Supersymmetry – THIS IS PART 3 OF 4

To reduce the size of this section's PostScript file, we have divided it into three PostScript files. We present the following index:

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R-parity violation can lead to new production processes, such as s-channel sneutrino production, which also are being investigated [17].

Visible signals from the lightest neutralino are also realized in special cases of GMSB which predict $\widetilde{\chi}_1^0 \rightarrow \gamma\,\widetilde{g}_{3/2}$ with a lifetime short enough for the decay to occur inside the detector. The most promising topology consists of two energetic photons and missing energy resulting from $e^+e^- \rightarrow \widetilde{\chi}_1^0\widetilde{\chi}_1^0$. (In the canonical scenario, such events also would appear for $e^+e^- \rightarrow \widetilde{\chi}_2^0\widetilde{\chi}_2^0$ followed by $\widetilde{\chi}_2^0 \rightarrow \gamma\widetilde{\chi}_1^0$ which can be expected in certain regions of parameter space.) The LEP experiments have observed no excess over the expected number of background events [18], leading to a bound on the neutralino mass of about 70 GeV/c^2. As an example, the L3 upper limit on the number of signal events is plotted as a function of neutralino mass in Fig. 7. When the results are combined [13], the limit is $M_{\widetilde{\chi}_1^0} > 75$ GeV/c^2. Single-photon production has been used to constrain the process $e^+e^- \rightarrow \widetilde{g}_{3/2}\widetilde{\chi}_1^0$.

At the time of this writing, LEP was colliding beams at $\sqrt{s} = 183$ GeV. No signals for supersymmetry were reported in conferences; rather, preliminary limits $M_{\widetilde{\chi}^\pm} \gtrsim 91$ GeV/c^2 were shown [19]. In coming years the center of mass energy will be increased in steps up to a maximum of 200 GeV.

II.5. Supersymmetry searches at proton machines: Although the LEP experiments can investigate a wide range of scenarios and cover obscure corners of parameter space, they cannot match the mass reach of the Tevatron experiments (CDF and DØ). Each experiment has logged approximately 110 pb^{-1} of data at $\sqrt{s} = 1.8$ TeV—ten times the energy of

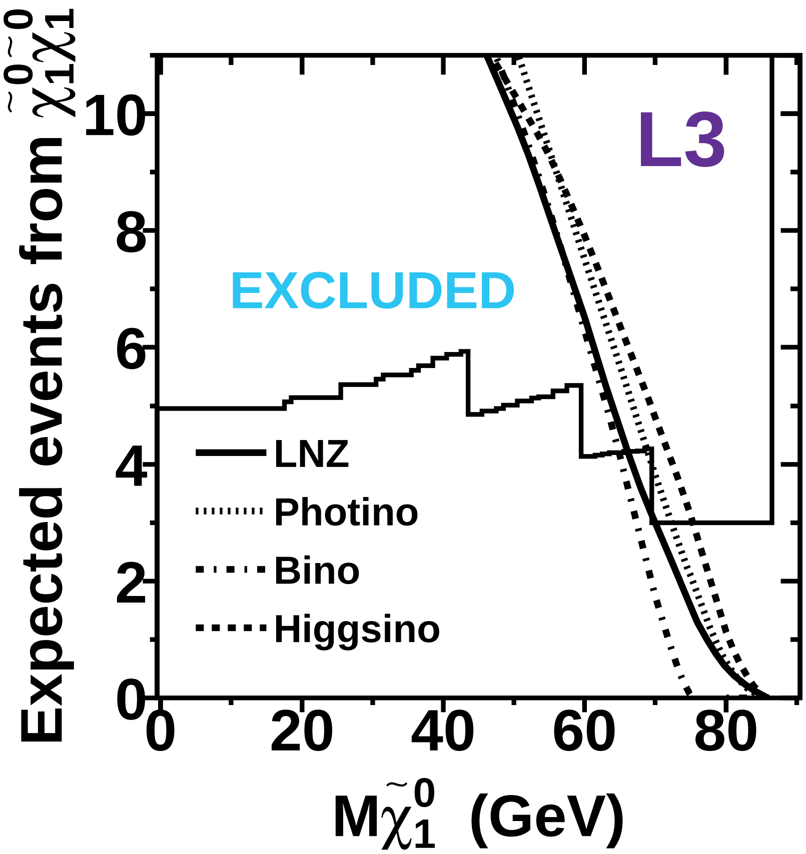

Figure 7: Upper limit on the number of acoplanar photon events as a function of the neutralino mass, from the L3 Collaboration [18]. The theoretical cross section depends on the field content of the neutralino, shown here for pure photinos, binos, and Higgsinos. 'LNZ' refers to a particular model [4].

LEP 2. Although the full energy is never available for annihilation, the cross sections for supersymmetric particle production are large due to color factors and the strong coupling.

The main source of signals for supersymmetry are squarks (scalar partners of quarks) and gluinos (fermionic partners of gluons), in contradistinction to LEP. Pairs of squarks or gluinos are produced in s, t and u-channel processes, which decay directly or via cascades to at least two LSP's. The key distinction in the experimental signature is whether the gluino is heavier or lighter than the squarks, with the latter occurring naturally in mSUGRA models. The u, d, s, c, and b squarks are assumed to have similar masses; the search results are reported in terms of their average mass $M_{\widetilde{q}}$ and the gluino mass $M_{\widetilde{g}}$.

The classic searches [20] rely on large missing transverse energy $\not\!\!E_T$ caused by the escaping neutralinos. Jets with high transverse energy are also required as evidence of a hard interaction; care is taken to distinguish genuine $\not\!\!E_T$ from fluctuations in the jet energy measurement. Backgrounds from W, Z and top production are reduced by rejecting events with identified leptons. Uncertainties in the rates of these processes are minimized by normalizing related samples, such as events with two jets and one or more leptons. The tails of more ordinary hard-scattering processes accompanied by multiple gluon emission are estimated directly from the data.

The bounds are displayed in the $(M_{\widetilde{g}}, M_{\widetilde{q}})$ plane and have steadily improved with the integrated luminosity. The latest result from the CDF Collaboration is shown in Fig. 8, which also shows a recent result from DØ. If the squarks are heavier than the gluino, then $M_{\widetilde{g}} \gtrsim 180$ GeV/c^2. If they all have the same mass, then that mass is at least 260 GeV/c^2, according to the DØ analysis. If the squarks are much lighter than the gluin (in which case they decay via $\widetilde{q} \to q\widetilde{\chi}_1^0$), the bounds from UA1 and UA2 [21] play a role giving $M_{\widetilde{g}} \gtrsim 300$ GeV/c^2. All of these bounds assume there is no gluino lighter than 5 GeV/c^2.

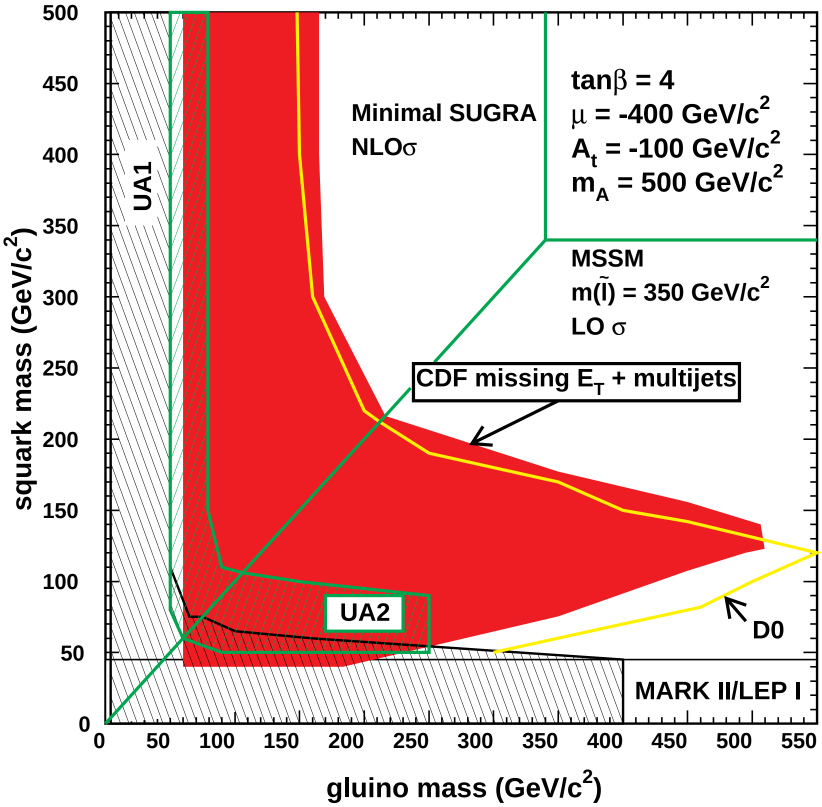

Figure 8: Excluded ranges of squark and gluino masses, derived from the jets+ $\not{E}_T$ analysis of the CDF Collaboration [20]. Also shown are recent results from DØ, and much older limits from the CERN proton experiments UA1 and UA2.

Since these results are expressed in terms of the physical masses relevant to the production process and experimental signature, the excluded region depends primarily on the assumption of nearly equal squark masses with only a small dependence on other parameters such as μ and $\tan\beta$. Direct constraints on the theoretical parameters m_0 and $m_{1/2} \approx 0.34\, M_3$, shown in Fig. 9, have been obtained by the DØ Collaboration assuming the mass relations of the mSUGRA model. In particular, m_0 is keyed to the squark mass and $m_{1/2}$ to the gluino mass, while for the LEP results these parameters usually relate to slepton and chargino masses.

Charginos and neutralinos may be produced directly by annihilation ($q\overline{q} \rightarrow \widetilde{\chi}_i^{\pm}\widetilde{\chi}_j^0$) or in the decays of heavier squarks ($\widetilde{q} \rightarrow q'\widetilde{\chi}_i^{\pm}, q\widetilde{\chi}_j^0$). They decay to energetic leptons (for example, $\widetilde{\chi}^{\pm} \rightarrow \ell\nu\widetilde{\chi}_1^0$ and $\widetilde{\chi}_2^0 \rightarrow \ell^+\ell^-\widetilde{\chi}_1^0$) and the branching ratio can be high for some parameter choices. The presence of energetic leptons has been exploited in two ways: the 'trilepton' signature and the 'dilepton' signature.

The search for trileptons is most effective for the associated production of $\widetilde{\chi}_1^{\pm}\widetilde{\chi}_2^0$ [22]. The requirement of three energetic leptons reduces backgrounds to a very small level, but is efficient for the signal only in special cases. The results reported to date are not competitive with the LEP bounds.

The dilepton signal is geared more for the production of charginos in gluino and squark cascades [23]. Jets are required as expected from the rest of the decay chain; the leptons should be well separated from the jets in order to avoid backgrounds from heavy quark decays. Drell-Yan events are rejected with simple cuts on the relative azimuthal angles of the leptons and their transverse momentum. In some analyses the Majorana nature of the gluino is exploited by requiring two leptons with

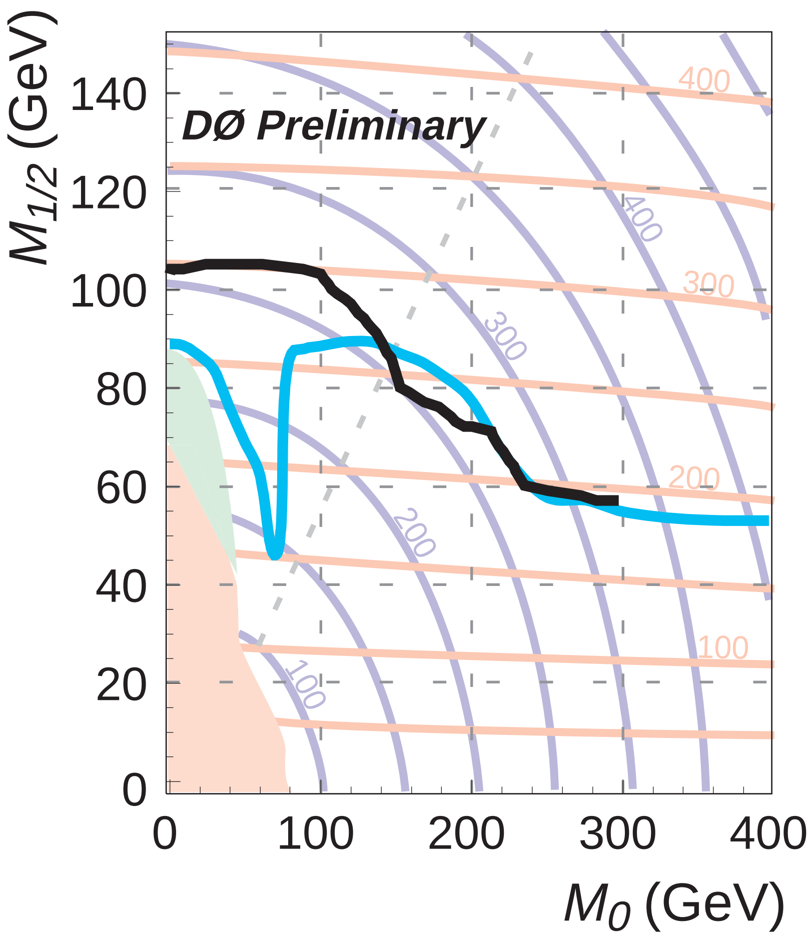

Figure 9: Bounds in the $(m_0, m_{1/2})$ plane obtained by the DØ Collaboration from their searches for squarks and gluinos [20]. The dark solid line shows the result from the jets+ $\not\!\!E_T$ selection, and the grey solid line shows the result from the dielectron selection. The radial contours give the squark mass in this plane, and the nearly horizontal lines give the gluino mass. Parameter values in the shaded region lead to unphysical conditions.

the same charge, thereby greatly reducing the background. In this scenario limits on squarks and gluinos are almost as stringent as in the classic jets+ $\not\!\!E_T$ case.

It should be noted that the dilepton search complements the multijet+ $\not\!\!E_T$ search in that the acceptance for the latter is reduced when charginos and neutralinos are produced in the decay cascades—exactly the situation in which the dilepton signature is most effective.

A loophole in the squark-gluino bounds has recently been addressed using dijet mass distributions [24]. If gluinos are lighter than about 5 GeV/c^2, $\not\!\!E_T$ is very small and the classic jets+ $\not\!\!E_T$ searches are no longer effective. Resonant production of squarks would have a large cross section, however, and if the squarks are not very heavy, broad peaks in the dijet mass distributions are expected. Comparison of the observed spectrum with theoretical estimates rules out light gluinos if squarks are lighter than about 600 GeV/c^2.

The top squark is different from the other squarks because its SM partner is so massive: large off-diagonal terms in the squared-mass matrix lead to large mixing effects and a possible light mass eigenstate, $M_{\widetilde{t}_1} \ll M_{\widetilde{q}}$. Analyses designed to find light stops have been performed by DØ [25]. The first of these was based on the jets+ $\not\!\!E_T$ signature expected when the the stop is lighter than the chargino. A powerful limit $M_{\widetilde{t}} \gtrsim 90$ GeV/c^2 was obtained, provided the neutralino was at least 30 GeV/c^2 lighter than the stop as depicted in Fig. 3. (These searches are sensitive to the $c\widetilde{\chi}_1^0$ channel which does not apply below the dotted line.) More recently a search for the pair-production of light stops decaying to $b\widetilde{\chi}_1^{\pm}$ was performed. The presence of two energetic electrons was required; backgrounds from W's were greatly reduced. Regrettably this experimental bound does not yet improve existing bounds on stop masses.

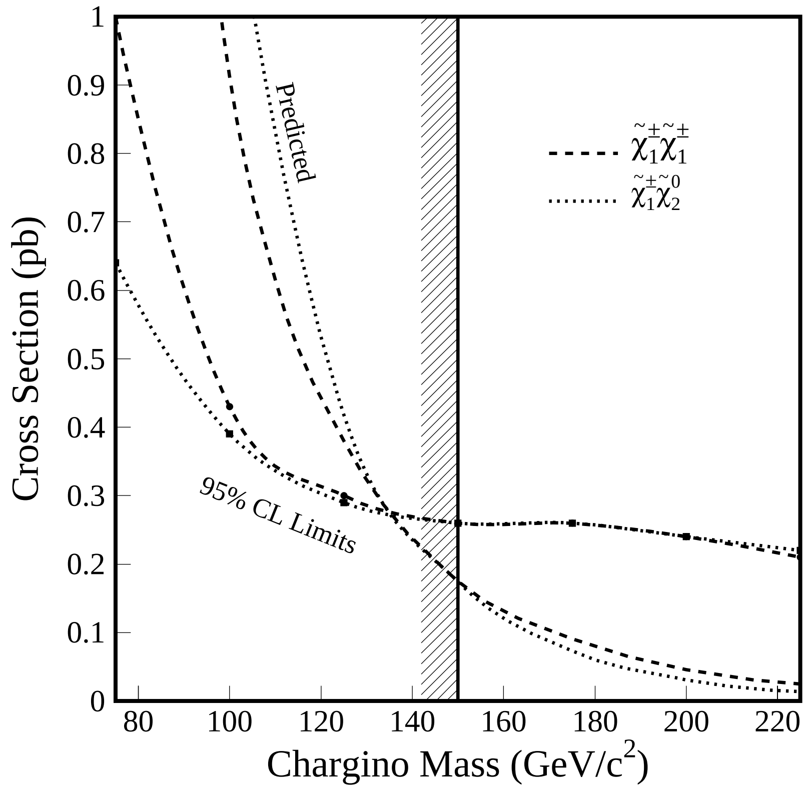

Figure 10: Comparison of the DØ upper limits on chargino and neutralino cross sections with theory in a GMSB scenario, plotted as a function of the chargino mass [28]. The vertical line shows the result obtained from the combined chargino and neutralino exclusions. It corresponds to $M_{\widetilde{\chi}_1^0} \gtrsim 75$ GeV/c^2.

An anomalous event observed by the CDF Collaboration [26] sparked much theoretical speculation [27]. It contains two energetic electrons, two energetic photons, large $\not\!\!E_T$, and

Table 1: Lower limits on supersymmetric particle masses. 'GMSB' refers to models with gauge-mediated supersymmetry breaking, and 'RPV' refers to models allowing R-parity violation.

particle		Condition	Lower limit (GeV/c^2)	Source
$\widetilde{\chi}_1^{\pm}$	gaugino	$M_{\widetilde{\nu}} > 200\ \mathrm{GeV}/c^2$	86	LEP 2
		$M_{\widetilde{\nu}} > M_{\widetilde{\chi}^{\pm}}$	67	LEP 2
		any $M_{\widetilde{\nu}}$	45	Z width
	Higgsino	$M_2 < 1\ \mathrm{TeV}/c^2$	79	LEP 2
	GMSB		150	DØ isolated photons
	RPV	$LL\overline{E}$ worst case	73	LEP 2
		$LQ\overline{D}$ $m_0 > 500\ \mathrm{GeV}/c^2$	83	LEP 2
$\widetilde{\chi}_1^0$	indirect	any $\tan\beta$, $M_{\widetilde{\nu}} > 200\ \mathrm{GeV}/c^2$	25	LEP 2
		any $\tan\beta$, any m_0	14	LEP 2
	GMSB		75	DØ and LEP 2
	RPV	$LL\overline{E}$ worst case	23	LEP 2
$\widetilde{e}_R$	$e\widetilde{\chi}_1^0$	$\Delta M > 10\ \mathrm{GeV}/c^2$	75	LEP 2 combined
$\widetilde{\mu}_R$	$\mu\widetilde{\chi}_1^0$	$\Delta M > 10\ \mathrm{GeV}/c^2$	75	LEP 2 combined
$\widetilde{\tau}_R$	$\tau\widetilde{\chi}_1^0$	$M_{\widetilde{\chi}_1^0} < 20\ \mathrm{GeV}/c^2$	53	LEP 2
$\widetilde{\nu}$			43	Z width
$\widetilde{\mu}_R$, $\widetilde{\tau}_R$		stable	76	LEP 2 combined
$\widetilde{t}_1$	$c\widetilde{\chi}_1^0$	any θ_{mix}, $\Delta M > 10\ \mathrm{GeV}/c^2$	70	LEP 2 combined
		any θ_{mix}, $M_{\widetilde{\chi}_1^0} < \frac{1}{2}M_{\widetilde{t}}$	86	DØ
	$b\ell\widetilde{\nu}$	any θ_{mix}, $\Delta M > 7\ \mathrm{GeV}/c^2$	64	LEP 2 combined
$\widetilde{g}$	any $M_{\widetilde{q}}$		190	DØ jets+$\not{E}_T$
			180	CDF dileptons
$\widetilde{q}$	$M_{\widetilde{q}} = M_{\widetilde{g}}$		260	DØ jets+$\not{E}_T$
			230	CDF dileptons

little else. Since it is difficult to explain this event with SM processes, theorists have turned to SUSY. While some models are based on canonical MSSM scenarios (without gaugino mass unification), others are based on GMSB models with selectron production followed by $\widetilde{e} \to e\widetilde{\chi}_1^0$ and $\widetilde{\chi}_1^0 \to \gamma\,\widetilde{g}_{3/2}$. These models predict large inclusive signals for $p\overline{p} \to \gamma\gamma + X$ given kinematic constraints derived from the properties of the CDF event. The Tevatron experiments have looked for such events, and have found none [28], aside from the one anomalous event. These results have been translated into the bound $M_{\widetilde{\chi}_1^0} > 75$ GeV/c^2, as shown in Fig. 10 from the DØ Collaboration. This bound is as good as that derived from the combination of the four LEP experiments.

II.6. Supersymmetry searches at HERA and fixed-target experiments: The electron-proton collider (HERA) at DESY runs at $\sqrt{s} = 310$ GeV and, due to its unique beam types, can be used to probe certain channels more effectively than LEP or the Tevatron.

The first of these is associated selectron-squark production [29] through t-channel neutralino exchange. Assuming the conservation of R-parity, the signal consists of an energetic isolated electron, a jet, and missing transverse momentum. No signal was observed in 20 pb^{-1} of data and limits were placed on the sum $\frac{1}{2}(M_{\widetilde{e}} + M_{\widetilde{q}})$. They are weaker than the latest ones from LEP.

A more interesting opportunity comes in SUSY models with R-parity violation, in particular, with a dominant $LQ\overline{D}$ interaction [30]. Squarks would be produced directly in the s-channel, decaying either directly to a lepton and a quark via R-parity violation or to a pair of fermions and a chargino or neutralino, with the latter possibly decaying via R-parity violation. Less than 3 pb^{-1} were used to look for a squark resonance above SM backgrounds. All possible topologies were considered, so model-independent bounds on the R-parity–violating parameter λ'_{111} could be derived as a function of the squark mass. The special case of a light $\widetilde{t}_1$ was also considered, and limits derived on λ'_{131} as a function of $M_{\widetilde{t}}$. These were improved by considering also the pair-production of stops via photon-gluon fusion (see the Listings for more information).

Limits from SUSY searches in fixed-target or beam-dump experiments were surpassed long ago by the colliders. An important exception is the search for the light gluino, materializing as a long-lived supersymmetric hadron called the R^0 [6]. These could be produced in fixed-target experiments with hadron beams and observed via their decay in flight to a low mass hadronic state: $R^0 \to \pi^+\pi^-\widetilde{\chi}^0_1$ or $\eta\widetilde{\chi}^0_1$. The KTeV Collaboration at Fermilab have searched for R^0's in their neutral-kaon data and found no evidence for this particle in the $\pi^+\pi^-\widetilde{\chi}^0_1$ channel, deriving strong limits on its mass and lifetime [31], as shown in Fig. 11. A complementary search for supersymmetric baryons was performed by the E761 Collaboration with a charged hyperon beam [32].

II.7. Conclusions: A huge variety of searches for supersymmetry have been carried out at LEP, the Tevatron, and HERA. Despite all the effort, no signal has been found, forcing the experimenters to derive limits. We have tried to summarize the interesting cases in Table 1. At the present time there is little room for SUSY particles lighter than M_W. The LEP collaborations will analyze more data taken at higher energies, and the Tevatron collaborations will begin a high luminosity run in a couple of years. If still no sign of supersymmetry appears, definitive tests will be made at the LHC.

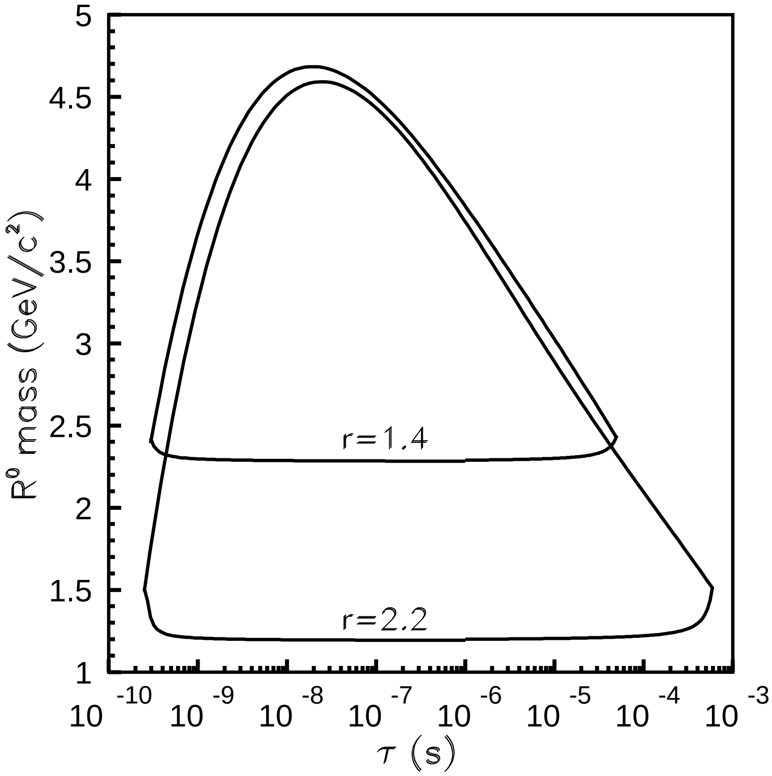

Figure 11: Ranges of R^0 mass and lifetime excluded at 90% CL by the KTeV Collaboration [31]. The ratio of the R^0 to the $\widetilde{\chi}_1^0$ mass is r.

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