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A SEARCH FOR PARTICLES WITH MAGNETIC CHARGE PRODUCED IN e^+e^- ANNIHILATIONS AT $\sqrt{s}$ = 35 GeV

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Abstract

By seeking to identify magnetically charged particles by their trajectories in a magnetic field, we set limits on the production of monopoles and dyons, via the process $e^+e^- \to \gamma^* \to M\overline{M}$, of masses up to 17 GeV and of magnetic charges between 10e and 70e.

1 Introduction

It has long been postulated[1,2] that the existence of monopoles would be sufficient to explain the quantisation of electric charge, and to symmetrise Maxwell's equations. Recently, the rôle of monopoles in Grand Unified Theories[3] and some possible indications of their discovery[4,5] have renewed theoretical and experimental interest in this particle. The quantisation of charge is postulated to follow from the requirement of quantum mechanics that the electric charge e and the magnetic charge g be related by $eg = \frac{1}{2}n\hbar c$, where n is an integer. A monopole of $g = \frac{137}{2}e$ is known as a Dirac monopole. The mass of the monopole is unknown, and while popular theories concentrate on masses of around 10^{15} GeV, other theories[6] have suggested lower masses and there is no known reason why they should not exist in the range accessible to present accelerators. The magnitude of the magnetic charge is also unknown. It might even possess intrinsic electric charge, q (in a particle known as a dyon). A monopole is usually assigned the magnetic charge of an integer multiple of the Dirac charge, $\frac{137}{2}e$ (or of $3 \times \frac{137}{2}e$ if the fundamental charge is taken to be that of quarks of charge $\frac{1}{3}$) but given the theoretical uncertainties and importance of this particle it is prudent for experimenters to cover as wide a range of charge g - including fractional Dirac charges - as possible.

Searches based on accelerators have, of course, the limitation that the maximum accessible monopole mass is set by the beam energy. In several "direct" searches evidence for the passage of monopoles has been looked for by studying materials previously placed near the interaction point for the signs of heavily ionising tracks[7,8,9,10]. Alternatively, "indirect" searches have hoped to extract or otherwise detect monopoles after the exposure of some material which could have trapped them. These methods rely heavily on details of how a magnetically charged particle, M, interacts with matter.

A recently published paper[11] contains an elegant alternative to the "direct" method by considering the effect of the solenoidal field in an e^+e^- detector on the trajectory of monopoles. This is an interesting extension of the so-called Type II method of Amaldi et al.[7]. The solenoidal field would exert a force on the particle causing it to accelerate in the direction parallel to the solenoid's axis and thereby appear curved in the detector's $(s - z)$ view, where s is defined as the distance a track travels if projected onto the $r - \phi$ plane, the plane perpendicular to the beampipe and z is the direction of the positron beam. The discovery of magnetically charged particles by such a method is dependent on models of how the monopole interacts with matter only in so far that it relies on an ionisation trail, and that energy loss by ionisation does not prevent the monopole from reaching a triggering part of the detector. We have employed the method of [11] in an extended search for $M\overline{M}$ production in e^+e^- collisions at 35 GeV, using the TASSO detector at DESY.

Particles with zero magnetic charge, in the absence of multiple scattering, appear straight in the $s - z$ view: this fact is often used in track finders[12] where it is common to use a parameterisation of the form

$$z = z_0 + s \tan\lambda$$

λ being the dip angle of the track relative to the $r - \phi$ plane, and z_0 the intercept in z at the point of the track's distance of closest approach at the nominal beam axis. To account for the additional force it is sufficient to add a term in s^2 resulting in the parabolic

$$z = z_0 + s \tan\lambda + s^2 C$$

where C is related to the curvature in this view. There are several reasons why this parameterisation is not perfect. For example, the fact that the $M\overline{M}$ pair is relativistic, and energy losses (dE/dx), multiple scattering and radiative effects will modify this relationship, but it holds sufficiently well to be useful for wide ranges of the parameters important in this analysis.

Figure 1 shows a simulated event in the TASSO detector of the process $e^+e^- \to \gamma^* \to M\overline{M}$ together with the parabolic fit in the $s - z$ view. Note that for monopoles with no electric charge, as in this case, the tracks appear straight in $r - \phi$.

We have made several simple assumptions in this analysis. One concerns the binding energy a pair of such particles could have. Dirac[2] made one very tentative prediction (based on a relativistic hydrogen model) of 0.5 GeV for monopoles of one Dirac charge which would cause a negligible effect at TASSO's top energies if monopoles were light and a significant one if they were heavier than 15 GeV. Since we have no predictions for this quantity we will simply ignore the possibility. We have presupposed that the monopole will not decay nor otherwise produce jets. We assume that monopoles are produced back-to-back through the single photon mechanism. We have ignored the possibility of a dominant two photon production mechanism[13], for which the efficiencies in the TASSO detector would be much reduced. The spin of monopoles is also unknown but we have assumed an isotropic distribution.

The previous study[11] was undertaken by the CLEO collaboration working with e^+e^- data at beam energies of about 5.3 GeV. Their trigger requirement imposed an upper limit of approximately 10e on the magnetic charge of M which could be detected. The work presented here will extend the region covered to masses of M up to 17 GeV and to magnetic charges of up to approximately 70e.

2 Monopoles in the TASSO detector

The data analysed in this study were acquired with the TASSO detector[14] installed at one of the intersection regions of the e^+e^- collider PETRA. The tracking information was taken from the central drift chamber[15]. This chamber is cylindrical, contains 15 layers of sense wires at radii from 36.7 cm to 122.2 cm and sits in a 0.5 Tesla solenoidal field. Hits in the $r - \phi$ projection are found by measuring drift times to wires that are parallel to the beampipe. These hits are referred to as DC0° hits. The z readings used to find the tracks in $s - z$ are found by measuring drift times to the DCα wires, which are at angles ranging from 3.3° to 4.5° with respect to the beampipe. The 15 sense wire layers are made up of 9 layers of DC0° wires and 6 layers of DCα wires. During the 1986 runs, which were the only ones used in this analysis, approximately 15% of the fourth α layer was dead. Two additional wire chambers, situated between the beampipe and the drift chamber, provided no z information;

one, the Cylindrical Proportional Chamber (CPC), contributed to the trigger and the $r - \phi$ track finding.

This analysis also depends on the TASSO inner time-of-flight counters in two respects: with the CPC, they are part of the trigger for back-to-back events, and by measuring the time of flight (TOF) they reduce our background from cosmic ray events. These 48 counters are arrayed cylindrically around the drift chamber at a radius of 132 cm, that is, within the TASSO solenoid. They subtend 82% of 4π, have a 98% hit efficiency for minimum ionising particles and have an r.m.s. time resolution of 350 psecs. All other TASSO triggers were much less efficient for monopole-like events and have been ignored.

A track is found in $s - z$ by projecting the $r - \phi$ track onto the $s - z$ plane and then using the projected DCα hits that could be associated with the track in $r - \phi$ to find the best fitting linear or parabolic track.

Events which have triggered the detector will get written to the so-called PASS 1 tapes. Physically significant events such as multihadronic annihilations, Bhabhas, muon pairs, etc. would then proceed through the TASSO analysis chain with high efficiency, but in the standard analysis chain each track is fitted with a straight line in the $s - z$ view, and the cuts χ^2_{s-z}/n.d.f. < 25 and $|z_0| < 10$ cm are made. These cuts would reject monopole events within wide ranges of mass and charge which would otherwise be detectable in the TASSO detector. Consequently, we have analysed the events at the PASS 1 stage.

3 Data Reduction

In 1986 TASSO obtained 110 pb^{-1} of data, amounting to 40 million triggers written to 1650 PASS 1 tapes, with tracks fitted linearly in the $s - z$ view. Since this analysis requires us to refit tracks in $s - z$, we found ways to reduce the sample before doing so. For an event to be accepted for refitting we required :

1. There must be exactly 2 tracks with apparent momentum > 4.0 GeV/c and no other tracks greater than 0.3 GeV/c.
2. The two high momentum tracks must be back-to-back in $r - \phi$ to within 10°. (This allows for multiple scattering and initial and final state bremsstrahlung.)
3. The nearest point in $r - \phi$ of each track to the interaction must be less than 1 cm.
4. The $r - \phi$ fit must be good ($\chi^2_{r-\phi}$/n.d.f. < 3).
5. The difference in TOF for each track must be less than 5 nsec and both the TOF values must be between -3 and 25 nsec.
6. Both high momentum tracks should have either ≤ 4 DCα hits in $s - z$ or χ^2_{s-z}/n.d.f. > 1 (that is, be poorly reconstructed in $s - z$ with a linear fit.)

The first four cuts ensure that good two-prong events are found as seen in $r - \phi$, with the first cut removing nearly all of the $\gamma\gamma$ background. The fifth removes the great majority of cosmic ray events whilst the last cut removes most of the non-magnetic two prong events where tracks are well described by a linear $s - z$ fit.

These cuts reduced the data to 18,199 PASS 1 events which were reconstructed using the FELIX[16] trackfinder with the circle fit to $r - \phi$ unchanged but a modification in the $s - z$ fit to find parabolæ. TASSO's vertex detector, the VXD, was not used in this reconstruction. This fit included a constraint to the nominal event vertex to help overcome the effects of the long lever arm to the drift chamber.

An event was then accepted only if both high momentum tracks had at least five DCα hits (or four if the track passed through the dead region in the fourth α layer) and were back-to-back in $s - z$ to within 20°.

Note that this fit could also be applied to tracks straight in $s - z$: for Bhabhas, the parameter C was found to be a narrow Gaussian centred at zero. This is shown in figure 2. For comparison, we also show the C distribution for two representative sets of simulated monopoles.

4 Simulating the Monopoles

Simulated $M\overline{M}$ events possessing a wide range of values of various parameters were produced in order to establish their detection efficiencies in the TASSO data. $M\overline{M}$ events were generated isotropically and stepped through all parts of the TASSO detector out to the coil.

We generated monopoles and dyons at intervals in the plane defined by monopole mass and charge with masses up to the beam energy and magnetic charges between 0e and 90e. At each step, the monopole was allowed to undergo various processes: it could multiple scatter, radiate photons or suffer energy loss by dE/dx. The effects of the magnetic charge of the monopoles modify the standard equations for ionisation losses and multiple scattering by the factor

$$\left(\frac{g^2\beta^2 + q^2}{e^2}\right)$$

This follows from theoretical predictions[17,18,19] for the average values for these effects. For the dE/dx energy loss, there is no rigorous prediction for the width or shape of the distribution. Consequently, we implemented an energy loss mechanism in which the energy loss per unit length was equal to the theoretical average loss for the medium being traversed, but which was smeared by Gaussians of widths which were appreciable fractions of the average energy loss. By varying the width of the Gaussian distribution in energy loss we could gauge the sensitivity of our acceptance to this parameter. The effect of random noise hits was studied too.

Since we were relying on the non-standard fits to the $s - z$ projection of tracks in TASSO, we ensured that the distributions of fit residuals in all the drift chamber DCα layers in the

$s - z$ view of the Monte Carlo closely simulated the data. Since the resolution in the $s - z$ view relies heavily on the resolution of the fits to the $r - \phi$ view, the residuals from the fits in this projection were also tuned. Bhabha events and muon pairs from the 1986 data were used as the input for this tuning.

5 Results

From the curvature coefficients, C_i, of the parabolæ fitted to the two high momentum tracks, we define the quantities C_1, C_2 and ΔC where

$$|C_1| < |C_2| \quad \text{and} \quad \Delta C = |C_2| - |C_1|$$

Monopoles would inhabit a region of $|C_i|$ vs. ΔC space close to the $\Delta C = 0$ axis and with $|C_i| > 0$. The tail of the distribution of the magnetically neutral background determines how close to $|C_i| = 0$ one can accept - which in turn determines the experimental limits in mass and magnetic charge acceptance.

By projecting this space onto the $|C_1| - \Delta C$ axis, we produce a distribution which contains all the information necessary to distinguish magnetically neutral events from $M\overline{M}$ events over much of the mass - charge plane.

There are two sets of these distributions as C_1 and C_2 may take the same or opposite signs. $C_1C_2 < 0$ indicates oppositely signed curvatures as would be expected for $M\overline{M}$ events and the $C_1C_2 > 0$ distribution should exclude well-reconstructed $M\overline{M}$ events.

In figure 3a we have plotted $|C_1| - \Delta C$ for the 1986 data, for both $C_1C_2 < 0$ and $C_1C_2 > 0$. From this figure we can make the cut

$$|C_1| - \Delta C > 0.0011 \quad \text{for} \quad C_1C_2 < 0$$

and thereby define a region that would be unambiguously populated by $M\overline{M}$ events. We see that there is no indication of the presence of $M\overline{M}$ events in the $C_1C_2 < 0$ distribution. Figure 3b compares the curvature characteristics of the 1986 data with those of two monopole Monte Carlo datasets.

We find that this cut retains high efficiency over most of the experimentally accessible mass – charge plane. The losses occur at low monopole mass and low magnetic charge. In the case of the low mass monopoles, their high momenta lead to low curvatures. For the low charge monopoles the coupling to the field is too weak to cause much curvature. In both cases the tracks are relatively straight, and so merge into the non-magnetic background.

The cuts lead to efficiencies for detecting monopoles between masses of 0 and 18 GeV and magnetic charges between 0e and 75e, shown in figure 4.

We now consider various effects which might alter these calculated efficiencies by studying representative combinations of monopole mass and magnetic charge. In figure 5a, we consider

the effect of incoherent noise on the reconstruction efficiency. As might be expected, in a high noise environment the efficiency drops slightly, since noise hits result in track hit misassociation. For the 1986 runs there was an average of about 10 hits in the drift chamber not attributed to tracks in Bhabha events, with, on average, one of these being in an $s - z$ projection of one of the tracks.

The effect of δ-ray production was also investigated. If monopoles do produce energetic δ-rays prolifically this would decrease the track finding efficiency by causing hit confusion. In the absence of theoretical predictions for the δ-ray spectrum from monopoles, we have assumed their production mechanism is identical to the case of the passage of electrically charged particles, but their rate is increased by a factor of $g^2\beta^2/e^2$. Monte Carlo studies find negligible effect for 'heavy' monopoles of 15 GeV, where β is low. In the worse case, for $g = 70e$ (the limit of our detection) and masses of 5 – 10 GeV, our efficiency is approximately halved. At lower values of g the effect is smaller. At $g = 40e$ for these masses it would appear to be at most a 10% effect.

The effects of the fluctuations in energy loss for monopoles are shown in figure 5b. We have smeared the average energy loss by various amounts up to 25% of the average value of dE/dx in each detector medium and find it makes no measureable impact on the monopole detection efficiency.

We then imposed electric charge on the simulated candidates. The results are shown in figure 5c. Efficiencies for dyons of unit electric charge appear to be no lower than those of monopoles, but they drop off rapidly for dyons with multiple charge. This is almost entirely due to the effect of the momentum cut made: doubly charged dyons are interpreted as having half their actual transverse momentum and so on.

6 Conclusions

Having made the cuts as described, we find no candidate events in the region which would be unambiguously populated by monopoles. We have been guided by a measure of the distribution of non-magnetic background to determine cuts, and then accepted the effects on our efficiencies that these cuts produce.

We assign an upper limit of 2.30 events to each combination of magnetic charge and mass and using the data in the efficiency plot (figure 4), we can compile a 90% confidence level limit on monopole production. We have normalised this upper limit to the point-like QED cross section. Figure 6 shows the distributions in the upper limit of R where

$$R = \frac{\sigma(e^+e^- \to M\overline{M})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

for various combinations of monopole mass and magnetic charge. As can be inferred from figure 5c, the limits on dyon production are at comparable levels for dyons of unit electric charge and much weaker at greater charges. Figure 6 shows how our result compares to previously published results. It can be seen that this analysis has bridged the gap between the CLEO result[11] and the earlier direct accelerator searches which were insensitive to low values of g. The PEP result[10] was only sensitive to charges greater than 30e and relied on a knowledge of the permanent effects of the passage of a monopole through various substances. The similar PETRA result[8] and the ISR result[9] were only sensitive to monopoles of greater than about 50e.

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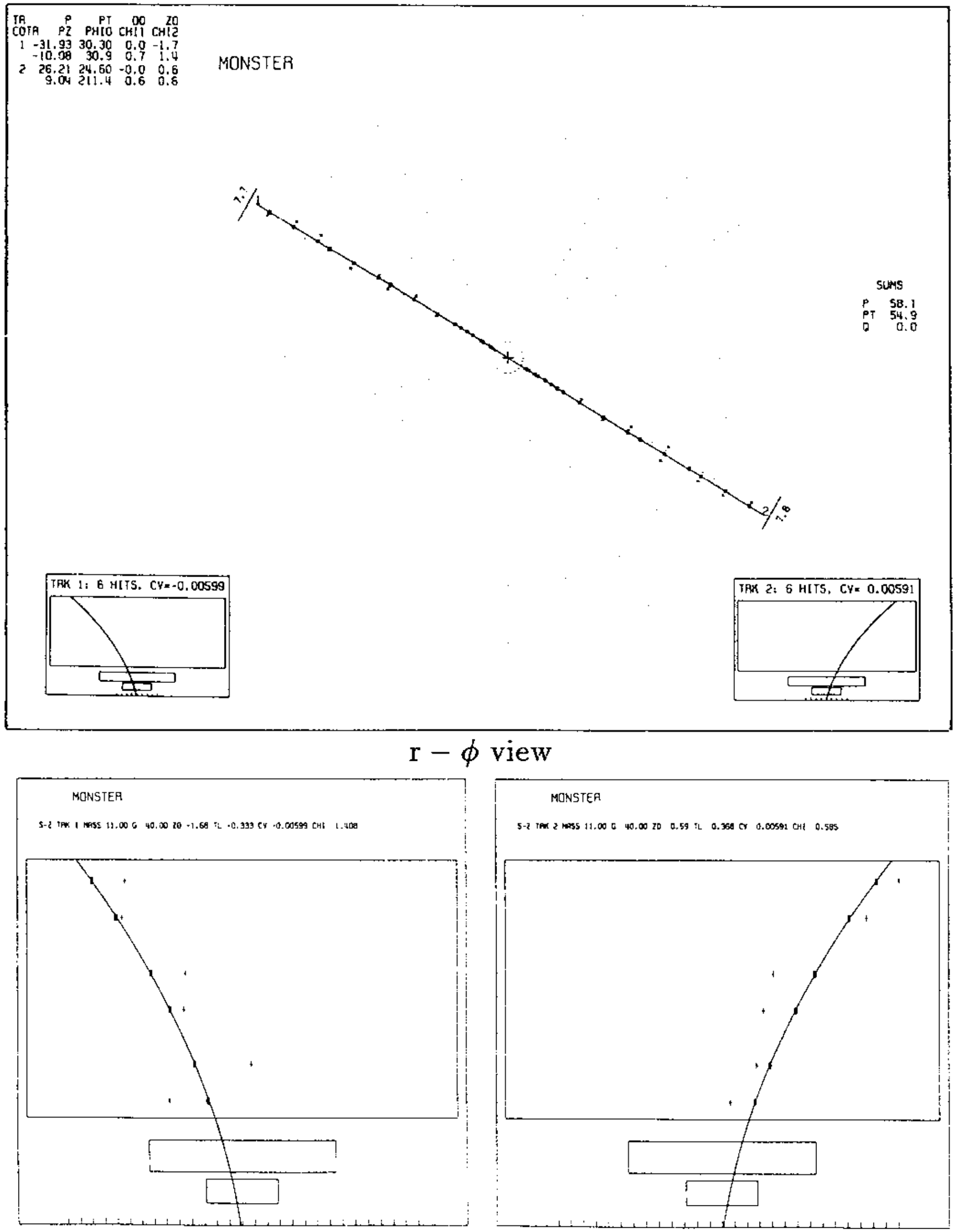
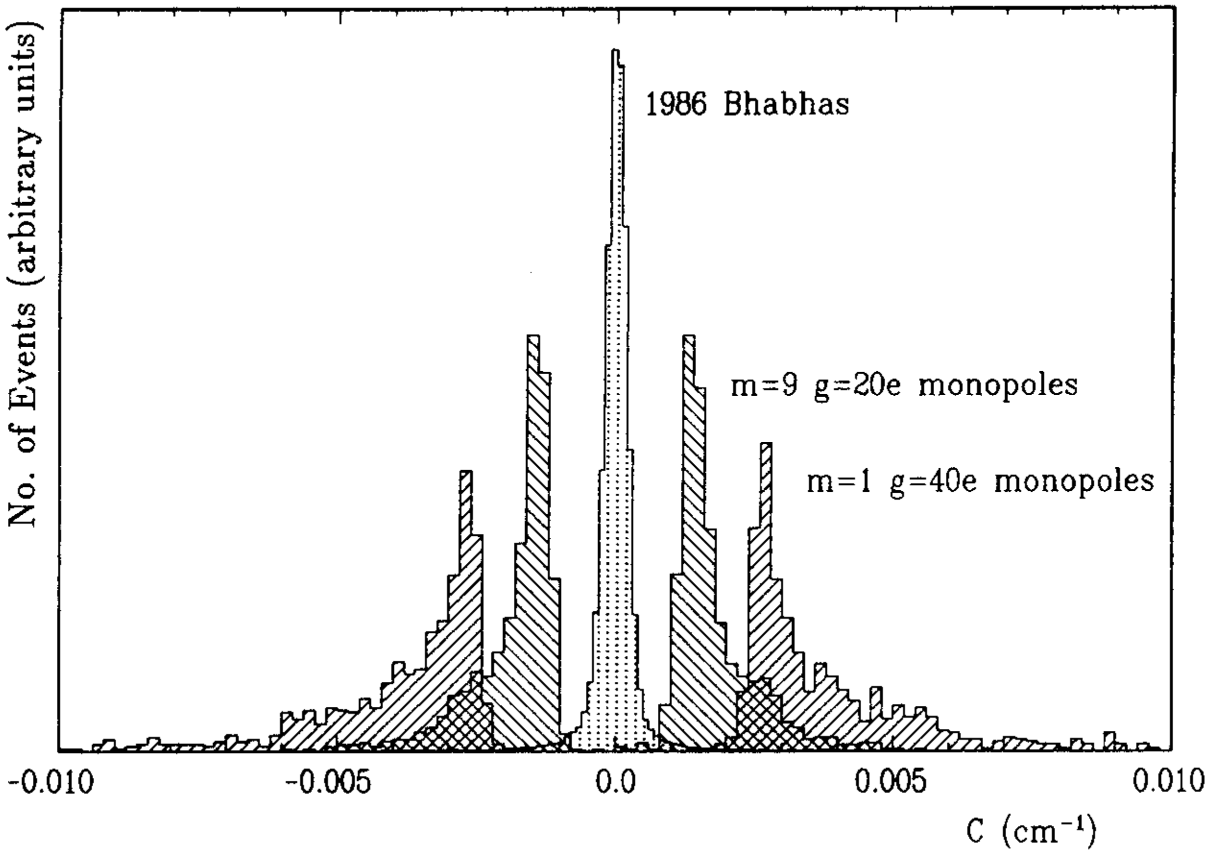
List of Figures



$r - \phi$ view

$s - z$ views

Figure 1



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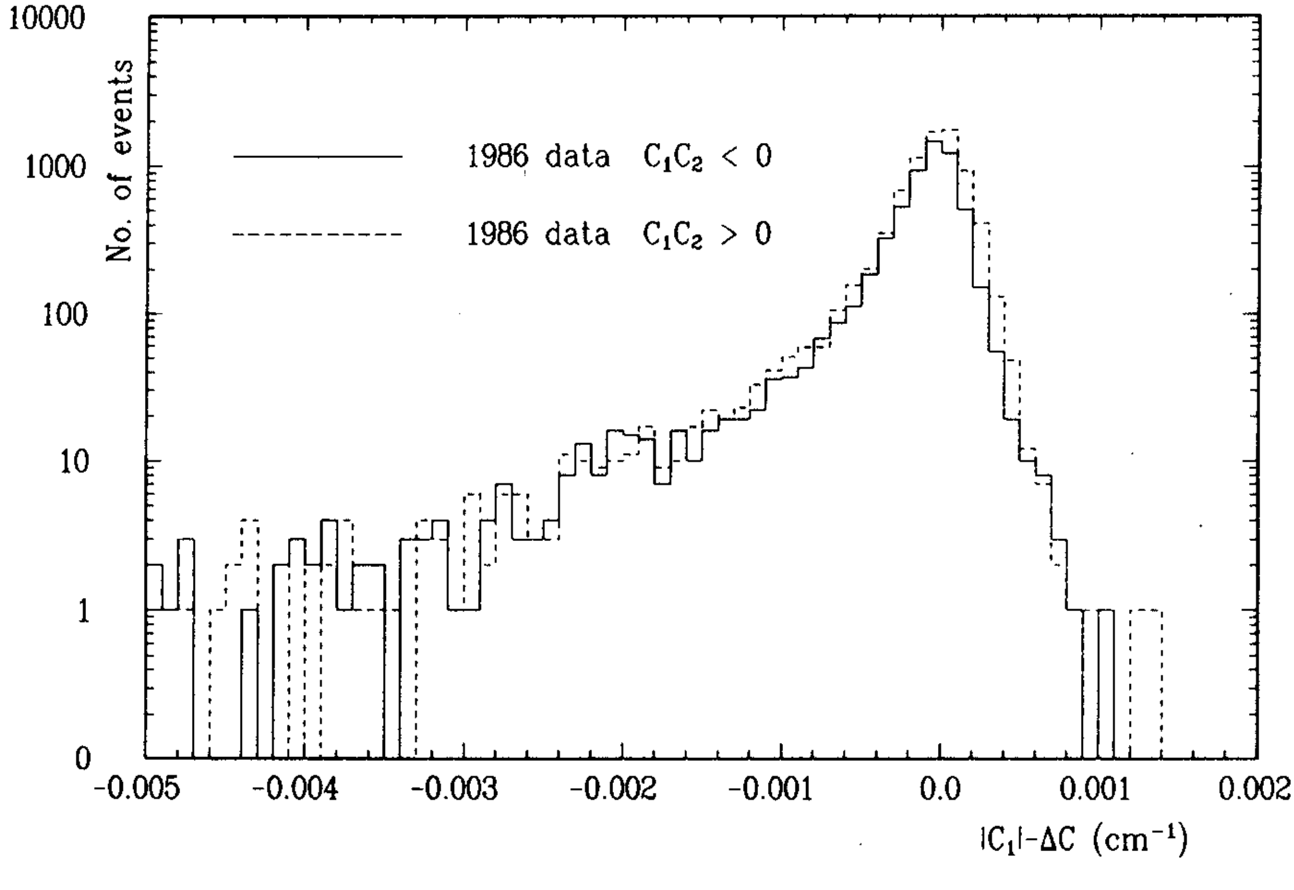

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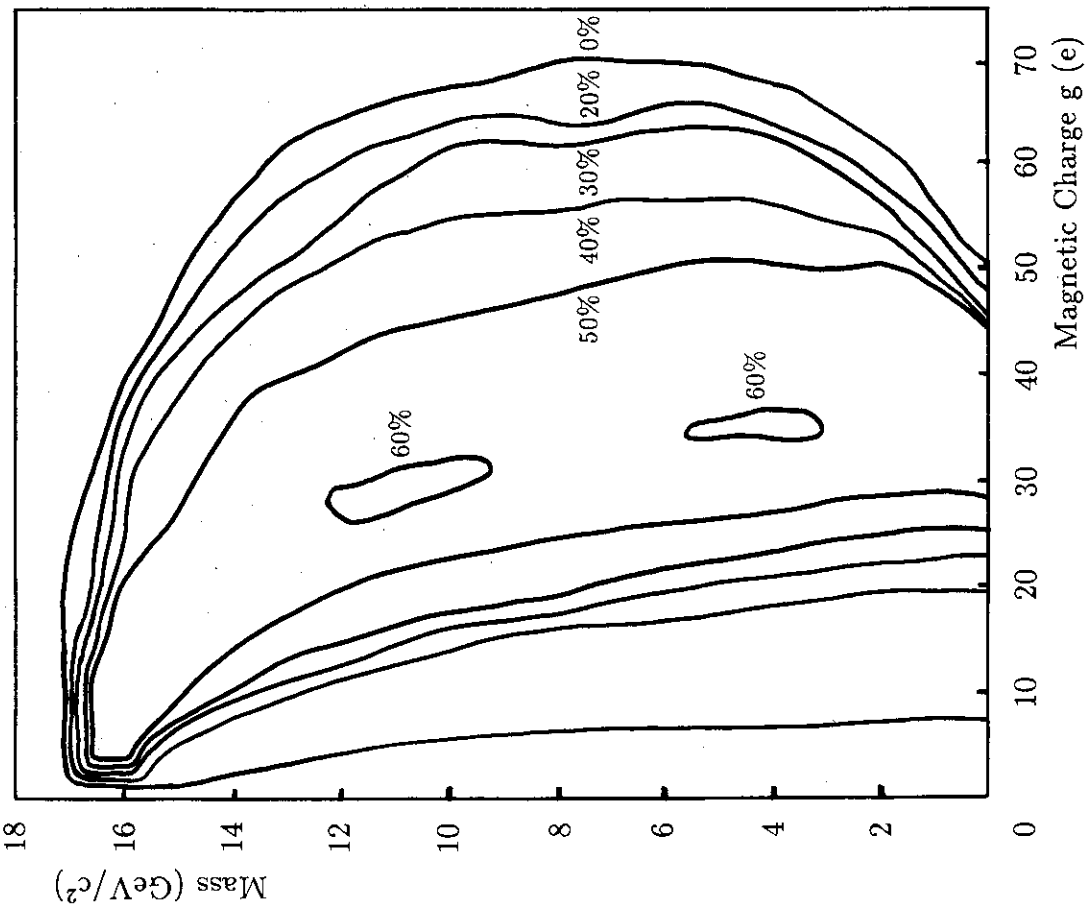
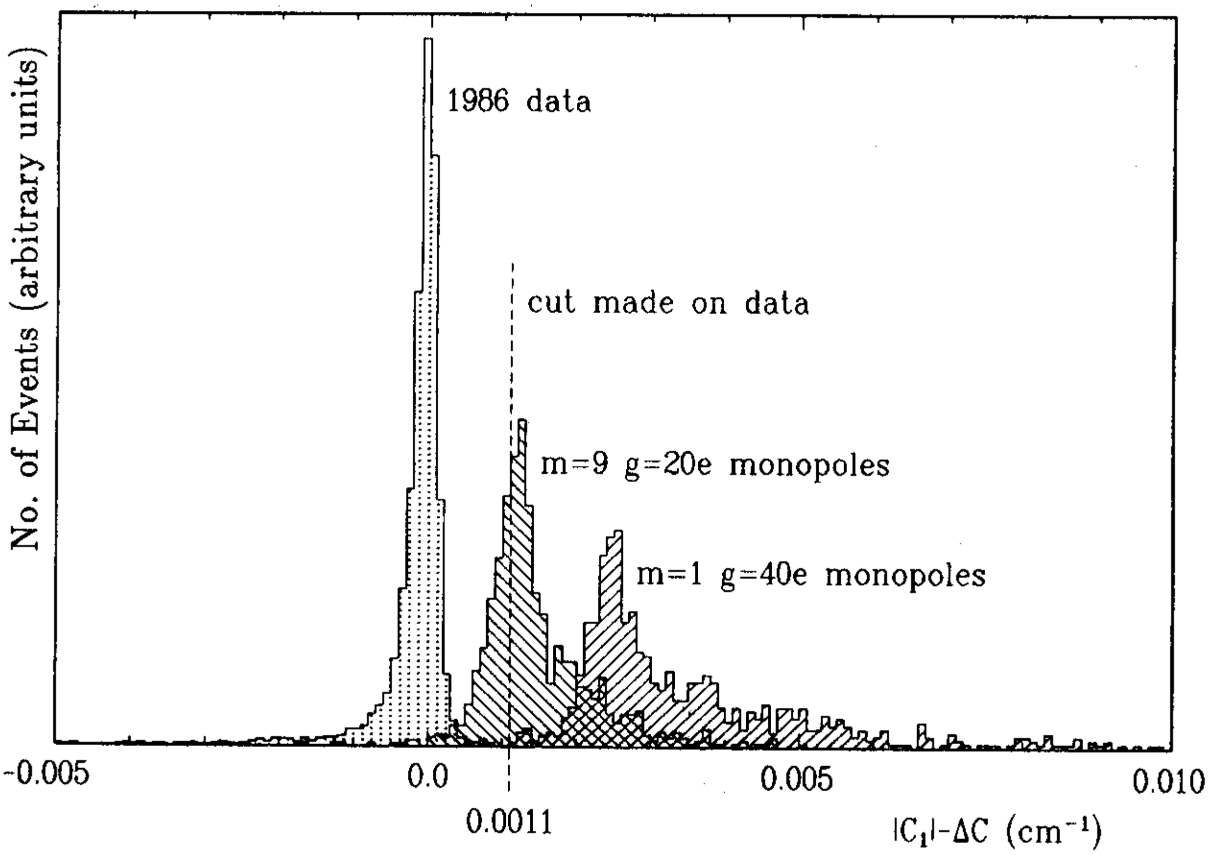


Figure 4



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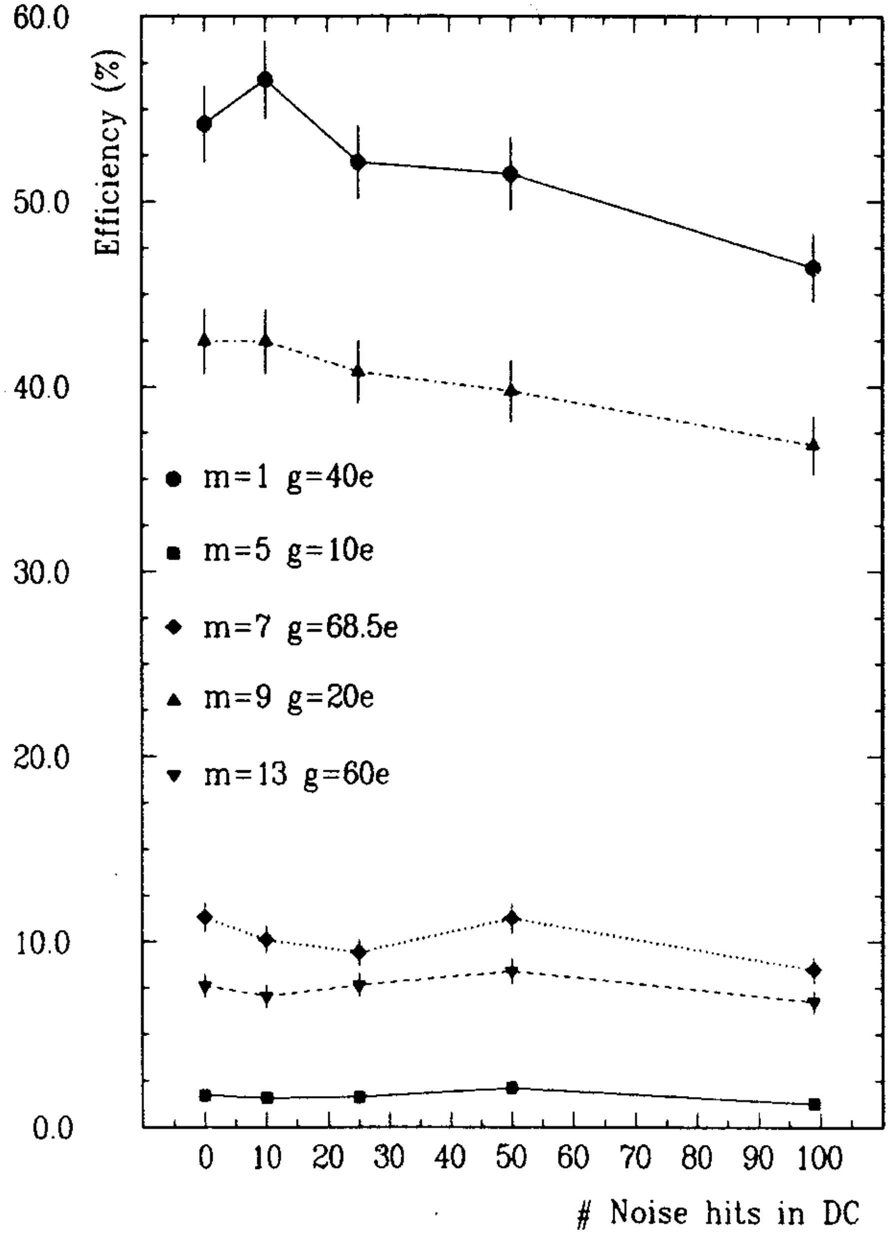

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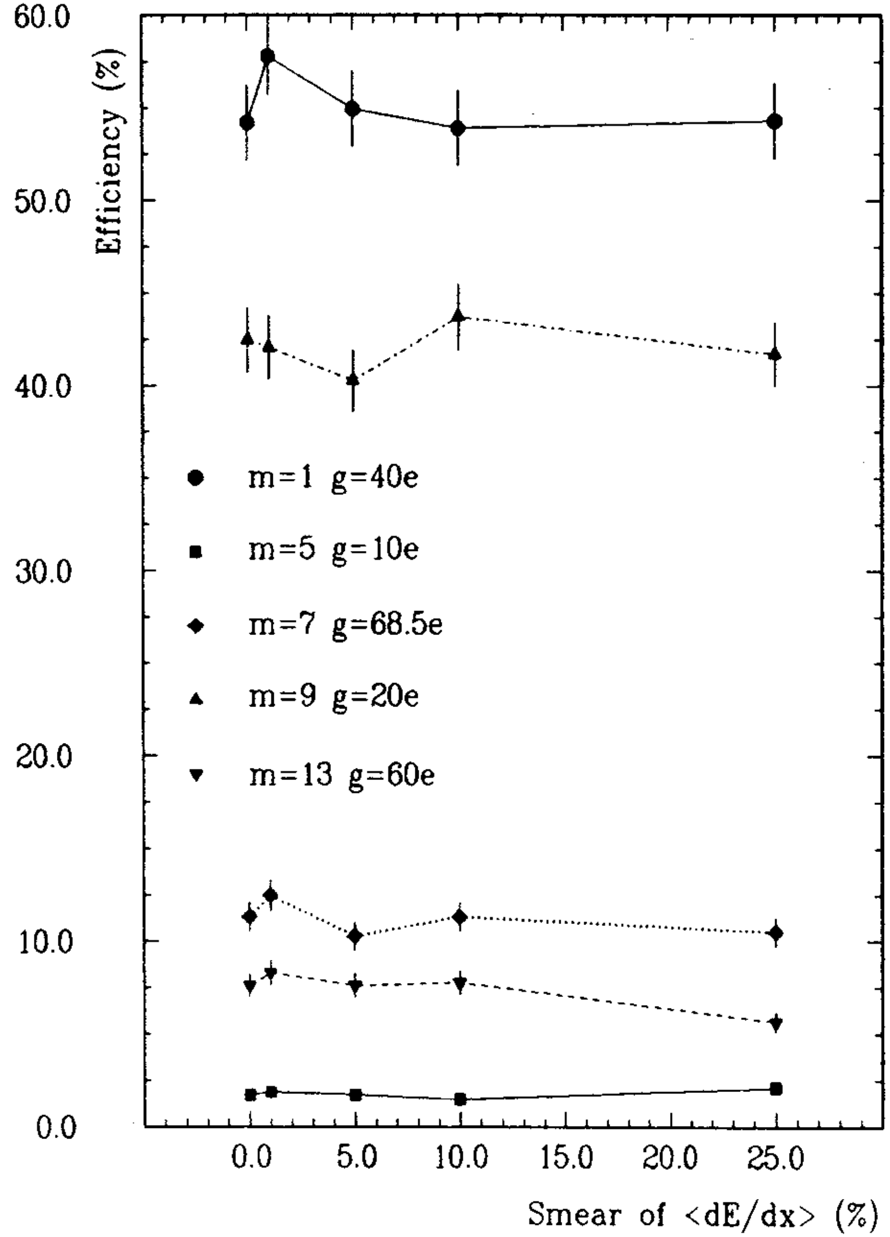

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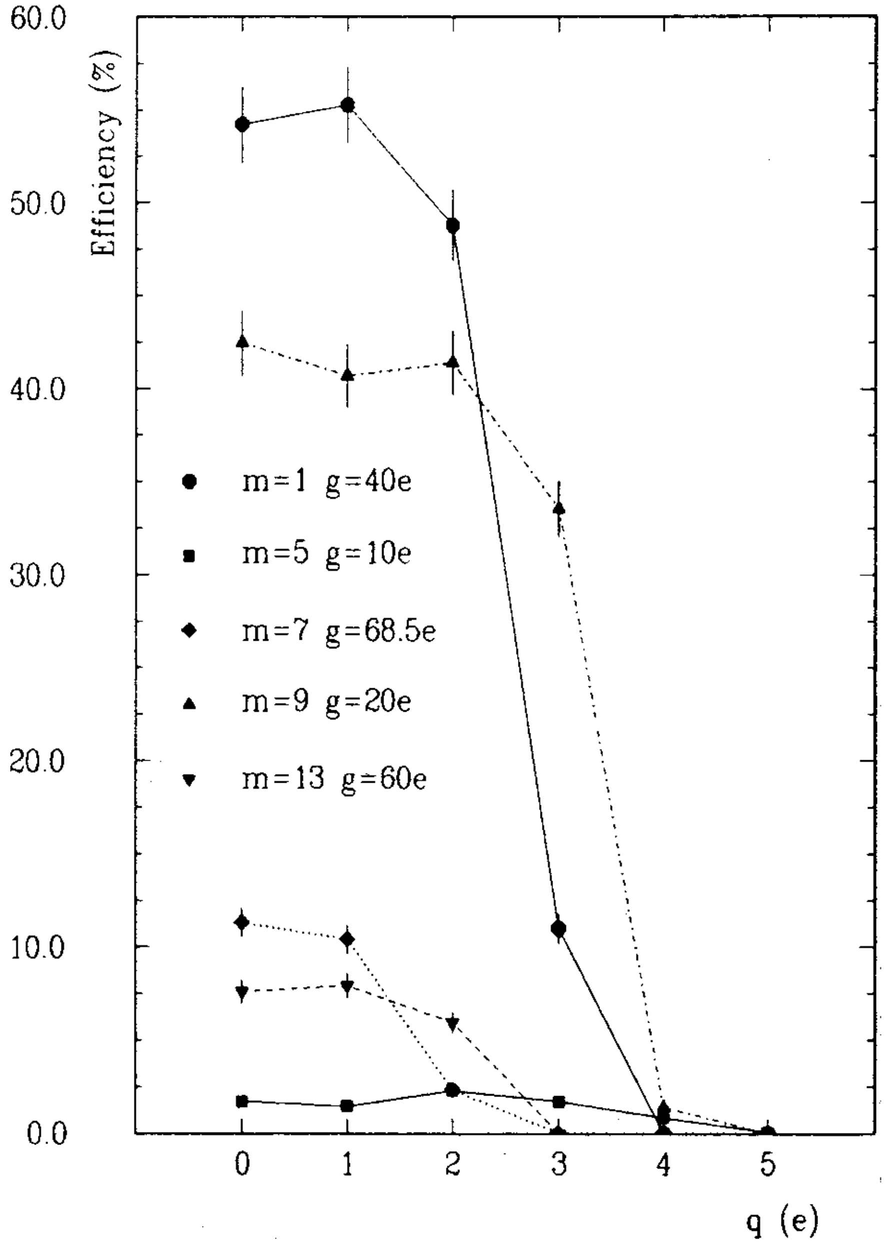

Figure 5c

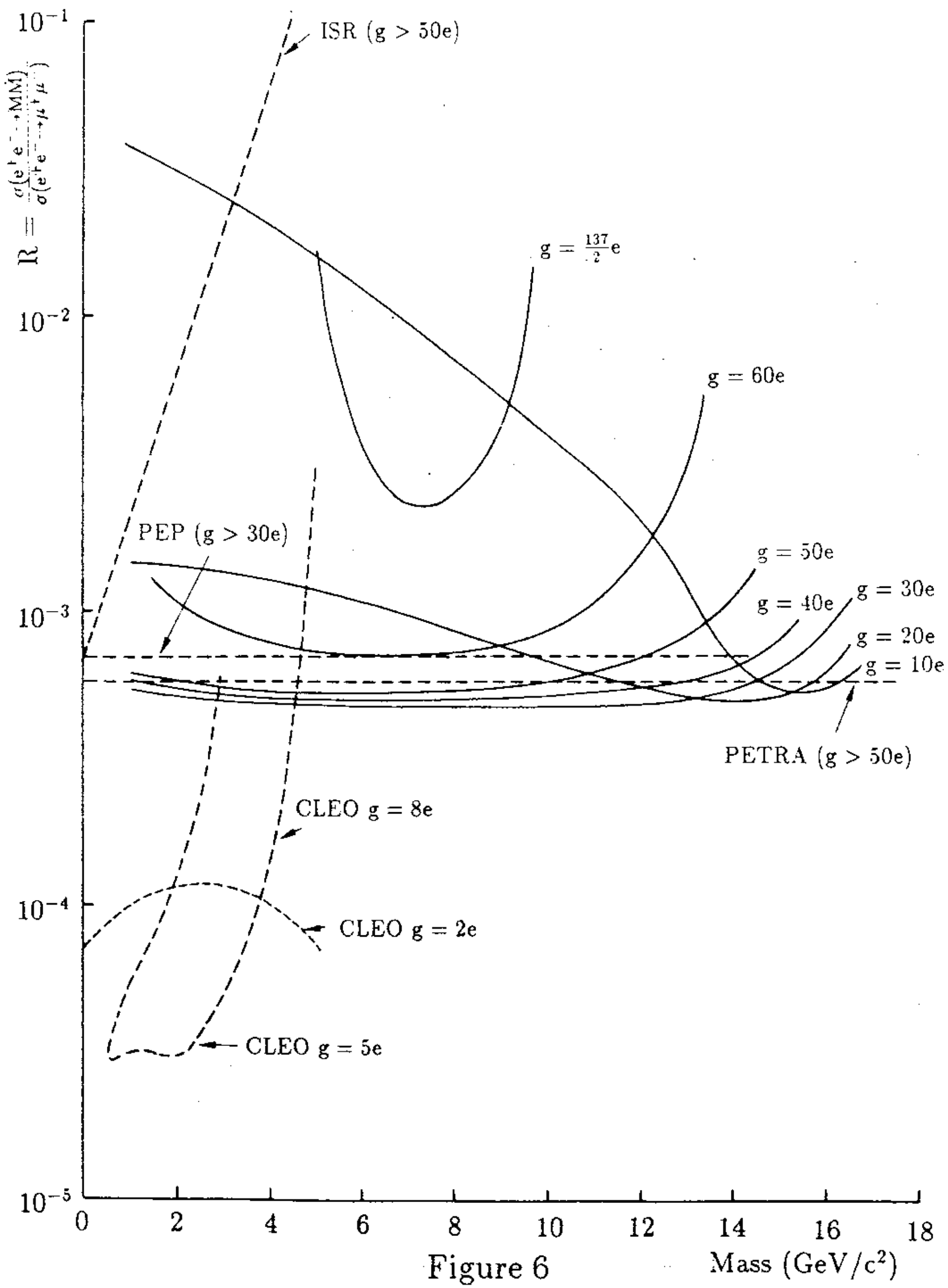

Figure 6