CP violation in stop cascade decays at the LHC

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arXiv:1008.2206

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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
  $\Rightarrow$ so far most analyses concentrated on the ILC
  see Kittel, arXiv:0904.3241 for a recent review
  $\Rightarrow$ 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

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CP phases in the MSSM

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

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

  $\Rightarrow$ strong bounds on ϕ_i and ϕ_μ from EDMs

  $\Rightarrow$ large phases possible if accidental cancellations occur

  see e.g. Ellis, Lee, Pilaftsis arXiv:0808.1819

  $\Rightarrow$ or 1st and 2nd generation of squarks are heavy

  $\Rightarrow$ 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

  $\Rightarrow$ 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:

$$\mathcal{T} = \overrightarrow{p_1} \cdot (\overrightarrow{p_2} \times \overrightarrow{p_3})$$

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

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

- 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 $\tilde{\chi}_2^0$

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

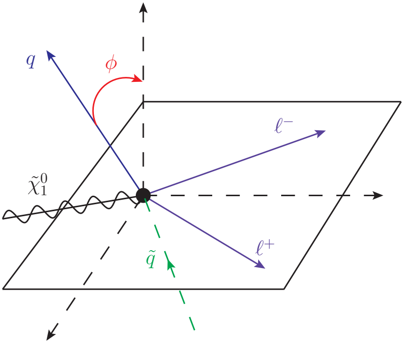
Moortgat-Pick, KR, Tattersall, Wienemann arXive:0908.2631

- 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 $\tilde{t}_L$, $\tilde{t}_R$

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

with:
$$m_{LL}^2 = \widetilde{M}_Q^2 + m_Z^2 \cos 2\beta\,(\tfrac{1}{2} - \tfrac{2}{3} s_W^2)$$
$$m_{RR}^2 = \widetilde{M}_U^2 + \tfrac{2}{3} m_Z^2 \cos 2\beta\, s_W^2$$

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

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

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

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

Outline

Chosen scenario

- mSUGRA parameters:
  $m_0 = 65$ GeV, $m_{1/2} = 210$ GeV, $A_0 = 0$, $\tan\beta = 5$, 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	$\tilde{t}_1 \to \tilde{\chi}_2^0 t$	$\tilde{t}_1 \to \tilde{\chi}_1^0 t$	$\tilde{t}_1 \to \tilde{\chi}_1^+ b$	$\tilde{t}_1 \to \tilde{\chi}_2^+ b$	$\tilde{\chi}_2^0 \to \tilde{\ell}_R \ell$	$\tilde{\ell}_R \to \tilde{\chi}_1^0 \ell$
BR	7.5%	34.5%	50%	8%	23%	100%

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

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

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

- stop decay and leptonic 2-body decay of neutralino

$$\tilde{t}_1 \to \tilde{\chi}_2^0 + t \to \tilde{\ell}\,\ell + b\,W$$

Deppisch, Kittel 0905.3088

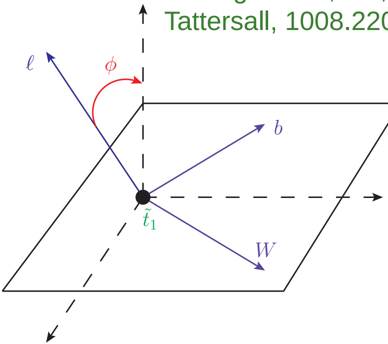
- triple product of lepton momentum and top decay products

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

Moortgat-Pick, KR, Tattersall, 1008.2206

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

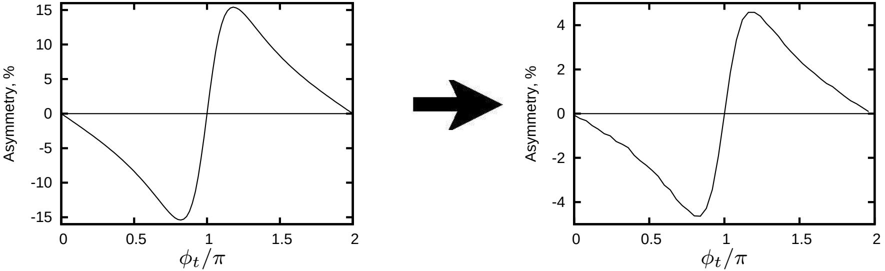
$$\mathcal{A}_{CP} = \frac{N(\mathcal{T}_{\ell W b} > 0) - N(\mathcal{T}_{\ell W b} < 0)}{N(\mathcal{T}_{\ell W b} > 0) + N(\mathcal{T}_{\ell W b} < 0)}$$



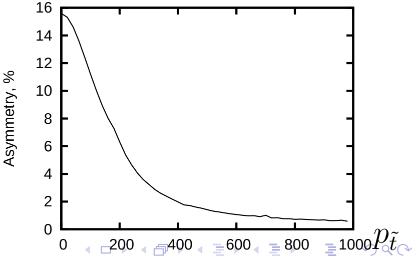
Dilution due to boosts

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

$\mathcal{A}_{\rm CP}$ with PDFs



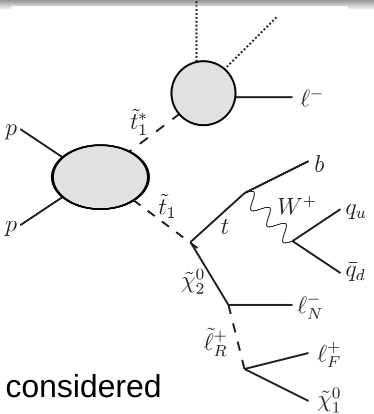
- asymmetry as a function of the stop momentum in the laboratory frame
- high and undetermined boost decreases the asymmetry



Momentum reconstruction

Mass conditions:

$$
\begin{aligned}
m^2_{\tilde{t}_1} &= (p_{\tilde{\chi}^0_2} + p_t)^2 \\
m^2_{\tilde{\chi}^0_2} &= (p_{\tilde{\ell}} + p_{\ell_1})^2 \\
m^2_{\tilde{\ell}} &= (p_{\tilde{\chi}^0_1} + p_{\ell_2})^2 \\
m^2_{\tilde{\chi}^0_1} &= p^2_{\tilde{\chi}^0_1}
\end{aligned}
$$



- 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

Outline

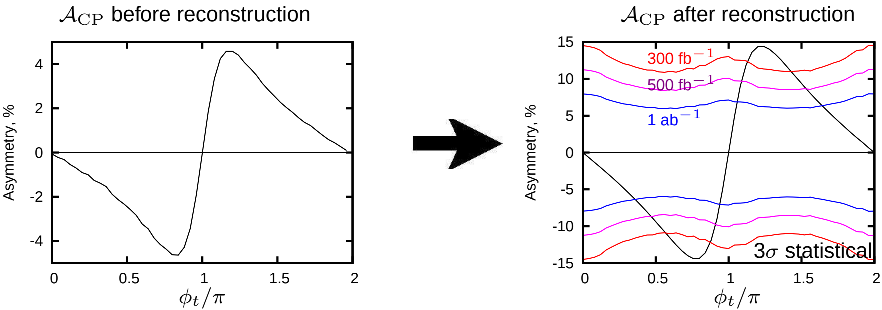
Selection procedure

- final state: $pp \to \tilde{t}_1\, \tilde{t}_1^* \to \ell^+\, \ell^-\, \underbrace{b\, \overbrace{j\, j}^{W}}_{t} + \ell^\pm\, b + E_{\rm miss} + {\rm jets}$
- selection cuts

$$p_T(j) \geq 20\ \mathrm{GeV}\,, \qquad |\eta| \leq 2.5$$
$$p_T(\ell_{e,\mu}) \geq 10\ \mathrm{GeV}\,, \qquad M_{\ell^+\ell^-} \geq 10\ \mathrm{GeV}$$

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

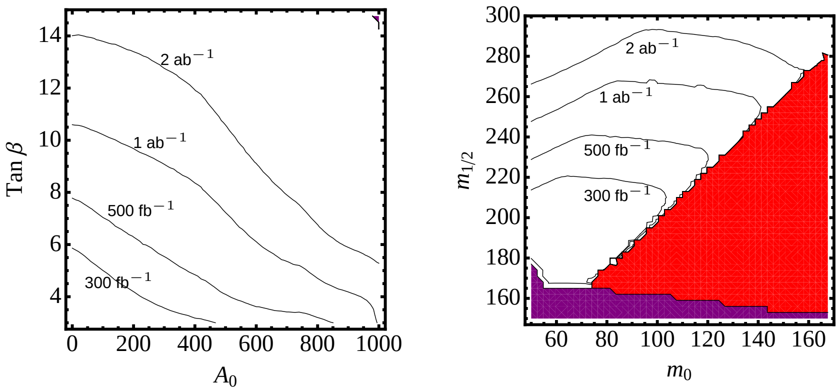
CP-odd asymmetry after reconstruction



- 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 $t\bar{t}$, $t\bar{t}\ell^+\ell^-$ and diboson backgrounds included
- red: no two-body decay $\tilde{\chi}_2^0 \to \tilde{\ell}^\pm\ell^\mp$
- 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

- $pp \to \tilde{g}\tilde{g}/\tilde{g}\tilde{q}$ followed by $\tilde{g} \to \tilde{b}\bar{b}$ 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:

$$\begin{aligned} \text{Number of jets} &< 6 \\ p_T(\text{hardest jet}) &< 200\text{ GeV} \\ p_T(\text{2nd jet}) &< 130\text{ GeV} \\ p_T(\text{3rd jet}) &< 80\text{ GeV} \\ p_T(b\text{ jets}) &< 150\text{ GeV} \\ p_T(\text{leptons}) &< 100\text{ GeV} \end{aligned}$$

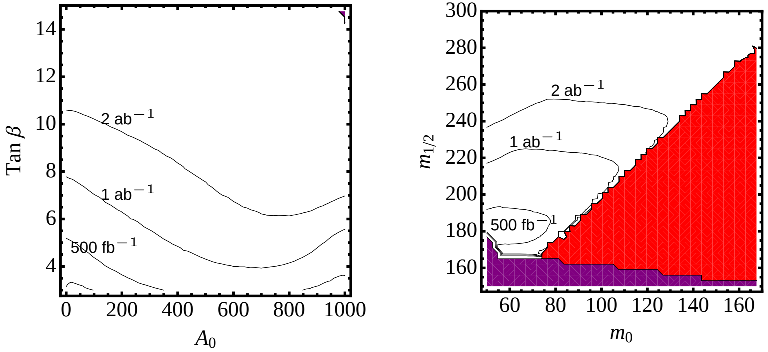
Signal-to-background ratio

	$\tilde{t}_1\tilde{t}_1^*$	SUSY	$\tilde{t}_1\tilde{t}_1^*$/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

$\Rightarrow$ kinematic reconstruction significantly improves S/B ratio

Observation reach with SUSY backgrounds

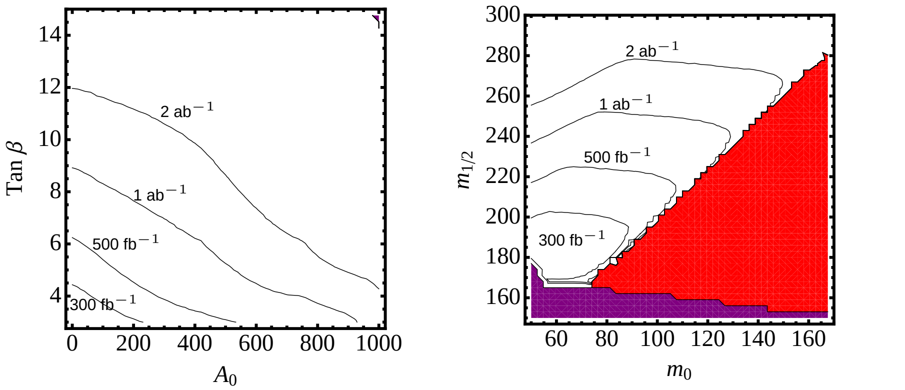
Minimum luminosity required for 3σ observation



- 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 backgorund



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

Outline

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:
  $\Rightarrow$ more detailed experimental study is in progress