

Improving the parameterization of silicon vertex detector resolution distributions for the tagging of bottom and charm-flavored hadron decays for the Collider Detector at Fermilab experiment

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Abstract

This project was concerned with parameterizing the silicon vertex detector (SVX) resolution distributions, especially those of the r - ϕ plane, so that bottom quark jets (b jets) could be tagged more efficiently with a "jet probability" algorithm. Fits of the sum of four zero-mean Gaussians were produced on cuts of the data that incorporated the number of SVX shared hits (0, 1, 2, ≥ 3), the number of SVX hits (3, 4, 5, 6, 7 or 8), the transverse momentum (Pt) in GeV/c ($0.5 \leq Pt < 2$, $2 \leq Pt < 5$, $Pt \geq 5$), and the innermost SVX layer hit (0, 1, ≥ 2). As of yet it is inconclusive as to whether or not these fits improved efficiency of the b tagging jet probability algorithm.

1. Introduction

The Collider Detector at Fermilab (CDF) is a 5000-ton collection of a wide variety of particle sensing devices [1]. It is one of two experiments (the other being D0, or D-zero) which resides on the Tevatron collider. The Tevatron collider, a circular accelerator, accelerates bunches of protons and antiprotons (p, pbar) in opposite directions through a single, toroidal beam pipe toward a collision of 2 TeV maximum impact energy [1]. The collisions, called events, are capable of producing thousands of exotic composite particles and many presumably elementary particles, which are important for our understanding of the forces of nature. CDF has already made several important contributions to particle physics during Run I in the late 80's and mid 90's, such as the discovery of the predicted sixth quark known as "top" in 1995. Since then CDF has been upgraded and improved for Run II which is recently underway for the

purpose of studying the heavy top and bottom quarks' properties; and for possibly revealing evidence for the theoretical mass-giving particle known as the Higgs¹ boson [1].

One important aspect of the CDF experiment is its ability to recognize, or tag, the bottom and charm quark decays. The bottom quark participates in the decay modes of the top quark and predicted Higgs boson, and the charm is a signature particle of bottom decays. This fact makes the bottom and charm's tracks prime specimens for the tagging of a top or Higgs. However, quarks cannot be detected individually or directly themselves but must be recognized by the collimated "jets" of particles that result from decays of their associated hadrons² (mesons and baryons) [2]. B jets (jets caused by bottom-flavored hadron decays) are particularly effective for tagging because bottom hadrons are relatively long-lived (usually around 1.5 picoseconds). This means that the tracks of individual particles born of b jets will have originated from some point of a significant finite distance away from the center of impact (or primary vertex). We can extrapolate these tracks back to the location closest to the impact that they could possibly have come from using data from a silicon vertex detector (SVX, SVX II for Run II) as well as other encapsulating detectors; and the fact that charged particles follow circular paths in the presence of the detector's solenoidal 1.4 T magnetic field. The distance from the primary vertex to this closest possible originating location is known as the impact parameter (denoted D_0 in the r - ϕ plane, which I will describe later). A distribution of the ratio of this distance divided by its associated error ($D_0\text{Err}$) for all zero-lifetime particle tracks is known as the SVX resolution distribution ($D_0/D_0\text{Err}$). When fit with a function this distribution becomes a powerful tool capable of quickly and efficiently tagging b jets. Our project is to parameterize and fit the SVX resolution distribution so that we can tag potential b jets based on a combination of the integrals of a group of tracks' statistics (the jet probability).

2. The Signed Impact Parameter

Nearly all particle tracks will have a non-zero impact parameter due to limits in the detector's resolution and refresh rate, or even due to cosmic rays that happen to pass through. Tracks may also have signed impact parameters, with the sign determined by the angle between the jet axis and the line of the impact parameter [2]. Fig 1 shows two tracks A and B with impact parameters of equal magnitude but

opposite sign. Track A is positively signed because its closest possible position to the primary vertex is at an acute angle with the jet axis. Similarly, Track B is negatively signed because the line of its impact parameter is at an obtuse angle to the jet axis. Giving a sign to the impact parameter in this way is useful

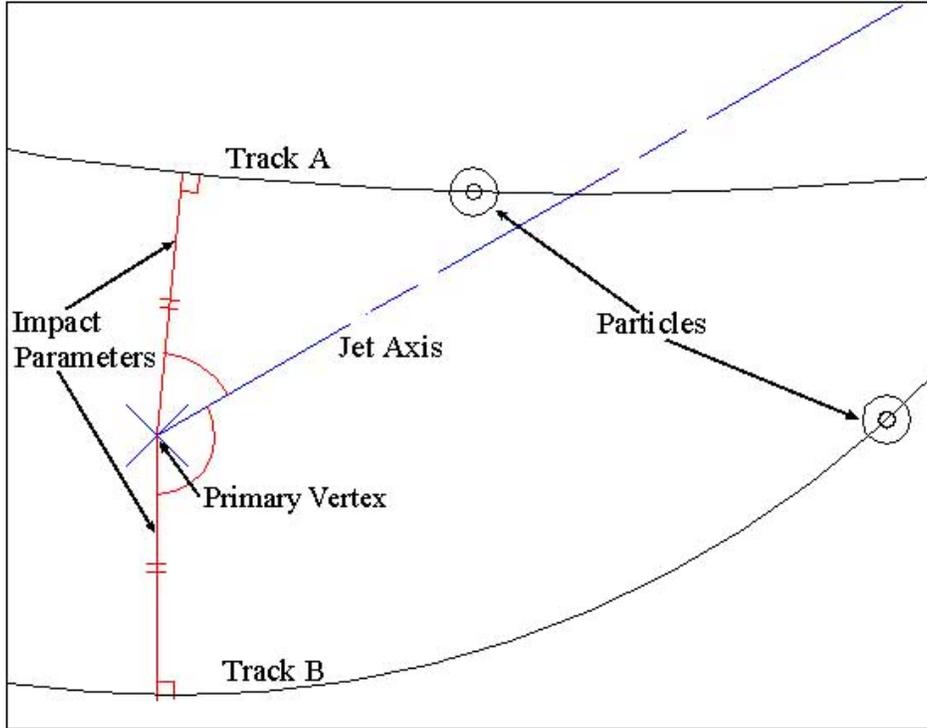


FIGURE 1

Two tracks with equal but opposite impact parameters.

especially if fitting real data because tracks spawned by b-hadron decays³ always possess acute angles to the jet axis due to a greater velocity parallel to the axis than normal to it. This fact corresponds to b jet tracks carrying positive signed impact parameters under ideal conditions. Unfortunately, resolution effects can cause b jet tracks to wrongly exhibit negative signed impact parameters; however, b jet tracks will still bias toward the positive side.

So with this sign convention we establish a simple and reasonably efficient method for cutting b jet tracks out of the background tracks (which themselves are equally probable to have positive or negative impact parameters), which we can then fit a distribution of without too much jet contamination. Fig. 2 shows a distribution of the signed impact parameter of non-b jet tracks and a distribution of b jet only

tracks. This figure is a good demonstration of the b jet track preference for a positive impact parameter as opposed to the background's indifference.

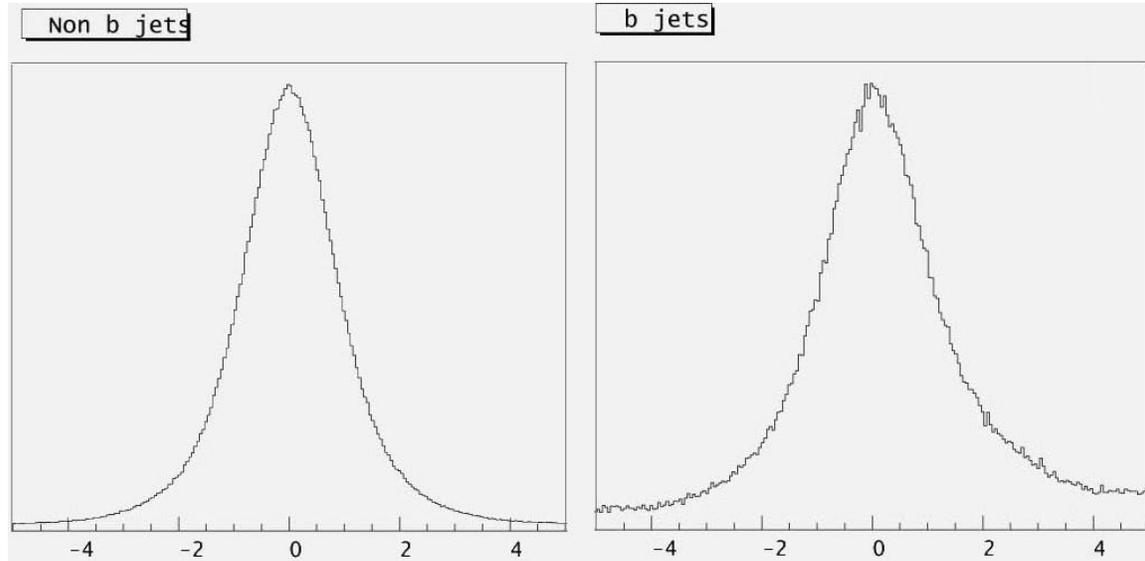


FIGURE 2

Left: the SVX resolution distribution; contains only particle tracks originating from zero-lifetime particle decays. It is shown to be unbiased with respect to the sign of the impact parameter.

Right: a similar distribution containing only b jet tracks. It is shown to be biased toward positive signed impact parameters.

3. Silicon Vertex Detector

SVX II consists of three 29 cm long sections of five layers of 12-sided concentric cylindrical shells of silicon detectors ranging from 2.5450 cm to 6.5200 cm with the intermediate silicon layers (ISL) providing an additional three layers out to 10.6450 cm from the center of the beam pipe [3]. A vertical plane normal to the beam pipe would yield an irregular yet radially symmetric dodecagonal cross-section of the five layers in what is known as the r - ϕ plane, the plane in which my research mainly focuses (see Fig. 3).⁴ The central portion of Fig. 3 represents SVX II while the outer portion indicates the ISL. In practice, the silicon layers are numbered consecutively and with letters "a" and "b" starting with 0a at the center, then 0b, 1a, and ending with 4b. Oftentimes the innermost layer of silicon is referred to as "layer 00".

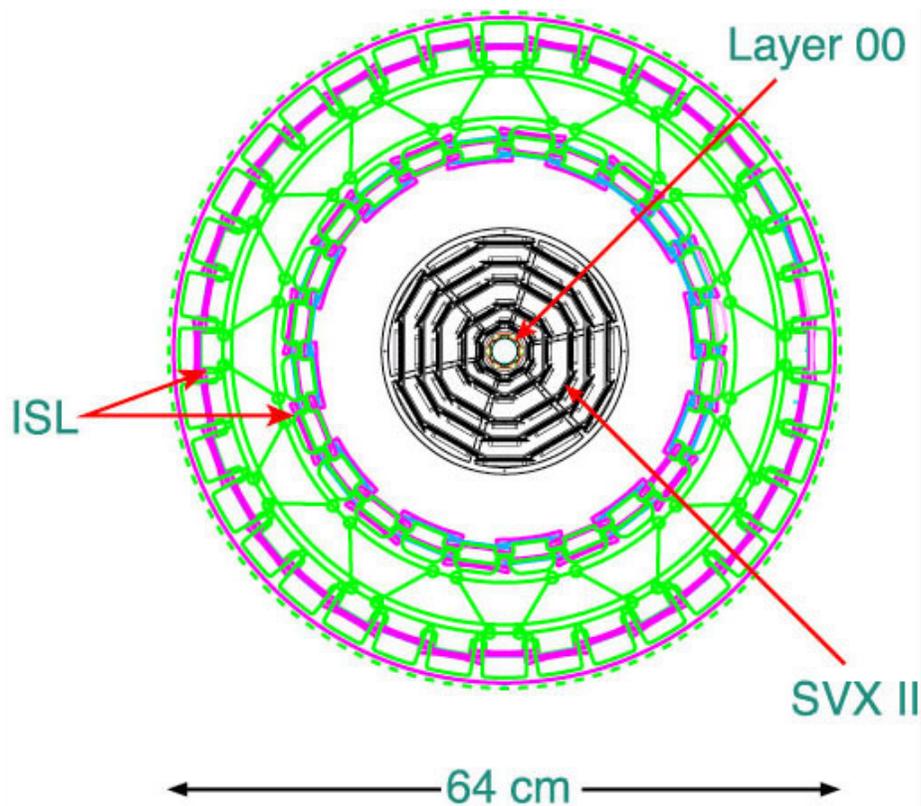


FIGURE 3

A diagram of the silicon vertex detector in the r - ϕ plane.

Each layer of the silicon detectors is composed of hundreds of narrow silicon crystal strips, which are separated by 60 to 65 microns for readout in r - ϕ . When a charged particle passes through the crystal, electrons absorb some of the energy and escape from the crystal's lattice. If the correct voltage (80 to 150 V) is applied across the crystal, the electrons produce signals in electrodes running along the silicon. These signals then travel to amplifiers which reside at the ends of each strip [4]. Once a signal is digitized and stored we say that the detector registered a "hit". If the detector's software attributes a single hit to multiple tracks (which can easily happen when tracks intersect), the hit is called a shared hit. These sorts of hits are inherently less precise than a non-shared hits considering that they may not even belong to a track to which they are assigned. Equivalently, tracks that possess one or more shared hits will have a large error associated with their impact parameters. Because the SVX resolution function is the ratio of the impact

parameter over its error, these tracks are pushed out into the tails of SVX distributions, and are thereby given less weight in parameterizing the SVX resolution function.

4. Categorizing SVX Resolution Data

Every particle track embodies several statistics that can be used to categorize it. The statistics we use to categorize the SVX resolution data are combinations of the number of silicon layers hit, the number of shared hits, the transverse momentum of the tracks, the innermost layer of silicon that was hit; and we also remove tracks stricken with a low quality rating (tracks which do not fit circular arcs well). These cuts on the data are important because their distributions each have their own unique features, meaning that discriminating information is lost in a cumulative set of data. Also, because we work with computer simulations of collider interactions, we are able to remove all b jet tracks from the SVX resolution distribution with no more than a simple case statement. This ability is greatly beneficial. With it, we need not limit our SVX resolution distributions to tracks with only negative signed impact parameters like we would with real data; on the contrary, we can also include the positive signed tracks. This in effect doubles our set of useable data while clearing it completely of b jet tracks. With twice the data we can generate better-defined SVX resolution distributions, which promotes more accurate fits of the data. It is very important to have the most accurate fits as each track's assigned probability of existing in a b jet originates from its integral on these fits. From this track probability a given jet is assigned a probability of being a b jet or just an uninteresting particle scattering.

5. Track Probability

When the SVX resolution distribution is fit with a function, every quantity $D0/D0Err$ can be assigned a probability of being characterized by a zero-lifetime particle. If we were to fit a set of real detector resolution data, meaning that we would only fit the left side of the distribution, the formula for the track probability would be as follows:

$$P_{track}(s; N_{hit}, N_{shr}, L_{inner}, p_t) = \int_{-\infty}^{-|s|} R(t, N_{hit}, N_{shr}, L_{inner}, p_t) dt \quad (1)$$

where P_{track} is the track probability, s is the D0/D0Err, N_{hit} is the number of silicon layers hit, N_{shr} is the number of shared hits L_{inner} is the innermost silicon layer hit, p_t is the transverse momentum, and R is the normalized SVX resolution function [2]. This formula defines the likelihood that a given value of D0/D0Err should have the value s or less. However, since we are not limited to the negative side of the distribution with our simulations, we combine both sides by applying the absolute value and our track probability becomes

$$P_{track}(s; N_{hit}, N_{shr}, L_{inner}, p_t) = \int_s^{\infty} R(t, N_{hit}, N_{shr}, L_{inner}, p_t) dt \quad (2)$$

defining an equivalent track probability in which a quantity D0/D0Err is likely to have the observed value s or greater. If we were to plot a distribution of the track probabilities of a given sample of zero-lifetime particles under the influence of perfect parameterization, we would find a perfectly flat spread from zero to one. This is because we would encounter just as many tracks with each value of D0/D0Err as our function had predicted would occur. Fig. 4 shows a track probability distribution of zero-lifetime particles under the influence of an imperfect parameterization. The distribution is flat for higher probabilities, meaning the fit was accurate for low values of D0/D0Err. Unfortunately, the description of high D0/D0Err values, or low probability values, was not quite as accurate, leading to an excess of tracks near zero (there were more tracks at this assigned probability than expected). Fig. 5 shows a track probability distribution of a sample of b jet tracks. This distribution is flat at higher zero-lifetime probabilities and strongly peaked at lower probabilities. This is because relatively short-lived b hadrons are well characterized by the SVX resolution function while the longer-lived hadrons are not. That is, there are far more tracks with higher values of D0/D0Err (corresponding to higher impact parameters) than is expected by the function that describes zero-lifetime particles. Because the b jet track probabilities are packed so tightly at the low end of the distribution and the background remain relatively flat throughout, setting a cut at some upper-limiting value will effectively retrieve most b jet tracks without selecting a large number of background noise. This is the significance of track probability.

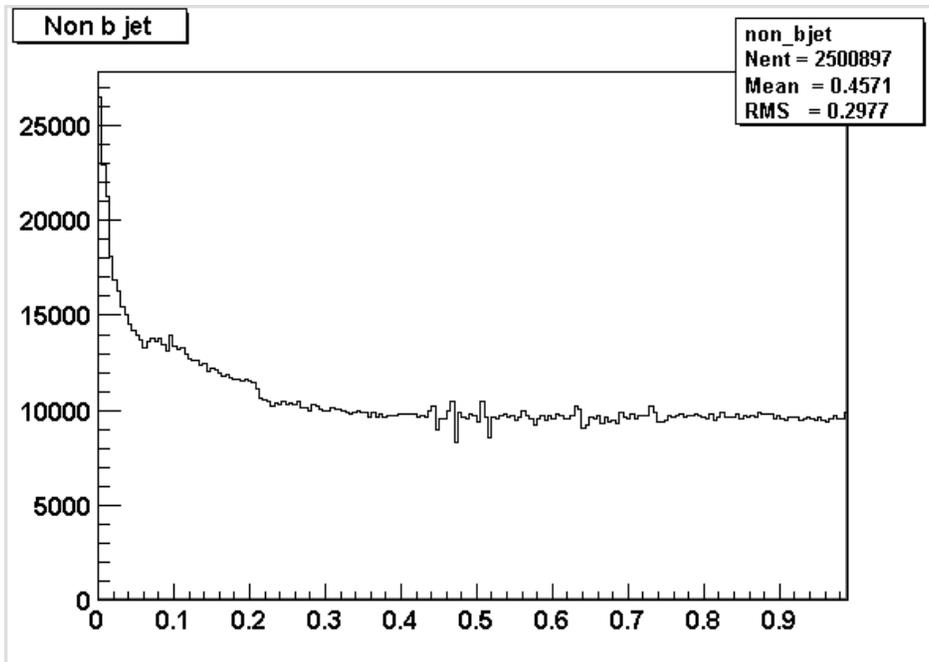


FIGURE 4

An example of a track probability distribution of zero-lifetime particle tracks. A peak exists near zero because SVX resolution function poorly described the low probability region of the resolution distribution.

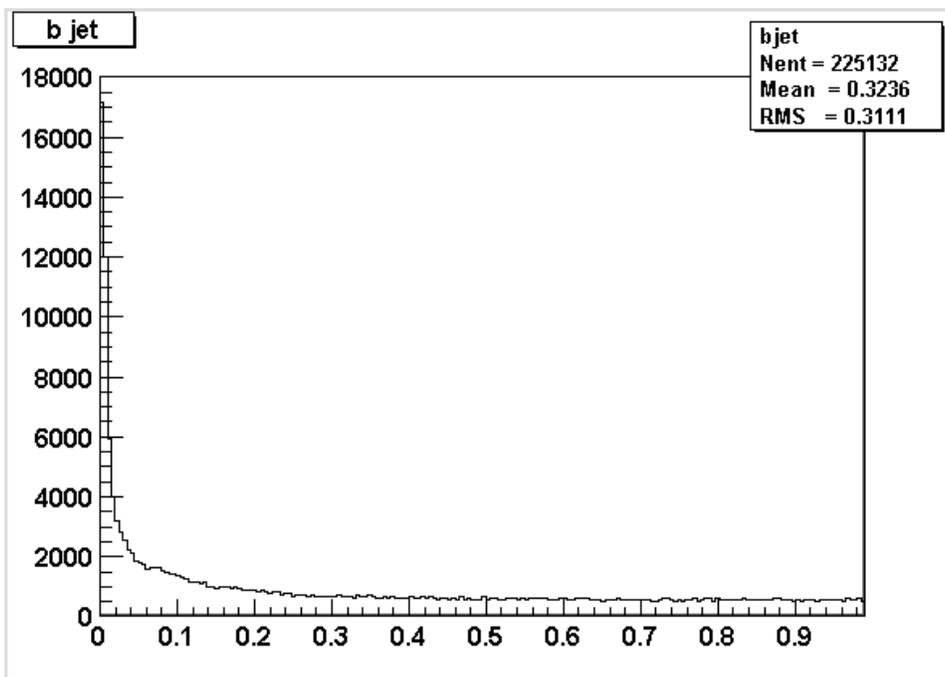


FIGURE 5

A track probability distribution of tracks arising from b jets.

6. Jet Probability

Jet probability is the algorithm used to assign many tracks which appear to make up a single jet a collective probability of having originated from zero-lifetime particles. It is roughly the product of the track probability of all the tracks in a jet constructed in such a way that, like track probability, will be flat for non b jet (zero-lifetime) tracks. Also like the track probability, jet probability distributions peak near zero because of the b jet tracks' high impact parameters (see Fig. 6). Because each jet probability embodies multiple tracks, even greater distinction exists between b jets and background noise. With this distinction we can choose a particular rejection factor of non-b jets or a particular acceptance factor for b jets and let an experiment run. This method enjoys a major advantage over its rival method, secondary vertex reconstruction. That advantage is its tunability. The secondary vertex is the three-dimensional point from which a track appears to have actually originated as opposed to its closest possible birth location. It is not tunable in that the method accepts or rejects tracks based on whether it found the secondary vertex or not.

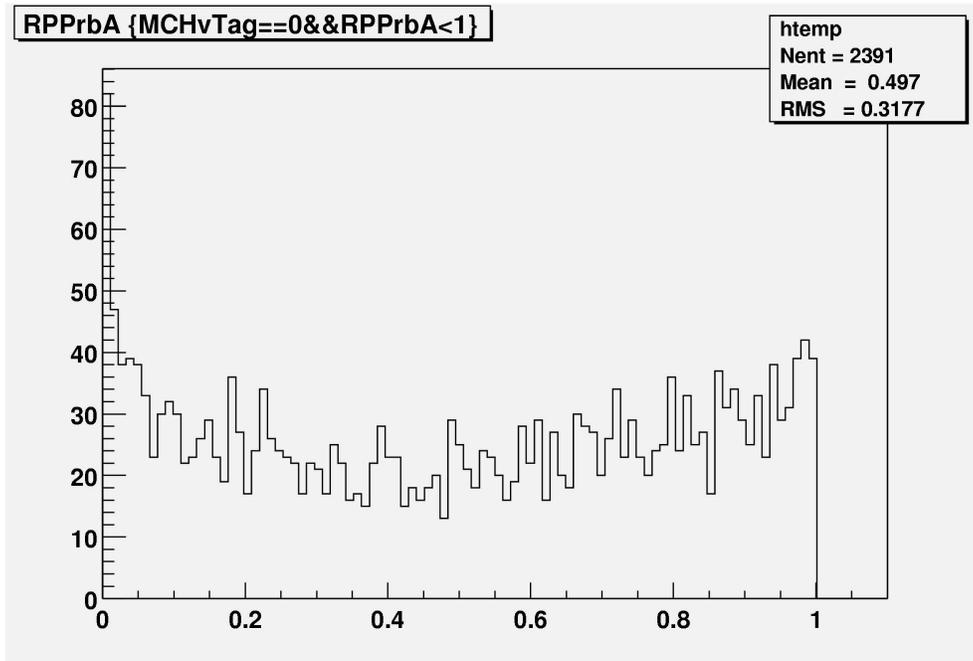


FIGURE 6

A jet probability distribution for all tracks. The peak near zero exists mostly because of b-flavored hadron decays.

7. Plotting and Fitting SVX Resolution Distributions

When plotting histograms of SVX resolution data with fixed binning, we run into the problem of sparse and scattered data within the tails of the distributions if not enough data is present (see Fig. 7). The histograms in the figure demonstrate this quandary well as bins on either side of the distribution are strewn about the plot. The problem with this incoherent jumble at the ends of the of data is that not only does it lend itself poorly to fitting, but that the right tail of the distribution is where we are most likely to find tracks from b jets. So if these tails are poorly described by a function, there is a greater likelihood that a jet will be incorrectly tagged.

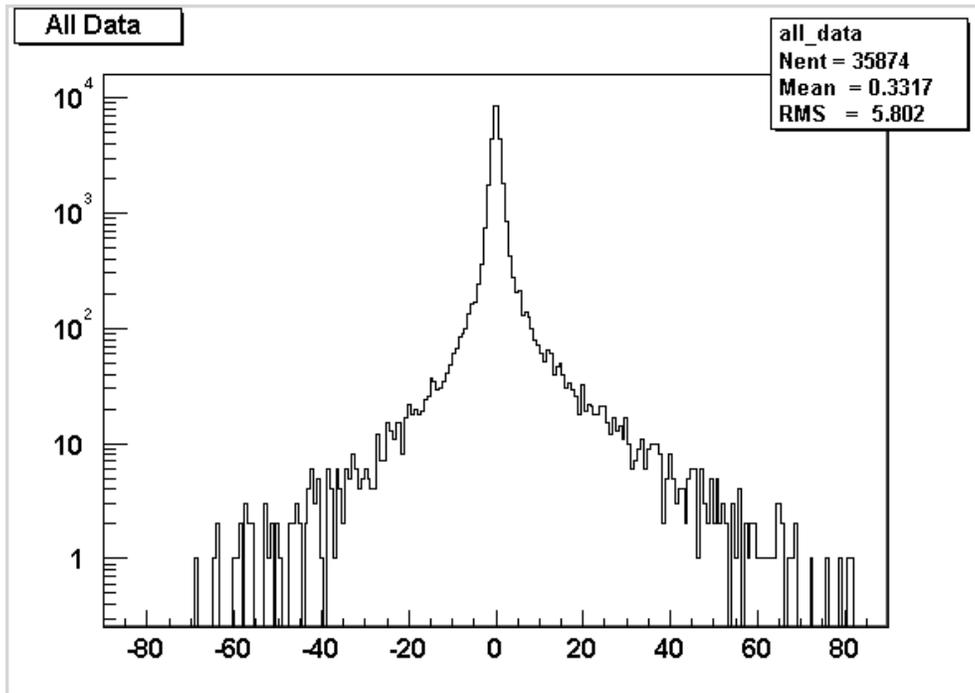


Figure 7

The SVX resolution distribution under a logarithmic scale on the y-axis to allow for a complete view of the tails.

One simple way to overcome this problem, and to assign a greater weight to tracks of high impact parameters and low errors, is to fill the histograms with the natural log of the impact parameter divided by its error ($\ln(|D0 / D0Err|)$). The effect of this transformation is to compress the entire set of data, and especially its distant regions, along a much shorter line (see Fig 8). This compression is greatly beneficial for fitting purposes in that it makes the outer regions of the distribution, which are best described by b jet tracks, a more prominent feature for a function to conform to. After trying several combinations of polynomials, exponentials, normal Gaussians, and Gaussians transformed for the logarithmic space, we

found that the sum of four transformed Gaussians with means forced to zero worked the best. This formula corresponds to the sum of four normal Gaussians with means of zero on the untransformed axis and is composed of eight parameters. When all the parameters are calculated via a likelihood fit with respect to the cuts made of the number of silicon layers hit (3-6, 7 or 8), the number of shared hits (0-2, ≥ 3), the innermost silicon layer hit (0, 1, ≥ 2), the transverse momentum in GeV/c ($0.5 \leq P_t < 2$, $2 \leq P_t < 5$, $P_t \geq 5$), and a quality cut is made, we are presented with 180 distributions with eight parameters per distribution making for a total of 1440 parameters. These parameters are then passed onto software that performs the jet probability calculations.

8. Conclusion

Technical difficulties with computing resources and software versions have thus far prohibited conclusive results as to whether we improved jet probability tagging of bottom and charmed quark hadron decays. We did manage; however, to construct highly automated routines for parameterizing the SVX resolution distribution meaning that conclusive results can be obtained immediately following computing resource readiness.

References

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Acknowledgements

Prof. Darin Acosta

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National Science Foundation

¹ The Higgs boson is an essential component to the Standard Model of Fundamental Particles and Interactions.

² Hadrons are particles affected by the strong interaction. They consist of color-neutral combinations of a quark and antiquark (meson) or three quarks (baryons).

³ Bottom-flavored hadron decays in the Tevatron are overwhelmingly dominated by b meson decays as opposed to bottom-flavored baryon decays.

⁴ The other plane involved in the research was the r-z plane. It is the plane that vertically splits the beam pipe along its length.