Hunting the invisible sneutrinos at the ILC

Status report

Tania Robens

in collaboration with J. Kalinowski, W. Kilian, J. Reuter, K. Rolbiecki

RWTH Aachen

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Sneutrinos in the MSSM

- standard way of sneutrino mass determination:
  threshold scans, measure cross sections decay products
- typical:

$$\tilde{\nu} \longrightarrow \widetilde{\chi}^{\pm}\, l^{\mp} \tag{1}$$

- in some points of parameters space: $m_{\widetilde{\chi}} > m_{\tilde{\nu}}$, dominant decay $\tilde{\nu} \longrightarrow \widetilde{\chi}^{0}\, \nu$
- decay products invisible
- but: can nevertheless "see" the $\tilde{\nu}$ in $\widetilde{\chi}^{\pm}$ decays (inverse of (1))
- already explored by Freitas ea, 05

What's new ??

- idea: redo the analysis using full matrix element for both signal and backgrounds

$\Rightarrow$ include all interference effects

$\Rightarrow$ get a handle on complicated final states (up to 10 particles in the final state)

- for this: using Monte Carlo Event Generator `WHIZARD`
- authors: W. Kilian, T. Ohl, J. Reuter (LC-TOOL-2001-039, arXiv: 0708.4233 [hep-ph])
- so far: LO Monte Carlo Event Generator for $2 \rightarrow n$ particle processes
- $\mathcal{M}$ generation: `O'Mega`, full matrix element generation
- initial state radiation and beamstrahlung automatically included

Signal and (MS)SM backgrounds

- chargino decay through sneutrinos: leptonic decay mode

$$e^+\,e^- \;\longrightarrow\; \widetilde{\chi}_1^+\widetilde{\chi}_1^- \;\longrightarrow\; (\tilde{\bar{\nu}}_e\,\tilde{\nu}_\mu\,e^-\,\mu^+ \longrightarrow)\,\widetilde{\chi}_1^0\,\widetilde{\chi}_1^0\,e^-\,\mu^+\,\nu_\mu\,\bar{\nu}_e$$

signal: $e^-\,\mu^+ + \mathbf{E_{miss}}$

- many background processess !! 23 considered in our study
- SM backgrounds: mainly (W (pair)production, τ pair production)

$$e^+e^- \;\longrightarrow\; \text{anything} \longrightarrow e^-\,\mu^+\,n_i\nu_i\,n_j\bar{\nu}_j(\gamma\,\gamma\,...)$$

- SUSY backgrounds: SUSY version of above processes
  $\Rightarrow$ additional $\widetilde{\chi}_1^0$s

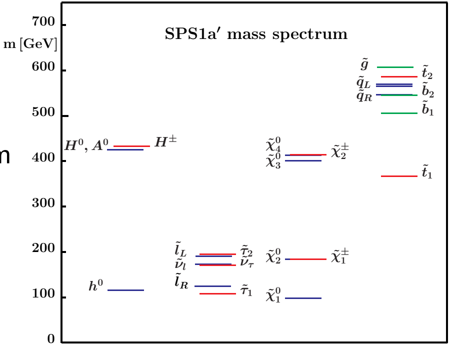
$$e^+e^- \longrightarrow \text{anything} \longrightarrow \widetilde{\chi}_1^0\,\widetilde{\chi}_1^0\,n_i\nu_i\,n_j\bar{\nu}_j(\gamma\,\gamma\,...)$$

- $+$: backgrounds with additional visible particles vanishing in the beampipe

Point SPS1a'

- mSUGRA scenario
- according to Snowmass Points (Allanach ea, 02), in agreement with cosmology data/ WMAP ($\tilde{\chi}_1^0$ as DM candidate)

spectrum $\Longrightarrow$



light sleptons
heavy squarks
some light $\tilde{\chi}$s
all masses < 1 TeV

Signal and background w/o cuts

Large SM backgrounds ($\sqrt{s} = 500\,\mathrm{GeV}$)

(including initial state radiation and beamstrahlung)

$$\sigma_{\textbf{signal}} = 3.97 \pm 0.01\,\mathrm{fb}$$

- $\sigma_{\gamma\tau} = 25.495 \pm 0.004\,\mathrm{pb}$ $(e^+e^-e^+\mu^-\nu_\mu\bar{\nu}_e\nu_\tau\bar{\nu}_\tau)$
  photon induced τ pairproduction
- $\sigma_{\gamma\,c} = 1.089 \pm 0.004\,\mathrm{pb}$ $(e^+e^-e^+\mu^-\nu_\mu\bar{\nu}_e j\,j)$
  photon induced charm pairproduction (jets vanish in beampipe)
- $\sigma_{\mathrm{WW}} = 152.42 \pm 0.41\,\mathrm{fb}$ $(e^-\mu^+\nu_\mu\bar{\nu}_e)$
  WW (pair) production
- $\sigma_\tau = 32.7 \pm 0.1\,\mathrm{fb}$ $(e^-\mu^+\nu_\mu\bar{\nu}_e\nu_\tau\bar{\nu}_\tau)$
  τ pairproduction
- $\sigma_{\tau\,e} = 26.64 \pm 0.10\,\mathrm{fb}$ $(e^-\mu^+\nu_\mu\bar{\nu}_e\nu_\tau\bar{\nu}_\tau)$
  $\tau^+\,e^-$ production and decay
- $\sigma_{\tau\,\mu} = 15.57 \pm 0.05\,\mathrm{fb}$ $(e^-\mu^+\nu_\mu\bar{\nu}_e\nu_\tau\bar{\nu}_\tau)$
  $\tau^-\,\mu^+$ production and decay

Signal-size (MS)SM backgrounds ($\sqrt{s} = 500\,\mathrm{GeV}$)

(including initial state radiation and beamstrahlung)

$$\sigma_{\textbf{signal}} = 3.97 \pm 0.01\,\mathrm{fb}$$

- $\sigma_{\tau W} = 2.978 \pm 0.009\,\mathrm{fb}$ $(e^-\mu^+\nu_\mu\,\bar{\nu}_e\nu_\tau\,\bar{\nu}_\tau\nu_\tau\,\bar{\nu}_\tau)$
  τ from WW production
- $\sigma_{\gamma W} = 2.192 \pm 0.012\,\mathrm{fb}$ $(e^-e^+e^-\mu^+\nu_\mu\,\bar{\nu}_e\nu_\tau\,\bar{\nu}_\tau)$
  photon induced WW production
- $\sigma_{\tilde{\tau}} = 4.107 \pm 0.007\,\mathrm{fb}$ $(e^-\mu^+\nu_\mu\,\bar{\nu}_e\nu_\tau\,\bar{\nu}_\tau\widetilde{\chi}^0_1\widetilde{\chi}^0_1)$
  stau pairproduction
- $\sigma_{\tilde{\tau}\,e} = 3.69 \pm 0.03\,\mathrm{fb}$ $(e^-\mu^+\nu_\mu\,\bar{\nu}_e\nu_\tau\,\bar{\nu}_\tau\widetilde{\chi}^0_1\widetilde{\chi}^0_1)$
  $\tilde{\tau}\,e^-$ production and decay
- $\sigma_{\tilde{\tau}\nu_\tau} = 2.74 \pm 0.09\,\mathrm{fb}$ $(e^-\mu^+\nu_\mu\,\bar{\nu}_e\nu_\tau\,\bar{\nu}_\tau\nu_\tau\,\bar{\nu}_\tau\widetilde{\chi}^0_1\widetilde{\chi}^0_1)$
  stau-neutrino production (mainly from $\widetilde{\chi}$ production)
- $\sigma_{\tilde{\tau}\,\mu} = 2.62 \pm 0.02\,\mathrm{fb}$ $(e^-\mu^+\nu_\mu\,\bar{\nu}_e\nu_\tau\,\bar{\nu}_\tau\widetilde{\chi}^0_1\widetilde{\chi}^0_1)$
  $\tilde{\tau}\,\mu^+$ production and decay

Backgrounds: summary

- a lot of numbers... summary:
- before cuts:

$$\frac{\text{signal}}{\text{background}} = \mathcal{O}(10^{-4})$$

- 5 ‰ of background SUSY-induced:

$$\frac{\text{total SUSY}}{\text{background}} = \mathcal{O}(10^{-4})$$

- largest background: photon-induced $\tau\tau, c\bar{c}$ production
- of course, this is no surprise...

Handling backgrounds: cuts

- many different backgrounds with different kinematics (between 4 and 10 final state particles)

⇒ need cuts which significantly suppress backgrounds, don't kill too much of the signal

- example: very large background: photon induced $\tau\tau$ production

$$\sigma_{\gamma\tau} = 25.495 \pm 0.004\,\mathrm{pb},\ \sigma_{\text{signal}} = 3.97 \pm 0.008\,\mathrm{fb}$$

factor 10^4 difference

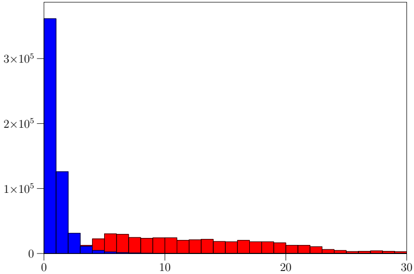
- background: results in low energy τs with litte $p_\perp$, leptons emitted back to back

⇒ suppression $\mathcal{O}(10^6)$ from

$$p_\perp(e,\mu) \geq 2\,\mathrm{GeV}, -172^o \leq \Delta\,\phi \leq 172^o$$

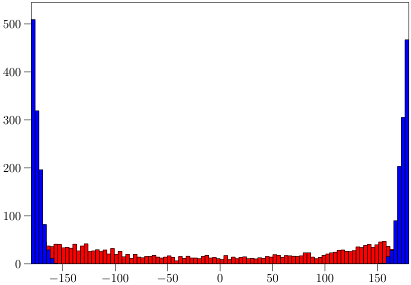
Example: cuts on photon induced $\tau\tau$ backgrounds

$p_\perp$ and $\Delta\phi$ distributions of signal, $\tau\tau$ background
normalized to same σ_{tot}



$p_\perp(e^-)$[GeV]

cut on $p_\perp$ cuts out 99.58 % of background, 11 % of signal



$\Delta\,\phi$ [deg]

renormalized after $p_\perp$ cuts

cut on $\Delta\phi$ cuts out 99.68 % of background, 25 % of signal

Cross sections including cuts

In the end: Mastercuts for all backgrounds

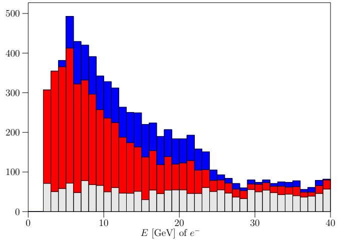
$$2\,\mathrm{GeV} \leq p_\perp(e,\mu) \leq 1\,\mathrm{TeV},\; 4\,\mathrm{GeV} \leq p_\perp(e)+p_\perp(\mu) \leq 1\,\mathrm{TeV}$$
$$1\,\mathrm{GeV} \leq E(e,\mu) \leq 40\,\mathrm{GeV},\; -150^o \leq \Delta\phi \leq 150^o,$$
$$15^o \leq \theta(e) \leq 155^o,\; 25^o \leq \theta(\mu) \leq 165^o$$

$$\sigma_{\text{signal}} \longrightarrow 1.639 \pm 0.003\,\mathrm{fb}\;(41\%)$$
$$\sigma_{\gamma\tau} \longrightarrow 0.234 \pm 10^{-5}\,\mathrm{fb}\;(\mathcal{O}(10^{-5}))$$
$$\sigma_{WW} \longrightarrow 0.794 \pm 0.002\,\mathrm{fb}\;(0.5\%)$$
$$\sigma_{\tilde{\tau}} \longrightarrow 0.978 \pm 0.002\,\mathrm{fb}\;(24\%)$$
$$\sigma_{\tilde{\tau}\,e} \longrightarrow 1.102 \pm 0.008\,\mathrm{fb}\;(30\%)$$
$$\sigma_{\tilde{\tau}\nu_\tau} \longrightarrow 0.72 \pm 0.02\,\mathrm{fb}\;(24\%)$$
$$\sigma_{\tilde{\tau}\mu} \longrightarrow 0.966 \pm 0.008\,\mathrm{fb}\;(37\%)$$

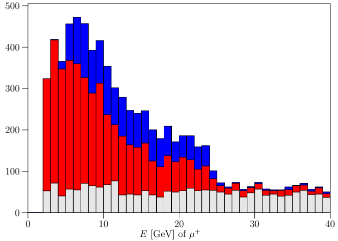
SM almost dissappeared; still large SUSY backgrounds

Energy distributions including cuts

for SPS1a', $\sqrt{s} = 500\,\mathrm{GeV}$, $\int \mathcal{L} = 1\mathrm{ab}^{-1}$,



$E(e^-)\,[\mathrm{GeV}]$



$E(\mu^+)\,[\mathrm{GeV}]$

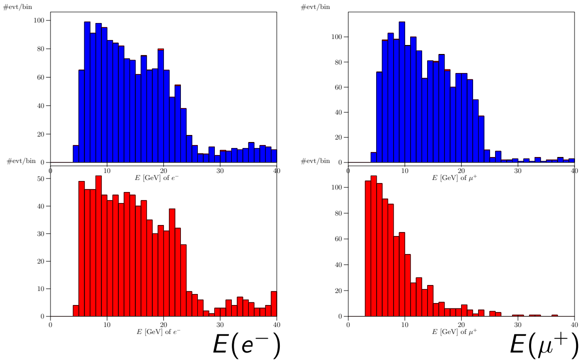
signal, SUSY background $\tilde{\tau}\, l$ (54%), $\tilde{\tau}\tilde{\tau}$ (25%), $\tilde{\tau}\tilde{\tau}\nu_\tau\bar{\nu}_\tau$ (17%)
SM background WW (49%), WW via $\tau\, l$ (33%), ...

signal/ background = 0.30

Messy SUSY backgrounds

largest problem: "semi-signal" decays, eg

$$e^+e^- \rightarrow \widetilde{\chi}^+\widetilde{\chi}^- \rightarrow e^-\tau^+\,\bar{\nu}_e\nu_\tau\,\widetilde{\chi}_1^0\widetilde{\chi}_1^0 \rightarrow e^-\mu^+\nu_\mu\,\bar{\nu}_e\nu_\tau\,\bar{\nu}_\tau\widetilde{\chi}_1^0\widetilde{\chi}_1^0$$



signal, semisignal: very similar kinematics, hard to find cuts

$\widetilde{\chi}^{\pm}$ and $\tilde{\nu}$ mass determination (1)

- SPS1a': $\widetilde{\chi}_1^{\pm}$ and $\tilde{\nu}_e$ nearly mass degenerate

$$m_{\widetilde{\chi}^{\pm}} \; = \; 183.67\,\mathrm{GeV}, \;\; m_{\tilde{\nu}} \; = \; 173.52\,\mathrm{GeV}$$

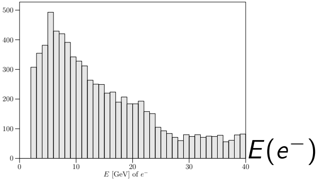
- $\tilde{\nu}$ decays to $\widetilde{\chi}^0$, ν: can only be observed indirectly
- determination from lepton energy (Freitas ea, 05):

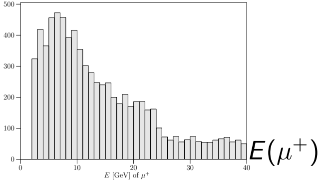
$$m_{\widetilde{\chi}^{\pm}} \; = \; \sqrt{s}\,\frac{\sqrt{E_{\mathrm{min}}\,E_{\mathrm{max}}}}{E_{\mathrm{min}}+E_{\mathrm{max}}}, \;\; m_{\tilde{\nu}} \; = \; m_{\widetilde{\chi}^{\pm}}\sqrt{1-\frac{2\,(E_{\mathrm{min}}+E_{\mathrm{max}})}{\sqrt{s}}},$$

$E_{\mathrm{min,\,max}}$: edges of lepton energy distributions;
$\widetilde{\chi}_1^{\pm}$, $\tilde{\nu}_e$ are assumed onshell

E_{min} hard in this case $\Rightarrow$ remember distributions...

$\tilde{\chi}^{\pm}$ and $\tilde{\nu}$ mass determination (2)





- next idea: take $m_{\tilde{\chi}}$ from threshold scans (much better anyway)
- use

$$m_{\tilde{\nu}}^2 = m_{\tilde{\chi}}^2 \left(1 - \frac{4\,E_{\max}}{\sqrt{s}}\,\frac{1}{1+\sqrt{1-\frac{4\,m_{\tilde{\chi}}^2}{s}}}\right)$$

- readoff: $E_{\max} = 24 \pm 1\,(2)\,\mathrm{GeV}$, use $m_{\tilde{\chi}} = 184 \pm 1\,\mathrm{GeV}$
- obtain

$$m_{\tilde{\nu}} = 174 \pm 3\,(5)\,\mathrm{GeV}\,\checkmark \quad (\text{input: } 172.52\,\mathrm{GeV})$$

$\tilde{\chi}^{\pm}$ and $\tilde{\nu}$ mass determination: improvements

- determination works, but still 1 % error

possible improvements

- find better cuts $\Longrightarrow$ also determine E_{min}
- use a fitting procedure for $m_{\tilde{\nu}}$ using E_{max}, σ ($\Rightarrow$ Freitas ea) (work in progress)
- use more sophisticated fitting procedures (χ^2 bin by bin/ use full kinematic information as eg lepton energy correlations/ ...)
- ...

Summary and Outlook

- Invisible sneutrinos become visible in leptonic decays of charginos at the ILC, mass determination is possible
- using full matrix elements for $2 \to n$ processes involved, including all (SUSY and SM) backgrounds
- all processes are generated with initial state radiation and beamstrahlung
- so far: backgrounds sufficiently suppressed
- determination of both upper and lower edge not that easy
- possible improvement: better cuts, fitting routines
- compare to previous analysis by Freitas ea (work in progress)
- in the long run: different scenarios
- in the long long long run: extend to NLO (feasible ??)
- read about this in arXiv:0803.4161

Thanks for listening

SM backgrounds contributing after cuts

$$\sigma_{\text{sign, nc}} = 3.97\,\text{fb}, \qquad \sigma_{\text{sign, cut}} = 1.639\,\text{fb}$$

final states	main int. state	σ_{nc} [fb]	σ_{cut} [fb]
$e^-\mu^+\bar{\nu}_e\nu_\mu$	WW	152.42	0.736
$e^-\mu^+\bar{\nu}_e\nu_\mu\nu_\tau\bar{\nu}_\tau$	$WW \to \tau^+e^-\nu\nu$	26.64	0.317
$e^-e^+e^-\mu^+\bar{\nu}_e\nu_\mu\nu_\tau\bar{\nu}_\tau$	$\tau\tau\, e^-e^+$ (γ induced)	25495	0.274
$e^-\mu^+\bar{\nu}_e\nu_\mu\nu_\tau\bar{\nu}_\tau$	$WW \to \tau^-\mu^+\nu\nu$	15.57	0.174
$e^-\mu^+\bar{\nu}_e\nu_\mu\nu_\tau\bar{\nu}_\tau\nu_\tau\bar{\nu}_\tau$	$WW \to \tau\tau\nu\nu$	2.978	0.146
$e^-e^+e^-\mu^+\bar{\nu}_e\nu_\mu$	$WW\, e^-e^+$ (γ induced)	2.192	0.140
$e^-e^+e^-\mu^+\bar{\nu}_e\nu_\mu\nu_\tau\bar{\nu}_\tau$	$eeWW \to ee\tau\mu\nu\nu$(γ ind)	0.405	0.070
$e^-e^+e^-\mu^+\bar{\nu}_e\nu_\mu\nu_\tau\bar{\nu}_\tau$	$eeWW \to ee\tau e\nu\nu$(γ ind)	0.379	0.064

MSSM backgrounds contributing after cuts

$$\sigma_{\text{sign, nc}} = 3.97\,\text{fb}, \qquad \sigma_{\text{sign, cut}} = 1.639\,\text{fb}$$

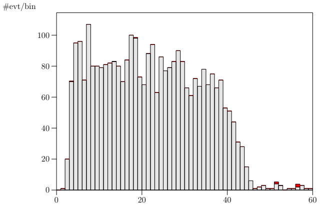
final states	main int. state	σ_{nc} [fb]	σ_{cut} [fb]
$e^-\mu^+\bar{\nu}_e\,\nu_\mu\nu_\tau\bar{\nu}_\tau\widetilde{\chi}^0\widetilde{\chi}^0$	$\widetilde{\chi}\widetilde{\chi} \,\rightarrow\, \tau^+e^-\nu\nu\widetilde{\chi}^0\widetilde{\chi}^0$	3.691	1.102
$e^-\mu^+\bar{\nu}_e\,\nu_\mu\nu_\tau\bar{\nu}_\tau\widetilde{\chi}^0\widetilde{\chi}^0$	$\tilde{\tau}\tilde{\tau}$	4.107	0.978
$e^-\mu^+\bar{\nu}_e\,\nu_\mu\nu_\tau\bar{\nu}_\tau\widetilde{\chi}^0\widetilde{\chi}^0$	$\widetilde{\chi}\widetilde{\chi} \,\rightarrow\, \tau^-\mu^+\nu\nu\widetilde{\chi}^0\widetilde{\chi}^0$	2.617	0.966
$e^-\mu^+\bar{\nu}_e\,\nu_\mu\nu_\tau\bar{\nu}_\tau\nu_\tau\bar{\nu}_\tau\widetilde{\chi}^0\widetilde{\chi}^0$	$\widetilde{\chi}\widetilde{\chi} \,\rightarrow\, \tilde{\tau}\tilde{\tau}\nu_\tau\bar{\nu}_\tau$	2.744	0.656
$e^-\mu^+\bar{\nu}_e\,\nu_\mu\nu_\tau\bar{\nu}_\tau\nu_{e,\mu}\bar{\nu}_{e,\mu}\widetilde{\chi}^0\widetilde{\chi}^0$	$\widetilde{\chi}^0\widetilde{\chi}^0 \,\rightarrow\, \tilde{\tau}\tilde{\tau}\nu_{e,\mu}\bar{\nu}_{e,\mu}$	0.501	0.162

Results for $\sqrt{s} = 800\,\mathrm{GeV}$

- in principle: many more particles enter the game (approaching thresholds for other $\widetilde{\chi}\widetilde{\chi}$ productions)

$\Rightarrow$ Signal gets more complicated !!

- some backgrounds enhanced, others reduced
- after smart cuts $\Rightarrow$ similar signal/ background ratio as before
- largest problem: "higher" edge gets significantly smeared out, also for signal only



$E(e^-)$, signal only

$$E_{\mathrm{max}} \stackrel{!}{=} 44.5\,\mathrm{GeV}$$

total readoff (not shown here):

$$E_{\mathrm{max}} = 43 \pm 1\,(2)\,\mathrm{GeV}$$

$$\Rightarrow m_{\tilde{\nu}} = 173 \pm 2\,(3)\,\mathrm{GeV} \checkmark$$

Superpotential and breaking parts

- Superpotential in MSSM

$$W = \bar{u} y_u Q H_u - \bar{d} y_d Q H_d - \bar{e} y_e L H_d + \mu H_u H_d$$

- soft SUSY breaking terms, gauge sector

$$\frac{1}{2}(M_1 \widetilde{B}\widetilde{B} + M_2 \widetilde{W}^a \widetilde{W}^a + M_3 \tilde{g}\tilde{g}) + h.c.$$