PROCEEDINGS OF SCIENCE

Quark production in high energy electron positron collisions: from strange to top

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The process $e^+e^- \to q\bar{q}$ with $q\bar{q} = s\bar{s}, c\bar{c}, b\bar{b}, t\bar{t}$ plays a central role in the physics programs of high energy electron-positron colliders operating from the O (100GeV) to O (1TeV) center of mass energies. Furthermore, polarised beams as available at the International Linear Collider (ILC) are an essential input for the complete measurement of the helicity amplitudes that govern the production cross section. Quarks, specially the heaviers, are likely messengers to new physics and at the same time they are ideal benchmark processes for detector optimisation. All four processes call for superb primary and secondary vertex measurements, a high tracking efficiency to correctly measure the vertex charge and excellent hadron identification capabilities. Strange, charm and bottom production are already available below the $t\bar{t}$ threshold. We will show with detailed detector simulations of the International Large Detector (ILD) that production rate and the forward backward asymmetries of the the different processes can be measured at the 0.1% to 0.5% level and how systematic errors can be controlled to reach this level of accuracy. The importance of operating at different center of mass energies and the discovery potential in terms of Randall-Sundrum models with warped extra dimensions will be outlined.

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1. Introduction

One of the physics observations that is anticipated at the future lepton colliders is the measurement of electroweak coupling between neutral vector bosons (Z^0 and γ, potentially Z') and a quark pair through the $e^+e^- \to q\bar{q}$ process. In the current Standard Model (SM), there is no definitive answer to explain the mass hierarchy of fermions. In fact, many models for the physics Beyond Standard Model (BSM), such as composite top model [1] or Randall-Sundrum model [2], offers predictions to the aforementioned couplings in order to explain the hierarchy problem. Since the couplings between Z boson and fermion pair depends on the fermion helicities, it is also important to apprehend the initial and final states of the particles. The experimental approach for the measurements of coupling between Z boson and $q\bar{q}$ ($q = c, b$) was first made by LEP and SLC collaborations through $e^+e^- \to c\bar{c}$ and $e^+e^- \to b\bar{b}$ at the Z-pole [3]. In the experiment, one can determine the couplings by measuring the the forward and backward asymmetry parameter (A_{FB}) which is defined as:

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} \tag{1}$$

where σ_F (σ_B) is the $e^+e^- \to q\bar{q}$ cross section which goes to the forward (backward) hemisphere respect to the electron beam. These cross sections are determined from the polar angle of reconstructed track of q ($\cos\theta_q$) while the polar angle of reconstructed $\bar{q}$ is flipped ($\cos\theta_q = \cos(\theta_{\bar{q}} + \pi)$) in order to double the statistics. Therefore, having a precise measurements in forward and backward cross section leads to the precision measurements of the couplings. In this analysis, the experimental methods and precision level of coupling measurements at the next generation lepton collider is introduced to demonstrate its capability and sensitivities towards new physics, using the full detector simulation of $e^+e^- \to s\bar{s},\ c\bar{c},\ b\bar{b}$ and $t\bar{t}$.

2. ILC & ILD

International Linear Collider (ILC) [4] is the electron-positron collider which is expected to run at $\sqrt{s} = 250$ GeV at its launch. It has 20 km in length and has a capability to extend towards 30 km for $\sqrt{s} = 500$ GeV. One of the key features of the ILC is the well defined initial and final states of the particles upon collision, since it can polarize both electron and positron beams. Such feature will enable the ILC to measure various physical observables to the high precision, thus distinguishing theories on BSM (Fig.1). International Large Detector (ILD) [6] is one of the detector complexes (along with SiD) that is going to be used upon running at the ILC. Its central trackers and highly granular calorimeters facilitates the high precision tracking and measurements for individual particles, which is governed by the Particle Flow Algorithm, known as PFA [7]. PFA reconstructs Particle Flow Objects (PFO) of all the particle within an event, identifying individual charged and neutral particles, including the constituents inside the jets.

3. Event Reconstruction

The events are generated using WHIZARD [8], along with parton shower simulation stimulated by Pythia [9]. The generated particles were then processed via full ILD GEANT4 detector

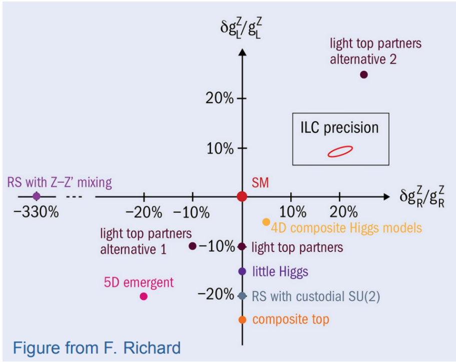


Figure 1: Predicted deviations of Z couplings to the left and right handed top quark [5]

simulation, which was used to produce the results shown here. $\sqrt{s}$ = 250 GeV collision energy was used for $s\bar{s}$, $c\bar{c}$, $b\bar{b}$ production, and $\sqrt{s}$ = 500 GeV for $t\bar{t}$ process. After the detector simulation process, 2 jets were reconstructed using Durham algorithm.

3.1 Flavor Tagging

b and c tags are the essential parameters to distinguish b and c jets from $e^+e^- \longrightarrow c\bar{c}$, $b\bar{b}$ and the $t\bar{t}$ events. Tagging of each jet requires precise measurement of impact parameter since such long lived particles will decay at secondary vertices, which varies between different two flavors. Such parameter is requested upon Interim Design Report of the ILD with specific resolution ($\sigma_{r\phi}$) [10].

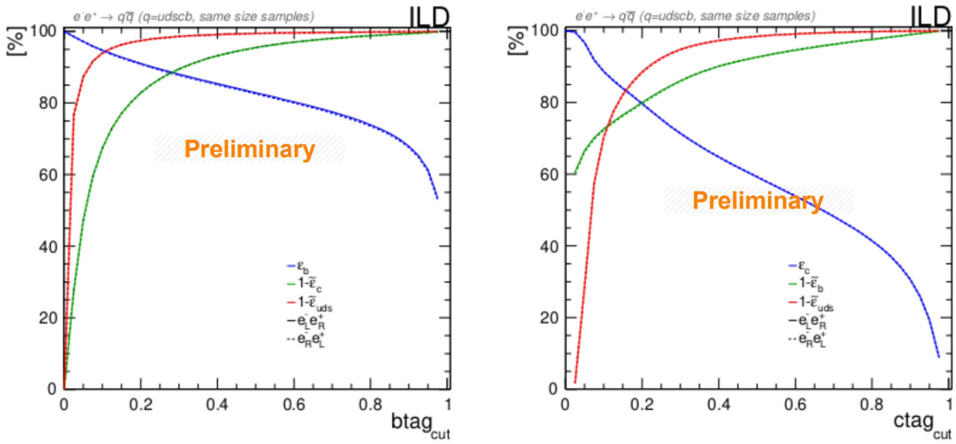
$$\sigma_{r\phi} = 5\ \mu\text{m} \oplus \frac{10}{p\ (\text{GeV})\ \sin^{3/2}\theta}\ \mu\text{m} \tag{2}$$

In the Figure 2, the tagging efficiency and purity of b and c tags in ILD are shown as a function of each flavor tagging cut. The performance of both b and c tagging both suggest their resilience towards other flavor backgrounds. After flavour tagging of the jets, sum of the charges of PFOs associated to each secondary vertex is used to form the vertex charge. For the $b\bar{b}$ and $t\bar{t}$ process, this is the primary method to identify the generated quark charge, called *vertex method*.

3.2 dE/dx Measurements

Kaon identification can be the primary identifier for all flavors discussed in this analysis (s, c, b, t) since they all could contain charged K at some point in their decay chain. Identification of charged Ks will give the information of the generated quarks, which is essential in calculating the A_{FB} for all $e^+e^- \longrightarrow q\bar{q}$ process here. In order to identify the charged Ks, dE/dx information is used. dE/dx is the quantity of ionization energy loss within the differential distance and it is measured inside the Time Projection Chamber (TPC) of the ILD. When dE/dx of the reconstructed particle is plotted against its momentum (Fig.3(a)), the distribution can be approximated by the Bethe-Bloch formula, which is unique to individual particle. For the particle identification, dE/dx *distance* is used with following definition:

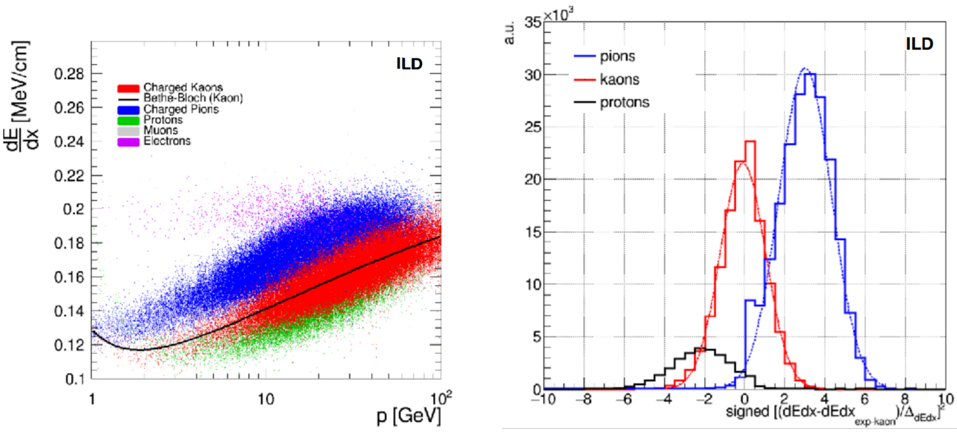
$$\text{dE/dx distance} = \text{signed}\left[\left(\frac{(dE/dx - dE/dx_{exp-Bethe})}{\Delta_{dE/dx}}\right)^2\right] \tag{3}$$



(a) (b)

Figure 2: Flavor tagging performance for c (left) and b (right). ϵ_c (ϵ_b) is the tagging efficiency after c (b) tag cuts. $1-\tilde{\epsilon}_b$ ($1-\tilde{\epsilon}_c$) are the c (b) tagging purity under b (c) background. $1-\tilde{\epsilon}_{uds}$ is the flavor tagging efficiency under uds background. Finally, dotted and solid lines represent the same quantity with $e^-_R e^+_L$ and $e^-_L e^+_R$ beam polarization, respectively. [11]

where $dE/dx_{exp-Bethe}$ is dE/dx value expected from Bethe-Bloch formula, $\Delta_{dE/dx}$ is statistical error for dE/dx measurements, and the +/- sign that was lost upon squaring the quantity will be retained afterwards (thus "signed"). Such distribution is plotted in the Figure 3(b). Ks are selected from the central region of dE/dx distance plot where its distribution is abundant over the others, mainly from π and proton contributions. At the current working point, purity and efficiency for K identification using this method are 90 % and 80 %, respectively, for both $b\bar{b}$ and $c\bar{c}$ analysis. Particle identification using dE/dx distance is called *Kaon method*.



(a) (b)

Figure 3: (a) dE/dx plotted against momentum for each particle ($e, \mu, K^\pm, p, \pi$). (b) dE/dx distances from kaon Bethe-Bloch formula.

4. Asymmetry Measurements

As discussed in Section 1, particle charge measurement is the key to precisely measure A_{FB}. For this analysis, integrated luminosity of 4,600 fb^{-1} was taken for $s\bar{s}$ process, 900 fb^{-1} for $c\bar{c}$ and $b\bar{b}$ process, 3,200 fb^{-1} for $t\bar{t}$ process. Polar angle distribution is the vital information for seeking the asymmetry parameter. In Figure 4, polar angle distribution for 4 different processes with beam polarization of $e^-_L e^+_R$ are plotted with fit to the differential angular cross section:

$$\frac{d\sigma}{d\cos\theta} = S \times \left(1 + \cos^2\theta\right) + A \times \cos\theta \tag{4}$$

where S and A are the symmetrical and asymmetrical parameter for the differential cross sections, respectively. Throughout four processes, all of their polar angle has the best agreement with leading-order predictions, despite $s\bar{s}$, $c\bar{c}$ and $b\bar{b}$ has drop in the reconstruction efficiency above $\cos\theta > 0.8$ due to the lack of acceptance of the detector at the forward region.

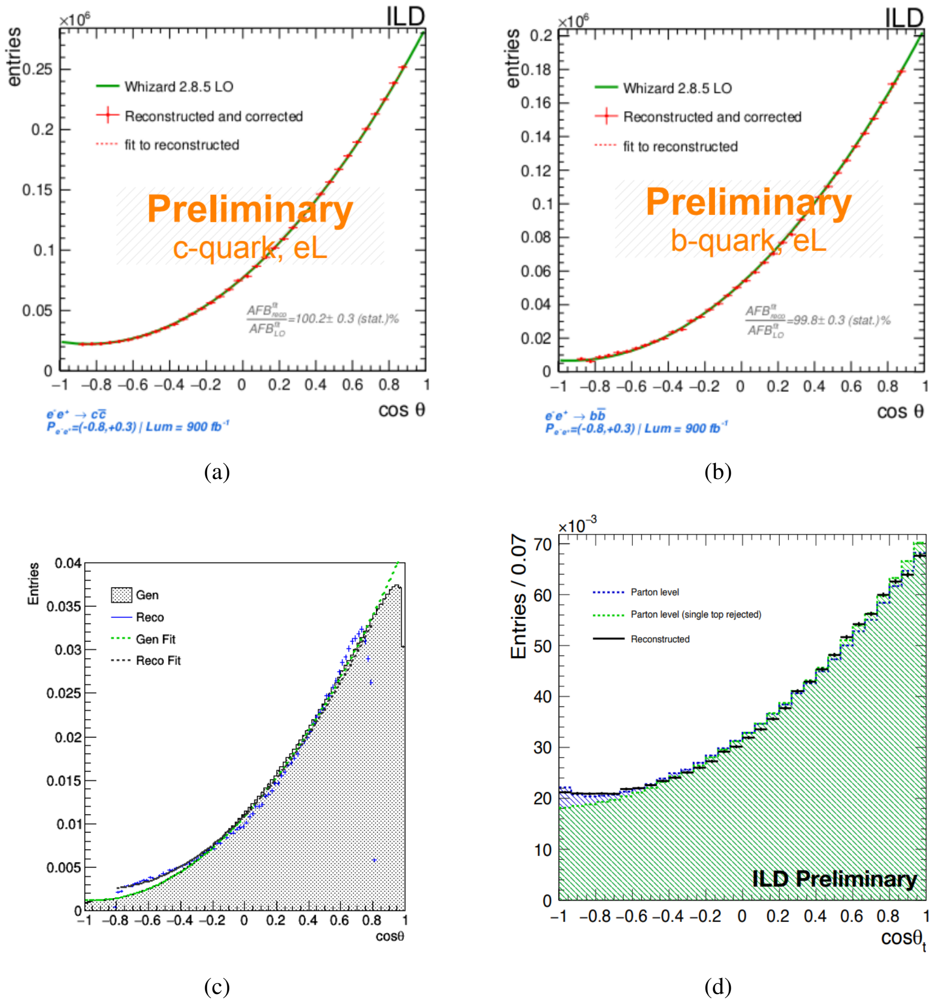


Figure 4: Polar angle distirbutions of 4 different processes plotted with generated $q\bar{q}$ polar angle. (a) $c\bar{c}$, (b) $b\bar{b}$, (c) $s\bar{s}$, (d) $t\bar{t}$

5. Conclusion

Throughout this paper, the analysis methods for $e^+e^- \to q\bar{q}$ at the ILC was demonstrated. Quark pair production with four different flavors ($s\bar{s}, c\bar{c}, b\bar{b}, t\bar{t}$) were generated with full detector simulation at the ILD. Vertex charge and dE/dx distance measurements were used to identify the particle charge and as a result, their reconstructed polar angle distribution showed great agreement with generated distribution. Moreover, flavor tag studies from $c\bar{c}$ and $b\bar{b}$ analysis demonstrated high performance in both efficiency and purity.

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