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A Strategy for the Precision Measurement of M_W at the Threshold of the W-pair Production

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Abstract

A data-driven maximum likelihood scanning strategy (BES method), which has been successfully used to measure the τ mass, is proposed to measure M_W near the threshold of the W^+W^- production at LEP phase II. The Monte Carlo study has shown that with about 45 pb^{-1} per experiment, and combining the number of W^+W^- events from the 4 LEP experiments, one could obtain an accuracy on M_W of 77 MeV (statistical error only) with the data-driven maximum likelihood search, which optimizes the beam energy points for scanning during the M_W measurement. With the proposed luminosity at the threshold, the statistical error is dominant in the uncertainties of the measurement. However, the large width of the W and the initial state radiative correction decrease the sensitivity of the BES method.

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1 Introduction

The mass of W boson is one of the fundamental constants in nature. Particularly, it is a key parameter in the Standard Model. M_W and M_Z define $\sin^2\theta_W$. Furthermore, via various corrections, the Standard Model predicts the correlation between M_W and other fundamental parameters. Thus the precision measurement of M_W will provide a precision test of the electroweak theories, and probe new physics phenomena.

Measurements of M_W were carried out in experiments at $p\bar{p}$ collision with an accuracy of 200MeV. On the other hand, the mass of the Z has been precisely measured by LEP experiments with an accuracy of about 7 MeV. Thus one of the major tasks of the experiments in the LEP phase II is the precision measurement of the mass of the W boson. Several methods to measure M_W in the LEP phase II have been discussed extensively[1][2].

The BES (BEijing Spectrometer) collaboration made a precision measurement of the mass of the τ lepton at the Beijing Electron-Positron Collider (BEPC), using a data-driven maximumlikelihood method at the threshold of the τ -pair production. The method optimized the scanning strategy of the BES beam energy. It is the most efficient method to measure the τ mass, and was very successful.

The BES method could and should be applied to the measurement of M_W in the LEP phase II. This report suggests a possible scenario to measure M_W at the threshold of the W-pair production. In Chapter II we introduce the BES method. Chapter III suggests a scenario to measure M_W at the LEP phase II with the BES method. Chapter IV discusses the detailed Monte Carlo simulation to estimate the accuracy and the luminosity needed for using the BES method to the M_W measurement. The chapter V discusses the advantages and the disadvantages of the method. In chapter VI we make some remarks. Chapter VII contains the conclusions.

2 The BES method to measure the τ mass

There existed several measurements of M_τ before the BES measurement. All of them were done at $\sqrt{s}$ well above the threshold of the τ pair production soon after the discovery of the τ . At that time, physicists were more interested in the spin of the τ and the production cross section as a function of $\sqrt{s}$ to check its QED point-like feature. The world average value of M_τ was $1784.1^{+2.7}_{-3.6}$ MeV according to the Particle Data Group 1992. This value together with the τ life time measured before the LEP experiments gave a value of G_F^τ/G_F^μ more than two standard deviations smaller than 1, and created a puzzle to the lepton universality for many years.

BES made a precision measurement of M_τ at the threshold of the $\tau^+\tau^-$ production [6]. BEPC scanned in the limited range of $\sqrt{s}$ from 3.544 GeV to 3.567 GeV. To optimize the energy points in the scan, BES used the data-driven maximum likelihood search strategy. The first energy point was chosen to be the value of M_τ from the Particle Data Group 1992. The second energy point was chosen to be one standard deviation lower than the first point. The third energy point and the next energy points were chosen according to $E_{beam} = M_\tau^{fit} - 0.3$ MeV, where M_τ^{fit} is obtained from a maximum likelihood fit to the measured cross sections of the existing scan points. The Monte Carlo studies have shown that the most sensitive beam energy point is 0.3 MeV below M_τ , which is a turning point in the cross section curve as a function of $\sqrt{s}$. If the calculated change of the beam energy was smaller than the smallest step of the beam energy in BEPC (0.2 MeV), data taking with the current beam energy was continued. The history of the energy scan is shown in Fig. 1. Only the $\tau\tau \rightarrow e\mu\nu's$ channel was used for the maximum likelihood fit during data taking. This channel is very clean, and the backgrounds are well understood from analyzing the data in the region of the J/Ψ . With 10 energy points of a total integrated luminosity of $5pb^{-1}$, an accuracy of 0.5 MeV was obtained. The new value of M_τ is $1776.9_{-0.5}^{+0.4} \pm 0.2$ MeV[6]. The decay channels to identify $\tau\tau$ events were extended to all 1 - 1 prong events in the further data analysis, and an accuracy of 0.3 MeV was obtained. The final value of M_τ is $1776.9_{-0.3}^{+0.2} \pm 0.2$ MeV. This is about 7 MeV, i.e. more than two standard deviations, lower than the value of the Particle Data Group of 1992.

To check the beam energy scale, BEPC ran twice at the J/Ψ , and three times at the $\Psi(2S)$ during the M_τ measurement. To keep the energy scale, BEPC was running without a stop for the whole period of the measurement, including the New Year and the Chinese New Year of 1992. To check the event selection and the detector efficiency of the $\tau^+\tau^-$ events, BEPC also ran at three higher energy points above the threshold to obtain a $\tau^+\tau^-$ sample with higher statistics.

The new value of M_τ was confirmed soon by the measurements from the ARGUS and the CLEO II experiments. With the new value of M_τ together with the latest results of the τ life time from the LEP experiments, the puzzle of the lepton universality has been solved.

3 Using the BES method to measure M_W at LEP160

A careful study was carried out to investigate the possibility to make a precision measurement of M_W at the threshold of the W-pair production at LEP160 with the

BES method, similar to the M_τ measurement at BEPC. Since there are 4 experiments at LEP, it is necessary to reach an agreement about the running strategy between them. We suggest running at E_{beam} between 79 and 81 GeV for about 45 pb^{-1} per experiment. To use the BES method for choosing E_{beam} at each point, one could add the number of WW events from the 4 experiments at each energy point, and use it as input to the maximum likelihood fit. During the measurement, the LEP experiments have to obtain the number of the WW events at each energy point very quickly, typically several hours after the data taking of an energy point is finished.

The accuracy of the M_W measurement depends on both the luminosity and the efficiency of the identification of the W-pair events. The efficiency of the identification includes two factors: the branching ratios of the decay channels used in the identification, and the detector acceptance in the channels.

The BES method requires that the WW event sample has to be as clean as possible. And the sample has to be obtained very quickly during data taking for the data-driven maximum likelihood search to determine the next energy point.

The two major decay channels of WW events are $l^\pm \nu JJ$ (one charged lepton plus two jets) and $JJJJ$ (four jets). The $l^\pm \nu JJ$ channel is very clean, and is easy to be identified. The identification of the $JJJJ$ events from WW is more complicated, and the backgrounds from non-WW events have to be studied. If the Monte Carlo studies on the selection of the $JJJJ$ events cannot be satisfactory when the LEP phase II is started, we suggest that only events from the $l^\pm \nu JJ$ channel are included in the fit during data taking. The more sophisticated data analysis of the $JJJJ$ events could be done afterwards, and included in fitting to obtain the final result with the best accuracy, as the BES collaboration did.

4 The Monte Carlo Studies on the M_W Measurement with the BES Method

We made a detailed Monte Carlo simulation on the application of the BES method to the measurement of M_W to estimate the accuracy, and to optimize the running strategy.

Using the event generator of LEPWW[3], we take σ_{Born} , the Born level formula of the production cross section of $e^+e^- \rightarrow W^+W^-$, folded with Γ_W , the width of W, in the following way:

$$\sigma(E_{beam}) = \frac{\int_{E_{beam}-3\Gamma_W}^{E_{beam}+3\Gamma_W} \sigma_{Born} \sigma_{BW} dx}{\int_{E_{beam}-3\Gamma_W}^{E_{beam}+3\Gamma_W} \sigma_{BW} dx}$$

where

$$\sigma_{BW} = \frac{1}{2\pi} \frac{\Gamma_W}{(x - M_W)^2 + \Gamma_W^2/4}.$$

We store the cross section as a function of E_{beam} in numerical form for the calculation of the maximum likelihood fit. The numerical form of the cross section speeds up the calculation during fitting, and is easier to include further corrections into the calculation of the W-pair production near the threshold. The input values of M_W and Γ_W to the program are 80.22 GeV and 2.12 GeV according to the Particle Data Group 1992.

Γ_W has a large effect on the cross section of the W-pair production at the threshold. Fig. 2 compares σ_{WW} as a function of E_{beam} , with and without Γ_W folded, as well as the initial state radiative corrections (ISR) included. Γ_W decreases the rise of σ_{WW} dramatically near the threshold. The initial state radiative corrections decrease the cross section by about 30% further. These render the BES method less sensitive to the measurement of M_W .

Some corrections were not yet included in our calculation:

- the Coulomb interaction;
- non-equal M_W in the W^+W^- production;
- the beam energy spread (about 100 MeV).

However, the effects of these corrections on the production cross section near the threshold are much smaller compared to those of Γ_W and the initial state radiative corrections. For example, the Coulomb interaction increases the cross section only by about 6% near the threshold[5], because of the large width of the W suppresses the Coulomb singularity. We believe that the basic conclusion from the following studies will remain valid even after these corrections will have been included.

To obtain the best accuracy in the measurement of M_W with minimum luminosity, one has to maximize the efficiency of the identification of W^+W^- events. The efficiency of the identification includes two factors: the branching ratios of the decay channels used in the identification, and the detector acceptance in the channels. There are some studies on the classification of W-pair events for the L3 detector in the LEP phase II[7].

Good decay channels for the mass measurement are isolated energetic e or μ plus two jets ($l^\pm \nu JJ$). The e or μ could come from a W decay directly, or from a W-to- τ cascade decay. The branching ratio of this decay mode is about 24%. Assuming the branching ratio of the W decay into two jets to be 69%, the branching ratio of W-pair decay into $l^\pm \nu JJ$ is about 33%. According to the Monte Carlo studies, the acceptance is larger than 80%. The channel is very clean, and the signal is easy to be identified. The background is estimated to be less than 0.5%. Another candidate of the decay channels of W-pair events is the one into 4 jets ($JJJJ$). It

has a branching ratio of 48%. Monte Carlo studies with full detector simulation showed that the acceptance of the $JJJJ$ events from W -pair decay is more than 90%. But the backgrounds from non- WW events have to be investigated. More effort in the Monte Carlo simulation on the backgrounds is necessary.

If only the $l^\pm\nu JJ$ channel is identified for the measurement, then the global efficiency is 27.8%. If both the $l^\pm\nu JJ$ channel and the $JJJJ$ are used, the global efficiency will be 71%. For this study, we assume that both the $l^\pm\nu JJ$ channel and the $JJJJ$ channel are used in the measurement with backgrounds of 0.5%. The results can be easily rescaled to the case where only $l^\pm\nu JJ$ events are used for the measurement.

At each energy point, the average number of observed events is expected to be

$$N = L \cdot \sigma(E_{beam}) \cdot eff.$$

where L is the total luminosity of the 4 LEP experiments at each energy point, and $eff.$ is the global efficiency, including both the branching ratio and the detector acceptance. The statistical fluctuation is simulated according to a Poisson distribution. At each point, a background of 0.5% was calculated and smeared in the same way as the signal.

For the first 4 beam energy points, 80.80 GeV, 80.65 GeV, 80.50 GeV and 80.35 GeV were chosen without a fit. Starting from the fifth energy point, the maximum likelihood method was used to determine M_W^{fit} . The beam energy of the next point was chosen to be $M_W^{fit} + 0.45\text{GeV}$. The Monte Carlo studies show that the most efficient energy point in the measurement is 0.45 GeV above M_W^{fit} , when the initial state radiative corrections are included. One repeats the procedure to obtain 10 measurement points in total. The final value of M_W will be obtained from a fit to all measurements.

To determine the statistical error of the measurement, the whole process was repeated 500 times. We obtained distributions of M_W for total luminosities of 30 pb^{-1} , 45 pb^{-1} , 60 pb^{-1} and 90 pb^{-1} per experiment respectively, shown in Fig. 3. Every entry in the histogram corresponds to a fit of M_W with 10 energy points determined by the data-driven maximum likelihood method. For example, each experiment collects a total luminosity of 45 pb^{-1} for 10 points, i.e. 4.5 pb^{-1} per experiment per energy point, or 18 pb^{-1} per energy point for the 4 LEP experiments. The mean value of M_W from the histogram is 80.22 GeV, and the Gaussian fit yields the same number as mean value. The statistical error (the standard deviation from a Gaussian fit) of the measurement from the Monte Carlo studies is 77.0 MeV or 76.6 MeV from the *R.M.S.* of the histogram.

The resolution of M_W in the BES method as a function of the luminosity per experiment is shown in Table 1. The table also lists the total number of W^+W^- events collected in the 4 experiments as a function of luminosity. The optimal total

luminosity is 45 pb^{-1} per experiment. In the following studies, we always take this luminosity as our basic assumption.

$L/exp. (\text{pb}^{-1})$	15	30	45	60	90	120
Mean of $M_W (\text{GeV})$	80.20	80.23	80.22	80.22	80.22	80.22
$\Delta M_W (\text{MeV})$	126.0	89.1	77.0	66.8	53.4	46.4
Average number of events	142	284	425	553	855	1142

Table 1: The resolution of M_W at different luminosity per experiment.

The effect of the background level on the results was studied. Table 2 gives the mean value and the resolution of M_W as a function of the background level. The mean value of M_W is not affected by the level of the backgrounds. The resolution is not very sensitive to the background level. It means that as long as the background contamination is understood, events from the $JJJJ$ channel could be used for the measurement even if the sample may be not very clean.

Background (%)	0.5	1.0	2.0	3.0	5.0
$M_W (\text{GeV})$	80.22	80.22	80.22	80.22	80.22
$\Delta M_W (\text{MeV})$	77.0	80.0	77.0	76.7	78.8

Table 2: The effect of the backgrounds on the mean value and the resolution of M_W (Gaussian fit)

The Monte Carlo studies show that the detection efficiency of the W-pair events must be well understood. Table 3 shows how the mean value of M_W and its error varies as function of a systematic shift in the detection efficiency. The wrong efficiency will shift the mean value of M_W . However, the shift is still much smaller compared to the statistical error.

$\Delta eff.(\%)$	+ 1.0	+ 2.0	- 1.0	- 2.0
$M_W (\text{GeV})$	80.23	80.25	80.21	80.19
$\Delta M_W (\text{MeV})$	80.8	78.4	76.9	75.41

Table 3: The effect of the systematical error in the efficiency on the mean value and the resolution of M_W .

In the maximum likelihood fit, Γ_W is an input parameter, and fixed. The uncertainty on Γ_W would effect on the mean value of M_W and its resolution from fitting. If the real Γ_W is different from the input value of Γ_W by $\Delta\Gamma_W$, the changes in the mean value of M_W and its resolution were calculated by Monte carlo simulation, as shown in Table 4.

$\Delta\Gamma_W(\text{GeV})$	+ 0.11	+ 0.0	- 0.11
$M_W(\text{GeV})$	80.26	80.22	80.18
$\Delta M_W(\text{MeV})$	75.3	77.0	79.1

Table 4: The effect of the systematical error in Γ_W on the mean value and the resolution of M_W .

These Monte Carlo studies show that the systematical errors from the uncertainties in the detector acceptance and the background estimation are much smaller than the statistical error, which is limited by the luminosity available at the W^+W^- threshold.

5 The Advantages and the Disadvantage of the method

The BES method could yield an accuracy of about 80 MeV in the measurement of M_W for an integrated luminosity of 45 pb^{-1} per LEP experiment. That is much more efficient than any other method proposed so far.

The measurement of M_W near the WW production threshold[1] discussed so far uses the wide beam energy range from 80 to 100 GeV. Thus such a measurement is not very sensitive to M_W , and gives a poor result. For example, if one includes the initial state radiative correction, the statistical error in the measurement discussed in reference[1] would become more than 200 MeV, while the statistical error in the BES method with the same luminosity, is less than 100MeV.

As a comparison, a similar Monte Carlo study on the scanning by a fixed step of the beam energy was carried out too. Using a fixed beam energy step of 500 MeV and 10 points between 78.5 and 83.0 GeV with the various total luminosities the results are summarized in Fig. 4 compared with the results from the BES method. It shows clearly the advantage of the BES method. The results from the method with the fixed beam energy step could be improved, if one uses a small beam energy step around the world average value of M_W . However, if the world average value of M_W is too far away from the real value of M_W , one may run LEP at an energy range which is not sensitive to the measurement of M_W .

The BES method is the most simple and straightforward method to measure M_W . This method requires only to identify events from the W -pair decay inclusively, without a classification of each individual decay mode. This reduces the systematic errors. The resolutions in energy and momentum are not important for this method. It is much less sensitive to detector resolutions and detector simulations compared to other methods. Thus it is possible to combine the measurements of the 4 LEP

experiments directly during the data taking for the fit. The method of the end point of the energy/momentum spectrum of leptons from the W-decay depends strongly on the energy resolution of the electrons and the momentum resolution of the muons, as well as on the quality of the simulation. The energy deposit (sometimes, even showering) of muons in a hadron calorimeter is difficult to be calculated. It decreases the sensitivity of the method. The method of the invariant mass of two jets from W decay depends on the resolution of the hadron calorimeter, which is not good usually. The kinematic constraint fitting method could partly solve the problem, but the systematic uncertainty from the hard radiative photon which escaped along the beam pipe is unknown, and may introduce a larger error.

Because the method is simple and the systematic errors are small, it is easier to combine the M_W measurements from the 4 experiments, and obtain a reliable and precise value of M_W .

The last, but not least, advantage of the method is that running near the threshold of the W-pair production around $\sqrt{s}$ of 160 GeV requires much less RF power for LEP. That makes running the LEP machine easier, particularly at the beginning of LEP phase II.

The major disadvantage of the method is that much less W-pair events are obtained because of running near the threshold of the W-pair production. That would decrease the statistics for the studies of the triple gauge boson coupling. However, the total luminosity required by the method is just a small fraction of the total luminosity expected for LEP phase II. We believe that such a price is worthwhile.

6 Some Remarks

The method requires the good understanding of the production cross section of W-pair near threshold. Many corrections have to be carefully calculated and to be included into the Monte Carlo event generator of the W-pair production. Unfortunately, so far the theoretical calculation on the production cross section of W-pair near the threshold is almost ignored because its advantages have not been recognized so far. One has to encourage theoretical physicists to make large efforts on it.

The machine performance has a very large effect in the accuracy of the method. The absolute energy scale and the stability of the LEP beams make significant contributions to the systematic errors. One has also to discuss with the LEP machine experts about the LEP beam energy range, the beam energy spread and its measurements, as well as the reproducibility of the running conditions, and the minimum step of the beam energy. The good performance of LEP during the measurement

is one of the key issues in the method.

According to preliminary studies[8], the depolarization measurement could be done up to E_{beam} of 70 GeV. Then the beam energy scale around 80 GeV could be extrapolated with the magnet measurement. Thus one could expect that the uncertainty on the absolute beam energy scale could be less than 20 MeV. And one could expect the minimum beam energy step to be less than 5 MeV. Thus one could expect that with the proposed luminosity, the statistical error is much larger than the systematical errors from the performances of the LEP machine.

Using the BES method in LEP phase II requires:

- The performances of the LEP machine should be well-understood, well-controlled, well-measured and reproducible.
- The selection of W^+W^- events to be used in the LEP experiments should be well-understood and agreeing with measurements.

The above two requirements should be fulfilled after the first year of running in LEP phase II. Thus the best time for LEP phase II to measure M_W with the BES method is the second year. However, if the LEP machine would have problems to provide enough RF power for higher energies, running at the threshold to measure M_W would be an alternative choice for the first year of LEP phase II.

In addition, to understand the backgrounds from non- W^+W^- events, LEP should run at energies below the threshold of the W^+W^- production before the M_W measurement with the BES method.

7 Conclusion

The Monte Carlo studies show that it is promising to use the BES method to measure M_W at LEP160. Combining the measurements from the 4 LEP experiments with a data driven maximum likelihood search strategy, one could obtain a resolution (statistical error only) of 77 MeV for 45 pb^{-1} , or 67 MeV for 60 pb^{-1} luminosity per experiment. Because the limitation of the total luminosity available at the threshold, the statistical error is dominant in the uncertainties of the measurement.

More careful studies are needed on the theoretical calculation of the cross section of the W^+W^- production near the threshold, and on optimizing the running strategy, e.g. the luminosity at each energy point, number of energy points, and to search for the most sensitive point. From the experience of the M_τ measurement at BES, further improvements in the accuracy of the M_W measurement by the method are possible.

The method is most straightforward and simple. However, the large width of the W decreases the sensitivity of the method in the case of the M_W measurement.

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Figure Captions

- Fig. 1 The history of the energy scan in the M_τ measurement at BES.
- Fig. 2 The cross section of the W-pair production as a function of $\sqrt{s}$. The dotted line is the Born approximation, and the dashed line is folded with Γ_W according to the formula in chapter 4. The full line includes both Γ_W and the initial state radiative (ISR) correction.
- Fig. 3 The M_W distribution from the Monte Carlo simulation with the BES method for different total luminosity per experiment: a) 30 pb^{-1} ; b) 45 pb^{-1} ; c) 60 pb^{-1} ; d) 90 pb^{-1} .
- Fig. 4 The comparison of the resolution of M_W (MeV) of the BES method with the method of the fixed step of E_{beam} (500 MeV) for different luminosities.

Fig. 1

Fig. 2

Fig. 3

Fig. 4