Studying light sneutrinos at the ILC and physical implications

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Introduction

1. Observation of neutrino oscillations reveals complex structure in neutral lepton sector
   $\rightarrow$ Natural extension of SM by **right-handed neutrino**
   $\rightarrow$ **Seesaw mechanism** can explain neutrino masses

2. In Supersymmetry:
   - MSSM extended by scalar partner $\tilde{\nu}_{\rm R}$ of right-handed neutrino
   - $\tilde{\nu}_{\rm R}$ **Majorana masses** generates splitting between R and L sneutrinos

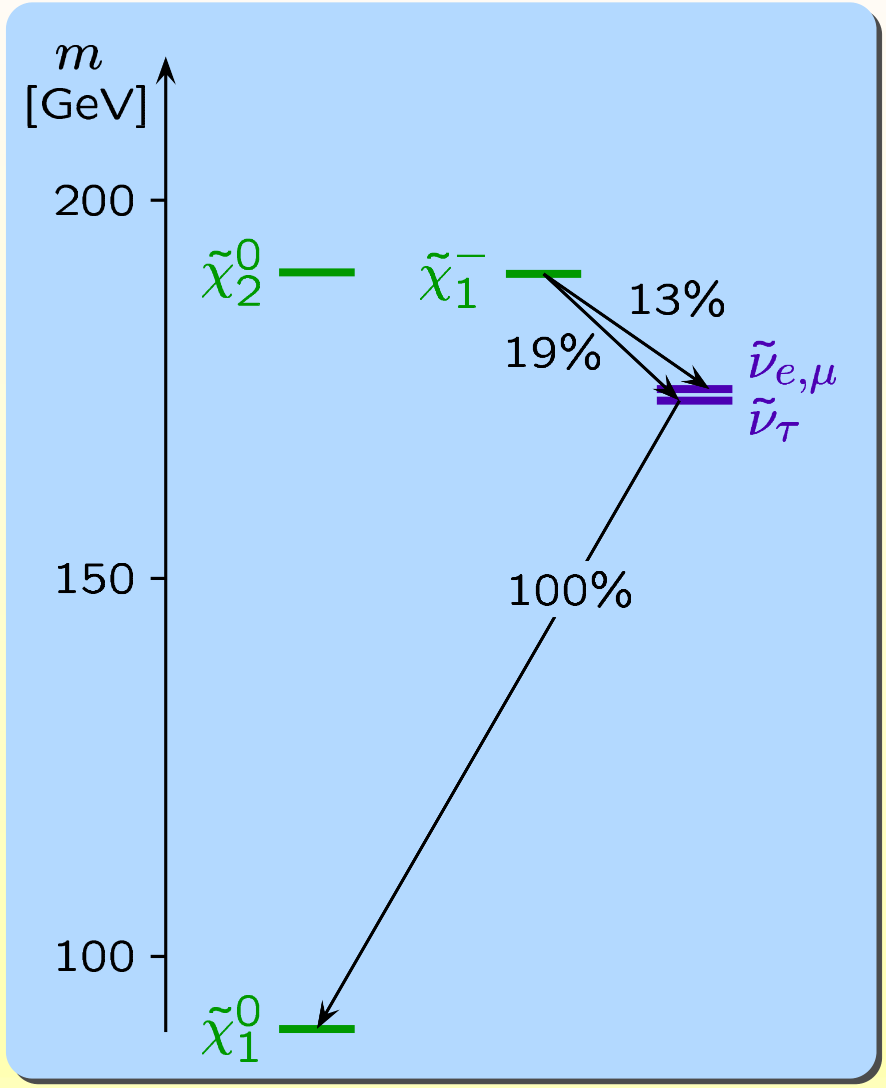
3. Central questions:
   - Masses of $\tilde{e}_{\rm L}, \tilde{\mu}_{\rm L}$ and $\tilde{\nu}_{e{\rm L}}, \tilde{\nu}_{\mu{\rm L}}$ related to high-scale SUSY breaking and to GUT and EW gauge symmetry breaking
   - $3^{\rm rd}$ gen. sleptons affected by τ Yukawa coupling and seesaw scale

Light sneutrinos

If $m_{\tilde{\nu}} \gtrsim M_2$: visible decays

$$\tilde{\nu}_l \to \nu_l \, \tilde{\chi}^0_2$$
$$\hookrightarrow \tau^+ \tau^- \tilde{\chi}^0_1$$
$$\to l^- \, \tilde{\chi}^+_1$$
$$\hookrightarrow \tau^+ \bar{\nu}_\tau \, \tilde{\chi}^0_1$$

For light sneutrinos:
Only invisible decay $\tilde{\nu}_l \to \nu_l \, \tilde{\chi}^0_1$



SPS1a' scenario

Sneutrinos in chargino decays

- Sneutrinos can be studied in decays of charginos:

$$\tilde{\chi}_1^\pm \to \tilde{\nu}_l^{(*)} l^\pm \qquad\qquad \text{BR} = 13\%\ (e,\mu),\ 19\%\ (\tau)$$

- Determine $m_{\tilde{\chi}_1^\pm}$ and $m_{\tilde{\nu}}$ from edges of spectrum of lepton energy E_l:

$$m_{\tilde{\chi}_1^\pm} = \sqrt{s}\,\frac{\sqrt{E_{\text{min}}E_{\text{max}}}}{E_{\text{min}}+E_{\text{max}}}, \qquad m_{\tilde{\nu}_l} = m_{\tilde{\chi}_1^\pm}\sqrt{1-\frac{2(E_{\text{min}}+E_{\text{max}})}{\sqrt{s}}}$$

- E_l distribution almost uniform

$\rightarrow$ Chargino polarization effects average out largely when integrating over scattering angle

Signal and backgrounds

Consider flavor-asymmetric final state:

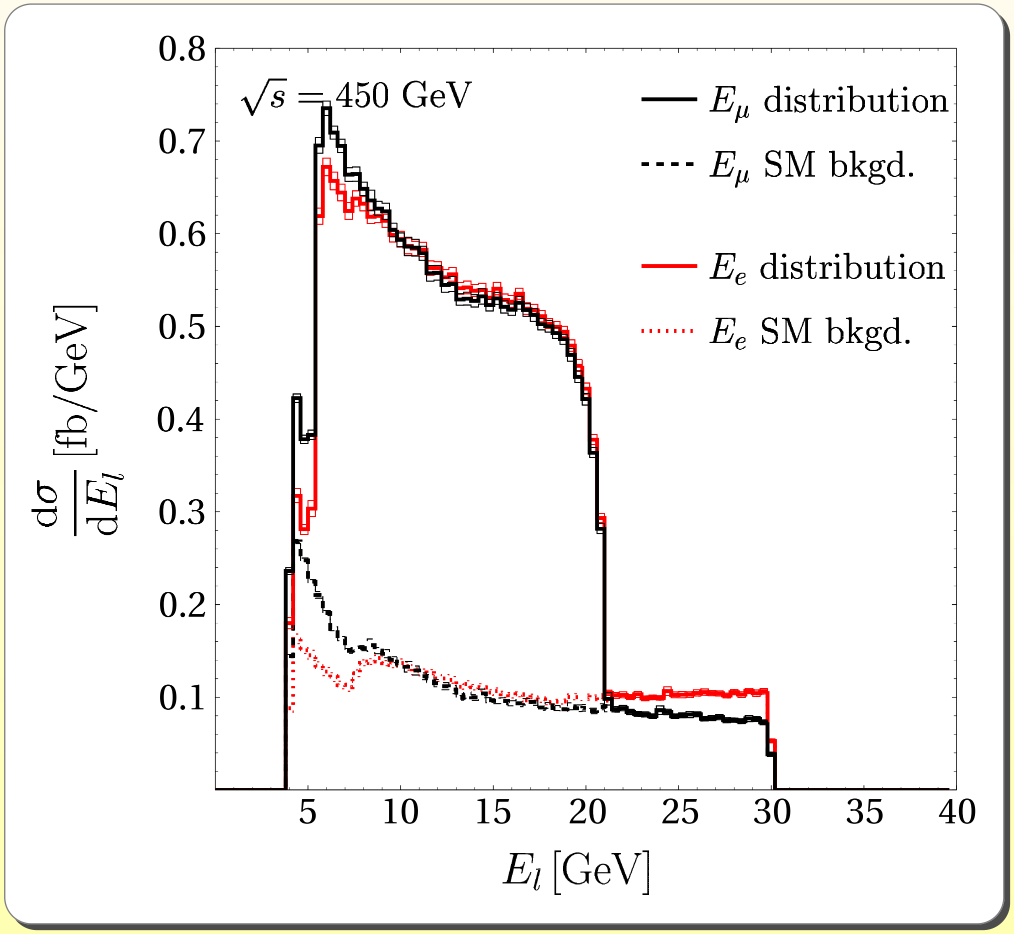
$e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^- \to e^\pm\mu^\mp + \not{E}$

Main SM backgrounds:

$e^+e^- \to W^+W^-$, $We\nu$

Also $\tau \to e, \mu$ cascades from:

$e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^- \to l^\pm\tau^\mp + \not{E}$
$e^+e^- \to W^+W^- \to l^\pm\tau^\mp + \not{E}$
$e^+e^- \to We\nu \to e^\pm\tau^\mp + \not{E}$
$e^+e^- \to \tilde{\tau}_1^+\tilde{\tau}_1^- \to \tau^\pm\tau^\mp + \not{E}$
$e^+e^- \to \tilde{\chi}_{1,2}^0\tilde{\chi}_2^0 \to \tau^\pm\tau^\mp + \not{E}$

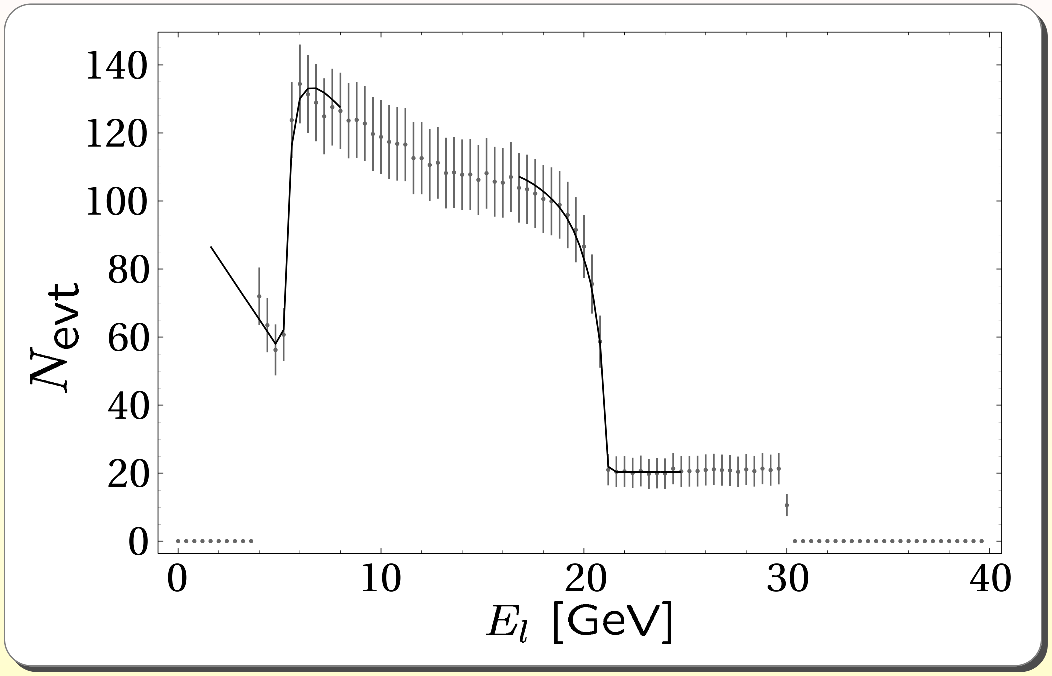


Cuts to reduce background:

$|\cos\theta_e| < 0.90|$, $|\cos\theta_\mu| < 0.95|$
4 GeV $< E_l <$ 30 GeV
$|\cos\theta_{\text{miss}}| < 0.9$

Determination of masses

- Fit to boxshaped spectrum



from e spectrum	from μ spectrum
$E_{\mathrm{min,e}} = 5.30^{+0.07}_{-0.06}$ GeV	$E_{\mathrm{min},\mu} = 5.30^{+0.08}_{-0.07}$ GeV
$E_{\mathrm{max,e}} = 21.0^{+0.07}_{-0.07}$ GeV	$E_{\mathrm{max},\mu} = 21.1^{+0.07}_{-0.07}$ GeV
$m_{\tilde{\chi}_1^\pm} = 180.4^{+0.7}_{-0.7}$ GeV	$m_{\tilde{\chi}_1^\pm} = 180.4^{+0.8}_{-0.7}$ GeV
$m_{\tilde{\nu}_e} = 169.5^{+0.7}_{-0.6}$ GeV	$m_{\tilde{\nu}_e} = 169.5^{+0.8}_{-0.7}$ GeV

Measurement of τ-Sneutrinos

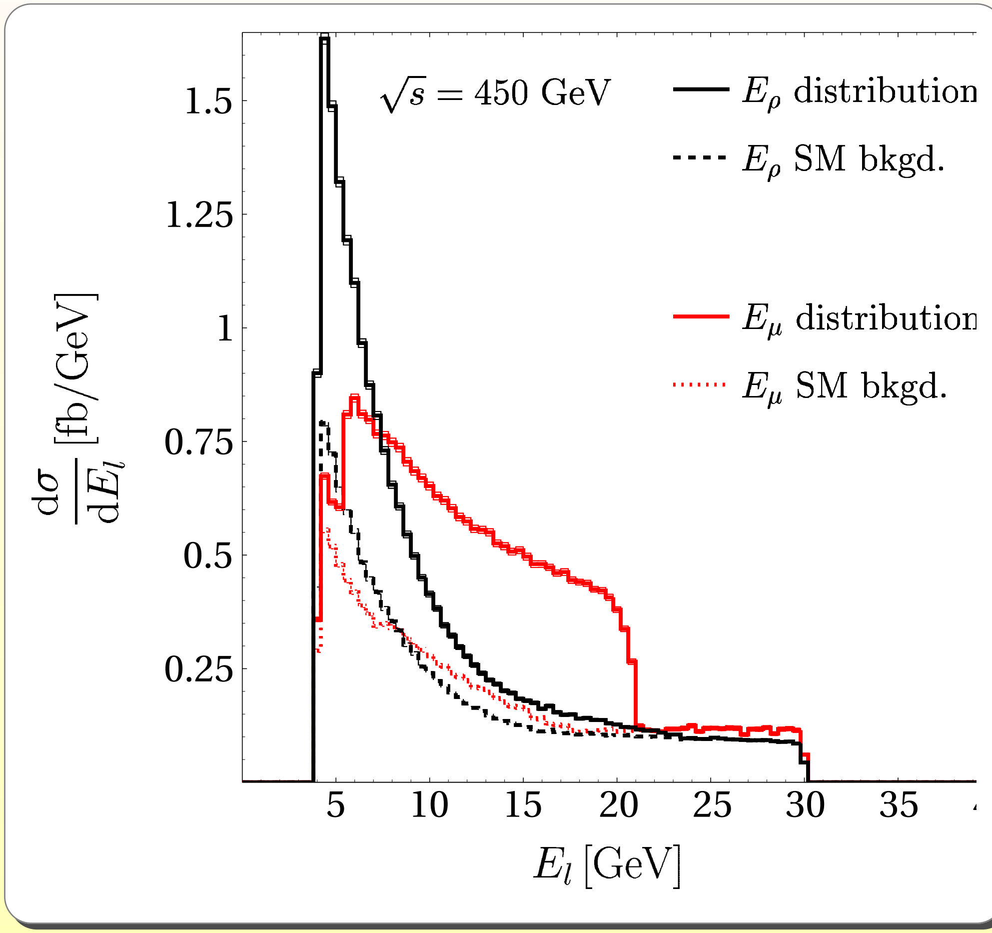
$e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^- \to \mu^\pm\tau^\mp + \not{E}$

Backgrounds from
$e^+e^- \to W^+W^-$, $\tilde{\tau}_1^+\tilde{\tau}_1^-$, $\tilde{\chi}_{1,2}^0\tilde{\chi}_2^0$
including $\tau \to \mu$ cascades

Tau identification through hadronic final states
$\tau \to \rho\nu_\tau$, $\tau \to \pi\nu_\tau$, $\tau \to 3\pi\nu_\tau$

Total BR 65%

Here kinematics of all channels approximated by ρ decay



$\to$ Lower edge for E_{had} spectrum smeared out due to τ decay

$\to$ Fit to upper endpoint: $E_{\text{max},\tau} = 24.5^{+1.0}_{-1.0}$ GeV

$\Rightarrow m_{\tilde{\nu}_\tau} = 167.6^{+0.9}_{-0.8}$ GeV

Sneutrinos in $e\gamma$ collisions

Production of sneutrinos in association with charginos:

$e^-\gamma \to \tilde{\nu}_e\,\tilde{\chi}_1^- \to \tilde{\nu}_e\,\tilde{\nu}_\mu^*\,\tilde{\chi}_1^-$

Photon beam from scattering of laser photons off e^- beam with
$\to$ Resulting γ spectrum with sharp edge at

$$E_{\gamma,\mathrm{max}} = \frac{4E_0E_\mathrm{b}}{4E_0E_\mathrm{b} + m_\mathrm{e}^2}\,E_\mathrm{b} \approx 0.8$$

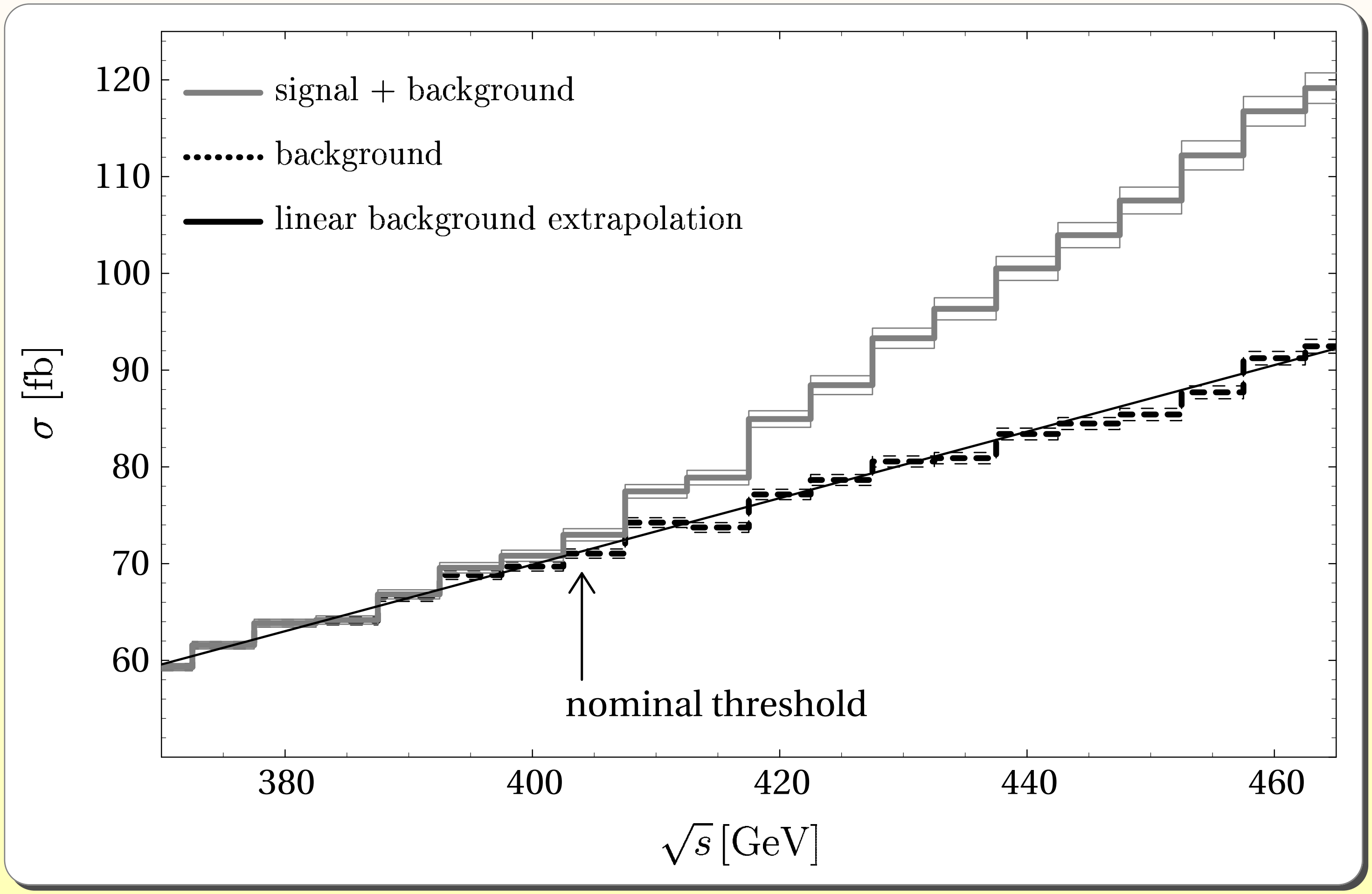
Production cross-section S-wave near threshold: $\sigma \sim \beta$

$$\sigma[e_\mathrm{L}^-\gamma_\mathrm{L} \to \tilde{\nu}_e\tilde{\chi}_1^-] = \frac{2\pi\alpha\beta}{s^2}\,\frac{V_{11}^2}{s_\mathrm{W}^2}\,m_{\tilde{\chi}_1^\pm}^2$$

$$\times \sum_{\lambda=\pm1}(1+\lambda\beta)\left[\sqrt{(1-\beta^2)s/m_{\tilde{\chi}_1^\pm}^2} - (1+\lambda\beta)\right]^2 + \mathcal{O}(\beta^2)$$

Largest background: $e^-\gamma \to \nu_e W^- \to \nu_e\,\bar{\nu}_\mu\,\mu^-$
Reduction through $E_\mu < 25$ GeV and $\cos\theta_\mu < 0$

Threshold scan



- Scan with 6 points for 380...430 GeV, 10 fb^{-1} each
- Fit result: $m_{\tilde{\nu}_e} = 169.8 \pm 3.2$ GeV

Extraction of GUT parameters and seesaw scale

Precision measurements of sleptons and sneutrinos allow to explore

- Universality of soft scalar mass parameters at high scale
- D-terms associated with GUT breaking
- Seesaw scale in ν physics

Example: SO(10) GUT model with

- **16**-plet matter superfields for each generation
- **10**-plet standard Higgs superfields
- **126**-plet Higgs superfield for ν_{R} Majorana masses

Assume universal sfermion mass parameter at GUT scale,
potentially modified by D-terms: Kolda, Martin '96

$$m_{\mathrm{E}}^2 = m_{16}^2 + D_U, \quad m_{\mathrm{L}}^2 = m_{16}^2 - 3D_U, \quad m_{\mathrm{R}}^2 = m_{16}^2 + 5D_U.$$

Neutrino masses

Assuming Yukawa unification for up-quark and neutrinos and similar pattern for Majorana mass matrix

→ hierarchical ν_L spectrum with nearly bi-max mixing

→ ν_R spectrum also hierarchical

$$M_{\mathrm{R},1} \sim \kappa_u^2 m_u^2/m_{\nu 3}$$
$$M_{\mathrm{R},2} \sim \kappa_c^2 m_c^2/m_{\nu 3} \qquad \kappa_f \sim \mathcal{O}(10)$$
$$M_{\mathrm{R},3} \sim m_t^2/m_{\nu 3} \approx 6 \times 10^{14}\ \mathrm{GeV}$$

Choose high scale SUSY parameters according SPS1a' scenario:

$M_{1/2} = 250$ GeV, $m_{16} = 70$ GeV, $A_0 = -300$ GeV, $D_U = 0$
$\tan\beta = 10$, $\mu > 0$

RGE running

Running of scalar masses down to electroweak scale modified by 3rd generation lepton and neutrino Yukawa couplings:

$$m^2_{\tilde{\tau}_R} = m^2_{\tilde{e}_R} - 2\Delta_\tau + m^2_\tau$$
$$m^2_{\tilde{\tau}_L} = m^2_{\tilde{e}_L} - \Delta_\tau - \Delta_{\nu_\tau} + m^2_\tau$$
$$m^2_{\tilde{\nu}_{\tau L}} = m^2_{\tilde{\nu}_{eL}} - \Delta_\tau - \Delta_{\nu_\tau}$$

Scalar masses at electroweak scale also depend on m_{16} and D_U

Fundamental parameters from slepton mass measurements:

Martyn '03

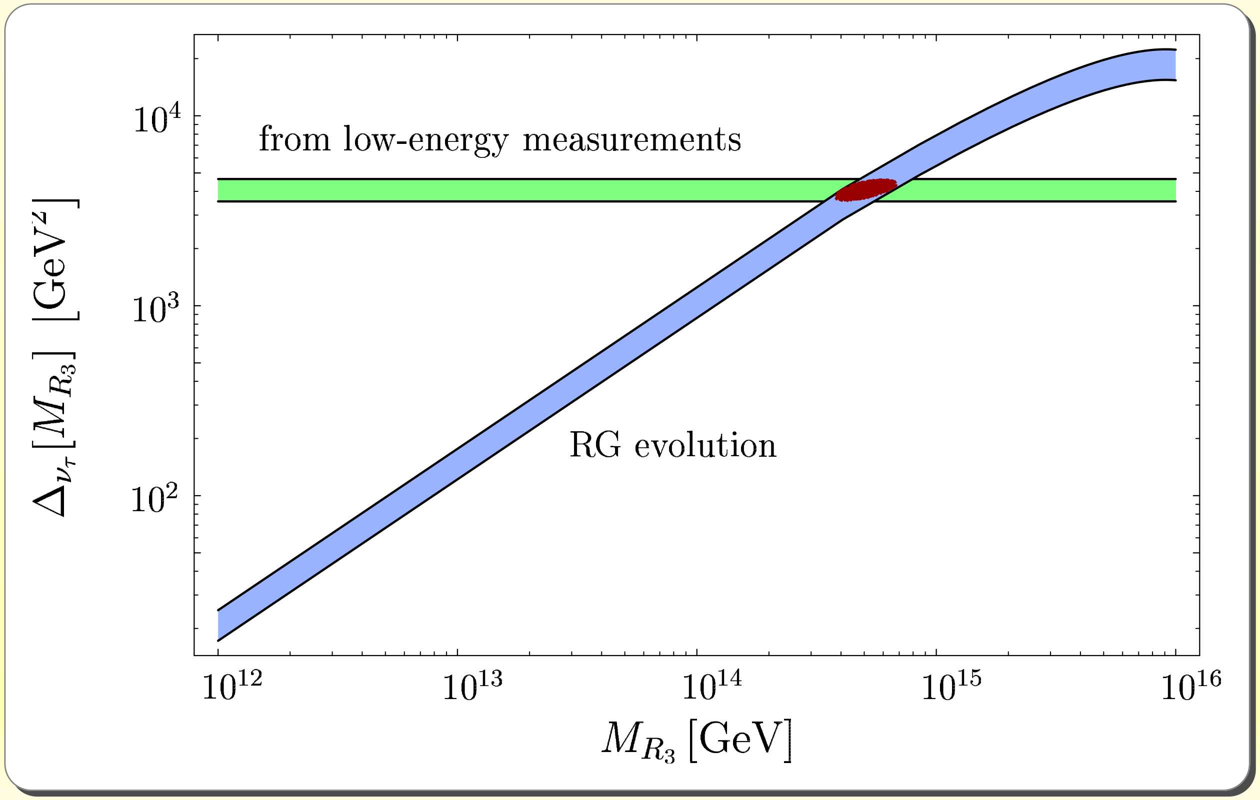
Freitas, Martyn, Nauenberg, Zerwas '04

	nominal value	extracted value
$m^2_{\tilde{\nu}_{e\mathrm{L}}} - m^2_{\tilde{e}_\mathrm{L}}$	-6175 GeV^2	-6280^{+255}_{-260}
m_{16}	70 GeV	$70.0^{+0.3}_{-0.2}$
D_U	0	0^{+30}_{-40}
Δ_τ	0.64×10^3 GeV^2	$0.63^{+0.28}_{-0.27} \times 10^3$
Δ_{ν_τ}	4.07×10^3 GeV^2	$4.1^{+0.55}_{-0.56} \times 10^3$

Determination of Seesaw scale

From RGE: $$\Delta_{\nu_\tau}[M_{R_3}] \simeq \frac{m_{\nu_3} M_{\mathrm{R}_3}}{16\pi^2 (v \sin\beta)^2} \left(3m_{16}^2 + A_0^2\right) \log \frac{M_{GUT}^2}{M_{\mathrm{R}_3}^2}$$

Can be used to extract value for $M_{R_3} \approx 6 \times 10^{14}$ GeV:



$\Rightarrow M_{R_3} = 3.7 \ldots 6.9 \times 10^{14}$ GeV

Conclusions

- If $m_{\tilde{\nu}} < m_{\tilde{\chi}_1^\pm}$, L-sneutrinos can be measured excellently in chargino decays

- Sneutrino mass measurements with precision better than 1% can be achieved from decay energy spectra

- Independent cross-checks may be performed from the threshold in $e^- \gamma \to \tilde{\nu}_e \, \tilde{\chi}_1^-$

- Running of scalar masses from GUT to electroweak scale opens sensitivity to extract GUT scale **SUSY breaking parameters**, as well as neutrino **seesaw scale** with good precision.

  $\rightarrow$ Right-handed neutrino mass could be determined indirectly