# CP violation in the MSSM at the LHC

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# Outline

1. **Introduction**
2. **Main Project**
   - Neutralinos
   - Triple Product Correlations
3. **Results**
   - Results
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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 produces several orders of magnitude too little CP violation for Baryogensis.
- Consequently, we require new CP violating terms to explain the asymmetry we see in the universe.

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

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## My Project

The goal of my project is to determine if CP-violating effects in the electroweak part of the MSSM can be observed at the LHC.

- Most detailed phenomenological analysis has been based on the ILC .
- Choose process that has the most promising possibility for CP discovery at LHC.

Process studied:

$$g\,g \Longrightarrow \tilde{t}\,\bar{\tilde{t}} \Longrightarrow t\,\tilde{\chi}_2^0 \Longrightarrow \tilde{\chi}_1^0\,l^+\,l^- \tag{1}$$

For this channel to work we assumed that:

$$M_{\tilde{\chi}_2^0} < M_{\tilde{e}_{L,R}}, \quad M_{\tilde{\chi}_2^0} - M_{\tilde{\chi}_1^0} < M_Z \tag{2}$$

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Process studied:

$$g\, g \Longrightarrow \tilde{t}\, \bar{\tilde{t}} \Longrightarrow t\, \tilde{\chi}^0_2 \Longrightarrow \tilde{\chi}^0_1\, l^+\, l^- \tag{1}$$

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## CP Phase

I 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.

$$M_i = |M_i|e^{i\phi_i}, \qquad \mu = |\mu|e^{i\phi_\mu}, \qquad A_f = |A_f|e^{i\phi_f} \tag{3}$$

- For the neutralino sector though only the phase of $M_1$ and $\mu$ are important (the phase of $M_2$ can always be rotated away).
- Physical phases $\phi_i$ and $\phi_\mu$ imply CP odd observables (unique determination of CP Phases) that can in principle be large as they are already present at tree level.

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# Neutralinos

The supersymmetric partners of the $\gamma$, $Z$, $H_1^0$, $H_2^0$ mix to produce mass eigenstates called neutralinos.

- In general, both weak and mass eigenstates are Majorana fermions.
- Majorana fermions mean the particle and antiparticle are identical.
- The neutralino mass eigenstates are found by diagonalising the 4X4 neutralino mass matrix.

# Mass matrix

We choose the bino-wino-Higgsino basis (Les Houches):

$$\psi_j^0 = (-i\lambda^1, -i\lambda^3, \psi_{H_1}^0, \psi_{H_2}^0) \tag{4}$$

The mass terms of the neutralino system can then be written as:

$$\mathcal{L}_m = -\frac{1}{2}(\psi^0)^T \mathcal{M}_N \psi^0 + h.c \tag{5}$$

with

$$\mathcal{M}_N = \begin{pmatrix} M_1 & 0 & -m_Z s_W c_\beta & m_Z s_W s_\beta \\ 0 & M_2 & m_Z c_W c_\beta & -m_Z c_W s_\beta \\ -m_Z s_W s_\beta & m_Z c_W c_\beta & 0 & -\mu \\ m_Z s_W s_\beta & -m_Z c_W s_\beta & -\mu & 0 \end{pmatrix} \tag{6}$$

## Diagonalisation

The matrix is diagonalised by a unitary mixing matrix $N$:

$$N^*\mathcal{M}_N N^\dagger = \mathrm{diag}(m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_3^0}, m_{\tilde{\chi}_4^0}) \tag{7}$$

where $m_{\tilde{\chi}_i^0}, i = 1, .., 4$ are the (non-negative) masses of the physical neutralino states.
The lightest neutralino is then decomposed as:

$$\tilde{\chi}_1^0 = N_{11}\tilde{B} + N_{12}\tilde{W} + N_{13}\tilde{H}_1 + N_{14}\tilde{H}_2 \tag{8}$$

with the bino ($f_B$), wino ($f_W$) and Higgsino ($f_H$) fractions defined as:

$$f_B = |N_{11}|^2, \quad f_W = |N_{12}|^2, \quad f_{H_1} = |N_{13}|^2, \quad f_{H_2} = |N_{14}|^2 \tag{9}$$

The LSP will hence be mostly bino, wino or Higgsino according to the smallest mass parameter, $M_1$, $M_2$ or $\mu$.

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## Time reversal

Useful tool for studying CP odd observables are Triple Product Correlations.

- Construct two observables:

$$\mathcal{T}_a = \overrightarrow{p_1}^c \cdot (\overrightarrow{p_2} \times \overrightarrow{p_3}) \tag{10}$$

$$\mathcal{T}_b = \overrightarrow{p_1} \cdot (\overrightarrow{p_2}^c \times \overrightarrow{p_3}^c) \tag{11}$$

- Naive time reversal operation, T, reverses 3-momenta $\overrightarrow{p_i} \rightarrow -\overrightarrow{p_i}$ and polarisations.
- Note that under, T:

$$\mathcal{T}_a \xleftrightarrow{T} -\mathcal{T}_b \tag{12}$$

# CP violation

If we cannot distinguish the two reactions but we know that they occur with an equal probability, T invariance requires we see no correlation of the form:

$$\mathcal{T} = \overrightarrow{p_1} \cdot (\overrightarrow{p_2} \times \overrightarrow{p_3}) \tag{13}$$

- Asymmetry will vanish under T conservation.
- Assuming CPT holds (if final-state interactions and finite-width effects are unimportant), T violation is equivalent to CP violation.
- Triple product correlations as a CP indicator are a tree level effect.
  - Observables are not suppressed by loops as is the case with B-physics.

## CP odd observables

Require at least a three body decay mediated by a particle that is not a scalar (allow spin correlations).

- Correlations cannot occur from decays solely of a neutralino.
- Triple products originate from the covariant products:

$$i\epsilon_{\mu\nu\rho\sigma}p_0^\mu p_1^\nu p_2^\rho p_3^\sigma \tag{14}$$

- This comes from:

$$\mathrm{tr}(\gamma^\mu\gamma^\nu\gamma^\rho\gamma^\sigma\gamma^5) \tag{15}$$

## Realising CP asymmetry

In our process choose triple product from decay chain:

$$\mathcal{T} = \overrightarrow{p_t} \cdot (\overrightarrow{p_{l^+}} \times \overrightarrow{p_{l^-}}) \tag{16}$$

- Momentum conservation forces $l^+$, $l^-$ and $\chi_0^0$ to define a plane.
- A non-zero expectation value of $\mathcal{T}$, implies a non-zero average angle between the plane and the z-axis ($p_t$).
- Define asymmetry parameter:

$$\eta = \frac{N_+ - N_-}{N_+ + N_-} = \frac{N_+ - N_-}{N_{total}} \tag{17}$$

where:

$$N_+ = \int_0^1 \frac{d\Gamma}{d\cos\theta} d\cos\theta, \qquad N_- = \int_{-1}^0 \frac{d\Gamma}{d\cos\theta} d\cos\theta, \tag{18}$$

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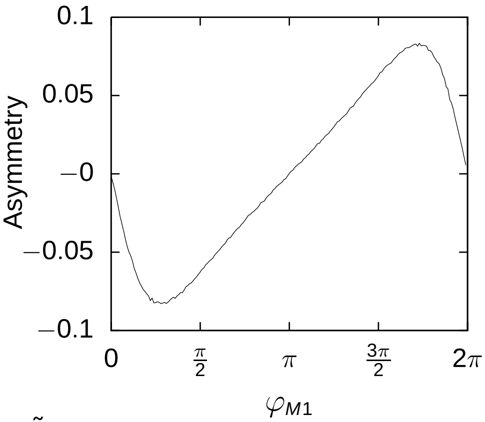
# Example Scenario

| | |
|---|---|
| $M_1$ | 109 |
| $M_2$ | 240 |
| $\mu$ | 220 |
| $\tan\beta$ | 10 |
| $A_t$ | -610 |
| $M_{\tilde{Q}}$ | 511 |
| $M_{\tilde{U}}$ | 460 |
| $M_{\tilde{L}}$ | 298 |
| $M_{\tilde{E}}$ | 224 |



$\tilde{t} = 391, \quad \tilde{\chi}_2^0 = 177, \quad \tilde{\chi}_1^0 = 101, \quad \tilde{e}_L = 301, \quad \tilde{e}_R = 228$

- Large asymmetries possible due to complex interplay between couplings.

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# Summary

- New forms of CP violation are required to explain asymmetry we see in the universe.
- MSSM can contain new phases that lead to CP violation.
- These phases can produce large asymmetries at the LHC.

- Further Work
    - Include top spin correlations.
    - Find number of reconstructed events required to perform measurement.
    - Implement in Monte-Carlo to further explore viability.