On the angular correlations of b-jets in $p\bar{p}$ collisions at 1.96TeV

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Chapter 1

Introduction

The research in $b$-quark production at hadron colliders has long been driven by an apparent discrepancy between predicted and observed values of the $b$-quark production cross section. Frixione et al. [1] suggested an alternative approach in comparing data to theory, where instead of the $b$-quarks itself, jets containing $b$-flavor are observed. Using this method, the contradiction between theory and experiment appeared to disappear [2], however as uncertainties in both theory and experiment remain large further research is required. To gain more insight in the production of $b$-quarks, it is useful to look at diagrams at higher order in the strong coupling constant $\alpha_s$ that contribute to the $b\bar{b}$ production cross section.

This research uses data from the DØ detector at Fermilab to look at angular correlations in $b$-jet production. Angular correlations between $b$-jets are particularly sensitive to the higher order $b\bar{b}$ production processes of gluon splitting and flavor excitation. To determine the number of $b$-jets in a sample, a kinematic difference between $b$ and lighter jets is exploited. The resulting $\Delta \phi$ distribution can be fitted to Monte Carlo simulations at different orders in $\alpha_s$, or compared directly to theoretical predictions.

In his PhD thesis [3] B.Wijngaarden first performed this analysis, on a sample corresponding to an integrated luminosity of $7 \text{ Sb}^{-1}$. He found a relative contribution of higher order processes that was consistent with theoretical predictions of the PYTHIA event generator.

With the available data of the DØ detector now adding up to $1 \text{ fb}^{-1}$, this analysis is redone in this master thesis. The larger number of events available plus a considerable increase in $b$-jet tagging efficiency reduces the statistical error on the data drastically. Therefore the theory can be tested to a much higher precision with the result of this analysis than was possible before.

The first section of this thesis will explain some theoretical background, showing which processes are considered when looking at hadronic production of $b\bar{b}$ pairs. Then a section will be spent on a description of the DØ detector at the Tevatron accelerator at Fermilab. The next section will explain the data and Monte Carlo simulated samples used in this research, the triggers used in
data acquisition, and the methods used in the analysis of the data. The last two sections will show results and draw conclusions.
Chapter 2

Theoretical Background

2.1 Diagrammatic picture of $b\bar{b}$ production

This study looks at $b\bar{b}$ production from $p\bar{p}$ collisions, where the process is studied at tree level up to third order in the strong coupling constant $\alpha_s$. At lowest order there are four diagrams that contribute to $b\bar{b}$-production. These are shown in figure 2.1.

The quarks in these diagrams carry ‘color’-charge, the charge associated with the strong interaction. Colored particles are never found isolated. Instead they are always bound into groups of two (mesons) or three (baryons), to form a colorless state (three different colors, or a color and a anti-color). This means that the final state particles in these diagrams will not be observed directly in the detector. Instead, they will combine with other quarks, which are created out of the energy of the incoming particles, through a series of gluon radiations (a quark emitting a gluon) and gluon splittings (a gluon splitting up into a quark/anti-quark pair). This process is known as hadronization.

In the process of creating a colorless state for the original quark, many other particles are created. All these particles move in about the same direction as the original quark, and what is found in the detector is a tightly collimated bunch of particles, called a jet. How exactly you define a jet depends on circumstances, a jet in the DØ detector will be defined in the next chapter.

At third order in $\alpha_s$ two additional production processes are distinguished, one called flavor excitation (see figure 2.2), the other gluon splitting (figure 2.3). These diagrams all have three particles in their final state, and therefore more events are expected with a smaller angle between the two $b$-flavored jets.

In a real collision all these diagrams contribute to the total production cross section, and the $\Delta\phi$-distribution obtained from data will be some superposition of the three distributions shown here. A fit of these three distributions to the data will provide a measure of the importance of higher order diagrams in $b\bar{b}$ production.
Figure 2.1: The four lowest order diagrams for beauty production in hadronic collisions

Figure 2.2: The flavor excitation diagrams for beauty production in hadronic collisions
The interference between these three diagrams is assumed to be small, and the PYTHIA event generator, which is used in B. Wijngaarden’s thesis, neglects it completely.

As the lowest order diagrams have only two particles in the final state, the jets that are found in the detector are expected to be approximately back-to-back. In fact, the final state particles can radiate additional (hard) gluons, which changes the angle between the two jets (a hard gluon means a gluon that is emitted with a high transverse momentum with respect to the momentum of the original particle). Some additional smearing has to be taken into account due to fragmentation and detector resolution effects. Figure 2.4 shows a Monte Carlo (MC) simulation of the distribution of the azimuthal separation $\Delta \phi$ of the b-flavored jets originating from different production processes. The higher order diagrams, which have more than two particles in the final state show a contribution at small $\Delta \phi$. The azimuthal angle is defined in the plane perpendicular to the beam axis, and is therefore independent of boosts along the beam line. This difference in $\Delta \phi$ distribution can be exploited to check that b-quark production is adequately understood.
2.2 Jets or Quarks

There is an apparent inconsistency between measuring $b$-jet or $b$-quark cross section. When comparing data to theory, the $b$-quark cross section is off by factor of about 3, but when looking at $b$-jets, this gap is no longer there. Frixione et al. [1] were the ones to propose not to try and reconstruct the $b$-quarks kinematic variables, but to look at the object that is directly observable, the jet containing $b$-flavor. The advantage of looking at jets rather than quarks will now be explained.

To calculate the full process from quark creation to jet formation, it is necessary to split the calculation into two parts: the perturbative part of the high energy interaction, and the non-perturbative formation of hadrons.

The high energy interaction is calculated using a series expansion of Feynman diagrams, where for this analysis loops in the diagrams were not taken into account.

The non-perturbative hadronization and jet formation is modeled by the so-called fragmentation functions, which are semi-empirical models describing the splitting of one quark (or gluon) into a jet of colorless particles.

The major challenge when trying to count $b$-quarks is that they are not directly observable. What is observable is the jet of particles, with somewhere in there the hadron containing a $b$-quark. Both this hadron and the other particles in the jet take some fraction of the original $b$-quarks momentum. This fraction is given by the fragmentation model used in the calculations.

To find the number of $b$-quarks as a function of the original quark’s transverse momentum $p_T = |p| \sin \theta$, a relation is used between the $p_T$ of the muon (which comes from B-hadron decay) and the $p_T$ of the original quark. The distribution of muon $p_T$ thus gives a distribution of $b$-quark $p_T$, which can be compared to distributions from QCD calculations. However, the fragmentation function used to get this relation between muon and quark $p_T$ is a source of large uncertainty in this type of analysis. As the spectrum declines steeply toward higher $p_T$, a small miscalculation in $p_T^b$ already results in a large difference in calculated cross section.

To make matters worse, the calculation of the isolated $b$-quark $p_T$ spectrum also requires knowledge of the fragmentation function. These are used to regulate collinear and infrared divergences that occur in calculating quark production diagrams.

These uncertainties can be avoided to some extent by looking at the directly observable $b$-jets. Calculating distributions of $b$-jets as a function of the jet’s transverse energy $E_T^{jet} (E_T = E \sin \theta)$ is safer [1], because no thought has to be given to the fraction of the jet $p_T$ carried by the original $b$-quark: all $p_T$ is contained inside the jet, which makes calculation and measurement of the $b$-jet $p_T$ much less involved. By switching the focus of both the theoretical calculation and the data analysis from the $b$-quarks kinematics, which is hard to calculate
and impossible to measure directly, to the $b$-jet’s kinematics, which are easier both to calculate and to measure, a large source of uncertainty in the analysis is removed.

This method has already been used successfully in references [2] and [3], and it will be used in this thesis as well.
Chapter 3

Experiment

3.1 Description of the machine

Most of the information in this section was found in the DØ NIM paper [4], where the detector is discussed in much more detail than is needed here. The following is to get a general idea of the features and capabilities of the DØ detector at Fermilab, insofar as relevant for this analysis. A schematic of the detector is shown in figure 3.1. In this figure the three main components of the detector are shown: Central tracker, calorimeter, and muon system. In this description, \( z \) denotes the position along the beam line, \( \phi \) the azimuthal angle in the plane perpendicular to the beam line and \( \theta \) the polar angle with respect to the beam line. The pseudorapidity \( \eta \) is defined as \( \eta = -\ln(\tan(\theta/2)) \). Forward angle here means the directions at high \( |\eta| \).

3.1.1 Tracking

The tracking system of DØ consists of two parts: the Silicon Microstrip Tracker (SMT) and the Central Fiber Tracker (CFT). These systems are used to detect charged particles. The tracker is built up of several layers, 4 in the SMT and 8 in the CFT. Tracks are reconstructed by combining hits in 2 or more layers. These tracks can then be traced back to their point of origin. This way the primary vertex where the original hard scatter took place can be found. When reaction products from the hard scatter are sufficiently long lived the secondary vertices where they decay can also be reconstructed. This provides a handle to find B hadrons, which typically have a decay length of the order of 1mm.

The SMT is shown in figure 3.2. It covers about 3 m\(^2\) with silicon strip detectors divided over 6 barrels, 12 small F-disks and 4 large H-disks. The barrels cover a region along the beam line of \(-51 \text{ cm} < z < 51 \text{ cm}\). The F-disks are
mounted in between and directly at the end of the barrels. The four large H disks are mounted at $z = \pm 100.4$ cm and $z = \pm 121.0$ cm.

The barrel sensors are placed in four concentric double layers, with each double layer containing two overlapping sub-layers, covering all angles in $\phi$. Most of the barrel sensors are double-sided silicon ladders, with 2° stereo angle. In the barrels at the end, single sided sensors are used in layer 1 and 3, where in the 4 central barrels layer 1 and 3 contain double sided sensors with 90° stereo angle.

Around the SMT lies the Central Fiber Tracker (CFT), a scintillator based tracking system, which covers the region of pseudorapidity $|\eta| < 2$. The CFT consists of 8 layers of scintillating fibers mounted on concentric cylinders. Each cylinder supports one doublet layer of fibers aligned with the beam, and one at a stereo angle of alternately 3° and −3°. The second layer of the doublet is positioned so that the fibers fill the gap between those of the first layer, resulting in a detection efficiency better than 99%. The scintillators are read out by Visual Light Photon Counters, which are connected by 11 m long clear fiber light guides.
The whole of the central tracking system is surrounded by a 2.8 m long 2 T superconducting solenoid. It’s magnetic field is used to determine the momentum of the particles that leave tracks in the central tracker.

### 3.1.2 Calorimetry

The calorimeter of DØ is used to measure the energy of photons, electrons and hadrons produced in $p\bar{p}$ collisions. Furthermore, by identifying and combining clusters of energy deposits in the calorimeter, jets can be reconstructed which indicate quarks or gluons in the final state of the interaction.

Figure 3.3 shows a schematic of the DØ calorimeter. The calorimeter system is divided in three parts: the barrel, covering $|\eta| < 0.8$, and the two end-caps, covering $|\eta| < 4$. A cut-through view is shown in figure 3.4. In this figure the granularity as a function of $\eta$ and distance $r$ from the beam pipe can be seen. Progressing from the beam pipe outward, the calorimeter contains first an electromagnetic section, which is about 20 radiation lengths ($X_0$) thick. Then comes the fine hadronic layer, of about three hadronic interaction lengths ($\lambda_A$), and at the outside the coarse hadronic layer, which has a thickness of again about $3\lambda_A$.

A view of a one detection unit cell of the detector is shown in figure 3.5, which also shows the copper read-out strips. Particles entering the calorimeter will undergo an (electromagnetic or hadronic) interaction with the absorber plates. This induces a shower of particles, which ionize the sensitive material in the gaps between absorbers. A high voltage across the gaps causes the electrons to drift toward the readout strips. The number of particles formed in the shower is a measure of the energy of the incident particle.

Argon is used throughout the calorimeter as the sensitive material. As absorbent, uranium is used in the EM calorimeter. Thin (6 mm) plates of uranium-
niobium (2%) alloy is used in the inner layer of the hadronic calorimeter, where thicker (4.65 cm) plates are used further outward, which are made of copper in the central calorimeter and steel in the end-caps.

### 3.1.3 Muon System

Most particles that are produced in a $p\bar{p}$ collision will be absorbed by the large amounts of material in the tracking and calorimeter systems. Two notable exceptions to this rule are muons and neutrino’s. The latter barely interact with anything at all, and easily traverse amounts of matter as large as, e.g., the earth.

Muons do interact with the detector material, but typically lose much less of their energy in these interactions than other particles, and therefore have a higher chance to be found outside the calorimeter. Muons therefore provide a cleaner signal of ‘interesting’ events than for instance electrons or photons. At DO, a muon system is set up outside the calorimeter and tracking. It consists of three layers of muon detectors, and its own toroid magnet. This way, a measurement of the muon’s $p_T$ can be made independent of the central tracker. The track found in the muon system can then be combined with a track in the central tracker, to get a better measurement of the muon $p_T$.

The muon system is split in two parts: the Wide Angle MUon System (WAMUS) and the Forward Angle MUon System (FAMUS).
The WAMUS contains three detector systems [5]: drift chambers, Cosmic Cap and Bottom scintillators, and the $A\phi$ scintillator counters. A toroid magnet between the first and second layer from the inside provides a 1.7 T magnetic field.

The drift chambers are made of rectangular Proportional Drift Tubes (PDT’s), of extruded aluminum. One tube’s cross section measures 10 $\times$ 5.5 cm. The PDT’s are stacked in 3 or 4 layers, as is shown in figure 3.6. The size of the chambers vary, with a maximum size of 100 $\times$ 225 inch. The drift chambers are positioned in three layers, with the innermost layer (layer A) located inside the toroid magnet, and the two outer layers (B & C) outside. The WAMUS muon system covers about 55% of the central muon region with three layers of chambers, and about 90% is
covered by at least two layers. The anode wire of the drift tubes is oriented along the magnetic field lines of the toroid, perpendicular to the beam line. This way the PDT’s provide a good measurement of the muon’s $p_T$.

The WAMUS scintillator counters are divided in two systems: the Cosmic Cap and Bottom counters, located near the layer B and C PDT’s, and the A$\phi$ scintillators, located on the layer A PDT’s, inside the toroid. The Cosmic Cap and Bottom counters are used to identify muons from cosmic rays. The A$\phi$ counters are used for a fast level 1 muon trigger. The counters in all layers are used for a time stamp to ascertain from which bunch crossing the muons passing through the PDT’s originate. The A$\phi$ scintillators are essential for identifying the low $p_T$ muons used in this analysis.

The FAMUS muon system, covering $1 < |\eta| < 2$ also contains three layers of drift chambers, and three layers of scintillator counters. It has its own toroidal magnet, which provides a field of $\sim 1.9$ T. For the drift chambers, Mini Drift Tubes are used, which are more resistant to the high levels of radiation that must be endured in the forward region of the detector than the PDT’s used in the WAMUS system. The three layers of scintillation counters in the forward region are used for triggering, and for the rejection of out-of-time background signals.
3.2 Reconstruction of jets and muons

3.2.1 Muons

Muons can be found in two places in the detector. As was stated before, a hit in the muon system provides a relatively clean signal of a muon, because other particles lose all their energy before reaching the muon system. A muon that is found in the muon system is called a local muon. A muon also leaves a signature in the central tracker. By extrapolating the track from the central tracker to the muon system or vice versa, a match can be made between hits in these two systems. Muons found in both systems are called central track-matched or global muons [6].

Reconstructed muons are divided into separate types and qualities. Muon types are defined according to the number of hits in the different parts of the muon system (\(nseg\)). Table 3.1 shows the precise definition of \(nseg\). A positive value of this variable indicates that hits in the muon system were matched with tracks in the central tracking system (global), a negative value indicates muons that were only found in the muon detectors (local).

Reconstructed muons are also divided in terms of quality, where muon quality is divided in TIGHT, MEDIUM or LOOSE. This research uses \(nseg=3\) (so, central track-matched) muons of MEDIUM quality (med3 muons). Med3 muons are defined as follows:

- At least two Layer A PDT hits
- At least one Layer A scintillator hit
- At least two Layer BC PDT hits (BC meaning a hit in layer B or C)
- At least one Layer BC scintillator hit (unless the number of BC PDT hits < 4)

3.2.2 Jets

Jets used in this analysis are reconstructed using the Improved Legacy Cone Algorithm (JCCB). Very briefly, this algorithm looks for the tower in the calorimeter with the highest energy (the seed), and then defines a cone in \((\eta, \phi)\)-space including all towers in the cone that have a distance to the seed in \((\eta, \phi)\) given by \(\Delta \eta^2 + \Delta \phi^2 \leq R\). For this analysis \(R = 0.5\) was chosen. The algorithm then looks within the cone for the tower of the next highest energy. The towers are merged,
and a new axis is calculated, and then again a tower of high energy is searched for. This is continued until either there are no more towers with high energy left (in which case the jet is stored), or the total energy of the jet candidate is too low (in which case the jet is discarded). Then the next starting point (seed) is looked for, until there are no towers with energies above a certain threshold are found.

This is a simplified version of the algorithm. Introducing a threshold to the energy of the seed towers introduces problems when the final state particles radiate soft or collinear gluons. What’s more, some way of merging or splitting nearby jets is needed. More details on how this is dealt with can be found in [8].

The Jet ID group recommends certain cuts on jet quality, which were faithfully applied in this analysis. For completeness, these cuts are shown in table 3.2. They are cuts on the fraction of jet energy which is found in the electromagnetic calorimeter \((EMF)\) and the fraction of jet energy found in the coarse hadronic layers \((CHF)\). Both these cuts are applied to remove jets that are dominated by noise in the hadronic calorimeter. The cut on \(f_{90}\), which denotes the fraction of towers that contains 90% of the jet energy, removes fake jets that are the result of adding up several noisy channels [7].

<table>
<thead>
<tr>
<th>Jet Quality Cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>(0.05 &lt; EMF &lt; 0.95)</td>
</tr>
<tr>
<td>(CHF &lt; 0.4)</td>
</tr>
<tr>
<td>(f_{90} &lt; 0.5)</td>
</tr>
</tbody>
</table>

Table 3.2: Jet quality cuts from the jet ID group [7]

To determine the ‘true’ jet energy from the energy deposited in the calorimeter, several corrections have to be taken into account. They are combined in the JES (Jet Energy Scale) correction [9]. This correction takes into account the fact that not all the energy of the actual jet is included in the cone that was found with the jet finding algorithm described above. Also noise from pile-up of previous events, radioactive decay of the uranium, electronics noise and additional \(p\bar{p}\) interactions need to be accounted for. When studying jets with an associated muon, as is done in this analysis, the fact that the muon does not deposit all its energy in the calorimeter, and often is accompanied by a neutrino, which is hardly ever seen at all, has to be corrected for as well. This correction, however, was not available for this thesis.
Chapter 4

Method

4.1 Introduction to the method

This section describes the manipulations on the data that are done to obtain a $\Delta \phi$ distribution of $b\bar{b}$ jet pairs that is as pure as possible. The steps are the following.

First, events are selected on-line by the trigger software. This trigger has a certain efficiency, and is often prescaled (see next section), two facts that have to be taken into account when comparing data to theory or MC.

Reconstruction of jets and muons is prone to systematic errors. To minimize these errors, minimum quality demands are set on the reconstructed objects, as described in sections 3.2.1 and 3.2.2.

For the events that pass the trigger and quality cuts a way of identifying jets containing heavy flavor (b-tagging) is needed. Two different, independent algorithms for b-tagging are used in this analysis.

The resulting sample still contains a number of events with c and lighter jets. The purity of the sample can be obtained by exploiting kinematic differences between b-jets and other flavors, using a method called $p_T^{rel}$ fitting which will be explained in section 4.3.

This results in a close approximation of the ‘true’ $\Delta \phi$ distribution. This distribution can be fitted to MC predictions of second and third order processes. This will result in a measure of the relative importance of higher order diagrams in $b\bar{b}$ production, which can be compared to theoretical predictions. All these steps are described in the following sections.

Besides the data, also the Monte Carlo generated samples that are used to model the data are subject to some manipulation. Therefore a section will be spent on how $p_T^{rel}$ templates are obtained from the various MC samples.

All analysis code was written in the Common Analysis Format (CAF) framework version p18.07.00, a ROOT based framework for data analysis used at DØ [10, 11]. It consists of many tools for event selection, plotting, and provides
an interface to the CAF trees in which the data from the detector and the MC simulations are stored.

4.2 Triggers

With a collision frequency delivered by the Tevatron of 2.5 MHz, the amount of information generated by the DØ detector is much bigger than what can ever be stored on disk. Therefore, before data is stored, it must be decided which events might contain interesting physics. Most collisions are discarded, and events are written at a rate of about 50 Hz [4, 12, 13].

To decide which events to keep and which to discard, a trigger system is used which is divided in three levels. Each subsequent level examines fewer events, and hence has more time to look at the event in greater detail. Different sets of triggers (trigger lists) have been used over the course of Run II of the Tevatron, denoted by trigger list version number. In this analysis triggers from trigger list version 12, 13 and 14 are used. With these triggers a dataset with a total integrated luminosity of $\sim 670 \text{ pb}^{-1}$ is available for this analysis.

The level 1 trigger, examines all events. While the level 1 trigger is being processed, the event is stored in a First In First Out (FIFO) pipeline, where the event reaches the end of the pipeline as the level 1 trigger decision is available. The specialized hardware that processes the level 1 trigger information is also pipelined, so that has 3.5 $\mu$s to reach a decision. The level 1 output rate is about 2 kHz.

The Level 1 trigger used in this analysis requires 1 muon trigger, based on the scintillators and wire chambers of the muon system, with no constraint on $p_T$. It also requires one calorimeter trigger tower with an transverse energy $E_T = E \sin \theta > 3 \text{ GeV}$.

At level 2, simple physics objects (muons, jets) are created from the detector output, where also different parts of the detector can be combined to create higher quality physics objects and examine correlations in all L2 physics objects. The level 2 trigger reduces the event rate by a factor of 2 to about 1 kHz.

<table>
<thead>
<tr>
<th>Trigger name</th>
<th>Trigger list</th>
<th>Corr. Integr. Luminosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>MU_JT25_L2M0</td>
<td>v12.00-v12.99</td>
<td>193.06</td>
</tr>
<tr>
<td>MUJ2_JT30_LM3</td>
<td>v13.30-v13.99</td>
<td>223.94</td>
</tr>
<tr>
<td>MUJ1_JT35_LM3</td>
<td>v14.30-v14.99</td>
<td>249.81</td>
</tr>
</tbody>
</table>

Table 4.1: Triggers that were used in this analysis, with the total luminosity recorded by that trigger. Only the events that contain usable data are used when determining this luminosity. The luminosity is corrected for the average trigger prescale.
### Trigger Name

<table>
<thead>
<tr>
<th>Trigger Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>JT_8TT</td>
<td></td>
</tr>
<tr>
<td>JT_15TT</td>
<td></td>
</tr>
<tr>
<td>JT_25TT</td>
<td></td>
</tr>
<tr>
<td>JT_25TT_NG</td>
<td></td>
</tr>
<tr>
<td>3JT10</td>
<td></td>
</tr>
<tr>
<td>JT45TT</td>
<td></td>
</tr>
<tr>
<td>3CJT5</td>
<td></td>
</tr>
<tr>
<td>4JT12</td>
<td></td>
</tr>
<tr>
<td>JT_65TT</td>
<td></td>
</tr>
<tr>
<td>4CJT5</td>
<td></td>
</tr>
<tr>
<td>JT_95TT</td>
<td></td>
</tr>
<tr>
<td>JT_125TT</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.2: Jet triggers used to select event for the muon trigger efficiency calculation. Triggers marked with (1) are used for the trigger list v12 triggers only, all the others are available in all trigger lists.

Only one L2 muon trigger but two distinct jet triggers were used in this analysis. The L2 muon trigger requires a muon without imposing a $p_T$ threshold. A jet is required with transverse energy $E_T > 10$ GeV (trigger list version 12) or $E_T > 8$ GeV (trigger lists version 13 and 14), respectively.

To make the level 3 trigger decision, the entire event is read out, digitized and sent to a computing farm, where more advanced algorithms can be used to further reduce the event rate to the required 50 Hz. The level 3 trigger used in this analysis reconstructs calorimeter jets with a simple cone algorithm, and then requires an $E_T$ threshold of 25 GeV (trigger list v12), 30 GeV (trigger list v13) or 35 GeV (trigger list v14). The triggers at all three levels combine into one unique name, which is given in table 4.1, together with the luminosity recorded using this trigger.

As sometimes the requirements of the triggers do not reduce the data acquisition (DAQ) rate enough, a prescale is added to artificially reduce the number of events examined by a trigger. The luminosity that is given in table 4.1 is scaled down with the average prescale factor of that trigger.

When comparing MC to data, the trigger efficiency for each event has to be taken into account. The caf_trigger package of the CAF framework is used, which calculates the chance that a given trigger fires on any of the objects in an event, and then uses this to calculate the probability of the trigger firing on this event. For the jet trigger, the efficiencies (also called turn on curves) from the jetid_eff package are used. Projections of the 2D turn on curves on the $E_T$ and $\eta$ axes are shown in figures 4.1 and 4.2.

The muon trigger efficiency calculation had to be redone, as the efficiencies from the muon id group were based on a sample of muons originating from Z decay, which typically have a much higher $p_T$ than the relatively soft muons that were used in this analysis.

To calculate the muon trigger efficiency, a sample is needed based on a selection that is independent of the muon trigger. For this purpose a data sample was selected based on all available jet-only triggers. These are triggers requiring only one or more calorimeter trigger towers with certain energy cuts. They are listed in table 4.2. The firing of these triggers is uncorrelated with a muon that might...
be found in the reconstruction of this event.

In this sample all muons are selected that meet the quality demands given in section 3.2.1. Then the Level 1, 2 and 3 trigger objects that were used in the trigger decision making are retrieved. The offline reconstructed muons are matched to the trigger objects, to see which offline muons fired the trigger. The number of muons that match the trigger objects at all levels divided by the total number of muons found offline then gives the muon trigger efficiency.

To get an absolute measurement of the trigger efficiency, also the prescale factor of the trigger has to be taken into account. This was not done here, first because the average prescale factor of this trigger was close to one, and this effect is not expected to be big, and second, the prescale only changes the absolute value of the efficiency, but not its dependence on any of the variables. So the shape of the efficiency curves is not affected, and therefore also the shape of the $p_T^{rel}$ templates for which the efficiency curves remains unchanged.

The results of this calculation, projected on the $\eta$, $\phi$ and $p_T$ axes are shown in figures 4.3 to 4.8. Errors in these plots are binominal statistical errors. Based
on these plots, and to keep enough events in each bin to get a reliable estimate of the trigger efficiency, a 2D turn on curve as a function of $\eta$ and $\phi$ was used, integrated over $p_T$. The variation in $p_T$ and $\phi$ is of equal magnitude, however, the $\phi$ dependence changed as a function of $\eta$, which is why this parametrization was chosen.

### 4.3 Distribution fitting

Using the current b-tagging algorithms, it is not always possible on an event-by-event basis, to determine whether a jet originates from a $b$ or a lighter quark, or a gluon. This means that after the selections and tagging as described in the next section, the sample will still be contaminated by a significant fraction of $udsc$-quarks and gluons. It is however possible to determine the total contamination fraction of a sample, by looking at the distribution of the muon $p_T$ with respect
to the jet + muon momentum axis (see for reference figure 4.9). The so-called \( p_{T}^{rel} \) distributions of MC \( b \)- and \( c \)-quark samples are shown in figures 4.10 and 4.11 respectively. As these distributions are quite distinct, a fit to the data of these distributions will give a reliable estimate of the total fraction of \( b \)-quarks in a sample.

In principle also the \( p_{T}^{rel} \)-distribution of a sample of \( uds \)-quarks and gluons should be considered, but as it turns out [3], this distribution is so similar to the \( c \)-quark distribution, that it is almost indistinguishable. Hence fitting a distribution from a \( c \)-quark MC sample will give the same background fraction as fitting a combination of \( c \) and lighter jets.

The fitting is done using the ROOT class TFractionFitter, which does a maximum likelihood fit of several template distributions such as shown in figures 4.10 and 4.11, taking into account the statistical errors both in data and in Monte Carlo. To get a better prediction of the true \( b \)-quark distribution, the MC templates are fluctuated within their statistical errors, and the likelihood is maximized as a function of this fluctuation [14, 15]. Different MC samples simulating different production processes are used to create the total \( p_{T}^{rel} \) template. All the templates belonging to the same final state (\( b\bar{b} \) or \( c\bar{c} \)) are kept at fixed ratios by the TFractionFitter. The fixed ratios are determined from the average cross section for the process as calculated by the simulation program PYTHIA.

Fitting this distributions was done in different bins in \( \Delta \phi \) and \( E_{T} \). In every bin the total number of \( b \)-jets can be determined, resulting in a relatively clean \( b \)-jet \( \Delta \phi \)-distribution. It is this distribution that is compared to those of the MC samples of direct-\( bb \) events and and those containing the gluon splitting and flavor excitation events. This finally gives the measure of how important the higher order diagrams shown in section 2.1 are in the production of \( bb \)-pairs.

### 4.4 B-tagging

Mesons carrying B flavor most of the time decay into lighter mesons through weak interactions before reaching the detector material. Therefore, the creation of \( b \)-mesons has to be inferred from the kinematics of the jet that is observed in the detector. A total of four of these so called b-tagging strategies have been adopted in the past. Three of them were similar, in that they were all based on the relatively long lifetime of the B hadron (around 1.5 ps). One was based on
the decay of the $b$-quark to leptons (Soft Lepton Tag, SLT [16]).

The lifetime of a $B$ hadron combined with a typical boost of $\gamma \sim 8$ gives a displacement of the vertex of the order of a few mm, which can be resolved by the DØ tracking system. The Secondary Vertex Tag uses this large displacement. This tagger reconstructs the position of the decay vertex, and measures the path length traveled by the particle before decaying [17]. Another frequently used tagger, which was also used in the research by B. Wijngaarden [3], is the Jet Lifetime Probability tagger [18], which looks at the impact parameter of the particles in the jet with respect to the primary vertex, and uses this to determine the chance that all particles in the jet come from the Primary Vertex (PV). The CSIP (Counting Signed Impact Parameter) tagger makes a cut on the significance (the value divided by its error) of the impact parameter of the particles to determine the jet flavor.

Recently, all existing taggers except for the SLT have been combined in a Neural Network (NN) tagger [19]. This tagger takes variables from all the lifetime based taggers as input, and outputs a value indicating the chance that the jet is a heavy flavored jet. This NN provides a tag that is independent of the SLT.
In this research the angular separation of two b-jets is discussed, and therefore two (independent) flavor taggers are needed. One jet is needed with an associated muon (the muon jet), to be able to perform the $p_T^{rel}$ fit. The SLT method is used to find this jet. To find the other jet (called the away jet from now on), the Neural Network tagger is used.

4.4.1 SLT

The SLT, or Soft Lepton Tagger, is based on the fact that B-hadrons decay to a muon with a branching ratio of $10.95\%$. The chance of a B-hadron to decay to a c-flavored hadron is almost 100\%, and for a c-flavored hadrons to decay to a muon $9.58\%$[20]. This means that almost 20\% of all jets containing b-flavor can be associated with a muon. As the chance of a lighter hadron to decay to a muon is much smaller, b and c jets can be identified by associating a muon with a jet.

The association of a muon to a jet is based on muon+jet kinematics, where different qualities, and hence different efficiencies, of the tagger are based on the quality of the muon. The kinematic cuts and quality demands on jet and muon are listed in table 4.3. These are the cuts of the med3 operating point of the SLT, which was used in this analysis. This operating point has an average efficiency in MC of 12.3\%. As explained in [16], a scale factor has to be applied to the efficiency of the SLT tagger when comparing data to MC, which in this case is 0.945.

4.4.2 NN-tagger

The other three taggers mentioned earlier, the SVT, JLIP and CSIP taggers, all use the long lifetime of the b-quark to distinguish it from lighter jets. All three taggers look at the lifetime in a different way, but all three provide useful, and to certain extend independent, information. The NN tagger contains an intelligent way to combine important variables from all three algorithms to get a better result.

The variables are combined by using them as input to a neural network, which is subsequently trained on MC samples of $b\bar{b}$, $c\bar{c}$ and $q\bar{q}$ events, to effectively recognize b-quark jets.

The variables used in the NN tagger are listed in table 4.4. A short explanation of each follows:

**SVT DLS** The decay length of the secondary vertex is defined as $|L| = |\vec{r}_{SV} - \vec{r}_{PV}|$ [17]. The vector $\vec{r}$ is defined as the distance from the beam in the plane perpendicular to the beam axis. The decay length significance is defined as $DLS = |L|/\sigma_L$. 

25
JLIP Prob  The JLIP tagger used the signed impact parameter (distance of closest approach to the PV) of tracks in a jet to determine the probability that the jet originates from the PV. The sign of the impact parameter is a ‘physics sign’: positive if the particle crosses the jet axis before the PV (as expected when it’s the product of a decay), negative if it crosses the jet axis behind the SV. Due to finite resolution, tracks of particles that do not originate from a decay are expected to have a symmetrical distribution of positive and negative IPs. Tracks in jets containing heavy flavor are expected to have an enhanced positive tail [18].

The negative part of the distribution of IPs from data can thus be used to determine the distribution of IPs from particles that do not originate from a decay. The probability that a particle originates from the PV based on its IP is then defined as the probability to find a particle with that IP according to this distribution. With the distribution given by $f(x)$:

$$P(IP) = \frac{\int_{-\infty}^{IP} f(x) dx}{\int_{-\infty}^{\infty} f(x) dx}$$

(4.1)

Combining the probabilities of all tracks within the cone of a jet gives the probability of the jet containing a decay vertex.

CSIP Comb  The CSIP tagger uses the same definition of the physics signed impact parameter. The impact parameter significance is defined as $IP/\sigma_{IP}$. The NN tagger uses a weighted combination of the tracks IP significances.

The rest of the variables should be clear from the table. More details of this procedure can be found in DØNotes [17, 18, 19, 21].

By setting a minimum value on the output of the neural net, the required combination of higher efficiency or lower fake rate can be chosen. For this research, the MEDIUM operating point was chosen.

In the DØNote [19] this operating point which corresponds to an average efficiency of about 60%, depending on jet $p_T$ and $\eta$.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SVT DLS</td>
<td>Decay Length Significance of the Secondary Vertex</td>
</tr>
<tr>
<td>CSIP Comb</td>
<td>Weighted combination of the track IP Significances</td>
</tr>
<tr>
<td>JLIP Prob</td>
<td>Probability that the jet originates from the PV</td>
</tr>
<tr>
<td>$\chi^2_{red}$</td>
<td>Chi Square per degree of freedom of the SV fit</td>
</tr>
<tr>
<td>SVT $N_{tracks}$</td>
<td>Number of tracks used to reconstruct the SV</td>
</tr>
<tr>
<td>SVT Mass</td>
<td>Mass of the SV</td>
</tr>
<tr>
<td>SVT Num</td>
<td>Number of SVs found in the jet</td>
</tr>
</tbody>
</table>

Table 4.4: Variables used as input for the NN.
### Table 4.5: MC dataset definitions used in this research

<table>
<thead>
<tr>
<th>Details</th>
<th>Nr. of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>QCD inclusive with $b + \mu$</td>
<td>53000</td>
</tr>
<tr>
<td>$Z/\gamma \rightarrow bb + \mu$</td>
<td>105750</td>
</tr>
<tr>
<td>$c \bar{c}$ samples for $p_T^{rel}$ templates</td>
<td></td>
</tr>
<tr>
<td>Details</td>
<td>Nr. of events</td>
</tr>
<tr>
<td>$Z/\gamma \rightarrow cc + \mu$</td>
<td>107750</td>
</tr>
</tbody>
</table>

#### 4.5 Data event selection

The data in this sample was reconstructed using the p17.09.03 version of the d0reco package. Only events from the BID subskim were used. This skim stores data with one medium quality, $|nseg| = 3$ muon associated with a jet within a radius of 0.7 in $(\eta, \phi)$. The event must contain a jet with an $E_T$ of at least 10 GeV.

This analysis looks at the separation in $\phi$ of two $b$-flavored jets, so obviously only events containing at least two jets are allowed. These jets need to pass the quality cuts as recommended by the jetID group, which are listed in table 3.2 [7].

By requiring one jet to be associated with a muon of certain quality (Soft Lepton Tag), the fraction of jets in a tagged sample carrying $b$-flavor as opposed to $c$-flavor can be determined using the $p_T^{rel}$-fitting method, see section 4.3. The other jet in the event then has to be tagged with the NN tagger, which is independent of the SLT. Events where more than two jets are tagged are discarded, to avoid having to choose which tagged jets are correlated. These events comprise 1.3% of the entire dataset.

#### 4.6 Monte Carlo and $p_T^{rel}$ templates

The Monte Carlo simulations used in this analysis use algorithms based on random numbers to perform the complicated integrals that are dictated by the Field Theory that describes subatomic reactions. Besides calculating the matrix elements (as given by the Feynman diagrams in section 2.1), jet formation and the detector response to the reaction is also simulated. This produces a sample with (in principle) the same numbers as if it were real output from the detector. This allows the experimenter to compare the detector response that he recorded with the response he expects from theory.

In order to get enough statistics in MC, several datasets were used. They are listed in table 4.5. To create the required distributions, first one jet with an associated muon is required. The SLT tagging software is used for this, with the
same cuts as in table 4.3. The same cuts on jet and muon quality are required as in data. The event is weighted with the chance that the event would have satisfied the trigger conditions of the triggers listed in table 4.1. One must take into account that three different triggers were used for three different subsets of the data. The total event weight is calculated as:

$$W_{tot} = \frac{1}{L_{tot}} \sum_i P_i L_i$$  \hspace{1cm} (4.2)

Where \(P_i\) is the chance that trigger \(i\) fired for the event, and \(L_i\) the total luminosity recorded with that trigger. This way properly weighted \(p_T^{rel}\) distributions are created. The distributions are all simultaneously fit to the data, with the relative fraction of the two \(b\)-samples fixed by the ratio of the cross section of the simulated production processes, and the sum of all fractions fixed to 1.
Chapter 5

Results

The goal of this analysis is to obtain a distribution of angular separation between two $b$-jets. In the first section the data is presented after the event selection and $b$-tagging has been performed. With that data, $p_T^{rel}$ fits are performed to determine the fraction of $b$-jets in this sample in bins of $E_T$ and $\Delta \phi$. The result of these fits are presented in the second section of this chapter. The last section will show the $\Delta \phi$ distribution and compare it to previous results.

5.1 Data and MC distributions

The distributions of the data are shown as a function of for variables, $E_{T}^{\text{mujet}}$, $p_T^{rel}$, $\Delta \phi$ and $p_T^{\mu}$ in figures 5.1 to 5.4. The statistical errors (vertical error bars, horizontal error bars indicate the bin width) are shown in these plots, but are mostly too small to be seen.
Figure 5.3: $\Delta \phi$-distribution of the complete dataset

Figure 5.4: $p_T^{\mu}$-distribution of the complete dataset

The same distributions can also be made for the MC samples, except for $\Delta \phi$ as no attempt is made to tag an away jet in MC. These are shown in figures 5.5 to 5.13.

One feature of these plots that needs attention is the difference in shape of the $E_T^{\text{mujet}}$ distribution of the data (figure 5.1) and that of the QCD inclusive MC sample (figure 5.5). If no weights for the trigger efficiency are applied, the energy distribution of the muon jets in the MC sample is much steeper than in data, because the data has been triggered by a trigger that only becomes efficient at higher $E_T$. However, after applying the correction, the MC simulated distribution is significantly flatter than the one that was obtained from data. The same can be said for the $p_T^{\mu}$ distribution, which might be more harmful to the final result, as the fits are done unbinned in $p_T^{\mu}$.

Figure 5.2 shows a rather soft $p_T^{\text{rel}}$ distribution in data, indicating that there is still a large number of $c$ and lighter jets in the sample. Indeed, $p_T^{\text{rel}}$ fits estimate a $b$ fraction in data of about 50%.

### 5.2 $p_T^{\text{rel}}$ fits

In this analysis the fits of $p_T^{\text{rel}}$ were done in 5 bins of $E_T^{\text{mujet}}$ and 18 bins in $\Delta \phi$. The results of all $p_T^{\text{rel}}$ fits are shown in the appendix. Figure 5.14 shows, as an example, a fit done on unbinned data. The points with error bars are the data points. The dotted line is the MC prediction for the $c$-quark content of the sample, the dashed line is the prediction for the $b$-quark content. The solid line is the total MC prediction. The MC $p_T^{\text{rel}}$ distributions as shown in these plots are the predictions after the content of each bin was fluctuated within its statistical errors to better fit the data.
The $\chi^2$ that is given in the plot is calculated from the likelihood ratio:

$$\lambda = L(y; n)/L(m; n)$$

(5.1)

where $L(y; n)$ is the likelihood of the MC prediction $y$ describing the data $n$. The variable $m$ indicates the ‘true’ result, which is unknown. Instead, for the $\chi^2$ calculation the data set $n$ is used. The $\chi^2$ is given by:

$$\chi^2 = -2 \ln(\lambda)$$

(5.2)

This variable follows a $\chi^2$ distribution [14, 22]. The reduced $\chi^2$ is given by:

$$\chi^2_{\text{red}} = \chi^2/NDF$$

(5.3)

with NDF the number of degrees of freedom in the fit. An indication of a good fit is a $\chi^2_{\text{red}}$ that is close to 1. The value of $\chi^2_{\text{red}}$ of this fit is rather high, due to the very small errors in this plot. There will be extra sources of error from systematics that have not been included yet, however as the fit improves when binning in $E_T$, as can be seen in the plots in the appendix, it is also possible that the discrepancy here is due to a poor simulation of the $E_T$ and $\Delta \phi$ distributions in MC.

### 5.3 $\Delta \phi$ distribution

From the fitted fraction of $b$-jets as they are given in the appendix the total number of $b\bar{b}$ jet pairs in each of the 18 bins in $\Delta \phi$ can be determined. The resulting $\Delta \phi$ distributions, in 5 bins of $E_T$ with $20 < E_T < 70$, are shown in figure 5.15. A fit to the data unbinned in $E_T$ is compared to the previous result in B. Wijngaarden [3] in figure 5.16.

Uncertainties in these $\Delta \phi$ distributions are much smaller than those of the previous analysis, which is due to a bigger dataset and higher tagging efficiency. The errors shown in figures 5.15 and 5.16 are the quadratic sum of the statistical error in the data and the error in the $p_T^{\text{jet}}$ fraction fit. The total error is dominated by the statistical error in the MC simulation.

Except for the one data point at $\Delta \phi = 0.6$ the agreement between the new and the old data is good. The bump at small separation angle that was already there in the old data has become more significant with the better statistics. From figure 5.15 it can be seen that it is most pronounced at low $E_T$. The lower or higher bump at small $\Delta \phi$ is an indication of less or more contribution from the gluon splitting diagrams.
Figure 5.5: $E_T^{\text{mujet}}$-distribution QCD inclusive with $b + \mu$ dataset

Figure 5.6: $p_T^{\text{rel}}$-distribution QCD inclusive with $b + \mu$ dataset

Figure 5.7: $p_T^{\mu}$-distribution QCD inclusive with $b + \mu$ dataset

Figure 5.8: $E_T^{\text{mujet}}$-distribution $Z \to b\bar{b}$ dataset
Figure 5.9: $p_T^{rel}$-distribution $Z \rightarrow b\bar{b}$ dataset

Figure 5.10: $p_T^{\mu}$-distribution $Z \rightarrow b\bar{b}$ dataset

Figure 5.11: $E_T^{mujet}$-distribution $Z \rightarrow c\bar{c}$ dataset

Figure 5.12: $p_T^{rel}$-distribution $Z \rightarrow c\bar{c}$ dataset
Figure 5.13: $p_T^µ$-distribution $Z \to c\bar{c}$ dataset
Figure 5.14: Template fit to the unbinned dataset
Figure 5.15: \( \Delta \phi \) distributions of the data in 5 bins in \( E_T \). The last plot shows the result of adding all distributions in the five \( E_T \) bins.
Figure 5.16: Comparing the result of a fit that is not binned in $E_T$, the shape of the $\Delta \phi$ distribution is comparable from the one found by B. Wijngaarden. See figure 7.4 in his thesis [3], which was copied here. The circles and error bars are Wijngaarden’s results, the points with thinner error bars are the results of this analysis.
Chapter 6

Conclusions

The Δφ distribution presented in this analysis, gives a significant improvement in statistical uncertainty over the final result of B. Wijngaarden’s research. By fitting $p_T^{rel}$ distributions in bins of Δφ and $E_T$, a more accurate estimate of the importance of the higher order processes in $b\bar{b}$ production can be made.

However, before final conclusions can be made, there are still some issues that need to be addressed. Here are a few.

$p_T^\mu$ dependence of $p_T^{rel}$ distribution The $p_T^{rel}$ distributions were fitted in bins of $E_T^{mujet}$ and Δφ only, in order to preserve MC statistics. The $p_T^{rel}$ variable is independent of boosts along the B hadron momentum axis, and approximately independent of boosts along the $\mu$+jet axis and $p_T^\mu$. However, the extra uncertainty integrating over $p_T^\mu$ introduces should be determined.

JES correction Uncertainties in the Jet Energy Scale correction have gone down since B. Wijngaarden’s results were published, but it is a source of systematic error that should be investigated.

The $E_T$ of the jets in this analysis was not corrected for the muon that is present in the tagged jets. This means the muon jet energy was systematically measured too low. The correction for this effect was not available yet, but will have to be applied to get a more reliable result from this analysis.

Jet and Muon identification There could be a difference between the identification of muons and jets in MC and data. It is not clear how much this difference might influence the result of this analysis, but it should be investigated.

Jet trigger efficiency As stated in the previous chapter, the weights applied to MC events do not lead to a similar distribution in $E_T$ of the muon jets in MC and Data. Rather, the weighting seems to overcompensate for the trigger efficiency at low $E_T$. The efficiency measurement and event weight calculation
should be studied in more detail. Also the statistical uncertainty in the efficiencies needs to be taken into account.

As the jet trigger efficiency is practically zero for low $E_T$ jets, the jets in the low part of the distribution must come from events triggered by a second, high $E_T$ jet. If in MC the energy distribution over jets in one event is somehow different, this might explain the flatter $E_T$ distribution found in MC.

Fake away tags in $\Delta \phi$ distribution In principle, this way of determining the b-jet content only looks at the fraction of muon jets (SLT tagged jets) that originate from a b-quark. The away jet, tagged by the NN, still could be a background jet that was fake tagged.

In his thesis B. Wijngaarden looked at the effect of this possibility of fake tagged away jets in the $\Delta \phi$ distribution, and found a fake fraction after $p_T^{\text{rel}}$ fitting of $(0.4 \pm 0.6\%)$. This source of uncertainty was not investigated here. As this analysis uses a different tagger, the calculation of the away jet fake rate should be redone, and taken into account when comparing data to theory. As the NN tagger is more powerful than the JLIP algorithm used by Wijngaarden, with a reduction in fake rate by a factor of $\sim 3$ for a fixed efficiency, the number of fakes in the final sample is expected to be much smaller.

MC statistics The uncertainty in the fit is now dominated by MC statistics. It would be very useful to try and get more MC events, both for the $p_T^{\text{rel}}$ template fitting and for the creation of $\Delta \phi$ distributions.

Comparison to theory With a $\Delta \phi$ distribution that is much more accurate than previous results, it is interesting to see what will come out of a comparison with higher order processes in MC. The bump at low $\Delta \phi$ hints at a higher contribution of gluon splitting events compared to what was found by Wijngaarden, indicating a shift in fractions in the direction of the input of PYTHIA. However, a MC simulations are needed to quantify this statement. Also a comparison of the total $\Delta \phi$ distribution with MC@NLO would be interesting.

Finally, by normalizing the data to the total integrated luminosity a new measurement of the $b$-jet cross section can give a more stringent test of the theoretical prediction of the $b\bar{b}$-jet production cross section.
Acknowledgments

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Bibliography


Appendix: Binned $p_{T}^{rel}$ Fit results

In this appendix the results of the $p_{T}^{rel}$ fits are shown. Each plot has the bin numbers in the top left corner, in the title of the histogram. The bin size in $E_{T}$ is 10 GeV. $E_{T}$ ranges from 20 GeV to 70 GeV. The bin size in $\Delta \phi$ is $\pi/18$, ranging from $0 - \pi$. 
Figure 1: Results of $p_T^{rel}$ fits, for $20 < E_T < 30$, and each fit made in one bin of $\Delta \phi$. The width of one $\Delta \phi$ bin is $\pi/18$, starting with $\Delta \phi = 0$ in the left upper and $\Delta \phi = \frac{1}{2} \pi$ in the right lower plot.
Figure 2: Results of $p_T^{el}$ fits, for $20 < E_T < 30$, and each fit made in one bin of $\Delta \phi$. The width of one $\Delta \phi$ bin is $\pi/18$, starting with $\Delta \phi = \frac{1}{2} \pi$ in the left upper plot and $\Delta \phi = \pi$ in the right lower plot.
### Figure 3: Results of $p_T^{rel}$ fits, for $30 < E_T < 40$, and each fit made in one bin of $\Delta \phi$. The width of one $\Delta \phi$ bin is $\pi/18$, starting with $\Delta \phi = 0$ in the left upper and $\Delta \phi = \frac{1}{2}\pi$ in the right lower plot.
Figure 4: Results of $p_T^{rel}$ fits, for $30 < E_T < 40$, and each fit made in one bin of $\Delta \phi$. The width of one $\Delta \phi$ bin is $\pi/18$, starting with $\Delta \phi = \frac{1}{2} \pi$ in the left upper and $\Delta \phi = \pi$ in the right lower plot.
Figure 5: Results of $p_T^{rel}$ fits, for $40 < E_T < 50$, and each fit made in one bin of $\Delta \phi$. The width of one $\Delta \phi$ bin is $\pi/18$, starting with $\Delta \phi = 0$ in the left upper and $\Delta \phi = \pi/2$ in the right lower plot.
Figure 6: Results of $p_T^{jet}$ fits, for $40 < E_T < 50$, and each fit made in one bin of $\Delta \phi$. The width of one $\Delta \phi$ bin is $\pi/18$, starting with $\Delta \phi = \frac{1}{2} \pi$ in the left upper and $\Delta \phi = \pi$ in the right lower plot.
Figure 7: Results of $p_T^{rel}$ fits, for $50 < E_T < 60$, and each fit made in one bin of $\Delta\phi$. The width of one $\Delta\phi$ bin is $\pi/18$, starting with $\Delta\phi = 0$ in the left upper and $\Delta\phi = \frac{1}{2}\pi$ in the right lower plot.
Figure 8: Results of $p_T^{el}$ fits, for $50 < E_T < 60$, and each fit made in one bin of $\Delta \phi$. The width of one $\Delta \phi$ bin is $\pi/18$, starting with $\Delta \phi = \frac{1}{2}\pi$ in the left upper and $\Delta \phi = \pi$ in the right lower plot.
Figure 9: Results of $p_T^{rel}$ fits, for $60 < E_T < 70$, and each fit made in one bin of $\Delta \phi$. The width of one $\Delta \phi$ bin is $\pi/18$, starting with $\Delta \phi = 0$ in the left upper and $\Delta \phi = \frac{1}{2} \pi$ in the right lower plot.
Figure 10: Results of \( p_T^{rel} \) fits, for \( 60 < E_T < 70 \), and each fit made in one bin of \( \Delta \phi \). The width of one \( \Delta \phi \) bin is \( \pi/18 \), starting with \( \Delta \phi = \frac{1}{2} \pi \) in the left upper and \( \Delta \phi = \pi \) in the right lower plot.