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Electrons from Bottom Quark Production in Polarized pp Collisions at STAR

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Abstract

We investigate STAR's ability to measure bottom quark decays in the pp spin running, using the EMC to trigger on electrons and the SVT to select which electrons are daughters of long-lived particles. We conclude that STAR is well suited for such measurements.

1 Introduction

According to Leading Order Quantum Chromodynamics, production of heavy flavor quarks occurs through two processes: quark-antiquark annihilation ($q\overline{q} \to Q\overline{Q}$) and gluon fusion ($gg \to Q\overline{Q}$). Because RHIC is a pp collider, there are no valence antiquarks, so the gluon-induced process dominates. As it turns out, even in a $p\overline{p}$ collider would have the gluon initial state dominate, although without doing the calculation it is not obvious that this would be true. This process is therefore an interesting candidate to probe the spin carried by the gluons in a proton: unlike direct photons, both incoming partons are gluons; unlike jets, there is effectively only a single process that contributes to the observable final state.

As shown by Karliner[1] there are still large spin-dependent effects in bottom quark production even at Next-To-Leading Order. NLO QCD shows spin asymmetries in the 20-30% ballpark at b transverse momenta near 20 GeV. As will be shown below, this is where we have substantial sensitivity. In this note we focus entirely on b quark production, since the validity of the heavy quark approximation for the charm case is debatable.

2 Measurement Technique

To measure the spin asymmetry in bottom quark production, we need to trigger on and reconstruct bottom quark decays. We focus on decays involving leptons, because they compose a large fraction (approximately 10%) of b decays and because leptons are rare, and therefore potentially triggerable. At STAR, the lepton of choice is the electron, since we have an electromagnetic calorimeter but no muon detection. The two most promising decays are $b \to eX$ and $b \to J/\psi X$ followed by $J/\psi \to e^+e^-$.

We leave the discussion of the J/ψ modes for another note. More work needs to be done to determine whether the better channel is the inclusive $b \to J/\psi X$ or if we are better off focusing on exclusive decays like $B^+ \to J/\psi K^+$.

Returning to semileptonic decays, perhaps the simplest analysis would be to measure the rate of inclusive electrons as a function of beam spin orientation. Unfortunately, only about half of the reconstructed electron candidates are electrons from b decays. The remainder are either hadrons that "fake" electrons or neutral mesons that decay to photons which subsequently convert to electron-positron pairs in the material. In either case, the parent meson had a large transverse momentum, and is therefore highly likely to have been part of a jet. There is no reason to think that the asymmetry in ordinary jets is the same as in heavy flavor production, so measuring the b component depends critically on measuring and removing this background. Measurements relying on the subtraction of two numbers of comparable magnitude, one measured, one calculated, are notoriously difficult. Often they have been shown to differ from the true value by more than their quoted uncertainties.

An obvious attempt to fix this would be to require these events to be more "b-like". One element that has been successfully used to improve the purity is to require the presence of a charmed meson near the electron. The signature therefore becomes a peak in the $K^-\pi^+$ (for example) spectrum at the D^0 mass in events where the D^0 and the electron are near enough to each other to be the daughters of a b meson. The combinatoric background can be measured by looking at right and wrong flavored D-mesons: $e^- + D^0$ is an example of a right sign combination (consistent with a $\overline{B}$ meson decay) and $e^+ + D^0$ is an example of a wrong sign combination (inconsistent with the decay of either a a B-meson or a $\overline{B}$-meson.) Unfortunately the complete branching fractions for these decays is typically 30 times smaller than for the inclusive $b \to eX$ decays. After kinematic cuts and reconstruction efficiencies, this mode can end up with expected yields two or three orders of magnitude below the inclusive electron yields.

Clearly we need something in between. A technique that does that was developed by CDF[2] to measure the ratio of the b quark cross sections at two different center-of-mass energies: 1800 GeV (their standard running condition) and 630 GeV (the energy of the CERN $Sp\overline{p}S$, to compare with UA1)

This method starts with a lepton (in their case a muon), and finds the track of highest transverse momentum near the lepton. This track is likely to be a b daughter as well. These two tracks are constrained to come from a common point, and the projection onto the transverse plane of the displacement from the primary vertex to this point is calculated. If this is ahead of the primary vertex (i.e. the flight distance is positive) by 250 microns or more, the event is placed into the Positive Flight Distance sample. Conversely, if this is behind the primary vertex by at least 250 microns, the event is placed into the Negative Flight Distance sample. Because negative flight distances are unphysical, we have a measurement of how many tracks are reconstructed with incorrect flight distances, and we can subtract the number Negative Flight Distance events from the number of Positive Flight Distance events to determine the number of real reconstructed b hadrons. Note that if the non-leptonic track is not a b daughter this technique still works: the calculated flight distance is proportional to the signed impact parameter of the lepton, a quantity which also separates b hadrons from background.

Because CDF is interested in a ratio of cross-sections, it is unnecessary for them to calculate the absolute efficiency and acceptance for this method - they cancel in the ratio. Likewise, because we at STAR are interested in calculating an asymmetry, the acceptances and efficiencies cancel for us too. We merely have to measure yields per unit luminosity.

3 Yields

In this section, we attempt to calculate the yields we expect at STAR for an 800 pb^{-1} run at $\sqrt{s} = 500$ GeV. This is done by starting with the CDF measurement at $\sqrt{s} = 630$ GeV, correcting for different acceptance and efficiency, and finally using PYTHIA to calculate the change in cross section between 630 GeV and 500 GeV. Because b production is a gluon-induced process, the pp and $p\overline{p}$ cross sections should be the same at the same energy.

3.1 CDF Results

CDF has made public[2] their results for b production at 630 GeV. With a muon p_T threshold of 6.2 GeV, they see 164 ± 21 events above background in 463 nb^{-1} of data.

3.2 Luminosity

CDF's measurement represents 463 nb^{-1} of data. STAR's spin run will include 800 pb^{-1} (or 800,000 nb^{-1}) of data: 1730 times more.

3.3 p_T Thresholds

The p_T threshold at STAR will be determined by the trigger and dataset handling capacity of STAR. At Level 0, studies show a 7 GeV single EMC tower threshold has a rate of approximately 200 Hz. The bulk of these events are due to hadronic interactions, and we expect a reduction of a factor of approximately 6 from using even crude SMD information in the trigger. That gets us to of order 35 Hz. Isolation and shower shape cuts will reduce this rate further, and TPC tracking at Level 3 will allow us to make an E/p cut. All in all, our lowest single tower threshold will be somewhere near 7 GeV. We therefore select 9 GeV as the threshold for electrons in this analysis, to be a little conservative, and to account for things like trigger resolution, shower leakage outside a single trigger tower and the like.

We then use the same Monte Carlo that CDF used to calculate the difference in acceptance between their cut at 6.2 GeV and ours at 9 GeV. This assumes that the p_T spectrum is the same at 630 GeV and 500 GeV, and we know that this is not the case: the 500 GeV spectrum will be softer. However, NLO QCD calculations using the MRS-A' parton distributions are readily available at 630 GeV but not at 500 GeV. The estimated uncertainty caused by doing this is 25%.

In a sample of 8600 events passing the CDF cuts, 1959 pass the more stringent $p_T(l) > 9$ GeV cut as well. So the lepton kinematic requirements reject 77% of the leptons with $p_T(l) > 6.2$ GeV.

Figure 1 shows the p_T spectrum of the parent B hadron for events that pass all of our selection requirements. (The CDF requirement with the higher lepton p_T threshold.)

3.4 Geometric Acceptance

CDF's muon detectors used in the analysis being discussed covered only the region from $|\eta| < 0.6$ and only about 75% of ϕ. At STAR, we should be able to cover $|\eta| < 0.8$ (that leaves us 0.2 units of rapidity for isolation and shower shape requirements) and all of ϕ.

We assume that the fraction of the luminous region covered by the SVT will be the same as the fraction covered by CDF's SVX: about 60%.

Putting this together, our acceptance is about 1.78 times that of CDF.

3.5 Lepton Identification

Muons are easy to identify. Hang up enough steel, and anything charged that comes out the back of the steel must be a muon. Electrons are identified by how well their electromagnetic interactions match an average or ideal electron. Many requirements can be imposed, all with some efficiency.

The efficiency we assume here is 50%. This includes fiducial efficiencies, but is nonetheless quite conservative: it would allow us to place extremely tight cuts on electron identification.

3.6 Cross-Section

Running PYTHIA, we learn that the cross section for b quarks with $p_T(b) > 20$ GeV at $\sqrt{s} = 500$ GeV is roughly half of what it is at $\sqrt{s} = 630$ GeV. This statement is dependent on parton distributions at the 10-15% level.

3.7 Yields

We can now put it all together: the STAR yield is the CDF yield (164 ± 21), times the relative luminosity (1730), times the change in acceptance from the different p_T threshold (0.23), times the geometric acceptance factor (1.77), times the lepton identification probability (0.5) times the change in cross-section (0.5). This gives us an expected yield of 29,000 reconstructed $b \rightarrow eX$ events. There is at least a $\pm 30\%$ uncertainty on this number.

4 Reconstruction in the SVT

A major difference between the CDF and STAR detectors is their silicon. CDF uses a strip detector, and STAR uses a drift detector. The drift detector trades resolution for the ability to handle the high occupancies of Au-Au collisions, and a reasonable question to ask is if it has the resolution to handle this analysis. Fortunately, the answer seems to be "yes".

The CDF Monte Carlo predicts the shape of the long-lifetime tail in the transverse flight distance distribution fairly accurately: if one turns the problem around and asks what the b lifetime is given the Monte Carlo and the measured distribution, one gets results consistent within uncertainties (of 10-15%) of the world average. For STAR's kinematic cuts, this same Monte Carlo predicts the shape of the b tail to be an exponential with a mean transverse flight distance of 2.44 mm.

This 2.44 mm is close to what we expect. The average b p_T is 23 GeV, and the B meson mass is 5.3 GeV. We therefore have a boost of $\gamma = 4.2$. The b lifetime is 460 μm/c, so we expect an average flight distance of about 2 mm.

There are two sources of background. One is prompt tracks; these will form a Gaussian distribution centered at zero flight distance with width corresponding to the detector resolution. (For a two track vertex, this is about 700 μm[3].) The other is tracks that have been mismeasured, and these events have a two-sided exponential distribution with average flight distances of ± 3 mm.

The most common source of mismeasurement is an error in pattern recognition: the wrong hit on the innermost silicon layer is associated with the track, and that pulls the impact parameter distribution which is dominated by that hit. This is a function entirely of local track density, and in this note we take it to be the same for CDF at 630 GeV as STAR at 500 GeV. It's probably a little better at STAR, so this is somewhat conservative.

To understand these effects, we wrote a toy Monte Carlo that generated b and background events. 44% of the events were b events, which were generated using an exponential lifetime distribution smeared with our 700 μm resolution. 33% were prompt events also smeared with our 700 μm resolution. The remaining 22% were generated using the two sided exponential distribution characteristic of the tails of the background. This distribution (with the appropriate resolution factor) matches the CDF data fairly well, although it perhaps overestimates the size of the tails. Since this is our most severe background, this errs on the side of conservatism.

The results are shown in Figure 2. The top curve is all of the data, and the lower curve is the signal: the positive side with the negative side subtracted off. The SVT resolution is obviously adequate for this measurement, although the question of whether the 250 μm transverse flight cut is optimal is raised. It appears that perhaps that cut could be tightened slightly: perhaps to a millimeter or so.

5 Improvements

No analysis is completed, merely abandoned. Nonetheless, there are two obvious next steps. The first is to optimize the cuts on transverse flight distance. This will obviously have to wait until we get a measurement of the background, but the Monte Carlo suggests that we can get somewhat better significance by requiring a flight of something closer to a millimeter.

The second is to attempt to measure not just the integrated b asymmetry above some threshold, but to measure it as a function of $p_T(b)$, or at least as a function of what we measure, $p_T(e-h)$. We can try and improve this range by relaxing the $p_T(e)$ requirement to some value below 9 GeV. This will put us in a region of reduced trigger efficiency, but because we are measuring an asymmetry, much of the effect of this inefficiency will cancel. We can also consider taking lower p_T electron at some prescale factor. All in all, it appears that a measurement over a factor of 3 in p_T (and therefore x) is not unreasonable.

6 Conclusions

We expect something like 29,000 reconstructed $b \to eX$ events over the course of the STAR run. The signal to background for these events will probably be substantially better than 1:1, which will allow us to measure the asymmetry in b quark production to better than about 1%. For an expected analyzing power of -25%, this corresponds to a 4 or 5% measurement on the gluon spin asymmetry for gluons with $x = 0.08$ or so. While there is probably room for improvement in the measurement technique, the STAR detector is adequate for measuring gluon spins with heavy flavor decays.

References

[1] M. Karliner and R.W. Robinett, hep-ph/9310346

[2] T. LeCompte, J. Lewis, S. Tkaczyk for the CDF Collaboration, FERMILAB-CONF-96/176-E

[3] T. Ullrich, private communication.

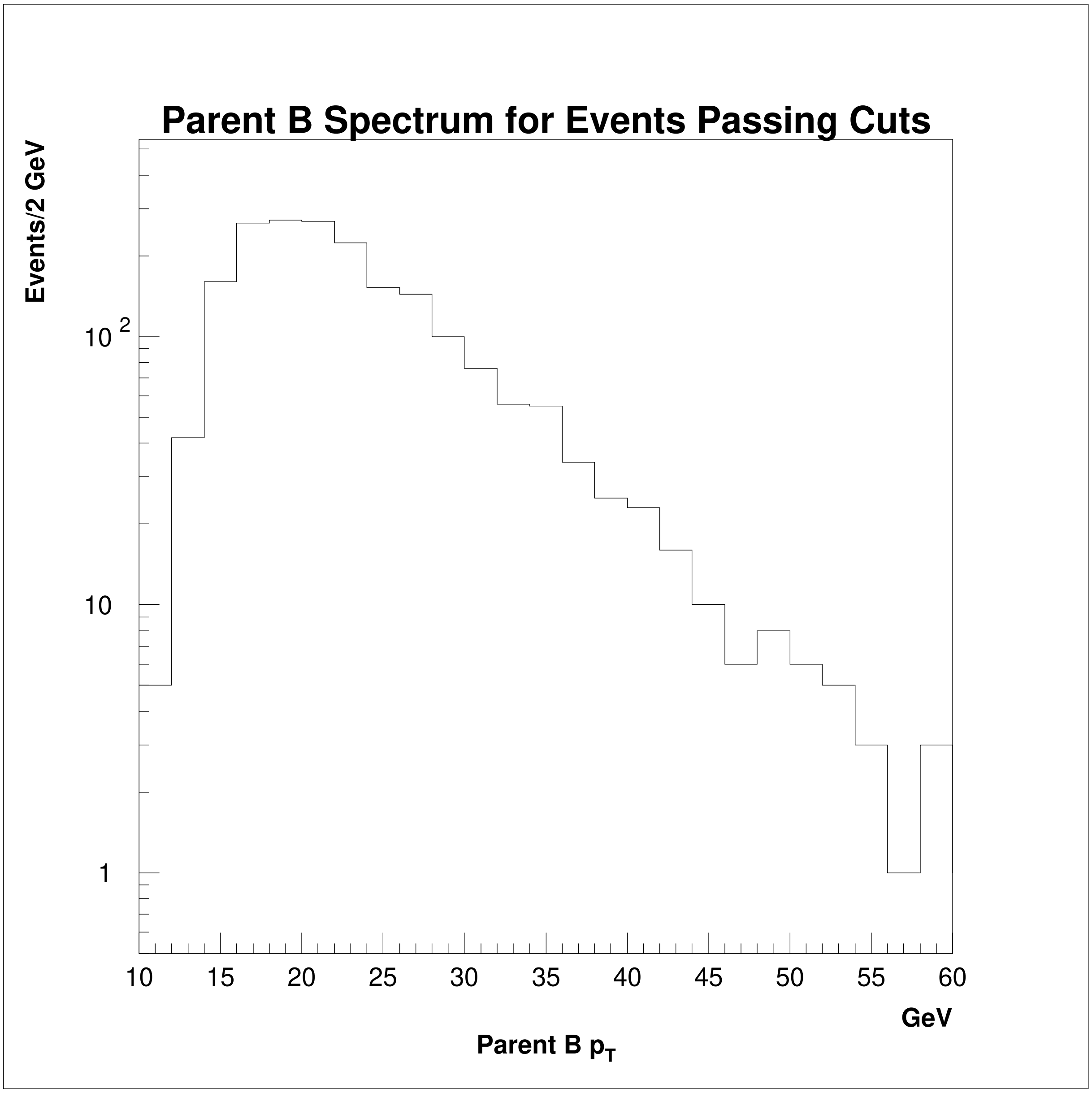

Figure 1: Monte Carlo results for the parent B spectrum in events where there is a lepton with $p_T > 9$ GeV and a second track that form a secondary vertex displaced by at least 2.5 mm. The calculation uses MRS-A parton distributions for $\sqrt{s} = 630$ GeV $p\overline{p}$ collisions. The spectrum at STAR is likely to be a little softer than shown.

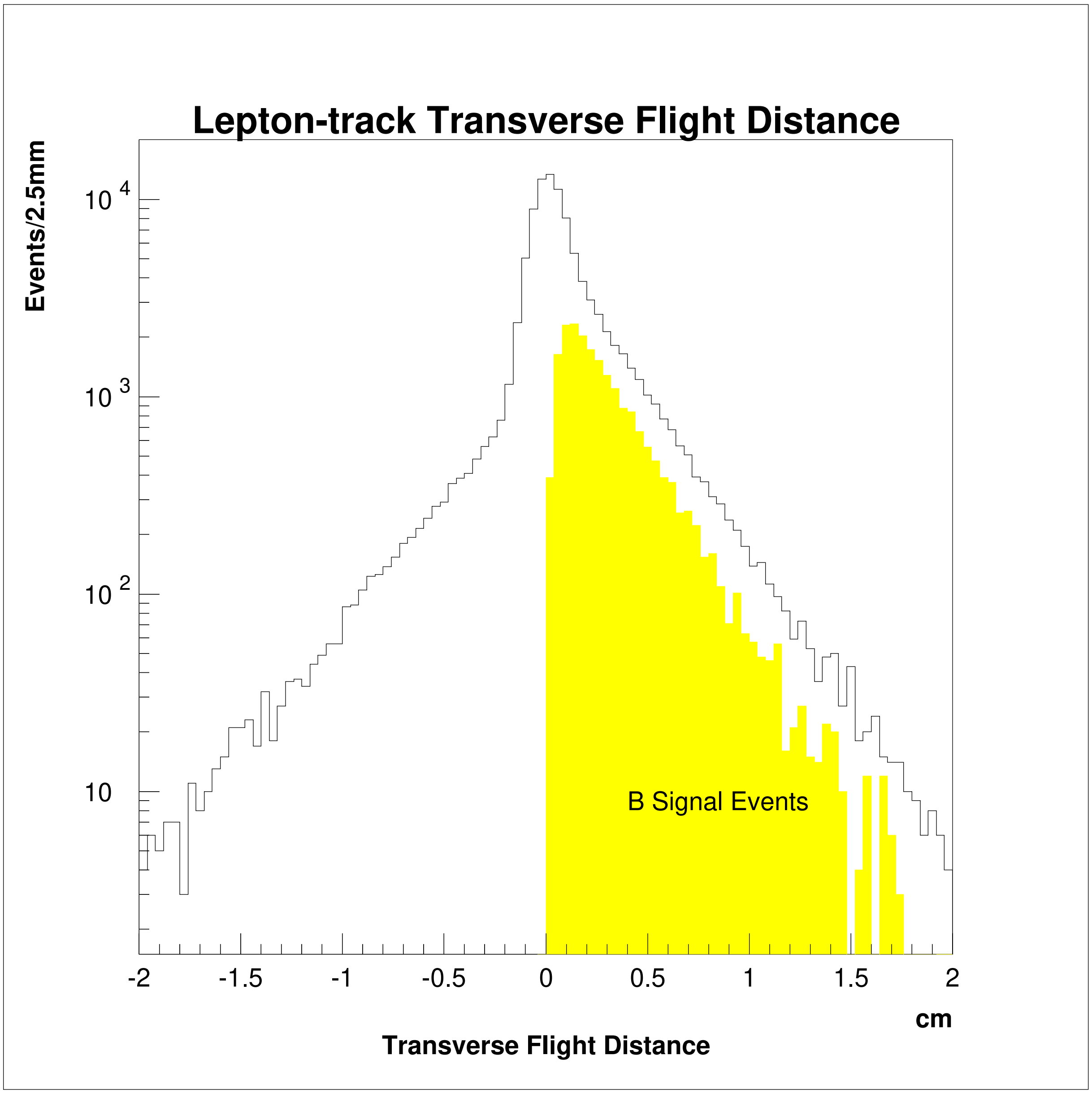

Figure 2: The transverse flight distance for the electron-track combinations. The top line is the expected distribution. The shaded region is the excess at positive flight distances. It is obtained by folding over the negative contribution and subtracting.