# Invisible Electroweak Particles at the ILC: Single-Photon Processes

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

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# Motivation

- Higgs particle was finally discovered at the LHC on July 4, 2012, and the last piece of the Standard Model has been completed.
- There are also clear hints that lead us to go beyond SM, e.g.
  - Hierarchy problem
  - Dark Matter
  - Neutrino mass
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- It's reasonable to expect more new partices to be discovered.
- But, unfortunately, we haven't seen anything else so far, even with such an unprecedented high energy and high luminosity at the LHC.

# Motivation

- It's still possible that the NP is hidden in compressed spectra.
- The mass splitting between charged and neutral particles is sitting into a narrow window, where they decay very softly, but still quickly enough so that we won't see them as displaced vertices or charged tracks.
- 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

# Framework

- Generically, we are considering scenarios with the following features:
  - A (nearly) degenerate non-colored pair $X^-$ and $X^0$.
  - All other new states are heavy and essentially decoupled.
  - Couple to SM sector only via $\gamma$, $Z$ and $W^\pm$.
- If $X^-$ and $X^0$ are (nearly) degenerate, it would be difficult to detect the decay. Even $X^-$ would essentially become invisible.
- For pair production of invisible particles, we need an extra hard photon to detect events (mono-photon).

  [*M. Perelstein et al., PRD* **70**, *077701 (2004)*]
- More specifically, we choose three benchmark scenarios within the framework of MSSM: higgsino scenario, wino scenario, and slepton scenario.

# Higgsino Scenario $H_{1/2}$

- Two spin-1/2 Higgsino doublets

$$\tilde{H}_d = [\tilde{H}^0_{dL}, \tilde{H}^-_{dL}] \quad \text{and} \quad \tilde{H}_u = [\tilde{H}^+_{uL}, \tilde{H}^0_{uL}]$$

- Realized if $\mu \ll$ other parameters.
- Dirac chargino and Dirac neutralino

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

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

- Interactions

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

# Wino Scenario $W_{1/2}$

- A spin-1/2 Wino triplet

$$\tilde{W} = [\tilde{W}_L^+, \tilde{W}_L^0, \tilde{W}_L^-]$$

- Realized if $M_2 \ll$ other parameters.
- Dirac chargino and Majorana neutralino

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

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

- 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 $L_0$

- A spin-0 left-handed Slepton doublet

$$\tilde{\ell}_L = [\tilde{\ell}_L^-, \tilde{\nu}_\ell^0]$$

- Realized if $\tilde{m}_{\ell_L} \ll$ other parameters. Degeneracy $\Rightarrow \tan\beta = 1$.
- Interactions

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

- Quartic 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

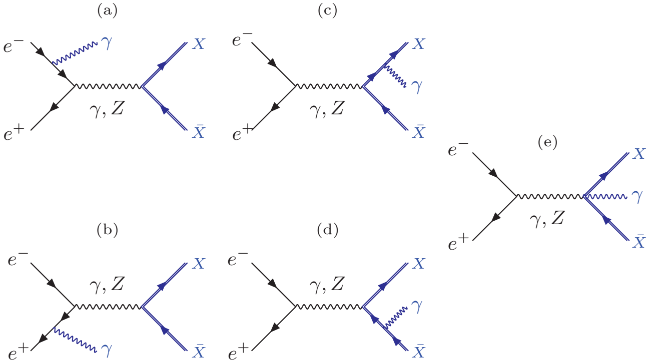
- So far, these new states we are considering are degenerate at tree level.
- A finite mass splitting through radiative corrections will take place after EWSB.
  - For -ino cases, it comes from one-loop photon and Z-boson corrections.

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

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

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

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

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

- $\mathcal{K}(\beta_q)$ 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 from ISR:

P-wave for spin-0, S-wave for spin-1/2

# 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.

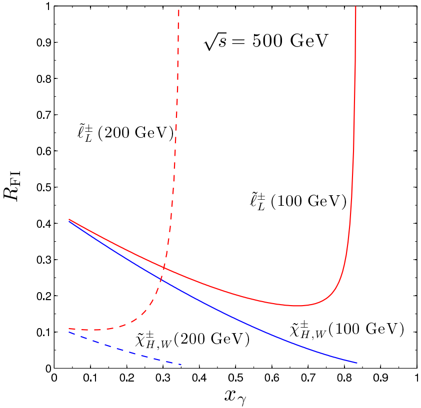
- Near Threshold, $\mathcal{F}_2^X \sim \beta_q^3$.
- BUT

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

- Both spin-0 and spin-1/2 have S-wave patterns, due to quartic terms in $L_0$ scenario.
- Does it spoil the spin determination? No.

# ISR vs. FSR

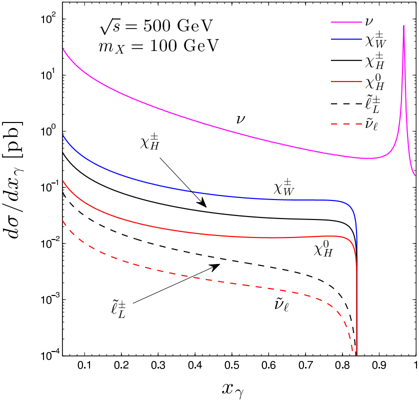
- In principle, the FSR part could be dangerous to the threshold pattern, at least qualitatively. However,




- The FSR part is quantitatively small near the threshold.

# SM Background

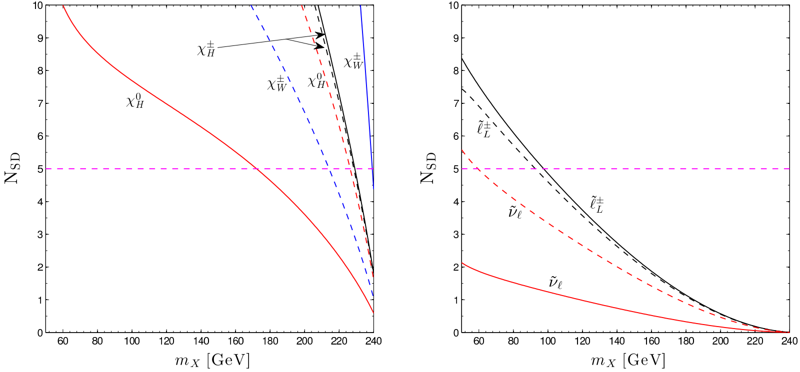
- Background $e^+e^- \to \gamma\nu\bar{\nu}$.
  - Kinematic cut: on the recoil mass squared $q^2 = (1 - x_\gamma)s$, if $m_X > m_Z/2$, to remove the Z-pole, $\sqrt{q^2} > 2m_X$.
  - The t-channel W-exchange is purely left-handed. $\Rightarrow$ Beam polarization.



# Statistical Significance

- Define a theoretical significance

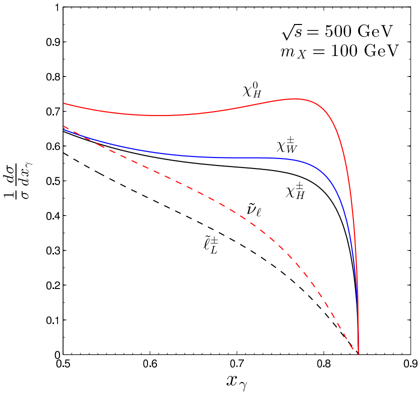
$$N_{SD} = \frac{N_S}{\sqrt{N_S + N_B}} = \frac{\sigma}{\sqrt{\sigma + \sigma_B}} \sqrt{\mathcal{L}}$$




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

# Threshold Excitation

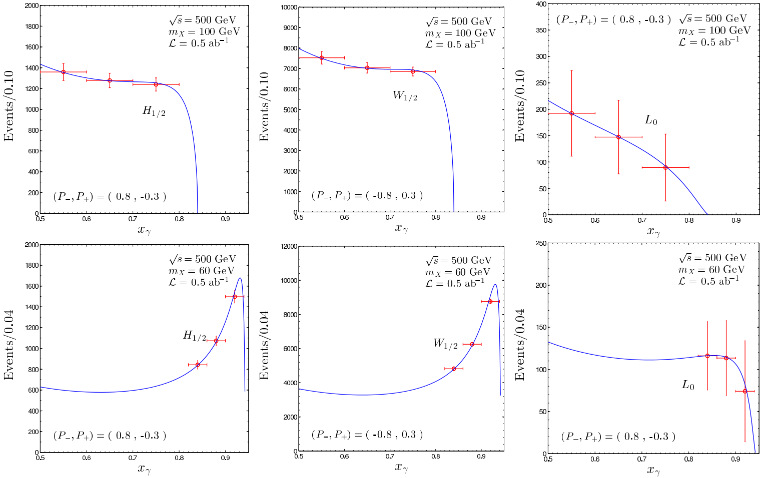
- The threshold excitation pattern is a powerful observable in not only mass measurement but also spin determination.




- The FSR near threshold is numerically very small.
- S-wave for spin-1/2, while “P-wave-like” for spin-0.

# Threshold Excitation

- For ILC with $\sqrt{s} = 500$ GeV and $\mathcal{L} = 0.5\ \mathrm{ab}^{-1}$,

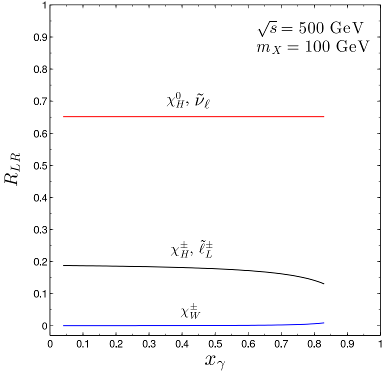


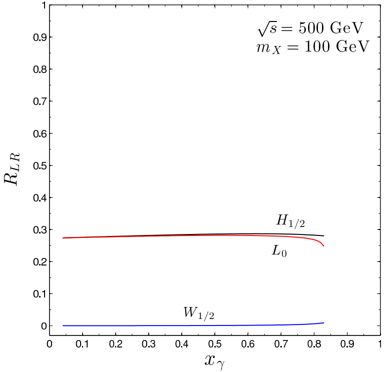

The statistical error bars correspond to the background fluctuation $\sqrt{N_B}$.

# Polarization Dependence

- Define the ratio of polarized cross sections

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

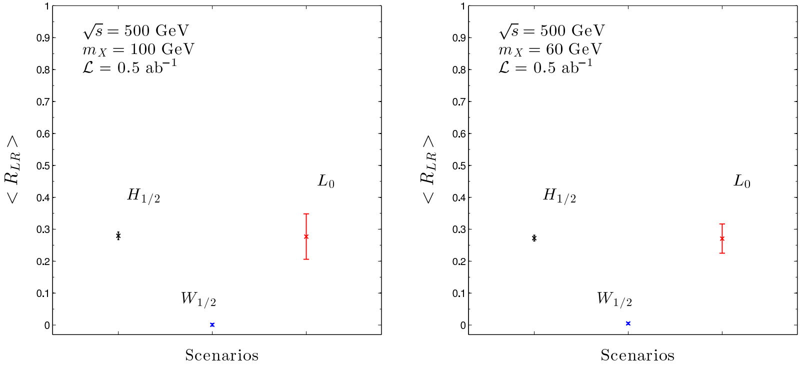



- Each scenario has its own unique value.

# Polarization Dependence

- Assume both polarizations $(P_-, P_+) = (\mp 0.8, \pm 0.3)$ are available, from which the LR ratio can be extracted.




The statistical error bars correspond to the background fluctuation $\sqrt{N_B}$.

# Alternative Methods

- Unlike Dirac neutralino $\chi_H^0$, the Majorana $\chi_W^0$ can mediate fermion number violating processes. Thus, $e^-e^-$ collider mode can differentiate between Higgsino and Wino scenarios

$$e^-e^- \to \nu_e\nu_e W^-W^- \to \nu_e\nu_e\chi_W^-\chi_W^-$$

- For a few hundrde MeV mass splitting, the most important decay modes would be $X^- \to X^0\pi^-, X^0e^-\bar{\nu}_e$ and $X^0\mu^-\bar{\nu}_\mu$ with low $p_T$.

- If decay products can be observed, we would gain additional information on the spin, as well as coupling chirality.

# Summary

- $e^+e^- \to \gamma + \not{E}$ for scenarios with (nearly) degenergate EW particles.
- Both ISR and FSR contributions are taken into account.
- Inspite of FSR contamination, photon energy dependence near threshold alows spin determination.
- longitudinal beam polarizations are very powerful tools in discriminating different scenarios.
- Our results clearly demonstrate the strong physics potential of the ILC in detecting the invisible particles.