CP violation in the MSSM at the LHC

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IOP HEP Conference 2008

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Outline

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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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 μ are important (the phase of M_2 can always be rotated away).
- Physical phases ϕ_i and ϕ_μ imply CP odd observables (unique determination of CP Phases) that can in principle be large as they are already present at tree level.

Outline

Neutralinos

The supersymmetric partners of the γ, 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:

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

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

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

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 μ.

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2. **Main Project**
    - Neutralinos
    - Triple Product Correlations
3. Results
    - Results
    - Summary

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 χ_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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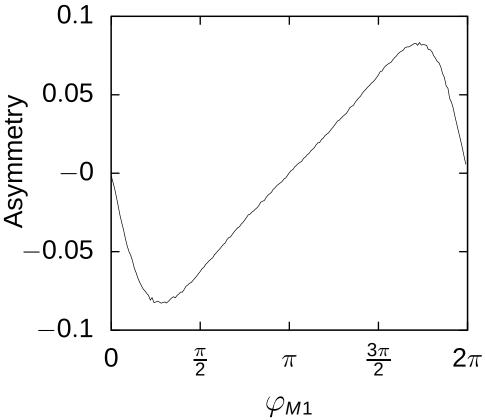
Example Scenario

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



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

- 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.