Probing the Majorana Nature and CP Properties of Neutralinos

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– Mechanism –

$$e^+e^- \to \chi_i\chi_j \oplus \chi_i \to \chi_j f\bar{f} \oslash \chi_i \to \chi_j Z$$

– References –

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

Kalinowski, ActaPPB34, 2003

SYC, PRD69, 2004

SYC, Y.G. Kim, PRD69, 2004

SYC, B.C. Chung, Kalinowski, Y.G. Kim, Rolbiecki, hep-ph/0504112

Spin-1/2 Neutral Superpartners

Neutralinos are mixtures of gauginos/higgsinos with EWSB.

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

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

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

Light Sparticles ∋ LSP: Best CDM candidate

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

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

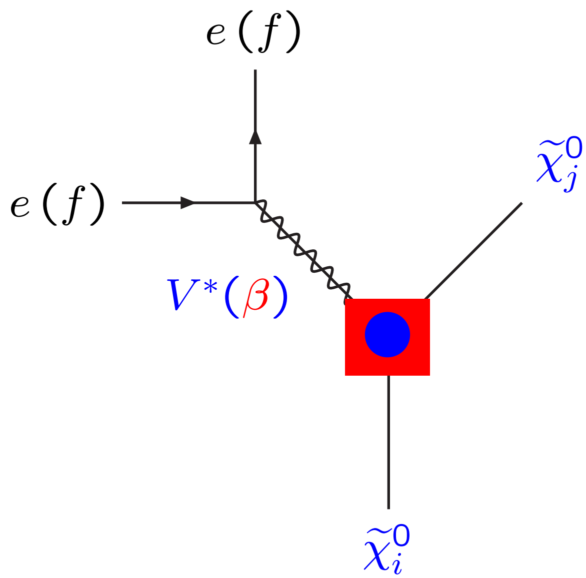
CP $\oplus$ $\eta^i = \pm\eta^j$ $\Rightarrow$ $\Im\mathrm{m}(C_{ij})/\Re\mathrm{e}(C_{ij}) = 0$ $\Rightarrow$ Only A/V

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 χ_i 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.



$\Rightarrow$: $e^+e^- \to \chi_i\chi_j$

$\Uparrow$: $\chi_i \to \chi_j f\bar{f}$

Z : $\chi_i \to \chi_j\, Z$

s–channel Z

$\oplus$ t–channel $\widetilde{f}_{L,R}$

$\oplus$ u–channel $\widetilde{f}_{L,R}$

$m_f/m_e \approx 0 \Rightarrow$ characteristic amplitude structure

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

Both $\mathcal{E}^\mu$ and $\mathcal{F}^\mu$ are of both V and A (P violation), and (almost) real.

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

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

$$\Updownarrow$$

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

L: orbital angular momentum of the final state system near threshold

Why different?: Negative particle-antiparticle intrinsic parity

Complex phases spoil the CP relations.

Derivation of $\eta_{\rm CP} = \pm\sqrt{-1}$

Assume that the decay process of a neutral vector boson V^0 to $\chi\chi$ conserves CP and consider the case when the outgoing neutralinos are non–relativistic.

Since the final state should obviously be anti–symmetric, it must then be a state with ${}^{2S+1}L_J = {}^3P_1$, since this is the only non–relativistic, antisymmetric state with $J = 1$.

$$O_{\rm CP}\,|\chi(\vec{p},s)\rangle = \eta_{\rm CP}\,|\chi(-\vec{p},s)\rangle \quad\Rightarrow\quad O_{\rm CP}\,|\chi\chi;{}^3P_1\rangle = \eta^2_{\rm CP}\,(-1)^L\,|\chi\chi;{}^3P_1\rangle$$

Since $O_{\rm CP}[V^0] = +1$ and $L[\chi\chi] = 1$, the CP conservation demands that $\eta_{\rm CP} = \pm\sqrt{-1}$.

Derivation of $\eta_{\rm CP} = \pm\sqrt{-1}$

Opposite threshold behaviors for production and decays

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

$$\Updownarrow \qquad\qquad \Updownarrow$$

$$\mathcal{D}ec : \mathcal{F}^\mu \left[\bar{u}(\chi_j)\,(A_\mu, V_\mu)\,\overline{\overline{u(\chi_i)}}\right] \sim \overline{\overline{(1,\beta)}} \quad [\,\beta \sim \sqrt{(m_i-m_j)^2-m_{ff}^2}\,]$$

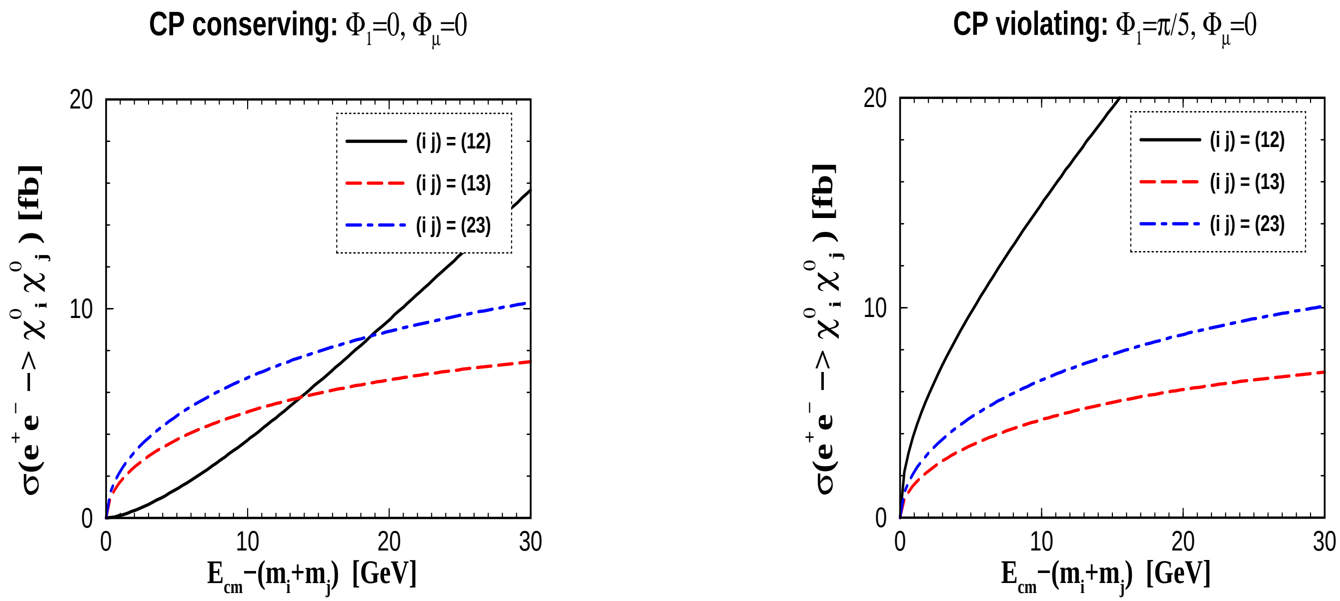
$\sqrt{s}$: e^+e^- c.m. energy and m_{ff}: 2-fermion inv. mass

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.: $(\beta,\beta) \Rightarrow$ both S–waves

Production of 3 neutralino pairs

$\tan\beta = 10, |M_1| = 100.5, M_2 = 190.8, |\mu| = 365.1, m_{\tilde{e}_L} = 208.7, m_{\tilde{e}_R} = 144.1$ GeV

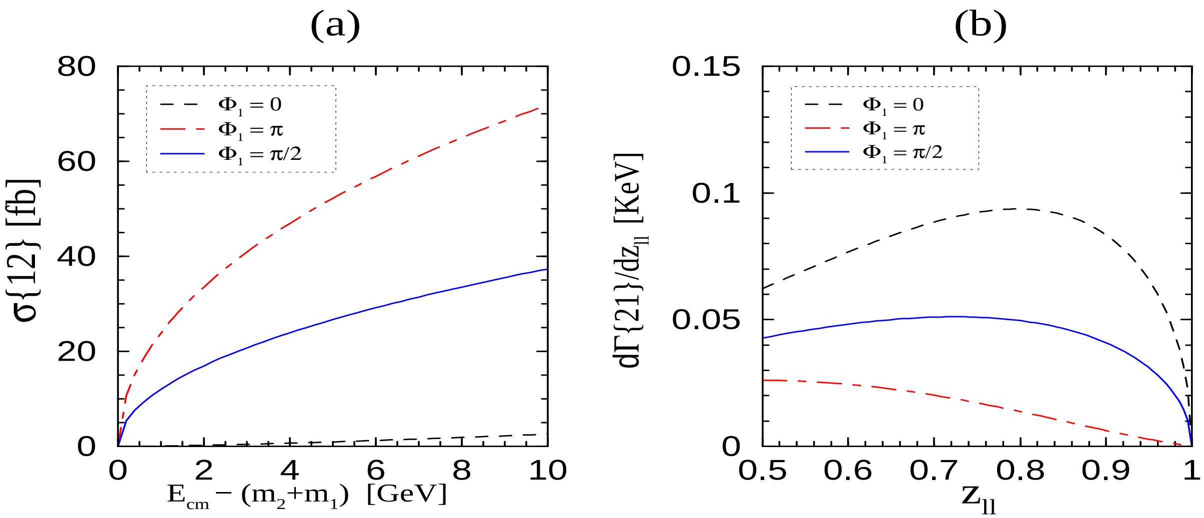


Left: (13) & (23): S–waves but (12): P-wave ⇒ CP inv.

Right: All S–waves ⇒ CP violation in the neutralino system.

Three different threshold scans are needed.

$\tan\beta = 10, |M_1| = 100, M_2 = 150, |\mu| = 100\,\text{GeV}, \Phi_\mu = 0, m_{\tilde{f}_L} = 250, m_{\tilde{f}_R} = 200$ 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 ⊕ $\mathcal{D}$: S/P–wave

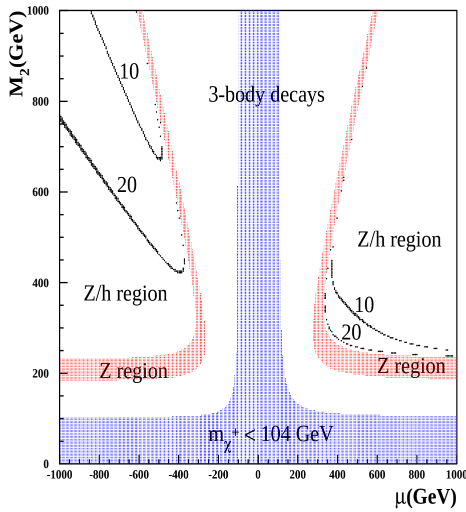
$\Phi_1 = \pi/2 \Rightarrow$ both $\mathcal{P}$ and $\mathcal{D}$: S–waves $\Rightarrow$ CP Violation

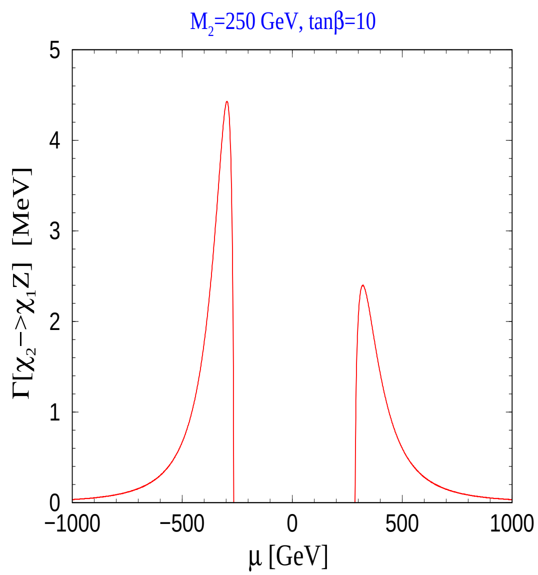
The light (12) pair may be sufficient for claiming CP violation!!

Global structures sensitive to sfermion/neutralino spectra ⇒ Detailed analyses

Possibility: Branching ratios

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





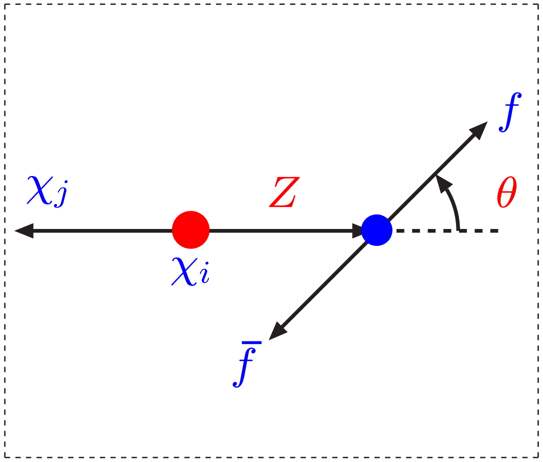
Condition: $2m_Z \lesssim M_2 \lesssim 2|\mu|$ ⊕ large higgsino comp. for $\tilde{\chi}^0_2 \to \tilde{\chi}^0_1\, Z$

$\tilde{\chi}^0_{3,4} \to \tilde{\chi}^0_1\, Z$ allowed for most parameter space

The decoupling scenario for the Higgs system is assumed.

Z helicity reconstruction

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



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

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

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 $\eta^i = \pm\eta^j$

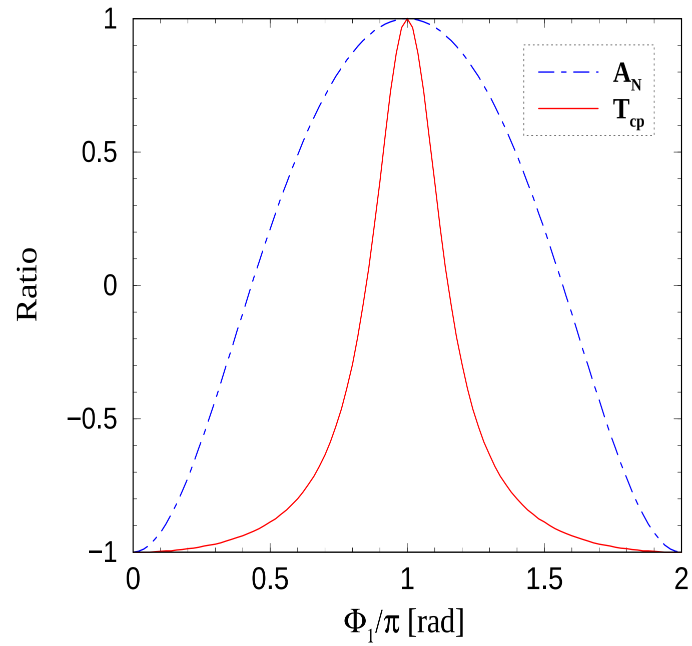
CP noninv.: $\mathcal{A}_N \neq \pm 1$

$\mu_i = m_i/m_Z$ and $\xi_f = 2v_f a_f/(v_f^2+a_f^2)$

A probe of CP violation

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

$\tan\beta = 10, M_2/|\mu| = .25/.5\,\text{TeV}, \Phi_\mu = 0$



$\Phi_\mu = 0$ ⊕ 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.

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

Symmetric 2–lepton energy distribution

Direct/indirect CP observables

χ exchange in $e^- e^- \to \tilde{e}^- \tilde{e}^-$

Most ambitious to measure all relevant SUSY parameters

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.

Fully–Correlated Production–Decay Chains

Loop Corrections??

Dominant Background Processes

Event Generations

Realistic Simulations