Measuring b-$\bar{b}$ correlations in ATLAS

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Abstract

The measurement of the relative production angle of b-$\bar{b}$ quark pairs serves as an excellent probe of QCD, particularly with regard to those contributions from higher order matrix elements. The very high rates of b production that will be achieved at the LHC will enable ATLAS to collect high statistics of b hadron decays, which offer the potential for high quality measurements of b-$\bar{b}$ correlations.

Here, a novel technique is presented where one b quark direction is measured through the reconstruction of a J/ψ meson, and the other via its semi-leptonic decay to a muon. This technique potentially represents a considerable improvement on previous measurements that have used dimuon samples, where backgrounds are much higher and the presence of resonant decays to two muons demand the application of cuts on the μ–μ opening angle or invariant mass. The studies presented use a full simulation of the relevant components of the ATLAS detector to demonstrate the suitability of both the technique and the ATLAS instrumentation for making such a measurement. These results represent the beginning of an effort within the ATLAS collaboration to make a full study of the potential for measurements of b-$\bar{b}$ correlations at the LHC.

1 Introduction

Progress has been made in recent years in understanding heavy flavour production on both experimental and theoretical sides. Generally, however current descriptions of b production in hadronic collisions have met with only a degree of success. Whilst many features of the production properties are well described by perturbative QCD, success in understanding the data is still limited. Notably cross-sections measured at the Tevatron remain a factor 2 above the theoretical prediction.

The potential sources of such a discrepancy are various. Radiative corrections are very large, and so it is possible that higher order terms could be the source of the short-fall. Theoretically substantial progress has been made through the achievement of full next-to-leading order (NLO) calculations within perturbative QCD [1],[2],[3]. It is seen that the cross-section contributions from $O(\alpha^3)$ terms at Tevatron energies are of the same size as the $O(\alpha^2)$ contribution. Whilst the higher order (NNLO) terms cannot be explicitly calculated, there are several techniques available to approximate their contribution.

The processes contributing to heavy quark production in hadronic collisions can be divided into those described as 'flavour creation', 'flavour excitation' and 'parton showering'. Flavour creation refers to the situation where the heavy quark pair originates in the hard interaction from either quark-anti-quark annihilation or gluon-gluon fusion, i.e. $q\overline{q} \rightarrow Q\overline{Q}$ or $gg \rightarrow Q\overline{Q}$. Flavour excitation refers to the process $qQ \rightarrow qQ$ or $gQ \rightarrow gQ$, where the heavy quark Q comes from the sea of the initial particle. In the case of parton showering the hard parton interaction involves only light quarks and gluons, and the heavy quark pair emerges from 'soft physics' effects. Flavour creation is a leading order process and forms a larger part of the total heavy flavour cross-section at lower than at higher energies. In contrast flavour excitation and parton showering are largely contained in the NLO diagrams, and will contribute a greater part of the total heavy flavour cross-section at LHC than at any previous machine. One of the very few experimental techniques to show how these various processes contribute is the study of the angular correlation between the two b quarks in a heavy flavour event.

Additional techniques are required in the calculation of perturbative QCD, most generally to handle soft physics effects, that are beyond the LO and NLO diagrams explicitly considered above. These can be handled in a variety of ways, and a full discussion is beyond this note. (See [4] for more details.) However here we have used the results offered by several calculations, including FMNR [3], the HVQJET Monte Carlo, a 'semihard' approach [5], and PYTHIA [6].

Traditionally b-$\overline{\text{b}}$ angular correlations have been measured using dimuon events, where it is assumed that both muons are the products of semi-leptonic b decays. Thus the azimuthal separation distribution, $\Delta\phi_{\mu\mu}$, is made and some extrapolation to the b-$\overline{\text{b}}$ correlation calculated. The variety of predictions of $\Delta\phi_{\mu\mu}$ at LHC offered by the available calculations is summarised for some of these approaches in Figure 1, taken from [4]. Figure 2 shows a recent measurement from the D0 experiment [7] and a comparison of the data with a theoretical calculation from the HVQJET program. Similar measurements have been made by the CDF experiment [8]. It can be seen that the contributions from the $O(\alpha^2)$ (LO) processes is very small at lower $\Delta\phi_{\mu\mu}$. At LHC the NLO terms will dominate even more in this region. Figure 1b shows the relative contribution of each process at the LHC, for the same measurement, $\Delta\phi_{\mu\mu}$.

A potential source of cross-section beyond peturbative QCD is through the contribution of non-perturbative effects, such as an intrinsic k_T of the incoming parton. Such a primordial parton transverse momentum has been advocated as an explanation of certain features of direct

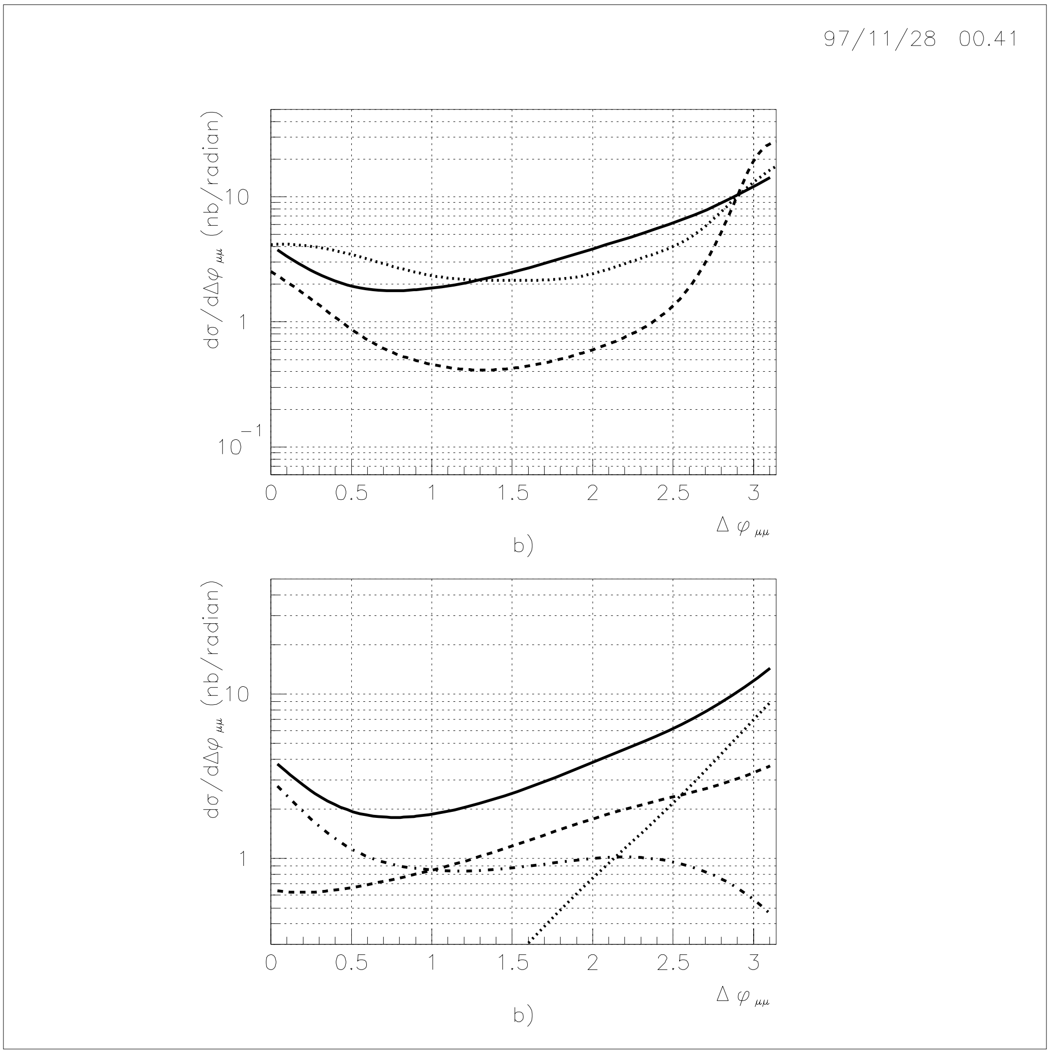

Figure 1 Azimuthal μμ correlations at LHC, $\Delta\phi_{\mu\mu}$ distribution, a) shows the prediction of PYTHIA (solid curve), peturbative QCD (dashed curve), and a semi-hard approach (dotted curve). b) shows the PYTHIA prediction (solid curve) and the relative contributions from the constituent processes; flavour excitation (dotted curve), gluon-gluon fusion (dashed curve), gluon splitting (dash-dotted curve). (Figure from Baranov and Smizanska, [4])

photon data [9]. The parton transverse momentum enhances the final state transverse momentum distributions: a study of prompt photon production data from the Tevatron [10] suggests a mean parton transverse momentum, k_T, of up to 4 GeV. It should however be noted that such a k_T is unphysically large. The angular correlation between b quarks in the transverse plane is particularly sensitive to such effects, and whilst the LHC data will be less sensitive to such an effect than the Tevatron, studies suggest that the effect on the angular distribution could be dramatic. The dependence of the azimuthal correlation on k_T is shown in Figure 3, using a calculation from the FMNR program, for Tevatron energies. In Figure 1 the calculated $\Delta\phi_{\mu\mu}$ distributions from PYTHIA include some contribution from initial parton k_T since this is an implicit component of the program's calculation.

In this note a single, novel way of measuring the angular correlation between b quarks is presented. The study exploits the high performance of the ATLAS muon system, and uses full

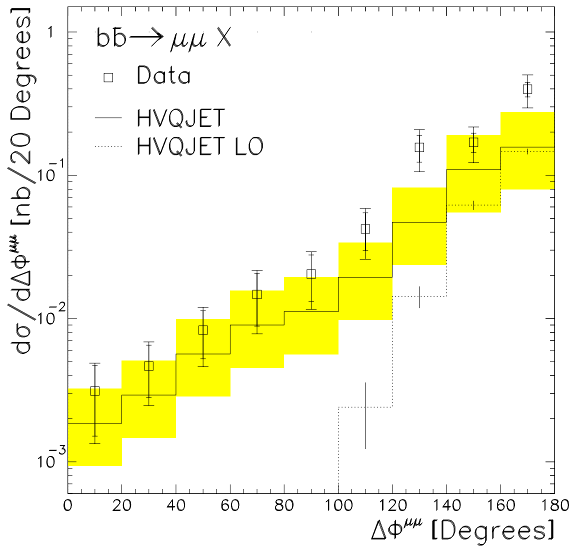

Figure 2 A measurement from D0 of the angular correlation, $\Delta\phi_{\mu\mu}$, compared with predictions from HVQJET. The points represent the D0 data, the solid histogram the NLO prediction and the grey band the uncertainty on that prediction. The dotted curve represents the LO prediction.

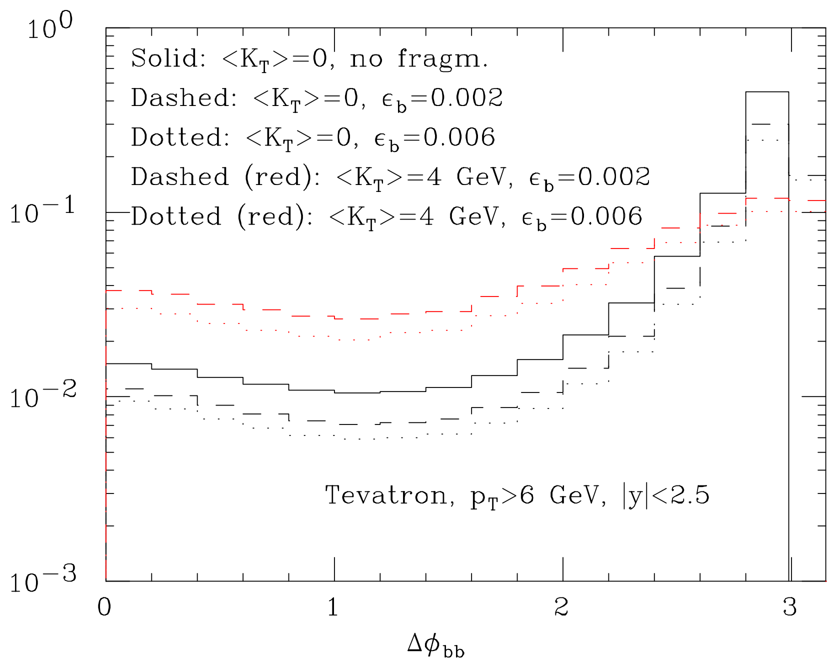

Figure 3 The azimuthal bb correlation distribution, $\Delta\phi_{bb}$, from the FMNR program, at Tevatron energies, shown for various values of the intrinsic angular momentum of the incoming parton, k_T. A value of k_T=4 GeV, suggested by direct photon data, results in a dramatic change in the correlation distribution. (Figure from P.Nason, [9]).

simulation of the relevant detector systems and reconstructs muons using both Muon Spectrometer and Inner Detector information. These in turn are used to reconstruct J/ψ mesons. The extraction of the azimuthal correlation distribution is performed by measuring the angular separation between the reconstructed J/ψ meson and any additional muon in the event. No detailed consideration has been made of the background at this stage, but it is seen that backgrounds from decays to μ of K and π mesons are much reduced relative to the two muon approach. In the two muon analysis it becomes essential to make cuts on the μ–μ invariant mass to exclude pairs of muons that come from the same b quark. Such backgrounds arise from cascade decays, i.e. $b \rightarrow c\mu$, $c \rightarrow s\mu$, and from resonance decays to di-muons. Such a demand is an implicit cut on the separation of pairs of muons. This results in the efficiency falling rapidly at low $\Delta\phi_{\mu\mu}$, making very substantial efficiency corrections inevitable. Here a channel is used in which no such cut should be necessary and thus the resulting model-dependent corrections should be unnecessary.

2 Event simulation and reconstruction

Events are generated using the PYTHIA program, and passed through the ATLAS detector simulation and reconstruction code. Muon tracks in the muon spectrometer are matched and combined with Inner Detector tracks. In events containing two or more muons J/ψ candidates are found.

The heavy flavour events used in this study are b events generated by PYTHIA 5.7, with the demand that the event contains one B_d meson that decays via the process $B_d \rightarrow J/\psi + K^0_s$, where the J/ψ decays to $\mu\mu$. Additionally it is demanded that the other b quark in the event decays semileptonically to μ. Any other b quarks in the event are left to hadronise and decay according to the standard PYTHIA conditions. The events are processed through the ATLAS detector simulation package, DICE. This contains a full and detailed GEANT simulation of the components of the ATLAS detector, in particular the Inner Detector and Muon Spectrometer used in this analysis. The geometry of the detector sub-systems is accurately described by the simulation, as currently envisaged.

No background arising from sources other than the hard interaction in PYTHIA modelled is simulated. Pile-up (detector activity arising from Minimum Bias events that overlay the hard scatter of interest) is not simulated. This is not likely to significantly affect the performance of either the muon of tracking detectors at low luminosity LHC running. This will be studied in the near future.

Tracks in the Inner Detector (ID) are reconstructed using the IPatRec code [11], and muons are identified in the Muon Spectrometer using the MUONBOX package [12]. No track or muon demands are made beyond those present in the reconstruction codes. Identified muons are matched to and combined with Inner Detector tracks using the MUID (MUon IDentification) code [13]. This is a package that matches muons to ID tracks using a detailed treatment of energy losses in the material of the calorimeters, and using the full covariance matrix of both the ID track and the identified muon. Those tracks successfully matched to muon information are considered to be muon candidates and the parameters of the ID track at the vertex are used to describe the muon in the analysis that follows.

The rate at which muons are matched to an ID track other than that of a true muon has been investigated. For the sample under study this fake rate is found to be 0.4%. The low rate of fake matches, despite the dense jet environment of the B hadron decay, is due to the high resolution of both the ATLAS muon Spectrometer and Inner Detector. Muons arising from the decay of K and π mesons will also be present in the sample, but are reconstructed with a lower efficiency than prompt muons owing to the matching constraints of the MUID package. The ‘kink’ of the meson decay is sufficient for most of them to fail this matching procedure, and the sample of reconstructed muons contains only 2 from several thousand that are from K or π decays. Explicit rejection of such muons is being investigated in ATLAS, and will be reported shortly - however no such rejection is used here. The efficiency for reconstruction of prompt muons in the sample is shown in Figure 4 as a function of p_T for muons with $|\eta|<2.7$. For muons with $p_T>6$ GeV this is close to 95%. The dominant reason for the fall-off of efficiency at $p_T < 6$ GeV is

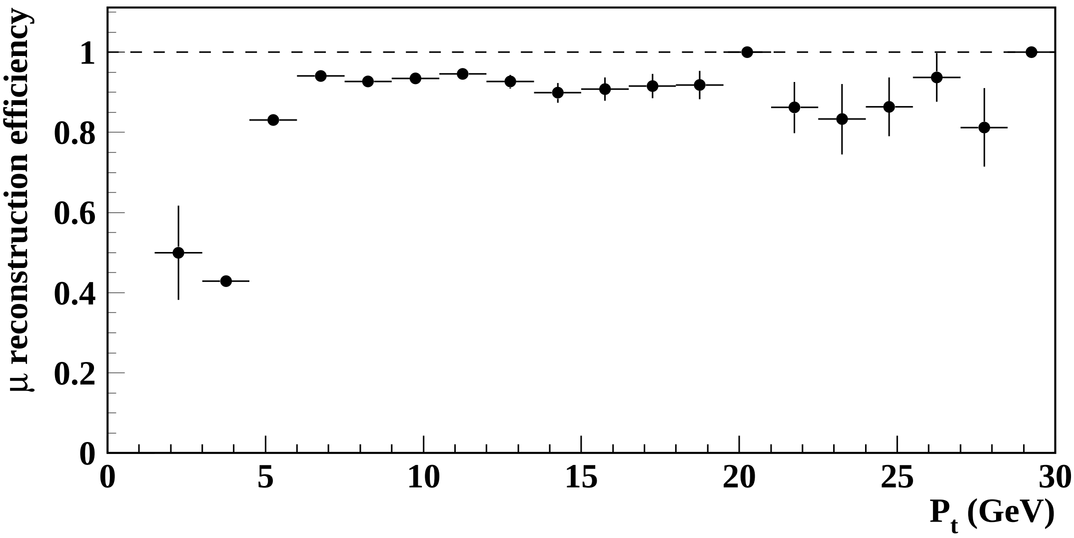

Figure 4 The efficiency for reconstruction of muons in the B_d event sample, where $|\eta|<2.7$.

the presence of the material of the ATLAS calorimetry in front of the muon spectrometer. It is expected that reconstruction efficiency can be increased for these softer muons through the use of the calorimeter data in the reconstruction algorithm, to extract an estimation of the energy loss in the calorimeter. This work is in progress.

J/ψ mesons are reconstructed by considering all pairs of oppositely charged muons in an event and constructing their invariant mass. In every event the pair of muons with the invariant mass closest to the true J/ψ mass is considered as a J/ψ candidate. The resulting distribution for the B_d sample is shown in Figure 5. The J/ψ mass is seen to be reconstructed accurately (very few J/ψ where both true muons are found is reconstructed more than 3σ from the peak), and the resolution on the mass peak is around 41 MeV. A muon pair is considered a good J/ψ if its invariant mass is seen to lie within 3σ of the nominal J/ψ mass. The background in the region of the peak is small. (It should be noted however that all events in the sample contain a $J/\psi \rightarrow \mu\mu$ decay.)

In principal better discrimination between J/ψ products and other muons in the event can be achieved through the use of vertex information. No such information has been used in this analysis, but will be incorporated in future iterations.

The aim of this analysis is to measure the angle in ϕ between the J/ψ and any third muon in the event, $\Delta\phi_{J/\psi-\mu} = \phi_{J/\psi} - \phi_{\mu}$. It is important to demonstrate that the efficiency for reconstructing muons is not dependent upon their angular separation, in order to reduce the dependence of the efficiency on $\Delta\phi_{J/\psi-\mu}$. Figure 6 shows the efficiency of J/ψ reconstruction as a function of the angular separation of the muons of the J/ψ. A demand has been made that both muons have p_T

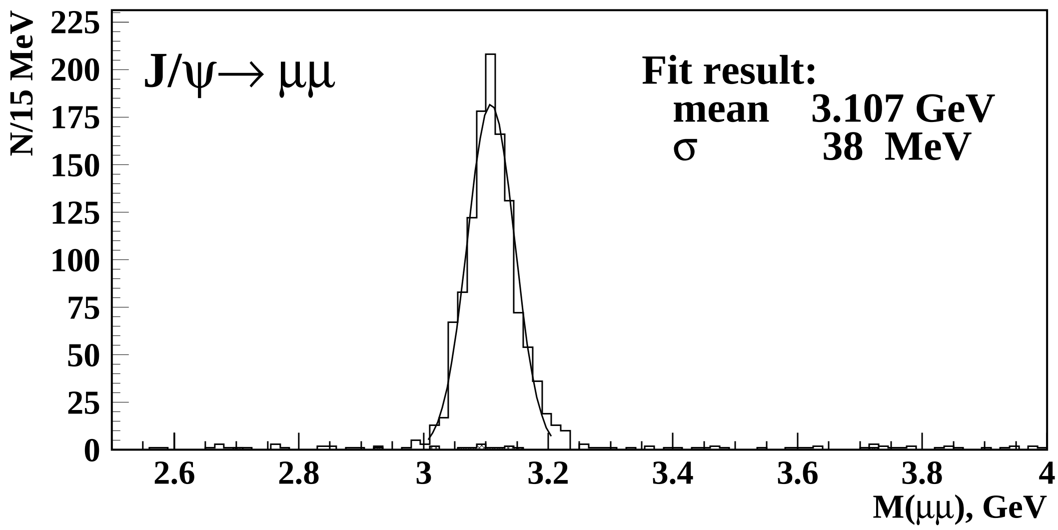

Figure 5 The reconstructed J/ψ mass peak, and the details of a Gaussian fit to it.The shaded area represents those pairs of muons which are not from a true J/ψ decay.

> 5 GeV. There is some evidence that efficiency is degraded where the muons are less well separated, though this is not expected given the resolution of the ATLAS tracking detectors. This

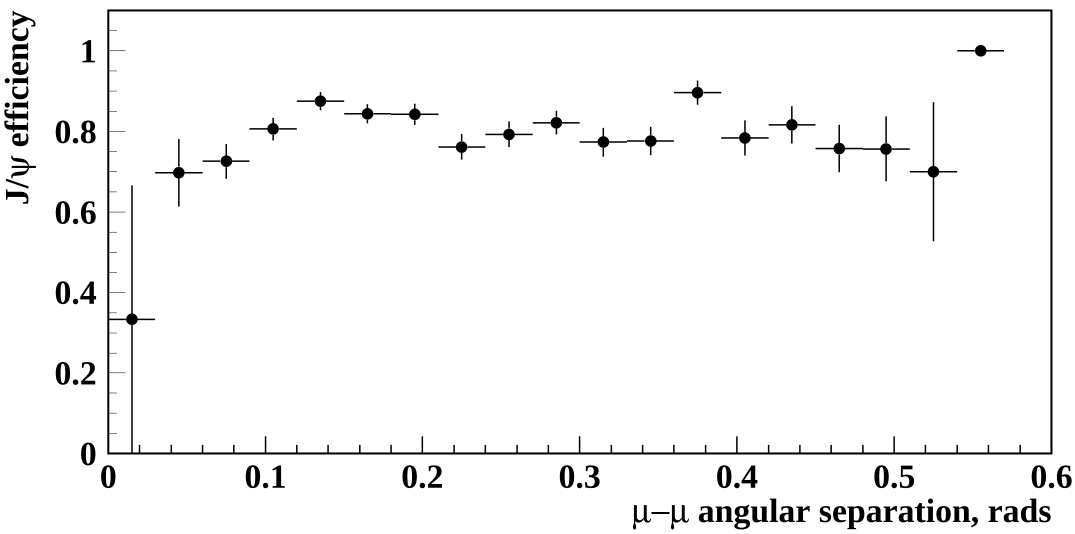

Figure 6 The efficiency for reconstruction of J/ψ as a function of the angular separation of the decay products.

phenomenon is under investigation.

One pattern recognition problem that has been observed in these data, is the phenomenon of multiple muon spectrometer tracks being matched to a single Inner Detector track. This appears to be a consequence of spurious tracks being found in the muon spectrometer (or, more precisely of single muons being reconstructed as two separate muons). This occurs for less than 1% of muons, the problem occurring in 2% of the B_d events. This is being investigated.

3 Measurement of b-$\bar{b}$ correlations

The azimuthal angular correlation distribution, $\Delta\phi_{J/\psi\text{-}\mu}$ is constructed by considering those events where a J/ψ meson has been reconstructed and one or more additional muons is present. This technique is likely to prove superior to the measurement of b-$\bar{b}$ correlations using $\Delta\phi_{\mu\mu}$, where the azimuthal separation of two muons is considered, largely due to the background suppression offered by the J/ψ demand. The presence of the J/ψ will reduce the statistics available to an analysis relative to the μμ channel, but the huge statistics available at the LHC experiments are likely to make this unimportant, except at very high p_T. The expected number of events reconstructed in ATLAS after three years LHC running at low luminosity (corresponding to 30 fb^{-1}) is 2.8×10^6 for the inclusive channel bb $\rightarrow$ J/ψ (μμ) X + μ, and 2.1×10^5 with the same lepton content but J/ψ produced semi-exclusively.

The D0 analysis [7] of $\Delta\phi_{\mu\mu}$ shown in Figure 2 utilises a dimuon sample containing only 45% of muon pairs from bb, 38% muon pairs where one μ is the product of a K or π decay, and 14% contamination from cc decays. A similar analysis from CDF [8] uses a sample containing 52% of dimuons where both muons are a direct b hadron decay product. Purer samples for b-$\bar{b}$ correlation studies can be produced using J/ψ-μ correlations. Due to the presence of states decaying to dimuons (such as the J/ψ) as well as to cascade decays (i.e. b $\rightarrow$ cX $\rightarrow$ μY) it is necessary in measurements of μ–μ correlations to make cuts on the μ–μ invariant mass in order to exclude such muons. This necessitates a model-dependent correction in the low $\Delta\phi_{\mu\mu}$ region. In an analysis of J/ψ-μ correlations no such cut should be necessary.

The $\Delta\phi_{J/\psi\text{-}u}$ distribution i.e. the azimuthal angular separation of the J/ψ and the third muon, arising from this analysis using a simulation of ATLAS data is shown in Figure 7 for generated data and that reconstructed in the ATLAS simulation. Figure 7a, at the generator level, shows events containing a J/ψ and a third muon; the background shown corresponds to those events containing four b quarks. These latter events correspond to parton showering processes discussed in Section 1. The presence of four b quarks makes the measurement of the angle between any two of those irrelevant for the true bb correlations measurement. This is a background, that in the absence of the development of any cuts to exclude it, will have to be estimated, or in principle measured, and subtracted. In the data sample used here the production rate of such 4 b events has been increased relative to that expected through a consequence of forcing the decay of the initial pair of b quarks to μ and J/ψ respectively. The background found in this analysis from such events is likely to be over-estimated several times. Also shown is the low level of background from K/π decays, in the simulated events containing a real J/ψ $\rightarrow$ μμ decay. Figure 7b shows the reconstructed data where both a J/ψ meson and an additional muon have been reconstructed. The 4 b quark background reconstructed is also shown; this background is seen to be both small and flat in $\Delta\phi_{J/\psi\text{-}\mu}$. Little background from K/π decays is seen. There will be additional background from cascade decays, where a muon is found that is a product of charm decay. Initial studies in ATLAS [13] suggest that the level of such background is close to 10% in events containing J/ψ decays. Such muons will have a strong correlation with the direction of the true b decay muon, and so will have the effect of degrading the resolution of the $\Delta\phi_{J/\psi-\mu}$ measurement. It is likely that such background can be rather accurately modelled and treated in the extraction of the true b-$\bar{b}$ angle from the measurement. This will be studied in the near future.

A study of the resolution on the measurement of $\Delta\phi_{J/\psi\text{-}\mu}$ indicates that the measurement is unbiased, and has a resolution of ~2 mrads.

The efficiency for reconstructing the muon in such events is shown as a function of $\Delta\phi_{J/\psi\text{-}\mu}$ in Figure 8. It is seen that the efficiency is flat with the exception of the first bin in $\Delta\phi_{J/\psi\text{-}\mu}$. It is clearly important to ensure that the efficiency as a function of $\Delta\phi_{J/\psi\text{-}\mu}$ is as flat as possible, to minimise corrections to the distribution which may introduce uncertainties.

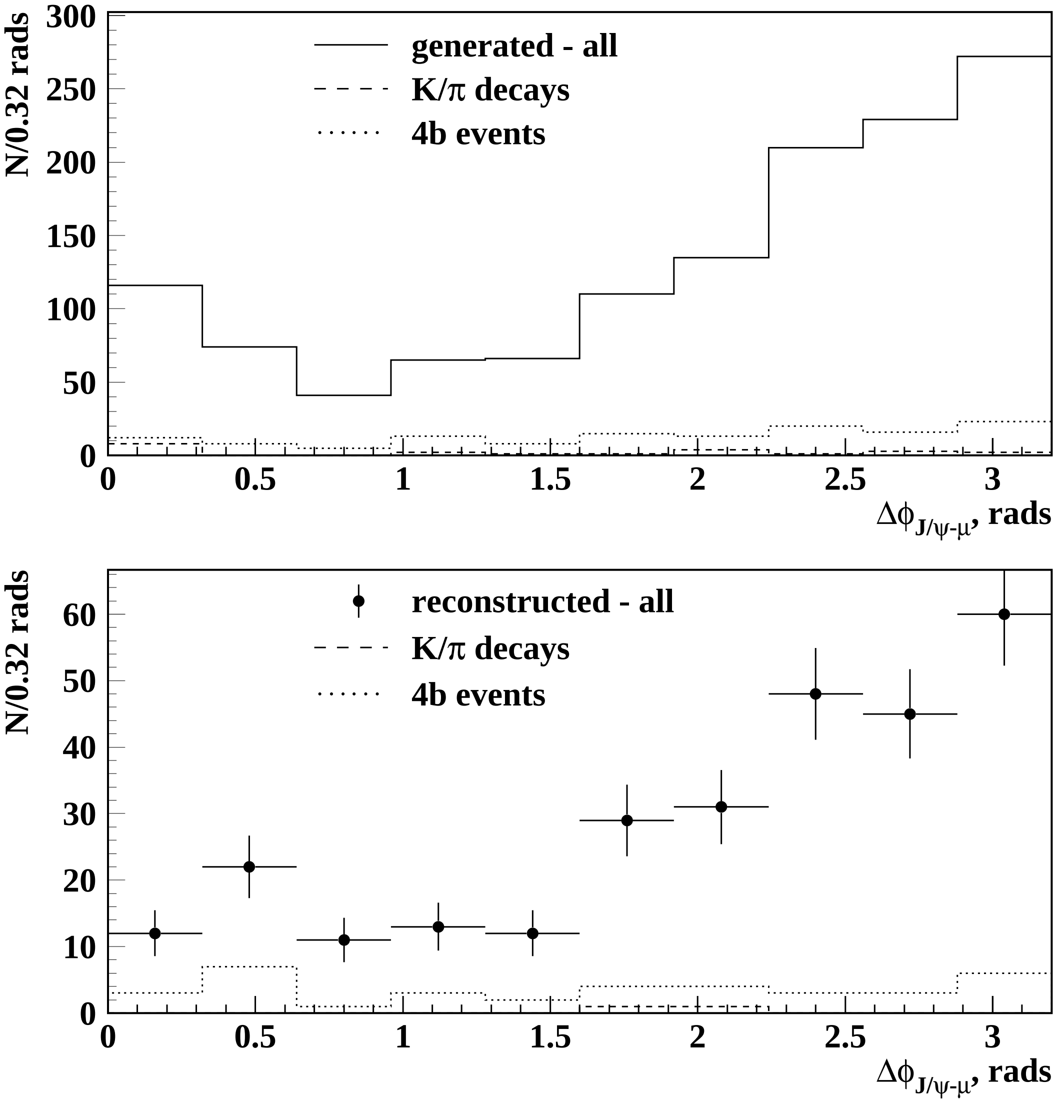

Figure 7 The $\Delta\phi_{J/\psi\text{-}\mu}$ distribution to measure b-$\bar{b}$ correlations at ATLAS. a) The generator level; all muons are shown in simulated events containing a J/ψ and a third muon. The open histogram represents the generated distribution of such muons; the dashed histogram represents the fraction of these that are the products of K/π decays; the dotted histogram represents those in events containing 4 b quarks. b) Reconstructed; all events where a J/ψ and a third muon have been reconstructed are shown, with the 4 b quark background shown by the dotted histogram. No K/π decays are reconstructed as good muons.

4 Conclusions

A preliminary study has been made of the possibility of making an analysis of b-$\bar{b}$ correlations at ATLAS using the $\Delta\phi_{J/\psi\text{-}\mu}$ distribution, the azimuthal separation of a J/ψ and a muon. This technique is likely to be superior to current methods used at the Tevatron with muon-muon correlations due to the expected background reduction, and the independence from any invariant mass cut. Using a full simulation of the Inner Detector and the Muon Spectrometer of the ATLAS detector it is shown that such a distribution can be extracted from heavy flavour events at LHC.

Whilst no detailed background studies have been performed, the results of the analysis suggest that backgrounds from K/π decays are small, and that backgrounds from events containing 4 b quarks are relatively flat in $\Delta\phi_{J/\psi\text{-}\mu}$. Studies of other backgrounds are in progress.

The efficiency of the reconstruction of muons with this technique is also relatively flat in$\Delta\phi_{J/\psi\text{-}\mu}$, and so we conclude that corrections to the measured $\Delta\phi_{J/\psi\text{-}\mu}$ distribution are likely to be small, with the exception of the first bin. Efforts will continue to investigate possible pattern recognition effects that may be reducing the efficiency in this region.

This work represents the start of an effort within ATLAS to address all the issues surrounding the measurement of b-$\bar{b}$ angular correlations. Investigations of the detector-related and theoretical issues are underway. In the near future we will present detailed and comprehensive analyses of both the new channel investigated here, as well as the dimuon channel.

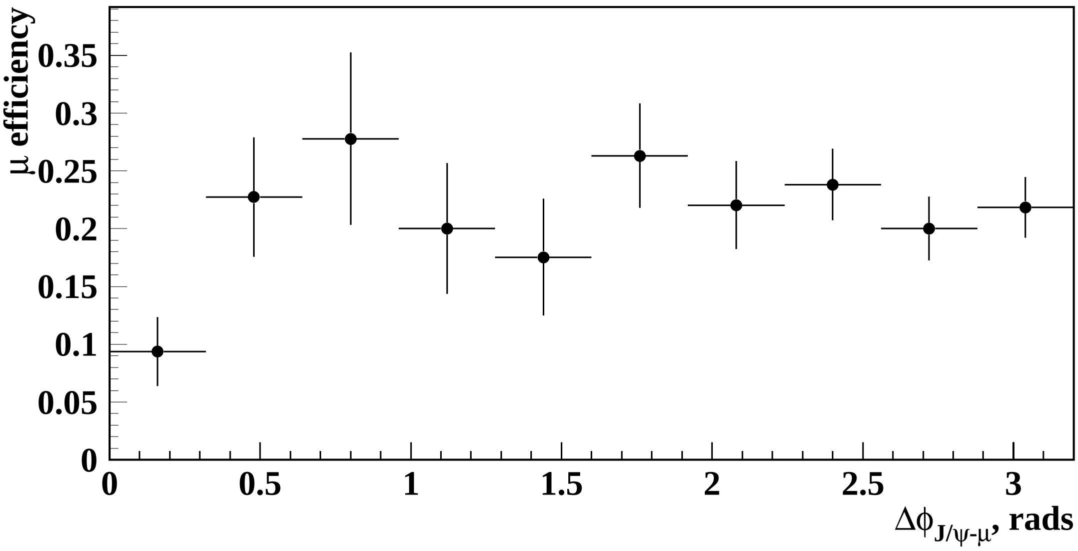

Figure 8 The efficiency for reconstructing the third muon in an event, where a J/ψ meson has been reconstructed, as a function of the generated J/ψ–μ angle, $\Delta\phi_{J/\psi\text{-}\mu}$

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