Probing the Majorana Nature and CP Properties of Neutralinos

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– Mechanism –

$$e^+e^- \to \tilde{\chi}_i^0 \tilde{\chi}_j^0 \oplus \tilde{\chi}_i^0 \to \tilde{\chi}_j^0 f \bar{f} \oslash \tilde{\chi}_i^0 \to \tilde{\chi}_j^0 Z$$

– References –

Majorana, NuCi14, 1937

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Petcov, PLB139, 1984

Bilenky, Khristova, Nedelcheva, BJP13, 1986

Gunion, Haber, PRD37, 1988

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Moortgat–Pick, Fraas, EPJC25, 2002

SYC, Kalinowski, Moortgat–Pick, Zerwas, EPJC22, 2001

Kalinowski, ActaPPB34, 2003

Aguilar–Saavedra, Teixeira, NPB675, 2003

SYC, hep–ph/0308060 (to appear in PRD)

SYC, Y.G. Kim, PRD69, 2004

⋮

LCWS2004 @ Paris, France

Characteristics

- Spin-$1/2$ Superpartners

  – Neutralinos are mixtures of gauginos/higgsinos with EWSB.

$$\mathcal{M}_N = \begin{pmatrix} |M_1|\,\mathrm{e}^{i\Phi_1} & 0 & -m_Z\,c_\beta s_W & m_Z\,s_\beta s_W \\ 0 & M_2 & m_Z\,c_\beta c_W & -m_Z\,s_\beta c_W \\ -m_Z\,c_\beta s_W & m_Z\,c_\beta c_W & 0 & -|\mu|\,\mathrm{e}^{i\Phi_\mu} \\ m_Z\,s_\beta s_W & -m_Z\,s_\beta c_W & -|\mu|\,\mathrm{e}^{i\Phi_\mu} & 0 \end{pmatrix}$$

$$\widetilde{\chi}_i^0 = N_{i1}\,\widetilde{B} + N_{i2}\,\widetilde{W}^3 + N_{i3}\,\widetilde{H}_1^0 + N_{i4}\,\widetilde{H}_2^0$$

  – Phases $\Phi_1 \oplus \Phi_\mu$ render the matrix N complex, violating CP.

- Light Sparticles $\ni$ LSP: Best DM candidate

- Majorana: $\psi = \psi^c \equiv C\bar{\psi}^{\mathrm{T}} \quad \Rightarrow$ Characteristic Couplings

$$\overline{\psi}_i\,[J_\mu^{ij}]\,\psi_j = \overline{\psi}_i\,[i\Im\mathrm{m}(C_{ij})\,\gamma_\mu + \Re\mathrm{e}(C_{ij})\,\gamma_\mu\gamma_5]\,\psi_j$$

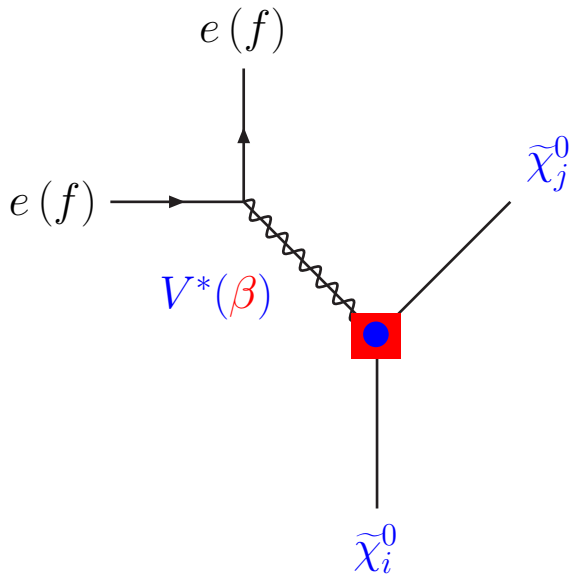
CP $\oplus\ \eta^i = \pm\eta^j$	$\Rightarrow$	$\Im\mathrm{m}(C_{ij})/\Re\mathrm{e}(C_{ij}) = 0$	$\Rightarrow$ Only A/V
CP Violation	$\Rightarrow$	$\Im\mathrm{m}(C_{ij})/\Re\mathrm{e}(C_{ij}) \neq 0$	$\Rightarrow$ Both A/V

  – $\eta^i = \pm\sqrt{-1}$ is the $\widetilde{\chi}_i^0$ intrinsic parity

  – Diagonal couplings C_{ii} must be real (*cf.* $\not\ni$ e–charges).

  – CP inv.: at least one of three cyclic pairs $C_{ij,jk,ki}$ is real.

Mechanism



$\Rightarrow$: $e^+e^- \to \widetilde{\chi}_i^0 \widetilde{\chi}_j^0$

$\Uparrow$: $\widetilde{\chi}_i^0 \to \widetilde{\chi}_j^0 f \bar{f}$

Z : $\widetilde{\chi}_i^0 \to \widetilde{\chi}_j^0 Z$

- 5 diagrams: s–channel $Z \oplus t$–channel $\widetilde{f}_{L,R} \oplus u$–channel $\widetilde{f}_{L,R}$
- $m_f/m_e \approx 0$ lead effectively to the characteristic amplitude structure

$$\mathcal{P}(e^+e^- \to \tilde{\chi}_i^0 \tilde{\chi}_j^0) \sim \mathcal{E}^\mu \left[\bar{u}(\chi_i)\, J_\mu^{ij}\, v(\chi_j) \right]$$
$$\mathcal{D}(\tilde{\chi}_i^0 \longrightarrow \tilde{\chi}_j^0\, f \bar{f}) \sim \mathcal{F}^\mu \left[\bar{u}(\chi_j) J_\mu^{ij}\, u(\chi_i) \right]$$

  - Both $\mathcal{E}^\mu$ and $\mathcal{F}^\mu$ are of both V and A (P violation).
  - $\mathcal{E}^\mu$ and $\mathcal{F}^\mu$ are real and momentum–dependent.
  - For on-shell Z, $\mathcal{F}^\mu$ replaced by the Z polarization vector Z^μ.
  - $\mathcal{E}^\mu$ and $\mathcal{F}^\mu$ w/ only spatial components near threshold

- Opposite CP relations for production and decays

$$\mathcal{P} \;:\; 1 = +\eta^i\eta^j\,(-1)^L$$
$$\Updownarrow$$
$$\mathcal{D} \;:\; 1 = -\eta^i\eta^j\,(-1)^L \Leftarrow \eta^i = \eta^j\,(-1)^L$$

  - L: neutralino–pair orbital ang. mom. near threshold
  - Why different?: Negative particle-antiparticle intrinsic parity
  - Complex phases spoil the CP relations.

- Opposite threshold behaviors for production and decays

$$\mathcal{P} : \mathcal{E}^\mu \left[\bar{u}(\chi_i)\,(A_\mu, V_\mu)\,\underline{\underline{v(\chi_j)}}\right] \sim \underline{\underline{(\beta, 1)}} \quad [\,\beta \sim \sqrt{s - (m_i + m_j)^2}\,]$$
$$\Updownarrow \qquad\qquad \Updownarrow$$
$$\mathcal{D} : \mathcal{F}^\mu \left[\bar{u}(\chi_j)\,(A_\mu, V_\mu)\,\overline{\overline{u(\chi_i)}}\right] \sim \overline{\overline{(1, \beta)}} \quad [\,\beta \sim \sqrt{(m_i - m_j)^2 - m_{ff}^2}\,]$$

  - $\sqrt{s}$: e^+e^- c.m. energy and m_{ff}: 2-fermion inv. mass
  - CP inv.: $\eta^i = \pm\eta^j \Rightarrow \mathcal{P}/\mathcal{D} : (P/S, S/P) \sim (\beta^3/\beta, \beta/\beta^3)$
  - CP non-inv.: (β, β), *i.e.* both S–waves

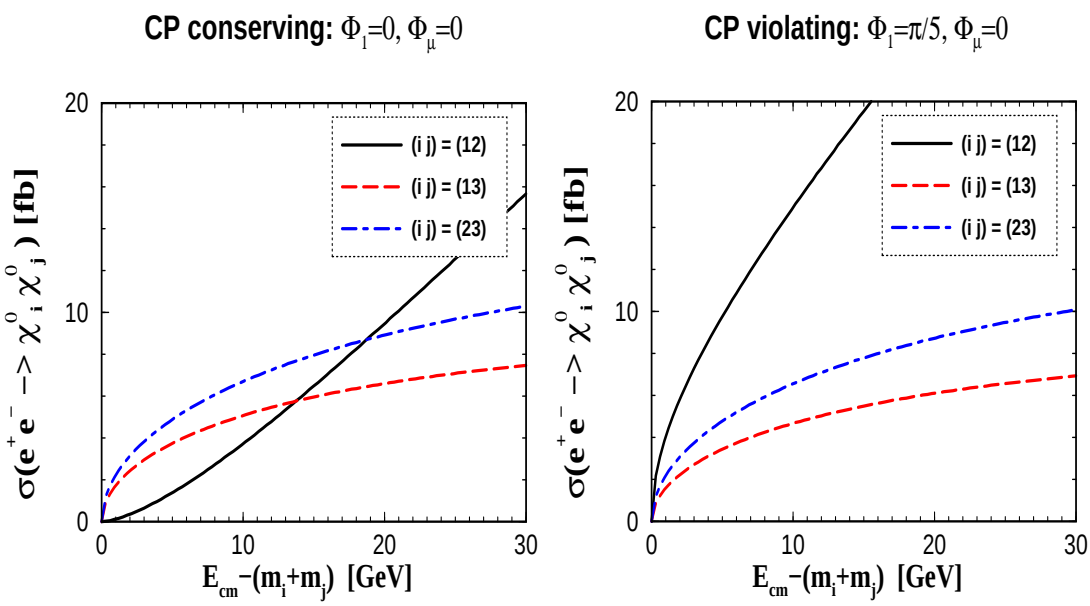
Pair–production $\oplus$ 3–body Decays

Recipe 1: Production of 3 neutralino pairs

[Kalinowski, Acta PPB34, 2003]

$\tan\beta = 10, |M_1| = 100.5\,\mathrm{GeV}, M_2 = 190.8\,\mathrm{GeV}, |\mu| = 365.1\,\mathrm{GeV}$

$m_{\tilde{e}_L} = 208.7$ GeV, $m_{\tilde{e}_R} = 144.1$ GeV



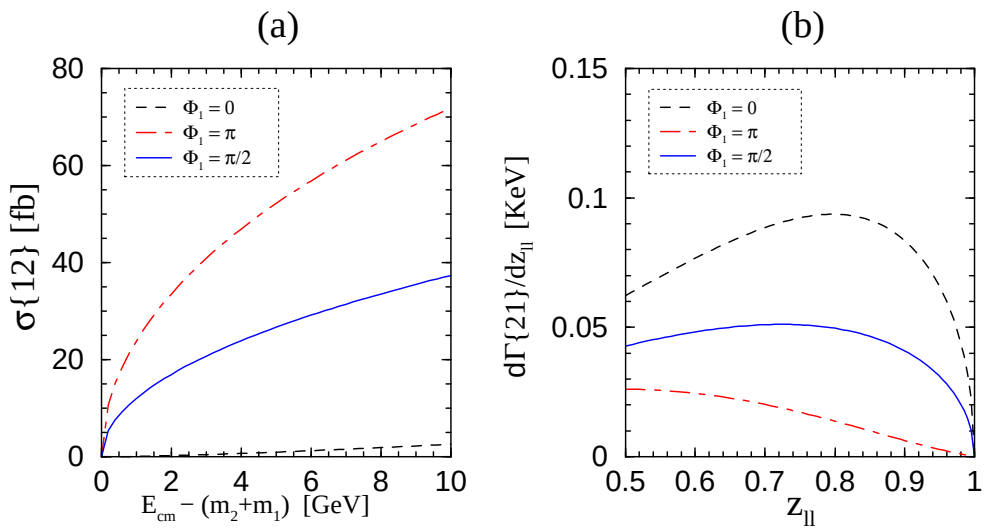
- Left: (13) & (23): S–waves but (12): P-wave $\Rightarrow$ CP inv.
- Right: All S–waves $\Rightarrow$ CP violation in the neutralino system.
- Three different threshold scans are needed.

Recipe 2: Production $\oplus$ decay correlations

[SYC, hep–ph/0308060, to appear in PRD]

$\tan\beta = 10, |M_1| = 100\,\mathrm{GeV}, M_2 = 150\,\mathrm{GeV}, |\mu| = 100\,\mathrm{GeV}, \Phi_\mu = 0$

$m_{\tilde{f}_L} = 250$ GeV, $m_{\tilde{f}_R} = 200$ GeV



- Condition: $m_i - m_j < m_Z, m_{\tilde{f}_{L,R}}$, *i.e.* no 2-body modes allowed
- $\Phi_1 = 0/\pi$: $\eta^i = \pm\eta^j \Rightarrow \mathcal{P}$: P/S–wave $\oplus$ $\mathcal{D}$: S/P–wave
- $\Phi_1 = \pi/2 \Rightarrow$ both $\mathcal{P}$ and $\mathcal{D}$: S–waves $\Rightarrow$ CP Violation

◇ The light (12) pair may be sufficient for claiming CP violation!!

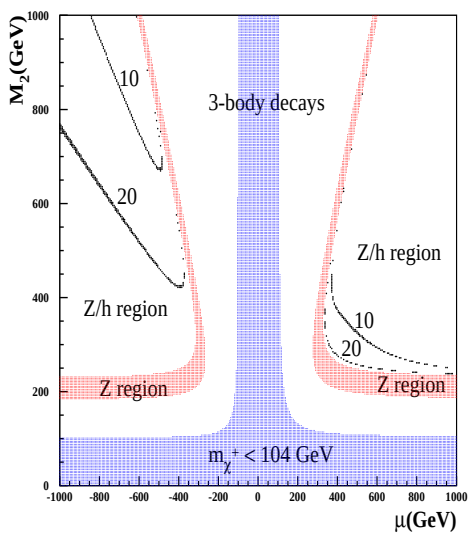
- Global structures are sensitive to sfermion/neutralino spectra
  $\Rightarrow$ Detailed analyses needed [Nojiri, Yamada, PRD60, 1999]
- $m_i - m_j > m_Z \Rightarrow$ clean 2–body decays, $\tilde{\chi}_i^0 \to \tilde{\chi}_j^0 Z$, expected.

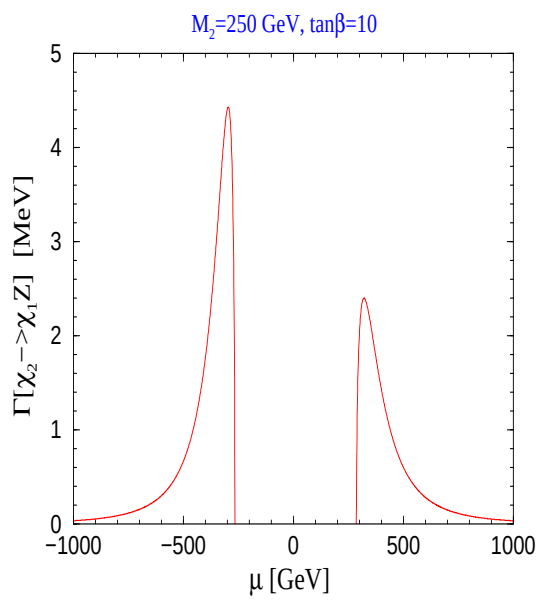
$\tilde{\chi}_i^0 \to \tilde{\chi}_j^0 Z$

Possibility: Branching ratios

[SYC and Y.G. Kim, PRD69, 2004]

$\tan\beta = 10, \quad |M_1| \approx 1/2\, M_2$ and $m_h = 115$ GeV

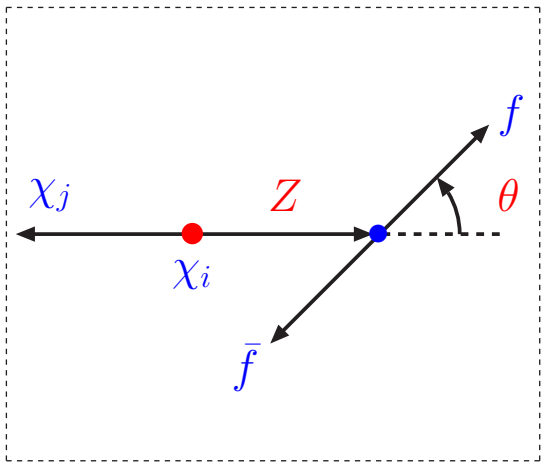




- <u>Condition</u>: $2m_Z \lesssim M_2 \lesssim 2|\mu| \oplus$ large higgsino comp. for $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 Z$
- $\tilde{\chi}_{3,4}^0 \to \tilde{\chi}_1^0 Z$ allowed for most parameter space
- The decoupling scenario for the Higgs system is assumed.

Recipe 3: Z polarization

- Z helicity reconstruction



$$\frac{d\Gamma_{\rm corr}}{dc_\theta} = (\Gamma[+] + \Gamma[-])\,(1 + c_\theta^2) + (\Gamma[+] - \Gamma[-])2\xi_f c_\theta + 2\Gamma[\,0\,]s_\theta^2$$

$$\begin{aligned} \Gamma[\pm] &\sim \mu_i^2 + \mu_j^2 - 1 - 2\mu_i\mu_j\,\mathcal{A}_N \\ \Gamma[\,0\,] &\sim \lambda_Z + \mu_i^2 + \mu_j^2 - 1 - 2\mu_i\mu_j\,\mathcal{A}_N \end{aligned}$$

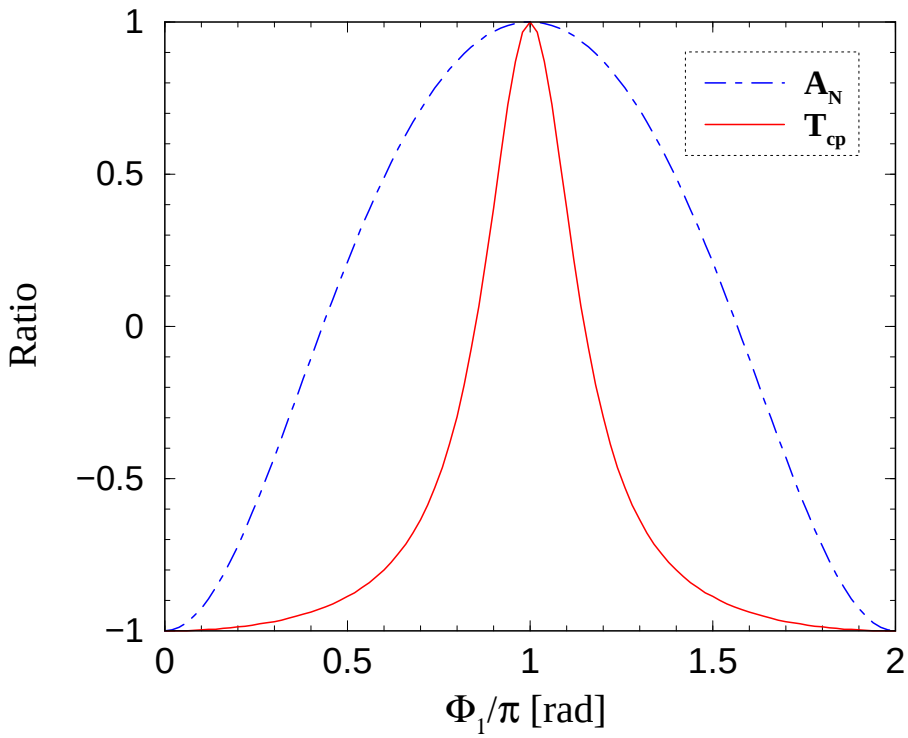
$$\mathcal{A}_N = \frac{|V|^2 - |A|^2}{|V|^2 + |A|^2}$$

- Majorana: $\Gamma[+] = \Gamma[-] \Rightarrow$ no forward-backward asymmetry
- CP inv.: $\mathcal{A}_N = \mp 1$ and $\Gamma[0]/\Gamma[\pm] = (\mu_i \mp \mu_j)^2$ for $\eta^i = \pm\eta^j$
- CP noninv.: $\mathcal{A}_N \neq \pm 1$
- $\mu_i = m_i/m_Z$ and $\xi_f = 2v_f a_f/(v_f^2 + a_f^2)$

- A probe of CP violation

$$\mathcal{T}_{\rm CP} = \frac{\Gamma[\,0\,]/\Gamma[\pm] - (\mu_i^2 + \mu_j^2)}{2\mu_i\mu_j}$$

$\tan\beta = 10, M_2 = 250\,\mathrm{GeV}, |\mu| = 500\,\mathrm{GeV}, \Phi_\mu = 0$



– $\Phi_\mu = 0 \oplus$ large $|\mu|$ to avoid severe EDM constraints

– Large $\tan\beta$ renders $\mathcal{T}_{\rm CP}$ insensitive to Φ_μ

– Neutralino masses must known before measuring the ratios.

Summary

Neutralinos: Majorana–type couplings $\otimes$ CP violation with phases

$\Uparrow$

Pair production $\oplus$ 3-body decays $\oslash$ $\chi_i \to \chi_j Z$

- Recipe 1: Thres. scans of production of 3 non–diagonal cyclic pairs
- Recipe 2: Thres. scans of production/decay of a non-diagonal pair
- Recipe 3: Measure Z–polarization as a powerful diagnostic tool.
- Production/decay spin/angular correlations [Moortgat-Pick, Fraas, 200]
- Symmetric 2–lepton energy distribution [Petcov, 1984]
- Direct/indirect CP observables [Hesselbach, this workshop]
- $\widetilde{\chi}^0$ exchange in $e^-e^- \to \tilde{e}^-\tilde{e}^-$ [Aguilar–Saavedra, Teixeira, 2003]
- Most ambitious approach is to measure all relevant SUSY parameters. [See, for instance, SYC, Kalinowski, Moortgat–Pick, Zerwas, 2001]

Conclusion

Once neutralinos are produced copiously at LC, their Majorana nature and CP properties can be probed with good precision through production/decay threshold scans or by Z polarization measurements.