Probing the Majorana Nature and CP Properties of Neutralinos

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I. Introduction

- **Supersymmetry (SUSY)**

✓ one of the most interesting and natural extension of the Standard Model
✓ the search for SUSY is one of main goals at the LHC and ILC

- **Neutralinos**

✓ spin-1/2 Majorana superpartners of neutral gauge bosons and Higgs bosons
✓ expected to be among the light SUSY particles that can be produced copiously at future high energy colliders

❖ **In this talk, we focus on probing**

the Majorana nature and CP properties of neutralinos *through*

$$\tilde{\chi}_i^0(\hat{n}) \to \tilde{\chi}_1^0 l^+ l^-$$

the charge self-conjugate three-body decays of polarized neutralinos

- The analysis of the CP properties and Majorana nature of neutralino taking into account full spin correlation between production and decay processes

G.Moortgat-Pick and H.Fraas (1999)
G.Moortgat-Pick, H.Frass, A.Bartl and W.Majerotto (1999)
G.Moortgat-Pick, A.Bartl, H.Frass and W.Majerotto (2000)
G.Moortgat-Pick and H.Fraas (2002)
A.Bartl, H.Frass, S.Hesselbach, K.Hohenwarter-Sodek, G.Moortgat-Pick (2004)

- Neutralino pair production and three body decay as probes of CP violation and Majorana nature

S.Y.Choi (2003)

- Two body decays of probing the Majorana nature and CP violation

S.Y.Choi and Y.G.Kim (2004)

- CP asymmetries in neutralino production with subsequent two-body decays

A.Bartl, H.Frass, O.Kittel and W.Majerotto (2004)

- Neutralinos produced in $\tilde{e}_L^{\pm}$ decays are 100 % polarized

$$\tilde{e}_L^- \to e^- \tilde{\chi}_2^0$$ Netagive helicity

[Aguilar-Saavedra,04]

$$\tilde{e}_L^+ \to e^+ \tilde{\chi}_2^0$$ Positive helicity

- The rest frame of the neutralino $\tilde{\chi}_2^0$ can be reconstructed in some cascade processes, *e.g.* [Aguilar-Saavedra and Teixeira ,03]

$$e^+ e^- \to \tilde{e}_L^+ \tilde{e}_L^- \to e^+ \tilde{\chi}_1^0 e^- \tilde{\chi}_2^0 \to e^+ \tilde{\chi}_1^0 e^- \tilde{\chi}_1^0 \mu^+ \mu^-$$

if CM energy and particle masses are known.

⇒ We provide a systematic combined analysis of the **polarized** neutralino decay $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \mu^+ \mu^-$ in **its rest frame**

II. Neutralino mass matrix

In the basis $(\tilde{B}, \tilde{W}^0, \tilde{H}_1^0, \tilde{H}_2^0)$

$$\begin{pmatrix} M_1 & 0 & -M_Z \cos\beta \sin\theta_W & M_Z \sin\beta \sin\theta_W \\ 0 & M_2 & M_Z \cos\beta \cos\theta_W & -M_Z \sin\beta \cos\theta_W \\ -M_Z \cos\beta \sin\theta_W & M_Z \cos\beta \cos\theta_W & 0 & -\mu \\ M_Z \sin\beta \sin\theta_W & -M_Z \sin\beta \cos\theta_W & -\mu & 0 \end{pmatrix}$$

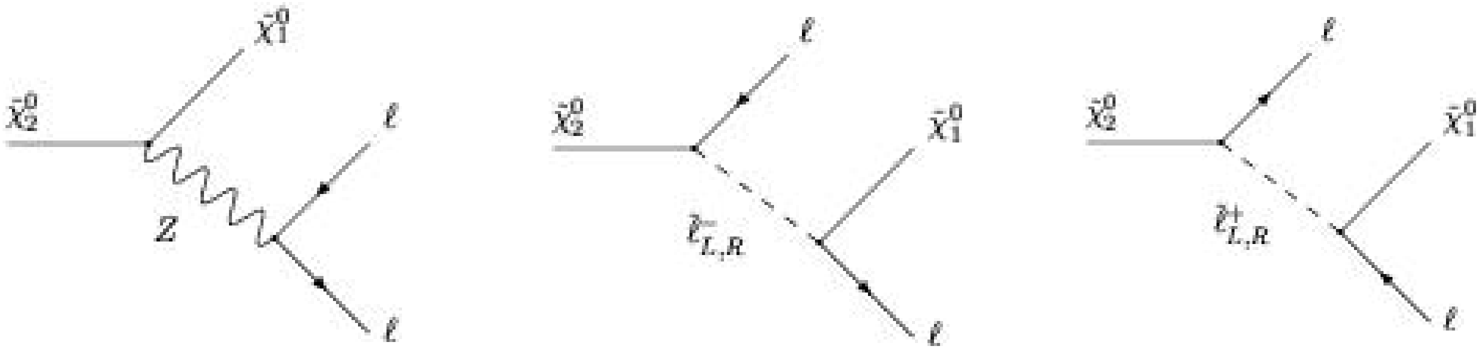
$$\tilde{\chi}_i^0 = N_{i1} \tilde{B} + N_{i2} \tilde{W}^0 + N_{i3} \tilde{H}_1^0 + N_{i4} \tilde{H}_2^0$$

- ✓ All $N_{i\alpha}$ are purely real or purely imaginary in the CP invariant case.
- ✓ Two non-trivial phases may be attributed to M1 and mu ,

$$M_1 = |M_1| e^{i\Phi_1}, \mu = |\mu| e^{i\Phi_\mu}$$

and render the matrix N complex, violating CP.

III. Three-body leptonic neutralino decays



$$\tilde{\chi}_2^0(m_2,\hat{n}) \to \tilde{\chi}(q) + l^-(q_-) + l^+(q_+)$$

$\hat{n}$: neutralino spin 3-vector

- Decay matrix elements

$$D(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 l^+ l^-) \propto D_{\alpha\beta}[\overline{u}(\tilde{\chi}_1^0)\gamma^\mu P_\alpha u(\tilde{\chi}_2^0)][\overline{u}(l^-)\gamma_\mu P_\beta v(l^+)]$$

with bilinear charges $D_{\alpha\beta}(\alpha,\beta = L,R)$

- Differential decay distribution

$$d\Gamma \propto F_0(x_-,x_+) + (\hat{q}_- \cdot \hat{n})F_1(x_-,x_+) + (\hat{q}_+ \cdot \hat{n})F_2(x_-,x_+) + \hat{n} \cdot (\hat{q}_- \times \hat{q}_+)F_3(x_-,x_+)$$

with four kinematic funtions $F_i(x_-,x_+)(i=0-3)$ where $x_\pm = 2E_\pm / m_2$

▪ Implications of CP and CP$\tilde{T}$ invariance for the neutralino decay

Since neutralinos are the Majorana particles,

❖ CP invariance leads to the relations

$$D_{LR} = \eta_1\eta_2 D_{RR}(t \leftrightarrow u)$$
$$D_{RL} = \eta_1\eta_2 D_{LL}(t \leftrightarrow u)$$

$$\Longrightarrow$$

$$F_0(x_-, x_+) = +F_0(x_+, x_-)$$
$$F_1(x_-, x_+) = -F_2(x_+, x_-)$$
$$F_3(x_-, x_+) = -F_3(x_+, x_-)$$

where $\eta_{1,2} = \pm i$ are the intrinsic CP parities of $\tilde{\chi}^0_{1,2}$

❖ CP$\tilde{T}$ invariance (satisfied if Z-boson and slepton widths are neglected)

($\tilde{T}$: naïve time reversal transformation)

$$D_{LR} = -D^*_{RR}(t \leftrightarrow u)$$
$$D_{RL} = -D^*_{LL}(t \leftrightarrow u)$$

$$\Longrightarrow$$

$$F_0(x_-, x_+) = +F_0(x_+, x_-)$$
$$F_1(x_-, x_+) = -F_2(x_+, x_-)$$
$$F_3(x_-, x_+) = +F_3(x_+, x_-)$$

❖ CP & CP$\tilde{T}$ invariance : D_{LR} etc. pure real for $\eta_1 = \eta_2$

pure imaginary for $\eta_1 = -\eta_2$

IV. Numerical Analyses

- We adopt an mSUGRA scenario

m0 = 150 GeV, m1/2 = 200 GeV, A0 =-650 GeV, tan(beta) = 10, sgn(mu) > 0

- Particle Masses

$$m_{\tilde{\chi}_1^0} = 78.1\ \text{GeV}, \quad m_{\tilde{\chi}_2^0} = 148.5\ \text{GeV} \quad (M_1 = 80\ \text{GeV}, \quad M_2 = 158\ \text{GeV}, \quad \mu = 415\ \text{GeV})$$

$$m_{\tilde{e}_L} = 207.7\ \text{GeV}, \quad m_{\tilde{e}_R} = 173.1\ \text{GeV}$$

- Branching Ratios

$$Br(\tilde{e}_L \to \tilde{\chi}_2^0 e) = 28.4\%, \quad Br(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \mu^+ \mu^-) = 4.6\%$$

- Production cross sections with unpolarized e+e- beams at sqrt(s)=500 GeV

$$\sigma\{\tilde{e}_L^+ \tilde{e}_L^-\} = 80.7\ \text{fb}, \quad \sigma\{\tilde{e}_R^\pm \tilde{e}_L^\mp\} = 113.5\ \text{fb}$$

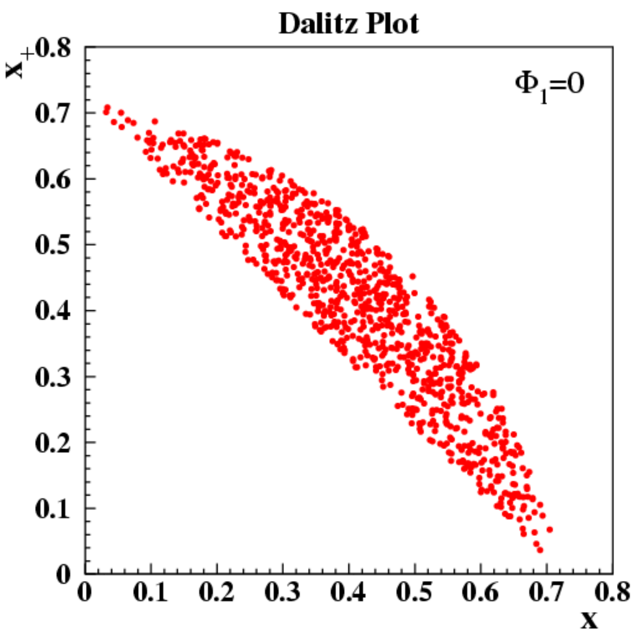
- With integrated luminosity of 1000 fb^-1,
  a sufficient number of events for the decay are expected to be selected.
  In MC simulation, we assume 1000 neutralino decay events are selected.

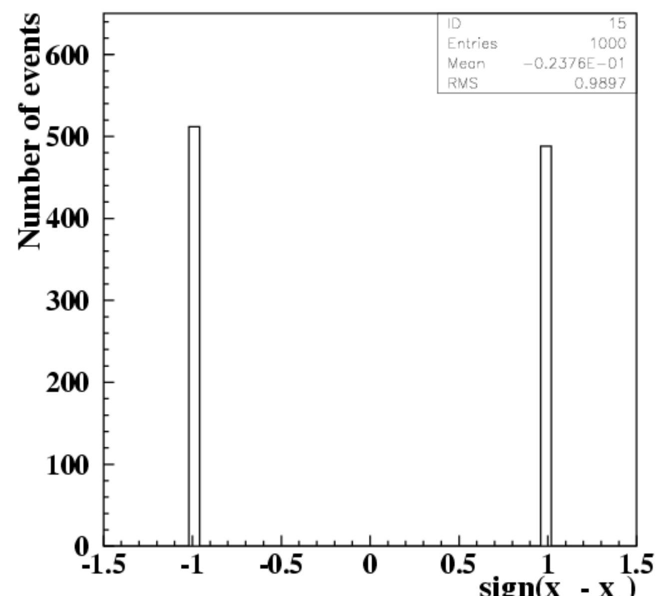
4.1 Lepton energy distribution

- $$\frac{d^2\Gamma}{dx_- dx_+} \propto F_0(x_-, x_+)$$ where $x_\pm = 2E_\pm / m_2$
- $F_0(x_-, x_+) = F_0(x_+, x_-)$ to a good approximation (exactly in CP-invariant case)

Majorana nature of neutralinos

Symmetric distribution of events on (x-,x+) Dalitz plane





$\mathrm{sign}(x_- - x_+)$

- $\Delta N_{ev} \approx 24$ is within the expected error $\sqrt{1000}$ □ 32

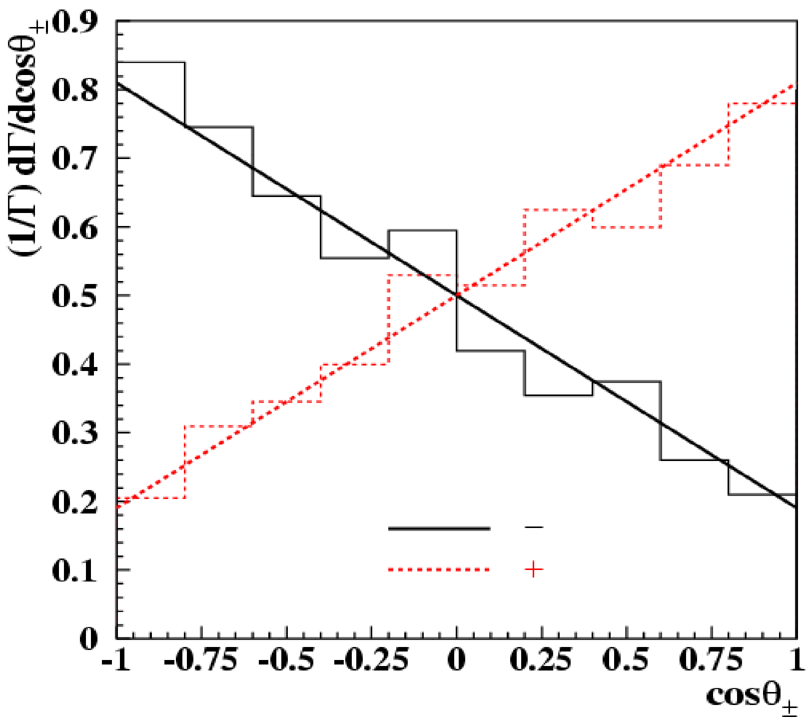
4.2 Lepton angular distribution

- Lepton angle distribution w.r.t neutralino polarization vector

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_\pm} = \frac{1}{2}(1 \pm \eta_\pm \cos\theta_\pm) \qquad \text{with} \qquad \cos\theta_\pm \equiv \hat{q}_\pm \cdot \hat{n}$$

- $F_1(x_-, x_+) = -F_2(x_+, x_-) \Longrightarrow \eta_- = \eta_+$

Majorana nature of neutralino — the slope of the angle distribution



$\Phi_1 = 0$

4.3 Lepton invariant mass and opening-angle distribution

- Near the end point of the lepton invariant mass distribution

  $\tilde{\chi}_1^0$ is produced nearly at rest, $\beta \approx \sqrt{1 - m_{ll}/(m_2 - m_1)}$

  Mandelstam variables $s \approx (m_2 - m_1)^2, \ t \approx u \approx m_1 m_2$

$$|D|^2 \approx r_{21}(1 - r_{21})^2 \{[\mathrm{Re}(D_{LL})]^2 + [\mathrm{Re}(D_{RR})]^2\} + O(\beta^2) \qquad (r_{21} \equiv m_1 / m_2)$$

⇩

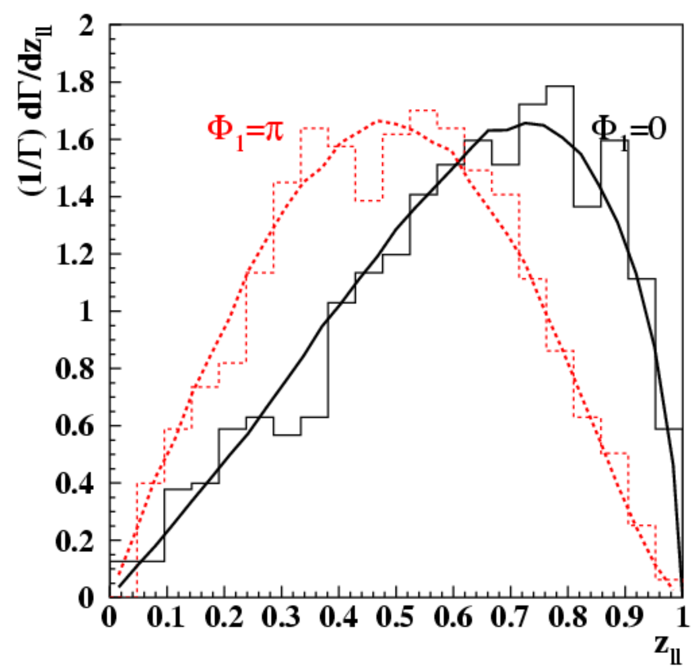
- Invarinat mass distribution decreases

✓ steeply if D_{LL} etc. are purely real

$$\text{when } \eta_1 = \eta_2 \quad (\Phi_1 = 0 \ \text{ case})$$

✓ slowly if D_{LL} etc. are purely imaginary

$$\text{when } \eta_1 = -\eta_2 \quad (\Phi_1 = \pi \ \text{ case})$$



- Selection rule of the orbital angular momentum by CP symmetry

$$\eta_2 = \eta_1 (-1)^L$$ (L : orbital angular momentum of the final system)

L=0 (steep S-wave) for $\eta_1 = \eta_2$ $(\Phi_1 = 0 \text{ case})$
L=1 (slow P-wave) for $\eta_1 = -\eta_2$ $(\Phi_1 = \pi \text{ case})$

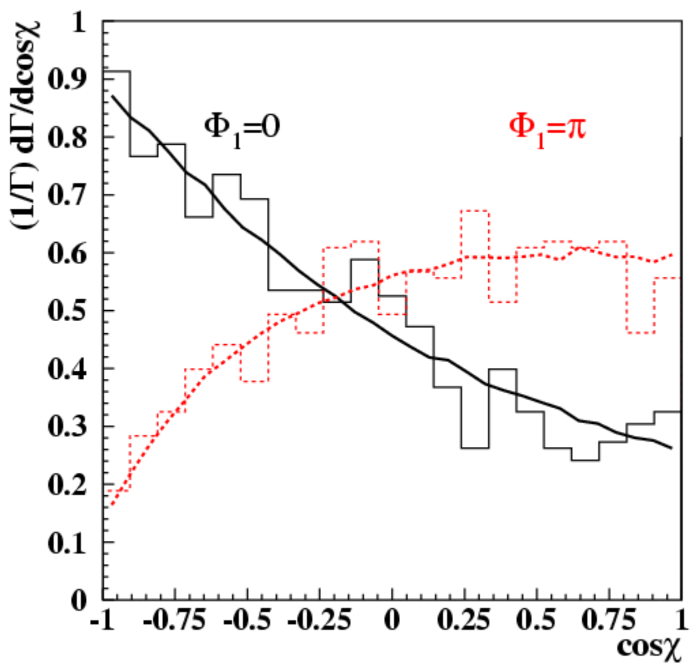
- Decay distribution w.r.t. the opening angle between two leptons

$$\cos\chi \equiv \hat{q}_- \cdot \hat{q}_+$$

✓ $$m_{ll}^2 = \frac{m_2^2}{2} x_+ x_- (1 - \cos\chi)$$

: maximum for $\cos\chi = -1$
for given x- and x+

✓ Angular momentum conservation forces L=0 for $\cos\chi = -1$



4.4 CP-odd triple spin / momentum product

- A CP-odd (CP$\tilde{T}$-even) distribution

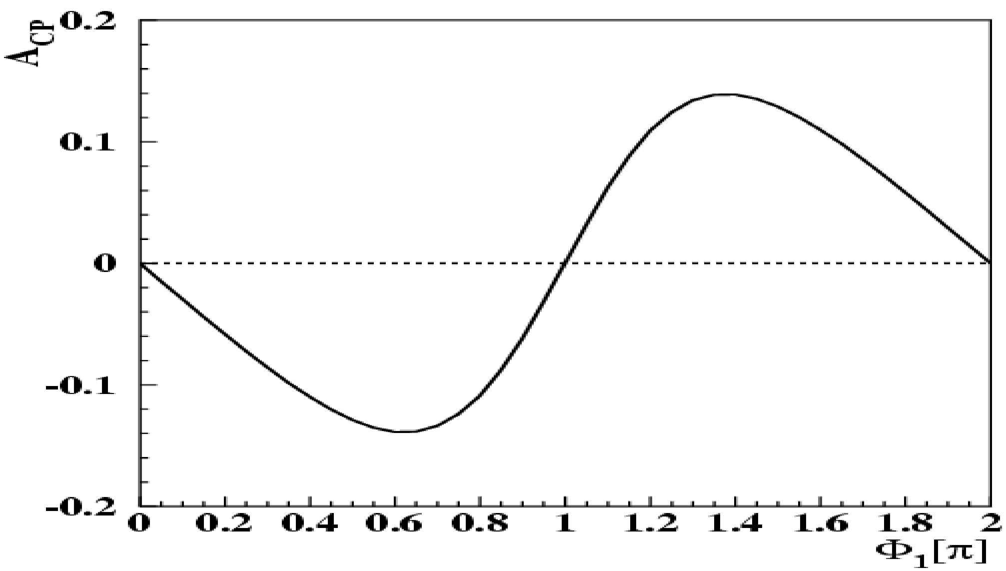
$$F_{CP}(x_-, x_+) = \frac{1}{2}[F_3(x_-, x) + F_3(x_+, x_-)]$$

- A CP-odd quantity related to the above CP-odd distribution

$$O_{CP} = \hat{n} \cdot (\hat{q}_+ \times \hat{q}_-)$$

$$\Rightarrow \quad A_{CP} \equiv \frac{N(O_{CP} > 0) - N(O_{CP} < 0)}{N(O_{CP} > 0) + N(O_{CP} < 0)} = \frac{\int (\sin\chi / 2) F_{CP}(x_-, x_+) dx_- dx_+}{\int F_0(x_-, x_+) dx_- dx_+}$$

A_{CP}



(with $\Phi_\mu = 0$)

Φ_1

V. Conclusions

- We have performed a systematic analysis of the polarized neutralino decay $\tilde{\chi}_2^0(\hat{n}) \to \tilde{\chi}_1^0 l^+ l^-$ in its rest frame for probing the Majorana nature and CP properties of neutralinos

- The Marorana nature of the neutralinos can be checked through
  lepton energy distribution,
  lepton angle distribution w.r.t neutralino polarization vector
  to a good approximation in CP non-invariant case (exactly in CP invariant case)

- The relative CP parity of two neutralinos can be identified by measuring
  threshold behavior of the lepton invariant mass distribution and/or
  the opening angle distribution of lepton pairs.

- The CP violation in the neutralino system could be detected by measuring
  the asymmetry on the CP-odd quantity $O_{CP} = \hat{n} \cdot (\hat{q}_+ \times \hat{q}_-)$