CP violation in the MSSM at the LHC

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(arXiv:0809.1607)

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Outline

1. **Introduction**
   - CP Violation
   - SUSY Particles
   - Triple Product Correlations
2. **Stop Production**
   - Parton Level
   - Including PDFs
3. **Squark-Gluino Production**
   - Process
   - Results
   - Momentum Reconstruction
4. **Summary**

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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 Model) can contain several complex parameters that can all contribute.

Introduction

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Our Project

We explore methods of determining if CP violating effects in the electroweak part of the MSSM can be observed at the LHC.

- Most detailed phenomenological analyses has 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).
- Previously studies by Bartl et al, did not include production process and by Langacker et al, only estimated effect of PDFs.
  (Phys.Rev.D70:095007,2004: Bartl, Christova, Hohenwarter-Sodek, Kernreiter)
  (JHEP 0707:055,2007: Langacker, Paz, Wang, Yavin)

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.

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

- For the neutralino sector only the phase of M_1 and μ are important (the phase of M_2 can always be rotated away).
- Physical phases ϕ_i, ϕ_μ and ϕ_f generate CP odd observables (unique determination of CP phases) that can in principle be large as they are already present at tree level.

Neutralinos

The supersymmetric partners of the B, $W^{\pm}$, H_1^0, H_2^0 mix to produce mass eigenstates called neutralinos.

Mixing matrix:

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

$M_1 = U(1)$ Gaugino Mass Parameter

$M_2 = SU(2)$ Gaugino Mass Parameter

Diagonalisation

The matrix is diagonalised by a unitary mixing matrix N:

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

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:

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

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

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

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

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 $|A_t| \gg |\mu| \cot\beta$.

Time reversal

Triple Product Correlations are a useful tool for studying CP odd observables.

- Construct an observable:

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

- Naïve time reversal operation, T_N, reverses 3-momenta $\vec{p_i} \to -\vec{p_i}$ and polarisations.
- Assuming CPT_N holds (final-state interactions and finite-width effects are negligible), T_N violation is equivalent to CP violation.
- Asymmetry will vanish under CP conservation.
- 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).

- Observable correlations cannot occur solely from decays of a neutralino.
- Triple products originate from the Dirac Trace that produces the covariant product:

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

- The covariant product can be expanded in terms of explicit 4-momentum components:

$$E_a \overrightarrow{p_b} \cdot (\overrightarrow{p_c} \times \overrightarrow{p_d}) + ...$$

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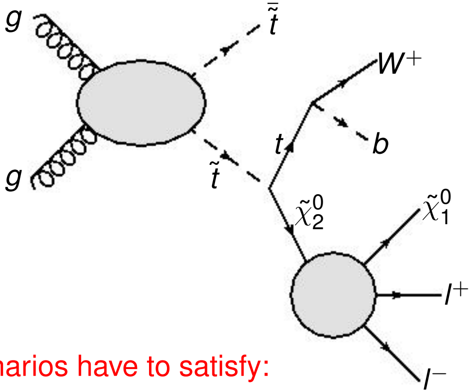
Process

Process studied:

$$\begin{aligned} g\,g &\Longrightarrow \tilde{t}\,\bar{\tilde{t}}, \\ \tilde{t} &\Longrightarrow t\,\tilde{\chi}_2^0, \\ \tilde{\chi}_2^0 &\Longrightarrow \tilde{\chi}_1^0\,l^+\,l^-. \end{aligned}$$



For this channel to work all scenarios have to satisfy:

$$M_{\tilde{\chi}_2^0} < M_{\tilde{e}_{L,R}}, \qquad M_{\tilde{\chi}_2^0} - M_{\tilde{\chi}_1^0} < M_Z.$$

Realising CP asymmetry

Process allows three different triple products to be studied:

$$\mathcal{T}_t = \vec{p}_t \cdot (\vec{p}_{\ell+} \times \vec{p}_{\ell-}) \,, \quad \mathcal{T}_b = \vec{p}_b \cdot (\vec{p}_{\ell+} \times \vec{p}_{\ell-}) \,, \quad \mathcal{T}_{tb} = \vec{p}_t \cdot (\vec{p}_b \times \vec{p}_{\ell\pm}).$$

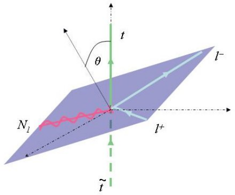
- $\mathcal{T}_t$ only sensitive to phase, ϕ_{M_1}.
- $\mathcal{T}_b$ and $\mathcal{T}_{tb}$ sensitive to both ϕ_{M_1} and ϕ_{A_t}.
- Charge identification is required as CP conjugate process has an asymmetry of the opposite sign.
  - For $\mathcal{T}_t$ and $\mathcal{T}_{tb}$ we require opposite decay chain i.d ($\tilde{t} \to \tilde{\chi}^+ b$ dominant).
  - For $\mathcal{T}_b$, leptonic decay of W is an alternative.

(arXiv:0809.1607, J. Ellis et al)

Realising CP asymmetry

I choose an example triple product:

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



Momentum conservation forces l^+, l^- and $\tilde{\chi}_1^0$ to define a plane in the rest frame of $\tilde{\chi}_2^0$.

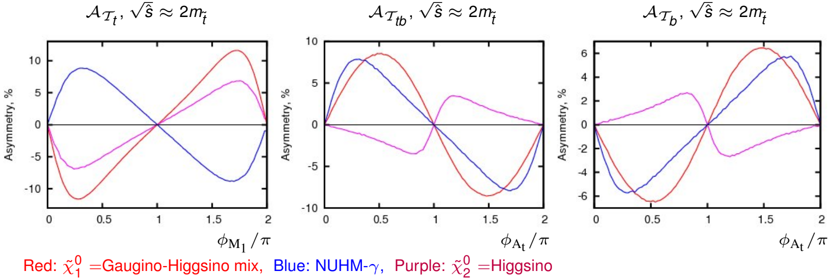
- A non-zero expectation value of $\mathcal{T}$, implies a non-zero average angle between the plane and the z-axis (p_t).
- Define asymmetry parameter:

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

where:

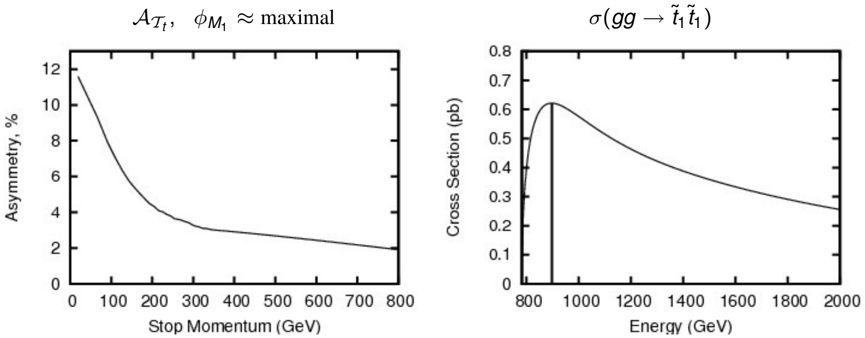
$$N_+ = \int_0^1 \frac{d\Gamma}{d\cos\theta} d\cos\theta, \qquad N_- = \int_{-1}^0 \frac{d\Gamma}{d\cos\theta} d\cos\theta,$$

Parton Level Asymmetry



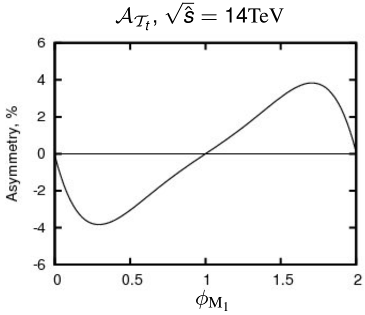
- All asymmetries in %.
- Asymmetries at the parton level can be as large as 10%.
- Various scenarios with three body decay of $\tilde{\chi}_2^0$ show similar results.
- CP odd observable

Kinematics of $\tilde{t}_1$



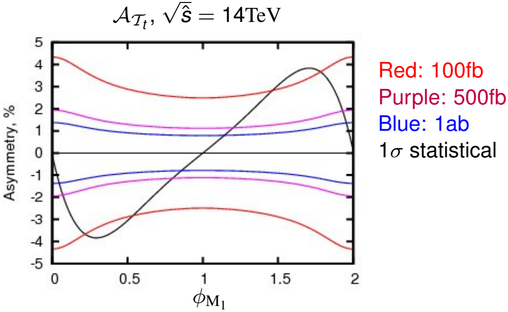
- $\tilde{t}_1$ are boosted due to production process and PDFs.
- Asymmetry is maximal in rest frame of decaying particle.
- Dilution of asymmetry due to t flipping orientation in comparison to plane defined by $l^+ l^-$.

Hadronic Level Asymmetry



- After including production process and folding in PDF's, asymmetry drops to $\approx 4\%$ maximum.
- Similar for each triple product.
- All results generated analytically, cross-checked with Herwig++.

Hadronic Level Asymmetry



- Cross section of production $\approx$ 1.5pb (Analytical, Herwig++, Madgraph).
- $BR(\tilde{t}_1 \rightarrow \tilde{\chi}^0_2 t) \approx 10\%$, $BR(\tilde{\chi}^0_2 \rightarrow \tilde{\chi}^0_1 \ell^+ \ell^-) \approx 4\%$.
- If cuts, detector effects.... etc are included, discovery potential looks very difficult even if large phases are present.

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Process

Process studied:

$$\begin{aligned} q\,g &\Longrightarrow \tilde{q}_L\,\tilde{g}, \\ \tilde{q}_L &\Longrightarrow \tilde{\chi}_2^0\,q, \\ \tilde{\chi}_2^0 &\Longrightarrow \tilde{\chi}_1^0\,l^+\,l^-. \end{aligned}$$

- Process takes advantage of the dominant SUSY production channel at the LHC.
- Again the scenario has to satisfy:

$$M_{\tilde{\chi}_2^0} < M_{\tilde{e}_{L,R}}, \qquad M_{\tilde{\chi}_2^0} - M_{\tilde{\chi}_1^0} < M_Z.$$

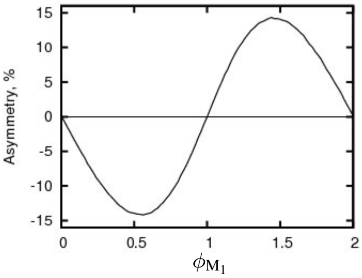
- As $\tilde{q}$ decays directly into a quark jet only one triple product can be reconstructed (sensitive to ϕ_{M_1}):

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

- Charge identification not required as $\tilde{q}$ dominates over $\overline{\tilde{q}}$.

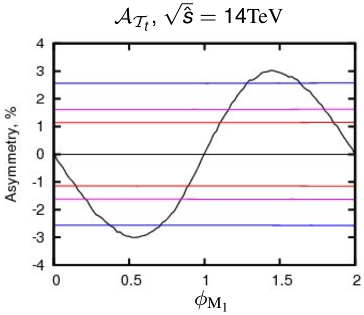
Partonic Level Asymmetry

$\mathcal{A}_{\mathcal{T}_t}, \sqrt{\hat{s}} \approx 2m_{\tilde{t}}$



- Asymmetry can be as large as 15%.
- mSugra scenario chosen with favourable features.
  - Large branching ratios for our decay chain.
  - Coupling character of $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$ here produce large asymmetry.

Hadronic Level Asymmetry



Red: 100fb
Purple: 50fb
Blue: 20fb
3σ statistical

- Dilution again seen in the asymmetry observable.
- Increased production cross section and branching ratios.
  - Significantly reduce the luminosity required.
- Cross section of production $\approx$ 17pb.
- $BR(\tilde{q}_L \to \tilde{\chi}_2^0 q) \approx 30\%$, $BR(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell^+ \ell^-) \approx 10\%$
- Hints could be seen at the LHC.

Momentum Reconstruction (work in progress)

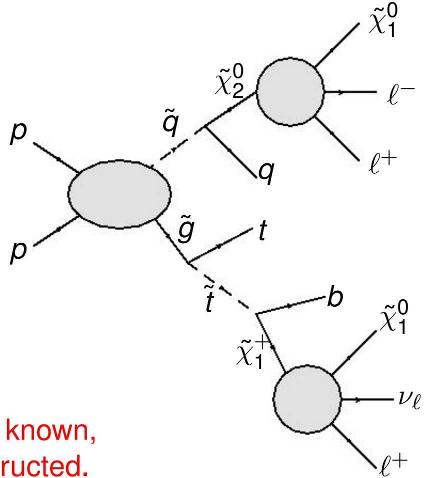
- Main problem with measuring asymmetries at the LHC is the dilution due to boosted frames.
- We reconstruct the frame of the decaying particle and the full asymmetry is restored.
- Reconstruct LSP momentum using the set of invariant equations.
- Also investigate the effect of boosting into the frames of the visible decay products.

(hep-ph/0312317: Nojiri, Polesello and Tovey)

Process

Mass conditions:

$$
\begin{aligned}
m_{\tilde{q}} &= (P_{\tilde{\chi}_2^0} + P_q)^2, \\
m_{\tilde{\chi}_2^0} &= (P_{\tilde{\chi}_1^0} + P_{\ell^+} + P_{\ell^-})^2, \\
m_{\tilde{g}} &= (P_{\tilde{t}} + P_t)^2, \\
m_{\tilde{t}} &= (P_{\tilde{\chi}_1^+} + P_b)^2, \\
\overrightarrow{p}^T_{miss} &= \overrightarrow{p}^T_{\tilde{\chi}^0_{1A}} + \overrightarrow{p}^T_{\tilde{\chi}^0_{1B}} + \overrightarrow{p}^T_{\nu_\ell}.
\end{aligned}
$$



- Assuming particle masses are known, momenta of $\tilde{\chi}_0^1$ can be reconstructed.
- By boosting into rest frame of decaying $\tilde{q}$, parton level asymmetry is recovered.

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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.
- Initial study of $\tilde{t}$ production was unpromising for LHC.
- New study using $\tilde{q}\tilde{g}$ much more hopeful.
- Data from ILC will be crucial to constrain parameter space of MSSM.
- Using momentum reconstruction further improves the situation.

Extra Slides

Extra slides on CP constraints and other possible MSSM CP observables

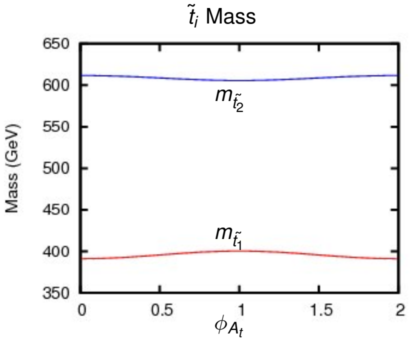
CP Constraints

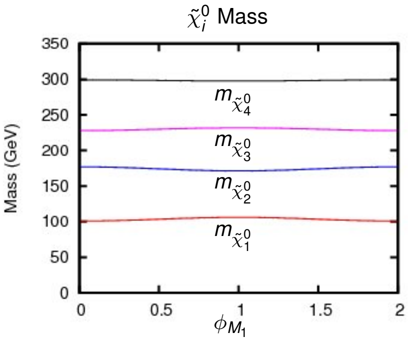
Certain combinations of the CP violating phases are constrained by experimental upper bounds on various EDMs (Electric Dipole Moments).

- Ignoring possible cancellations ϕ_μ is the most severely constrained.
  - Contributes at the one loop level to EDMs.
  - We set to zero in our analysis.
- 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.

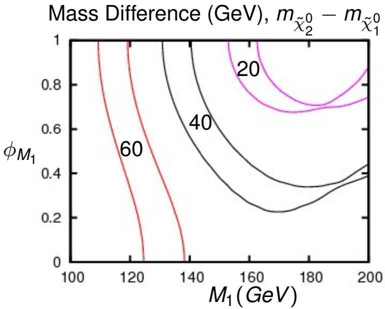
Variation of Mass with CP Phase





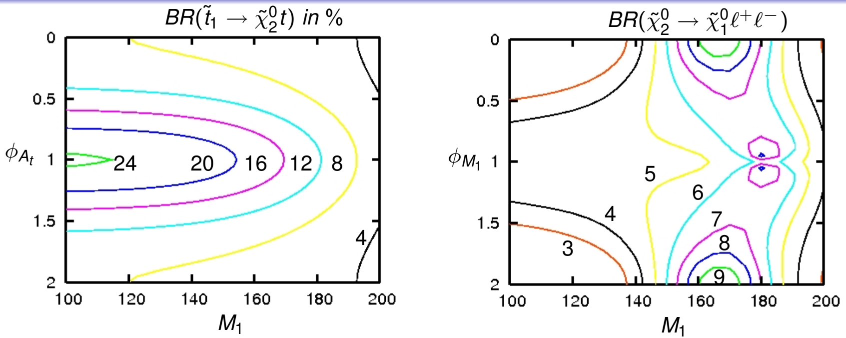
- Masses of both $\tilde{t}$ and $\tilde{\chi}_i^0$ vary with phase.
- CP even quantity.
- An absolute mass measurement at the LHC will not be accurate enough to constrain the phase.

Mass Difference



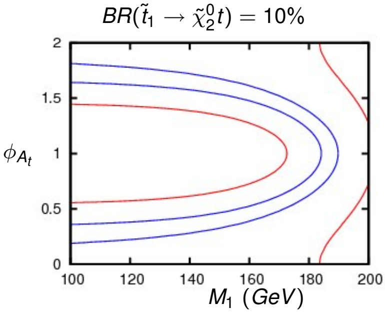
- Assumed a 1% experimental error.
- Assumed a 5% error in determination of M_2.
- A measurement of the mass difference $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$ looks potentially more promising if the mass difference happens to be small (<40 GeV).

Branching Ratios



- Both $BR(\tilde{t}_1 \to \tilde{\chi}^0_2 t)$ and $BR(\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 \ell^+ \ell^-)$ vary with phase.
- Both couplings and phase space factors are responsible for behaviour.
- CP even quantity.
- Highly scenario dependent.

Measurement of Branching Ratios



Red: 50% Accuracy

Blue: 10% Accuracy

- Parameter space allowed when the experimental accuracy of the branching ratio measurement is 50%, Δ_1 (LHC) or 10%, Δ_2 (LC).
- Analysis assumes all other scenario parameters are known
- Measurement only looks likely with a future Linear Collider.