CP VIOLATION IN SUSY DECAY CHAINS
AT THE LHC

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work in progress in collaboration with:
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supersymmetry can introduce new sources of CP violation
these may be needed to explain baryon asymmetry of the universe
new CP phase can be measured or excluded in high energy physics experiments
⇒ so far most analyses concentrated on the ILC

see Kittel, arXiv:0904.3241 for a recent review
⇒ challenging at the LHC

Ellis, Moortgat, Moortgat-Pick, Smillie, Tattersall arXiv:0809.1607
Deppisch, Kittel arXiv:0905.3088

We show that in spite of the difficult experimental environment the measurement of CP-odd effects may be possible at the LHC.
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CP phases in the MSSM

- CP phases enter in the gaugino/higgsino mass parameters and trilinear couplings:

  \[ M_i = |M_i|e^{i\phi_i}, \quad \mu = |\mu|e^{i\phi_\mu}, \quad A_f = |A_f|e^{i\phi_f} \]

-⇒ strong bounds on these phases from EDMs
-⇒ large phases possible if accidental cancellations occur
  see e.g. Ellis, Lee, Pilaftsis arXiv:0808.1819
-⇒ or 1st and 2nd generation of squarks are heavy

- CP phases can be probed by
  asymmetries in cross sections and decay widths,
  asymmetries of triple products of momenta and/or spins
  ⇒ such CP- and T-odd observables provide unambiguous way of detecting CP violation in the model
Introduction

Triple products

Triple product correlations of momenta are a useful tool for studying **CP violation** effects

- construct an observable:

\[ T = \vec{p}_1 \cdot (\vec{p}_2 \times \vec{p}_3) \]

- it is T-odd and CP-odd if higher order effects and finite widths can be neglected

- originates from Dirac traces in matrix element

\[ \text{Tr} \left[ \gamma^\mu \gamma^\nu \gamma^\rho \gamma^\sigma \gamma^5 \right] \rightarrow i\epsilon_{\mu\nu\rho\sigma} p_a^{\mu} p_b^{\nu} p_c^{\rho} p_d^{\sigma} \]

- together with **imaginary part of couplings** give rise to CP-odd asymmetries
**CP-odd asymmetries**

Example of triple product in 3-body neutralino decay:

\[ \mathcal{T}_t = \vec{p}_t \cdot (\vec{p}_{l^+} \times \vec{p}_{l^-}) \]

- Count the number of events \( N_+ \) where \( \vec{p}_t \) points above the plane defined by leptons vs. the number of events \( N_- \) when it points below it.
- Define the asymmetry as:

\[ A_{CP} = \frac{N_+ - N_-}{N_+ + N_-} \]
Neutralino sector of MSSM

- Neutralino mass matrix in gauge eigenstate basis
  \((\tilde{B}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0)\)

  \[
  M_{\tilde{\chi}^0} = \begin{pmatrix}
  M_1 & 0 & -m_Z c_\beta s_W & m_Z s_\beta s_W \\
  0 & M_2 & m_Z c_\beta c_W & -m_Z s_\beta c_W \\
  -m_Z c_\beta s_W & m_Z c_\beta c_W & 0 & -\mu \\
  m_Z s_\beta s_W & -m_Z s_\beta c_W & -\mu & 0
  \end{pmatrix}
  \]

- Diagonalization of mass matrix

  \[
  \text{diag}(m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_3^0}, m_{\tilde{\chi}_4^0}) = N^* M_{\tilde{\chi}^0} N^{-1}
  \]

- When \(M_1\) and/or \(\mu\) are complex mixing matrix \(N\) has non-trivial complex structure

- Complex elements of \(N\) appear in neutralino couplings triggering CP-odd effects
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Chosen scenario

- mSUGRA parameters:
  \[ m_0 = 150 \text{ GeV}, \quad m_{1/2} = 200 \text{ GeV}, \quad A_0 = -650 \text{ GeV}, \quad \tan \beta = 10 \]

- resulting masses in GeV and branching ratios:

<table>
<thead>
<tr>
<th></th>
<th>( m_{\tilde{\chi}^0_1} )</th>
<th>( m_{\tilde{\chi}^0_2} )</th>
<th>( m_{\tilde{\chi}^\pm_1} )</th>
<th>( m_{\tilde{g}} )</th>
<th>( m_{\tilde{q}_L} )</th>
<th>( m_{\tilde{t}_1} )</th>
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<tbody>
<tr>
<td></td>
<td>78.1</td>
<td>148.4</td>
<td>148.2</td>
<td>496.5</td>
<td>480</td>
<td>171.0</td>
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</table>

<table>
<thead>
<tr>
<th>Mode</th>
<th>( \tilde{g} \rightarrow \tilde{t}_1 \overline{t} + \text{c.c.} )</th>
<th>( \tilde{q}_L \rightarrow \tilde{\chi}^\pm_1 q' )</th>
<th>( \tilde{q}_L \rightarrow \tilde{\chi}^0_2 q )</th>
<th>( \tilde{t}_1 \rightarrow \tilde{\chi}^+_1 b )</th>
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<tbody>
<tr>
<td>BR</td>
<td>53.8%</td>
<td>65%</td>
<td>33%</td>
<td>98.1%</td>
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</table>

<table>
<thead>
<tr>
<th>Mode</th>
<th>( \tilde{\chi}^+<em>1 \rightarrow \tilde{\chi}^0_1 \tau^+ \nu</em>\tau )</th>
<th>( \tilde{\chi}^+<em>1 \rightarrow \tilde{\chi}^0_1 \ell^+ \nu</em>\ell )</th>
<th>( \tilde{\chi}^0_2 \rightarrow \tilde{\chi}^0_1 \tau^+ \tau^- )</th>
<th>( \tilde{\chi}^0_2 \rightarrow \tilde{\chi}^0_1 \ell^+ \ell^- )</th>
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<tbody>
<tr>
<td>BR</td>
<td>37.2%</td>
<td>2 \times 12.2%</td>
<td>59.3%</td>
<td>2 \times 4.5%</td>
</tr>
</tbody>
</table>

- introduce the complex phase for the bino mass parameter

\[ M_1 = |M_1| e^{i\phi_1} \quad 0 \leq \phi_1 < 2\pi \]
Squarks production and decay

- production rates at 14 TeV

<table>
<thead>
<tr>
<th>Particle</th>
<th>Total Coloured</th>
<th>$\tilde{g}$</th>
<th>$\tilde{q}_L$</th>
<th>$\tilde{q}_L^*$</th>
<th>$\tilde{q}_L + \tilde{g}$</th>
<th>$\tilde{q}_L^* + \tilde{g}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross Section (pb)</td>
<td>148</td>
<td>59.2</td>
<td>30.0</td>
<td>8.3</td>
<td>18.2</td>
<td>3.1</td>
</tr>
</tbody>
</table>

- high production rate of squarks
- squarks dominate over antisquarks
- left squarks decay to $\tilde{\chi}_2^0$ with $BR = 33\%$
CP asymmetry in neutralino 3-body decay

- neutralinos $\tilde{\chi}^0_2$ appear copiously in the $\tilde{q}_L$ decay chain
- leptonic 3-body decay of neutralino
  \[ \tilde{\chi}^0_2 \rightarrow \tilde{\chi}^0_1 \ell^+ \ell^- \]
- triple product of lepton momenta and a quark from $\tilde{q}_L$ decay
  \[ T_{q\ell\ell} = \vec{p}_q \cdot (\vec{p}_{\ell^+} \times \vec{p}_{\ell^-}) \]
- sensitive to phase of $M_1$
- asymmetry up to 15% in $\tilde{\chi}^0_2$ rest frame

\[ A_{CP} = \frac{N(T_{q\ell\ell} > 0) - N(T_{q\ell\ell} < 0)}{N(T_{q\ell\ell} > 0) + N(T_{q\ell\ell} < 0)} \]
dilution due to boost of squarks and admixture of antisquarks ($\#\tilde{q}_L/\#\tilde{q}^*_L \sim 3.6/1$)

high production rate of $\tilde{q}_L + \tilde{q}^*_L \sim 38$ pb gives high statistics

hints could be seen at the LHC at higher luminosity

if we could go back to the neutralino rest frame...
dilution due to boost of squarks and admixture of antisquarks ($\#\tilde{q}_L/\#\tilde{q}_L^* \sim 3.6/1$)

- high production rate of $\tilde{q}_L + \tilde{q}_L^* \sim 38$ pb gives high statistics
- hints could be seen at the LHC at higher luminosity
- if we could go back to the neutralino rest frame...
Hadronic level asymmetry

\[ A_{CP}, \sqrt{s} = 14 \text{TeV} \]

- Red: 100 fb\(^{-1}\)
- Purple: 50 fb\(^{-1}\)
- Blue: 20 fb\(^{-1}\)

3\(\sigma\) statistical

- dilution due to boost of squarks and admixture of antisquarks \((\#\tilde{q}_L/\#\tilde{q}_L^* \sim 3.6/1)\)
- high production rate of \(\tilde{q}_L + \tilde{q}_L^* \sim 38\) pb gives high statistics
- hints could be seen at the LHC at higher luminosity
- if we could go back to the neutralino rest frame...
Mass conditions:

\[ m_{\tilde{q}_L}^2 = (p_{\tilde{\chi}_2} + p_q)^2 \]
\[ m_{\tilde{\chi}_2}^0 = (p_{\tilde{\chi}_1} + p_{\ell^+} + p_{\ell^-})^2 \]
\[ m_{\tilde{\chi}^+}^2 = (p_{\tilde{\chi}_1} + p_{\ell^+} + p_{\ell^-})^2 \]
\[ m_{\tilde{\chi}^-}^2 = (p_{\tilde{\chi}_1} + p_{\ell^-} + p_{\ell^+})^2 \]
\[ m_{\tilde{\chi}_1}^2 = p_{\tilde{\chi}_1}^2 \]
\[ m_{\tilde{\chi}_1}^0 = p_{\tilde{\chi}_1}^0 \]
\[ m_{\tilde{\chi}_1}^+ = (p_{\tilde{\chi}_1} + p_{\ell^+} + p_{\ell^-})^2 \]
\[ \vec{p}_{miss}^T = \vec{p}_{\tilde{\chi}_1}^0 + \vec{p}_{\tilde{\chi}_1}^0 + \vec{p}_{\nu_\ell} \]

- 8 unknowns vs. 8 equations
- assuming particle masses are known, momenta of intermediate particles can be reconstructed
Some tricky details

- up to 4 possible real solutions
  ⇒ take only events where all solutions have the same sign of triple product

- background due to signal process with $\tilde{\chi}_2^0$ decaying to taus followed by leptonic tau decays to same flavor leptons
  
  $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \tau^+ \tau^- \rightarrow \tilde{\chi}_1^0 \ell^+ \nu_\ell \bar{\nu}_\tau \ell^- \bar{\nu}_\ell \nu_\tau$

  ⇒ usually does not give the same sign triple product for different solutions

- combinatorics
  ⇒ no real solutions in case of wrong assignments of particles in most cases
using reconstructed momenta we can calculate triple product in the rest frame of the neutralino $\tilde{\chi}_2^0$

asymmetry becomes clearly visible after boost in the triple product distribution
Asymmetry returns to parton level magnitude
substantially increases statistical significance of any result
good prospects for 3-σ discovery or exclusion for wide range of φ₁ values
Experimental issues

- uncertainties in particle masses

- momenta of final particles smeared in the detector...
  \[ \Rightarrow \text{simulations in progress} \]

SUSY backgrounds:

\[ \tilde{g}\tilde{q}_L \to (\tilde{b}_{1,2}b) + (\tilde{\chi}^0_2q) \to (\tilde{\chi}^-_1tb) + (\tilde{\chi}^0_2q) \to (ltb) + (\ell\ell q) + E_{\text{miss}} \]

\[ \tilde{g}\tilde{q}_L \to (\tilde{b}_{1,2}b) + (\tilde{\chi}^0_2q) \to (\tilde{t}_1Wb) + (\tilde{\chi}^0_2q) \to (\ell bWb) + (\ell\ell q) + E_{\text{miss}} \]

\[ \tilde{g}\tilde{g} \to (\tilde{t}_1t) + (\tilde{b}_{1,2}b) \to (\tilde{\chi}^-_1bt) + (\tilde{t}_1Wb) \to (\ell bt) + (\ell b\ell b) + E_{\text{miss}} \]

\[ \tilde{g}\tilde{g} \to (\tilde{t}_1t) + (\tilde{t}_1t) \to (\tilde{\chi}^-_1bt) + (\tilde{\chi}^-_1b\ell b) \to (\ell bt) + (\ell b\ell b) + E_{\text{miss}} \]

\[ \Rightarrow \text{need further studies} \]

\[ \Rightarrow \text{hopefully cannot pass reconstruction process} \]
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Conclusions

- squark decays are a promising channel for studying CP violation at the LHC
- suppression of asymmetries by boosts can be overcome by momentum reconstruction
- reconstruction significantly improves sensitivity by enhancing the signal
- information from LHC on CP violation could direct future searches at a linear collider

Outlook:
⇒ more detailed experimental study is in progress