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A Note On Measuring Charm and Bottom Forward-Backward Asymmetries at the Tevatron

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Abstract

The forward-backward asymmetry A^t_{FB} in top quark production at the Tevatron has been seen to be anomalously large both by CDF and D0. Parton-level asymmetries as large as 50%, with a large error bar, have been extracted from the data. It is important to measure other quark asymmetries if possible, as these would help clarify the source of any new physics behind A^t_{FB}. In this note it is argued that asymmetries in $b\bar{b}$ and $c\bar{c}$ should be accessible to the Tevatron experiments, using the full data sets. A crude study suggests that muon asymmetries in high-p_T dijet events, with suitable use of muon and jet kinematics and (inefficient) heavy flavor tagging, might allow detection of $A^c_{FB}, A^b_{FB} \sim 0.3$. Were it possible to make heavy flavor tagging at high p_T efficient, or mistags rare, then the sensitivity of the measurement of A^b_{FB} could be significantly better.

Recent measurements by both the CDF and DZero experiments at the Tevatron [1, 2, 3] have shown a persistent and anomalously large forward-backward asymmetry in top quark production. This exciting discrepancy with the Standard Model has generated a substantial amount of theoretical activity explaining the effect.

The asymmetry is observed mainly in events in which the $t\bar{t}$ invariant mass is above 450 GeV [3]. The observed top quark asymmetries have been converted into a $t\bar{t}$-frame partonic-level asymmetry, the quantity that can be directly extracted from a Lagrangian at leading order. This inferred asymmetry in [3] is very large, though with a substantial error bar: $A^t_{FB} = 0.475 \pm 0.114$, far above the next-to-leading-order QCD expectation.

If this anomalous asymmetry is real, and is due to new physics affecting the third generation more generally, a similar effect might impact the bottom quark. In particular one would expect this if new physics affects the t_L, and perhaps even if it only affects t_R. Or perhaps the asymmetry lies in the up-quark sector and affects the charm quark. It is also possible that only the t_R, of all quarks, is affected, and no anomalous asymmetry is present in either bottom or charm quarks. Thus, the measurement of bottom and charm quark asymmetries is important in diagnosing any new physics that may be generating A^t_{FB}. These observables are also attractive in that a different set of issues are involved, compared to the A^t_{FB} case, in converting a lab-frame or parton-frame measured asymmetry to the intrinsic partonic asymmetry, the essential quantity for comparing with theory.[1]

The purpose of this note is to argue that the charm and bottom forward-backward asymmetries, A^c_{FB} and A^b_{FB}, might be experimentally accessible at the Tevatron, using methods similar to those suggested long ago in [4], with the full data sets at D0 and CDF.[2] We will check that a 10 inverse fb data set gives each experiment a sample of dijet events with a single non-isolated muon that is large enough to make such measurements plausible.

To determine the combination of techniques required for these difficult measurements lies far beyond the reach of a non-expert; all that will be attempted here is to motivate the measurement by showing the possibility of

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[1] The extraction of A^t_{FB} in the partonic frame is highly non-trivial, as it requires understanding angular distributions of the final state particles, various detector effects, and the process by which the $t\bar{t}$ events are reconstructed. It seems very difficult, without precisely repeating the CDF analysis, to appreciate fully the subtleties involved.

[2] While this study was underway, a paper appeared [5] that also suggests that the measurement of A^b_{FB} is both important and possible.

success. In particular, only a very cursory study is performed, with many limitations, and one could certainly do a better job, accounting properly for jet reconstruction, missing energy from neutrinos, next-to-leading-order effects, and a tracing of systematic errors. However, to be more precise and accurate would require a detailed understanding of the multivariate heavy-flavor taggers that the experimentalists have designed, among other subtleties.

Indeed a very large uncertainty, especially for A^b_{FB}, comes from the unknowns in heavy-flavor tagging. The most experimentally interesting region, for comparison with what is observed in A^t_{FB}, is at high invariant mass. But tagging at high p_T (of order 150–250 GeV) poses many challenges [6], so far little studied, as statistics at these p_Ts is low, and few measurements at these energies have required heavy flavor tagging.[3] The results presented below therefore have very large error bars from this source.

The essential experimental ingredients in measuring these asymmetries are the kinematics of the jets and of the muons embedded within them, heavy flavor tagging using displaced vertices and tracks, and the measurement of the charges of the muons, which are correlated with the charges of the produced quarks.[4] The method for measuring an asymmetry boils down to the following:

- Select dijet events, at high invariant mass m_{jj} and low to moderate $|\eta|$, that contain at least one embedded muon.
- Use variables such as p_T^{jet}, p_T^{rel} (the transverse momentum of the muon relative to the jet) and $z_\mu = p_T^\mu / p_T^{jet}$ (the fractional momentum of the jet carried by the muon) to separate, statistically, the different sources of muons.
- Use track-based heavy-flavor tagging information within the two jets to change the mix of sources for the observed muon.

Then observe the forward-backward asymmetry of the μ^- events (combined with the backward-forward asymmetry of the μ^+ events) in the dijet frame.

Let us take a moment to recall all the reasons why the muon observed in a jet does not directly correlate to its parent parton's charge. Charm quarks

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[3] The author thanks Y. Gershtein and G. Watts for discussions on this point.

[4] Electrons will not be considered here, as they are difficult to detect efficiently in jets at CDF and D0. Their inclusion might help marginally, but perhaps this issue is best left to the experimentalists.

generally produce a muon with the same charge as the parent quark. But bottom quarks do not, because (a) mixing of neutral B mesons converts $b\bar{q} \to \bar{b}q$, and (b) a cascade decay in which a bottom hadron decays hadronically to a charm hadron, which then decays semileptonically, produces a muon of opposite charge to the b charge. A gluon can split to $b\bar{b}$ and $c\bar{c}$, so a muon from an ensuing heavy-flavor decay has a random charge.[5]

To explore whether the asymmetry measurements are feasible, let us step through the results of a crude but instructive study using Pythia [7]. The numbers below will not be accurate for many reasons (K factors are not included, jets are not actually reconstructed, effects of the neutrinos are not accounted for, many experimental subtleties are not considered, Pythia is not entirely trustworthy in heavy flavor production and decay, etc.) but are intended to be illustrative and motivate more careful experimental studies.

Let us start with a pure dijet sample, with a cut on m_{jj} of 450 GeV (above which scale A^t_{FB} is observed to be anomalously large) and requiring the p_T of the leading jet be above 150 GeV (which is high enough to fire a dijet trigger.) The leading-order cross-section is about 300 pb. Within this sample, select the events with at least one non-isolated muon of $p_T > 20$ GeV and $|\eta| < 2$. The corresponding cross-section for this preselection sample is of order 1.8 pb. At CDF, where the muon system extends only out to $|\eta| \sim 1.1$, an acceptance factor of order 0.85 should be included in the following discussion.

Note that the muon is not needed for triggering. An alternative strategy at D0 would be to also include muon-triggered events out to $|\eta| = 1.6$, with a lower requirement on the p_T of the jet. This might marginally increase statistics, though it runs the risk that, if the asymmetry decreases too fast at low m_{jj}, the signal itself may decrease to outweigh any statistical advantage. The optimal method will depend on triggering considerations and will require detailed study.

Some effort will be required to ensure muons from top and electroweak processes are negligible or are carefully removed. Top quark pair production can largely be rejected by event shape and jet counting, while electroweak processes such as W plus jets and single top, important backgrounds as they are significantly forward-background asymmetric, must be modeled, using the kinematic regions where the muon from the W is isolated and extrap-

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[5] The same is largely true for muons that come from decays of light hadrons in flight, though this will be irrelevant because of their small numbers in event samples with rather hard muons. Fake muons from punchthrough have a charge bias, but this should be forward-backward symmetric.

olating to where it is not. We will assume this can be done with sufficient confidence. An irreducible asymmetric background comes from $d\bar{d} \to s\bar{c}$, $\bar{s}c$ via W exchange. This appears to be too small to impact the low-precision measurements of asymmetries considered here, but should be removed when converting the measurement to a limit or observation of A_{FB}.

The preselected 1.8 pb sample is divided roughly into[6]

- 1.0 pb of qq, $q\bar{q}$, qg, $\bar{q}g$, and gg scattering, of which 0.25 pb creates a gg final state,
- 0.35 pb of qQ, $\bar{q}Q$, $q\bar{Q}$, $\bar{q}\bar{Q}$, gQ, $g\bar{Q}$ (where $Q = c, b$) scattering, of which 0.05 pb involves a gluon in the final state,
- 0.15 pb of $c\bar{c}$ production, of which about 5% is from gg initial states,
- 0.3 pb of $b\bar{b}$ production, of which about 5% is from gg initial states.

The muons in these events come predominantly from heavy flavor if a heavy quark is present, with a rate just above 10% per b quark, and about half of this for charm. (About a third of the muons in a b jet are "wrong-sign", opposite in sign to the b quark charge.) In the other events, they come mostly from gluons splitting to bottom and charm quarks. About 2.5% of the muons come from other sources (such as decays of lighter hadrons in flight.)

A number of events have two muons; most of these are in the same jet. Some come from gluon splitting to two heavy mesons. About half the di-muon events come from $b\bar{b}$, and less than half of these have one muon in each jet. Because the various di-muon subsamples are all small, their importance to the measurement is marginal, and in any case too complex to be investigated here. We set them aside for a more careful analysis to consider properly.

Now let us turn to the asymmetries. Somewhat remarkably, we are best off first considering A^c_{FB}. With 10 inverse fb, the preselected sample contains about 18000 events, including about 1500 $c\bar{c}$ events. Since $\sqrt{18000} \sim 134$, there is already 3σ statistical sensitivity to an $A^c_{FB} \sim 0.3$.

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[6] The fragmentation functions for b and c hadrons within b and c jets are not too well known at high p_T, and Pythia perhaps makes the distribution of the muon p_T a bit too hard, which would cause an overestimate of the signal. However, conversely, the preselection criteria chosen here are not optimized, and the muon p_T cut used here might be higher than necessary. This will require detailed study using data.

The situation for A^b_{FB} is slightly worse. The dilution of the true asymmetry by wrong-sign muons in b jets reduces the observed asymmetry by a factor of about three. Without any additional effort, there is statistical sensitivity only to $A^b_{FB} \sim 0.45$.

Given that the top quark asymmetries are claimed to be perhaps as large as 50%, these simple measurements are already of considerable scientific interest, and they don't even require use and understanding of heavy-flavor tagging at high p_T. But the drawback of this very simple approach is that the actual observed asymmetries are very small: statistical significance of 3σ corresponds to an asymmetry of order 2%. It is easy to imagine that any observation would be complicated by concerns about systematic errors.

We should therefore ask the following questions. First, can we enhance the purity of the $c\bar{c}$ or $b\bar{b}$ sample, or decrease the wrong-sign muon contribution in b jets, so as to increase the statistical sensitivity of the measurement? If not, can we at least maintain the sensitivity while increasing the observed size of the asymmetry, potentially reducing systematic effects? And can we find a control sample that will allow increased confidence that an observed asymmetry is due to the underlying particle physics?

With regard to the first two questions, a number of different attempts and considerations suggest that improved sensitivity in A^b_{FB} (but not A^c_{FB}) is possible, while a larger observed asymmetry with comparable sensitivity is possible in both cases. A sketch of these arguments now follows.

First, let us consider the obvious method of heavy-flavor tagging, whose usefulness is very sensitive to its poorly known effeciency and fake rate. For scale, imagine that heavy-flavor tagging were as good as it is at lower p_T. Suppose we applied tagging to the other jet (the jet with no muon, or perhaps the jet with the lower p_T muon if both jets contain one). If we were to assume, naively, a 50% flavor tagging efficiency for bottom quarks, a 15% rate for charm quarks, a 1% mistag rate for light quarks and a 3% mistag rate for gluons (remembering that the gluon has a substantial probability to split to bottom quarks and charm quarks, and quoted mistag rates have already backed this probability out) we get a sample that is 75% pure $b\bar{b}$, with a total cross-section of 0.2 pb. This improves the sensitivity for A^b_{FB} by a factor of more than 2, immediately putting a 3σ measurement of $A^b_{FB} \sim 0.2$ within reach, with an observed A^b_{FB} (accounting for dilution both by backgrounds and wrong-sign muons) of about 5%. Meanwhile, the sensitivity to a charm asymmetry significantly decreases.

Unfortunately, heavy-flavor tagging is not likely to work nearly so well at high p_T. A more conservative estimate, such as a 30% b-tagging rate and a 5% mistag rate, would almost eliminate the gain in efficiency. The reality at CDF seems to lie somewhere between [6].

Tagging both jets simultaneously is not helpful. The cost in signal is too high.[7] But tagging *at least one* jet is useful. Even with the conservative tagging just mentioned, it appears a gain in sensitivity of 1.5 would be possible. This alone would bring sensitivity to A_{FB}^b up to the initial sensitivity to A_{FB}^c.

There are alternatives to tagging. Measurement of A_{FB}^b (but not A_{FB}^c) can be improved by reducing the number of wrong-sign muons. There are two natural avenues: demand a large p_T^{rel}, or demand a large $z_\mu = p_T^\mu / p_T^{jet}$. The former is more commonly used, but when both jets and muons have large p_T, the measurement of a small $p_T^{rel} \sim 2$ GeV requires knowing the jet angle precisely. The resolution on this quantity may become a problem[8] at these energies, especially in the presence of the neutrino that accompanies the jet. The variable z_μ (after the missing p_T from the neutrino is added back into the jet p_T) may not suffer as badly at high p_T. Demanding a cut on z_μ of order 0.2 or 0.25 seems to improve sensitivity to A_{FB}^b by about 20% while increasing the size of the observed asymmetry by about a factor of 2.

Another method to enhance the asymmetry (but not the statistical sensitivity) is to raise the cut on the jet p_T. (One could also consider a cut on the muon p_T, but this is obviously correlated with z_μ and jet p_T, which are themselves largely uncorrelated.) This cut reduces the backgrounds from processes with initial-state gluons and/or heavy-quarks. As an example, the current study suggests that a jet p_T cut of 225 GeV reduces the signal by about 1/2 and background by about a 1/4. Sensitivity is very slightly degraded, for both A_{FB}^b and A_{FB}^c, but any observed asymmetry would nearly double in size.

Finally, in measurements of this type it is important to have control samples, in which no new-physics asymmetry is expected. One could lower the muon p_T cut below 20 GeV, but experimental study is required to understand what new backgrounds would enter into that sample. Within the original preselection sample, we have already found that raising jet p_T and z_μ cuts ought to increase any partonic asymmetries, and so therefore reversing the jet p_T and z_μ cuts would provide control samples. Looking at low z_μ

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[7] In making estimates, it is important to keep in mind that the flavor mix of the jet containing the muon is different from that of the other jet.

[8] The author thanks G. Watts for discussions on this point.

enhances wrong-sign muons and should reduce any A^b_{FB} to an unmeasurable degree. Looking in the lower jet p_T bins reduces both $c\bar{c}$ and $b\bar{b}$ relative to backgrounds, and any asymmetries should disappear. These control samples consist of about half the original pre-selection set, with somewhat less than 10000 events. Obtaining higher-statistics control samples will be challenging.

Taking these ideas together brings us to the following tentative conclusions. A preselection along the lines of what was suggested here allows already for some sensitivity. Suppose an asymmetry is observed; then the hypothesis that it comes from heavy flavor requires that it come dominantly from the higher jet-p_T bins (and the central region in η.) If it does, then the question is whether it is from b or c. Methods to reduce wrong-sign muons from $b \to c \to \mu$ cascades, such as the use of z_μ or p_T^{rel} of the muon, enhance A^b_{FB} but hurt A^c_{FB}. The usefulness of track- and vertex-based tagging within the two jets — in particular the requirement that at least one of the two jets be so-tagged — depends very sensitively on the details of tagging and mistagging at high p_T. If tagging works well, it can improve the sensitivity to A^b_{FB} by a factor of more than 2; if it works poorly, it might still give improved sensitivity of perhaps a factor of 1.5. Either way, tagging can help determine whether an asymmetry comes from an underlying A^b_{FB} or from an underlying A^c_{FB}, since standard tagging will reduce A^c_{FB} to unobservable levels.[9] How to optimize these methods will require much more detailed study than is possible here. But it seems likely that, relative to the preselected sample's 3σ sensitivity of $A^c_{FB} \sim 0.3$ and $A^b_{FB} \sim 0.45$, which corresponds to an observed asymmetry of order 2%, the observed asymmetries can be further enhanced by a factor of at least 2 without a loss of sensitivity; and for A^b_{FB}, the sensitivity can probably be improved by a factor between 1.5 and 2.5.

It is natural to ask whether measurements of this type are possible at the LHC. This issue requires a separate study, but seems very challenging, for many reasons. The sources of $b\bar{b}$ and $c\bar{c}$ are largely from gg, and have no asymmetry in the parton frame. Even for those events that stem from $q\bar{q}$ initial states, the pp hadronic initial state requires one to measure the direction of the q in the initial state statistically, using the boost of the partonic frame. There are huge $gg \to gg$ backgrounds that produce muons from gluon

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[9] A specialized tagging strategy that could enhance charm at such high p_T while sufficiently rejecting both bottom and other sources of muons seems difficult to imagine, but is clearly worth some additional thought.

splitting, and large boosted sources of qQ and gQ scattering. Furthermore, the fact that boosted events are required, and that the initial pp state carries a definite charge, could interplay with detector angular acceptance in tricky ways that would be difficult to untangle. The advantage of the Tevatron for this particular fqmeasurement is its relative clarity and simplicity. Perhaps some progress may be made at LHC by requiring a muon in each of the two jets, and using the huge statistical advantage that the LHC will eventually possess at these energy scales.

It has been argued here that measurements at the Tevatron of forward-backward asymmetries of order 30% in charm and/or bottom production should be detectable at both experiments, with the possibility of further improvement for A^b_{FB} if one is optimistic regarding tagging at high p_T. The results of this article are crude, with large and unquantifiable error bars, and need to be reconsidered carefully by the Tevatron experiments. Even if the conclusions of this article prove qualitatively correct, these measurements will be difficult. However, the scientific benefits to carrying out these measurements — null tests of the Standard Model, and indeed of a very wide class of theories beyond the Standard Model — would make them worthwhile to perform.

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