

# Quark charge identification for $e^+e^-$ to $q\bar{q}$ study

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## Abstract

The process  $e^+e^- \rightarrow q\bar{q}$  plays an important role in electroweak precision measurements. We are studying this process with ILD full simulation. The key for the reconstruction of the quark pair final states is quark charge identification (ID). We report the progress of charge ID study in detail. In particular, we investigate the performance of the charge ID for each decay mode of the heavy hadrons to know the possibilities of improvements of the charge ID.

## 1 Introduction

Two-quark final states in the high energy  $e^+e^-$  collisions are important for precise measurements of the electroweak interaction. These simple processes have low background and the uncertainty has a little effect on QED calculation. We are studying the  $e^+e^- \rightarrow q\bar{q}$  final states in the International Linear Collider (ILC) for a probe to new physics. The angular distribution with respect to the beam axis is used to calculate the sensitivity to new physics beyond the Standard Model[1]. Identification of quark charge is necessary to separate the angular distribution of positive and negative quarks. The efficiency of quark charge ID in the previous study[2] was about 60%, which causes significant performance degradation due to the misidentification of the quark charge. For the performance improvement, we investigate the performance of charge ID of the current software for each decay mode of  $b$  hadrons.

## 2 Simulation condition

We utilized ILCSoft[3] version v01-16 for this study. The event samples of  $e^+e^- \rightarrow b\bar{b}$  was generated in center of mass energy of 250 GeV by WHIZARD 1.95[4]. The full Monte Carlo simulation (MC) was done with Mokka based on Geant4 framework with the reference geometry of the International Large Detector (ILD) concept used in the studies of Detailed Baseline Design report[5], ILD\_v1\_o5 model. The model includes silicon pixel and strip detectors, a time projection chamber, precisely segmented electromagnetic and hadron calorimeters (ECAL and HCAL) and a 3.5 Tesla solenoid magnet. Event reconstruction was done with Marlin processors, including tracking and particle flow reconstruction by PandoraPFA algorithm[6] to obtain track-cluster matching. The reconstructed particles were clustered to two jets with Durham[7] algorithm.

## 3 Vertex finder and quark charge identification

The key feature to reconstruct the quark charge is a vertex finder. We used LCFIPlus[8] to reconstruct vertices. In the LCFIPlus, all tracks are firstly processed with a primary vertex finder based on tear-down technique, with the beam constraint to remove most of tracks consistent to come from the interaction point. Then remaining tracks are processed with a secondary vertex finder based on build-up technique. It does not restrict the number of vertices per jet to reconstruct, but after the jet clustering it combines the

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35 vertices if there are more than two vertices in the jet with refitting vertex positions. In addition, it uses  
 36 tracks which are consistent to cross the line of the primary vertex and secondary vertices to formulate  
 37 additional pseudo-vertices, which aims to recover vertices having only one track. Overall fraction of  
 38 having two vertices in  $b$  quark jet with the current implementation is around 40%, and having one or  
 39 more vertices is around 80%. In the following discussion, we treat two vertices separately if we obtain  
 40 two vertices in a jet, and treat the vertex as combined vertices of  $b$  and  $c$  decay if we obtain only one  
 41 vertex.

42 To separate  $b$  and  $\bar{b}$ , the charges of the second and third vertex are calculated as the sum of track  
 43 charge associated to the vertices.

44 There are four ways of obtaining quark charge as follows:

- 45 • jet charge (charge sum of all tracks in the jet) ( $\Sigma_{\text{all}}^{\text{jet}}$ )
- 46 • vertex charge
  - 47 – charge sum of tracks associated to the second vertex ( $\Sigma_{\text{vtx}}^{2\text{nd}}$ )
  - 48 – charge sum of tracks associated to the third vertex (if found) ( $\Sigma_{\text{vtx}}^{3\text{rd}}$ )
  - 49 – charge sum of tracks associated to the second and third vertex ( $\Sigma_{\text{vtx}}^{2\text{nd}3\text{rd}}$ )

50 For jets with two vertices found, we can use  $\Sigma_{\text{vtx}}^{2\text{nd}}$  and  $\Sigma_{\text{vtx}}^{3\text{rd}}$  to separate  $b$  decay, but for jets with only  
 51 one vertex found, we can only use  $\Sigma_{\text{vtx}}^{2\text{nd}3\text{rd}}$ . For jets without vertices found, we have to use  $\Sigma_{\text{all}}^{\text{jet}}$  but this  
 52 is not discussed in this study.

## 53 4 Decay modes of B mesons

54 The purpose of charge ID is to distinguish jets from  $b$  quarks and jets from  $\bar{b}$  quarks. Each  $b$  or  $\bar{b}$  quark  
 55 formulates a  $b$  hadron after fragmentation, which is usually in the core of the jet. Table 1 shows  $b$   
 56 hadrons obtained from  $b$  and  $\bar{b}$  quarks separately. The charge of the  $b$  quark is closely related to the  
 57 quark constituents in the final state  $b$  hadrons, for example  $B^-$  and  $\bar{B}^0$  only come from  $b$  quark and not  
 58 from  $\bar{b}$  quark, and  $B^+$  and  $B^0$  only come from  $\bar{b}$  quark and not from  $b$  quark if we ignore quark-antiquark  
 59 oscillation. If we can separate  $B^0$  and  $\bar{B}^0$ , this can enhance the charge ID performance significantly,  
 60 compared to just identify the charge of the  $b$  hadrons. This can be realized by observing decay of  $B$   
 61 mesons. Here we only focus on the  $B^+$ ,  $B^0$  and those antiparticles, however, similar discussion can be  
 62 done with other decay modes as well.

$b$		$\bar{b}$	
-1	0	0	+1
$B^-(\bar{u}b)$	$\bar{B}^0(d\bar{b})$	$B^0(d\bar{b})$ 42.2%	$B^+(u\bar{b})$ 41.9%
$B_c^-(\bar{c}b)$	$\bar{B}_s^0(s\bar{b})$	$B_s^0(s\bar{b})$ 8.0%	$B_c^+(c\bar{b})$
$\Xi_b^-(d\bar{s}b)$	$\Lambda_b^0(u\bar{d}b)$	$\Lambda_b^0(\bar{u}d\bar{b})$ 6.4%	$\Xi_b^+(\bar{d}\bar{s}\bar{b})$ 0.61%
$\Omega_b^-(s\bar{s}b)$	$\Xi_b^0(u\bar{s}b)$	$\Xi_b^0(\bar{u}\bar{s}\bar{b})$ 0.59%	$\Omega_b^+(\bar{s}\bar{s}\bar{b})$ 0.010%

Table 1: List of semistable  $b$  hadrons produced from  $b$  and  $\bar{b}$  quarks. The production ratio, obtained from MC information, is also shown for  $\bar{b}$ , which ignores  $b$ - $\bar{b}$  oscillation. Production of charmed  $b$  hadrons ( $B_c$ ), which usually decay to lighter  $b$  hadrons initially, are included in the fraction of lighter  $b$  hadrons.

63 Table 2 shows the dominant decay modes of  $B^+$  and  $B^0$  mesons. As shown in the tables, there is  
 64 some discrepancy of the branching ratios between PDG values and those obtained from the MC samples,  
 65 which may be due to the  $b$ - $\bar{b}$  oscillation. For the  $B^+$  decay, the dominant decay mode is  $B^+ \rightarrow \bar{D}^0 X$ ,  
 66 which gives positive vertex on the decay of  $B^+$  and neutral vertex on the subsequent decay of  $\bar{D}^0$ . In  
 67 the case of  $B^0$  decay, there are two dominant decay modes,  $B^0 \rightarrow \bar{D}^0 X$  and  $B^0 \rightarrow D^- X$ . For the latter  
 68 decay, the decay vertex of  $B^0$  should be positive and the subsequent  $D^-$  decay should be negative, which

69 should have separation power from  $\bar{B}^0$ . For this separation, separation of second and third vertices is  
70 critical.

Decay modes	BR in PDG	BR in MC	Decay modes	BR in PDG	BR in MC
$B^+ \rightarrow D^0 X$	79%	70.51%	$B^0 \rightarrow \bar{D}^0 X$	47.4%	40.24%
$B^+ \rightarrow D^- X$	9.9%	9.81%	$B^0 \rightarrow D^- X$	36.9%	27.59%
$B^+ \rightarrow D^0 X$	8.6%	4.21%	$B^0 \rightarrow D_s^+ X$	10.3%	4.21%
$B^+ \rightarrow D_s^+ X$	7.9%	4.80%	$B^0 \rightarrow D^0 X$	8.1%	11.55%
$B^+ \rightarrow D^+ X$	2.5%	1.65%	$B^0 \rightarrow D^+ X$	<3.9%	6.91%

Table 2: Branching ratios (BR) of  $B^+$  (left) and  $B^0$  (right) mesons. BR in PDG is from [9], and BR in MC is from the event sample.

## 71 5 Current performance of charge ID

72 The performance of charge ID with LCFIPlus is checked with  $B^+$  and  $B^0$  data. After separation of the  
73 decay mode with MC information,  $b$  and  $\bar{b}$  quarks are assigned to jets using MC-track matching. The  
74 reconstructed vertices are examined and  $\Sigma_{\text{vtx}}^{2\text{nd}}$ ,  $\Sigma_{\text{vtx}}^{3\text{rd}}$  and  $\Sigma_{\text{vtx}}^{2\text{nd}3\text{rd}}$  are calculated for each jet.

75 Table 3 shows those observables of  $B^+$  decays, categorized by the number of reconstructed vertices  
76 and  $B^+$  decay modes (with only first and second dominant decay). For the events with 1 vertex found, it  
77 shows that positive  $\Sigma_{\text{vtx}}^{2\text{nd}3\text{rd}}$  is much more than negative charge, which proves that charge ID is possible.  
78 However, there is significant amount of “neutral” vertex, which limits the charge ID performance. For  
79 the events with 2 vertices found, the positive  $\Sigma_{\text{vtx}}^{2\text{nd}}$  dominates more than with 1 vertex case, thus gives  
80 better performance of charge ID. For the special case of  $B^+ \rightarrow \bar{D}^- X$ ,  $\Sigma_{\text{vtx}}^{2\text{nd}}$  should be +2 and  $\Sigma_{\text{vtx}}^{3\text{rd}}$  should  
81 be -1, which is much easier to identify.

particle	$B^+$ (all decay)			$B^+ \rightarrow \bar{D}^0 X$ (79%)			$B^+ \rightarrow \bar{D}^- X$ (9.9%)		
	1	2		1	2		1	2	
		2nd	3rd		2nd	3rd		2nd	3rd
symbol	$\Sigma_{\text{vtx}}^{2\text{nd}3\text{rd}}$	$\Sigma_{\text{vtx}}^{2\text{nd}}$	$\Sigma_{\text{vtx}}^{3\text{rd}}$	$\Sigma_{\text{vtx}}^{2\text{nd}3\text{rd}}$	$\Sigma_{\text{vtx}}^{2\text{nd}}$	$\Sigma_{\text{vtx}}^{3\text{rd}}$	$\Sigma_{\text{vtx}}^{2\text{nd}3\text{rd}}$	$\Sigma_{\text{vtx}}^{2\text{nd}}$	$\Sigma_{\text{vtx}}^{3\text{rd}}$
charge < 0	8.67%	8.06%	22.8%	7.52%	7.21%	16.6%	17.2%	7.85%	67.6%
charge = 0	35.5%	18.5%	53.0%	38.6%	18.1%	6.07%	20.0%	8.75%	20.0%
charge > 0	55.7%	73.3%	24.0%	53.8%	74.6%	22.6%	62.7%	83.3%	12.3%

Table 3: Reconstructed charge of the vertices in  $B^+$  decay. The left 3 columns show the charge of all decay modes, and the right 6 columns show the charge of two dominant decay modes.

82 Separation of  $B^0$  and  $\bar{B}^0$  is apparently more difficult since the total charge of  $B^0$  and subsequent  
83 charm hadron is neutral. There are two dominant decay modes of  $B^0$ :  $B^0 \rightarrow \bar{D}^0 X$  and  $B^0 \rightarrow D^- X$ .  
84 The former is quite difficult to distinguish from  $\bar{B}^0 \rightarrow D^0$ , since both of second and third vertices are  
85 neutral. There may be some possibility to identify kaons to check their charge, but this is beyond the  
86 current study. In  $B^0 \rightarrow D^- X$  case we have a chance to separate from  $\bar{B}^0$  since the first  $B^0$  vertex should  
87 be positive and subsequent charm vertex should be negative, as shown in Table 4. Here the separation  
88 is nearly impossible with one vertex found, but with two vertices there is a significant difference on the  
89 positive and negative fractions of  $\Sigma_{\text{vtx}}^{2\text{nd}}$  and  $\Sigma_{\text{vtx}}^{3\text{rd}}$ , which gives separation power of  $B^0$  and  $\bar{B}^0$ .

## 90 6 Summary and prospects

91 We investigated the performance of quark charge ID to be used in  $e^+e^- \rightarrow q\bar{q}$  study. By separating decay  
92 modes, we have a chance to separate  $b$  and  $\bar{b}$  by using tracks from second and third vertices independently.  
93 However, misidentification of the vertex charge is still to be improved. The main reason should be tracks  
94 missed to be clustered into the vertex. We will investigate to recover those tracks by checking behaviour  
95 of the vertex finder more precisely. There is a trial of such a vertex recovery[10] which should be revisited.

particle	$B^0 \rightarrow \bar{D}^- X$ (36.9%)		
number of vertex	1	2	
		2nd	3rd
charge < 0	29.5%	11.8%	72.3%
charge = 0	33.2%	17.6%	17.5%
charge > 0	37.1%	70.5%	10.0%

Table 4: Reconstructed charge of the vertices in  $B^0 \rightarrow \bar{D}^- X$  decay.

96 It is also important to increase the fraction of events which can find two vertices since having two  
97 vertices gains the performance significantly. We can also consider to use zero-vertex events by looking  
98 for secondary particles with larger impact parameters or jet leptons. Investigation of charm jets should  
99 also be done as a future plan.

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## 103 References

- 104 [1] H. Yamashiro et al., Study of fermion pair productions at the ILC with center-of-mass energy of 250  
105 GeV, Proc. LCWS2017, arXiv:1801.04671.
- 106 [2] H. Yamashiro, Master thesis at Kyushu University (2018),  
107 <http://epp.phys.kyushu-u.ac.jp/thesis/2018MasterYamashiro.pdf> (Japanese)
- 108 [3] <http://ilcsoft.desy.de/portal/>
- 109 [4] W. Kilian, T. Ohi, J. Reuter, Eur. Phys. J. **C71** (2011) 1742.
- 110 [5] T. Behnke *et al.*, The International Linear Collider Technical Design Report - Volume 4: Detectors.  
111 2013, arXiv:1306.6329.
- 112 [6] M. A. Thomson, Nucl. Instrum. Meth. **A611** (2009) 25-40.
- 113 [7] S. Catani *et al.*, Phys. Lett. **B269** (1991) 432-438.
- 114 [8] T. Suehara, T. Tanabe, Nucl. Instrum. Meth. **A808** (2016) 109-116.
- 115 [9] M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. **D98** (2018) 030001
- 116 [10] S. Bilokin, R. Pöschl, F. Richard, Measurement of  $b$  quark EW couplings at ILC, arXiv:1709.04289.