Slepton cascade decays at ILC

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Summary

Slepton cascade decays in SUSY:

1. Why?
2. What for?
3. When?
4. How?

Why?

- Final state momenta reconstructed kinematically

  Pair production of SUSY particles ☞ two $\tilde{\chi}_1^0$ in final state

  Decay of charginos ☞ additional ν

  Too many unknown momenta unless kinematical relations among particle momenta exist

- Multi-lepton final states ☞ Small backgrounds

  (Sometimes signals small as well)

What for?

Kinematical reconstruction of sparticle masses

Example: $m^2_{\tilde{e}_L} = p^2_{\tilde{e}_L}$ / $p_{\tilde{e}_L}$ reconstructed from decay products

Measurement of spin-related quantities $\left[\begin{array}{l} \text{spin} \\ \text{spin analysing power const.} \\ \text{CP asymmetries} \\ \dots \end{array} \right.$

- Spin direction easy to obtain
- Reconstruction of rest frames possible

When?

Necessary to have slepton decays to other particles than LSP

Example:

$$\tilde{e}_L^\pm \to e^\pm \tilde{\chi}_2^0 \to e^\pm f\bar{f}\,\tilde{\chi}_1^0$$
$$\tilde{\nu}_e \to e^- \tilde{\chi}_1^+ \to e^- f\bar{f}'\tilde{\chi}_1^0$$

Additionally:

In scenarios with $\tilde{\chi}_2^0$ 3-body decays: sizeable CP violation

☞ scenario similar to SPS1a with heavier sfermions and complex M_1, μ

SUSY scenario

RGE evolution, masses and mixings calculated with SPheno

M_1	$102.0 \ \ e^{i\phi_1}$ GeV
M_2	192.0 GeV
μ	$377.5 \ \ e^{i\phi_\mu}$ GeV
$\tan\beta$	10
$m_{\tilde{e}_R}$, $m_{\tilde{\mu}_R}$	224.0 GeV
$m_{\tilde{e}_L}$, $m_{\tilde{\mu}_L}$	264.5 GeV
$m_{\tilde{\nu}_e}$	252.4 GeV
$m_{\tilde{u}_L}, m_{\tilde{c}_L}$	571.5 GeV
$m_{\tilde{d}_L}, m_{\tilde{s}_L}$	577.0 GeV

For $\phi_1 = \phi_\mu = 0$ they correspond to

$$
\begin{aligned}
m_{1/2} &= 250 \text{ GeV} \\
m_{\tilde{E}} = m_{\tilde{L}} = m_{H_i} &= 200 \text{ GeV} \\
A_E &= -200 \text{ GeV}
\end{aligned}
$$

$$m_{\tilde{\chi}_1^0} \simeq 99 \text{ GeV}, \quad m_{\tilde{\chi}_1^-}, m_{\tilde{\chi}_2^0} \simeq 178 \text{ GeV}, \quad m_{\tilde{\chi}_2^-} \simeq 401 \text{ GeV}$$

More

How?

Selectron pair production and cascade decay: ▸ See diagrams

$$e^+e^- \to \tilde{e}^+_{L,R}\tilde{e}^-_{L,R} \to \left[\begin{array}{l} e^+\tilde{\chi}^0_1\; e^-\tilde{\chi}^0_2 \to e^+\tilde{\chi}^0_1\; e^-\tilde{\mu}^+\mu^-\chi^0_1 \\ e^+\tilde{\chi}^0_2\; e^-\tilde{\chi}^0_1 \to e^+\mu^+\mu^-\tilde{\chi}^0_1\; e^-\tilde{\chi}^0_1 \end{array} \right.$$

[JAAS, PLB ’04]

Sneutrino pair production and cascade decay: ▸ See diagrams

$$e^+e^- \to \tilde{\nu}^*_e\tilde{\nu}_e \to e^+\tilde{\chi}^-_1\; e^-\tilde{\chi}^+_1 \to \left[\begin{array}{l} e^+\bar{\nu}_\mu\mu^-\tilde{\chi}^0_1\; e^-q\bar{q}'\tilde{\chi}^0_1 \\ e^+\bar{q}q'\tilde{\chi}^0_1\; e^-\nu_\mu\mu^+\tilde{\chi}^0_1 \end{array} \right.$$

[JAAS, NPB ’05]

Also in $e^- e^-$ collisions:

See diagrams

$$e^- e^- \longrightarrow \tilde{e}^-_{L,R} \tilde{e}^-_{L,R} \longrightarrow e^- \tilde{\chi}^0_1 \, e^- \tilde{\chi}^0_2 \longrightarrow e^- \tilde{\chi}^0_1 \, e^- f \bar{f} \tilde{\chi}^0_1$$

[JAAS, Teixeira, NPB '03]
[JAAS, LC-TH '03]

Use full $2 \to n$ resonant matrix elements ☞ Finite width and spin effects included

Details of the calculation

ISR and beamstrahlung effects are included

We perform a parton-level analysis, with a Gaussian smearing of charged lepton and jet energies

$$\frac{\Delta E^e}{E^e} = \frac{10\%}{\sqrt{E^e}} \oplus 1\% \qquad \frac{\Delta E^j}{E^j} = \frac{50\%}{\sqrt{E^j}} \oplus 4\% \qquad \frac{\Delta E^\mu}{E^\mu} = 0.02\%\, E^\mu$$

Kinematical cuts $p_T \geq 10$ GeV, $\quad |\eta| \leq 2.5, \quad \Delta R \geq 0.4$

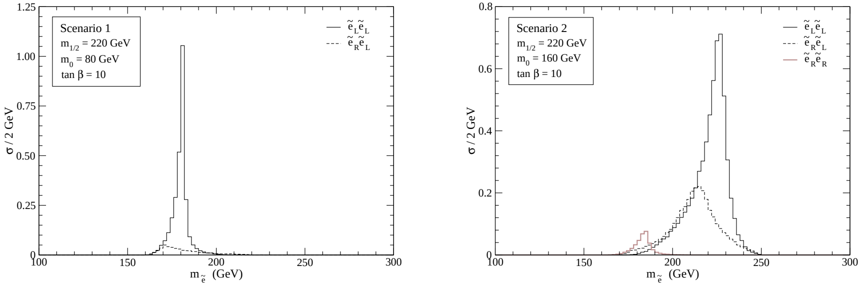
Reconstruct momenta requiring energy-momentum conservation and the kinematics of the cascade decays

Outcome:
- For $\tilde{\chi}_2^0$ and hadronic $\tilde{\chi}_1^\pm$ decay $p_{\tilde{\chi}_1^0}$ can be reconstructed
- In $\tilde{\chi}_1^\pm$ leptonic decay only $p_\nu + p_{\tilde{\chi}_1^0}$ can be determined

Mass reconstruction

Example: $e^- e^- \to \tilde{e}^-_{L,R} \tilde{e}^-_{L,R} \to e^- e^- f \bar{f} \tilde{\chi}^0_1 \tilde{\chi}^0_1$

$f = \mu$ $f = q$

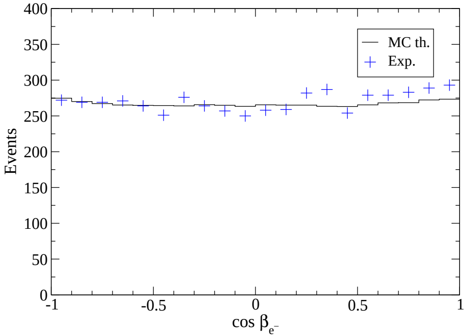


Selectron masses not used in reconstruction procedure

Reconstruction done assuming two equal mass particles produced

Decay of scalars

Example: $\tilde{\nu}_e \to e^- \tilde{\chi}_1^+$

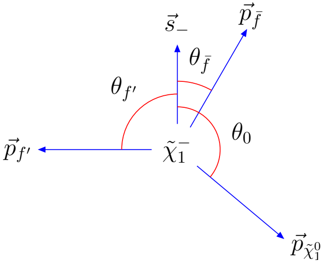


β_{e^-} $\longrightarrow$ angle with respect to an arbitrary axis orthogonal to the beam line

Flat distribution indicates that $\tilde{\nu}_e$ is scalar and $\tilde{\chi}_1^+$ has half-integer spin

Decay of gauginos

Example: $\tilde{\chi}_1^- \to \bar{f} f' \tilde{\chi}_1^0$ $\qquad \Gamma^- \equiv \Gamma(\tilde{\chi}_1^- \to \bar{f} f' \tilde{\chi}_1^0)$



$$\frac{1}{\Gamma^-}\frac{d\Gamma^-}{d\cos\theta_{\bar{f}}} = \frac{1 + h_{\bar{f}}\cos\theta_{\bar{f}}}{2}$$

$$\frac{1}{\Gamma^-}\frac{d\Gamma^-}{d\cos\theta_{f'}} = \frac{1 + h_{f'}\cos\theta_{f'}}{2}$$

$$\frac{1}{\Gamma^-}\frac{d\Gamma^-}{d\cos\theta_0} = \frac{1 + h_0^-\cos\theta_0}{2}$$

$\bar{f} = \bar{\nu}, \bar{u}, \bar{c}, \quad f' = \mu^-, d, s \quad \vec{s}_-$ is the spin direction

$h_{\bar{f}}, h_{f'}, h_0^-$ constants between -1 and 1

For charge-conjugate decay $\tilde{\chi}_1^+ \to f\bar{f}'\tilde{\chi}_1^0$

Angular distributions in $\tilde{\chi}_1^+$ rest frame given by analogous equations

Determined by constants h_f, $h_{\bar{f}'}$, h_0^+

- If CP is conserved: $h_f = -h_{\bar{f}}, \;\; h_{\bar{f}'} = -h_{f'}, \;\; h_0^+ = -h_0^-$
- If CP is broken, these equalities hold at tree level up to small particle width effects

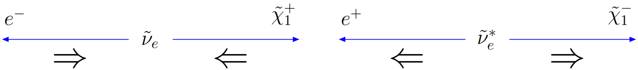
But what is the spin direction?

Sneutrino decays given by the Lagrangian

$$\mathcal{L}_{\tilde{\nu}_e e \tilde{\chi}_1^-} = -g V_{11}\, \bar{e}\, P_R\, \tilde{\chi}_1^-\ \tilde{\nu}_e - g V_{11}^*\, \overline{\tilde{\chi}_1^-}\, P_L\, e\, \tilde{\nu}_e^*$$

e massless $\Rightarrow$ helicity = chirality

$$\tilde{\nu}_e \longrightarrow e^- \tilde{\chi}_1^+ \qquad\qquad \tilde{\nu}_e^* \longrightarrow e^+ \tilde{\chi}_1^-$$



$$\tilde{\chi}_1^+ \longrightarrow h = -1 \qquad\qquad \tilde{\chi}_1^- \longrightarrow h = 1$$

See $\tilde{\chi}_1^+ \tilde{\chi}_1^-$

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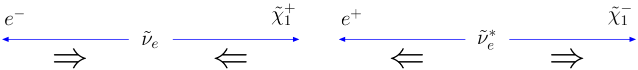

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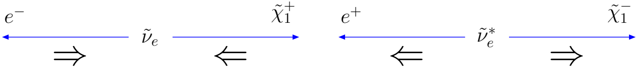

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See $\tilde\chi_1^+ \tilde\chi_1^-$

OK... But angular distributions – why?

- Show that charginos and neutralinos have spin
- Can be theoretically predicted [Djouadi et al., EPJC ’01]
  Measured precisely ☞ measure them
- Could help determine SUSY parameters?

Determination of angular distributions

Example: $t\bar{t}$ production at LHC

[Hubaut et al., SN-ATLAS ’05]
[JAAS et al., ATL-COM in prep.]

- Generate a reference sample of simulated events
- Calculate correction functions f relating theoretical and simulated results
- Apply the correction functions to a second sample

Here:

- Generate a “possible experimental result” according to the expected distribution (using Poisson statistics)
- Calculate h considering only the regions where $f = 1$

Signal and backgrounds

$e^+e^- \to \tilde{\nu}_e \tilde{\nu}_e^* \to e^+ \bar{\nu}_\mu \mu^- \tilde{\chi}_1^0 \; e^- q\bar{q}' \tilde{\chi}_1^0$ Cross section: 17.56 fb

SUSY backgrounds (SPHENO):

$$e^+e^- \to \tilde{\chi}_1^\pm \tilde{\chi}_2^\mp \to \left[\begin{array}{l} \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp Z \\ \tilde{\chi}_1^\pm \tilde{\chi}_2^0 W^\mp \end{array} \right.$$

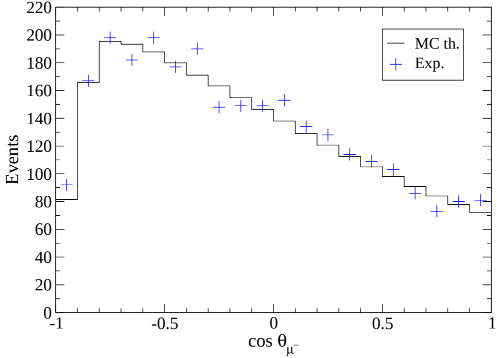
$$e^+e^- \to \tilde{\chi}_2^0 \tilde{\chi}_{3,4}^0 \to \chi_2^0 \tilde{\chi}_1^\pm W^\mp$$

with $Z \to e^+e^-$, $\tilde{\chi}_2^0 \to e^+e^- \tilde{\chi}_1^0$, $\tilde{\chi}_1^\pm$ and $W^\mp$ decaying one hadronically and the other leptonically $\longrightarrow$ Total: 0.1 fb

SM background: six-fermion production $e^+e^- \to e^+e^- \mu\nu_\mu q\bar{q}'$
Cross section calculated with LUSIFER: 4 fb

☞ Expected to be highly reduced with cuts

Distribution of μ^-



Fit: $h_{\mu^-} = -0.270 \pm 0.016$

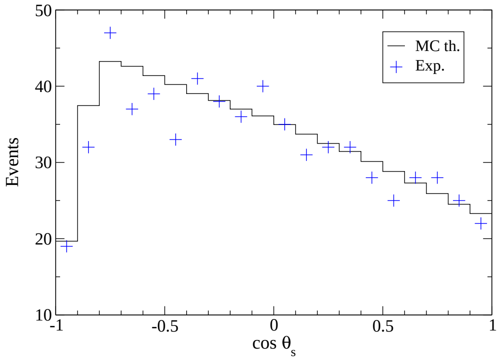
Th: $h_{\mu^-} = -0.252$

Fit performed excluding bins with $\cos\theta_{\mu^-} \simeq -1$

Inclusion of $\tilde{\chi}_1^+ \to \nu_\mu \mu^+ \tilde{\chi}_1^0$ decays would improve statistics

Systematics $\lesssim$ 5% ?

Distribution of s quark



Fit: $h_s = -0.151 \pm 0.020$

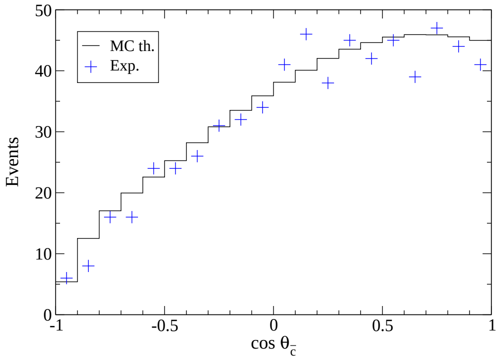
Th: $h_s = -0.149$

Jets distinguished using c tagging and μ charge $\longrightarrow$ σ reduced by a factor of 4

Fit performed excluding bins with $\cos\theta_{\mu^-} \simeq -1$

Inclusion of $\tilde{\chi}_1^+ \to c\bar{s}\tilde{\chi}_1^0$ decays would improve statistics

Distribution of c antiquark



Fit: $h_{\bar{c}} = 0.387 \pm 0.044$

Th: $h_{\bar{c}} = 0.339$

Jets distinguished using c tagging and μ charge $\rightarrow$ σ reduced by a factor of 4

Fit performed excluding bins with $\cos\theta_{\mu^-} \simeq -1, 1$

Inclusion of $\tilde{\chi}_1^+ \rightarrow c\bar{s}\tilde{\chi}_1^0$ decays would improve statistics

SUSY CP violation – why?

- No *a priori* symmetry to ensure ϕ_1, ϕ_μ real in MSSM
- EDM constraints allow for cancellations and large phases ϕ_1
- Asymmetries in $\tilde{\chi}_2^0$, $\tilde{\chi}_1^\pm$ decays sensitive to both phases
- Large $\tilde{\chi}_1^0$ mass allows sizeable triple-product CP asymmetries of order $O(0.1)$ at tree level

CP asymmetries sensitive to ϕ_1

- Triple-product asymmetry in $e^+e^- \to \tilde{\chi}_2^0 \tilde{\chi}_1^0 \to \ell^+\ell^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$
  [Bartl et al., JHEP '04]
  [JAAS, NPB '04]
- Triple-product asymmetry in selectron cascade decays
  [JAAS, PLB '04]
- Triple-product asymmetry in sneutrino cascade decays
  [JAAS, NPB '05]
- Triple-product asymmetry in chargino production
  [Bartl et al., PLB '04]
- Azimuthal asymmetries with transversely polarised beams
  [Bartl et al., '05]

CP violation

Example: $\tilde{\chi}_2^0$ decays

Define triple product

$$Q = \vec{s} \cdot \left(\vec{p}_{\mu^-} \times \vec{p}_{\mu^-} \right)$$

$$\begin{array}{ccc} \vec{s} & \rightarrow & \text{spin of } \tilde{\chi}_2^0 \\ \vec{p}_{\mu^-} & \rightarrow & \text{momentum of } \mu^- \\ \vec{p}_{\mu^+} & \rightarrow & \text{momentum of } \mu^+ \end{array}$$

Define the T-odd, CP-odd asymmetry

$$A = \frac{N(Q > 0) - N(Q < 0)}{N(Q > 0) + N(Q < 0)}$$

See more

CP violation

Example: $\tilde{\chi}_1^\pm$ decays

Define triple product

$$Q_{12} = \vec{s}_\pm \cdot (\vec{p}_{\bar{q}_1} \times \vec{p}_{q_2})$$

$\vec{s}_\pm \rightarrow$ spin of $\tilde{\chi}_1^\pm$
$\vec{p}_{\bar{q}_1} \rightarrow$ momentum of $\bar{q}_1 = \bar{c}, \bar{s}$
$\vec{p}_{q_2} \rightarrow$ momentum of $q_2 = s, c$

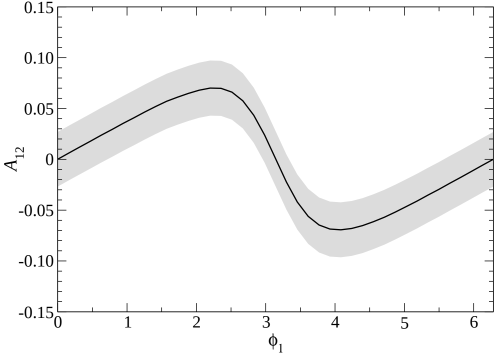
Define the T-odd, CP-odd asymmetry (summing $\tilde{\chi}_1^+$ and $\tilde{\chi}_1^-$ decays)

$$A_{12} = \frac{N(Q_{12} > 0) - N(Q_{12} < 0)}{N(Q_{12} > 0) + N(Q_{12} < 0)}$$

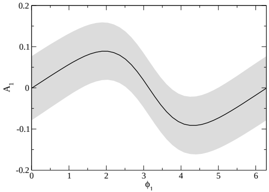
See more

Comparison

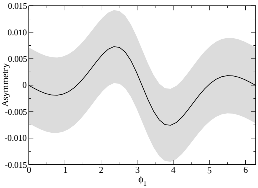
ISR, beamstrahlung, backg. included



$\tilde{\nu}_e$ cascade decays: 2.6 σ



$\tilde{e}_L$ decays: 1.3 σ



$\tilde{\chi}_2^0 \tilde{\chi}_1^0$ production: 1.1 σ

Conclusions

Cascade decays: Why ILC?

- Reconstruction of final state momenta possible
- Large slepton production cross sections due to t channel exchange diagrams
- Good b tagging, b / $\bar{b}$ separation, c tagging possible
- ... and small backgrounds

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(ϕ_1, ϕ_μ) values compatible with the electron EDM

ϕ_1	ϕ_μ	ϕ_1	ϕ_μ
0	0	π	0
$\pi/8$	-0.0476	$7\pi/8$	-0.0454
$\pi/4$	-0.0876	$3\pi/4$	-0.0845
$3\pi/8$	-0.1136	$5\pi/8$	-0.1114
$\pi/2$	-0.1218		

plus $(\phi_1, \phi_\mu) \to (-\phi_1, -\phi_\mu)$

Back

$\tilde{\chi}_1^+ \tilde{\chi}_1^-$ production

In $e^+e^- \to \tilde{\chi}_1^+ \tilde{\chi}_1^-$ the produced charginos are polarised

[Choi et al., EPJC '99]

Determination of spin-related quantities seems difficult:

- Chargino momenta cannot be determined
- Large background $e^+e^- \to W^+W^- \to \ell^\pm \nu jj$
  (3.5 pb at 500 GeV with $P_{e^+} = 0.6$, $P_{e^-} = -0.8$)

In $e^+e^- \to \tilde{\chi}_2^0 \tilde{\chi}_1^0$ the produced neutralinos are polarised too

[Moortgat-Pick et al., EPJC '99]

but the same problems arise

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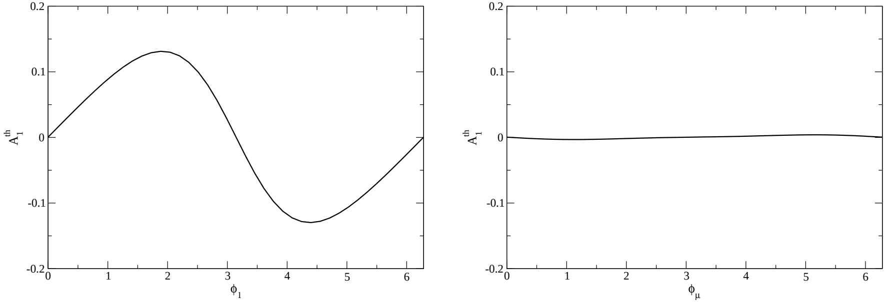
Theoretical value of the CP asymmetry A_1



Dependence on ϕ_μ negligible

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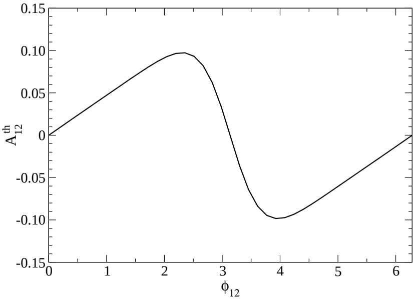
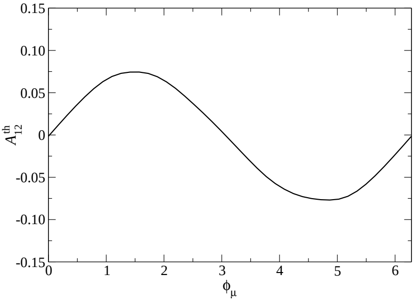
Theoretical value of the CP asymmetry A_{12}





Dependence on ϕ_μ non-negligible for ϕ_μ values required by electron EDM

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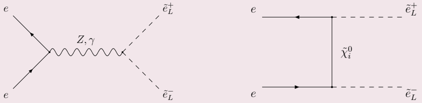
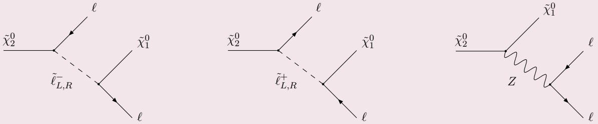
Feynman diagrams

Selectron pair production



Neutralino decay



Scenario used: intermediate particles off-shell

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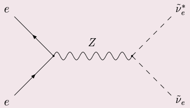
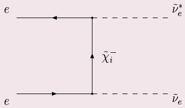
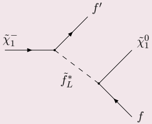
Feynman diagrams

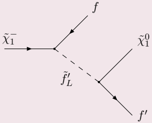
Sneutrino pair production

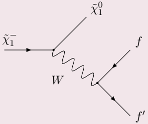




Chargino decay







Scenario used: decay is three-body but dominated by W exchange

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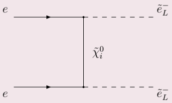
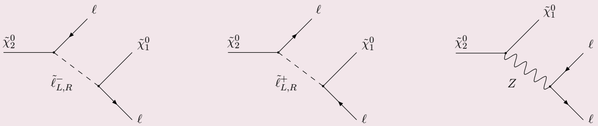
Feynman diagrams

Selectron pair production



Neutralino decay



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