# CP-violation in SUSY cascades at the LHC

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

## Our Project

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

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

(arXiv:0908.2631, G.Moortgat-Pick, K.Rolbiecki, J.Tattersall, P.Wienemann)

- 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).
- Other Studies
  - (Phys.Rev.D70:095007,2004: Bartl, Christova, Hohenwarter-Sodek, Kernreiter)
  - (JHEP 0707:055,2007: Langacker, Paz, Wang, Yavin)
  - (arXiv:0905.3088: Deppisch, Kittel)

## 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).

- $\phi_\mu$ 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 $N$:

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

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 $\mu$.

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

## 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 $\phi_{\tilde{t}}$.

## Time reversal

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

- Construct an observable:

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

- Naïve time reversal operation, $T_N$, reverses 3-momenta $\overrightarrow{p_i} \to -\overrightarrow{p_i}$ 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 three independent momenta with mediation by a particle that is not a scalar (allow spin correlations).

- Observable correlations cannot occur solely from decays of a neutralino unless the LSP is reconstructed.
- 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:

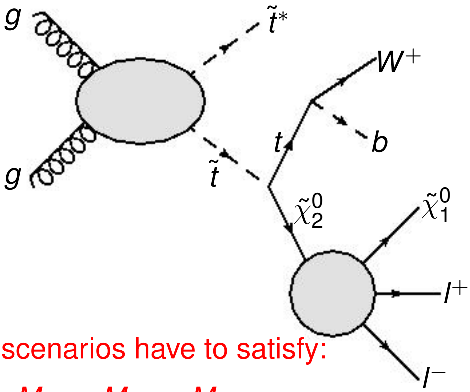
$$E_a\, \overrightarrow{p_b} \cdot (\overrightarrow{p_c} \times \overrightarrow{p_d}) + \ldots\ldots..$$

## Outline

## Process

Process studied:

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




- For this channel to work all scenarios have to satisfy:

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

- Masses and branching ratios also have a phase dependence but will be too weak to be seen at the LHC.
- Other studies: (arXiv:0905.3088: Deppisch, Kittel).

## Realising CP asymmetry

Process allows three different triple products to be studied:

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

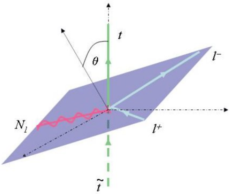
- $\mathcal{T}_t$ only sensitive to phase, $\phi_{M_1}$.
- $\mathcal{T}_b$ and $\mathcal{T}_{tb}$ sensitive to both $\phi_{M_1}$ and $\phi_{A_t}$.
- Charge identification is required as CP conjugate decay has an asymmetry of the opposite sign.
  - For $\mathcal{T}_t$ and $\mathcal{T}_{tb}$ we require 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 $\tilde{\chi}_2^0$.

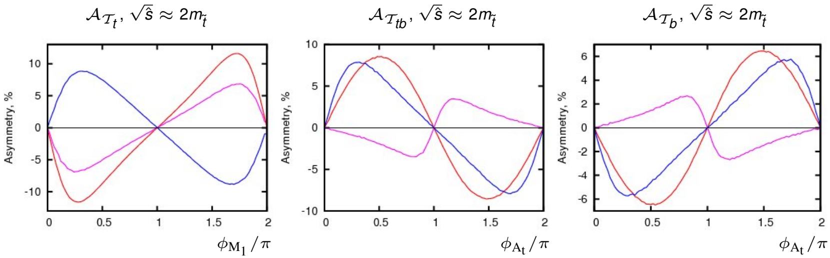
- A non-zero expectation value of $\mathcal{T}$, implies a non-zero average angle between the plane and the z-axis ($p_t$).
- Define asymmetry parameter:

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

where:

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

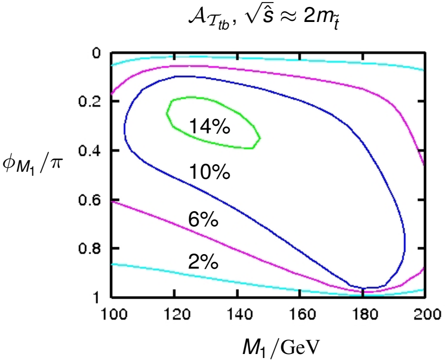
## Parton Level Asymmetry




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

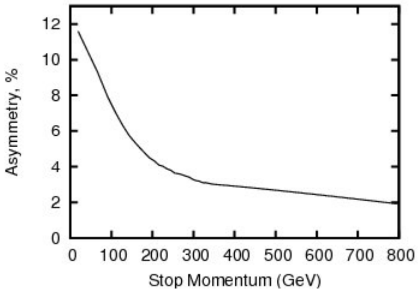
- All asymmetries in %.
- Asymmetries at the parton level can be as large as 10%.
- Various scenarios with three body decay of $\tilde{\chi}_2^0$ show similar results.
- T-odd observable

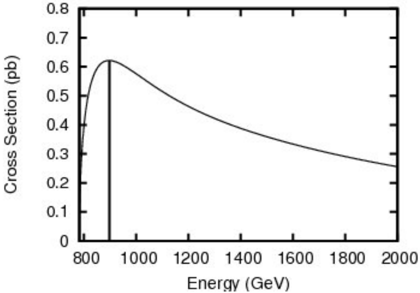
## Parton Level Asymmetry




- As an example we vary $M_1$ 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.

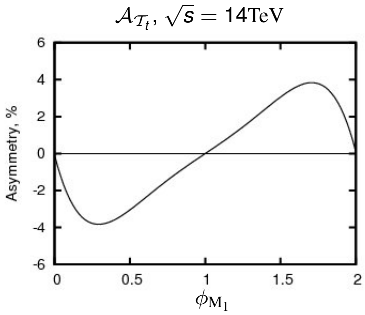
# Kinematics of $\tilde{t}_1$



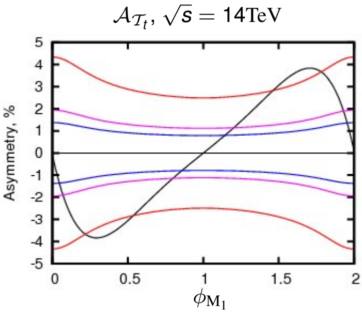

- $\tilde{t}_1$ are boosted due to production process and PDFs.
- Asymmetry is maximal in rest frame of decaying particle.
  - $\epsilon_{\mu\nu\rho\sigma} p^{\mu}_{\tilde{\chi}^0_2} p^{\nu}_t p^{\rho}_{\ell+} p^{\sigma}_{\ell-} \longrightarrow m_{\tilde{\chi}^0_2} \overrightarrow{p_t} \cdot (\overrightarrow{p_{\ell+}} \times \overrightarrow{p_{\ell-}})$.
- 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: $100\text{fb}^{-1}$
Purple: $500\text{fb}^{-1}$
Blue: $1\text{ab}^{-1}$
$1\sigma$ statistical

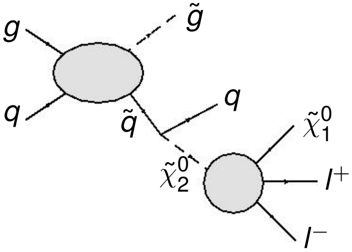
- Cross section of production $\approx$ 1.5pb (Analytical, Herwig++, Madgraph).
- $BR(\tilde{t}_1 \to \tilde{\chi}_2^0 t) \approx 10\%$, $BR(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell^+ \ell^-) \approx 4\%$.
- If cuts, detector effects.... etc are included, discovery potential looks very difficult even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

# Outline

# Process

Process studied:

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




- One of the dominant SUSY production channels at the LHC.
- Kinematic constraints:

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

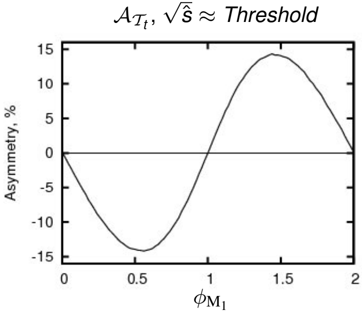
- Triple product to be reconstructed (sensitive to $\phi_{M_1}$):

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

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

(arXiv:0908.2631, G.Moortgat-Pick, K.Rolbiecki, J.Tattersall, P.Wienemann)

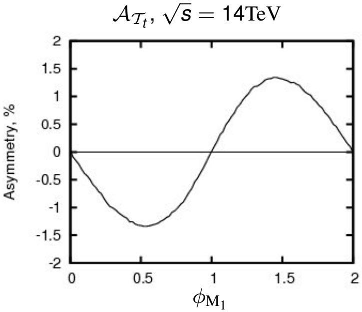
# Partonic Level Asymmetry




| 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 |

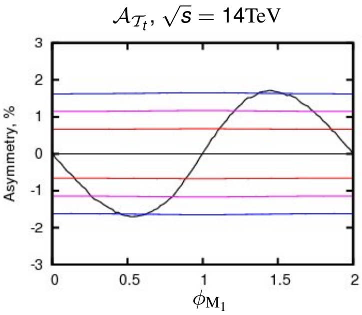
- Asymmetry can be as large as 15%.
- mSugra scenario chosen.
  - Reasonable branching ratios for our decay chain.
  - Coupling character of $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$ here produce large asymmetry.

## 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: 300fb$^{-1}$
Purple: 100fb$^{-1}$
Blue: 50fb$^{-1}$
3$\sigma$ statistical

- Cross section of production $\approx$ 40pb.
- $BR(\tilde{q}_L \to \tilde{\chi}_2^0 q) \approx 30\%$, $BR(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell^+ \ell^-) \approx 10\%$
- Cuts and momentum smearing included.
- Hints could be seen at the LHC.

## Momentum Reconstruction

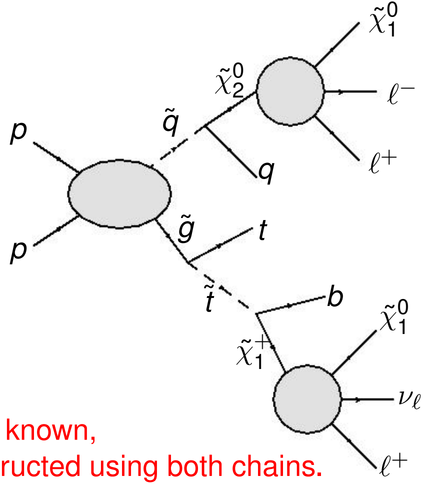
Main problem with measuring asymmetries at the LHC is the dilution due to boosted frames.

- In the rest frame of the decaying particle the asymmetry is maximal.
- LSP escapes the experiment undetected.
- Reconstruct LSP momentum using the set of invariant equations.
- We reconstruct the frame of the decaying particle and the asymmetry is restored.

## Process

Mass conditions:

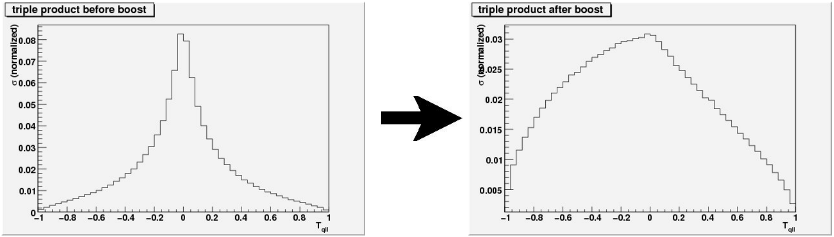
$$
\begin{aligned}
m_{\tilde{q}}^2 &= (P_{\tilde{\chi}_2^0} + P_q)^2, \\
m_{\tilde{\chi}_2^0}^2 &= (P_{\tilde{\chi}_1^0} + P_{\ell^+} + P_{\ell^-})^2, \\
m_{\tilde{g}}^2 &= (P_{\tilde{t}} + P_t)^2, \\
m_{\tilde{t}}^2 &= (P_{\tilde{\chi}_1^+} + P_b)^2, \\
m_{\tilde{\chi}_1^+}^2 &= (P_{\tilde{\chi}_1^0}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




- Assuming particle masses are known, momenta of $\tilde{\chi}_1^0$ can be reconstructed using both chains.
- By boosting into rest frame of decaying $\tilde{q}$, parton level asymmetry is recovered.

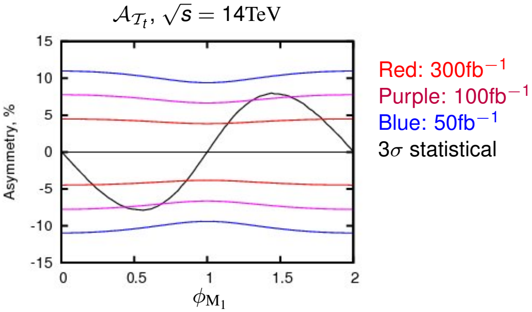
## Boost Example

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




- Asymmetry returns to near parton level magnitude.
  - Still $\tilde{q}^*$ in sample.
  - Complications with multiple solutions.
  - Cuts and momentum smearing included.
- Much larger asymmetry may be seen.

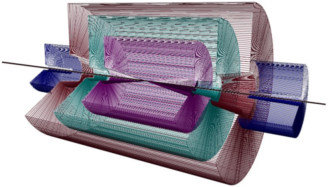
## Experimental factors

To be a realistic study need to include many experimental factors

- 2% momentum smearing expected on leptons, 10% on jets, MET from ATLAS TDR.
  $\Rightarrow$ Has very little effect on triple product distribution
  $\Rightarrow$ Momentum reconstruction efficiency is harmed but not substantially
- $\sim$10GeV error assumed on SUSY particles
  $\Rightarrow$ Has very little effect as long as mass differences are known more accurately
- Experimental cuts reduce number of events
  $\Rightarrow$ 10GeV pT for leptons, and 20GeV invariant mass.
  $\Rightarrow$ 100GeV hardest jet, 25GeV for others.

# Experimental simulation

- *Delphes* is a new tool that allows quick detector simulation.



(arXiv:0903.2225: S. Ovyn, X. Rouby, V. Lemaitre)

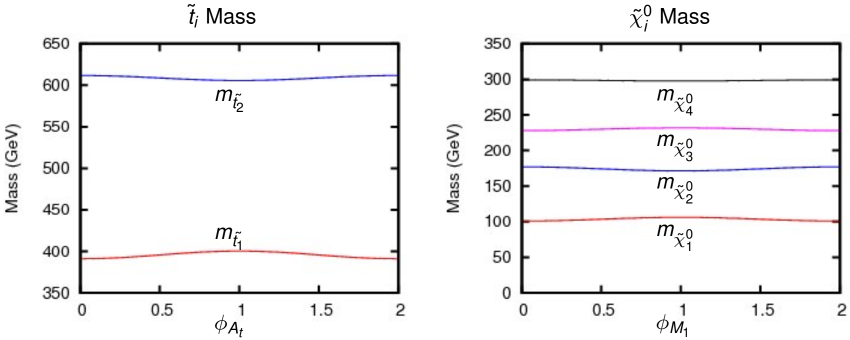
- Long term plan is to complete a detector simulation to verify observables.
- Some issues with reading `Herwig++` hep-mc files but should be resolved soon.
- Work in collaboration with P Bechtle, B Gosdzik, G Moortgat-Pick, K Rolbiecki, P Wienemann.

## 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.
- Initial study of $\tilde{t}$ production would require large luminosity.
- New study using $\tilde{q}\tilde{g}$ much more hopeful.
- Using momentum reconstruction further improves the situation.
- Data from ILC will be crucial to determine the parameters of the MSSM.

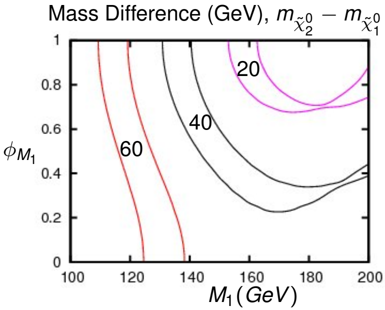
# Extra Slides on Masses and Branching Ratios

# Variation of Mass with CP Phase



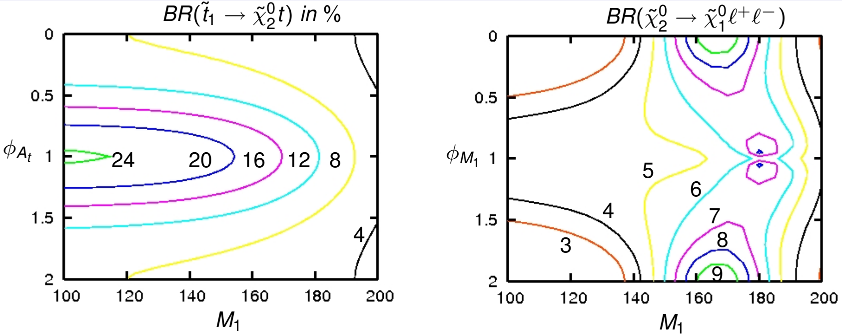

- Masses of both $\tilde{t}$ and $\tilde{\chi}_i^0$ vary with phase.
- CP even quantity.
- An absolute mass measurement at the LHC will not be accurate enough to constrain the phase.

# Mass Difference



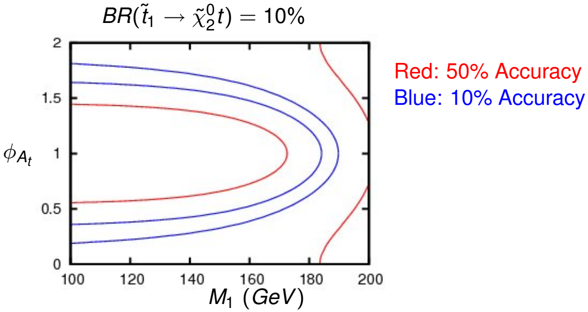

- Assumed a 1% experimental error.
- Assumed a 5% error in determination of $M_2$.
- A measurement of the mass difference $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$ looks potentially more promising if the mass difference happens to be small (<40 GeV).

## Branching Ratios




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

## Measurement of Branching Ratios




- 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.

## Momentum Reconstruction Procedure

Solve 6 linear equations via matrix in terms of $E_{\tilde{\chi}^0_{1a}}$ and $E_{\tilde{g}ME}$,

$$\mathcal{M}\begin{pmatrix} A \\ B \\ C \\ D \\ E \\ F \end{pmatrix} = \begin{pmatrix} \frac{1}{2}(m^2_{\tilde{\chi}^0_1} - m^2_{\tilde{\chi}^0_2}) + P_{\ell^+_a}\cdot P_{\ell^-_a} + E_{\tilde{\chi}^0_{1a}}(E_{\ell^+_a} + E_{\ell^-_a}) \\ \frac{1}{2}(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{q}}) + P_{\ell^+_a}\cdot P_q + P_{\ell^-_a}\cdot P_q + E_{\tilde{\chi}^0_{1a}}E_q \\ \frac{1}{2}(m^2_b + m^2_{\tilde{\chi}^+_1} - m^2_{\tilde{t}}) + P_{\ell^+_b}\cdot P_b + E_{\tilde{g}ME}E_b \\ \frac{1}{2}(m^2_{\tilde{t}} + m^2_t - m^2_{\tilde{g}}) + P_{\ell^+_b}\cdot P_t + P_b\cdot P_t + E_{\tilde{g}ME}E_t \\ p^T_{miss}(x) \\ p^T_{miss}(y) \end{pmatrix}.$$

Use above solution and two quadratic equations to produce quartic equation that can then be solved,

$$Q_4E^4_{\tilde{g}ME} + Q_3E^3_{\tilde{g}ME} + Q_2E^2_{\tilde{g}ME} + Q_1E_{\tilde{g}ME} + Q_0 = 0\,.$$