第 28 卷 第 11 期 高 能 物 理 与 核 物 理 Vol.28, No.11
2004 年 11 月 HIGH ENERGY PHYSICS AND NUCLEAR PHYSICS Nov., 2004

Measurement of the Integrated Luminosity at $\sqrt{s}=3.650, 3.686$ GeV for the BES Detector *

CHI Shao-Peng[1,2;1)] MO Xiao-Hu[1,2] ZHU Yong-Sheng[1]
1(Institute of High Energy Physics, CAS, Beijing 100049, China)
2(China Center of Advanced Science and Technology, Beijing 100080, China)

Abstract The integrated luminosity for the two sets of BES data, collected at $\sqrt{s}=3.650, 3.686$GeV in 2002 and 2003, are carefully studied, and measured to be $(6.42\pm0.24)\mathrm{pb}^{-1}$ and $(19.72\pm0.86)\mathrm{pb}^{-1}$. The result provides basic input parameter in the measurements of cross sections at the above two energy points.

Key words integrated luminosity, cross section, $\psi(2S)$ resonance, continuum

1 Introduction

In the e^+e^- collider experiment, the integrated luminosity $\mathscr{L}$ is a basic parameter which is directly related with the production cross section:

$$\sigma_{e^+e^-\to X}=\frac{N^{obs}_{e^+e^-\to X}}{\mathscr{L}\cdot\varepsilon_{e^+e^-\to X}}, \tag{1}$$

where $N^{obs}_{e^+e^-\to X}$ is the observed events number and $\varepsilon_{e^+e^-\to X}$ the detection efficiency for the final state X. At the continuum region, the production cross section is merely contributed by QED process; while at the resonance region, *i.e.* J/ψ, $\psi(2S)$ and so on, the cross section also contains the contribution from resonance decay.

By the end of the rum year of 2002, BES had collected 14 Million $\psi(2S)$ data, with these large data sample, many studies could be made with unprecedented precision. However, as pointed out in Ref.[1], for $\psi(2S)$ study at e^+e^- annihilation experiment, the contribution due to continuum process usually plays a very important role for certain process, such as $\omega\pi^0$, $\pi^+\pi^-$ and so on. With the off-resonance data sample one can measure the QED amplitude for certain final state X, and then derive the QED contribution for X state at the resonance region, which is necessary for extracting the property of the resonance decay. By virtue of suggestion put forth in Ref.[1], the data set at 3.650GeV were taken in 2003 run year, by which the background from QED process could be studied in detail. The common parameter used to normalize the two data sets here is the integrated luminosity.

In principle, any QED process can be used to determine the integrated luminosity. The formula is the following:

$$\mathscr{L}=\frac{N^{obs}_{QED}}{\sigma_{QED}\cdot\varepsilon\cdot\varepsilon_{trg}}, \tag{2}$$

Where N^{obs}_{QED} is the observed events number, σ_{QED} the production cross section determined by Monte Carlo generator, ε and ε_{trg} the reconstruction-selection efficiency and trigger efficiency for selected final state. In practice, the Bhabha events are often adopted due to their large cross section and high measuring precision. Other events such as $\gamma\gamma$ and Di-muon events, whose cross sections are much smaller than that of Bhabha's, are usually used as a cross check[2]. In the BES experiments, the trigger efficiency is almost 100% for hadron, e^+e^- and $\mu^+\mu^-$ final states[3]. In the following analyses, the trigger efficiency is treated as 100%, which will introduce negligible error.

Received 20 February 2004, Revised 28 April 2004
* Supported by National Natural Science Foundation of China (19991483) and 100 Talents Programme of CAS (U-25)
1) E-mail: chisp@mail.ihep.ac.cn

2 Luminosity at 3.686 GeV

2.1 Method

At $\psi(2S)$ resonance region ($E_{cm}=3.686$ GeV), we mainly utilize Bhabha events to determine the integrated luminosity. Here the key issue is to distinguish two kinds of processes: one from Bhabha process and the other from $\psi(2S)$ decay. If we notice that the electron (positron) track from $\psi(2S)$ decay has a symmetric distribution along z-axis while that from Bhabha process has a prominently asymmetric distribution, we can take advantage of the distribution distinction to subtract the resonance contribution. The details could be found in Ref. [4], according to which the integrated luminosity could be calculated as follows

$$\mathscr{L}=\frac{A_2-A_1}{(1-2\alpha)\cdot\sigma_{\mathrm{QED}}\cdot\varepsilon}, \qquad (3)$$

where α is defined as

$$\alpha=\frac{x_1}{x_1+x_2}$$

and ε is the reconstruction-selection efficiency of Bhabha events. Here $A_1(A_2)$ represents the total number of the e^+e^- events with electron falling in the region $\cos\theta_{e^-}<0(\cos\theta_{e^-}>0)$[1)]; $x_1(x_2)$ represents the number of Bhabha events within corresponding region; and the factor $(1-2\alpha)$ compensates the event loss due to (A_2-A_1). A_1 and A_2 can be acquired from the selected data sample, σ_{QED} is provided by generator, and α can be evaluated from the Monte Carlo (M.C.) simulation sample for Bhabha events.

2.2 Event selection

To select e^+e^- events, as the first step, two tracks with maximum deposit energy in the Barrel Shower Counter (BSC) of the BES[5] are selected, and they must satisfy

$$R\mathrm{esc}=\sqrt{(\tilde{E}_{\mathrm{dep1}}-1)^2+(\tilde{E}_{\mathrm{dep2}}-1)^2}<0.65, \qquad (4)$$

Where $\tilde{E}_{\mathrm{dep}}=E_{\mathrm{bep}}/E_{\mathrm{beam}}$ is the normalized deposit energy. We also require two charged tracks with total charge zero and $|\cos\theta_e|\leqslant 0.72$. Because the Monte Carlo simulation does not model the deposit energy well in the rib region of the BSC, an additional cut is applied on the z-coordinate of the first hit layer: $0.1<|z_{sc}|<0.85$ or $|z_{sc}|>1.05$m.

In order to eliminate the contamination of e^+e^- pair events from cascade decay $\psi(2S)\rightarrow XJ/\psi, J/\psi\rightarrow e^+e^-$ at $\psi(2S)$ peak energy, we require that the normalized momentum $\tilde{p}=p/E_{\mathrm{beam}}$ must satisfy $\tilde{p}_1\geqslant 0.95$ or $\tilde{p}_2\geqslant 0.95$ or $\tilde{p}_1+\tilde{p}_2\geqslant 1.82$. Fig. 1 shows the comparison of distributions of deposit energy and momentum between selected e^+e^- events and simulated events, respectively. The consistency is fairly good.

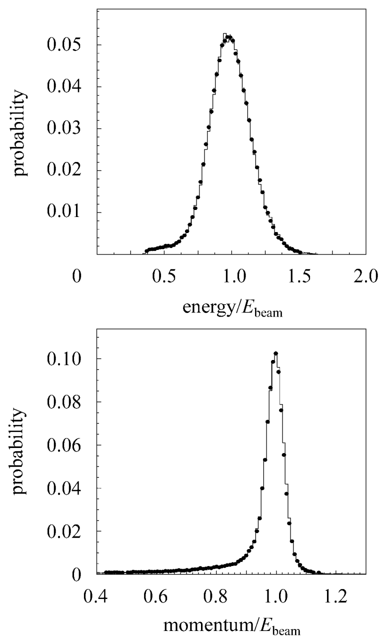

Fig. 1. Normalized deposit energy and momentum distribution for e^+e^- events at 3.686 GeV (Histogram for Monte Carlo simulation and dots with error bar for data).

2.3 Luminosity calculation

From the $\cos\theta$ distribution of the selected e^+e^- events and Monte Carlo simulation, we obtain $A_2-A_1=663683$, $\alpha=0.130677$ for electron tracks, and $A_2-A_1=661683$, $\alpha=0.130072$ for positron tracks, respectively. When calculating the luminosity, the average values of A_2-A_1 and α are used. For our selection criteria, we obtain $\varepsilon=0.397$ and $\sigma_{\mathrm{QED}}=114.5$ nb (with M.C. production angel $\cos\theta<0.8$). Substituting all these values into Eq. (3), we acquire the integrated luminosity, at 3.686 GeV to be 19720.5 nb^{-1}.

1) $A_1(A_2)$ also represents the total number of the e^+e^- events with positron falling in the region $\cos\theta_{e^+}>0(\cos\theta_{e^+}<0)$.

3 Luminosity at 3.650 GeV

3.1 Luminosity calculation

At continuum region (E_{cm} = 3.650 GeV), the event selection is the same as that at $\psi(2S)$ resonance region except the momentum cut erased because the contribution due to the resonance at the continuum region is tiny enough to be neglected. Fig.2 shows the comparison of distributions of deposit energy and momentum between selected e^+e^- events for data and corresponding Monte Carlo simulation. It is clear that the two kinds of samples agree with each other fairly well.

After event selection, we get a total of 319422 Bhabha events, the corresponding efficiency $\varepsilon = 0.4235$ and the production cross section $\sigma_{QED} = 116.7$ nb. Using Eq.(2), we obtain the luminosity at 3.650 GeV to be 6463.1 nb^{-1}.

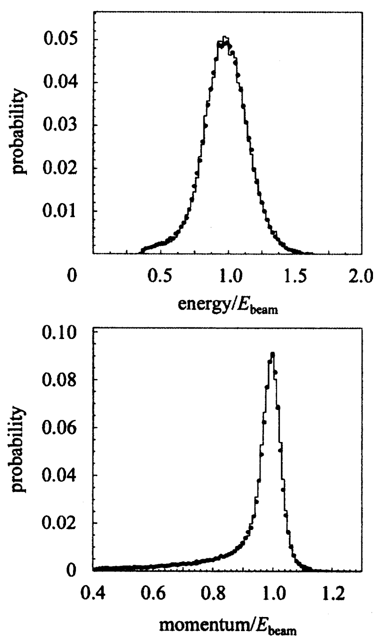

Fig.2. Normalized deposit energy and momentum distribution for e^+e^- events at 3.650GeV (Histogram for Monte Carlo simulation and dots with error bar for data).

3.2 Cross checks

In order to ensure the correctness of the luminosity measurement, we use Bhabha sample selected by another method1) to evaluate the luminosity at 3.650 GeV as a cross check. The result is 6368.3 nb^{-1}. The difference is around 1.5% with respect to the aforementioned result.

4 Error analysis

In the light of Eq.(2), the statistic error of luminosity is composed of three terms: N^{obs}_{QED}, σ_{QED} and ε. For N^{obs}_{QED} and σ_{QED}, the relative statistic error is determined by the number of selected events and generated events, that is

$$\upsilon_N = \frac{1}{\sqrt{N^{obs}_{QED}}}, \text{and } \upsilon_\sigma = \frac{1}{\sqrt{N^{prod}_{M.C.}}},$$

where $N^{prod}_{M.C.}$ denotes the produced number of M.C. events. For efficiency ε, the error can be derived from binomial distribution[8]:

$$\upsilon_\varepsilon = \sqrt{\frac{\varepsilon(1-\varepsilon)}{N^{prod}_{M.C.}}}.$$

For Bhabha event, the relative statistic errors at 3.686 and 3.650 GeV are all at the level of 0.5%.

So far as the systematic error is concerned, we first acquire the distribution of a variable for data and M.C. simulation, and this selection variable is used as a cut to select the candidate events. Then the efficiency difference between the data and M.C. simulation for all the used cuts is taken as the systematic uncertainty for the efficiency. The distributions for the selection variables are easy to be realized for Monte Carlo sample, because the sample itself is pure. As to data, the difficulty to obtain the distributions lies in two respects: one is the defect due to cut damage, the other the blemish due to background contamination. We first take the error analysis of deposit energy as an example to expound how to obtain a reliable data sample and get the error. Then we give a brief explanation for error analyses of other criteria.

Because it is difficult to eliminate the contamination from channel $\psi(2S) \to e^+e^-$, we used the data at continuum region(E_{cm} = 3.650 GeV) to avoid the contamination due to resonance decay. So there are totally four variables to be used for Bhabha event selection: deposit energy (R_{esc}), rib constraint(z_{sc}), angle distribution ($\cos\theta$) and charge condition ($Q_{1\&2}$). For deposit energy, we construct the quantity R_{esc}

1) This method is to avoid the discrepancies between the M.C. simulation and Data angular distributions due to ribs in the BSC by calculating the selecion efficiency of Data and M.C. simulation separately. Details can be seen in Refs.[6,7].

whose definition is given in Eq.(4), to separate electrons from muons and hadrons. Since we want to study R_{esc}, in order to avoid cut-damage, we utilize alternative requirements instead of R_{esc} itself to discard contamination. We require

(1) two selected tracks could not be identified as muon-tracks by μ-counter;

(2) the energy loss (dE/dx) of two selected tracks in main drift chamber must be large enough to effectively suppress the muons as well as hadrons background.

Using these two requirements together with the other needed cuts, we could obtain comparatively pure Bhabha data sample. Fig.3 shows the distribution of R_{esc} of Bhabha event for data and Monte Carlo simulation at $\sqrt{s}=3.650\mathrm{GeV}$, where the arrow indicates the cut we adopted.

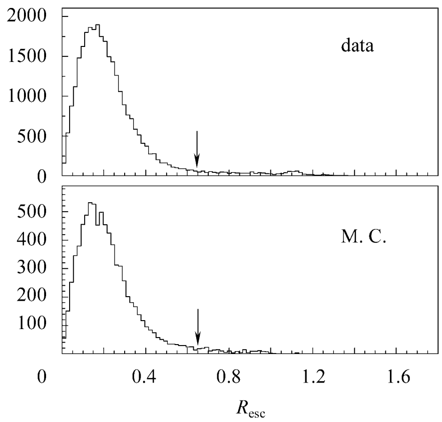

Fig.3. The distributions of R_{esc} for experimental data and Monte Carlo simulation (the arrow indicates the position of our cut).

For different cut-values involving R_{esc}, we can calculate the remaining fractions of both data and Monte Carlo samples. Here we use symbol R_i to represent the remaining fractions:

$$R_i=\frac{\text{the remaining number of events after cut}}{\text{the original number of events}},$$

where the subscript i denotes different cut. The difference between data and M.C. simulation for fractions(R_i) is treated as the uncertainty of certain cut. Fig.4(a) shows the fraction R_i for R_{esc} cut and the relative difference(υ) between data and M.C. simulation.

Similarly, we can obtain the uncertainty distribution for $\cos\theta$-cut as shown in Fig.4(b). Here we generate the Bhabha Monte Carlo within the range $|\cos\theta|<0.80$ and use the data sample and Monte Carlo sample both of which satisfy the requirement $|\cos\theta|<0.78$ as the original sample to avoid the edge effect.

For z_{sc}-constraint, we introduce a step number N for different z_{sc} cut, which is defined as

$$0.01\cdot N<|z_{sc}|<0.95-0.01\cdot N \text{ or } |z_{sc}|>0.95+0.01\cdot N\ m.$$

Here N is an integer and when N is larger than 10, its value will be fixed for the '$0.01\cdot N<|z_{sc}|$' part because the consistence between data and Monte Carlo is fairly well at the central part with $0.1<|z_{sc}|$. Fig.4(c) shows R_i for z_{sc} cut and υ between data and M.C. simulation.

As to charge condition, we use the quantity $\delta\phi_{sc}$ which is defined as

$$\delta\phi_{sc}=|\phi_{sc1}-\phi_{sc2}|-180°,$$

where ϕ_{sc1} and ϕ_{sc2} are ϕ information of two tracks in BSC, to suppress the $\gamma\gamma$ event and subtract backgrounds. Fig.5 shows the distribution of $\delta\phi_{sc}$ of data and Monte Carlo samples. The detailed description of this condition could be found in Refs. [6,7].

In addition, we could study the uncertainty of momentum cut with continuum data sample since there is almost no contamination from $\psi(2S)\to e^+e^-$ at continuum region. We use all event selection cuts of the continuum to obtain the distribution of momentum of data and Monte Carlo samples. Then we can obtain the uncertainty distributions shown in Fig.4(d), where N is a step number for different monmentum cut, defined as

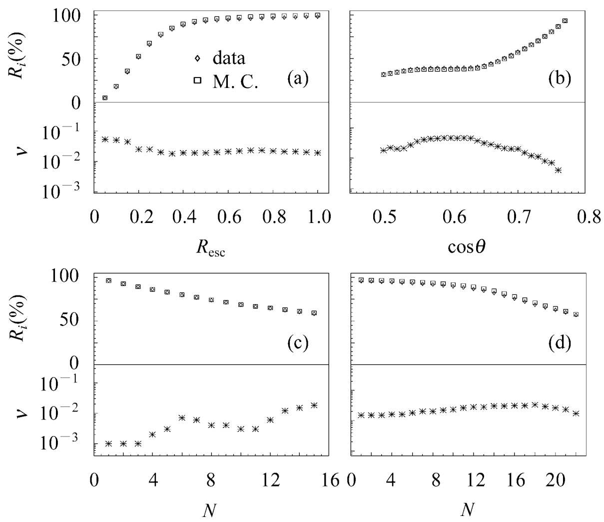

Fig.4. Uncertainty distribution for R_{esc}, $\cos\theta$, z_{sc} and momentum cut. (Here R_i is the remaining fractions of data and Monte Carlo samples with different cut and ν the relative difference between two fractions).

(a) Value of R_i and ν for the R_{esc} cut; (b) Value of R_i and ν for the $\cos\theta$ cut; (c) Value of R_i and ν for the z_{sc} cut; (d) Value of R_i and ν for the momentum cut.

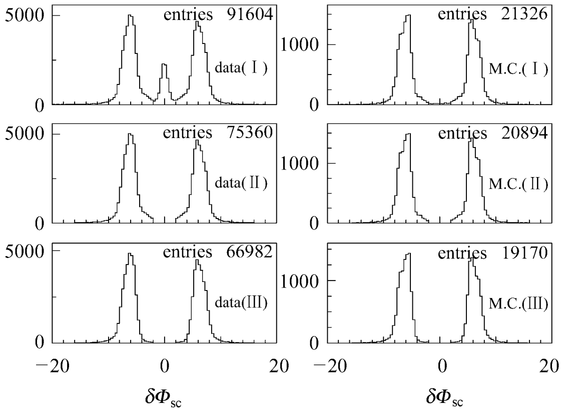

Fig.5. The distribution of $\delta\phi_{sc}$ of data and Monte Carlo samples: the top two distributions are for data and Monte Carlo samples before $\delta\phi_{sc}$ cut($|\delta\phi_{sc}|>2°$) and charge cut; the middle wo for samples after $\delta\phi_{sc}$cut but before charge cut; and the bottom two for samples after the $\delta\phi_{sc}$ cut and charge cut.

$\tilde{p}_1 \geqslant 0.84+0.01\cdot N$ or $\tilde{p}_2 \geqslant 0.84+0.01\cdot N$ or $\tilde{p}_1+\tilde{p}_2 \geqslant 1.71+0.01\cdot N$.

All the systematic errors of various variables are listed in Table 1.

Table 1. The systematic error for Bhabha selection.

requirement	error(%)
$R_{esc}<0.65$	2.2
$\cos\theta<0.72$	1.2
the rib cut	0.3
charge cut	2.3
momentum cut*	2.6
total error	4.3

* This cut is used only for $\sqrt{s}=3.686$GeV region. For $\sqrt{s}=3.650$GeV region, the total error is 3.4%.

5 Summary

We use Bhabha events to evaluate the luminosity at 3.686 and 3.650 GeV to be

$$\mathscr{L}_R=(19.72\pm0.10\pm0.85)\text{pb}^{-1},$$

and

$$\mathscr{L}_C=(6.46\pm0.03\pm0.22)\text{pb}^{-1},$$

respectively. Here the first error is the statistic while the second the systematic. As a cross check, we also determined the luminosity at 3.650 GeV to be 6.37 pb^{-1}, which correspond to Bhabha event selected with the alternative criteria. As a conservation estimation, we use the average of the two measured values at 3.650 GeV as the center value, the quadrature sum of statistic error 0.03 pb^{-1}, systematic error 0.22 pb^{-1} and the maximum difference 0.09 pb^{-1} between two values as the final error, that is

$$\overline{\mathscr{L}}_C=(6.42\pm0.24)\text{pb}^{-1}.$$

Using $\mathscr{L}_R$ and $\overline{\mathscr{L}}_C$, we work out the ratio of luminosity between the resonance and continuum regions:

$$r_L=\frac{\mathscr{L}_R}{\overline{\mathscr{L}}_C}=(3.07\pm0.09),$$

where the systematic errors of $\mathscr{L}_R$ and $\overline{\mathscr{L}}_C$ cancel out except the one due to momentum cut.

At last, we would like to mention two byproducts of our luminosity measurement. First, using the method introduced in section 2.1, we can also derive the branching fraction of $\psi(2S)\to e^+e^-$, that is:

$$\mathscr{B}_{\psi(2S)\to e^+e^-}=(9.7\pm0.6)\times10^{-3}.$$

This value agrees fairly well with the BES scan result[9]:

$$\mathscr{B}_{\psi(2S)\to e^+e^-}=(9.3\pm0.8)\times10^{-3}.$$

Second, if we adopt 676.3 nb provided by Ref.[10] as the total cross section of $\psi(2S)$ decay, we can obtain the total number of $\psi(2S)$ events:

$$N_{\psi(2S)}=\mathscr{L}_R\cdot\sigma=(13.34\pm0.57)M.$$

This value agrees with $(14.02\pm0.56)M$, which was determined in Ref.[11]. The consistency for these two results between our measurements and other ones could be considered as one indirect cross check for our luminosity study.

Thanks are due to Prof. J. C. Chen for helpful discussion about luminosity determination.

References

1 WANG P, YUAN C Z, MO X H. HEP & NP, 2003, **27**(6): 465 - 473 (in Chinese)
(王平,苑长征,莫晓虎.高能物理与核物理,2003,**27**(6):465—473)
2 HUANG G S et al. HEP & NP, 2000, **24**(5): 373—378 (in Chinese)
(黄光顺等.高能物理与核物理,2000,**24**(5):373—378)
3 FU C D (BES Memo). Measurement of the Trigger Efficiency of $\psi(2S)$, 2003
4 CUI X Z, GU Y F. HEP & NP, 2000, **24**(1): 4—10 (in Chinese)
(崔象宗,顾以藩.高能物理与核物理,2000,**24**(1):4—10)
5 BAI J Z et al. Nucl. Instrum. Methods, 1994, **A344**: 319;
BAI J Z el al. Nucl. Instrum. Methods, 2001, **A458**: 627
6 WANG Z Y et al. HEP & NP, 2001, **25**(2): 89—94 (in Chinese)
(王志勇等.高能物理与核物理,2001,**25**(2):89—94)
7 CHI S P, ZHU Y S, MO X H, WANG P (BES Memo). Measurement of ψ'' Resonance Parameters, 2003
8 MO X H, ZHU Y S. HEP & NP, 2003, **27**(6): 474—478 (in Chinese)
(莫晓虎,朱永生.高能物理与核物理,2003,**27**(6):474—478)
9 BAI J Z et al. Phys. Lett., 2002, **B550**: 24
10 MO X H (BES Memo). Study of Inclusive Hadronic Event, 2003
11 MO X H el al. HEP & NP, 2004, **28**(5): 455—462 (in Chinese)
(莫晓虎等.高能物理与核物理,2004,**28**(5):455—462)

北京谱仪$\sqrt{s}=3.650, 3.686$ GeV数据样本的积分亮度测量*

迟少鹏[1,2;1)] 莫晓虎[1,2] 朱永生[1]
1(中国科学院高能物理研究所 北京 100049)
2(中国高等科学技术中心 北京 100080)

摘要 利用Bhabha散射过程测定了北京谱仪(BESⅡ)在2002年和2003年收集的质心系能量$\sqrt{s}=3.650$, 3.686 GeV数据样本的积分亮度为$(6.42\pm0.24)\mathrm{pb}^{-1}$和$(19.72\pm0.86)\mathrm{pb}^{-1}$.这些结果为此两能量值处的各种过程的反应截面测量提供了必需的基本参数.

关键词 积分亮度 截面 $\psi(2S)$共振 连续态

2004-02-20收稿,2004-04-28收修改稿
*国家自然科学基金(19991483),中国科学院百人计划(U-25)资助
1)E-mail:chisp@mail.ihep.ac.cn