Ultrarelativistic sneutrinos at the LHC and sneutrino-antisneutrino oscillation

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SUSY10, Bonn, Germany, August 24th

Outline

Based on: D.K. Ghosh, TH, K. Huitu, S. Roy, arXiv:1005.1802

Motivation

- SM: $m_\nu = 0$
- Solar and atmospheric neutrino experiments $\Rightarrow m_\nu \neq 0$
- $\Rightarrow$ Add $\Delta L = 2$ Majorana neutrino mass terms $\left(\frac{1}{2} m \bar{\nu}^c \nu\right)$
- $\Rightarrow$ In SUSY theories, $\tilde{\nu} - \tilde{\nu}^*$ mixing and a mass splitting $\Delta m_{\tilde{\nu}}$
- $\Rightarrow \tilde{\nu} - \tilde{\nu}^*$ oscillation (analogous to $B^0 - \bar{B}^0$ flavour oscillation)

Hirsch, Klapdor-Kleingrothaus, Kovalenko, PL **B398** (97)

Grossman, Haber, PRL **78** (97)

Oscillation Probability at Rest

- $|\tilde{\nu}\rangle$ state evolution assuming that the sneutrinos are produced at rest:

$$|\tilde{\nu}(t)\rangle = \frac{1}{\sqrt{2}}\left[e^{-i(m_1 - i\Gamma_{\tilde{\nu}}/2)t}|\tilde{\nu}_1\rangle + ie^{-i(m_2 - i\Gamma_{\tilde{\nu}}/2)t}|\tilde{\nu}_2\rangle\right], \qquad (1)$$

where $|\tilde{\nu}_1\rangle$ and $|\tilde{\nu}_2\rangle$ are the physical mass eigenstates and $\Gamma_1 \approx \Gamma_{\tilde{\nu}} \approx \Gamma_2$

- $\Rightarrow$ The time-integrated probability of a sneutrino oscillating into an antisneutrino:

$$P(\tilde{\nu} \to \tilde{\nu}^*) = \frac{x_{\tilde{\nu}}^2}{2(1 + x_{\tilde{\nu}}^2)}, \qquad (2)$$

where

$$x_{\tilde{\nu}} \equiv \frac{\Delta m_{\tilde{\nu}}}{\Gamma_{\tilde{\nu}}} \qquad (3)$$

General State Evolution

- Is it correct to assume that the sneutrinos are produced at rest, e.g., at the LHC?
- $\Rightarrow$ Let's consider the $|\tilde{\nu}\rangle$ state evolution at (x, t):

$$|\tilde{\nu}(x,t)\rangle = \frac{1}{\sqrt{2}}\left[e^{-i(Et-p_1x)}|\tilde{\nu}_1\rangle + ie^{-i(Et-p_2x)}|\tilde{\nu}_2\rangle\right], \qquad (4)$$

  where $|\tilde{\nu}_1\rangle$ and $|\tilde{\nu}_2\rangle$ are the physical mass eigenstates and p_1 and p_2 are the respective three-momenta
- Here, we assume that the mass eigenstates move with the same energy E but different three-momenta p_1 and p_2

Oscillation Probability for a Moving Sneutrino

- The oscillation probability becomes

$$\begin{aligned} P_{\tilde{\nu}\to\tilde{\nu}^*} &= |\langle\tilde{\nu}^*|\psi(x,t)\rangle|^2 \\ &= \frac{1}{4}\left[e^{i(p_1-p_1^*)x} + e^{i(p_2-p_2^*)x} - e^{i(p_2-p_1^*)x} - e^{i(p_1-p_2^*)x}\right] \\ &= \frac{1}{4}\left[e^{-2\,\mathrm{Im}(p_1)x} + e^{-2\,\mathrm{Im}(p_2)x} - e^{i(p_2-p_1^*)x} - e^{i(p_1-p_2^*)x}\right] \end{aligned} \quad (5)$$

- The three-momenta can be written as $p_i = \sqrt{E^2 - m_i^2 + i\Gamma m_i}\ (i = 1, 2)$
- Here, we assume $\Gamma_1 \approx \Gamma \approx \Gamma_2$

Oscillation Probability for a Moving Sneutrino

- Assuming a very small Γ and $E \gg \Gamma, m_1, m_2$,

$$p_i \simeq \sqrt{E^2 - m_i^2}\left[1 + \frac{i\Gamma m_i}{2(E^2 - m_i^2)}\right], \quad (6)$$

$$\Rightarrow \mathrm{Re}(p_i) \simeq E - \frac{m_i^2}{2E} \quad \text{and} \quad \mathrm{Im}(p_i) \simeq \frac{\Gamma m_i}{2E}. \quad (7)$$

- Working out all the mathematics, one gets in the end

$$P_{\tilde{\nu}\to\tilde{\nu}^*} = |\langle\tilde{\nu}^*|\psi(x,t)\rangle|^2 \quad (8)$$
$$= \frac{1}{4}\left[e^{-\frac{\Gamma m_1}{E}x} + e^{-\frac{\Gamma m_2}{E}x} - 2\cos\left(\frac{\Delta m^2}{2E}x\right)e^{-\frac{\Gamma}{2E}(m_1+m_2)x}\right],$$

where $\Delta m^2 \equiv m_1^2 - m_2^2$.

Oscillation Probability for a Moving Sneutrino

- Assuming $\Delta m \ll m_1, m_2$, we have $m_1 \approx m_2 \equiv m$ and get

$$P_{\tilde{\nu}\to\tilde{\nu}^*} = |\langle\tilde{\nu}^*|\psi(x,t)\rangle|^2 = \frac{1}{2}\left[1 - \cos\left(\frac{\Delta m^2}{2E}x\right)\right]e^{-\frac{\Gamma m}{E}x}, \quad (9)$$

- The integrated probability, at a distance L, of a $|\tilde{\nu}\rangle$ oscillating into an $|\tilde{\nu}^*\rangle$ is given by ($\alpha \equiv \frac{\Gamma m}{E}$ and $\beta \equiv \frac{\Delta m^2}{2E}$)

$$\begin{aligned} P(L) &= \frac{\int_0^L dx\,|\langle\tilde{\nu}^*|\psi(x,t)\rangle|^2}{\int_0^\infty dx\,\langle\psi(x,t)|\psi(x,t)\rangle} \\ &= \frac{e^{-L\alpha}}{2(\alpha^2+\beta^2)}\Big[-\alpha^2 + (-1+e^{L\alpha})\beta^2 \\ &\quad + \alpha^2\cos(L\beta) - \alpha\beta\sin(L\beta)\Big]. \quad (10) \end{aligned}$$

Oscillation Probability for a Moving Sneutrino

- For a very large L, i.e., when $L\alpha \gg 1$, we get

$$P(L) = \frac{\beta^2}{2(\alpha^2 + \beta^2)} = \frac{x_{\tilde{\nu}}^2}{2(1 + x_{\tilde{\nu}}^2)}, \tag{11}$$

  which is independent of L and where we have used $\Delta m^2 = 2m\Delta m$ and $x_{\tilde{\nu}} \equiv \frac{\Delta m}{\Gamma}$.
- The last step of Eq. (11) is the same result as in the case when the sneutrinos are produced at rest.
- With $L\alpha \gg 1$, when $x_{\tilde{\nu}} = 1$, $P(L) = 0.25$
- With $L\alpha \gg 1$, when $x_{\tilde{\nu}} \gg 1$, $P(L) = 0.5$

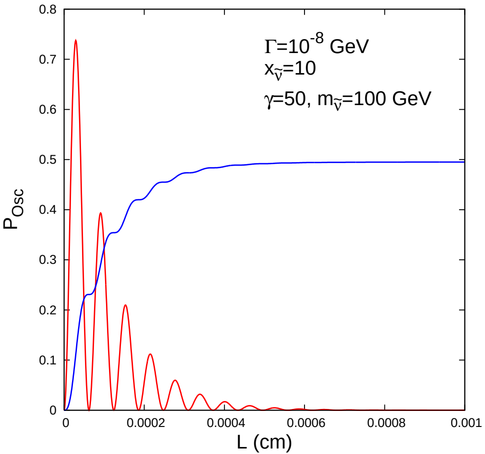

Figure: Sneutrino oscillation probabilities as a funtion of *L*. The red solid line is the unintegrated oscillation probability, whereas the blue solid line is the integrated probability.

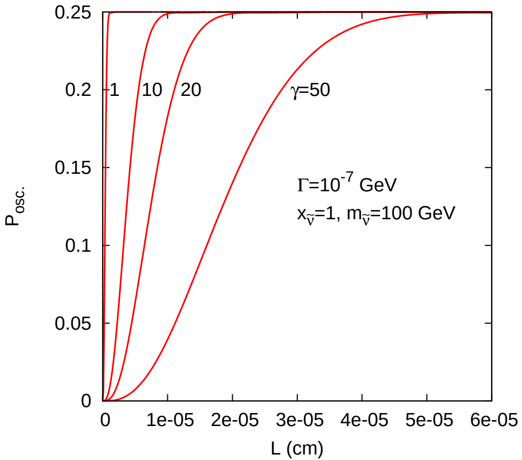

Figure: Dependence of the sneutrino oscillation probability on the boost factor γ when $\frac{\Delta m}{\Gamma} = 1$, $\Gamma = 10^{-7}$ GeV, and $m_{\tilde{\nu}} = 100$ GeV.

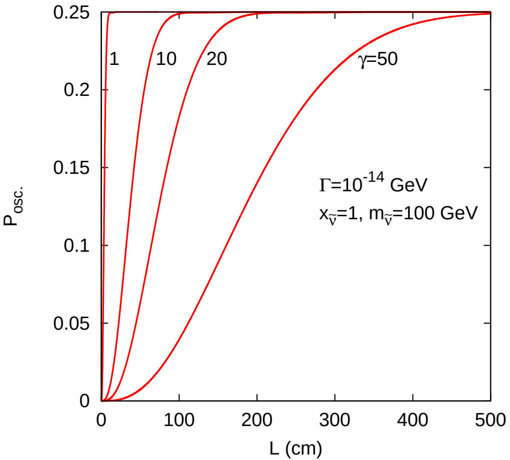

Figure: Dependence of the sneutrino oscillation probability on the boost factor γ when $\frac{\Delta m}{\Gamma} = 1$, $\Gamma = 10^{-14}$ GeV, and $m_{\tilde{\nu}} = 100$ GeV.

Motivation for a Scenario at the LHC

- We have just seen that, if Γ is much smaller (i.e., $\sim 10^{-14}$ GeV or so), the L- and γ-dependences are much more pronounced $\Rightarrow$ Use the new formula (Eq. (10)).
- This small Γ is possible, e.g., in a scenario where the left-handed $\tilde{\nu}$ NLSP is nearly degenerate to the lighter $\tilde{\tau}_1$ LSP and the dominant decay channel for the $\tilde{\nu}_\tau$ is

$$\tilde{\nu}_\tau \rightarrow \tilde{\tau}_1^- + \pi^+, \tag{12}$$

  with a total decay width $\Gamma \sim 10^{-14}$ GeV.
- In some models with an extra $U(1)_{B-L}$, the oscillation of $\tilde{\nu}_R$ can be important. In such cases, $\Gamma_{\tilde{\nu}_R}$ can be as small as $\sim 10^{-14}$ GeV.
- The left-chiral sneutrino decay width can also be reduced if it has a significant mixing with the right-chiral counterpart.

The Scenario

- Consider a mass spectrum with a $\tilde{\nu}_\tau$ NLSP and a $\tilde{\tau}_1$ LSP.
- Include a tiny R-parity violating coupling $\Rightarrow$ $\tilde{\tau}_1$'s decay outside the detector, leaving a heavily ionized charged track.
- $m_{\tilde{\nu}_\tau} = 100$ GeV, $m_{\tilde{\tau}_1} = 99.7$ GeV, $\theta_{\tilde{\tau}} = \pi/4$ (stau mixing).
- $M_1 = 120$ GeV, $M_2 = 240$ GeV, $\mu = -250$ GeV, $\tan\beta = 6$, $m_{A^0} = 600$ GeV, and $A_\tau = 250$ GeV.
- $\Rightarrow \Gamma_{\tilde{\nu}_\tau} \approx 1 \times 10^{-14}$ GeV and $BR(\tilde{\nu}_\tau \to \tilde{\tau}_1^- + \pi^+) \approx 93\%$.

Signals at the LHC

- When $\tilde{\nu}_\tau \to \tilde{\tau}_1^- + \pi^+$ dominates, one can see the signals

$$pp \to \tilde{\nu}_\tau \tilde{\tau}_1^+ \to \tilde{\tau}_1^- \tilde{\tau}_1^+ + \pi^+ \quad \text{(no osc.)}, \tag{13}$$
$$pp \to \tilde{\nu}_\tau \tilde{\tau}_1^+ \to \tilde{\nu}_\tau^* \tilde{\tau}_1^+ \to \tilde{\tau}_1^+ \tilde{\tau}_1^+ + \pi^- \quad \text{(osc.)}. \tag{14}$$

- $\tilde{\nu}_\tau$ is long-lived (decay length $\sim$ 3 cm) $\Rightarrow$ A displaced $\tilde{\tau}_1$ vertex (a very spectacular signal, free from backgrounds).
- Two heavily ionized charged tracks with opposite curvatures when no oscillation and with same curvatures when oscillation.
- We assume that these stau tracks can be distinguished from the muon tracks due to the slower velocity of staus.

Signals at the LHC

- Similarly, one should look at the signals

$$pp \rightarrow \tilde{\nu}_\tau^* \tilde{\tau}_1^- \rightarrow \tilde{\tau}_1^+ \tilde{\tau}_1^- + \pi^- \quad \text{(no osc.)}, \tag{15}$$

$$pp \rightarrow \tilde{\nu}_\tau^* \tilde{\tau}_1^- \rightarrow \tilde{\nu}_\tau \tilde{\tau}_1^- \rightarrow \tilde{\tau}_1^- \tilde{\tau}_1^- + \pi^+ \quad \text{(osc.)}. \tag{16}$$

- $\Rightarrow$ The opposite-sign stau signal (OS) $pp \rightarrow \tilde{\tau}_1^+ \tilde{\tau}_1^-$ from both $\tilde{\nu}_\tau \tilde{\tau}_1^+$ and $\tilde{\nu}_\tau^* \tilde{\tau}_1^-$ productions with $(1 - P_{\text{eff.}})$
- $\Rightarrow$ The same-sign stau signal (SS) $pp \rightarrow \tilde{\tau}_1^+ \tilde{\tau}_1^+$ or $\tilde{\tau}_1^- \tilde{\tau}_1^-$ from either $\tilde{\nu}_\tau \tilde{\tau}_1^+$ or $\tilde{\nu}_\tau^* \tilde{\tau}_1^-$ productions with $P_{\text{eff.}}$

Δm [GeV]	10^{-14}		10^{-13}		10^{-10}	
	Cross section in fb					
Signal	OS	SS	OS	SS	OS	SS
$\sqrt{s} = 7$ TeV	31.0	8.1	20.6	18.6	20.3	18.8
$\sqrt{s} = 12$ TeV	52.0	13.6	34.4	31.2	34.1	31.6
$\sqrt{s} = 14$ TeV	60.2	15.8	39.9	36.1	39.4	36.5

Table: Here, $L = 0.10$ m. The SS cross sections for $\sqrt{s} = 14$ TeV are $\sim 4 - 14\%$ higher with the non-relativistic oscillation probability formula.

- We select the signal events with the following criteria:
  1. $|\eta^{\tilde{\tau}_1}| < 2.5$
  2. $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} > 0.7$ for the two staus
  3. $p_T^{\tilde{\tau}_1} > 20$ GeV
  4. $0.3 < \beta\gamma < 2.0$ (the upper limit reduces the muon background considerably)

Results

- Define the asymmetry $A = \frac{\sigma(\mathrm{SS})-\sigma(\mathrm{OS})}{\sigma(\mathrm{SS})+\sigma(\mathrm{OS})}$.
- For $\sqrt{s} = 14$ TeV with $\Delta m = 10^{-10}$ GeV and assuming an integrated luminosity of 100 fb^{-1}, we get $A = -0.038 \pm 0.011$.
- A gives direct information about the oscillation probability and is independent of initial state parton densities and other uncertainties.
- In fact, $P_{\mathrm{eff.}} = (1 + A)/2$.
- In the example above, $P_{\mathrm{eff.}} = 0.48$
- If $|\vec{p}|$ of the stau track and the corresponding $\beta\gamma$ at the LHC can be measured, then one can get an estimate of the stau mass $m_{\tilde{\tau}_1} = \frac{|\vec{p}|}{\beta\gamma}$ (see the plot next page).

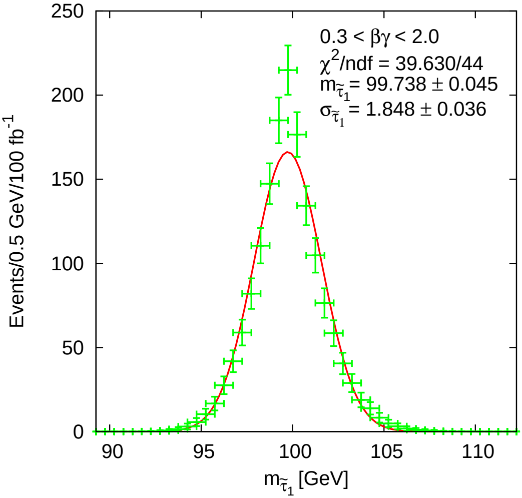

Figure: The measured stau mass from the SS signal with $\sqrt{s} = 14$ TeV, $\Delta m = 10^{-14}$ GeV, and $L = 0.10$ m. The cuts are used.

Conclusions

- $\tilde{\nu} - \tilde{\nu}^*$ oscillation is a very important tool to look for lepton number violation at the LHC.
- At the LHC, the sneutrinos can be ultrarelativistic, and one should appropriately take into account the boost factor $\gamma = \frac{E}{m}$ and the L-dependence while calculating the probability of the oscillation.
- The effect is more pronounced when $\Gamma_{\tilde{\nu}}$ is very small ($\sim 10^{-14}$ GeV). This can be realized in many different SUSY scenarios.
- A very interesting signal at the LHC could be two same-sign heavily ionized charged tracks and a soft pion, which can probe Δm all the way down to $\sim 10^{-14}$ GeV with an integrated luminosity as low as 10 fb^{-1}.

Conclusions

- (When the *RPV* coupling is larger, the $\tilde{\tau}_1$'s decay inside the detector or promptly, leading to different signals (not discussed in this talk).)