A_5	A_6	cuts
$\tilde{d}$	0.1	-2.2×10^{-2}	2.5×10^{-3}	-7.4×10^{-2}	4.1×10^{-2}	-8.4×10^{-3}	Eq. 10
	0.1	-2.1×10^{-2}	2.9×10^{-3}	-7.5×10^{-2}	3.6×10^{-2}	-6.4×10^{-3}	Eqs. 10, 11
$f \sin\phi_f$	-	-	-	-5.3×10^{-3}	-1.6×10^{-2}	1.6×10^{-2}	Eq. 10
	-	-	-	-5.8×10^{-3}	-1.7×10^{-2}	1.7×10^{-2}	Eqs. 10, 11

- With 23k events/year the statistical fluctuation $(at\ 3\sigma)$ for the aforementioned asymmetries is $A_{stat} \sim 1.9 \times 10^{-2}$

	$\tilde{A}_1$	$\tilde{A}_2$	$\tilde{A}_3$	cuts
$\tilde{d}$	5.6×10^{-2}	-4.1×10^{-3}	1.8×10^{-2}	Eq. 10
	5.5×10^{-2}	-3.5×10^{-3}	1.8×10^{-2}	Eqs. 10, 11
$f \sin \phi_f$	-5.4×10^{-3}	-2.6×10^{-2}	5.6×10^{-3}	Eq. 11
	-6.2×10^{-3}	-2.7×10^{-2}	4.0×10^{-3}	Eqs. 10, 11

TABLE III: Integrated asymmetries without full top momentum reconstruction for $\tilde{d}$ or $f \sin \phi_f$ $= 5 \times 10^{-4}$ GeV^{-1} with the cuts defined in Eqs. 10, 11.

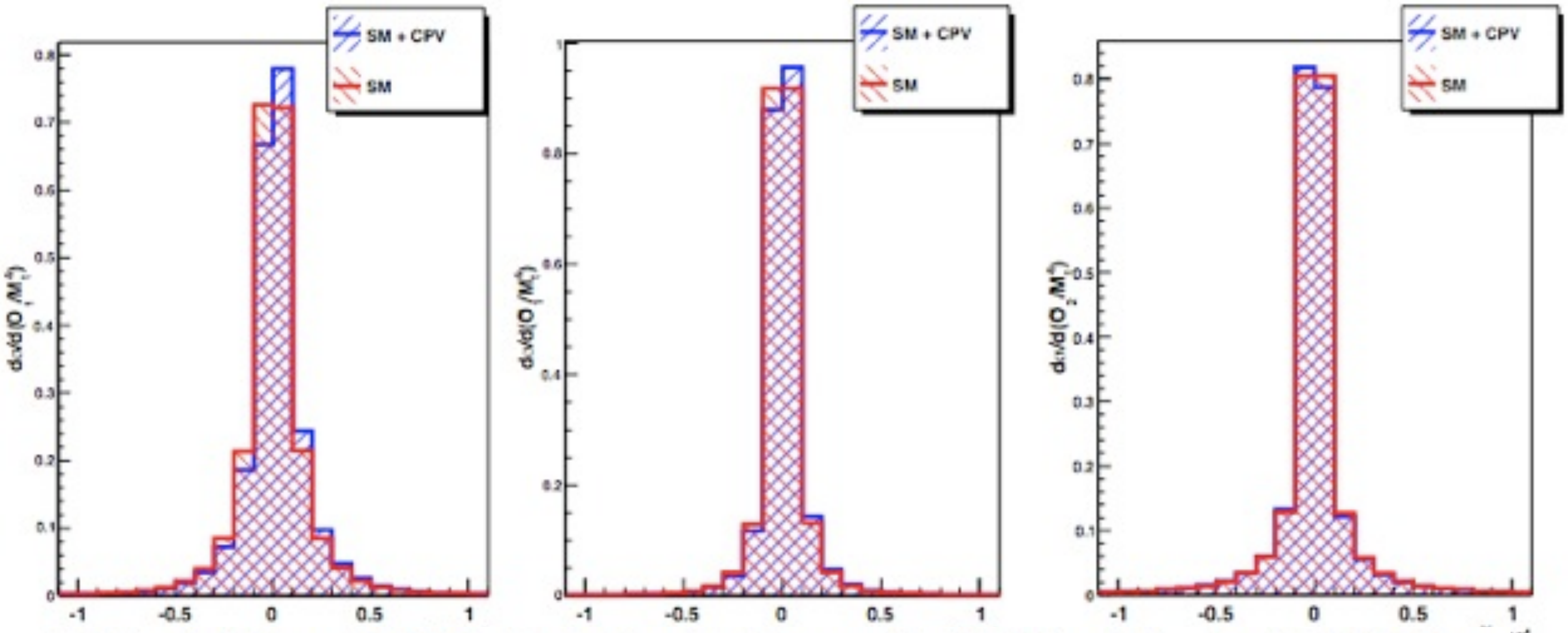


FIG. 1: $d\sigma/d\mathcal{O}_1$ and $d\sigma/d\tilde{\mathcal{O}}_1$ distributions for the cases $\tilde{d} = 0$ (SM) and $\tilde{d} = 5 \times 10^{-4}$ GeV^{-1} as well as $d\sigma/d\tilde{\mathcal{O}}_2$ for $f \sin\phi_f = 5 \times 10^{-4}$ GeV^{-1}.

LHC sensitivity

- Define, $d_t \equiv \tilde{d}\, m_t, \quad f_t \equiv f\, m_t$

$$\begin{aligned}\tilde{A}_1 &= 0.64\, d_t - 0.072\, f_t \sin\phi_f \\ \tilde{A}_2 &= -0.041\, d_t - 0.32\, f_t \sin\phi_f \\ \tilde{A}_3 &= 0.21\, d_t + 0.047\, f_t \sin\phi_f .\end{aligned}$$

- With one year of LHC run, 5σ sensitivity requires

$$|d_t| \geq 0.05, \quad |\tilde{d}| \geq 3.0 \times 10^{-4}\ \mathrm{GeV}^{-1}$$
$$|f_t \sin\phi_f| \geq 0.10, \quad |f \sin\phi_f| \geq 6.0 \times 10^{-4}\ \mathrm{GeV}^{-1}$$

Strong interaction phases

- This can be isolated by employing CP-even observables

$$\mathcal{O}_a = \tilde{q}\cdot(p_{\mu^+}+p_{\mu^-})\,\epsilon(p_{\mu^+},p_{\mu^-},p_b+p_{\bar{b}},\tilde{q})$$
$$\mathcal{O}_b = \tilde{q}\cdot(p_{\mu^+}-p_{\mu^-})\,\epsilon(p_{\mu^+},p_{\mu^-},p_b-p_{\bar{b}},\tilde{q}).$$

A_a	A_b	cuts
4.2×10^{-3}	-3.1×10^{-2}	Eq. 10
3.0×10^{-3}	-2.7×10^{-2}	Eqs. 10, 11

  – 5σ LHC sensitivity with 1 year data requires,

$$|f_t \sin\delta_f| \geq 0.10 \quad |f \sin\delta_f| \geq 6.0\times10^{-4}.$$

Summary

- We have estimated asymmetries due to anomalous top quark coupling both production and decay level.
- LHC sensitivities corresponding to these couplings has also been estimated using the asymmetries.
- We also noted that the true CP phases can be isolated from the strong interacting phases.