Probing the Neutralino System through Leptonic Neutralino Decays

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Introduction/Motivation

- **Presence of $\tilde{\chi}^0$: One of the characteristic features of SUSY**
  $\Rrightarrow$ **Majorana super partners of neutral gauge boson and Higgs particle**
  $\Rrightarrow$ **Best dark matter candidate**
- **Dirac vs. Majorana under CP :** [Kayser(1982);Moortgat-Pick,Fraas(2002)]
  $|f_D(\overrightarrow{p},\lambda)\rangle \to |\overline{f_D}(-\overrightarrow{p},-\lambda)\rangle$
  $|f_M(\overrightarrow{p},\lambda)\rangle \to \eta^{CP}|f_M(-\overrightarrow{p},-\lambda)\rangle, \;\; \text{w/} \;\; \eta^{CP} = \pm i$
- **Probe $\tilde{\chi}^0$ at the ILC**
  - **Majorana Nature of $\tilde{\chi}^0$**
  - **CP–violation in the Neutralino System**
  - **Complete reconstruction of SUSY parameters**

Q) Can probe the Majorana nature of $\tilde{\chi}^0$ and CP–violation in the $\tilde{\chi}^0$–system ?

$\Rrightarrow$ **$\tilde{\chi}^0$–Pair production(and 3–body decay)**

$\Rrightarrow$ **$\tilde{\chi}^0$–Decay : 2 or 3 body decay**

Neutralino System [S.Y.Choi,Kalinowski,Moorgat–Pick,Zerwas]

- $\tilde{\chi}_i^0$: Mixtures of the gauginos($U(1)$ and $SU(2)$) and the higgsinos
- Basic parameters : $\{|M_1|e^{i\Phi_1}, |M_2|, |\mu|e^{i\Phi_\mu}, \tan\beta\}$
- Diagonalization of $\tilde{\chi}^0$ mass matrix : Complex and symmetric $\mathcal{M}$

  $(\tilde{B}^0, \tilde{W}^3, \tilde{H}_1, \tilde{H}_2)$ basis $\to$ $\tilde{\chi}_i^0$ (Majorana fields)

  $\mathcal{M}_{diag} = N^* \mathcal{M} N^\dagger$, $\quad N : 4 \times 4$ Unitary matrix
- Parametrization of mixing matrix : $N = MD$ (i.e. Majorana and Dirac)

  $M = \mathrm{diag}\{e^{i\alpha_1}, e^{i\alpha_2}, e^{i\alpha_3}, e^{i\alpha_4}\}$: 3 phases

  $\to$ One overall Majorana phase is nonphysical

  $D = R_{34}R_{24}R_{14}R_{23}R_{13}R_{12}$: 6 angles and 6 phases

  $\Rightarrow$ 9 physical phases

  - Necessary cond. for CP-viol.: Non-vanishing one of the 9 phases

Neutralino Pair Production

$e^+e^- \to \tilde{\chi}^0_i \tilde{\chi}^0_j$: [S.Y.Choi,Kalinowski,Moorgat–Pick,Zerwas;Choi;Choi,H.S.Song,W.Y.Song]

- Transition matrix element :

  $$T\left(e^+e^- \to \tilde{\chi}^0_i \tilde{\chi}^0_j\right) = \frac{e^2}{s} Q_{\alpha\beta} \left[\bar{v}(e^+)\gamma_\mu P_\alpha u(e^-)\right] \left[\bar{u}(\tilde{\chi}^0_i)\gamma^\mu P_\beta v(\tilde{\chi}^0_j)\right]$$

- Selection rule in CP–invariant theories (Majorana nature of $\tilde{\chi}^0$) :

  $1 = \eta^i \eta^j (-1)^L, \quad \eta^i = \pm i$ (intrinsic CP parity of $\tilde{\chi}^0_i$)

  - CP–inv. case :

    axial vector current(same CP parity): $\Re\mathrm{e}\,(N_{ik}N^*_{jl}) \to$ P-wave

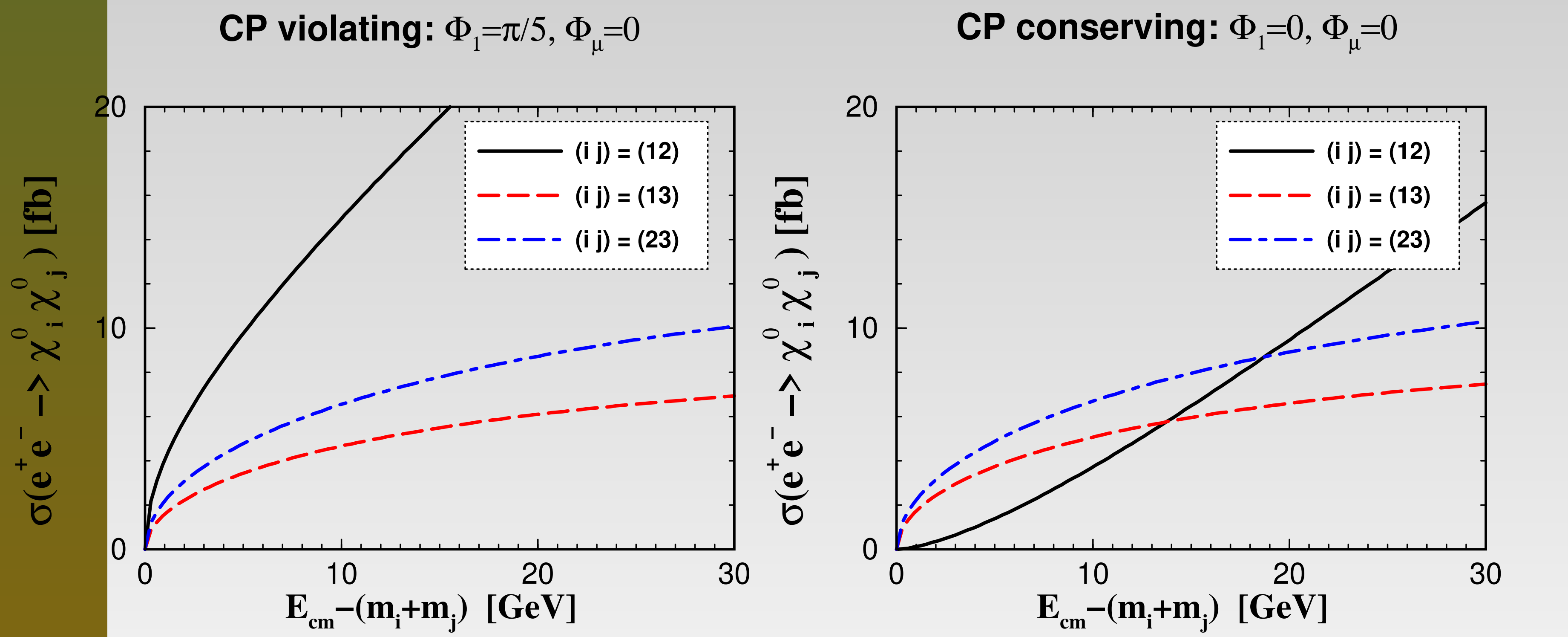
    vector current(opposite CP parity): $\Im\mathrm{m}\,(N_{ik}N^*_{jl}) \to$ S-wave

  - CP–noninv. case: Mixture of S- and P-wave excitation

- Threshold behavior of the total cross section $\sigma\{ij\}(i \neq j)$:

  $$\sigma\{ij\} \approx \frac{4\pi\alpha^2\, m_i m_j}{(m_i+m_j)^4}\, \beta \left\{ |\,\Im\mathrm{m}\, G_R|^2 + |\,\Im\mathrm{m}\, G_L|^2 \right\} + \mathcal{O}(\beta^3)$$

[J.Kalinowski,Acta Phys.Polon.B34,3441(2003)]



2-Body decay [S.Y.Choi,Y.G.Kim]

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

Due to the Majorana properties of $\tilde{\chi}^0$

- Vector coupling and axial vector coupling :

  $V = -\frac{i}{2}\Im\mathrm{m}\,(N_{j3}N^*_{i3} - N_{j4}N^*_{i4})$: pure imaginary

  $A = \frac{1}{2}\Re\mathrm{e}\,(N_{j3}N^*_{i3} - N_{j4}N^*_{i4})$: pure real

- Relation between polarized decay widths :

  (even in the CP–noninvariant theory)

  $\Gamma[\,\tilde{\chi}^0_i \to \tilde{\chi}^0_j Z(+)] = \Gamma[\,\tilde{\chi}^0_i \to \tilde{\chi}^0_j Z(-)]$

  $\Rrightarrow$ Powerful method to probe Majorana nature in $\tilde{\chi}^0_i \to \tilde{\chi}^0_j Z$

Z-boson polarization can be reconstructed from Z–decay (i.e. $Z \to l^+ l^-$)

Leptonic 3–Body decay only

Selectron decays : 100% polarized $\tilde{\chi}^0$ source

[Aguilar-Saavedra(04);Aguilar-Saavedra,Teixeira(03)]

$\Rrightarrow$ Helicity of $\tilde{\chi}^0$: fixed by the charge and chirality of decaying selectron

$\Rrightarrow$ Selectron and Neutralino rest frames can be reconstructed

$\tilde{\chi}^0_i \to \tilde{\chi}^0_j \ell^+ \ell^-$:

- Decay matrix element :

  $$D\left(\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 \ell^- \ell^+\right) = \frac{e^2}{s'} D_{\alpha\beta}\left[\bar{u}(\tilde{\chi}^0_1)\gamma^\mu P_\alpha u(\tilde{\chi}^0_2)\right]\left[\bar{u}(\ell^-)\gamma_\mu P_\beta v(\ell^+)\right],$$

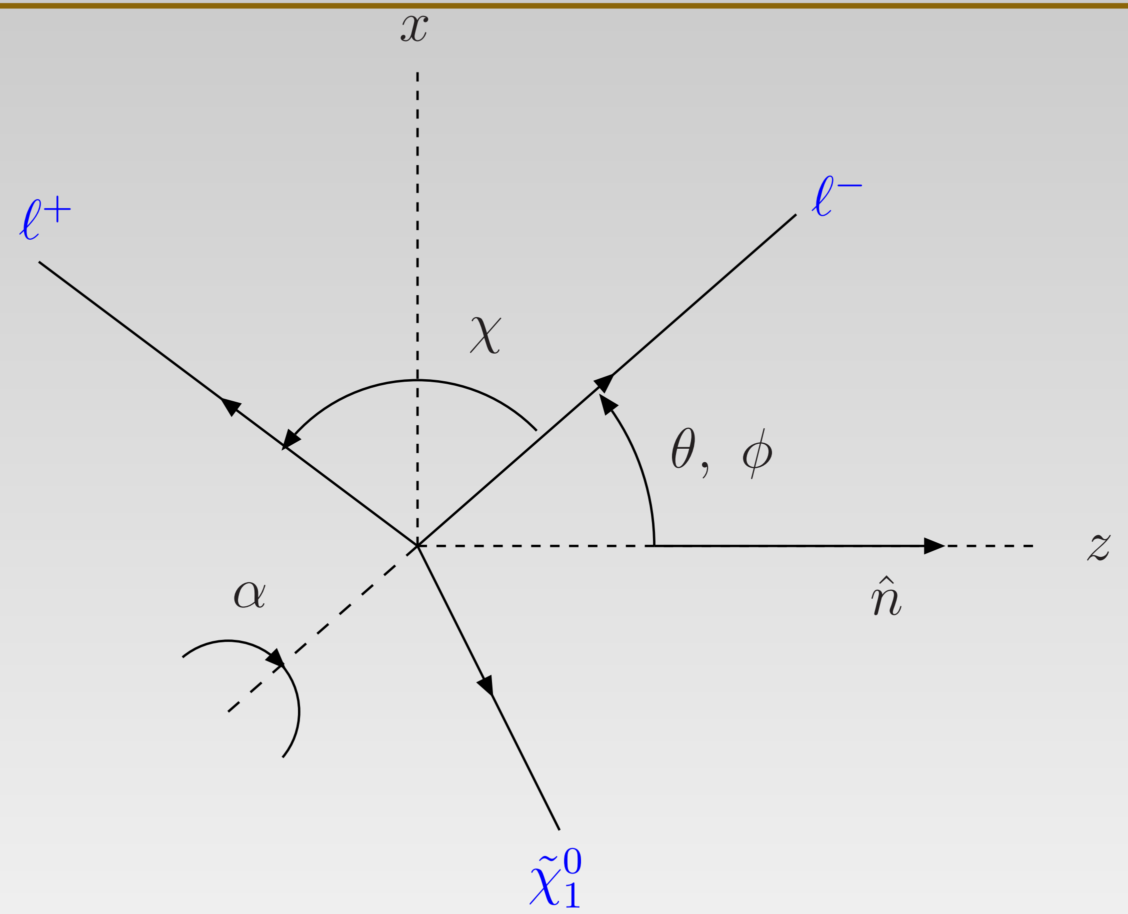
- Selection rule for 3–body decay in the CP–invariant theories :

  $$1 = (-1)\eta^i \eta^j (-1)^L, \quad \eta^i = \pm i$$

- Decay rate with initial $\tilde{\chi}^0_2$–polarization

  $$\frac{d^5\Gamma}{[d\Phi]^5} = F_0(x_1, x_2) + \hat{n}\cdot\hat{p_1} F_1(x_1, x_2) + \hat{n}\cdot\hat{p_2} F_2(x_1, x_2) + \hat{n}\cdot(\hat{p_1}\times\hat{p_2}) F_3(x_1, x_2)$$

Kinematical frame work for $\tilde{\chi}^0$ 3–body decay



Kinematical configuration of the momenta in the initial neutralino rest mass frame for the three–body neutralino decay $\tilde{\chi}_i \to \tilde{\chi}_1 \ell^+ \ell^-$.

3–body decay continue

To probe Majorana nature and CP–violation

- Dalitz plot (x_1 and x_2); $\mathrm{Sign}(x_1 - x_2)$
- Two lepton invariant mass distribution near the end point :

$$\Rightarrow \frac{d\Gamma\{ij\}}{dz_{ff}} \approx C(m_i, m_j)\beta' \left\{ |\,\Re\mathrm{e}\, G'_R|^2 + |\,\Re\mathrm{e}\, G'_L|^2 \right\} + \mathcal{O}(\beta'^3)$$

  - CP–inv. case :

    S-wave : axial vector current (same CP parity)

    $\rightarrow \Re\mathrm{e}\,(N_{ik}N^*_{jl})$: Steep S-wave

    P-wave : vector current (opposite CP parity)

    $\rightarrow \Im\mathrm{m}\,(N_{ik}N^*_{jl})$: Slow P-wave

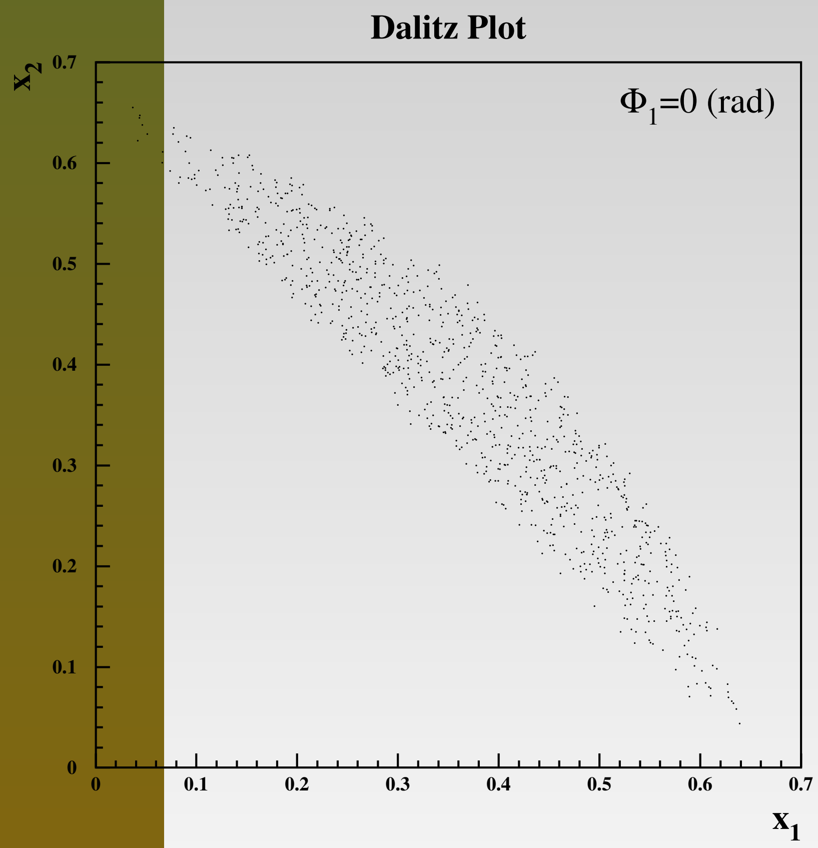
  - CP–viol. case : Mixture of S- and P-wave excitation

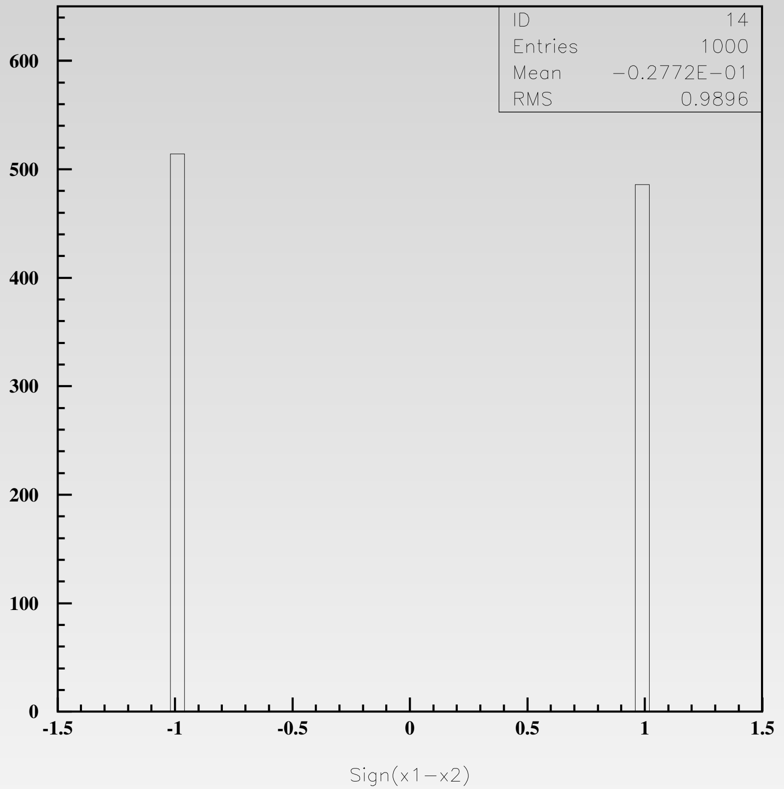
- $\hat{n} \cdot (\hat{p_1} \times \hat{p_2})$ (as a CP-odd observable)

Numerical example

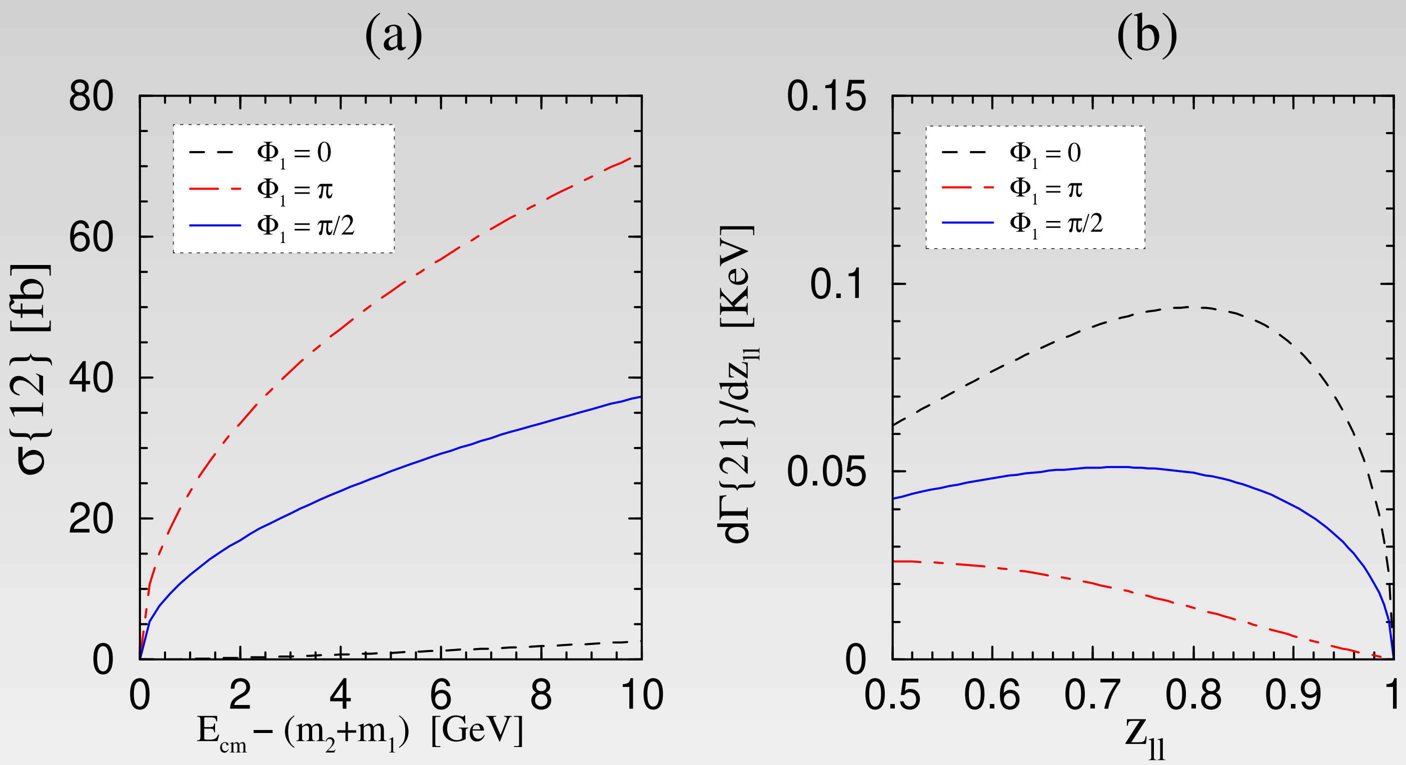
- **SUSY parameter set :**
  $\tan\beta = 10$, $M_1 = 100$ **GeV,** $M_2 = 180$ **GeV,** $\mu = 400$ **GeV,**
  $\Phi_2 = \Phi_\mu = 0$, $m_{\tilde{l}_L} = 250$ **GeV and** $m_{\tilde{l}_R} = 200$ **GeV.**
- **Numerical results**
  $A_E \equiv \langle \mathrm{Sign}(x_1 - x_2) \rangle \simeq -0.028$ **, for** $N = 1000$ **w/**$x_{1,2} = \frac{2E_{\ell\mp}}{m_{\tilde{\chi}^0_2}}$
  $A_{CP} \equiv \langle \mathrm{Sign}(\hat{n} \cdot (\hat{p}_{\ell^-} \times \hat{p}_{\ell^+})) \rangle \simeq 0.33$ **, for** $\Phi_1 = \frac{\pi}{2}$
  w/ $\Delta A_{CP} \equiv \sqrt{\frac{1-A^2_{CP}}{N}} \simeq 0.02$, **for** $N = 1000$
  For dilepton inv. mass distribution
  - **CP–invariant case :** $\Phi_1 = 0,\ \pi$
    - $\Phi_1 = 0$ **: Steep S-wave (same CP parity)**
    - $\Phi_1 = \pi$ **: Slow P-wave (opposite CP parity)**
  - **CP–non-invariant case :** $\Phi_1 = \frac{\pi}{2}$
    Mixture of S-and P-wave

Numerical examples : Majorana nature – Dalitz plot, Sign$(x_1 - x_2)$

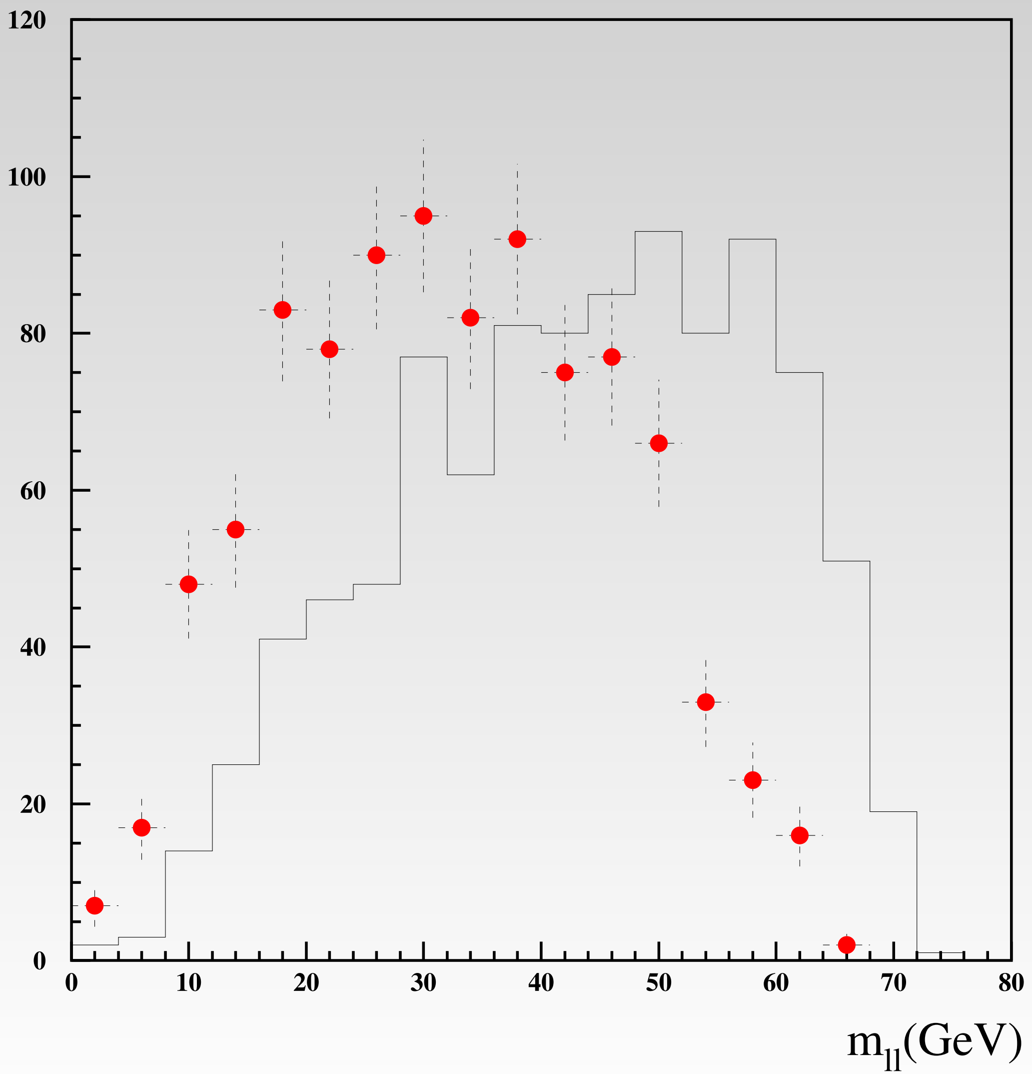




[S.Y.Choi,PRD69,096003(2004)]



example continue – dilepton inv. mass distribution



Summary and Conclusion

Probing Neutralino properties :

- **$\tilde{\chi}^0$ pair production (and cascade 3–body decay)**
  Threshold behavior of $\tilde{\chi}^0$ production
- **2–body decay :**
  Powerful relation between polarized decay widths
- **3–body decay :**
  Two lepton invariant mass distribution near the end point

It is possible to have qualitative indication of CP-violation and Majorana nature in the Neutralino system via $\tilde{\chi}^0$ pair production and 2-or 3-body decay channel.