CP-violation in SUSY cascades at the LHC

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Introduction

In the Standard Model, the only source of CP violation comes from the complex phase within the CKM matrix.

- The phase of the CKM in the Standard Model contains too little CP violation for Baryogensis.
  (Phys. Rept. 401, 1 (2005): Chung, Everett, Kane, King, Lykken and Wang)
- Consequently, we require new CP violating terms to explain the asymmetry we see in the universe.

MSSM (Minimal Supersymmetric Standard Model) contains several complex parameters that can all contribute.

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Our Project

We explore methods for determining the CP violating effects in the electroweak part of the MSSM at the LHC.

- Most detailed phenomenological analyses have been based on a future LC.
- Precise determination of phases only expected at a LC.
- Crucial for future search strategy to use LHC data to learn as much as possible.
- Choose processes with the most promising discovery potential at LHC (coloured states).

Previous Studies

Production	Decay	Paper
$\tilde{t}\tilde{t}^*$	$\tilde{t} \to \tilde{\chi}_2^0 t, \tilde{\chi}_2^0 \to \tilde{\ell}\ell$	A. Bartl, E. Christova, K. Hohenwarter-Sodek, T. Kernreiter, hep-ph/0409060 F. Deppisch and O. Kittel, 0905.3088
$\tilde{t}\tilde{t}^*$	$\tilde{t} \to \tilde{\chi}_2^0 t, \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell\ell$	P. Langacker, G. Paz, L.-T. Wang, I. Yavin, hep-ph/0702068 J. Ellis, F. Moortgat, G. Moortgat-Pick, J. M. Smillie J. Tattersall, 0905.3088
$\tilde{b}\tilde{b}^*$	$\tilde{b} \to \tilde{\chi}^+ t, \tilde{\chi}^+ \to \tilde{\nu}_\ell \ell$	A. Bartl, E. Christova, K. Hohenwarter-Sodek, T. Kernreiter, hep-ph/0610234 F. Deppisch and O. Kittel, 1003.5186
$\tilde{q}\tilde{g}$	$\tilde{q} \to \tilde{\chi}_2^0 q, \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell\ell$	G. Moortgat-Pick, K. Rolbiecki, J. Tattersall, P. Wienemann, 0908.2631

CP Phase

We consider the MSSM with parameters defined at the weak scale.

- In this framework the gaugino and higgsino mass parameters and the trilinear couplings can have complex phases.

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

- CP-even observables
  - Affect sparticle masses and couplings.
  - Influence cross sections and branching ratios.
- Generate CP odd observables (unique determination of CP phases) that can in principle be large as they are already present at tree level.

CP Constraints

Certain combinations of the CP violating phases are constrained by experimental upper bounds on various EDMs (Electric Dipole Moments).

- ϕ_μ is the most severely constrained.
  - Contributes at the one loop level to EDMs.
- ϕ_{M_1} also contributes at the one loop level to EDMs.
  - Accidental cancellations may allow it to become less constrained.
- The phases of the third-generation trilinear couplings, $\phi_{A_{t,b,\tau}}$ have weaker constraints.
  - Only contribute to EDMs at the two-loop level.

(arXiv:0710.5117, Kraml) ref therein.

Stop Mixing

The Stop mixing matrix is given by:

$$\mathcal{M}_{\tilde{t}} = \begin{pmatrix} M^2_{\tilde{t}_{LL}} & e^{-i\phi_{\tilde{t}}}|M^2_{\tilde{t}_{LR}}| \\ e^{i\phi_{\tilde{t}}}|M^2_{\tilde{t}_{LR}}| & M^2_{\tilde{t}_{RR}} \end{pmatrix},$$

with off diagonal terms:

$$M^2_{\tilde{t}_{RL}} = (M^2_{\tilde{t}_{LR}})^* = m_t(A_t - \mu^* \cot\beta),$$

and phase:

$$\phi_{\tilde{t}} = \arg[A_t - \mu^* \cot\beta].$$

We note that we have $\phi_{\tilde{t}} \approx \phi_{A_t}$ for $|A_t| \gg |\mu| \cot\beta$.

Stop sector of the MSSM

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

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

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

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

- Stop interactions can be parametrised in terms of $\cos\theta_{\tilde{t}}$ and $\phi_{\tilde{t}}$.

Triple Products

Triple Product Correlations of momenta are a useful tool for studying CP-violating effects.

- Construct a T_N-odd observable:

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

- It is CP-odd (by CPT_N) if higher order effects and finite widths can be neglected.
- Originates from Dirac traces in matrix element:

$$\mathrm{tr}(\gamma^\mu \gamma^\nu \gamma^\rho \gamma^\sigma \gamma^5) \longrightarrow i\epsilon_{\mu\nu\rho\sigma} p_a^\mu p_b^\nu p_c^\rho p_d^\sigma.$$

- Together with imaginary part of couplings gives rise to CP-odd asymmetries.
- The covariant product can be expanded in terms of explicit 4-momentum components:

$$E_a \, \overrightarrow{p_b} \cdot (\overrightarrow{p_c} \times \overrightarrow{p_d}) \pm \text{........}$$

Chosen Scenario

- mSUGRA parameters:

Parameter	m_0	$m_{1/2}$	$\tan\beta$	sign(μ)	A_0
Value	65	210	5	+	0

- 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

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

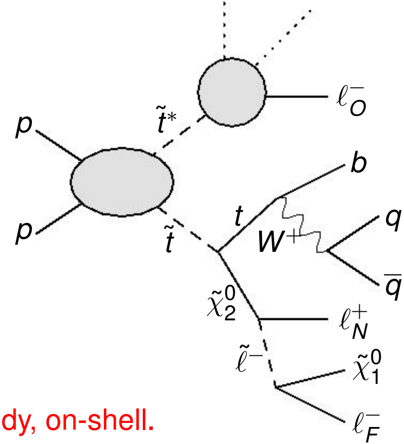
- Stop production cross section $\sigma(pp \to \tilde{t}_1 \tilde{t}_1^*)$ = 3.4pb.
- Introduce the complex phase for the stop trilinear coupling:

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

Process

Process studied:

$$\begin{aligned} p\,p &\Longrightarrow \tilde{t}\,\tilde{t}^*, \\ \tilde{t} &\Longrightarrow t\,\tilde{\chi}_2^0, \\ \tilde{\chi}_2^0 &\Longrightarrow \tilde{\ell}^-\,\ell_N^+, \\ \tilde{\ell}^- &\Longrightarrow \tilde{\chi}_1^0\,\ell_F^-, \end{aligned}$$

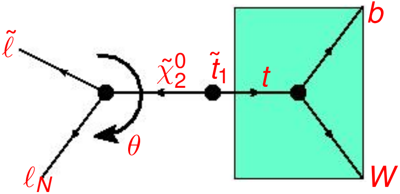


- All SUSY decays are 2-body, on-shell.
- Top required to decay hadronically for reconstruction.
- Opposite $\tilde{t}_1^*$ decay required to have single charged lepton in final state.

Realising CP asymmetry

I choose an example triple product:

$$\mathcal{T}_t = \overrightarrow{p_{\ell_N}} \cdot (\overrightarrow{p_t} \times \overrightarrow{p_b})$$



Two-body decay forces t, b and W to define a plane.

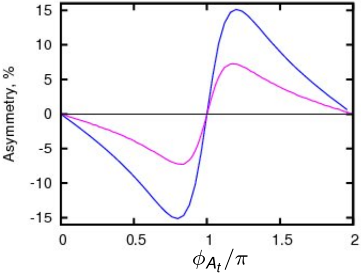
- A non-zero expectation value of $\mathcal{T}$, implies a non-zero average angle between the plane and p_ℓ.
- Define asymmetry parameter:

$$\eta = \frac{N_+ - N_-}{N_+ + N_-} = \frac{N_+ - N_-}{N_{total}}$$

where:

$$N_+ = \int_0^1 \frac{d\Gamma}{dcos\theta} dcos\theta, \qquad N_- = \int_{-1}^0 \frac{d\Gamma}{dcos\theta} dcos\theta,$$

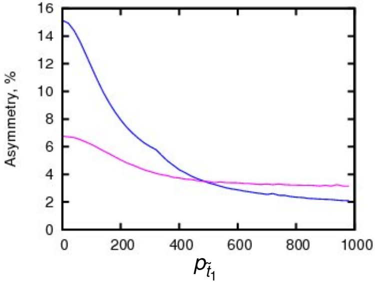
Partonic Level Asymmetry



Blue: $\mathcal{T}_t = \overrightarrow{p_{\ell_N}} \cdot (\overrightarrow{p_t} \times \overrightarrow{p_b})$
Purple: $\mathcal{T}_b = \overrightarrow{p_b} \cdot (\overrightarrow{p_{\ell_N}} \times \overrightarrow{p_{\ell_F}})$

- Asymmetry $\approx 15\%$ maximum at the parton level in the $\tilde{t}_1$ rest frame.
- Maximum asymmetry for triple product $\mathcal{T}_t = \overrightarrow{p_{\ell_N}} \cdot (\overrightarrow{p_t} \times \overrightarrow{p_b})$.
  - $\mathcal{T}_b = \overrightarrow{p_b} \cdot (\overrightarrow{p_{\ell_N}} \times \overrightarrow{p_{\ell_F}})$ not a 'true' triple product.
- T-odd observable.

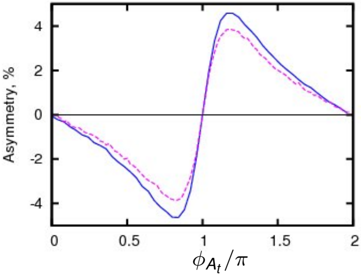
Kinematics of $\tilde{t}_1$



Blue: $\mathcal{T}_t = \overrightarrow{p_{\ell_N}} \cdot (\overrightarrow{p_t} \times \overrightarrow{p_b})$
Purple: $\mathcal{T}_b = \overrightarrow{p_b} \cdot (\overrightarrow{p_{\ell_N}} \times \overrightarrow{p_{\ell_F}})$

- $\tilde{t}_1$ are boosted due to production process and PDFs.
- Asymmetry is maximal in rest frame of decaying particle.
  - $\epsilon_{\mu\nu\rho\sigma} p^{\mu}_{\tilde{t}_1} p^{\nu}_{\ell_N} p^{\rho}_{t} p^{\sigma}_{b} \longrightarrow m_{\tilde{t}_1} \overrightarrow{p_{\ell_N}} \cdot (\overrightarrow{p_t} \times \overrightarrow{p_b})$.
- Dilution of asymmetry due to ℓ_N flipping orientation in comparison to plane defined by *tb*.

Including PDF's and production process



Blue: $\mathcal{T}_t = \overrightarrow{p_{\ell_N}} \cdot (\overrightarrow{p_t} \times \overrightarrow{p_b})$
Purple: $\mathcal{T}_b = \overrightarrow{p_b} \cdot (\overrightarrow{p_{\ell_N}} \times \overrightarrow{p_{\ell_F}})$

- After including production process and folding in PDF's, asymmetry drops to $\approx 4\%$ maximum.
- Far less dilution seen for triple product $\mathcal{T}_b = \overrightarrow{p_b} \cdot (\overrightarrow{p_{\ell_N}} \times \overrightarrow{p_{\ell_F}})$.
- All results generated analytically, cross-checked with Herwig++.

Momentum Reconstruction

Main problem with measuring asymmetries at the LHC is the dilution in the lab frame.

- In the rest frame of the decaying particle the asymmetry is maximal.
- Reconstruct LSP momentum using the set of invariant equations:

$$\begin{aligned}
m^2_{\tilde{\chi}^0_1} &= (P_{\tilde{\chi}^0_1})^2, \\
m^2_{\tilde{\ell}^\pm} &= (P_{\tilde{\chi}^0_1} + P_{\ell^\pm_F})^2, \\
m^2_{\tilde{\chi}^0_2} &= (P_{\tilde{\chi}^0_1} + P_{\ell^\pm_F} + P_{\ell^\mp_N})^2, \\
m^2_{\tilde{t}_1} &= (P_{\tilde{\chi}^0_1} + P_{\ell^\pm_F} + P_{\ell^\mp_N} + P_t)^2.
\end{aligned}$$

- We reconstruct the frame of the decaying particle on an event by event basis and the asymmetry is restored.

(Phys. Rev. D71 (2005) 035008: K. Kawagoe, M. M. Nojiri, and G. Polesello)

Momentum Reconstruction Procedure

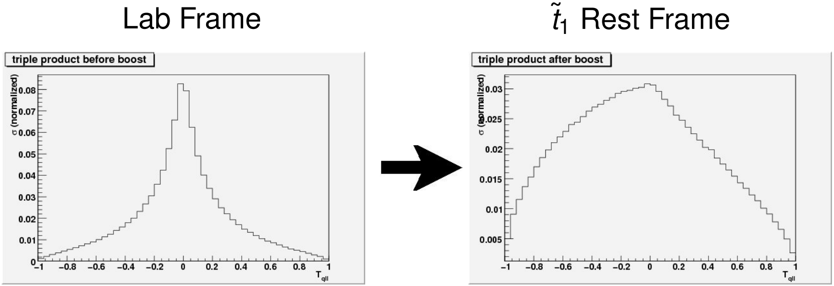
Solution Procedure:

- Assume particle masses are previously measured.
  - Mass errors of up to 20 GeV tested.
- Solve for three linear equations first.
- Then solve final quadratic equation $(P_{\tilde{\chi}_1^0}) \rightarrow$ All events have at least 2 solutions.

Experimental procedure:

- Try to reconstruct event with all combinatorial particle assignments.
- Only use real physical solutions.
- Effective discrimination between near and far leptons.
- Boost to rest frame for all solutions but only select events with the same sign triple product.

Boost Example



- Using events generated by `Herwig++`, improvement in rest frame can clearly be seen.
- Angle between *tb* plane and ℓ_N is enhanced.
  - Asymmetry becomes more resolvable.

Hadronic Level Study

Final state: $pp \to \tilde{t}_1 \tilde{t}_1^* \to \ell^+ \ell^- bjj + \ell^\pm b + E_{miss} + jets$.

We perform the study at the hadronic level using `Rivet`.

- Tri-lepton final state required (1 OSSF).
- At least one b-jet, 60% efficiency.
- At least two additional jets.
- A top candidate with mass $150 < M_{jjb} < 190\mathrm{GeV}$ and a W with mass $70 < M_{jj} < 90\mathrm{GeV}$.
- Anti-$\mathrm{k_t}$ jet algorithm used (R=0.5).
- Selection cuts:

$$\begin{aligned} p_{Tj_i} &> 20\mathrm{GeV}, & p_{T\ell_i} &> 10\mathrm{GeV}, \\ |\eta| &< 2.5, & M_{\ell^+\ell^-} &> 10\mathrm{GeV}. \end{aligned}$$

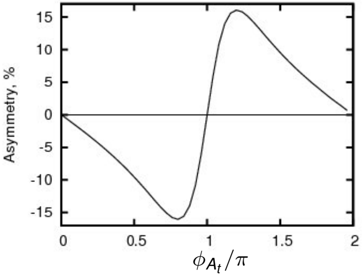
- Lepton jet isolation, Δ R = 0.5.

Standard Model Backgrounds

Following standard model backgrounds included:

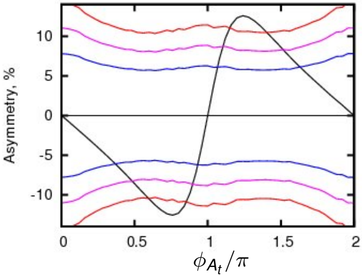
- Generated by `Herwig++`:
  - $t\bar{t}$, Drell-Yan (Z, γ, W), W+jet, Z+jet, WW, WZ, ZZ, $W\gamma$, WZ.
- Generated by `Madgraph`:
  - $t\bar{t}\ell^+\ell^-$,
- Only $t\bar{t}\ell^+\ell^-$ events seen $\lesssim$ 1% of signal.
- No jet mis-tagging included.
- $t\bar{t}$ background could still be an issue $\rightarrow$ Needs full experimental study.

Hadronic Level Asymmetry



- After momentum reconstruction, asymmetry $\approx$ 15% maximum recovered.
- Slight dilution ($\approx$ 1.5%) due to hadronic smearing of rest frame.
- Slight enhancement ($\approx$ 1.5%) due to removal of small triple products.

Luminosity Reach

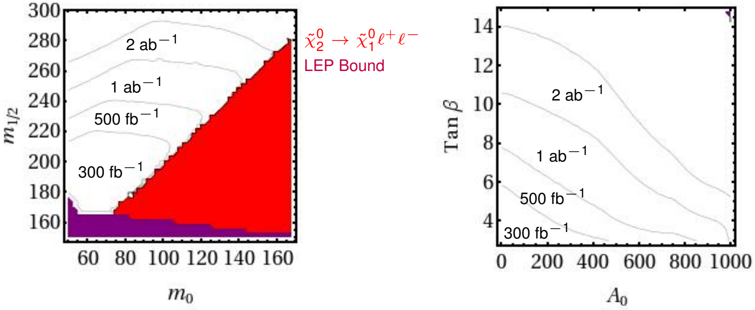


Red: 300fb^{-1}
Purple: 500fb^{-1}
Blue: 1ab^{-1}

3σ statistical

- Expected luminosity reach at the LHC.
- Includes cross sections and branching ratios that both alter with phase ϕ_{A_t}.

Luminosity Reach



- Low mass scenario requires less luminosity since production cross section higher.
- Maximum asymmetry is reduced as A_0 increases ($|A_t|$ is smaller).
- An increase in tanβ reduces $\tilde{\chi}_2^0 \rightarrow \tilde{\ell}\ell$ branching ratio.

SUSY Background

Final state:

- $\ell^+\ell^- bjj + \ell^\pm b + E_{miss} + jets$

Most significant background are other SUSY channels.

- $pp \to \tilde{g}\tilde{g}/\tilde{g}\tilde{q}$ followed by $\tilde{g} \to \tilde{b}_i$ has far higher rate.
- Momentum reconstruction significantly reduces background.
- Extra cuts needed → SUSY background has higher average p_T and more jet activity.

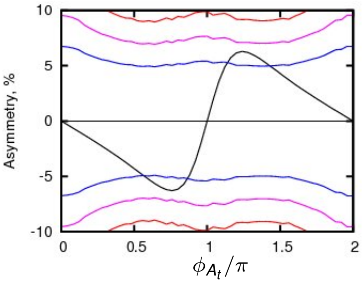
Cuts used:

$$\begin{aligned}
p_T(\text{Hardest Jet}) &< 200\ \text{GeV}, \\
p_T(\text{2nd Jet}) &< 130\ \text{GeV}, \\
p_T(\text{3rd Jet}) &< 80\ \text{GeV (if applicable)}, \\
p_T(\text{Any } b \text{ Jet}) &< 150\ \text{GeV}, \\
p_T(\text{Any Lepton}) &< 100\ \text{GeV}, \\
\text{Number of jets} &< 7.
\end{aligned}$$

SUSY Background

	$\tilde{t}_1 \tilde{t}_1^*$	SUSY	Signal/Background
Cross Section (pb^{-1})	3.44	80.1	
Events with 500 fb^{-1}	1.7×10^6	4×10^7	0.043
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

SUSY Background - Luminosity Reach

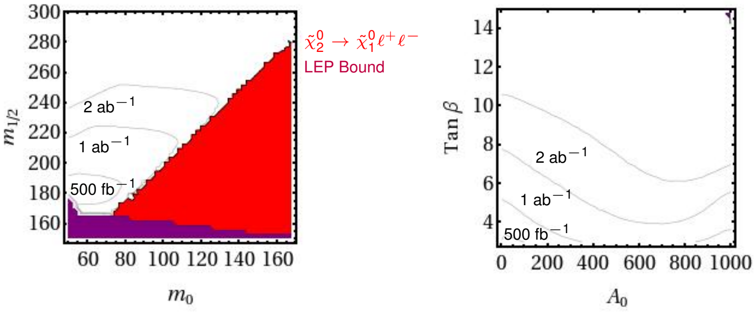


Red: 300fb^{-1}
Purple: 500fb^{-1}
Blue: 1ab^{-1}

3σ statistical

- After reconstruction and cuts, SUSY background $\approx$ signal.
  - Asymmetry halved.
- Significant luminosity required to see asymmetry in this scenario.

SUSY background - Luminosity Reach



- mSUGRA parameter space reach challenging.
- Scenarios with heavy $\tilde{g}/\tilde{q}_{1st,2nd}$ will be better.
- If SUSY spectra known, background may be estimated and subtracted.
  - Asymmetry recovered.
  - Need information on cross sections and branching ratios.

Summary

- New forms of CP violation are required to explain the baryon asymmetry we see in the universe.
- MSSM can contain new phases that lead to CP violation.
- SUSY decays of $\tilde{t}_1$ can produce large CP-odd asymmetries.
- Diluted by PDFs and production process.
- Momentum reconstruction offers a way to observe these at the LHC.
- SUSY background processes causes dilution unless understood.
- Precise determination of the MSSM parameters will require the LC.