A CP-odd Observable for LHC

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New CP-odd observable in H ---> t anti-t.
G. Valencia, Yili Wang., **hep-ph/0512127.**

Published in **Phys.Rev.D73:053009,2006**

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CP Violation at LHC

- Find ``naive T''-odd (triple products), CP violating correlations that could be explored at LHC
  - suitable for high energy processes (i. e. jets)
  - want triple products that are really CP-odd
  - LHC initial state pp can be a problem
- Construct it from final state variables
- Look for $\bar{t}\,t$ production with subsequent top decay $t \rightarrow b\,W$

Parton CM asymmetry

- Construct CP-odd triple product : $\varepsilon(p_t, p_{\bar{t}}, p_b, p_{\bar{b}})$
- In parton CM: $t\bar{t}b\bar{b}X \xrightarrow{CP} \bar{t}t\bar{b}b\bar{X}$

$$\sqrt{s}\,\overrightarrow{p_t}\cdot(\overrightarrow{p_b}\times\overrightarrow{p_{\bar{b}}}) \xrightarrow{CP} \sqrt{s}(-\overrightarrow{p_{\bar{t}}})\cdot(-(\overrightarrow{p_{\bar{b}}})\times-(\overrightarrow{p_b}))$$

$$= -\sqrt{s}\,\overrightarrow{p_t}\cdot(\overrightarrow{p_b}\times\overrightarrow{p_{\bar{b}}})$$

Can be studied with the counting asymmetry:

$$A_{CP} \equiv \frac{N_{events}(\vec{p}_{\bar{b}}\cdot(\vec{p}_b\times\vec{p}_t)>0) - N_{events}(\vec{p}_{\bar{b}}\cdot(\vec{p}_b\times\vec{p}_t)<0)}{N_{events}(\vec{p}_{\bar{b}}\cdot(\vec{p}_b\times\vec{p}_t)>0) + N_{events}(\vec{p}_{\bar{b}}\cdot(\vec{p}_b\times\vec{p}_t)<0)}$$

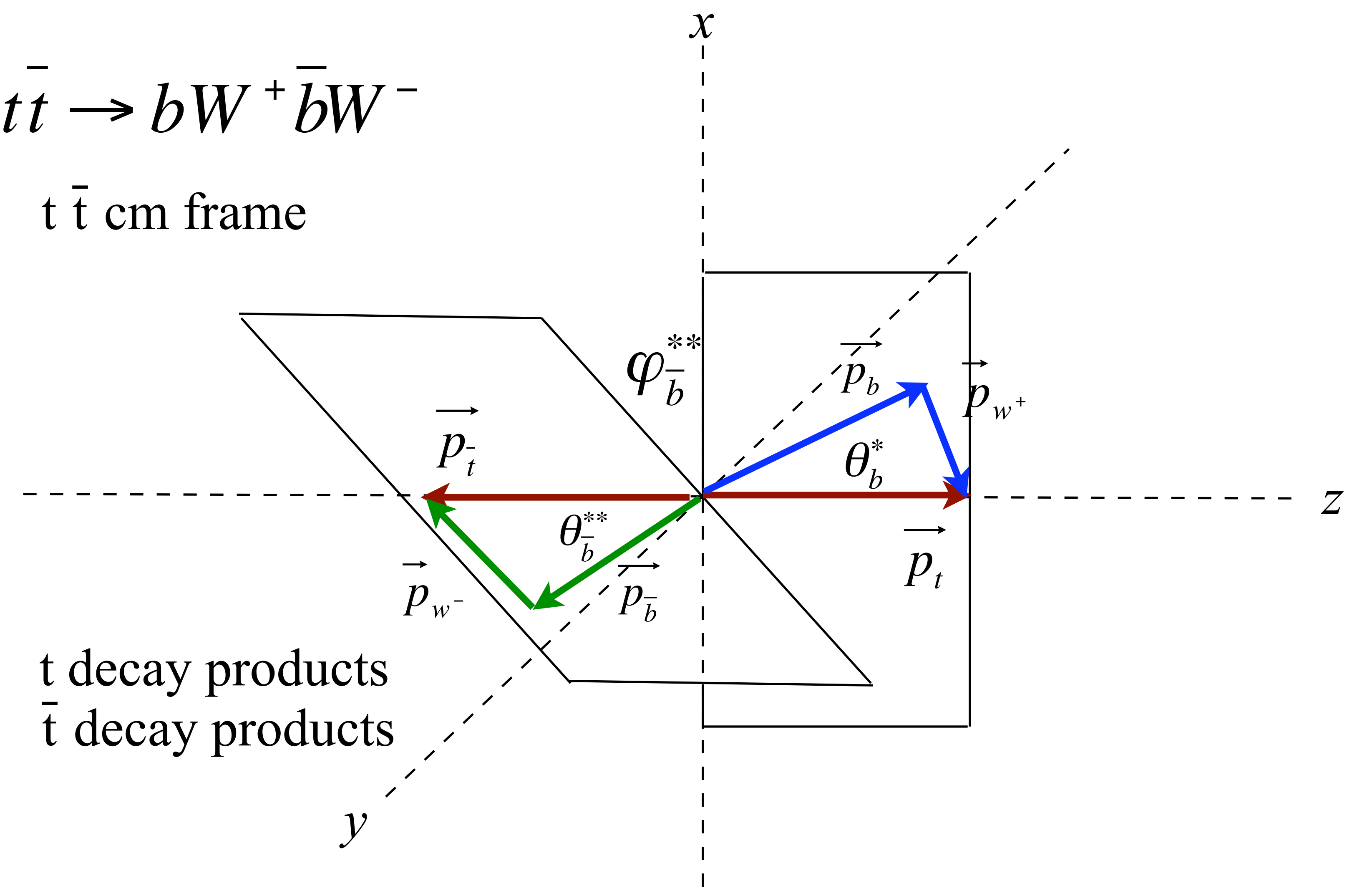
kinematics in parton cm frame

$$t\bar{t} \rightarrow bW^+\bar{b}W^-$$

— t $\bar{\text{t}}$ cm frame

— t decay products

— $\bar{\text{t}}$ decay products



Example: H decay

- Start with simple example: CP nature of a Higgs (heavy enough to decay into top pairs)
- coupling: $-\frac{m_t}{v} H \bar{t}(A + iB\gamma_5)t$.
- CP violation if both A, B non-zero at the same time (multi-Higgs models)
- Look for $H \to \bar{t}\, t$ decays with subsequent top decay $t \to b\, W$
- $\Gamma \sim |A|^2 + |B|^2$ but $A_{CP} \sim A\, B$

One finds:

$$\Gamma(H \to t\bar{t}) = N_c \frac{M_H}{32\pi} \frac{g^2 m_t^2}{M_W^2} \sqrt{1 - \frac{4m_t^2}{M_H^2}} \Big[(|A|^2 + |B|^2) \times \left(1 - \frac{2m_t^2}{M_H^2}\right) - 2(|A|^2 - |B|^2) \frac{m_t^2}{M_H^2} \Big]. \qquad (5)$$

$$A_{CP} \equiv \frac{\hat{\Gamma}}{\Gamma} = \frac{\pi}{4} \sqrt{1 - \frac{4m_t^2}{M_H^2}} \frac{AB}{|A|^2 + |B|^2} \frac{(1 - \frac{2M_W^2}{m_t^2})^2}{(1 + \frac{2M_W^2}{m_t^2})^2} \times \left(\frac{1}{1 - \frac{2m_t^2}{M_H^2} - 2\frac{|A|^2 - |B|^2}{|A|^2 + |B|^2} \frac{m_t^2}{M_H^2}} \right) \qquad (12)$$

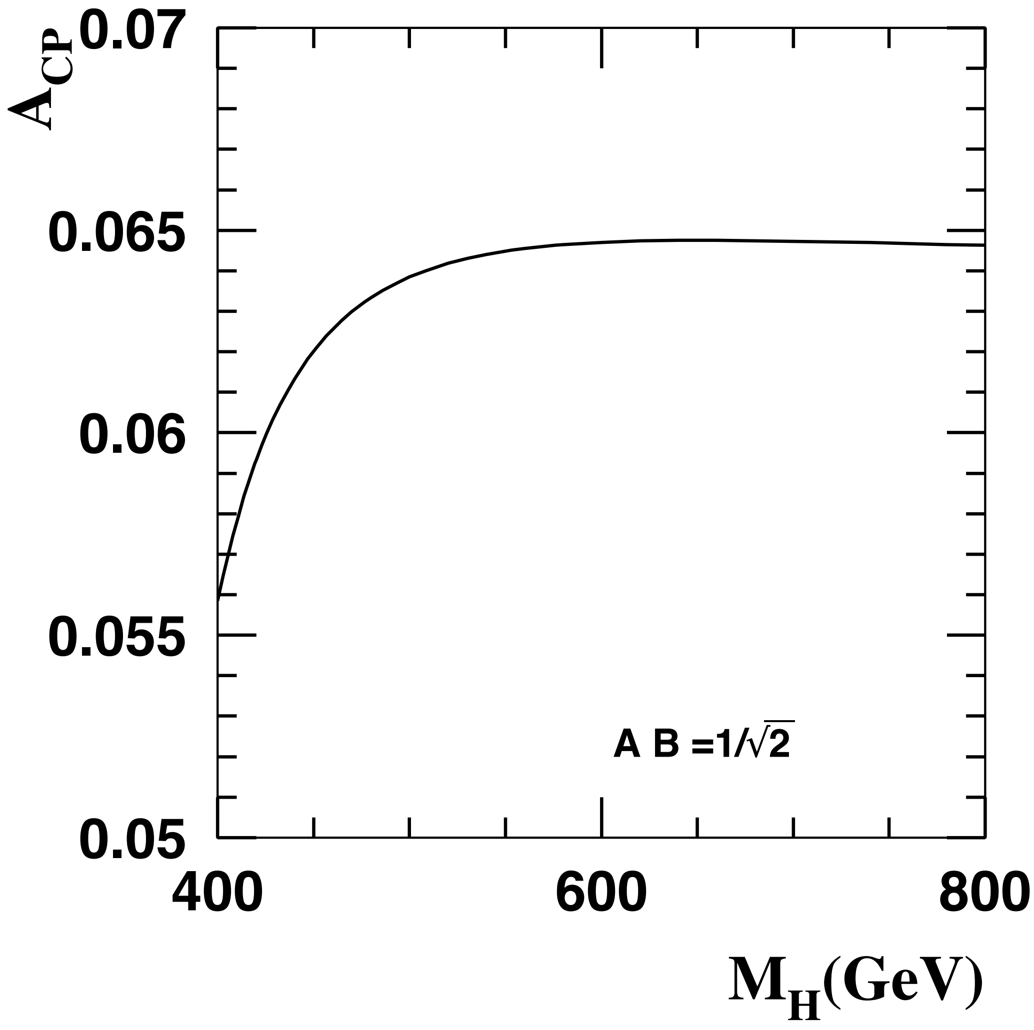
How large can it be?

- With some assumptions:
  - lightest neutral mass eigenstate dominate
  - different vevs have comparable sizes
- Weinberg finds

$$|AB| \leq \frac{1}{\sqrt{2}}$$

- and shows models where the upper bound is reached (Phys.Rev. D42 (1990) 860)
- this leads to an asymmetry as large as 6.5%

In H decay (H rest frame)



LHC?

- In calculating A_{CP} we didn't ``use the LHC''
- so $X \rightarrow X_{CP}$ didn't affect us
- treat the LHC as a "Higgs factory" and start with the H as initial state
- to what extent can we do the same for $\bar{t}\, t$ initial states? (under investigation)
- start by assuming we can:

Non-resonant $t\,\bar{t}$ production

- At the LHC the signal gets diluted by non-resonant t pair production (in our example for CP violation)
- Other sources of CP violation (e.g. top-quark color edm) affect other diagrams
- To complete our example we need other diagrams that produce color singlet top-quark pairs:

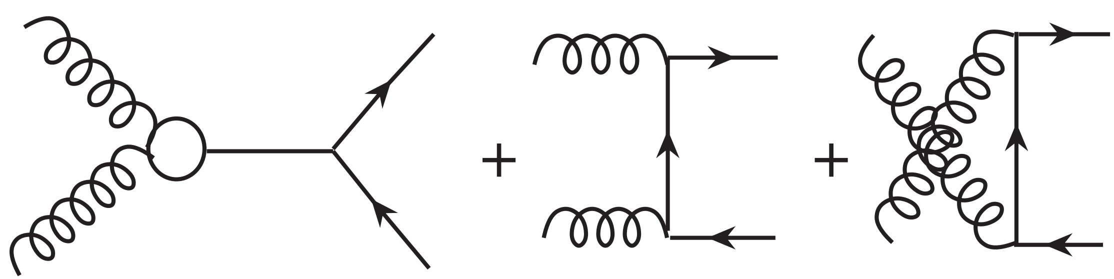


FIG. 3. Three diagrams responsible for *CP* asymmetry in top-quark pair production.

CP asymmetry in $g\, g \to t\, \bar{t}$

- Calculation is more complicated. We used helicity amplitudes for spin density matrix
- Narrow width approximation for $t\, \bar{t}$

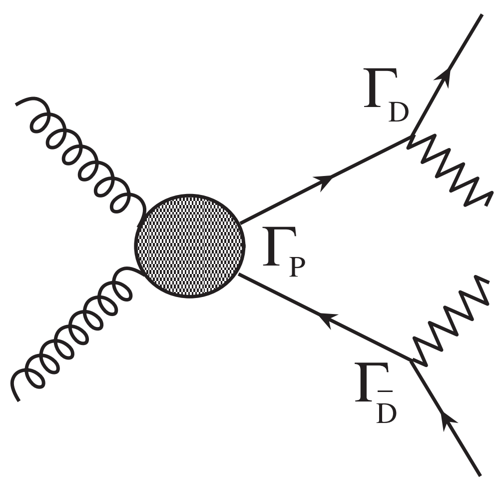


FIG. 4. Decomposition of $t\bar{t}$ production and decay vertices with helicity amplitudes.

Defining:
$$\bar{u}_{t\lambda}\Gamma_P v_{\bar{t}\sigma}\bar{v}_{\bar{t}\sigma'}\gamma^0\Gamma_P^\dagger\gamma^0 u_{t\lambda'} \to \frac{1}{4}\sum_{\lambda_1,\lambda_2}\mathcal{M}_{\mathcal{P}}(\lambda_1,\lambda_2,\lambda,\sigma) \times \mathcal{M}_{\mathcal{P}}{}^*(\lambda_1,\lambda_2,\lambda',\sigma'),$$

and:
$$\mathcal{T}_t(\lambda',\lambda) \equiv \bar{u}_{t\lambda'}\not{p}_b(1-\gamma_5)u_{t\lambda}$$
$$\mathcal{T}_{\bar{t}}(\sigma,\sigma') \equiv \bar{v}_{\bar{t}\sigma}\not{p}_{\bar{b}}(1-\gamma_5)v_{\bar{t}\sigma'}.$$

We find:
$$|\mathcal{M}|^2 = \frac{g^4}{64}\left(\frac{\pi}{M_t\Gamma_t}\right)^2\left(2-\frac{m_t^2}{M_W^2}\right)^2\delta(p_t^2-m_t^2)\delta(p_{\bar{t}}^2-m_t^2) \times \sum_{\lambda_1,\lambda_2,\lambda,\lambda',\sigma,\sigma'}\mathcal{M}_{\mathcal{P}}(\lambda_1,\lambda_2,\lambda,\sigma)\mathcal{M}_{\mathcal{P}}{}^{\star}(\lambda_1,\lambda_2,\lambda',\sigma') \times \mathcal{T}_t(\lambda',\lambda)\mathcal{T}_{\bar{t}}(\sigma,\sigma'). \tag{25}$$

Production helicity amplitudes

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TABLE I. $t+u$ channel $gg \to t\bar{t}$ and $gg \to H \to t\bar{t}$ helicity amplitudes. The former should be multiplied by g_s^2 and the latter by $(gm_t/2M_W)$. Color factors have not been included and the kinematic factors refer to the t quark in the parton CM frame: $\tau_t = 4m_t^2/s$, $\beta = \sqrt{1-\tau_t}$, $\gamma = (1-\beta^2)^{-1/2}$.

$g, g \to t\bar{t}$	$t+u$ channels	s-channel
$+, + \to +, +$	$\frac{2\sqrt{\tau_t}(1+\beta)}{\beta^2\cos^2\theta-1}$	$\frac{s^{3/2}}{2(s-M_H^2)}(F_b - iF_a)(B + iA\beta)$
$+, + \to -, -$	$\frac{2\sqrt{\tau_t}(1-\beta)}{\beta^2\cos^2\theta-1}$	$\frac{s^{3/2}}{2(s-M_H^2)}(F_b - iF_a)(B - iA\beta)$
$-, - \to +, +$	$\frac{2\sqrt{\tau_t}(1-\beta)}{1-\beta^2\cos^2\theta}$	$-\frac{s^{3/2}}{2(s-M_H^2)}(F_b + iF_a)(B + iA\beta)$
$-, - \to -, -$	$\frac{2\sqrt{\tau_t}(1+\beta)}{1-\beta^2\cos^2\theta}$	$-\frac{s^{3/2}}{2(s-M_H^2)}(F_b + iF_a)(B - iA\beta)$
$-, + \to -, -$	$\frac{2\beta\sin^2\theta}{\gamma(1-\beta^2\cos^2\theta)}$	0
$-, + \to -, +$	$\frac{2\beta\sin\theta(1+\cos\theta)}{\beta^2\cos^2\theta-1}$	0
$-, + \to +, -$	$\frac{2\beta(\cos\theta-1)\sin\theta}{\beta^2\cos^2\theta-1}$	0
$-, + \to +, +$	$\frac{2\beta\sin^2\theta}{\gamma(\beta^2\cos^2\theta-1)}$	0
$+, - \to -, -$	$\frac{2\beta\sin^2\theta}{\gamma(1-\beta^2\cos^2\theta)}$	0
$+, - \to -, +$	$\frac{2\beta(\cos\theta-1)\sin\theta}{\beta^2\cos^2\theta-1}$	0
$+, - \to +, -$	$\frac{2\beta\sin\theta(1+\cos\theta)}{\beta^2\cos^2\theta-1}$	0
$+, - \to +, +$	$\frac{2\beta\sin^2\theta}{\gamma(\beta^2\cos^2\theta-1)}$	0

t decay vertices

TABLE II. t and $\bar{t}$ decay factors as defined in the text. The first column should be multiplied by E_b and the second column by $E_{\bar{b}}$, the b and $\bar{b}$ energies in the parton center of mass frame.

λ, λ'	$\mathcal{T}_t(\lambda, \lambda')$	$\mathcal{T}_{\bar{t}}(\lambda, \lambda')$
$-, -$	$\sqrt{s}(1+\beta)(1-\cos\theta\cos\theta_b-\sin\theta\sin\theta_b\cos\phi_b)$	$\sqrt{s}(1-\beta)(1-\cos\theta\cos\theta_{\bar{b}}-\sin\theta\sin\theta_{\bar{b}}\cos\phi_{\bar{b}})$
$-, +$	$2m_t(-\sin\theta\cos\theta_b+\cos\theta\sin\theta_b\cos\phi_b-i\sin\theta_b\sin\phi_b)$	$2m_t(-\sin\theta\cos\theta_{\bar{b}}+\cos\theta\sin\theta_{\bar{b}}\cos\phi_{\bar{b}}+i\sin\theta_{\bar{b}}\sin\phi_{\bar{b}})$
$+, -$	$2m_t(-\sin\theta\cos\theta_b+\cos\theta\sin\theta_b\cos\phi_b+i\sin\theta_b\sin\phi_b)$	$2m_t(-\sin\theta\cos\theta_{\bar{b}}+\cos\theta\sin\theta_{\bar{b}}\cos\phi_{\bar{b}}-i\sin\theta_{\bar{b}}\sin\phi_{\bar{b}})$
$+, +$	$\sqrt{s}(1-\beta)(1+\cos\theta\cos\theta_b+\sin\theta\sin\theta_b\cos\phi_b)$	$\sqrt{s}(1+\beta)(1+\cos\theta\cos\theta_{\bar{b}}+\sin\theta\sin\theta_{\bar{b}}\cos\phi_{\bar{b}})$

- Notice that the azimuthal angles that characterize the correlation only appear in the “mixed” helicity factors
- CP violation arises from interference between amplitudes with different helicities for the top intermediate state

Comments

- The resulting asymmetry is purely CP violating (as expected), even though the calculation included absorptive phases in Higgs production vertex
- For LHC use CTEQ6M pdf's at $\sqrt{S}$ = 14 TeV
- The asymmetry is smaller than in Higgs decay in our model since non-resonant production is larger and CP conserving
- $q\,\bar{q}$ annihilation very small contribution to asymmetry (no interference with resonant diagram)

A_{CP} *is* solid line

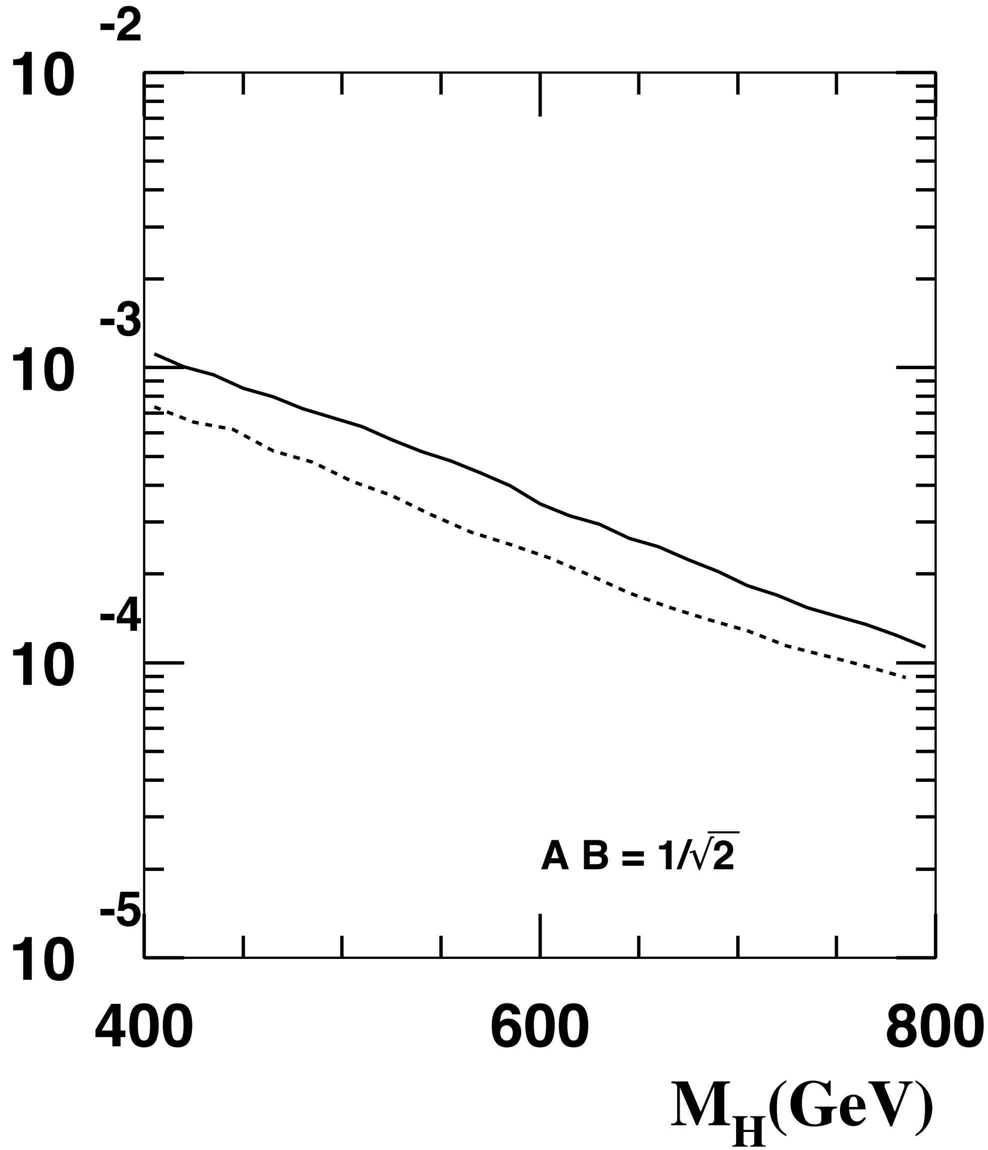


FIG. 7: Normalized CP violating asymmetry at the LHC for $A, B = 1/\sqrt{2}$. The solid and dotted curves correspond to the asymmetries A_{CP}, Eq. 30, and $\hat{A}_{CP}$, Eq. 31 respectively. In this case both contributions to the asymmetry are included and they are normalized to the total $pp \to t\bar{t}$ cross-section.

More dilution

- The asymmetry also requires reconstruction of t and b directions in parton CM frame (H rest frame)

$$A_{CP} \equiv \frac{N_{\text{events}}(\vec{p}_{\bar{b}} \cdot (\vec{p}_b \times \vec{p}_t) > 0) - N_{\text{events}}(\vec{p}_{\bar{b}} \cdot (\vec{p}_b \times \vec{p}_t) < 0)}{N_{\text{events}}(\vec{p}_{\bar{b}} \cdot (\vec{p}_b \times \vec{p}_t) > 0) + N_{\text{events}}(\vec{p}_{\bar{b}} \cdot (\vec{p}_b \times \vec{p}_t) < 0)} \tag{13}$$

- This is not CP-odd in the lab frame, however it is possible to construct more complicated asymmetries for the lab frame - more dilution
- With reconstruction of top and bottom momenta directions in the lab frame a CP-odd example is:

$$\hat{A}_{CP} \equiv \frac{N_{\text{events}}((\vec{p}_{\bar{t}} - \vec{p}_t) \cdot (\vec{p}_b \times \vec{p}_{\bar{b}}) > 0) - N_{\text{events}}((\vec{p}_{\bar{t}} - \vec{p}_t) \cdot (\vec{p}_b \times \vec{p}_{\bar{b}}) < 0)}{N_{\text{events}}((\vec{p}_{\bar{t}} - \vec{p}_t) \cdot (\vec{p}_b \times \vec{p}_{\bar{b}}) > 0) + N_{\text{events}}((\vec{p}_{\bar{t}} - \vec{p}_t) \cdot (\vec{p}_b \times \vec{p}_{\bar{b}}) < 0)}.$$

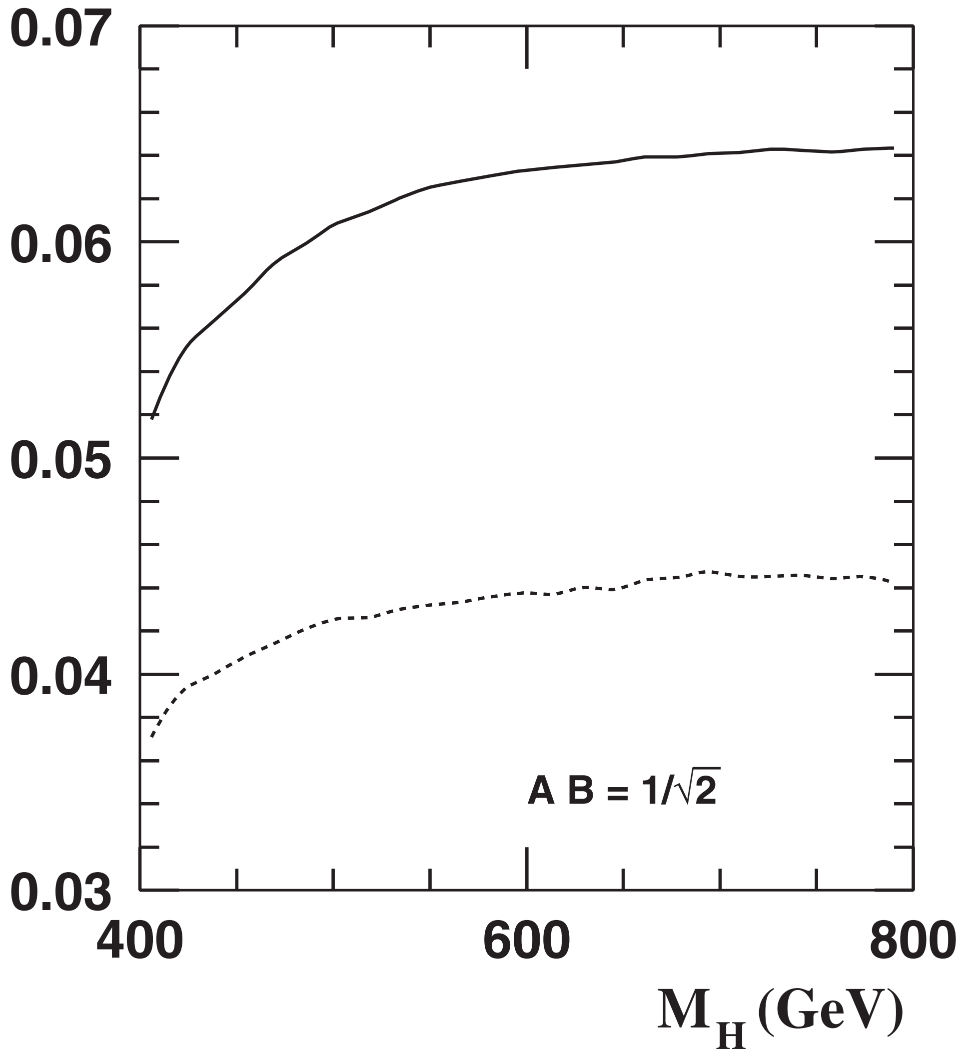
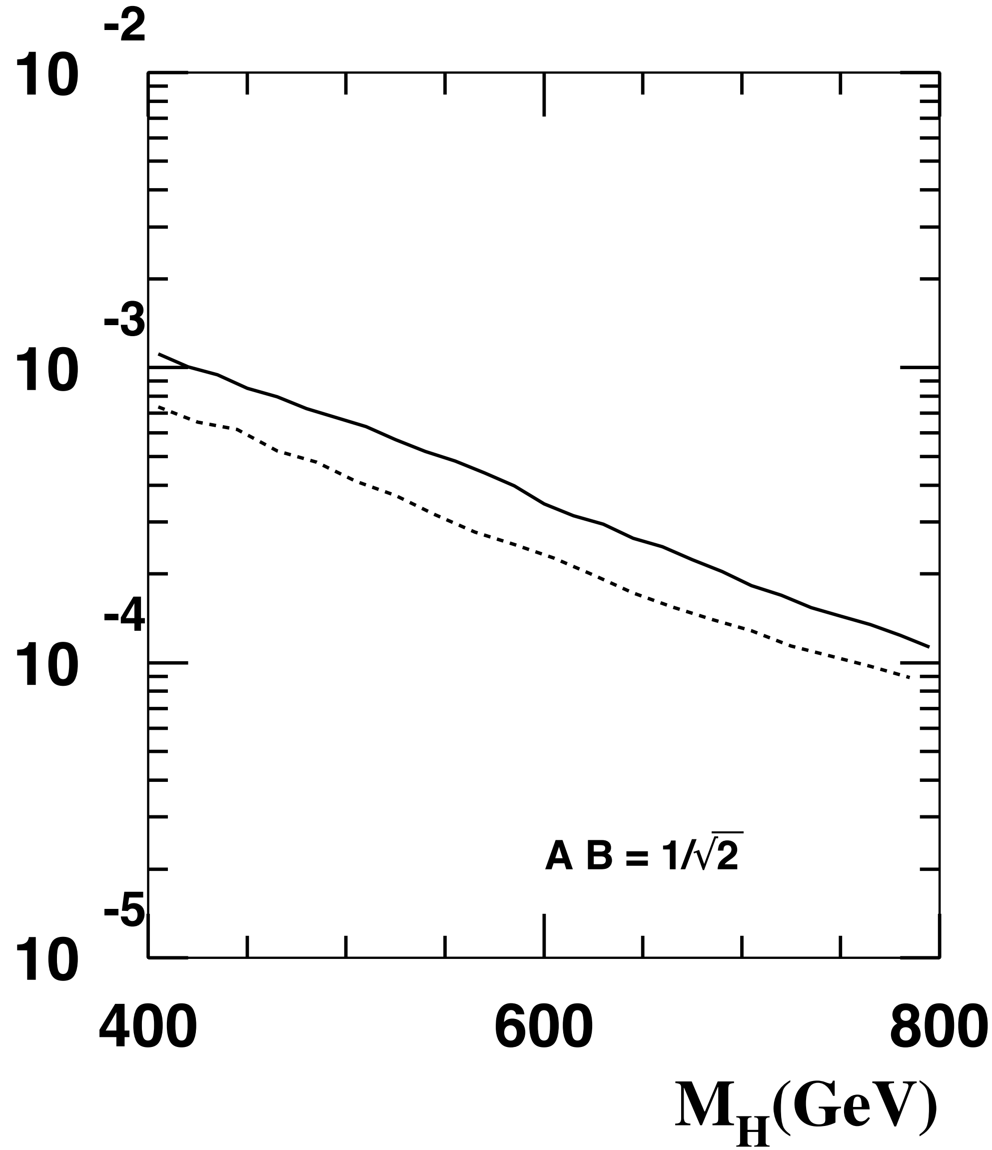


FIG. 6. *CP* asymmetry for *s*-channel Higgs production and subsequent decay at the LHC. The solid and dotted curves correspond to the asymmetries A_{CP}, Eq. (30), and $\hat{A}_{CP}$, Eq. (31) respectively.



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- The observable can be generalized at the cost of further dilution, for example, if the top momentum can't be reconstructed one could use

$$\tilde{A}_{CP} \equiv \frac{N_{\text{events}}((\vec{p}_{\ell^+} - \vec{p}_{\ell^-}) \cdot (\vec{p}_b \times \vec{p}_{\bar{b}}) > 0) - N_{\text{events}}((\vec{p}_{\ell^+} - \vec{p}_{\ell^-}) \cdot (\vec{p}_b \times \vec{p}_{\bar{b}}) < 0)}{N_{\text{events}}((\vec{p}_{\ell^+} - \vec{p}_{\ell^-}) \cdot (\vec{p}_b \times \vec{p}_{\bar{b}}) > 0) + N_{\text{events}}((\vec{p}_{\ell^+} - \vec{p}_{\ell^-}) \cdot (\vec{p}_b \times \vec{p}_{\bar{b}}) < 0)}.$$

- We have assumed that the final state consists of reconstructed particle-antiparticle pairs. If this is not true there can be CP conserving background to the asymmetries (or what happens to X?)

Conclusions

- We have presented an example of a triple product correlation for the LHC that is CP-odd
- Since the LHC is a pp collider, our signal relies on the CP properties of the final state.
- We have estimated the asymmetry in a simple model of CP violation for Higgs decay
- Detailed studies of background, reconstruction, etc are under study

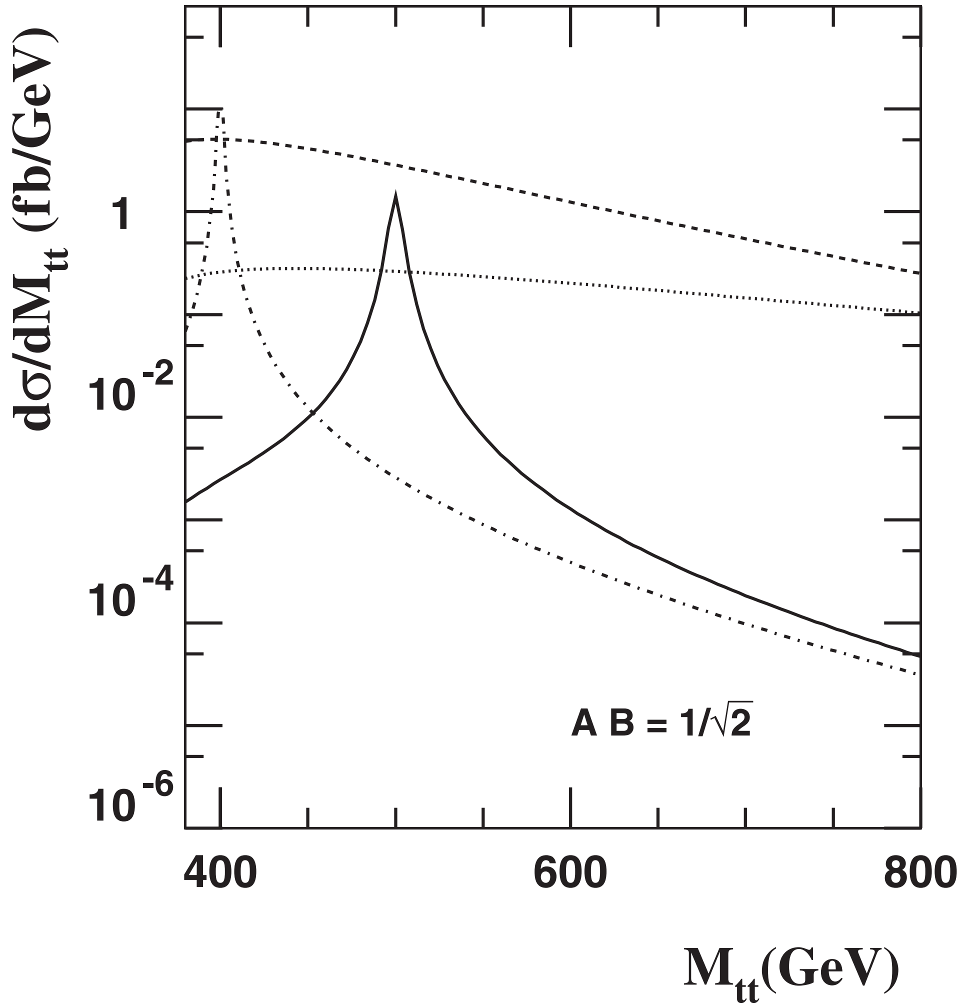

FIG. 5. $t\bar{t}$ production mechanisms at the LHC. The larger cross section indicated by the dashed line corresponds to gluon fusion. The dotted line indicates light $q\bar{q}$ annihilation. We also show the resonant Higgs production for two different values of the Higgs mass.