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Search for Narrow Vector Resonances in the Z Mass Range

The L3 Collaboration

Abstract

The hadronic lineshape of the Z has been analyzed for evidence of signals of new, narrow vector resonances in the Z-mass range. The production rate of such resonances would be enhanced due to mixing with the Z. No evidence for new states is found, and it is thus possible to exclude, at the 95 % confidence level, a quarkonium state in the mass range from 87.7 to 94.7 GeV.

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Introduction

The measurement of hadron production in high-energy e^+e^- collisions was first proposed and implemented at Frascati [1] with ADONE. The classic example of such a situation is the $\rho - \omega$ interference [2] in the vicinity of 780 MeV. The search for narrow vector resonances is of great interest because they would correspond to the bound states of new heavy quarks or to new gauge particles. We have searched for narrow resonances produced in the reaction $e^+e^- \to$ hadrons.

The production of a narrow vector resonance is strongly enhanced due to mixing with the Z if the resonance mass (M_V) is within the Z mass range, that is if $|M_V - M_Z| \lesssim \Gamma_Z$.

Both vector ($J^{PC} = 1^{--}$) and axial vector (1^{++}) resonances can mix with the Z. If the new resonance is a quarkonium of SU(3) colour quarks, such as the the top or a fourth generation b′, its mixing with the Z can be calculated using potential models developed for lower mass quarkonia. It can be shown that the decay width of the resonance is increased by approximately two orders of magnitude due to the mixing. This enhancement makes our search sensitive to such resonances over the full mass range we study, in spite of the coarse sampling of center-of-mass energies in the data.

We report here on a search carried out over the mass range $87 < M_V < 95$ GeV with the L3 detector at LEP, using a total e^+e^- luminosity of 18.2 pb^{-1} accumulated in the period from 1989 through 1991. This search is also sensitive to resonances formed of constituents with new quantum numbers provided that the resonance couples to the Z so that mixing can take place.

Searches for narrow resonances produced in radiative decays of the Z have been reported by the L3 Collaboration [3] and others [4].

The L3 Detector

The L3 detector covers 99% of 4π [5]. It consists of a central tracking chamber (TEC), a high-resolution electromagnetic calorimeter composed of bismuth germanium oxide (BGO) crystals, a ring of scintillation counters, a uranium and brass hadron calorimeter with proportional wire chamber readout, and a high precision muon spectrometer. These detectors are located in a 12 m diameter magnet which provides a uniform field of 0.5 T along the beam direction. Forward BGO arrays, on either side of the detector, measure the luminosity by detecting small angle Bhabha events.

The hadronic cross section

The cross section for $e^+e^- \rightarrow$ hadrons , σ_h, measured at 24 center-of-mass energies, is presented in Table 1. The details of the analysis have been reported in previous publications [6, 7]. In addition to the statistical error shown in Table 1, there are systematic errors associated with the selection of hadronic events and the acceptance. The systematic error for hadrons at the Z peak is estimated for each of the three running periods in 1989, 1990 and 1991 to be 1.0 %, 0.3 % and 0.2 %, respectively. The systematic errors at different center-of-mass energy points are partially correlated. We conservatively treat this as a point-to-point error in the following analysis. In contrast, the systematic error in the luminosity, which is evaluated to be 2.0 %, 1.0 % and 0.6 % for the same three periods, is independent of beam energy and, therefore, is not considered further in this analysis.

$\sqrt{s}$ (GeV)	σ_h (nb)	Period		$\sqrt{s}$ (GeV)	σ_h (nb)	Period
88.231	4.53±0.11	1990		91.278	30.30±0.62	1989
88.279	5.45±0.40	1989		91.529	29.62±0.59	1989
88.480	5.17±0.09	1991		91.967	24.51±0.24	1991
89.236	8.50±0.14	1990		92.226	21.78±0.26	1990
89.277	8.76±0.41	1989		92.280	20.82±0.79	1989
89.470	10.08±0.12	1991		92.966	14.36±0.16	1991
90.228	18.12±0.18	1991		93.228	12.36±0.16	1990
90.238	18.60±0.25	1990		93.276	12.56±0.55	1989
90.277	19.77±0.70	1989		93.716	10.02±0.13	1991
91.030	30.41±0.74	1989		94.223	8.20±0.14	1990
91.230	30.38±0.12	1990		94.278	7.17±0.54	1989
91.222	30.26±0.13	1991		95.036	7.04±0.86	1989

Table 1: The measured cross section, σ_h, for $e^+e^- \rightarrow$ hadrons. Quoted errors are statistical only.

The experimental cross section is compared to the Standard Model prediction to search for the signal of a new resonance. We use only the lineshape of the Z resonance predicted by the Standard Model and ignore the absolute normalization. The Standard Model cross section is calculated using the ZFITTER program [8] with four adjustable parameters: α_s, M_Z, M_t and M_H. The last two parameters are the masses of the top quark and the Higgs particle, respectively. The strong coupling α_s is constrained to the range 0.124 ± 0.005 which has been determined from a study of hadronic Z and τ decays [7]. The other parameters must be fit from the data.

In order to make the overall fit to the Z resonance insensitive to a possible narrow resonance, the fit value of the Z resonance curve at each center-of-mass energy, E_i, is calculated using all data except those points within the interval $[E_i \pm 0.75]$ GeV, and the Standard Model parameters are determined from the remaining data. The resulting cross section, $\sigma_{\mathrm{SM}}(\mathrm{E_i})$, is compared with the omitted data points in order to determine local deviations from the Standard Model lineshape. This procedure is repeated for each group of data points.

The uncertainty in the theoretical cross section is estimated by repeating the fits with extreme values of the parameters within the ranges given below:

$$\begin{aligned} \alpha_{\mathrm{s}} &= 0.124 \pm 0.005, \\ \mathrm{M_Z} &= 91.195 \pm 0.007 \ \mathrm{GeV}, \\ \mathrm{M_t} &= 45 - 200 \ \mathrm{GeV}, \\ \mathrm{M_H} &= 50 - 1000 \ \mathrm{GeV}. \end{aligned}$$

The changes in the predicted cross section are found to be limited to the range ±0.2 nb for all energies $\mathrm{E_i}$ in the data. We therefore assign a systematic error $\delta\sigma_{\mathrm{SM}} = 0.20$ nb to the Standard Model cross section.

We derive upper and lower limits ($\sigma^{\pm}$) on the cross section (σ_{V}) for a new resonance which is observed either as an enhancement or as a reduction over the Z lineshape predicted by the Standard Model. For the 95% C.L. bounds $\sigma_{\mathrm{V}} > \sigma^-$ and $\sigma_{\mathrm{V}} < \sigma^+$ we obtain:

$$\sigma^+ = (\sigma_{\mathrm{h}} + 1.64\Delta\sigma_{\mathrm{h}}) - (\sigma_{\mathrm{SM}} - \delta\sigma_{\mathrm{SM}})$$

$$\sigma^- = (\sigma_{\mathrm{h}} - 1.64\Delta\sigma_{\mathrm{h}}) - (\sigma_{\mathrm{SM}} + \delta\sigma_{\mathrm{SM}})$$

where σ_{h} is the measured cross section with a standard deviation $\Delta\sigma_{\mathrm{h}}$ obtained by summing in quadrature the statistical and the systematic errors.

Fig. 1 shows σ^+ and σ^- versus $\sqrt{\mathrm{s}}$. For each data point a bar is drawn between σ^+ and σ^- representing the allowed range of the deviation of the measurement of the cross section at that energy from the Standard Model fit. For the data points with high statistics $\sigma^{\pm}$ lie within the band ±0.5 nb, which corresponds to ±1.5% of the cross section at the peak of the Z resonance. We do not observe any significant deviations from the Standard Model lineshape that could be interpreted as the signal of a new resonance.

Limits on resonances

We use the experimental limits on the deviation of the hadronic cross section from the Standard Model lineshape to set limits on the production of new narrow resonances.

The production cross section of a narrow vector resonance in the Z mass region is proportional to the strength of its mixing with the Z [9, 10]. Following the formalism of Ref. [10], this mixing is parametrized by the off-diagonal mass term, $\delta\mathrm{m}^2$, in the 2×2 mass matrix of the $\mathrm{Z} - \mathrm{V}$ system. The resonance acquires a decay width, Γ_{V}, which is proportional to $(\delta m^2)^2$ and which can be expressed as:

$$\Gamma_V \approx \frac{(\delta m^2)^2}{M_Z^2 \Gamma_Z}$$

for the case where $M_V \approx M_Z$. To the extent that $\Gamma_V \gg \Gamma^0{}_V$, where $\Gamma^0{}_V$ is the bare width of the resonance, the resonance will decay essentially as a Z. The Z resonance parameters, however, are not significantly modified by the mixing. The narrow resonance signal consists of an interference effect in the Z production cross section at the center of mass energy $\sqrt{s} \approx M_V$.

In Fig. 2 we show the predicted deviation of the hadronic cross section from the Standard Model value for five resonance masses. We use the value of $\delta m^2 = 18$ GeV^2, which is applicable to a toponium state in this mass range with $\Gamma_V \approx 16$ MeV. However, the interference effects that are produced are general and apply to any resonance mixing with the Z. The characteristic features are a dip in the cross section for the case $M_V = M_Z$ and a dispersion shaped interference pattern for other values of M_V. The sharp features of a resonance signal are smeared further by the intrinsic energy spread of the LEP beams. This effect has been included in the plots of Fig. 2 by convoluting them with a gaussian of $\sigma = 50$ MeV [11].

We use the predicted interference signal to calculate an upper limit on the parameter δm^2 as a function of M_V. For each value of M_V, incrementing in 10 MeV steps, the predicted deviation in the cross section is compared to data while varying δm^2. The resulting 95 % C.L. upper limit on δm^2 is shown in Fig. 3. The upper limit is in the range 10 - 30 GeV^2 for resonance masses in the interval from 88 to 94.5 GeV.

The mixing parameter for quarkonium of u-type quarks is given by:

$$\delta m^2 = 2\sqrt{3}|\psi(0)|\sqrt{M_V}\left[\frac{e(1-\frac{8}{3}\sin^2\theta_W)}{4\sin\theta_W\cos\theta_W}\right],$$

where e is the positron electric charge and $\psi(0)$ is the wave-function of the $Q\bar{Q}$ bound state at the origin, which can be calculated from potential models. We plot in Fig. 3 the expected value of δm^2 for ground-state quarkonia of u-type and d-type quarks with $|\psi(0)|^2 \approx 64$ GeV^3 [12]. The upper limit on δm^2 rules out, at the 95 % C.L., new resonances of d-type quarks in the mass range $87.7 < M_V < 94.7$ GeV, while resonances of u-type quarks are excluded in the mass ranges $87.9 < M_V < 88.7$ GeV and $89.1 < M_V < 94.3$ GeV. These limits are valid for the ground state quarkonium. This search is less sensitive to the radial excitations of the ground state and to the 1^{++} state, whose mixing with the Z is suppressed by a smaller $|\psi(0)|$.

The limits on the resonance mass can be translated to limits on the quark mass, M_Q, through:

$$2M_Q = (M_V + E_b)$$

where E_b is the binding energy. Assuming that $E_b = 1$ GeV [13] we exclude the mass range $44.4 < M_Q < 47.8$ GeV for d-type quarks and the range $45.0 < M_Q < 47.5$ GeV for u-type quarks, without any assumptions about their decay modes. These limits extend the model-independent limits of $M_{b'} > 45$ GeV [14] obtained from the width of the Z and $M_t > 45$ GeV [15], obtained from the width of the W, both at the 95 % C.L. Model-dependent mass limits have been reported in Ref. [16] and [17].

Our search is also sensitive to resonances formed of constituents with new quantum numbers. Even if the resonance does not couple to ordinary fermions, its mixing with the Z, via virtual loops, would produce a signal in the Z mass range. The upper limit on δm^2, shown in Fig. 3, applies to such a resonance as well and can be used to constrain the coupling of its constitutents to the Z, subject to assumptions about $|\psi(0)|$.

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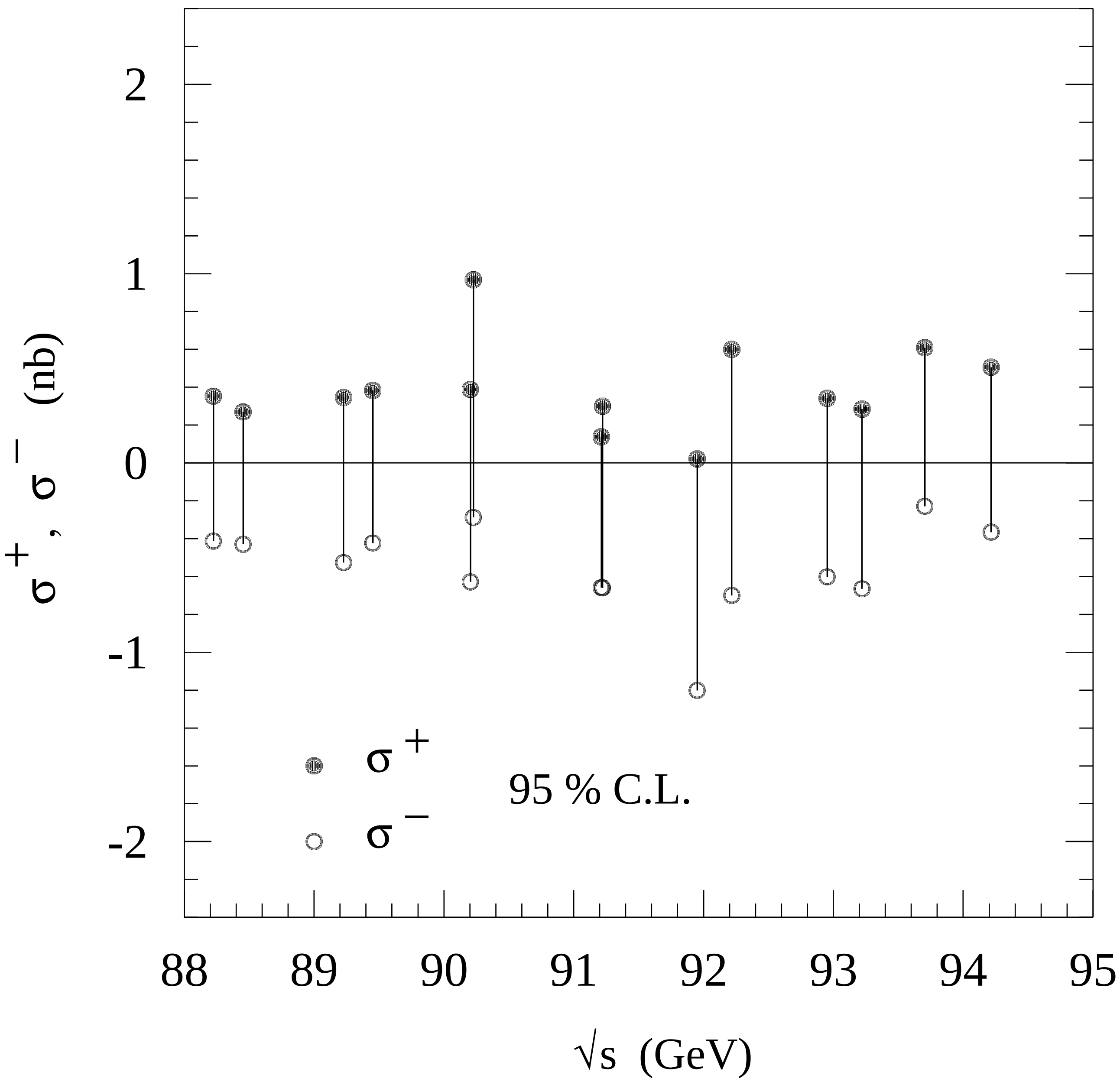
Figure Captions

Figure 1: The 95 % C.L. limits σ^+ and σ^- versus center-of-mass energy. Each bar represents the interval outside of which a fluctuation in the cross section due, for example, to an interfering narrow resonance is excluded. The limits are shown for the data taken in 1990 and 1991 (see text).

Figure 2: Predicted deviation of the hadronic cross section from the Standard Model value due to the presence of narrow resonances mixing with the Z. Resonances with a mass of $\mathrm{M_V - M_Z} = (-2,\ -1,\ 0,\ +1\ \text{ and }\ +2)$ GeV have been simulated, including the effect of the energy spread of the LEP beams. The value of the mixing parameter is chosen for a quarkonium state of charge 2/3 quarks.

Figure 3: Limits on the mixing parameter $\delta \mathrm{m}^2$ as a function of the resonance mass. We exclude, at the 95 % C.L., values of $\delta \mathrm{m}^2$ above the histogram (shaded region). The value of $\delta \mathrm{m}^2$ expected from a potential model is plotted for quarkonia of d-type (dotted line) and u-type (dashed line) quarks. Resonances whose mixing with the Z is larger than the limits shown on $\delta \mathrm{m}^2$ are excluded by this search.



σ^+, σ^- (nb)
2
1
0
-1
-2
88
89
90
91
92
93
94
95
$\sqrt{s}$ (GeV)
σ^+
σ^-
95 % C.L.

Figure 1

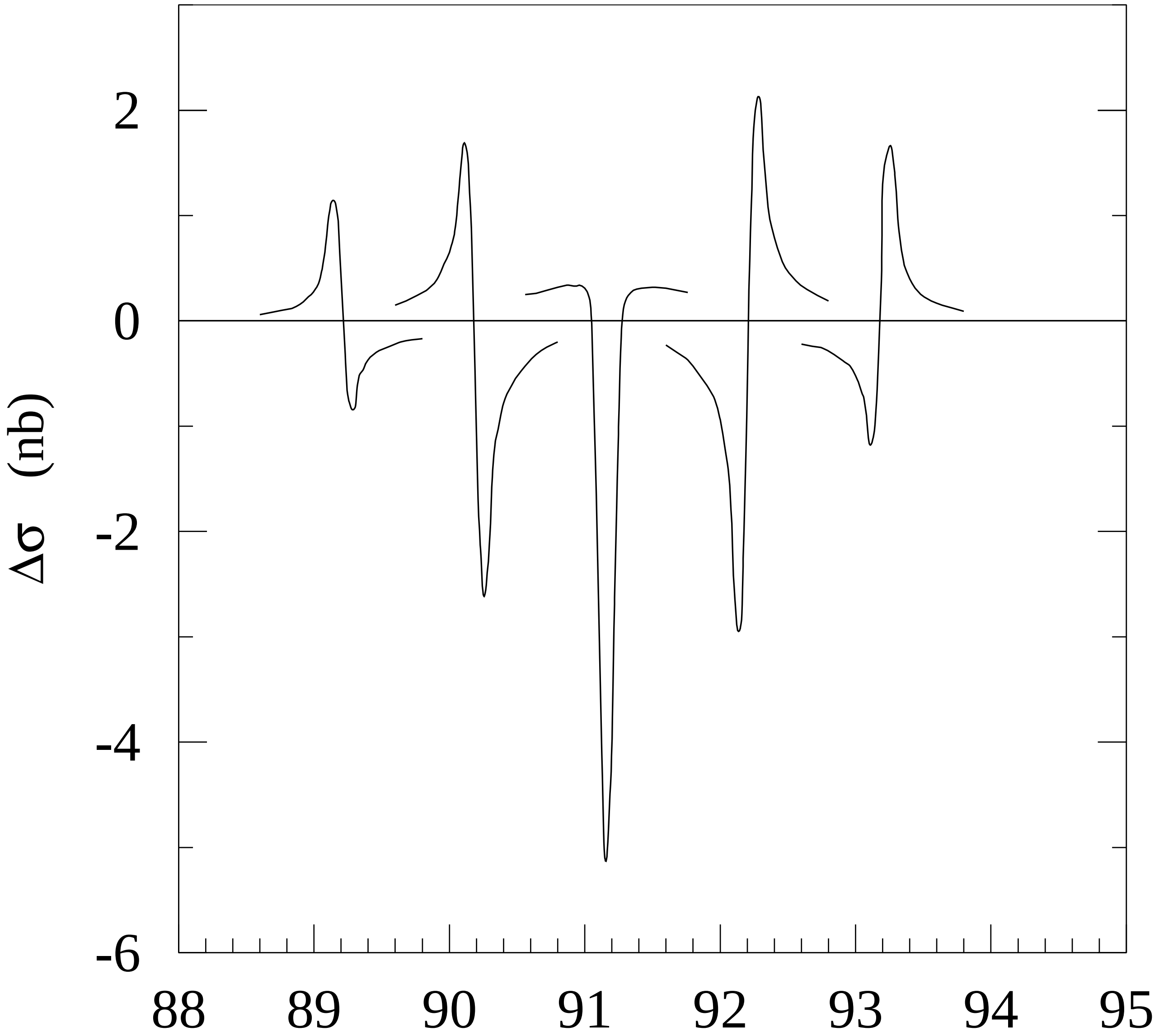


Figure 2

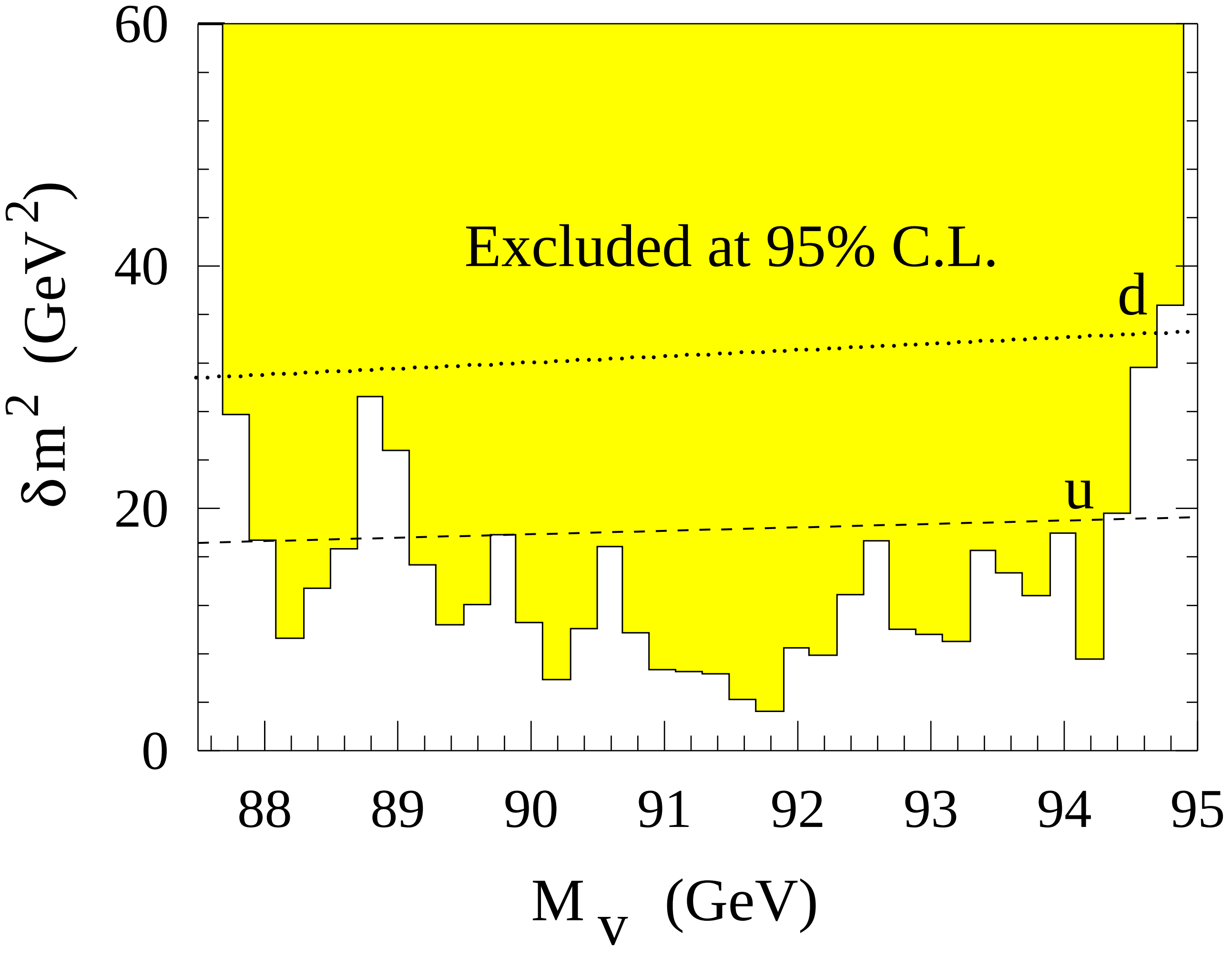

60
40
20
0
δm 2 (GeV 2)
Excluded at 95% C.L.
d
u
88
89
90
91
92
93
94
95
M V (GeV)

Figure 3