Measurement of CP violation in the MSSM neutralino sector with the ILD

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- Neutralino decays and CP asymmetry
- Event reconstruction method
- Simulation and event selection
- Mixing matrix fit

SUSY and CP violation

- 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 topologies

→ Can we measure SUSY CP violation at the ILC?

Neutralino sector

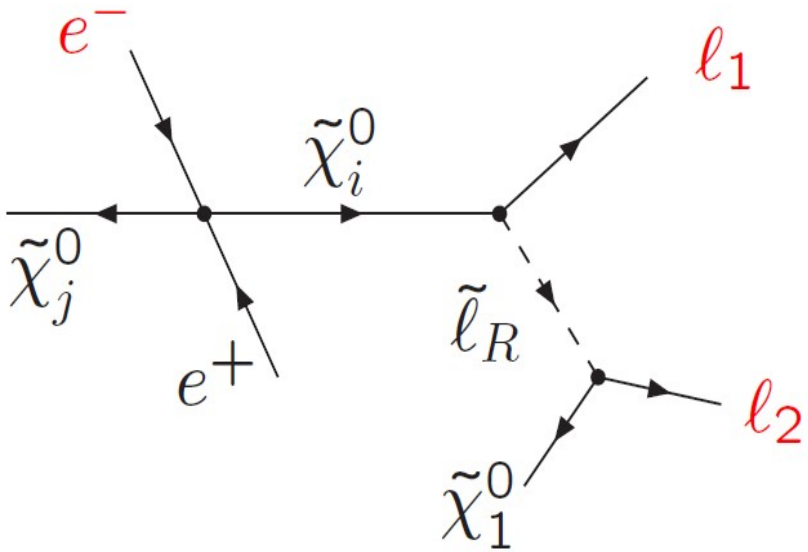
- We use the complex MSSM in this study
- Neutralino mass matrix in gauge eigenstate basis:

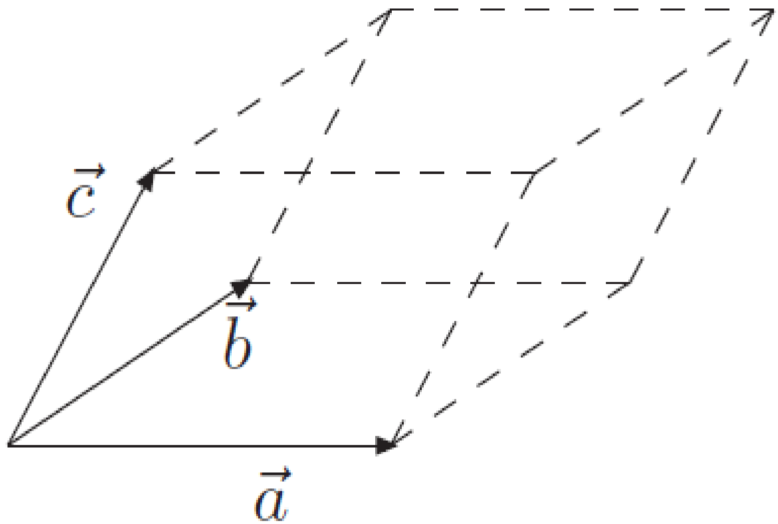
$$\mathcal{M}_0 = \begin{pmatrix} M_1 & 0 & -m_Z \sin(\theta_W)\cos(\beta) & m_Z \sin(\theta_W)\sin(\beta) \\ 0 & M_2 & m_Z \cos(\theta_W)\cos(\beta) & -m_Z \cos(\theta_W)\sin(\beta) \\ -m_Z \sin(\theta_W)\cos(\beta) & m_Z \cos(\theta_W)\cos(\beta) & 0 & -\mu \\ m_Z \sin(\theta_W)\sin(\beta) & -m_Z \cos(\theta_W)\sin(\beta)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

- 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



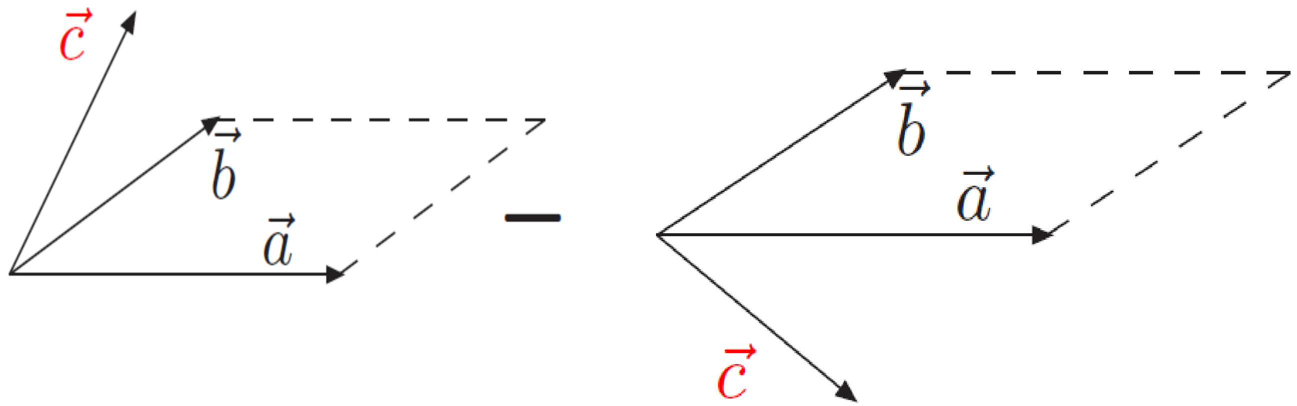


- Consider neutralino pair production (i = 2,3, j = 1) with leptonic decays (l=e,μ)
- Neutralino polarization normal to production plane is CP sensitive
  → CP-odd observable from triple product of momenta:

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

CP asymmetry

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



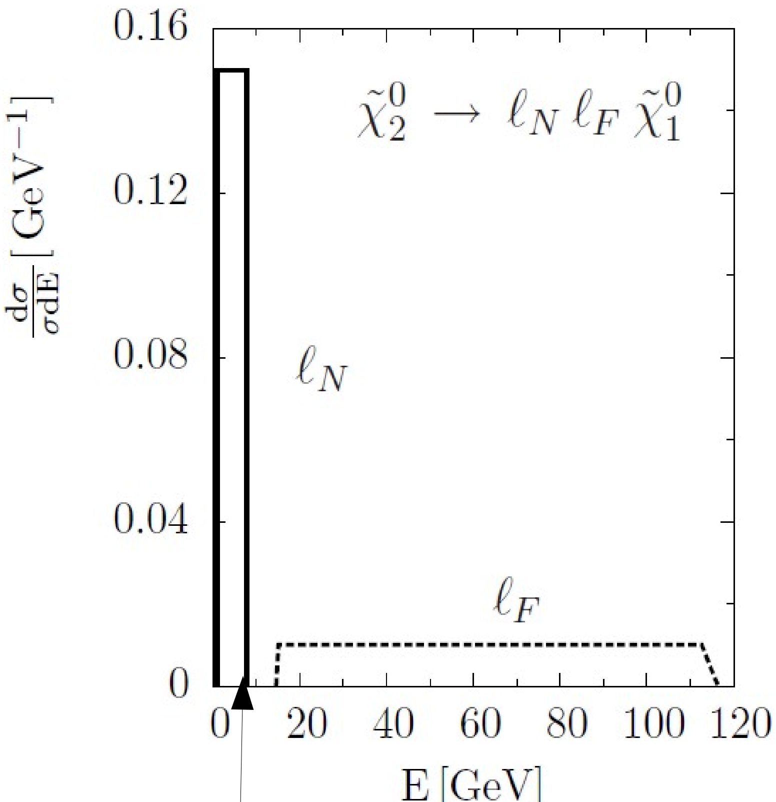
- Measurement of CP asymmetry as counting experiment
  → Measure number of events with positive and negative sign of triple product
  → Have to distinguish between χ_2 and χ_3 decays
- Note: Each (CP-even) background event will reduce measured asymmetry!
  → Find very pure event selection and/or subtract remaining background

Benchmark scenario

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

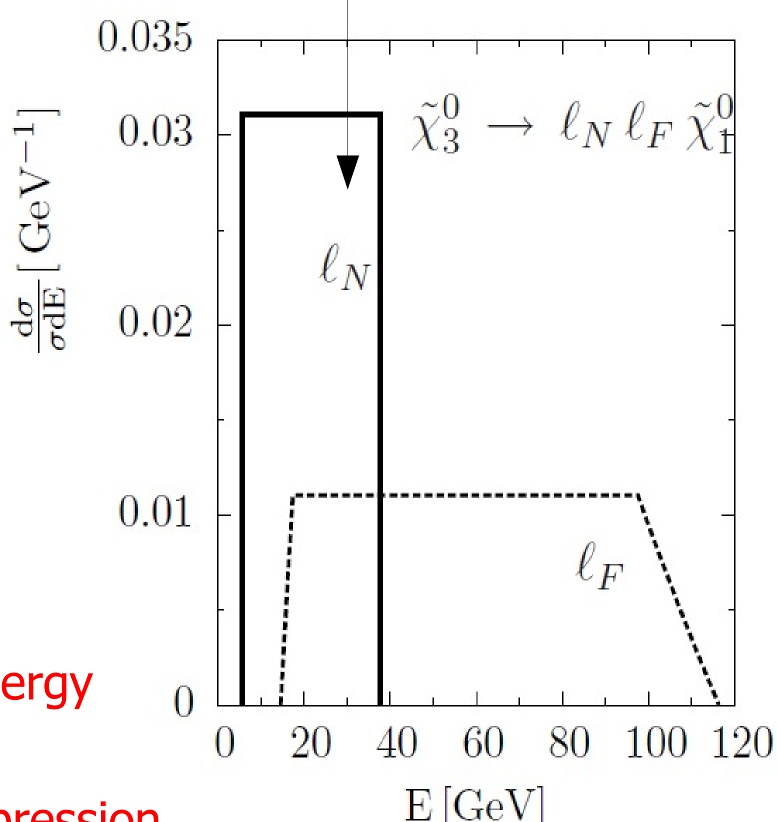
masses	$m_{\tilde{\chi}_1^0} = 118$ GeV	$m_{\tilde{\chi}_1^\pm} = 146$ GeV
	$m_{\tilde{\chi}_2^0} = 169$ GeV	$m_{\tilde{\chi}_2^\pm} = 330$ GeV
	$m_{\tilde{\chi}_3^0} = 181$ GeV	$m_{\tilde{\tau}_1} = 165$ GeV
	$m_{\tilde{\chi}_4^0} = 330$ GeV	$m_{\tilde{\tau}_2} = 280$ GeV
	$m_{\tilde{\nu}} = 268$ GeV	$m_{\tilde{\nu}_\tau} = 268$ GeV
cross sections	$\sigma(e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0) = 244$ fb	$\sigma(e^+e^- \to \tilde{e}_R^+\tilde{e}_R^-) = 304$ fb
	$\sigma(e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_3^0) = 243$ fb	$\sigma(e^+e^- \to \tilde{\mu}_R^+\tilde{\mu}_R^-) = 97$ fb
branching ratios	$\mathrm{BR}(\tilde{\chi}_2^0 \to \tilde{\ell}_R\ell) = 55\%$	$\mathrm{BR}(\tilde{\chi}_2^0 \to \tilde{\tau}_1\tau) = 45\%$
	$\mathrm{BR}(\tilde{\chi}_3^0 \to \tilde{\ell}_R\ell) = 64\%$	$\mathrm{BR}(\tilde{\chi}_3^0 \to \tilde{\tau}_1\tau) = 36\%$
asymmetries	$\mathcal{A}(\tilde{\chi}_1^0\tilde{\chi}_2^0) = -9.2\%$	$\mathcal{A}(\tilde{\chi}_1^0\tilde{\chi}_3^0) = 7.7\%$

Lepton energy distributions



Very low energetic leptons!

Reject events with both leptons in overlap region



- If knowledge about masses is assumed, energy distributions are known

  → Use in event selection, selectron BG suppression

Reconstruction method

- Not enough constraints to completely reconstruct whole event!
- But: Test kinematic on-shell conditions for 2-body decays

→ Is the selected event a neutralino candidate event?

→ Similar conditions for background processes, e.g. slepton or W pair-production

→ Is the selected event (also) a candidate background event?

→ Conditions allow to select events that are exclusively neutralino event candidates and to distinguish χ_2 from χ_3

Reconstruction method - Test

- Test reconstruction method on MC level
  → good separation between signal and background
  → Inefficiencies due to ISR and other effects, that change CM energy

			system solved *only*			
			$\tilde{\chi}_1^0\tilde{\chi}_2^0$	$\tilde{\chi}_1^0\tilde{\chi}_3^0$	$\tilde{\ell}_R^+\tilde{\ell}_R^-$	W^+W^-
truth process	64 k	$\tilde{\chi}_1^0\tilde{\chi}_2^0$	41566	788	103	860
truth process	74 k	$\tilde{\chi}_1^0\tilde{\chi}_3^0$	100	25535	432	1222
truth process	200 k	$\tilde{\ell}_R^+\tilde{\ell}_R^-$	181	1801	45390	3507
truth process	8.8 k	W^+W^-	0	13	38	6805
		purity	99%	91%	99%	55%
		efficiency	65%	35%	23%	77%

Very low energetic leptons
→ unlikely to fulfill another condition

High energetic leptons
→ Events can fulfill slepton or W condition

Signal and background simulation

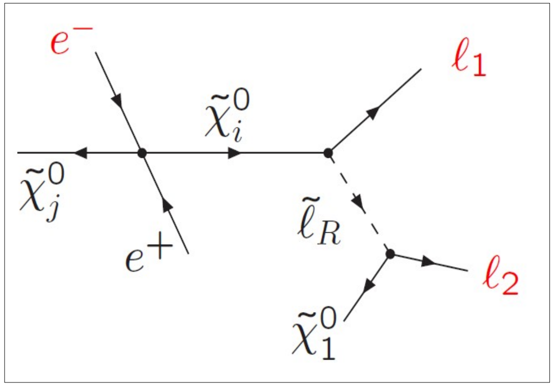
- All SUSY signal and SUSY background events generated with Whizard 1.96 with modified omega file to introduce complex parameters
- Beam polarisation $P(e^+,e^-) = (-0.6,0.8)$
- Cross checked results with Herwig++

  → Good agreement
- Events passed through full ILD detector simulation

  → Effects of ISR and beamstrahlung taken into account
- For SM backgrounds we use LoI mass production
- All relevant processes have been used, including γγ backgrounds

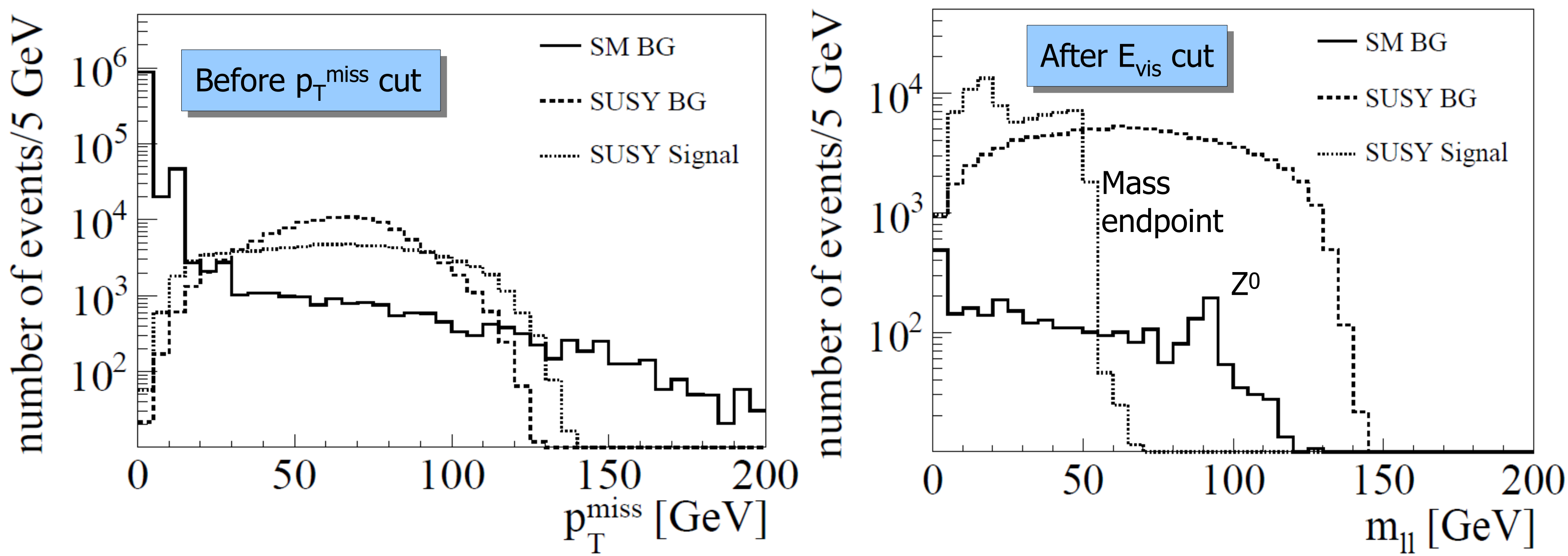
Thanks to Jan Engels and Steve Aplin for the simulations!

Event preselection



initial selection	no significant activity in BCAL
	number of all tracks $N_{\text{tracks}} \leq 7$
lepton selection	$\ell^+\ell^-$ pair with $\ell = e, \mu$
	$\theta > 8°$, min. energy $E > 3$ GeV
	lower energetic ℓ with $E < 18$ GeV, or
	higher energetic ℓ with $E > 38$ GeV
	higher energetic ℓ with $E \in [15, 150]$ GeV
	$\theta_{\text{acop}} > 0.2\pi$, $\theta_{\text{acol}} > 0.2\pi$
final preselection	$\mathbf{p}_{\text{T}}^{\text{miss}} > 20$ GeV
	$E_{\text{vis}} < 150$ GeV
	$m_{\ell\ell} < 55$ GeV

Event preselection



→ Sample can already be cleaned up efficiently with simple cuts

Event preselection (500 fb^{-1})

class	final state	after lepton selection	after preselection
signal	$\tilde{\chi}^0_1\tilde{\chi}^0_2 \to \tilde{\chi}^0_1\tilde{\chi}^0_1\ell\ell\ (\ell \neq \tau)$	31543	28039
	$\tilde{\chi}^0_1\tilde{\chi}^0_3 \to \tilde{\chi}^0_1\tilde{\chi}^0_1\ell\ell\ (\ell \neq \tau)$	49084	45966
SUSY	$\tilde{\ell}\tilde{\ell} \to \tilde{\chi}^0_1\tilde{\chi}^0_1\ell\ell\ (\ell \neq \tau)$	108302	34223
	$\tilde{\chi}^0_1\tilde{\chi}^0_1\tau\tau$	5147	4076
	$\tilde{\chi}^0_1\tilde{\chi}^0_1\ell\ell\nu\nu$	681	528
SM	$\ell\ell\nu\nu$	8241	1196
	$\tau\tau$	13017	360
	$\ell\ell\ (\ell \neq \tau)$	24113	0
	$ff\ (f \neq e, \mu, \tau)$	1380	0
	$\gamma\gamma$	917355	272

- Select events that solve ONLY ONE of the event reconstruction conditions:

class	only $\tilde{\chi}^0_1\tilde{\chi}^0_2$	only $\tilde{\chi}^0_1\tilde{\chi}^0_3$	only $\tilde{\ell}^+_R\tilde{\ell}^-_R$	only W^+W^-
$\tilde{\chi}^0_1\tilde{\chi}^0_2 \to \tilde{\chi}^0_1\tilde{\chi}^0_1\ell\ell\ (\ell \neq \tau)$	18343	615	51	855
$\tilde{\chi}^0_1\tilde{\chi}^0_3 \to \tilde{\chi}^0_1\tilde{\chi}^0_1\ell\ell\ (\ell \neq \tau)$	290	20132	372	635
all SUSY background	1153	3055	5626	951
all SM background	87	256	44	81
purity	92%	84%	92%	–
efficiency	29%	27%	–	–

- Main background from slepton pair production (similar mass as neutralinos)

→ Use selected events to calculate asymmetry

Asymmetry measurement

Problems:

- Asymmetry shifted to lower values due to background contamination

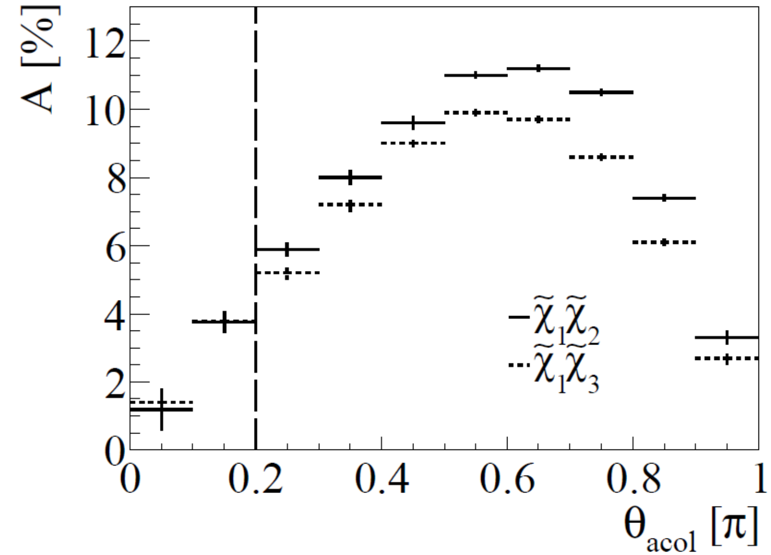
  → Study background in detail and correct for effects

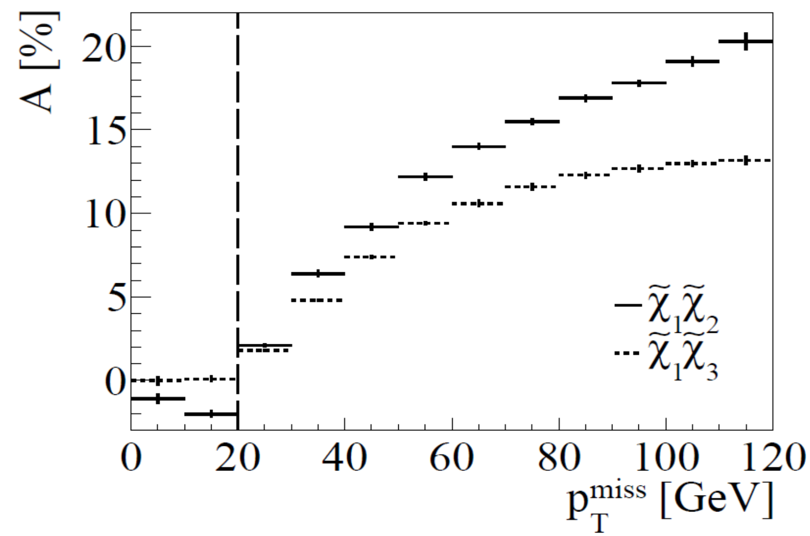
- Asymmetry shifted to higher values due to cut bias

  → Study bias in MC

  → Whizard and Herwig consistently show 2% effect for our selection

- Effects taken into account in fit





Fit of neutralino mass matrix

$$m_{\tilde\chi^0_1} = 117.3 \pm 0.2 \text{ GeV},$$
$$m_{\tilde\chi^0_2} = 168.5 \pm 0.5 \text{ GeV},$$
$$m_{\tilde\chi^0_3} = 180.8 \pm 0.5 \text{ GeV},$$
$$\sigma(\tilde\chi^0_1\tilde\chi^0_2) \times \mathrm{BR}(\tilde\chi^0_2 \to \tilde\ell_R \ell) = 130.9 \pm 1.4 \text{ fb},$$
$$\sigma(\tilde\chi^0_1\tilde\chi^0_3) \times \mathrm{BR}(\tilde\chi^0_3 \to \tilde\ell_R \ell) = 155.7 \pm 1.6 \text{ fb},$$
$$\sigma(\tilde\chi^0_2\tilde\chi^0_2) \times \mathrm{BR}(\tilde\chi^0_2 \to \tilde\ell_R \ell)^2 = 4.8 \pm 0.3 \text{ fb},$$
$$\sigma(\tilde\chi^0_3\tilde\chi^0_3) \times \mathrm{BR}(\tilde\chi^0_3 \to \tilde\ell_R \ell)^2 = 26.3 \pm 0.7 \text{ fb},$$
$$\sigma(\tilde\chi^0_2\tilde\chi^0_3) \times \mathrm{BR}(\tilde\chi^0_2 \to \tilde\ell_R \ell) \times \mathrm{BR}(\tilde\chi^0_3 \to \tilde\ell_R \ell) = 28.9 \pm 0.7 \text{ fb},$$
$$\mathcal{A}^{\mathrm{CP}}(\mathbf{p}_{e^-}, \mathbf{p}_{\ell_N}, \mathbf{p}_{\ell_F})_{\tilde\chi^0_1\tilde\chi^0_2} = -11.3\% \pm 0.7\%,$$
$$\mathcal{A}^{\mathrm{CP}}(\mathbf{p}_{e^-}, \mathbf{p}_{\ell_N}, \mathbf{p}_{\ell_F})_{\tilde\chi^0_1\tilde\chi^0_3} = +10.9\% \pm 0.7\%.$$

→

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

'True' CP asymmetry corrected for background, cut bias eliminated in fit

- 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 with ILD
- Fit of neutralino mass matrix

  → CP asymmetry necessary to solve CP-phase ambiguities

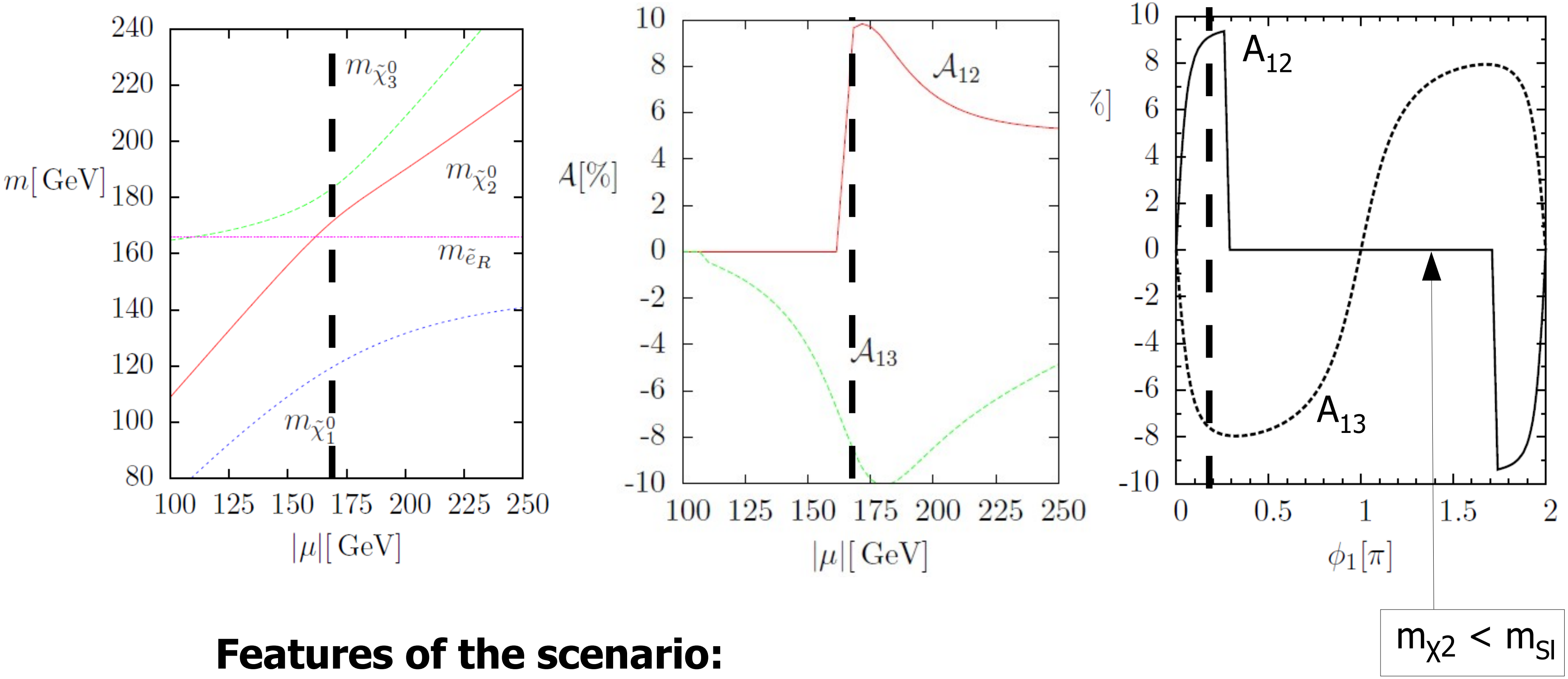
Next steps:

- Disentangle effects from several phases

  → Measure CP asymmetries in other sectors

  → CP-violating rate asymmetries due to loop induced effects

Benchmark scenario



Features of the scenario:

- Large asymmetries
- Efficient distinction between near and far lepton

  → Not used for asymmetry determination, but for event selection

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: $E_{ecal}/E_{tot} < 0.5$, $E_{tot}/p_{Track} < 0.3$

  → Relax cuts for low energetic muons
- We do not use any PandoraID functionality

  → Known to have bugs (in the version used for BG production)

  → Very simple event topology, no jets, only 2 tracks!