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Measurement of the e^+e^- Invariant Mass
Distribution in $\bar{p}p$ Collisions at $\sqrt{s} = 1.8$ TeV

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Abstract

We have measured the cross section as a function of invariant mass for isolated electron pairs produced in $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV for pair masses $M > 30$ GeV/ c^2 . We find good agreement between the measured distribution and the Standard Model prediction for the Drell-Yan production mechanism. Additional heavy neutral vector bosons (Z') are excluded for $M_{Z'} < 387$ GeV/ c^2 (95% confidence level) assuming Standard Model couplings. A lower limit of 2.2 TeV (95% confidence level) is placed on the electron-quark compositeness scale parameter Λ_{LL}^- associated with an effective contact interaction.

We present a measurement of the electron pair production cross section in $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV for pair masses $M > 30$ GeV/c². In the parton model, isolated lepton pairs are produced in $\bar{p}p$ collisions by the Drell-Yan mechanism [1]. The cross section is a convolution of parton distribution functions and the subprocess cross section at the effective center of mass energy \hat{s} . In the Standard Model, this subprocess is the result of either virtual photon or real or virtual Z production. For the mass range of this measurement the cross section is dominated by the Z resonance. For low pair masses the cross section rises due to virtual photon production. At sufficiently low masses (outside the scope of this analysis) the distribution is expected to be sensitive to the parton distribution functions [2]. Above the Z resonance the cross section is expected to fall off rapidly due to the $1/\hat{s}$ behavior of the virtual boson propagator, thereby providing a window on phenomena outside the Standard Model. In particular, additional neutral vector bosons are expected in many extensions of the Standard Model [3]. Such bosons would be directly observed as additional resonances in this distribution. In addition, a flattening of the cross section at high mass (above the Z) is expected in composite models where leptons and quarks share constituents [4].

The data presented here were collected with the Collider Detector at Fermilab (CDF), corresponding to an integrated luminosity of 4.05 pb⁻¹. We summarize the essential features of the CDF detector relevant to this analysis [5]. Planes of scintillation (beam-beam) counters located at small angles to the beam signal an inelastic $\bar{p}p$ collision. Vertex time projection chambers (VTPC) provide a measurement of the event vertex as well as tracking information out to a radius of 22 cm from the beam axis and cover the pseudorapidity range $|\eta| < 3.5$ ($\eta \equiv -\ln \tan(\theta/2)$, where θ is the polar angle with respect to the proton beam.) At larger radii, an 84 layer central tracking chamber (CTC) immersed in a 1.4 T magnetic field provides tracking

with high efficiency and measures momenta with a precision of $\Delta p_T/p_T \approx 0.001 p_T (GeV/c)^{-1}$ over the pseudorapidity range $|\eta| < 1.2$. At larger pseudorapidities ($1.2 < |\eta| < 1.4$) tracks are measured with reduced efficiency and momentum resolution. Electromagnetic (EM) and hadronic energy is detected by calorimeters arranged in a projective tower geometry. The central ($|\eta| < 1.1$) EM scintillator calorimeter is $18 X_0$ thick with an energy resolution that scales with transverse energy ($E_T \equiv E \sin \theta$) as $(\sigma(E)/E)^2 = (0.135/\sqrt{E_T})^2 + (0.020)^2$. The plug ($1.1 < |\eta| < 2.4$) EM gas calorimeter is $18 X_0$ thick at 0° incidence having an energy resolution of $(\sigma(E)/E)^2 = (0.28/\sqrt{E})^2 + (0.02)^2$. An electromagnetic shower position resolution of several millimeters is obtained in the central region using proportional strip chambers embedded at a depth of $6 X_0$ and in the plug using orthogonal readout strips.

Events for this measurement were collected using an inclusive electron trigger. This trigger required a central calorimeter energy cluster with at least 12 GeV of transverse energy and the ratio of hadronic to electromagnetic energy (H/E) to be less than 0.125 and with an associated track in the CTC of transverse momentum $p_T > 6$ GeV/c. An online hardware processor made the CTC track parameters available at the trigger decision time. The efficiency of this trigger has been studied using data collected at lower trigger thresholds and using W and Z events from independent triggers. We find that this trigger is $(97.3 \pm 0.5)\%$ efficient for $E_T > 15$ GeV. To avoid trigger saturation effects at very high E_T (> 150 GeV), a trigger requiring only a calorimeter energy cluster with $E_T > 60$ GeV was available ensuring essentially 100% trigger efficiency for such events.

Dielectron events are selected from this sample by making strict requirements on a central (trigger) calorimeter energy cluster while imposing less restrictive criteria for the

second electron. The event vertex is required to be within 60 cm (2σ) of the center of the detector along the beam direction. The trigger electron ($E_T > 15 \text{ GeV}$) selection uses the ratio of H/E and lateral EM shower shape as well as position and momentum matching between the shower and a CTC track. The second electron, detected as a cluster in either the central (CC event) or plug (CP event) calorimeters, is required to satisfy $E_T > 7 \text{ GeV}$ and is identified on the basis of H/E , VTPC tracking, and lateral shower shape alone. In order to ensure uniform detection efficiency, the clusters are required to be in a fiducial region of the calorimeter. In addition, an isolation requirement is made on both clusters. As a measure of isolation we define $I = (E_C - E_T)/E_C$, where E_C is the total transverse energy within a cone of radius 0.4 in η - ϕ space centered on the cluster (ϕ is the azimuthal angle), and require $I < 0.1$ for both clusters. In order to increase the acceptance for high mass pairs we also accept events where the second electron is identified as an isolated, high p_T ($> 20 \text{ GeV}/c$) track (CT event). The track is required to extrapolate outside the fiducial region of the calorimeter and is required to be well reconstructed in the CTC by demanding a minimum number of hits in the inner half of the CTC. The track isolation requirement is that the distance in η - ϕ space between the high p_T track and the nearest track with $p_T > 5 \text{ GeV}/c$ be greater than 0.4 units. The isolation requirement for the trigger electron in the event is the same as for the CC and CP events. This sample of isolated dielectron events consists of 156 CC, 145 CP, and 105 CT events.

Efficiencies for the electron identification using calorimetric criteria are derived from the data using Z candidate events (defined by $75 < M < 105 \text{ GeV}/c^2$) selected with looser criteria. One cluster was required to satisfy the trigger electron requirements allowing efficiencies to be determined with the second electron. The efficiency is measured to be

$(88 \pm 2)\%$ for the trigger electron criteria and $(96 \pm 1)\%$ for the second electron criteria in both the central and plug regions, where the errors are statistical only. The systematic uncertainty on these efficiencies is estimated to be 4% by varying the background contribution under the Z peak as measured in side band regions taken above and below the peak. The track efficiency is measured from W events detected on the basis of an isolated EM cluster and missing transverse energy requirements alone. For $|\eta| < 1.2$ this efficiency is measured to be 94%, the small inefficiency being entirely due to the isolation requirement. In the region $1.2 < |\eta| < 1.4$ fewer CTC layers are available for pattern recognition resulting in a reduced efficiency which we measure to be $(39 \pm 6)\%$. For very high energy electrons ($E > 100 \text{ GeV}$) we expect shower leakage to lower the electron selection efficiency because of the software H/E threshold in the offline event reconstruction. A parameterization of the H/E cut efficiency as a function of electron energy was determined from the H/E distribution measured with test beam electrons of momenta 50, 100, 150 GeV/c . For electrons with $E = 150 \text{ GeV}$, the H/E cut efficiency is measured to be $(98 \pm 1)\%$. Analysis of the test beam data, extrapolated to 200 GeV , predicts an efficiency of $(92 \pm 3)\%$.

The primary background sources to the Drell-Yan process are dijet and W-jet events where the jets produce electron candidates passing our identification requirements. Fake electrons are produced from π^\pm, π^0 overlaps and π^\pm undergoing a charge exchange interaction in the EM calorimeter. Real background electrons result from converted photons originating from π^0 decay and from semi-leptonic decays of heavy (b,c) quarks. Electron candidates produced in jets are characterized by their relative lack of isolation. We characterize the isolation of the event by the maximum isolation of the two EM clusters (I_{max}) for CC and CP events, and by the isolation of the trigger cluster for the CT events. A clear signal of

isolated events is evident in the distribution of I_{max} for events satisfying all requirements except isolation (figure 1b). In order to extract the magnitude of the background remaining after the isolation requirement ($I_{max} < 0.1$) this distribution was fit to a gaussian (signal) plus polynomial (background) for CC, CP, and CT events separately. The background is assumed to extrapolate to zero at $I_{max} = 0$. This assumption has been checked with a sample of electrons identified as originating from photon conversions. This method gives 13, 10, and 6 background events in these event classes. We estimate a 10% systematic uncertainty in this background determination. The shape of the invariant mass distribution of the background was determined from the non-isolated ($I_{max} > 0.1$) pairs with mass greater than $12 \text{ GeV}/c^2$. An additional non-isolated background in the CT sample comes from W events where an accompanying jet contains an isolated high p_T track. This background was estimated to be 4 ± 2 events by using the shape of the track isolation distribution in a sample of W events. A small isolated background from $Z \rightarrow \tau\tau \rightarrow ee$ is also expected. The distribution in mass of this background was calculated from Monte Carlo, and the magnitude (4 ± 1 events) was determined by normalization to the number of observed $Z \rightarrow ee$ events. The normalized background contributions were summed and fit to a double exponential. The fit is superimposed on the mass distribution of the isolated pairs in figure 1a.

To obtain the cross section, the fitted background was subtracted from the data and the resulting distribution was corrected for all inefficiencies. The total efficiency as a function of electron pair mass was calculated using the ISAJET [6] event generator convoluted with the geometric and kinematic acceptance and detection efficiency. The efficiency falls off sharply at low mass due to the E_T threshold requirements, reaches 38% at the Z mass peak, and flattens to an essentially constant 51% at high mass ($> 200 \text{ GeV}/c^2$) where the events

are more centrally produced. QCD effects on the production kinematics are included by initial state parton evolution in ISAJET. We have checked that the generator adequately reproduces the observed transverse and longitudinal momentum distributions for Z events. We have also checked the relative rates of CC:CP:CT events in the Z mass region which are predicted to be in the ratio 1:1.20:0.80 by our Monte Carlo. The observed ratio is $1:(1.05 \pm 0.14): (0.79 \pm 0.11)$, in good agreement with expectation.

The absolute cross section normalization was obtained from the event rate of the beam-beam counters and a measurement of the effective cross section of these counters by extrapolation from lower energy measurements [7]. The cross section times branching ratio (σB_Z) for Z production was obtained by summing the differential cross section over a mass range including the Z mass peak and multiplying by a factor calculated from the Monte Carlo to correct for both the finite integration range and the continuum contribution. Contributions to the systematic uncertainty of this measurement are 4% from selection efficiencies, 2.5% from the effect of the $Z p_T$ distribution uncertainty on the acceptance correction, 5.0% from the effect of the parton distribution uncertainty on the acceptance correction, 1.5% from the integration range, < 1% from the background subtraction and 6.8% from the luminosity determination. This measurement of σB_Z is in good agreement with our published Z cross section based on an independent analysis [7]. Nine events with $M > 110 \text{ GeV}/c^2$ are observed corresponding to an integrated cross section for $M > 110 \text{ GeV}/c^2$ of $4 \pm 1 \text{ pb}$, consistent with the Drell-Yan expectation of 4 pb .

The shape of the Drell-Yan invariant mass distribution is most sensitively demonstrated by the integral distribution, $\sigma(M) = \int_M^\infty d\sigma$. The shape of this distribution is compared with a lowest order Drell-Yan calculation (normalized to the number of observed

Z events) in figure 2. We have smeared the calculated distribution by a mass dependent gaussian resolution function and included the effect of the running of α_s . The excellent agreement even in the low mass region where the background is rising rapidly is a result of the background subtraction. We use the distribution of events above the Z to set a limit on the cross section times branching ratio ($\sigma B_{Z'}$) for additional heavy neutral bosons (Z'). This limit is calculated as a function of Z' mass using the maximum likelihood technique. The Z' mass distribution was calculated with a width that scales the Standard Model Z width by a factor $M_{Z'}/M_Z$. Calculated cross sections are normalized to the observed Z cross section so that systematic errors common to the efficiency and luminosity do not contribute to the limit. The remaining systematic uncertainties are 6% due to the statistical error on the normalization, 1% due to the energy dependent H/E efficiency, and 2% due to the parton distribution functions and QCD corrections. These have been included in the 95% confidence level limit on $\sigma B_{Z'}$ for Z' masses less than 200 GeV/c^2 shown in figure 3. Also shown is the theoretical $\sigma B_{Z'}$ calculated with Standard Model couplings, normalized to our measured Z cross section.

We expect that high mass pairs ($M > 200 GeV/c^2$) will have a dramatic signature of two isolated high E_T electrons. We searched for high mass pairs by relaxing selection criteria on central electrons, requiring only isolation and $H/E < 0.1$. An additional 20 events are observed above the Z peak ($M > 110 GeV/c^2$), consistent with a predicted increase in background of 23 events. No additional events are observed above a mass of 200 GeV/c^2 . Convoluting the systematic uncertainty of 9.4% with the Poisson limit gives an absolute limit on the observed integral cross section above 200 GeV/c^2 of $\sigma(200) < 1.31 pb$ at 95% confidence level. For a Z' with Standard Model couplings we exclude $M_{Z'} < 387 GeV/c^2$ at

95% confidence level. We can also set a limit on the scale Λ_{LL}^{\mp} of an effective (contact) lepton-quark interaction which would signal lepton-quark compositeness. The choice \mp corresponds to constructive (destructive) interference with the dominant up quark contribution to the cross section [8]. Based on the absence of events above a mass of $200 \text{ GeV}/c^2$ we set limits at 95% confidence level of $\Lambda_{LL}^{-} > 2.2 \text{ TeV}$ and $\Lambda_{LL}^{+} > 1.7 \text{ TeV}$. The integral distributions for these values of Λ_{LL}^{\mp} are compared to the observed distribution in figure 2.

In conclusion, we have measured the cross section for electron pair production with masses $M > 30 \text{ GeV}/c^2$. We find good agreement between the integrated cross section and the Standard Model prediction for the Drell-Yan production mechanism. Based on the distribution of events below $200 \text{ GeV}/c^2$ and the absence of events above $200 \text{ GeV}/c^2$ we set a limit on cross section times branching ratio for an additional heavy neutral boson. We have checked that this limit is insensitive to variations by a factor of two of the Z' width. In addition this limit is independent of the Z' coupling to quarks, making it valid for a large class of models down to masses approaching the Z mass.

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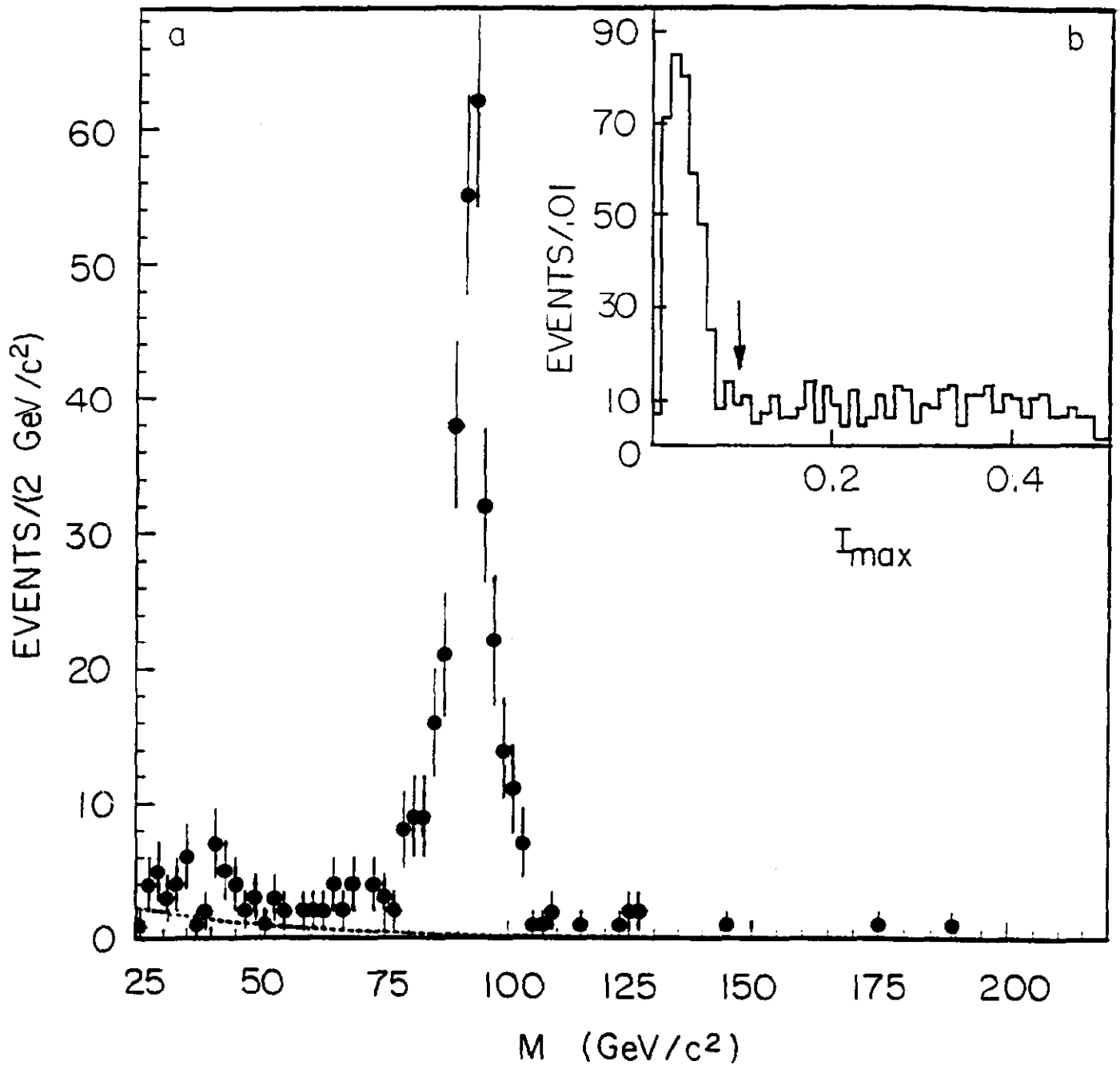


Figure 1: The mass distribution of isolated pairs is shown in (1a) together with the normalized background (dashed line). In the isolation distribution in figure 1b the signal of isolated pairs is evident near $I_{max} = 0$. The arrow indicates the location of our cut.

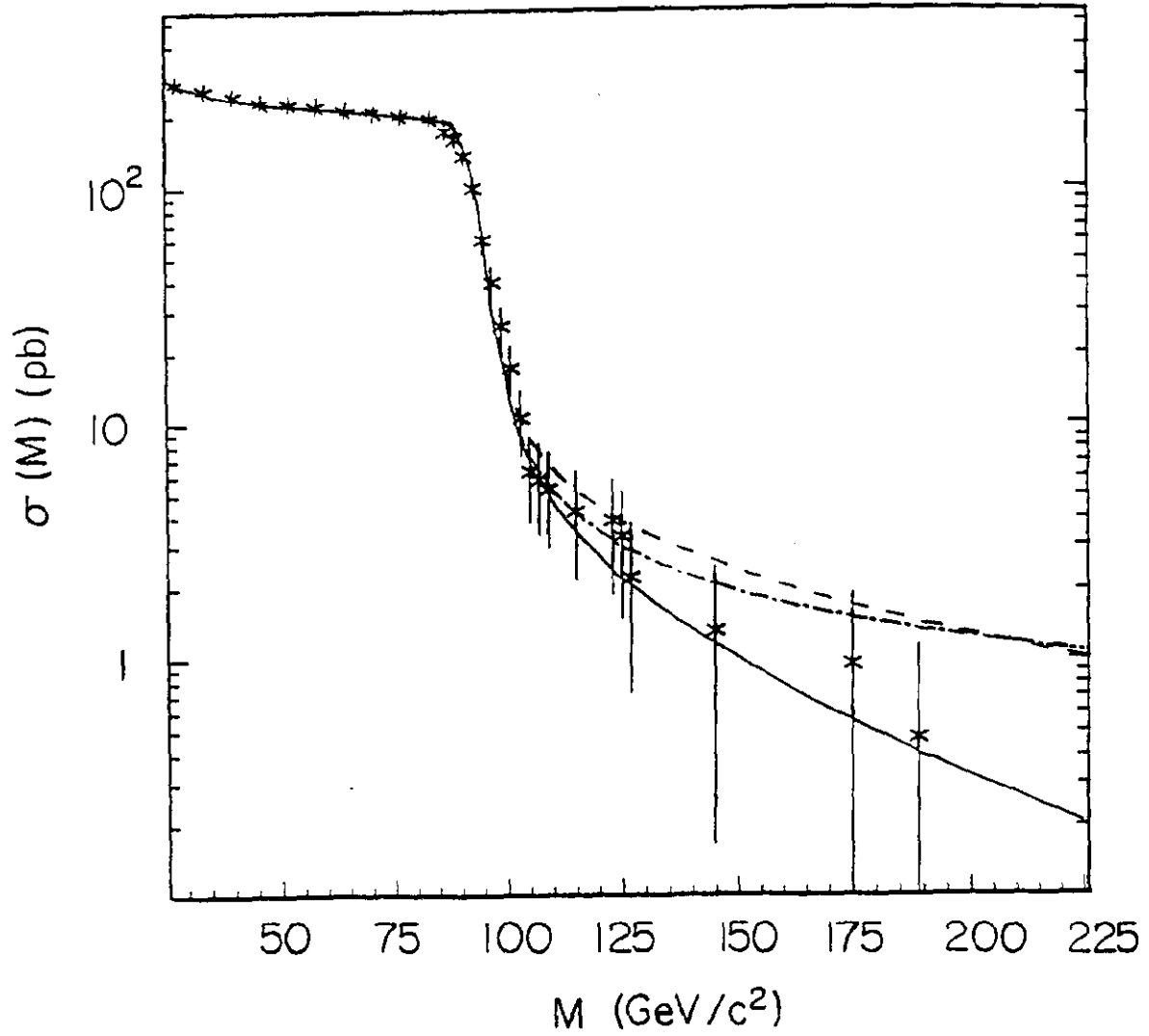


Figure 2: The integral distribution, $\sigma(M) = \int_M^\infty d\sigma$, as a function of pair mass M . The distribution is compared to a lowest order Drell-Yan prediction (solid curve). Also shown are the predictions for compositeness scale parameters $\Lambda_{LL}^- = 2.2 \text{ TeV}$ (dashed line) and $\Lambda_{LL}^+ = 1.7 \text{ TeV}$ (dot-dashed line).

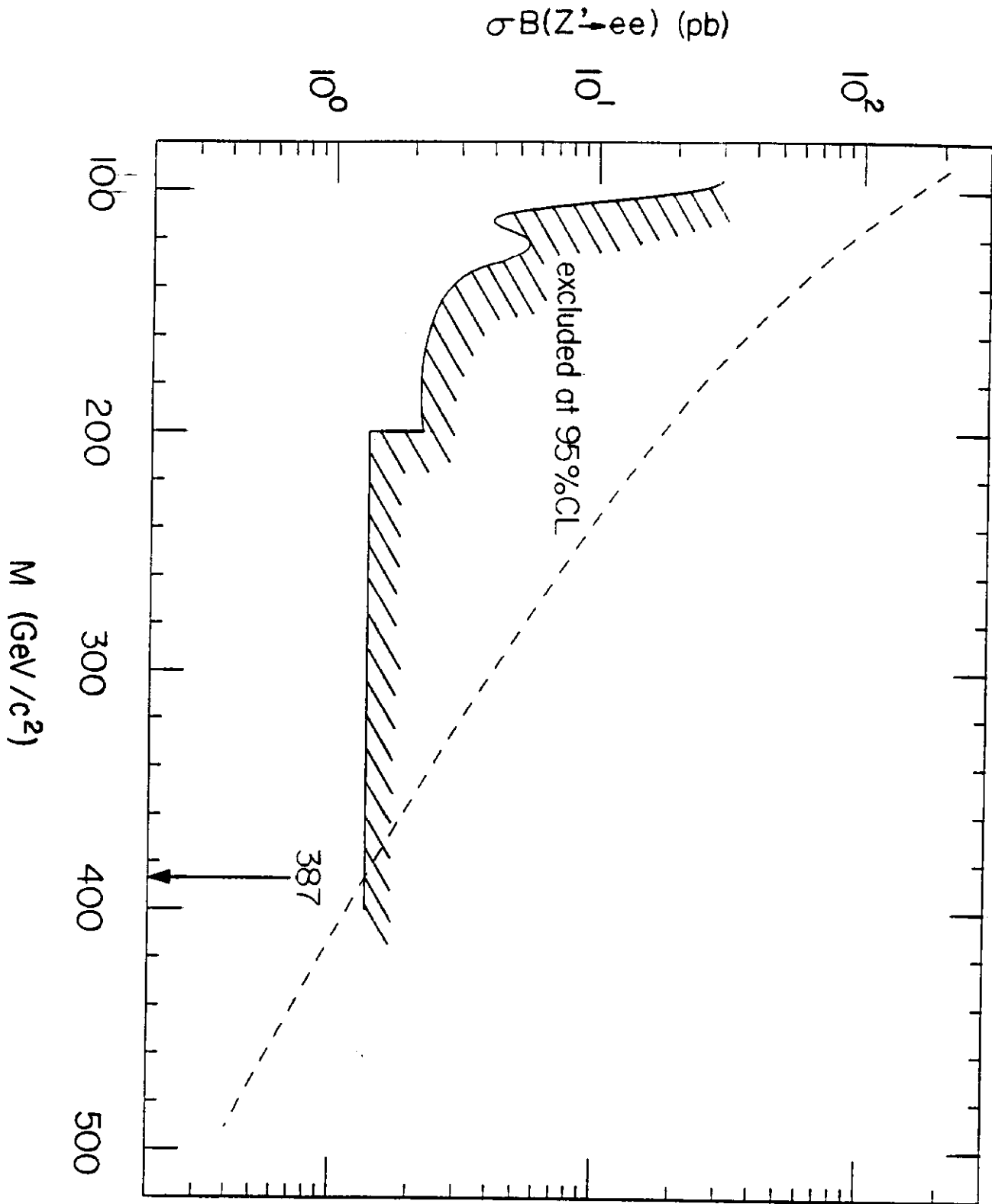


Figure 3: The 95% confidence level limit for $\sigma B_{Z'}$ as a function of $M_{Z'}$, calculated by a maximum likelihood technique for $M < 200 \text{ GeV}/c^2$ and by the absence of events for $M > 200 \text{ GeV}/c^2$. The shaded region is excluded. The dashed line is $\sigma B_{Z'}$ with Standard Model couplings.