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Muon Identification Using the Efficiencies Ratio Method at BES II *

GUO Yun-Jun[1,2;1)] HE Kang-Lin[2;2)]

1 (Nanjing University, Nanjing 210093, China)
2 (Institute of High Energy Physics, CAS, Beijing 100049, China)

Abstract The momentum and polar angle depended position resolution and hit efficiency in each layer of BES(II) muon detector are calibrated by using cosmic ray and hadron samples. Based on the calibration results, the efficiencies ratio function is constructed to separate μ/π effectively and applied in physics analysis.

Key words muon identification, cosmic ray, position resolution, hit efficiency, efficiencies ratio

1 Introduction

Muon identification plays a crucial role in many important physics topics at τ-charm energy region, such as: searching for the pure leptonic decay of $D^+_{(s)} \to \mu^+\nu_\mu$ to measure f_D/f_{D_s}, and the study of the decay of $\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$, $c \to \mu^+\nu_\mu\bar{s}$, where c and $\bar{s}$ represent the charm and anti-strange quark. The momentum of muon from the above decay modes lies below 1.2GeV/c, an effective identification for low momentum muons must be required. In this paper, we present a hit efficiencies ratio method in muon identification at BES II.

2 The BES II muon identifier

BES is a conventional solenoidal magnetic detector that is described in detail in Ref. [1]. BES II is the upgraded version of the BES detector[2]. The BES and BES II muon identifier consists of 189 modules, each module consists of 8 proportional muon counting tubes, interspersed with three layers of absorbing iron shields. It is schematically shown in Fig. 1(a). The entire muon structure resides outside the solenoidal coil, and the iron shield is also used as a flux return for the magnetic field.

Each counting tube has 8 single-wire cells, arranged in two offset sub-layers to solve the left-right ambiguity problem. The z-position of the muon hits is determined by charge division between the two ends of the muon counter. The ϕ position is determined by the tube size. The resolution thus attained has been 5cm in the z-direction, and 3cm in the ϕ-direction.

3 The selection of cosmic ray sample

A large and pure cosmic ray sample which covers large momentum range is collected by the BES detector with ~1Hz event rate during the data taking. In the cosmic sample, muons are the main components, hadrons and other electromagnetic particles are filtered by the iron yoke, only a few percent($<1\%$) of hadron background remains[3]. Generally, as shown in Fig. 1(a), two tracks with opposite charge will be reconstructed when a single cosmic ray passes through the detector. The "up-track" traverses from the outer most detector (muon counter) to the beam pipe whose azimuth angle ϕ is less than π; the "down-track" tra-

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1) E-mail: guoyj@ihep.ac.cn
2) E-mail: hekl@ihep.ac.cn

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verses from the beam pipe to the outer detector whose azimuth angle ϕ is greater than π.

The selection of cosmic ray proceeds as follows[3]. There are two charged tracks with good helix measurements in the main drift chamber. The number of hits in the muon counter is required to be greater than 3. The total energy deposits in the barrel shower counter is required to be less than 1.5GeV to reject the Bhabha events. Each charged track must have a good TOF measurement. Compared with the collision event, the event start time (T_0) of cosmic ray has a shift

$$T_0 = (T_1 + T_2)/2, \tag{1}$$

where T_1 and T_2 are the measured time-of-flight in the upside and downside barrel TOF counters, which are produced by a single cosmic ray track. The T_0 calculated in Eq. (1) will be applied to correct the drift time in the track reconstruction process.

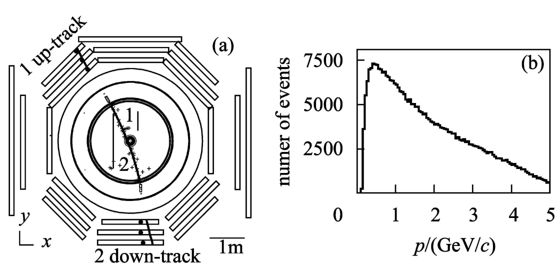

Fig. 1. (a) Schematic view of the muon identifier in xy-plane and an event display for cosmic ray; (b) The momentum distribution for cosmic muon sample.

The track parameters are improved after the T_0 correction in the reconstruction. Further selections are employed to the above sample: 1) If only one down-track is found, it must be near the interaction point (IP) by the requirement of $|R_{xy}| < 5$cm and $|z| < 30$cm, where R_{xy} and z are the closest approach of the track to the IP in xy-plane and z direction; 2) The time difference of the two TOF counters is required to be greater than 5ns; 3) The differences of the two track vertex are required to be less than 3mm at xy-plane and less than 25mm in z direction; 4) The difference of the two track momentums satisfies $\Delta p < 0.1 \times p \times \sqrt{1+p^2}$, where $p = (p_1 + p_2)/2$, p_1 and p_2 are the momentum of two tracks, the factor of 0.1 corresponds to a 3σ cut with σ being the momentums resolution. After the above criteria, the down-track will be an “ideal” muon track. Here and below, the muon track in the cosmic ray sample is implicitly to be the down-track. Fig. 1(b) shows the distribution of momentum for muons in the sample.

Hadron may be misidentified as a muon. Most of kaons can be easily rejected by using TOF information. Pion has similar behavior with muon in inner detectors, and must be distinguished by muon counter. To study the punch-through of hadrons, large pion samples from the J/ψ → ρπ and J/ψ → $\omega\pi^+\pi^-$ are selected. The muon and pion samples are divided into two categories: one is for detector calibration; another one goes for the muon ID performance checks.

4 The position resolution of muon counter

The differences in ϕ and z direction between the projected and measured position $\Delta\phi = \phi_{\text{proj}} - \phi_{\text{hit}}$ and $\Delta z = z_{\text{proj}} - z_{\text{hit}}$ are checked with muon samples in different momentum range, where the subscript “proj” indicates for the projected position to the muon counter from the inner tracking system, and the “hit” indicates for the measured position by the muon counter. As shown in Fig. 2, the position resolution in each layer is momentum depended, which can be parameterized as

$$\sigma_{\phi,z}(p) = a + \frac{b}{p-c}, \tag{2}$$

where σ_ϕ and σ_z are the position resolutions in ϕ and z direction, p the momentum of muon, a, b and c the parameters which are determined from data. The multiple scattering effect in material is described by the $\sim 1/p$ form in the second term of Eq. (2).

The position resolution obtained from cosmic ray sample only shows the downside information of the detector. The μ-pair events of $e^+e^- \to (\gamma)\mu^+\mu^-$ are selected to study the angular uniformity of the muon counter. The distributions of deviation numbers $\Delta\phi/\sigma_\phi$ and $\Delta z/\sigma_z$ in ϕ and $\cos\theta$ partitions are checked for both the μ-pair and cosmic ray samples, where the $\cos\theta$ is defined as

$$\cos\theta = \frac{z_{\mathrm{proj}}}{\sqrt{x_{\mathrm{proj}}^2 + y_{\mathrm{proj}}^2 + z_{\mathrm{proj}}^2}}, \tag{3}$$

where the (x_{proj}, y_{proj}, z_{proj}) are the coordinates of projected position from the inner tracking system.

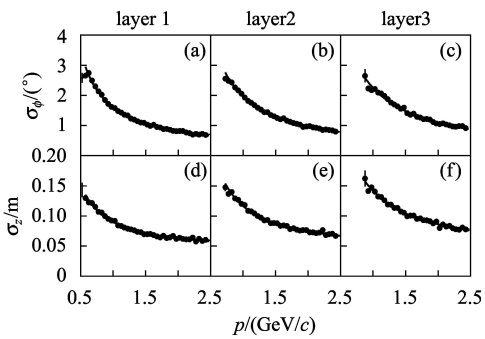

Fig. 2. The variations of muon counter position resolution σ_ϕ and σ_z with momentum in each layer. The cross points represent the values obtained from data, and the curves are indicated by the fitting to Eq. (2).

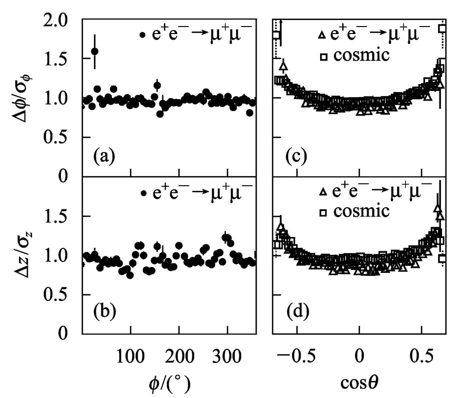

Fig. 3. The average number of deviations of $\Delta\phi/\sigma_\phi$ and $\Delta z/\sigma_z$ in the second layer of muon detector. (a) and (b), the variations for the μ-pair events in ϕ partitions($0 < \phi < 2\pi$); (c) and (d), the variations for both the μ-pair and cosmic ray events in $\cos\theta$ partitions.

Figs. 3(a) and 3(b) show the average number of $\Delta\phi/\sigma_\phi$ and $\Delta z/\sigma_z$ for μ-pair events in the ϕ partitions. The variations in ϕ direction are quite flat (around 1) over all counters. The deviation number of $\Delta\phi/\sigma_\phi$ and $\Delta z/\sigma_z$ in $\cos\theta$ partitions for the μ-pair and the cosmic ray events are shown in Figs. 3(c) and 3(d), respectively. The variations of position resolutions in θ direction are consistent well for μ-pair and cosmic ray samples, and can be parameterized as

$$\sigma_{\phi,z}(\cos\theta) \propto (1+\cos^2\theta). \tag{4}$$

Therefore, the position resolution in ϕ and z of muon counter in each layer can be factorized as a product of two functions which are described in Eqs. (2) and (4). The validation of

$$\sigma_{\phi,z} = \sigma_{\phi,z}(\cos\theta) \times \sigma_{\phi,z}(p) \tag{5}$$

are confirmed by the μ-pair events, and will be applied in physics analysis.

5 The efficiencies of muon hit

When a charged particle passes through the BES detector, it will lose energy by ionization and/or interaction with the detector material. The inner most layer of iron yoke constrains the low threshold of muon momentum to $\sim$0.55GeV/c. Muons and hadrons with momentum above the cut-off threshold will have a possibility to reach and fire the muon detector.

An effective hit in one layer is defined if a hit satisfies $|\Delta\phi|/\sigma_\phi < 4$. A good hit in one layer is defined if an effective hit satisfies the additional requirement of $|\Delta z|/\sigma_z < 6$. The hit may occur in single counting tube or double counting tubes. For a muon candidate, at least one good hit layer and at least one double-tube hit is required. This will help to suppress the noise hits and insure a reliable measurement in muon counter.

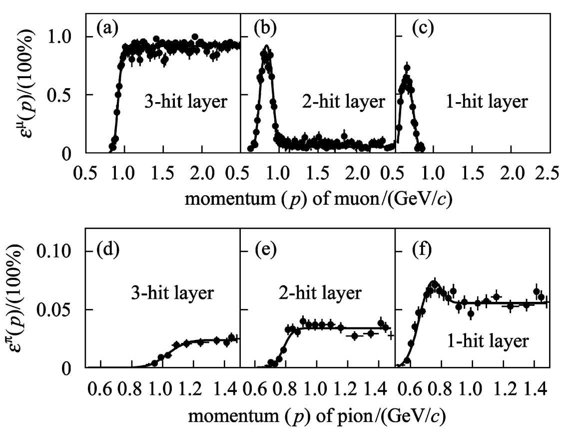

Fig. 4. The efficiencies of n ($n=1,2,3$) effective hit layers in the $\cos\theta$ interval 0.05—0.10 vary as functions of momentum for muons ((a), (b) and (c)) and pions ((d), (e) and (f)).

The information in muon detector for a charged particle can be described by the number of effective hit layers. The problem becomes to determine the hit efficiencies from the muon and pion samples. Figs. 4(a) and 4(b) show the average efficiencies of one, two and three effective hit layers vary as functions of momentum in $\cos\theta$ partitions for muon and pion samples, respectively. For muon, when the momentum increases, the efficiency will increase firstly, and then saturate to a constant for three hit layers; or then drop to ~ 0 for one or two hit layers since more layers are fired at high momentum. The efficiency-momentum curve for pion will saturate to a constant at $\sim$1.2GeV/c, $\sim$0.9GeV/c and $\sim$0.8GeV/c, corresponding to three, two and one hit layer. The Landau fluctuation of energy loss in the heavy and thick absorber distributes approximately like a Gaussian[4]. The efficiency-momentum curve can be fitted with an error function (erf(x)[4])

$$\varepsilon(p)=\frac{1}{2}\varepsilon_{\rm inf}\left[1+{\rm erf}\left(\frac{p-p_{\rm thr}}{\sqrt{2}\sigma_{E_{\rm loss}}}\right)\right] \tag{6}$$

for three hit layers or with the difference of two error functions for one and two hit layers, where $\varepsilon_{\rm inf}$ represents the efficiency at large momentum, the slope of error function $\sigma_{E_{\rm loss}}$ represents for the standard deviation of energy loss in iron yoke, and $p_{\rm thr}$ represents the momentum threshold at 50% point of efficiency curve.

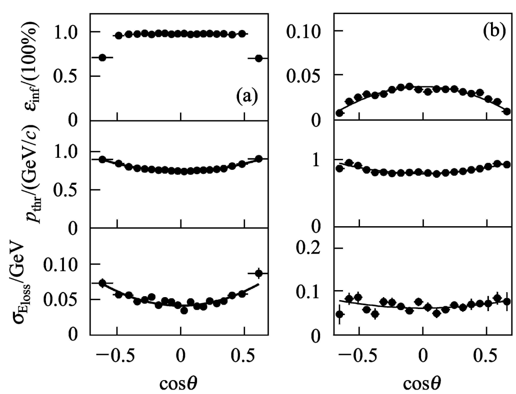

Fig. 5. The $\varepsilon_{\rm inf}$, $p_{\rm thr}$ and $\sigma_{E_{\rm loss}}$ from two hit layers efficiency curves vary as functions of $\cos\theta$ for (a) muons and (b) pions.

The parameters of $\varepsilon_{\rm inf}$, $p_{\rm thr}$ and $\sigma_{E_{\rm loss}}$ for muon and pion are drawn in Figs. 5(a) and 5(b), respectively. The ionization related parameters $p_{\rm thr}$ and $\sigma_{E_{\rm loss}}$ for muon and pion are very similar, both of them can be expressed as a function of

$$p_{\rm thr},\sigma_{E_{\rm loss}}\propto(1+\alpha\cos^2\theta), \tag{7}$$

where the positive parameter α's can be determined from data. The $\varepsilon_{\rm inf}$ for muon is almost a constant over all range of $\cos\theta$ except the geometry boundary in z direction. The drops of $\varepsilon_{\rm inf}$ at large value of $|\cos\theta|$ can be corrected by using the μ-pair sample. With the increasing of the path length, more interacted pions will be absorbed by the iron yoke. The $\varepsilon_{\rm inf}$ for pion reduced at large value of $|\cos\theta|$, and could be expressed as

$$\varepsilon_{\rm inf}^{\pi}\propto(1+\beta\cos^2\theta), \tag{8}$$

where the negative parameter β's can be determined from data.

6 Applying the efficiencies ratio method to muon identification

For a charged particle, the sum of probabilities of zero, one, two and three effective layers in muon detector must equal to one. Thus we can treat the n-layer hit efficiency as a "Likelihood" to do muon identification. The probability density function (PDF) can be constructed with the following variables: the number of effective hit layers, the momentum and the $\cos\theta$ of charged track. The likelihood function $\mathscr{L}$ will take the simple form

$$\mathscr{L}(H)\equiv\mathscr{L}(H;n,p,\cos\theta)=\varepsilon_n^H(p,\cos\theta), \tag{9}$$

where H is the hypothesis of particle (muon or hadron), ε_n^H the n-layer hit efficiency in muon counter, n the number of effective hit layers, p the momentum, $\cos\theta$ is calculated by Eq. (3) using the position information. Generally, the fraction of the likelihood

$$\mathscr{F}(\mu)=\frac{\mathscr{L}(\mu)}{\mathscr{L}(\mu)+\mathscr{L}(\pi)} \tag{10}$$

is a powerful variable to discriminate the signal from backgrounds. For μ/π separation at BES, $\mathscr{F}(\mu)$ is just a ratio function of muon's hit efficiency to pion's hit efficiency.

If muon comes from $e^+e^-\to(\gamma)\mu^+\mu^-$ process, or comes from the decay of J/ψ, its momentum is far away from the $p_{\rm thr}$ and high enough to fire two and three layers in muon detector. The dependency of ε

to momentum and hit position becomes not so obvious. Thus we have $\varepsilon^{\mu} \sim 100\%$ and $\varepsilon^{\pi} \sim 5\%$. This will lead to $\mathscr{F}(\mu) \sim 1$.

The decay constant $f_{\rm D}$ is an important measurement in charm physics. The momentum of muon in the rare decay mode of $\rm D^{+} \rightarrow \mu^{+}\nu_{\mu}$ distributes between 0.75—1.15GeV/c. The momentum and $\cos\theta$ depended ε must be taken into account. To reject the large contamination of hadron's punch-through, at least two hit layers are required. The resulting muon identification efficiency and pion contamination rate in different momentum ranges are drawn in Fig. 6.

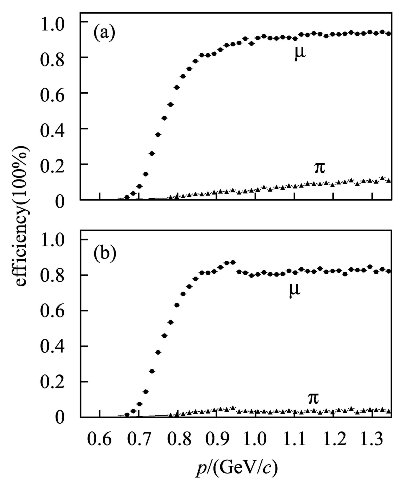

Fig. 6. The variations of muon identification and pion contamination rate in different momentum ranges. (a) At least two layer hits are required. (b) An additional cut $\mathscr{F}(\mu) > 0.95$ is required. The muon and pion samples come from the real data, the selection procedure is illustrated in Section 3.

As shown in Fig. 6(b), a requirement of $\mathscr{F}(\mu) > 0.95$ is very effective to reduce the contamination of hadrons, especially for the momentum above 0.95GeV/c. In the $f_{\rm D}$ measurement at BES-Ⅱ experiment, the average efficiency of muon identification is about 80%, while the pion misidentification rate is less than 5%. The muon ID efficiency agrees well with the BES-Ⅰ measurements[5, 6]. After the successful running in more than ten years, the operation and the performance of BES(Ⅱ) muon detector are smooth and stable.

At BESIII[7], we will have 9 layers of Resistive Plate Chambers (RPC) in the barrel and 8 layers in the endcap with the magnetic return yokes together to form a muon detector. The cut-off momentum threshold reduces to 0.50GeV/c. The updated detector provides more information on the muon track measurements and requires more reliable muon identification to match the accuracy of physics. The construction of PDF for likelihood analysis presented in this paper can be applied in BESIII with the additional information from muon tracking and the characters of electromagnetic shower in the calorimetry. The sophisticated methods, such as the artificial neural network[8] and the boosted decision tree method[9], can also be applied in the particle identification at BESIII.

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北京谱仪 II 上利用效率比方法进行 μ 鉴别的研究*

郭云均[1,2;1)]　何康林[2;2)]

1 (南京大学　南京　210093)
2 (中国科学院高能物理研究所　北京　100049)

摘要　北京谱仪 II 的 μ 探测器的位置分辨和击中效率与带电粒子的动量和入射位置有关, 利用选取的宇宙线样本和强子样本对 μ 探测器逐层进行了标度, 并利用构造的效率比函数在物理分析中有效地识别 μ 和强子.

关键词　μ 鉴别　宇宙线　位置分辨　击中效率　效率比方法

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1) E-mail: guoyj@ihep.ac.cn
2) E-mail: hekl@ihep.ac.cn