# CP violation in the MSSM at the LHC

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Soon to be published:
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## Outline

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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) can contain several complex parameters that can all contribute.

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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).

# 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 $\mu$ are important (the phase of $M_2$ can always be rotated away).
- Physical phases $\phi_i$, $\phi_\mu$ and $\phi_f$ 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).

- Ignoring possible cancellations $\phi_\mu$ is the most severely constrained.
  - Contributes at the one loop level to EDMs.
  - We set to zero in our analysis.
- $\phi_{M_1}$ 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.

# 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 $N$:

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

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:

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

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 $\mu$.

# 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 $\vec{p_i} \rightarrow -\vec{p_i}$ 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:

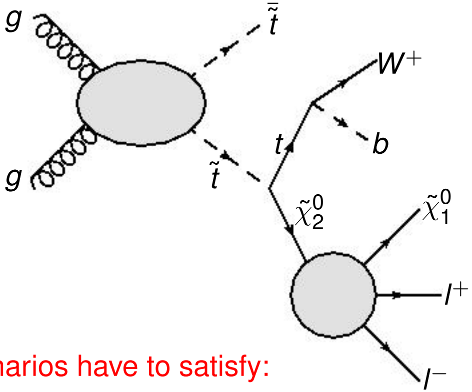
$$E_a\,\overrightarrow{p_b}\cdot(\overrightarrow{p_c}\times\overrightarrow{p_d}) + \ldots\ldots..$$

## Outline

# 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:

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

# Realising CP asymmetry

Process allows three different triple products to be studied:

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

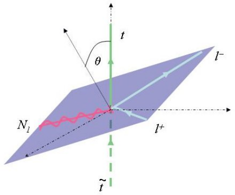
- $\mathcal{T}_t$ only sensitive to phase, $\phi_{M_1}$.
- $\mathcal{T}_b$ and $\mathcal{T}_{tb}$ sensitive to both $\phi_{M_1}$ and $\phi_{A_t}$.
- Charge identification is required as CP conjugate process has an asymmetry of the opposite sign.
  - For $\mathcal{T}_t$ and $\mathcal{T}_{tb}$ we require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

(Eur.Phys.J.C60:633-651,2009, J. Ellis, F. Moortgat, G. Moortgat-Pick, J.M. Smillie, J. Tattersall)

## 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 $\tilde{\chi}_2^0$.

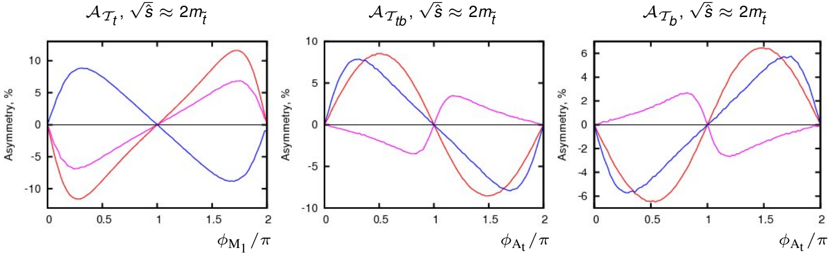
- A non-zero expectation value of $\mathcal{T}$, implies a non-zero average angle between the plane and the z-axis ($p_t$).
- Define asymmetry parameter:

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

where:

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

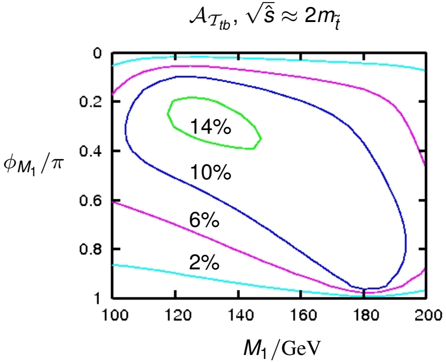
# Parton Level Asymmetry




Red: $\tilde{\chi}_1^0$ =Gaugino-Higgsino mix, Blue: NUHM-$\gamma$, Purple: $\tilde{\chi}_2^0$ =Higgsino

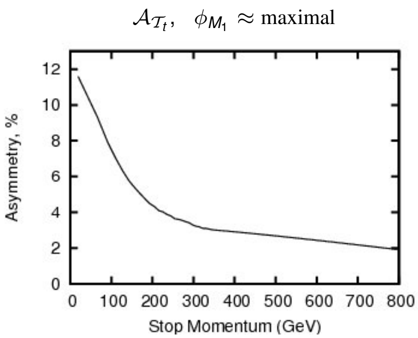
- All asymmetries in %.
- Asymmetries at the parton level can be as large as 10%.
- Various scenarios with three body decay of $\tilde{\chi}_2^0$ show similar results.
- CP odd observable

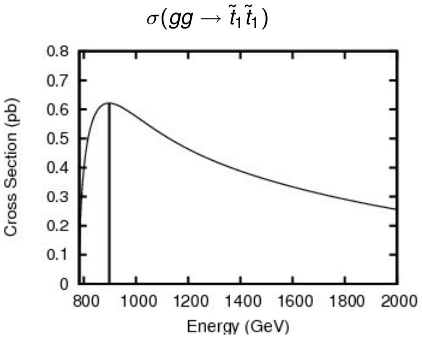
# Parton Level Asymmetry




- As an example we vary $M_1$ between over the range allowed by our mass constraints.
- Similar values for asymmetry found over whole range.
- Common trilinear couplings can also be varied and asymmetries are again found to be similar.

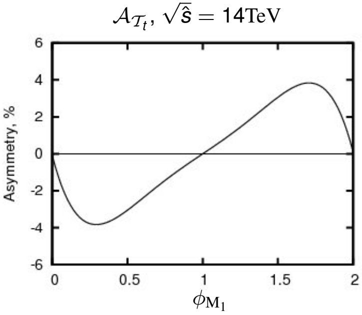
# Kinematics of $\tilde{t}_1$



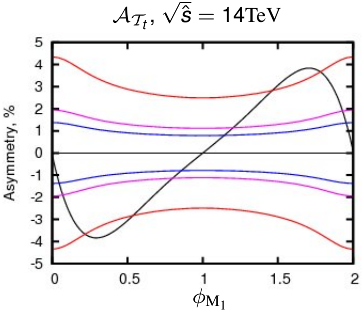

- $\tilde{t}_1$ are boosted due to production process and PDFs.
- Asymmetry is maximal in rest frame of decaying particle.
- Dilution of asymmetry due to $t$ flipping orientation in comparison to plane defined by $l^+ l^-$.

# 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




Red: 100fb$^{-1}$
Purple: 500fb$^{-1}$
Blue: 1ab$^{-1}$
1$\sigma$ statistical

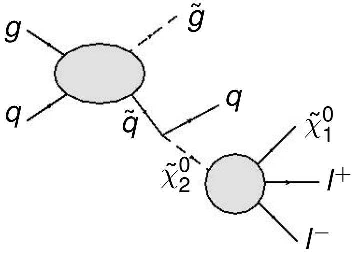
- Cross section of production $\approx$ 1.5pb (Analytical, Herwig++, Madgraph).
- $BR(\tilde{t}_1 \to \tilde{\chi}_2^0 t) \approx 10\%$, $BR(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell^+ \ell^-) \approx 4\%$.
- If cuts, detector effects.... etc are included, discovery potential looks very difficult even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

# Outline

# Process

Process studied:

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




- Process takes advantage of one of the dominant SUSY production channel at the LHC.
  - Kinematic constraints:

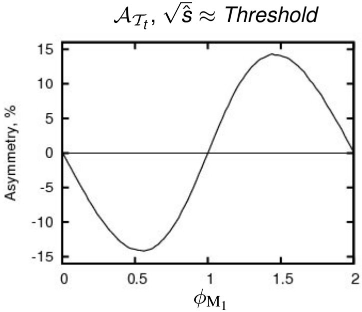
$$M_{\tilde{\chi}^0_2} < M_{\tilde{e}_{L,R}}, \qquad M_{\tilde{\chi}^0_2} - M_{\tilde{\chi}^0_1} < M_Z.$$

  - Triple product to be reconstructed (sensitive to $\phi_{M_1}$):

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

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

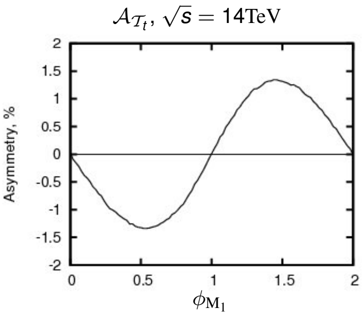
# Partonic Level Asymmetry




| Parameter | Value | Particle | Mass | Particle | Mass |
|---|---|---|---|---|---|
| $m_0$ | 150 | $\tilde{g}$ | 496.5 | $\tilde{\chi}_1^0$ | 78.1 |
| $m_{1/2}$ | 200 | $\tilde{d}_L$ | 484.1 | $\tilde{\chi}_2^0$ | 148.4 |
| $A_0$ | -650 | $\tilde{d}_R$ | 466.4 | $\tilde{\chi}_1^\pm$ | 148.2 |
| $\tan\beta$ | 10 | $\tilde{u}_L$ | 477.9 | $\tilde{\chi}_2^\pm$ | 436.0 |
| sign $\mu$ | $+$ | $\tilde{u}_R$ | 465.9 | $\tilde{e}_L$ | 207.5 |
| $M_1$ | 80.5 | $\tilde{b}_1$ | 397.2 | $\tilde{e}_R$ | 173.1 |
| $M_2$ | 153.3 | $\tilde{b}_2$ | 462.6 | $\tilde{\nu}_e$ | 192.0 |
| $M_3$ | 484.6 | $\tilde{t}_1$ | 171.0 | $\tilde{\tau}_1$ | 149.4 |
| $\mu$ | 419.0 | $\tilde{t}_2$ | 498.0 | $\tilde{\tau}_2$ | 212.5 |
| | | | | $\tilde{\nu}_\tau$ | 187.2 |

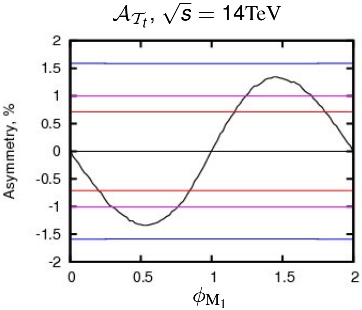
- Asymmetry can be as large as 15%.
- mSugra scenario chosen with favourable features.
  - Large branching ratios for our decay chain.
  - Coupling character of $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$ here produce large asymmetry.

# Hadronic Level Asymmetry




- Asymmetry drops significantly at the LHC for three reasons.
  - $\tilde{q}$ are boosted due to production process and PDFs.
  - $\tilde{q}^*$ are present in the sample.
  - $\tau$'s that decay leptonically are indistinguishable.
- Asymmetry drops to $\sim$ 1.5% maximum.

# Hadronic Level Asymmetry




Red: $100\text{fb}^{-1}$
Purple: $50\text{fb}^{-1}$
Blue: $20\text{fb}^{-1}$
$3\sigma$ statistical

- 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.

## Outline

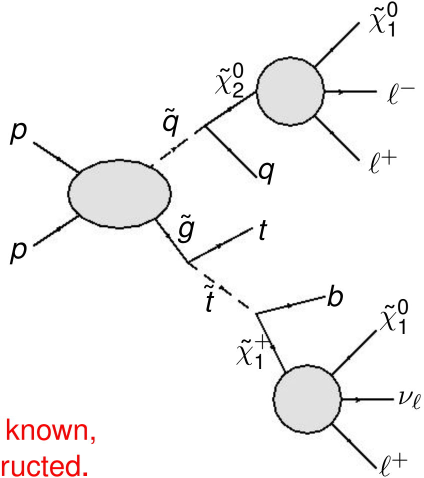
# Momentum Reconstruction

- 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.

# Process

Mass conditions:

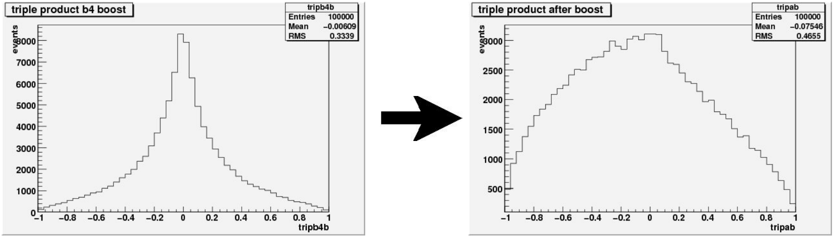
$$\begin{aligned}
m_{\tilde{q}}^2 &= (P_{\tilde{\chi}_2^0} + P_q)^2, \\
m_{\tilde{\chi}_2^0}^2 &= (P_{\tilde{\chi}_1^0} + P_{\ell^+} + P_{\ell^-})^2, \\
m_{\tilde{g}}^2 &= (P_{\tilde{t}} + P_t)^2, \\
m_{\tilde{t}}^2 &= (P_{\tilde{\chi}_1^+} + P_b)^2, \\
m_{\tilde{\chi}_1^+}^2 &= (P_{\tilde{\chi}_1^0}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




- 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.

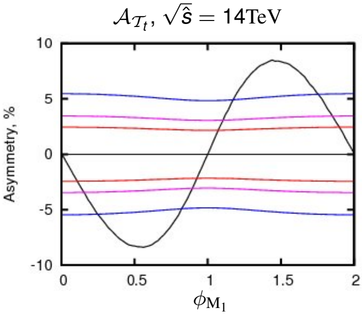
# Boost Example

Lab Frame $\tilde{\chi}_2^0$ Rest Frame




- Using events generated by `Herwig++` effect of boost can clearly be seen.
- Angle between $\ell^+, \ell^-$ plane and $q$ is enhanced.
    - Asymmetry becomes more resolvable.

# Results




Red: 100fb$^{-1}$
Purple: 50fb$^{-1}$
Blue: 20fb$^{-1}$
3$\sigma$ statistical

- Asymmetry returns to near parton level magnitude.
  - Still $\tilde{q}^*$ in sample.
  - Complications with multiple solutions.
- Substantially increases statistical significance of any result.

## Outline

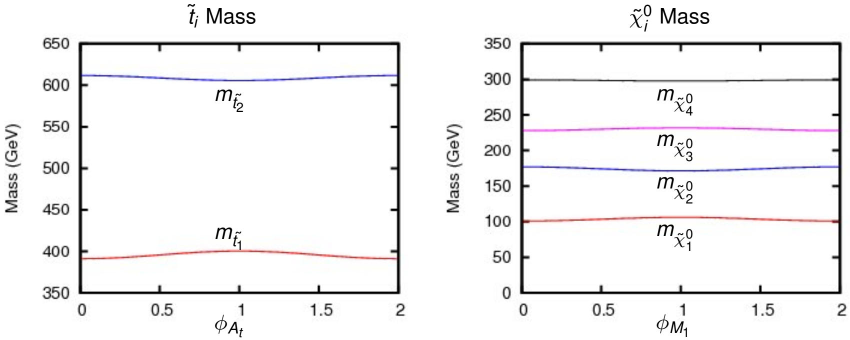
## Summary

- 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 would require large luminosity.
- 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

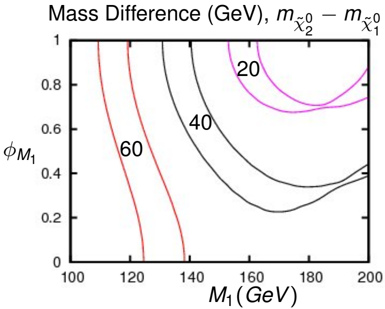
Extra slides on other possible MSSM CP observables

# Variation of Mass with CP Phase



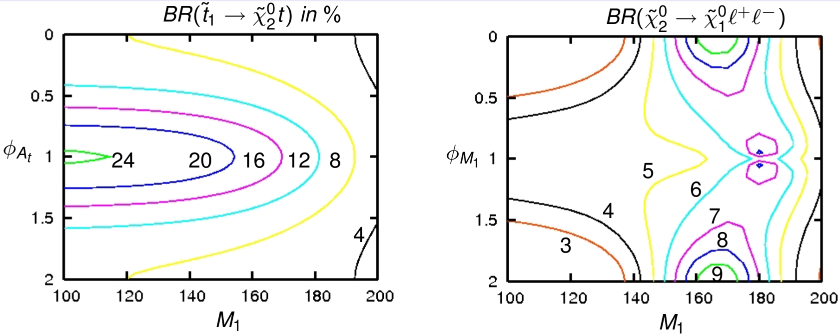

- Masses of both $\tilde{t}$ and $\tilde{\chi}_i^0$ vary with phase.
- CP even quantity.
- An absolute mass measurement at the LHC will not be accurate enough to constrain the phase.

## Mass Difference



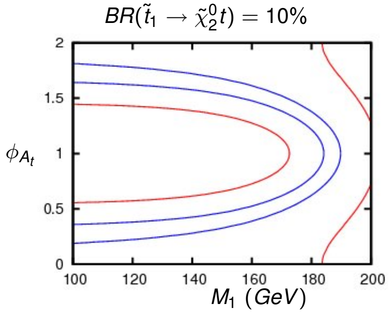

- Assumed a 1% experimental error.
- Assumed a 5% error in determination of $M_2$.
- A measurement of the mass difference $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$ looks potentially more promising if the mass difference happens to be small (<40 GeV).

## 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%, $\Delta_1$ (LHC) or 10%, $\Delta_2$ (LC).
- Analysis assumes all other scenario parameters are known
- Measurement only looks likely with a future Linear Collider.