Characterizing Invisible Electroweak Particles through Single-Photon Processes in e^+e^- Colliders

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Based on work with S.Y. Choi, T. Han, J. Kalinowski, K. Rolbiecki

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  - Neutrino mass
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- It's reasonable to expect more new partices to be discovered. For example, in Supersymmetry, we have a whole set of new particles.
- But, unfortunately, we haven't seen anything else so far, even with such an unprecedented high energy and high luminosity at the LHC.

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- Future e^+e^- colliders, e.g. ILC, may provide us with some methods to deal with this case.
  - Clean environment
  - Fixed c.m. frame
  - Longitudinal beam polarizations
  - Better precision

Framework

- Generically, we are considering scenarios with the following features:
  - Only a (nearly) degenerate non-colored pair of an electrically-charged particle X^- and a neutral particle X^0 with masses $m_Z/2 < m_X < 250\,\mathrm{GeV}$
  - All other new states are heavy and essentially decoupled.
  - They couple to SM leptons and quarks only via EW gauge boson γ, Z and $W^\pm$.

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- If X^- and X^0 are (nearly) degenerate, it would be difficult to detect the decay. Even X^- would essentially become invisible.
- More specifically, we choose three benchmark scenarios within the framework of MSSM: higgsino scenario, wino scenario, and slepton scenario.

Higgsino Scenario $H_{1/2}$

- The only accessible SUSY particles are two spin-1/2 Higgsino doublets, $\tilde{H}_d = [\tilde{H}^0_{dL}, \tilde{H}^-_{dL}]$ and $\tilde{H}_u = [\tilde{H}^+_{uL}, \tilde{H}^0_{uL}]$.
- $\mu << M_1, M_2$, so that the new states are degenerate. No mixing.
- Dirac mass terms from combining degenerate states

$$\mu \left(\overline{\tilde{H}^-_{uR}} \tilde{H}^-_{dL} + \overline{\tilde{H}^+_{dR}} \tilde{H}^+_{uL} \right) - \mu \left(\overline{\tilde{H}^0_{uR}} \tilde{H}^0_{dL} + \overline{\tilde{H}^0_{dR}} \tilde{H}^0_{uL} \right)$$

$$\Rightarrow \qquad \mu \, \overline{\chi^-_H} \, \chi^-_H + \mu \, \overline{\chi^0_H} \, \chi^0_H$$

$$\chi^-_H = \tilde{H}^-_{dL} + \tilde{H}^-_{uR} \quad \text{and} \quad \chi^0_H = \tilde{H}^0_{dL} - \tilde{H}^0_{uR}$$

- Interactions

$$\begin{aligned} \mathcal{L}^H_{V\chi\chi} = {} & e \, \overline{\chi^-_H} \gamma^\mu \chi^-_H \, A_\mu + e \, \frac{(1/2 - s^2_W)}{c_W \, s_W} \, \overline{\chi^-_H} \gamma^\mu \chi^-_H \, Z_\mu \\ & - \frac{1}{2} \, \frac{e}{c_W \, s_W} \, \overline{\chi^0_H} \gamma^\mu \chi^0_H \, Z_\mu - \frac{e}{\sqrt{2} s_W} \left(\overline{\chi^0_H} \gamma^\mu \chi^-_H \, W^+_\mu + \text{h.c.} \right) \end{aligned}$$

Wino Scenario $W_{1/2}$

- The only accessible SUSY particles are a spin-1/2 Wino triplet, $\tilde{W} = [\tilde{W}_L^+, \tilde{W}_L^0, \tilde{W}_L^-]$.
- $M_2 << M_1, \mu$. Degeneracy. No mixing.
- 1 Dirac mass term + 1 Majorana mass term

$$M_2\,(\overline{\tilde{W}_R^+}\tilde{W}_L^+ + \overline{\tilde{W}_R^0}\tilde{W}_L^0 + \overline{\tilde{W}_R^-}\tilde{W}_L^-) \quad \Rightarrow \quad \overline{\chi_W^-}\,\chi_W^- + \frac{1}{2}\,M_2\,\overline{\chi_W^0}\,\chi_W^0$$

$$\chi_W^- = \tilde{W}_L^- + \tilde{W}_R^- \quad \text{and} \quad \chi_W^0 = \tilde{W}_L^0 + \tilde{W}_R^0$$

- Interactions

$$\mathcal{L}_{V\chi\chi}^W = e\,\overline{\chi_W^-}\gamma^\mu\chi_W^-\,A_\mu + e\,\frac{(1-s_W^2)}{c_W\,s_W}\,\overline{\chi_W^-}\gamma^\mu\chi_W^-\,Z_\mu \\ - \frac{e}{s_W}\left(\overline{\chi_W^0}\gamma^\mu\chi_W^-\,W_\mu^+ + \text{h.c.}\right)$$

- Note: There is no $\overline{\chi_W^0}\gamma^\mu\chi_W^0 Z_\mu$ coupling.

Left-handed Slepton Scenario L_0

- The only accessible SUSY particles are a spin-0 left-handed Slepton doublet, $\tilde{\ell}_L = [\tilde{\ell}_L^-, \tilde{\nu}_\ell^0]$.
- $\tilde{m}_{\ell_L} << $ all other M. Degeneracy requires $\tan\beta = 1$.

$$\Delta m^2 = m^2_{\tilde{\ell}_L^-} - m^2_{\tilde{\nu}_\ell} = -m_Z^2 \cos 2\beta \, c_W^2$$

- Interactions

$$\begin{aligned}\mathcal{L}^L_{V\tilde{\ell}_L\tilde{\ell}_L} &= e\,\tilde{\ell}_L^+ \overleftrightarrow{\partial_\mu} \tilde{\ell}_L^- \, A^\mu + e\,\frac{(1/2 - s_W^2)}{c_W\, s_W}\,\tilde{\ell}_L^+ \overleftrightarrow{\partial_\mu} \tilde{\ell}_L^- \, Z^\mu \\ &\quad - \frac{1}{2}\,\frac{e}{c_W\, s_W}\,\tilde{\nu}_\ell^\star \overleftrightarrow{\partial_\mu} \tilde{\nu}_\ell \, Z^\mu - \frac{e}{\sqrt{2} s_W}\left(\tilde{\nu}_\ell^\star \overleftrightarrow{\partial_\mu} \tilde{\ell}_L^- \, W^{+\mu} + \text{h.c.}\right)\end{aligned}$$

- Contact terms

$$\mathcal{L}^L_{\gamma Z \tilde{\ell}_L^- \tilde{\ell}_L^-} = e^2 \tilde{\ell}_L^+ \tilde{\ell}_L^- A_\mu A^\mu + 2e^2\,\frac{(1/2 - s_W^2)}{c_W\, s_W}\,\tilde{\ell}_L^+ \tilde{\ell}_L^- A_\mu Z^\mu$$

Radiatively-induced Mass Splitting

- So far, these new states we are considering are degenerate at tree level.
- A finite mass splitting through radiative corrections will take place after EWSB.
  - For -ino cases, it comes from one-loop photon and Z-boson corrections.

$$\Delta m_H = m_{\chi_H^\pm} - m_{\chi_H^0} = \frac{\alpha}{4\pi}\mu\left[f(m_Z/\mu) - f(0)\right]$$

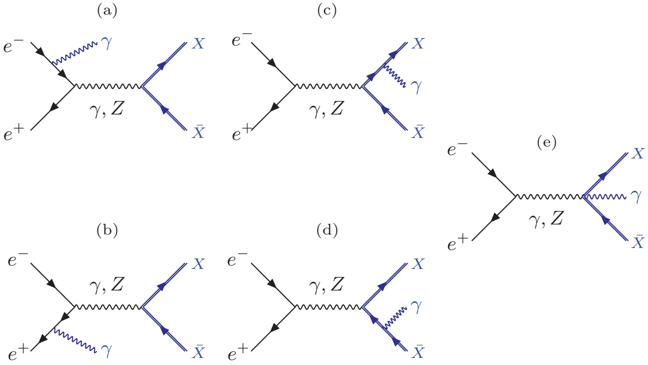
$$\Delta m_W = m_{\chi_W^\pm} - m_{\chi_W^0} = \frac{\alpha}{4\pi s_W^2}M_2\left[f(m_W/M_2) - c_W^2 f(m_Z/M_2) - s_W^2 f(0)\right]$$

Roughly, $\Delta m_{H,W} \lesssim \mathcal{O}(100\,\mathrm{MeV})$.

  - For slepton case, extra contributions from the D-term.
- In any case, we would naively expect $\Delta m \sim \alpha m_Z$. In the following discussion, we just assume they are nearly degenerate.

Single-photon Processes $e^+e^- \to \gamma + \not{E}$

- To detect the pair production of invisible particles, we need to trigger on an associated hard photon, plus large missing energy.
- Since we also treat charged particles as invisible, both Initial State Radiation and Final State Radiation would contribute



Initial State Radiation

- The ISR part is universal and can be factorized out

$$\frac{d\sigma[e^+e^- \to \gamma X\bar{X}]_{\rm ISR}}{dx_\gamma\, d\cos\theta_\gamma} = \mathcal{R}(s; x_\gamma, \cos\theta_\gamma) \times \sigma\left[e^+e^- \to X\bar{X}\right](q^2)$$

where $\beta_q = \sqrt{1 - 4m_X^2/q^2}$ $\quad q^2 = (1-x)s$

$$\mathcal{R}(s; x_\gamma, \cos\theta_\gamma) = \frac{\alpha}{\pi}\frac{1}{x_\gamma}\left[\frac{1+(1-x_\gamma)^2}{1+4m_e^2/s - \cos^2\theta_\gamma} - \frac{x_\gamma^2}{2}\right]$$

$$\sigma\left[e^+e^- \to X\bar{X}\right](q^2) = \frac{2\pi\alpha^2}{3}\beta_q \mathcal{P}(X; P_-, P_+; q^2)\,\mathcal{K}(\beta_q)$$

- $\mathcal{K}(\beta_q)$ is the kinematical factor

$$\mathcal{K}(\beta_q) = \begin{cases} \beta_q^2 & \text{spin-0 charged slepton or sneutrino} \\ 2(3-\beta_q^2) & \text{spin-1/2 chargino or neutralino} \end{cases}$$

- Different threshold excitation patterns.

Final State Radiation

- The FSR part is NOT universal

$$\frac{d\sigma[e^+e^- \to \gamma X^+X^-]_{\rm FSR}}{dx_\gamma\, d\cos\theta_\gamma} = \frac{3}{8}\left[(1+\cos^2\theta_\gamma)\mathcal{F}_1^X(s;x_\gamma) + (1-3\cos^2\theta_\gamma)\mathcal{F}_2^X(s;x_\gamma)\right] \times \sigma\left[e^+e^- \to X^+X^-\right](s)$$

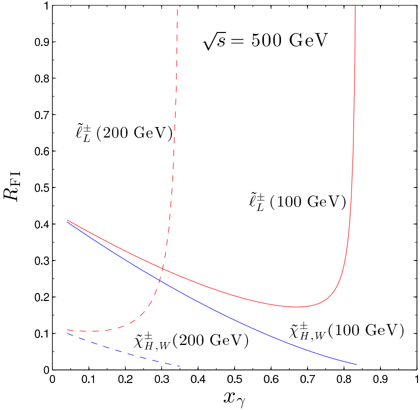
  where $\mathcal{F}_1^X(s;x_\gamma)$ and $\mathcal{F}_2^X(s;x_\gamma)$ are process-dependent.
- Near Threshold, $\mathcal{F}_2^X \sim \beta_q^3$.
- BUT

$$\mathcal{F}_1^X(s;x_\gamma) \;\to\; \frac{\alpha}{\pi}\beta_q \begin{cases} 1/2\beta_s & \text{for spin-0 charged sleptons} \\ 4\beta_s/(3-v_X^2) & \text{for spin-1/2 charginos} \end{cases} \quad \text{as } x_\gamma \to \beta_s^2$$

- Even in L_0 scenario, cross section is proportional to β_q near threshold, due to the momentum-independent contact terms.

ISR vs. FSR

- The FSR part has been ignored in most previous analyses on single-photon processes, without providing serious detailed and quantitative arguments.

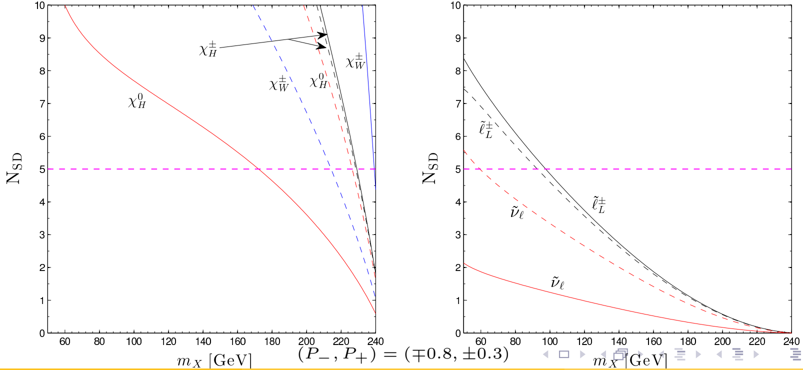


- The FSR definitely needs to be included especially for L_0 scenario.

Statistical Significance

- Background $e^+e^- \to \gamma\nu\bar{\nu}$.
  - Kinematic cut: on the recoil mass squared $q^2 = (1-x_\gamma)s$, if $m_X > m_Z/2$, to remove the Z-pole, $\sqrt{q^2} > 2m_X$.
  - The t-channel W-exchange is purely left-handed. ⇒ Beam polarization.
- Define a theoretical significance

$$N_{SD} = \frac{N_S}{\sqrt{N_S + N_B}} = \frac{\sigma}{\sqrt{\sigma + \sigma_B}}\sqrt{\mathcal{L}}$$

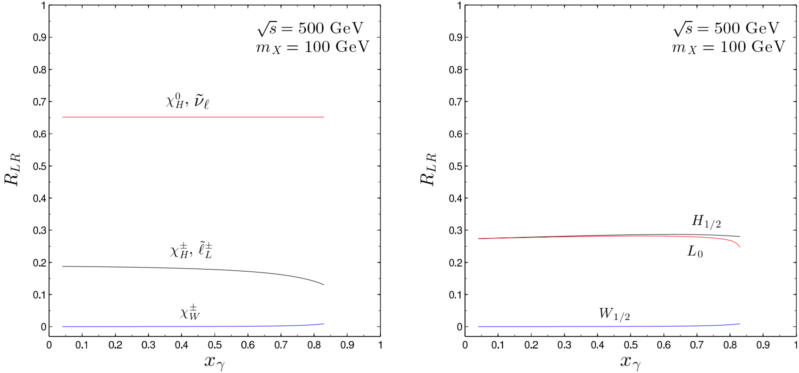


$(P_-, P_+) = (\mp 0.8, \pm 0.3)$

Polarization Dependence

- Define the ratio of polarized cross sections

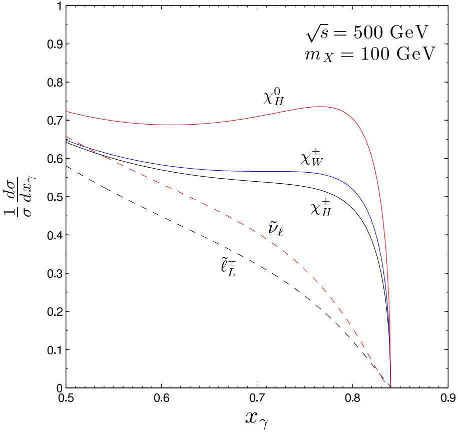
$$\mathcal{R}_{LR}(X;x_\gamma) = \frac{d\sigma(e^+e^-_R \to \gamma X\bar{X})/dx_\gamma}{d\sigma(e^+e^-_L \to \gamma X\bar{X})/dx_\gamma}$$



- Each scenario has its own unique value.

Threshold Excitation

- The threshold excitation pattern is a powerful observable in not only mass measurement but also spin determination.



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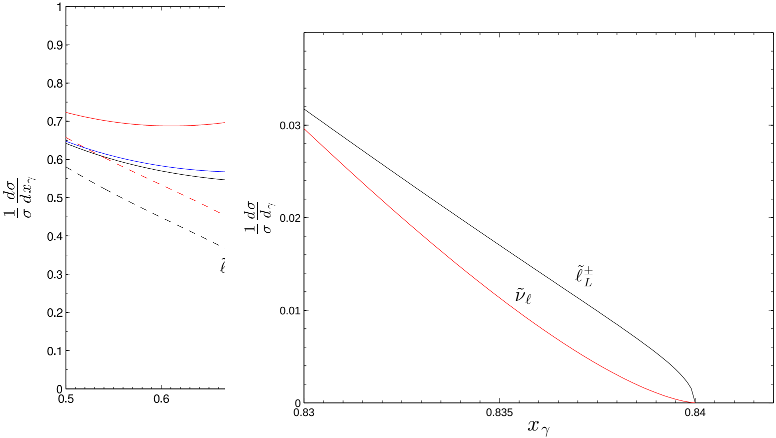

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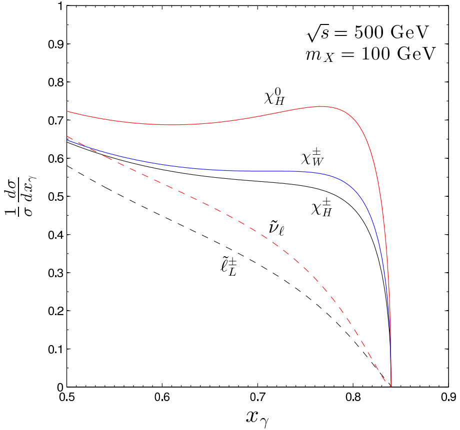

- S-wave excitations for spin-1/2 charginos and neutralinos, while "P-wave-like" excitations for spin-0 sleptons.

A Few Comments on the Decay Detection

- For a few hundrde MeV mass splitting, the most important decay modes are $X^- \to X^0\pi^-, X^0 e^- \bar{\nu}_e$ and $X^0\mu^-\bar{\nu}_\mu$ with low p_T.
- The proposed International Large Detector (ILD) at the ILC can be expected to have tracking efficiency of 60% down to p_T values of 200 MeV. [arXiv:1306.6329]
- On the other hand, the inner layer of the ILD vertex detector would extend down to the radius of 1.6 cm.
- A combination of massive tracks, displaced vertices, and soft decay products can cover a larger range of mass differences. But our inclusive single-photon analysis is still a powerful discrimination method.
- If decay products can be observed, we would gain additional information on the spin, as well as coupling chirality.

Summary

- Given the null search results, we considered $e^+e^- \to \gamma + \not{E}$ for three scenarios with (nearly) degenergate particles.
    - Higgsino scenario $\tilde{H}_d = [\tilde{H}^0_{dL}, \tilde{H}^-_{dL}]$ and $\tilde{H}_u = [\tilde{H}^+_{uL}, \tilde{H}^0_{uL}]$
    - Wino scenario $\tilde{W} = [\tilde{W}^+_L, \tilde{W}^0_L, \tilde{W}^-_L]$
    - Slepton scenario $\tilde{\ell}_L = [\tilde{\ell}^-_L, \tilde{\nu}^0_\ell]$
- Both ISR and FSR contributions are taken into account.
    - ISR approximation is valid for heavy fermions.
    - It could be dangerous to neglect FSR contribution for scalars.
- We demonstrated the strong physics potential of the ILC in detecting the invisible particles.
    - The LR ratios shows that longitudinal beam polarizations are very powerful tools in discriminating different scenarios.
    - The threshold excitation pattern is very crucial in spin determination.