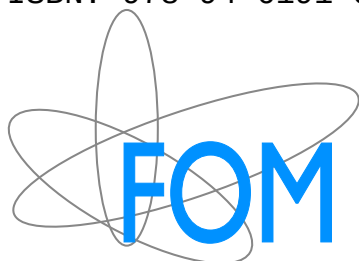


Unfolding single-particle efficiencies and the Outer Tracker in LHCb

Fabian Jansen

Cover by Patrick Jansen (www.patrickjansen.net)
Printed by Ipskamp Drukkers
Copyright 2011 by F.M.Jansen, all rights reserved
ISBN: 978-94-6191-096-7



This work is part of the research programme of the Foundation for Fundamental Research on Matter (FOM), which is part of the Netherlands Organisation for Scientific Research (NWO).

VRIJE UNIVERSITEIT

Unfolding single-particle efficiencies and the Outer Tracker in LHCb

ACADEMISCH PROEFSCHRIFT

ter verkrijging van de graad Doctor aan
de Vrije Universiteit Amsterdam,
op gezag van de rector magnificus
prof.dr. L.M. Bouter,
in het openbaar te verdedigen
ten overstaan van de promotiecommissie
van de faculteit der Exacte Wetenschappen
op vrijdag 16 december 2011 om 9.45 uur
in de aula van de universiteit,
De Boelelaan 1105

door

Fabian Jansen

geboren te Dalfsen

promotor: prof.dr. M.H.M. Merk
copromotoren: dr. N. Tuning
 dr. A. Pellegrino

voor mama

Table of contents

Introduction	1
I The Outer Tracker detector in LHC<i>b</i>	3
1 The LHC<i>b</i> experiment	5
1.1 Tracking detectors	5
1.2 Particle identification	9
1.3 The trigger	11
2 The Outer Tracker	13
2.1 A straw-tube detector	13
2.2 The Outer Tracker Front End electronics	18
3 Outer Tracker module installation	23
3.1 Quality assurance during module installation	23
3.2 Detector response with a ^{55}Fe source	25
3.2.1 The ^{55}Fe Test	25
3.2.2 ^{55}Fe Test results	27
4 Outer Tracker Front End electronics quality assurance	31
4.1 Front End Tester	31
4.1.1 Threshold characteristics	33
4.1.2 Time linearity check	37
4.1.3 Synchronization	39
4.1.4 Noise pickup	40
4.2 OTIS Differential Non-Linearity	41
4.2.1 DNL from dedicated tests	44
4.2.2 DNL from OTIS Tester	49
4.2.3 DNL from noise scans	52
4.2.4 DNL conclusion	52
II Single-particle efficiencies from multi-body processes	55
5 Motivation	57

6	Unfolding single-particle efficiencies	61
6.1	Introductory discussion	61
6.2	Unfolding single-particle efficiencies	62
6.2.1	Folded efficiencies	62
6.2.2	Unfolding efficiencies	63
6.2.3	The iteration implementation	66
6.2.4	Efficiency scale invariance	68
6.3	Validation of the iterative method	68
6.3.1	Iterative results	69
6.3.2	Statistical error	71
6.3.3	Non-factorisable effects	77
6.4	Correcting the angular distributions in $B_d \rightarrow \mu^+ \mu^- K^*$	77
6.4.1	Event samples	78
6.4.2	The reweighting procedure	78
6.4.3	Results	81
6.5	Conclusion	82
7	Single-particle asymmetries from charm decays	89
7.1	Charm decays in 2010 data	90
7.1.1	Trigger and event selection	90
7.1.2	Signal and background estimation	91
7.1.3	Momentum distributions	93
7.2	The $K^{+/-}$ detection efficiency asymmetry	98
7.2.1	Asymmetry extraction	98
7.2.2	Non-factorisable effects	100
7.2.3	The $K^{+/-}$ efficiency asymmetry from data	104
7.3	Asymmetries in $D^0/\bar{D}^0 \rightarrow K^{-/+} \pi^{+/-}$ decays	110
7.3.1	Asymmetry extraction	110
7.3.2	Asymmetry from $D^0/\bar{D}^0 \rightarrow K^\mp \pi^\pm$ data	112
7.4	Conclusion	124
A	Iteration scale convergence	127
B	Closest single-particle projections	129
B.1	A least-squares approximation	130
B.2	Corollary: successive improvements	132
	Bibliography	134
	Summary	139
	Populaire samenvatting	141
	Acknowledgments	145

Introduction

After some forty years and despite various indications for new physics, the Standard Model is still the authoritative theory of elementary particles and their interactions. With great success it describes the fundamental, quantum behavior of the smallest elements that are found in nature. However, the Standard Model cannot be the conclusive theory of elementary particles. Among others it omits gravity as a fundamental force, does not account for dark matter and fails to explain the dominance of matter over anti-matter in the universe.

The $LHCb$ experiment is one of the four main experiments at the LHC at CERN that will test the limits of the Standard Model. The experiment uses a detector that is tailored for the study of flavor physics, which makes it optimally suited to study some of the most prominent research topics in High Energy Physics: the origin of the Charge-Parity asymmetry in nature, believed to be a necessary condition for matter over anti-matter dominance, and the search for physics beyond the Standard Model in the rare decays of B hadrons.

One of the key measurements of the $LHCb$ experiment is the rare decay $B_d \rightarrow \mu^+ \mu^- K^*$. New physics can significantly alter the angular distributions in this decay from their Standard Model predictions. However, experimental inefficiencies may also affect the angular distributions, and it is thus essential to correct for the influence of efficiencies if new physics is to be searched for in this channel.

The $LHCb$ detector globally consists of charged particle tracking detectors and particle identification systems. The Outer Tracker subdetector is part of the $LHCb$ tracking system, responsible for measuring deflected particle tracks in the larger, lower occupancy part of the detector acceptance. It is a gaseous detector composed of 53k long, thin straw tubes, designed and built to detect charged particles with a precision of $200 \mu\text{m}$ and near to 100% efficiency. The straws are situated in detector modules and are read out by dedicated Front End electronics.

The Outer Tracker was installed in the $LHCb$ detector in 2007, and the mass production of over 400 Front End electronics boxes was finished in 2008.

A first part of this manuscript focuses on the Outer Tracker subdetector. Just prior to its installation in the $LHCb$ detector, the Outer Tracker detector modules and support frames were once more tested in situ for their functioning within specifications. The tests and their results are described, with emphasis on an individual response test of nearly half of the 53k straw tubes.

Furthermore, fully assembled Front End electronics boxes were subjected to a series

of quality control tests. The various tests are described and the electronics intrinsic Differential Non-Linearity is examined in detail.

A second part of the manuscript develops a method that iteratively determines the efficiencies with which individual particles are measured from a well known multi-body process. Development of the method is motivated by the search for new physics in the angular distributions of the rare decay $B_d \rightarrow \mu^+ \mu^- K^*$, where the efficiencies of the outgoing particles can be determined from the Standard Model dominated control channel $B_d \rightarrow J/\psi K^*$.

The method is developed and is validated in fast simulation studies, while the efficiency correction of the angular distributions is performed on full Monte Carlo simulation.

Finally the generic nature of the method is exploited with October 2010 LHCb measurements of the charm meson decays $D^0/\bar{D}^0 \rightarrow K^+ K^-$ and $D^0/\bar{D}^0 \rightarrow K^\mp \pi^\pm$. In a completely data-driven way the momentum dependencies of the $K^{+/-}$ and $\pi^{+/-}$ detection efficiency asymmetries are determined, as well as a momentum dependence of the asymmetry between the D^0 and $\bar{D}^0$ differential production cross sections.

Part I

The Outer Tracker detector in LHC*b*

Chapter 1

The LHC*b* experiment

The Large Hadron Collider beauty experiment (LHC*b*) is one of the four major experiments at the Large Hadron Collider (LHC) at CERN next to the ALICE, ATLAS and CMS experiments. The LHC*b* experiment is specifically designed for the precise measurement of beauty-hadron decays and thereby tailored for the search for physics beyond the Standard Model in CP violation and the rare decays of B hadrons.

The LHC (Ref.[1]), a proton-proton collider with a 27 km circumference, has been designed to provide collisions at an unprecedented 14 TeV center-of-mass energy, at a luminosity of $10^{34} \text{ cm}^2\text{s}^{-1}$ and with a 40 MHz bunch crossing rate. The machine had commenced operation toward the end of 2008, but suffered an accident that caused a full year delay. Since its restart at a moderate 900 GeV center-of-mass energy in November 2009, the machine has achieved a world record breaking 7 TeV center-of-mass energy in 2010, which is the foreseen collision energy for physics studies during the 2011 physics run.

In inelastic proton-proton collisions, B and anti- B hadrons are preferably produced in a narrow forward or backward cone, i.e. with small angles with respect to the proton beams. For this reason the LHC*b* detector has been built as a one-arm forward spectrometer, with an angular coverage of 15-300 mrad in the horizontal (bending) plane and 15-250 mrad in the vertical (non-bending) plane. Fig.1.1 shows a side view of the detector. An extensive description of the LHC*b* experiment can be found in Ref.[2].

Contrary to the other experiments, LHC*b* operates at a lower luminosity of $2\text{--}5 \times 10^{32} \text{ cm}^2\text{s}^{-1}$. This choice has been made to reduce the number of pile-up events, i.e. events with multiple proton-proton collision per bunch crossing and with too many particles in the detector acceptance. However, during the 2009-2010 period no luminosity restrictions were placed.

1.1 Tracking detectors

To determine charged particle momenta the detector includes a warm dipole magnet with two possible polarities. The magnetic field points either upward (in the positive y direction), or downward (in the negative y direction), which are denoted as the Magnet

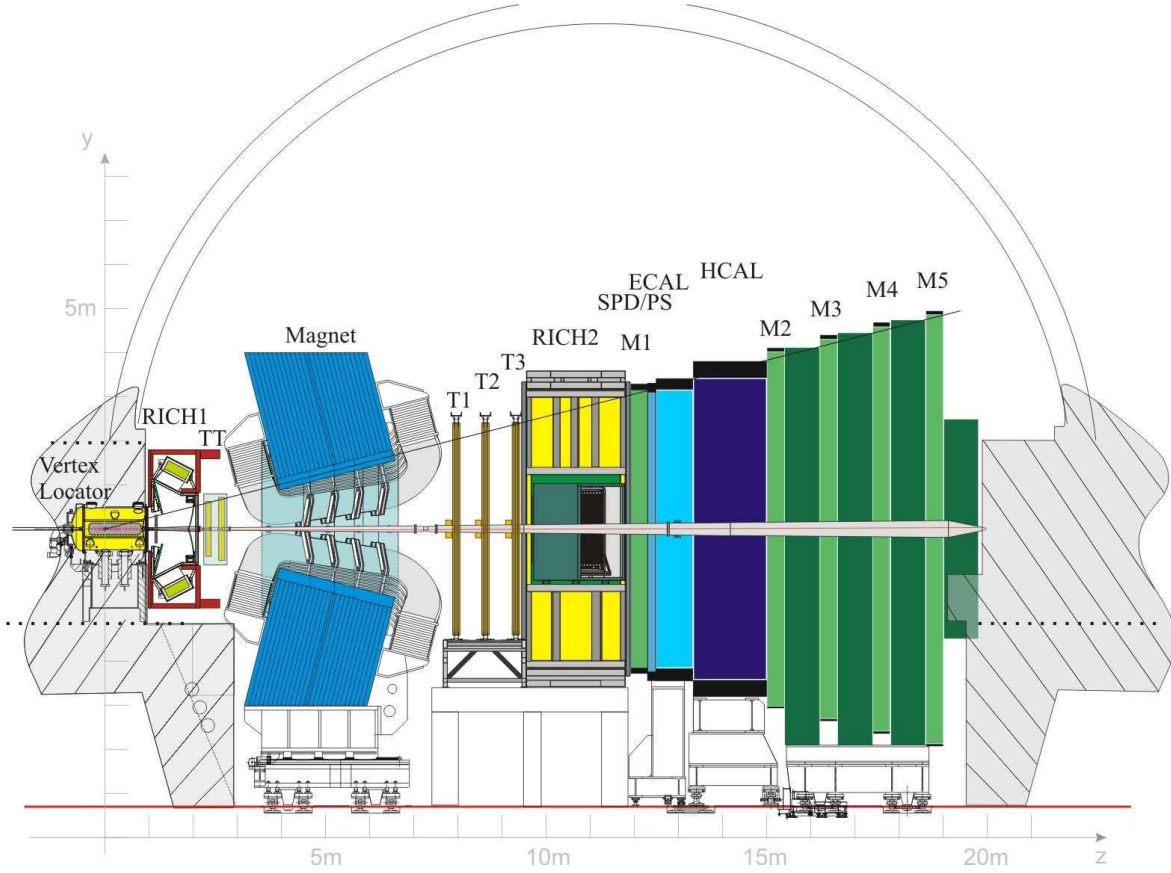


Figure 1.1: *The LHCb detector, side view.*

Up and Magnet Down configurations respectively. The magnet provides an integrated field of about 4 Tm corresponding to a transverse momentum kick of around 1.2 GeV in the horizontal plane.

Particle tracks are determined with the VELO detector and the Tracker Turicensis before (upstream of) the magnet and the Inner and Outer Tracker after (downstream of) the magnet.

The Vertex Locator

The Vertex Locator (VELO) justifies its name as the foremost subdetector in the precise determination of primary and secondary vertices. It is built around the collision region and detects particles with 300 μm thick silicon strip sensors, that are either r or ϕ sensors as shown in Fig.1.2(a), measuring the radial and azimuthal coordinates of tracks respectively.

The sensors are placed on either side along the beam over a length of approximately 1 m, such that tracks can be reconstructed with a polar angle down to 15 mrad. RF-boxes on either side house the sensors and maintain a vacuum that is separated from the machine vacuum by a thin corrugated aluminium sheet. The sensors and inner

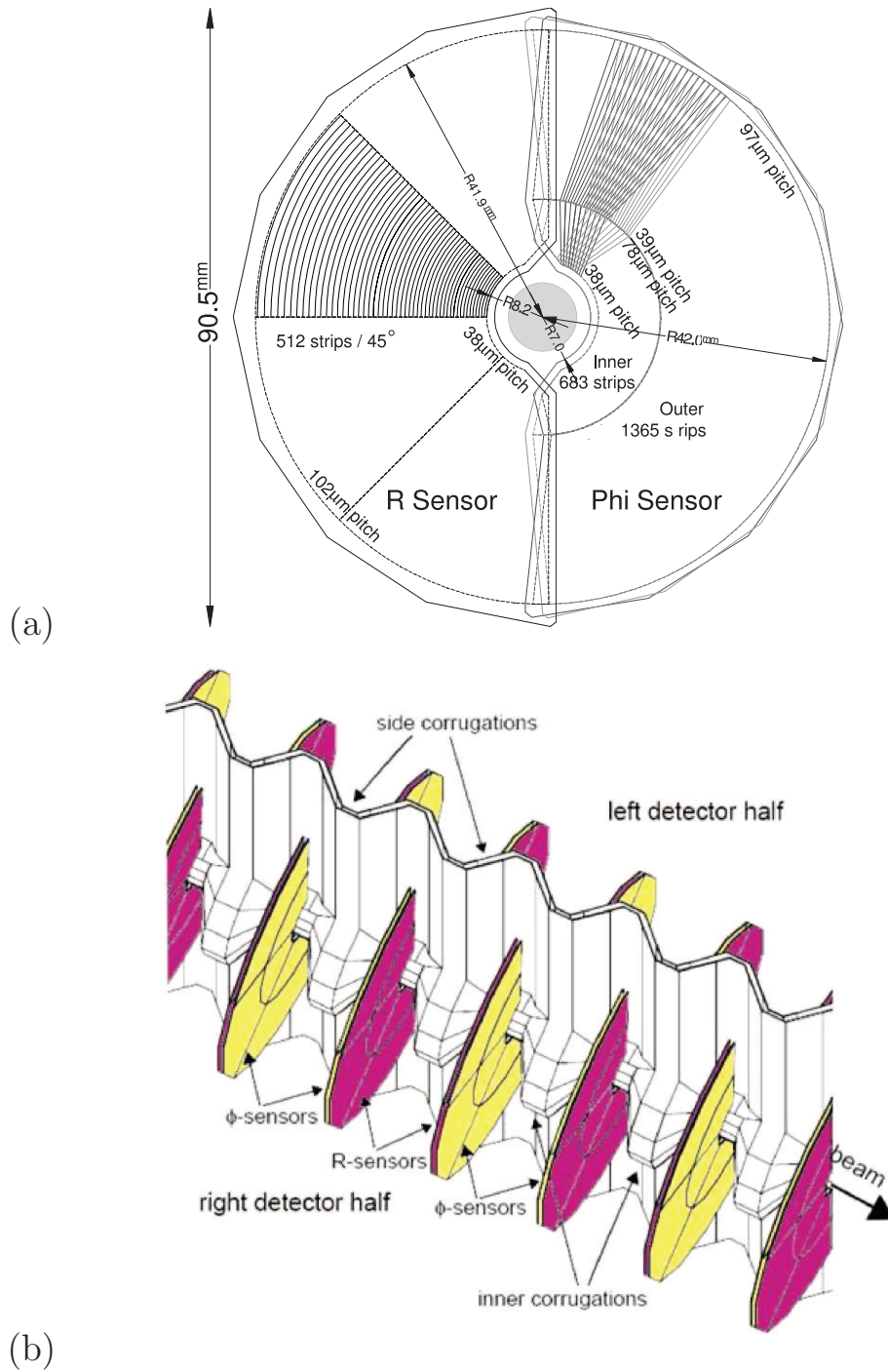


Figure 1.2: (a) The Velo r sensor (left) and ϕ sensor (right). (b) The Velo sensors separated by the RF-foils.

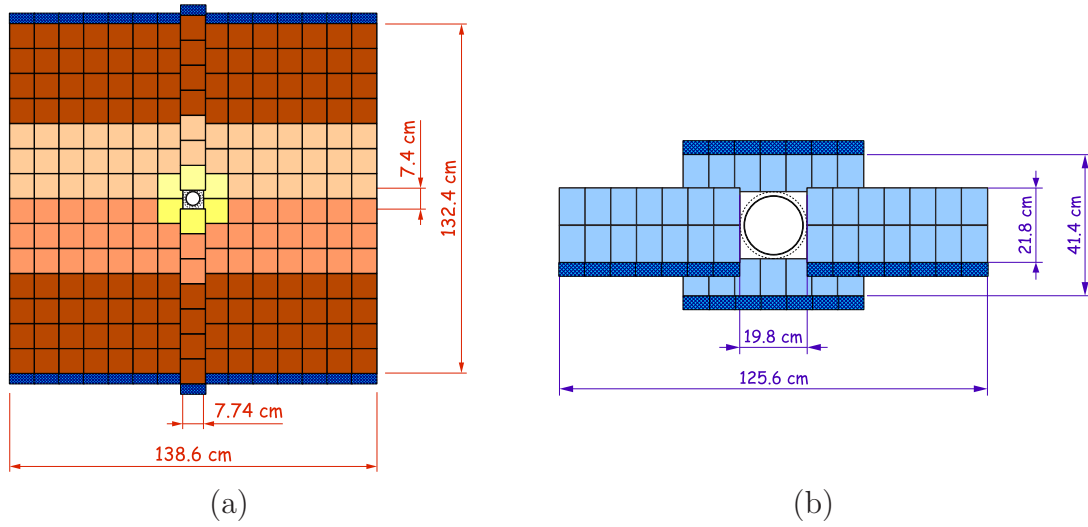


Figure 1.3: (a) Front view of a TT x layer. Different readout sectors are indicated by different shadings. (b) Front view of an IT x layer. The dark areas are readout electronics, the light areas the silicon ladders.

faces of the RF-foils are shown in Fig.1.2(b).

To obtain a high precision on reconstructed primary and secondary vertex positions, the sensors are placed as close as possible to the incoming proton beams, at approximately 8 mm from the beam axis during stable running, but they are retracted from the beam during injection. The hit resolution of the sensors ranges from approximately $8\text{ }\mu\text{m}$ at their inner region to $20\text{ }\mu\text{m}$ at their outer region.

The Tracker Turicensis

The Tracker Turicensis (TT) and the Inner Tracker (IT) have been developed in a joint Silicon Tracker (ST) project. The Tracker Turicensis is located just in front of the magnet, while the Inner Tracker together with the Outer Tracker make up the tracking stations downstream of the magnet.

The TT covers the full LHCb acceptance and consists of four detection layers of $500\text{ }\mu\text{m}$ thick silicon strip sensors in a x - u - v - x stereo view, meaning that the strips make an angle of 0° , -5° , 5° and 0° with the vertical axis respectively. Fig.1.3(a) shows an x type layer. The sensors are 96.4 mm wide and 94.4 mm long and contain 512 readout strips each, which provide a spatial resolution of about $50\text{ }\mu\text{m}$.

The Inner Tracker

Downstream of the LHCb magnet particle tracks are measured by three tracking stations called T-stations. In every station the larger outside part of the geometrical acceptance is covered by the gaseous, straw tubes based Outer Tracker (OT). In the inner region of the acceptance, directly around the beam, the particle flux is too dense

for a gaseous detector and this region is covered by the Inner Tracker.

Each Inner Tracker station consists of four cross-shaped layers of silicon strip sensors in a x - u - v - x stereo view. An x type layer is shown in Fig.1.3(b). The top and bottom sensors are $310\text{ }\mu\text{m}$ thick, the left and right sensors $410\text{ }\mu\text{m}$ thick and every sensor is 76 mm wide, 110 mm long and contains 384 readout strips, providing a resolution of approximately $60\text{ }\mu\text{m}$.

The Outer Tracker

The Outer Tracker is built using 53k gaseous straw tubes of approximately 5 mm diameter and 2.5 m length. Each of the three T-stations consists of four layers of Outer Tracker modules in the same x - u - v - x stereo view as the TT and IT, where each module contains two staggered layers of straw tubes. The Outer Tracker is described in detail in Ch.2.

1.2 Particle identification

To determine the types of the final state particles produced in an event, the LHC***b*** experiment uses two ring imaging Cerenkov detectors, a calorimeter system and a muon detector.

The Ring Imaging Cerenkov detectors

The Ring Imaging Cerenkov detectors (RICH1 and RICH2) are primarily used to distinguish between charged kaons and pions. The RICH1 is located upstream of the magnet, between the VELO and the TT, while the RICH2 is located downstream of the magnet following the T-stations. Schematic overviews of the two RICH detectors are shown in Fig.1.4.

The RICH1 covers a polar angle acceptance down to 25 mrad and has been designed to identify particles with momenta in the range $1\text{--}60\text{ GeV}$ by using aerogel and C_4F_{10} as radiators. The RICH2 on the other hand covers an acceptance up to $120(100)\text{ mrad}$ in the horizontal(vertical) plane and identifies particles in the momentum range $15\text{--}100\text{ GeV}$ using CF_4 .

The calorimeters

The Calorimeter system is situated behind the RICH2, between muon stations M1 and M2 and consists in downstream order of a scintillator pad detector (SPD), a preshower detector (PS), an electromagnetic calorimeter (ECAL) and a hadronic calorimeter (HCAL).

The ECAL has been designed to fully contain showers of electrons and photons. It has been built in a shashlick way with alternating layers of 4 mm scintillator material and 2 mm lead perpendicular to the beam axis. The HCAL thereafter absorbs the energy of remaining hadrons with 3 mm scintillator and 10 mm iron oriented parallel to the beam.

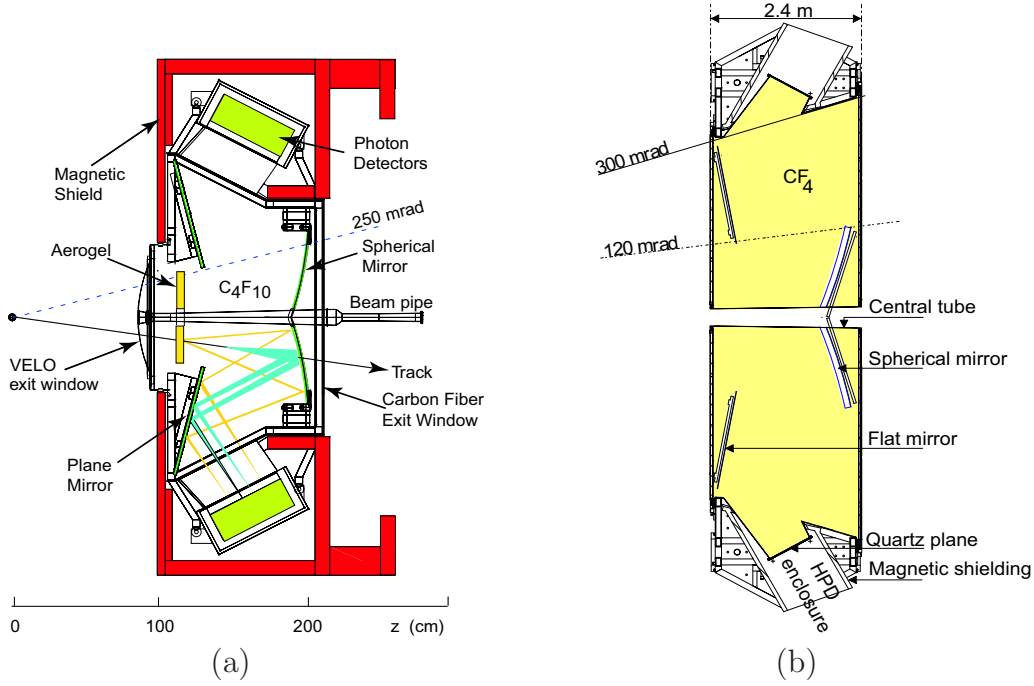


Figure 1.4: Schematic overview of the RICH detectors. (a) Side view of the RICH1. (b) Top view of the RICH2.

In order not to have too large variations in particle densities, the ECAL and HCAL have been segmented with smaller cell sizes closer to the beam. The ECAL has been divided in three regions, an $x \times y = 65 \times 65$ cm inner region, a 194×145 cm middle region and a 388×242 cm outer region with 4 cm, 6 cm and 12 cm square cells respectively. The HCAL has two divisions of 210×184 cm and 420×341 cm with 13 cm and 26 cm square cells.

The SPD and PS have both been built from 15 mm thick scintillator material and have a 15 mm lead sheet in between them as a shower initiator. The SPD detects charged particles and in conjunction with the ECAL is used to separate electrons and photons. The PS on the other hand is used to separate electrons and photons from light hadrons.

The muon spectrometer

The muon spectrometer is drawn in Fig.1.5. It is composed of five stations (M1-M5). Station M1 is situated in front of the calorimeter system, while M2-M5 follow the calorimeter and are interlaced with 80 cm iron absorbers. Station M1 is used to measure the transverse momentum in the Level-0 trigger.

All stations are divided into four regions, with decreasing granularity when moving away from the beam line. Additionally the granularity decreasing from station to station when moving downstream. The dimensions of the regions as well as their granularity scale according to 1:2:4:8, for which the occupancy over the detector surface is roughly constant.

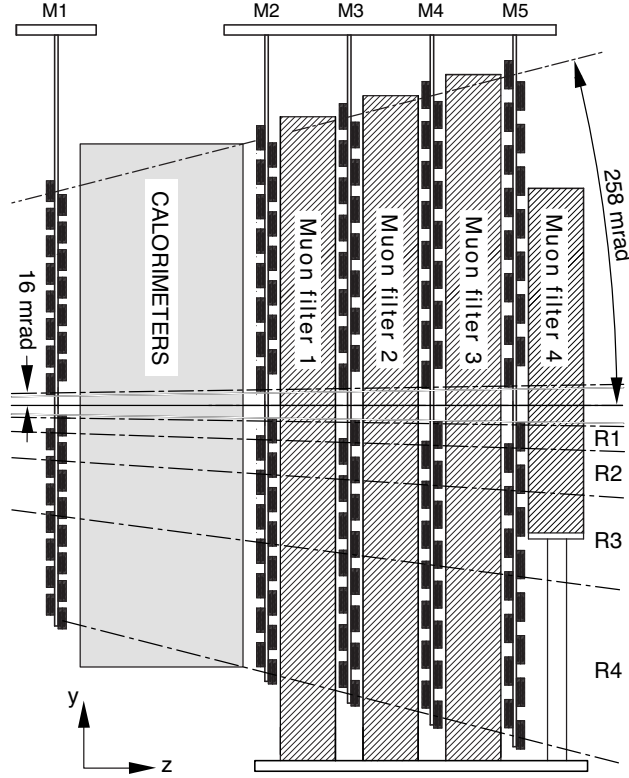


Figure 1.5: Setup of the muon spectrometer.

All stations consist of multi-wire proportional chamber, except for the inner most region of station M1, which due to the high particle flux is composed of triple-GEM detectors.

1.3 The trigger

The LHCb trigger system consists of three stages. The first is the Level-0 hardware trigger (L0). Following are two C++ based triggers running on the Event Filter Farm: High Level Trigger 1 (Hlt1) and High Level Trigger 2 (Hlt2).

The L0 trigger reduces the 40 MHz bunch crossing rate to 1 MHz. It searches for muons or muon pairs in the muon spectrometer with high transverse momentum, or for particles (electrons, photons, hadrons) with high transverse energy in the calorimeter system. In addition information from the SPD is used to avoid events with a large particle multiplicity.

The Hlt1 reduces the rate to approximately 30 kHz. It includes a number of trigger lines, that search the event for particle tracks with good track quality, high (transverse) momentum and/or large impact parameter.

The Hlt1 output rate is sufficiently low for the numerous Hlt2 trigger lines that use full event reconstruction and selections. These finally reduce the rate to about 2 kHz.

Chapter 2

The Outer Tracker

In the LHC*b* experiment the VERtEX LOcator determines the trajectories of charged particles close to their production point, while a set of tracking stations downstream of the LHC*b* magnet measures the momenta of the charged particles. Two techniques are interlaced in these stations: the silicon-strips Inner Tracker covers the “hottest” region around the beam-pipe (2%), while the straw-tubes Outer Tracker identifies particles in the remainder of the LHC*b* acceptance (98%).

The Outer Tracker consists of multiple layers of thin straws, that individually detect particles through gas ionization and amplification. The design of the Outer Tracker is chosen to meet the LHC*b* physics requirements of a position resolution of 200 μm , while coping with occupancies of at most 10% and a trigger rate of 1 MHz at a luminosity in the region of $2\text{--}5 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$ to (Ref.[2]).

This chapter describes the Outer Tracker straw-tube detector. Sec.2.1 summarizes its structure, while Sec.2.2 describes the Outer Tracker Front End electronics.

2.1 A straw-tube detector

Fig.2.1 illustrates the Outer Tracker detector geometry, which can be summarized as follows.

1. The *Outer Tracker* consists of three tracking stations spaced about 0.7 m from each other.
2. Each *tracking station* consists of four layers of 18 detector modules, nine modules on the A-side (positive x -direction) and nine on the C-side (negative x -direction). Mechanically each (F-type) module spans the full vertical acceptance of the detector (S-type modules are an exception, see point 5). The detector modules are arranged in x - u - v - x stereo views: the first and fourth layer of modules (x) are mounted vertically, while the modules of the second and third layer (u and v) possess a small stereo angle of -5° and $+5^\circ$ respectively with respect to the vertical direction.
3. Two pairs of *C-frames* per station support the four layers of detector modules,

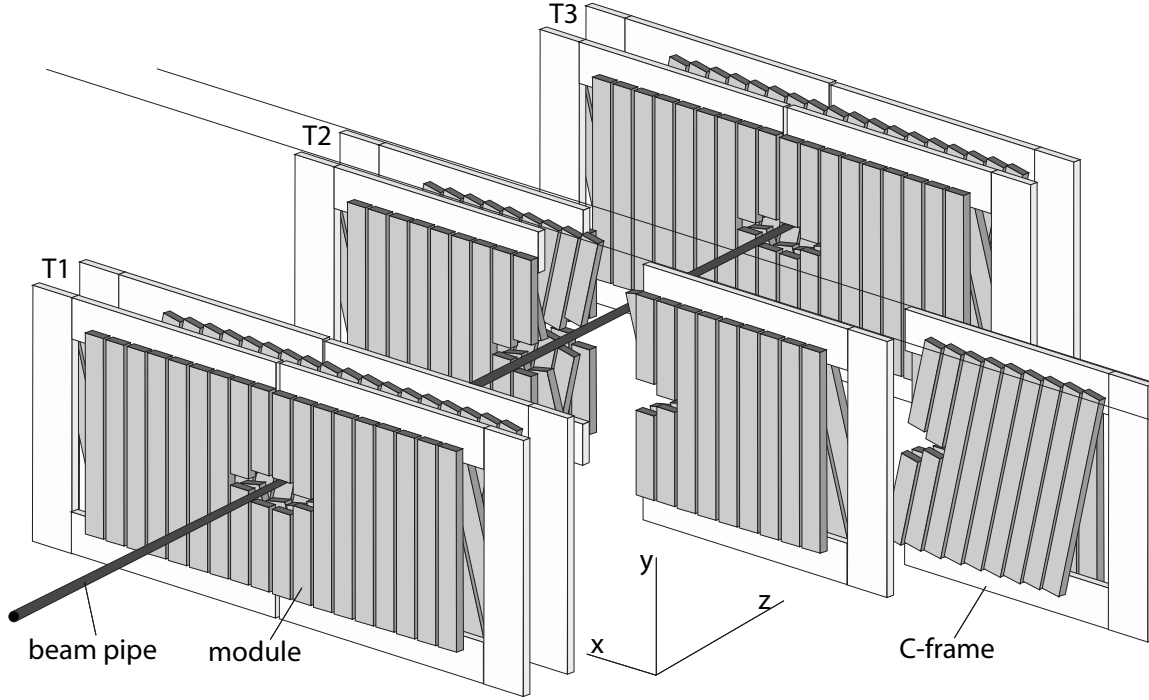


Figure 2.1: *The LHCb Outer Tracker detector. Three tracking stations (T1, T2 and T3), each accommodating four layers of detector modules in x-u-v-x stereo views. The support frames (C-frames) can move in and out of the detector acceptance.*

where each *C-frame* hosts nine modules on both its front and its rear side. The *C-frames* can be independently moved out for maintenance.

4. A detector *module* contains two staggered layers of 64 straw-tubes divided in an upper and a lower half. With respect to gas distribution a module is a single unit, but internally the upper and lower straws are electrically decoupled. Hereby the two halves of a module act as separate detection units and are individually read out by Front End electronics boxes at the top and bottom of the module.
5. The four innermost modules of every layer, directly around the beam pipe (of the S-type rather than the F-type), contain shorter straw-tubes, so that there is a region in the center that is not covered by straws. This region, where the occupancy is too large for straw-tube technology, is covered by the silicon-strips Inner Tracker. The very innermost module moreover is “half-width”, containing two staggered layers of 32 straw tubes (not explicitly visible in Fig.2.1).

Straw-tubes

Fig.2.2(a) illustrates the working principle of a straw-tube. A traversing particle ionizes molecules of the gas inside a straw. Due to the potential difference between anode wire and cathode straw, the liberated electrons drift towards the wire, while the ions drift

towards the straw boundary. As soon as the electrons pass into the gas amplification region, the electric field becomes so large that they build up enough energy to ionize further atoms, hereby creating an avalanche. Both electrons and ions induce a current on the anode wire with a sharp rise-time followed by a long “ion tail”.

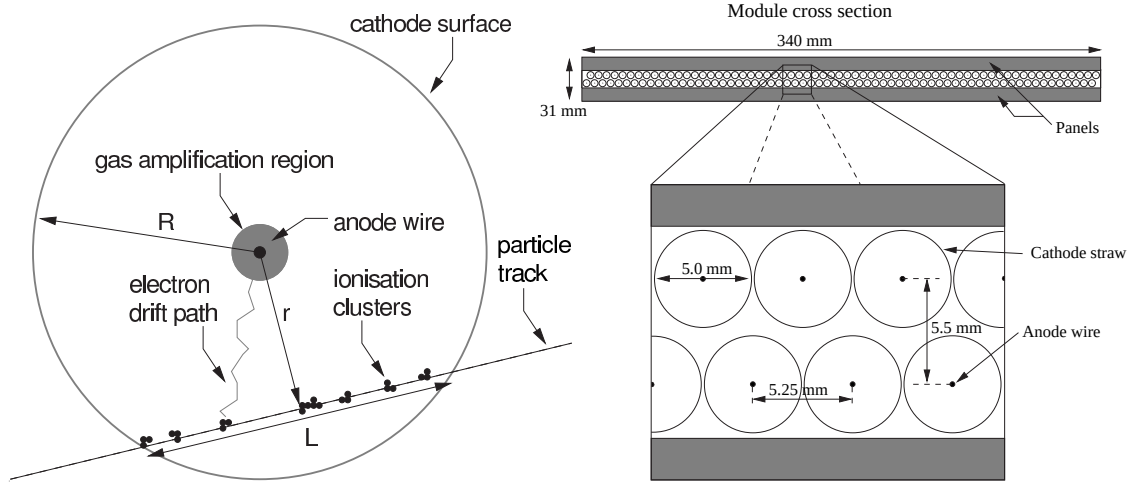


Figure 2.2: a) Cross section and working principle of a straw-tube. b) Cross section of a module showing the two staggered layers of straw-tubes.

The straws have an inner diameter of 4.9 mm. The anode is a 25 μm diameter gold-plated tungsten sense wire and is centered by two wire locators along the straw-tube length and wire supports at the straw’s ends.

The straw outer rim is a composite of two layers. Its inner cathode layer is 40 μm thick Kapton XC-160 with a 25% doping of carbon for conductivity, whereas the outer layer is made of aluminium-laminated kapton foil, with 25 μm kapton for gas tightness and 12.5 μm aluminium for shielding (prevention of straw-to-straw cross talk).

Tab.2.1 summarizes the operational characteristics of the Outer Tracker straw-tubes.

Modules

An Outer Tracker detector module is a 490cm high $\times$ 34cm wide $\times$ 3cm deep box, containing two staggered layers of straw-tubes supported by panels (see Fig.2.2(b)).

The support panels have a layered structure as indicated in Fig.2.3. A Rohacell core between Carbon Fiber Composite skins provides stiffness. On the straw side a kapton foil ensures gas tightness, while an aluminium layer provides shielding and grounding. The radiation length thickness ($X/X_0 \approx 0.8\%$) of the individual modules sum up to a total of $\sim 10\%$ of X_0 for the entire Outer Tracker (Ref.[3]).

Feed-through boards at both ends serve as the interface between module and Front End electronics. They provide the electrical connections for the sense wires and ensure common grounding of straws and panels.

straw diameter	4.9 mm
maximum straw length	2.4 m
counting gas	70/28.5/1.5% Ar/CO ₂ /O ₂
nominal High Voltage	1550 V
nominal gas gain	6×10^4
primary electrons for a Minimum Ionizing Particle (MIP)	1 e/330 μ m
maximum drift time	44 ns
wire signal propagation speed	3.8 ns/m
nominal threshold	800 mV $\approx$ 4 fC
average efficiency (MIP)	>98%
average noise rate	<0.01%

Table 2.1: Operational characteristics of a straw-tube.

***C*-frames**

The *C*-frame is a C-shaped rigid aluminium frame that supports the Outer Tracker detector modules. The *C*-frame carries all the cables needed to operate the Front End electronics: High Voltage (HV), Low Voltage, optical data fiber and Experiment Control System (ECS) and Timing and Fast Control (TFC). Furthermore, it contains the water cooling system for the Front End electronics, as well as the pipes for the distribution of gas to the detector modules. All *C*-frames can move independently from the beam pipe along the guiding rails of their support structure.

A photograph of a *C*-frame, equipped with detector modules and taken during installation, is shown in Fig.2.4.

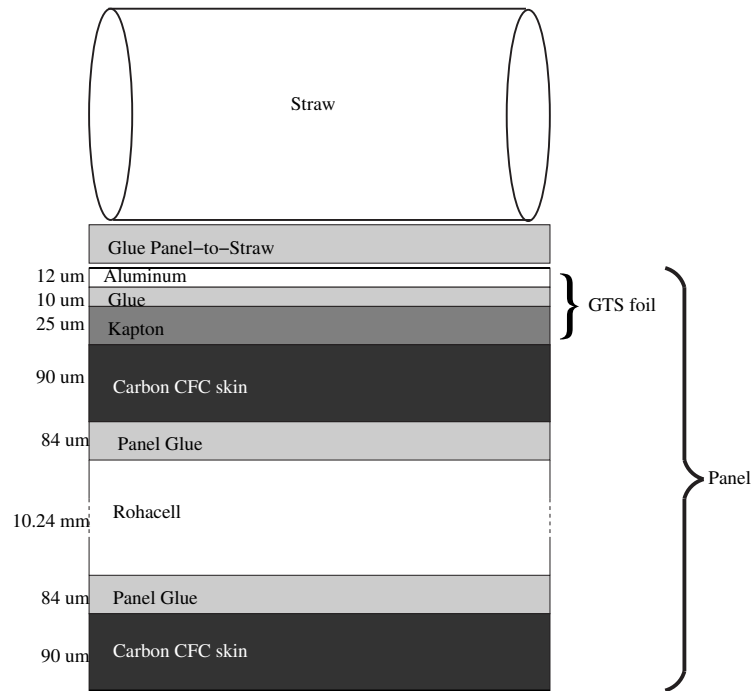


Figure 2.3: *Cross section of a module support panel.*



Figure 2.4: *C-frame equipped with modules and Front End electronics. The frame is in mid air, being transferred from an assembly structure (C-cage) to its position in the LHCb detector.*

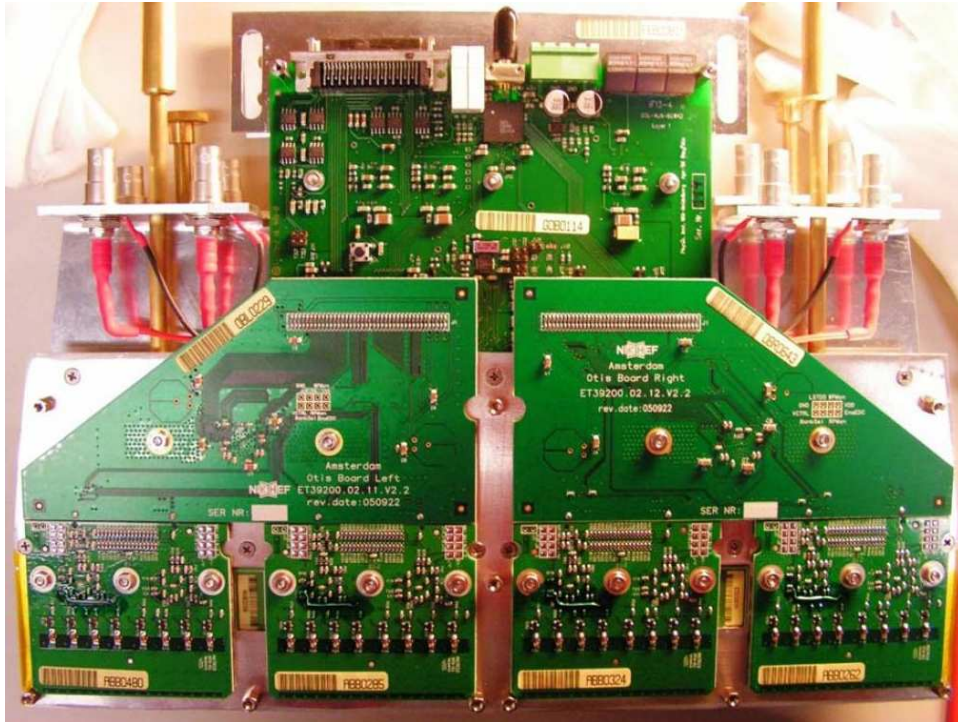


Figure 2.5: A Front End electronics box with the cover taken off to show the front side.

2.2 The Outer Tracker Front End electronics

An Outer Tracker module is read out at the top and bottom end by Front End electronics boxes (Ref.[4, 5]). The Front End boxes connect to the feed-through boards, that are built into the ends of the module. A Front End box is a collection of interconnected circuit boards, attached to an aluminium chassis and shielded by aluminium covers. The different circuit boards perform different actions in the read-out of the straw-tubes. An uncovered Front End box is shown in Fig.2.5 and is drawn schematically in Fig.2.6.

A Front End box comprises:

- Four *High Voltage* boards, that plug directly into a module's feed-through board. They distribute the high-voltage to the 128 anode wires and pass the straw signals to the rest of the Front End electronics (in Fig.2.5 hidden behind the aluminium chassis).
- Eight *ASDBLR* boards that, two at a time, connect to the four HV board and amplify the signals received from these. A board contains two ASDBLR chips, that is two 8-channel Amplifier-Shaper-Discriminator with ion-tail cancellation and *BaseLine Restoration*.
- Four OTIS boards for time measurement, that each take the output of two ASD-BLR boards. The OTIS board houses a 32 channel TDC-chip that digitizes the

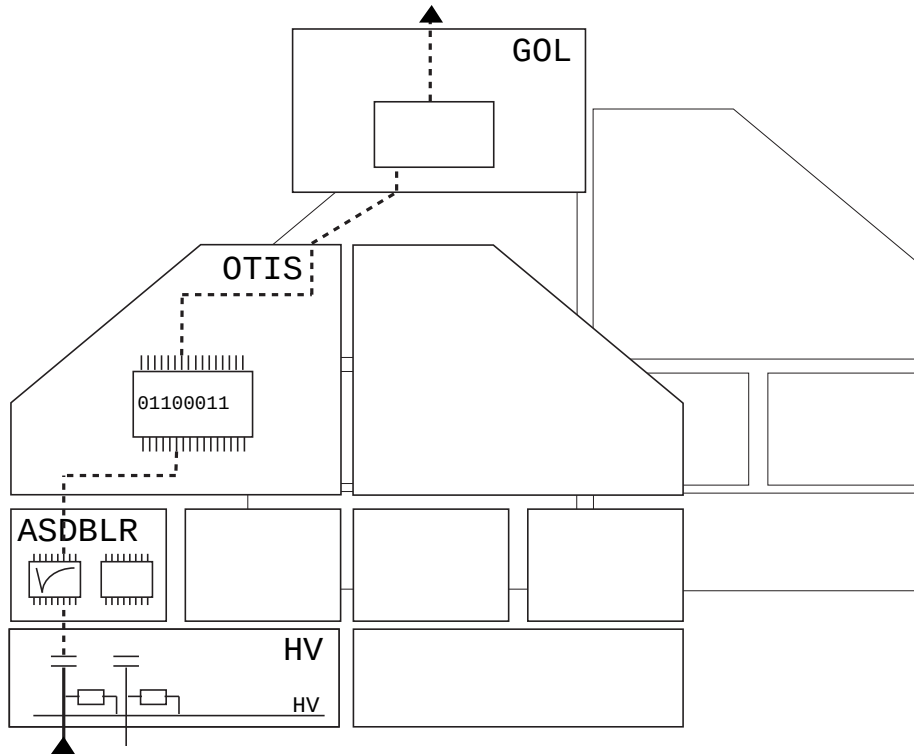


Figure 2.6: *Schematic overview of the Outer Tracker Front End electronics showing the High Voltage, ASDBLR, OTIS and GOL boards and the trace of a straw signal through these.*

hit signal time into a 6+2-bit differential output.

- A single *GOL*/Auxiliary board that reads out the four OTIS boards of a Front End box. The GOL serializes the time information and ships it to the off-detector electronics through a 1.6 Gbit/s optical link.

HV board

The High Voltage board provides 32 channels with a common high-voltage. Pre-resistors of $1\text{ M}\Omega$ in front of every channel decouple the anode wires from each other and prevent large currents in case of shorts in the drift-tubes. Small hit-charges caused by particles are decoupled from the high-voltage supply by 330 pF capacitors. The large density of channels and relatively large high-voltage demand insulation of the capacitors to avoid discharges across the board surface. This is obtained by embedding the capacitors into the multilayer structure of the circuit board.

ASDBLR

The ASDBLR (Ref.[6]) amplifies the charge signal from an anode wire and discriminates it against an adjustable threshold voltage to obtain a binary output signal. The two

ASDBLR ASIC on an ASDBLR board are eight-channel radiation hard (7 MRad) amplifiers. The ASIC is originally designed for the ATLAS Transition Radiation Tracker (Ref.[7]). However, its pulse shaping characteristics are matching the design of the Outer Tracker.

The current induced by a particle has a sharp sub-nanosecond rise time, but is followed by a long ion-tail which spans tens of bunch crossings. To prevent signal build-up at the discriminator stage, the ion-tails have to be eliminated. In the ASDBLR, the amplified signal is passed to a stage where it is shaped (7.5 ns peaking time) and where its tail is restored to baseline. This process of signal shaping and baseline restoring cancels the long ion-tails and effectively reduces the dead-time to less than 20 ns.

The ASDBLR board contains two test-pulse inputs for even-numbered or odd-numbered channels. Pulses with two possible amplitudes are routed through the Front End electronics to the ASDBLR input, either as large-amplitude pulses (Test-Pulse High), or as small-amplitude pulses (Test-Pulse Low). The test pulse capability allows for testing and/or debugging of the Front End electronics.

To retain a high efficiency and a precise time measurement, the ASDBLR threshold should be set as low as possible, while at the same time high enough to suppress noise. For this it is important that the charge-to-voltage conversion of the eight channels of an ASDBLR chip are uniform. Furthermore it is preferable to use a common threshold settings, rather than to tune each chip individually. Therefore, the ASDBLR chips were carefully pre-selected with respect to threshold uniformity (Ref.[8]). The typical operational threshold of the Outer Tracker channels is 800 mV, for which the average straw efficiency is 98% with noise levels below 0.01% (Ref.[9]).

OTIS

The OTIS board houses the radiation hard (30 MRad) OTIS chip (Outer Tracker Time Information System), which digitizes the arrival times from two ASDBLR boards (32 channels).

The ASDBLR chips provides binary signals to the OTIS, which acquires the state “high” when a signal surpasses the ASDBLR threshold. The OTIS digitizes the binary signals with respect to the 40 MHz LHC bunch crossing clock and stores the result in a pipeline buffer for read-out upon a Level-0 trigger.

The arrival time is encoded into a 6 bit fine-time, such that a hit is placed in one of 64 TDC bins of 391 ps. The fine-times of 32 channels are written into a 164-word-deep pipeline buffer, which covers the 4 μ s Level-0 trigger latency.

Since the spread in arrival time for different particles can be more than 50 ns, due to different Time-Of-Flight, drift-time and wire signal propagation time, three consecutive bunch crossings are searched for hits. Upon an L0 accept three bunch crossings are copied into a 48-word-deep derandomizer buffer, which therefore can cope with maximally 16 consecutive triggers. The first hit in the three bunch crossing search interval (75 ns) is retrieved. The 6 bits are then supplemented with an additional two bits indicating to which of the three bunch crossings the fine-time belongs to¹.

¹00 for the 1st, 01 for the 2nd, 10 for the 3rd bunch crossing and 11 if no hit is found.

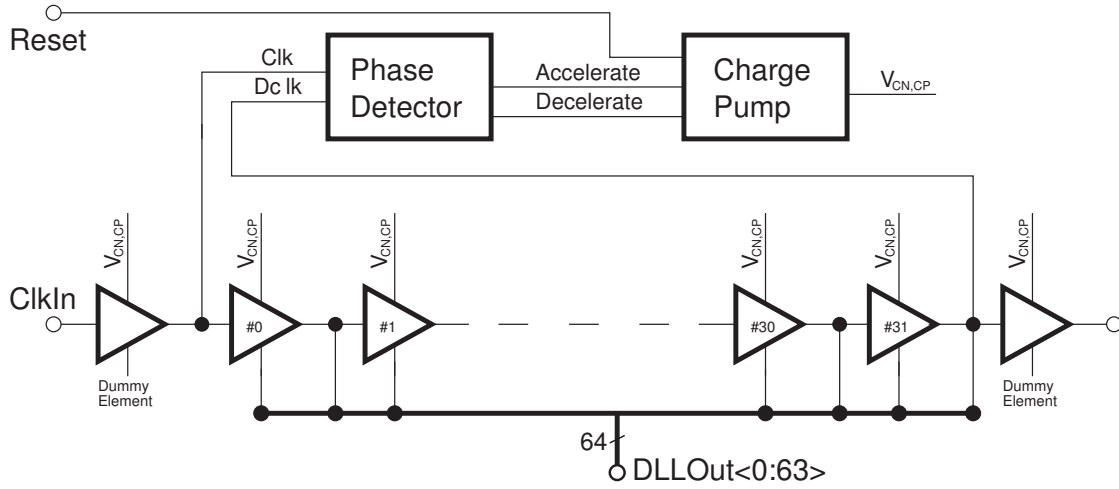


Figure 2.7: The Delay Locked Loop (DLL) implemented in the OTIS chip. A chain of 32 delay elements delays the clock signal. The phase difference between clock and delayed clock feeds back as the control voltages to the delay elements.

For the digitization procedure the OTIS chip implements a Delay Locked Loop (DLL) for each of its 32 channels. A schematic of the DLL is shown in Fig.2.7. Digitization is performed with respect to the 40 MHz bunch crossing clock. The bunch crossing clock gets delayed by a chain of 32 voltage-controlled delay elements. Each delay element consists of two delay stages. It is intended that each of the 2×32 stages contributes 391 ps delay, such that the total delay is one clock cycle of 25 ns. To achieve this total delay, both the undelayed clock and the delayed clock are fed into a phase detector. Depending on the phase difference between the clocks, the phase detector (and charge pump) adjusts the voltages with which the delay elements are controlled. When the phase difference disappears, the DLL is in lock state and each delay element contributes 2×391 ps nominal delay.

The two delay stages of the delay elements provide the references for digitization of the hit time. This is done by latching each of the 2×32 delay stages to the binary signal arriving from the ASDBLR. The output of delay stage number n is a clock signal that has been delayed by $n \times 391$ ps. Upon the rising edge of this delayed clock, the state of the ASDBLR binary signal (“high” or “low”) is copied into hit register number n . A series of interconnected AND gates with an inverter each then compares the 64 hit registers and extracts the first 0-1 transition (see Fig.2.8). The stage where the first transition occurs is then encoded into the signal’s 6-bit fine time.

The two halves of a bunch crossing interval are separately pre-encoded, such that the hit time encoding can proceed in parallel with the data sampling of the following bunch crossing: The encoding is dead-time free.

The OTIS TDC chips have been tested at several stages. All chips were pre-selected

Additionally the Front End Electronics can be operated in *multiple hit mode* as apposed to the herein described *single hit mode*. Multiple hit mode is foreseen to read out every bunch crossing, but has not yet been commissioned.

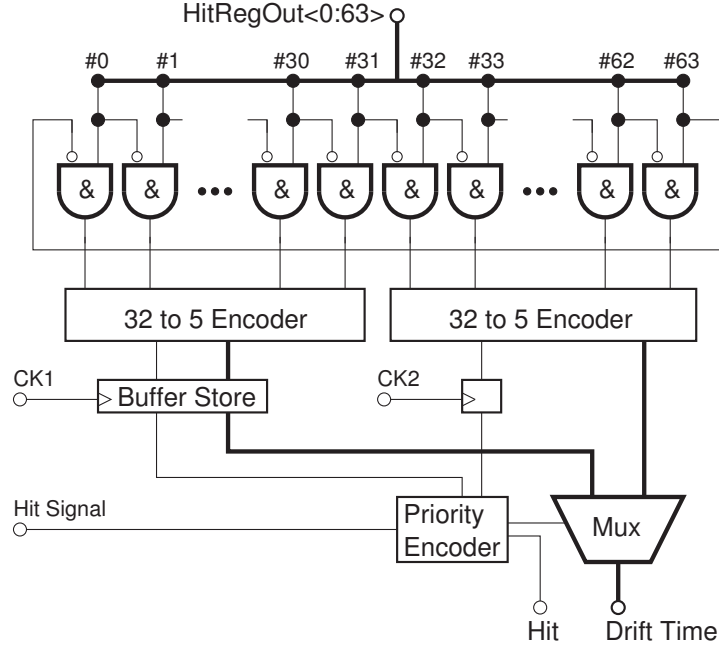


Figure 2.8: *OTIS hit encoding scheme. Every AND gate outputs hit register hr_n & $!hr_{n-1}$, thereby finding the first 0-1 transition. The zeroth hit register is compared to the last.*

through tests with a probe station. Further tests were performed after chip bonding onto the OTIS board and again after glob-topping (Ref.[10, 11, 12]).

GOL

The GOL/Auxiliary board contains the radiation hard (1 MRad) Gigabit Optical Link ASIC. It takes the hit information from 128 channels of all four OTIS, serializes it with 8/10 bit Giga-bit Ethernet encoding and ships it off-station via single optical fiber operating at 1.6Gb/s.

The board furthermore distributes all timing and fast control signals (bunch clock, L0 trigger accept, resets, etc.) and test-pulse signals. It delivers supply voltages to the GOL, the OTIS and ASDBLR and allows to change settings on the OTIS and ASDBLR chips via the Experiment Control System.

Chapter 3

Outer Tracker module installation

No wonder it broke.

Ana Paula Ribeiro Atayde, referring to the 2008 LHC accident, during a tour of the LHCb experiment, getting a first hand view of the large scale and complexities of particle physics experiments.

During the years 2006 and 2007 the Outer Tracker subdetector was installed into the LHCb spectrometer. For this purpose a special steel frame, called *C*-cage, had been erected inside the LHCb cavern, inside of which two Outer Tracker *C*-frames were simultaneously assembled with straw-tube modules and once more subjected to quality assurance tests prior to their actual mounting into the LHCb detector.

This chapter reports these quality assurance tests with particular emphasis on the response of the individual straw-tubes to a radioactive iron source.

3.1 Quality assurance during module installation

The Outer Tracker *C*-frames were delivered to the LHCb site preassembled, but without detector modules and Front End electronics. The *C*-frames had been equipped with High Voltage cables, Low Voltage cables and optical fibers, running from a patch panel at the side of each frame to the positions where they were to be connected to the Front End electronics, as well as with cooling pipes for water cooling of the electronics and gas pipes for distribution of the Ar/CO₂/O₂ gas to the detector modules. The cabling had been verified during assembly prior to shipment for correct functioning and geometrical allocations, while the cooling system had been tested for leakages (Ref.[13]). While being assembled inside the *C*-cage, a *C*-frame was subjected to a series of quality assurance tests.

Before a *C*-frame was equipped with detector modules:

- the gas tightness of the gas supply lines was checked,
- the High Voltage dark currents in air were measured,

- the voltage drops over the Low Voltage supply cables were measured,
- the power attenuation of the optical fibers was measured.

After the detector modules had been installed onto the *C*-frame :

- the gas tightness was rechecked,
- the High Voltage dark currents were again measured,
- the response of individual straw-tubes to a ^{55}Fe source was determined.

All tests data were stored for back reference.

Sec.3.2 covers in detail the final test, measuring the response of individual straw-tubes to a ^{55}Fe source. The other quality assurance tests are summarized below. A more extensive account of the quality assurance tests performed during module installation can be found in Ref.[14].

Gas tightness of the gas supply lines

The four gas supply pipes of a *C*-frame were filled with CO_2 at an overpressure of approximately 10 mbar and after 4 minutes the pressure decay was registered. The pressure drop did not exceed 1 mbar/minute, except for two lines which decayed with less than 1.5 mbar/minute, which was deemed acceptable.

High Voltage test in air

The HV cables were connected to a dummy Front End electronics box and provided with 1800 V High Voltage. The dark currents did not exceed the foreseen 10 nA maximum.

Low Voltage test

The Low Voltage cables provide a positive and negative bias voltage to the Front End electronics. To test the voltage drop over the cables, they were supplied with $+7/-7$ V at 4.1/2.1 A respectively, while being connected to a dummy load resistor that simulates the presence of a Front End electronics box. The voltage over the load then typically ranged between +6 V and +6.5 V for the positive bias and between -6.75 V and -6.5 V for the negative bias, exceeding the minimally required +6 and -6 V respectively.

Optical fiber attenuation

All fibers that carry the serial data from the Front End electronics boxes were measured for power attenuation with a 850 μm wavelength light source. No fiber measured a power attenuation less than -30 dBm, where typically a broken fiber reads an attenuation of -50 dBm.

Gas tightness of the detector modules

The gas tightness of every detector module was measured by applying an overpressure between 5 and 6 mbar and subsequently reading the pressure decay during a period of 9 minutes. After correcting for known leakages of previously connected modules, the pressure drop at 5 mbar overpressure was determined (Ref.[14]). The measured leak rates showed good agreement with the values previously determined during module production (Ref.[15, 16]) and are acceptable.

High Voltage test

Four High Voltage cables were connected through a dummy Front End electronics box to a detector module filled with CO_2 . After a period of about 3 minutes the dark currents at 1600 V High Voltage were measured. These did not exceed the specified maximum of 100 nA for 32 sense wires.

3.2 Detector response with a ^{55}Fe source

A measurement of the straw-tubes' response to a radioactive iron source was performed for Outer Tracker detector modules belonging to the A-side of the LHCb detector. (*C*-frames belonging to the C-side had already been installed.) Since one *C*-frame contains over 4000 straw-tubes, initially the ^{55}Fe test was envisaged as a test of a random sample of straw-tubes. However, the rapid automation of the test procedure allowed the responses of nearly all individual straw-tubes of the A-side modules to be measured.

The response of a straw-tube depends on a large number of parameters, e.g. changing the Argon content from its foreseen 70% with 1% leads to an increase in gas gain of about 12%, a decrease in atmospheric pressure of 10 mbar raises the gain by approximately 5% and increasing the HV from 1500 V with 5 V enhances the gas gain with 4% (Ref.[15, 17]). A precise control or monitoring of the test conditions were unavailable, by which the ^{55}Fe test was intended as a global functionality test rather than a quantitative measurement of straw-tube performance.

3.2.1 The ^{55}Fe Test

The test setup, used to measure a straw-tube response, consists of the following parts.

- Bottles of premixed 70/30% Ar/ CO_2 gas.
- A gas system to provide a gas flow rate of approximately 3 l/hr/module (Ref.[18]). A bubbler at the end of a gas line controls the overpressure in the modules, while a bubbler parallel to the gas line protects against pressure overshoots.
- A 12 MBq ^{55}Fe monochromatic X-ray source.
- A CAEN 127 power supply to provide (1520 V) High Voltage to the straw-tube anode wires.

- A custom built circuit board for amplification of the signals from the sense wires.
- A Tektronix TDS 200 digital oscilloscope to measure the amplified analog output.
- A laptop computer running Labview to control the amplifier board, read out the oscilloscope and store the pulse-height data to file.

The ^{55}Fe source emits 5.9 keV photons. Upon complete absorption in Argon a photon creates on average 220 primary electrons in a straw (0.035 fC). In a fraction of events, 3keV of the photon's energy may escape detection in the form of Argon characteristic radiation. Fig.3.1(a) shows the main photo peak, containing the greater part $\sim 85\%$ of the spectrum, and the escape peak characteristic for Argon. The height of a photon induced pulse is proportional to the gas gain.

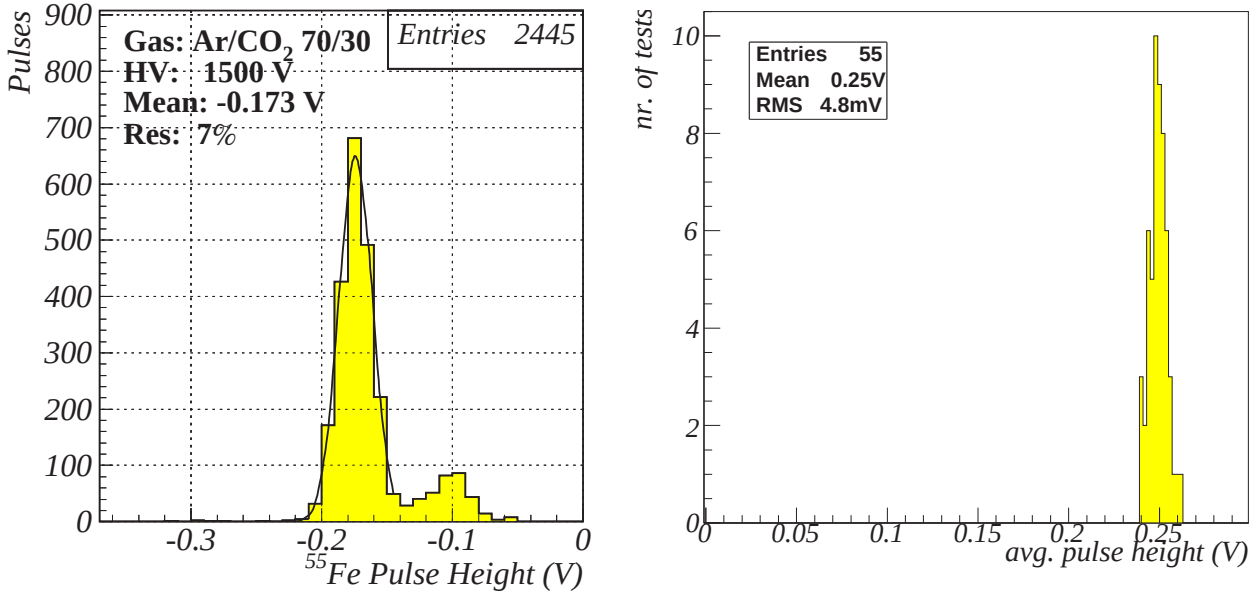


Figure 3.1: (a) The pulse-height spectrum from ^{55}Fe at 1500 V as determined at Nikhef during module production. (b) Measurement of the 128-pulse-average height at 1520 V, repeated 55 times, shows the reproducibility of the ^{55}Fe method: the average pulse height of a randomly chosen channel (ch 40BU of mod F095) varies by ± 5 mV.

The source is placed at a distance of approximately 40 cm from the module end and at a small distance from the module surface to ensure a high pulse rate. At a typical distance of 10 cm from the surface the source illuminates about 10 straw-tubes, and thus has to be repositioned along the width of a module while testing. The recorded pulse rate at this distance is approximately 100 Hz for the front mono-layer of straw-tubes and approximately 20 Hz for the rear mono-layer. The rate of background pulses (cosmics or spurious noise) is less than 1 Hz.

The amplifier board connects to one mono-layer of 64 straw-tubes and has to be reconnected when going from front to rear mono-layer. It provides grounding and

High Voltage connection for the straw-tubes and houses two amplifiers connected to HV decoupling capacitors and 1 M Ω resistors. The amplifiers are VV50 low-noise charge amplifiers, meaning that the output voltage is proportional to the charge signal from the anode wire. The amplifiers have been selected such that the response of the two is equal to within approximately 2%. Via a relais the amplifier board can be remotely operated to switch between channels. The ^{55}Fe pulses typically measure a height between -300 mV and -200 mV.

The analog output pulses are read out by a digital oscilloscope, with a threshold set to -40 mV to suppress noise. When triggered, the oscilloscope collects and averages 128 pulses within a 10 s timeout window; if the number of 128 pulses is not reached within the timeout window, then the channel is either unresponsive, or the source has to be repositioned. The 128-pulse-average is read from the oscilloscope and written to file together with straw position and trigger time.

The reproducibility of the method is demonstrated in Fig.3.1(b), where 55 independent measurements of an average pulse-height are shown. The results of these checks (applied to a straw of both mono-layers) show a 5 mV RMS.

3.2.2 ^{55}Fe Test results

As an example, the ^{55}Fe test results of the X-oriented modules of C-frame T1-Q13-XU are shown in Fig.3.2. The full set of test results can be found in Ref.[14].

The Outer Tracker modules were tested over a period of four months from January to April 2007. As previously discussed, during this time the precise control or monitoring of test conditions (atmospheric pressure, High Voltage, exact gas composition) were unavailable, in light of which the evaluation of test results is restricted to the identification of “bad” straw-tubes, which are correspondingly categorized as follows.

- Dead channels:
channels that repeatedly have insufficient pulses within the 10 s timeout window¹.
- Low pulse-height:
channels that repeatedly have low pulse-height. Typically these are noisy channels, where excessive noise pulses lower the 128-pulse-average.
- High pulse-height:
channels that repeatedly measure a high pulse-height as a result of discharges that contribute large pulses to the pulse average and even may saturate the amplifier.

The results for the straw-tubes that are characterized as bad are compared to quality checks performed during module production. Fig.3.3 illustrates such comparison.

In total 32 bad channels have been found out of the 26k tested. The list of bad channels as determined by the ^{55}Fe test during installation of the Outer Tracker modules is given in Tab.3.1.

¹It should be noted that there are channels that did not respond due to a faulty or broken channel-0 on the circuit board, which was not noticed in time for these straws to be retested.

C-frame	Layer	Module		Monolayer		Ch	Sign.	Category (history)
		Pos	Serial nr	A/B	Z+/-			
T1-Q13-XU	L1(U)	3	F 076	B	+	0L	dead	bent pin (?)
T1-Q13-XU	L1(U)	4	F 077	A	-	0L	dead	bent pin (?)
T1-Q13-XU	L1(U)	7	F 195	B	+	48L	dead	?
T1-Q13-XU	L1(U)	8	S1U 024	B	+	22U	high	?
T1-Q13-XU	L1(U)	8	S1L 064	A	-	46L	high	noisy at Nikhef
T1-Q13-XU	L1(U)	8	S1L 064	A	-	55L	high	noisy at Nikhef
T1-Q13-XU	L1(U)	9	S2L 079	B	+	44L	dead	no signal at Nikhef
T1-Q13-VX	L2(V)	3	F 082	B	-	10L	low	?
T1-Q13-VX	L2(V)	3	F 082	B	-	11L	low	?
T1-Q13-VX	L2(V)	7	F 200	A	+	21U	dead	disconn. (Heidelberg)
T1-Q13-VX	L2(V)	8	S1U 026	A	+	0U	low	bad gas flow at Nikhef
T1-Q13-VX	L2(V)	9	S2U 038	B	+	34U	low	noisy at Nikhef
T1-Q13-VX	L2(V)	9	S2U 038	B	+	47U	low	noisy at Nikhef
T1-Q13-VX	L2(V)	9	S2U 038	B	+	52U	low	noisy at Nikhef
T1-Q13-VX	L3(X)	8	S1L 065	A	-	36L	dead	no signal at Nikhef
T1-Q13-VX	L3(X)	8	S1L 065	A	-	59L	low	noisy at Nikhef
T2-Q13-XU	L0(X)	8	S1U 125	A	-	20L	dead	no signal at Nikhef
T2-Q13-XU	L1(U)	6	F 201	A	-	4L	dead	?
T2-Q13-XU	L1(U)	8	S1L 068	B	+	63L	low	bad gas flow at Nikhef
T2-Q13-VX	L2(V)	8	S1U 010	A	+	0U	low	noisy at Nikhef
T2-Q13-VX	L2(V)	8	S1U 010	A	+	12U	dead	no signal at Nikhef
T2-Q13-VX	L2(V)	8	S1U 010	A	+	32U	low	noisy at Nikhef
T2-Q13-VX	L2(V)	8	S1U 010	A	+	34U	dead	no signal at Nikhef
T2-Q13-VX	L2(V)	8	S1U 010	A	+	57U	high	noisy at Nikhef
T3-Q13-XU	L1(U)	9	S2U 041	A	-	59U	dead	no signal at Nikhef
T3-Q13-VX	L2(V)	1	F 120	B	-	0U	dead	bent pin (?)
T3-Q13-VX	L2(V)	2	F 158	A	+	0U	dead	bent pin (?)
T3-Q13-VX	L2(V)	4	F 007	B	-	U	high	noisy at Nikhef
T3-Q13-VX	L2(V)	4	F 007	B	-	L	high	noisy at Nikhef
T3-Q13-VX	L3(X)	2	F 129	A	-	63L	low	bad gas flow at Nikhef
T3-Q13-VX	L3(X)	2	F 129	A	-	0U	low	bad gas flow at Nikhef
T3-Q13-VX	L3(X)	6	F 128	B	+	63L	high	noisy at Nikhef

Table 3.1: *The list of bad channels as determined with the ^{55}Fe pulse-height measurement. Channels denoted as “bent pin (?)” may be the result of a faulty or broken channel-0 on the test circuit board, which was not noticed in time for these channels to be retested.*

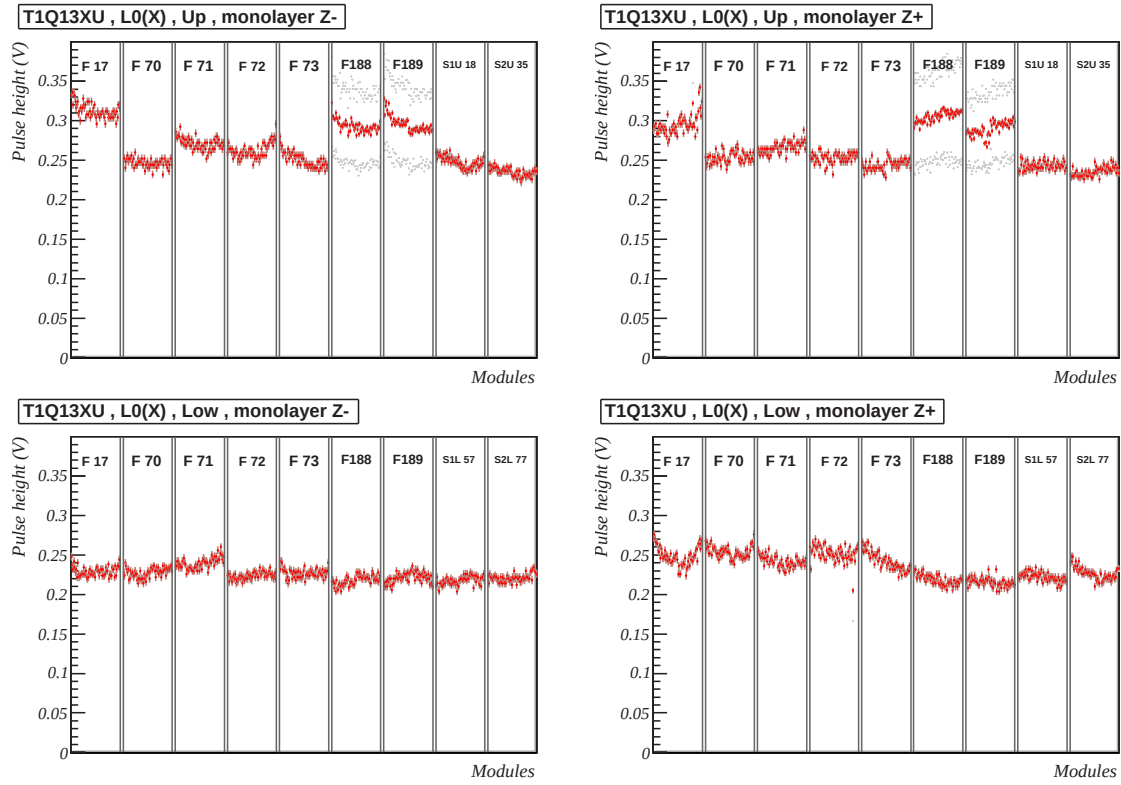


Figure 3.2: Average ^{55}Fe pulse-heights of T1-Q13-XU X. The upper and lower module halves are shown in the top and bottom plots respectively. The front and rear mono-layer of straws are shown in the left and right plots respectively. The upper halves of modules F188 and F189 have been measured twice (on different days); both measurements are shown as well as their average.

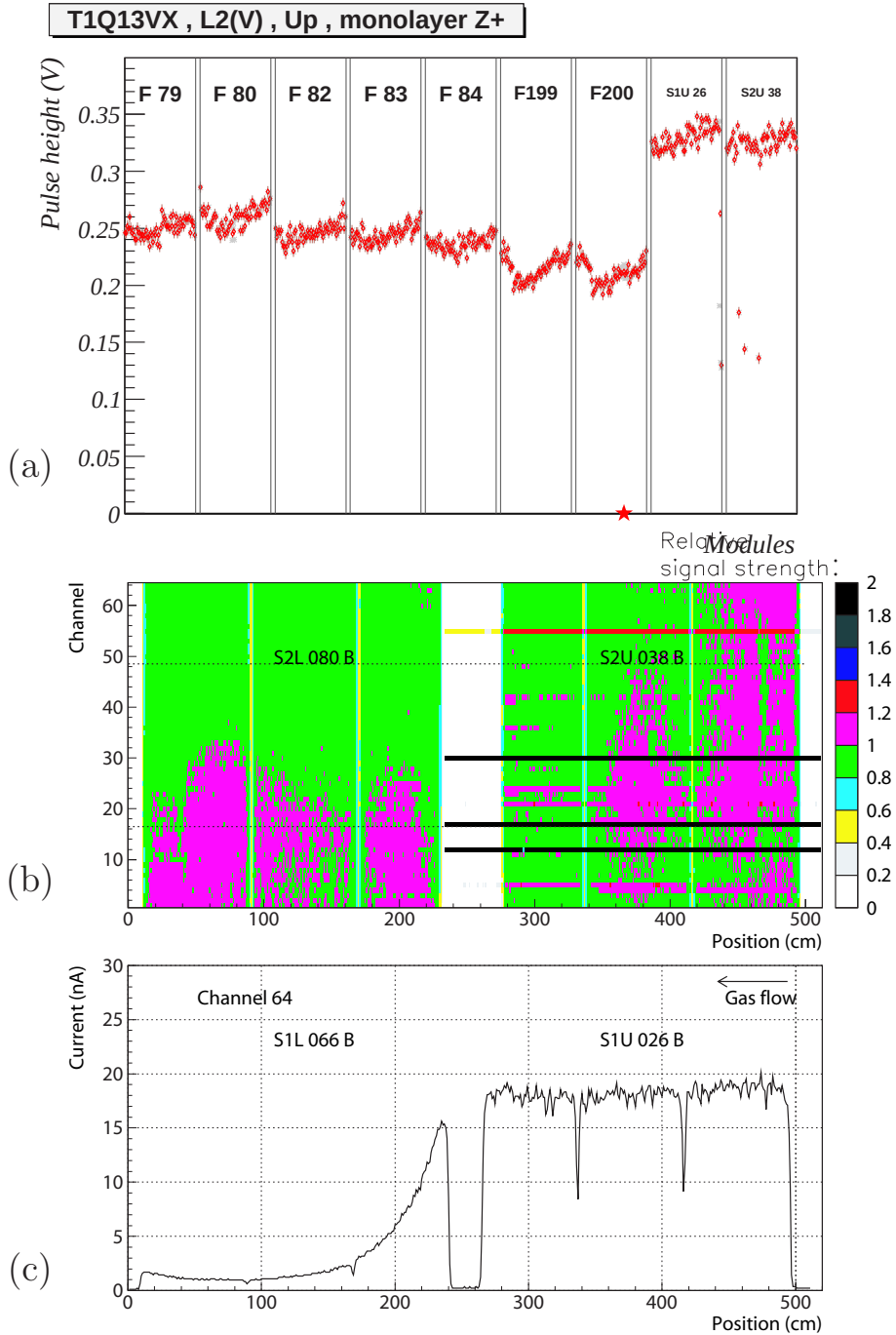


Figure 3.3: (a) The ^{55}Fe test results for one half monolayer are shown. The dead and low pulse-height channels can be seen. The dead channel in module F200 had been disconnected during module production. (b) The 3 channels in S2U 038 with low average signal response suffer from large noise rate, as can be seen from the ^{90}Sr scan taken during module production as channels with large dark current. (c) The two channels in S1U 026 with low average signal response suffer from bad gas flow, as was found with the ^{90}Sr scan during module production (outermost channel 64 is shown). Therefore the two channels on the side of S1U 026 need more time to reach the correct gas composition.

Chapter 4

Outer Tracker Front End electronics quality assurance

It is a sign from God. If we choose to ignore it, He will cross us.

Antonio Pellegrino, when asked whether a small, only sporadically appearing feature should be investigated¹.

The period from October 2006 to November 2008 saw the mass production of over 400 Outer Tracker Front End electronics boxes. The quality of the Front End electronics is assured by several tests performed at different stages in production, of individual electronics components as well as of assembled Front End electronics boxes.

This chapter presents the quality assurance tests performed on the Outer Tracker Front End electronics boxes during their mass production.

4.1 Front End Tester

The Front End electronics components (HV-board, ASDBLR, OTIS, GOL, see section 2.2) are extensively tested prior to their assembly into Front End boxes (Ref.[19, 8, 12, 10, 11, 20]). In addition, during the *Front End Test* measurements are done on an assembled Front End box as a whole (Ref.[21]), which is the final quality assurance test performed on all 472 Front End boxes in the period from October 2006 to November 2008.

The Front End Test is performed with a setup onto which an assembled Front End box is connected. It is schematically drawn in Fig.4.1. The setup is interfaced with a PC running Labview that controls both the test setup and the Front End box. The main feature of the Front End Tester is that it generates input signals similar to those originating from a straw sense wire with a variation in signal intensity and timing of 0.5 fC and 150 ps respectively.

A Front End box is subjected to a series of tests. Each test is performed in steps, where at each step a certain parameter is varied. A step is performed by sending 2000 pulses to the Front End box at 1 kHz. First, 2000 pulses are injected only into the even

¹Quote slightly edited for a more flattering word choice.

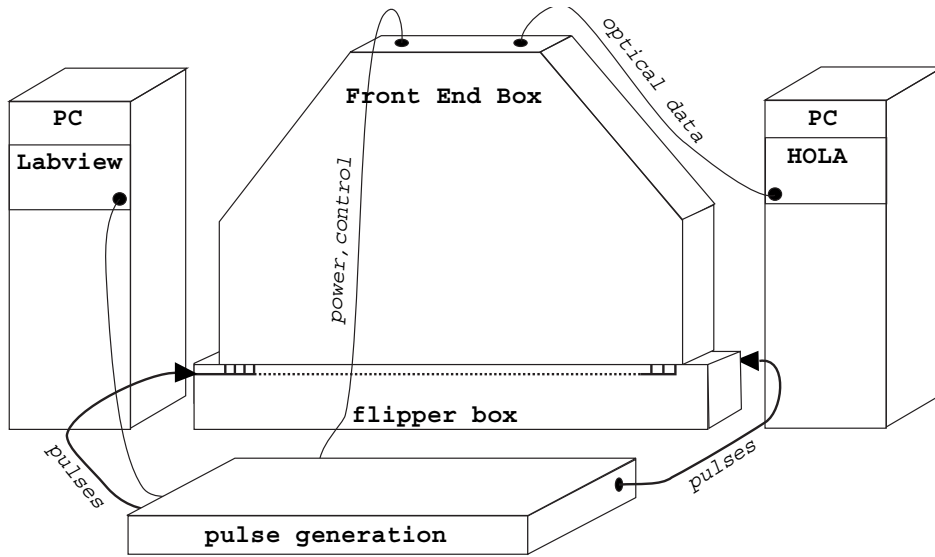


Figure 4.1: *Schematic of the Front End Test setup. The flipper box provides the physical connection of the Front End box to the test setup. The Hola program decodes (and zero suppresses) the raw hit data and checks the consistency of event headers.*

numbered channels of the box and subsequently into the odd numbered channels; this allows the measurement of the cross talk between neighboring channels.

The readout of the Front End box is synchronized with the pulse injection. For each step and each pulse the digitized hit time (if any) of every channel is written to file. The Front End characteristics that are thus studied are the following.

1. Four measurements test the relation between discriminator threshold and injected charge.
 - (a) Threshold Scan
 - (b) Threshold Scan with Test-Pulse High
 - (c) Threshold Scan with Test-Pulse Low
 - (d) Amplitude Scan
2. A Time-Delay Scan tests the time linearity of the channel responses.
3. A Latency Scan tests the synchronization of pipeline buffers.
4. A Noise Scan measures noise pickup at different threshold levels.

If any of these tests measure values beyond specifications, then the appropriate component is replaced and the test is repeated. All test results are stored for back reference; the validating tests can be found at Ref.[22].

4.1.1 Threshold characteristics

A Front End box contains in total sixteen ASDBLR chips, each of which amplifies the charges of eight straw sense wires and discriminates the resulting pulses against an adjustable threshold, which can be set individually per ASDBLR chip via the Front End electronics slow control. Channels may differ in amplification, which will effectively result in different discriminator thresholds on different channels. Therefore care has been taken to select ASDBLR chips with a uniform distribution of threshold characteristics.

Threshold vs. charge

In the ideal case there is a one-to-one correspondence between the threshold V_{thr} and the smallest charge Q_{in} on the amplifier input that is still measured as a hit. That is, for a threshold V_{thr} all input charges with size greater than Q_{in} are detected, while all input charges with size smaller than Q_{in} are not. In other words, if for a certain channel $f_{ch}(Q_{in})$ is the amplifier response to an input charge, then the probability to measure the hit with a threshold value V_{thr} is ideally:

$$P(Q_{in}|V_{thr}) = \begin{cases} 1 & V_{thr} \leq f_{ch}(Q_{in}) \\ 0 & V_{thr} > f_{ch}(Q_{in}) \end{cases} \quad (4.1)$$

However, invariably a signal will pick up noise. In the presence of Gaussian noise σ_Q , the probability to measure a charge Q_{in} given a threshold V_{thr} is:

$$P(Q_{in}|V_{thr}) = \int_{Q_{thr}}^{\infty} dQ \frac{e^{-\frac{(Q-Q_{in})^2}{2\sigma_Q^2}}}{\sqrt{2\pi}\sigma_Q} = \frac{1}{2} - \frac{1}{2}\text{erf}\left(\frac{Q_{thr} - Q_{in}}{\sqrt{2}\sigma_Q}\right) \quad (4.2)$$

where $Q_{thr} = f_{ch}^{-1}(V_{thr})$ is the charge equivalent of the threshold value. Instead of a step-function as in the ideal case Eq.4.1, the response distribution takes on the shape of an error-function as is drawn in Fig.4.2(a).

A response with this shape is typically obtained when scanning the input charge amplitude, that is, when injecting pulses of varying sizes, while keeping the threshold fixed. The width σ_Q of the response function is a measure for the noise in the amplifier channel, i.e. the Equivalent Noise Charge.

Analogously the threshold response distribution, given an input charge, can be modeled as

$$P(V_{thr}|Q_{in}) = \int_{V_{thr}}^{\infty} dV \frac{e^{-\frac{(V-f_{ch}(Q_{in}))^2}{2\sigma_V^2}}}{\sqrt{2\pi}\sigma_V} = \frac{1}{2} - \frac{1}{2}\text{erf}\left(\frac{V_{thr} - f_{ch}(Q_{in})}{\sqrt{2}\sigma_V}\right), \quad (4.3)$$

for which an example is drawn in Fig.4.2(b). This threshold response is typically obtained when scanning the threshold, i.e. when injecting pulses of fixed size, while varying the threshold value. The threshold value at which half the generated input pulses are measured is named the *Half-Efficiency Threshold* $V_{thr}^{[50\%]}$. In the Gaussian noise model it provides the best estimator of the threshold characteristic $f_{ch}(Q_{in})$. The

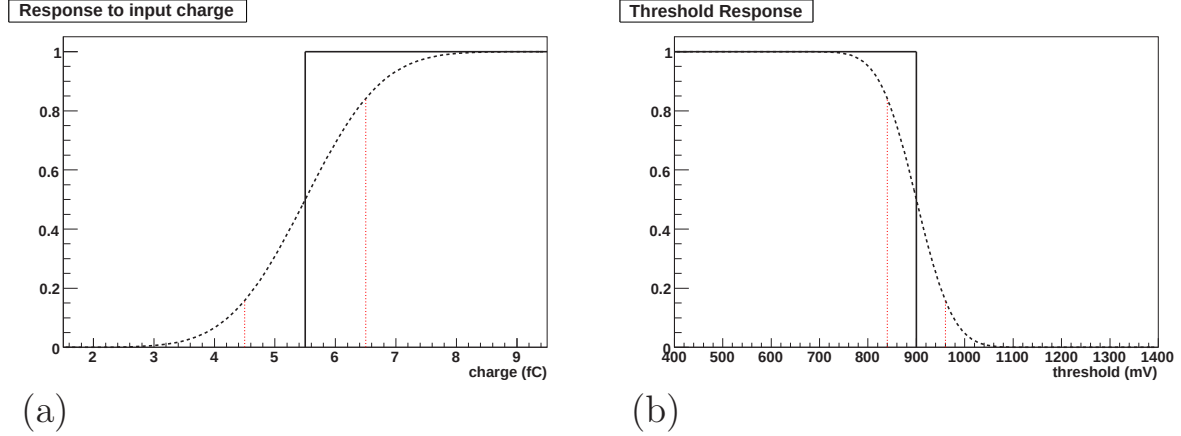


Figure 4.2: *Input charge and threshold responses (illustrative examples). (a) Hit efficiency for varying input charges with fixed threshold. (b) Hit efficiency for fixed input and varying threshold settings.*

Ideally both distributions have a sharp cutoff (solid lines). In the presence of Gaussian noise they follow error-function distributions (dashed lines). The width of the distributions, represented by the dotted vertical lines, is determined by the noise.

width σ_V measures the spread in amplifier output (Volt) at given input charge due to noise pickup².

The amplitude and threshold scans are complementary ways to investigate an amplifier's threshold characteristics. By determining the Half-Efficiency Threshold for different values of the input charge, the characteristic relation between measured voltage and input charge can be obtained. This has been discussed in Ref.[8] and the results therein can be parameterized as

$$Q(fC) = e^{0.0033 V_{thr}^{[50\%]}(mV) - 1.25}, \quad (4.4)$$

which is shown in Fig.4.3.

Threshold and amplitude scans

Four tests are implemented in the Front End Test to measure the threshold characteristics of the Front End box channels. The tests differ in which parameter is varied at each step or what type of charges are injected into the Front End box.

The cardinal test is the Threshold Scan. In this, pulses of fixed charge, generated by the Front End Tester setup, are injected into the Front End box, while at each step the threshold setting is increased. Two additional tests, Threshold Scan Test-Pulse Low and Threshold Scan Test-Pulse High, perform the same function, using the Front End electronics test-pulse facility. In the Amplitude Scan on the other hand, the threshold

²Due to the non-linear charge-voltage relation (see Fig.4.3) the width σ_V depends on the input charge; a smaller width is seen for increasing input charges.

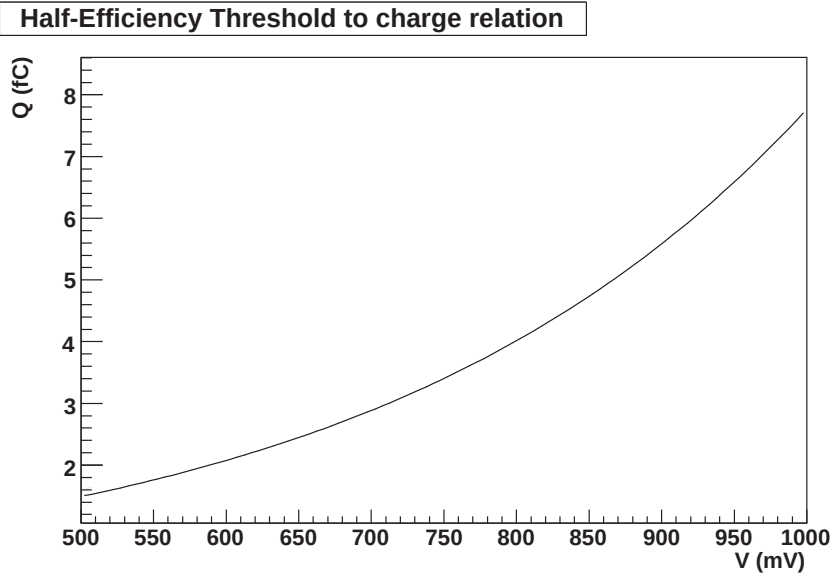


Figure 4.3: A parameterization of the ASDBLR threshold characteristic derived from the results in Ref.[8].

Test	pulse type	held fixed	fC	mV
Threshold Scan	FE Tester	charge	5.5	900*
Threshold Scan TPL	test-pulse	charge	3.5	750*
Threshold Scan TPH	test-pulse	charge	9	1050*
Amplitude Scan	FE Tester	threshold	4*	800
Noise Scan	FE Tester	charge	0	

Table 4.1: Settings of the Threshold and Amplitude Scans. (A star* indicates an equivalent charge or voltage value derived from equation 4.4).

setting is held fixed, while the size of generated input pulses is increased at every step. The settings of each of the four tests are summarized in Tab.4.1.

Inhomogeneities in the charge-injection system (flipper box) cause systematic variations in the amount of charge at the input of different Front End channels. Measuring $V_{thr}^{[50\%]}$ of several boxes determines the systematic variations, which are corrected for in subsequent Threshold Scans.

Fig.4.4(a) shows the Threshold Scan for a particular channel together with an error-function fitted to the data (least squares fit). The fit provides the Half-Efficiency Threshold $V_{thr}^{[50\%]}$, the width σ_V of the error-function and a goodness-of-fit parameter determined as the least-squares error per degree of freedom. Fig.4.4(b) shows the fitted values for all 128 channels of a Front End box in a summary plot.

During preselection, only ASDBLR chips have been selected with a threshold spread smaller than 30 mV at 5 fC input charge (Ref.[8]). In the Front End Test, where

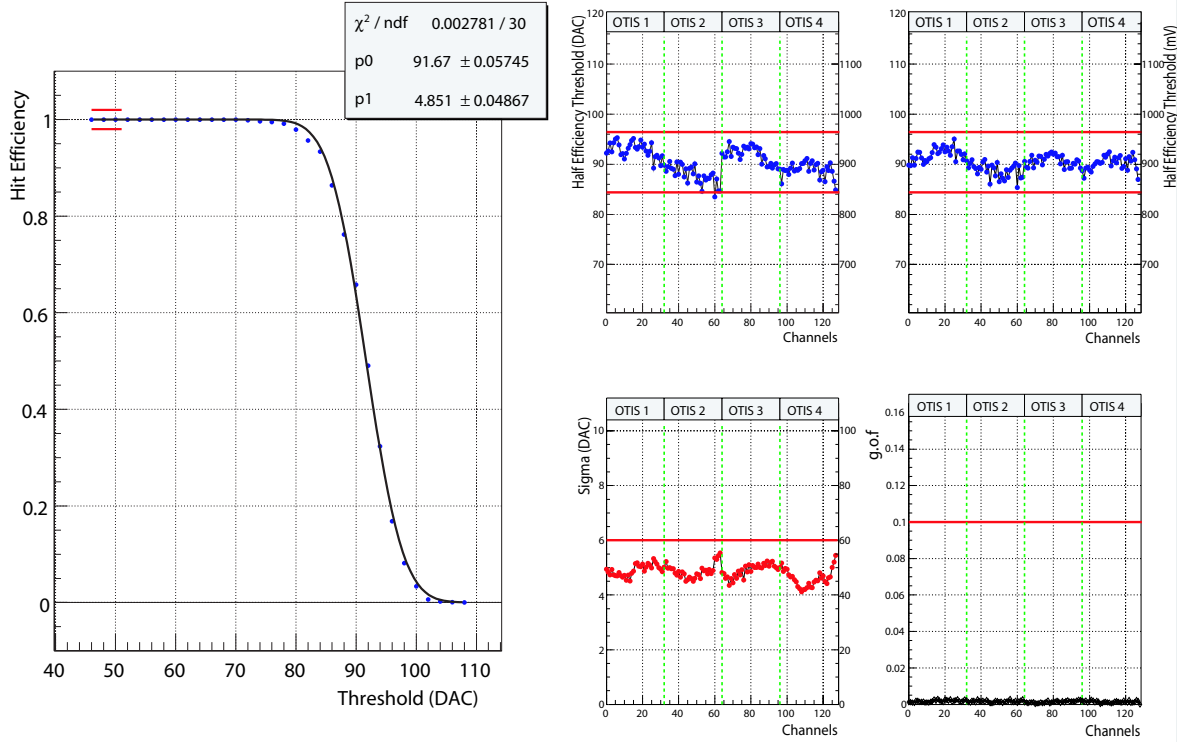


Figure 4.4: (a) Threshold Scan of channel 32 of Front End box 421. An error-function is fitted to the data points. (b) Threshold Scan summary plot for all 128 channels of Front End box 421. The top two plots contain the Half-Efficiency Threshold values of all channels; the one on the right side has been corrected for systematic effects due to inhomogeneities in the charge-injection system. The bottom left plot shows the width and the bottom right plot the goodness-of-fit (g.o.f.).

Test	pulse type	charge (fC)	threshold (mV)
Time-Delay Scan	FE Tester	5.5	800
Latency Scan	Test-Pulse High	9	800

Table 4.2: Settings for the Time-Delay and Latency Scan. The size of input pulses as well as the threshold setting are held fixed.

chips are mounted on ASDBLR boards, the uniformity requirement is a less stringent ± 60 mV (input charge ≈ 5.5 fC), represented by the horizontal lines in the top right plot of Fig.4.4. If any channel is outside of this window, then the corresponding ASDBLR board is replaced. The goodness-of-fit parameter is used to spot channels with abnormal threshold response. The width σ_V is given an upper limit of 60 mV, but no ASDBLR that otherwise performs within specifications has been seen to violate this limit.

The two other threshold scans, Threshold Scan Test-Pulse Low and Threshold Scan Test-Pulse High, in principle measure the same characteristics, but their results are not used for selection. They do, however, rely on the proper functioning of the Front End box test-pulse capability and as such are rather used to check the test-pulse lines to every channel. Defunct test-pulse lines are permitted; only if all the lines of an ASDBLR chip are deviant is the ASDBLR board replaced.

The Amplitude Scan is also closely correlated to the Threshold Scan and is used as a cross-check.

4.1.2 Time linearity check

Four OTIS TDC chips digitize the arrival times of pulses from 32 channels each. Digitization is performed with respect to the 25 ns LHC bunch crossing interval in 64 TDC bins, giving an intrinsic time resolution of 391 ps. Upon a trigger, three consecutive bunch crossings are searched for hits and the first hit (if any) is read out.

The linearity of the digitization procedure is tested with a Time-Delay Scan. In this scan, input pulses of fixed size and generated by the Front End Tester setup are injected into the Front End box at fixed threshold, while the time at which the pulses are administered is increased in steps. The Time-Delay Scan settings are shown in Tab.4.2.

Figure 4.5(a) shows the TDC spectrum for a particular channel at one of the steps of the Time-Delay Scan, where a Gaussian is fit to the histogram. The fitted mean as a function of the pulse delay is shown in Fig.4.5(b). A straight-line is then fit to the data. The straight-line fit results for all 128 channels of a Front End box are summarized in Fig.4.5(c).

The relation between a delay step given by the Front End Tester setup and the physical delay in seconds had not been exactly calibrated. Moreover, delays are generated separately for the front-side channel (1-64) and for the back-side channel (65-128). For this reason, the slopes in Fig.4.5(c) differ between front- and back-side channels and neither of them are strictly equal to one. Therefore, Time-Delay Scans are compared relatively between neighboring channels and between Front End boxes to spot timing discrepancies.

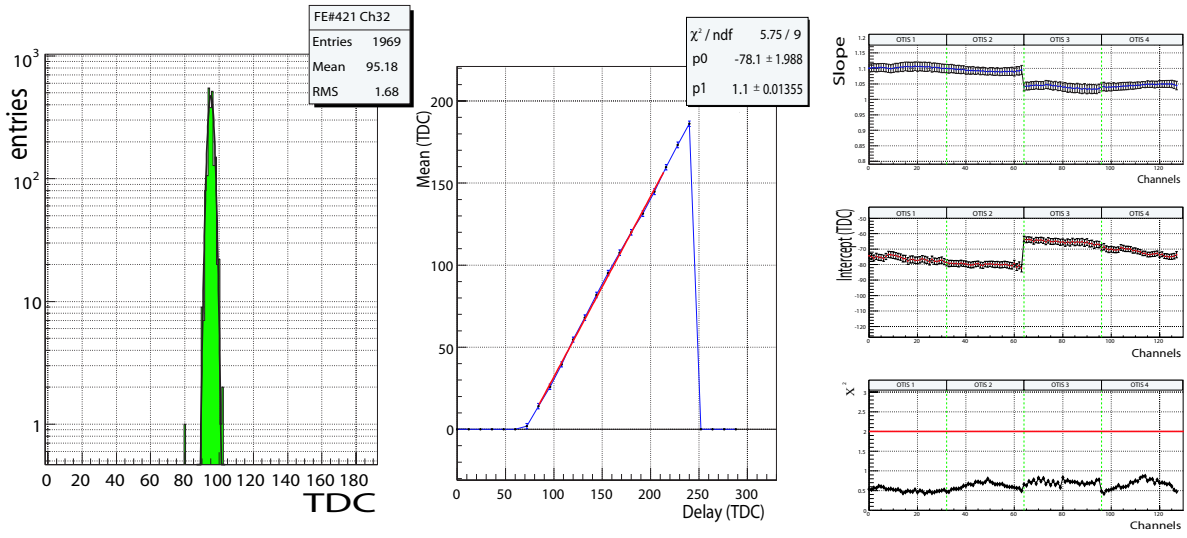


Figure 4.5: Results of a Time-Delay Scan of Front End box 421. (a) One of the steps in a Time-Delay Scan of channel 32. The TDC spectrum is fitted with a Gaussian giving a mean and a width. (b) Time-Delay Scan of channel 32 of Front End box 421. The mean of each step as a function of the delay. A straight-line fit to the data is depicted by the solid line. The x-axis intercept (here at 70 TDC) is due to the Front End Tester setup. (c) The slopes (top), intercepts (middle) and goodness-of-fit (χ^2/dof) (bottom) of the straight-line fits of all channels summarized.

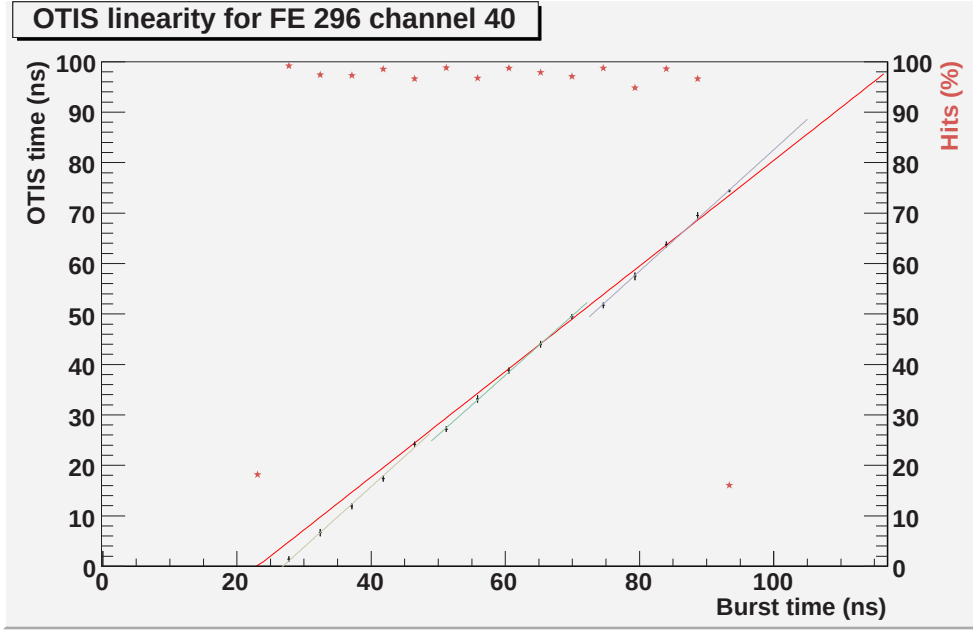


Figure 4.6: *Time-Delay Scan of channel 40 of Front End box 296. The three consecutive bunch crossing in the read-out window are both fit together with a straight line, and fit individually with straight lines. The individual fits result in steeper lines than the global fit does. (The stars and right vertical axis hold the fraction of registered pulses at each delay step.)*

The width of the TDC spectrum is a measure of the timing resolution. By combining all steps and all channels the timing resolution of a Front End box in the Front End Test setup has been estimated to be 1.3 TDC bins or 0.5 ns (Ref.[21]).

The time linearity is affected by a systematic effect shown in Fig.4.6, that has been labeled the *large bin-0 effect*: for every 64 TDC bins, in which the 25 ns bunch crossing interval gets divided, the zeroth bin is anomalously large at the expense of the sizes of the following 63 bins. As a result the linearity in one bunch crossing exhibits a steeper slope and appears to be somewhat shifted/delayed with respect to the previous bunch crossing. This observation triggered a systematic analysis of the OTIS' *Differential Non-Linearity*, which is discussed in more detail in the next section 4.2.

4.1.3 Synchronization

Drift time information is stored in a 4 μ s pipeline buffer in the OTIS chip awaiting an L0 trigger decision. The Latency Scan tests whether all channel pipelines work in phase. The test settings can be read from Tab.4.2.

During the test the pipeline pointer offset (latency) is varied in steps of 12.5 ns (half bunch crossings). All channels should show the same six steps containing valid hits. If not, the appropriate OTIS board is replaced.

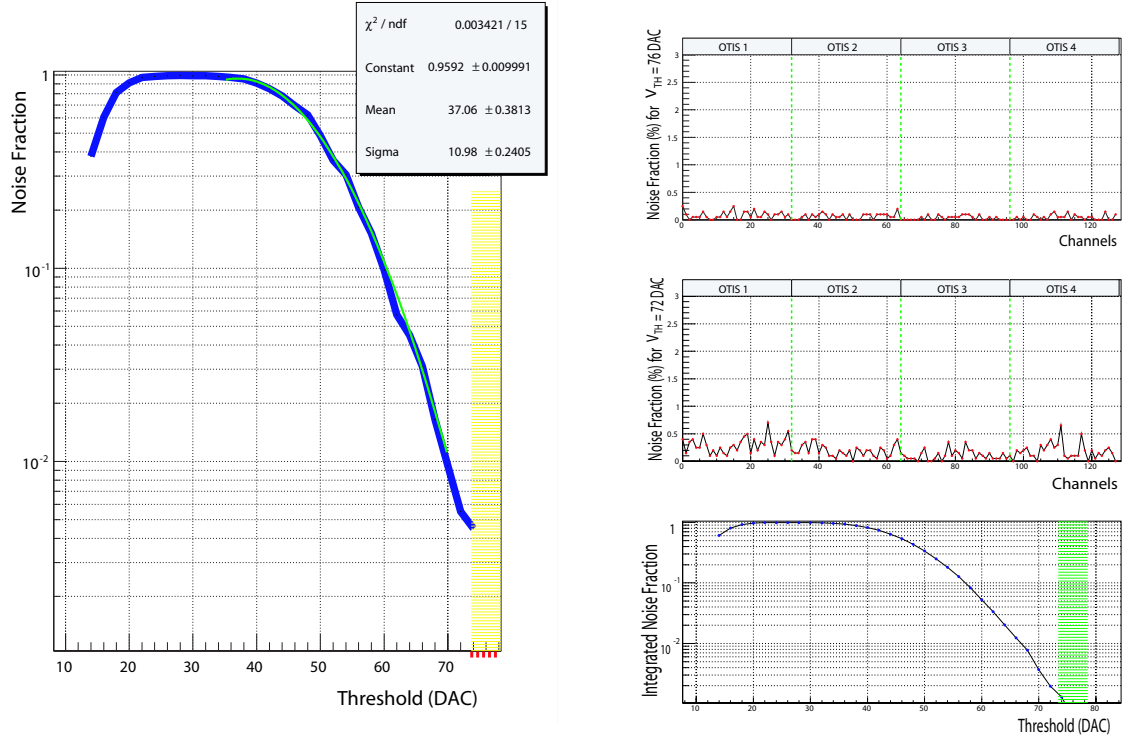


Figure 4.7: (a) Noise Scan of channel 32 of Front End box 421. (b) Noise Scan summary plot for all 128 channels of Front End box 421. The top and the middle plot contain the noise fraction in percent of all channels for threshold settings of 760 mV and 720 mV respectively. The bottom plot shows the channel-average noise fraction as a function of threshold setting.

4.1.4 Noise pickup

In the Noise Scan, the rate of noise hits is measured as a function of discriminator threshold. To this end the Front End box is not supplied with any input pulses, while the threshold setting is increased. The noise rate is the fraction of the 2000 triggers in which a hit is registered.

Fig.4.7(a) shows the Noise Scan results for a particular channel. Above a threshold setting of 40 DAC $\approx 400 \text{ mV}$, the noise rate drops off rapidly to below 1% for thresholds over 70 DAC $\approx 700 \text{ mV}$, comparable to operational settings (typically 800-900 mV). For extremely low threshold settings below 20 DAC the amplifier goes into oscillation, which tends to saturate the output signal and shows up as a decrease in hit rate.

Fig.4.7(b) shows a summary of the Noise Scan of all 128 channels of a Front End box. If any channel had a noise rate higher than 1% at a threshold of 760 mV, the corresponding ASDBLR was replaced.

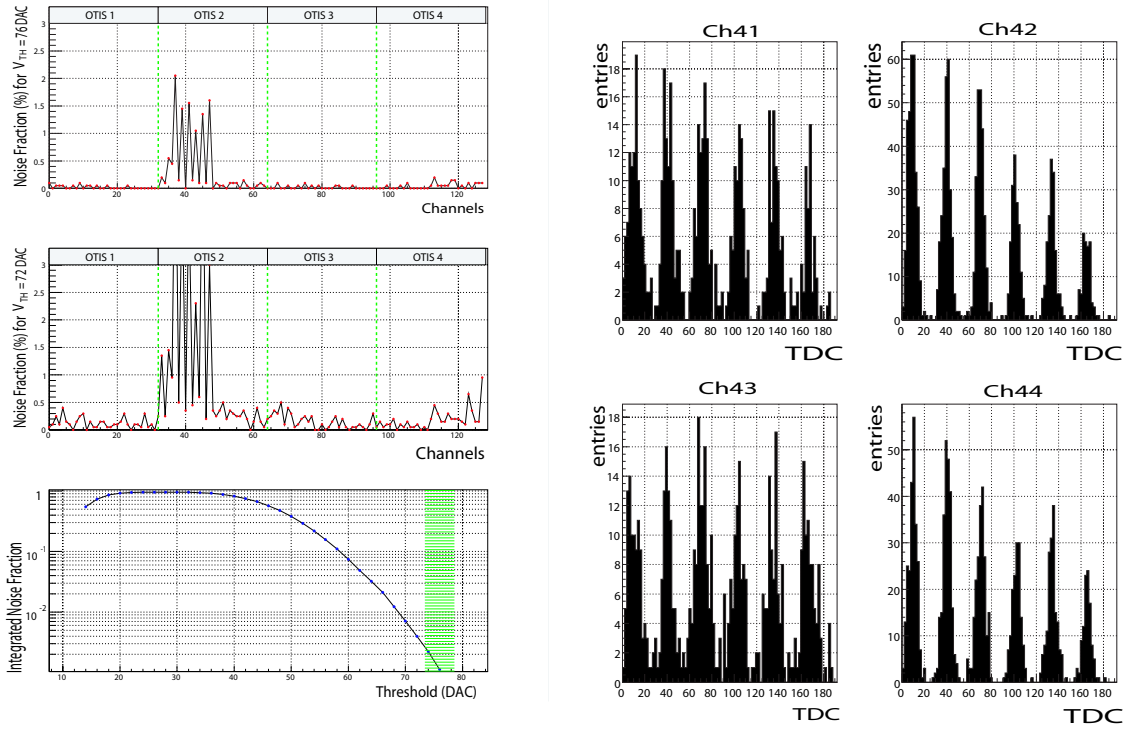


Figure 4.8: (a) *Noise Scan summary plot of Front End 359. A high noise rate is seen for channels 32-47. (b) A closer look at the drift-time spectra obtained with the Noise Scan for high noise channels (at a threshold setting of 540 mV) shows a 80 MHz pickup.*

Bunch clock pickup

Some channels were found to exhibit a high noise rate, as is shown in Fig.4.8(a). Looking at the drift-time spectra for these channels as in Fig.4.8(b) the pickup of a 80 MHz signal was clearly identified as the cause. A detailed investigation showed the culprit to be a trace in the OTIS board, running close to the OTIS chip and picking up the 40 MHz bunch crossing clock, which induces a signal in the affected channels on its up- and down-going flanks.

The clock pickup problem is suppressed by shielding all OTIS chips of the Front End box front- and right-side OTIS with a copper cover.

4.2 OTIS Differential Non-Linearity

During the course of Front End box quality control measurements, a slight but systematic channel non-linearity was observed for some Front End channels (see Fig.4.6). The channel drift-times are digitized with respect to the 25 ns LHC bunch crossing interval in 64 TDC bins. Ideally, all TDC bins have the same size; the *Differential Non-Linearity*, or DNL, is the degree in which the 64 TDC bins differ in their sizes.

The measurement of DNL has been an integral part in the production and testing of the OTIS TDC chip (Ref.[12]). However, the observed non-linearity triggered the re-analysis of the OTIS DNL. On the one hand a dedicated test was created to examine the bin structures of a selected set of Front End boxes. On the other, previously performed tests were more closely scrutinized with respect to DNL, to cross-check the findings of the dedicated test. Thus, the OTIS Differential Non-Linearity has been studied with three methods.

1. Dedicated tests with a random pulser.
This systematically studies the DNL's dependence on supply voltages and temperature for a selection of Front End boxes.
2. A re-analysis of the OTIS Tester results.
The OTIS Tester is a setup to determine the functionality of OTIS boards prior to their mounting into a Front End box. As part of the test, the DNL for channels 0, 15, 16 and 31 is measured.
3. A re-analysis of the Noise Scans made with the Front End Tester.
Although not specifically designed for the task, a Noise Scan does provide insight into the sizes of TDC bins.

The Differential Non-Linearity measures the degree in which the TDC bins differ in their sizes. Typically the DNL of a channel is determined with a measurement where many pulses are generated at random times. If the randomly generated times have a flat probability distribution, then the number of hits recorded in each TDC bin is proportional to the size of that bin. If N_i is the number of hits recorded in TDC bin i , then the DNL of bin i is defined as the difference in hits between itself and its preceding neighbor:

$$\text{DNL}_i \stackrel{\text{def}}{=} \frac{N_i - N_{i-1}}{\langle N \rangle}, \quad (4.5)$$

where $\langle N \rangle$ is the average number of hits per TDC bin and where bin number 0 is compared with the last bin number 63. The DNL of the channel is subsequently defined as the difference between the maximum and minimum DNL_i -values:

$$\text{DNL} \stackrel{\text{def}}{=} \max(\text{DNL}_i) - \min(\text{DNL}_i) \quad (4.6)$$

As such, the DNL is a measure of the maximum variation in bin sizes. The same measure, but expressed in units of time, is:

$$\Delta\text{TDC}(ps) \equiv \text{DNL} \times 390.625(ps). \quad (4.7)$$

Figure 4.9 shows drift-time spectra obtained with random input pulses. The difference in size between even and odd TDC bins is immediately visible. The reason for this *even-odd difference* can be found in the delay elements of the OTIS Delay Locked Loop (Fig.2.7). The DLL consists of 32 delay elements where each element has two delay stages. Since the two delay stages see different capacitive loads, they may give rise to

different time delays, i.e. different TDC bin sizes. Note that although the even and odd delay stages are separated, the total delay of all 32 elements will still be locked to one clock cycle. From the definition in Eq.4.6, the maximum DNL value arising from an even-odd difference is 4.

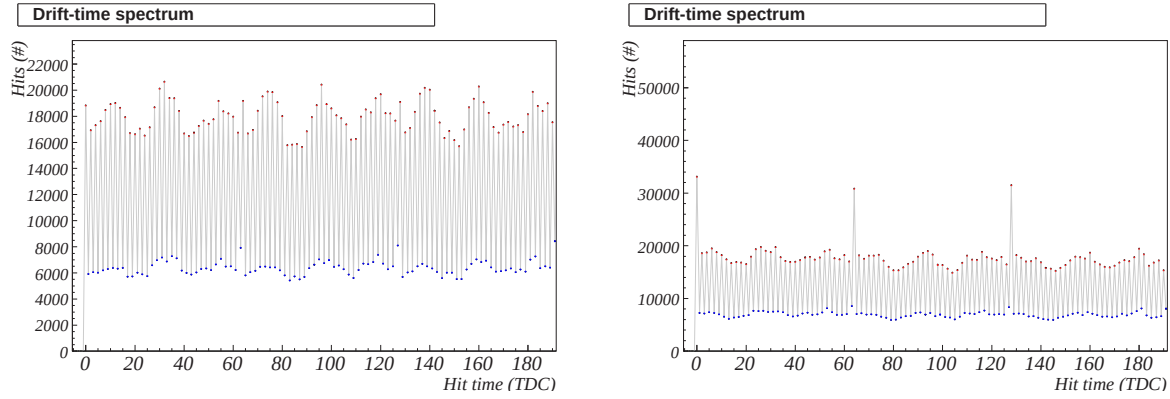


Figure 4.9: Two examples of a drift-time spectrum, where the 192 TDC bins (75 ns) readout window is randomly filled with hits. (a) An even-odd difference is seen for OTIS 3 of Front End 087 at 66 °C (32 channels combined). (b) A large bin 0 in each bunch crossing is seen in addition to an even-odd difference for OTIS 3 of Front End 087 at 25 °C (32 channels combined).

Fig.4.9(b) in addition exhibits the so called *large bin-0 effect*, the actual cause for the slight non-linearity observed with the Front End Tester (see Fig.4.6). The zeroth TDC bin of each bunch crossing cycle (bins 0, 64 and 128 in Fig.4.9(b)) is considerably larger than the subsequent bins.

The TDC bin structure, and thus DNL, depends on the analogue and digital OTIS supply voltages VddA and VddD, respectively. These dependencies had been studied for a previous version of the OTIS chip (Ref.[12]). For that version the TDC bin-0 had been found to actually have a substantially smaller size. The cause was a “slow running” DLL (see the paragraph on the OTIS in section 2.2 for an explanation of the DLL): each delay element adds a delay that is greater than nominal; the zeroth delayed clock is compared with the last, which has caught up significantly, leaving just a small period for hits to correspond to the zeroth delay stage. This type of behavior was deemed dangerous, since the potential “disappearance” of the bin-0 altogether triggers a fault in the logic that will render the result of the hit finding undefined.

The OTIS’ analogue and digital supply voltages are set by resistors on the GOL/Aux board. The slow running DLL was corrected temporarily by a change in the values of the VddA/VddD combination, and structurally in a subsequent OTIS chip submission. The effect in Fig.4.9(b) is essentially the result of an “over-correction”: a “fast running” DLL, where each element adds a delay that is smaller than nominal. The hit finder compares the zeroth delay stage with the last, 63rd, which has not sufficiently caught up, causing a disproportionally large period for hits to correspond to the zeroth delay stage. Tuning this over-correction could be achieved by a different choice of VddA/VddD,

which is the subject of the following dedicated studies of DNL.

4.2.1 DNL from dedicated tests

The bin structure dependence on supply voltages and temperature is studied in Front End boxes equipped with a modified GOL board, with which the supply voltages can be varied and the temperature can be measured. The Front End box is supplied with pulses that have a flat time distribution. The Front End boxes and settings in the dedicated DNL tests, described below, are summarized in Tab.4.3.

		VddA/D scan	temperature scan
FE	OTIS		VddA/D
295	OBL0626 OBR0956 OBL0494 OBR0528	yes	
323	OBL0021/0650 OBR1081 OBL0310 OBR0156	yes	2.3/2.5 V 2.4/2.6 V 2.5/2.5 V 2.5/2.7 V
385	OBL0235 OBR0985 OBL0416 OBR1026	yes	
87	OBL0844 OBR0923 OBL0755 OBR0878	yes	2.7/2.5 V
394	OBL1032 OBR0364 OBL0742 OBR1035		2.7/2.5 V

Table 4.3: Front End boxes and settings in dedicated DNL tests, as described in the text. The setting VddA/D=2.7/2.5 V is the operational setting implemented in the current and final OTIS version.

DNL vs. VddA/D

The bin structure is measured for various combinations of the analogue and digital supply voltages. Fig.4.10 shows the results for one of the OTIS for different combinations. Based on the various Front End boxes and combinations (Tab.4.3) three qualitative trends are observed.

1. The even-odd difference in the sizes of TDC bins scales with the difference between VddA and VddD.
2. Large bins 0, 64 and 128 are observed for large values of VddA (2.6-2.7 V).
3. An excessive amount of hits in bin 0, but not in bins 64 and 128, is seen for small values of VddA (2.2-2.3 V).

The last behavior at small V_{ddA} is the result of a slow running DLL: as previously pointed out, this can ultimately lead to undefined values, which are assigned the digital drift-time 00 000000, causing a disproportionally large number of measured hits in the very first bin (number 0).

The operational supply voltage $V_{ddA}=2.7$ V on the contrary ensures a large bin 0 in every bunch crossing (a fast running DLL). Although such large bin 0 contributes to the DNL, it was deemed a safer choice than the precarious behavior that occurs at low V_{ddA} settings.

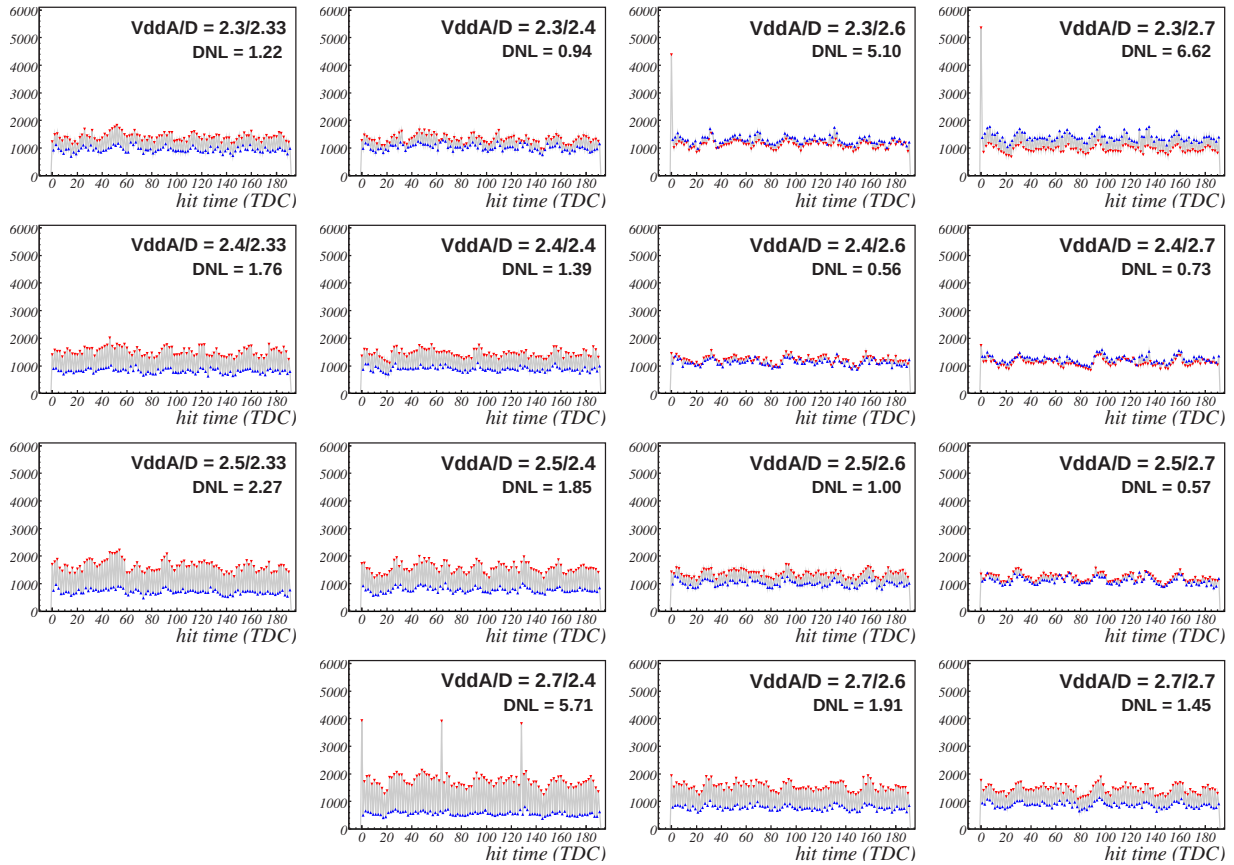


Figure 4.10: *TDC structure of Front End 323 OTIS 4 for various combinations of analog and digital supply voltages V_{ddA} and V_{ddD} . (Combinations including $V_{ddA}=2.2, 2.6$ V or $V_{ddD}=2.5$ V are not shown. For these see Ref.[23].)*

DNL vs. temperature

The temperature of the electronics was measured in several places in different ways. A Negative Temperature Coefficient thermo-resistor (NTC) is part of the GOL board in every Front End box. In addition a thermocouple was placed close to the thermo-resistor and a Pt100 temperature probe on the front side of the GOL board. Finally a Pt100 probe was mounted directly on the OTIS chip. In Fig.4.11 are displayed how the electronics warms up over time and the relation between the GOL and OTIS

temperature. After an hour the electronics reaches a stable temperature, with the GOL chip at 55° and the OTIS at 40°.

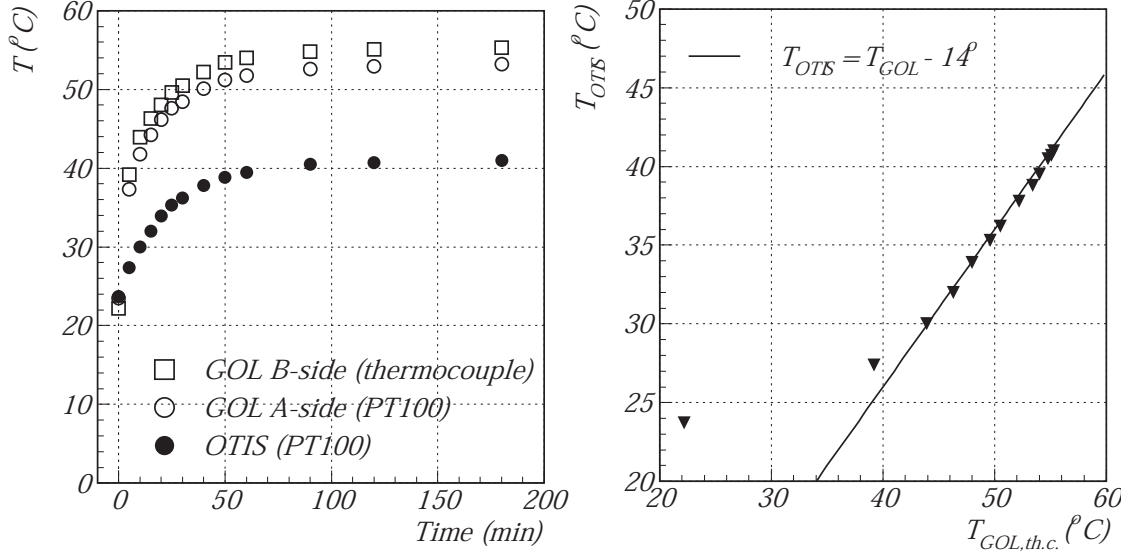


Figure 4.11: Temperature evolution of a Front End box without cooling and the relation between OTIS and GOL temperatures.

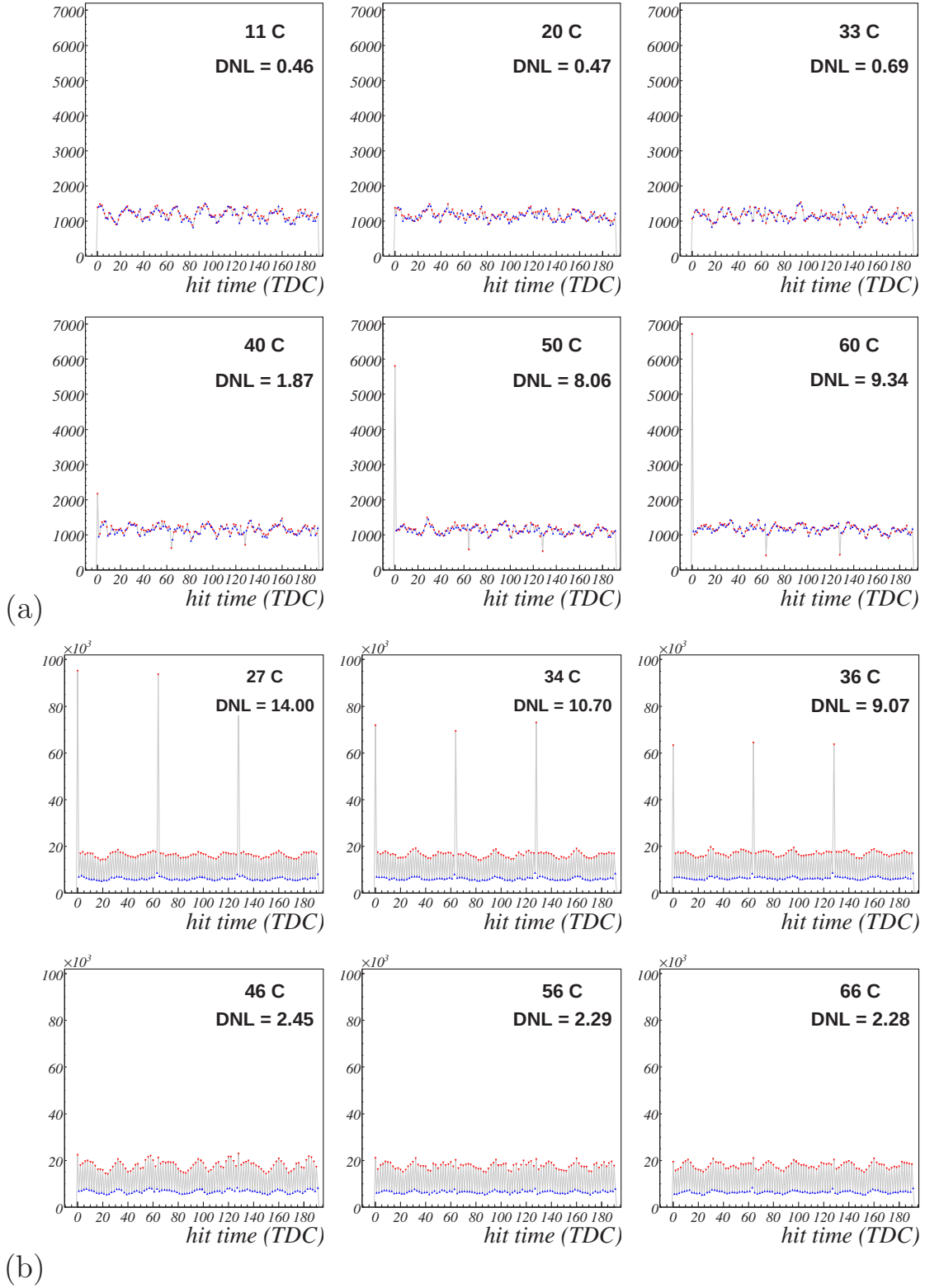
To see the effect of temperature on the DNL, the TDC bin structure is measured as a function of temperature for various settings of the analogue and digital supply voltages. Results for the operational setting $V_{ddA}/D = 2.7/2.5$ V and the setting $V_{ddA}/D = 2.3/2.5$ are shown in Fig.4.12. For $V_{ddA}/D = 2.7/2.5$ V (Fig.4.12(b)) the sizes of the bins 0, 64 and 128 decrease with increasing temperature, while for $V_{ddA}/D = 2.3/2.5$ V (Fig.4.12(a)) the very first bin (bin number 0) is observed to grow with increasing temperatures; the result of the undesired behavior due to a slow running DLL. These observations support the choice of a rather large analogue supply voltage of $V_{ddA}=2.7$ V.

The distribution of bin sizes of Front Ends 87 and 394 for the operational supply voltages $V_{ddA}/D = 2.7/2.5$ V are shown for various temperatures in figures 4.13 and 4.14 respectively, which shows the sizes of all TDC bins of all 128 channels of the Front Ends. The bin size is calculated as:

$$\text{bin size (ps)} = 75 \text{ (ns)} \times \frac{N \text{ hits in bin}}{N \text{ hits in readout window}}. \quad (4.8)$$

The temperatures shown correspond to operational temperatures; on May 21 2010 GOL temperatures ranging from 27°C to 45°C were registered in situ in the detector (peaking around 34°C).

Fig.4.15 shows the distribution of the ratio (average odd bin size)/(average even bin size). The ratio varies between 0.2 and 0.5 with on average the odd-numbered bins being a factor 0.4 smaller than the even-numbered bins. The ratio is fairly constant with temperature.



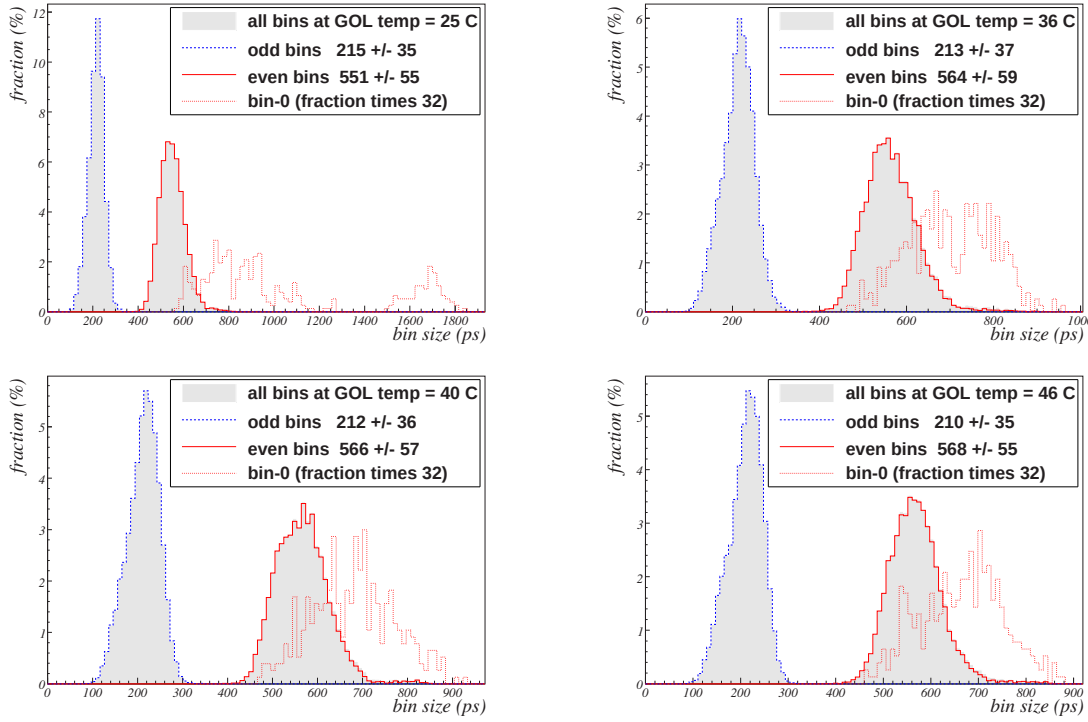


Figure 4.13: Bin size distributions at operational supply voltages $V_{ddA/D} = 2.7/2.5$ V of Front End 87 for various GOL temperatures.

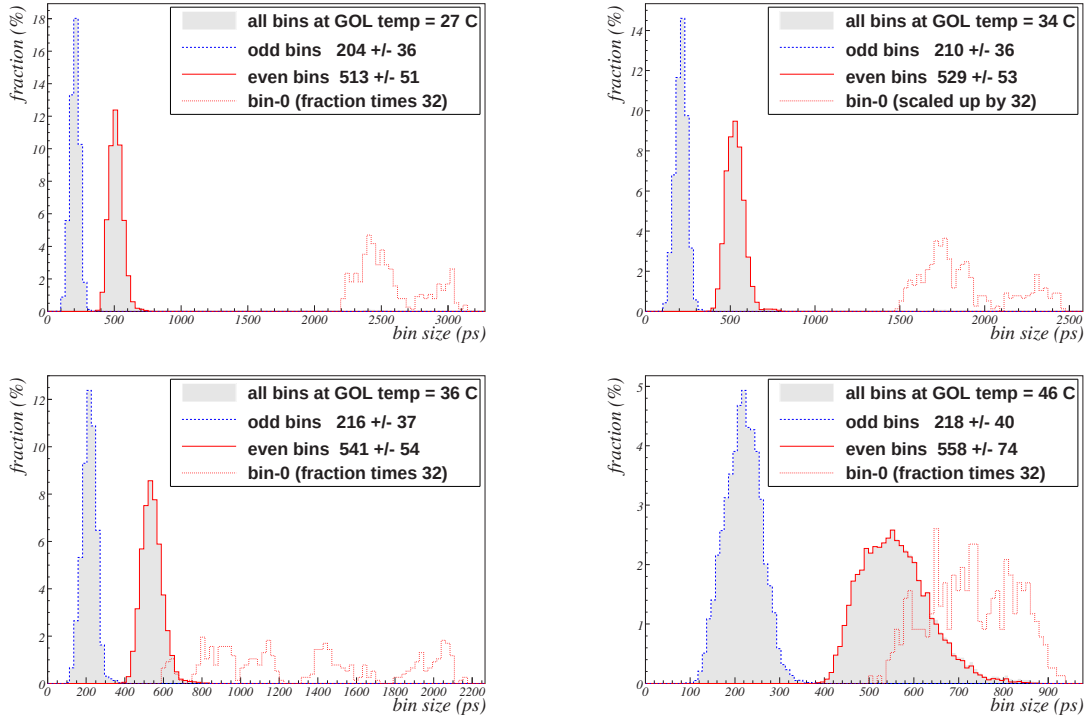


Figure 4.14: Bin size distributions at operational supply voltages $V_{ddA/D} = 2.7/2.5$ V of Front End 394 for various GOL temperatures.

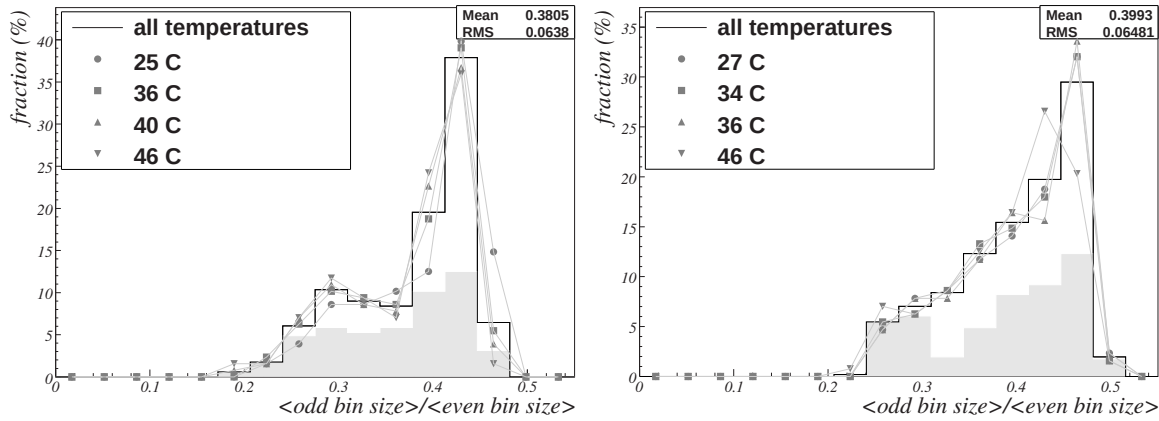


Figure 4.15: Ratio of average odd bin size over average even bin size (excluding bins 0, 64 and 128) for channels of Front End box 87 (left) and 394 (right) at operational analogue and digital supply voltage setting ($V_{ddA/D} = 2.7/2.5$ V) and temperatures. (The shaded regions are from the even channels, the blank regions from the odd channels.)

4.2.2 DNL from OTIS Tester

The OTIS chips, once bonded on to the OTIS boards, were subjected to functionality tests before and after glob'topping³, preceding the boards' assembly onto Front End boxes. For this, an extended version of the existing OTIS wafer tester had been used (Ref.[12]). In particular, with one million random test-pulses (of type Test-Pulse High) the DNL was acquired, but only for channels 0, 15, 16 and 31.

During the tests, the TDC spectra of the four channels were not inspected, merely their DNL values were registered: in practice OTIS boards were accepted when all four channels showed DNL values below 9 and tagged as "HIGH-DNL" otherwise.

Following the non-linearity studies, the OTIS Tester results were more closely scrutinized on the TDC bin structure. Fig.4.16(a) shows an example OTIS Tester result. The high DNL values are due to the large bin-0. This was generally found to be the case for boards tagged as "HIGH-DNL", confirming the high bin-0 effect as the cause for the slight non-linearities.

Apart from a high bin-0 (and an even-odd difference), a further structure can be observed that is common to all OTIS Tester results: a larger amount of hits in the first 100 TDC bins than in the following bins. This structure was shown to be an artifact of the OTIS Tester setup, that vanishes if the threshold is increased⁴.

In Fig.4.17 the DNL values of all accepted OTIS boards are shown.

³Covering the chips with a protective layer.

⁴In the OTIS Tester setup, the inputs of the amplifiers are not properly terminated, thereby giving rise to signal reflections.

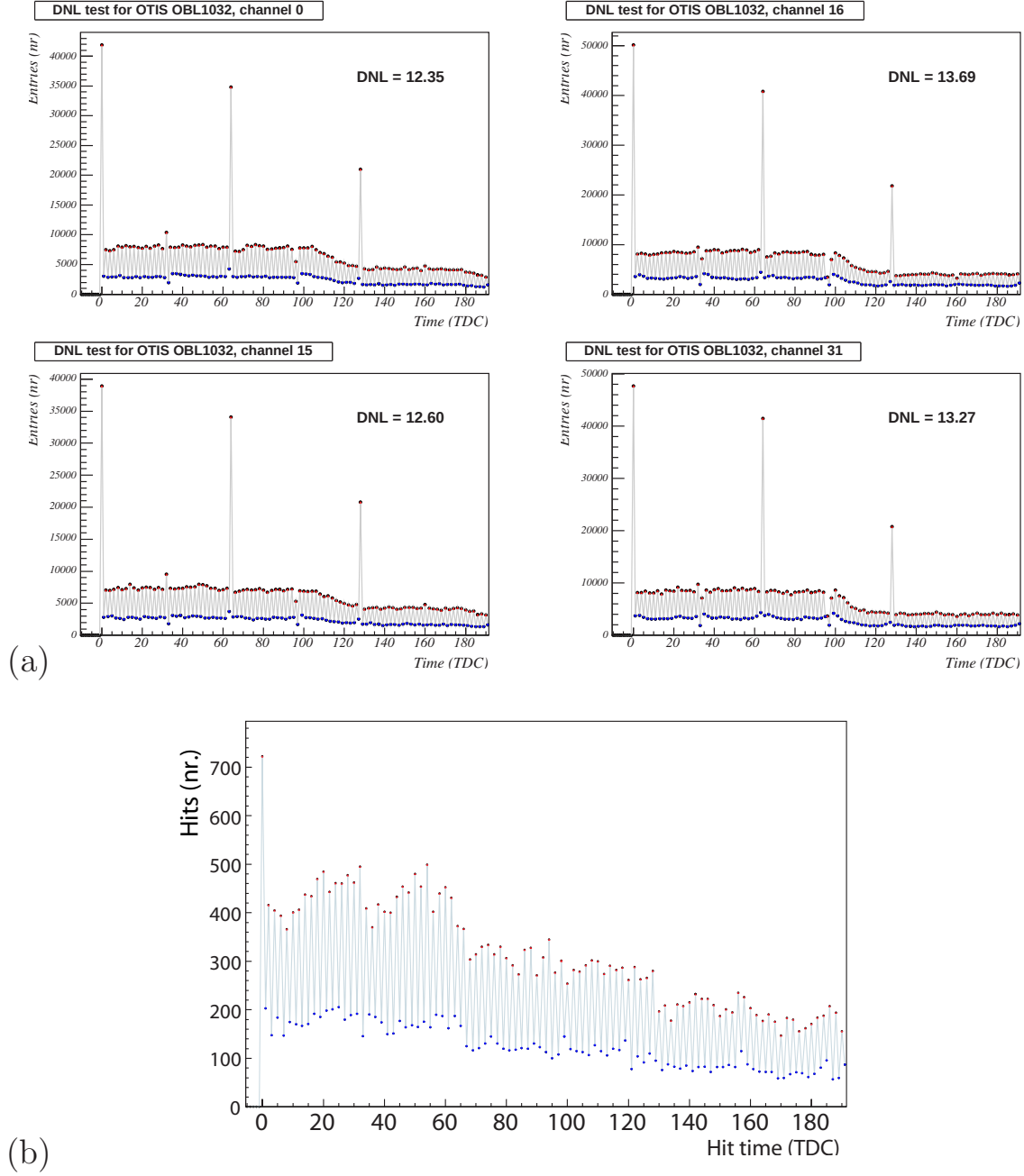


Figure 4.16: Test results for OBL1032 (FE394 OTIS1). (a) OTIS Tester results. The DNL is dominated by the large bin-0. (b) Noise Scan spectrum at 440 mV threshold (all channels combined). The bin-0 is less prominent.

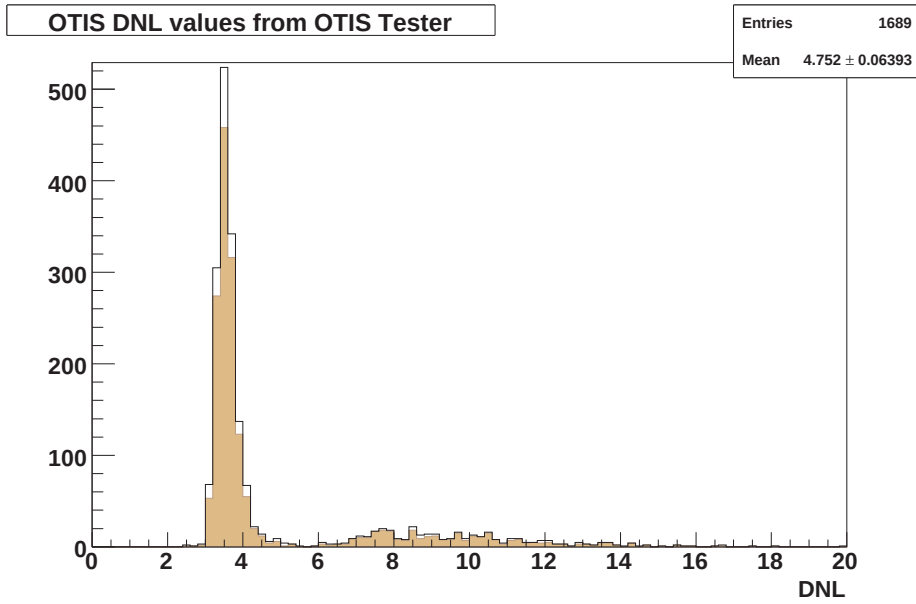


Figure 4.17: *OTIS board DNL's as measured by the OTIS Tester. The DNL values are the averages of four channels (channels 0, 15, 16 and 31), obtained from the last OTIS Tests performed on each OTIS boards. The filled region are DNL values from OTIS boards that are implemented in the Front End electronics boxes (the other are spare or rejected for different reasons). Of these, the majority of channels have DNL values between 3 and 5 and OTIS with DNL values greater than 5 constitute 19% of the total.*

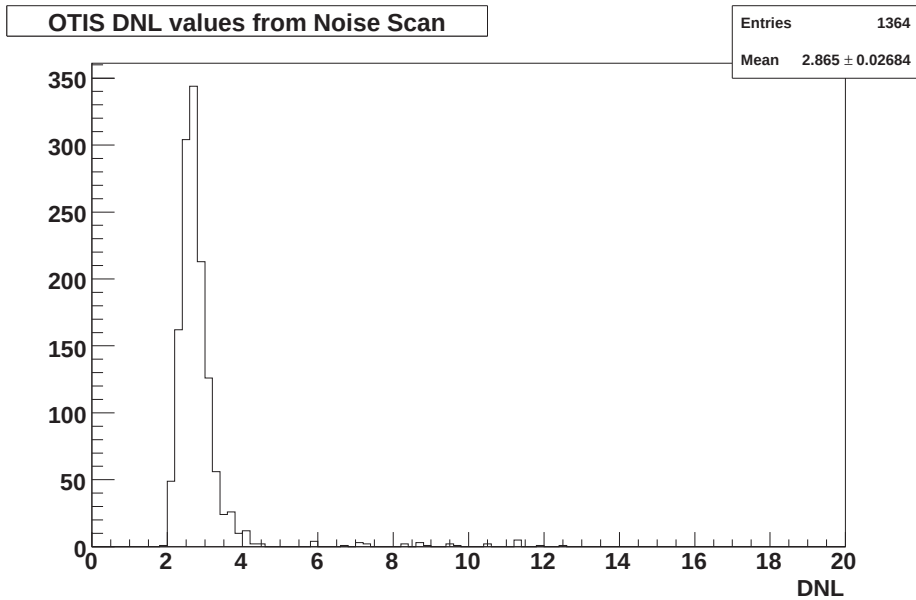


Figure 4.18: *OTIS board DNLs as estimated from Noise Scans. The DNL values are those of 32 OTIS channels and three bunch crossing intervals combined, at a threshold value of 440 mV.*

4.2.3 DNL from noise scans

The Noise Scan, as part of the Front End Test, records hits for all 128 channels of a fully assembled Front End box. A total of 2000 triggers are given, while no input signal is supplied to the Front End, in order to determine the noise rate (see Sec.4.1.4). The noise data were also used to study the DNL.

At operational threshold values above 700 mV the noise rate is around 10^{-3} and produces too little statistics for the study of Differential Non-Linearity. Therefore, noise measurements at lower threshold values are used. To further increase the statistics, the responses of all 32 channels of one OTIS chip are combined.

Fig.4.16(b) shows the TDC spectrum as obtained with a Noise Scan⁵. Comparing two plots, it is clear that the high bin-0 is less prominent in the Noise Scan. The same observation can be made by comparing Fig.4.18, showing the DNL's of all OTIS boards obtained from Noise Scans, to Fig.4.17. From the Noise scans the DNL values are generally smaller than those obtained with the OTIS Tester. The Noise Scan is performed as one of the last scans in the Front End Test procedure, at a point where the Front End box has been warmed up, in contrast to an OTIS Test and also to the Linearity Scan, which is the first one performed in a Front End Test. The difference between OTIS Test and Noise Scan confirms the temperature dependence of the DNL, where the large bin-0 effect decreases with temperature (Fig.4.12(b)).

4.2.4 DNL conclusion

Drift-time measurement in Outer Tracker channels is performed by the OTIS TDC chips in the Outer Tracker Front End electronics boxes. Each 25 ns bunch crossing interval is divided into 64 TDC bins, which ideally have an equal size of 391 ps.

Deviations in bin size from the ideal 391 ps are described by a channel's Differential Non-Linearity, or DNL. The DNL has been shown to depend on the OTIS analogue and digital supply voltages VddA and VddD and on the OTIS temperature.

In the OTIS, DNL is caused by a difference in even and odd TDC bin sizes and by a disproportionally large bin-0. An even-odd difference can cause at most a DNL of 4; higher DNL values indicate a large bin-0 effect.

At the operational supply settings ($V_{ddA/D} = 2.7/2.5$ V) and temperature (25° - 45°), the greater part of the channels ($>80\%$) have a DNL value below 5, with the odd TDC bins being on average a factor 0.4 smaller than the even TDC bins and the bin-0 having a size less than 1.2 ns.

A disproportionally large bin-0 causes a shift in time of the subsequent TDC bins. If a large bin-0 effect and even-odd differences are not taken into account, then this biases the time measurement for high DNL values towards smaller hit times.

Fig.4.19 shows the difference between the real hit time and the measured hit time assuming equal size bins (391 ps), as a function of the measured hit time, for different

⁵The Noise Scan spectrum shows a decline, which is inherent in the drift time measurement; a hit at an early time negates the possibility to register a hit at a later time in the same 75 ns readout window. No attempt has been made to compensate the DNL for this trend.

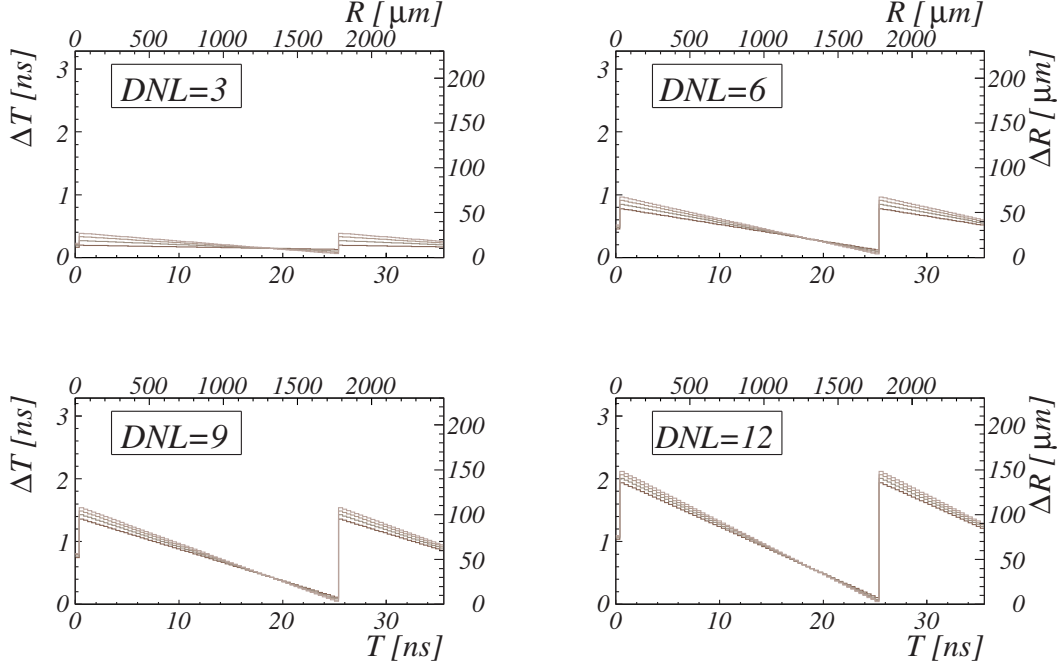


Figure 4.19: The difference between real hit time and measured hit time (i.e. the hit time assuming equal size bins), as a function of the measured hit time and for different DNL values. For each DNL value, different values of $\langle \text{odd bin size} \rangle / \langle \text{even bin size} \rangle$ are drawn (0.2, 0.3, 0.4 and 0.5). The R and ΔR axis are acquired assuming a linear RT -relation with an average drift velocity of $70 \mu m/ns$.

DNL values. The difference in real and measured track distance is shown as well, assuming a linear RT -relation with an average drift velocity of $70 \mu m/ns$ (Ref.[9]).

For the small portion of channels with abnormally high DNL values a bias is introduced that is up to $\sim 100 \mu m$, to be compared to the Outer Tracker resolution of $\sim 200 \mu m$. However, for common DNL values around 3, which compose the vast majority of channels, the bias in distance is estimated to be small (less than $30 \mu m$). In the current Outer Tracker detector the Differential Non-Linearity will not be a limiting factor on the drift time resolution.

Part II

Single-particle efficiencies from multi-body processes

Chapter 5

Motivation

In LHC***b*** the decay $B_d \rightarrow \mu^+ \mu^- K^*$ is a benchmark measurement in the search for physics beyond the Standard Model. With a branching fraction of 1.05×10^{-6} it is considered a rare B decay. The (new) physics of the decay is encoded in the distribution of three decay angles θ_l , θ_k and ϕ and the invariant mass squared q^2 of the dimuon pair. These angles are illustrated in Fig.5.1

The angular distributions with which the outgoing particles originate from the decay are sensitive to new physics contributions, which can advance these distributions beyond their Standard Model prediction. Particularly interesting is the relation between q^2 and the angle θ_l . The distribution of this angle shows a sizable asymmetry, where the μ^+ comes out in a preferred direction, which depends on the dimuon invariant mass. This *Forward-Backward Asymmetry* (AFB) is predicted by the Standard Model, but can be significantly altered by new physics contributions as is shown in Fig.5.2.

However, the angular distributions are also sensitive to an experimental inefficiency. Momentum dependent efficiencies such as detector acceptance, trigger and event selection can favor certain decay angles over others and thereby affect the measured angular distributions. An analysis of $B_d \rightarrow \mu^+ \mu^- K^*$ thus requires the effects of an experimental inefficiency on the angular distributions to be determined if new physics is to be measured. Different strategies exist for this task, which all have their merits and their drawbacks.

A typical way to estimate the event efficiency is to obtain it from a Monte Carlo simulation, where the entire experiment is simulated, including event generation, detector response simulation, triggering, reconstruction and event selection. Determining efficiencies from simulation relies on the proper description of the detector for many aspects such as the event multiplicity, the detector material, response, resolution, magnetic field and alignment. It requires good understanding of the detector and confidence that all known data-Monte Carlo discrepancies are properly taken into account. This strategy has been employed for the first LHC***b*** measurement of $B_d \rightarrow \mu^+ \mu^- K^*$ (Ref.[24]); the resulting AFB is shown in Fig.5.3.

An alternative way considered in this thesis is to determine the efficiency from control channels, i.e. from channels with a similar event topology but for which the underlying physics is well known. The control channel efficiency is known by comparing its mea-

surement with its theoretically well known underlying distribution without the need for a detector simulation. Such a strategy, however, relies on the overlap between the control channel and the signal channel.

The decay $B_d \rightarrow J/\psi K^*$ is a typical control channel for the signal channel $B_d \rightarrow \mu^+ \mu^- K^*$. Its decay amplitude is dominated by Standard Model physics and its angular distributions have been measured to great precision at the B -factories. The control channel involves the same outgoing particles, but since the dimuon invariant mass in the control channel is restricted to the J/ψ mass, it does not access the entire phase space that the signal channel occupies.

The limited overlap between signal and control channel faces this strategy with a difficulty. If one intends to get the efficiency in terms of the decay angles, then the control channel can only determine this for one specific value of the dimuon invariant mass and not for the entire range needed by the signal channel. On the other hand, the experiment does not “see” the decay angles, but rather the experiment is efficient or inefficient in measuring the outgoing particles and their momenta. One can therefore propose that the efficiency is the product of efficiencies to measure the outgoing particles, expressed in terms of their momenta.

This proposition is one of *efficiency factorization*, the assumption that the total event efficiency is the product of efficiencies to measure the outgoing particles individually, i.e. the product of *single-particle efficiencies*. Under this assumption the total efficiency in signal channel and in control channel are built from the same single-particle efficiencies, regardless of the limited overlap in decay topology. After determining the single-particle efficiencies from the control channel, they can be combined to correct the angular distributions of the signal channel for efficiency effects.

In Ch.6 an iterative method is introduced that determines single-particle efficiencies from a multi-body control channel. The method is developed in Sec.6.2 and validated against a toy efficiencies in Sec.6.3. Then in Sec.6.4 it is used on full Monte Carlo simulation in an exercise to obtain the single-particle efficiencies from the control channel $B_d \rightarrow J/\psi K^*$, and use these to correct the angular distributions in the signal channel $B_d \rightarrow \mu^+ \mu^- K^*$ for efficiency effects.

The iterative method was developed as a way to correct the angular distributions in $B_d \rightarrow \mu^+ \mu^- K^*$ for efficiency effects. However, the first 2010 LHC***b*** measurements had insufficient data to perform the efficiency correction. On the other hand the applicability of the iterative method extends beyond determining single-particle efficiencies, and it has been chosen to use this method to determine particle asymmetries, rather than efficiencies, from measurements of charm meson decays. This completely data-driven analysis is described in Ch.7.

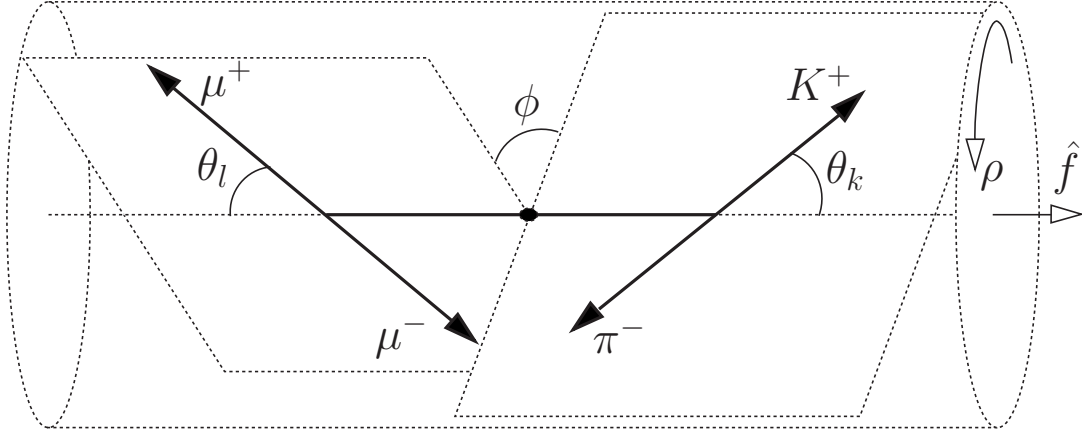


Figure 5.1: Geometrical definition of the decay $B_d \rightarrow \mu^+ \mu^- (K^* \rightarrow K^+ \pi^-)$. The angles are defined as follows:

- θ_l is the angle in the dimuon rest frame between the direction of the positively charged muon and the negative K^* flight direction. For the conjugate decay $\bar{B}_d \rightarrow \mu^+ \mu^- (\bar{K}^* \rightarrow K^- \pi^+)$ the angle is taken with the negatively charged muon.
- θ_k is the angle in the K^* rest frame between the direction of the kaon and the positive K^* direction.
- ϕ is the angle between the decay planes of the K^* and the dimuon pair in the B_d rest frame.

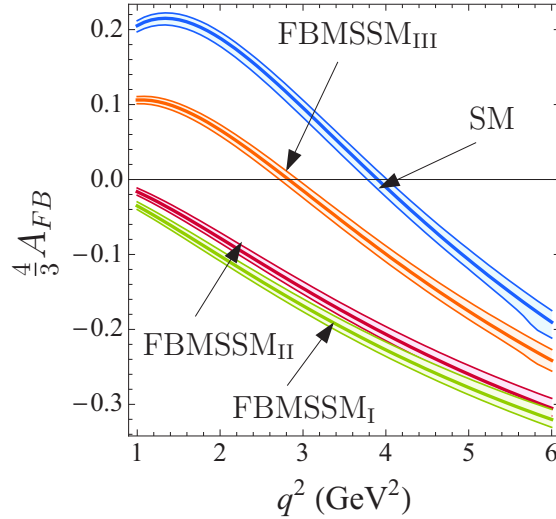


Figure 5.2: The Forward-Backward Asymmetry $A_{FB} = [N(\theta_l < \pi/2) - N(\theta_l > \pi/2)]/N(\text{all } \theta_l)$, expectation from Standard Model and three scenarios in the Flavor Blind Minimal Super Symmetric Model (Ref.[25]).

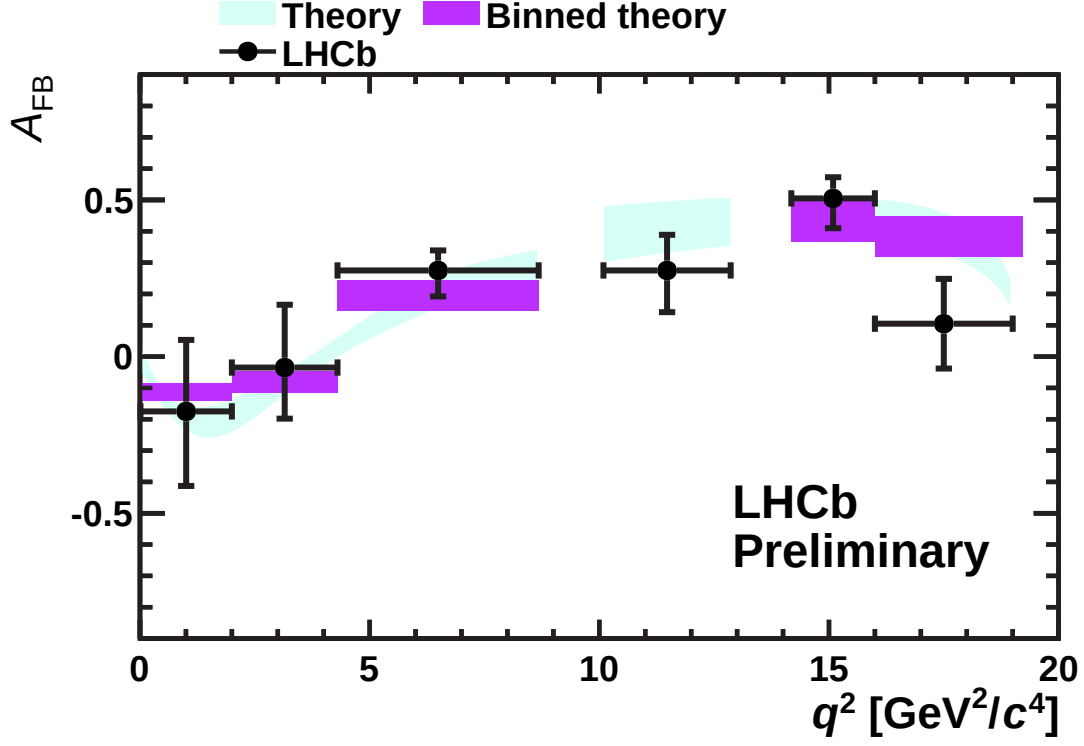


Figure 5.3: The Forward-Backward Asymmetry from 2011 LHCb data on $B_d \rightarrow \mu^+\mu^-(K^* \rightarrow K^+\pi^-)$ (Ref.[24]). (Binned) Theory is the Standard Model prediction. The A_{FB} here has been defined negative with respect to Fig.5.2 and covers a larger range in q^2 .

Chapter 6

Unfolding single-particle efficiencies

First make the plots. Then worry what is wrong with them.

Niels Tuning

In this chapter a method is developed that determines the efficiencies with which individual particles are measured from a well known multi-body process, a control channel.

The method relies on *efficiency factorization*, i.e. on the assumption that the total efficiency to measure the multi-body process is the product of efficiencies to measure the outgoing particles individually, i.e. the product of *single-particle efficiencies*. If the total efficiencies is indeed factorisable, then the method correctly retrieves the single-particle efficiencies. If, however, the total efficiency does not factorize, then the method approximates it with a product of single-particle efficiencies.

Motivation for the method was given in Ch.5 for the analysis of the rare and new physics sensitive decay $B_d \rightarrow \mu^+ \mu^- K^*$, where the efficiencies in measuring the charged decay products can be determined from the Standard Model dominated control channel $B_d \rightarrow J/\psi K^*$, which are then combined to estimate the efficiency in the signal channel $B_d \rightarrow \mu^+ \mu^- K^*$.

6.1 Introductory discussion

The difficulty in determining particle efficiencies from a multi-body process lies in three aspects. First, the efficiency to measure a particle generally depends on the momentum of the particle. Second, the momenta of the outgoing particles in a multi-body process are generally not independent. And finally, to measure the process, each of the particles needs to be measured; if one particle is not measured, then the entire event is not reconstructed, and as a result the other outgoing particles are lost as well.

If a particle's efficiency was to be determined by simply dividing its measured momentum distribution by its underlying momentum distribution, before such things as detector acceptance, trigger and event selection take their toll, then the result is likely not to be correct. The reason is that the measured momentum distribution of the particle is not only affected by its own efficiency, but is also influenced by the efficiency distributions of the other outgoing particles. And since the outgoing particles are cor-

related, an inefficiency for one outgoing particle will cut a specific region of phase space for the other outgoing particles as well.

The above formulated is basic. The experiment has efficiencies to measure different particles. However, in measuring a multi-body process like a decay, the measurement does not distinguish the individual particle efficiencies, but sees only the combination/product of them, making it hard to distinguish how the experiment was inefficient for which particle with which momentum. It is said that the individual particle efficiencies are *folded in* with the multi-body process.

This problem is addressed in the following sections, where a method is developed that iteratively unfolds the individual, momentum dependent particle efficiencies, termed single-particle efficiencies, from an underlying multi-body process.

6.2 Unfolding single-particle efficiencies

In this section a method is derived that correctly obtains single-particle efficiencies from a multi-body process. The method compares a measurement with its well known underlying distribution and iteratively unfolds the single-particle efficiencies from the underlying process.

For simplicity the efficiencies and the iteration procedure are discussed within the context of a two-body decay. However, the rationale applies in general to any multi-body final state.

6.2.1 Folded efficiencies

As was pointed out in the introductory discussion, a correct single-particle efficiency is generally *not* acquired by naively dividing the particle's measured momentum distribution by its theoretically predicted distribution. To elaborate on this consider the two-body decay $H \rightarrow h_1 h_2$

Suppose that $N(p_1, p_2)$ decays are produced in collisions with momenta p_1 and p_2 for particles h_1 and h_2 respectively (the underlying distribution of events). Furthermore, suppose that the two outgoing particles are subject to detection efficiencies $\epsilon_1(p_1)$ and $\epsilon_2(p_2)$ (and that the total efficiency to measure the decay factorizes, i.e. $\epsilon(p_1, p_2) \equiv \epsilon_1(p_1)\epsilon_2(p_2)$).

Then the daughter particles are produced with momentum distributions

$$N_{\text{prod}}(p_1) = \int dp_2 N(p_1, p_2) \quad (6.1)$$

$$N_{\text{prod}}(p_2) = \int dp_1 N(p_1, p_2) \quad (6.2)$$

and they are measured, after efficiencies, distributed according to

$$N_{\text{meas}}(p_1) = \int dp_2 N(p_1, p_2) \epsilon_1(p_1) \epsilon_2(p_2) \quad (6.3)$$

$$N_{\text{meas}}(p_2) = \int dp_1 N(p_1, p_2) \epsilon_1(p_1) \epsilon_2(p_2). \quad (6.4)$$

Naively then, the efficiency for particle h_1 for example is determined at

$$E_1(p_1) = \frac{N_{\text{meas}}(p_1)}{N_{\text{prod}}(p_1)} = \epsilon_1(p_1) \frac{\int dp_2 N(p_1, p_2) \epsilon_2(p_2)}{\int dp_2 N(p_1, p_2)} \neq \epsilon_1(p_1) \quad (6.5)$$

This will produce an efficiency $E_1(p_1)$, which is generally not equal to the real underlying single-particle efficiency $\epsilon_1(p_1)$, that went into the measurement.

The reason why Eq.6.5 does not reproduce the true single-particle efficiency was pointed out in the introductory discussion. If particle h_2 is not detected, then the entire decay is not reconstructed and particle h_1 is lost as well. More specifically, since the momenta of the two particles are correlated through the underlying production process $N(p_1, p_2)$, an inefficiency in particle h_2 will cut a specific region of particle h_1 's phase space.

In short, the single-particle efficiencies $\epsilon_1(p_1)$ and $\epsilon_2(p_2)$ are folded in with the production process $N(p_1, p_2)$. For this reason the efficiency $E_1(p_1)$ of Eq.6.5 is referred to as an *effective efficiency*, to distinguish it from the true underlying single-particle efficiency $\epsilon_1(p_1)$.

The inequality of Eq.6.5 is demonstrated in Fig.6.1. A toy-efficiency on the momentum of the pion is applied on a sample of 650.000 Monte Carlo truth generated $B_d \rightarrow K^* J/\psi$ events. In the decay $B_d \rightarrow K^* J/\psi$, the momentum of the outgoing kaon and that of the outgoing pion exhibit a sizable correlation, as can be clearly seen in Fig.6.1(a). The kaons themselves are not subjected to an efficiency, but since the kaons are strongly correlated with the pions, it nevertheless appears as if there is a non-flat acceptance for the kaon momentum as well, which is visible in Fig.6.1(b).

6.2.2 Unfolding efficiencies

To retrieve the proper underlying efficiencies, they have to be unfolded from the underlying production process. Starting from Eq.6.3 and Eq.6.4, single-particle efficiencies $e_1(p_1)$ and $e_2(p_2)$ for particles h_1 and h_2 respectively, are formally defined by¹

$$e_1(p_1) \stackrel{\text{def}}{=} \frac{N_{\text{meas}}(p_1)}{\int dp_2 N(p_1, p_2) e_2(p_2)} \quad (6.6)$$

$$e_2(p_2) \stackrel{\text{def}}{=} \frac{N_{\text{meas}}(p_2)}{\int dp_1 N(p_1, p_2) e_1(p_1)}. \quad (6.7)$$

¹The efficiencies are purposefully given roman symbols to indicate that they are mathematical solutions to a set of equations, and to distinguish them from physical, underlying efficiencies indicated by Greek symbols. Of course the whole purpose is to get the roman symbols equal to the Greek symbols.

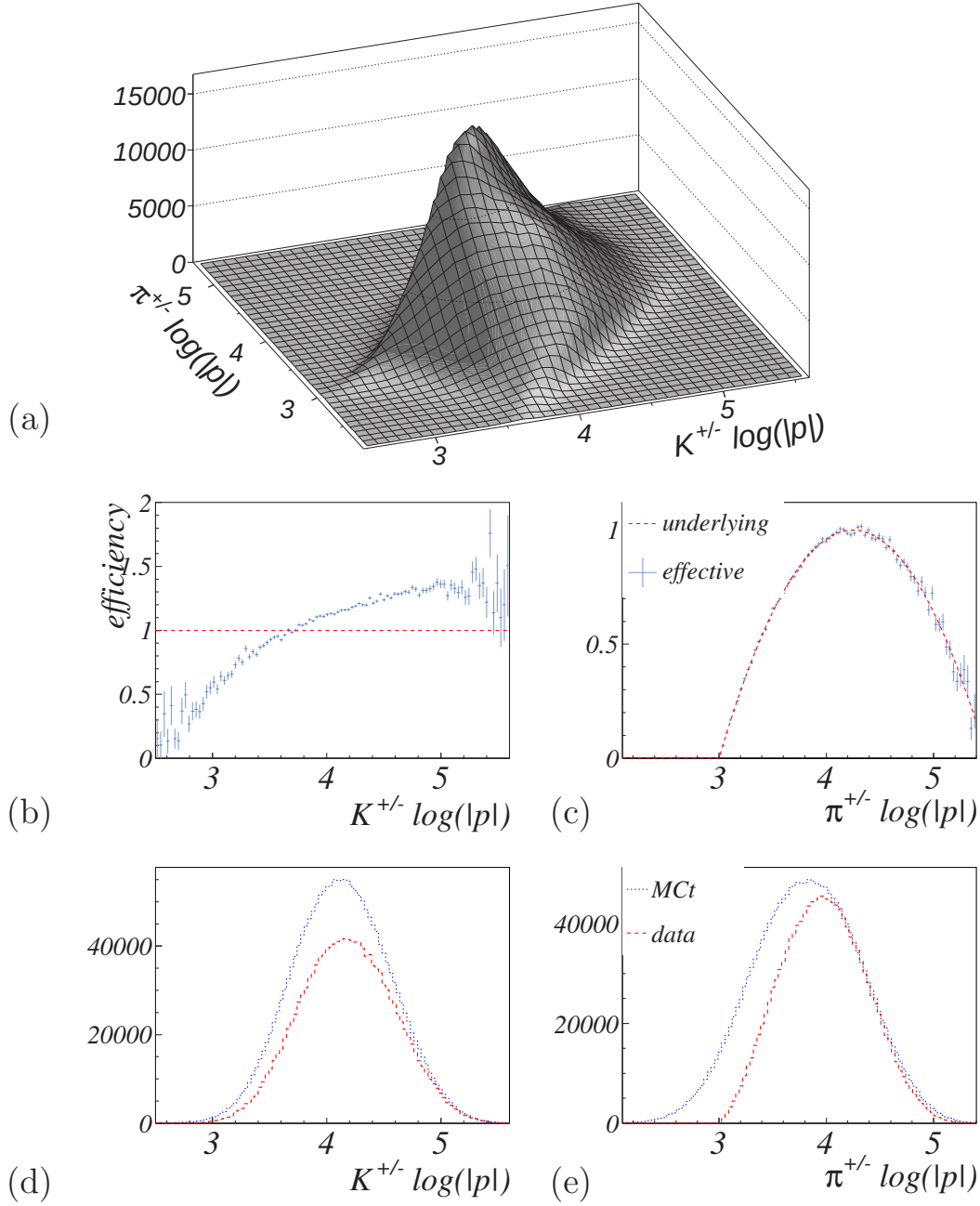


Figure 6.1: $B_d \rightarrow K^* J/\psi$ events are subjected to a toy efficiency of only the pions. Due to correlations the kaons, too, appear to have a non-flat acceptance. (a) The correlation between the momentum of the kaon and that of the pion in $B_d \rightarrow K^* J/\psi$ is shown (Monte Carlo prediction). The momenta $|p|$ are in MeV. (b) The flat kaon efficiency (dashed line) and the measured effective efficiency (error bars). The effective efficiency has been scaled to unit average to facilitate comparison. (c) The toy input and the measured pion efficiencies. The kaon (d) and pion (e) momentum distributions before (dotted lines) and after (dashed lines) efficiencies.

The two efficiencies e_1 and e_2 are, however, interdependent through the equations' denominators. As a result, analytical solutions are practically unobtainable. They can, however, be determined iteratively, as will be pointed out below.

Eq.6.6 and Eq.6.7 define single-particle efficiencies $e_1(p_1)$ and $e_2(p_2)$. In their numerators they take the number of measured events for the two outgoing particles. These are given by Eq.6.3 and Eq.6.4 for an underlying efficiency that is factorisable, i.e. that is the product of single-particle efficiencies. Indeed, the equations Eq.6.6 and Eq.6.7, with Eq.6.3 and Eq.6.4 substituted for their respective numerators, are naturally solved by $e_1(p_1) = \epsilon_1(p_1)$ and $e_2(p_2) = \epsilon_2(p_2)$. Therefore, for a factorisable underlying efficiency the single-particle efficiencies defined by Eq.6.6 and Eq.6.7 are equal to the true underlying single-particle efficiencies².

In general, letting go of the factorization assumption, the number of measured events for both particles, and thus the numerators of Eq.6.6 and Eq.6.7, are given by

(6.8)

$$N_{\text{meas}}(p_1) = \int dp_2 N(p_1, p_2) \epsilon(p_1, p_2) N_{\text{meas}}(p_2) = \int dp_1 N(p_1, p_2) \epsilon(p_1, p_2) \quad (6.9)$$

where $\epsilon(p_1, p_2)$ is the true underlying and unknown efficiency for the process $H \rightarrow h_1 h_2$, whether or not it is factorisable.

Note that even if the true underlying efficiency is not factorisable, then Eq.6.6 and Eq.6.7 will *still* define single-particle efficiencies $e_1(p_1)$ and $e_2(p_2)$, but they will consequently not exactly reproduce the true underlying efficiency.

In the following, factorization of the underlying efficiency will be assumed. Single-particle efficiencies obtained from a non-factorisable underlying efficiency are discussed in paragraph 6.3.3.

The numerators in Eq.6.6 and Eq.6.7 are the number of times a particle is measured with a certain momentum. These can thus be obtained from data. The denominators on the other hand are the number of times a particle is produced with a certain momentum, but where each of these events is weighted with the efficiency of the other particle. This weighted number of events is obtained from well known theoretical prediction, in practice that is from Monte Carlo truth.

In this way, Eq.6.6 and Eq.6.7 acquire the general iterative form

$$e_1^{(n+1)}(p_1) = \frac{N_{\text{meas}}(p_1)}{N_{\text{weighted MCt}}(p_1)} = \frac{\int dp_2 N_{\text{meas}}(p_1, p_2)}{\int dp_2 N_{\text{MCt}}(p_1, p_2) e_2^{(n)}(p_2)} \quad (6.10)$$

$$e_2^{(n+1)}(p_2) = \frac{N_{\text{meas}}(p_2)}{N_{\text{weighted MCt}}(p_2)} = \frac{\int dp_1 N_{\text{meas}}(p_1, p_2)}{\int dp_1 N_{\text{MCt}}(p_1, p_2) e_1^{(n)}(p_1)} \quad (6.11)$$

²Up to a multiplicative factor; see paragraph 6.2.4

6.2.3 The iteration implementation

The simplest way to implement the iterative unfolding of single-particle efficiencies embodied by Eq.6.10 and Eq.6.11 is with a binned method, i.e. by incorporating the data, the theoretical prediction (MC truth) and the single-particle efficiencies into histograms. Let i denote a bin in p_1 and let j denote a bin in p_2 . Then a translation of Eq.6.10 implementing bins reads

$$e_1^{(n+1)}(i) = \frac{N_{\text{meas}}(i)}{N_{\text{weighted MCt}}(i)} = \frac{\sum_j N_{\text{meas}}(i, j)}{\sum_j N_{\text{MCt}}(i, j) e_2^{(n)}(j)}, \quad (6.12)$$

and a similar translation for Eq.6.11.

The interpretation of Eq.6.12 is straightforward. On the left-hand side is the next iteration of the single-particle efficiency of particle h_1 in bin i . The numerator on the right-hand side is the number of measured events in bin i of particle h_1 (it is the same in every iteration step). To get the denominator on the right-hand side, the set of Monte Carlo truth events in bin i is counted, but where each event obtains a weight equal to the previously iterated efficiency of particle h_2 for that event.

The iteration procedure of Eq.6.12 will in general, however, not converge. For example, suppose that for some iteration step n the two efficiencies e_1 and e_2 obtain the correct functional shape, but are too large or too small by factors c_1 and c_2 respectively, i.e. $e_1^{(n)}(i)/\epsilon_1(i) = c_1$ and $e_2^{(n)}(j)/\epsilon_2(j) = c_2$. Then on the next step $n+1$ the efficiencies will be off by factors $1/c_2$ and $1/c_1$ respectively, and another step later again by c_1 and c_2 . So, the resulting single-particle efficiencies will at best oscillate³.

For the purpose of convergence, the iteration procedure (Eq.6.12) is supplemented with a damping factor

$$\left[\frac{e_1^{(n)}(i)}{e_1^{(n+1)}(i)} \right]^y \left[\frac{e_1^{(n)}(i)}{e_1^{(n-1)}(i)} \right]^\alpha, \quad (6.13)$$

with suitable powers $0 < y, \alpha < 1$. Implementing the damping factor into Eq.6.12 builds the *central iteration equation to retrieve single-particle efficiencies* for two outgoing particles:

$$e_1^{(n+1)}(i) = e_1^{(n)}(i) \left[\frac{\sum_j N_{\text{meas}}(i, j)}{\sum_j N_{\text{MCt}}(i, j) e_1^{(n)}(i) e_2^{(n)}(j)} \right]^{1-y} \left[\frac{e_1^{(n)}(i)}{e_1^{(n-1)}(i)} \right]^\alpha, \quad (6.14)$$

accompanied by a similar equation for $e_2^{(n+1)}(j)$.

It is possible to show (appendix A) that, given that the single-particle efficiencies obtain the correct functional shape, then they will converge⁴.

³In case there are more than two outgoing particles, the denominator in Eq.6.12 will include $e_2^{(n)}(j)e_3^{(n)}(k)\dots$, in which case the iteration procedure will in fact diverge rather than oscillate.

⁴The parameters y and α for which this holds, for m particles, are

$$\max\left(1 - \frac{4}{m}, 0\right) < y < 1 \\ 1 + m(1 - y) - 2\sqrt{m(1 - y)} < \alpha < 1 \quad (6.15)$$

In section 6.2.1 an example was given in Fig.6.1, where due to pion-kaon correlations in $B_d \rightarrow K^* J/\psi$ decays, an inefficiency on the pion momentum induces an effective inefficiency for the kaon as well.

Fig.6.2 shows the kaon- and pion-efficiencies for the same example, but now as obtained by the iteration equation Eq.6.14 (the effective efficiencies are included for comparison). The iteration procedure reproduces both the underlying input efficiency of the pion and the flat acceptance of the kaon.

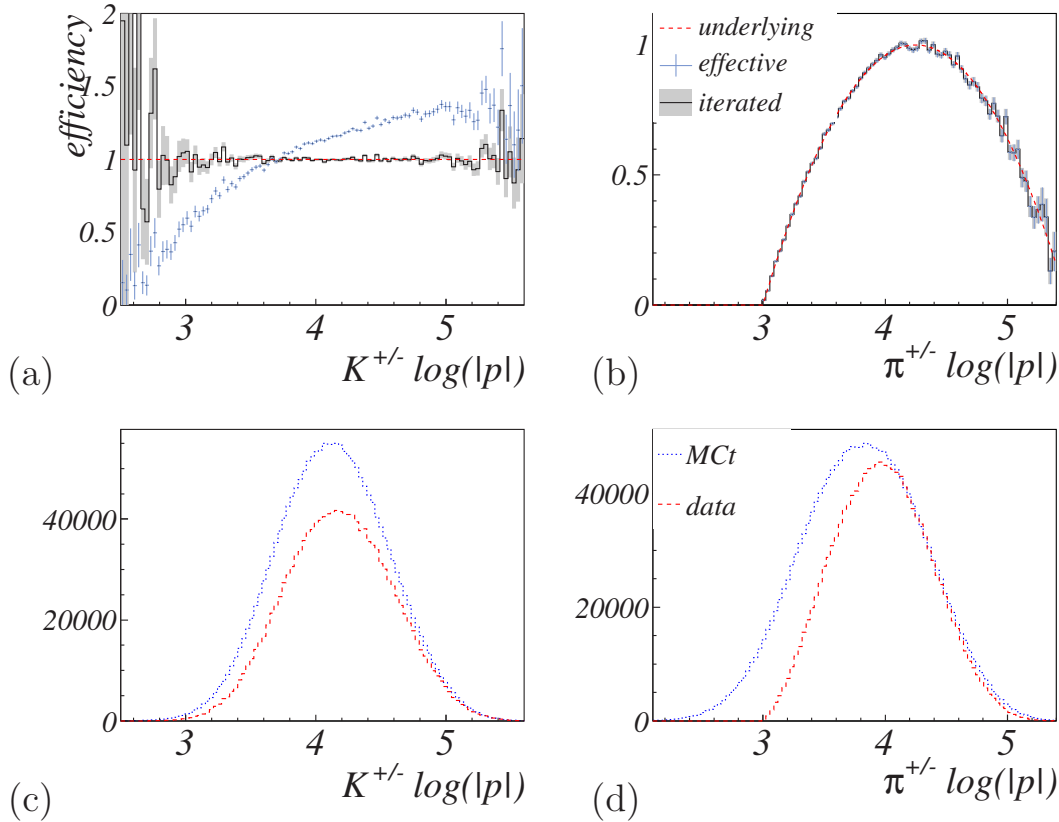


Figure 6.2: The iterative procedure applied to the same Monte Carlo example illustrated in Fig.6.1. The dashed red lines in (a) and (b) are the toy input efficiencies; only the pions experience an efficiency cut. The blue error bars are the measured effective efficiencies, in which is folded the correlation between the kaons and pions. The solid black lines plus error band are the single-particle efficiencies as retrieved by Eq.6.14. The distributions in (c) and (d) are the number of events before (dotted blue line) and after (dashed red line) efficiencies.

and convergence will ultimately proceed with $(e/\epsilon)^{\sqrt[3]{\alpha}}$. The parameters are typically chosen as $y = 1 - 1/m$ and $\alpha = 1/2$.

6.2.4 Efficiency scale invariance

If the underlying efficiency is factorisable, then a measurement of a two-body decay will have a total efficiency $\epsilon \equiv \epsilon_1 \epsilon_2$. It is important to note that the two single-particle efficiencies in this measurement always appear as a product. The efficiency for particle h_1 can very well be twice as large. As long as the efficiency for particle h_2 is twice as small, the total efficiency in the measurement remains the same. That is, as far as the decay $H \rightarrow h_1 h_2$ is concerned, the efficiencies ϵ_1 and ϵ_2 are indistinguishable from the efficiencies $\epsilon'_1 = c\epsilon_1$ and $\epsilon'_2 = \epsilon_2/c$.

This signifies that the individual scales of the single-particle efficiencies are lost and only their product has an interpretable value. Single-particle efficiencies can therefore be determined, but modulus a multiplicative scale.

So a measurement of $H \rightarrow h_1 h_2$ does not change if the efficiencies of particles h_1 and h_2 are scaled by constant factors c and $1/c$ respectively. The question remains though, whether the single-particle efficiencies can be modified with *non-constant* factors $f_1(p_1)$ and $f_2(p_2)$ respectively without changing the measurement. This question is relevant, because the momenta in a decay are not independent; the product $f_1(p_1)f_2(p_2)$ need not be equal to 1 for all p_1, p_2 , but just for those p_1, p_2 seen by the decay.

In particular, in a decay the momenta are restricted by the invariant mass of the mother particle, that is by $E_1 E_2 - \vec{p}_1 \cdot \vec{p}_2 = \frac{1}{2}[m_m^2 - m_1^2 - m_2^2]$. Fortunately, such a mass constraint mixes all of the momentum components and does not allow any momentum component of one particle to be written in terms of solely the other particle's momentum components. Because of this, non-constant factors $f_1(p_1)$ and $f_2(p_2)$ cannot multiply to 1 for all the momenta p_1, p_2 allowed by the mass constraint.

If the momenta of the outgoing particles are (only) restricted by mass constraints, then a single-particle efficiency can be uniquely unfolded up to a multiplicative scale.

Special care has to be taken if additional restrictions are placed. If, for example, only events are considered where the mother particle has fixed absolute momentum $|p_m|$ and thus fixed energy E_m , then the energy of one daughter particle is completely determined by the energy of the other daughter particle.

In this case an example of non-constant factors are $f_1(p_1) = \exp(cE_1)$ and $f_2(p_2) = \exp(cE_2 - cE_m)$ with *arbitrary parameter* c . That is, for the process $H \rightarrow h_1 h_2$ considered only at fixed energy E_m , the efficiencies ϵ_1 and ϵ_2 are indistinguishable from the efficiencies $\epsilon'_1 = \epsilon_1 \exp(cE_1)$ and $\epsilon'_2 = \epsilon_2 \exp(cE_2 - cE_m)$.

6.3 Validation of the iterative method

In this section the iterative method, derived in the previous section (Eq.6.14), is validated against toy input efficiencies.

The method retrieves single-particle efficiencies in bins of the momentum of the outgoing particles. As an input it takes a set of measurements and a set of Monte Carlo truth events. Since there are a finite number of events, both measured and

Monte Carlo truth, the number of events that occupy the bins will show statistical fluctuations around their expected numbers. These fluctuations will propagate into the values of the single-particle efficiencies. In paragraph 6.3.2 the error on the single-particle efficiencies is estimated.

The iterative method and the error estimate are validated against a number of scenarios, with different numbers of particles, different numbers of bins, and different sizes for the measured and Monte Carlo truth data sets.

The validation studies are performed with a factorisable input efficiency, i.e. where the toy input efficiency is explicitly chosen to be the product of single-particle efficiencies. In reality an underlying efficiency may not be factorisable. Non-factorisable effects are discussed in paragraph 6.3.3.

The validation studies are performed with a sample of 2.6M $B_d \rightarrow (J/\psi \rightarrow \mu^+ \mu^-)(K^* \rightarrow K^+ \pi^-)$ events (Monte Carlo truth simulation). To obtain a “measurement”, i.e. the numerators to the iterative method, events are randomly removed according to toy efficiency functions. To ensure statistical independence a different set of events is taken for the theoretical prediction, i.e. for the denominators to the method. Subsequently the iterated single-particle efficiencies are determined and are compared to the toy input efficiencies.

A dependence of the efficiencies on the absolute momentum and pseudorapidity of the particles is considered. The toy input efficiencies used in the validation studies are shown in Fig.6.3. The shapes of these are loosely based on full Monte Carlo simulation of Standard Model $B_d \rightarrow \mu^+ \mu^- K^*$ events. For versatility the muons are given a different shape than the kaon and pion input efficiencies.

Eq.6.14 defines the iteration procedure for two outgoing particles. For the validation studies the iteration procedure is generalized to more than two outgoing particles. Generalization of Eq.6.14 to e.g. four outgoing particles yields

$$e_1^{(n+1)}(i) = e_1^{(n)}(i) \left[\frac{\sum_{jkl} N_{\text{meas}}(i, j, k, l)}{\sum_{jkl} N_{\text{MCT}}(i, j, k, l) e_1^{(n)}(i) e_2^{(n)}(j) e_3^{(n)}(k) e_4^{(n)}(l)} \right]^{1-y} \left[\frac{e_1^{(n)}(i)}{e_1^{(n-1)}(i)} \right]^\alpha, \quad (6.16)$$

accompanied by three equivalent equations for particles 2, 3 and 4 and bins labeled i, j, k, l are bins in $^{10} \log(p) \times \eta$ space of the four outgoing particles.

As was pointed out in paragraph 6.2.4, the individual scales of the single-particle efficiencies are lost and their correct scales can in fact not be reproduced individually. To be able to compare the resulting single-particle with the toy input efficiencies, the resulting single-particle efficiencies are normalized to the toy input efficiencies.

On the other hand the total scale of the product of resulting single-particle efficiencies should match that of the total toy input efficiency. This match, however, is implicit in the iteration procedure (and in fact proved in appendix A).

6.3.1 Iterative results

Results of the iterative method are shown in Fig.6.4-Fig.6.7.

The events after input efficiencies (numerators) and events before efficiencies (denominators) are independent with 120.000 and 240.000 events respectively. The result-

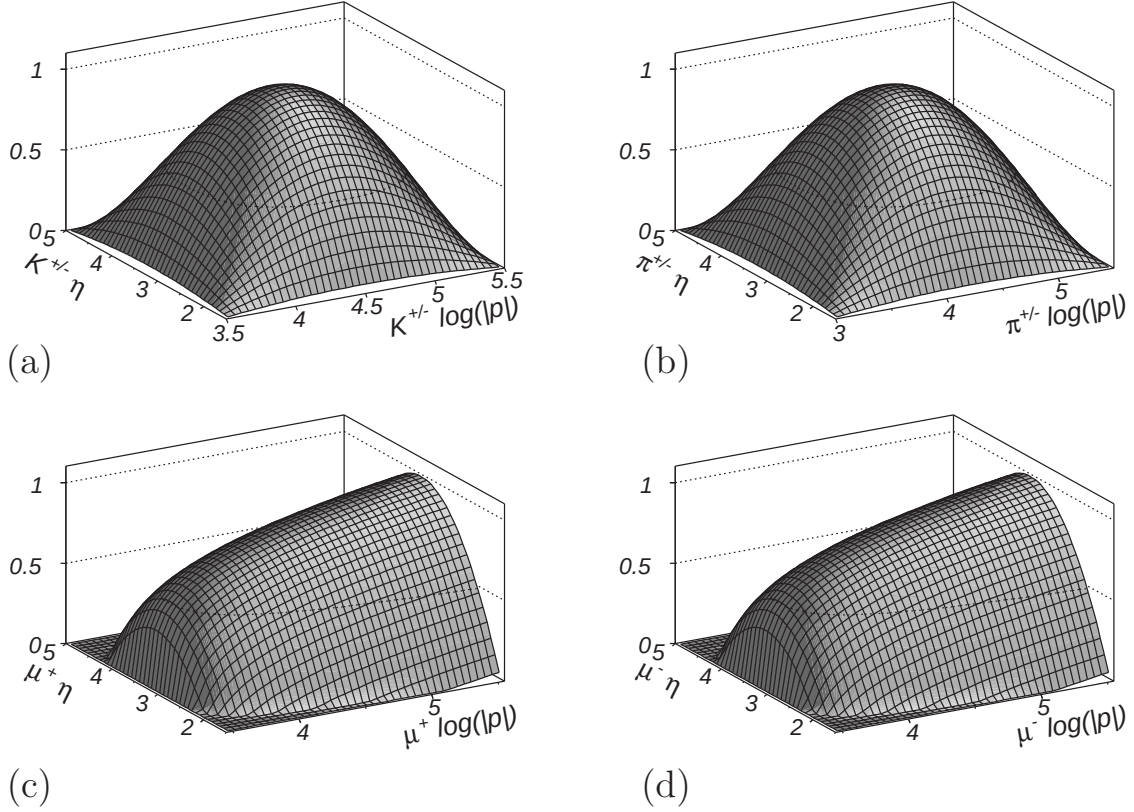


Figure 6.3: Toy single-particle input efficiencies used in validating the iterative method. The toy kaon and pion efficiencies (a) and (b) have been chosen factorisable in their own momentum variables $^{10}\log(|p|)$ and η , while the toy muon efficiencies (c) and (d) have not. The total momentum $|p|$ is in MeV. The total (factorisable) efficiency in the validation studies is the product of these toy input efficiencies.

ing single-particle efficiencies have been obtained in 20×20 bins in $^{10}\log(|p|) \times \eta$ space for each of the four outgoing particles, with $|p|$ in MeV.

The figures show selected slices in both $^{10}\log(|p|[\text{MeV}])$ and η , for $|p| = 10 \text{ GeV}$ and $\eta = 4$. The effective efficiencies (naive efficiencies without unfolding) are drawn as well for comparison.

The resulting single-particle efficiencies show good agreement with the toy input efficiencies. In particular it is seen that the iterative method correctly retrieves the underlying efficiency where the effective efficiencies show large deviations due to particle correlations (see the kaon and pion η slices in Fig.6.4 and Fig.6.5).

6.3.2 Statistical error

Since the sets of measured and of Monte Carlo truth events are of finite size, they will suffer from statistical variations. Such variations will have an impact on the resulting iterated single-particle efficiencies.

The efficiencies are interdependent (see Eq.6.10 and Eq.6.11), but to estimate the statistical error on a single-particle efficiency, the efficiencies of other particles are taken as constant at their iterated values. Error estimation is then done on the basis of the number of measured and Monte Carlo truth events.

The variance on a single-particle efficiency is expanded in the central moments of the number of measured and Monte Carlo truth events. Up to and including the second central moments (i.e. the variances), and following Poisson statistics for the number of events in a bin, the error on a single-particle efficiency is estimated by

$$\sigma_1(i) \approx e_1(i) \sqrt{\frac{1}{N_{\text{meas}}(i)} + \left[1 + \frac{3}{N_{\text{meas}}(i)}\right] \frac{\sum_j N_{\text{MCt}}(i, j) e_2(j)^2}{\left[\sum_j N_{\text{MCt}}(i, j) e_2(j)\right]^2}} \quad (6.17)$$

To verify the proper estimate of the statistical uncertainty, the error estimated by Eq.6.17 has been studied using toy input efficiencies. Studies have been performed for different numbers of particles in the iterative method, different numbers of bins per particle and different sizes of the measured and Monte Carlo truth data sets; these are tabulated in Tab.6.1.

nr. of final state part. (with an input eff.)	2 ($K\pi$) , 3 ($K\pi\mu^+$) , 4 ($K\pi\mu^+\mu^-$)
nr. of bins (for each particle) : $^{10}\log(p) \times \eta$	10×10 , 20×20 , 30×30 , 40×40
average nr. of measured events per bin	100 , 300 , 600
average nr. of MC truth events per bin	100 , 300 , 600

Table 6.1: *All combinations of the above parameters have been used to validate the iterative method and its statistical error estimate.*

The pull distribution between the iterated and the toy input efficiencies is determined on 100.000 randomly chosen points in the $^{10}\log(|p|) \times \eta$ phase space of every

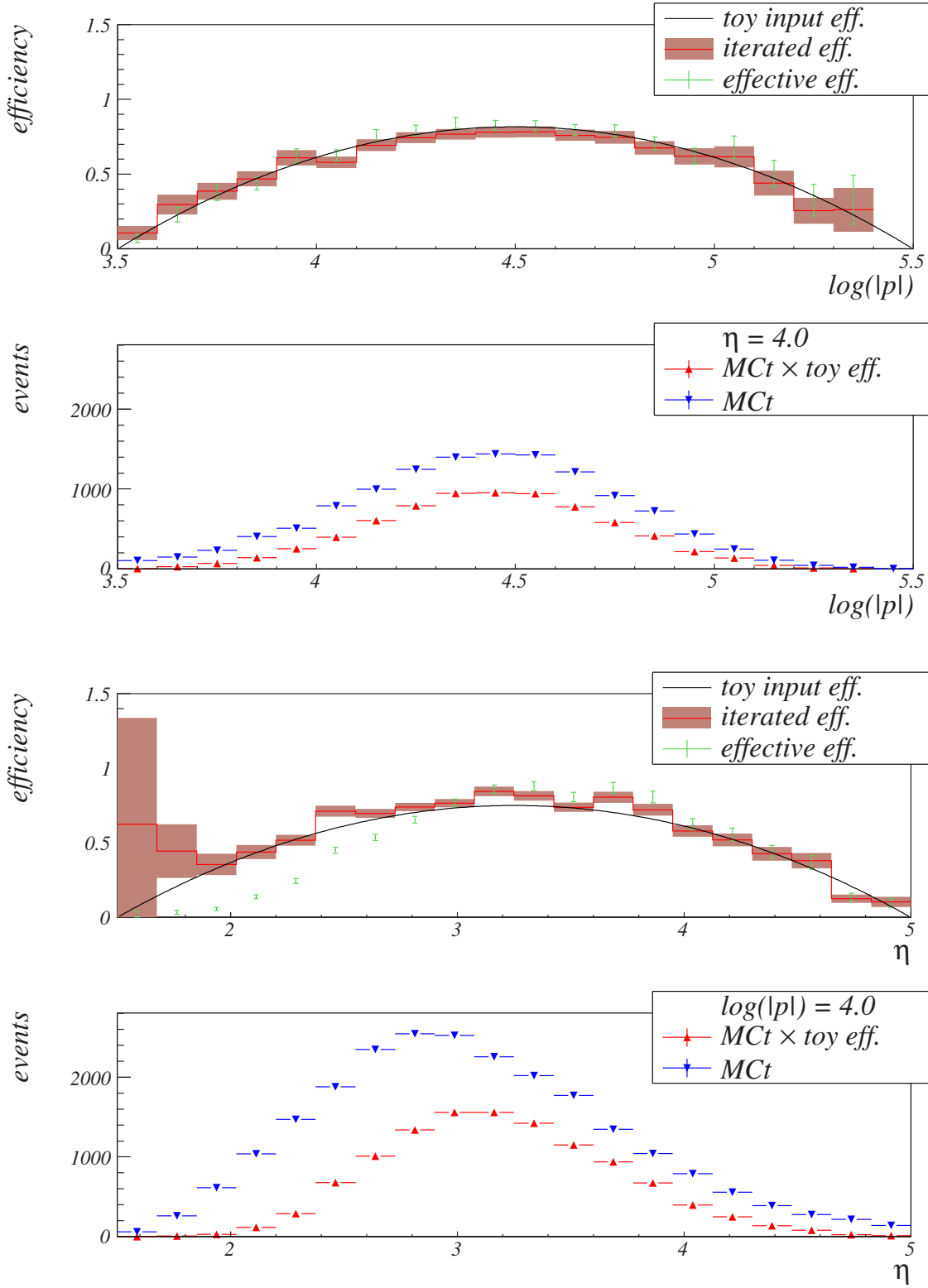


Figure 6.4: Iteration results of the $K^\pm$ in a $^{10}\log(|p|)$ [MeV]-slice at $\eta = 4$ and in a η -slice at $|p| = 10$ GeV. Both the iterated and effective efficiency have been normalized to the toy input efficiency.

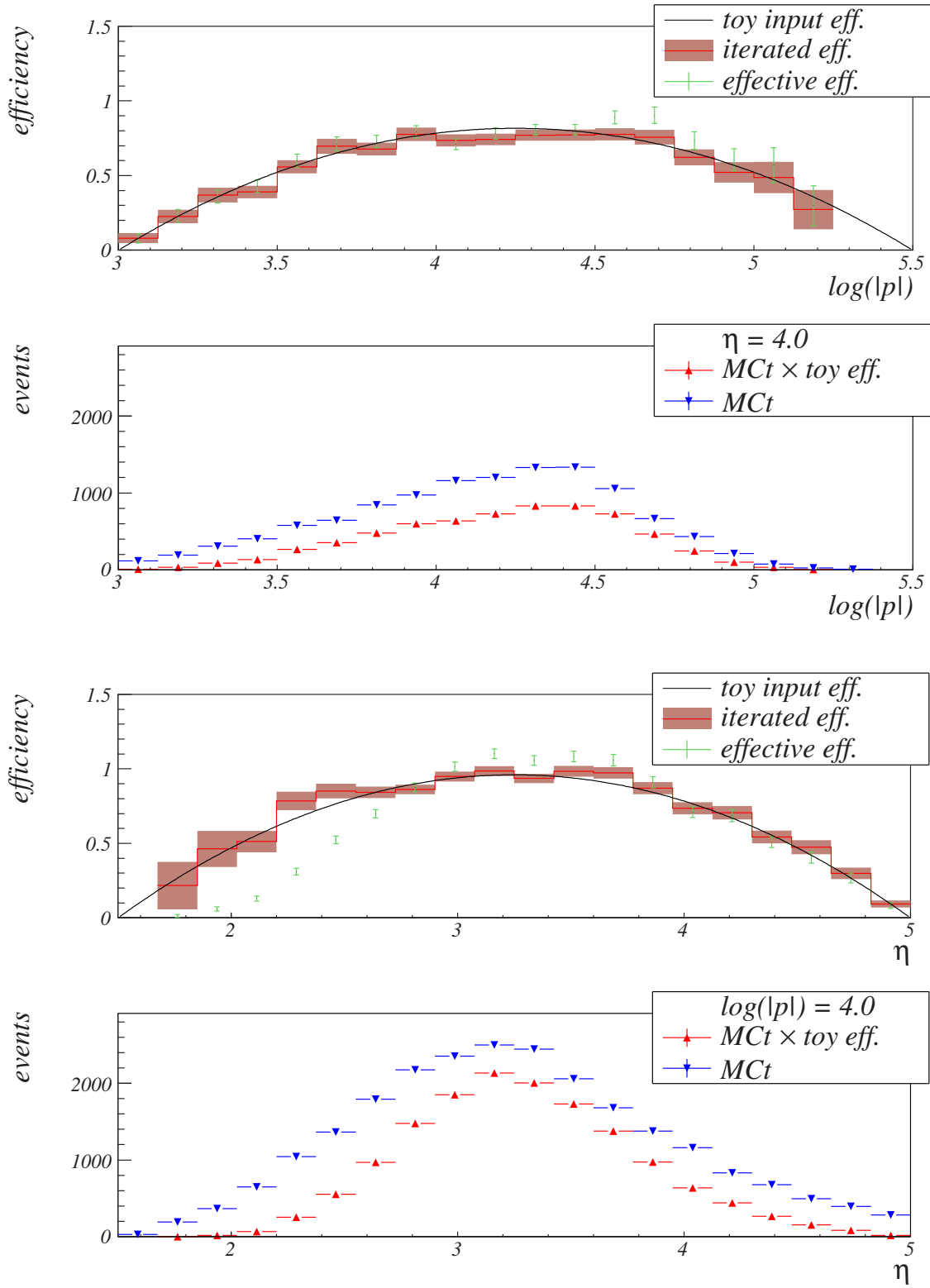


Figure 6.5: Iteration results of the $\pi^\pm$ in a $^{10}\log(|p|)$ [MeV]-slice at $\eta = 4$ and in a η -slice at $|p| = 10$ GeV. Both the iterated and effective efficiency have been normalized to the toy input efficiency.

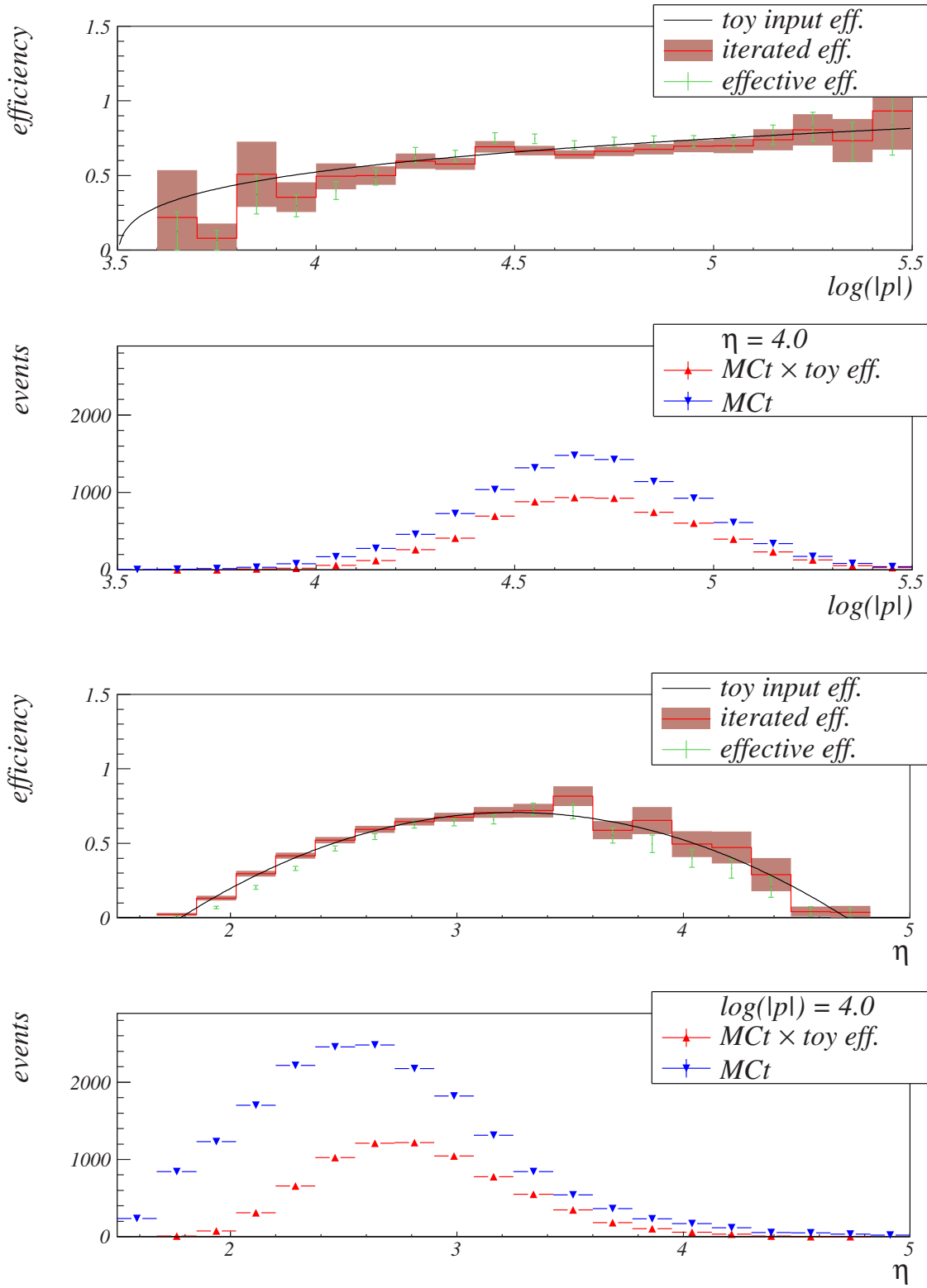


Figure 6.6: Iteration results of the μ^+ in a $^{10}\log(|p|)$ [MeV]-slice at $\eta = 4$ and in a η -slice at $|p| = 10$ GeV. Both the iterated and effective efficiency have been normalized to the toy input efficiency.

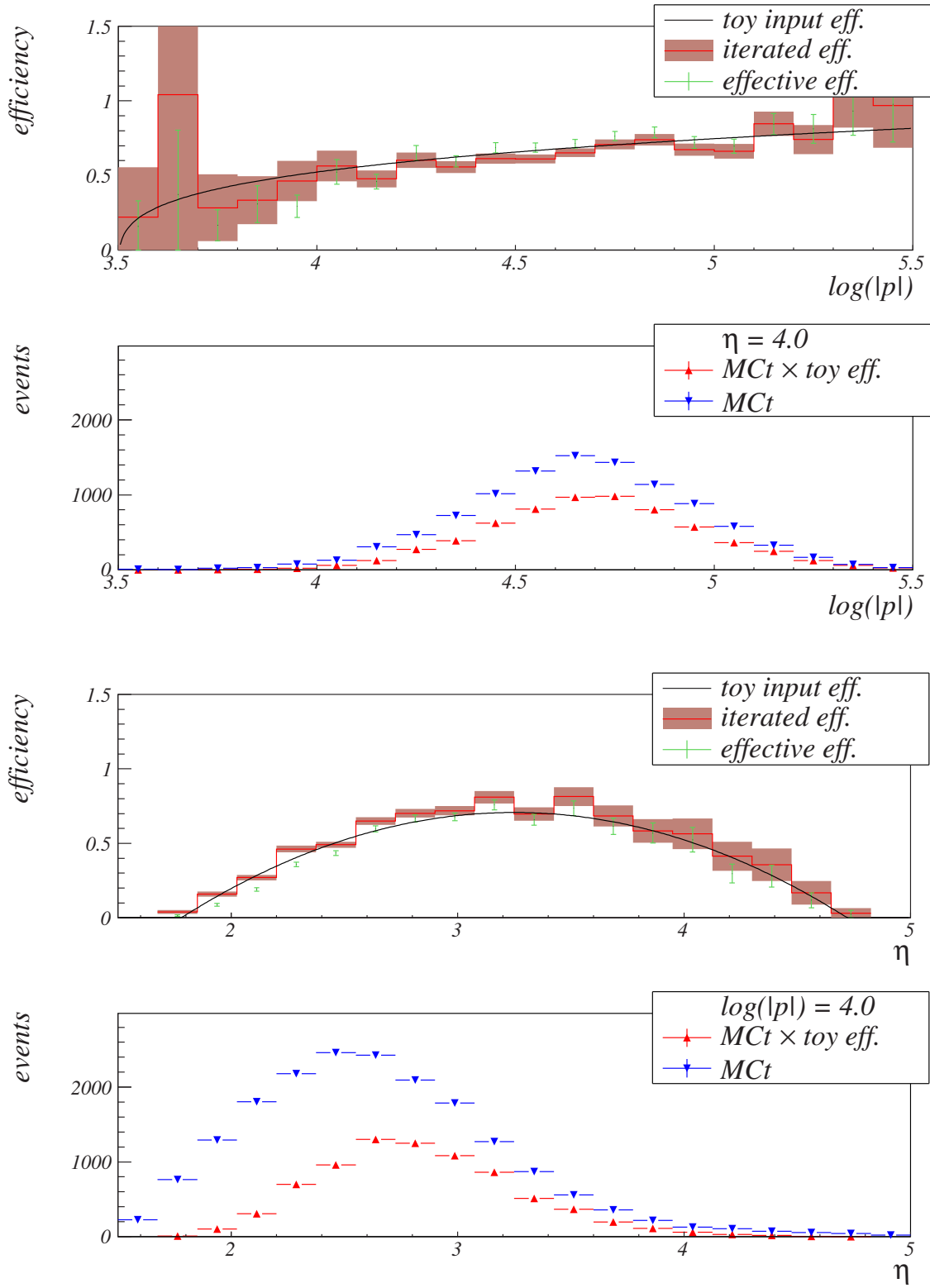


Figure 6.7: Iteration results of the μ^- in a $^{10}\log(|p| \text{ [MeV]})$ -slice at $\eta = 4$ and in a η -slice at $|p| = 10 \text{ GeV}$. Both the iterated and effective efficiency have been normalized to the toy input efficiency.

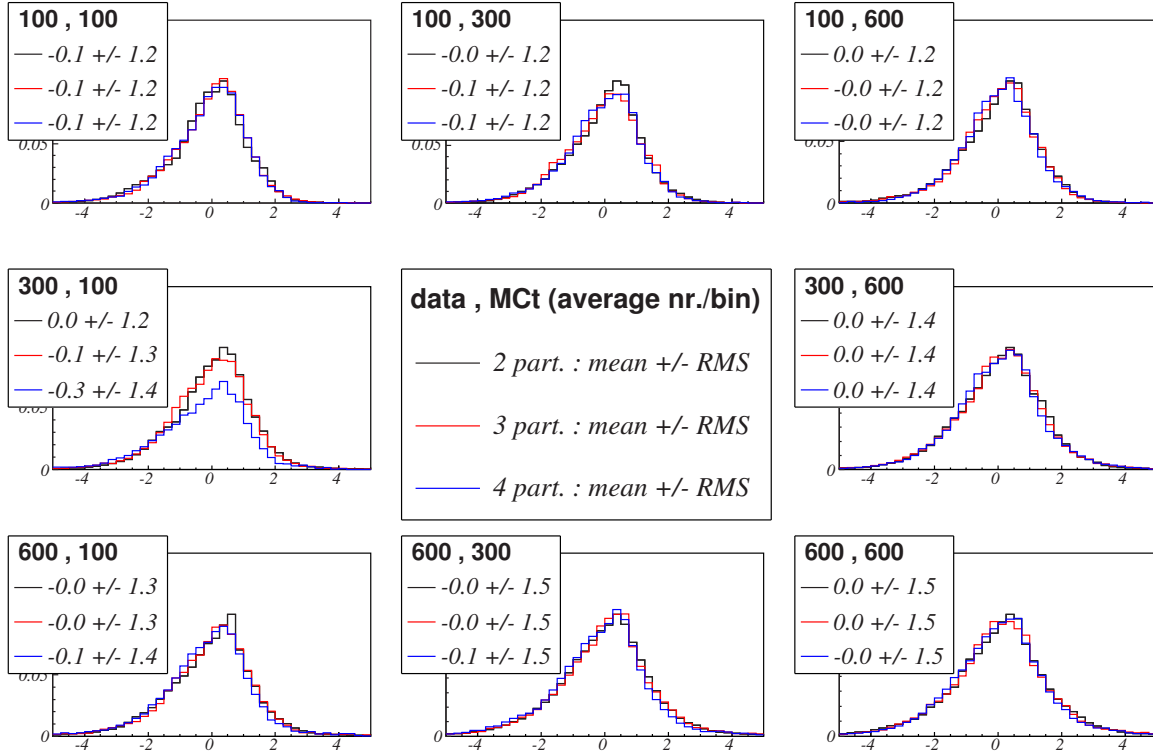


Figure 6.8: Pull distributions between the resulting and input single-particle efficiencies for the case where 20×20 bins per particle were used (see Tab.6.1). “Data” and “MCt” respectively denote events with and without single-particle input efficiencies applied. “# part.” denotes the number of final state particles to which an efficiency is applied.

particle.

It has been observed that the pull distributions are quite stable with respect to the different configurations in Tab.6.1; approximately Gaussian with mean ranging from -0.3 to 0.3 and RMS between 1.1 and 1.9 depending on the particular configuration.

The pull distributions do not show a significant dependence on the number of outgoing particles that are considered. Only for four outgoing particles and few (order of 100) average Monte Carlo truth events per bin a large tail in the pull distribution can be observed, which disappears with increasing Monte Carlo truth statistics.

The width of the pull distributions generally decreases with an increasing number of bins (from 1.8 at 10×10 bins down to 1.2 at 30×30 bins, for 300×600 average data $\times$ MC truth events per bin) and increases with an increasing number of available events. The latter can be seen in Fig.6.8, an example that shows the pull distributions for the case of 20×20 bins per particle.

This behavior of the pull widths is considered the result of a bin size effect, where large bins cannot accommodate for a variation of the underlying efficiency over the bin volume. Then, when increasing the number of bins (keeping the average number of events and thus the error estimate per bin the same) the underlying efficiency is more closely approximated by a binned distribution, thereby decreasing the pull. While

increasing the statistics per bin (keeping the binning the same) decreases the error estimate in a bin and thus increases the pull.

The bin size effect is moreover confirmed by taking a pull between a smoothed version of the iterated single-particle efficiencies and the underlying efficiencies⁵, for which it is observed that the pull distributions improve significantly (RMS between 1.0 and 1.1 in nearly all cases and at most 1.3 for few bins and high statistics).

The above shows that the statistical error estimate behaves as expected.

6.3.3 Non-factorisable effects

The iterative method relies on the assumption of efficiency factorization. In reality the underlying efficiency of the multi-body process may contain contributions that are not factorisable.

The factorization assumption depends on the particular analysis, on the trigger and event selection cuts that are included. Selections on for example a (transverse) momentum, particle identification, or track quality are particle specific and thus factorisable. On the other hand selections that involve multiple particle momenta, like a flight distance of a mother particle, or a vertex quality can introduce non-factorisable correlations.

As stated earlier, even if the underlying efficiency is not entirely factorisable, then the iterative method will nevertheless find single-particle efficiencies. However, their product will consequently not match the underlying efficiency everywhere. Rather, the product of the resulting single-particle efficiencies will be a factorized approximation to the non-factorisable underlying efficiency.

Appendix B provides alternative definitions for single-particle efficiencies other than those of Eq.6.6 and Eq.6.7. These alternative definitions are based on arguments that guarantee them to provide a best possible factorized approximation to a non-factorisable underlying efficiency. However, a translation of these definitions into a generally convergent iterative method has yet been unsuccessful.

6.4 Correcting the angular distributions in $B_d \rightarrow \mu^+ \mu^- K^*$

In Ch.5 the iterative method was motivated as a means to correct the angular distributions in the new physics sensitive rare decay $B_d \rightarrow \mu^+ \mu^- K^*$ for efficiency effects using the control channel $B_d \rightarrow J/\psi K^*$. In this section this approach to an efficiency correction is studied on full Monte Carlo simulation.

⁵Smoothing with a parallel developed continuously differentiable quadratic interpolation between neighboring bins; a spline algorithm.

6.4.1 Event samples

The event samples for $B_d \rightarrow \mu^+ \mu^- K^*$ and $B_d \rightarrow J/\psi K^*$ used in this section are taken from Monte Carlo generation⁶, which contain at least one decay on the generator level (Monte Carlo truth) within the LHCb acceptance. The number of available events is about 2.6M for either decay.

Events emulating the recorded detector data are obtained by passing the Monte Carlo generated events through a simulation of the LHCb detector and the reconstructed decays through a set of event selection cuts. The selection cuts are displayed in Tab.6.2.

Events are selected based on a number of criteria. Cuts are placed on the quality of the reconstructed tracks and vertices (χ_{track}^2/DoF and χ_{vertex}^2). The daughter particles are required to have large momenta ($|p|$ and p_t cuts) and are distinguished by particle identification (the log-likelihood difference DLL between two particle hypotheses). Furthermore the B_d mother is selected by its mass and topologically by a detached vertex, via cuts on the impact parameters (χ_{IP}^2), the B_d flight distance ($\chi_{flightdistance}^2$) and the requirement that it points back to the primary collision vertex ($\cos(\alpha_{pointing})$, where the angle is between the momentum and flight distance).

The $B_d \rightarrow \mu^+ \mu^- K^*$ events that represent the signal measurement correspond to approximately five nominal years of data taking.

Fig.6.9 shows the reconstructed B_d mass spectrum from $B_d \rightarrow K^* \mu^+ \mu^-$ at different stages in the event selection. Since the events necessarily contain a B_d decay, the amount of (combinatoric) background is relatively small.

6.4.2 The reweighting procedure

Single-particle efficiencies for the kaon, pion and muon decay products are iteratively obtained from the control channel $B_d \rightarrow J/\psi K^*$. Once determined, their product provides an estimate for the efficiency in the signal channel $B_d \rightarrow \mu^+ \mu^- K^*$.

The angular distributions of the signal channel can then be corrected for efficiency effects by assigning a weight to each measured event that is equal to the inverse of its estimated efficiency. The angular distributions of the *reweighted* signal events should thereafter sum up to the underlying distributions, before such things as detector acceptance and event selection take their effect. However, applying a correction in this way suffers from a basic problem: those parts of momentum phase space that have zero efficiency will not have any events to reweight and are therefore not recovered.

For the angular distributions it is possible to overcome this problem by reweighting events with an average efficiency as explained below.

In the decay the momenta of the outgoing particles p_K , p_π , p_{μ^+} and p_{μ^-} are determined on the one hand by the decay angles θ_l , θ_k , ϕ and the dimuon invariant mass q^2 and on the other hand by the B_d momentum P_B ⁷. The distribution of the decay angles

⁶MC2010-00007608-sim07-reco06-nu1-magDown and MC2010-00007611-sim07-reco06-nu1-magDown respectively

⁷There are three additional decay parameters, which determine the orientation of the decay (ρ and

Bd2KstMuMu Early Signal pre-selection		Analysis selection	
DiMuon For Early Bd2KstMuMu StdVeryLooseDetachedKst2KPi			
B_d	$M > 5050 \text{ MeV}$		
B_d	$\Delta M < 500 \text{ MeV}$		
B_d	$\cos(\alpha_{pointing}) > 0.9999$	B_d	$\cos(\alpha_{pointing}) > 0.99995$ *
B_d	$\chi^2_{flightdistance} > 100$	B_d	$\chi^2_{flightdistance} > 900$ *
B_d	$\chi^2_{IP} < 64$	B_d	$\chi^2_{IP} < 9$ *
B_d	$\chi^2_{vertex}/DoF < 36$	B_d	$\chi^2_{vertex} < 16$ *
K^*	$\cos(\alpha_{pointing}) > -0.95$ *	K^*	$\chi^2_{vertex} < 25$ *
$K^\pm$	$\chi^2_{track}/DoF < 10$	$K^\pm$	$\chi^2_{track}/DoF < 2$
		$K^\pm$	$\chi^2_{IP} > 16$ *
		$K^\pm$	$DLL(K - \pi) > -1$
		$K^\pm$	$DLL(K - p) > -1$
		$K^\pm$	$ p > 1 \text{ GeV}$
		$K^\pm$	$p_t > 200 \text{ MeV}$
$\pi^\pm$	$\chi^2_{track}/DoF < 10$	$\pi^\pm$	$\chi^2_{track}/DoF < 2$
		$\pi^\pm$	$\chi^2_{IP} > 16$ *
		$\pi^\pm$	$DLL(K - \pi) < 25$
		$\pi^\pm$	$ p > 1 \text{ GeV}$
		$\pi^\pm$	$p_t > 200 \text{ MeV}$
DiMuon For Early Bd2KstMuMu			
StdVeryLooseDiMuon			
$\mu\mu$	$\cos(\alpha_{pointing}) > -0.95$ *	$\mu\mu$	$\chi^2_{vertex} < 25$ *
$\mu^\pm$	$\chi^2_{track}/DoF < 10$	$\mu^\pm$	$\chi^2_{track}/DoF < 2$
		$\mu^\pm$	$\chi^2_{IP} > 9$ *
		$\mu^\pm$	$DLL(\mu - \pi) > -5$
		$\mu^\pm$	$ p > 3 \text{ GeV}$

Table 6.2: The $B_d \rightarrow K^* \mu^+ \mu^-$ early signal stripping line pre-selection (02-09-2010) and analysis selection cuts (Ref.[26]). Selection cuts that are in principle not factorisable are indicated with a star *.

sample	MC truth	pre-selected	selected
$B_d \rightarrow K^* J/\psi$ measurement	1110025	538904	77342
$B_d \rightarrow K^* J/\psi$ MC prediction	1516542		
$B_d \rightarrow K^* \mu^+ \mu^-$ measurement	554988	366151	36571

Table 6.3: Sizes of the event samples, that are used in a full Monte Carlo exercise to correct the angular distributions in $B_d \rightarrow K^* \mu^+ \mu^-$ for efficiency effects.

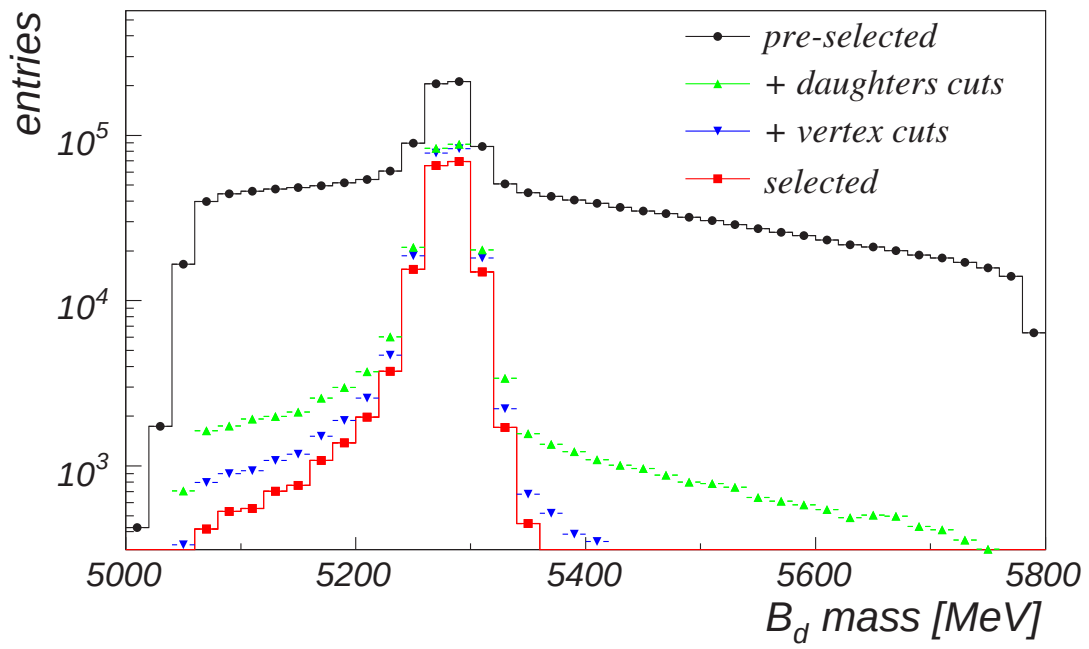


Figure 6.9: The B_d mass distribution of $B_d \rightarrow K^* \mu^+ \mu^-$ at different stages in selection (Monte Carlo prediction). See also Tab.6.2.

and the B_d momentum spectrum are independent. A particular set of θ_l , θ_k , ϕ and q^2 will thus combine with the entire B_d momentum spectrum and cover a wide range of outgoing particle momenta.

This fact can be exploited by expressing the underlying angular distribution in terms of the measured distribution

$$N_{\text{underl}}(q^2, \theta_l, \theta_k, \phi) = \frac{N_{\text{meas}}(q^2, \theta_l, \theta_k, \phi)}{\int d^3 P_B P(P_B) e_K e_\pi e_{\mu^+} e_{\mu^-}} = \frac{N_{\text{meas}}(q^2, \theta_l, \theta_k, \phi)}{\langle e_K e_\pi e_{\mu^+} e_{\mu^-} \rangle}, \quad (6.18)$$

where $P(P_B)$ is the underlying B_d momentum distribution. That is, the θ_l , θ_k , ϕ and q^2 of a single measured $B_d \rightarrow \mu^+ \mu^- K^*$ event is combined with the whole B_d momentum spectrum to form outgoing particle momenta. The event is then reweighted with the average of the efficiencies of all the possible combinations of outgoing particle momenta. Note that in this way the averaging will also cover regions of phase space with zero efficiency, such that these are indeed taken into account in the reweighting.

The averaging requires knowledge of the B_d momentum spectrum, but since the same spectrum is used to obtain the single-particle efficiencies from $B_d \rightarrow J/\psi K^*$ this adds no additional restriction.

In principle the average efficiency can be obtained on a per-event basis by performing the averaging for each measured event. However, per-event averaging is very time consuming, so for the Monte Carlo study described in this section an alternative and faster approach is implemented, where the average efficiency is determined in advance in bins of $(q^2, \theta_l, \theta_k, \phi)$.

6.4.3 Results

For all of the four outgoing particles $K^\pm$, $\pi^\pm$, μ^+ and μ^- the single-particle efficiencies are determined from $B_d \rightarrow J/\psi K^*$ events in 20×20 bins in $^{10} \log(|p|) \times \eta$ phase-space. B_d and $\bar{B}_d$ decays are combined, such that the iterated kaon and pion efficiencies are averages of the K^+ and K^- and of the π^+ and π^- efficiencies respectively.

The resulting single-particle efficiencies are shown in figures 6.10 to 6.13⁸. The effective efficiencies, where particle correlations are not unfolded, are shown as well.

A large difference between the iteration results and the effective efficiencies are particularly visible in figures 6.10 and 6.11 for the kaons and pions. This shows that the decay topology has a significant effect on the detection and selection of kaons and pions.

Fig.6.14 shows the influence of efficiencies on the angular distribution in $B_d \rightarrow J/\psi K^*$ itself. In particular the distribution of θ_k is seen to be greatly influenced by the event acceptance. After unfolding single-particle efficiencies from the underlying event, the angular distributions are largely restored to the underlying ones.

The result of reweighting the angular distributions in $B_d \rightarrow \mu^+ \mu^- K^*$, using the ef-

$\hat{f}$ in Fig.5.1). These are uniformly distributed for the spinless B_d mesons and are implicit.

⁸The dependencies on the variables $^{10} \log(p)$ and η separately in these figures have been obtained by integrating/averaging over the other variable.

efficiencies determined with the control channel $B_d \rightarrow J/\psi K^*$, are shown in Fig.6.15. Good agreement between the reweighted and underlying distributions is observed.

It is seen that the acceptance and the selection cuts do not have a very large effect on most angular distributions in $B_d \rightarrow \mu^+ \mu^- K^*$, where the measured distributions retain the form of the underlying ones. Only the θ_k distributions shows a significant difference between measured and underlying. Very backward produced pions, $\cos(\theta_k) \approx 1$, tend to have rather small transverse momentum, and therefore this region in $\cos(\theta_k)$ suffers from the p_t -cut of Tab.6.3. The θ_k -distribution is to a large extent recovered by reweighting with single-particle efficiencies.

6.5 Conclusion

Efficiencies in detecting particles are invariably folded in with the multi-body process by which the particles are produced. Because of this, the usual exercise where a particle's measured momentum spectrum is divided by its underlying momentum spectrum, does not result in the correct particle efficiency.

In this chapter an iterative method has been developed that correctly unfolds single-particle efficiencies from a multi-body process. The method has been implemented as a binned method.

The error on single-particle efficiencies is estimated on the basis of the number of measured and Monte Carlo truth events, holding the other particle efficiencies constant. The iterative method and error estimate have been validated with toy input efficiencies applied to Monte Carlo generated $B_d \rightarrow K^* J/\psi$ events and seen to produce reliable results.

Furthermore, the method has been applied on full Monte Carlo simulation, where the angular distributions in the new physics sensitive rare decay $B_d \rightarrow \mu^+ \mu^- K^*$ are corrected for efficiency effects by determining the single-particle efficiencies from the control channel $B_d \rightarrow J/\psi K^*$.

For this and in addition to the iterative method a reweighting procedure has been used, that does not suffer from the absence of measurements in regions of phase space where the efficiency is zero. The combination of the iterative method and the reweighting procedure shows good agreement between the underlying angular distributions and the measured angular distributions after they are corrected for efficiency effects.

In this chapter the iterative method has been explained as a way to determine single-particle efficiencies. However, the applicability of the method reaches further than determining efficiencies and in the next chapter the method is used to compare between LHCb measurements of charm decays, rather than between a measurement and its predicted underlying distribution. In this way single-particle asymmetries will be determined, rather than efficiencies.

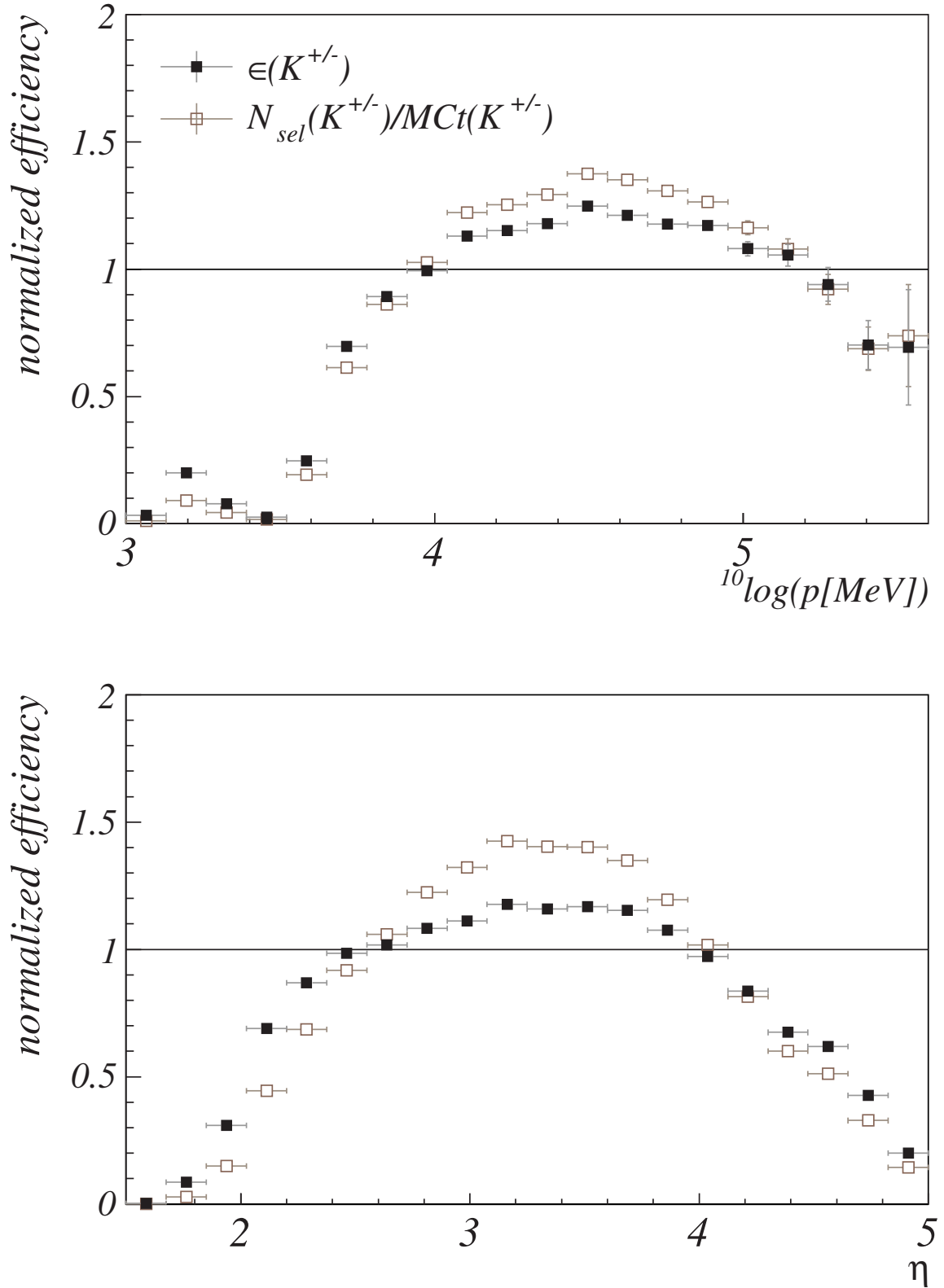


Figure 6.10: The (normalized) $K^\pm$ efficiency from $B_d \rightarrow J/\psi K^*$ (Monte Carlo simulation, K^+ and K^- average). The effective efficiency $N_{sel}/N_{MCtruth}$ is shown for reference.

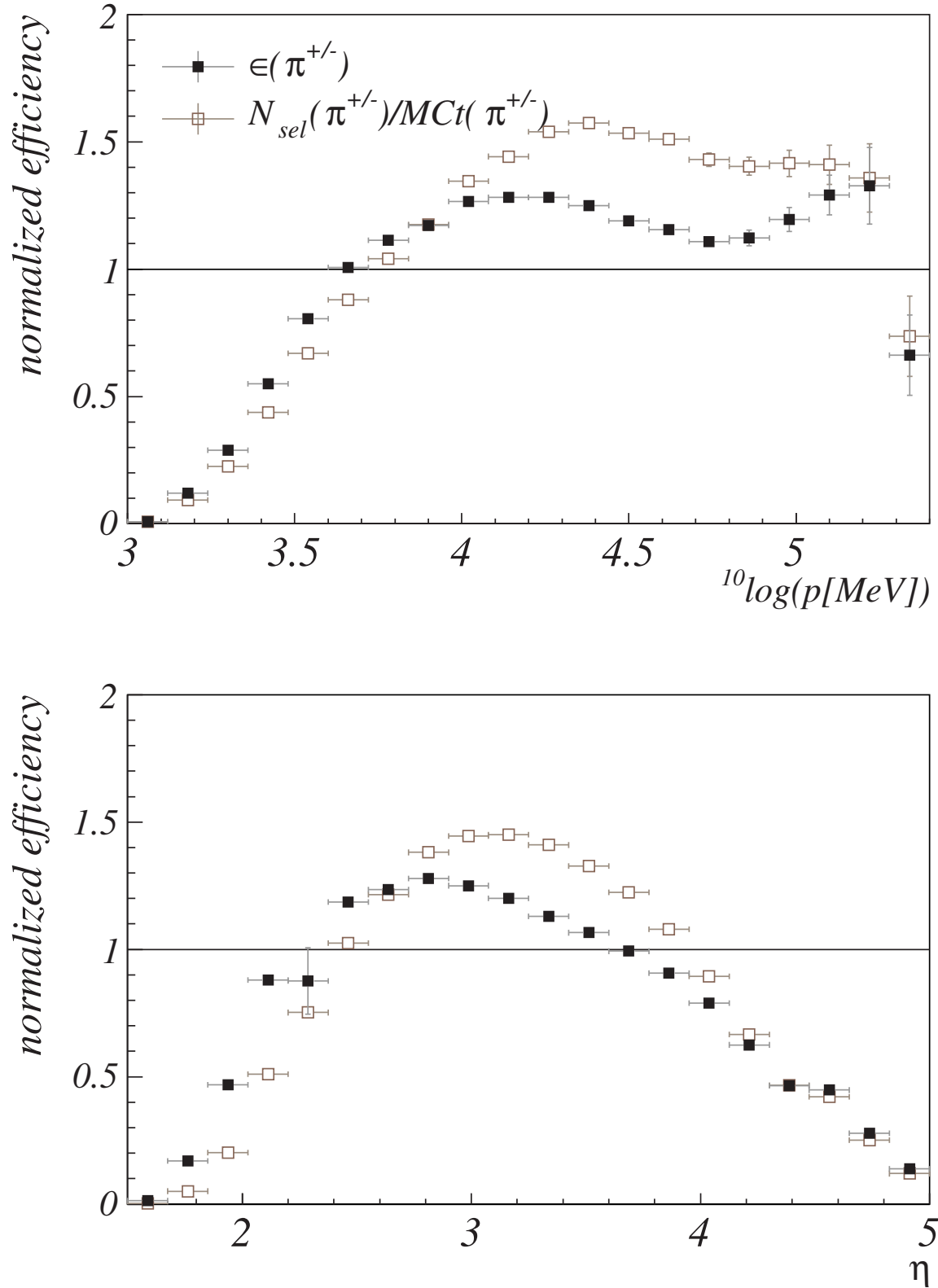


Figure 6.11: The (normalized) $\pi^\pm$ efficiency from $B_d \rightarrow J/\psi K^*$ (Monte Carlo simulation, π^+ and π^- average). The effective efficiency $N_{sel}/N_{MCtruth}$ is shown for reference.

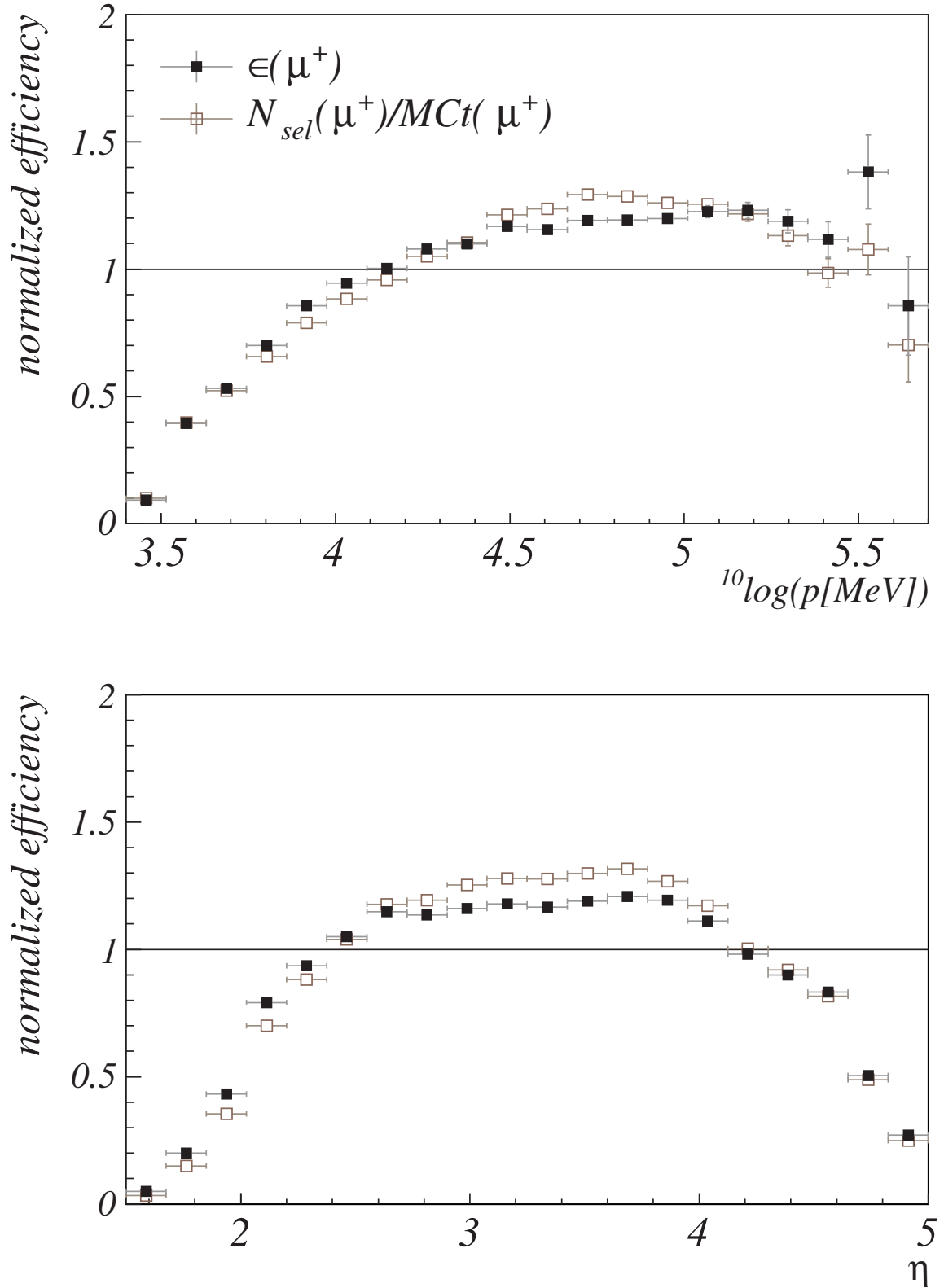


Figure 6.12: The (normalized) μ^+ efficiency from $B_d \rightarrow J/\psi K^*$ (Monte Carlo simulation). The effective efficiency $N_{sel}/N_{MCtruth}$ is shown for reference.

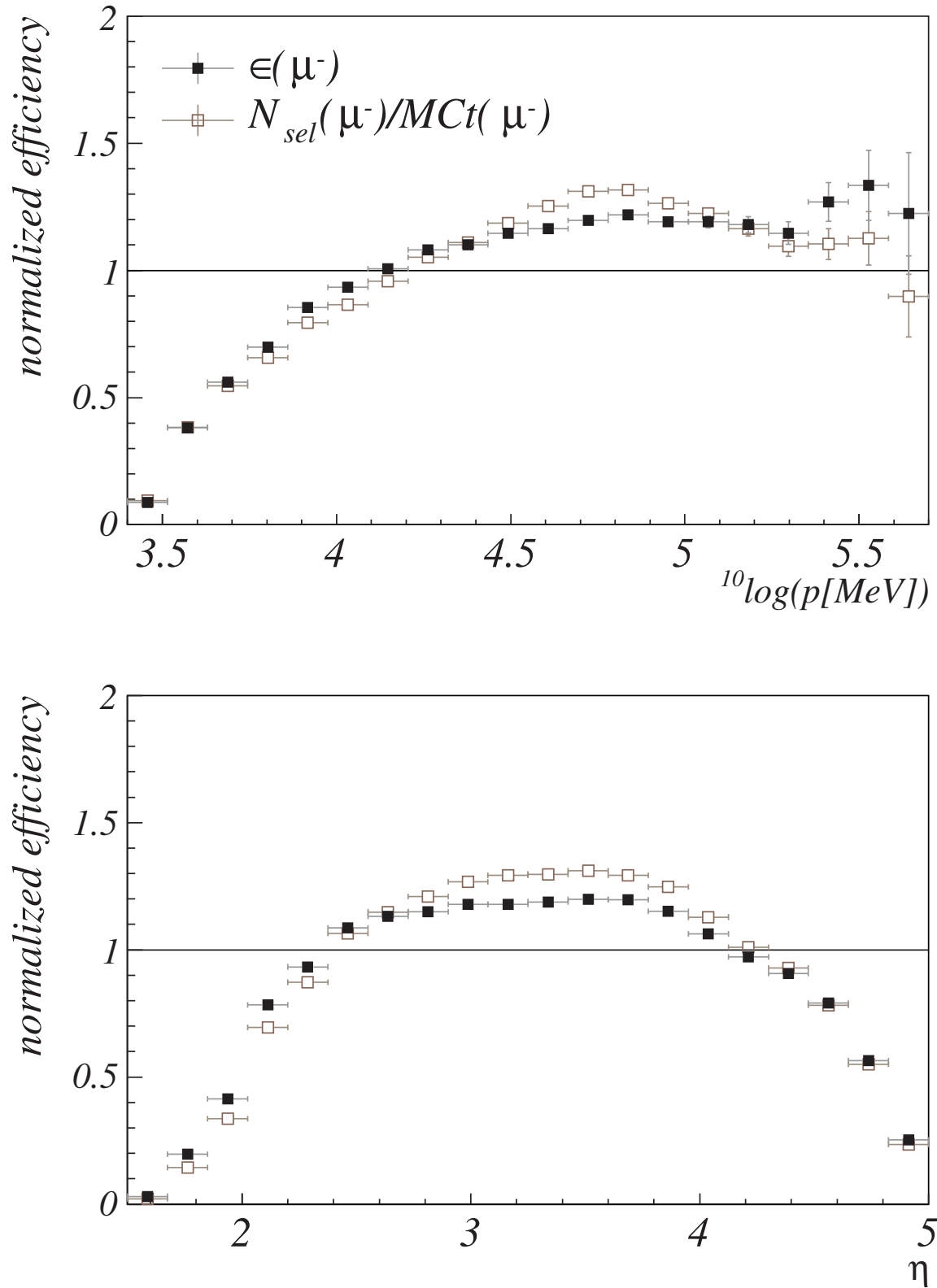


Figure 6.13: The (normalized) μ^- efficiency from $B_d \rightarrow J/\psi K^*$ (Monte Carlo simulation). The effective efficiency $N_{sel}/N_{MCtruth}$ is shown for reference.

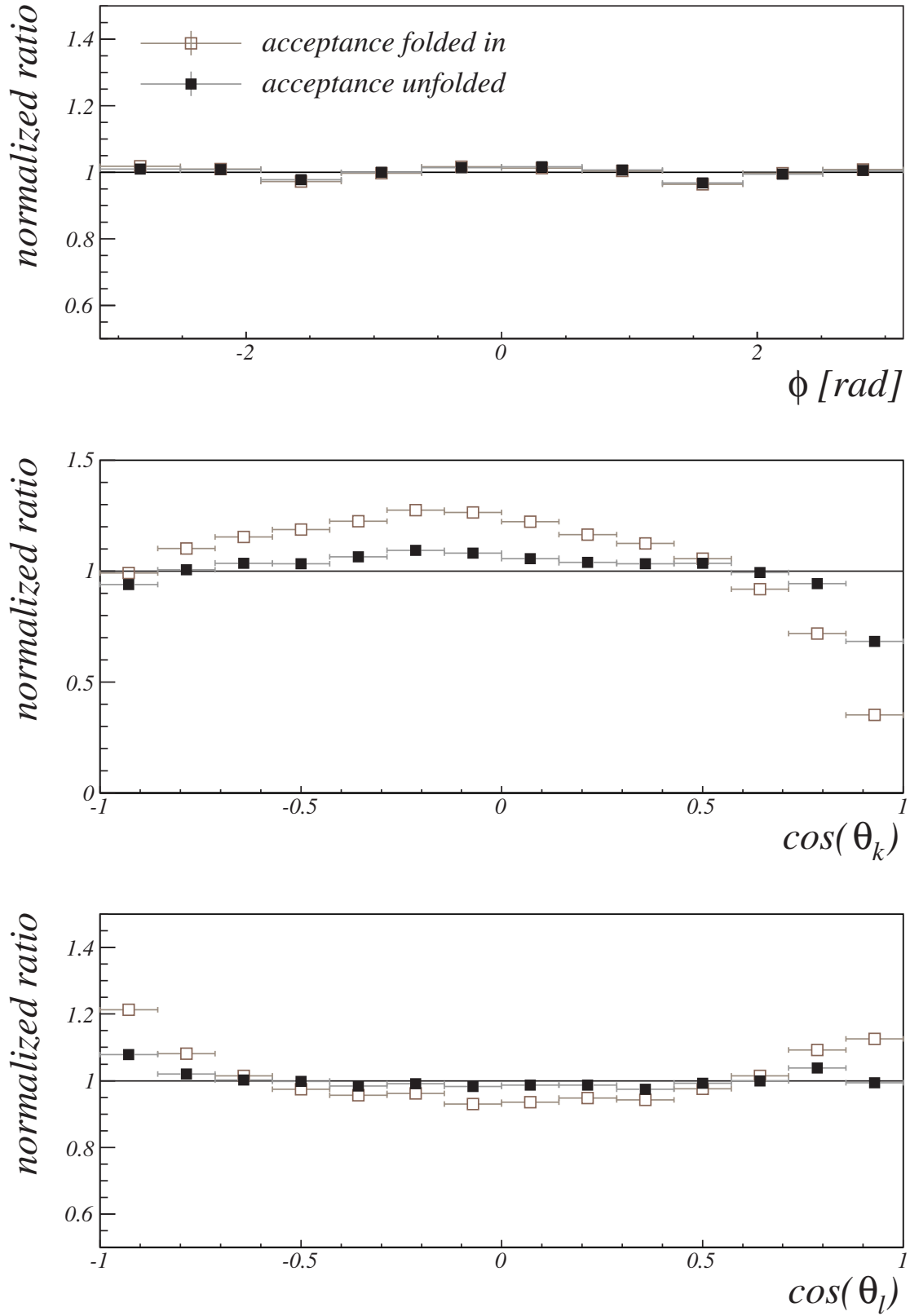


Figure 6.14: Angular distribution in a measurement of $B_d \rightarrow J/\psi K^*$ (full Monte Carlo simulation) divided by the angular distribution in Monte Carlo truth. Experimental efficiencies of the decay products influence the angular distributions (acceptance folded in). After the iterative method unfolds the efficiencies the angles are brought back to their underlying distributions (acceptance unfolded).

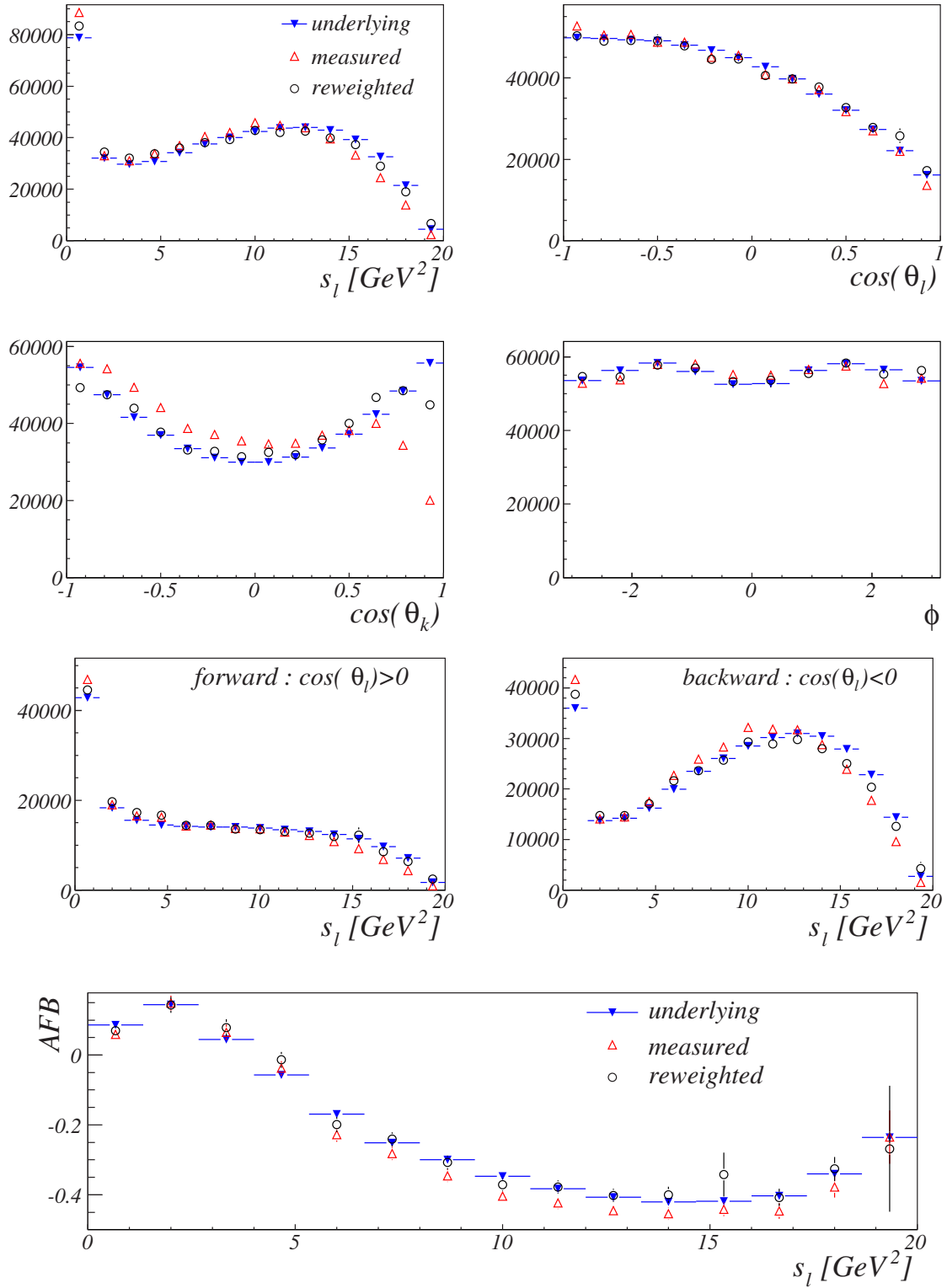


Figure 6.15: The Angular distributions in $B_d \rightarrow K^* \mu^+ \mu^-$ reweighted with single-particle efficiencies determined from $B_d \rightarrow K^* J/\psi$ (full Monte Carlo simulation). The “measured” distributions have been normalized to the underlying ones to easy comparison.

Chapter 7

Single-particle asymmetries from charm decays

It's one or the other, 50-50. Yet somehow there's always a greater chance to get it wrong.

Marcel Merk, deducing the magnetic field polarity.

In the previous chapter an iterative method has been developed to obtain single-particle efficiencies from a multi-body process. The measurement of a multi-body process was compared with the Monte Carlo (truth) prediction of its underlying physics and iteratively the single-particle efficiency distributions were unfolded.

The method was applied on full Monte Carlo simulation in an exercise to determine the kaon, pion and muon efficiencies from the well known $B_d \rightarrow J/\psi K^*$ channel and use these to correct the angular distributions in the new physics sensitive $B_d \rightarrow \mu^+ \mu^- K^*$ channel for efficiency effects. Unfortunately the first 2010 LHCb measurements were insufficient to perform the efficiency correction on data.

However, the comparison does not need to be between a measurement and Monte Carlo truth; any two data sets can be compared. The method will iteratively uncover whatever causes a particle in one set to be distributed differently from a particle in the other set. In this chapter this basic property is exploited to determine *relative* single-particle efficiencies by comparing measurements, 2010 LHCb measurements of charm meson decays. As such, the method is used in a completely data-driven way to determine asymmetries between particles rather than efficiencies of particles.

The analysis in this chapter makes use of LHCb measurements of charm meson decays. The charm decays that are considered and the asymmetries that are determined are:

1. $D^0/\bar{D}^0 \rightarrow K^+ K^-$ (untagged)

From this decay the asymmetry between the K^+ and K^- detection efficiencies is determined.

2. $D^0 \rightarrow K^- \pi^+$ and $\bar{D}^0 \rightarrow K^+ \pi^-$.

From these two decays the asymmetry between the π^+ and π^- detection effi-

Decay mode	Branching fraction
$D^0/\bar{D}^0 \rightarrow K^+K^-$	$(3.94 \pm 0.07) \times 10^{-3}$
$D^0 \rightarrow K^-\pi^+, \bar{D}^0 \rightarrow K^+\pi^-$	$(3.89 \pm 0.05) \times 10^{-2}$
$D^0 \rightarrow K^+\pi^-, \bar{D}^0 \rightarrow K^-\pi^+$	$(1.48 \pm 0.07) \times 10^{-4}$ (doubly Cabibbo suppressed)

Table 7.1: Branching fractions for charm decays into K^+K^- and $K^\mp\pi^\pm$ (Ref.[27]).

ciencies and the asymmetry between the D^0 and $\bar{D}^0$ production cross section are determined.

The branching fractions of these are tabulated in Tab.7.1. It should be noted that only the momentum dependencies of the asymmetries will be obtained; no assumptions will be made to determine the scales (averages) of the asymmetries.

7.1 Charm decays in 2010 data

In the 2010 data taking period the LHCb detector has taken data at a center of mass energy of 7 TeV and with a total luminosity of 37 pb^{-1} . Data in the magnetic field down configuration, corresponding to 18 pb^{-1} , were taken with two consistent trigger configurations and are considered for the analysis in this chapter.

The resulting events have necessarily passed the LHCb trigger system and, in addition, have passed loose event selections, so called stripping lines, to reduce the data size¹.

7.1.1 Trigger and event selection

One of the stripping lines is tailored for the selection of the charm decays that are considered in this chapter². The cuts that select the charm decay candidates are tabulated in Tab.7.2.

Events are selected by the quality of the reconstructed tracks and vertices (Track- χ^2/DoF and Vertex- χ^2) and by requiring a large transverse momentum for the daughter particles and the reconstructed charm mother. Charged kaons and pions are separated by particle identification (the log-likelihood difference DLL between K and π hypotheses on reconstructed tracks). The $D^0/\bar{D}^0$ meson is selected by its mass and topologically by a detached decay vertex, via the daughter impact parameters ($\text{IP}_{\min}\text{-}\chi^2$) and the proper lifetime of the reconstructed charm meson ($c\tau$). Additionally, the angle in $\cos(\theta)$ between a kaon or pion daughter and the charm flight direction in the charm center of mass is uniformly distributed for real $D^0/\bar{D}^0$ decays, but peaks at ± 1 for candidates from (combinatoric) background. This region is explicitly avoided.

The selected events have necessarily passed the LHCb trigger. The LHCb trigger system consists of three stages: Level-0 (L0), High level trigger 1 (Hlt1) and High level

¹This analysis uses events from the *Charm Stripping*: LHCb, Collision10, Beam3500GeV-VeloClosed-MagDown, Real Data + Reco08-Stripping12c, 90000000, 9284, CHARMFULL.DST

²The stripping line D02HHForPromptCharm.

Global Cuts					
nr. of primary vertices			1, 2, or 3		
tracks			<	400	
SPD(multiplicity)			<	500	
IT clusters			<	1000	
VELO tracks			<	200	
kaon/pion selection			$D^0/\bar{D}^0$ selection		
Track- χ^2/DoF	<	5	Vertex- χ^2	<	9
p_t	>	250 MeV	p_t	>	2 GeV
$\text{IP}_{\text{min}}\text{-}\chi^2$	>	9	$c\tau^{(a)}$	>	100 μm
kaon DLL(K- π)	>	2	ΔMass	<	75 MeV
pion DLL(K- π)	<	-2	$ \cos(\theta) $	<	0.9

Table 7.2: Summary of the stripping selection line *D02HHForPromptCharm*; $D^0/\bar{D}^0 \rightarrow K^+K^-$ and $D^0/\bar{D}^0 \rightarrow K^\mp\pi^\pm$ candidates are selected. ^(a) $c\tau$ is determined using a lifetime fitting procedure requiring $\chi^2(\text{lifetime fit}) < 9$.

trigger 2 (Hlt2), where each stage consists of multiple trigger lines. It is observed that the selected events have primarily passed a specific trigger line at each stage³. These specific trigger lines are summarized in table Tab.7.3. The fractions of events that have passed the trigger lines are tabulated in Tab.7.4. The majority (90%) of the selected events has been triggered by the specific Hlt2 line and the reconstructed candidate itself caused the trigger in 99% of the events.

The final event selection to extract asymmetries is summarized in Tab.7.5. The requirement that the specific L0 line has been triggered independently of the signal candidate (TIS) is discussed in Sec.7.2.2. A trigger of the Hlt2 line by the signal candidate (TOS) is specifically required, because for these events the signal and background fractions can be estimated as described in the next subsection 7.1.2. A 25 MeV mass window will be considered as a signal region for the reconstructed charm mesons, the same window imposed by the Hlt2 trigger line. As shown in the next subsection this window amounts to approximately 3σ and 4σ of the signal peaks for $D^0/\bar{D}^0 \rightarrow K^\mp\pi^\pm$ and $D^0/\bar{D}^0 \rightarrow K^+K^-$ events respectively.

7.1.2 Signal and background estimation

The Hlt2 trigger line adds a mass cut of 25 MeV around the D^0 mass, which is too restricted to estimate the background from the sidebands. A second trigger line therefore implements the same trigger selection cuts, except for a larger mass window of 1700-2100 MeV⁴. However, it is prescaled with a factor 1/100 to reduce its trigger rate. Events triggered by the wide-mass version are used to estimate signal and background for the candidates triggered by the unscaled, mass-restricted Hlt2 line. Signal and

³L0Hadron, Hlt1TrackAllL0 and Hlt2CharmOSTF2Body.

⁴Hlt2CharmOSTF2BodyWideMass

L0Hadron			
$E_t(\text{calo. cluster})$	$>$	3.6 GeV	
$\text{Spd}(\text{mult.})^{(a)}$	$<$	900/450	(500)
Hlt1TrackAllL0		Hlt2CharmOSTF2Body	
track hits	> 9	VELO tracks	< 350 (200)
missed VELO hits	< 3	unfitted forward tracks	< 120
at least one track with		kaon/pion selection	
$\text{IP}_{\min}$	> 0.1 mm	$\text{IP}_{\min}\text{-}\chi^2$	> 2 (9)
p_t	> 1.85 GeV	p_t	> 800 MeV
p	> 13.3 GeV	p	> 5 GeV
$\text{Track-}\chi^2/\text{DoF}$	< 3	$\text{Track-}\chi^2/\text{DoF}$	< 5 (5)
		$D^0/\bar{D}^0$ selection	
		$\text{Mass}^{(b)}$	in 1839-1889 MeV
		$\text{Vertex-}\chi^2/\text{DoF}$	< 10
		$\text{Flight Distance-}\chi^2/\text{DoF}$	> 25
		p_t	> 2 GeV (2 GeV)
		$\cos(\alpha)$	> 0.99985
		Tracks DOCA	< 0.1 mm
		Max. p_t daughters	> 1.5 GeV

Table 7.3: Summary of the trigger lines that are primarily traversed by selected charm candidates. The values in brackets are stripping selection cuts that supersede the trigger cuts (see Tab.7.2). ^(a)Two trigger configurations (TCK) have been used, with $\text{Spd}(\text{Mult}) < 900$ and $\text{Spd}(\text{Mult}) < 450$. ^(b)The mass window is for any of a K^+K^- , $\pi^+\pi^-$, or $K^\mp\pi^\pm$ hypothesis on the reconstructed tracks.

	L0Hadron	Hlt1TrackAllL0	Hlt2CharmOSTF2Body
Decision	63%	88%	90%
TOS	60%	93%	99%
TIS	49%	11%	1%

Table 7.4: The fractions of selected events corresponding to positive trigger decisions, relative to all events that passed the stripping selection. TIS and TOS denote the requirement that the trigger line has been triggered independently of the signal candidate and by the signal candidate, respectively. The fractions of Trigger-On-Signal (TOS) and Trigger-Independent-of-Signal (TIS) events are with respect to positive trigger decisions.

event selection	D02HHForPromptCharm (Tab.7.2)	
trigger selection	line	requirement
Level-0 trigger	L0Hadron (Tab.7.3)	TIS
High level trigger 1	Any line	
High level trigger 2	Hlt2CharmOSTF2Body (Tab.7.3)	TOS
signal mass region	1864 ± 25 MeV	

Table 7.5: *Trigger and event selections for $D^0/\bar{D}^0 \rightarrow K^+ K^-$ and $D^0/\bar{D}^0 \rightarrow K^\mp \pi^\pm$ decays. Events are from October 2010 LHCb measurements in the Magnet Down configuration.*

candidate	events	signal fraction	S/B
$K^+ K^-$	84,482	0.83 ± 0.01	4.9 ± 0.3
$K^- \pi^+$	337,400	0.969 ± 0.003	31 ± 3
$K^+ \pi^-$	346,589	0.965 ± 0.004	28 ± 3

Table 7.6: *Signal candidates after the final event selection of Tab.7.5. The signal fractions and signal over background rates are estimated in Sec.7.1.2, Fig.7.2.*

background fits will be performed in a 50 MeV window around the D^0 mass.

As a source for a peaking background $D^0 \rightarrow K^- \pi^+$ and $\bar{D}^0 \rightarrow K^+ \pi^-$ decays with misidentified daughters have been considered. Fig.7.1 shows the misidentified mass distribution in case of a pion→kaon misidentification and in case of a double misidentification. The first will be misidentified as $K^+ K^-$ pairs; however, only at mass values exceeding the fit window. The second will misidentify between $D^0 \rightarrow K^- \pi^+$ and $\bar{D}^0 \rightarrow K^+ \pi^-$ candidates, but the misidentified mass distribution is approximately flat.

The mass distributions are modeled by a Gaussian signal on top of a linear background in a 1864 ± 50 MeV mass window. Fig.7.2 shows the fits to the invariant mass distributions for the decay candidates.

7.1.3 Momentum distributions

Fig.7.3 shows the momentum distributions of the reconstructed $D^0/\bar{D}^0$ decay candidates selected as in Tab.7.5, while Fig.7.4 shows the kinematic distributions of the kaon and pion daughter particles. The loss of kaons and pions that fly in the vertical direction ($\phi = \pm\pi/2$ rad) is due to the presence of the Velo RF-foil around $x=0$, while in the horizontal plane ($\phi = 0, \pm\pi$ rad) there is a loss of particles that are bent into the beam pipe (Ref.[28]). The structure at low (transverse) momentum is a result of the Hlt1 and Hlt2 trigger selection cuts in addition to the stripping selection (see Tab.7.2 and Tab.7.3).

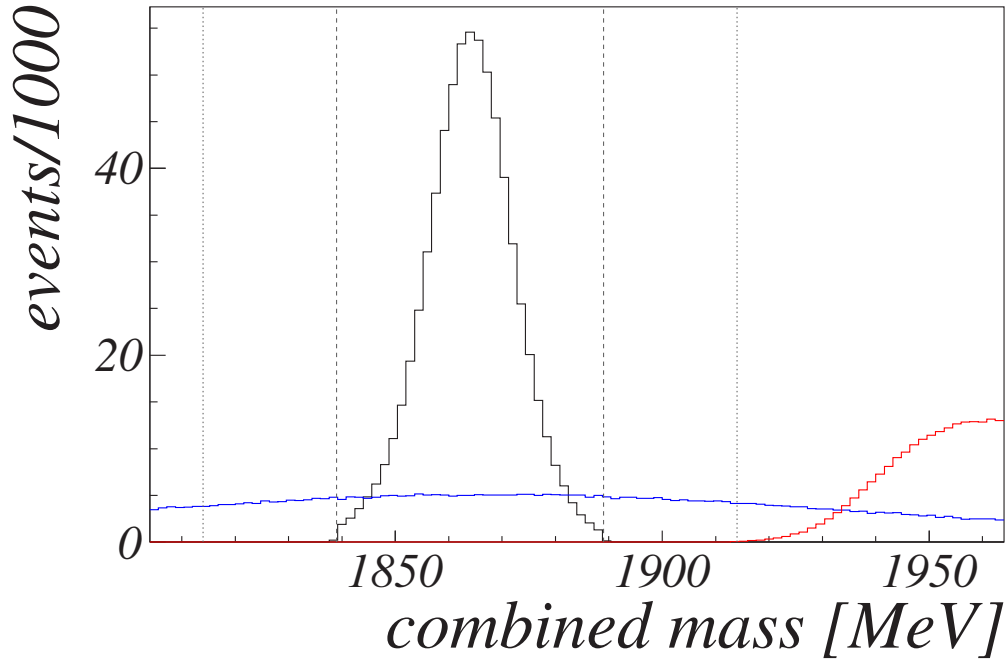
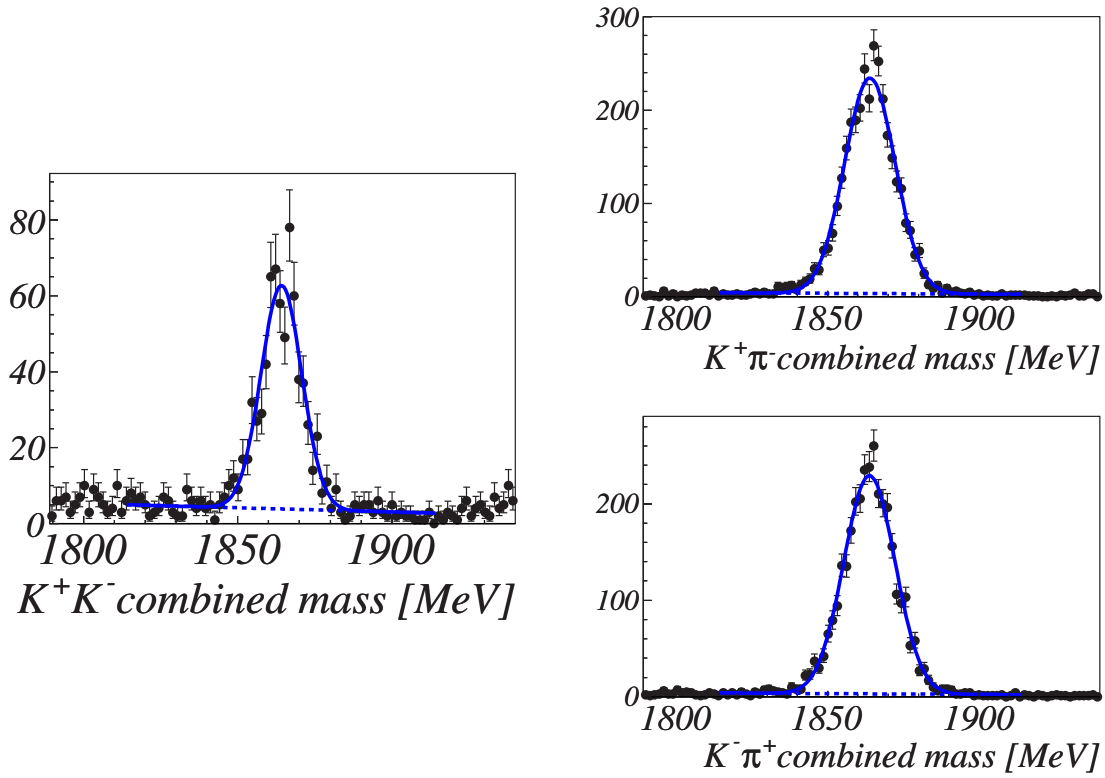


Figure 7.1: Mass distributions of $D^0/\bar{D}^0 \rightarrow K^\mp \pi^\pm$ decays (black line), the distribution when the pion is purposefully misidentified as a kaon (red line), and in case of double misidentification, pion as kaon and kaon as pion (blue line). The 1864 ± 50 MeV fit window is indicated by the dotted vertical lines; the 1864 ± 25 MeV signal window by the dashed lines.



	signal mass mean, sigma	signal fraction	in 1864 ± 25 MeV signal window	
			signal fraction	S/B
K^+K^-	1864.2 , 6.6 MeV	0.63 ± 0.02	0.83 ± 0.01	4.9 ± 0.3
$K^-\pi^+$	1863.8 , 8.5 MeV	0.91 ± 0.01	0.969 ± 0.003	31 ± 3
$K^+\pi^-$	1864.0 , 8.4 MeV	0.90 ± 0.01	0.965 ± 0.004	28 ± 3

Figure 7.2: *Estimation of Gaussian signal + linear background for final selection charm candidates (Tab.7.5). Data selected by a prescaled (factor 1/100), wide-mass version of the Hlt2 line has been used for the fits, such that background can be estimated from the sidebands.*

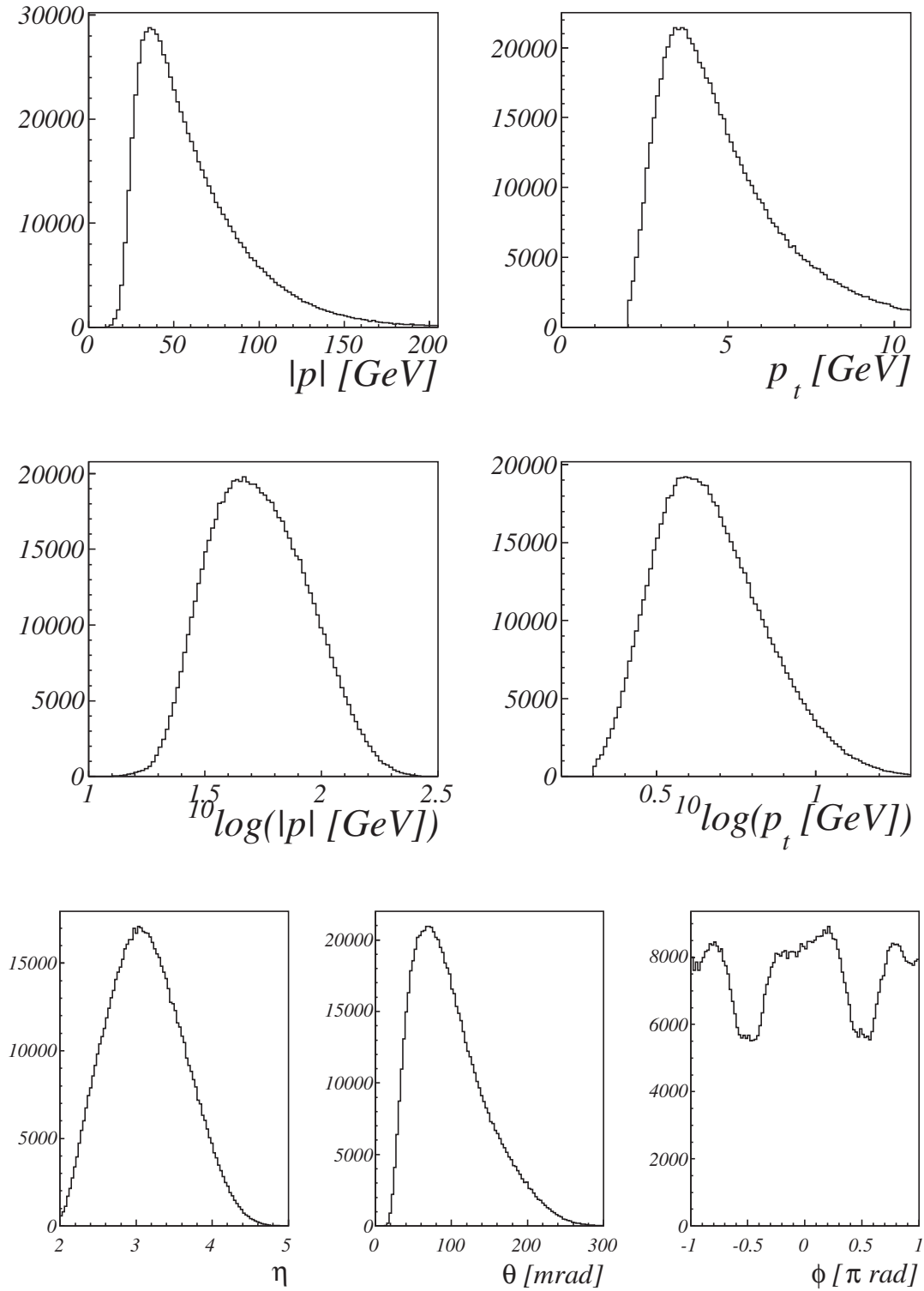


Figure 7.3: Momentum distributions of the reconstructed $D^0/\bar{D}^0$ in the final selection, all three decay channels combined.

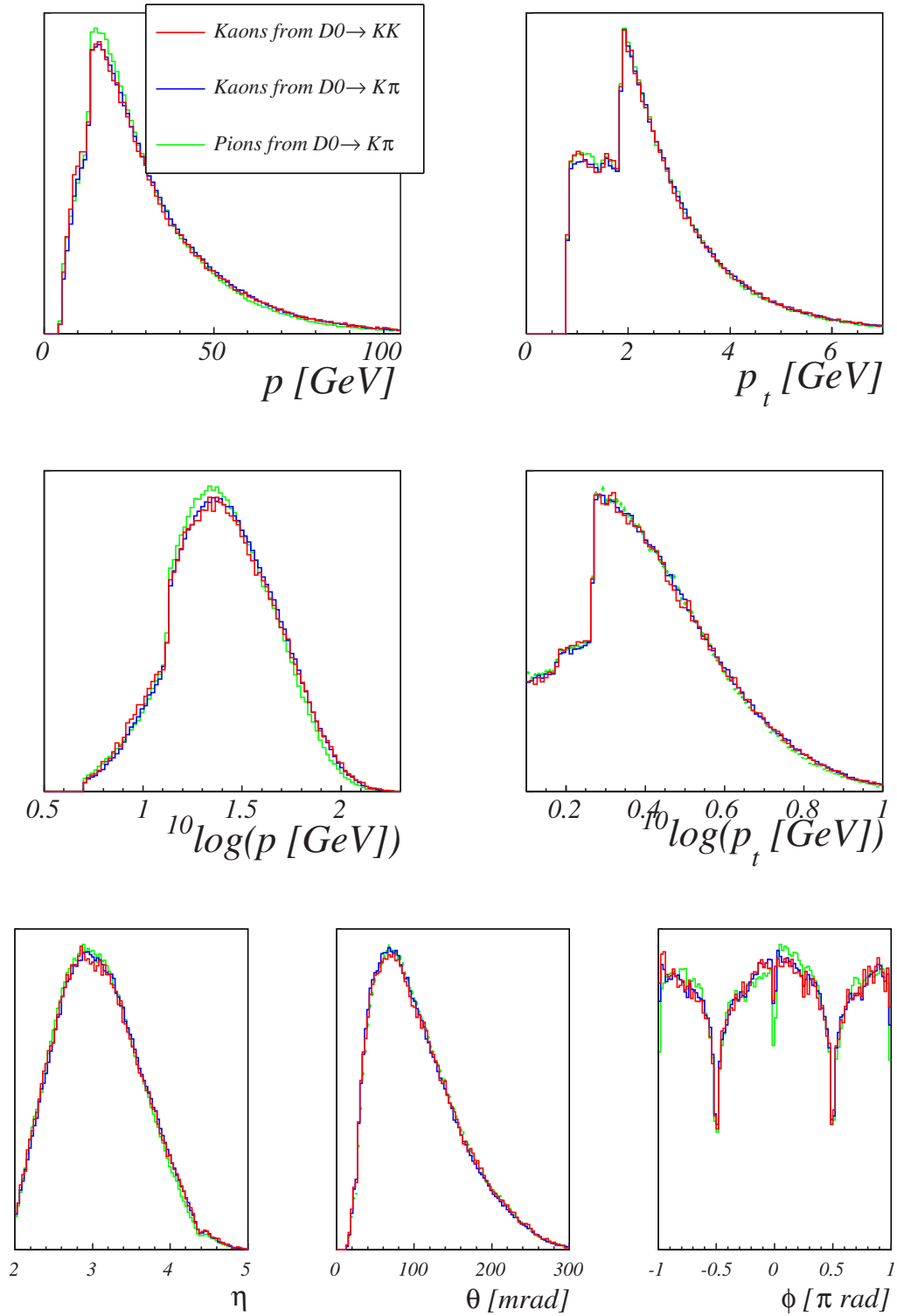


Figure 7.4: Momentum distributions of the reconstructed $D^0/\bar{D}^0$ -daughter particles in the final selection. The distributions have been normalized to ease their comparison. The vertical scale is linear.

7.2 The $K^{+/-}$ detection efficiency asymmetry

The asymmetry between the K^+ and K^- detection efficiencies is extracted from $D^0/\bar{D}^0 \rightarrow K^+K^-$ decays. The asymmetry is determined as the ratio of the K^+ detection efficiency $\epsilon_{det}^{K^+}$ and the K^- detection efficiency $\epsilon_{det}^{K^-}$ at the same value of kaon momentum, i.e. the asymmetry is determined as the ratio

$$A_K^\pm(p) \equiv \epsilon_{det}^{K^+}(p)/\epsilon_{det}^{K^-}(p). \quad (7.1)$$

It should be remarked, that in the following the asymmetry can only be determined up to an arbitrary overall multiplicative scale.

7.2.1 Asymmetry extraction

The difficulty in determining the efficiency asymmetry is similar to the discussion in the previous chapter. The measured momentum distribution of the K^+ is not only affected by the detection efficiency of the K^+ itself, but because the charm decay correlates the two outgoing kaons, it is also influenced by the efficiency distribution of the accompanying K^- .

Naively dividing the K^+ and K^- measured momentum spectra then does not correctly reproduce the efficiency asymmetry, since it does not account for particle correlations. Instead, the iterative method of the previous chapter 6 is employed to unfold the $K^{+/-}$ efficiency asymmetry from the underlying decay topology.

Consider the illustration in Fig.7.5. For every $D^0/\bar{D}^0 \rightarrow K^+K^-$ decay where the K^+ has a momentum p and the K^- momentum q (config.(a)), there is an equally likely decay with the momenta of the outgoing kaons interchanged (config.(b)), since the spinless charm mesons decay isotropically. However, the efficiencies with which these two configurations are measured are not necessarily the same, despite the fact that a K^+ in one and a K^- in the other configuration have equal momentum. A measurement can result in different numbers for the two decay configurations, depending on the relative efficiencies in these

$$N_{\text{meas.}}(p_{K^+}, q_{K^-}) = N_{\text{meas.}}(q_{K^+}, p_{K^-}) \times \frac{\epsilon(p_{K^+}, q_{K^-})}{\epsilon(q_{K^+}, p_{K^-})}. \quad (7.2)$$

The total efficiency in a measurement of a multi-body process like $D^0/\bar{D}^0 \rightarrow K^+K^-$ has two parts:

- An acceptance for the process prior to trigger and event selection. This is determined by the acceptance for the outgoing particles separately; it is a combination of single-particle efficiencies $\epsilon_{det}^h(p_h)$ (*det* for detector and *h* for hadron).
- A reconstruction and selection efficiency due to the trigger and event selections. These include selection cuts on the outgoing particles individually, leading to single-particle efficiencies. However, they also include cuts that depend on particles simultaneously, and will thus generally induce a non-factorisable efficiency $\epsilon_{sel}^{h_1 h_2}(p_1, p_2)$ (*sel* for selection).

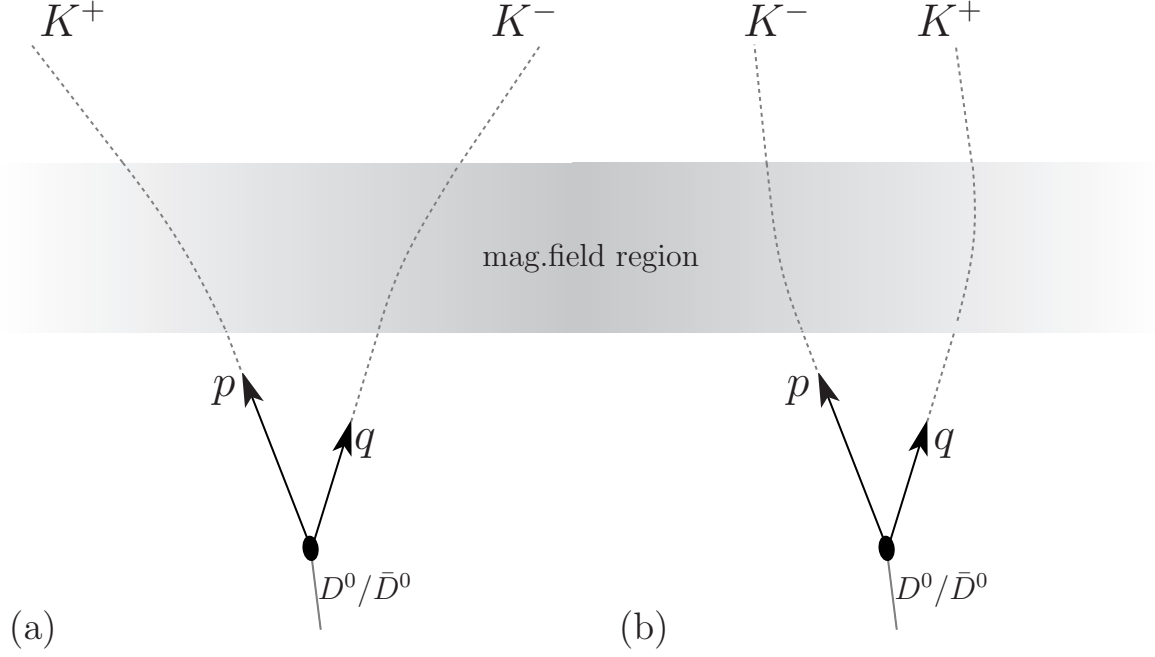


Figure 7.5: An illustration of $D^0/\bar{D}^0 \rightarrow K^+K^-$ decays in the lab frame.

Note that the momenta of the outgoing kaons between (a) and (b) are reversed. In the first configuration (a) the K^+ comes out with a momentum p and the K^- with momentum q . The second configuration (b) has the momenta reversed; here, the K^- comes out with momentum p and the K^+ with momentum q .

Decays as the above are equally likely, since they both conserve momentum. In fact, they occur in equal numbers, since the spinless mesons decay isotropically.

However, the efficiencies with which the two configurations are measured are not necessarily equal. In the figure the LHCb magnetic field is illustrated as one source for different efficiencies; the K^+ in (a) bends outward, while the K^- in (b) with the same momentum bends inward.

In a measurement of $D^0/\bar{D}^0 \rightarrow K^+ K^-$ decays, the total asymmetry in the efficiencies with which the two configurations in Fig.7.5 are measured is then

$$\frac{\epsilon(p_{K^+}, q_{K^-})}{\epsilon(q_{K^+}, p_{K^-})} = \frac{\epsilon_{sel}^{K^+ K^-}(p_{K^+}, q_{K^-})}{\epsilon_{sel}^{K^+ K^-}(q_{K^+}, p_{K^-})} \underbrace{\frac{\epsilon_d^{K^+}(p)}{\epsilon_d^{K^-}(p)}}_{A_K^\pm(p)} \underbrace{\frac{\epsilon_d^{K^-}(q)}{\epsilon_d^{K^+}(q)}}_{A_K^\pm(q)^{-1}}. \quad (7.3)$$

The event selection for charm decays is summarized in Tab.7.5. It makes no distinction between positively and negatively charged particles and the selection efficiency is assumed to be symmetric:

$$\epsilon_{sel}^{K^+ K^-}(p_{K^+}, q_{K^-}) \equiv \epsilon_{sel}^{K^+ K^-}(q_{K^+}, p_{K^-}). \quad (7.4)$$

Then, from relation Eq.7.2 with total efficiency asymmetry shown in Eq.7.3 and under the premise of a symmetric selection as in Eq.7.4, the asymmetry between the K^+ and K^- detection efficiencies is formally determined by integrating over all possibilities for one of the momenta (q in this case)

$$A_K^\pm(p) = \frac{\int d^3q N_{\text{meas.}}(p, q_{K^-})}{\int d^3q N_{\text{meas.}}(q_{K^+}, p) A_K^\pm(q)^{-1}} = \frac{N_{\text{meas.}}^{K^+}(p)}{N_{\text{reweighted meas.}}^{K^-}(p)}. \quad (7.5)$$

The $K^{+/-}$ efficiency asymmetry is determined with Eq.7.5, an equivalent of Eq.6.6 and Eq.6.7 in chapter 6. It is self-dependent through the equation's denominator. It is in fact this self-dependence which accounts for decay correlations between the outgoing kaons. The iterative method of Ch.6 is employed to solve Eq.7.5 and determine the momentum dependence of the asymmetry.

7.2.2 Non-factorisable effects

Eq.7.5 determines the $K^{+/-}$ efficiency asymmetry under the assumption that event selection is symmetric (Eq.7.4)⁵. This assumption is based on the trigger and stripping selection cuts of Tab.7.3 and Tab.7.2 respectively, which do not explicitly distinguish between positively and negatively charged kaons. However, care must be taken with the L0Hadron trigger, because implicitly it does make a distinction. The effect of the L0 trigger is pointed out below; in the event selection of Tab.7.5 the bias from events triggered on signal (TOS) is avoided by the explicit requirement of an L0 trigger independent of the signal candidate (TIS).

L0Hadron trigger effects

Contrary to Hlt1 and Hlt2 trigger lines, the L0 does not trigger on reconstructed tracks, but rather on calorimeter clusters with a large transverse energy ($E_t > 3600$ MeV). As a result, both the momentum of a particle and its charge become important. This is illustrated in Fig.7.6.

⁵Strictly speaking the required assumption is more relaxed: the non-factorisable selections need to be symmetric. Factorisable selections like track quality or particle identification do not necessarily need to be symmetric; an asymmetry in these is then included in the $K^{+/-}$ efficiency asymmetry.

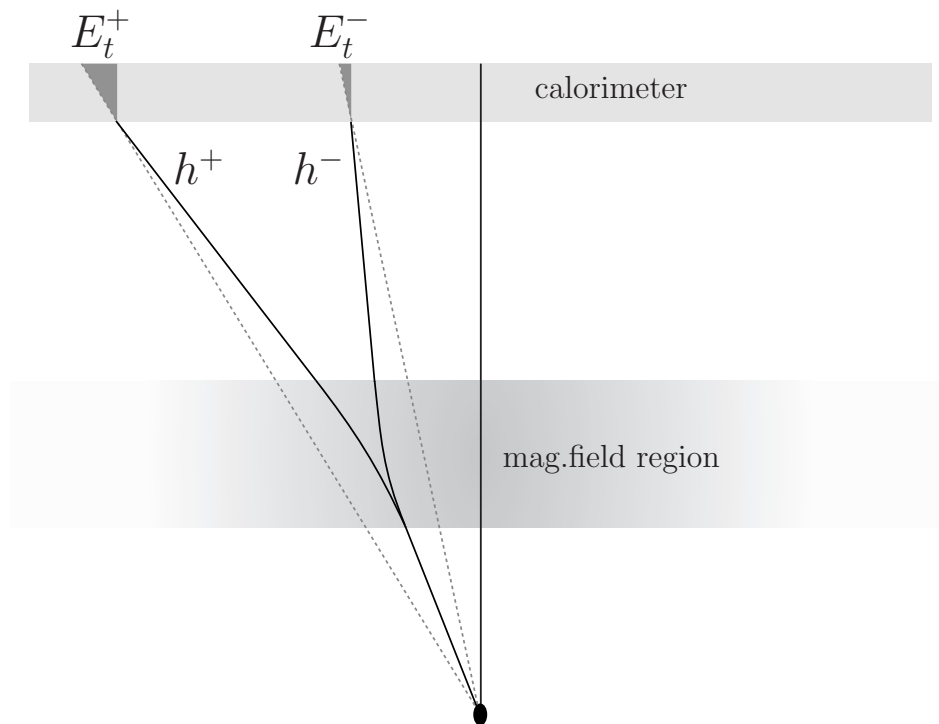


Figure 7.6: Positively and negatively charged particles with the same momentum are deflected differently by the LHCb magnetic field. The position and the transverse energy of a particle in the calorimeter depend both on the momentum and on the charge of the particle.

Because of the LHCb magnetic field, positively and negatively charged particle will hit the calorimeter at different positions and moreover outbending particles will have an (artificially) larger transverse energy in the calorimeter than inbending particles. The L0 trigger thus does not equally treat positively and negatively charged particles, even when they have the same initial momentum.

The effect of the L0 trigger on the $K^{+/-}$ efficiency asymmetry is illustrated in Fig.7.7. Input are events where the L0 line was explicitly triggered by the K^+ and/or K^- (TOS). For comparison the asymmetry is shown for events that were triggered independently of the K^+ and K^- (TIS).

Three slices of the asymmetry $\epsilon^{K^+}/\epsilon^{K^-}$ are drawn as a function of the kaon momentum azimuth angle ϕ (bottom plots). (Note that $\phi = 0$ corresponds to the positive x -direction). The absolute momentum of the kaons in the three slices is the same, $16 < |p| < 28$ GeV, while the polar angle θ of the momentum is increased in every slice. The position where the K^+ and K^- hit the calorimeter and the their transverse energy in the calorimeter are shown as well (top and middle plots respectively)⁶.

For a relatively small polar angle $58 < \theta < 107$ mrad (1st slice), neither a K^+ , nor a K^- with the particular $|p|$ and θ provide enough transverse energy to trigger the L0. Yet, the charged kaon that bends towards the center appears to have a larger detection efficiency. For example, looking at the region around $\phi = 0$ (positive x -axis) where the K^- bend inward and the K^+ outward, the asymmetry is in favor of the K^- efficiency.

For a larger polar angle in $107 < \theta < 155$ mrad (2nd slice) kaons hit the calorimeter in wider rings; the “center-effect” is no longer dominant.

Finally, for a relatively large polar angle $155 < \theta < 203$ mrad (3rd slice) the charged kaons that bend outward hit the calorimeter with enough transverse energy to set off the L0 trigger, leading to a higher efficiency. Looking for example again at the region around $\phi = 0$, the outbending K^+ have a calorimeter E_t above threshold, contrary to the inbending K^- .

It is thus seen, that the requirement of an L0 trigger by the signal daughters (TOS) favors outbending particles when they gain sufficient transverse energy to set off the trigger whereas the oppositely charged inbenders do not. On the other hand, when neither charged particles gain enough transverse energy it is seen that the requirement favors particles that bend towards the calorimeter center. A possible explanation for the latter can be a larger occupancy in the center, making it more likely for the daughter particle to overlap with a triggered cluster.

In principle, an asymmetry in triggering the L0 poses no limitation; it would be included as part of the $K^{+/-}$ efficiency asymmetry. However, since the L0 can be triggered by the K^+ or by the K^- emerging from the $D^0/\bar{D}^0$, it depends on both kaons in a non-factorisable way; it is not the product of two individual trigger efficiencies⁷.

To circumvent the inclusion and the non-factorisability of an L0 trigger asymmetry, the final candidate selection (Tab.7.5) only considers events that have been triggered

⁶These are estimates from a P_t -kick formalism.

⁷In fact the TOS slices in Fig.7.7 are single-particle approximations of the non-factorisable L0 trigger asymmetry (see also Sec.6.3.3).

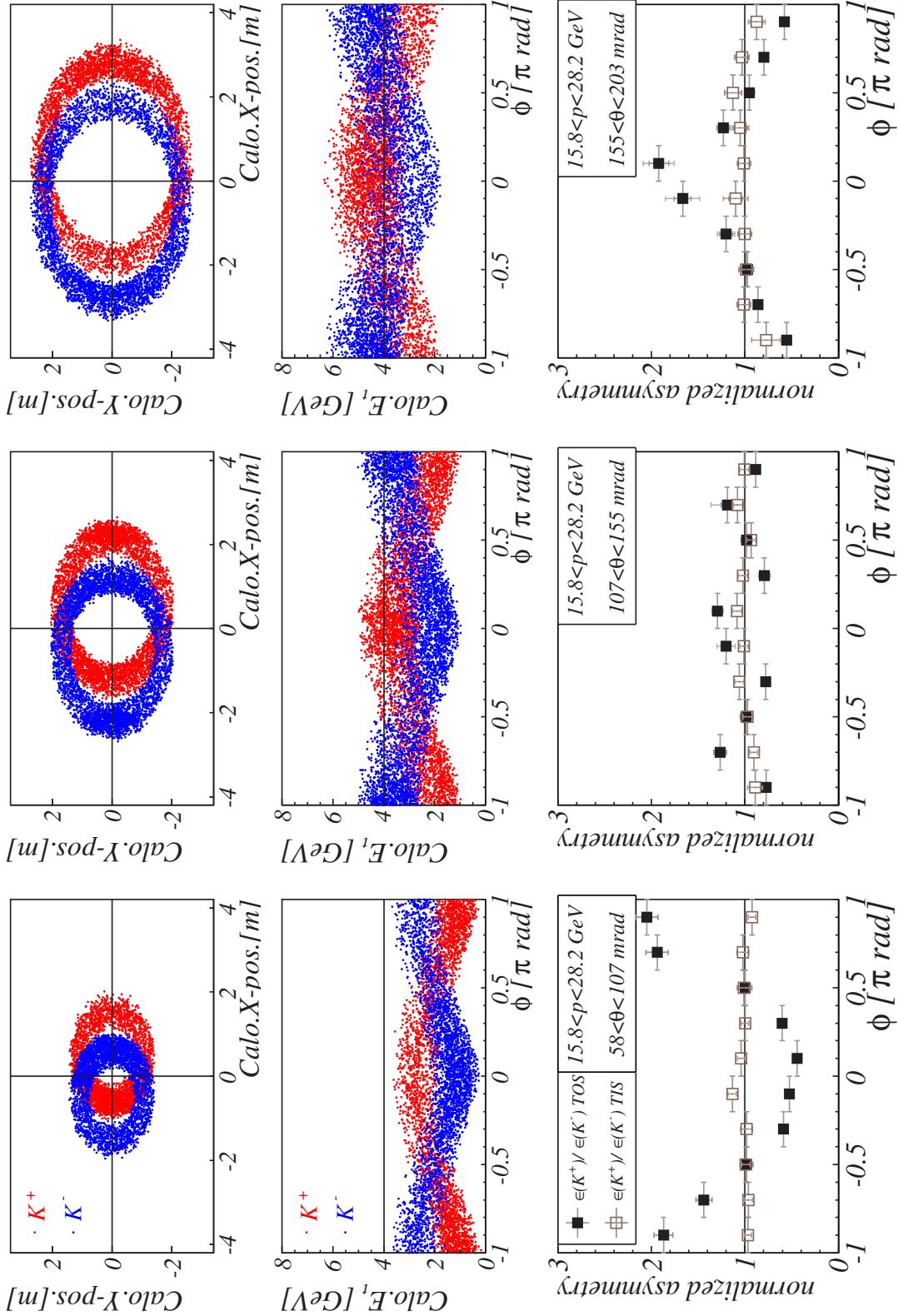


Figure 7.7: Three slices in the azimuth angle ϕ of the $K^{+/-}$ efficiency asymmetry are shown for fixed kaon absolute momentum and three values of the polar angle θ . The position of kaons (top plots) and the transverse energy of the kaons (middle plots) in the calorimeter has been estimated using a P_t -kick formalism. The bottom plots hold the asymmetry for events labeled as L0-TOS and labeled as L0-TIS.

momentum variable	binning
absolute momentum as $^{10}\log(p \text{ [MeV]})$	6 bins in $[3.7, 5]$
polar angle $\theta[\text{mrad}]$	6 bins in $[10, 300]$
azimuth angle $\phi[\pi \text{ rad}]$	10 bins in $[-1, 1]$

Table 7.7: *Momentum binning for determining the $K^{+/-}$ detection asymmetry. The smallest and largest bin edges are floated to include overflow.*

independently of the decay candidate (TIS)⁸.

7.2.3 The $K^{+/-}$ efficiency asymmetry from data

The $K^{+/-}$ efficiency asymmetry is determined by solving Eq.7.5 with the iterative method of Ch.6. The asymmetry is considered in bins of three momentum variables. The choice of momentum variables and their binning are shown in Tab.7.7.

A finer binning is chosen for the azimuth angle ϕ to incorporate the structure that is seen in this variable in Fig.7.4.

The sample of 84k selected K^+K^- -pairs is randomly split in two data sets, to avoid statistical correlations between the K^+ momentum spectrum and the K^- momentum spectrum, which are input to the numerator and denominator of Eq.7.5 respectively.

Since the asymmetry can only be determined up to a multiplicative scale (see Sec.6.2.4 for an explanation), it is presented in a normalized way.

The asymmetry is determined as a 3D distribution binned in the full $|p| \times \theta \times \phi$ phase space. Projections of the asymmetry are presented to show the average dependence on the individual momentum variables. These are made by taking a weighted average over the other two variables⁹.

Apart from a symmetric selection, determination of the $K^{+/-}$ efficiency asymmetry relies on the equal probability to produce a K^+K^- pair and a pair with the momenta interchanged as in Fig.7.5. In $D^0/\bar{D}^0 \rightarrow K^+K^-$ decays this equality is intrinsic since the spinless charm mesons decay isotropically. On the other hand kaon pairs in (combinatoric) background need not be produced in equal amounts in both configurations if the (normalized) differential production cross sections for background K^+ and K^- are not identical. The background level has been estimated at 17%. A $K^{+/-}$ background asymmetry is expected to be very small (Ref.[29], less than 2%) and therefore a $K^{+/-}$ background asymmetry has a negligible effect on the $K^{+/-}$ efficiency asymmetry (less than 0.4%).

The $K^{+/-}$ efficiency asymmetry is shown in all three momentum variables in Fig.7.8. For a small part of phase space with low momentum and relatively large polar angle

⁸The criterion used is to be triggered independently of daughter 1 *and* independently of daughter 2, rather than independently of the composite; the difference between the two classifications is minimal, about 1%.

⁹The weight is $N_{\text{reweighted meas.}}^{K^-} (^{10}\log(p), \theta, \phi)$ (see Eq.7.5). The result is equivalent to the asymmetry obtained were it considered just to depend on the one momentum component.

(5-9 GeV and $\theta > 200$ mrad) the asymmetry is dominated by the LHCb geometrical acceptance, where K^+ are swept out for azimuth angles $|\phi| < \pi/2$ (positive x-axis), and K^- for $|\phi| > \pi/2$ (negative x-axis).

Figures 7.9, 7.10 and 7.11 show the average asymmetry (projections) as functions of the individual momentum variables. For reference is shown the effective asymmetry $N(K^+)/N(K^-)$, that is obtained by simply dividing the measured spectra without correcting for decay correlations. The decay correlations do not significantly alter the asymmetry, since the K^+ and K^- detection efficiencies are compatible.

For low momentum Fig.7.9 suggests an asymmetry in favor of the K^+ efficiency, compared to high momentum. This is in agreement with expectations based on the different hadronic cross sections of the K^+ and K^- with the LHCb detector material (Ref.[30]), where the K^- has a larger hadronic cross section at low momentum¹⁰.

By using existing data for the K^+ and K^- hadronic cross sections (Ref.[27]) a $K^{+/-}$ efficiency asymmetry can be estimated based on material interactions by

$$\exp\left(-\frac{\Delta\sigma(p)}{\langle\sigma_{10}\rangle} \frac{L}{\lambda_{10}}\right), \quad (7.6)$$

where $\Delta\sigma(p) = \sigma^{K^+}(p) - \sigma^{K^-}(p)$ is the difference in hadronic cross sections, $\langle\sigma_{10}\rangle = \frac{1}{2}(\sigma^{K^+}_{(10\text{ GeV})} + \sigma^{K^-}_{(10\text{ GeV})})$ is the average charged kaon hadronic cross section at a reference momentum of 10 GeV and L/λ_{10} is the average LHCb radiation length fraction with respect to the reference momentum. Fitting Eq.7.6 to the $K^{+/-}$ efficiency asymmetry yields the line in Fig.7.9 and estimates the average LHCb radiation length fraction at 20 ± 10 % with respect to the charged kaon average length at 10 GeV.

No significant dependence on the polar angle θ is visible from Fig.7.10, but following the above argument, a slight increase in material budget for increasing polar angle is suggested.

¹⁰Contrary to the K^+ , the K^- can form hyperons Λ^0 and Σ^- in interactions with hadronic matter.

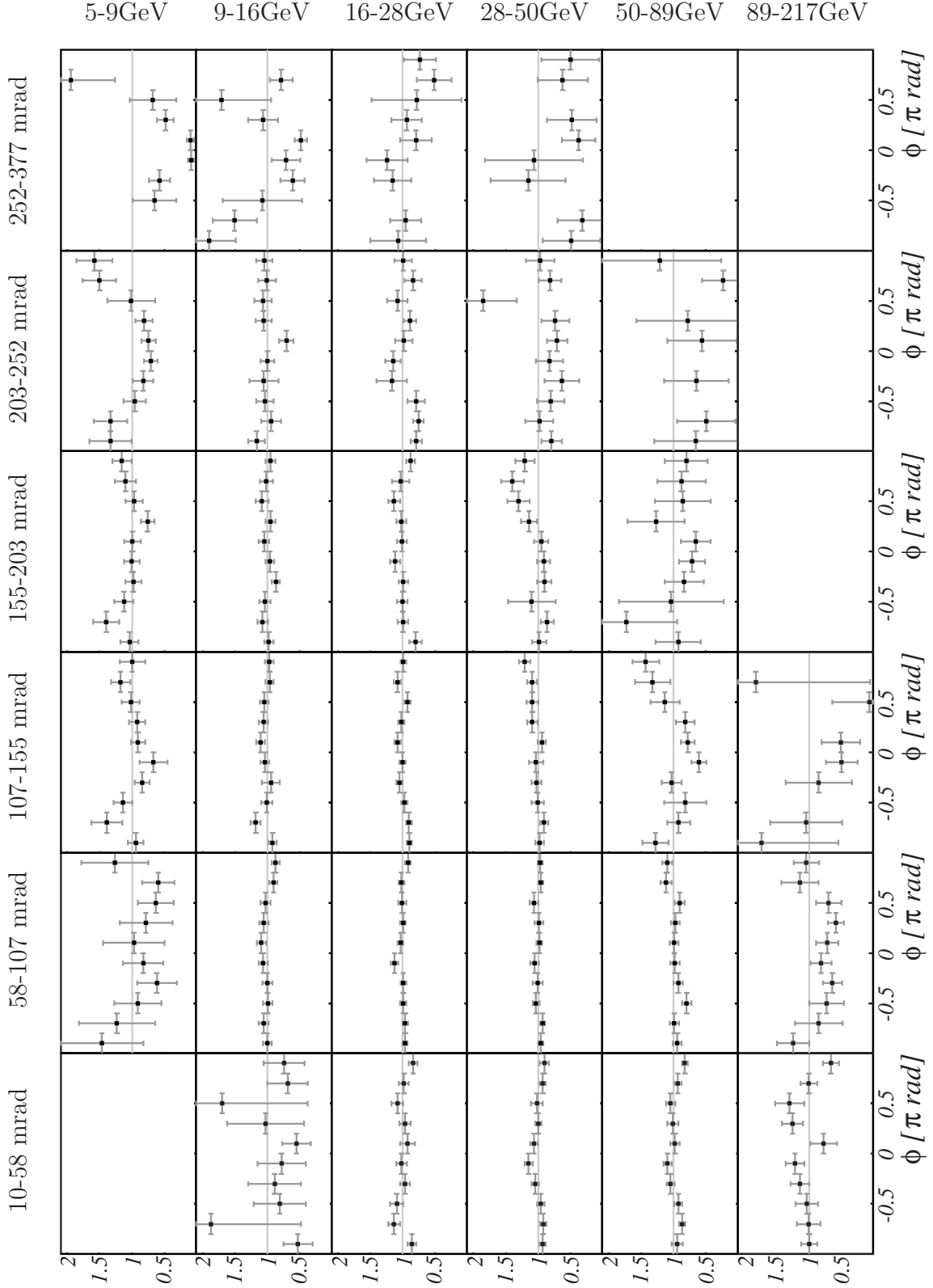


Figure 7.8: The normalized $K^{+/-}$ efficiency asymmetry from $D^0/\bar{D}^0 \rightarrow K^+ K^-$ events. The asymmetry is drawn as a function of the momentum azimuth angle ϕ , for different bins of the absolute momentum $|p|$ and polar angle θ .

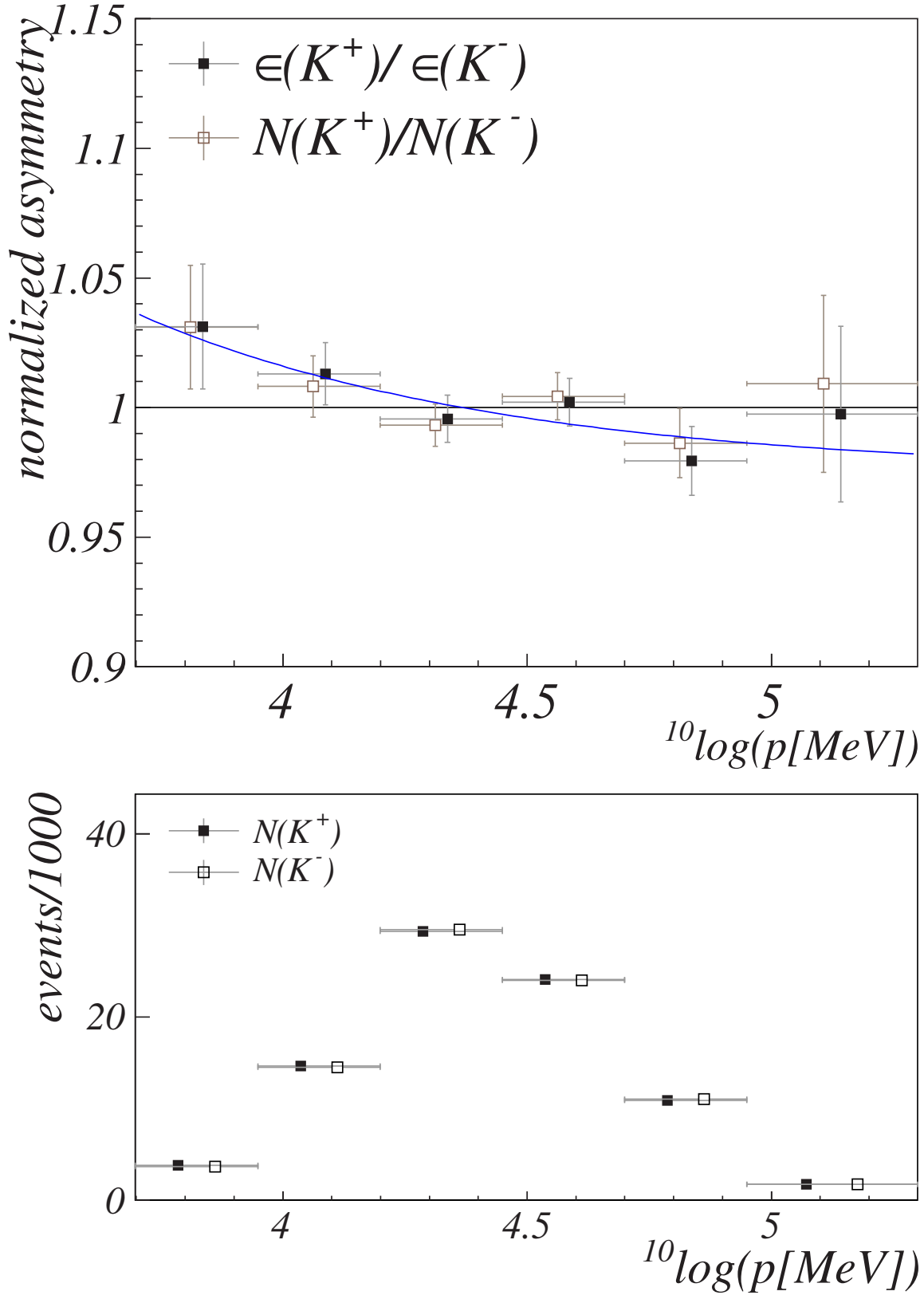


Figure 7.9: Top plot: The average dependence of the normalized $K^{+/-}$ efficiency asymmetry on the absolute momentum. The normalized effective asymmetry $N(K^+)/N(K^-)$ is shown for reference. The line is a fit of the asymmetry based on the difference between the K^+ and K^- hadronic cross sections with the detector material. Bottom plot: The measured momentum distributions of K^+ and K^- . The points have been slightly horizontally displaced for illustration purposes.

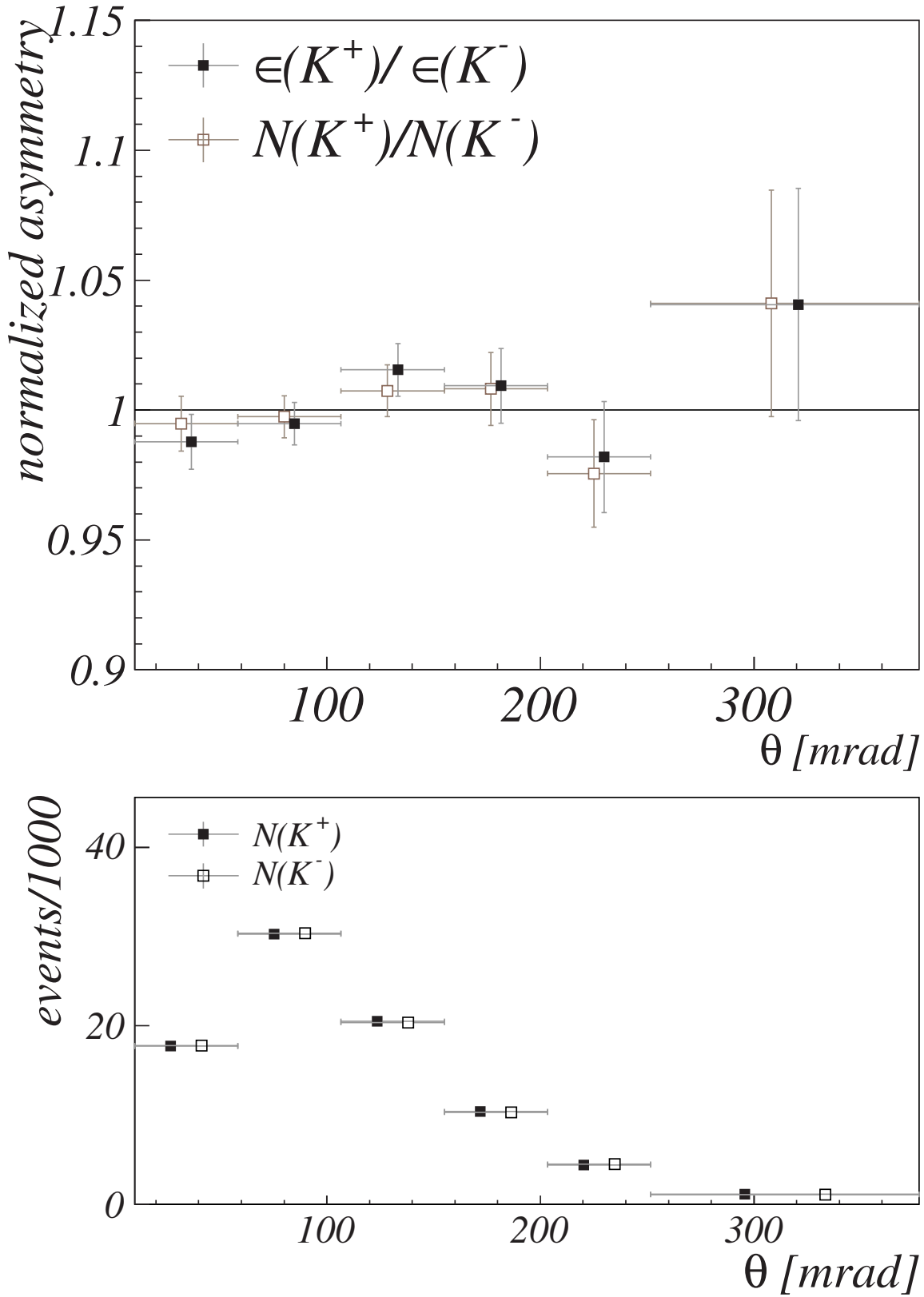


Figure 7.10: *Top plot: The average dependence of the normalized $K^{+/-}$ efficiency asymmetry on the polar angle. The normalized effective asymmetry $N(K^+)/N(K^-)$ is shown for reference. Bottom plot: The measured polar angle distributions of K^+ and K^- . The points have been slightly horizontally displaced for illustration purposes.*

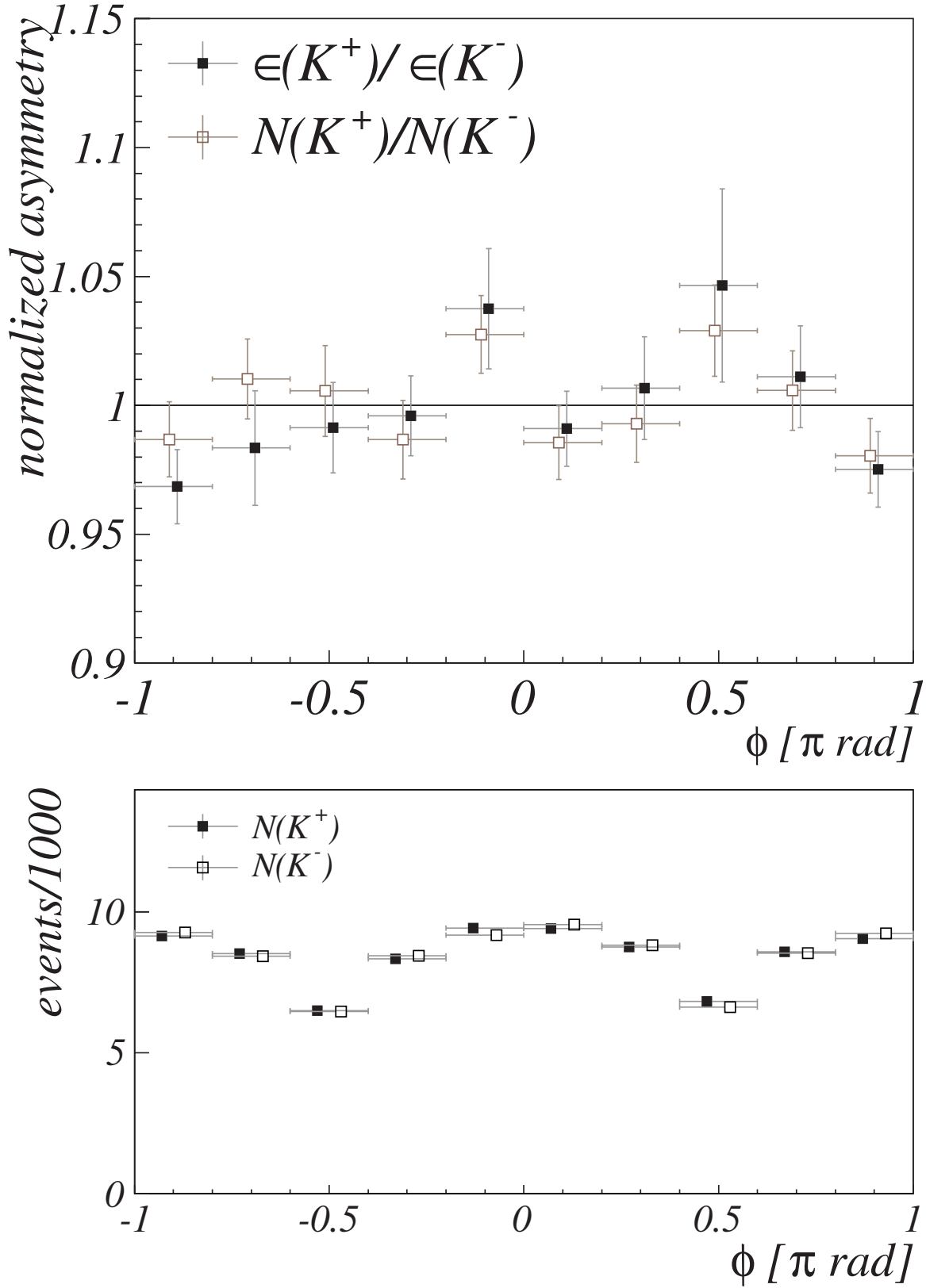


Figure 7.11: Top plot: The average dependence of the normalized $K^{+/-}$ efficiency asymmetry on the azimuth angle. The normalized effective asymmetry $N(K^+)/N(K^-)$ is shown for reference. Bottom plot: The measured azimuth angle distributions of K^+ and K^- . The points have been slightly horizontally displaced for illustration purposes.

7.3 Asymmetries in $D^0/\bar{D}^0 \rightarrow K^{-/+}\pi^{+/-}$ decays

The asymmetry between the π^+ and π^- detection efficiencies and the asymmetry between the D^0 and $\bar{D}^0$ differential production cross sections are extracted from $D^0 \rightarrow K^-\pi^+$ and $\bar{D}^0 \rightarrow K^+\pi^-$ decays, using the previously determined $K^{+/-}$ efficiency asymmetry. The $\pi^{+/-}$ efficiency asymmetry is determined as the ratio of the π^+ detection efficiency $\epsilon_{det}^{\pi^+}$ and the π^- detection efficiency $\epsilon_{det}^{\pi^-}$ at the same value of pion momentum, and the cross section asymmetry is determined as the ratio of the D^0 differential production cross section σ_{D^0} and the $\bar{D}^0$ differential production cross section $\sigma_{\bar{D}^0}$. That is, the asymmetries are determined as the ratios

$$A_\pi^\pm(p_\pi) = \epsilon_{det}^{\pi^\pm}(p_\pi) / \epsilon_{det}^{\pi^\mp}(p_\pi) \quad (7.7)$$

$$A_D(P_D) = \sigma_{D^0}(P_D) / \sigma_{\bar{D}^0}(P_D), \quad (7.8)$$

where as before, the two asymmetries are only determined up to arbitrary multiplicative scales.

7.3.1 Asymmetry extraction

Due to their opposite charm flavor content the D^0 ($c\bar{u}$) and $\bar{D}^0$ ($\bar{c}u$) can be produced asymmetrically in proton-proton collisions. However, in a measurement the momentum spectra of the mesons are also influenced by the detection efficiencies of their charged kaon and pion decay products. Since these efficiencies may not be symmetric, an asymmetry in the differential production cross sections cannot be obtained by simply dividing D^0 and $\bar{D}^0$ measured momentum spectra.

Instead, the momentum spectra are first corrected for the $K^{+/-}$ efficiency asymmetry obtained in the previous section. Thereafter, the iterative method of Ch.6 is used to simultaneously unfold the $\pi^{+/-}$ efficiency asymmetry and the $D^0/\bar{D}^0$ differential production cross section asymmetry from the underlying decay topology.

Consider the illustration in Fig.7.12. A $K^-\pi^+$ pair emerging from the decay of a D^0 with momentum P_D is equally likely to have a pion momentum p_π (and thus kaon momentum $P_D - p_\pi$), as a $K^+\pi^-$ pair from a $\bar{D}^0$ with the same momentum. However, D^0 and $\bar{D}^0$ are not necessarily produced in equal amounts and moreover the efficiencies with which $K^-\pi^+$ and $K^+\pi^-$ pairs are measured are not necessarily equal despite having the same momenta for the pions and for the kaons. A measurement can result in different numbers for the two decays, depending on the relative D^0 and $\bar{D}^0$ production cross sections and on the relative efficiencies

$$N_{\text{meas.}}^{K^-\pi^+}(P_D, p_\pi) = N_{\text{meas.}}^{K^+\pi^-}(P_D, p_\pi) \frac{\sigma_{D^0}(P_D)}{\sigma_{\bar{D}^0}(P_D)} \frac{\epsilon^{K^-\pi^+}(P_D - p_\pi, p_\pi)}{\epsilon^{K^+\pi^-}(P_D - p_\pi, p_\pi)}. \quad (7.9)$$

As in Sec.7.2.1 the efficiency is composed of acceptances for the outgoing particles ϵ_{det}^h and a reconstruction and selection efficiency $\epsilon_{sel}^{h_1 h_2}$ due to trigger and event selections.

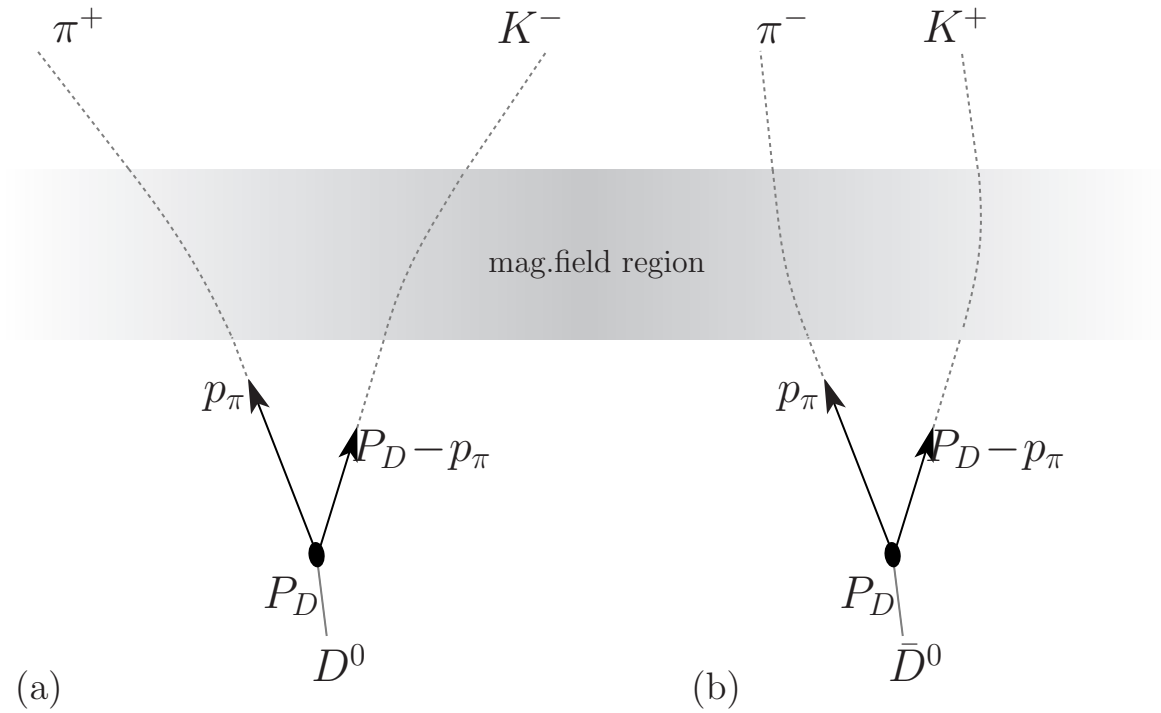


Figure 7.12: Illustration of a $D^0 \rightarrow K^- \pi^+$ (a) and $\bar{D}^0 \rightarrow K^+ \pi^-$ decay (b) in the lab frame. Since the charm mesons decay isotropically, the D^0 in (a) and $\bar{D}^0$ in (b) with the same momentum P_D have equal probability to decay with the π^+ and π^- respectively coming out with a momentum p_π (and the kaons with momentum $P_D - p_\pi$).

The total asymmetry in the efficiencies with which the two decays are measured is then

$$\frac{\epsilon^{K^-\pi^+}(P_D - p_\pi, p_\pi)}{\epsilon^{K^+\pi^-}(P_D - p_\pi, p_\pi)} = \frac{\epsilon_{sel}^{K^-\pi^+}(P_D - p_\pi, p_\pi)}{\epsilon_{sel}^{K^+\pi^-}(P_D - p_\pi, p_\pi)} \underbrace{\frac{\epsilon_d^{K^-}(P_D - p_\pi)}{\epsilon_d^{K^+}(P_D - p_\pi)}}_{A_K^\pm(P_D - p_\pi)^{-1}} \underbrace{\frac{\epsilon_d^{\pi^+}(p_\pi)}{\epsilon_d^{\pi^-}(p_\pi)}}_{A_\pi^\pm(p_\pi)}. \quad (7.10)$$

The event selection of Tab.7.5 does not distinguish between positively and negatively charged particles and is assumed to be symmetric

$$\epsilon_{sel}^{K^-\pi^+}(p_K, p_\pi) \equiv \epsilon_{sel}^{K^+\pi^-}(p_K, p_\pi). \quad (7.11)$$

Then, from Eq.7.9 with the efficiency asymmetry Eq.7.10 and under the premise of symmetric event selection as in Eq.7.11 the $\pi^{+/-}$ efficiency asymmetry and the $D^0/\bar{D}^0$ differential production cross section asymmetry are determined by

$$A_\pi^\pm(p) = \frac{\int d^3P_D N_{\text{meas.}}^{K^-\pi^+}(P_D, p_\pi) A_K^\pm(P_D - p_\pi)}{\int d^3P_D N_{\text{meas.}}^{K^+\pi^-}(P_D, p_\pi) A_D(P_D)} = \frac{N_{\text{K-weighted meas.}}^{\pi^+}(p_\pi)}{N_{\text{D-weighted meas.}}^{\pi^-}(p_\pi)} \quad (7.12)$$

and

$$A_D(P_D) = \frac{\int d^3p_\pi N_{\text{meas.}}^{K^-\pi^+}(P_D, p_\pi) A_K^\pm(P_D - p_\pi)}{\int d^3p_\pi N_{\text{meas.}}^{K^+\pi^-}(P_D, p_\pi) A_\pi^\pm(p_\pi)} = \frac{N_{\text{K-weighted meas.}}^{K^-\pi^+}(P_D)}{N_{\text{\pi-weighted meas.}}^{K^+\pi^-}(P_D)} \quad (7.13)$$

The $K^{+/-}$ efficiency asymmetry has been determined from $D^0/\bar{D}^0 \rightarrow K^+K^-$ events in Sec.7.2. With this one known, the iterative method of Ch.6 is employed to solve Eq.7.12 and Eq.7.13 to obtain the momentum dependencies of the $\pi^{+/-}$ efficiency asymmetry and the $D^0/\bar{D}^0$ differential production cross section asymmetry.

7.3.2 Asymmetry from $D^0/\bar{D}^0 \rightarrow K^\mp \pi^\pm$ data

The $\pi^{+/-}$ efficiency asymmetry and the $D^0/\bar{D}^0$ differential production cross section asymmetry are determined by solving equations 7.12 and 7.13 with the iterative method of Ch.6. Both asymmetries are considered in bins of three momentum variables. The choice of momentum variables and their binning are shown in Tab.7.8. The binning for the pion momentum is chosen in accordance with that of the kaon momentum in Sec.7.2.3.

As before, the asymmetries are determined up to a multiplicative scale; only the relative momentum dependencies are obtained (see Sec.6.2.4) and the asymmetries will therefore be presented in a normalized way.

The amount of background is small ($\sim 3\%$), and the effect of small $K^\pm$ and $\pi^\pm$ production asymmetries in background (Ref.[29]) is considered negligible.

	momentum variable	binning
$\pi^{+/-}$	absolute momentum as $^{10}\log(p \text{ [MeV]})$	6 bins in [3.7 , 5]
	polar angle $\theta[\text{mrad}]$	6 bins in [10 , 300]
	azimuth angle $\phi[\pi \text{ rad}]$	10 bins in [-1 , 1]
$D^0/\bar{D}^0$	transverse momentum as $^{10}\log(p_t \text{ [MeV]})$	10 bins in [3.3 , 4.2]
	pseudorapidity η	10 bins in [2 , 4.8]
	azimuth angle $\phi[\pi \text{ rad}]$	10 bins in [-1 , 1]

Table 7.8: *Momentum binning for determining the asymmetries from $D^0/\bar{D}^0 \rightarrow K^\mp \pi^\pm$ decays. The smallest and largest bin edges are floated to include overflow.*

The $\pi^{+/-}$ efficiency asymmetry from data

Fig.7.13 shows the $\pi^{+/-}$ efficiency asymmetry in all three momentum variables. The LHCb geometrical acceptance is responsible for the asymmetry in the small part of the pion phase space with low momentum (5-9 GeV) and large polar angle ($\theta > 200$ mrad).

In the remaining phase space significant deviations from being constant are observed as a function of ϕ (e.g. in 16-28 GeV and 155-203 mrad). In comparison the number of $K^{+/-}$ pairs that made Fig.7.8 is not large enough to confirm the same ϕ dependence for the $K^{+/-}$ efficiency asymmetry.

Figures 7.14, 7.15 and 7.16 show the integrated asymmetry in the individual momentum variables. Most prominent in these is the dependence on the pion momentum azimuth angle ϕ , which implies a larger detection efficiency for outbending pions than for inbending pions.

The cause for the bending dependent asymmetry is unresolved. In Sec.7.2.2 it has been suggested that inbending particles have a larger probability to overlap with a triggered calorimeter cluster than outbending particles in the L0 trigger, thereby favoring inbenders in TOS events. The suggestion agrees with the bending dependence seen here for TIS events, where an overlap lowers the probability of an(other) independently triggered cluster. On the other hand, particle properties such as track quality, particle identification, or impact parameter may also cause an asymmetry if these should systematically differ between in- and outbending tracks.

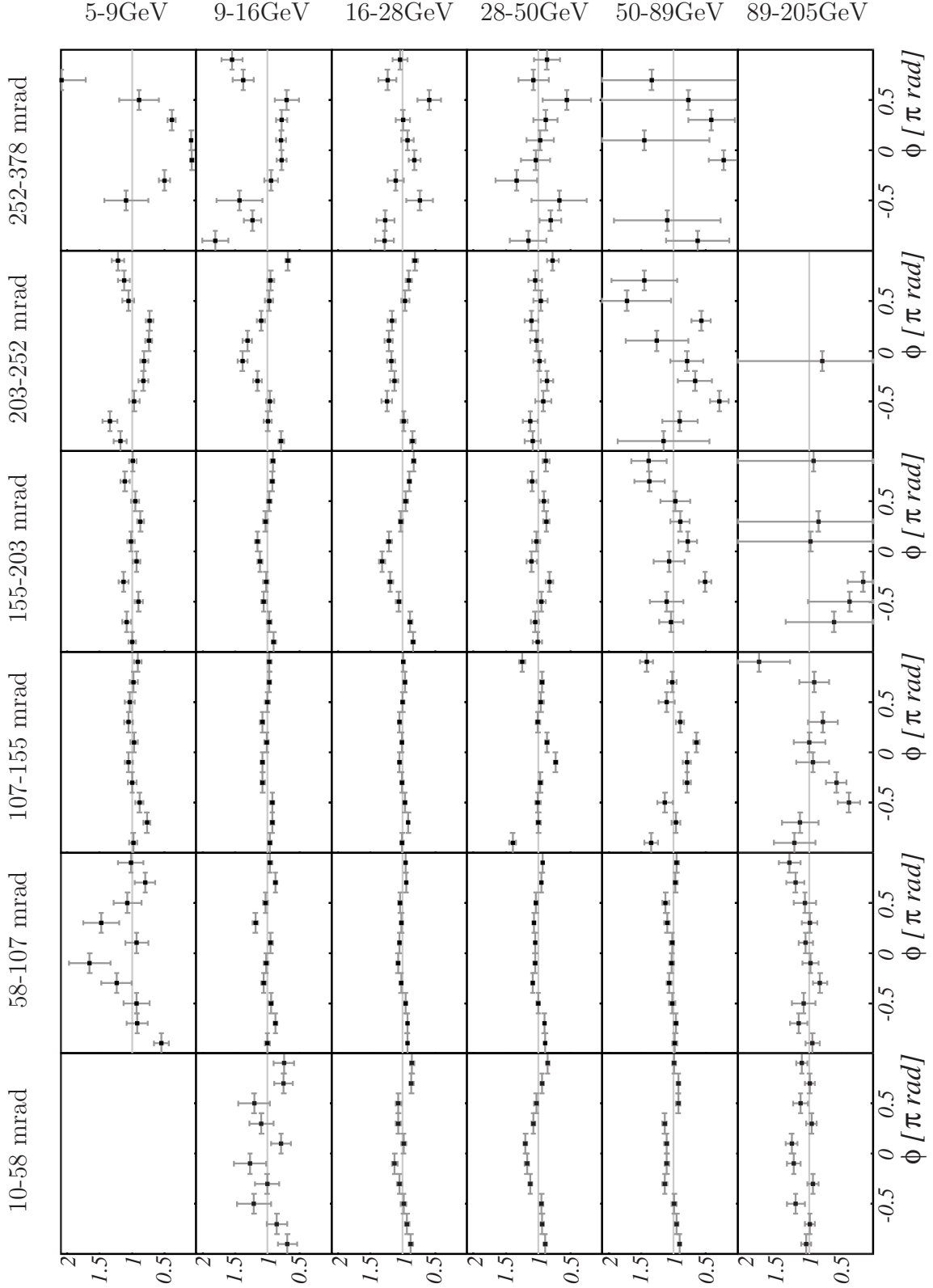


Figure 7.13: The normalized $\pi^{+/-}$ efficiency asymmetry from $D^0/\bar{D}^0 \rightarrow K^\mp \pi^\pm$ events. The asymmetry is drawn as a function of the momentum azimuth angle ϕ , for different bins of the absolute momentum $|p|$ and polar angle θ .

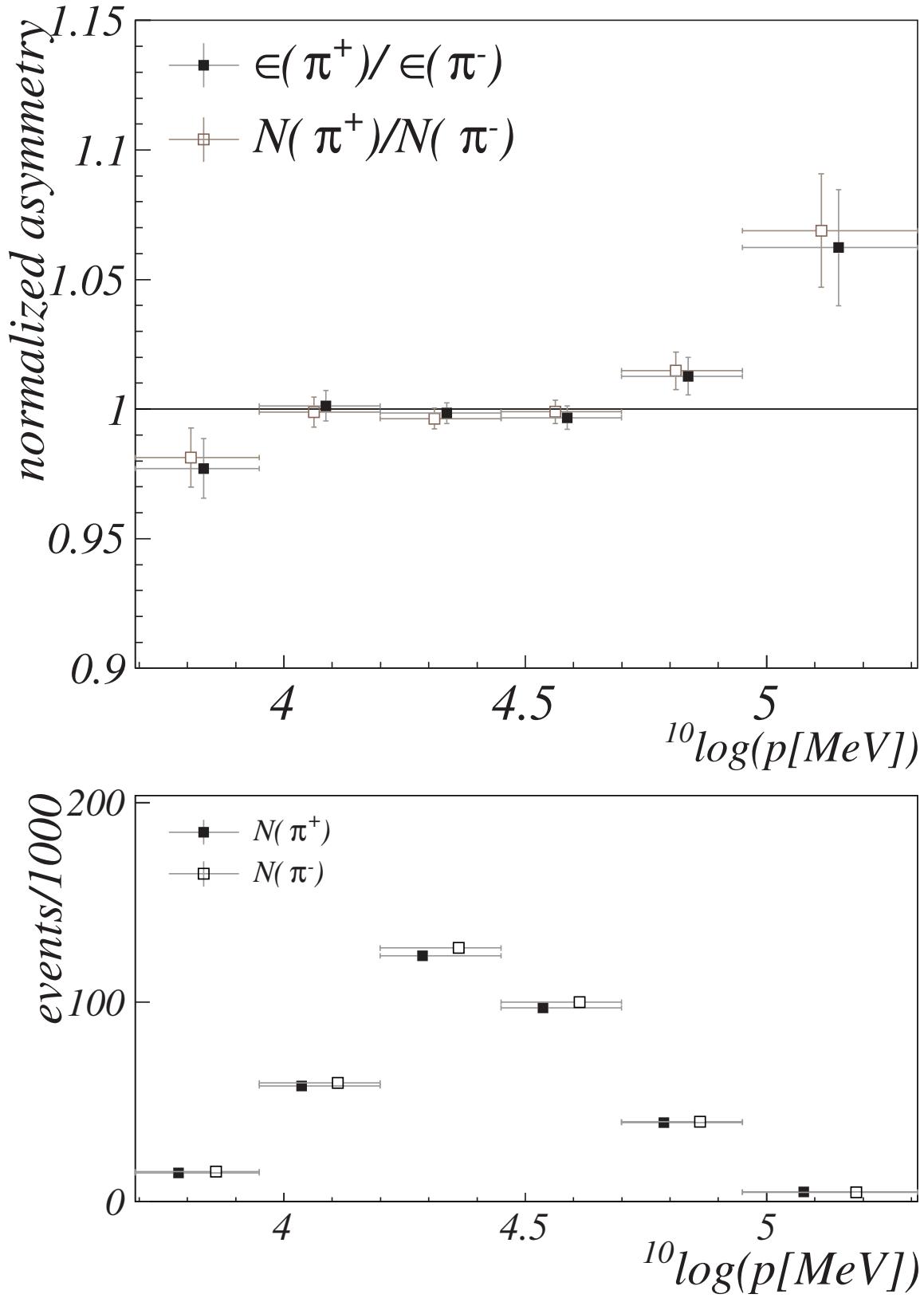


Figure 7.14: Top plot: The average dependence of the normalized $\pi^{+/-}$ efficiency asymmetry on the absolute momentum. The normalized effective asymmetry $N(\pi^+)/N(\pi^-)$ is shown for reference. Bottom plot: The measured momentum distributions of π^+ and π^- . The points have been slightly horizontally displaced for illustration purposes.

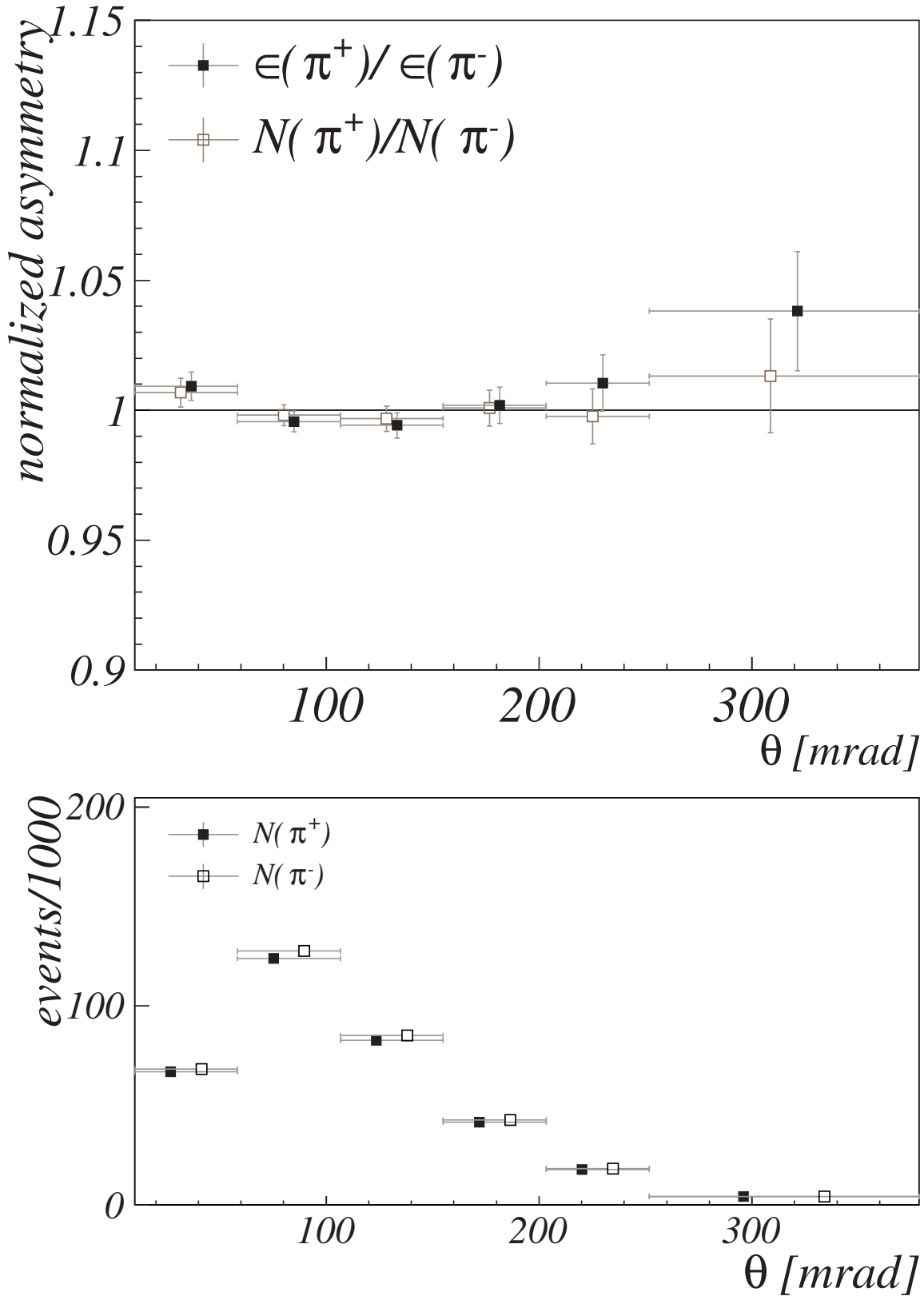


Figure 7.15: Top plot: The average dependence of the normalized $\pi^{+/-}$ efficiency asymmetry on the polar angle. The normalized effective asymmetry $N(\pi^+)/N(\pi^-)$ is shown for reference. Bottom plot: The measured polar angle distributions of π^+ and π^- . The points have been slightly horizontally displaced for illustration purposes.

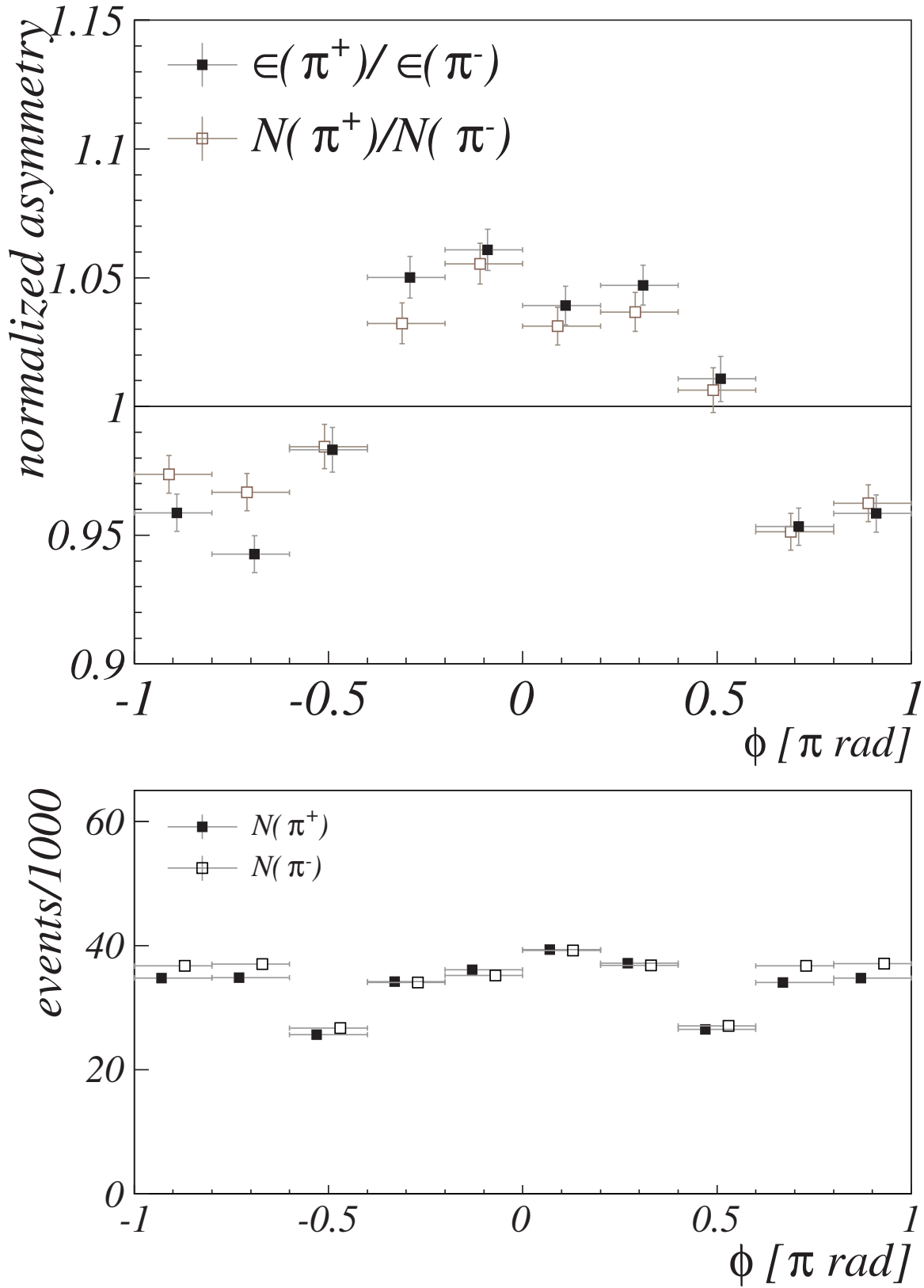


Figure 7.16: Top plot: The average dependence of the normalized $\pi^{+/-}$ efficiency asymmetry on the azimuth angle. The normalized effective asymmetry $N(\pi^+)/N(\pi^-)$ is shown for reference. Bottom plot: The measured azimuth angle distributions of π^+ and π^- . The points have been slightly horizontally displaced for illustration purposes.

variable	χ^2/DoF (p-value)	χ^2/DoF (p-value) scaled
ϕ (Fig.7.17)	10.6/9 (31 %)	-
p_t (Fig.7.18)	13.8/9 (13 %)	11.8/9 (22 %)
η (Fig.7.19)	29.2/9 (0.06 %)	24.9/9 (0.3 %)

Table 7.9: Results of χ^2 -tests on the average $D^0/\bar{D}^0$ cross section asymmetries as functions of the three momentum variables with respect to being constant. The results labeled as 'scaled' are after scaling the uncertainties with the $\sqrt{\chi^2/\text{DoF}}$ of the ϕ variation as indicated in the text.

The $D^0/\bar{D}^0$ differential production cross section asymmetry from data

Due to their opposite charm flavor content the D^0 and $\bar{D}^0$ can be produced asymmetrically in proton-proton collisions. However, for unpolarized protons such an asymmetry should not extend to the azimuth angle ϕ .

Fig.7.17 shows the $D^0/\bar{D}^0$ differential production cross section asymmetry as a function of the azimuth angle. Shown are the asymmetry $\sigma_{D^0}/\sigma_{\bar{D}^0}$, the effective asymmetry $N(K^-\pi^+)/N(K^+\pi^-)$ obtained by naively dividing the D^0 and $\bar{D}^0$ measured momentum spectra, and the same effective asymmetry but after correcting for the $K^{+/-}$ efficiency asymmetry.

The effective asymmetry shows a significant variation of approximately $\pm 5\%$. After correcting for the difference between the K^+ and K^- detection efficiencies this effective asymmetry increases somewhat, implying that the difference between the measured D^0 and $\bar{D}^0$ spectra is predominantly caused by their oppositely charged pion daughters. Finally, the cross section asymmetry after correcting for the $K^{+/-}$ efficiency asymmetry and after uncorrelating the $D^0/\bar{D}^0$ from their pion decay products is indeed flat in the azimuth angle as expected.

The remaining variation in ϕ has a $\sqrt{\chi^2/\text{DoF}}$ of $\sqrt{10.6/9} = 1.1$ and is used to scale the uncertainties on the cross section asymmetries in transverse momentum p_t and pseudorapidity η .

In Fig.7.18 and Fig.7.19 the $D^0/\bar{D}^0$ differential production cross section asymmetry is shown as a function of transverse momentum and pseudorapidity respectively. χ^2 -test results of these with respect to the hypothesis of a constant, non-varying asymmetry are shown in Tab.7.9.

No significant transverse momentum dependence is observed in Fig.7.18. On the other hand, the asymmetry as a function of pseudorapidity in Fig.7.19 implies a small but significant dependence, where the asymmetry at approximately $\eta=3$ is about 4% higher than the central and forward regions. Note that the uncorrected effective asymmetry $N(K^-\pi^+)/N(K^+\pi^-)$, due to the asymmetric π^+ and π^- detection efficiencies, suggests a different behavior, a slightly increasing asymmetry with increasing η .

Fig.7.20 shows the asymmetries as determined in another analysis (Ref.[31]). This analysis uses the full dataset of 37 pb^{-1} collected by LHCb in 2010. It combines

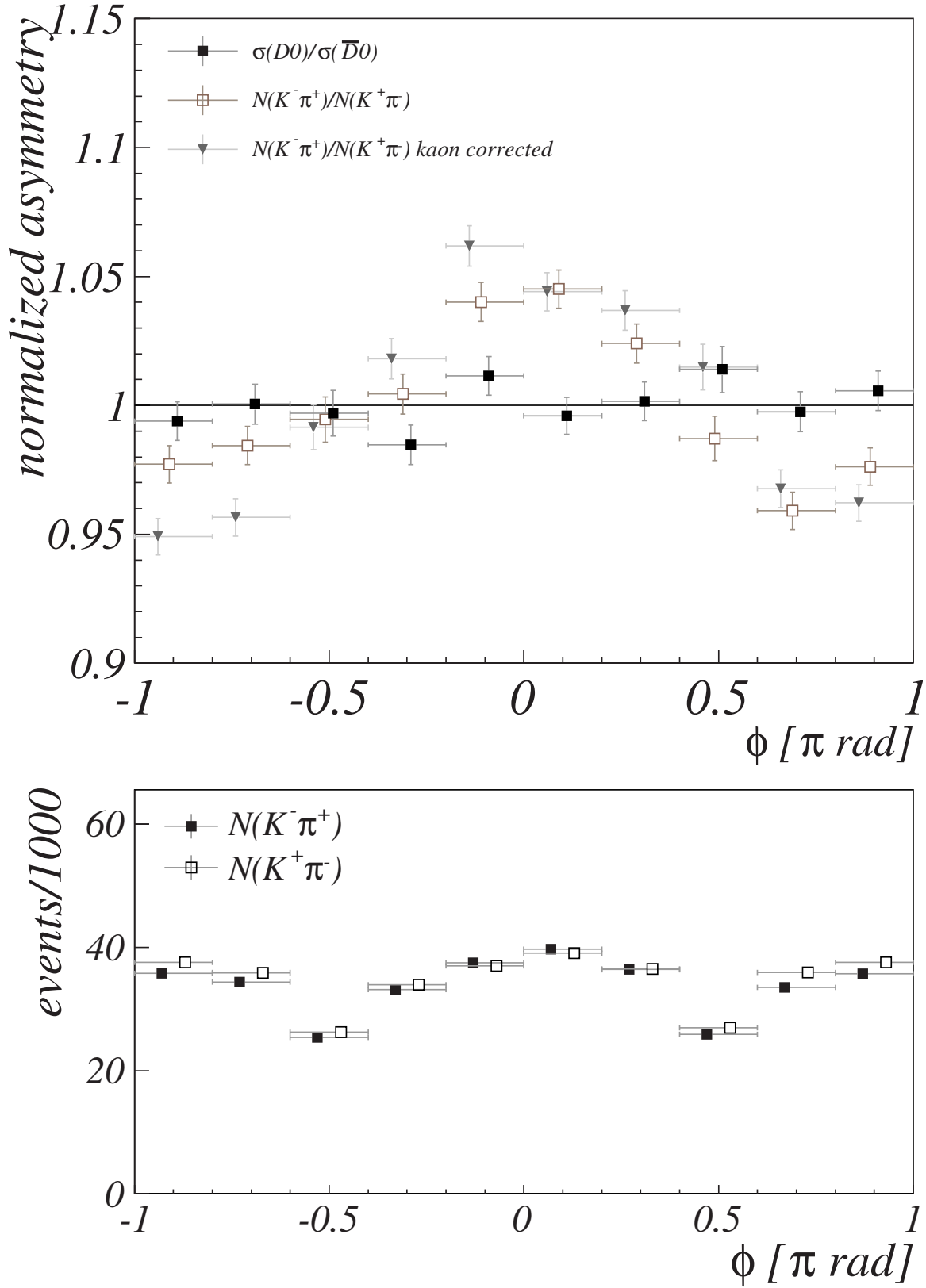


Figure 7.17: *Top plot: The average dependence of the normalized $D^0/\bar{D}^0$ differential production cross section asymmetry on the azimuth angle. The normalized effective asymmetry $N(K^-\pi^+)/N(K^+\pi^-)$ is shown for reference, as well as the effective asymmetry after correcting for the $K^{+/-}$ efficiency asymmetry. Bottom plot: The measured D^0 and $\bar{D}^0$ azimuth angle distributions. The points have been slightly horizontally displaced for illustration purposes.*

measurements of prompt $D^0 \rightarrow K^- \pi^+$ and $D^{*+} \rightarrow D^0 \pi^+$ decays and their conjugate decays to extract the $D^0/\bar{D}^0$ cross section asymmetry. The asymmetry is determined in 2D bins of transverse momentum and pseudorapidity. The measured raw asymmetries in the different decay channels are combined in order to cancel detection asymmetries of daughter particles and extract the $D^0/\bar{D}^0$ cross section asymmetry.

Also this analysis does not observe a significant dependence of the cross section asymmetry on the transverse momentum, but neither does it significantly disclose a dependence on pseudorapidity. The η dependence in the analysis is less prominent than the one suggested here in Fig.7.19, possibly since the analysis does not unfold the daughter particles' detection asymmetries from the decay topologies.

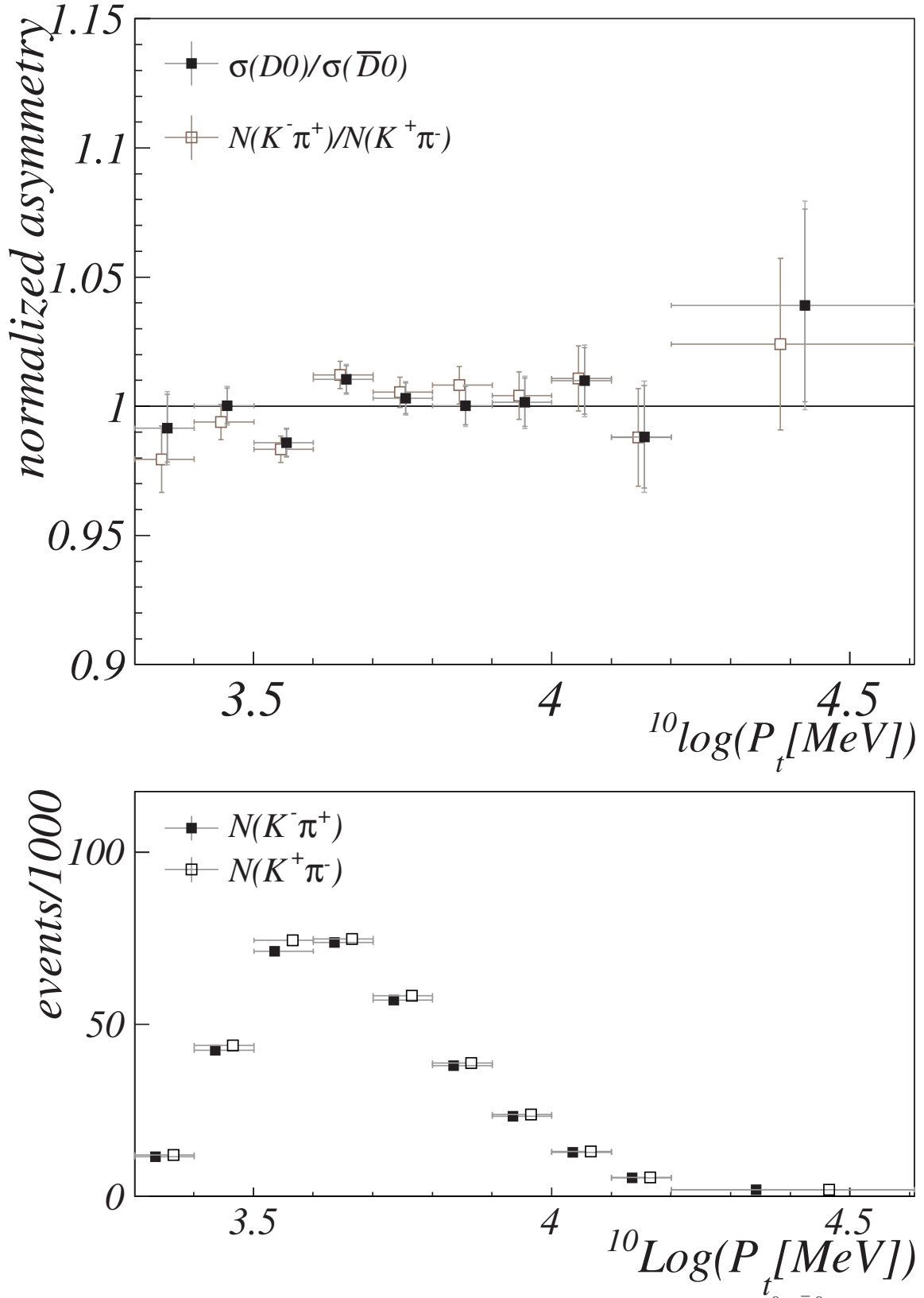


Figure 7.18: *Top plot: The average dependence of the normalized $D^0/\bar{D}^0$ differential production cross section asymmetry on the transverse momentum. The normalized effective asymmetry $N(K^- \pi^+)/N(K^+ \pi^-)$ is shown for reference. Bottom plot: The measured D^0 and $\bar{D}^0$ transverse momentum distributions. The points have been slightly horizontally displaced for illustration purposes.*

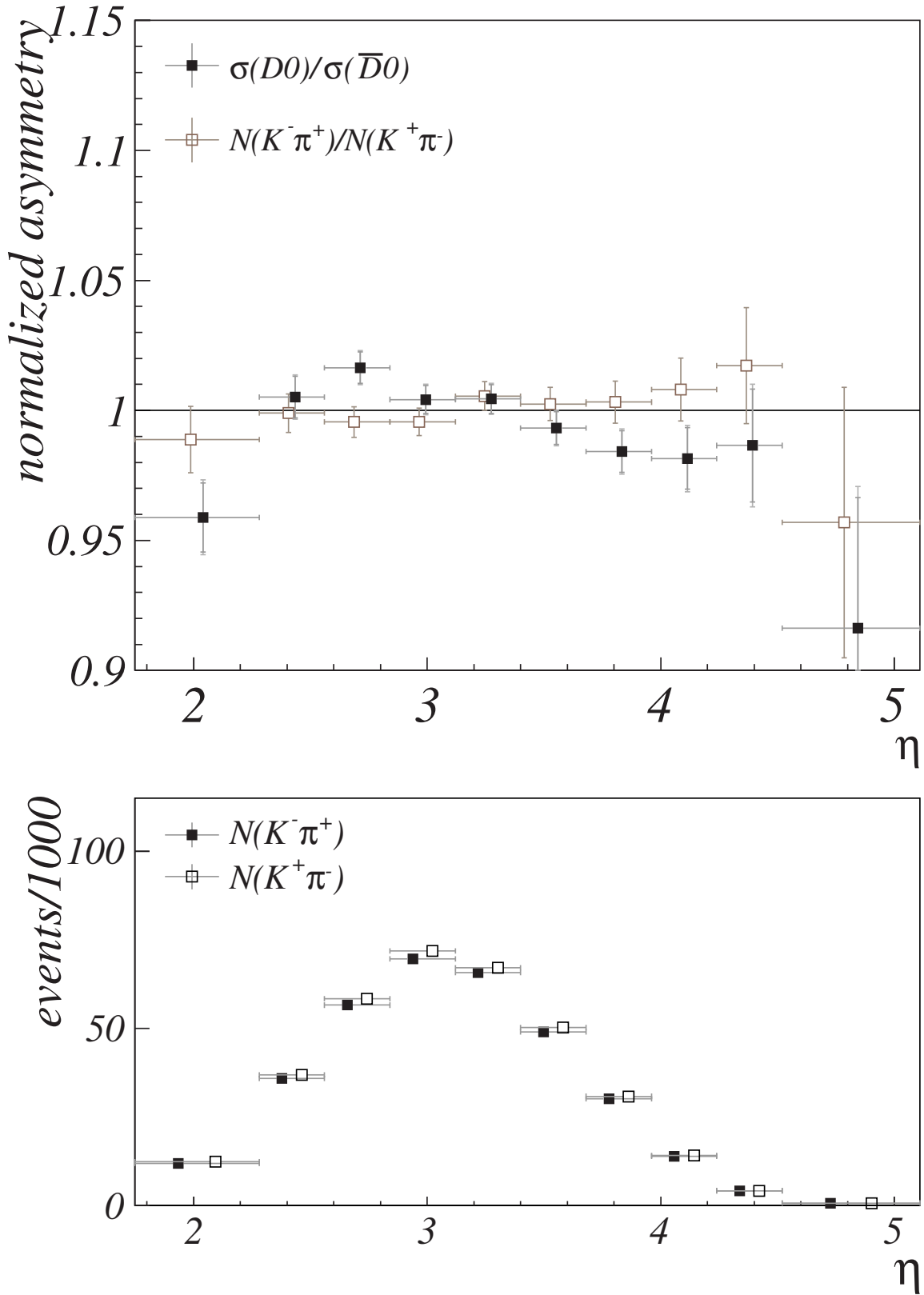


Figure 7.19: The average dependence of the normalized $D^0/\bar{D}^0$ differential production cross section asymmetry on the pseudorapidity. The normalized effective asymmetry $N(K^-\pi^+)/N(K^+\pi^-)$ is shown for reference. Bottom plot: The measured D^0 and $\bar{D}^0$ pseudorapidity distributions. The points have been slightly horizontally displaced for illustration purposes.

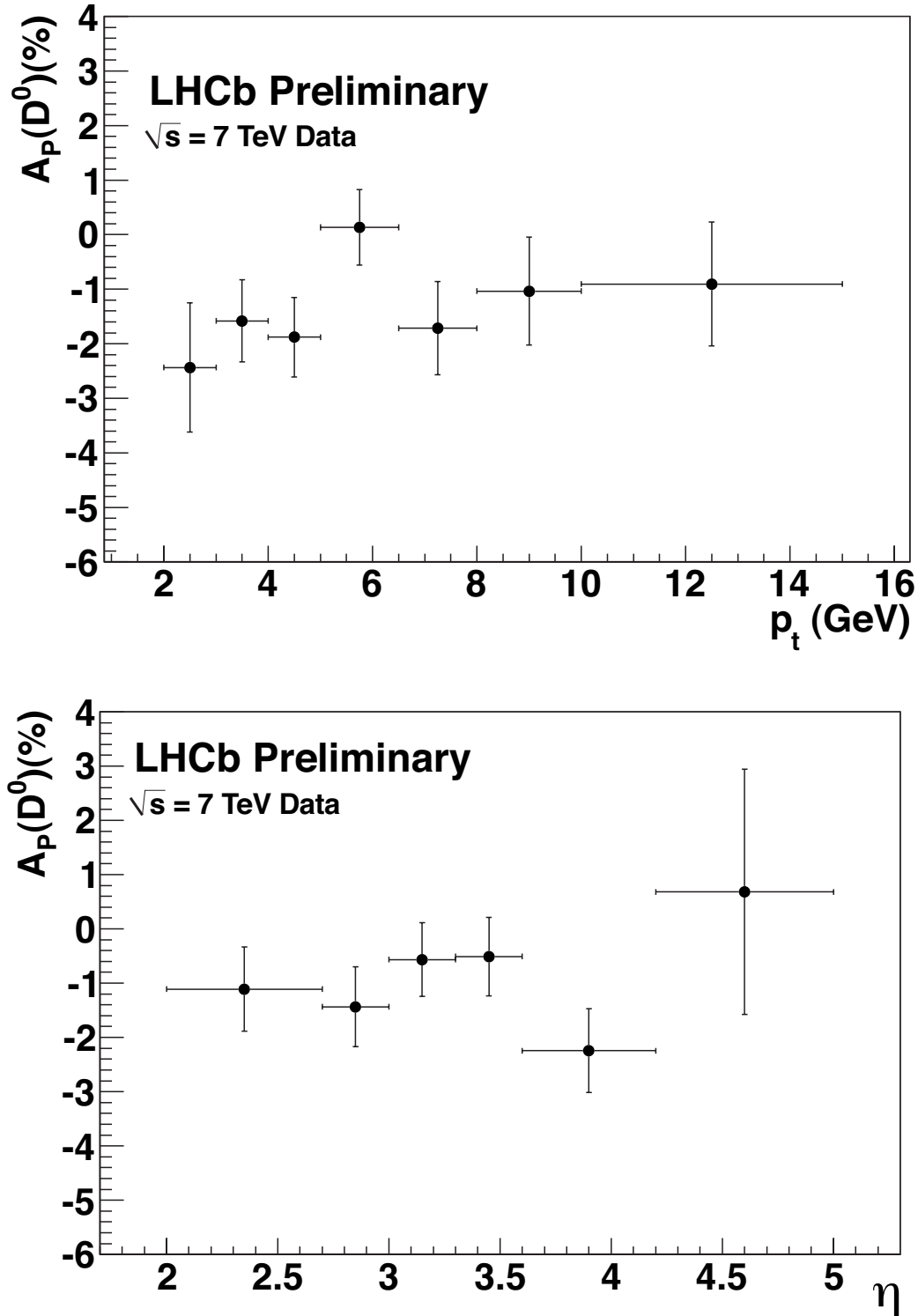


Figure 7.20: The $D^0/\bar{D}^0$ differential production cross section asymmetry presented in BEAUTY 2011. The asymmetry is here defined as $[N(D^0) - N(\bar{D}^0)]/[N(D^0) + N(\bar{D}^0)] \approx \frac{1}{2}[N(D^0)/N(\bar{D}^0) - 1]$ and is absolute (unnormalized).

7.4 Conclusion

In chapter 6 an iterative method has been developed that unfolds momentum dependent properties of single particles from an underlying multi-body process. In this chapter the method has been used on LHC**b** measurements of charm meson decays, to determine a momentum dependence of an asymmetry between the K^+ and K^- detection efficiencies and of an asymmetry between the π^+ and π^- detection efficiencies, as well as a momentum dependence of an asymmetry between the D^0 and $\bar{D}^0$ differential production cross sections.

The $K^{+/-}$ efficiency asymmetry has been determined from $D^0/\bar{D}^0 \rightarrow K^+ K^-$ decays. The obtained asymmetry is consistent with expectations from K^+ and K^- hadronic cross sections with the LHC**b** detector material, showing an approximately 4% larger K^+ than K^- efficiency for low momentum below 10 GeV compared to high momentum.

With the $K^{+/-}$ efficiency asymmetry known the $\pi^{+/-}$ efficiency asymmetry and the $D^0/\bar{D}^0$ cross section asymmetry have been unfolded from $D^0 \rightarrow K^- \pi^+$ and $\bar{D}^0 \rightarrow K^+ \pi^-$ decays. The $\pi^{+/-}$ efficiency asymmetry shows a significant dependence on the azimuth angle of approximately 10%. The cause for the dependence is unresolved; a possibility can be the L0 trigger in conjunction with a larger occupancy in the calorimeter center.

The $D^0/\bar{D}^0$ cross section asymmetry initially shows a large dependence on the azimuth angle ϕ , but after it is uncorrelated from the $K^{+/-}$ and $\pi^{+/-}$ efficiency asymmetries, it is flat in ϕ as expected. As a function of transverse momentum the cross section asymmetry shows no significant dependence and is compatible with an alternative LHC**b** analysis on $D^0 \rightarrow h^+ h^-$ decays. However, a pseudorapidity dependence is implied with the asymmetry at approximately $\eta = 3$ about 4% larger than in the central and forward regions.

Perspective

Particle momentum correlations in multi-body (decay) processes can cause artificial effects if not properly accounted for. These effects arise when particles are considered individually, like e.g. efficiencies, by considering particles individually, because doing so implicitly entails integrating over the phase space of the rest of the event. And since the momenta of particles in multi-body processes are generally correlated, the individual particle quantities, although inherently independent, *will* affect each other.

A careful consideration is thus required of what phase space is integrated over to determine which quantity.

This consideration has been the topic of the second part of this thesis, wherein a general method has been developed, tested and applied, that does account for the momentum correlations that arise in multi-body processes. The method considers the particles individually, but iteratively unfolds their single-particle quantities from the underlying, correlated multi-body processes.

The method can be applied in data-MC truth comparisons to determine particle efficiencies and in completely data-driven comparisons to determine particle asymmetries. In fact, the method can be applied to any two data sets on a multi-particle phase space. Whenever the two sets contain the same correlating mechanisms, they differ

only by single-particle quantities. The iterative method then assures that the single-particle quantities are correctly unfolded from the underlying, correlating multi-body processes.

Appendix A

Iteration scale convergence

The binned iteration equation for n outgoing particles is the generalization of Eq.6.14 to n particles.

$$e_i^{(n+1)}(b_i) = \left[\frac{\sum_{b_1, \dots, b_{i-1}, b_{i+1}, \dots, b_n} N_{\text{measured}}(b_1, \dots, b_n)}{\sum_{b_1, \dots, b_{i-1}, b_{i+1}, \dots, b_n} N_{\text{MCt}}(b_1, \dots, b_n) \prod_{j=1}^n e_j^{(n)}(b_j)} \right]^{1-y} \left[\frac{e_i^{(n)}(b_i)}{e_i^{(n-1)}(b_i)} \right]^\alpha, \quad (\text{A.1})$$

where b_i denotes a bin for particle i . For a factorisable underlying efficiency the numerator in Eq.A.1 is

$$N_{\text{measured}}(b_1, \dots, b_n) \equiv N_{\text{MCt}}(b_1, \dots, b_n) \epsilon_1(b_1) \cdots \epsilon_n(b_n). \quad (\text{A.2})$$

Additionally, define the ratio between iterated and underlying efficiency

$$c_i^{(n)}(b_i) \equiv \frac{e_i^{(n)}(b_i)}{\epsilon_i(b_i)}. \quad (\text{A.3})$$

With the above the ratios are determined by

$$c_i^{(n+1)}(b_i) = \left[\frac{\sum_{b_1, \dots, b_{i-1}, b_{i+1}, \dots, b_n} N_{\text{MCt}}(b_1, \dots, b_n) \prod_{j=1}^n \epsilon_j^{(n)}(b_j)}{\sum_{b_1, \dots, b_{i-1}, b_{i+1}, \dots, b_n} N_{\text{MCt}}(b_1, \dots, b_n) \prod_{j=1}^n \epsilon_j^{(n)}(b_j) \prod_{j=1}^n c_j^{(n)}(b_j)} \right]^{1-y} \left[\frac{e_i^{(n)}(b_i)}{e_i^{(n-1)}(b_i)} \right]^\alpha \quad (\text{A.4})$$

Now, suppose that the form of a single-particle efficiencies $e_i^{(n)}(b_i)$ assumes the correct shape, such that it differs from $\epsilon_i(b_i)$ only by the same scale for each of its bins. In other words, suppose that $c_i^{(n)}(b_i) = c_i^{(n)}$. In this case the iteration reduces to

$$c_i^{(n+1)} = \left[c_i^{(n)} \right]^{\alpha+y} \left[c_i^{(n-1)} \right]^{-\alpha} \prod_{j \neq i} \left[c_j^{(n)} \right]^{-(1-y)} \quad (\text{A.5})$$

Taking the product over all particles i

$$c^{(n+1)} \stackrel{\text{def}}{=} \prod_{i=1}^n c_i^{(n+1)} = [c^{(n)}]^{\alpha+y-(m-1)(1-y)} [c^{(n-1)}]^{-\alpha} \quad (\text{A.6})$$

Write the solution to this recursion relation as $c^{(n+k)} \stackrel{\text{def}}{=} [c^{(n)}]^{u_k} [c^{(n-1)}]^{v_k}$, then

$$\begin{pmatrix} u_{k+1} \\ v_{k+1} \end{pmatrix} = \begin{bmatrix} 1 + \alpha - m(1-y) & 1 \\ -\alpha & 0 \end{bmatrix} \begin{pmatrix} u_k \\ v_k \end{pmatrix} \quad (\text{A.7})$$

or

$$\begin{pmatrix} u_k \\ v_k \end{pmatrix} = \begin{bmatrix} 1 + \alpha - m(1-y) & 1 \\ -\alpha & 0 \end{bmatrix}^k \begin{pmatrix} u_0 \\ v_0 \end{pmatrix} ; \quad \begin{matrix} u_0 = 1 \\ v_0 = 0 \end{matrix} \quad (\text{A.8})$$

The matrix in Eq.A.7 and Eq.A.8 has eigenvalues

$$\lambda_{\pm} = \frac{1}{2}[1 + \alpha - m(1-y)] \pm \frac{1}{2}\sqrt{[1 + \alpha - m(1-y)]^2 - 4\alpha} \quad (\text{A.9})$$

with corresponding eigenvectors $[u, v]_{\pm} = [\lambda_{\pm} - \alpha, -\alpha m]$. With these, the matrix can be diagonalized and written as

$$\begin{bmatrix} (\lambda_+ - \alpha) & (\lambda_- - \alpha) \\ -\alpha m & -\alpha m \end{bmatrix} \begin{bmatrix} \lambda_+ & 0 \\ 0 & \lambda_- \end{bmatrix} \begin{bmatrix} \alpha m & (\lambda_- - \alpha) \\ -\alpha m & -(\lambda_+ - \alpha) \end{bmatrix} / \alpha m (\lambda_+ - \lambda_-) \quad (\text{A.10})$$

so that

$$u_k = \frac{\lambda_+^{k+1} - \lambda_-^{k+1}}{\lambda_+ - \lambda_-} - \alpha \frac{\lambda_+^k - \lambda_-^k}{\lambda_+ - \lambda_-} \quad (\text{A.11})$$

$$v_k = -\alpha m \frac{\lambda_+^k - \lambda_-^k}{\lambda_+ - \lambda_-} \quad (\text{A.12})$$

For $4\alpha > [1 + \alpha - m(1-y)]^2$, the eigenvalues are complex as $\lambda_{\pm} = \sqrt{\alpha} \exp(\pm i\phi)$, where $\tan(\phi) = \sqrt{(4\alpha - [1 + \alpha - m(1-y)]^2)} / [1 + \alpha - m(1-y)]$. In this case

$$u_k = \sqrt{\alpha}^k \frac{\sin((k+1)\phi) - \sqrt{\alpha} \sin(k\phi)}{\sin(\phi)} \quad (\text{A.13})$$

$$v_k = -\sqrt{\alpha}^k m \sqrt{\alpha} \frac{\sin(k\phi)}{\sin(\phi)} \quad (\text{A.14})$$

For $\alpha < 1$ the limit $k \rightarrow \infty$ has both powers u_k and v_k going to zero, so that $c^{(n+k)} \rightarrow 1$.

The choice of α taken from the above that ensures convergence of scale is

$$\max(0, 1 + m(1-y) - 2\sqrt{m(1-y)}) < \alpha < \min(1, 1 + m(1-y) + 2\sqrt{m(1-y)}) \quad (\text{A.15})$$

Appendix B

Closest single-particle projections

In Sec.6.2.2 expressions are given that define single-particle efficiencies from an underlying production process (Eq.6.10 and Eq.6.11).

The efficiency for a multi-body process generally is a multiparticle-momentum dependent expression. A single-particle efficiency on the other hand depends only on the momentum of one of the outgoing particles. In this sense the single-particle efficiencies are *projections* of the true underlying efficiency, i.e. reductions of the underlying efficiency to individual particle momenta.

If the underlying efficiency is factorisable, then it is by definition the product of such projections. The iteration procedure of Sec.6.2.3 is set up to correctly unfold these projections from the underlying production process.

However, as is pointed out in Sec.6.3.3, if the true underlying efficiency is not factorisable then Eq.6.10 and Eq.6.11 still define single-particle efficiencies, but these projections will consequently not completely reproduce the true underlying efficiency everywhere in multi-particle phase space.

An immediate after-thought to this is whether the single-particle efficiencies defined by Eq.6.10 and Eq.6.11 are in any sense the *closest* projections, i.e. the best approximations to the true underlying efficiency. Here “closest” refers to a minimum of some measure of distance between the underlying efficiency and its approximation by the product of single-particle efficiencies.

The usual measure of distance between functions is the sum of squared differences (or integral over the squared difference). In this section expressions are derived for the single-particle efficiencies that minimize this distance, i.e. a least-squares method.

The resulting expressions, representing the closest single-particle projections, are different from the ones derived in Sec.6.2.2 (Eq.6.10 and Eq.6.11), which are the basis for the iteration procedure used throughout chapters 6 and 7. In this sense the single-particle efficiencies obtained in these chapters are *not* the best approximations *if* the underlying efficiency is not factorisable.

However, a translation of the closest single-particle projections as derived below into a generally converging iterative method has not (yet) been successful.

B.1 A least-squares approximation

As in Sec.6.2 consider a two-body decay $H \rightarrow h_1 h_2$. Suppose that $N(p_1, p_2)$ decays are produced in collisions where outgoing particles h_1 and h_2 have momenta p_1 and p_2 respectively (the underlying event distribution). The process is subject to a (non-factorisable) underlying efficiency $\epsilon(p_1, p_2)$, which is to be approximated by the product of single-particle efficiencies $e_1(p_1)$ and $e_2(p_2)$, i.e. as $\epsilon(p_1, p_2) \approx e_1(p_1)e_2(p_2)$.

In a two-body decay the momenta of the outgoing particles do not occupy all of two-body phase space, but are restricted to specific combinations (at least to those combinations that build the mass of the mother particle). Denote this restricted phase space by $\mathcal{H}$, i.e. $\mathcal{H} = \{(p_1, p_2) | N(p_1, p_2) \neq 0\}$.

Furthermore, say that two functions $f(p_1, p_2)$ and $f'(p_1, p_2)$ are equivalent when they are equal on $\mathcal{H}$

$$f \equiv f' \text{ iff } f(p_1, p_2) = f'(p_1, p_2) \text{ for all } (p_1, p_2) \text{ in } \mathcal{H}. \quad (\text{B.1})$$

This equivalence is introduced, since the decay is only sensitive to the efficiency in the restricted part of the two-body phase space $\mathcal{H}$.

The usual inner product between two functions $f(p_1, p_2)$ and $g(p_1, p_2)$ is given by

$$f \cdot g = \int_{\mathcal{H}} dp_1 dp_2 f(p_1, p_2) g(p_1, p_2). \quad (\text{B.2})$$

Such an inner product naturally defines a norm

$$\|f\|^2 = f \cdot f = \int_{\mathcal{H}} dp_1 dp_2 f^2(p_1, p_2). \quad (\text{B.3})$$

This norm in turn defines the usual distance between functions

$$d_u(f, g)^2 = \|f - g\|^2 = \int_{\mathcal{H}} dp_1 dp_2 [f(p_1, p_2) - g(p_1, p_2)]^2. \quad (\text{B.4})$$

Alternatively an inner product can be defined by

$$f \cdot g = \int dp_1 dp_2 N(p_1, p_2) f(p_1, p_2) g(p_1, p_2), \quad (\text{B.5})$$

which defines the distance

$$d_b(f, g)^2 = \|f - g\|^2 = \int dp_1 dp_2 N(p_1, p_2) [f(p_1, p_2) - g(p_1, p_2)]^2. \quad (\text{B.6})$$

The second notion of distance, defined by Eq.B.6, determines the distance between functions on the basis of $H \rightarrow h_1 h_2$ events. It gives preference to those parts of phase space in which a large number of decays are produced, i.e. for large $N(p_1, p_2)$. As such this distance is biased towards the specific decay $H \rightarrow h_1 h_2$, in contrast to the “unbiased” distance of Eq.B.4.

The distances between the underlying efficiency and its single-particles approximation are thus given in two ways by

$$d_u^2 = \int_{\mathcal{H}} dp_1 dp_2 [\epsilon(p_1, p_2) - e_1(p_1)e_2(p_2)]^2 \quad (\text{B.7})$$

$$d_b^2 = \int dp_1 dp_2 N(p_1, p_2) [\epsilon(p_1, p_2) - e_1(p_1)e_2(p_2)]^2. \quad (\text{B.8})$$

The minimum of either of these distances is the one for which its derivatives with respect to the single-particle efficiencies $e_1(p_1)$ and $e_2(p_2)$ vanish¹

$$\frac{\delta d_u^2}{\delta e_1(p_1)} = 2 \int_{\mathcal{H}} dp_2 e_2(p_2) [\epsilon(p_1, p_2) - e_1(p_1)e_2(p_2)] = 0 \quad (\text{B.9})$$

$$\frac{\delta d_u^2}{\delta e_2(p_2)} = 2 \int_{\mathcal{H}} dp_1 e_1(p_1) [\epsilon(p_1, p_2) - e_1(p_1)e_2(p_2)] = 0 \quad (\text{B.10})$$

and

$$\frac{\delta d_b^2}{\delta e_1(p_1)} = 2 \int dp_2 N(p_1, p_2) e_2(p_2) [\epsilon(p_1, p_2) - e_1(p_1)e_2(p_2)] = 0 \quad (\text{B.11})$$

$$\frac{\delta d_b^2}{\delta e_2(p_2)} = 2 \int dp_1 N(p_1, p_2) e_1(p_1) [\epsilon(p_1, p_2) - e_1(p_1)e_2(p_2)] = 0, \quad (\text{B.12})$$

such that the closest projections are defined by

$$e_{u1}(p_1) = \frac{\int_{\mathcal{H}} dp_2 \epsilon(p_1, p_2) e_{u2}(p_2)}{\int_{\mathcal{H}} dp_2 e_{u2}^2(p_2)} \quad (\text{B.13})$$

$$e_{u2}(p_2) = \frac{\int_{\mathcal{H}} dp_1 \epsilon(p_1, p_2) e_{u1}(p_1)}{\int_{\mathcal{H}} dp_1 e_{u1}^2(p_1)} \quad (\text{B.14})$$

for the unbiased approach and

$$e_{b1}(p_1) = \frac{\int dp_2 N(p_1, p_2) \epsilon(p_1, p_2) e_{b2}(p_2)}{\int dp_2 N(p_1, p_2) e_{b2}^2(p_2)} \quad (\text{B.15})$$

$$e_{b2}(p_2) = \frac{\int dp_1 N(p_1, p_2) \epsilon(p_1, p_2) e_{b1}(p_1)}{\int dp_1 N(p_1, p_2) e_{b1}^2(p_1)} \quad (\text{B.16})$$

for the biased approach.

In terms of the number of underlying events before efficiency $N(p_1, p_2)$ and of measured events after efficiency $N_{\text{meas}}(p_1, p_2) = N(p_1, p_2)\epsilon(p_1, p_2)$ the closest single-particle projections are finally defined by

$$e_{u1}(p_1) = \frac{\int dp_2 \frac{N_{\text{meas}}(p_1, p_2)}{N(p_1, p_2)} e_{u2}(p_2)}{\int_{\mathcal{H}} dp_2 e_{u2}^2(p_2)} \quad (\text{B.17})$$

$$e_{u2}(p_2) = \frac{\int dp_1 \frac{N_{\text{meas}}(p_1, p_2)}{N(p_1, p_2)} e_{u1}(p_1)}{\int_{\mathcal{H}} dp_1 e_{u1}^2(p_1)}. \quad (\text{B.18})$$

¹These derivatives are determined by variational calculus and the fundamental lemma of the calculus of variations is assumed to hold.

and

$$e_{b1}(p_1) = \frac{\int dp_2 N_{\text{meas}}(p_1, p_2) e_{b2}(p_2)}{\int dp_2 N(p_1, p_2) e_{b2}^2(p_2)} \quad (\text{B.19})$$

$$e_{b2}(p_2) = \frac{\int dp_1 N_{\text{meas}}(p_1, p_2) e_{b1}(p_1)}{\int dp_1 N(p_1, p_2) e_{b1}^2(p_1)}. \quad (\text{B.20})$$

The biased approach will provide a better approximation for the particular decay $H \rightarrow h_1 h_2$. This, however, may not be the case when the resulting single-particle efficiencies are applied to a different process involving the same outgoing particles h_1 and h_2 , where the unbiased approximation may be a better choice.

For a factorisable underlying efficiency both the biased approach and the unbiased approach as well as the expressions Eq.6.10 and Eq.6.11 of Sec.6.2.2 will obtain the same (and correct) single-particle efficiencies.

B.2 Corollary: successive improvements

In the previous Sec.B.1 the underlying efficiency is given factorized approximations in terms of single-particle efficiencies. These single-particle efficiencies are in fact the first order in a series of improved approximations

$$\epsilon(p_1, p_2) \approx e_1^{(1)}(p_1) e_2^{(1)}(p_2) + e_1^{(2)}(p_1) e_2^{(2)}(p_2) + e_1^{(3)}(p_1) e_2^{(3)}(p_2) + \dots \quad (\text{B.21})$$

The higher order improvements are obtained by minimizing the successive measures of distance

$$(d_u^{(i)})^2 = \int_{\mathcal{H}} dp_1 dp_2 \left[\epsilon^{(i)}(p_1, p_2) - e_1^{(i)}(p_1) e_2^{(i)}(p_2) \right]^2 \quad (\text{B.22})$$

$$(d_b^{(i)})^2 = \int dp_1 dp_2 N(p_1, p_2) \left[\epsilon^{(i)}(p_1, p_2) - e_1^{(i)}(p_1) e_2^{(i)}(p_2) \right]^2, \quad (\text{B.23})$$

for the unbiased and biased approach respectively, and with

$$\epsilon^{(i+1)}(p_1, p_2) = \epsilon^{(i)}(p_1, p_2) - e_1^{(i)}(p_1) e_2^{(i)}(p_2) \quad (\text{B.24})$$

and

$$\epsilon^{(1)}(p_1, p_2) = \epsilon(p_1, p_2) \quad (\text{B.25})$$

That is, the first order $e_1^{(1)}(p_1) e_2^{(1)}(p_2)$ is obtained as a factorized approximation to the underlying efficiency $\epsilon(p_1, p_2)$, the same as in the previous section. Then every successive order $e_1^{(i+1)}(p_1) e_2^{(i+1)}(p_2)$ is obtained as a factorized approximation to the difference that remains between the underlying efficiency and its approximation to order i , i.e. as $e_1^{(i+1)}(p_1) e_2^{(i+1)}(p_2) \approx \epsilon(p_1, p_2) - \sum_{j=1}^{i-1} e_1^{(j)}(p_1) e_2^{(j)}(p_2)$.

The minimized distance between the underlying efficiency and its approximation at order i is then given by

$$\int_{\mathcal{H}} dp_1 dp_2 \left[\epsilon(p_1, p_2)^2 - \sum_{j=1}^i \left[e_1^{(j)}(p_1) e_2^{(j)}(p_2) \right]^2 \right] \quad (\text{B.26})$$

$$\int dp_1 dp_2 N(p_1, p_2) \left[\epsilon(p_1, p_2)^2 - \sum_{j=1}^i \left[e_1^{(j)}(p_1) e_2^{(j)}(p_2) \right]^2 \right] \quad (\text{B.27})$$

for the both approaches, which indeed decreases with each successive order.

Minimizing Eq.B.22 and Eq.B.23 and expressing in terms of the number of underlying events before efficiency $N(p_1, p_2)$ and of measured events after efficiency $N_{\text{meas}}(p_1, p_2) = N(p_1, p_2)\epsilon(p_1, p_2)$ defines each successive single-particle improvement as

$$e_{u1}^{(i)}(p_1) = \frac{\int dp_2 \left[\frac{N_{\text{meas}}(p_1, p_2)}{N(p_1, p_2)} - \sum_{j=1}^{i-1} e_{u1}^{(j)}(p_1) e_{u2}^{(j)}(p_2) \right] e_{u2}^{(i)}(p_2)}{\int_{\mathcal{H}} dp_2 (e_{u2}^{(i)}(p_2))^2} \quad (\text{B.28})$$

$$e_{u2}^{(i)}(p_2) = \frac{\int dp_1 \left[\frac{N_{\text{meas}}(p_1, p_2)}{N(p_1, p_2)} - \sum_{j=1}^{i-1} e_{u1}^{(j)}(p_1) e_{u2}^{(j)}(p_2) \right] e_{u1}^{(i)}(p_1)}{\int_{\mathcal{H}} dp_1 (e_{u1}^{(i)}(p_1))^2} \quad (\text{B.29})$$

for the unbiased approach and

$$e_{b1}^{(i)}(p_1) = \frac{\int dp_2 \left[N_{\text{meas}}(p_1, p_2) - N(p_1, p_2) \sum_{j=1}^{i-1} e_{b1}^{(j)}(p_1) e_{b2}^{(j)}(p_2) \right] e_{b2}^{(i)}(p_2)}{\int dp_2 N(p_1, p_2) (e_{b2}^{(i)}(p_2))^2} \quad (\text{B.30})$$

$$e_{b2}^{(i)}(p_2) = \frac{\int dp_1 \left[N_{\text{meas}}(p_1, p_2) - N(p_1, p_2) \sum_{j=1}^{i-1} e_{b1}^{(j)}(p_1) e_{b2}^{(j)}(p_2) \right] e_{b1}^{(i)}(p_1)}{\int dp_1 N(p_1, p_2) (e_{b1}^{(i)}(p_1))^2} \quad (\text{B.31})$$

for the biased approach.

Bibliography

- [1] European Organization for Nuclear Research. *LHC Machine. Journal of Instrumentation*, 3(JINST 3 S08001), Aug. 2008.
- [2] The LHCb collaboration and A. Augusto Alves Jr. *et al.* *The LHCb Detector at the LHC. Journal of Instrumentation*, 3(JINST 3 S08005), Aug. 2008.
- [3] N. Tuning J. Nardulli. *A Study of the Material in an Outer Tracker Module.* LHCb-2004-114. LHCb public note.
- [4] A. Berkien *et al.* *The LHCb Outer Tracker Front End Electronics.* LHCb-2005-025. LHCb public note.
- [5] A. Berkien *et al.* *The front end electronics of the LHCb straw tube tracker. Nuclear Instruments and Methods in Physics Research A*, 617(doi:10.1016/j.nima.2009.10.048):329–331, 2010.
- [6] B. Hommels. *The Tracker in the Trigger of LHCb.* PhD thesis, Nikhef, 2006.
- [7] G. Aad *et al.* The ATLAS collaboration. *The ATLAS Experiment at the CERN Large Hadron Collider. Journal of Instrumentation*, 3(JINST 3 S08003), Aug. 2008.
- [8] E. Simioni *et al.* *Selection of ADSLBR chip for LHCb Outer Tracker FE.* LHCb-2005-088. LHCb public note.
- [9] G.W. van Apeldoorn *et al.* *Beam Tests of Final Modules and Electronics of the LHCb Outer Tracker in 2005.* LHCb-2005-076. LHCb public note.
- [10] R. Muckerheide. *Entwicklung eines Serientests für den TDC-Auslesechip der LHCb Spurkammern.* Master’s thesis, Physicalisches Institut Heidelberg, 2005.
- [11] J. Knopf. *Aufbau eines Auslesesystems für die Äusseren Spurkammern des LHCb-Detektors.* Master’s thesis, Physicalisches Institut Heidelberg, 2004.
- [12] U. Stange. *Development and Characterization of a Radiation Hard Readout Chip for the LHCb Outer Tracker Detector.* PhD thesis, Physicalisches Institut Heidelberg, 2005.
- [13] private communications. *Procedures for the Service-Test on the LHCb Outer Tracker C-frames.* LHCb-2006-029. LHCb internal note.

- [14] private communications. *Test and Assembly of the Outer Tracker C-frames and Detector Modules at Installation*. LHCb-2008-033. LHCb internal note.
- [15] G. van Apeldoorn *et al.* *Outer Tracker Module Production at NIKHEF - Quality Assurance*. LHCb-2004-078. LHCb public note.
- [16] private communications. *Gas-Tightness Tests of the LHCb Outer Tracker Modules Produced at NIKHEF*. LHCb-2004-092. LHCb internal note.
- [17] private communications. *The Dependence of the Signal Strength on the Applied Voltage and Gas Mixture of the LHCb Outer Tracker Detector*. LHCb-2005-093. LHCb internal note.
- [18] private communications. *Gas Propagation Studies in the Outer Tracker*. LHCb-2007-066. LHCb internal note.
- [19] E. Simioni. *New Physics From Rare Beauty*. PhD thesis, Nikhef, 2010.
- [20] H. Deppe *et al.* *The OTIS Reference Manual*. LHCb-2008-010. LHCb public note.
- [21] A. Pellegrino *et al.* *OT FE-Box Test Procedures*. LHCb-2007-122. LHCb public note.
- [22] Outer tracker homepage.
- [23] private communications. *Linearity Measurements with the OTIS TDC for the Outer Tracker*. LHCb-2008-080. LHCb internal note.
- [24] 2011 Europhysics Conference on High-Energy Physics. *Angular analysis of $B^0 \rightarrow K^{*0} \mu^+ \mu^-$* , 2011.
- [25] W. Altmannshofer *et al.* *Symmetries and Asymmetries of $B \rightarrow K^* \mu^+ \mu^-$ Decays in the Standard Model and Beyond*. *JHEP*, 01:19, 2009.
- [26] B. Adevn *et al.* (The LHCb Collaboration). *Roadmap for selected key measurements of LHCb*. LHCb-PUB-2009-029, arXiv:0912.4179v3[hep-ex].
- [27] K. Nakamura *et al.* (Particle Data Group). *Review of Particle Physics*. *Journal of Physics G*, 37, 2010.
- [28] Hans dijkstra, private communications.
- [29] private communications. *Generator study of the production asymmetry in lhcb*. LHCb-2007-124. LHCb internal note.
- [30] R. Lambert. *LHCb Hybrid Photon Detectors and Sensitivity to Flavour Specific Asymmetry in Neutral B-Meson Mixing*. PhD thesis, The University of Edinburgh, 2008.

-
- [31] BEAUTY 2011, 13th International Conference on B-physics at Hadron Machines. *A Search for time-integrated CP violation in $D^0 \rightarrow h^+ h^-$ decays and a measurement of the D^0 production asymmetry*, 2011.

Summary

This manuscript covers two very different topics within the context of the LHC*b* experiment. The first part focuses on the Outer Tracker subdetector, while in the second part a novel algorithm is developed to determine the experimental inefficiencies in measuring particles.

Part I, the Outer Tracker detector in LHC*b*

The Outer Tracker is a gaseous subdetector based on straw tube technology, that is part of the LHC*b* tracking system. The Outer Tracker detector modules and support frames had been constructed in various places. Upon arrival at CERN they were subjected to a final set of quality control tests immediately prior to their installation into the LHC*b* experiment. The gas distribution system, the high and low voltage supply systems and the optical readout were shown to be working within design specifications. Moreover, nearly half of the 53,760 thin straw tubes that constitute the Outer Tracker detection volume were individually tested with a radioactive iron source, with less than 0.1% unresponsive straws.

Signals from straw tubes are read out and processed by Front End electronics. Front End electronics boxes were assembled from the various specialized electronics components and tested for their defining characteristics. The threshold responses, time linearities, pipeline buffer synchronizations and noise levels were analyzed for each box and assured to be within specifications. The Differential Non-Linearity, an intrinsic feature of the electronics, was studied in detail and shown not to be a limiting factor on the Outer Tracker drift time resolution.

Part II, single-particle efficiencies from multi-body processes

A novel approach is developed to determine experimental inefficiencies in detecting particles. The approach chosen is based on multi-body control channels, i.e. on channels for which the underlying distribution of particles is well known. Such an approach, however, is complicated by inter-particle correlations, where particles do not only suffer from their own detection efficiencies, but because the multi-body process correlates the outgoing particles, they also suffer from each others detection efficiencies. This complication is addressed and solved with a method that iteratively unfolds the individual particle detection efficiencies from the multi-body topology.

This iterative method has been motivated by one of the key measurements of LHC*b*:

the rare decay $B_d \rightarrow \mu^+ \mu^- K^*$ that is sensitive to new physics. The efficiencies in measuring the outgoing particles in this channel can be obtained from the well known control channel $B_d \rightarrow J/\psi K^*$.

The method is developed and is validated in a series of fast simulation studies. Moreover, it is applied on full Monte Carlo simulation of $B_d \rightarrow J/\psi K^*$ and $B_d \rightarrow \mu^+ \mu^- K^*$ events and shown to produce reliable results.

The scope of the iterative method is, however, not restricted to determining efficiencies; it can for example also be applied to unfold asymmetries and for this purpose the method has been applied to October 2010 LHCb measurements of $D^0/\bar{D}^0 \rightarrow K^+ K^-$ and $D^0/\bar{D}^0 \rightarrow K^\mp \pi^\pm$ decays. In a completely data-driven way, the momentum dependencies of asymmetries between the K^+ and K^- detection efficiencies, between the π^+ and π^- detection efficiencies and between the D^0 and $\bar{D}^0$ differential production cross sections are determined.

The obtained $K^{+/-}$ efficiency asymmetry is found to be small and consistent with expectations based on hadronic cross sections of charged kaons with the detector material.

A significant variation in the azimuth angle within approximately 10% is found for the $\pi^{+/-}$ efficiency asymmetry. This dependence is yet unresolved; the L0 trigger in conjunction with a larger occupancy in the calorimeter center is suggested as a possible cause.

Initially the $D^0/\bar{D}^0$ cross section asymmetry shows a significant dependence on the azimuth angle ϕ , but after it is uncorrelated from the $K^{+/-}$ and $\pi^{+/-}$ efficiency asymmetries, it is flat in ϕ as expected. As a function of transverse momentum the cross sections asymmetry shows no significant dependence and is compatible with an alternative LHCb analysis on $D^0 \rightarrow h^+ h^-$ decays. On the other hand, a pseudorapidity dependence is implied where the asymmetry at approximately $\eta = 3$ is about 4% larger than in the central and forward regions.

The iterative method, in its generic form, presents a way to unfold single-particle quantities from the multi-body processes that correlate the momenta of the outgoing particles. This method is to be applied in those analyses that intend to determine single-particle quantities from measurements of multi-body channels.

Populaire samenvatting

Menig deeltjesfysicus zal zich het beruchte ongeluk herinneren met de LHC versneller op CERN in 2008, welk een vol jaar vertraging veroorzaakte tot de herstart van de versneller in November 2009.

In de lente van 2009 bezocht mijn vriendin Ana Paula me op CERN en kreeg zij een tour van het LHC*b* experiment. Ze werd meegenomen naar de enorme ondergrondse LHC*b* hal, waar ze een indruk kreeg van het experiment: Ze werd genavigeerd door de ca. 20 meter lange en 10 meter hoge LHC*b* detector, geleid langs de verscheidene subdetectoren, gewezen op de talloze componenten waaruit deze bestaan en kreeg uitleg over de rol die ze spelen in het meten van minuscule deeltjes met een enorme machine. Hierna sprak ze de legendarische woorden “No wonder it broke”².

Gezien de gigantische schaal van de LHC experimenten is het inderdaad geen wonder. Protonen moeten worden versneld tot een miljard kilometer per uur en miljoenen keren per seconde in botsing worden gebracht. In elke botsing worden honderden deeltjes gemaakt die door de detector worden verspreid en moeten duizenden elektrische signalen van detector-strootjes, strips, pads en pixels worden versterkt, vergeleken, gedigitaliseerd en gecombineerd binnen een fractie van een seconde. De detectoren zijn zo groot als een huis of nog groter, maar moeten de deeltjes meten met een precisie fijner dan een haar. Computer algoritmes moeten de immense hoeveelheid resulterende data verwerken en filteren, voor het zeer zeldzame geval dat zich iets baanbrekend en nooit tevoren gezien, maar abstract en raadselachtig heeft voorgedaan. En de talrijke detector onderdelen, elektronica componenten en subalgoritmes moeten worden ontworpen, gebouwd of geprogrammeerd, getest, gecalibreerd, gesynchroniseerd, opnieuw getest en maanden dan wel niet jaren hun werk doen voordat wetenschappers kunnen aantonen dat ze iets nieuws hebben gevonden in de quantum wereld van elementaire deeltjes, of dat deze wereld nog steeds hetzelfde werkt als tevoren bekend. Misschien is “No wonder it broke” wel te zwak uitgedrukt.

Van de talloze elementen van het LHC*b* experiment beschrijft dit proefschrift twee zeer verschillende. Het eerste gedeelte concentreert zich op de installatie van de Outer Tracker subdetector in het LHC*b* experiment en op de productie van de Front End elektronica voor deze. Het tweede gedeelte wordt een nieuwe methode ontwikkeld waarmee een aspect kan worden vastgelegd waarmee vele metingen in deeltjesfysica te maken hebben: een experimentele inefficiëntie om deeltjes te meten.

²Vertaald: “Geen wonder dat ie kapot ging.” Het feit dat het de LHC versneller was die kapot ging en niet de LHC*b* detector is een leek vergeven.

Deel I, de Outer Tracker detector in LHCb

De *Outer Tracker* subdetector is een cruciaal onderdeel in het bepalen van de banen die deeltjes door het LHCb experiment maken. De Outer Tracker bestaat uit 53,760 lange dunne verticale strootjes van zo'n 2.5 m lang en 5 mm breed. De strootjes registreren doorkomende deeltjes met behulp van gasontlading en -versterking. Ze zijn per 128 in twee lagen zij-aan-zij bevat in detector modules. Deze modules zijn op hun beurt bevestigd aan aluminium frames en de geregistreerde signalen worden aan de uiteindes van de modules uitgelezen door Front End elektronica.

De modules en frames waren op verscheidene plaatsen gebouwd. Bij aankomst op CERN werden de modules en frames in de ondergrondse LHCb hal onderworpen aan een laatste set van kwaliteitscontrole-tests alvorens ze werden geïnstalleerd in het LHCb experiment. Hun gasdistributiesysteem, voedingsystemen voor hoog- en laagspanning en optische uitleessysteem werden getest en er werd vastgesteld dat ze binnen de ontwerpspecificaties functioneren. Bovendien werd bijna de helft van de 53,760 strootjes individueel getest met behulp van een radioactieve ijzer bron, waaruit bleek dat meer dan 99.9% van de strootjes naar behoren de deeltjes meet.

Doorkomende deeltjes veroorzaken signalen in de strootjes die worden uitgelezen en verwerkt door Front End elektronica, waarbij verschillende elektronica componenten verschillende taken in de uitlezing verrichten. De componenten werden geassembleerd in Front End elektronica dozen, welke vervolgens werden getest met betrekking tot een aantal cruciale karakteristieken. De drempelwaardes, lineariteit, buffersynchronisatie en elektronische ruis werden geanalyseerd en componenten die afwijkende karakteristieken veroorzaakten werden vervangen. De Differentiele Niet-Lineariteit (DNL), een intrinsiek aspect van de elektronica, werd in detail bestudeerd en hiervoor werd aangetoond dat deze niet een beperkende factor is op de resolutie van de Outer Tracker.

Deel II, enkele-deeltjes efficiënties uit multi-deeltjes processen

In versneller experimenten worden deeltjes, protonen in het geval van LHCb, met hoge energie in botsing gebracht. Uit zo'n botsing komen talloze andere deeltjes als fragmenten te voorschijn, vliegen door het experiment heen en worden gemeten door de detector. Het laatste is echter enigszins te eenvoudig uitgedrukt, want wat echt wordt gemeten zijn de banen die de deeltjes door het experiment maken. Wat voor type deeltje er bij een baan hoorde en wat voor snelheid deze had moet achteraf door de fysici worden berekend.

Experimenten zoals LHCb zoeken doorgaans in de talloze deeltjes die uit een botsing komen naar deeltjes waarvan het bestaan kan worden verwacht, maar welke nog nooit zijn gezien. Echter, in de praktijk zullen zulke exotische deeltjes niet zelf een baan door de detector maken, maar zullen ze binnen een fractie van een seconde uit elkaar vallen in kleinere bekende deeltjes. Experimenten meten dus niet direct exotische deeltjes, maar zijn op zoek naar specifieke combinaties van bekende deeltjes met specifieke banen, die mogelijk duiden op een exotisch deeltje.

De exotische deeltjes, als ze al voorkomen, zullen slechts zeer zelden hun kop op steken. Om de kans op een exotisch deeltje te vergroten worden er ontzettend veel

botsingen per seconde gemaakt, zo'n 40.000.000. Maar niet al deze botsingen kunnen worden verwerkt, waardoor bij elke botsing een snelle schatting moet worden gemaakt of er mogelijk een exotisch deeltje aanwezig was: een selectie aan de hand van de banen die uit de botsing kwamen. Dit betekent echter dat niet elke baan van elk deeltje wordt gezien; sommige banen worden geselecteerd, andere banen niet. Hierbij komt ook nog dat bij voorbaat het experiment niet altijd alle deeltjes meet; soms wordt de baan van een deeltje simpelweg niet gemeten of herkend. Al met al is er dus een zekere efficiëntie om een deeltje te meten, die bovendien afhangt van de baan die het deeltje door de detector maakt.

Efficiënties maken het herkennen van exotische deeltjes lastig. Aan de ene kant kan een exotisch deeltje ervoor zorgen dat specifieke banen van sommige bekende deeltjes vaker voorkomen; en dit is precies waar fysici naar op zoek zijn. Maar aan de andere kant kan het ook zijn dat het experiment gewoon efficiënter is om die specifieke banen te meten, en lijkt het alleen maar of ze vaker voorkomen. Het is dus belangrijk om de efficiënties van het experiment goed te weten als je exotische deeltjes wilt meten.

In het tweede gedeelte van dit proefschrift is een nieuwe methode ontwikkeld die de efficiënties bepaalt waarmee deeltjes worden gemeten. De methode is gebaseerd op het gebruik van *controle kanalen*. Dit zijn welbekende combinaties van deeltjes waarvoor precies bekend is hoe vaak ze bepaalde banen door het experiment zouden moeten maken, zodat afwijkingen van deze hoeveelheden duiden op inefficiënties.

Er is een lastigheid die komt kijken bij het bepalen van efficiënties uit controle kanalen. Om een controle kanaal als zodanig te herkennen moet elk van zijn uitgaande deeltjes worden gemeten. De efficiëntie om het controle kanaal te meten is dus een combinatie van de efficiënties om de individuele deeltjes te meten. Echter, de banen van de deeltjes in het controle kanaal zijn doorgaans niet onafhankelijk, waardoor ook de individuele efficiënties afhankelijk van elkaar kunnen worden. Dit maakt het moeilijk om te bepalen waar het experiment inefficiënt was voor welk deeltje met welke baan. De methode in dit proefschrift lost deze moeilijkheid op een iteratieve manier op en bepaalt de individuele efficiënties van de deeltjes in het controle kanaal.

De iteratieve methode werd gemotiveerd door één van de meest belangrijke metingen van het LHCb experiment: het vervalsskanaal $B_d \rightarrow \mu^+ \mu^- K^*$, waar exotische deeltjes de banen van de uitgaande deeltjes aanzienlijk kunnen beïnvloeden. De benodigde efficiënties om de uitgaande deeltjes te meten kunnen met de iteratieve methode worden bepaald uit het controle kanaal $B_d \rightarrow J/\psi K^*$. De iteratieve methode is ontwikkeld en getest, en is toegepast op volledige Monte Carlo simulaties van botsingen met de vervallen $B_d \rightarrow J/\psi K^*$ en $B_d \rightarrow \mu^+ \mu^- K^*$ waarmee is gedemonstreerd dat de methode betrouwbare resultaten produceert.

Hoewel de iteratieve methode is ontwikkeld om efficiënties te bepalen, kan de methode over een groter bereik worden ingezet en als vervolg is de methode toegepast op LHCb metingen van de vervallen $D^0/\bar{D}^0 \rightarrow K^+ K^-$ en $D^0/\bar{D}^0 \rightarrow K^\mp \pi^\pm$ in October 2010 om op een volledig data-gedreven manier een asymmetrie te bepalen tussen de K^+ en K^- efficiënties, tussen de π^+ en π^- efficiënties, en tussen de D^0 en $\bar{D}^0$ differentiële werkzame productie doorsnedes.

De verkregen $K^{+/-}$ efficiëntie asymmetrie is klein en is consistent met verwachtingen gebaseerd op de hadronische werkzame doorsnedes van kaonen met het materiaal waaruit de LHCb detector bestaat.

Een significante variatie in de azimuth hoek binnen ongeveer 10% werd gevonden voor de $\pi^{+/-}$ efficiëntie asymmetrie. Deze afhankelijkheid is nog onverklaard; de L0 trigger samen met een grotere deeltjesdichtheid in het midden van de LHCb calorimeter wordt voorgesteld als mogelijke oorzaak.

Zonder de iteratieve methode toe te passen is een significante afhankelijkheid van de asymmetrie in de $D^0/\bar{D}^0$ werkzame doorsnedes van de azimuth hoek ϕ zichtbaar. Echter, nadat de iteratieve methode deze asymmetrie isoleert van de $K^{+/-}$ en $\pi^{+/-}$ efficiëntie asymmetriën, is zij vlak in ϕ zoals wordt verwacht. Als functie van de transversale impuls toont de werkzame doorsnede asymmetrie geen significante afhankelijkheid en is compatibel met een LHCb analyse van $D^0 \rightarrow h^+h^-$ vervallen. Aan de andere kant wordt een afhankelijkheid van pseudorapidity η gemeten, waarbij de asymmetrie bij ongeveer $\eta = 3$ zo'n 4% groter is dan in de centrale en voorwaatse regionen.

Bij het meten van deeltjes komen zekere grootheden kijken, zoals efficiënties, die op zich voor elk deeltje afzonderlijk zijn gegeven, maar die door correlaties tussen de deeltjesbanen met elkaar worden verweven. De iteratieve methode die hier is ontwikkeld is een manier om de grootheden te decorreleren. Ik stel dan ook voor om deze methode in de toekomst te gebruiken in analyses waarbij grootheden van afzonderlijke deeltjes moeten worden bepaald uit de meting van kanalen met meerdere uitgaande deeltjes.

Acknowledgments

Disclaimer

If you find that I have forgotten you, or you feel that my mention of you is insufficient, then please forgive me. It was not my intention; it is probably because, as you may well know, I have my head up my ... most of the time.

Let me first say some words in Dutch to my family before I continue in English.

Pa, ma, jullie geduld is onvoorstelbaar en mijn dank voor jullie onafgebroken steun zal ik nooit in woorden kunnen uitdrukken. Patrick, Marcel, bro's, jullie zullen altijd een motivatie voor me blijven zijn om, net als jullie, m'n eigen weg vol plezier voort te zetten. Oma, met veel plezier zal ik je onverminderende interesse in wat ik uitspook keer op keer blijven beantwoorden.

Back to English.

My dear Poppie, I know that my days with you have been far too short, my working hours far too long. Therefore I want to thank you for putting up with me, for your patience, for your continued support and motivation despite my large absence. You have always been my much needed 'fan' at home :-)

Dear bosses: Merk, you are truly the best chief anyone can wish for. Your knowledge and experience, together with a murderous carnival and mandatory beers at the first nice day of spring set the stage for a perfect working environment. Antonio, your knowledge of everything physics keeps amazing me, from electronics to particle theory. Your ability to make anyone feel welcome and appreciated stands out as unprecedented and I doubt I'll ever encounter a team leader like that again. Maestro Tuning, what am I going to do without your guidance and without your perpetual positivity. I am already jealous of all the PhD students that you will oversee in the future. Boyz, it has been an utmost pleasure working for you.

Allow me to single out my boy Gordon. Deuzer, we have been sharing the same this for fifteen years; I don't think mere acknowledgments will cut it so I won't try too hard. Just get your behind back here for some beers, laughs and a recount of some of the countless this we've been in.

My CERN time wouldn't have been any good without the boyz of OT installation: Loek, Oscar, Ruud, Ad. It was great fun scaling the C-cage with you. Many thanx to you guys for the many many restaurants and bars that we went to after work. And my Nikhef time wouldn't have been the same without the boyz of electronics: Tom, Albert, Giampiero. You guys taught me a lot. It truly was a pleasure working with

you. I can say that now I almost like electronics.

B-physics at Nikhef is a phenomenon more than a group, because of my bosses and most definitely because of the PhDs and postdocs. The gone-by generation of *B*-physics lackeys: Giani (Amore), Gaab (K-star-mu-mu master), Mr. Zupan, Peter (family man) Vankov, Tristan, Eduard (hustler) Simioni, Aras, Edwin, Jacopo, Hella, Nicola, Kazu, Vanya, Juan (the One) Pallacios. It was a pleasure not-working, having beers and generally slacking off with you guys. The running generation of *B*-physics lackeys: Daan, Barbara, Chiara, Serena, Ivan, Jeroen, Alexandr, Roel, Victor, Besma. I am confident that you will teach the newest generation all that we have learned about not-working, having beers and generally slacking off (and ok, perhaps some physics as well). The newest generation of *B*-physics lackeys: Siim, Pieter, Suvayu, Rose, Kristof, Maurizio, Francesco, Manuel, Rob. From the above it should be clear what I expect of you at the end of your time with Nikhef *B*-physics.

During my time at Nikhef (± 10 years) there have been too many of you that I shared laughs, beers, Friday drinks and whatnot with. But let me at least try to credit some of my usual suspects.

Giani Amore, many thanks for being my office mate, for sharing beers, coffees, complaints and too many working hours. Perhaps we'll work together again soon enough. Doctor Serra, many thanks for sharing offices, at Nikhef and at CERN, for many coffees (or dirty waters), discussions and white board sessions. Any group that has you will do very good to keep you. Sipho, it's been good to have someone in the same mess, to share complaints, prospects and a todo-list with. Gossie, the wolf in sheep's clothing, it's been fun ever since summer school, but I'm too scared to go out with you again. The FE-Test team: Giampiero, Pawel, Eduard, Tristan, you know you are all one hundred percent The Twente boyz: Bram (Baas), Jan (van de Buren), Bob (Beppie) Dirks, Gino Ginelli, thanx for the brilliant times. Perhaps you will let me win a board game one time ok. The Zwolle boyz: Peppie, Hein, Appie, Aukie Baas, Vedat. Thanx for reminding me about the *real* world. Jeroen, Ytsen, Deuzer, thanks for letting me have the final f(sh)ame. Nico (Bremse) Rem and the rest of team Muon: Rene, Gerrit, Willem and Mien. Thanx for actually making the many hours building the muon chambers fun.

And too many more: Akshay, Eva. From "my generation": Alex (tranquilo) Koutsman, Manouk, Egge, Hegoi, Dox, Manuel, Mathieu, Giada, PartyCentrum Heijboer. From the Masters of mechanics: Martijn, Michiel, Chef Berbee, Joop. Y'all have made my time at Nikhef a brilliant one.

Het was gezellig. Bedankt en tot ziens.

Faab