Study of low momentum track reconstruction for the BESIII main drift chamber*

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Abstract In order to overcome the difficulty brought by the circling charged tracks with transverse momentum less than 120 MeV in the BESIII Main Drift Chamber (MDC), a specialized method called TCurlFinder was developed. This tracking method focuses on the charged track reconstruction under 120 MeV and possesses a special mechanism to reject background noise hits. The performance of the package has been carefully checked and tuned by both Monte Carlo data and real data. The study shows that this tracking method could obviously enhance the reconstruction efficiency in the low transverse momentum region, providing physics analysis with more and reliable data.

Key words BESIII MDC, low transverse momentum, track reconstruction

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1 Introduction

The BESIII [1] is a high precision, general purpose detector designed for the high luminosity e^+e^- collider running at the tau-charm energy region, called the BEPCII [2]. The BESIII detector is composed of the main drift chamber (MDC), the electromagnetic calorimeter (EMC), the time of flight counters (TOF), the muon counter (MUC) and the 1 T superconducting magnet.

The BESIII MDC, located within a 1 T magnetic field, is designed to be a small-cell, low-mass drift chamber operated using a He/C_3H_8(60/40) gas mixture. The shape of the endplate is conical to provide the space required by the focusing magnets while allowing measurement of charged particle trajectories within $-0.93 \leqslant \cos\theta \leqslant 0.93$. The drift cell has an almost square shape. 6796 cells are arranged in 43 circular layers. The first 8 layers located in the inner chamber are stereo, and the following 12 layers located in the stepped section are all axial. The other 23 layers—16 stereo layers and 7 axial layers—are arranged in the outer section. Table 1 shows the layer configuration. The cell size is nearly 12 mm × 12 mm for the inner chamber and 16.2 mm × 16.2 mm for the outer chamber [3].

The main drift chamber is responsible for the detection of charged tracks. The MDC tracking pack-

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age uses the drift time of an ionized electron created by charged particles in MDC to calculate the particle's drift distance from the signal wire, and then provides the parameters of helix through which the particle flies. Because of the general requirements of the BESIII experiment, charged track reconstruction in the MDC should meet the following demands: 1) high reconstruction efficiency; 2) high precision of momentum and spatial resolution; 3) good secondary vertex reconstruction; 4) robustness against background noise, unequal magnetic field and other exogenous factors; and 5) small CPU time consumption.

From the point of view of reconstruction, in order to maximize the physics reach at the BESIII, it is very important to have wide coverage of the available phase space for efficient charged particle tracking, especially efficient tracking down to very low momentum and high resolution for the tracking parameters. Although we have already developed a main general tracking algorithm TSF [4], which works well in the normal transverse momentum region, tests in a low transverse momentum area still showed the need to improve the tracking ability.

The radius of each superlayer of the MDC and the $P_{\rm t}$ (transverse momentum) of the particle that can reach the corresponding superlayer is listed in Table 1. Because the MDC is located in a 1 T strong magnetic field, the charged particle flies through a helix, whose radius is determined by the particle's transverse momentum. Only the charged tracks with transverse momentum larger than 120 MeV travel in a helix with the diameter larger than 81 cm (the diameter of the MDC is 162 cm), thus they can fly out of the MDC. Other tracks will circle within the MDC, according to the radius of their helix. These circling tracks possess certain special characteristics:

1) Fewer superlayer tracks will pass through.

2) Within one superlayer, a hit may not distribute on all layers, and one single layer may have more than one hit. These two cases cause low tracking efficiency of the TSF method.

3) Circling tracks are hard to separate from each other.

Based on these characteristics, the low transverse momentum particles are difficult for a general tracking package TSF to reconstruct. What is more, insufficient tracking efficiency of particles with low transverse momentum will seriously undermine the ability and reliability of physics analysis on channels that contain these kinds of tracks. Therefore, we have developed a novel method, TCurlFinder, to deal with this challenge.

Table 1. Transeverse momentum allowed to fly through each superlayer and corresponding radius.

superlayer no.	1	2	3	4	5	6	7	8	9	10	11	outer
stereo/axial	stereo	stereo	axial	axial	axial	stereo	stereo	stereo	stereo	axial	axial	
radius/cm	11.5	16.2	24.6	31	37.5	44.8	51.4	57.9	64.2	71.6	77.1	81
$P_{\rm t}$ allowed/MeV	17	24	37	47	56	67	77	87	96	107	116	122

2 Track description and tracking theory

In the BESIII, the five main charged particles of concern are electron, pion, muon, kaon and proton, all of which will fly through a helix path in the MDC due to the 1 T magnetic field. Helix track α can be described using five parameters, $\alpha = (d_\rho, \phi_0, \kappa, d_z, \tan\lambda)^{\rm T}$:

1) d_ρ is the signed distance of the helix from the pivot in the x-y plane.

2) ϕ_0 is the azimuthal angle to specify the pivot with respect to the helix center.

3) κ is $1/P_{\rm t}$ and the sign of κ represents the charge of the track assigned by the track fitting.

4) d_z is the signed distance of the helix from the pivot in the z direction.

5) $\tan\lambda$ is the slope of the track, tangent of the dip angle.

Among these five parameters, d_ρ and ϕ_0 can describe a two-dimensional circle in the x-y plane.

The position (x, y, z) along the helix is given by [5]

$$\begin{cases} x = x_0 + d_\rho\cos\phi_0 + \dfrac{\alpha}{\kappa}\{\cos\phi_0 - \cos(\phi_0+\phi)\} \\ y = y_0 + d_\rho\sin\phi_0 + \dfrac{\alpha}{\kappa}\{\sin\phi_0 - \sin(\phi_0+\phi)\} \\ z = z_0 + d_z - \dfrac{\alpha}{\kappa}\tan\lambda\cdot\phi \end{cases}, \quad (1)$$

where α is the magnetic-field-constant, $\alpha = 1/cB = 10000/2.9979258/B[{\rm cm(GeV}/c)^{-1}]$ at the strength of magnetic field B [kGauss] and ϕ is the turning angle, which is an internal parameter with a sign and determines the location.

The corresponding circle has the signed radius of $\rho = \alpha/\kappa$, the momentum of that helix is $P_{\rm t} = 1/|\kappa|$, or it can be described by the turning angle ϕ as

$$\begin{pmatrix} p_x \\ p_y \\ p_z \end{pmatrix} = \frac{1}{|\kappa|} \begin{pmatrix} -\sin(\phi_0+\phi) \\ \cos(\phi_0+\phi) \\ \tan\lambda \end{pmatrix}. \tag{2}$$

The Least Square Method is used to do the helix fitting. χ^2 is defined as

$$\chi^2 = \sum_{i=1}^{\text{nhits}} \left(\frac{\text{drift}_i - \text{doca}_i}{\sigma_i}\right)^2, \tag{3}$$

where drift_i is the measurement value of the distance from hit to hit wire, doca_i is the fitted value of the distance of the closest approach and σ means the error of the drift distance. In track reconstruction, χ^2 is minimized using the Newton method [6].

Generally speaking, tracking methods fall into two categories: one is local and the other one is global. The local tracking method starts from certain primary hits and finds candidate hits by turns, while the general one processes more than one object simultaneously. Based on the consideration of the BESIII characteristics and the charged particles' traits, we choose the local tracking method.

3 The realization of software package

The TCurlFinder package is activated after a general main tracking process done by TSF, the main general tracking algorithm of the BESIII, which has proved to perform well in the region of transverse momentum larger than 120 MeV. TcurlFinder uses the hits left by TSF to reconstruct tracks. This mechanism can better utilize the ability of TCurlFinder in the low transverse momentum region while keeping the high quality of TSF in the high transverse momentum part unchanged.

TCurlFinder is composed of two main parts: 2D-Finder and 3D-Finder. The detailed workflow of the TCurlFinder package is shown in Fig. 1. In the 2D-Finder step, tracking starts with finding axial segments. Since low transverse momentum tracks usually have several hits within one layer, TCurlFinder creates axial segments using consecutive axial hits: within one superlayer, every axial hit has neighbor wires, as shown in Fig. 2. These neighbor wires are numbered 0–5. 2D-Finder will check whether the hit wire's neighbor is fired. If so, it will keep on checking whether the neighbor's neighbor is fired. This process will carry on until no new fired hit can be found and all of the consecutively found hits consistute an axial segment candidate. Due to the characteristics of a low transverse momentum track, we may find more than one segment candidate in a superlayer, thus only the candidate that can best fit a circle with an interactive point (IP) will be identified as an axial segment. 2D-Finder builds a preliminary 2D circle by IP and the axial segment in the outmost superlayer, and then expands the circle with axial segment candidates in the nearby superlayers. Afterwards, the expanded 2D circle will be added with all of the isolated axial hits having a distance of less than 1.5 cm from the circle in the salvage process. In the last step of 2D-Finder, a 2D circle that passes the IP is created (IP is included in the circle because all tracks that TCurlFinder tries to reconstruct are presumed to originate from the interactive point).

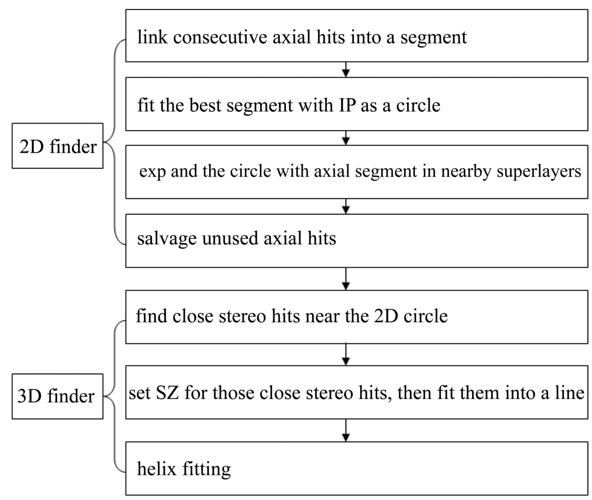

Fig. 1. The workflow of TCurlFinder.

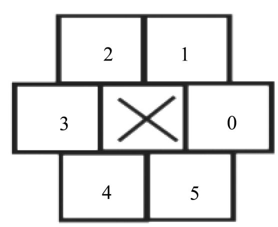

Fig. 2. The definition of neighbor: x represents one fired wire and 0–5 represent the sequentially numbered neighbor wires.

After 2D tracking in the r-phi plain, stereo hits, which are close to the 2D circle, will be directly used to build a 3D helix. Firstly, stereo hits that are close to the 2D track need to be found. As shown in Fig. 3(b), candidate stereo hits are selected if their drift circles are on a tangent with the charged track. Then we use the position information of these close stereo hits and s-z relationship to build a helix. As shown in Fig. 3(a), s is the signed length of the helix through which the charged track travels and z is the same as the z direction in the BESIII coordinate, and from the 3D perspective, the charged particle travels in a path of the helix, while this helix becomes a straight line when we project it in the s-z plane. So when 3D-Finder creates a helix in the s-z plane, it just needs to do a line fit to get the best 3D helix.

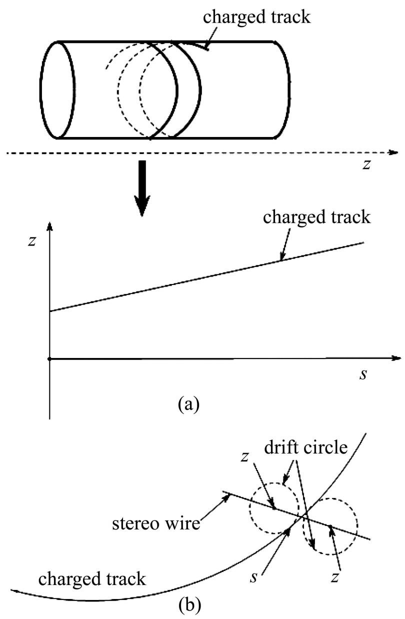

Fig. 3. (a) A helix in 3D transforms into a straight line in the s-z plane; (b) stereo hits are selected using the information of the drift circle and parameters of the charged track.

4 Performance of the tracking algorithm and adjustment

4.1 Checking and adjustment

Before real data reconstruction, Monte Carlo data should be applied to check the performance of the software package in order to enhance the tracking ability and quality.

The step of checking and adjustment has two parts: the 2D part and the 3D part. In the 2D part, the main purpose is to convincingly enhance the tracking efficiency since the low transverse momentum particles fly through fewer superlayers than the usual ones do and the two innermost superlayers in the BESIII are stereo superlayers, which means that axial hit information is very precious and needs to be well utilized. 2D tracking qualification and efficiency can be tuned by several parameters, such as minimum segment hit number, upper limit of χ^2 and so on. We carefully set and adjust these parameters to achieve a convincingly high level of 2D tracking efficiency, and the results are shown in Table 2. In the 2D part, tracking efficiencies for e, μ and π are higher than 98% (due to the charge symmetry here we only display particles with negative charge).

Table 2. 2D-Finder performance of Monte Carlo data under a 20% noise level.

	P_t=70 MeV	P_t=80 MeV	P_t=90 MeV
e^-	(99.3±0.3)%	(98.8±0.3)%	(99.5±0.2)%
μ^-	(99.9±0.1)%	(99.9±0.1)%	(99.9±0.1)%
π^-	(99.5±0.2)%	(99.4±0.2)%	(99.4±0.2)%

The next step is 3D reconstruction, using a 2D circle already found to build the 3D helix. As we have discussed, TCurlFinder will use stereo hits that are close to the 2D circle to build the 3D track. When the smallest distance between the stereo hit's position on the $z=0$ plane and the 2D track falls in a certain region, that stereo hit will be used to build the 3D track that corresponds to that 2D circle. In order to better utilize the high efficiency of 2D tracking, based on the physical structure of the BESIII MDC and careful adjustment, six different regions were set for each superlayer, respectively: 2.4, 2.7, 2.9, 3.4, 4.1, 5.0 cm.

We compared the reconstructed charged tracks' (whose transverse momentum is lower than 120 MeV) χ^2 (after helix fitting) distribution of both Monte Carlo data and real BESIII data, as shown in Fig. 4. The two χ^2 distributions have the same shape and the χ^2 of real BESIII data is larger than that of the Monte Carlo data. Now the χ^2 cut achieved with Monte Carlo data is set as 600, and this cut will cause an efficiency difference of 0.01% between Monte Carlo data and real data. After the Monte Carlo data being tuned further, similar to real data. we will tune the χ^2 cut again to make it compatible with the real data.

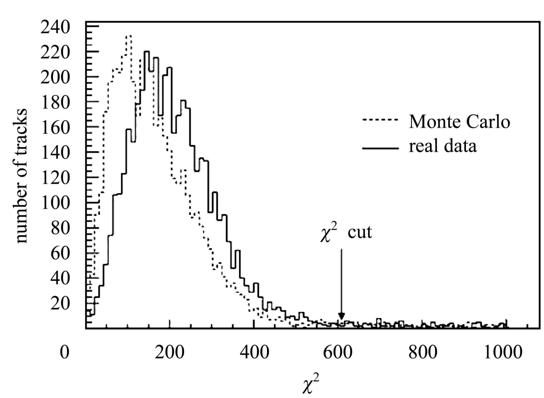

Fig. 4. Comparison of charged tracks' (with transverse momentum lower than 120 MeV) χ^2 distribution of both Monte Carlo data and real BESIII data.

There are two possible sources of the fake tracks. The first case is one track that may be reconstructed into two separate tracks by TSF and TCurlFinder seperately since TCurlFinder uses the hits left by TSF. The other one is that because a particle with low transverse momentum flies in a rotation path, more than one track may be reconstructed for the particle. Aiming at these two fake track sources, TCurlFinder possesses two specialized merging mechanisms to reject noise tracks. The first one is a merging mechanism inside the TCurlFinder, as shown in Fig. 5(a), $o_1(o_2)$ and o represent the center of the two 2D circles, which have a radius of $R_1(R_2)$ and R, respectively. If the two tracks have close 2D circle centers, $|o_1-o|<0.25R$ or $|o_2-o|<0.25R$, similar radius:$|R_1-R|<0.25R$ or $|R_2-R|<0.25R$, and the difference in z-direction is smaller than 25 cm, these two tracks will be identified as circle tracks originating from one single real track, and will be merged into one track. (That is, the track with more hits or the best χ^2). The latter one is the overall merging mechanism. It checks all track candidates with a transverse momentum less than 120 MeV, regardless of whether TSF or TCurlFinder reconstruct them. As shown in Fig. 5(b), t_0 and t_1 are two track candidates, and p_1 belongs to t_1, if $|R-r|<$ load (for axial hits load= 3 cm and for stereo hits load = 4 cm) p_1 will be counted as an overlaped point to t_0. Suppose Nall is the number of hits in track t_1, and Noverlap is the number of overlapped hits t_1 has, the overlapRatio = Noverlap/Nall. If overlapRatio >0.7, t_0 and t_1 will be merged, depending on which track is better.

Based on the adjustments and special mechanisms mentioned above, charged track reconstruction in the low transverse momentum region can achieve both high efficiency and a low fake track rate.

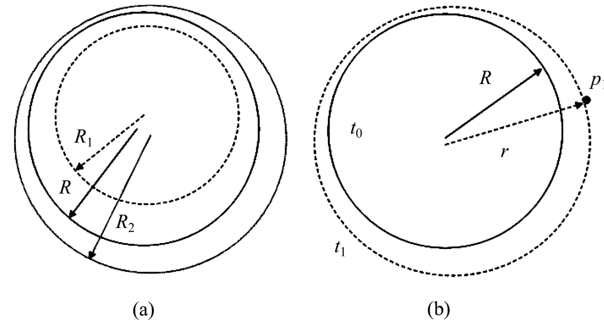

Fig. 5. (a) Merge mechanism in TCurlFinder; (b) merge mechanism between TSF and TCurlFinder.

4.2 Efficiency

Tracking efficiency is the preliminary performance indicator of the algorithm, and it is defined as

$$\varepsilon = N_{\rm rec}/N_{\rm mc}, \tag{4}$$

where $N_{\rm rec}$ is the number of reconstructed 'good' tracks and $N_{\rm mc}$ is the number of charged tracks generated in Monte Carlo. We use single π^- and μ^- Monte Carlo samples with transverse momentum ranging from 50 MeV to 400 MeV. The tracking efficiency is shown in Fig. 6.

With the results both from TSF only and from TSF plus TCurlFinder, the picture clearly shows that the tracking efficiency in the low transverse momentum region is obviously improved: the average enhancement in the transverse momentum region of 20–120 MeV is about 10%, at certain transverse momentum region the improvement is larger than 28%, while that in the high transverse momentum part, which is already high, is unchanged after TCurlFinder is applied.

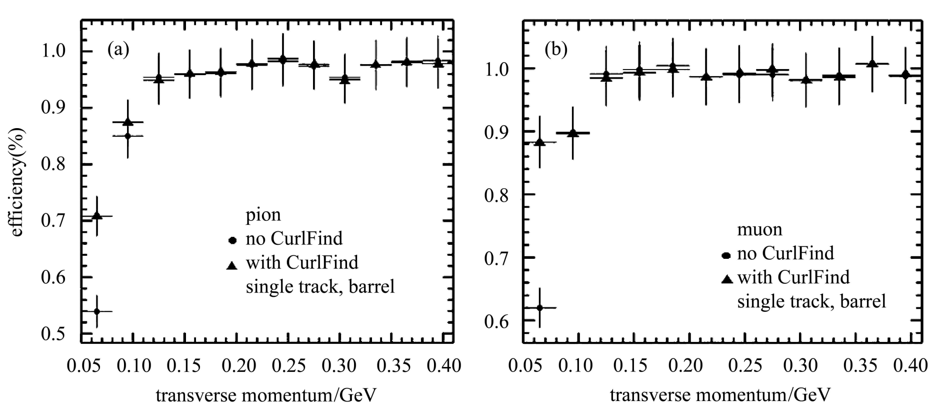

Fig. 6. (a) Comparison of tracking efficiency of Monte Carlo data of single π^-. (b) Comparison of the tracking efficiency of Monte Carlo data of single μ^-.

4.3 Spatial and momentum resolution

Besides the tracking efficiency, momentum and spatial resolution also play a key role in charged track reconstruction. The dual Gaussian is used to fit the residual distribution and the spatial resolution is calculated. The residual is defined as

$$\Delta d_i = \mathrm{drift}_i - \mathrm{doca}, \tag{5}$$

and the momentum resolution is likewise calculated. The residual is defined as

$$\Delta p_i = p_i^{\mathrm{rec}} - p^{\mathrm{mc}_i}. \tag{6}$$

The spatial resolution versus transverse momentum is shown in Fig. 7, which tells us that as the transverse momentum gets smaller, the spatial resolution becomes worse. This phenomenon can be explained by the following aspects: shorter path length of tracks; fewer hits; more serious multi-scattering; higher noise level; and more complicated s-t relationship.

In the BESIII, the expected momentum resolution is described as

$$\Delta p_{\mathrm{t}}/p_{\mathrm{t}} = (0.32\% p_{\mathrm{t}}) \oplus (0.37\%/\beta). \tag{7}$$

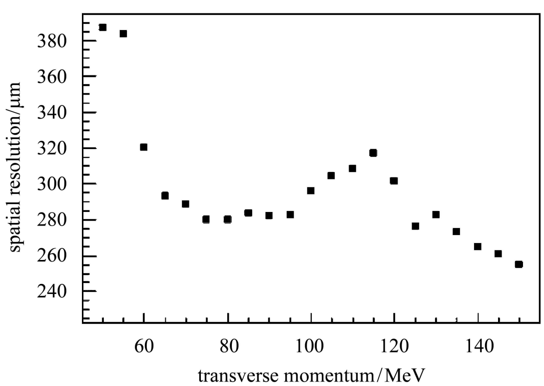

Fig. 7. Spatial resolution of Monte Carlo data of single π^-.

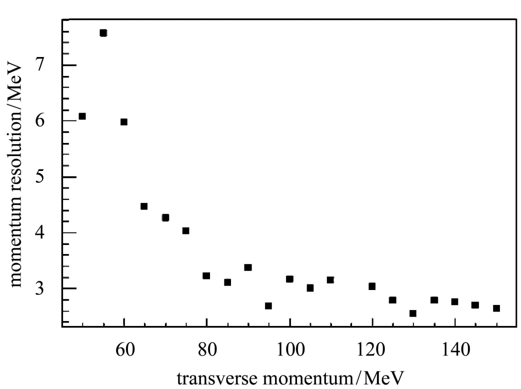

Fig. 8. Momentum resolution of Monte Carlo data of single π^-.

The first term on the right-hand side is the effect of position resolution; the second term is the effect of multiple scattering. The momentum resolution versus transverse momentum is shown in Fig. 8, which shows that the momentum resolution also becomes worse in the low transverse momentum region due to the fact that in this region the position resolution becomes worse and the effect of multiple scattering is more serious, but as momentum gets larger the momentum resolution will regain normal as the position resolution will.

5 Application in physics analysis

To further study the performance of low transverse momentum tracking, two typical decay channels that contain final charged particles with transverse momentum less than 120 MeV are used.

Process $\psi' \to \pi^+\pi^- J/\psi$, $J/\psi \to l^+l^-$ is used to measure the tracking efficiencies of π. Take π^+ as an example. The tracking efficiency is defined as $\epsilon = n_4/(n_3+n_4)$. Here, n_3 and n_4 are the numbers of events of $\psi' \to \pi^+\pi^- J/\psi$, $J/\psi \to l^+l^-$, in which 3 and 4 good charged tracks are successfully reconstructed, respectively. For the measurement of n_4, the following event selection criteria are required:

1) Track level

- $|v_z| > 20$ cm
- $v_r > 5$ cm
- $p < 2.0$ GeV/c
- $|\cos\theta| < 0.93$;

2) Event level

- nGood = 4
- $\Sigma Q = 0$
- 3.0 GeV/c^2 < $M_{l^+l^-}$ < 3.2 GeV/c^2 (assume the tracks with larger momenta are leptons; those with smaller momenta are pions)
- 1.4 GeV/$c < p_l <$ 1.7 GeV/c
- $p_\pi <$ 0.5 GeV/c
- cos(dang) < 0.98 (dang is the space angle between two tracks of pion; this selection is used to remove possible gamma conversion).

The number of events is extracted by fitting the invariant mass spectrum of J/ψ by RooFit package with extended mode, where the Crystal-Ball and 2nd order polynomial functions are used to describe the signal and background, respectively.

n_3 is determined with a similar method except that we only consider such events that only 3 good charged tracks are successfully reconstructed and the total charge is -1. Then we assume a track of π^+ is lost while its four-momentum can be deduced from the other three tracks. After that, the above selection criteria required to be fulfilled too and the number of events is obtained by the same fitter.

The comparison, which is shows in Fig. 9, of tracking efficiency of TSF only and TSF plus TCurlFinder can indicate that after TCurlFinder is applied, the tracking efficiency in the low momentum region is impressively improved by 10%, while keeping the high quality tracking efficiency of TSF in the high transverse momentum region unchanged.

A real data test is also done in this channel. New BESIII ψ' data taken during 2009 have been used to do this test. As shown in Fig. 10, an obvious tracking efficiency enhancement wihtin the low transverse momentum region can be seen, and this result is consistant with the Monte Carlo test.

In the other decay channel $\psi' \rightarrow \eta J/\psi$, $J/\psi \rightarrow l^+l^-$, $\eta \rightarrow \pi^+\pi^-\pi^0$ TCurlFinder also provides a promising improvement in the low transverse momentum region. As shown in Fig. 11, using the same inclusive Monte Carlo data, TSF plus TCurlFinder can provide the number of charged tracks reconstructed before physics analysis about 10% more than TSF can. And this result is consistent with the result of Monte Carlo data of the single particle.

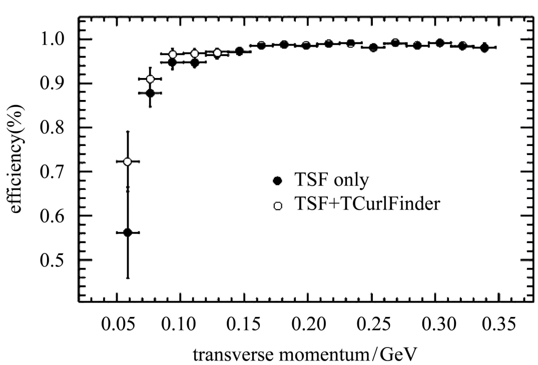

Fig. 9. A comparison of the tracking efficiency of TSF only and TSF plus TCurlFinder in $\psi' \rightarrow \pi^+\pi^- J/\psi$, $J/\psi \rightarrow l^+l^-$ using Monte Carlo data.

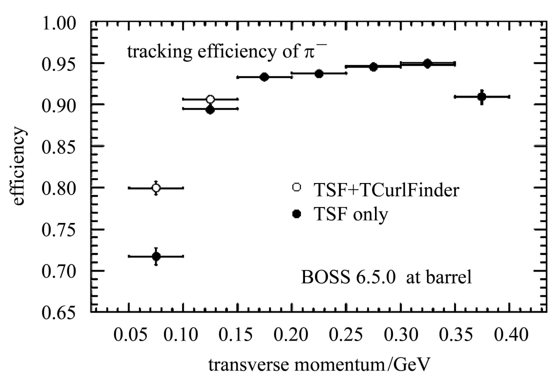

Fig. 10. A comparison of tracking efficiency of TSF only and TSF plus TCurlFinder in $\psi' \rightarrow \pi^+\pi^- J/\psi$, $J/\psi \rightarrow l^+l^-$ using real data.

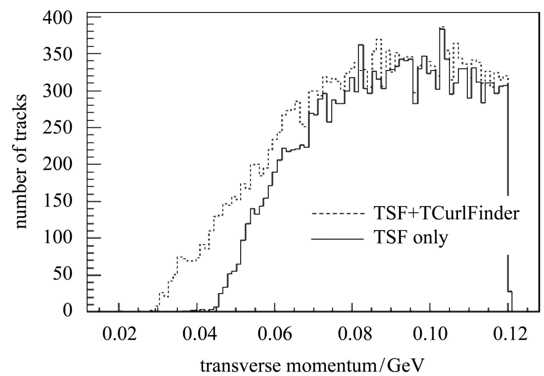

Fig. 11. A comparison of the number of tracks reconstructed by TSF only and by TSF plus TCurlFinder in $\psi' \rightarrow \eta J/\psi$, $J/\psi \rightarrow l^+l^-$, $\eta \rightarrow \pi^+\pi^-\pi^0$ in the transverse momentum region of 20–120 MeV.

Other than the enhancement of tracking efficiency, small time consumption is an important indicator of the tracking package, since the luminosity if the BEPC II is about 10^{33} cm^{-2}·s^{-1}, it means that more than 10^{10} events will be accumulated per year. Thus small CPU time spent on tracking is essential. We use the Monte Carlo data from process $\psi' \rightarrow \eta J/\psi$, $J/\psi \rightarrow l^+l^-$, $\eta \rightarrow \pi^+\pi^-\pi^0$ to study the time consumption of the tracking package TCurlFinder. This test

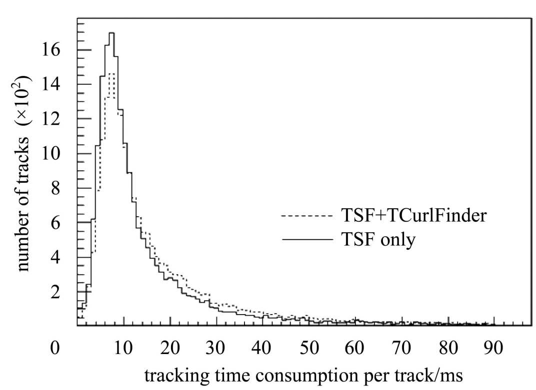

Fig. 12. A comparison of CPU time consumption of TSF only and TSF plus TCurlFinder.

is done in lxslc09, which has 8 Intel Xeon(R) quad-core CPU E5420 2.50 GHz, in IHEP, the time consumption of both TSF only and TSF plus TCurlFinder is shown in Fig. 12, which shows that the average time consumption of tracking per track is still under 15 ms and that after TCurlFinder is applied, the time spent on reconstruction per track is increased for a little bit, which we believe is worthy as far as the enhancement of tracking efficiency is concerned.

6 Conclusion

In order to enhance tracking efficiency in the low transverse momentum region, a novel tracking algorithm TCurlFinder is developed. This tracking package focuses on reconstruction of the charged tracks with transverse momentum less than 120 MeV. After the check and adjustment using both Monte Carlo and real data, the performance of TCurlFinder matches the expectation of achieving efficient tracking down to very low momentum with high quality under high chamber occupancy in the high luminosity environment. Due to the complexity of real data, Monte Carlo can hardly simulate all the factors that contribute to track reconstruction. Therefore, now we suffer from the difference between real data and Monte Carlo data. As the study of Monte Carlo goes further, this difference will be eliminated. More studies will be done very carefully to improve this algorithm, such as decreasing the CPU consumption, and the optimizing and tuning of the parameters of the code.

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