Third generation slepton mass measurements as probe for mSUGRA + RHN models

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J. K. Mizukoshi⋆

H. Baer, C. Balázs, X. Tata

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Outline

- Right-handed neutrino as a extension of mSUGRA model

  ⋆ New neutrino Yukawa interaction can affect slepton and sneutrino masses

- Precison SUSY mass measureaments at the LC

  ⋆ Well known energy end-points for the final state particles

  ⋆ What we have so far

  ⋆ $\tilde{\nu}_\tau$ mass determination

- Conclusions

The right-handed neutrinos

Motivation: Super-K suggests neutrino oscillation $(\nu_\mu - \nu_\tau) \Rightarrow$ neutrinos should be massive

- If neutrino masses are assumed to be hierarchical, Δm^2 from Super-K comes from ν_τ mass

Small mass to $\nu \Rightarrow$ possible explanation is the see-saw mechanism:

- Majorana mass M_N for the singlet ν from the superpotential
- Mass for the ν_R scalar partner expected to be $\sim M_N$
- Physical ν_R mass $\simeq f_\nu^2 v_u^2 / M_N$

Isolating the RHN effects on slepton and sneutrino masses

RGE for slepton and sneutrino masses

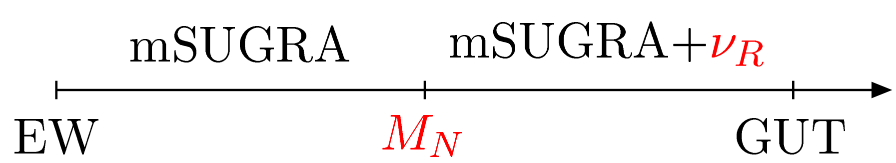
- Gauge interactions (generation independent)
- Yukawa interactions (significant for third generation)

Therefore, it is natural to construct $\Delta_R = m^2_{\tilde{e}_R} - m^2_{\tilde{\tau}_R}$ and $\Delta_L = m^2_{\tilde{e}_L} - m^2_{\tilde{\tau}_L}$ since

$$\frac{d\Delta_R}{dt} = \frac{2}{16\pi^2}(2f_\tau^2 X_\tau), \quad \frac{d\Delta_L}{dt} = \frac{2}{16\pi^2}(f_\tau^2 X_\tau + f_\nu^2 X_\nu)$$

where $t = \ln Q$ and

$$X_\tau = m^2_{\tilde{\tau}_L} + m^2_{\tilde{\tau}_R} + m^2_{H_d} + A_\tau^2, \quad X_\nu = m^2_{\tilde{\tau}_L} + m^2_{\tilde{\nu}_R} + m^2_{H_u} + A_\nu^2$$

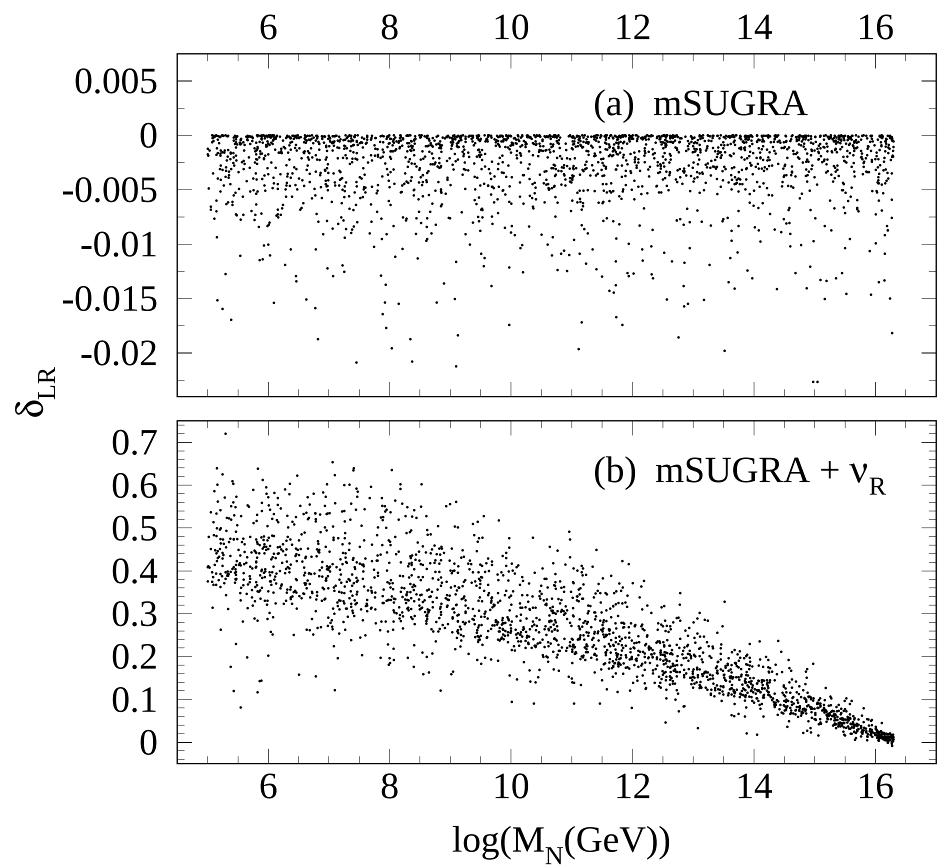


Because f_τ is not known, construct

$$(2\Delta_L - \Delta_R)_{M_N} \approx \frac{4}{16\pi^2} f_\nu^2 X_\nu \ln \frac{M_{GUT}}{M_N} \quad (= 0 \text{ if there is no} f_\nu)$$

The dimensionless version:

$$\delta_{LR} \equiv \frac{2\Delta_L - \Delta_R}{(m^2_{\tilde{e}_L} + m^2_{\tilde{e}_R} + m^2_{\tilde{\tau}_L} + m^2_{\tilde{\tau}_R})/4}$$



The distribution for δ_{LR} for a set of randomly generated (a) mSUGRA models, and (b) models with RHN, versus the $\tilde{\nu}_R$ mass M_N. Top and neutrino Yukawa couplings are assumed to unify at the GUT scale

Conceptually simple, however measurable quantities are $m_{\tilde{\tau}_1}$ and $m_{\tilde{\tau}_2}$ ($\tilde{\tau}_R$ and $\tilde{\tau}_L$ mixing).

Fortunately, it is usual that $\tilde{\tau}_1 \approx \tilde{\tau}_R$ and $\tilde{\tau}_2 \approx \tilde{\tau}_L$. So, it is useful to construct the measurable quantities:

$$\Delta_1 = m^2_{\tilde{e}_R} - m^2_{\tilde{\tau}_1}, \qquad \Delta_\nu = m^2_{\tilde{\nu}_R} - m^2_{\tilde{\nu}_\tau}$$

Isolating the ν_R effects:

$$\delta_{1\nu} = \frac{2\Delta_\nu - \Delta_1}{(m^2_{\tilde{\nu}_e} + m^2_{\tilde{\nu}_\tau} + m^2_{\tilde{e}_R} + m^2_{\tilde{\tau}_1})/4}$$

Constrains:

- Super-K measurement

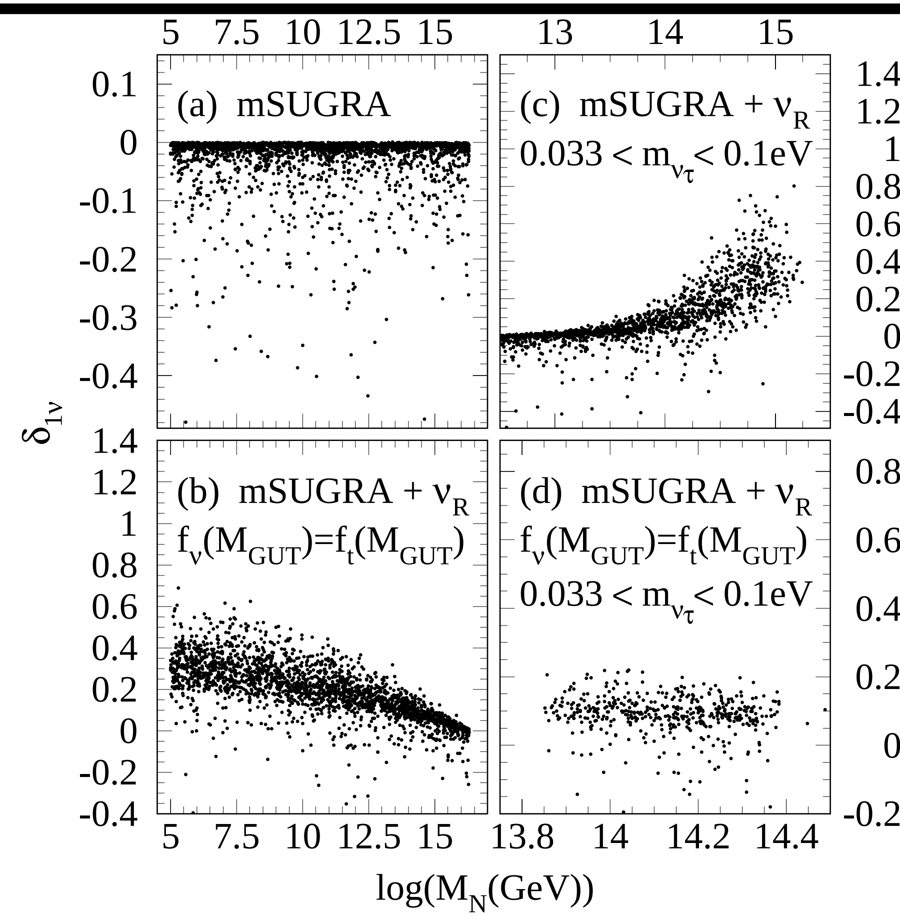
  $10^{-3}\,\mathrm{eV}^2 \leq \Delta m^2 \leq 10^{-2}\,\mathrm{eV}^2 \Rightarrow 0.033\,\mathrm{eV} \leq m_{\nu_\tau} \leq 0.1\,\mathrm{eV}$

- GUT constraint on Yukawa couplings: $f_\nu(M_{GUT}) = f_t(M_{GUT})$

- Super-K and GUT constraints $\Rightarrow M_N \gtrsim 10^{14}$ GeV

Distinguishing the models: upper bound for $\delta_{1\nu} \sim 0$ for mSUGRA and ~ 0.2 for mSUGRA+RHN, assuming the constraints above.

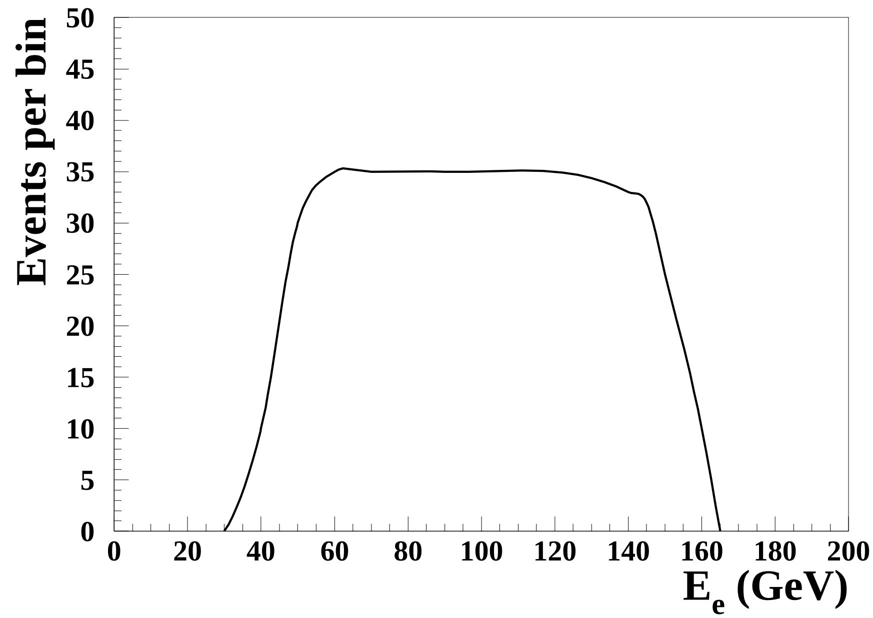
How precise can we measure slepton masses to distinguish $\delta_{1\nu} \sim 0$ from $\delta_{1\nu} \sim 0.2$?



The distribution of $\delta_{1\nu}$ versus the RHN mass M_N for the (a) mSUGRA model, (b) the RHN model with unification of top neutrino Yukawa couplings, (c) the RHN model with the ν_τ mass in the Super-K range, and (d) the RHN model with $f_t = f_\nu$ at the GUT scale and the Super-K constraint.

Precise mass measurements at the LC

At the LC, E_3 energy (of particle p_3) end-points well defined for the reaction $e^+e^- \to p_1 + p_2$, with $p_2 \to p_3 + p_4$.



Slepton mass measurements (assuming neutralino LSP):

- $m_{\tilde{e}_R}$ (T. Tsukamoto *et al.*, PRD51, 3153 (1995))

$$e^+e^- \to \tilde{e}_R\tilde{e}_R, \quad \tilde{e}_R \to e\widetilde{Z}_1 \quad (BR = 100\%)$$

⋆ $\sqrt{s} = 350$ GeV, $P_e = 95\%$ (right-handed e^-) and $\int \mathcal{L}dt = 20$ fb^{-1}

⋆ $\Delta m_{\tilde{e}} \sim 1\%$

- $m_{\tilde{\nu}_e}$ (H. Baer *et al.*, PRD54, 6735 (1996))

Cascade decays do not affect precise mass measurements

$$e^+e^- \to \tilde{\nu}_e\tilde{\nu}_e, \quad \tilde{\nu}_e \to e\widetilde{W}_1 \quad (BR \sim 60\%, \text{ typically})$$

and

$$\widetilde{W}_1^{(a)} \to q\bar{q}'\widetilde{Z}_1, \quad \widetilde{W}_1^{(b)} \to \mu\nu_\mu\widetilde{Z}_1$$

⋆ $\sqrt{s} = 500$ GeV, $P_e = 95\%$ (left-handed e^-) and $\int \mathcal{L}dt = 20$ fb^{-1}

⋆ $\Delta m_{\tilde{\nu}_e} \sim 1\%$

- $m_{\tilde{\tau}_1}$ (M. Nojiri *et al.*, PRD54, 6756 (1996))

$$e^+e^- \to \tilde{\tau}_1\tilde{\tau}_1, \quad \tilde{\tau}_1 \to \tau \widetilde{Z}_1 \quad (BR = 90\%, \text{typically})$$

⋆ Input $m_{\tilde{\tau}_1} = 150$ GeV and $m_{\widetilde{Z}_1} = 100$ GeV

⋆ $\sqrt{s} = 500$ GeV, $P_e = 95\%$ (right-handed e^-) and $\int \mathcal{L} dt = 100\ \mathrm{fb}^{-1}$

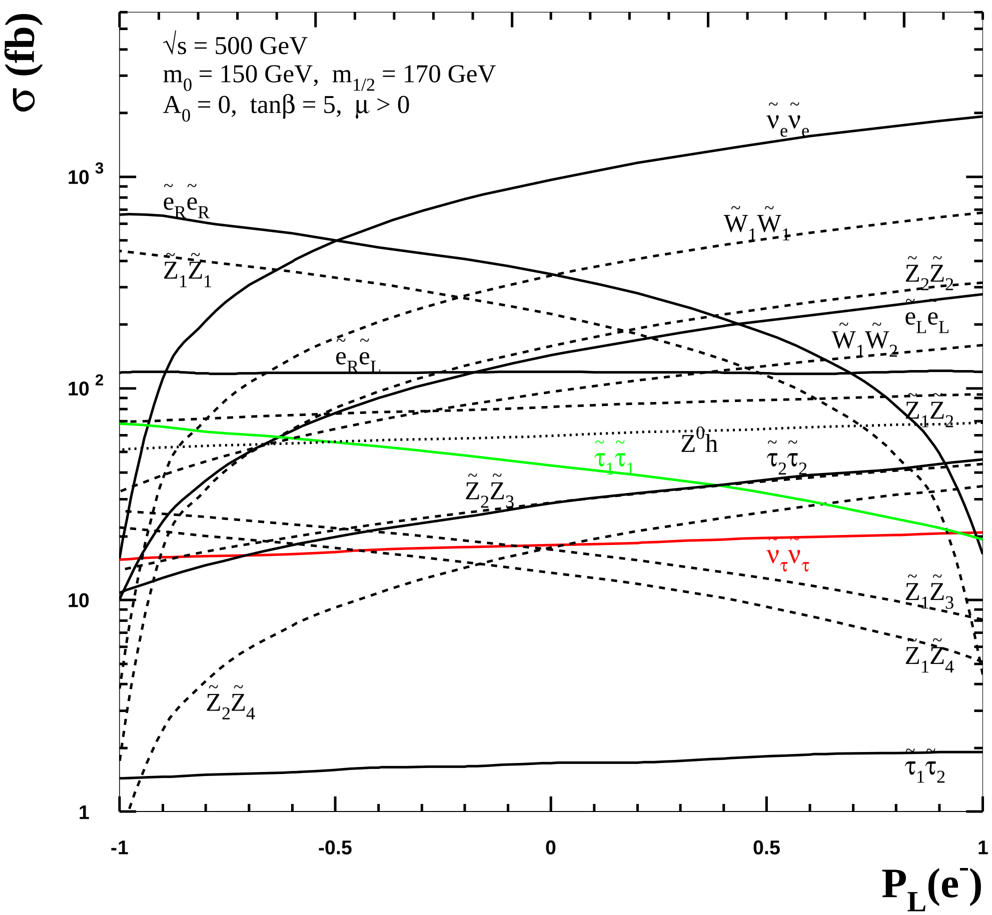
⋆ τ further decays leptonically or semi-hadronically $\Rightarrow$ measured end-points are shifted due to the missing energy

⋆ For $\tau \to \nu_\tau A$, E_A can depend strongly on $P(\tau)$

⋆ Considering the decay mode $\tau \to \nu_\tau \rho$, the two parameter fit $m_{\tilde{\tau}_1}$ and $m_{\widetilde{W}_1}$ on E_τ^{vis} distribution gives $\Delta m_{\tilde{\tau}_1} \sim 2\%$

Our $\tilde{\tau}_1$ mass analysis

- Parameter point in the mSUGRA: $m_0 = 150$ GeV, $m_{1/2} = 170$ GeV, $A_0 = 0,\ \tan\beta = 5$, and $\mu > 0$
- $\tilde{\tau}_1$ study is not an attempt to improve Nojiri *et al.* results. Actually our analysis is more simplified. The analysis is a check of our method
- ISAJET is used to generate SUSY pair production and decay
- ISR and beamstrahlung turned off



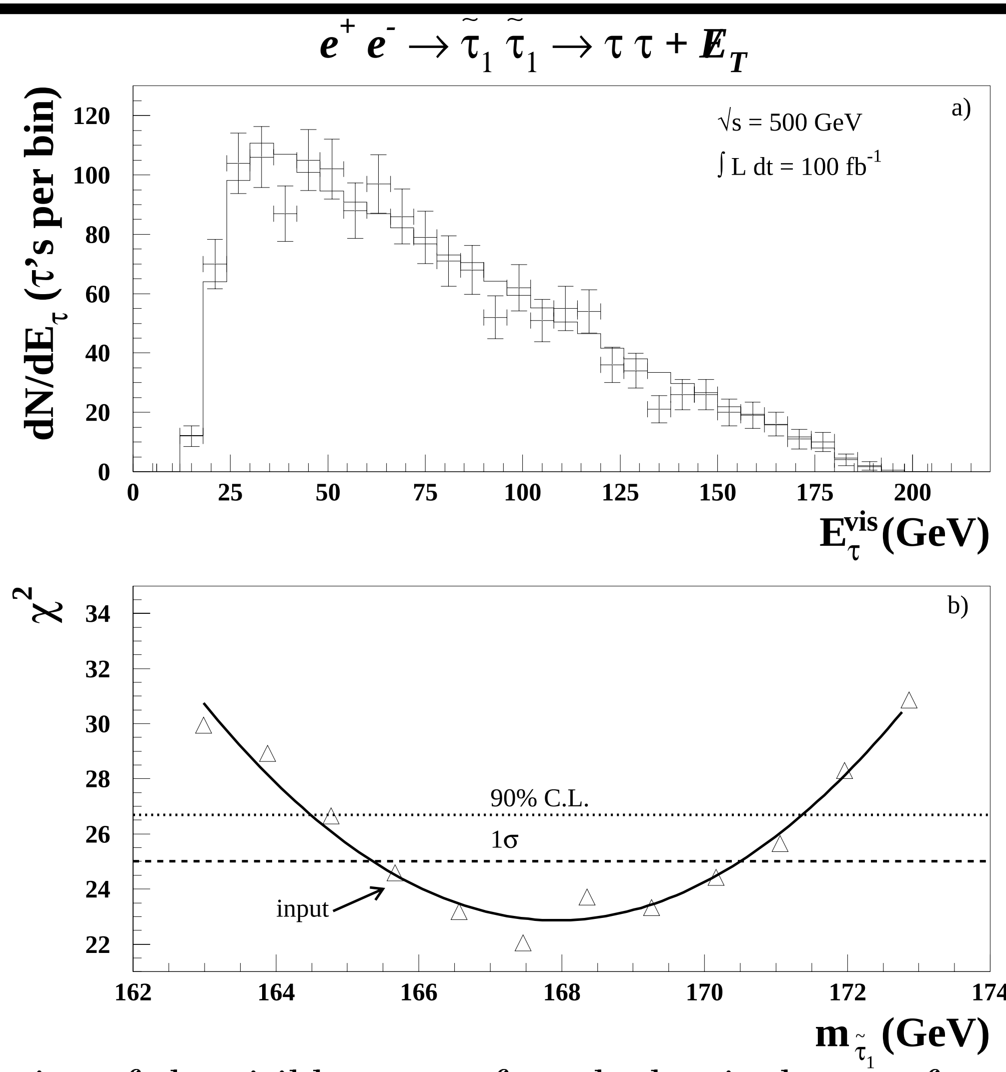
Cross sections for various SUSY production at e^+e^- collider with $\sqrt{s} = 500$ GeV versus the electron beam polarization. The solid lines show cross sections for $\tilde{f}$, the dashed lines for $\widetilde{Z}_i$ and $\widetilde{W}_i$ and the dotted lines for Higgs boson production mechanisms.

For the $m_{\tilde{\tau}_1}$ reconstruction:

- Signal: $e^+e^- \to \tilde{\tau}_1\tilde{\tau}_1 \to \tau\tau \not{E}_T$
- 95% right-handed polarized electron beam
- Neutralino mass is assumed to be well measured
- Cuts similar to $m_{\tilde{\mu}_R}$ analysis, except no cut on $|m_{\tau\tau} - M_Z|$
- Results

  ⋆ Cross section for the signal ~ 8 fb ($\sim 90\%$ of the total SUSY events)

  ⋆ Background from ZZ and WW are 0.3 fb and 0.1 fb, respectively



(a) The distribution of the visible energy from hadronic decays of taus produced via $e^+e^- \to \tau\tau \not{E}_T$ events. The solid histogram denotes the theory, while the points are the "data" for an integrated luminosity of 100 fb^{-1}. In (b), the values of χ^2 obtained by comparison of "data" for several values of $m_{\tilde{\tau}_1}$.

$m_{\tilde{\nu}_\tau}$ reconstruction

- Follow the same strategy as for $e^+e^- \to \tilde{\nu}_e\tilde{\nu}_e \to e\widetilde{W}_1 e\widetilde{W}_1 \to e\mu\nu\widetilde{Z}_1 + eqq\widetilde{Z}_1$. In this case, fit e energy
- Signal: $e^+e^- \to \tilde{\nu}_\tau\tilde{\nu}_\tau \to \tau\widetilde{W}_1\tau\widetilde{W}_1 \to \tau l\nu\widetilde{Z}_1 + \tau qq\widetilde{Z}_1$
- Change the polarization to be right-handed to reduce backgrounds

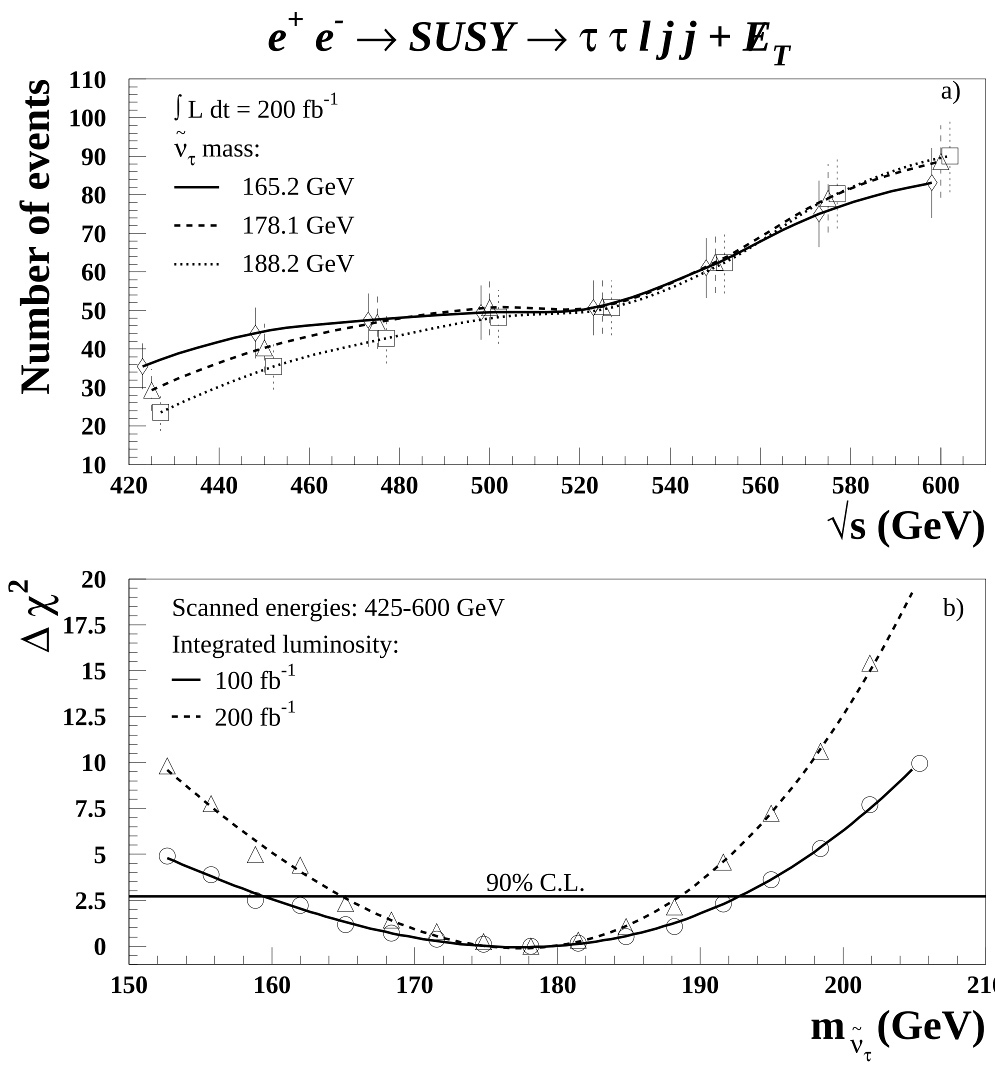
The reasons to not get a significant discrimination with $m_{\tilde{\nu}_\tau}$ variations:

- $\sigma(\tilde{\nu}_\tau\tilde{\nu}_\tau) \sim \sigma(\tilde{\nu}_e\tilde{\nu}_e)/100$ (with 95% left-handed polarization)
- Taus decay hadronically $\Rightarrow$ extra 4/9
- Visible energy of tau is reduced in respect to the total energy $\Rightarrow$ events may be below tau identification threshold (10 GeV) $\Rightarrow$ make energy distribution above 10 GeV insensitive to $m_{\tilde{\tau}}$ mass

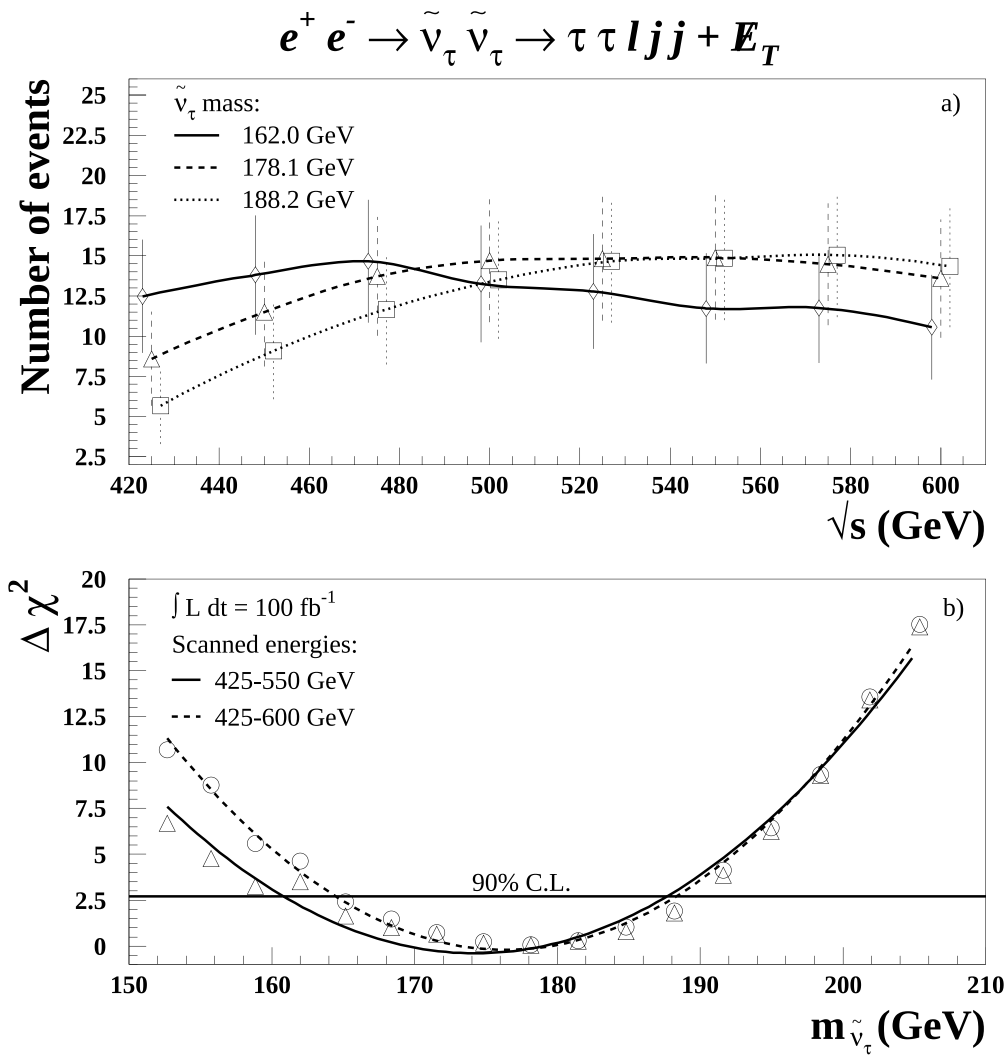
- Heavier charginos and neutralinos, as well as $\tilde{\tau}_2$ production may have significant contribution to the event topology
- Strategy does not work even for $\int \mathcal{L} dt = 500 - 1000\,\mathrm{fb}^{-1}$

Changing the strategy

- Center-of-mass energy scan for the $\tau\tau l j j + \not{E}_T$ events
- Since ISR, beamstrahlung and loop corrections have not taken into account, close kinematic threshold scan is not performed
- Minimum cuts: $E_\tau^{vis} \geq 10$ GeV and $\not{E}_T \geq 25$ GeV
- SM background is expected to be small
- 425 GeV $\leq \sqrt{s} \leq$ 600 GeV, with steps of 25 GeV



(a) The total number of events for $\tau\tau l j j + \not{E}_T$ topology from all SUSY processes for three different sneutrino masses versus the center-of-mass energy. (b) The values of $\Delta\chi^2$ versus $m_{\tilde{\nu}_\tau}$ from the energy scan, where test case has taken to be the "data".



(a) The total number of events for $\tau\tau ljj + \not{E}_T$ topology from the signal only for three different sneutrino masses versus the center-of-mass energy. (b) The values of $\Delta\chi^2$ versus $m_{\tilde{\nu}_\tau}$ from the energy scan, where test case has taken to be the "data".

Results

- With SUSY backgrounds (at 90% CL):

  $\star\ m_{\tilde{\nu}_\tau} = 178^{+15}_{-18}$ GeV for $\int \mathcal{L} dt = 100\ \mathrm{fb}^{-1}$

  $\star\ m_{\tilde{\nu}_\tau} = 178^{+10}_{-13}$ GeV for $\int \mathcal{L} dt = 200\ \mathrm{fb}^{-1}$

- Without SUSY backgrounds: similar precision can be obtained with half the integrated luminosity

Conclusion

- Are these precisions enough to discriminate the effects of RHN on $\delta_{1\nu}$?

  $\star$ With Yukawa couplings unification, neglecting $m_{\tilde{\tau}_1}$ measurement error, $m_{\tilde{\nu}_\tau}$ needs a precision of $\sim 2.5\%$

  $\star$ Without Yukawa couplings unification or allowing a more complicated framework (*e.g.* type III see-saw, where $m_\nu = f_\nu^2 v_u^2 M_S / M_N^2$) a discrimination might be possible

- Dedicated $m_{\tilde{\nu}_\tau}$ and $m_{\tilde{\tau}_2}$ studies are needed, since sfermion third generation may be special to probe new physics

Possible improvements on $m_{\tilde{\nu}_\tau}$ determination:

- SUSY background: heavy charginos and neutralinos may be kinematically suppressed
- τ identification: vertex detection, neural net algorithms,...
- ???

$\sqrt{s}$ (GeV)	$\sigma(\tilde{\nu}_\tau\tilde{\nu}_\tau)$ (fb)	$\sigma(\tilde{\tau}_2\tilde{\tau}_2)$ (fb)	$\sigma(\widetilde{W}_i\widetilde{W}_j, \widetilde{Z}_i\widetilde{Z}_j)$ (fb)
425	0.083	0.008	0.053
450	0.116	0.015	0.071
475	0.140	0.019	0.078
500	0.139	0.028	0.079
525	0.149	0.029	0.078
550	0.149	0.036	0.127
575	0.145	0.032	0.219
600	0.134	0.037	0.270

Cross sections in fb for the $\tau\tau\ell jj$ signal from $\tilde{\nu}_\tau\tilde{\nu}_\tau$ production, as a function of the center of mass energy $\sqrt{s}$ after the cuts. Also shown are the corresponding cross sections from $\tilde{\tau}_2\tilde{\tau}_2$ production, and from chargino and neutralino production.