Measurement of CP violation in the MSSM neutralino sector with ILD

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ILD meeting

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- SUSY and CP violation
- Neutralino decays and CP asymmetry
- Reconstruction method
- Simulation and event selection
- Mixing matrix fit
- Summary and outlook

SUSY and CP violation

- CP violation induced by complex phase in CKM matrix in the Standard Model
- CP violation in SM not enough to explain baryon asymmetry in the universe
- Supersymmetry can introduce new sources of CP violation

  → MSSM has 40 new CP violating phases
- Intensive theoretical studies of SUSY CP violation at ILC and LHC

  → CP asymmetries can reach several 10%, since effects appear on tree level
- Experimental studies ongoing for LHC experiments

  → LHC studies suffer from complicated event topology

→ Can we measure SUSY CP violation at the ILC?

(The presented results are preliminary, numbers will change)

Neutralino sector

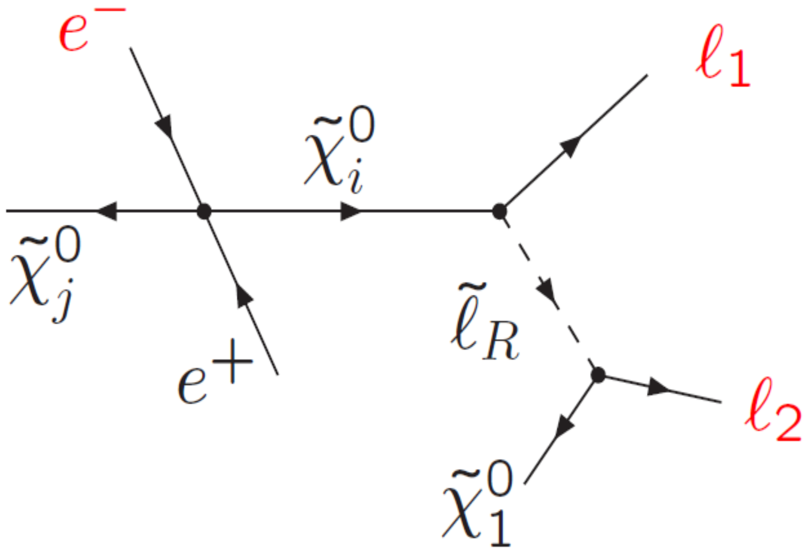
- We use the complex MSSM in this study
- Neutralino mass matrix in gauge eigenstate basis:

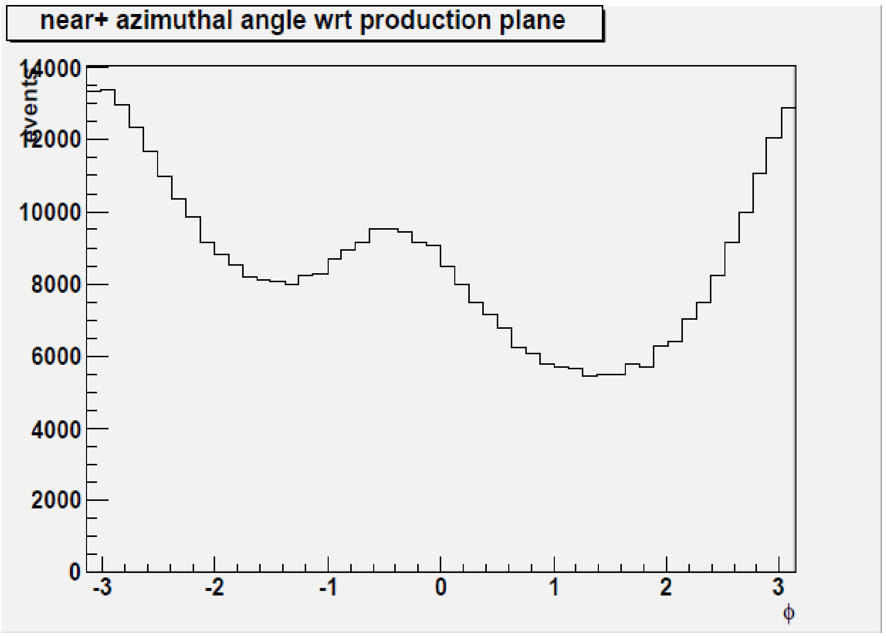
$$\mathcal{M}_0 = \begin{pmatrix} M_1 & 0 & -m_Z \sin(\theta_W)\cos(\beta) & m_Z \sin(\theta_W)\sin(\beta) \\ 0 & M_2 & m_Z \cos(\theta_W)\cos(\beta) & -m_Z \cos(\theta_W)\sin(\beta) \\ -m_Z \sin(\theta_W)\cos(\beta) & m_Z \cos(\theta_W)\cos(\beta) & 0 & -\mu \\ m_Z \sin(\theta_W)\sin(\beta) & -m_Z \cos(\theta_W)\sin(\beta) & -\mu & 0 \end{pmatrix}$$

- Mass parameters:
  - M1 = bino mass, can be complex
  - M2 = wino mass, complex phase rotated away by redefinition of fields
  - μ = higgsino mass, can be complex

→ Complex phases induce CP-odd effects in neutralino couplings

CP-odd observables



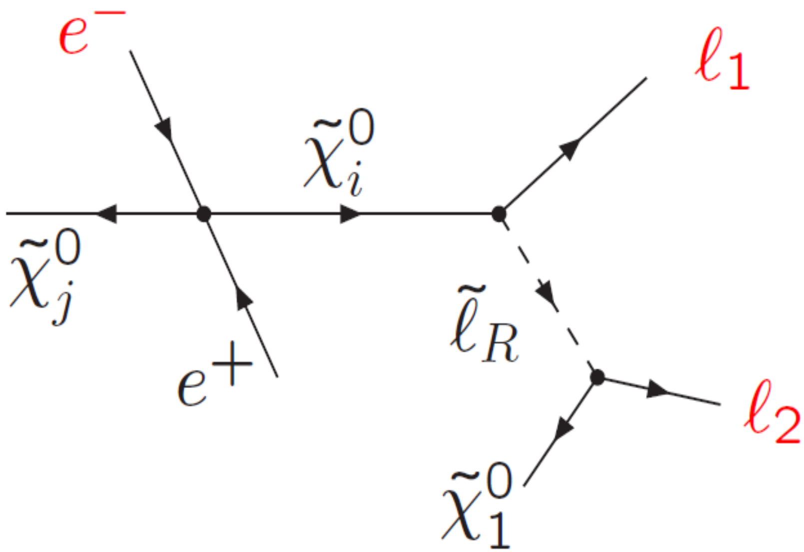


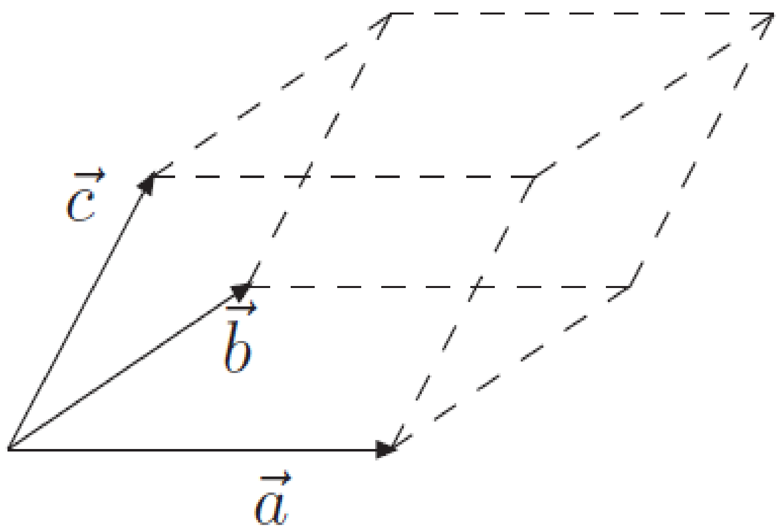
- Consider neutralino pair production (j = 1) with leptonic decays (l=e,μ)
- Neutralino polarization normal to production plane is CP sensitive

  → Leads to asymmetry in azimuthal angle distribution of leptons

  → Polarisation measurement of neutralinos via triple products

CP-odd observables



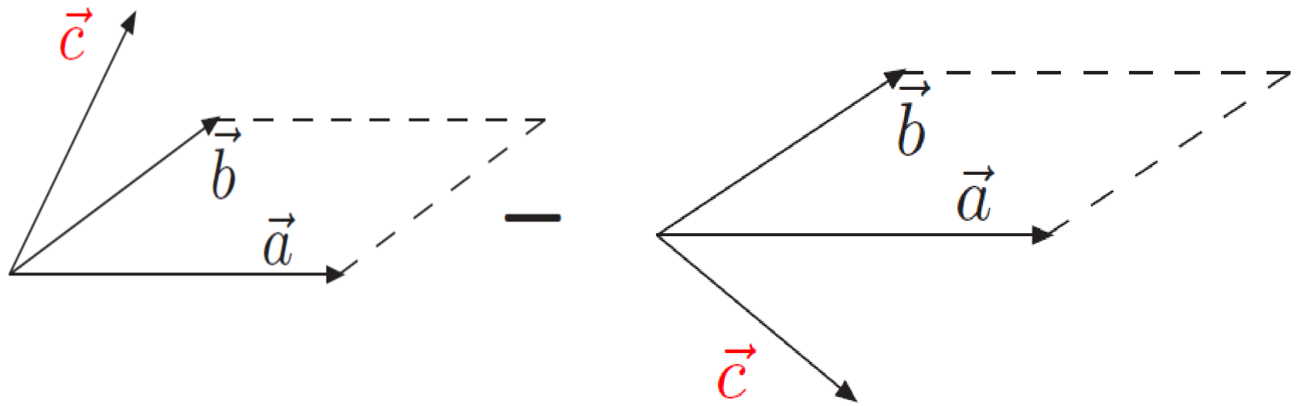


- CP-odd observable from triple product of momenta (or polarisations):

$$\mathcal{T} = [\vec{p}(e^-) \times \vec{p}(\ell_1)] \cdot \vec{p}(\ell_2)$$

CP asymmetry

$$A = \frac{N_+ - N_-}{N_+ + N_-} \quad \Leftrightarrow$$



- Measurement of CP asymmetry as counting experiment

  → Measure number of events with positive and negative sign of triple product
- Note: Each (CP-even) background event will reduce measured asymmetry!

  → Find very pure event selection and/or subtract remaining background
- Distinguish between neutralino2 and neutralino3 decays (sign of asymmetry)

→ Assume that mass spectrum already known from other measurements

Reconstruction method

- Not enough constraints to completely reconstruct the whole event due to not decaying lightest neutralino that is co-produced with decaying neutralinos
- Energies and momenta of neutralinos are fixed and can be calculated
- For leptonic decays a coordinate system can be chosen, such that

$$
\begin{aligned}
\mathbf{p}_{\ell_N} &= |\mathbf{p}_{\ell_N}|\ (0,0,1), \\
\mathbf{p}_{\ell_F} &= |\mathbf{p}_{\ell_F}|\ (\sin a, 0, \cos a), \quad a \in [0,\pi], \\
\mathbf{p}_{\tilde{\ell}} &= |\mathbf{p}_{\tilde{\ell}}|\ (\sin b \cos B, \sin b \sin B, \cos b), \quad b \in [0,\pi], \quad B \in [0, 2\pi]
\end{aligned}
$$

- The angles b and B expressed in terms of measured lepton momenta/energies

  → Calculate cosb and cosB for each event with 2 leptons

  → If |cosb| < 1 and |cosB| < 1 for a given event, the slepton momentum is physical and the event is a candidate neutralino event
- Similar conditions for background processes, e.g. slepton or W production

→ Use these conditions in the final event selection of events, that are exclusively neutralino event candidates

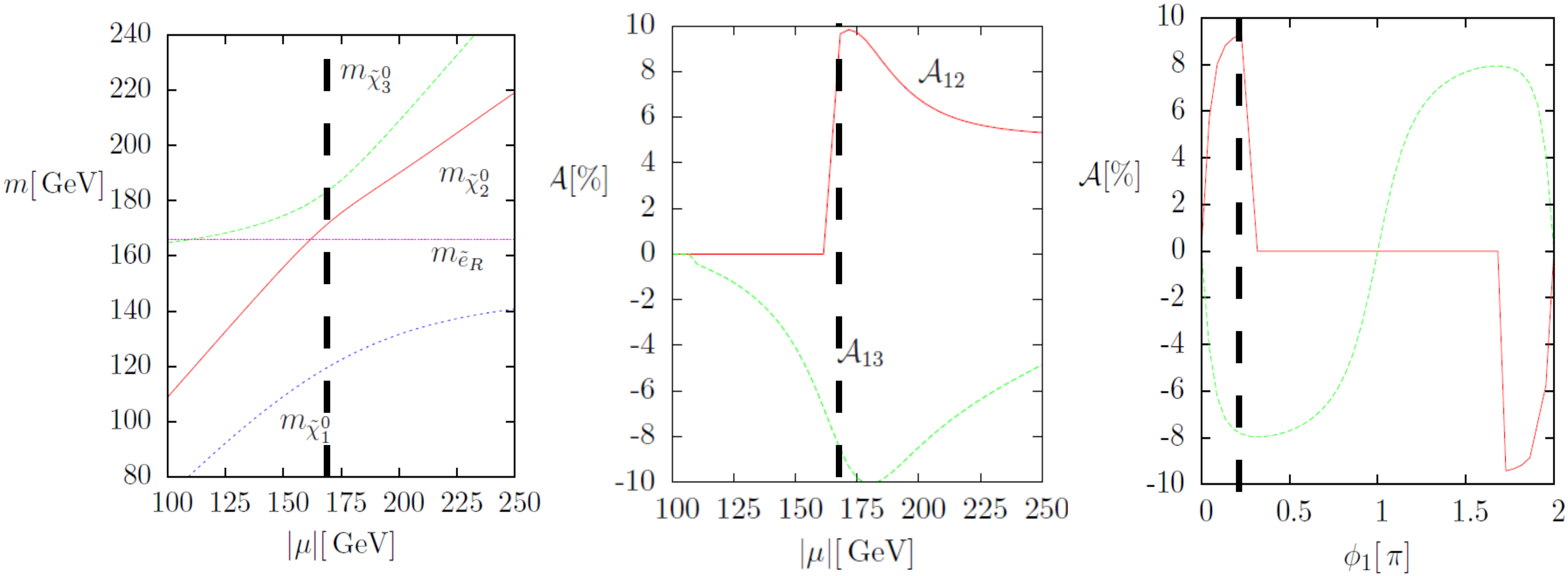
Benchmark scenario

M_2	M_1	$\|\mu\|$	ϕ_μ	ϕ_1	$\tan\beta$	$m_{\tilde{\ell}_R}$	$m_{\tilde{\ell}_L}$
300 GeV	150 GeV	165 GeV	0	0.2π	10	166 GeV	280 GeV

↓

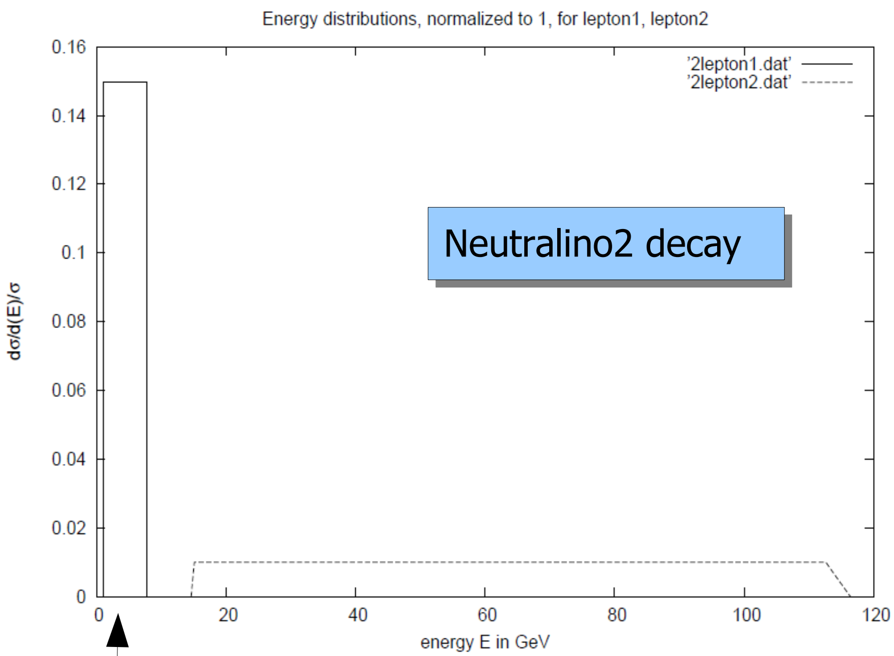
$m_{\chi_1^0} = 118$ GeV	$m_{\chi_1^\pm} = 146$ GeV	$\mathrm{BR}(\tilde{\chi}_2^0 \to \tilde{\ell}_R \ell) = 55\%$
$m_{\chi_2^0} = 169$ GeV	$m_{\chi_2^\pm} = 330$ GeV	$\mathrm{BR}(\tilde{\chi}_2^0 \to \tilde{\tau}_1 \tau) = 45\%$
$m_{\chi_3^0} = 181$ GeV	$m_{\tilde{\tau}_1} = 165$ GeV	$\mathrm{BR}(\tilde{\chi}_3^0 \to \tilde{\ell}_R \ell) = 64\%$
$m_{\chi_4^0} = 330$ GeV	$m_{\tilde{\tau}_2} = 280$ GeV	$\mathrm{BR}(\tilde{\chi}_3^0 \to \tilde{\tau}_1 \tau) = 36\%$
$m_{\tilde{\nu}} = 268$ GeV	$\sigma(e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0) = 244$ fb	$\sigma(e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_3^0) = 243$ fb

Benchmark scenario



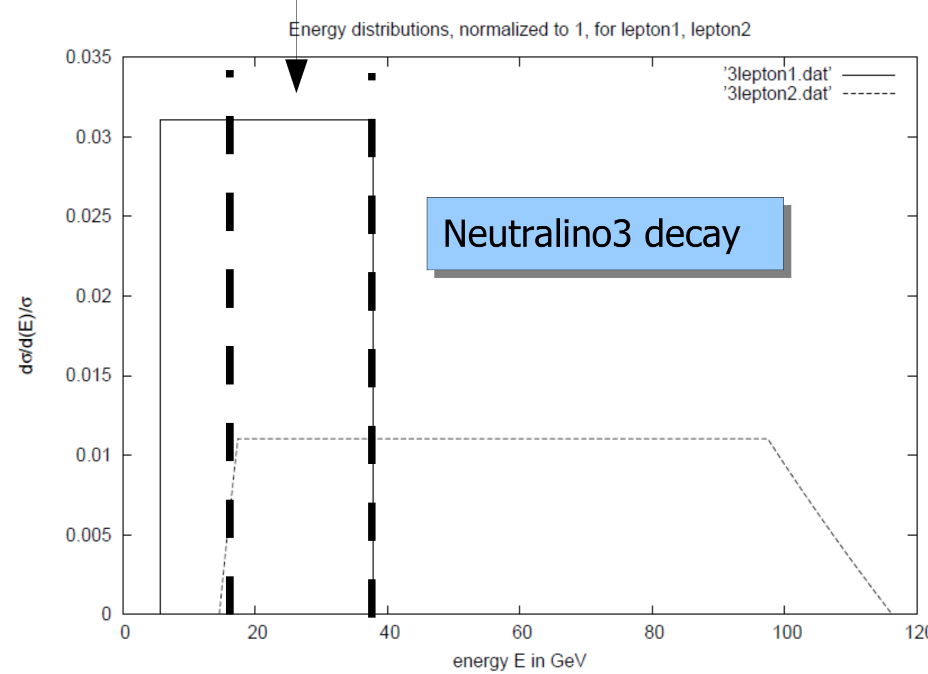
- Features of the scenario:
  - Large asymmetries
  - Efficient distinction between near and far lepton

Lepton energy distribution



Very low energetic leptons!

Reject events with both leptons in overlap region



- Since we know masses, we know energy distributions

  → Can be used in event selection

Signal and background simulation

- All SUSY signal and SUSY background events generated with Whizard 1.96 with modified omega file to introduce complex parameters
- Beam polarisation $P(e^+,e^-) = (-0.6,0.8)$
- We cross check the results with Herwig++

  → Good agreement

  → Slight differences for asymmetry treated by shifts in the fit
- For detector simulation we use ilc-sw version 01-10 and 01-11
- MarlinReco used for reconstruction
- For SM backgrounds we use LoI mass production (v01-06)
- All relevant processes have been used, including γγ backgrounds

→ Can we use different software versions for the analysis?

Lepton identification

- Lepton identification with cuts on calorimeter and track variables for PFOs:

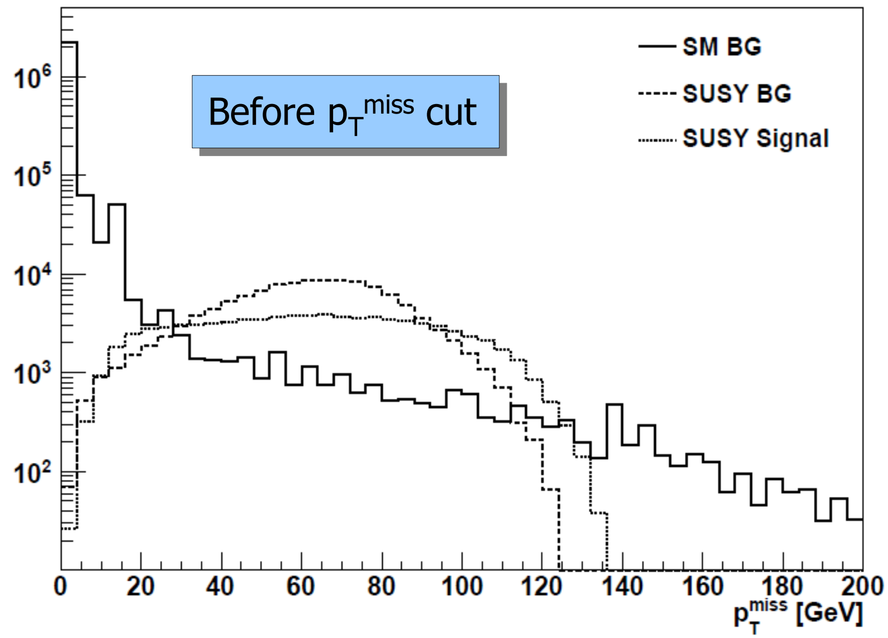
  → Electron identification: $E_{ecal}/E_{tot} > 0.6$, $E_{tot}/p_{Track} > 0.9$

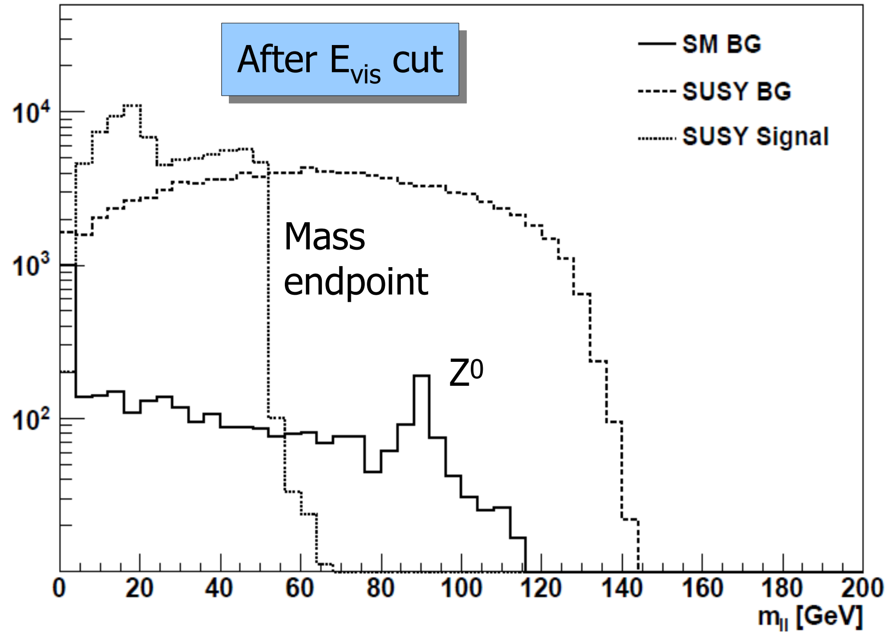
  → Muon identification: $E_{ecal}/E_{tot} < 0.5$, $E_{tot}/p_{Track} < 0.3$
- We do not use any PandoraID functionality

  → Have to compare different software versions

  → Very simple event topology, no jets, only 2 tracks!
- Started to look at ID efficiencies

Event preselection





- Reject events with activity in Bcal
- Select events with 2 OSSF leptons with E > 3 GeV and reject the overlap window for neutralino3 decays, use lepton energy distributions
- Acollinearity and acoplanarity larger than 0.2π
- N_{tracks} < 3 and P_T^{miss} > 20 GeV
- E_{vis} < 150 GeV and invariant lepton mass < 55 GeV

Event preselection (500 fb^{-1})

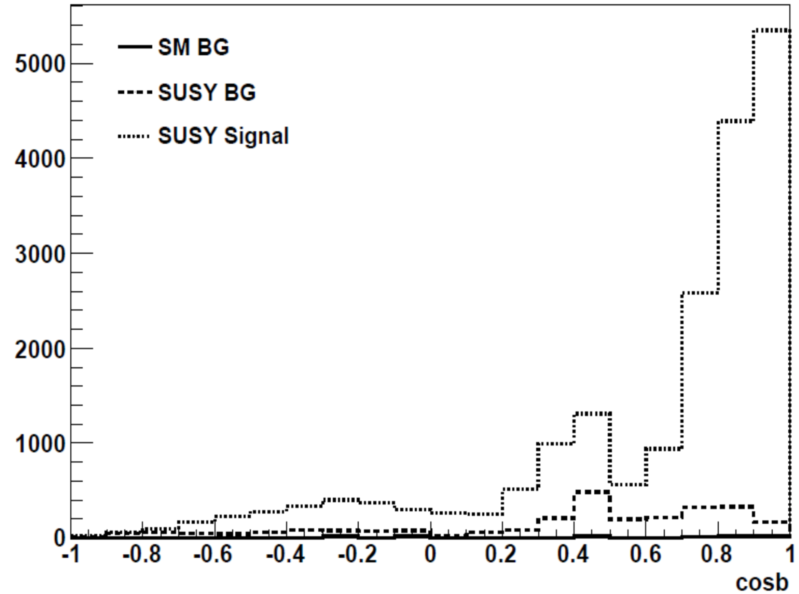
Class	Final state	After lepton selection	After preselection
Signal	$\tilde{\chi}_2^0\tilde{\chi}_1^0 \to \tilde{\chi}_1^0\tilde{\chi}_1^0\ell\ell$ $(\ell \neq \tau)$	32056	28387
	$\tilde{\chi}_3^0\tilde{\chi}_1^0 \to \tilde{\chi}_1^0\tilde{\chi}_1^0\ell\ell$ $(\ell \neq \tau)$	49831	46600
SUSY	$\tilde{l}\tilde{l} \to \tilde{\chi}_1^0\tilde{\chi}_1^0\ell\ell$ $(\ell \neq \tau)$	108883	34441
	$\tilde{\chi}_1^0\tilde{\chi}_1^0\tau\tau$	9215	6111
	$\tilde{\chi}_1^0\tilde{\chi}_1^0\ell\ell\nu\nu$	713	545
SM	$\ell\ell\nu\nu$	8794	1327
	$\tau\tau$	19844	674
	$\ell\ell$ $(\ell \neq \tau)$	27573	148
	ff $(f \neq e, \mu, \tau)$	176191	0
	others	$2.14921 \cdot 10^6$	309

- Select events that solve ONLY ONE of the neutralino reconstruction equations:

Class	only $\tilde{\chi}_2^0$	only $\tilde{\chi}_3^0$	only $\tilde{l}$	only W
$\tilde{\chi}_2^0\tilde{\chi}_1^0 \to \tilde{\chi}_1^0\tilde{\chi}_1^0\ell\ell$ $(\ell \neq \tau)$	17459	557	46	782
$\tilde{\chi}_3^0\tilde{\chi}_1^0 \to \tilde{\chi}_1^0\tilde{\chi}_1^0\ell\ell$ $(\ell \neq \tau)$	54	19648	334	479
SUSY	633	1803	4948	438
SM	64	167	34	84

- Signal efficiency ~30%, SUSY BG efficiency < 0.5%
- Main background from slepton pair production (similar mass as neutralinos)

Further cleaning?



- Ideally a background free sample is required

  → Final cut on cosb distribution possible to further reduce slepton background

  → ~800 background events remain in neutralino3 sample

  → Not used at the moment, we assume the knowledge about slepton background to subtract in asymmetry calculation

We need to be sure that cuts do not bias measured asymmetry!

→ cosb cut eventually does so, would have to correct for this

Fit of neutralino mass matrix

$$
\begin{aligned}
m_{\tilde\chi^0_1} &= 117.3 \pm 0.2 \text{ GeV} , \\
m_{\tilde\chi^0_2} &= 168.5 \pm 0.5 \text{ GeV} , \\
m_{\tilde\chi^0_3} &= 180.8 \pm 0.5 \text{ GeV} , \\
A_2 &= -9.3\% \pm 1\% , \\
A_3 &= 7.8\% \pm 1\% , \\
\sigma(\tilde\chi^0_1\tilde\chi^0_2) \times BR(\tilde\chi^0_2 \to \tilde\ell_R \ell) &= 130.9 \pm 1.4 \text{ fb} , \\
\sigma(\tilde\chi^0_1\tilde\chi^0_3) \times BR(\tilde\chi^0_3 \to \tilde\ell_R \ell) &= 155.7 \pm 1.6 \text{ fb} , \\
\sigma(\tilde\chi^0_2\tilde\chi^0_2) \times BR(\tilde\chi^0_2 \to \tilde\ell_R \ell)^2 &= 4.8 \pm 0.3 \text{ fb} , \\
\sigma(\tilde\chi^0_3\tilde\chi^0_3) \times BR(\tilde\chi^0_3 \to \tilde\ell_R \ell)^2 &= 26.3 \pm 0.7 \text{ fb} , \\
\sigma(\tilde\chi^0_2\tilde\chi^0_3) \times BR(\tilde\chi^0_2 \to \tilde\ell_R \ell) \times BR(\tilde\chi^0_3 \to \tilde\ell_R \ell) &= 28.9 \pm 0.7 \text{ fb}
\end{aligned}
$$

→

$$
\begin{aligned}
|M_1| &= 150.0 \pm 0.7 \text{ GeV} , \\
M_2 &= 300 \pm 5 \text{ GeV} , \\
|\mu| &= 165.0 \pm 0.3 \text{ GeV} , \\
\tan\beta &= 10.0 \pm 1.6 , \\
\phi_1 &= 0.63 \pm 0.05 , \\
\phi_\mu &= 0.0 \pm 0.2 .
\end{aligned}
$$

- 6 dimensional x^2 fit using MINUIT
- Only CP-even observables, except asymmetry
  → Resolving phase ambiguity is only possible due to inclusion of CP asymmetry

Summary and outlook

- SUSY provides additional CP violating phases
- CP asymmetries defined by triple products using leptonic neutralino decays
- Signal can be selected efficiently by event reconstruction
- CP asymmetry can be measured precisely with ILD
- Fit of neutralino mass matrix

  → CP asymmetry necessary to solve CP-phase ambiguities

To do

- Clarify comparability of software versions for our case

  → Do you have any suggestions?
- Can we directly fit distribution of azimuthal angles?
- Finalize write-up of analysis