Probing the Majorana Nature and CP Properties of Neutralinos

S.Y. Choi (Chonbuk National University)

– Mechanism –

\[ e^+e^- \rightarrow \tilde{\chi}_i^0 \tilde{\chi}_j^0 \oplus \tilde{\chi}_i^0 \rightarrow \tilde{\chi}_j^0 f \bar{f} \otimes \tilde{\chi}_i^0 \rightarrow \tilde{\chi}_j^0 Z \]

– References –

Majorana, NuCi14, 1937

Petcov, PLB139, 1984

Bilenky, Khristova, Nedelcheva, BJP13, 1986

Gunion, Haber, PRD37, 1988

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

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Characteristics

- **Spin-1/2 Superpartners**

  - Neutralinos are mixtures of gauginos/higgsinos with EWSB.

  \[
  M_N = \begin{pmatrix}
  |M_1| e^{i\Phi_1} & 0 & -m_Z c_\beta s_W & m_Z s_\beta s_W \\
  0 & M_2 & m_Z c_\beta c_W & -m_Z s_\beta c_W \\
  -m_Z c_\beta s_W & m_Z c_\beta c_W & 0 & -|\mu| e^{i\Phi_\mu} \\
  m_Z s_\beta s_W & -m_Z s_\beta c_W & -|\mu| e^{i\Phi_\mu} & 0
  \end{pmatrix}
  \]

  \[\tilde{\chi}_i^0 = N_{i1} \tilde{B} + N_{i2} \tilde{W}^3 + N_{i3} \tilde{H}_1^0 + N_{i4} \tilde{H}_2^0\]

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

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

- **Majorana:** $\psi = \psi^c \equiv C\psi^T \Rightarrow$ Characteristic Couplings

  \[\bar{\psi}_i [J_{ij}^\mu] \psi_j = \bar{\psi}_i [i \text{Im}(C_{ij}) \gamma_\mu + \text{Re}(C_{ij}) \gamma_\mu \gamma_5] \psi_j\]

  - \(\text{CP } \oplus \eta^i = \pm \eta^j \Rightarrow \text{Im}(C_{ij})/\text{Re}(C_{ij}) = 0 \Rightarrow \text{Only A/V}\)

  - \(\text{CP Violation} \Rightarrow \text{Im}(C_{ij})/\text{Re}(C_{ij}) \neq 0 \Rightarrow \text{Both A/V}\)

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

  - Diagonal couplings $C_{ii}$ must be real (cf. e–charges).

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

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

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

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

\[ \mathcal{P} : 1 = + \eta^i \eta^j (-1)^L \]
\[ \downarrow \]
\[ \mathcal{D} : 1 = - \eta^i \eta^j (-1)^L \iff \eta^i = \eta^j (-1)^L \]

– \( L \): 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

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

– \( \sqrt{s} \): \( e^+ e^- \) 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.: \( (\beta, \beta) \), i.e. both \( S \)-waves
Pair–production ⊕ 3–body Decays

Recipe 1: Production of 3 neutralino pairs

[Kalinowski, Acta PPB34, 2003]

\[ \tan \beta = 10, \ |M_1| = 100.5 \text{ GeV}, M_2 = 190.8 \text{ GeV}, |\mu| = 365.1 \text{ GeV} \]

\[ m_{\tilde{e}_L} = 208.7 \text{ GeV}, m_{\tilde{e}_R} = 144.1 \text{ GeV} \]

- 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.
Recipe 2: Production $\oplus$ decay correlations


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

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

- **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, $\tilde{\chi}_i^0 \rightarrow \tilde{\chi}_j^0 Z$, expected.
Possibility: Branching ratios

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

\[ \tan \beta = 10, \ |M_1| \approx 1/2 \ M_2 \text{ and } m_h = 115 \text{ GeV} \]

- **Condition**: \( 2m_Z \lesssim M_2 \lesssim 2|\mu| \oplus \text{large higgsino comp. for } \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 Z \)
- \( \tilde{\chi}_{3,4}^0 \rightarrow \tilde{\chi}_1^0 Z \) allowed for most parameter space
- The decoupling scenario for the Higgs system is assumed.
Recipe 3: $Z$ polarization

- $Z$ helicity reconstruction

\[ \frac{d\Gamma_{\text{corr}}}{dc_{\theta}} = (\Gamma[+] + \Gamma[-]) (1 + c_{\theta}^2) + (\Gamma[+] - \Gamma[-]) 2\xi f c_{\theta} + 2\Gamma[0] s_{\theta}^2 \]

\[ \Gamma[\pm] \sim \mu_i^2 + \mu_j^2 - 1 - 2\mu_i\mu_j A_N \]
\[ \Gamma[0] \sim \lambda Z + \mu_i^2 + \mu_j^2 - 1 - 2\mu_i\mu_j A_N \]

\[ A_N = \frac{|V|^2 - |A|^2}{|V|^2 + |A|^2} \]

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

\[ T_{\text{CP}} = \frac{\Gamma[0]/\Gamma[\pm] - (\mu_i^2 + \mu_j^2)}{2\mu_i\mu_j} \]

\[ \tan \beta = 10, M_2 = 250 \text{ GeV}, |\mu| = 500 \text{ GeV}, \Phi_\mu = 0 \]

- \( \Phi_\mu = 0 \oplus \text{large } |\mu| \) to avoid severe EDM constraints
- Large \( \tan \beta \) renders \( T_{\text{CP}} \) insensitive to \( \Phi_\mu \)
- 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 $\ominus \chi_i \rightarrow \chi_jZ$

- **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]
- $\tilde{\chi}^0$ exchange in $e^-e^- \rightarrow \tilde{e}^-\tilde{e}^-$ [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.