

Chargino Pair Production at Linear Collider and Split Supersymmetry

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Recently N. Arkani-Hamed and S. Dimopoulos proposed a supersymmetric model [1], dubbed “Split Supersymmetry” in Ref. [2], which can remove most of the unpleasant shortcomings of TeV Supersymmetry. In this model all scalars except one finely tuned Higgs boson are ultra heavy while the neutralino and chargino might remain light in order to achieve gauge coupling unification and accord with the dark matter density. In this paper, we investigated the impact of this new model on chargino pair production at next generation linear colliders. Our numerical results show that this process can be used to probe sneutrino mass up to 10 TeV. Therefore, precise measurements of chargino pair production at the linear colliders could distinguish Split Supersymmetry from TeV Supersymmetry.

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I. INTRODUCTION

The standard model (SM) of high energy physics has been rigorously tested by experiments, especially during the last decade of beautiful experiments at CERN, Fermilab and SLAC [3]. It is fair to say that no clear indication of new physics has emerged from the data. Furthermore, the unknown Higgs boson mass in the SM is predicted to be $m_H = 113_{-42}^{+62}$ GeV and $m_H \leq 237$ GeV at 95% c.l. by global fits of the data [3].

Despite the unprecedented success of the SM, we believe that the SM is an incomplete theory and new physics beyond the SM will eventually emerge at some scale higher than that of electro-weak symmetry breaking. The possible new physics will contribute quadratically to the mass of the fundamental Higgs boson due to its scalar nature. This phenomenon is the notorious fine-tuning or naturalness problem. In order to deal with this issue, several solutions have been proposed since 1970's of the last century: (1) new symmetries are introduced to protect the mass from quadratical radiative corrections. The popular choices are the fermion-boson symmetry (Supersymmetry) [4] or the global symmetry in little Higgs models [5]. We stress that in these two approaches the Higgs boson is naturally light. (2) Extra dimensions with low-scale gravity [6] have lowered the scale of new physics. (3) The Higgs boson is the composite particle of new fermions which are strongly interacting at the TeV scale. It should be emphasized that although the new strong dynamics (Technicolor, Topcolor etc.) [7] solves the fine-tuning problem and is also consistent with the data, it is difficult to obtain the preferred light Higgs boson mass without fine-tuning. If a light Higgs boson is observed from experiments, solution (3) will be disfavored. (4) The Higgs boson may be indeed finely tuned [1] and naturalness is no longer the guiding principle. This can be accomplished in the newly proposed supersymmetrical model [1]. In this paper we will investigate the impact from this novel idea on collider phenomenology.

The idea of the finely tuned Higgs boson was recently proposed by N. Arkani-Hamed and S. Dimopoulos [1] who were motivated by the fine-tuning issue of the Cosmological Constant, which has been set on solid ground as a consequence of the Wilkinson Microwave Anisotropy Probe (WMAP) observations [8]. The finely tuned supersymmetric model was also dubbed ‘‘Split Supersymmetry’’ (SS) in Ref. [2]. In such an approach the naturalness principle was replaced by one of gauge coupling unification and dark matter density. In the SS all the scalars except one finely tuned Higgs boson are ultra heavy while the neutralino

and chargino might remain light in order to achieve gauge coupling unification and accord with the dark matter density. It should be emphasized that SS can remove most of the unpleasant diseases of TeV supersymmetry, e.g. excessive flavor and CP violation, fast dimension-5 proton decay etc. [1, 2]. Since SS emerged it has already stimulated several investigations [2, 9], which were mainly focused on cosmological aspects and gauge coupling unification. Although cosmological studies can provide solid evidence for new physics, it says relatively little about the properties of new particles. Therefore studies about the SS impact on collider phenomenology are necessary. In this paper we investigate the chargino pair production at next generation linear colliders, especially whether we can distinguish SS from TeV Supersymmetry with this process. In order to discriminate SS from the usual TeV Supersymmetry, we need to know the mass of scalars which is one of the most important characteristics of SS.

It is clear that the ultra heavy scalars in SS can hardly be directly produced at either hadron or linear colliders. Therefore we should examine the virtual effects of scalars in neutralino and chargino production. We stress that the measurement of neutrino and chargino production at the LHC could provide important hints for SS: One of the most important production mechanism for neutralino and charginos at the LHC, i.e. as decay products of scalar quarks, is no longer allowed. However precise studies of chargino and neutralino production with relatively rare events in SS seem challenging due to the large QCD backgrounds at hadron colliders. In contrast linear colliders are more promising, especially chargino production which can potentially be used to reconstruct the chargino properties [10] as well as to determine the sneutrino mass.

II. FORMALISM

Due to R-parity conservation, supersymmetrical particles can only be produced in pairs. In Fig. 1 we show the Feynman diagrams for chargino pair production at linear colliders. This process occurs at tree level via s-channel photon and Z, as well as t-channel sneutrino exchanges. The transition amplitude can be expressed as [10]

$$T(e^+e^- \rightarrow \tilde{\chi}_i^- \tilde{\chi}_j^+) = \frac{e^2}{s} Q_{\alpha\beta} [\bar{v}(e^+) \gamma_\mu P_\alpha u(e^-)] [\bar{u}(\tilde{\chi}_i^-) \gamma_\mu P_\beta v(\tilde{\chi}_j^+)] \quad (1)$$

with chiralities $\alpha, \beta = L, R = (1 \mp \gamma_5)/2$. Here $i, j = 1, 2$ represent the indices of the chargino. In this paper we are concerned about the sneutrino contributions, so we will only explicitly present their expressions, and the others can be found in Ref. [10]. The sneutrino contributes to only Q_{LR} , which can be written as [14]

$$Q_{LR} = \begin{cases} 1 + \frac{D_Z}{s_W^2 c_W^2} \left(s_W^2 - \frac{1}{2} \right) \left(s_W^2 - \frac{3}{4} - \frac{1}{4} \cos(2\phi_R) \right) + \frac{D_{\tilde{\nu}}}{4s_W^2} (1 + \cos(2\phi_R)) & \text{for (11)} \equiv \tilde{\chi}_1^- \tilde{\chi}_1^+ \\ 1 + \frac{D_Z}{4s_W^2 c_W^2} \left(s_W^2 - \frac{1}{2} \right) \sin(2\phi_R) + \frac{D_{\tilde{\nu}}}{4s_W^2} \sin(2\phi_R) & \text{for (12)} \equiv \tilde{\chi}_1^- \tilde{\chi}_2^+ \\ 1 + \frac{D_Z}{s_W^2 c_W^2} \left(s_W^2 - \frac{1}{2} \right) \left(s_W^2 - \frac{3}{4} + \frac{1}{4} \cos(2\phi_R) \right) + \frac{D_{\tilde{\nu}}}{4s_W^2} (1 - \cos(2\phi_R)) & \text{for (22)} \equiv \tilde{\chi}_2^- \tilde{\chi}_2^+, \end{cases} \quad (2)$$

where $D_Z = s/(s - m_Z^2)$, $D_{\tilde{\nu}} = s/(t - m_{\tilde{\nu}}^2)$, $s_W = \sin(\theta_W)$ and $c_W = \cos(\theta_W)$ with θ_W is the weak angle, and

$$\begin{aligned} \cos(2\theta_R) &= -\frac{M_2^2 - |\mu|^2 + 2m_W^2 \cos(2\beta)}{\Delta_C}, \\ \sin(2\theta_R) &= -\frac{2m_W \sqrt{M_2^2 + |\mu|^2 - (M_2^2 - |\mu|^2) \cos(2\beta) + 2M_2 |\mu| \sin(2\beta)}}{\Delta_C} \end{aligned} \quad (3)$$

with

$$\Delta_C = \sqrt{(M_2^2 - |\mu|^2)^2 + 4m_W^4 \cos^2(2\beta) + 4m_W^2 (M_2^2 + |\mu|^2) + 8m_W^2 M_2 |\mu| \sin(2\beta)}. \quad (4)$$

Here M_2 and μ are $SU(2)$ gaugino and higgsino mass parameters, and as usual $\tan \beta = v_2/v_1$ is the ratio of the vacuum expectation values of the two neutral Higgs fields which break electroweak symmetry.

The unpolarized differential cross section and left-right asymmetry can be derived [10] as

$$\frac{d\sigma}{d \cos \Theta} = \frac{\pi \alpha^2}{2s} \lambda^{1/2} N \quad (5)$$

$$A_{LR}(\Theta) = \frac{N'}{N}, \quad (6)$$

where Θ is the angle between the e^- and $\tilde{\chi}_i^-$ and

$$\begin{aligned} N &= \left(1 - (\mu_i^2 - \mu_j^2)^2 + \lambda \cos^2 \Theta \right) Q_1 + 4\mu_i \mu_j Q_2 + 2\lambda^{1/2} \cos \Theta Q_3 \\ N' &= N [Q_1 \rightarrow Q'_1, Q_2 \rightarrow Q'_2, Q_3 \rightarrow Q'_3] \\ \mu_i &= \frac{m_{\tilde{\chi}_i}}{\sqrt{s}}, \quad \lambda = \left(1 - (\mu_i + \mu_j)^2 \right) \left(1 - (\mu_i - \mu_j)^2 \right). \end{aligned} \quad (7)$$

Here

$$Q_1 = \frac{1}{4} \left[|Q_{RR}|^2 + |Q_{LL}|^2 + |Q_{RL}|^2 + |Q_{LR}|^2 \right]$$

$$\begin{aligned}
Q_2 &= \frac{1}{2} \text{Re} [Q_{RR} Q_{RL}^* + Q_{LL} Q_{LR}^*] \\
Q_3 &= \frac{1}{4} [|Q_{RR}|^2 + |Q_{LL}|^2 - |Q_{RL}|^2 - |Q_{LR}|^2] \\
Q'_1 &= \frac{1}{4} [|Q_{RR}|^2 - |Q_{LL}|^2 + |Q_{RL}|^2 - |Q_{LR}|^2] \\
Q'_2 &= \frac{1}{2} \text{Re} [Q_{RR} Q_{RL}^* - Q_{LL} Q_{LR}^*] \\
Q'_3 &= \frac{1}{4} [|Q_{RR}|^2 - |Q_{LL}|^2 - |Q_{RL}|^2 + |Q_{LR}|^2].
\end{aligned} \tag{8}$$

From Eq. 8 we can see that the sneutrino can contribute to all the quartic charges Q_i and Q'_i ($i = 1 - 3$).

The differential cross section $\frac{d\sigma}{d\cos\Theta}$ and left-right asymmetry $A_{LR}(\Theta)$ are useful for large events analysis, while for fewer events we can define the integrated observables: the total cross section, forward-backward asymmetry and integrated left-right asymmetry respectively. Based on Eq. 5 and 7 they are

$$\begin{aligned}
\sigma &= \frac{\pi\alpha^2}{s} \lambda^{1/2} \left((1 - (\mu_i^2 - \mu_j^2)^2) Q_1 + 4\mu_i\mu_j Q_2 + \frac{1}{3}\lambda Q_1 \right), \\
A_{FB} &\equiv \frac{\int_{-1}^0 \frac{d\sigma}{d\cos\Theta} d\cos\Theta - \int_0^1 \frac{d\sigma}{d\cos\Theta} d\cos\Theta}{\int_{-1}^0 \frac{d\sigma}{d\cos\Theta} d\cos\Theta + \int_0^1 \frac{d\sigma}{d\cos\Theta} d\cos\Theta} = \frac{-\lambda^{1/2} Q_3}{(1 - (\mu_i^2 - \mu_j^2)^2) Q_1 + 4\mu_i\mu_j Q_2 + \frac{1}{3}\lambda Q_1} \\
A_{LR} &\equiv \frac{\int_{-1}^1 N' d\cos\Theta}{\int_{-1}^1 N d\cos\Theta} = \frac{(1 - (\mu_i^2 - \mu_j^2)^2) Q'_1 + 4\mu_i\mu_j Q'_2 + \frac{1}{3}\lambda Q'_1}{(1 - (\mu_i^2 - \mu_j^2)^2) Q_1 + 4\mu_i\mu_j Q_2 + \frac{1}{3}\lambda Q_1}.
\end{aligned} \tag{9}$$

III. NUMERICAL ANALYSIS

In the following, we study numerically the SS effects on the observables of chargino pair production at linear colliders. The SS parameter space will be analyzed first. Based on the gaugino mass unification assumption and the dark matter density constraint $0.094 < \Omega_{DM} h^2 < 0.129$, the allowed parameter space of SS can be classified into three categories [2]

1. Mixed region: M_2 and μ are comparable and below 1-2 TeV. In this region the lightest neutralino and chargino are always in a the mixed state of the higgsino and gaugino, and the mass of the chargino and neutralino can be as low as the present experimental limit. We stress that in this case the long-lived gluino might be found at the LHC and gluino lifetime can be used to probe scale of the ultra heavy scalar.
2. $\mu \approx 1.0 - 1.2$ TeV and the gaugino masses are arbitrarily larger than μ . The neutralino and chargino are considerably heavier.

3. $M_2 \approx 2.0 - 2.5$ and the other parameters are arbitrarily larger.

It is clear that the case (2) and (3) are not happy for colliders, so we will investigate the collider signature for case (1) only. We stress that the discovery reach of the LHC and next linear colliders can not cover the entire SS parameter space.

In the mixed region, the magnitude of both M_2 and μ can be as low as 200 GeV [15]. We take two typical points labelled as “**Pa**” and “**Pb**”

$$\begin{aligned} \mathbf{Pa} : \quad & M_2 = 200 \text{ GeV}, \mu = 200 \text{ GeV}, \tan \beta = 20, \sin(2\Phi_R) = -0.9655, \\ & \cos(2\Phi_R) = 0.2605, m_{\tilde{\chi}_1^\pm} = 147.5 \text{ GeV}, m_{\tilde{\chi}_2^\pm} = 266.8 \text{ GeV}; \end{aligned} \quad (10)$$

$$\begin{aligned} \mathbf{Pb} : \quad & M_2 = 1000 \text{ GeV}, \mu = 600 \text{ GeV}, \tan \beta = 20, \sin(2\Phi_R) = -0.3497, \\ & \cos(2\Phi_R) = -0.9369, m_{\tilde{\chi}_1^\pm} = 593.1 \text{ GeV}, m_{\tilde{\chi}_2^\pm} = 1010.5 \text{ GeV}. \end{aligned} \quad (11)$$

The characteristics for **Pa** are the light chargino and $|\sin(2\Phi_R)| \sim 1$ while for **Pb** chargino is heavy and $|\cos(2\Phi_R)| \sim 1$. It should be noted that the sign of μ does not affect chargino production.

In Fig. 2 we show the cross sections as a function of sneutrino mass for **Pa** with $\sqrt{s} = 800$ GeV. It is obvious that the three modes (11), (12) and (22) can all act as probes of the sneutrino mass. This feature is typical in the mixed region for low M_2 . Moreover one can distinguish the 1 TeV and 10 TeV sneutrino through the cross section measurements. For example, the cross sections for the (11) mode are 0.18 pb and 0.25 pb for a 1 TeV and 10 TeV sneutrino respectively, and for the (22) mode they are 0.19 pb and 0.23 pb respectively. We can also see that the cross sections for the (11) and (22) modes increase while for the (12) mode it decreases with sneutrino mass. This is because as the sneutrino mass increases, the contributions arising from t-channel sneutrino decrease, as noticed in Ref. [10], and the strong destructive effects for a light sneutrino in the (11) and (22) modes are weaker than for a heavy sneutrino.

In Fig. 3 and 4 the differential cross sections, A_{FB} , $A_{LR}(\Theta)$ and A_{LR} are given for **Pa** respectively. From diagrams (A)-(C) of both figures we can see that as the sneutrino mass increases, the differential cross sections and left-right asymmetry tend generally to be more symmetric, and again the three modes can all act as probes of the sneutrino mass. For A_{FB} , the (11) and (12) modes are more sensitive to the sneutrino mass than that of the (22), while for A_{LR} the (12) mode is more sensitive.

In Fig. 5 and 6 we show the cross sections, A_{FB} and A_{LR} as a function of sneutrino mass for **Pb** with $\sqrt{s} = 3$ TeV. For the cross section and A_{FB} , the (12) and (22) modes are sensitive to the sneutrino mass while the (11) mode is not. Moreover the (22) mode is more promising than that of the (12) because of its relatively large cross section. For A_{LR} , only the (12) mode is sensitive to the sneutrino mass. It is obvious that for all observables the (11) mode is not sensitive to the sneutrino mass because, from Eq. 2, $\cos(2\Phi_R) \sim -1$ makes sneutrino almost decouple from the (11) mode.

IV. DISCUSSIONS AND CONCLUSIONS

We have investigated the impact of Split Supersymmetry on chargino pair production at the next linear colliders. From the numerical discussions for two typical parameter sets **Pa** and **Pb** which are inferred from gauge coupling unification and constrained by the dark matter density, we can see that chargino pair production is sensitive to the sneutrino mass up to 10 TeV. For low M_2 all three modes (11), (12) and (22) are sensitive to the sneutrino mass, while for high M_2 the (22) mode is most promising. We stress that the analysis of all three modes (11), (12) and (22) is necessary in order to distinguish SS from TeV Supersymmetry.

In this study, we have only included tree-level contributions and are aware that higher order corrections [11] are likely to be non-negligible, especially for precise determination on scalar mass scale. Nevertheless, we feel that our approach is satisfactory for a preliminary study to gauge the potential of this process for distinguishing SS from TeV Supersymmetry.

It is known that beam polarization will be a very useful tool at the linear colliders to enhance signal, reduce background as well as extract couplings etc. [12]. In this paper we are more concerned about physical observable's dependence on the sneutrino contributions which are only explicitly present in Q_{LR} in Eq. 2. It is obvious that the beam polarization will enhance such kind of dependence, especially for double beams polarization.

If SS stands up to the scrutiny of LHC (no light scalars, except one Higgs boson, are found), TeV Supersymmetry will be at least highly disfavored. In order to test SS, it is necessary to exam the SUSY couplings relations at linear colliders, for example $M_W^X = M_W$ in mixed region [13]. It is very promising that precise test on such kinds of SUSY relations can be achieved [13]. We stress that the more solid conclusions can be drawn only after the real simulations.

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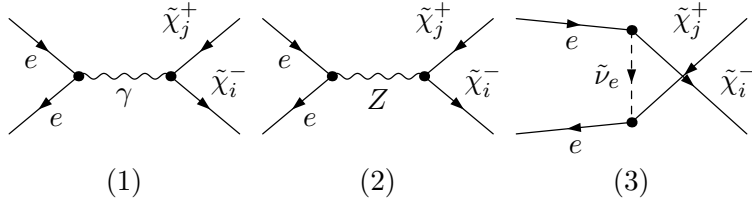


FIG. 1: Feynman diagrams for $e^+e^- \rightarrow \tilde{\chi}_i^- \tilde{\chi}_j^+$.

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[14] The CP phase Φ_μ is set to 0.

[15] See fig. 11 in Ref. [2].

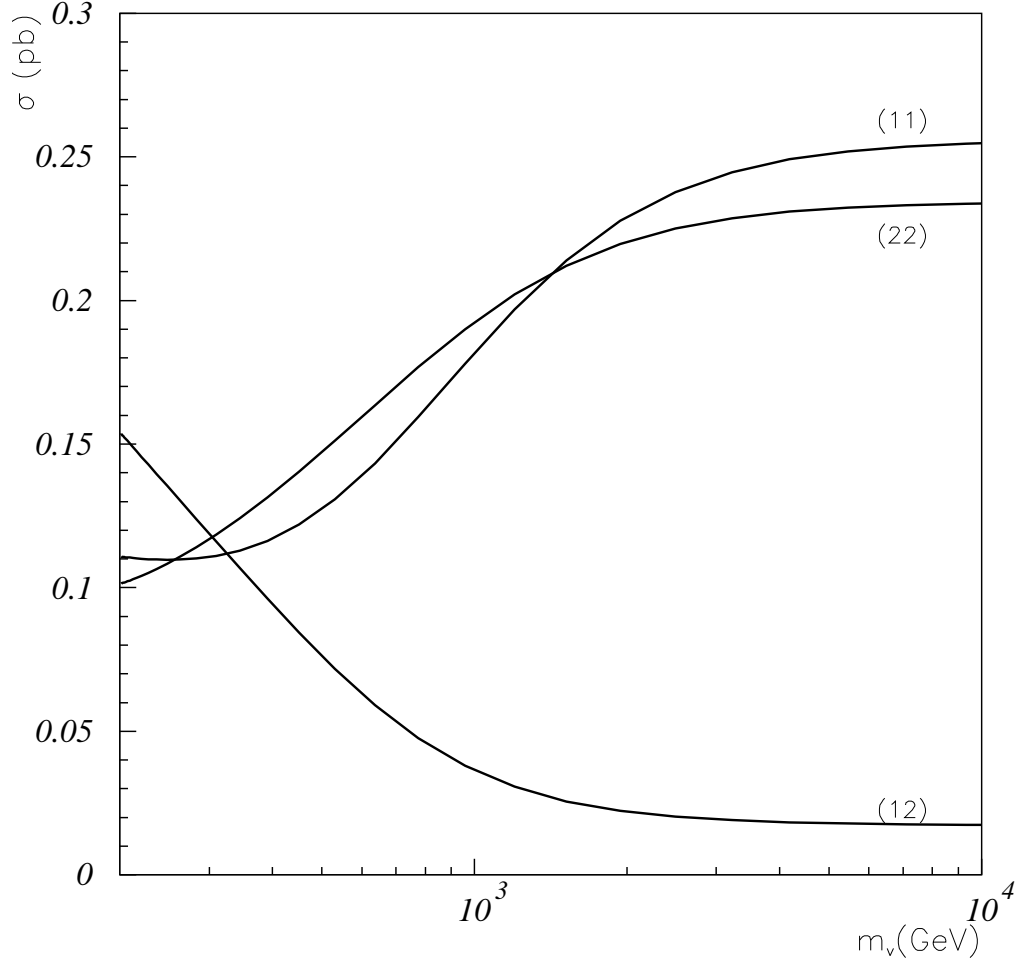


FIG. 2: Cross sections as a function of sneutrino mass for **Pa** with $\sqrt{s} = 800$ GeV. Definitions of (11), (12) and (22) are in Eq. 2.

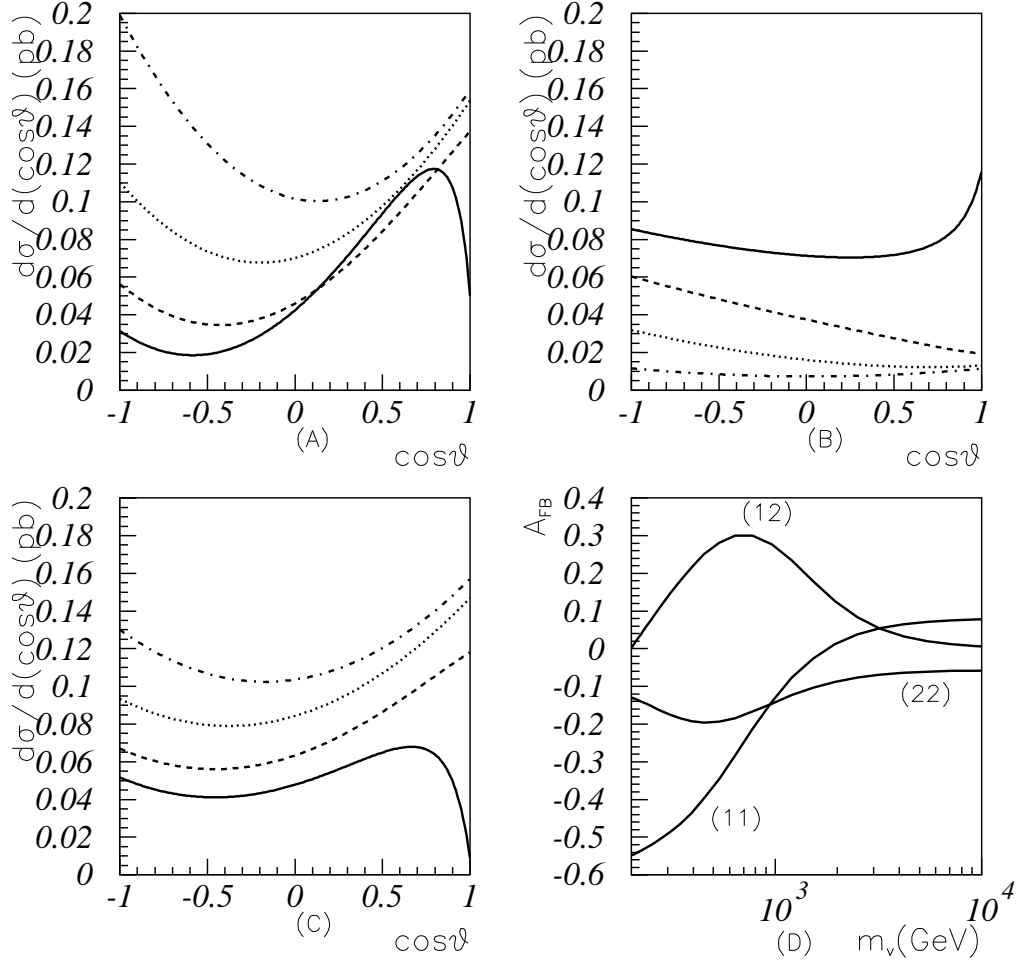


FIG. 3: Differential cross sections [(A)-(C)] and A_{FB} [(D)] as functions of $\cos(\Theta)$ and sneutrino mass for **Pa** with $\sqrt{s} = 800$ GeV. For (A)-(C) solid, dashed, dotted and dot-dashed lines represent $m_{\tilde{\nu}} = 200, 500, 10^3, 10^4$ GeV respectively.

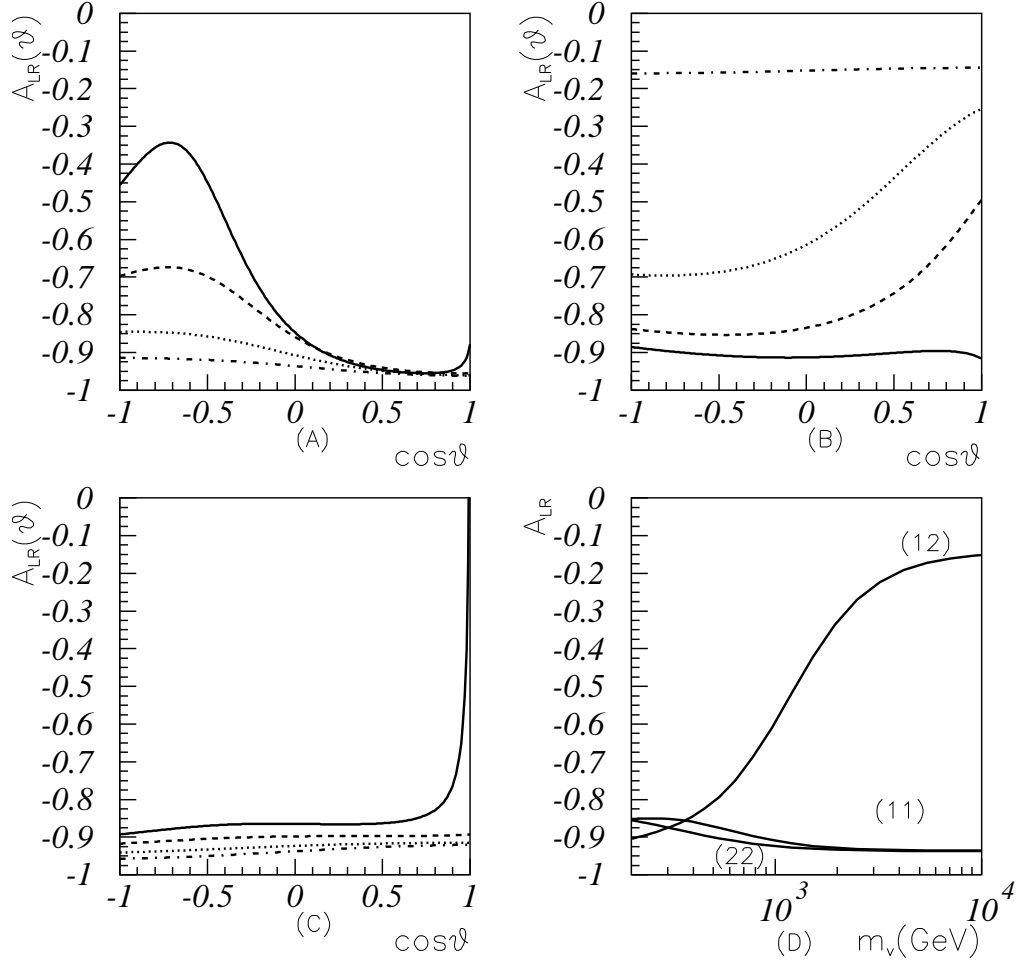


FIG. 4: $A_{LR}(\Theta)$ [(A)-(C)] and A_{LR} [(D)] as functions of $\cos(\Theta)$ and sneutrino mass for **Pa** with $\sqrt{s} = 800$ GeV. For (A)-(C) solid, dashed, dotted and dot-dashed lines represent $m_{\tilde{\nu}} = 200, 500, 10^3, 10^4$ GeV respectively.

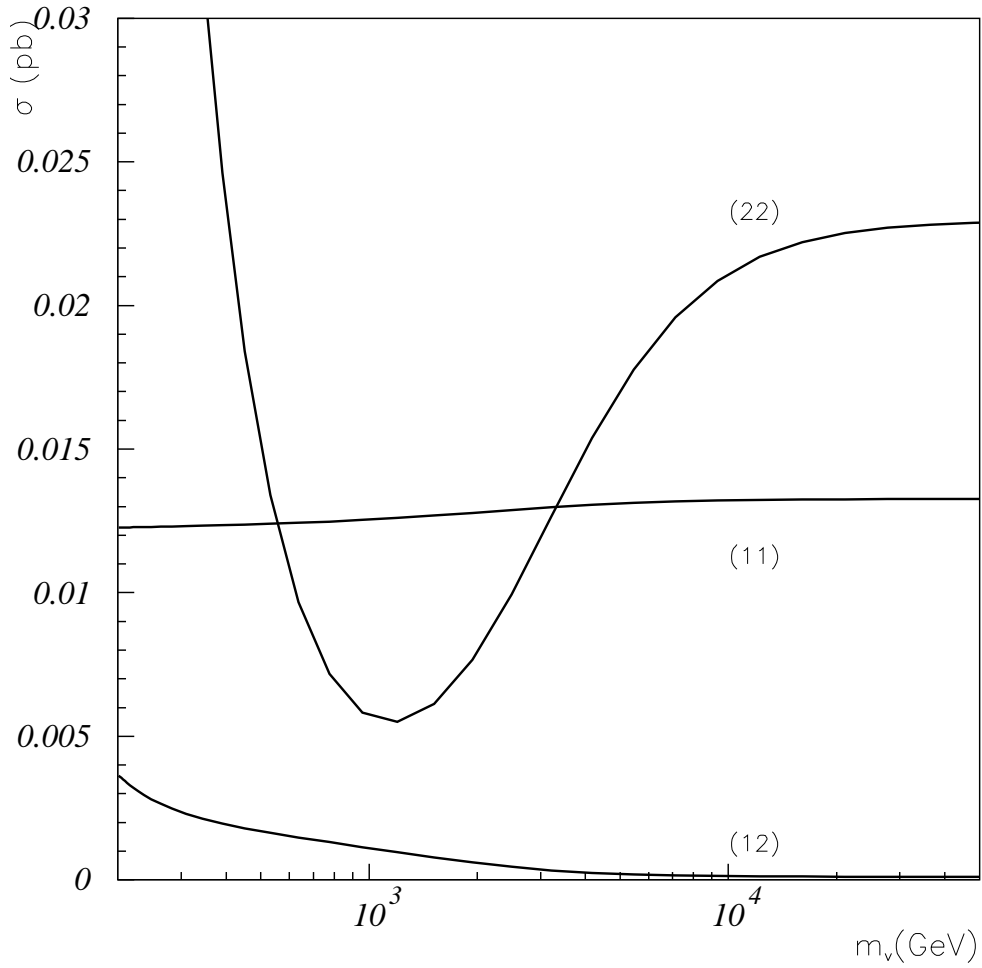


FIG. 5: Cross sections as a function of sneutrino mass for **Pb** with $\sqrt{s} = 3$ TeV.

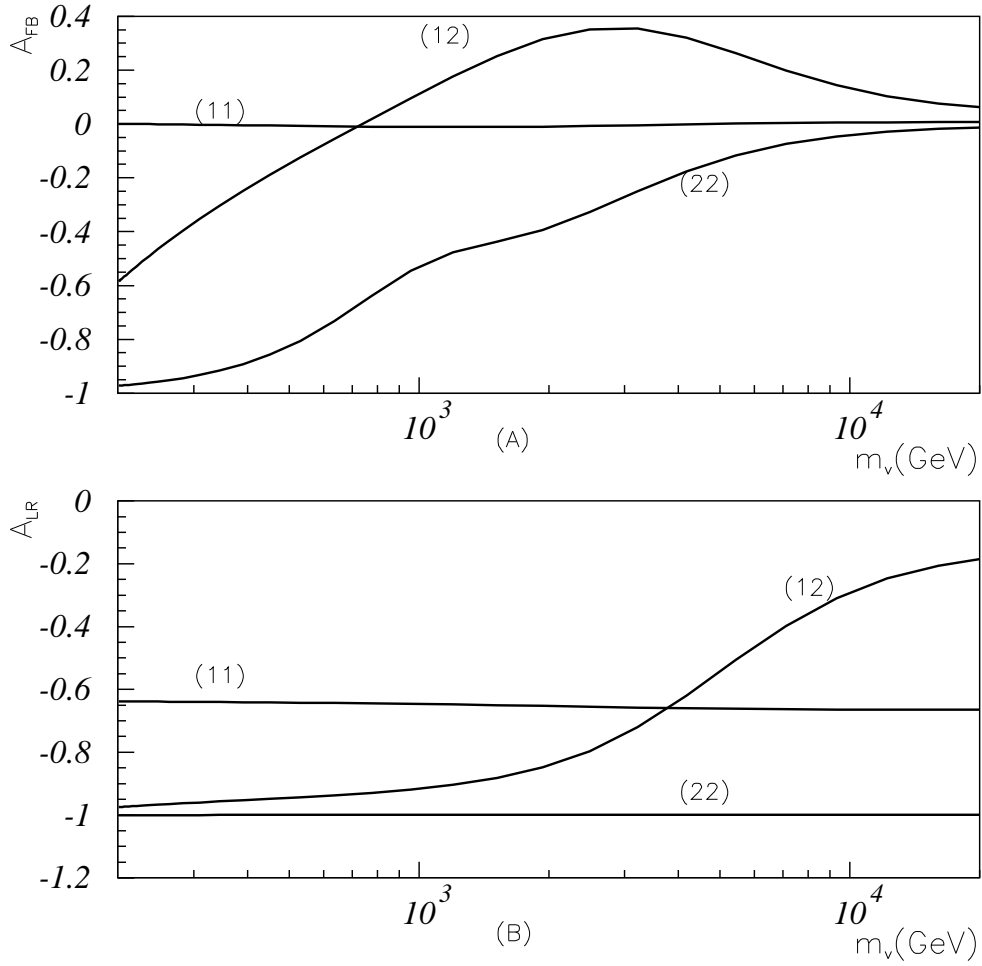


FIG. 6: A_{FB} [(A)] and A_{LR} [(B)] as a function of sneutrino mass for **Pb** with $\sqrt{s} = 3$ TeV.