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Abstract

A dedicated reconstruction algorithm to find decay vertices in the ATLAS muon spectrometer is presented. The algorithm searches the region just upstream of or inside the muon spectrometer volume for multi-particle vertices that originate from the decay of particles with long decay paths. The performance of the algorithm is evaluated using both a sample of simulated Higgs boson events, in which the Higgs boson decays to long-lived neutral particles that in turn decay to $b\bar{b}$ final states, and $pp$ collision data at $\sqrt{s} = 7$ TeV collected with the ATLAS detector at the LHC during 2011.
Standalone vertex finding in the ATLAS muon spectrometer

The ATLAS Collaboration

ABSTRACT: A dedicated reconstruction algorithm to find decay vertices in the ATLAS muon spectrometer is presented. The algorithm searches the region just upstream of or inside the muon spectrometer volume for multi-particle vertices that originate from the decay of particles with long decay paths. The performance of the algorithm is evaluated using both a sample of simulated Higgs boson events, in which the Higgs boson decays to long-lived neutral particles that in turn decay to $b\bar{b}$ final states, and $pp$ collision data at $\sqrt{s} = 7$ TeV collected with the ATLAS detector at the LHC during 2011.
1. Introduction

This paper describes an algorithm for reconstructing vertices originating from decays of long-lived particles to multiple charged and neutral particles in the ATLAS muon spectrometer (MS) [1]. Such long-lived states are predicted to be produced at the LHC by a number of extensions [2–7] of the Standard Model. The hidden valley scenario [6] is used as a benchmark to study and evaluate the performance of the vertex reconstruction of long-lived particles decaying in the MS. Because of its large volume, the ATLAS MS has good acceptance for a broad range of proper lifetimes and it also has good tracking capabilities at the individual chamber level. A design feature of the MS is low multiple scattering of charged particles, which makes it an ideal instrument for multi-track vertex
reconstruction. The vertex-reconstruction technique described in this paper was a key element in a search for a light Higgs boson decaying to long-lived neutral particles [8].

The paper is organized as follows: section 2 describes the muon spectrometer, section 3 discusses the benchmark model and the Monte Carlo (MC) samples, sections 4 and 5 describe the tracking and vertex-finding algorithms and section 6 discusses the performance of the vertex-finding algorithm.

2. Muon spectrometer

ATLAS is a multi-purpose detector [1], consisting of an inner tracking system (ID), electromagnetic and hadronic calorimeters and a muon spectrometer. The ID is inserted inside a superconducting solenoid, which provides a 2 T magnetic field parallel to the beam direction. The electromagnetic and hadronic calorimeters cover the region $|\eta| \leq 4.9$ and have a total combined thickness of 9.7 interaction lengths at $\eta = 0$. The MS, the outermost part of the detector, is designed to measure the momentum of charged particles escaping the calorimeter in the region $|\eta| \leq 2.7$ and provide trigger information for $|\eta| \leq 2.4$. It consists of one barrel and two endcaps, shown in figure 1, that have fast detectors for triggering and precision chambers for track reconstruction. Three stations of resistive plate chambers (RPCs) and thin gap chambers (TGCs) are used for triggering in the barrel and endcap MS, respectively. The precision tracking measurements are provided by monitored drift tube (MDT) chambers throughout the MS and cathode strip chambers (CSCs) in the innermost layer of the endcaps (see figure 1). In the barrel, the precision chambers extend to $|\eta| = 1$ and are arranged in three cylindrical shells, located at radii of $r \sim 5.0$ m, 7.5 m, and 10.0 m, as shown in figure 2. In the endcaps, the precision chambers cover the range $1 \leq |\eta| \leq 2.7$ and are arranged in three wheels with their faces perpendicular to the $z$-axis located at $|z| \sim 7.4$ m, 14.0 m, and 21.5 m. A system of three superconducting toroids (one barrel and two endcap toroids) provides the magnetic field for the MS. The barrel toroid is 25.0 m in length along the $z$-axis, and extends from $r = 4.7$ m to 10.0 m in radius; eight superconducting coils generate the field. The two endcap toroids, each with eight superconducting coils, are inserted in the barrel at each end. They have a length of 5.0 m, an inner bore of 1.65 m and an outer diameter of 10.7 m. The endcap coils are rotated in $\phi$ by 22.5° with respect to the barrel coils. Although the MS uses “air core” toroid magnets to minimize the amount of material traversed by particles, a non-negligible amount of material is present in the form of support structures, magnet coils and muon chambers.

2.1 Monitored drift tubes

In the barrel MS, the MDT chambers are placed around the eight superconducting coils that form the toroid magnet, as shown in figure 2. In the endcaps, MDT chambers are located either upstream or downstream of the endcap toroids; therefore, all the endcap chambers are located outside the magnetic field region. Because the toroidal magnetic field around the $z$-axis bends trajectories

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1ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the $z$-axis coinciding with the beam pipe axis. The $x$-axis points from the IP to the centre of the LHC ring, and the $y$-axis points upward. Cylindrical coordinates ($r, \phi$) are used in the transverse plane, $\phi$ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln \tan(\theta/2)$.
in the $r$–$z$ plane, the MDTs are oriented such that they measure $\eta$ with high precision. The chambers are divided into two types, depending on their position in $\phi$. Those chambers in the barrel (endcaps) that are located in between the magnet coils are referred to as large (small), while those centred on the magnet coil are small (large). The chamber naming scheme uses a three-letter acronym (e.g. BIL, EMS) to specify a chamber type. The first letter (B or E) refers to barrel or endcap chambers, respectively. The second letter specifies the station (inner, middle or outer) and the third letter refers to the sector (large or small).

The MDT chambers consist of two multilayers separated by a distance ranging between 6.5 mm (BIS chambers) and 317 mm (BOS, BOL and BML chambers). Each multilayer consists of three or four layers of drift tubes. The individual drift tubes are 30 mm in diameter and have a length of 2–5 m depending on the location of the chamber inside the spectrometer. Each tube is able to measure the drift radius (corresponding to the distance of closest approach of the charged particle to the central wire) with a resolution of approximately 80 $\mu$m [1]. In each multilayer the charged particle track segment can be reconstructed by finding the line that is tangent to the drift circles. These segments are local measurements of the position and direction of the charged particle. Figure 3 shows a charged particle traversing a BIL chamber.

Because the tubes are 2–5 m in length, the MDT measurement provides only a very coarse $\phi$ position of the track hit. In order to reconstruct the $\phi$ position and direction, the MDT measurements need to be combined with the $\phi$ coordinate measurements from the RPCs (TGCs) in the barrel (endcaps).

2.2 Trigger chambers

The RPCs provide the trigger signals and measure the $\phi$ coordinate for segments in the barrel MS.
Figure 2: Cross-sectional view of the barrel muon spectrometer perpendicular to the beam axis (non-bending plane). The MDT chambers in the small sectors are shown in light blue, the MDT chambers in the large sectors are shown in orange and the RPC chambers in red. The eight coils are also visible.

Figure 3: Portion of a muon spectrometer barrel chamber (BIL) with two four-layer multilayers. The drift circles are shown in dark gray and the charged particle trajectory is shown as the black line. The spacing between the two multilayers is 170 mm.

The chamber planes are located on both sides of the MDT middle stations and one of the two sides of the MDT outer stations. Each chamber has four layers of 3-cm-wide strips, where two layers measure $\eta$ and two layers measure $\phi$, referred to as RPC-eta and RPC-phi planes, respectively. Together, the two planes around the middle stations provide a low transverse momentum ($p_T$) trigger (up to 10 GeV), and the addition of the chambers in the outer stations allows for high-$p_T$ triggers. In the endcaps, the trigger signals and $\phi$ measurements are provided by the TGCs. Each TGC layer
consists of cathode strips that measure $\phi$ and anode wires that measure $\eta$. Measurements from the strips and wires are referred to TGC-phi and TGC-eta measurements, respectively. The strips have a width of 2–3 mrad, as seen from the interaction point (IP), and the wire-to-wire distance is 1.8 mm. The middle stations of MDTs in the endcaps are surrounded by seven layers of TGCs, three layers on the IP side and four layers on the opposite side.

2.3 Trigger system

The trigger system [9] has three levels called Level-1 (L1), Level-2 (L2) and the event filter (EF). The L1 trigger is a hardware-based system using information from the MS trigger chambers, and defines one or more regions-of-interest (RoIs). These are geometrical regions of the detector, identified by $(\eta, \phi)$ coordinates, containing potentially interesting physics objects. The L2 and EF (globally called the high-level trigger, HLT) triggers are software-based systems and can access information from all sub-detectors. A L1 low-$p_T$ muon RoI is generated by requiring a coincidence of hits in at least three of the four planes of the two inner RPC planes for the barrel and of the two outer TGC planes for the endcaps. A high-$p_T$ muon RoI requires additional hits in at least one of the two planes of the outer RPC plane for the barrel and in two of the three planes of the innermost TGC layer for the endcaps. The muon RoIs have a spatial extent in $(\Delta \eta \times \Delta \phi)$ of $0.2 \times 0.2$ in the barrel and $0.1 \times 0.1$ in the endcaps. At the HLT, the L1 RoI information seeds the reconstruction using the precision chamber information, resulting in sharp trigger thresholds up to muon momenta of $p_T = 40$ GeV.

The Muon RoI Cluster trigger [10] is specially designed to select events characterized by a particle decaying to multiple hadrons inside the MS. This trigger is seeded by a L1 multi-muon trigger that requires at least two muon RoIs with $p_T \geq 6$ GeV. At L2, the trigger selects events that have at least three muon RoIs in the barrel clustered in a cone with a radius $\Delta R \equiv \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} = 0.6$. The Muon RoI Cluster trigger is also required to satisfy track- and jet-isolation criteria [10]. In 2011 data taking, this trigger was only active in the barrel ($|\eta| \leq 1$).

3. Monte Carlo samples

3.1 Benchmark model

A hidden valley model with a light Higgs boson communicator [6] is used to evaluate the ATLAS detector response to highly displaced decays. In this model, a Higgs boson is produced via gluon fusion and decays to a pair of long-lived neutral pseudoscalars, $H \rightarrow \pi \pi$. Four different MC simulation samples are used for this study, corresponding to different choices of Higgs boson mass (120 GeV and 140 GeV) and $\pi$ mass (20 GeV and 40 GeV). Because the $\pi$ is a pseudoscalar, it decays predominantly to heavy fermions, $b\bar{b}$, $c\bar{c}$ and $\tau^+\tau^-$ in the ratio 85:5:8, as a result of the helicity suppression of the low-mass fermion–antifermion pairs. The mean proper lifetime of the $\pi$ (expressed throughout this paper as $\tau$ times the speed of light $c$) is a free parameter of the model. In the generated samples, $c\tau$ is chosen so that a sizeable fraction of the decays occur inside the MS. The PYTHIA generator [11] is used to simulate the production and decay of Higgs bosons and the MSTW 2008 leading-order parameterization [12] is used for the parton distribution functions in the
protons. The effect of multiple \( pp \) collisions occurring during the same bunch crossing (pile-up) is simulated by superimposing several minimum bias events on the signal event.\(^2\) The generated events are then processed through the full simulation chain based on GEANT4 [13, 14].

### 3.2 Displaced decays in the MS

For the purposes of triggering on \( \pi_{v} \) decays in the MS and reconstructing vertices, this study defines the “MS fiducial volume” as the region in which \( \pi_{v} \) decays are detectable. This fiducial volume is separated into barrel and endcap regions. The barrel MS fiducial volume is defined as the region with \(|\eta| \leq 1\), extending from approximately the outermost \( \sim 25 \) cm of the hadronic calorimeter to slightly upstream of the middle station of the MS (\( 3.5 \, \text{m} < r < 7.5 \, \text{m} \)). The endcap MS fiducial volume is defined as the region with \( 1 < |\eta| < 2.2 \), extending from just upstream of the inner endcap muon chambers to the outer edge of the endcap toroids (\( 7 \, \text{m} < |z| < 14 \, \text{m} \)). Figure 4 shows the probability for a \( \pi_{v} \) to decay inside the MS fiducial volume as a function of the \( \pi_{v} \) mean proper lifetime (\( c\tau \)). This figure indicates that displaced vertices are detectable over a wide range of mean proper lifetimes.

![Figure 4: The probability for a \( \pi_{v} \) to decay inside the fiducial volume of the muon spectrometer as a function of the \( \pi_{v} \) mean proper lifetime (\( c\tau \)).](image)

A decay of a \( \pi_{v} \) occurring in the MS results in high multiplicity jets of low-\( p_{T} \) particles (see figure 5) produced in a narrow region of the spectrometer. Typically the decay of a \( \pi_{v} \) produces a \( b\overline{b} \) pair that in turn produces approximately ten charged hadrons and five \( \pi^{0} \) mesons. Because of these low-\( p_{T} \) decay products, any decay occurring before the last sampling layer of the hadronic calorimeter would not produce a significant number of tracks in the MS. Thus, detectable decay vertices are located in the region between the end of the hadronic calorimeter and before the middle station of the muon chambers. For decays at the end of the hadronic calorimeter, the charged

\[^2\]The pile-up was simulated such that the distribution of the number of collision vertices in the MC simulation agrees with the 2011 data.
Figure 5: Transverse momentum ($p_T$) distributions for charged particles from $\pi_\nu$ decays, at generator level.

hadrons would traverse, on average, at least two stations (inner and middle); for decays after the inner MDT stations, the charged hadrons would traverse the middle and possibly the outer stations. As a consequence of the photons from the $\pi^0$ decays and the non-negligible amount of material in the MS, large electromagnetic (EM) showers are expected to accompany the charged particle tracks from $\pi_\nu$ decays in signal events. The effects of these EM showers can be seen in figure 6, which shows the total number of (a) MDT and (b) RPC (TGC) hits per event with a single $\pi_\nu$ decay occurring inside the barrel (endcap) MS. As these plots show, the MS has an average of $\sim$1000 hits in both the MDT and trigger systems. The hits are concentrated in a narrow region of the spectrometer, with $\sim$70% of the hits contained in a cone of radius $\Delta R = 0.6$ around the $\pi_\nu$ line-of-flight. The average MDT chamber occupancy is approximately 35% in this cone.

Figure 6: Distribution of the total number of (a) MDT and (b) trigger hits per event with a single $\pi_\nu$ decay occurring in the barrel ($|\eta| \leq 1$) and endcap ($1 < |\eta| < 2.2$) MS. Both plots show the MC mass point $m_H = 140$ GeV, $m_{\pi_\nu} = 20$ GeV. Similar results are found using the other MC samples.
A typical muon or $\pi^{\pm}$ traversing the MS leaves a track with 20–25 MDT hits, while the average number of hits per charged particle in displaced decay events is $\sim 100$. This indicates that on average, an event contains $\sim 75\%$ “noise” hits resulting from the EM showers. These extra hits cause problems for the standard muon-segment-finding routines, which are optimized to find charged tracks in a relatively clean environment. In order to reconstruct vertices in the MS, efficient tracking, especially at low $p_T$, is required; therefore a new reconstruction algorithm, capable of reconstructing low-momentum tracks in busy environments, is needed.

4. Tracklet finding and momentum reconstruction

4.1 Tracklet-finding technique

The spatial separation between the two multilayers inside a single MDT chamber provides a powerful tool for pattern recognition. The specialized tracking algorithm presented here exploits this separation by matching segments from multilayer 1 (ML1) with those from multilayer 2 (ML2). The algorithm starts by reconstructing single-multilayer straight-line segments that contain three or more MDT hits using a minimum $\chi^2$ fit. All segments that have a $\chi^2$ probability greater than 5% are kept.

In order to pair the segments belonging to the same charged particle, segments from ML1 are matched with those from ML2 using two parameters, $\Delta b$ and $\Delta \alpha$, as shown in figure 7(a). The parameter $\Delta b$ is taken to be the minimum of the two possible distances between the point where one segment crosses the middle plane and the line defined by the other segment, as illustrated in figure 7(b). For chambers in the magnetic field, $\Delta b \sim 0$ selects segments that are tangent to the same circle and hence belong to the same charged particle. The second parameter, $\Delta \alpha \equiv \alpha_1 - \alpha_2$, is the angle between the two segments. It can only be used for matching segments in the case of chambers outside the magnetic field region. If the chamber is inside the magnetic field region, $\Delta \alpha$ is the bending angle of the track inside the chamber and can be used to measure the track momentum for low-$p_T$ particles (see section 4.2). In the following, this paired set of single-multilayer segments and corresponding track parameters is referred to as a tracklet. Because of the large number of RPC (TGC) hits in signal events, the RPC-phi (TGC-phi) hits cannot be associated with the MDT barrel (endcap) tracklets. Consequently the tracklets reconstructed using this method do not have a precise $\phi$ coordinate or direction. Therefore, the tracklets are assigned the $\phi$ coordinate of the MDT chamber centre and are assumed to be travelling radially outward.

The intrinsic angular resolution of the single-multilayer MDT segments is derived from a fully simulated MC sample of high-momentum charged particles that produce straight-line segments in the MDT chambers. From this sample, the parameters $\Delta \alpha$ and $\Delta b$ are determined to have RMS values of 4.3 mrad and 1.0 mm, respectively, for segments containing three MDT hits.

The tracklet selection criteria are listed in table 1 for each of the muon chamber types. The variable $\Delta \alpha_{\text{max}}$ refers to the maximum amount of bending that is allowed inside the chamber for the two single-ML segments to be considered matched and corresponds to a minimum tracklet momentum

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3 For the purposes of plotting, the parameter $\Delta b$ is signed according to a local coordinate system with an origin defined as the point where the ML1 segment crosses the middle plane. In all other cases, $\Delta b$ is a positive definite quantity.

4 This sample contains single muons with $p_T = 1$ TeV, distributed evenly in the ranges $-\pi < \phi < \pi$ and $|\eta| < 1$ and is simulated using the full ATLAS simulation chain.
Figure 7: Schematic of a MS barrel chamber with one segment in multilayer (ML) 1 and one in multilayer 2. Shown in (a), the two single-multilayer segments reconstructed in the respective multilayers and (b) a close-up of the middle plane of the chamber. The variable $\alpha_{1(2)}$ is defined as the angle with respect to the $z$-axis of the segment in multilayer 1 (2). The parameter $\Delta \alpha$ is defined as $\Delta \alpha \equiv \alpha_1 - \alpha_2$ and $\Delta b$ is defined to be the distance of closest approach between the pair of segments at the middle plane of the MDT chamber. The middle plane of the chamber is the plane equidistant from multilayers 1 and 2, represented here by the dashed line.

of 0.8 GeV for chambers that are located inside the magnetic field. Tracklets are refit as a single straight-line segment spanning both multilayers if their $|\Delta \alpha|$ is less than 12 mrad.

In the endcaps, and in the BIS and BOS chambers in the barrel MS, the MDT chambers are outside the magnetic field region; therefore, segment pairs from these chambers are combined and refit as a single straight-line segment, containing at least six MDT hits. The combined segments result in a 0.2 mrad angular resolution compared to the 4.3 mrad resolution obtained with the two single-

| Chamber Type | Number of Layers | ML Spacing (mm) | $|\Delta \alpha_{\text{max}}|$ (mrad) | $|\Delta b_{\text{max}}|$ (mm) | Refit |
|--------------|-----------------|-----------------|-----------------|-----------------|-------|
| BIS          | 4               | 6.5             | 12              | 3               | Always |
| BIL          | 4               | 170             | 36              | 3               | if $|\Delta \alpha| < 12$ mrad |
| BMS          | 3               | 170             | 67              | 3               | if $|\Delta \alpha| < 12$ mrad |
| BML          | 3               | 317             | 79              | 3               | if $|\Delta \alpha| < 12$ mrad |
| BOS          | 3               | 317             | 12              | 3               | Always |
| Endcap       | 3               | 170             | 36              | 3               | if $|\Delta \alpha| < 12$ mrad |

Table 1: Relevant chamber parameters and the selection criteria for reconstructing tracklets in each of the MDT chamber types. Tracklets are refit as a single straight-line segment spanning both multilayers if they satisfy the criterion listed in the “Refit” column.
multilayer segments. This improvement in the angular resolution is due to the increased lever arm and additional MDT hits when fitting the segments spanning the two MLs.

### 4.2 Momentum and charge measurements

For segments found in the MS barrel chambers in the magnetic field, the measurement of \( \Delta \alpha \) can be used to calculate the tracklet momentum. The tracklet momentum can be determined using a relation of the form \( p = \frac{k}{|\Delta \alpha|} \), where the parameter \( k \) is derived for each muon chamber type.

From the uncertainty in \( \Delta \alpha \), calculated for each segment pair as \( \sigma_{\Delta \alpha} \equiv \sqrt{(\sigma_{\alpha_1})^2 + (\sigma_{\alpha_2})^2} \), the uncertainty in the momentum measurement can be shown to be \( \sigma_p/p \approx 0.06 \cdot p/\text{GeV} \) in the BML chambers, \( \sigma_p/p \approx 0.08 \cdot p/\text{GeV} \) in the BMS chambers and \( \sigma_p/p \approx 0.13 \cdot p/\text{GeV} \) in the BOL and BIL chambers.

The tracklet charge is obtained from \( q = \text{sign}(\Delta \alpha \cdot \hat{z}) \cdot z \cdot \hat{p}_z \), where \( \Delta \alpha \) is the bending angle, \( z \) is the position of the tracklet and \( \hat{p}_z \) is the direction of the tracklet as measured in ML1. The charge of the particle can be identified with an efficiency greater than 90% for reconstructed tracklets with momentum less than 7 GeV in the BML chambers, 5 GeV in the BMS chambers and 3 GeV in the BOL and BIL chambers.

### 4.3 Application of the tracking algorithm in MC signal events

The performance of the tracklet reconstruction algorithm has been studied using the MC signal events that have a displaced decay occurring inside the fiducial volume of the MS. Figure 8 shows the two-dimensional distribution of \( \Delta b \) versus \( \Delta \alpha \) for tracklets in the barrel and endcap regions. The segment combinations corresponding to real charged particles can be seen in the central region, while the diffuse background comes from the incorrect pairing of segments. This reconstruction method finds an average of nine (eight) tracklets per displaced decay in the barrel (endcaps) fiducial volume. In the barrel MS an average of six tracklets have an associated momentum measurement.

![Figure 8: Distributions of \( \Delta b \) vs \( \Delta \alpha \) from MC signal events for segment combinations (a) in the barrel MS region (\(|\eta| < 1\) and (b) in the endcap region (1 < |\( \eta \) | < 2.7). Both plots are normalized to unit area and show the MC mass point \( m_H = 140 \text{ GeV}, m_{\pi^0} = 20 \text{ GeV} \). Similar results are found using the other MC samples.](image-url)
Figure 9 shows the average number of tracklets with a momentum measurement reconstructed as a function of the displaced decay position, in \( \phi \), for one octant of the barrel MS. The extra material present in the barrel small sectors creates large EM showers that affect the reconstruction algorithm. As a result, near the centre of the small sectors (\( \phi \sim \pm 0.4 \)) there are approximately half as many tracklets reconstructed, on average, compared to a displaced decay occurring near the centre of the large sectors (\( \phi \sim 0 \)). In contrast, decays occurring in the fiducial volume of the endcap MS produce an average of eight tracklets, without momentum measurements, independent of the \( \phi \) coordinate of the decay.

Figure 10(a) shows the distribution of \( \Delta b \) in the barrel MS region for all segment combinations that satisfy the criteria for \( |\Delta \alpha| \) listed in table 1. Figure 10(b) shows the distribution of \( \Delta b \) in the endcap region for all segment combinations that have \( |\Delta \alpha| < 12 \) mrad and have been successfully refit as a single straight-line segment with \( \chi^2 \) probability greater than 5\%. The fraction of fake tracklets reconstructed can be estimated by using the side bands to measure the combinatorial background. The side bands are fit to a straight-line that is extrapolated to the signal region. Taking the ratio of the number of tracklets under the background fit to the total number of tracklets in the signal region gives a fake rate of \( \sim 25\% \) in the barrel and \( \sim 5\% \) in the endcaps. The lower fake rate in the endcap is due to the refit procedure, which selects only those combinations of single-ML segments that can be fit as a single straight-line segment with \( \chi^2 \) probability greater than 5\%.

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**Figure 9:** The average number of tracklets with a charge and momentum measurement reconstructed as a function of the position, in \( \phi \), of the displaced decay, for decays occurring in the barrel MS. All sectors have been projected such that the centre of a large sector corresponds to \( \phi = 0 \) and the centre of a small sector corresponds to \( \phi = \pm \pi/8 \).

### 5. Vertex reconstruction

Most of the MS barrel chambers (\( |\eta| < 1 \)) are immersed in a magnetic field while the endcap chambers (\( 1 < |\eta| < 2.7 \)) are all outside the field region. Thus, all tracklets reconstructed in the endcaps have no associated momentum measurement, while in the barrel, most of the tracklets
reconstructed from two segments have a $\Delta \alpha$ measurement that provides an estimate of the momentum. Due to this difference in tracklet reconstruction, different vertex-reconstruction algorithms are employed in the MS barrel and endcaps. In both cases, the algorithms have been tuned to maximize the vertex-finding efficiency at the expense of vertex-position resolution.

The barrel and endcap vertex-reconstruction algorithms, described in detail in the following sections, proceed as follows:

1. Tracklets are reconstructed in individual chambers.
2. The tracklets from all chambers are grouped into clusters using a cone algorithm.
3. The lines-of-flight in $\eta$ and $\phi$ of the long-lived particle are calculated using the tracklets and RPC-phi (barrel) or TGC-phi (endcaps) hits, respectively.
4. The clustered tracklets are mapped onto a single $r$–$z$ plane as defined by the $\phi$ line-of-flight.
5. The vertex position is reconstructed by back-extrapolating the tracklets; in the barrel the tracklets are extrapolated through the magnetic field, while in the endcaps the tracklets are extrapolated as straight lines.

The barrel and endcap vertex-reconstruction algorithms exclusively use the tracklets reconstructed in the barrel and endcap, respectively. For displaced decays occurring near $|\eta| = 1$, both algorithms can independently reconstruct vertices. In case there are two reconstructed vertices, it is left to the analysis make the final vertex selection.

5.1 Vertex reconstruction in the barrel MS

The barrel vertex-reconstruction algorithm begins by finding the cluster of tracklets to be used in the vertex routine. This is done by using a simple cone algorithm that has a cone of radius

Figure 10: Distributions of $\Delta b$ for segment combinations in (a) the barrel MS region ($|\eta| < 1$) and (b) the endcap MS region ($1 < |\eta| < 2.7$) for MC signal events. Segment combinations are required to satisfy the appropriate $\Delta \alpha$ criterion listed in table 1. In the case of the endcap combinations, they are required to have been successfully refit to a single straight-line with $\chi^2$ probability greater than 5%. Both plots show the MC mass point $m_H = 140$ GeV, $m_{\pi^*} = 20$ GeV. Similar results are found using the other MC samples.
\( \Delta R = 0.6 \) and its apex at the IP. Then the line-of-flight of the decaying particle in the \( \theta \) direction is reconstructed by drawing a line between the IP and the centroid of all tracklets in the cluster. Figure 11(a) shows the difference between the reconstructed and true \( \pi_v \) line-of-flight in \( \theta \). This method is able to reconstruct the \( \theta \) line-of-flight with an RMS of 21 mrad. The line-of-flight in the \( \phi \) direction is computed in two steps. First an approximate \( \phi \) line-of-flight is computed by using the \( \phi \) coordinate of each tracklet in the cluster to calculate an average \( \phi \). Then, using this \( \phi \) value and the \( \theta \) of the \( \pi_v \) line-of-flight, a cone of radius \( \Delta R = 0.6 \) with its apex at the IP is constructed and the average of all RPC-phi measurements within this cone is used to determine the \( \phi \) line-of-flight. Figure 11(b) shows the difference between the reconstructed and true line-of-flight in \( \phi \). This method is able to reconstruct the \( \phi \) line-of-flight with a RMS of 50 mrad, which corresponds to \( \sim 1/8 \) of a large MDT chamber.

Due to the lack of precise \( \phi \) information for the tracklets and to the inhomogeneous magnetic field \([1]\) in the MS, it is necessary to perform the vertex reconstruction in a single \( r-z \) plane. Therefore, the clustered tracklets are all mapped onto the \( r-z \) plane in which the reconstructed line-of-flight lies. The tracklets are then back-extrapolated, using the full magnetic field map, in this \( r-z \) plane to a series of lines parallel to the \( z \)-axis that are equally spaced along the line-of-flight. The distance, along the line-of-flight, between two adjacent lines is 25 cm and the lines cover the range from \( r = 3.5 \) m to \( r = 7.0 \) m. This results in 15 lines of constant radius for a line-of-flight at \( \eta = 0 \) and 22 lines at \( |\eta| = 1 \). Increasing the number of lines in this manner ensures that the vertex routine treats the entire \( |\eta| \) range uniformly, by extrapolating each tracklet a constant distance along the line-of-flight. Figure 12 illustrates how these lines of constant radius in the spectrometer are used to back-extrapolate the tracklets and to reconstruct the vertex.

The uncertainty arising from the lack of precise \( \phi \) information for each tracklet and hence lack of precise knowledge of the magnetic field, is evaluated by rotating the \( r-z \) plane by 200 mrad around

\[ \text{Figure 11: Distributions of the flight direction residuals in the (a) } \theta \text{ and (b) } \phi \text{ directions. Both plots show the MC mass point } m_H = 140 \text{ GeV, } m_{\pi_v} = 20 \text{ GeV. Similar results are found using the other MC samples.} \]

5The cone algorithm uses the position of each tracklet as a seed, and the cone containing the most tracklets is chosen as the optimal centre.

6For each tracklet the \( \phi \) coordinate is approximated using the centre of the associated MDT chamber, see section 4.1.
the $z$-axis\textsuperscript{7} and again extrapolating the tracklets to the lines of constant radius. The difference in the $z$ position of the rotated and nominal tracklet is calculated at each line, and taken to be the uncertainty associated with the imprecise knowledge of the magnetic field. This uncertainty is added, in quadrature, to the position uncertainty arising from the uncertainty in the measured momentum of the tracklet. For tracklets that do not have a momentum measurement, the only source of uncertainty arises from the uncertainty in the tracklet direction, $\alpha$. Only those tracklets with a total uncertainty $\sigma < 20$ cm are used by the vertex-finding algorithm.

At each line of constant radius, the average $z$ position of the tracklets is computed by weighting the extrapolated tracklet position by $1/\sigma^2$. The $\chi^2$ of this candidate vertex (whose $z$ coordinate is assumed to be the average $z$ position) is computed, assuming that the tracklets originate from the vertex point. If the $\chi^2$ probability for the vertex point is less than 5%, the tracklet with the largest contribution to the total vertex $\chi^2$ is dropped and the vertex point is recomputed. This is done iteratively, until there is either an acceptable vertex, with $\chi^2$ probability greater than 5%, or there are fewer than three tracklets left to compute the vertex point.

The reconstructed vertex position is taken to be the radius and the $z$ position on the line that had the largest number of tracklets used to create the candidate vertex point. If there are two (or more) lines of constant radius with the same number of tracklets, the line with the minimum $\chi^2$ is selected as the reconstructed vertex position. The difference in position between the reconstructed and true decay vertex are shown in figure 13.

Figure 12: Diagram illustrating the reconstruction technique employed in the barrel muon spectrometer. The display shows the simulated decay of a $\pi_v$ from the MC mass point $m_H = 140$ GeV, $m_{\pi_v} = 20$ GeV.

5.2 Vertex reconstruction in the endcap MS

Tracklets reconstructed in the endcap region ($1 < |\eta| < 2.7$) have no momentum or charge mea-

\textsuperscript{7}Each large MDT chamber is $\sim 400$ mrad wide, thus the rotation of 200 mrad corresponds to the maximum variation of position from the centre of the chamber.
Figure 13: Distributions of the vertex-reconstruction residuals in the (a) $z$ coordinate and (b) $r$ coordinate for decays in the barrel MS. Both plots show the MC mass point $m_H = 140$ GeV, $m_{\pi_L} = 20$ GeV. Similar results are found using the other MC samples.

measurements; thus a different approach to vertex finding is required. As discussed in section 3.2, detectable decays occur just upstream of or inside the endcap toroid. As a consequence, measurements of the charged particles’ trajectories are made after they have been bent by the magnetic field. This implies that the tracklets will need to be back-extrapolated as straight lines into the endcap toroid. Therefore, in the endcap MS, a simple linear extrapolation and minimization routine is used to reconstruct the decay vertices. The routine starts by grouping the tracklets that are clustered in $(\eta, \phi)$, using the same cone algorithm that is employed in the barrel vertex-reconstruction routine. The lines-of-flight in $\theta$ and $\phi$ are calculated as in the barrel, except the TGC-phi measurements are used instead of the RPC-phi measurements. The resolution in the lines-of-flight in both $\theta$ and $\phi$ is comparable to the resolution achieved in the barrel using the simulated signal samples. The clustered tracklets provide constraining equations of the form $\beta_i = -r \tan \alpha_i + z$, where $\beta_i$ is the $z$-intercept and $\alpha_i$ the angle of the $i$-th tracklet, which are used in a least squares regression fit of the vertex. The vertex position is then iterated, dropping the tracklet that is farthest from the vertex until the distance of closest approach between the farthest tracklet and the vertex is less than 30 cm. The vertex position is accepted if it is reconstructed using at least three tracklets, is within the endcap MS fiducial volume, and is upstream of the middle station ($|z| = 14$ m). Figure 14 shows the position of the reconstructed vertices with respect to the true decay point. The magnetic field in the endcap toroid bends the charged tracks while preserving the line-of-flight of the neutral long-lived particle. Because the tracklets are measured after the magnetic field and extrapolated back into the magnetic field region as straight lines, the vertex position is systematically shifted to larger values of $|z_{\text{reco}}|$ with respect to the true decay position. Due to the line-of-flight being preserved by the magnetic field, the reconstructed vertices are also shifted to larger values of $r_{\text{reco}}$. This effect lessens as the decay occurs closer to the outer edge of the endcap toroid ($|z| \sim 12.5$ m) and the charged particles experience less bending making the straight-line extrapolation used in the vertex reconstruction a better approximation. Figure 15 illustrates this reconstruction technique and the systematic shifts in both $r_{\text{reco}}$ and $|z_{\text{reco}}|$. 

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Figure 14: Distributions of the vertex-reconstruction residuals in the (a) $z$ coordinate and (b) $r$ coordinate for decays in the endcap MS for different ranges of $z_{\pi}$. Both plots show the MC mass point $m_H = 140$ GeV, $m_{\pi} = 20$ GeV. Similar results are found using the other MC samples.

Figure 15: Diagram illustrating the reconstruction technique employed in the endcap muon spectrometer. The display shows the simulated decay of a $\pi_{\nu}$ from the MC mass point $m_H = 140$ GeV, $m_{\pi} = 20$ GeV.

6. Performance

The performance of the vertex-reconstruction algorithms has been evaluated on both data and MC simulation. Data events corresponding to 1.94 fb$^{-1}$ collected in 2011 at $\sqrt{s} = 7$ TeV were analysed. The events in both data and MC simulation were required to pass the Muon RoI Cluster trigger. Additionally, the data events were required to have been collected during a period when all detector elements were operational.

6.1 Good vertex selection

Events with vertices that originate from detector noise, cosmic ray showers or punch-through...
hadronic jets\textsuperscript{8} can be rejected by imposing a series of selection criteria. Vertices found in the barrel MS are required to be consistent with the decay of a long-lived particle that originates at the IP. Therefore the sum of the $p_z$ of all tracklets used in the vertex fit is required to point away from the IP.\textsuperscript{9} Because the MS tracklets in the endcaps do not have an associated momentum measurement, it is not possible to extrapolate them through the endcap toroids. Therefore, the pointing requirement is only applied to vertices reconstructed in the barrel MS. The vertex is required to be in a region with high activity in the MDT and trigger chambers. To remove events with coherent noise in the MDTs, the vertex is required to be in a region of the detector with fewer than 3000 MDT hits and be reconstructed with tracklets from at least two different muon stations. Additionally, vertices can be required to be isolated from ID tracks and/or hadronic jets to reduce backgrounds and punch-through contamination. These isolation criteria are analysis dependent and therefore beyond the scope of this paper.

In order for a vertex to be considered good, the following criteria must be satisfied:

- **Tracklets**: The vertex must contain tracklets reconstructed from at least two different muon stations (i.e. inner + middle, middle + outer, inner + outer or small sector + large sector).

- **Vertex Pointing (barrel MS only)**: The sum of the momenta of all tracklets used in the vertex fit is required to point away from the IP ($\sum_{\text{tracklets}} p_z^{\text{tracklet}} \cdot z^{\text{vertex}} > 0$).

- **$N_{\text{MDT}}$**: The number of MDT hits contained in a cone of $\Delta R = 0.6$ around the vertex is required to be in the range $200 < N_{\text{MDT}} < 3000$.

- **$N_{\text{RPC(TGC)}}$**: The number of RPC-eta (TGC-eta) hits contained in a cone of $\Delta R = 0.6$ is required to be $N_{\text{RPC(TGC)}} > 100$ for vertices reconstructed in the barrel (endcap) MS.

Figure 16 shows distributions of the position of the good vertices in the ATLAS coordinate system for MC simulation. The depletion of vertices near $\eta = 0$ is due to the limited coverage of the RPC trigger chambers in this region and hence limited coverage of the Muon RoI Cluster trigger. Figure 16(b) shows that in the barrel MS the algorithm has a much lower efficiency near the magnet coils ($\phi \sim \pm (2n + 1) \pi/4$). Decays occurring in the region near the coils produce a larger number of noise hits, due to the large amount of material present in the magnet coil, which lowers the tracklet reconstruction efficiency (see figure 9). The effects of the reduced MDT coverage and the extra material present in the region of the feet supporting the detector is visible as a relative decrease in the number of reconstructed vertices in the region between $\phi = -1$ and $\phi = -2$.

The tracklets reconstructed in the BIS and BOS chambers, which are located near the magnet coils, do not have a momentum measurement, and these tracklets are extrapolated through the magnetic field as straight lines. Therefore BIS and BOS tracklets may have a large uncertainty in their extrapolation and are often rejected by the $\chi^2$ test described in section 5.1.

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\textsuperscript{8}A punch-through hadronic jet occurs when particles from a hadronic jet escape the calorimeter volume.

\textsuperscript{9}The pointing requirement is only applied to vertices in the region $|\eta| > 0.3$ to avoid inefficiencies due to the momentum resolution of the tracklets in the region where the sum of $p_z$ is expected to be $\sim 0$. 

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Figure 16: Distribution of the (a) \( \eta \) and (b) \( \phi \) positions of the good vertices in the barrel muon spectrometer for the Monte Carlo signal samples. Both plots show the MC mass point \( m_H = 140 \text{ GeV}, \) \( m_{\pi_v} = 20 \text{ GeV} \). Similar results are found using the other MC samples.

### 6.2 Vertex reconstruction efficiency

The efficiency for vertex reconstruction is defined as the fraction of simulated \( \pi_v \) decays occurring in the MS fiducial volume that have a reconstructed vertex satisfying all of the criteria described in section 6.1. Figure 17(a) shows the efficiency to reconstruct a vertex in the barrel MS for \( \pi_v \) decays that satisfy the Muon RoI Cluster trigger requirements and figure 17(b) the efficiency for those \( \pi_v \) decays that do not satisfy the trigger. When a \( \pi_v \) satisfies the trigger requirements, the vertex-reconstruction efficiency varies from \( \sim 50\% \) near the calorimeter face \( (r \sim 4 \text{ m}) \) to \( \sim 30\% \) for decays occurring close to the middle station \( (r \sim 7 \text{ m}) \). The efficiency decreases as the decay occurs closer to the middle station because the charged hadrons and photons (and their corresponding EM showers) have not spatially separated and are overlapping when they traverse the middle station. This reduces the reconstruction efficiency for tracklet reconstruction and consequently for vertex reconstruction. Those \( \pi_v \) that do not satisfy the Muon RoI Cluster trigger requirements have a lower reconstruction efficiency because these decays tend to have all of their decay products entering a single sector. Therefore the tracks and EM showers are often overlapping and the tracklet reconstruction efficiency is lower, which in turn reduces the vertex reconstruction efficiency. The efficiency for reconstructing vertices in the endcaps as a function of \(|z|\), shown in figure 18, is roughly constant from 7 m to 14 m and varies between 45\% and 60\% depending on the signal model parameters.

### 6.3 Performance on 2011 collision data

In 2011, the Muon RoI Cluster trigger was only active in the barrel MS region; therefore, no events with a vertex in the endcaps are found using this selection. The position of the vertices found in \( \eta \) and \( \phi \), after applying the criteria for a good vertex, are shown in figure 19 for those vertices reconstructed in 1.94 fb\(^{-1}\) of 2011 data. The vertices found in data show similar features in \( \eta \) and \( \phi \) as in the simulation (figure 16).

The position in \((r,z)\) of the good vertices reconstructed in data is shown in figure 20. The vertices tend to group around \(|z| \sim 4 \text{ m}\) and \(r \sim 4 \text{ m}\), near the gap region between the barrel and extended...
Figure 17: Efficiency for reconstructing a vertex for πν decays in the barrel muon spectrometer as a function of the radial decay position of the πν for (a) πν decays that satisfy the Muon RoI Cluster trigger and (b) πν decays that do not satisfy the Muon RoI Cluster trigger.

Figure 18: Efficiency for reconstructing a vertex for πν decaying in the endcap MS as a function of the absolute z position of the πν decay.

barrel calorimeters where particles can escape the calorimeter volume. The few events with a vertex in the endcap MS are due to events with activity in both the barrel and endcap MS. The activity in the barrel MS satisfies the Muon RoI Cluster trigger, while the activity in the endcaps produces the reconstructed vertex.

6.4 Data–Monte Carlo simulation comparison

To verify the performance of the MC simulation, collision data need to be compared with the MC simulation. This data–MC simulation comparison is analysis dependent and needs to be done in any analysis that makes use of this reconstruction algorithm. The systematic uncertainty associated with the vertex reconstruction algorithm will, in general, depend upon the event selection and vertex criteria employed in the analysis. A 2011 analysis searching for pair production of particles...
Figure 19: Distribution of the (a) $\eta$ and (b) $\phi$ position of the good vertices reconstructed in the data events that pass the Muon RoI Cluster trigger. The statistical uncertainty on the data points is represented by the yellow bands. The effect of extra material present in the feet is visible as a relative decrease in the number of vertices reconstructed in the region between $\phi = -1$ and $\phi = -2$.

Figure 20: Distribution of the position, in $(r,z)$, of all good vertices in the fiducial volume of the muon spectrometer in events that passed the barrel Muon RoI Cluster trigger from 1.94 fb$^{-1}$ of 7 TeV pp collision data.

decaying in the MS [8] performed a study comparing the response of the MS to punch-through jets in data and MC simulation. The punch-through events are similar to the signal events as they both contain low-energy photons and charged hadrons in a narrow region of the MS. The candidate punch-through jets were selected from a sample of events that passed a single-jet trigger. In addition, the punch-through jet was required to be in the barrel region of the calorimeter ($|\eta| < 1.5$), satisfy $p_T^{\text{jet}} > 20$ GeV and contain a minimum of 300 MDT hits in a cone of $\Delta R = 0.6$, centred around the jet axis. To verify that the jet was produced in the collision and not related to machine noise or cosmic rays, the jet was required to contain at least four tracks with $p_T > 1$ GeV in the ID. The analysis then compared the fraction of punch-through jets that produced a vertex in the barrel
MS as a function of the number of MDT hits in a cone of $\Delta R = 0.6$ centred around the jet axis. Figure 21 shows the ratio of data to Monte Carlo simulation for the fraction of punch-through jets that have a good vertex. The ratio, within uncertainty, is constant for all numbers of MDT hits in the jet cone. A straight line fit to these data points yields a constant of $1.01 \pm 0.15$. Therefore, the MC modelling is shown to reproduce data to within 15% and is independent of the number of MDT hits in the jet cone. This comparison was performed only in the barrel region, where there was trigger coverage during the 2011 data-taking period.

![Figure 21: The scale factor calculated by dividing the fraction of punch-through jets in data that have a good MS barrel vertex by the fraction in Monte Carlo simulation. The scale factor is calculated as a function of the number of MDT hits inside a cone of size $\Delta R = 0.6$, centred around the jet axis.](image)

7. Conclusions

In this paper a new algorithm to reconstruct multi-particle vertices inside the ATLAS muon spectrometer has been presented. This algorithm is able to reconstruct vertices with good efficiency in high-occupancy environments due to electromagnetic showers from $\pi^0$ decays. It can be used in searches for long-lived particles that decay to several charged and neutral particles in the muon spectrometer. The algorithm has been evaluated on a sample of simulated Higgs boson events in which the Higgs boson decays to long-lived neutral particles that in turn decay to $b\bar{b}$ final states. Using this benchmark model, the algorithm is found to have an efficiency of $\sim 30$–50% in the barrel muon spectrometer and $\sim 45$–60% in the endcap muon spectrometer. The performance of the algorithm is also evaluated on 1.94 fb$^{-1}$ of $pp$ collision data at $\sqrt{s} = 7$ TeV collected in ATLAS during the 2011 data-taking period at the LHC. A comparison between punch-through jets in data and Monte Carlo simulation shows that the algorithm is performing with good efficiency even in cases of high-chamber occupancy due to electromagnetic showers from $\pi^0$ decays.
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References


1 School of Chemistry and Physics, University of Adelaide, Adelaide, Australia
2 Physics Department, SUNY Albany, Albany NY, United States of America
3 Department of Physics, University of Alberta, Edmonton AB, Canada
4 (a) Department of Physics, Ankara University, Ankara; (b) Department of Physics, Gazi University, Ankara; (c) Division of Physics, TOBB University of Economics and Technology, Ankara; (d) Turkish Atomic Energy Authority, Ankara, Turkey
5 LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France
6 High Energy Physics Division, Argonne National Laboratory, Argonne IL, United States of America
7 Department of Physics, University of Arizona, Tucson AZ, United States of America
8 Department of Physics, The University of Texas at Arlington, Arlington TX, United States of America
9 Physics Department, University of Athens, Athens, Greece
10 Physics Department, National Technical University of Athens, Zografou, Greece
11 Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
12 Institut de Física d’Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain
13 (a) Institute of Physics, University of Belgrade, Belgrade; (b) Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
14 Department for Physics and Technology, University of Bergen, Bergen, Norway
15 Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States of America
16 Department of Physics, Humboldt University, Berlin, Germany
17 Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
18 School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
19 (a) Department of Physics, Bogazici University, Istanbul; (b) Department of Physics, Dogus University, Istanbul; (c) Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
20 (a) INFN Sezione di Bologna; (b) Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
21 Physikalisches Institut, University of Bonn, Bonn, Germany
22 Department of Physics, Boston University, Boston MA, United States of America
23 Department of Physics, Brandeis University, Waltham MA, United States of America
24 (a) Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; (b) Federal University of Juiz de Fora (UFJF), Juiz de Fora; (c) Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; (d) Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
25 Physics Department, Brookhaven National Laboratory, Upton NY, United States of America
26 (a) National Institute of Physics and Nuclear Engineering, Bucharest; (b) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca; (c) University Politehnica Bucharest, Bucharest; (d) West University in Timisoara, Timisoara, Romania
27 Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
28 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
29 Department of Physics, Carleton University, Ottawa ON, Canada
30 CERN, Geneva, Switzerland
31 Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America
32 (a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; (b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
33 (a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Department of Modern Physics, University of Science and Technology of China, Anhui; (c) Department of Physics, Nanjing University, Jiangsu; (d) School of Physics, Shandong University, Shandong; (e) Physics Department, Shanghai Jiao Tong University, Shanghai, China
34 Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
35 Nevis Laboratory, Columbia University, Irvington NY, United States of America
36 Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
37 (a) INFN Gruppo Collegato di Cosenza; (b) Dipartimento di Fisica, Università della Calabria, Rende, Italy
38 (a) AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; (b) Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
39 The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
40 Physics Department, Southern Methodist University, Dallas TX, United States of America
41 Physics Department, University of Texas at Dallas, Richardson TX, United States of America
42 DESY, Hamburg and Zeuthen, Germany
43 Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
44 Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
45 Department of Physics, Duke University, Durham NC, United States of America
46 SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
47 INFN Laboratori Nazionali di Frascati, Frascati, Italy
48 Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
49 Section de Physique, Université de Genève, Geneva, Switzerland
50 (a) INFN Sezione di Genova; (b) Dipartimento di Fisica, Università di Genova, Genova, Italy
51 (a) E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi; (b) High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
52 Il Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
53 SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
54 Il Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
55 Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France
56 Department of Physics, Hampton University, Hampton VA, United States of America
57 Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America
National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
Department of Physics, Massachusetts Institute of Technology, Cambridge MA, United States of America
Group of Particle Physics, University of Montreal, Montreal QC, Canada
P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
Nagasaki Institute of Applied Science, Nagasaki, Japan
Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
INFN Sezione di Napoli; Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy
Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America
Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
INFN National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
Department of Physics, Northern Illinois University, DeKalb IL, United States of America
Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
Department of Physics, New York University, New York NY, United States of America
Ohio State University, Columbus OH, United States of America
Faculty of Science, Okayama University, Okayama, Japan
Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, OK, United States of America
Department of Physics, Oklahoma State University, Stillwater OK, United States of America
Palacký University, RCPTM, Olomouc, Czech Republic
Center for High Energy Physics, University of Oregon, Eugene OR, United States of America
LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
Graduate School of Science, Osaka University, Osaka, Japan
Department of Physics, University of Oslo, Oslo, Norway
Department of Physics, Oxford University, Oxford, United Kingdom
INFN Sezione di Pavia; Dipartimento di Fisica, Università di Pavia, Pavia, Italy
Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America
Petersburg Nuclear Physics Institute, Gatchina, Russia
INFN Sezione di Pisa; Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa, Portugal;
Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain
Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
Czech Technical University in Prague, Praha, Czech Republic
Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
State Research Center Institute for High Energy Physics, Protvino, Russia
Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
Physics Department, University of Regina, Regina SK, Canada
Ritsumeikan University, Kusatsu, Shiga, Japan

INFN Sezione di Roma I; Dipartimento di Fisica, Università La Sapienza, Roma, Italy
INFN Sezione di Roma Tor Vergata; Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
INFN Sezione di Roma Tre; Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy

Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca;
Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat;
Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech;
Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda;
Faculté des sciences, Université Mohammed V-Agdal, Rabat, Morocco

DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay
(Commissariat à l’Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France
Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America

Department of Physics, University of Washington, Seattle WA, United States of America
Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
Department of Physics, Shinshu University, Nagano, Japan
Fachbereich Physik, Universität Siegen, Siegen, Germany
Department of Physics, Simon Fraser University, Burnaby BC, Canada
SLAC National Accelerator Laboratory, Stanford CA, United States of America
Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava;
Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic

Department of Physics, University of Cape Town, Cape Town;
Department of Physics, University of Johannesburg, Johannesburg;
School of Physics, University of the Witwatersrand, Johannesburg, South Africa

Department of Physics, Stockholm University; The Oskar Klein Centre, Stockholm, Sweden
Physics Department, Royal Institute of Technology, Stockholm, Sweden
Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States of America
Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
School of Physics, University of Sydney, Sydney, Australia
Institute of Physics, Academia Sinica, Taipei, Taiwan
Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
Department of Physics, University of Toronto, Toronto ON, Canada
TRIUMF, Vancouver BC; Department of Physics and Astronomy, York University, Toronto ON, Canada
Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
Department of Physics and Astronomy, Tufts University, Medford MA, United States of America
Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America
(a) INFN Gruppo Collegato di Udine; (b) ICTP, Trieste; (c) Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
Department of Physics, University of Illinois, Urbana IL, United States of America
Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain
Department of Physics, University of British Columbia, Vancouver BC, Canada
Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
Department of Physics, University of Warwick, Coventry, United Kingdom
Waseda University, Tokyo, Japan
Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
Department of Physics, University of Wisconsin, Madison WI, United States of America
Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
Department of Physics, Yale University, New Haven CT, United States of America
Yerevan Physics Institute, Yerevan, Armenia
Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France
—Also at Department of Physics, King’s College London, London, United Kingdom
—Also at Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa, Portugal
—Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
—Also at Faculdade de Ciencias and CFNUL, Universidade de Lisboa, Lisboa, Portugal
—Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
f Also at TRIUMF, Vancouver BC, Canada

g Also at Department of Physics, California State University, Fresno CA, United States of America

h Also at Novosibirsk State University, Novosibirsk, Russia

i Also at Department of Physics, University of Coimbra, Coimbra, Portugal

j Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France

k Also at Università di Napoli Parthenope, Napoli, Italy

l Also at Institute of Particle Physics (IPP), Canada

m Also at Department of Physics, Middle East Technical University, Ankara, Turkey

n Also at Louisiana Tech University, Ruston LA, United States of America

o Also at Dep Fisica and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal

p Also at Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America

q Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece

r Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain

s Also at Department of Physics, University of Cape Town, Cape Town, South Africa

t Also at CERN, Geneva, Switzerland

u Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan

v Also at Manhattan College, New York NY, United States of America

w Also at Institute of Physics, Academia Sinica, Taipei, Taiwan

x Also at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China

y Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan

z Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France

aa Also at School of Physical Sciences, National Institute of Science Education and Research, Bhubaneswar, India

abb Also at Dipartimento di Fisica, Università La Sapienza, Roma, Italy

ac Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia

ad Also at Section de Physique, Université de Genève, Geneva, Switzerland

ae Also at Departamento de Fisica, Universidade de Minho, Braga, Portugal

af Also at Department of Physics, The University of Texas at Austin, Austin TX, United States of America

ag Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary

ah Also at DESY, Hamburg and Zeuthen, Germany

ai Also at International School for Advanced Studies (SISSA), Trieste, Italy

aj Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, United States of America

ak Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia

al Also at Physics Department, Brookhaven National Laboratory, Upton NY, United States of America

am Also at Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
Also at Department of Physics, Oxford University, Oxford, United Kingdom
Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany
Also at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat à l’Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France
Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa
Deceased