

Probing CP violation in stop cascade decays at the LHC

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arXiv:1008.2206



Motivation

- supersymmetry can introduce new sources of CP violation
- CP violation is a necessary ingredient for baryogenesis
- new CP phases can be measured in high energy physics experiments
 - ⇒ so far most analyses concentrated on the ILC
see Kittel, arXiv:0904.3241 for a recent review
 - ⇒ challenging at the LHC
Ellis, Moortgat, Moortgat-Pick, Smillie, Tattersall arXiv:0809.1607
Deppisch, Kittel arXiv:0905.3088

We show that in spite of the difficult experimental environment the measurement of CP-odd effects may be possible at the LHC.

Moortgat-Pick, KR, Tattersall arXiv:0908.2631, arXiv:1008.2206

Outline

- 1 Introduction
- 2 CP violation in two-body stop decays
- 3 Observation at the LHC
- 4 Conclusions

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CP phases in the MSSM

- CP phases enter in the gaugino/higgsino mass parameters and trilinear couplings:

$$M_i = |M_i|e^{i\phi_i}, \quad \mu = |\mu|e^{i\phi_\mu}, \quad A_f = |A_f|e^{i\phi_f}$$

- ⇒ strong bounds on ϕ_i and ϕ_μ from EDMs
 - ⇒ large phases possible if accidental cancellations occur
see e.g. Ellis, Lee, Pilaftsis arXiv:0808.1819
 - ⇒ or 1st and 2nd generation of squarks are heavy
 - ⇒ weaker constraints for ϕ_t
- CP phases can be probed by
 - asymmetries in cross sections and decay widths,
 - asymmetries of triple products of momenta and/or spins
 - ⇒ such CP- and T-odd observables provide unambiguous way of detecting CP violation in the model

Triple products

Triple product correlations of momenta are a useful tool for studying **CP violation** effects

- construct an observable:

$$\mathcal{T} = \vec{p}_1 \cdot (\vec{p}_2 \times \vec{p}_3)$$

- it is T-odd and CP-odd if higher order effects and finite widths can be neglected
- originates from Dirac traces in matrix element

$$\text{Tr} [\gamma^\mu \gamma^\nu \gamma^\rho \gamma^\sigma \gamma^5] \longrightarrow i \epsilon_{\mu\nu\rho\sigma} p_a^\mu p_b^\nu p_c^\rho p_d^\sigma$$

- together with **imaginary part of couplings** give rise to CP-odd asymmetries

Example: CP asymmetry in 3-body $\tilde{\chi}_2^0$ decay

- leptonic 3-body decay of neutralino $\tilde{\chi}_2^0$

$$\tilde{q}_L \rightarrow \tilde{\chi}_2^0 + q \rightarrow \tilde{\chi}_1^0 \ell^+ \ell^- + q$$

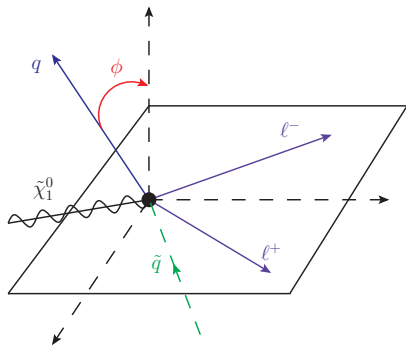
Moortgat-Pick, KR,
Tattersall, Wienemann
arXiv:0908.2631

- triple product of lepton momenta and a quark from \tilde{q}_L decay

$$\mathcal{T}_{q\ell\ell} = \vec{p}_q \cdot (\vec{p}_{\ell^+} \times \vec{p}_{\ell^-})$$

- count the number of events N_+ where \vec{p}_q points above the plane defined by leptons vs. the number of events N_- when it points below
- define the asymmetry as:

$$\mathcal{A}_{CP} = \frac{N_+(\mathcal{T}_{q\ell\ell} > 0) - N_-(\mathcal{T}_{q\ell\ell} < 0)}{N_+(\mathcal{T}_{q\ell\ell} > 0) + N_-(\mathcal{T}_{q\ell\ell} < 0)}$$



Stop sector of the MSSM

- mass matrix for scalar tops gauge eigenstates \tilde{t}_L, \tilde{t}_R

$$\mathcal{M}_{\tilde{t}}^2 = \begin{pmatrix} m_t^2 + m_{LL}^2 & m_t (A_t^* - \mu / \tan \beta) \\ m_t (A_t - \mu^* / \tan \beta) & m_t^2 + m_{RR}^2 \end{pmatrix}$$

with:

$$m_{LL}^2 = \widetilde{M}_Q^2 + m_Z^2 \cos 2\beta \left(\frac{1}{2} - \frac{2}{3} s_W^2 \right)$$

$$m_{RR}^2 = \widetilde{M}_U^2 + \frac{2}{3} m_Z^2 \cos 2\beta s_W^2$$

- diagonalize mass matrix with unitary matrix $U_{\tilde{t}}$

$$U_{\tilde{t}} \mathcal{M}_{\tilde{t}}^2 U_{\tilde{t}}^\dagger = \text{diag}(m_{\tilde{t}_1}^2, m_{\tilde{t}_2}^2)$$

- obtain mass matrix eigenstates \tilde{t}_1 and \tilde{t}_2

$$\begin{pmatrix} \tilde{t}_1 \\ \tilde{t}_2 \end{pmatrix} = U_{\tilde{t}} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix} = \begin{pmatrix} \cos \theta_{\tilde{t}} & \sin \theta_{\tilde{t}} e^{-i\phi_{\tilde{t}}} \\ -\sin \theta_{\tilde{t}} e^{i\phi_{\tilde{t}}} & \cos \theta_{\tilde{t}} \end{pmatrix} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix}$$

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Chosen scenario

- mSUGRA parameters:

$$m_0 = 65 \text{ GeV}, m_{1/2} = 210 \text{ GeV}, A_0 = 0, \tan \beta = 5, \text{sgn } \mu = +$$

- resulting masses in GeV and branching ratios:

$m_{\tilde{\chi}_1^0}$	$m_{\tilde{\chi}_2^0}$	$m_{\tilde{t}_1}$	$m_{\tilde{\ell}_L}$	$m_{\tilde{\ell}_R}$
77.7	142.4	347.7	163.4	110.8

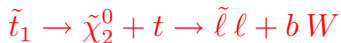
Mode	$\tilde{t}_1 \rightarrow \tilde{\chi}_2^0 t$	$\tilde{t}_1 \rightarrow \tilde{\chi}_1^0 t$	$\tilde{t}_1 \rightarrow \tilde{\chi}_1^+ b$	$\tilde{t}_1 \rightarrow \tilde{\chi}_2^+ b$	$\tilde{\chi}_2^0 \rightarrow \tilde{\ell}_R \ell$	$\tilde{\ell}_R \rightarrow \tilde{\chi}_1^0 \ell$
BR	7.5%	34.5%	50%	8%	23%	100%

- stop production cross section $\sigma(pp \rightarrow \tilde{t}_1 \tilde{t}_1^*) = 3.4 \text{ pb}$
- introduce the complex phase for the stop trilinear coupling

$$A_t = |A_t| e^{i\phi_t} \quad 0 \leq \phi_t < 2\pi$$

CP asymmetry in stop \tilde{t}_1 2-body decay

- stop decay and leptonic 2-body decay of neutralino



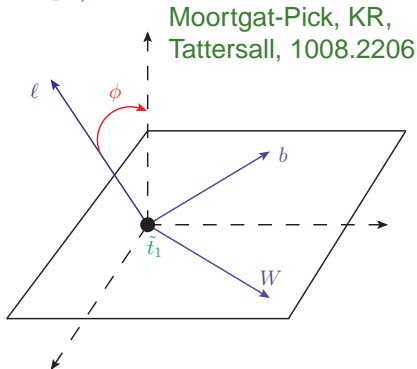
Deppisch, Kittel
0905.3088

- triple product of lepton momentum and top decay products

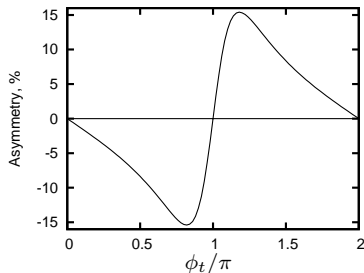
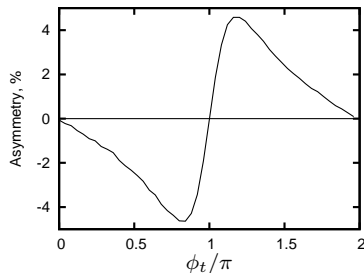
$$\mathcal{T}_{\ell W b} = \vec{p}_\ell \cdot (\vec{p}_W \times \vec{p}_b)$$

- sensitive to the phases of A_t and μ
- asymmetry up to 15% in \tilde{t}_1 rest frame

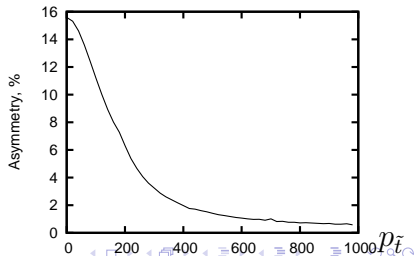
$$A_{CP} = \frac{N(\mathcal{T}_{\ell W b} > 0) - N(\mathcal{T}_{\ell W b} < 0)}{N(\mathcal{T}_{\ell W b} > 0) + N(\mathcal{T}_{\ell W b} < 0)}$$



Dilution due to boosts

 \mathcal{A}_{CP} in \tilde{t}_1 rest frame

 \mathcal{A}_{CP} with PDFs


- asymmetry as a function of the stop momentum in the laboratory frame
- high and undetermined boost decreases the asymmetry



Momentum reconstruction

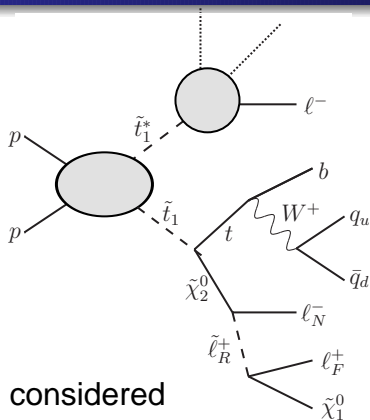
Mass conditions:

$$m_{\tilde{t}_1}^2 = (p_{\tilde{\chi}_2^0} + p_t)^2$$

$$m_{\tilde{\chi}_2^0}^2 = (p_{\tilde{\ell}} + p_{\ell_1})^2$$

$$m_{\tilde{\ell}}^2 = (p_{\tilde{\chi}_1^0} + p_{\ell_2})^2$$

$$m_{\tilde{\chi}_1^0}^2 = p_{\tilde{\chi}_1^0}^2$$



- decay of one stop has to be considered
- 4 unknowns (components of the LSP momentum) vs. 4 equations
- **assuming particle masses are known from other measurements, momenta of intermediate particles can be reconstructed**

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Selection procedure

- final state: $pp \rightarrow \tilde{t}_1 \tilde{t}_1^* \rightarrow \ell^+ \ell^- b \underbrace{j j}_{t}^W + \ell^\pm b + E_{\text{miss}} + \text{jets}$

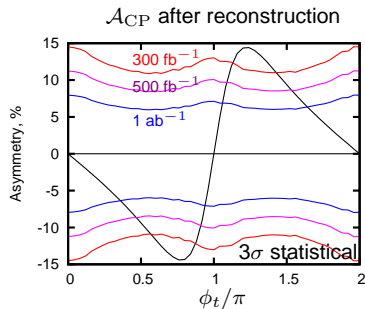
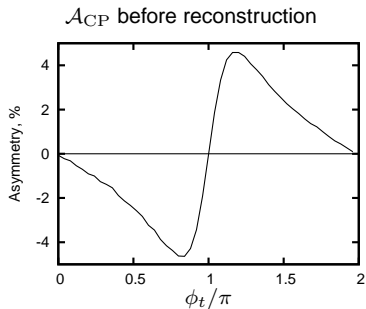
- selection cuts

$$p_T(j) \geq 20 \text{ GeV}, \quad |\eta| \leq 2.5$$

$$p_T(\ell_{e,\mu}) \geq 10 \text{ GeV}, \quad M_{\ell^+\ell^-} \geq 10 \text{ GeV}$$

- lepton isolation
- hadronization, shower & ISR
- require at least 1 b -jet tagged with $\epsilon = 0.6$
- a top candidate with mass $150 < M_{jjb} < 190 \text{ GeV}$ and a W candidate with mass $70 < M_{jj} < 90 \text{ GeV}$
- jet combinatorics, lepton combinatorics, multiple tops and W s

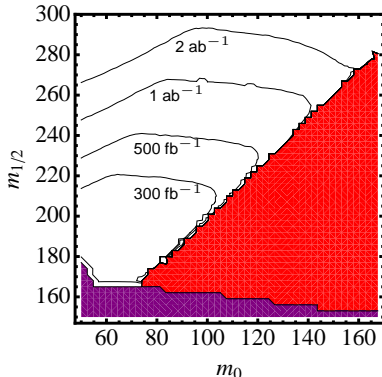
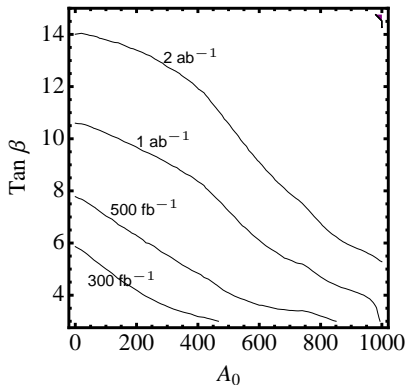
CP-odd asymmetry after reconstruction



- reconstruction enhances the signal by factor ~ 3
- horizontal lines show minimum lumiosity required for 3σ observation

Observation reach – $\tilde{t}_1\tilde{t}_1^*$ production only

Minimum luminosity required for 3σ observation



- SM $t\bar{t}$, $t\bar{t}l^+l^-$ and diboson backgrounds included
- **red**: no two-body decay $\tilde{\chi}_2^0 \rightarrow \tilde{\ell}^\pm \ell^\mp$
- **purple**: LEP excluded

SUSY background

Final state: $\ell^+ \ell^- b j j + \ell^\pm b + E_{\text{miss}} + \text{jets}$

The most significant background are other SUSY channels

- $pp \rightarrow \tilde{g}\tilde{g}/\tilde{g}\tilde{q}$ followed by $\tilde{g} \rightarrow \tilde{b}\bar{b}$ has far higher rate
- **momentum reconstruction significantly reduces background**
- extra cuts needed \Rightarrow SUSY background has higher average p_T and more jet activity

Cuts used:

Number of jets	<	6
p_T (hardest jet)	<	200 GeV
p_T (2nd jet)	<	130 GeV
p_T (3rd jet)	<	80 GeV
p_T (b jets)	<	150 GeV
p_T (leptons)	<	100 GeV

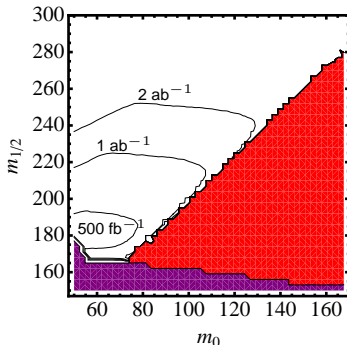
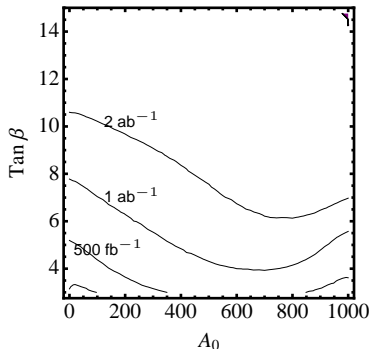
Signal-to-background ratio

	$\tilde{t}_1\tilde{t}_1^*$	SUSY	$\tilde{t}_1\tilde{t}_1^*/\text{SUSY}$
Cross Section [pb]	3.44	80.1	
Events with 500 fb^{-1}	1.7×10^6	4×10^7	
Events with 500 fb^{-1} Initial selection	32389	410735	0.079
Events with 500 fb^{-1} Top Reconstruction	7117	64729	0.11
Events with 500 fb^{-1} Kinematic Reconstruction	1213	3759	0.32
Events with 500 fb^{-1} Extra SUSY cuts	901	967	0.93

⇒ kinematic reconstruction significantly improves S/B ratio

Observation reach with SUSY backgrounds

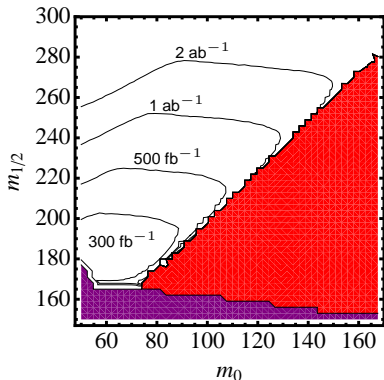
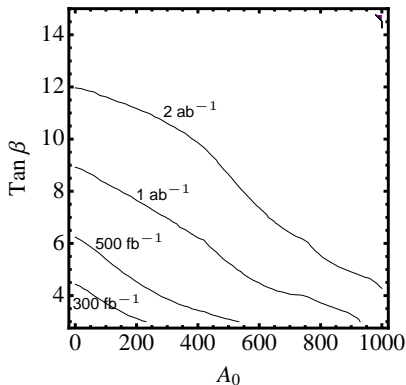
Minimum luminosity required for 3σ observation



- mSUGRA parameter space reach challenging
- scenarios with heavy \tilde{g}/\tilde{q} are more promising
- if SUSY spectra known, background may be estimated and subtracted

Observation reach

Minimum luminosity required for 3σ observation after subtracting SUSY background



- **red:** no two-body decay $\tilde{\chi}_2^0 \rightarrow \tilde{\ell}^\pm \ell^\mp$
- **purple:** LEP excluded

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Conclusions

- stop decays are a promising channel for studying CP violation at the LHC
- suppression of asymmetries by boosts can be overcome by momentum reconstruction
- reconstruction significantly improves sensitivity by enhancing the signal
- momentum reconstruction greatly improves S/B ratio
- information from LHC on CP violation could direct future searches at a linear collider
- Outlook:
 - ⇒ more detailed experimental study is in progress