

# Search for a Narrow Resonance in $e^+e^-$ to Four Lepton Final States

The *BABAR* Collaboration

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## Abstract

Motivated by recent models proposing a hidden sector with  $\sim$  GeV scale force carriers, we present a search for a narrow dilepton resonance in 4 lepton final states using  $536 \text{ fb}^{-1}$  collected by the *BABAR* detector. We search for the reaction,  $e^+e^- \rightarrow W'W' \rightarrow (l^+l^-)(l'^+l'^-)$ , where the leptons carry the full 4-momentum and the two dilepton pair invariant masses are equal. We do not observe a significant signal and we set 90% upper limits of  $\sigma(e^+e^- \rightarrow W'W' \rightarrow e^+e^-e^+e^-) < (15 - 70) \text{ ab}$ ,  $\sigma(e^+e^- \rightarrow W'W' \rightarrow e^+e^-\mu^+\mu^-) < (15 - 40) \text{ ab}$ , and  $\sigma(e^+e^- \rightarrow W'W' \rightarrow \mu^+\mu^-\mu^+\mu^-) < (11 - 17) \text{ ab}$  in the  $W'$  mass range between 0.24 and  $5.3 \text{ GeV}/c^2$ . Under the assumption that the  $W'$  coupling to electrons and muons is the same, we obtain a combined upper limit of  $\sigma(e^+e^- \rightarrow W'W' \rightarrow l^+l^-l'^+l'^-) < (25 - 60) \text{ ab}$ . Using these limits, we constrain the product of the SM-dark sector mixing and the dark coupling constant in the case of a non-Abelian Higgsed dark sector.

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# 1 Introduction

Recent cosmic ray measurements of the electron and positron flux from ATIC[1], FERMI[2], and PAMELA[3] have spectra which are not well described by galactic cosmic ray models such as GALPROP[4]. For instance, PAMELA shows an increase in the positron/electron fraction with increasing energy. No corresponding increase in the antiproton spectrum is observed. There have been two main approaches attempting to explain these features: astrophysical sources (particularly from undetected, nearby pulsars)[5] and annihilating or decaying dark matter.

Arkani-Hamed *et al.*[6] have introduced a class of theories containing a new “dark force” and a light, hidden sector. In this model, the ATIC and PAMELA signals are due to dark matter particles with mass  $\sim 400 - 800 \text{ GeV}/c^2$  annihilating into the gauge boson force carrier with mass  $\sim 1 \text{ GeV}/c^2$ , which they dub the  $\phi$ , which subsequently decays to Standard Model particles. If the  $\phi$  mass is below twice the proton mass, decays to  $p\bar{p}$  are kinematically forbidden allowing only decays to states like  $e^+e^-$ ,  $\mu^+\mu^-$ , and  $\pi\pi$ . If the dark force is non-Abelian, this theory can also accommodate the 511 keV signal found by the INTEGRAL satellite [7] and the DAMA modulation data [8].

The dark sector couples to the Standard Model through kinetic mixing with the photon. Thus low-energy/high luminosity  $e^+e^-$  experiments like *BABAR* are in excellent position to probe these theories. Recent papers by Batell *et al.* [9] and Essig *et al.* [10] have discussed the prospects for finding evidence for the dark sector at the B-Factories in the Abelian and non-Abelian cases, respectively. In the Abelian case, the signatures would be  $e^+e^- \rightarrow \gamma\phi \rightarrow \gamma l^+l^-$  or  $e^+e^- \rightarrow \phi h' \rightarrow 3(l^+l^-)$  (where  $h'$  is a “dark Higgs”). There are actually two non-Abelian scenarios: the Higgsed case and the confined case (“dark QCD”). In the Higgsed case there are at least three dark particles in play:  $A'$  which mixes with the photon, another gauge boson  $W'$ , and the dark Higgs  $h'$ . In this regime, signatures are  $e^+e^- \rightarrow W'W' \rightarrow l^+l^-l^+l^-$  (via a virtual  $A'$ ) and  $e^+e^- \rightarrow \gamma A' (\rightarrow W'W') \rightarrow \gamma l^+l^-l^+l^-$ , plus “Higgs'-strahlung” processes which may lead to missing energy. Finally, the confined case could lead to a proliferation of “dark mesons”, whose lowest mass states decay to leptons. Depending on the scenario and the coupling between the Standard Model and dark sectors, cross sections could be as large as a few femtobarns at *BABAR* which would translate to hundreds of events observed in the detector.

In this note we describe a search for the  $W'$  in the reaction  $e^+e^- \rightarrow W'W' \rightarrow l^+l^-l^+l^-$  in exclusive 4-lepton final states, where we require that the four leptons carry the full center of mass energy and that the two dilepton pairs have the same invariant mass.

## 2 The *BABAR* Detector and Dataset

The data used in this analysis were collected with the *BABAR* detector at the PEP-II asymmetric energy  $e^+e^-$  storage rings between 1999 and 2008 and correspond to an integrated luminosity of  $536 \text{ fb}^{-1}$ . This data was mostly at the  $\Upsilon(4S)$  peak but it also includes collisions at the  $\Upsilon(2S)$  and  $\Upsilon(3S)$  as well as off-resonant data.

To study signal efficiency and resolution,  $e^+e^- \rightarrow W'W' \rightarrow l^+l^-l^+l^-$  Monte Carlo (MC) samples were generated (where  $l=e$  or  $\mu$ ) for different values of  $W'$  mass using the MadGraph event generator[11]. There were  $10^4$  events generated at each mass value of: 0.3, 0.4, 0.5, 0.7, 1.0, 1.5, 2.0, 3.0, 4.0, and 5.0  $\text{ GeV}/c^2$ . To study backgrounds, we have inspected  $B\bar{B}$  ( $\sim 3x$  luminosity),  $uds$ ,  $c\bar{c}$ , and  $\tau\tau$  MC samples (each  $\sim 1x$  luminosity). In addition we created 4-lepton QED samples using the diag36 event generator[12].



A detailed description of the *BABAR* detector is given in [13]. Charged-particle trajectories are measured by a five-layer, double-sided silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH) coaxial with a 1.5 T magnetic field. Charged-particle identification is achieved by combining the information from a ring-imaging Cherenkov device (DIRC) with the ionization energy loss ( $dE/dx$ ) measurements from the DCH and SVT. Photons are detected in a CsI(Tl) electromagnetic calorimeter (EMC) inside the coil. Muon candidates are identified in the instrumented flux return (IFR) of the superconducting solenoid. We use GEANT4-based [14] software to simulate the detector response and account for the varying beam and environmental conditions.

### 3 Event Selection

We search for the exclusive pair production of a narrow resonance, consistent with the detector resolution, decaying to leptons and with a mass in the range between  $240 \text{ MeV}/c^2$  to  $\sqrt{s}/2$ . The signature is 4 leptons with zero total charge carrying the full beam momentum where the two dilepton invariant masses are equal. This topology, particularly the equal invariant masses, is quite unique and the only backgrounds are from 4-lepton QED processes. The full selection criteria are described below. We used 10% of the data as a test (*blind*) sample to choose our selection and signal extraction procedures before looking at the full dataset.

We begin by selecting events with:

- 4 charged tracks
- two leptons with  $p_{\text{CM}} > 1.5 \text{ GeV}/c$
- sum of the absolute value of momentum of all tracks  $> 6 \text{ GeV}/c^2$  or the total visible energy (lab)  $> 8 \text{ GeV}/c^2$

We reconstruct 4-lepton candidates from combinations of two  $W' \rightarrow l^+l^-$  candidates. The lepton candidates are chosen by their signatures in the EMC and IFR. The  $W'$  candidates are formed from  $e^+e^-$  or  $\mu^+\mu^-$  pairs. We then select events which satisfy the following criteria:

- $[N_e, N_\mu] = [4, 0], [2, 2], \text{ or } [0, 4]$
- $M_{\text{lepton}} > 10 \text{ GeV}/c^2$
- the helicity angle of a lepton pair, defined as the angle between the positive lepton and the lepton-pair flight direction, is required to be  $|\cos(\theta_H)| < 0.95$  for each pair
- to reduce background from photon conversions, we require the flight significance, defined as the  $W'$  candidates decay length from the interaction point divided by the error, is  $< 4\sigma$  for each pair
- to reduce background from radiative Bhabha events, we require the angle between the decay planes of the lepton pairs,  $\phi_{DPN} > 0.2$

The 4-lepton candidate is then fit constraining the four-momentum to the total beam momentum and the vertex to the interaction point.

At this point, we can exploit the fact that both dilepton pairs for our signal events have the same invariant mass. The 2-dimensional distributions of dilepton masses for each final state after

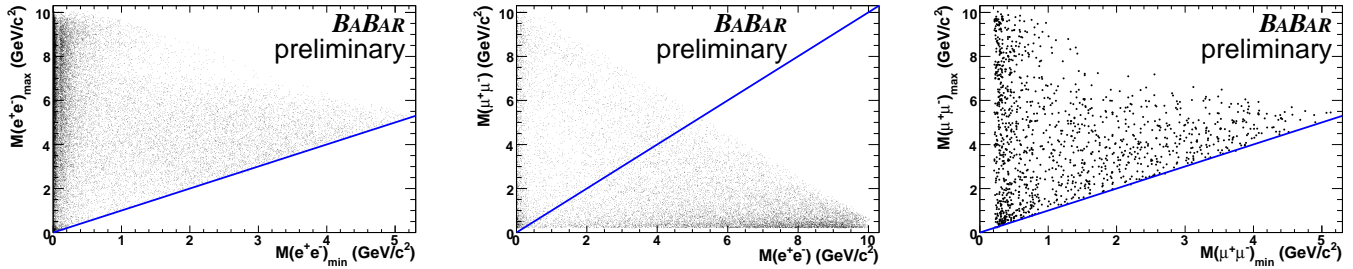


Figure 1: The dilepton invariant mass distributions from data for (left to right)  $e^+e^-e^+e^-$ ,  $e^+e^-\mu^+\mu^-$ , and  $\mu^+\mu^-\mu^+\mu^-$  after all other cuts. The solid lines denotes  $m_1 = m_2$ .

all of the above cuts for the blinding sample is shown in Figure 1. We define the transformed masses:

$$\bar{m} = (m_1 + m_2) / 2 \quad (1)$$

$$\Delta m = |m_1 - m_2| \quad (2)$$

where  $m_1$  and  $m_2$  are the dilepton invariant masses. The distribution of events for these variables is shown in Figure 2. We impose a cut on  $\Delta m$  (shown as the solid line in Figure 2) of  $\Delta m < 0.25 \text{ GeV}/c^2$  for  $\bar{m} < 1.0 \text{ GeV}/c^2$  and  $\Delta m < 0.50 \text{ GeV}/c^2$  for  $\bar{m} > 1.0 \text{ GeV}/c^2$ . Because of the threshold effects in  $\mu^+\mu^-\mu^+\mu^-$ , we tighten the  $\Delta m$  cut in a linear fashion below  $\bar{m} < 4 \times M(\mu)$ .

In the case of the  $e^+e^-e^+e^-$  and  $\mu^+\mu^-\mu^+\mu^-$  final state, there are two possible  $l^+l^-$  pair combinations. If both pairings pass all cuts, the pair with the smallest value of  $\Delta m$  is used. For data, we see two pairings passing all cuts except the  $\Delta m$  cut for 25% of  $e^+e^-e^+e^-$  events and for 44% of the  $\mu^+\mu^-\mu^+\mu^-$  events. Table 1 shows the progressive and total efficiencies for the three different final states of  $W'W' \rightarrow l^+l^-l^+l^-$  (assuming the mass of the  $W'$  is  $1 \text{ GeV}/c^2$ ) as well as the progressive efficiency for the data. As shown in the table, the loose cut on  $\Delta m$  is extremely powerful at reducing the background while not affecting the signal efficiency. After all selection, there are 28303 events remaining in our data sample; of these 16531 are  $e^+e^-e^+e^-$  events, 9592 are  $e^+e^-\mu^+\mu^-$  events, and 2180 are  $\mu^+\mu^-\mu^+\mu^-$  events.

## 4 Signal Extraction

Our aim is to perform a search for a narrow peak in the  $\bar{m}$  range from  $240 \text{ MeV}/c^2$  up to  $\sqrt{s}/2$ . After the selection described in the previous section, the expected backgrounds are quite low and we have decided to perform a cut-and-count analysis in bins of  $\bar{m}$ , using the the  $\Delta m$  variable to define the signal and background regions. The number of observed signal events in a  $\bar{m}$  bin is then:

$$N_{sig} = N_{signal\ region} - N_{bkg\ region} \times \frac{A_{signal}}{A_{background}} \quad (3)$$

where  $A_{signal}$  ( $A_{background}$ ) is the area of the signal (background)  $\Delta m$  region.

In this section, we will discuss the signal efficiency,  $\Delta m$  shapes (including the definition of signal and background regions) and background rates as a function of  $\bar{m}$  and the method we plan to use in extracting the signal yields and setting limits.

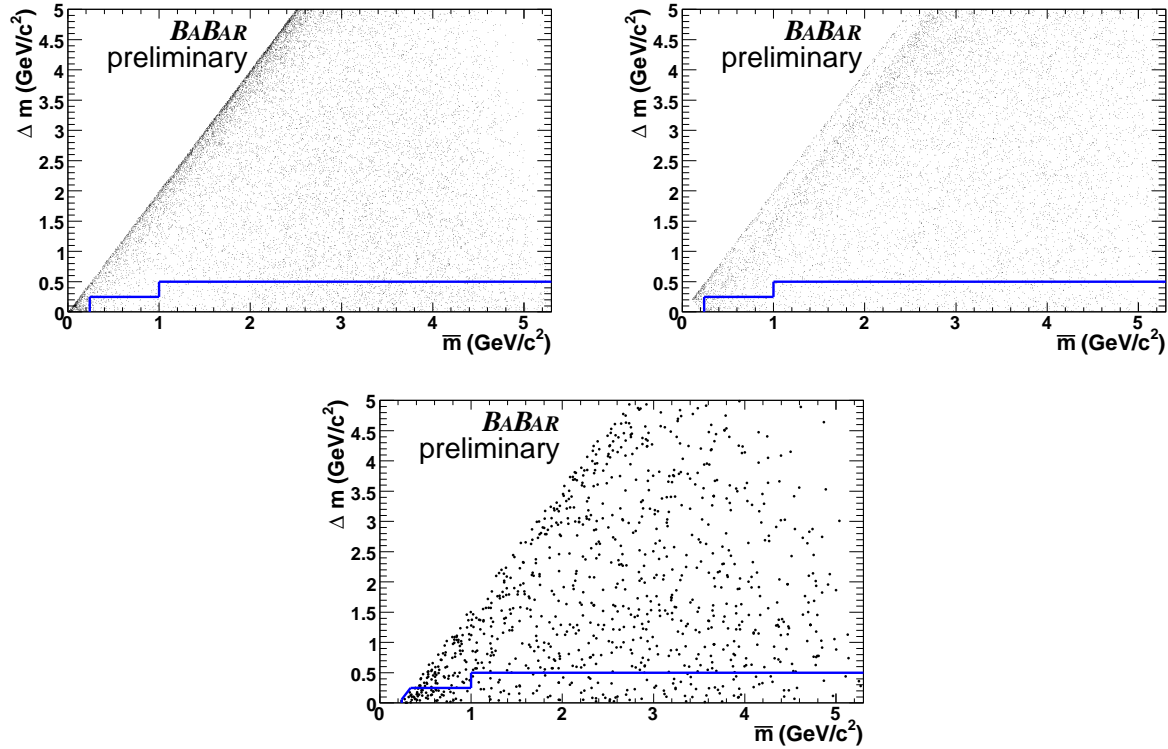


Figure 2: The transformed mass distributions,  $\Delta m$  vs  $\bar{m}$ , from data for (left to right)  $e^+e^-e^+e^-$ ,  $e^+e^-\mu^+\mu^-$ , and  $\mu^+\mu^-\mu^+\mu^-$  after all other cuts. The solid lines denotes the  $\Delta m$  cut value.

#### 4.1 Efficiency and $\Delta m$ resolution dependence on the $W'$ mass

The efficiency for different generated values of the  $W'$  mass is shown in Figure 3. The efficiency decreases from  $\sim 45\%$  at 1 GeV to 25 – 30% at high masses depending on the decay mode. There is a dip in efficiency for mass pairs around 500 MeV/ $c^2$  which is due to the opening angle of the lepton pair at this mass coinciding with the bending angle at the EMC, precluding us from identifying the two particles for a fraction of the events. The  $\Delta m$  resolution also varies significantly as a function of  $W'$  mass. Figure 4 shows the distributions of  $\Delta m$  for four different mass values. The resolution of  $\Delta m$  increases with increasing  $W'$  mass. Since the background  $\Delta m$  distribution is basically flat and roughly constant in  $\bar{m}$  (see Section 4.2), the effect is to reduce the sensitivity at higher masses.

Figure 5 shows the values of the  $\Delta m$  cut which retains 90% of the signal as a function of  $\bar{m}$ . We use this cut value to define the signal ( $\Delta m < cutVal$ ) and background ( $dm > cutVal$ ) regions for the cut-and-count signal extraction. Recall that the maximum value of  $\Delta m$  is 0.25(0.5) GeV/ $c^2$  for  $\bar{m} < (>)1.0$  GeV/ $c^2$ . The solid line is the result of a 4th-order polynomial fit which we use to extrapolate between  $\bar{m}$  points.

#### 4.2 Background composition

While we ultimately use the  $\Delta m$  sidebands to determine our background level, we have also used MC to study the composition of the background. In generic  $q\bar{q}$ ,  $B^0\bar{B}^0$ ,  $B^+B^-$ , and  $\tau^+\tau^-$  samples we find only a single event passing the cuts (a  $q\bar{q}$  event in the 4-electron final state). From this we

Table 1: Selection efficiencies relative to the previous cut with binomial errors for the three signal decay modes assuming  $M(W') = 1 \text{ GeV}/c^2$  and for onpeak data.

Cuts	Relative Efficiencies (%)			
	$\varepsilon_{W'W' \rightarrow 4e}$	$\varepsilon_{W'W' \rightarrow 2e2\mu}$	$\varepsilon_{W'W' \rightarrow 4\mu}$	$\varepsilon_{data}$
Preselection	$61.4 \pm 0.5$	$68.2 \pm 0.5$	$73.4 \pm 0.4$	— — — —
N(tracks)=4	$93.3 \pm 0.3$	$95.5 \pm 0.3$	$97.1 \pm 0.2$	$83.7 \pm 0.0$
N(leptons)	$99.9 \pm 0.1$	$100.0 \pm 0.0$	$100.0 \pm 0.0$	$98.7 \pm 0.0$
$M(4l) > 10 \text{ GeV}$	$87.2 \pm 0.5$	$93.2 \pm 0.3$	$98.1 \pm 0.2$	$66.2 \pm 0.0$
$ \cos(\theta_H)  < 0.95$	$99.9 \pm 0.1$	$99.6 \pm 0.1$	$98.8 \pm 0.1$	$18.2 \pm 0.0$
fit. sig. $< 4\sigma$	$97.2 \pm 0.2$	$96.5 \pm 0.4$	$99.1 \pm 0.1$	$54.6 \pm 0.1$
$\mu$ PID	$100.0 \pm 0.0$	$81.9 \pm 0.6$	$70.3 \pm 0.6$	$74.2 \pm 0.1$
$\phi_{DPN} > 0.2$	$92.4 \pm 0.4$	$93.2 \pm 0.4$	$93.6 \pm 0.4$	$37.0 \pm 0.1$
$\Delta(m)$	$98.3 \pm 0.2$	$99.8 \pm 0.1$	$99.6 \pm 0.1$	$3.8 \pm 0.1$
Total Efficiency	$43.7 \pm 0.5$	$44.5 \pm 0.5$	$44.8 \pm 0.5$	— — — —

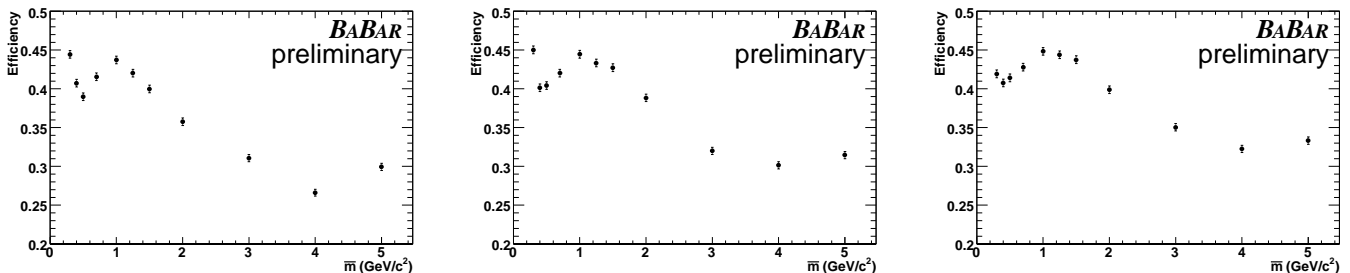


Figure 3: The signal efficiency versus  $W'$  mass for (left to right)  $W'W' \rightarrow e^+e^-e^+e^-$ ,  $W'W' \rightarrow e^+e^-\mu^+\mu^-$ , and  $W'W' \rightarrow \mu^+\mu^-\mu^+\mu^-$  after all cuts.

conclude that our background is dominated by QED processes.

We have generated  $e^+e^-\mu^+\mu^-$  and  $\mu^+\mu^-\mu^+\mu^-$  samples<sup>9</sup> using the `diag36` generator and compared the MC to our selected dataset. We find good agreement both in the scale and shape between data and the four-lepton QED MC. From the MC, we expect to observe  $16241 \pm 250$   $\mu^+\mu^-\mu^+\mu^-$  events in the full dataset while we observe  $15666 \pm 125$  (statistical errors only). For  $e^+e^-\mu^+\mu^-$  we expect  $219927 \pm 3450$  and observe  $185499 \pm 431$  events.

The background distributions in  $\Delta m$  and  $\overline{m}$ , after all selection, are shown in Figure 6. The background  $\Delta m$  distributions were fit with a line in different slices of  $\overline{m}$ , the slopes of which are plotted for the three modes in Figure 7, and the slopes are consistent with 0. When extracting the signal yields, we assume a uniform background distribution, and take into account the uncertainties in the slope as a systematic error. We use the full dataset for the above plots; any signal present would be completely washed out when projected onto the  $\Delta m$  or  $\overline{m}$  axis.

<sup>9</sup>Due to the enormous  $e^+e^-e^+e^-$  QED cross-section, this mode is difficult to generate efficiently.

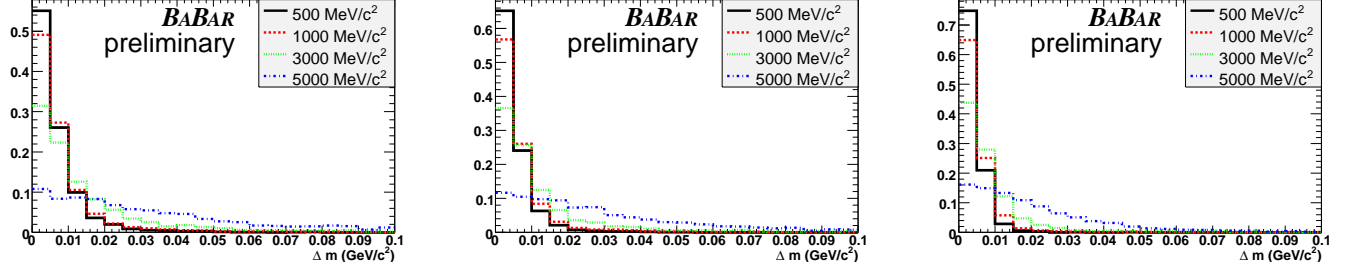


Figure 4: The  $\Delta m$  distributions for four different  $W'$  mass values (left to right)  $W'W' \rightarrow e^+e^-e^+e^-$ ,  $W'W' \rightarrow e^+e^-\mu^+\mu^-$ , and  $W'W' \rightarrow \mu^+\mu^-\mu^+\mu^-$  after all cuts.

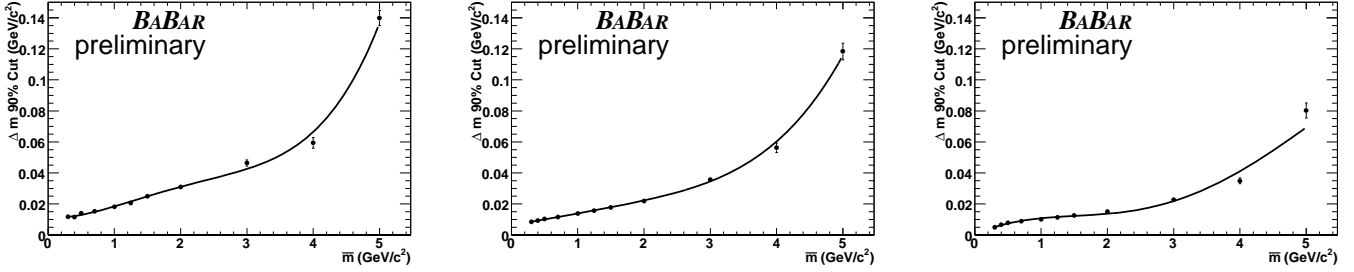


Figure 5: The values of the cut on  $\Delta m$  keeping 90% of signal events as a function of  $W'$  mass for (left to right)  $W'W' \rightarrow e^+e^-e^+e^-$ ,  $W'W' \rightarrow e^+e^-\mu^+\mu^-$ , and  $W'W' \rightarrow \mu^+\mu^-\mu^+\mu^-$ . The line is a fit to a fourth order polynomial. This cut defines our signal and background region.

### 4.3 Signal extraction and limit setting

In this analysis, our aim is to obtain a limit (or observe a signal) for  $e^+e^- \rightarrow W'W'$  as function of the presumed  $W'$  mass. To this end, search for a signal in steps of the average dilepton mass  $\bar{m}$ . We have chosen the  $\bar{m}$  bin size to be  $20 \text{ MeV}/c^2$ , which is a large enough range to fully contain any signal. Figure 8 shows the RMS of  $\bar{m}$  at the different mass points. We scan  $\bar{m}$  in steps of  $10 \text{ MeV}/c^2$ , half the bin size, so that at least one bin will fully contain the signal. Thus, in the  $\bar{m}$  range from  $0.24 - 5.3 \text{ GeV}/c^2$ , there are 507 total bins. We define the signal and background regions in  $\Delta m$  by cutting at a value of  $\Delta m$  so that the signal is 90% efficient, as discussed above.

With this framework, the number of background events in a given  $\bar{m}$  bin is quite small. Except at low  $\bar{m}$ , the expected number of background events in the entire  $\Delta m$  range is typically below 100 events in a  $\bar{m}$  bin, particularly for the  $\mu^+\mu^-\mu^+\mu^-$  mode where it is below 5 events. Thus there will be relatively large fluctuations in the background due to Poisson statistics and the limit setting procedure must take this into account. We use a profile likelihood technique[15] to set limits in the presence of nuisance parameters, such as the expected background yield. Using this technique, we obtain a confidence level ( $CL$ ) for the presence of signal defined as:

$$CL = \text{Prob}(-2 \log(\mathcal{L}_{s=0}) - 2 \log(\mathcal{L}_{max})) \quad (4)$$

where  $\mathcal{L}_{s=0}$  is the value of the likelihood at 0 signal events and  $\mathcal{L}_{max}$  is the maximum value of the likelihood.

Since in our dataset we will have 507 correlated measurements (204 independent measurements), each at a different  $\bar{m}$ , we need to determine a criteria for a signal observation. Simply asking whether

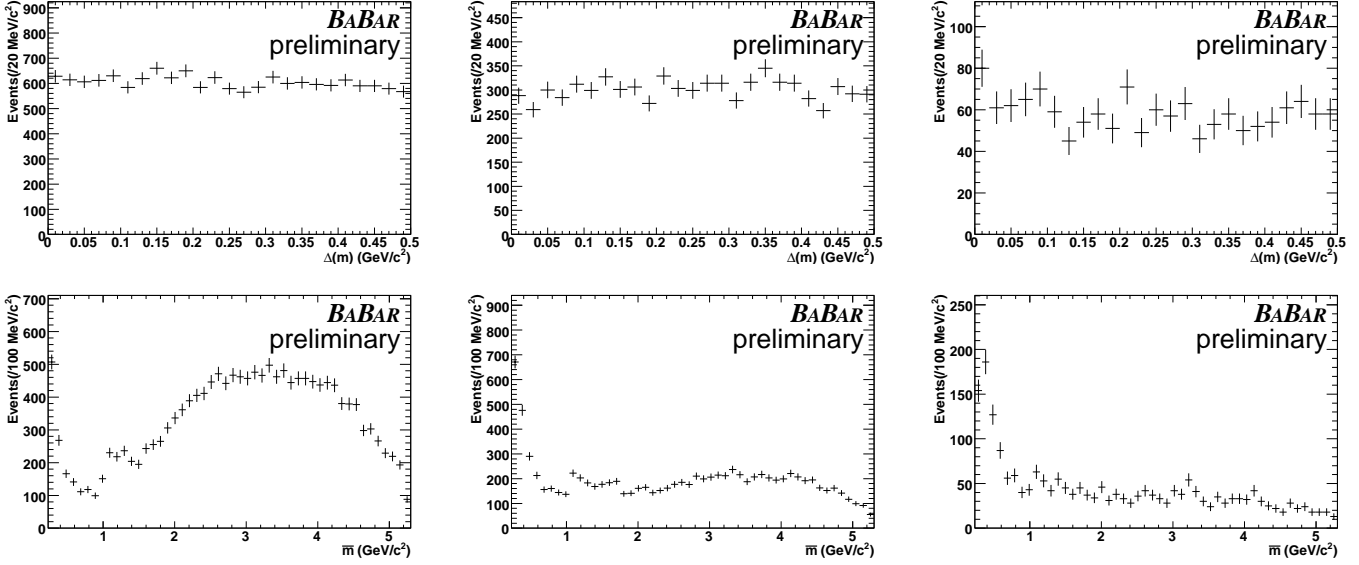


Figure 6: The background (top)  $\Delta m$  and (bottom)  $\bar{m}$  distributions for (left-to-right)  $e^+e^-e^+e^-$ ,  $e^+e^-\mu^+\mu^-$ , and  $\mu^+\mu^-\mu^+\mu^-$  from the full dataset. For the  $\Delta m$  plots, we have required  $\bar{m} > 1\text{GeV}$  to that all events have the same upper  $\Delta m$  value. The effect of the  $\Delta m$  cut increasing from  $0.25\text{ GeV}/c^2$  to  $0.5\text{ GeV}/c^2$  at  $\bar{m} = 1.0\text{ GeV}/c^2$  can be seen in the  $\bar{m}$  plots.

an individual bin has an observed yield in it  $> 3\sigma$  above 0 is not enough since the probability to observe at least 1  $> 3\sigma$  fluctuation in one of the  $\bar{m}$  bins is 0.3 (as determined from the simulation described below). We need to redefine the  $X\sigma$  levels for the new question “What is the chance that I see a background fluctuation above  $X\sigma$  in our 507 correlated trials?”. We have done this by generating many simulated datasets (toys) with the expected  $\bar{m}$  and  $\Delta m$  background distributions with 0 signal and plotting the highest value of the signal confidence level observed over that dataset, which we call  $CL_{max}$ . The results of these simulations are shown in Figure 9, plotting the more convenient variable  $-\ln(1 - CL_{max})$ . As a reference, the distribution of values  $-\ln(1 - CL)$  from a single bin (i.e. not the largest value in an  $\bar{m}$  scan) is shown in Figure 10. Table 2 shows the values of  $-\ln(1 - CL_{max})$  that correspond to 1-4 $\sigma$  fluctuations of the background (also displayed

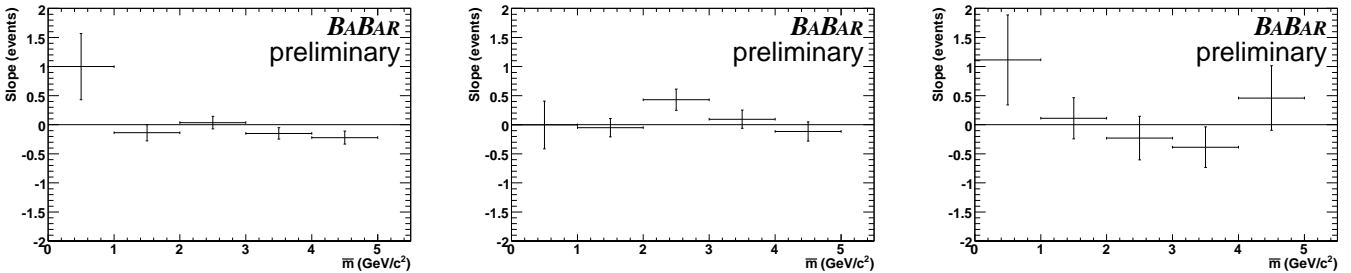


Figure 7: The slope of the background  $\Delta m$  distributions for (left-to-right)  $e^+e^-e^+e^-$ ,  $e^+e^-\mu^+\mu^-$ , and  $\mu^+\mu^-\mu^+\mu^-$  as a function of  $\bar{m}$ . The mean values of the slopes are:  $-0.11 \pm 0.06$ ,  $0.07 \pm 0.08$ , and  $-0.02 \pm 0.19$ .

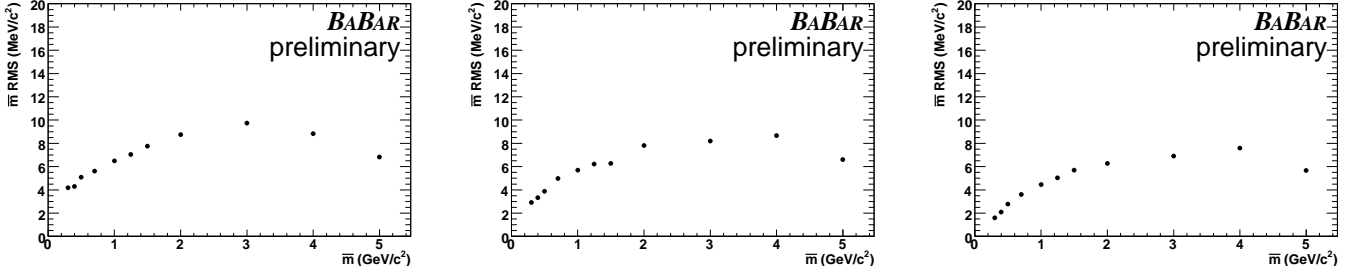


Figure 8: The  $\overline{m}$  RMS versus  $W'$  mass for (left to right)  $W'W' \rightarrow e^+e^-e^+e^-$ ,  $W'W' \rightarrow e^+e^-\mu^+\mu^-$ , and  $W'W' \rightarrow \mu^+\mu^-\mu^+\mu^-$ .

on the plot). Although the background levels are different, the values are consistent between the three modes.

Additionally, we calculate the combined max confidence level, defined as:

$$(1 - CL_{max,C}) = (1 - CL_{max,Ae})(1 - CL_{max,2e2\mu})(1 - CL_{max,4\mu}) \quad (5)$$

whose distribution for background-only toys is shown in the bottom right plot of Figure 9. If lepton universality holds, this limit is potentially more sensitive than the individual confidence levels and allows us to catch a signal that is not significant in any single final state. Our criteria to claim evidence of a signal is to observe the largest value of  $-\ln(1 - CL_{max})$  in any of  $e^+e^-e^+e^-$ ,  $e^+e^-\mu^+\mu^-$ ,  $\mu^+\mu^-\mu^+\mu^-$  or in the combined confidence level that is greater than the  $3\sigma$  values given in Table 2.

Table 2: Values of the 1-,2-,3-,4- $\sigma$  limits for  $-\ln(1 - CL_{max})$  in the three final states.

Signif.	$P(CL_{max}) < X$	$-\ln(1 - CL_{max})$			Combined
		$e^+e^-e^+e^-$	$e^+e^-\mu^+\mu^-$	$\mu^+\mu^-\mu^+\mu^-$	
$1\sigma$	0.84135	7.2	7.1	7.0	10.2
$2\sigma$	0.97725	9.3	9.2	9.0	12.4
$3\sigma$	0.99865	12.2	12.1	11.6	15.8
$4\sigma$	0.99997	16.3	16.1	14.5	19.2

## 5 Systematic Errors

There are two types of systematic errors in this analysis: systematics that effect both the yield and cross-section upper limits (e.g. errors due to uncertainties in the background shape) and systematics that just affect the cross-section (e.g. tracking efficiency errors). The second type of error does not effect the signal significance. Table 3 summarizes the values the systematic errors for the different sources described below.

- **$\Delta m$  background shape:** We assume that the background is uniform in  $\Delta m$  and with our limited MC statistics but we have no *a priori* reason to expect this. While the background  $\Delta m$  does look quite flat and does not appear to depend on  $\overline{m}$ , see Figure 7), we still need

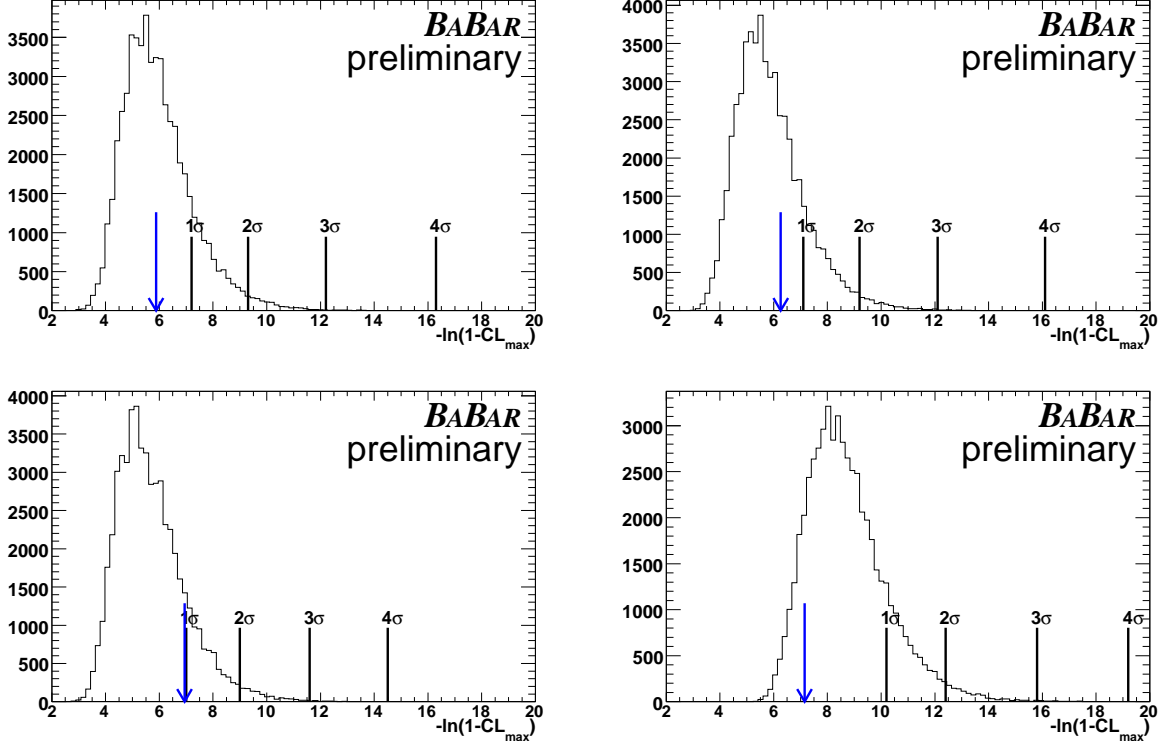


Figure 9: The distribution of  $-\ln(1-CL_{max})$  from toy with the arrow showing the value of  $-\ln(1-CL_{max})$  observed in data. The plots are (left to right, top to bottom)  $e^+e^-e^+e^-$ ,  $e^+e^-\mu^+\mu^-$ ,  $\mu^+\mu^-\mu^+\mu^-$ , and the three modes combined.

to account for uncertainties. Consequently, we estimate the  $\Delta m$  background shape from the data itself.

In order to estimate the size of this uncertainty, we have generated toy  $\overline{m}$  scans (background only) with a slope and calculated the signal yield assuming a slope of 0. The mean  $\Delta m$  slopes are given in the caption of Figure 7. For this study, we shift the mean value of the slope ( $B_m$ ) by:

- for  $B_m < 0$ , we assign the slope to be  $B_m - \sigma$
- for  $B_m > 0$ , we assign the slope to be  $-\sigma$

where  $\sigma_m$  is the error on the mean. We only use the negative slope values because we are primarily interested in how this biases us toward more signal. The results of this study are shown in Figure 11 as the observed signal yield bias vs  $\overline{m}$  for the three modes. The bias depends on  $\overline{m}$  because both the number of background events in the full  $\Delta m$  region and because the  $\Delta m$  signal/background region definitions depend on  $\overline{m}$ .

We incorporate this bias into a systematic error on the cross section by converting the bias in the number of events into a cross section in  $\overline{m}$  bins. The error is largest for the  $e^+e^-e^+e^-$  mode where at high  $\overline{m}$  is as large as  $\sim 5$  ab; for the other two modes this error is generally  $< 1$  ab.



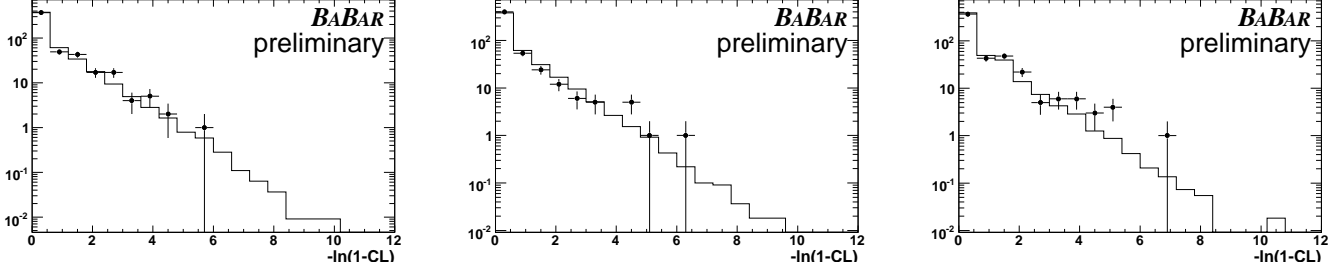


Figure 10: The distribution of values of  $-\ln(1 - CL)$  from (error bars) data and (solid histogram) toy for (left to right)  $e^+e^-e^+e^-$ ,  $e^+e^-\mu^+\mu^-$ , and  $\mu^+\mu^-\mu^+\mu^-$ .

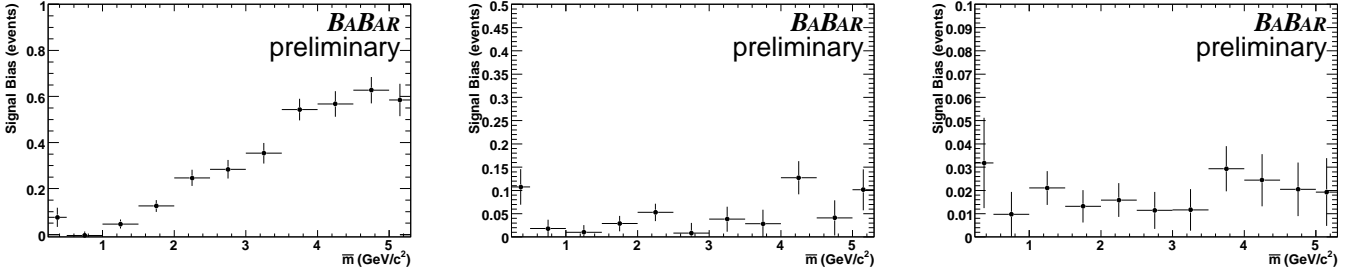


Figure 11: The positive signal yield bias due to the uncertainty in the background  $\Delta m$  slope as a function of  $\bar{m}$  for (left-to-right)  $e^+e^-e^+e^-$ ,  $e^+e^-\mu^+\mu^-$ , and  $\mu^+\mu^-\mu^+\mu^-$ .

- **$\Delta m$  signal shape:** We use MC at select mass values to interpolate the 90% efficiency  $\Delta m$  cut value to cover all masses. The interpolation is done with a polynomial and we vary the parameters of the polynomial within their errors to get the error in the  $\Delta m$  cut value. This is then translated into an efficiency error. The magnitude of this error is  $\sim 1\%$  and depends slightly on  $\bar{m}$ .
- **interpolation of total efficiency:** We use MC at select mass values to interpolate the total efficiency to all masses. The interpolation is done by interpolating the efficiency linearly between the MC mass points. We propagate the errors in the efficiency points due to MC statistics through the interpolation. In addition, we take the difference between a linear and quadratic interpolation and assign the difference, added in quadrature with the statistical error, as the systematic. The magnitude of this error is  $\sim 3\%$  and depends slightly on  $\bar{m}$ .
- **particle ID:** we assign a 1% error per electron and 2% error per muon on the cross sections to account for the systematic error in the PID efficiency. This is the dominant systematic error.
- **tracking efficiency:** we assign 0.21% error per track on the cross sections to account for the systematic error in the charged track reconstruction efficiency.
- **luminosity:** we assign a 1.1% error on the cross sections due to the uncertainty in the total luminosity.

We add these sources of systematic error in quadrature and scale the statistical 90% upper limit by the fractional systematic error to obtain the final upper limit. This error depends slightly on

$\bar{m}$  but is around 5% for  $e^+e^-e^+e^-$  (up to 10% for high  $\bar{m}$ ), 6.5% for  $e^+e^-\mu^+\mu^-$ , and 8.2% for  $\mu^+\mu^-\mu^+\mu^-$ .

Table 3: Sources of systematic uncertainties and their contributions.

Source	$e^+e^-e^+e^-$	$e^+e^-\mu^+\mu^-$	$\mu^+\mu^-\mu^+\mu^-$
$\Delta m$ bkg shape	0.4-5.5 ab	0.1-0.7 ab	0.1-0.3 ab
$\Delta m$ signal efficiency	1%	1%	1%
total signal efficiency	3%	3%	3%
particle ID	4%	6%	8%
tracking efficiency	0.8%	0.8%	0.8%
luminosity	1.1%	1.1%	1.1%

## 6 Results and Conclusions

The spectra for the entire dataset (including the 10% test sample) show no significant signal in any of  $e^+e^-e^+e^-$ ,  $e^+e^-\mu^+\mu^-$ ,  $\mu^+\mu^-\mu^+\mu^-$  final states, or the combination of the three. The summary of results is shown in Table 4. The distribution of observed signal events, after background subtraction, for all bins in  $\bar{m}$  is shown in Figure 12. The values of  $-\ln(1 - CL)$  versus  $\bar{m}$  are shown in Figure 13 and show no bins above the  $3\sigma$  value, shown on the plots. The raw distribution of  $-\ln(1 - CL)$  compared to toy simulations with only background is shown in Figure 10 and is in good agreement. The plots in Figure 9 compare the values of the  $-\ln(1 - CL_{max})$  observed in data with the distribution found in toy simulation.

Table 4: Summary of the  $-\ln(1 - CL_{max})$  observed in data.

	$-\ln(1 - CL_{max})$	$\bar{m}_{max}$ (GeV)
$e^+e^-e^+e^-$	5.88	5.27
$e^+e^-\mu^+\mu^-$	6.26	1.44
$\mu^+\mu^-\mu^+\mu^-$	6.94	2.23
Combined	7.15	1.66

Correcting for efficiency (Figure 3, using linear interpolation between points and including the 90% cut on  $\Delta m$ ) and scaling by the luminosity, we obtain a 90% upper limit for the cross section as shown in Figures 14 and 15. The points in these plots are the upper limit for each bin in  $\bar{m}$  while the solid lines are the averages of the upper limits in the  $\bar{m}$  region shown. We set upper limits of  $\sigma(e^+e^- \rightarrow W'W' \rightarrow e^+e^-e^+e^-) < (15 - 70)$  ab,  $\sigma(e^+e^- \rightarrow W'W' \rightarrow e^+e^-\mu^+\mu^-) < (15 - 40)$  ab, and  $\sigma(e^+e^- \rightarrow W'W' \rightarrow \mu^+\mu^-\mu^+\mu^-) < (11 - 17)$  ab depending on  $W'$  mass (taking the ranges from the averaged limits).

Assuming lepton universality ( $BR(W' \rightarrow e^+e^-) = BR(W' \rightarrow \mu^+\mu^-)$ ), we combine the three modes to obtain upper limits for the reaction  $e^+e^- \rightarrow W'W' \rightarrow l^+l^-l'^+l'^-$ . We obtain this limit by combining the individual profile likelihood functions for the three decay modes as a function of

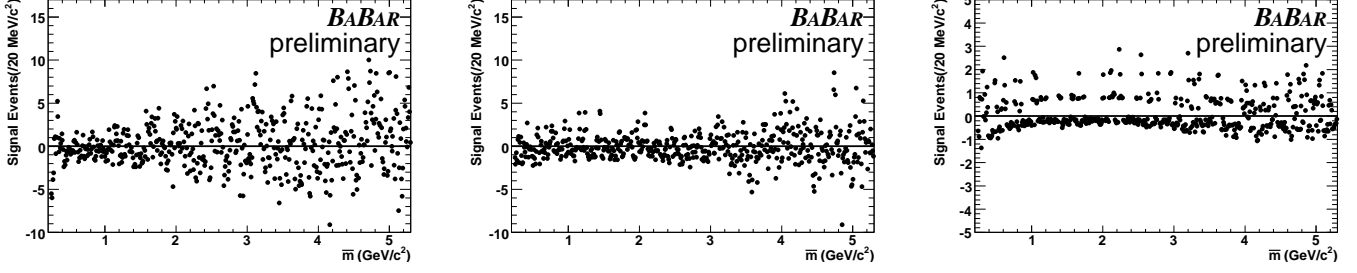


Figure 12: The number of signal events after background subtraction versus  $\bar{m}$  for (left to right)  $e^+e^-e^+e^-$ ,  $e^+e^-\mu^+\mu^-$ , and  $\mu^+\mu^-\mu^+\mu^-$ . The band structure evident in the  $\mu^+\mu^-\mu^+\mu^-$  plot is due to the very low number of events in this mode.

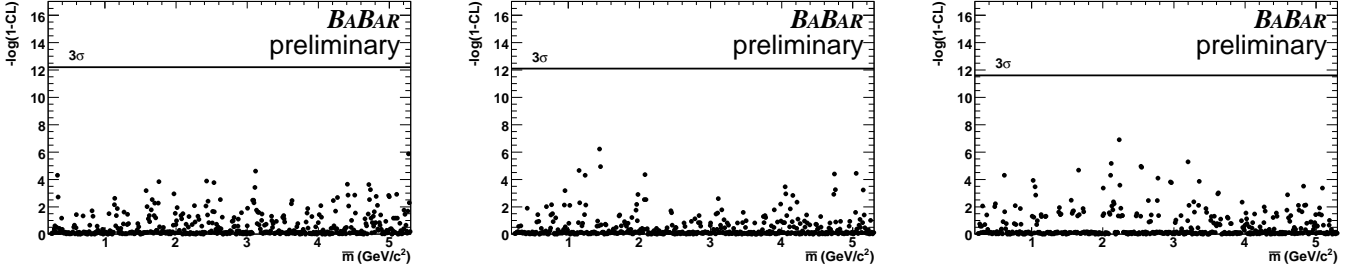


Figure 13: The value of  $-\ln(1 - CL)$  versus  $\bar{m}$  for (left to right)  $e^+e^-e^+e^-$ ,  $e^+e^-\mu^+\mu^-$ , and  $\mu^+\mu^-\mu^+\mu^-$ .

$e^+e^- \rightarrow W'W' \rightarrow l^+l^-l'^+l'^-$  cross section. The combined upper limit is shown in Figure 15; we set upper limits for  $\sigma(e^+e^- \rightarrow W'W' \rightarrow l^+l^-l'^+l'^-) < (25 - 60)$  ab.

From the combined upper limit, we derive limits on the possible couplings between the Standard Model and dark sectors. The cross section for  $e^+e^- \rightarrow W'W'$  has been calculated by Essig *et al.*[10]. For a dark photon  $A'$  mass less than the center of mass energy,  $E_{cm}$ , the cross section is given by:

$$\sigma(e^+e^- \rightarrow W'W')_{low} = N_c \frac{4\pi}{3} \frac{\varepsilon^2 \alpha_D \alpha}{E_{cm}^2} \sqrt{1 - \frac{4m_{W'}^2}{E_{cm}^2}} \left( 1 + \frac{2m_{W'}^2}{E_{cm}^2} \right) \quad (6)$$

while for an  $A'$  mass larger than  $E_{cm}$  the cross section is:

$$\sigma(e^+e^- \rightarrow W'W')_{high} = N_c \frac{4\pi}{3} \frac{\varepsilon^2 \alpha_D \alpha}{E_{cm}^2} \frac{E_{cm}^4}{m_{A'}^4} \sqrt{1 - \frac{4m_{W'}^2}{E_{cm}^2}} \left( 1 + \frac{2m_{W'}^2}{E_{cm}^2} \right) \quad (7)$$

where  $N_c$  is the number of colors in the dark sector,  $\varepsilon$  is the mixing parameter between the SM and the dark sector, and  $\alpha_D$  is the dark sector coupling constant. Figure 16 shows the upper limits we obtain on  $\varepsilon^2 \alpha_D$  assuming low  $A'$  mass, or on  $\frac{\varepsilon^2 \alpha_D}{m_{A'}^4}$  assuming large  $A'$  mass. For most of the mass range, we exclude values of  $\varepsilon^2 \alpha_D$  above  $2 \times 10^{-10}$  in the low  $A'$  mass scenario or values of  $\frac{\varepsilon^2 \alpha_D}{m_{A'}^4}$  above  $2 \times 10^{-14}$  in the high  $A'$  mass scenario. In the model of Ref [10], these limits exclude the preferred parameter region for  $A'$  masses above  $1.0 \text{ GeV}/c^2$ .

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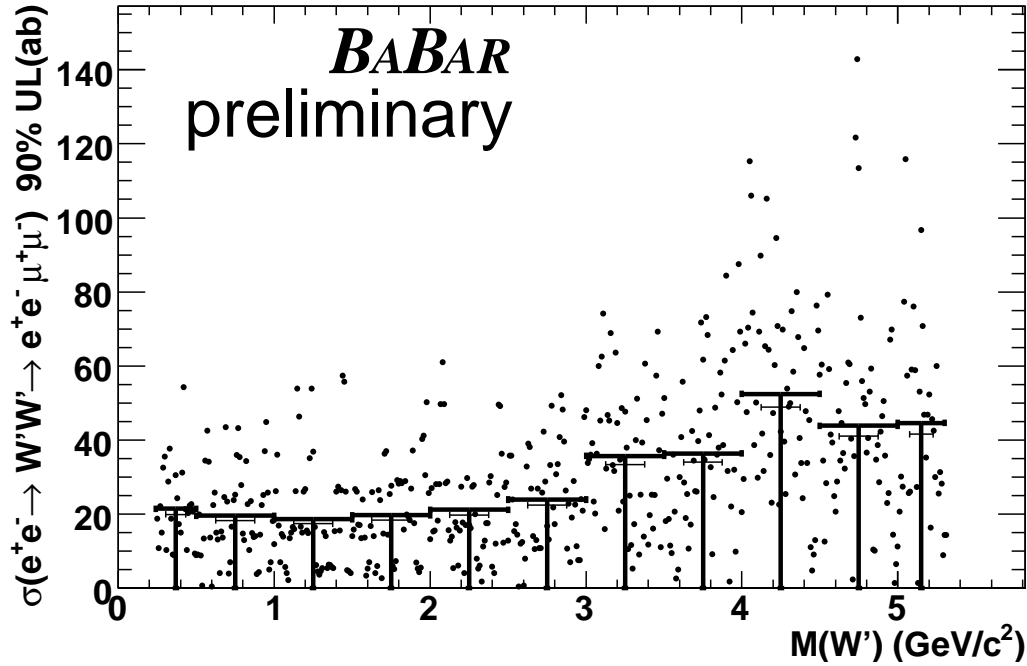
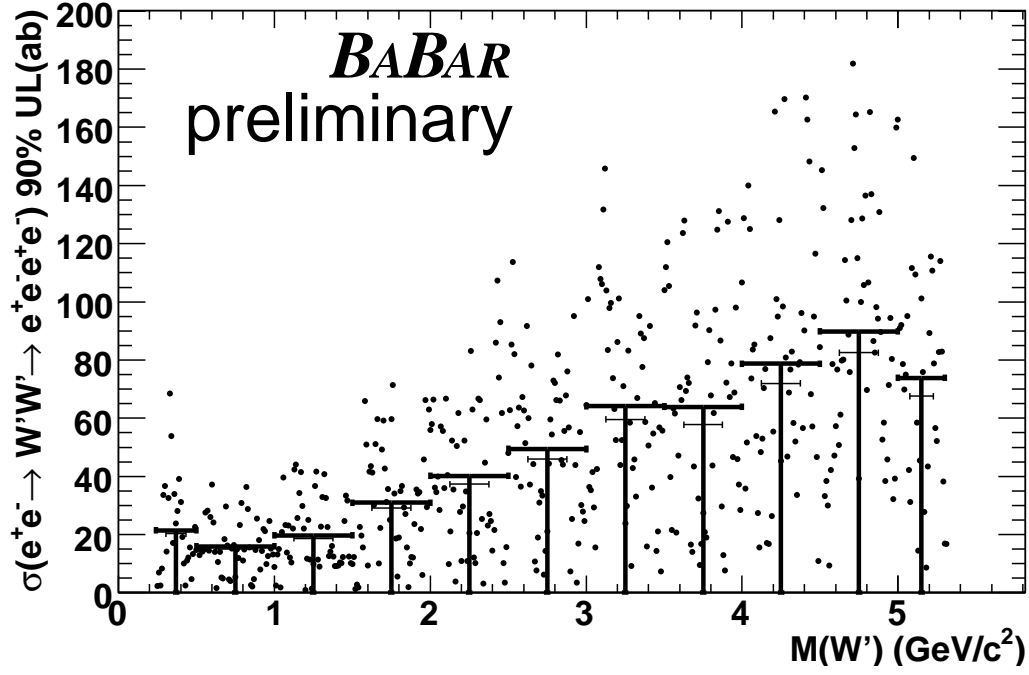


Figure 14: The cross section 90% upper limit versus  $\bar{m}$  for (top to bottom)  $e^+e^- \rightarrow W'W' \rightarrow e^+e^-e^+e^-$  and  $e^+e^- \rightarrow W'W' \rightarrow e^+e^- \mu^+ \mu^-$ . The points are the upper limit for each  $\bar{m}$  bin while the lines are the average of the limits over many bins.

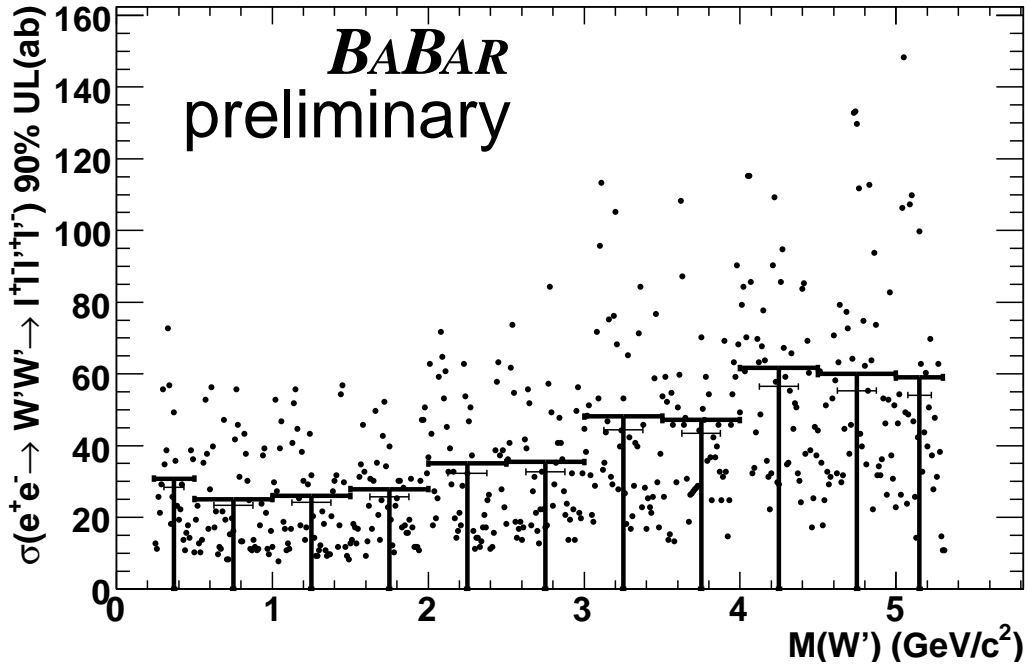
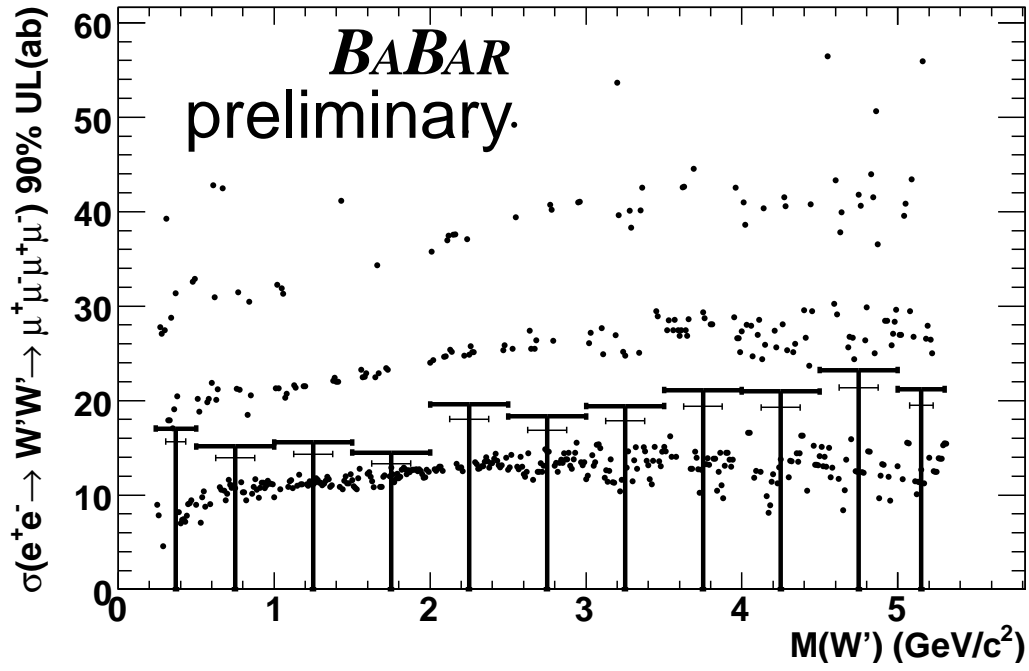


Figure 15: The cross section 90% upper limit versus  $\bar{m}$  for (top to bottom)  $e^+e^- \rightarrow W^+W^- \rightarrow \mu^+\mu^-\mu^+\mu^-$  and the combined  $e^+e^- \rightarrow W^+W^- \rightarrow l^+l^-l^+l^-$  assuming lepton universality. The points are the upper limit for each  $\bar{m}$  bin while the lines are the average of the limits over many bins. The band structure evident in the  $\mu^+\mu^-\mu^+\mu^-$  plot is due to the very low number of events in this mode.

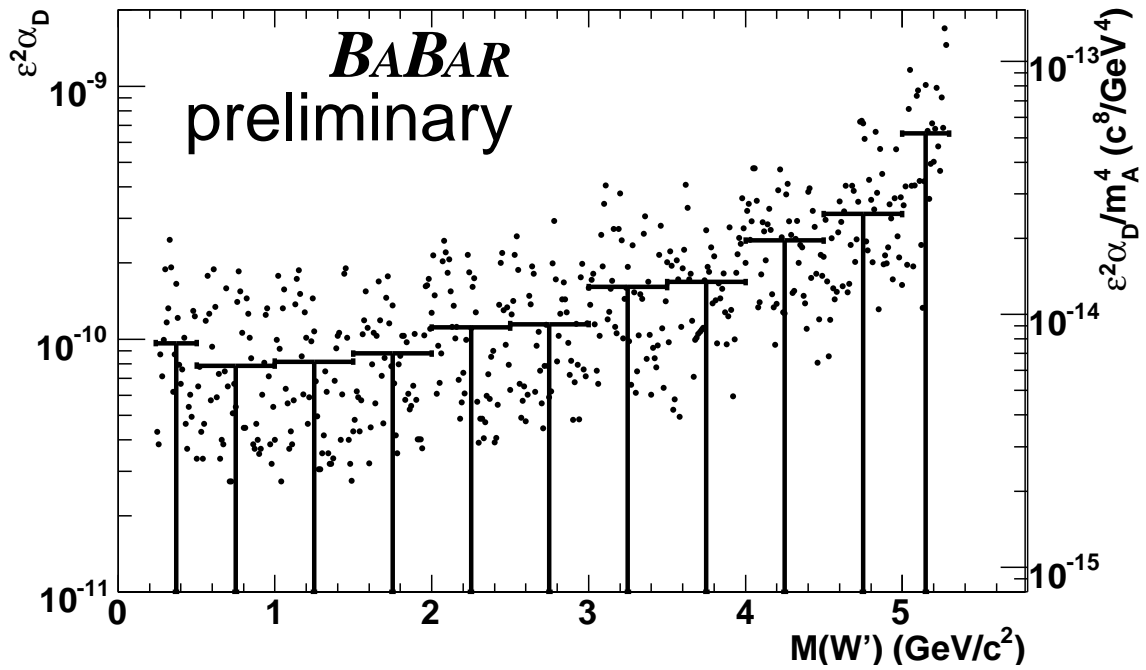


Figure 16: The 90% upper limit on  $\varepsilon^2\alpha_D$  (left axis) or  $\frac{\varepsilon^2\alpha_D}{m_{A'}^4}$  (right axis) versus  $m(W')$ . The points are the upper limit for each  $m(W')$  bin while the lines are the average of the limits over many bins.