

Searching R -parity-violating supersymmetry in semileptonic B -decays

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ABSTRACT

If R -parity is broken and the photino, although unstable, does not decay within the detector, then in new semileptonic B -decay modes a light ($\sim 2-3$ GeV) photino can be produced carrying missing energy. However, the photino, being massive, arranges a different kinematical configuration for the visible decay products as compared to a standard semileptonic event where the neutrino carries the missing energy. We study the above kinematic distributions in an attempt to explore the above scenario.

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In the Minimal Supersymmetric Standard Model (MSSM), one of the four neutralinos is the most favourable candidate to constitute the lightest supersymmetric particle (LSP), which is assumed to be stable. It is believed to weigh no less than ~ 20 GeV [1] when one compounds the non-observation of a gluino up to ~ 120 GeV at the hadron colliders with the theoretical assumption of the GUT-relation between the gaugino masses. But if one relaxes the above assumption and if the LSP is dominantly a gaugino (say, the photino), the above bound evaporates. At low energy e^+e^- machines light photinos can, in principle, be pair produced in a t -channel selectron-exchanged process. The anomalous single photon (ASP) experiment [2] was designed to search for such a mode at the e^+e^- storage ring PEP, operating at $\sqrt{s} = 29$ GeV, at SLAC. A hierarchy $m_{\tilde{\gamma}} \ll \sqrt{s} \ll m_{\tilde{e}}$ was assumed in the calculation of the radiative photino pair-production cross section. The presence of single photons, with transverse momentum that cannot be balanced by particles lost down the beam pipe, were demanded to establish the ASP events. From the non-observation of such events it was concluded that selectrons should be heavier than ~ 60 GeV¹. On the other hand, cosmology demands that the cross section of photino annihilation into electrons should not be too small, requiring either the photino not to be too light or the selectron not to be too heavy, to avoid the unwanted abundance of photinos in the Universe. In this *tug of war* if we consider a photino in the ball-park of ~ 2 – 3 GeV it is perhaps worth opening one more channel for it to decay into standard particles by relaxing the assumption of the so called “ R -parity conservation” [3]². In fact, such a light photino should better decay within 1 s (which corresponds to a width greater than 6.6×10^{-22} MeV) so that it does not live up to the nucleosynthesis era since injecting extra energy at this phase might turn out to be unacceptable. In this Letter we attempt to test the existence of such a light photino in the context of semileptonic B -decays [4]. If R -parity is broken *carefully* so that the photino remains stable within the detector, providing a new funnel for carrying missing energy, it can fake the Standard Model (SM) neutrino in a semileptonic event. First, we summarize very briefly the basic features of explicit R -parity violation (\mathcal{R}) and then discuss the strategy of uncovering the above scenario.

Normally searches for supersymmetric particles are carried out under the assumption that a discrete quantum number R , known as R -parity, and defined as $R = (-1)^{(3B+L+2S)}$ where $B \equiv$ baryon number, $L \equiv$ lepton number, and $S \equiv$ spin, is conserved. For all ordinary particles $R = 1$ and for all superparticles $R = -1$. However, requiring the theory to be supersymmetric, renormalizable, gauge-invariant and minimal in terms of field content does not enforce R -parity conservation. Substituting in the Yukawa interaction the $SU(2)$ -doublet lepton superfield in place of the Higgs superfield with the same gauge quantum number results in the first two terms of the following R -parity-

¹ See Fig. 5 of ref. [2] for the plots of $\sigma(e^+e^- \rightarrow \gamma\tilde{\gamma}\tilde{\gamma})$ as a function of $m_{\tilde{e}}$ for various $m_{\tilde{\gamma}}$ values.

²For an overview of various limits on the LSP, from accelerator searches, dark matter searches and those of cosmological and astrophysical origin, the reader is referred to *Supersymmetric Particle Searches*, H. Haber in ref. [1]. Of course, many of these limits will not apply when a light photino is considered in conjunction with R -parity violation.

violating superpotential, while the third term is also not forbidden by any symmetry,

$$\mathcal{W}_{\mathcal{R}} = \lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \lambda''_{ijk} U_i^c D_j^c D_k^c, \quad (1)$$

where L_i and Q_i are the $SU(2)$ -doublet lepton and quark superfields and E_i^c, U_i^c, D_i^c are the singlet superfields; λ_{ijk} is antisymmetric under the interchange of the first two indices, while λ''_{ijk} is antisymmetric under the interchange of the last two. It is obvious that there are 45 such Yukawa couplings: 9 each of the λ and λ'' types and 27 of the λ' variety. These couplings cannot all be arbitrary simultaneously and have to be *carefully* instigated so that the consistency with various experimental measurements is respected [3]. This requires that some of them are not dynamically active at the same time. For example, assuming all the λ'' couplings to be zero, which we adopt in any case for the rest of this paper, the bounds from the non-observation of proton decay and $n-\bar{n}$ oscillation are avoided. This assumption also makes it simpler to evade the cosmological bounds [5]. The L -violating couplings can, in principle, wash out the GUT-scale baryogenesis, but Dreiner and Ross [6] have argued that these bounds are highly model-dependent. If one of the L -violating couplings involving a particular lepton family is small ($< 10^{-7}$), so as to conserve the corresponding lepton flavour over cosmological time scales, then the primordial baryogenesis could be restored and, therefore, these bounds would no longer be effective.

The essential idea of this paper is the following: In the SM, one of the semileptonic decay channels of the b -quark is $b \rightarrow ce\bar{\nu}$. In the MSSM, if one relaxes the assumption of R -parity conservation minimally, assuming only one of the above-mentioned 45 Yukawa couplings, namely, λ'_{123} , to be non-zero³, and if the photino lies in the mass range ($\sim 2-3$ GeV), then the b -quark can have a $b \rightarrow ce\tilde{\gamma}$ decay mode. For the sake of simplicity we consider the photino ($\tilde{\gamma}$) as the lightest neutralino, which we argue later to be stable within the size of the relevant detectors. The $\tilde{\gamma}$ will mimic the behaviour of the SM ν providing an invisible channel of energy; however, owing to its massive nature it will arrange a different kinematical configuration of the visible decay products compared to the SM scenario. The magnitude of λ'_{123} that we allow for a given value of the photino mass ($m_{\tilde{\gamma}}$) is of course constrained from the experimental measurement of the semileptonic branching ratio. Our search strategy lies in comparing and contrasting the differential distributions in the two cases which, due to the difference in their kinematic configurations, could unveil the new physics signal to an observable scale.

We start with the consideration of B -meson decays at the quark level. In the SM, the decay matrix element of $b(P) \rightarrow c(k_2) + e(k_1) + \bar{\nu}_e(k_3)$ and its spin-sum-square are given by

$$\mathcal{M} = 2\sqrt{2}G_F V_{cb} \bar{e}(k_1) \gamma_\mu P_L \nu_e(-k_3) \bar{c}(k_2) \gamma^\mu P_L b(P),$$

³ This tacit assumption that only one R -parity-violating coupling is non-zero at a time – a standard practice in \mathcal{R} -phenomenology – is in accordance with a non-GUT set up, as otherwise if \mathcal{R} is embedded in a GUT scenario, one cannot avoid various R -parity-violating couplings occurring simultaneously from the GUT-multiplet structures.

$$\Sigma_{spin}|\mathcal{M}|^2 = 128 G_F^2 |V_{cb}|^2 (k_1 \cdot k_2)(k_3 \cdot P), \quad (2)$$

where the symbols have their usual significance. We neglect the electron mass and introduce $r_c = m_c/m_b$, $x = 2E_e/m_b$, where E_e is the energy of the electron in the b -quark rest frame. We obtain,

$$\begin{aligned} \frac{d\Gamma^{\text{SM}}}{dx} &= \frac{G_F^2 m_b^5}{192\pi^3} |V_{cb}|^2 f(x, r_c), \\ \Gamma^{\text{SM}} &= \int_0^{1-r_c^2} dx \frac{d\Gamma^{\text{SM}}}{dx}, \end{aligned} \quad (3)$$

where

$$f(x, r_c) = \frac{2x^2}{(1-x)^3} (1-x-r_c^2)^2 (3-5x+2x^2-r_c^2x+3r_c^2). \quad (4)$$

Now we turn our attention to the R -parity breaking sector. The part of the Lagrangian induced by λ'_{123} , the only one relevant for our purpose, is given by

$$\mathcal{L} = \lambda'_{123} [\bar{b}_R \nu_{eL} \tilde{s}_L + \bar{b}_R s_L \tilde{\nu}_{eL} - \bar{b}_R e_L \tilde{c}_L - \bar{b}_R c_L \tilde{e}_L + \overline{(\nu_{eL})^c} s_L \tilde{b}_R^* - \overline{(e_L)^c} c_L \tilde{b}_R^*] + \text{h.c.} \quad (5)$$

The new process, which mimics the semileptonic b -decay in the present situation, is

$$b(P) \rightarrow c(k_2) + e(k_1) + \tilde{\gamma}(k_3). \quad (6)$$

The above interaction proceeds through two different interfering channels. In one case, the b -quark decays to a c -quark and a virtual \tilde{e}_L induced by λ'_{123} and the latter in turn decays with an electromagnetic strength to a $\tilde{\gamma}$ and an electron. The decay matrix element is given by

$$\mathcal{M}_{1R} = \frac{\sqrt{2}e\lambda'_{123}}{m_{\tilde{e}_L}^2} [\bar{e}(k_1) P_R \tilde{\gamma}(-k_3) \bar{c}(k_2) P_R b(P)]. \quad (7)$$

In the other case, the b -quark emits a $\tilde{\gamma}$ and a virtual \tilde{b}_R and the latter decays into a c -quark and an electron via λ'_{123} . The decay matrix element in this case is given by⁴

$$\mathcal{M}_{2R} = -\frac{\sqrt{2}e\lambda'_{123}}{m_{\tilde{b}_R}^2} [\bar{c}(k_2) P_R e^c(-k_1) \bar{\tilde{\gamma}}(k_3) P_R b(P)]. \quad (8)$$

Using a simple Fierz transformation, we obtain the spin-summed and squared matrix element as

$$\begin{aligned} \Sigma_{spin}|\mathcal{M}_{1R} + \mathcal{M}_{2R}|^2 &= \left(\frac{2\sqrt{2}e\lambda'_{123}}{m_{\tilde{e}_L}^2} \right)^2 \left[(P \cdot k_2)(k_1 \cdot k_3) + \kappa^4 (P \cdot k_3)(k_1 \cdot k_2) \right. \\ &\quad \left. - \kappa^2 \{ (P \cdot k_2)(k_1 \cdot k_3) + (P \cdot k_3)(k_1 \cdot k_2) - (P \cdot k_1)(k_2 \cdot k_3) \} \right], \end{aligned} \quad (9)$$

⁴The sign difference between \mathcal{M}_{1R} and \mathcal{M}_{2R} has its root in the sign difference between the photino couplings to the left- and the right-type scalars [7].

where $\kappa = m_{\tilde{e}_L}/m_{\tilde{b}_R}$. Introducing $r_{\tilde{\gamma}} = m_{\tilde{\gamma}}/m_b$, the contribution to the R -parity induced width can be written as

$$\frac{d\Gamma_{\mathcal{R}}}{dx} = \frac{G_F^2 m_b^5}{192\pi^3} \left(\frac{e\lambda'_{123}}{g^2}\right)^2 \left(\frac{m_W}{m_{\tilde{e}_L}}\right)^4 8 \lambda^{1/2} \left(1, \frac{r_c^2}{1-x}, \frac{r_{\tilde{\gamma}}^2}{1-x}\right) x^2 \left[\left\{ f_1(1+\kappa^2)^2 - f_2\kappa^2 \right\} (1-x) - f_2(1-\kappa^2)^2 \left(1 - \frac{x}{2}\right) \right], \quad (10)$$

$$\Gamma_{\mathcal{R}} = \int_0^{1-(r_c+r_{\tilde{\gamma}})^2} dx \frac{d\Gamma_{\mathcal{R}}}{dx}, \quad (11)$$

where

$$\lambda(a, b, c) = a^2 + b^2 + c^2 - 2ab - 2bc - 2ca, \quad (12)$$

$$f_1 = \frac{1}{2} - \frac{r_c^2 + r_{\tilde{\gamma}}^2}{1-x} + \frac{1}{2} \frac{(r_c^2 - r_{\tilde{\gamma}}^2)^2}{(1-x)^2}, \quad (13)$$

$$f_2 = -1 - \frac{r_c^2 + r_{\tilde{\gamma}}^2}{1-x} + 2 \frac{(r_c^2 - r_{\tilde{\gamma}}^2)^2}{(1-x)^2}. \quad (14)$$

Now we discuss the results of our calculation:

1. We calculate the total (SM + \mathcal{R}) semileptonic branching ratio $B(b \rightarrow c + e + \text{invisible})$ and allow only as much admixture of λ'_{123} as saturates the uncertainty of the corresponding global average $(10.43 \pm 0.24)\%$ [1]⁵. In the absence of a precise SM prediction of the above, this approximation is reasonable. We display in Fig. 1 the 90% C.L. upper bound on the λ'_{123} as a function of $m_{\tilde{\gamma}}$ for fixed $m_{\tilde{b}_R} = 100$ GeV and for three different values of $m_{\tilde{e}_L} = 50, 100$ and 200 GeV, corresponding to $\kappa = 0.5, 1$ and 2, respectively. It may be noted that the existing 1σ limit $\lambda'_{123} < 0.26$ from the forward-backward asymmetry measurements in e^+e^- collisions, derived in [8], is based on an effective operator which goes like λ'/\tilde{m} , whereas in our case it scales like λ'/\tilde{m}^2 , \tilde{m} being a common scalar mass parameter. We also note that the Cabibbo-Kobayashi-Maskawa element V_{cb} enters the SM part of the calculation which is otherwise extracted from the semileptonic measurements [9]. Any non-standard contamination in the process would certainly affect the extraction. We keep our inclusive branching ratio consistent with experiment by assuming $V_{cb} = 0.04$ and saturating the uncertainty with λ'_{123} as mentioned earlier. We keep $m_b = 5$ GeV in our calculation.
2. For given values of photino- and scalar-masses, imposing the 90% C.L. limit of λ'_{123} from Fig. 1, we exhibit in Fig. 2 the electron energy distribution, *i.e.* $\frac{1}{\Gamma} \frac{d\Gamma}{dx}$,

⁵ We stay on the conservative side by using the average which assumes leptonic universality. We also note that the new graphs we consider contribute to the semi‘electronic’ b -decay mode only, thus violating the leptonic universality. However, the experimental uncertainty of each of the lepton flavour specific channels (see ref. [1] for details) is larger than the average and, therefore, the above universality violation is easily tolerable.

where Γ corresponds to (i) Γ_{SM} and (ii) $\Gamma_{\text{tot}} = \Gamma_{\text{SM}} + \Gamma_{\mathcal{R}}$. We notice that for fixed $m_{\tilde{\gamma}}$ and $m_{\tilde{b}_R}$, varying $m_{\tilde{e}_L}$ does not show any observable impact within the scale of the figures. More important in determining the shapes of the distributions are the external masses which affect the kinematical configurations and, of course, the scale of the new physics given by either $m_{\tilde{b}_R}$ or $m_{\tilde{e}_L}$; much less important in this case is the relative size of $m_{\tilde{b}_R}$ and $m_{\tilde{e}_L}$, which affects the dynamics of the new graphs.

3. In Fig. 3, we demonstrate the angular distribution (angle between the c -quark and the electron) for the two cases stated above. Here, too, we find that the shapes of the distributions are quite insensitive to the relative scales of $m_{\tilde{b}_R}$ and $m_{\tilde{e}_L}$, as in Fig. 2.

Two important issues need to be addressed in any discussion concerning semileptonic B -decays. One is the QCD correction and the other the hadronization effect. In the SM, the QCD corrections have been computed for massless leptons [10] and have been recently estimated [11] in the context of the 2-Higgs doublet model. The $\mathcal{O}(\alpha_S)$ correction reduces the SM prediction by $\sim 10\%$. In our case, given the smallness of λ'_{123} , the QCD corrections to the new graphs are unlikely to make a significant impact on our estimate. One also notes that the b -quark hadronizes much before it decays weakly. However, in a heavy quark system the spectator model works in a very reasonable way, which is evident from the consistency between the lifetime measurements of various B -hadrons [12]. At LEP, the b -quarks are energetic (45 GeV). But the distributions in the b -quark rest frame shown in our analysis can be readily compared with the observations made in the laboratory. The high-resolution silicon microvertex detector makes it possible to locate the primary decay vertex of the B -hadron from the direction of the c -quark jet and the charged lepton. Once the decay vertex is obtained, the flight direction of the b -quark is known and since its energy is fixed, the relevant boost factors relating the b -quark rest frame and the laboratory frame can be calculated.

At this stage we argue in favour of two essential hypotheses that we advocated in the beginning. We assumed that (i) the photino lifetime is not more than 1 s, meaning $\Gamma_{\tilde{\gamma}} \geq 10^{-22}$ MeV and (ii) the photino is invisible, *i.e.* it does not decay within a few metres, implying $\Gamma_{\tilde{\gamma}} \leq 10^{-13}$ MeV in its rest frame⁶. Now with λ'_{123} as the only R -parity breaking coupling, there are essentially two obvious decay modes of the photino. In the first case, the decay of the photino would go via the flavour-violating photino-quark-squark coupling⁷, where at one vertex the $\tilde{\gamma}$ decays to an s -antiquark and a virtual b -squark while the latter at the other vertex decays preferentially to an s -quark and

⁶To anticipate the latter number, assume, as an example, that a $\tilde{\gamma}$ is produced at rest in the b rest frame and consider a b -quark of mass 5 GeV in a 45 GeV jet at LEP. Now, counting a boost factor of 9, the $\tilde{\gamma}$ must have a life-time of 10^{-9} s in its rest frame, *i.e.* a width of 6.6×10^{-13} MeV, to travel at least ~ 3 m in the lab frame to escape detection.

⁷It arises from the mismatch between the squark and quark mass-matrices and is strongly restricted by flavour-changing neutral current constraints.

a ν *via* λ'_{123} . We define the flavour-violating parameter ‘ c ’ by scaling ‘ e ’ to ‘ ce ’ in the photino-quark-squark vertex. Then, for a photino of mass 2 (3) GeV, assuming $m_{\tilde{b}_R} = 100$ GeV, $\kappa = 1$ and reading the corresponding λ'_{123} values from Fig. 1, we estimate $\Gamma_{\tilde{\gamma}} \simeq 3c^2 \times 10^{-13}$ ($1.3c^2 \times 10^{-10}$) MeV. Suffice it to choose, therefore, $c \leq 0.03$ to enable the photino to fly safely out of the detector⁸. Indeed, the above estimates are somewhat crude and might be modified by hadronization effects, but are sufficient to demonstrate that a $\tilde{\gamma}$ can very well act as an invisible particle even in a R -parity-violating atmosphere. The other decay channel of the $\tilde{\gamma}$ is characterized by its splitting to a virtual b -quark and a virtual b -squark and their subsequent decays (the latter *via* λ'_{123}). These two different types of decays proceed with roughly similar strength. We note that with the above choice of ‘ c ’, the radiative decay of the photino ($\tilde{\gamma} \rightarrow \gamma\nu_e$ penguin) is well under control. We have also checked that the parameters can be adjusted reasonably well to ensure the other limit, *i.e.* $\Gamma_{\tilde{\gamma}} \geq 10^{-22}$ MeV.

Since in our scenario the LSP is stable inside a realistic detector even though R -parity is violated, the canonical LSP search strategy should, in principle, apply to our case as well. For example, the L3 Collaboration at LEP in a recent analysis [13] have excluded an LSP weighing below 18 GeV. However, this bound evaporates if $\tan\beta < 2$; moreover, the above analysis relies on the GUT-relation between the gaugino masses. The OPAL Collaboration at LEP [14] have looked for massive photinos decaying very fast within the detector *via* a λ_{123} -type coupling and excluded $m_{\tilde{\gamma}} = 4\text{--}43$ GeV for $m_{\tilde{e}_L} < 42$ GeV, and $m_{\tilde{\gamma}} = 7\text{--}30$ GeV for $m_{\tilde{e}_L} < 100$ GeV (95% C.L.). For such a fast decaying photino, they could not look for the window ($m_{\tilde{\gamma}} < 4$ GeV), since the $\tilde{\gamma}$ -pairs cannot be separated from the τ -pairs. The ALEPH Collaboration at LEP [15], dealing with a more general λ -type coupling and considering a general LSP rather than a pure photino, have improved the above exclusion zone and have also reported their negative results on other supersymmetric particles up to their kinematic limit ($< m_Z/2$). Our proposed mode of searching for a photino lighter than 4 GeV with a λ'_{123} -type coupling, therefore, covers a complementary zone in the supersymmetric parameter space. We point out though that our analysis relies on a simple assumption that the LSP is dominantly a photino.

We now comment how our analysis could be extended for a few other λ' -type couplings as well. Considering the fact that a μ in the final state in a semileptonic B -decay constitutes as viable a mode for detection as an e in the final state, taking care of the slight modification in the kinematics due to the μ -mass, our analysis could be carried out also for λ'_{223} , whose existing bound is 0.16 (D -decay, 2σ) [16]. λ'_{323} should be handled somewhat differently for phase-space consideration and also because the τ decaying within the detector would change the signal profile. Consideration of λ'_{113} in our analysis boils down to a replacement of a c -quark jet with a u -quark jet (the latter cannot be distinguished from a general hadronic activity): V_{ub} being much smaller than V_{cb} pro-

⁸ It should be remembered that in a detector, CLEO for example, where the B ’s are produced almost at rest, the boost factor of 9 counted for LEP is absent. Hence, the constraint on c should actually be a factor of ~ 3 stronger than quoted in the text.

vides less SM background than the situation involving λ'_{123} . Similarly, λ'_{213} could also be utilised for a μ in the final state. The existing limits [8] on λ'_{113} and λ'_{213} are 0.03 (charged-current universality, 2σ) and 0.09 (π -decay, 1σ) respectively. In a very recent analysis [17], $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ has been used to place stringent constraints on all of λ'_{123} , λ'_{223} , λ'_{113} and λ'_{213} . The bound on each of them is $0.012(m_{\tilde{d}_{Rk}}/100 \text{ GeV})$ at 90% C.L. As emphasized earlier, the crucial feature of our analysis lies in the kinematic properties. Moreover, each of the \tilde{e}_L -exchanged and \tilde{b}_R -exchanged processes of our analysis contributes with roughly the same magnitude, so that making \tilde{b}_R heavy – thereby evading the K^+ -decay bound – while keeping $\tilde{e}_L \sim 100 \text{ GeV}$, we have checked does not change our results much.

Finally, we comment that the ‘semileptonic anomaly’, namely the long-standing *irritation* that the SM prediction of the semileptonic branching ratio lies somewhat above what has experimentally been observed, still exists of course amidst various theoretical as well as experimental uncertainties. We admit that the picture considered above instead of curing the anomaly worsens it further, since the new process adds incoherently to the SM graph. Nevertheless, we keep ourselves strictly consistent by admitting only that much λ'_{123} which does not let the prediction of the inclusive branching ratio exceed its 90% C.L. observation.

The kind of scenario that we have dealt with in this paper, arguably lies in a corner of the vast supersymmetric parameter space, yet has the virtue of manifesting itself through a simple study of the kinematic configurations of the semileptonic decay products. It cannot be denied that R -parity violation and the simultaneous presence of a light photino might appear as a somewhat contrived scenario, although we have tried to motivate the former from the latter. But this could very well turn out to be a reality and one must ensure that it does not slip through the canonical supersymmetry search biased by a thick layer of theoretical prejudice of R -parity conservation and Grand Unification. Interestingly, the scenario, as we have demonstrated in this work, is very much within the B -physics reach at LEP or at CLEO. A thorough study incorporating the hadronization effect and implementing the full detector simulation appropriate to these colliders is, therefore, called for.

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References

- [1] Particle Data Group, *Phys. Rev.* **D40** (1994) 1173.
- [2] C. Hearty *et al.*, *Phys. Rev.* **D39** (1989) 3207.
- [3] C.S. Aulakh and R.N. Mohapatra, *Phys. Lett.* **B119** (1982) 136; F. Zwirner, *Phys. Lett.* **B132** (1983) 103; J. Ellis *et al.*, *Phys. Lett.* **B150** (1985) 142; G.G. Ross and J.W.F. Valle, *Phys. Lett.* **B151** (1985) 375; S. Dawson, *Nucl. Phys.* **B261** (1985) 297; S. Dimopoulos and L. Hall, *Phys. Lett.* **B207** (1987) 210; L. J. Hall and M. Suzuki, *Nucl. Phys.* **B231** (1984) 419; V. Barger, G.F. Giudice and T. Han, *Phys. Rev.* **D40** (1989) 2987; M. Nowakowski and A. Pilaftsis, Rutherford preprint RAL-TR-95-035, hep-ph/9508271; K.S. Babu and R.N. Mohapatra, *Phys. Rev. Lett.* **75** (1995) 2276; Light photino with \cancel{R} to resolve the KARMEN anomaly has been discussed recently by D. Choudhury and S. Sarkar, preprint CERN-TH/95-299, hep-ph/9511357.
- [4] The CLEO Collaboration, S. Henderson *et al.*, *Phys. Rev.* **D44** (1992) 2212; The ALEPH Collaboration, D. Buskulic *et al.*, *Z. Phys.* **C62** (1994) 179.
- [5] A. Bouquet and P. Salati, *Nucl. Phys.* **B284** (1987) 557; A.E. Nelson and S.M. Barr, *Phys. Lett.* **B246** (1990) 141; B.A. Campbell, S. Davidson, J. Ellis and K. Olive, *Phys. Lett.* **B256** (1991) 457; W. Fischler, G. Giudice, R.G. Leigh and S. Paban, *Phys. Lett.* **B258** (1991) 45.
- [6] H. Dreiner and G.G. Ross, *Nucl. Phys.* **B410** (1993) 188.
- [7] H. Haber and G. Kane, *Phys. Rep.* **117** (1985) 75, see p. 208 and 223.
- [8] Barger, Giudice and Han in [3].
- [9] C.S. Kim and A.D. Martin, *Phys. Lett.* **B225** (1989) 186.
- [10] A.F. Falk, Z. Ligeti, M. Neubert and Y. Nir, *Phys. Lett.* **B326** (1994) 145.
- [11] Y. Grossman, H. Haber and Y. Nir, *Phys. Lett.* **B357** (1995) 630.
- [12] See R.J. Morrison and J.D. Richman, in [1], p. 1602.
- [13] The L3 Collaboration, M. Acciarri *et al.*, *Phys. Lett.* **B350** (1995) 109.
- [14] The OPAL Collaboration, P.D. Acton *et al.*, *Phys. Lett.* **B313** (1993) 333.
- [15] The ALEPH Collaboration, D. Buskulic *et al.*, preprint CERN PPE/95-15, February 1995.
- [16] G. Bhattacharyya and D. Choudhury, *Mod. Phys. Lett.* **A10** (1995) 1699.
- [17] K. Agashe and M. Graesser, Berkeley preprint LBL-37823, hep-ph/9510439.

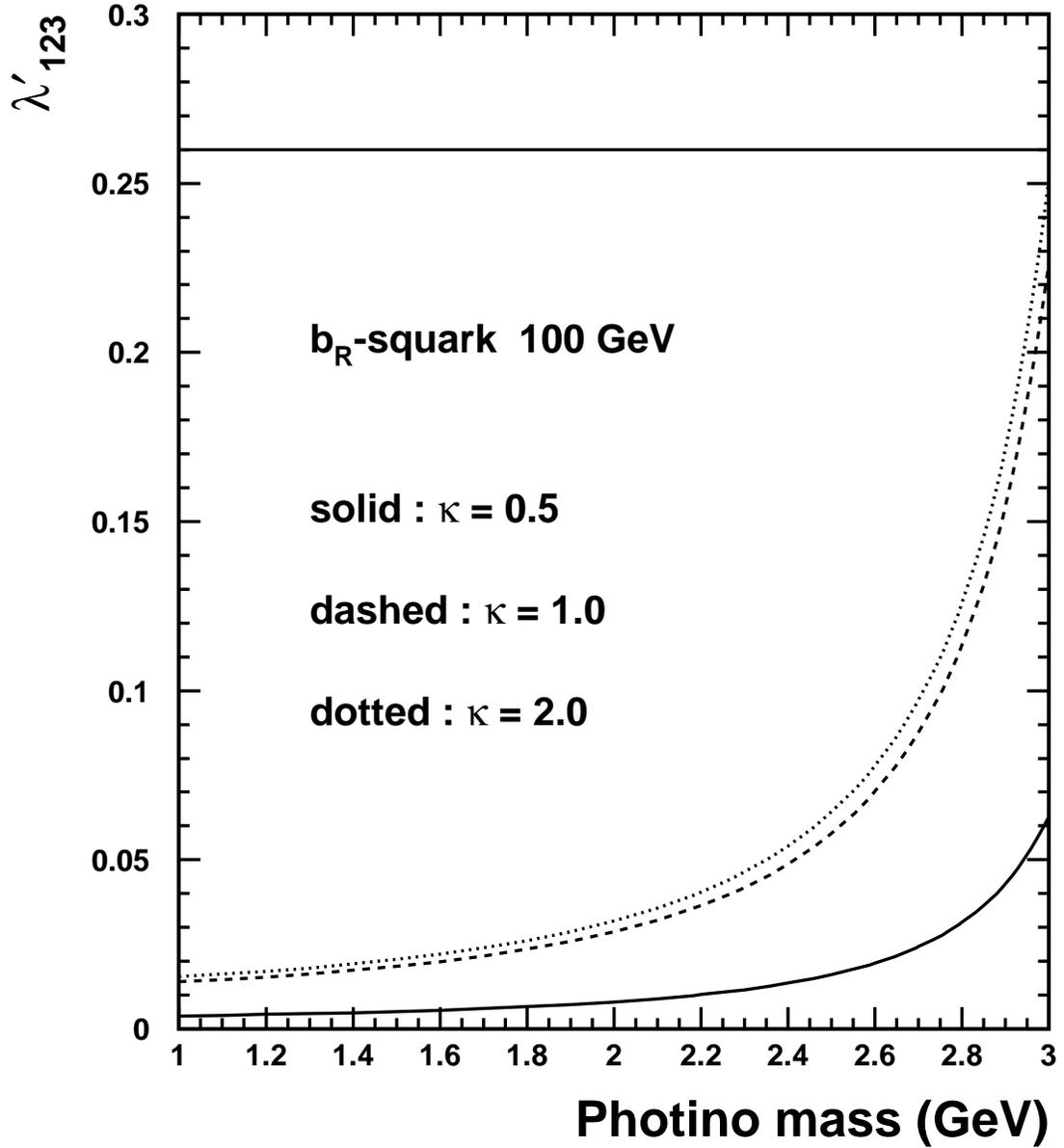


Figure 1: The 90% upper limit on λ'_{123} as a function of the photino mass for various combinations of scalar masses. For fixed $m_{\tilde{b}_R} = 100$ GeV, $\kappa = 0.5, 1, 2$ correspond to $m_{\tilde{e}_L} = 50, 100, 200$ GeV, respectively. The horizontal line is the 1σ bound derived in ref. [8] from forward-backward asymmetry of e^+e^- collisions at low energy.

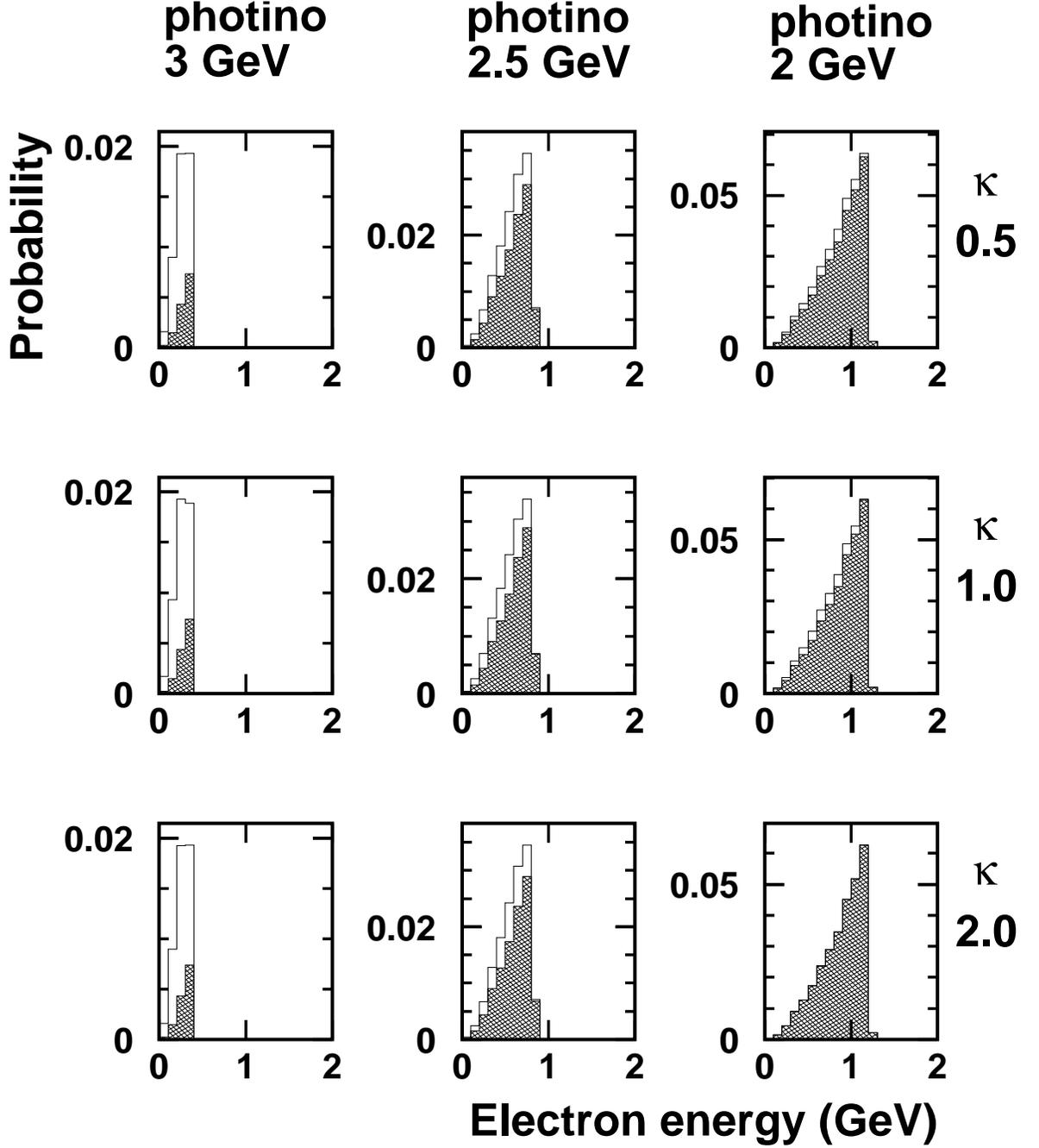


Figure 2: The electron-energy distribution in nine different cases. Those SM events which are within the kinematic boundary of the R -parity-violating mode are shown by the shaded area. In a given column these figures correspond to various choices of κ (as in Fig. 1) for a fixed $m_{\tilde{\gamma}}$, while in a given row they correspond to different values of $m_{\tilde{\gamma}}$ for a fixed κ .

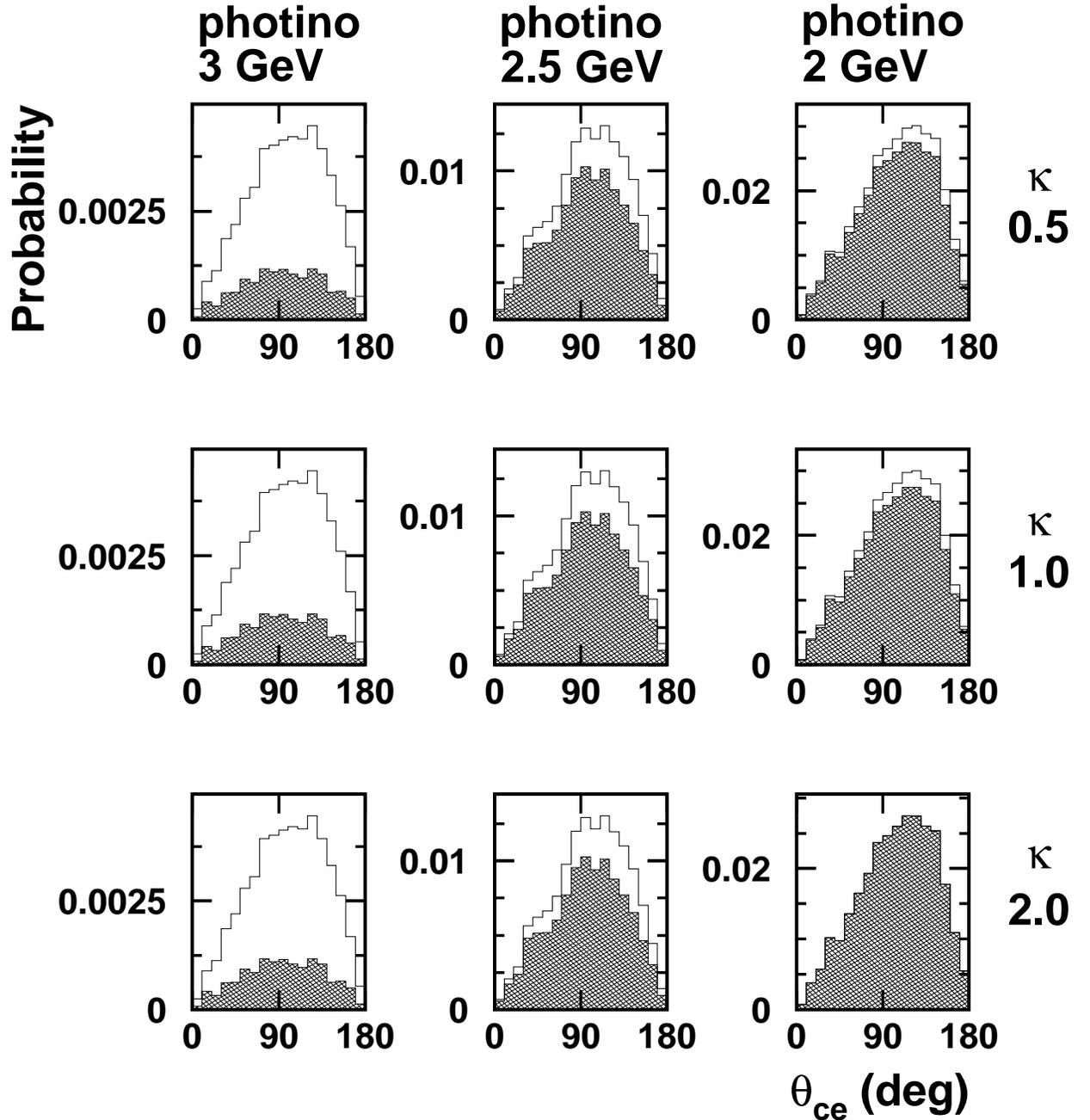


Figure 3: The charm quark–electron angle distribution in nine different cases. As in Fig. 2, SM events corresponding to electron energies within the allowed kinematic boundary of the R -parity-violating mode are shown by the shaded area. In a given column these figures correspond to various choices of κ (as in Fig. 1) for a fixed $m_{\tilde{\gamma}}$, while in a given row they correspond to different values of $m_{\tilde{\gamma}}$ for a fixed κ .