



University of
Zurich^{UZH}

New Approach for a Circle Hough Transform to Detect Cherenkov Rings in the LHC*b* RICH detector

Master thesis
of
Philipp Gloor

Mathematisch-naturwissenschaftliche Fakultät
der
Universität Zürich

Prof. Dr. P. Saha
Prof. Dr. U. Straumann
Dr. O. Steinkamp

Zürich 2016

Abstract

This thesis explores possible algorithms for the detection of rings of Cherenkov photons which are produced by particles travelling through a RICH detector in the LHC*b* experiment. These rings can be detected with the help of a Hough transform. After a brief introduction to LHC*b* and the RICH detector, this thesis gives a short introduction to the linear Hough transform (which detects straight lines) to give a rough idea about what a Hough transform can do. This is followed a brief look at the circle Hough transform (which detects circles). This part is split in 3 sections, discussing 1D, 2D and 3D Hough transforms. The 1D Hough transform can be used when the center of the circle is given and only its radius needs to be found. The 2D Hough transform looks for the position of circle centers ((x, y) coordinate) for a given radius. The 3D Hough transform is used when neither center nor radius of the ring are known. This is the case for the data from LHC*b* where there are data points (photons from several Cherenkov rings and noise hits) and the algorithm has to find all the rings.

Apart from the standard Hough transform with a 3D accumulator space this thesis develops a new approach for a Hough transform. This approach works on the basis that each circle is defined by 3 points. Given 3 points one can calculate the circumcenter (the center of the circle we are interested in) and the radius of the circumcircle.

For the development of these algorithms python was used in combination with different modules such as `numpy`, `scipy`, `matplotlib`. The source code for this thesis can be found on github.com [1].

Contents

Abstract	2
1 Introduction	9
1.1 LHC - Large Hadron Collider	9
1.2 The LHC <i>b</i> experiment	10
1.2.1 Particle identification	12
2 Theory	13
2.1 Cherenkov radiation	13
2.2 RICH detector	14
2.3 Hough transform	15
2.3.1 Linear Hough transform	16
2.3.2 Circle Hough transform	18
2.4 Datasets	18
2.5 Existing algorithm	19
3 Methods	21
3.1 Conventional Hough transforms	21
3.1.1 1D: Known center - find radius	21
3.1.2 2D: Known radius - find center	23
3.1.3 3D: All parameters unknown	27
3.2 Combinatorial triplet Hough transform	29
3.2.1 Generating the triplets	29
3.2.2 Calculating the Circle given 3 points	30
3.2.3 Ring finding	31
3.2.4 Removing duplicates	32
3.2.5 Combinatorics	35
3.2.6 Possible optimisation: average radius of random circles in a unit square	39
4 Results	42
4.1 1D Hough transform results	42
4.2 2D Hough transform	47
4.2.1 1 ring, 600 background hits	47
4.2.2 2 circles, 0 background hits	47
4.2.3 5 rings, 30 background hits	49
4.2.4 6 circles, 200 background hits	49
4.3 3D Hough transform Results	53
4.3.1 3D: Overview of the results	53

4.4	Combinatorial triplet Hough transform	56
4.4.1	Ring finding threshold	56
4.4.2	Cuts for removing duplicates	56
4.4.3	Comparing algorithm with the data	57
4.4.4	Excecution time	61
5	Conclusions	62
5.1	Outlook	63

List of Tables

2.1	Comparison of photoelectron yields (N_{pe})	18
4.1	1D Radius scores for the different events	44
4.2	2D Radius scores for the different events	47
4.3	Circle scores for 1 ring 600 background hits	53
4.4	3D Hough transform scores	55
4.5	Efficiencies for different thresholds	56
4.6	Efficiency and ghost rate for a fixed radius cut (0.003) and ring finding threshold (120) with varying center cut. The tighter the center cut is the more duplicate circles remain after the clean up.	58
4.7	Reducing ghost rate for a fixed center cut (0.003) with varying center cut. The tighter the center cut is the more duplicate circles fail being detected by the removeDuplicate code shown above	58
4.8	Results for all the cut combinations for radius and center cuts	58

List of Figures

1.1	The LHC ring with its four large experiments: ATLAS, CMS, ALICE and LHCb	9
1.2	LHCb detector	10
2.1	The geometry of the Cherenkov radiation	13
2.2	Cherenkov angle vs momentum for the different particles in different radiators	14
2.3	RICH-1 detector [9]	15
2.4	r - θ parametrisation	16
2.5	Example of a linear HT space	17
2.6	Example of a linear HT where points do not lie on a line	17
2.7	Number of points per circle (N_{pe}) for the 10'000 simulated events in the test data sample	19
2.8	Number of circles per event in the test data sample	19
2.9	Distribution of ring radiuses in the test data sample	20
3.1	Normal Distribution: Used as a weight function	22
3.2	Graph visualisation of a 1D radius histogram	23
3.3	2D weight matrix, first iteration	26
3.4	The circumradius (R) and the circumcenter (P) of a circle defined by three points (A, B, C).	30
3.5	The result of the combinatorial triplet Hough transform before cleaning up duplicates. The blue and purple circles are basically the same ring.	34
3.6	Histogram of duplicates	35
3.7	Complexity of the combinatorial triplet Hough transform	36
3.8	Number of combinations with $\binom{N}{3}$ compared to the number of combinations generated from $\binom{N/2}{3}$	37
3.9	The probability when splitting randomly a list of N points into two that one of the two sublists contains more than 10 points.	38
3.10	Radius distribution for background	41
4.1	These are the test events as generated by the simulation.	43
4.2	Circles found by the 1D Hough transform.	44
4.3	1D Radius scores for two events	45
4.4	Radius scores for the 1D Hough transform for the 5 rings with 0 background.	46
4.5	Circles found by the 2D Hough transform.	48
4.6	The rings generated by the simulation (left) and the rings found by the algorithm (right). The blue colored circle found by the algorithm is incorrect.	48
4.7	Center score for the 2D Hough transform for 2 rings with 0 background.	49
4.8	Two slices out of the 2D histogram	49

4.9	Scores in the (c_x, c_y) plane found by the 2D Hough transform for the event with 5 rings and 30 background hits.	50
4.10	Center scores for 6 circles with 200 background hits.	52
4.11	On the left side the wrong result obtained by the 2D Hough transform and the correct one on the right side	52
4.12	Circles found by the 3D Hough transform	54
4.13	Reversed cumulative distribution of the points per circle. The plot shows the ratio of circles with more than N points over the total number of circles	57
4.14	Runtimes of four different runs	61

List of Codesnippets

3.1	Pseudo Code 1D HT	22
3.2	Pseudo code 2D HT	24
3.3	Removing data points that lie on a ring	24
3.4	3D broadcasting	27
3.5	Calculation of weights and threshold check for 3D HT	28
3.6	Remove used points	28
3.7	Radius extraction algorithm	32
3.8	Center coordinate extraction	33
3.9	Pseudo code for removing possible duplicates	36

1 Introduction

1.1 LHC - Large Hadron Collider

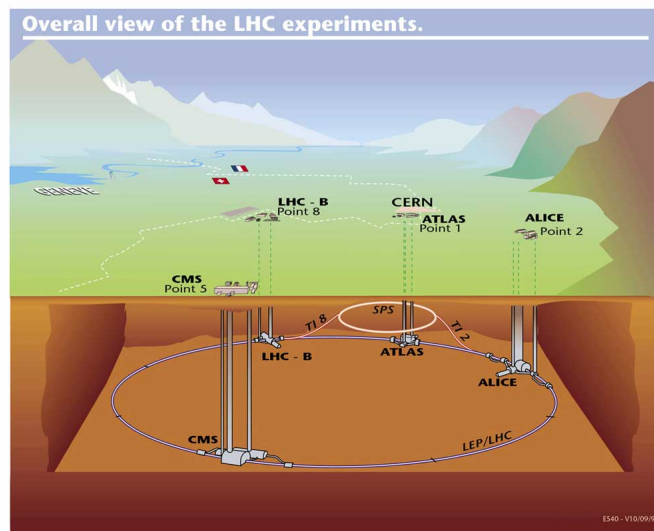


FIG. 1.1 – The LHC ring with its four large experiments: ATLAS, CMS, ALICE and LHC*b*

The Large Hadron Collider (LHC) is the largest and highest-energy particle accelerator in the world colliding protons on protons at beam energies of up to 6.5 TeV and lead ions at beam energies up to 5.5 GeV/nucleon. It was built by the European Organisation for Nuclear Research (CERN) from 1998 to 2008. It aims to test the predictions of different theories in high-energy particle physics, in particular for the search of the Higgs boson (which has been confirmed last year) and signs for possible new physics beyond the Standard Model of particle physics. The LHC lies in a tunnel 27 km in circumference and up to 100 m below the surface of the French-Swiss border near Geneva. The LHC was built in collaboration with over 10000 scientists and engineers from over 100 countries. The accelerator has been running with a center of mass energy of $\sqrt{s} = 13$ TeV since 20 May 2015.

The LHC hosts four large experiments [2–5]:

ATLAS/CMS

- The two multi-purpose experiments at the LHC with the main goal of probing $p - p$ collisions for direct searches of new particles.

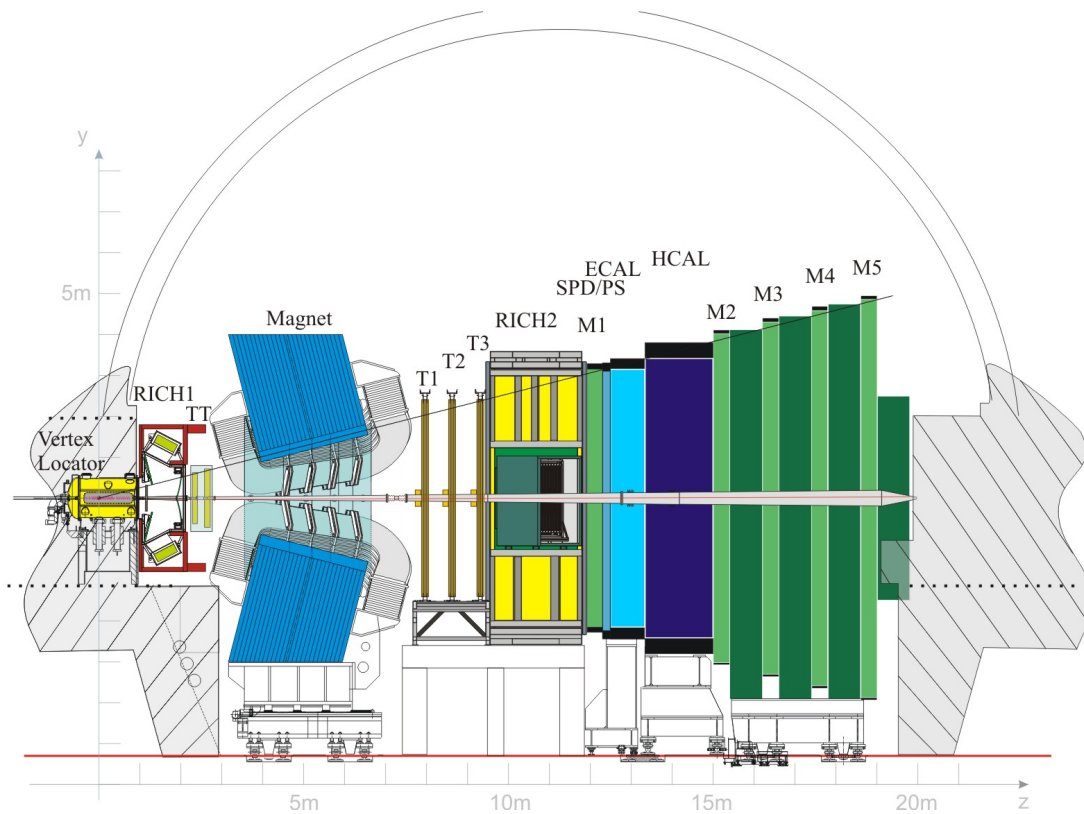


FIG. 1.2 – LHCb Detector: The beams collide inside the Vertex Locator. The RICH1 is positioned before the tracking station (TT) and the magnet. RICH2 is set up after the magnet and the tracking stations (T1-T3) and before the calorimeters (SPD/PS, ECAL, HCAL) and muon stations (M1-M5)

ALICE

- ALICE (A Large Ion Collider Experiment) is a general-purpose, heavy ion detector at the CERN LHC which focuses on QCD, the strong interaction sector of the Standard Model, e.g. searching for evidence for quark-gluon plasma.

LHCb

- LHCb is testing the Standard Model by confronting its predictions with precise measurements in CP violation and rare decays of particles containing b and c quarks.

1.2 The LHCb experiment

The main goal of the LHCb experiment is the study of decays of particles containing b and \bar{b} quarks (such as B -Mesons). During the $p - p$ collisions at the LHC these particles are produced mostly at small polar angles with respect to the beam axis. This is reflected in the design of the LHCb detector which is a forward arm spectrometer 20 meters long with subdetectors arranged along the beam pipe as shown in figure 1.2.

A brief overview of the detector parts [6].

VELO The VERTex LOcator surrounds the region where the beams collide and b/\bar{b} pairs are produced. The VELO measures the distance between the $p - p$ collision point and the point where the B particles decay. B particles are short-lived (decaying after typically 1 cm) thus their properties are not measured directly but inferred from the separation of these two points and the properties of their decay products.

RICH The RICH detectors are built for particle identification in particular to distinguish charged kaons from pions. One detector on each side of the magnet is used to cover different momentum ranges. RICH detectors work by measuring emissions of Cherenkov radiation which is produced if a particle travels faster than the speed of light through a certain medium (often compared to breaking the sound barrier). The emission angle depends on the speed of the particle, so knowing the speed and the momentum (from the curvature of the track induced by the magnet) the mass of the particle can be inferred.

Magnet Particles normally move in a straight line but a magnetic field causes the path of charged particles to curve according to the Lorentz force

$$\mathbf{F} = q (\mathbf{E} + (\mathbf{v} \times \mathbf{B}))$$

thus allowing to determine the charge sign of the particle. Also the track curvature can be used to measure the momentum of the particle.

Tracking System The tracking system is based on 4 planar tracking stations. It is used to determine the momentum of charged particles by measuring the bending of the trajectory in the magnetic field. Two types of tracking detectors are used in LHC*b*. In the silicon detector a passing particle generates electron-hole pairs which induce a charge on the readout strips. In the straw tube detector a particle ionises the gas molecules in gas-filled tubes which induce charges on a readout wire.

Calorimeters They are designed to stop particles and measure their energy. The design of the stations is sandwich like with alternating metal and scintillator plates. Interactions in the metal plate cause a secondary shower of charged particles which induce scintillation light in the scintillator plates. The energy lost is proportional to the amount of light emitted. Calorimetry is also the main way of identifying neutral particles (e.g. photons, neutrons).

Muon system Muons are easy to identify and play an important role in many analyses. There are five planar stations at the end of the detector each consisting of an iron absorber and a detection plane. The total area covered by these stations is about 435 m² [7]. The goal of the absorber is to stop all particles except muons who still can pass. The muons get detected in the gaseous detectors where their trajectory is measured.

1.2.1 Particle identification

An important requirement at LHC*b* is particle identification. This is handled by the calorimeters, Muon and RICH sub-detectors. The Calorimeters beside measuring energies and positions of electrons, photons and hadrons also provide identification of said particles e.g. by measuring the shape of the induced showers. The Muon system identifies muons to a very high level of purity.

Hadron identification i.e. separation of kaons, pions and protons is important for many analyses. The LHC*b* RICH system provides this, covering a momentum range of approximately 1–100 GeV. It is composed of two detectors. One is positioned upstream of the dipole magnet and the other one is positioned downstream of the dipole magnet. Their setup is briefly described in Section 2.2.

2 Theory

2.1 Cherenkov radiation

The speed of light in vacuum, $c = 299'792 \text{ km/s}$, is a universal physical constant. According to Einstein's special theory of relativity, c is the maximum speed at which all matter (or information) in the universe can travel. The speed at which light propagates in a medium is given by $\frac{c}{n}$, where n is the refractive index of the medium and can be significantly less than c .

Cherenkov radiation results when a charged particle travels through a dielectric medium with a speed greater than the speed of light through said medium. The velocity that must be exceeded is the phase velocity (v_{Phase} or short v_P) and not the group velocity ($v_{\text{Group}} = \frac{\partial \omega}{\partial k}$),

$$v_P = \frac{c}{n} = \frac{\lambda}{T} = \frac{\omega}{k},$$

where λ is the wavelength of the light, T the oscillation period, ω the angular frequency and k the wavenumber.

As a charged particle travels through the medium, it disrupts the local electromagnetic field. If the particle travels slower than the speed of light then the disturbance elastically relaxes to the equilibrium as the particle passes. However, if the particle travels at the speed $\beta \cdot c$ faster than the speed of light i.e. $\beta > 1/n$, the limited response speed of the medium means that a disturbance is left in the wake of the particle, and the energy in this disturbance radiates as a coherent shockwave.

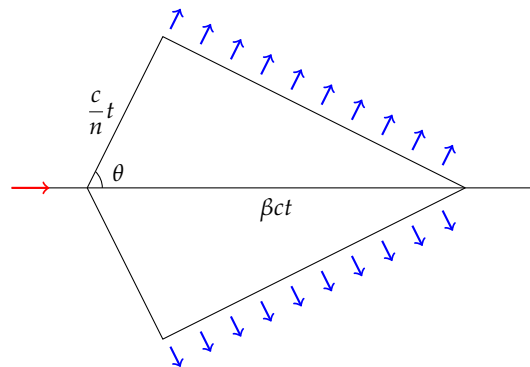


FIG. 2.1 – The geometry of the Cherenkov radiation

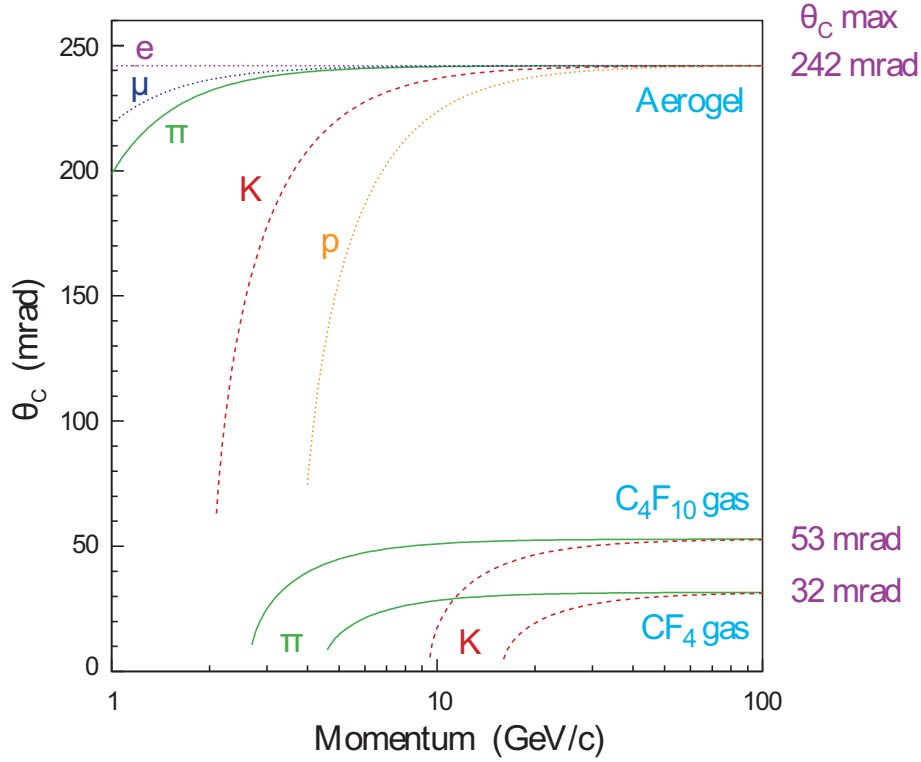


FIG. 2.2 – Cherenkov angle vs momentum for the different particles in different radiators

As illustrated in Figure 2.1, the shockwave is emitted under an angle

$$\cos \theta = \frac{x_p}{x_{em}} = \frac{\frac{c}{n}t}{\beta ct} = \frac{1}{n\beta} \quad (2.1)$$

with respect to the direction of flight of the particle. Figure 2.2 shows the Cherenkov angle vs momentum for different particles and different radiators in LHCb.

2.2 RICH detector

Particle identification is a fundamental requirement for many analyses at the LHCb experiment. LHCb is unique at the LHC in the sense that it uses RICH detectors for hadronic particle identification, unlike other LHC experiments such as ATLAS or CMS. The advantage of using RICH detector is that it yields superior particle identification performance. Using three different radiators, the RICH detectors cover a wide range of momentum (1-100 GeV/c).

Both RICH-1 and RICH-2 are located in low magnetic field regions to keep the trajectories of charged particles straight while they pass through the radiators. They both also have tilted spherical focusing primary mirrors and secondary flat mirrors to limit the length of the detector along the beam pipe and minimize the amount of detector material. The spherical focusing mirrors use the property that photons generated at a fixed angle with respect to the particle trajectory are focused onto a ring in the photon detector plane (via

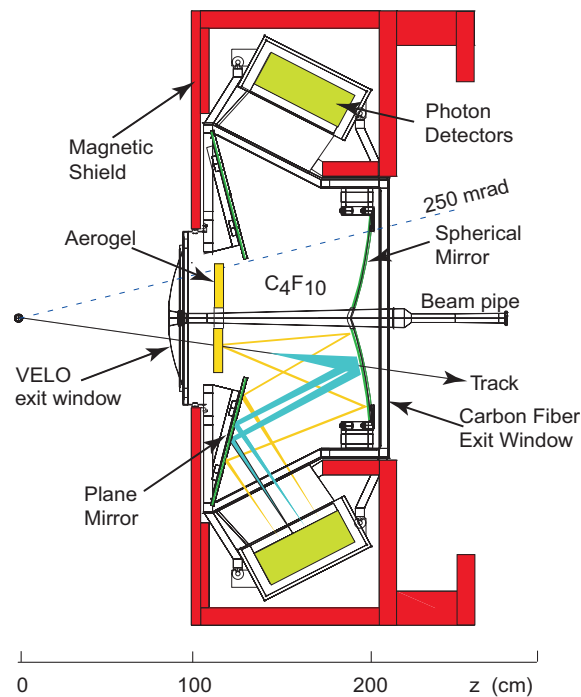


FIG. 2.3 – RICH-1 detector [9]

the secondary flat mirror) where hybrid photon detectors (HPD) are used to measure the spatial position of emitted Cherenkov photons. These photon detectors have a spatial resolution of $2.5 \text{ mm} \times 2.5 \text{ mm}$. The total area of the two detector planes in the RICH-1 detector is $1302 \text{ mm} \times 555 \text{ mm}$ each and $710 \text{ mm} \times 1477 \text{ mm}$ for RICH-2. The HPD is a vacuum photon detector in which a photoelectron, released from the conversion in a photocathode of an incident photon, is accelerated by and applied voltage onto a silicon detector [4].

The RICH-1 in front of the magnet covers the lower momentum range from 1-60 GeV/c. It uses two radiators 5 cm thick aerogel tiles with $n = 1.03$ which is suited for the lowest momentum tracks and directly behind about 1 m of C_4F_{10} ($n = 1.0014$) which covers the intermediate region of momentum. For the highest momentum tracks, gaseous CF_4 ($n = 1.0005$) is used in the RICH-2 [8].

There is a strong correlation between the polar angle and the momentum of the charged particles produced in *LHCb*. Particles with a larger polar angle tend to have lower momentum. This is why RICH-1 with the aerogel is located before the dipole magnet so tracks with low momentum will be covered before they are swept out of the acceptance by the magnet. See Figure 2.3 for a schematic of the RICH-1 detector.

2.3 Hough transform

The Hough transform [10] is a feature extraction technique used in image analysis, computer vision and digital image processing.

Its purpose is to find imperfect instances of objects within a certain class of shapes by a voting procedure. This voting procedure is carried out in a parameter space from which object candidates are obtained as local maxima in a so called accumulator space that is explicitly constructed by the algorithm for computing the Hough transform.

Initially the Hough transform was concerned with finding straight lines [11] but it has been extended to identifying positions of more complicated shapes, such as circles and ellipses.

2.3.1 Linear Hough transform

A linear function is often parametrized as:

$$f(x) = m \cdot x + b$$

where m is the slope of the line and b the intercept. For the Hough transform, however, this representation is not ideal. For a vertical line, m would go to infinity which gives an unbound parameter space for m . For this reason, Duda and Hart suggested the r - θ parametrization [10].

$$r = x \cos \theta + y \sin \theta \quad (2.2)$$

where r is the distance from the origin to the closest point on the line and θ is the angle between the x -axis and the line connecting the origin with that closest point.

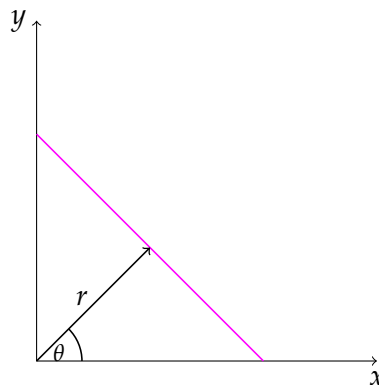


FIG. 2.4 – r - θ parametrisation

This means given a single point in the (x, y) plane, the set of all lines going through this point form a sinusoidal curve in r - θ space. Another point that lies on the same straight line in the (x, y) plane will produce a sinusoidal curve that intersects with the other at (r, θ) and so do all the points lying on the same straight line.

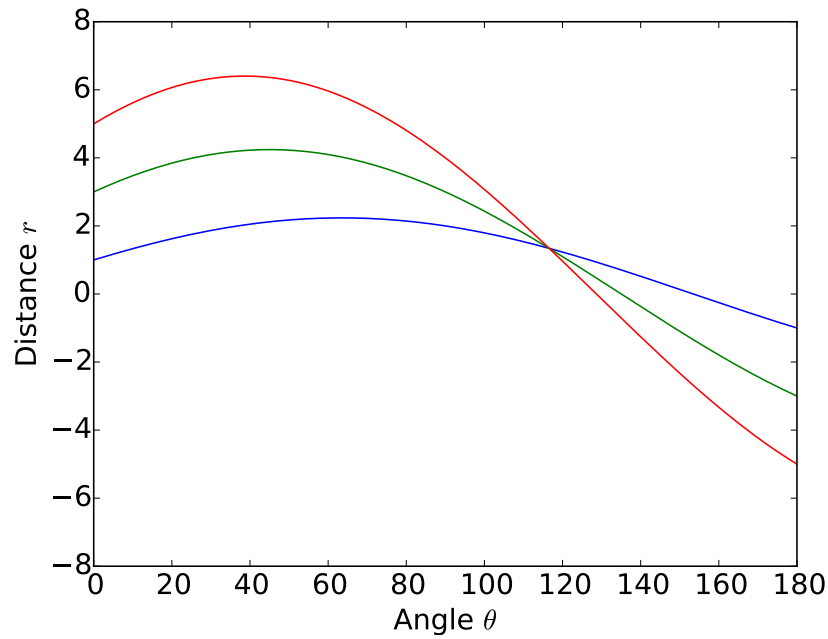


FIG. 2.5 – This is the accumulator space of 3 points on the same line. Each curve represents the set of possible lines going through one particular point. The curve then represents the $r - \theta$ parameters for each line of this set. Since there are three points there are three curves.

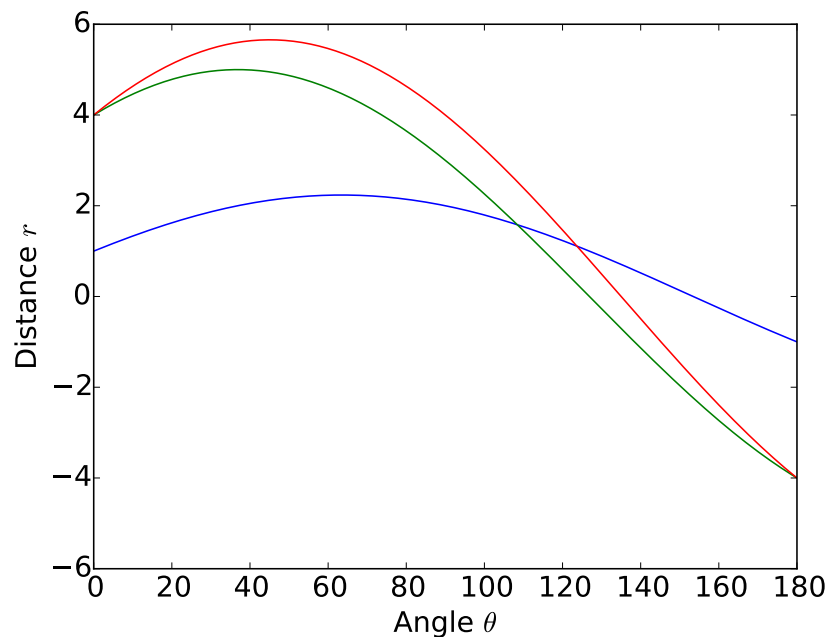


FIG. 2.6 – Example of a linear Hough transform where points do not lie on a line. Since any two points can form a line there are still intersections but never more than 2.

Radiator	Average N_{pe} from data	
	tagged $D^0 \rightarrow K^- \pi^+$	$pp \rightarrow pp \mu^+ \mu^-$
Aerogel	5.0 ± 3.0	4.3 ± 0.9
C_4F_{10}	20.4 ± 0.1	24.5 ± 0.3
CF_4	15.8 ± 0.1	17.6 ± 0.2

TAB. 2.1 – Comparison of photoelectron yields (N_{pe}) determined from $D^* \rightarrow D^0 \pi^+$ decays and $pp \rightarrow pp \mu^+ \mu^-$ events in data, using the selections and methods described in the text [12]

2.3.2 Circle Hough transform

For this thesis we are interested in circle detection so we need to adapt the linear Hough transform in order to find circles. In a two dimensional space (x, y) , a circle can be described by:

$$(x - c_x)^2 + (y - c_y)^2 = r^2 \quad (2.3)$$

Where (c_x, c_y) are the coordinates of the center of the circle and r is its radius. The possible parameters for the parameters space are now c_x, c_y and r . This means if the center of the circle is known the parameter space is one-dimensional, if the radius of the circle is known the parameter space is two-dimensional and of course if nothing is known the parameter space is three-dimensional.

2.4 Datasets

Two Monte-Carlo generated sets of simulated data were used for this thesis. The algorithms were trained on a data set of 250 simulated events and the performance of the algorithms was tested on a data set consisting of 10'000 simulated events with a total of 49'979 rings across all events. The properties of these events (radiuses, number of points per ring, number of rings per event) are taken from both simulation of LHCb events and real data taken from the experiment. The number of points per ring is determined by the photoelectron yield N_{pe} which is shown in Table 2.1. Figure 2.7 shows the number of points per circle and Figure 2.8 the number of circles per event for the test data set.

The average radius of Cherenkov rings can be found in [13]. Rings from the C_4F_{10} radiator in RICH-1 have radiuses generally smaller than 0.15 m. Rings from the aerogel have slightly bigger radiuses of around 0.20 m). All generated rings in the test data set have a radius that is smaller than 0.15 m. The distribution of the radiuses in the test data set is shown in Figure 2.9.

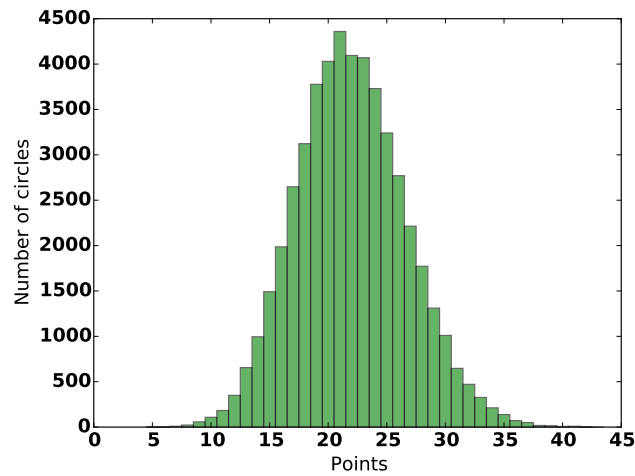


FIG. 2.7 – Number of points per circle (N_{pe}) for the 10'000 simulated events in the test data sample

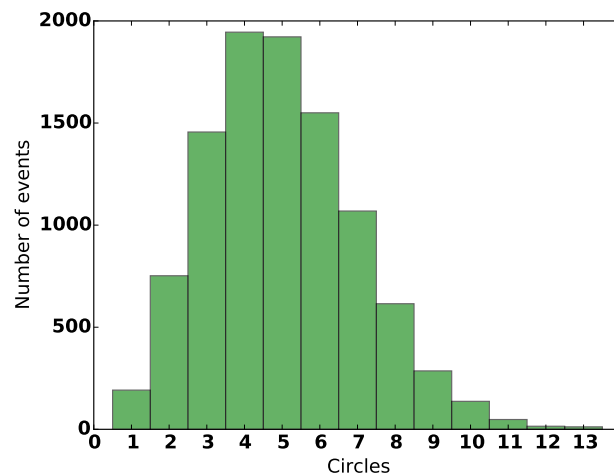


FIG. 2.8 – Number of circles per event in the test data sample

2.5 Existing algorithm

There is already an algorithm in place in LHCb [13]. The disadvantage of the existing algorithm is due to the fact that it uses tracks to reconstruct the circles. All charged tracks that are reconstructed by the tracking system are reflected at the RICH mirrors in order to define a center for a potential Cherenkov ring.

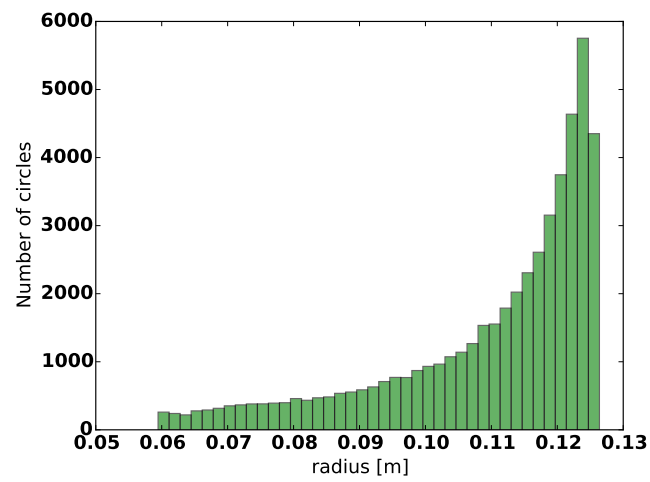


FIG. 2.9 – Distribution of ring radiuses in the test data sample

3 Methods

3.1 Conventional Hough transforms

In the following subsections we discuss conventional Hough transforms for the cases of a one, two and three dimensional parameter space (known center, known radius, unknown radius and center). These methods were mainly considered to get an idea of what was possible with the conventional Hough transform. The conventional Hough transforms use the accumulator space which is essentially a histogram. As such it depends on the size of the binning. The finer the binning is the higher the accuracy with which parameter (r and/or (x, y) coordinate) can be extracted. On the other hand the execution time depends on the binning; the finer the binning the longer the execution time.

For closer study the method of choice was the combinatorial triplet Hough transform discussed in section 3.2.

3.1.1 1D: Known center - find radius

In this case the centers of all circles are known and the algorithm has to find the radii. For the radius, a one dimensional array is defined with a minimum value and with a fixed stepsize to the maximum possible radius. For the example studied here, the minimum was chosen to be 0, the maximum radius to be 1 and the stepsize equal to 0.001. The following scoring function $\eta(r)$ was used to calculate the distance of a data point (x, y) from the given center (c_x, c_y) as a function of the radius r :

$$\eta(r) = (c_x - x)^2 + (c_y - y)^2 - r^2. \quad (3.1)$$

For $\eta(r) = 0$, the particular point (x, y) would lie on the circle of radius r with center (c_x, c_y) . A Gaussian distribution

$$w(\eta) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(\frac{-\eta^2}{2\sigma^2}\right), \quad (3.2)$$

is used to have a well defined value for such points. A point (x, y) that is not exactly on the circle will still contribute to the total score. The smaller the parameter σ , the tighter the range is in which a point will be considered lying on a circle or not.

The value from equation 3.2 is added to the bin in the radius histogram which corresponds to the value of r used to calculate the weight.

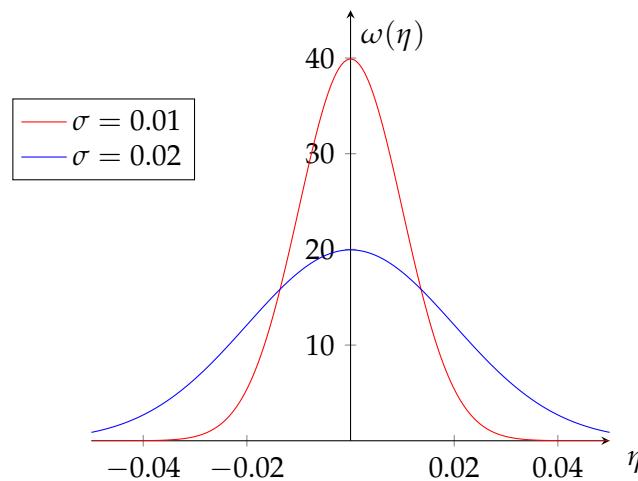


FIG. 3.1 – Using the probability density function of the normal distribution to calculate the score of a point in order to have a well defined maximum if a point lies directly on the circle and $\eta(r) = 0$. Increasing the σ increases the width of the function and by extension increases the score of points that do not lie directly on the circle

Equation 3.1 is of course just the circle equation with c_x, c_y being the known coordinates of the center of the circle, x, y are the data points and r is the radius. If many data points have the same distance r from the circle center there will be a high score for this particular radius. The index of the bin with the highest score can then be used to find the corresponding radius. The pseudo code for this Hough transform is shown in Code Snippet 3.1. An example of a resulting radius histogram is shown in figure 3.2

```

DIMENSION = 1001
r= linspace(0,1,DIMENSION)
for c_x, c_y in centers:
    scores = zeros(DIMENSION)
    for x,y in allPoints:
        s = 2*BIN_WIDTH
        eta = (c_x-x)**2 + (c_y-y)**2 - r**2
        scores += 1. / ( sqrt( 2 * Pi ) * s )
                * exp( -( eta ** 2 )
                    / ( 2 * s ** 2 ) )
    index = max(scores)
    circle = {}
    circle['center'] = c
    circle['radius'] = r[index]

```

CODE SNIPPET 3.1 – Pseudo code for the 1D Hough transform. r is an array of length 1001 so η will also be an array of length 1001. Scores is the array in which the score for each iteration is stored. For each point the score is computed and added to the scores array and at the end the index with the highest score is the index we need to extract the radius

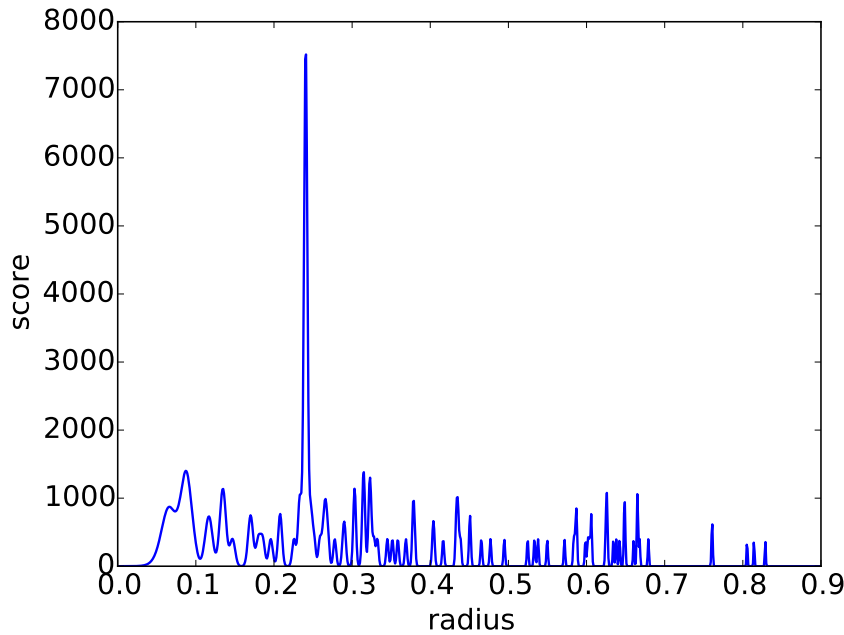


FIG. 3.2 – Visualisation of a 1D radius score histogram. The peak between 0.2 and 0.3 has by far the highest score and the bin position of the peak is the radius candidate for a given circle center (c_x, c_y)

Complexity

The complexity of this algorithm is of $\mathcal{O}(n)$ where n is the number of bins in the radius histogram.

3.1.2 2D: Known radius - find center

In this case the radius is known and the x and y coordinates of the center (c_x, c_y) are unknown. The accumulator is two dimensional. The range of that space is the dimension of the detection plane which for this thesis is set to $[-0.5, 0.5]$. The size of the bins is chosen to be 0.001 since the known radiuses given from the test data were given with this precision. If the detection plane was in reality 1 m by 1 m (approximately the dimension of the RICH detectors) the binning of the accumulator in each dimension is 1 mm which is better than the resolution of the HPDs (2.5 mm \times 2.5 mm). As in the one dimensional case we use the scoring function 3.1 in combination with the weight function 3.2. Since it is likely that two rings have very similar radiuses within the precision of the binning a mechanism has to be introduced to remove points from the data set that have been used for a ring. For two circles with the same radius the algorithm would only ever find the one with the higher score. To avoid this once a circle has been found a check for each data point is made to see whether or not it lies on the circle and if yes it is removed (see Code Snippet 3.3).

```

DIMENSION = 1001
xbins = linspace(-0.5,0.5,DIMENSION)
ybins = linspace(-0.5,0.5,DIMENSION)
x, y = broadcast_arrays( xbins[... , newaxis],
                        ybins[newaxis, ...] )

for r in Radiuses:
    weights = zeros( (DIMENSION, DIMENSION) )
    for xd, yd in allPoints:
        s = 2 * BIN_WIDTH
        eta = (xd-x)**2 + (yd-y)**2 - r**2
        weights += 1. / ( sqrt( 2 * pi ) * s )
                    * exp( -( eta ** 2 )
                    / ( 2 * s ** 2 ) )
    i, j = argmax(weights)
    removeUsedPoints()
    circle['Center'] = (xbins[i], ybins[j])
    circle['Radius'] = r

```

CODE SNIPPET 3.2 – Pseudo code for the 2D Hough transform. `xbins` and `ybins` are one-dimensional arrays of length 1001. Here we use array broadcasting in order to avoid for loops and the weights can be evaluated in one line.

```

for x, y in data_points:
    if ( x - c_x )**2 + ( y - c_y )**2 - r**2 < 0.002:
        <delete x, y from the list>

```

CODE SNIPPET 3.3 – Pseudo code for removing data points that lie on a ring. The value of 0.002 is twice the bin size to make sure all the points that belong to that ring will be removed. (c_x, c_y) is the center found by the algorithm and r is given from the data.

Complexity

The complexity of this algorithm is $\mathcal{O}(n \times m)$ where n and m are the number of bins per coordinate respectively of the histogram. The calculation of the weight has to be done for each data point of the 2D histogram. So in a 1000×1000 histogram with 400 data points we calculate 400'000'000 times the weight of a grid point. Reducing the dimensions of the histogram weakens the accuracy of the algorithm but can speed up the calculations considerably. With a 1000×1000 histogram the resolution in each space dimension is 1 mm. The RICH Technical Design Report states the resolution of the HPD is $2.5 \text{ mm} \times 2.5 \text{ mm}$.

The need (not entirely true – see below) to calculate the weight for each grid point and data point means that there is a loop over all data points and two loops over the x and y coordinates of the grid. To improve upon that there is the possibility of array broadcasting.

Array broadcasting

Consider following one dimensional arrays where both x and y are a 1D histograms binning entries from 1 to 4:

$$x = [1, 2, 3, 4]$$

$$y = [1, 2, 3, 4]$$

All combinations between an element of x and an element of y represent a 2D grid $((1, 1), (1, 2), \dots)$. To iterate through all those grid points one would have to create 2 for-loops iterating through x and y as shown in this pseudo code snippet:

```
def noBroadcast():
    a = np.random.randn(100)
    b = np.random.randn(100)
    for x in a:
        for y in b:
            print (1-x)^2 + (2-y)^2 - 9
```

This is not only slow but also does not look nice if there are even more loops (readability of the code). Broadcasting turns the one dimensional arrays of length n into two n by n matrices

$$x = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 2 & 2 & 2 & 2 \\ 3 & 3 & 3 & 3 \\ 4 & 4 & 4 & 4 \end{bmatrix}$$

and

$$y = \begin{bmatrix} 1 & 2 & 3 & 4 \\ 1 & 2 & 3 & 4 \\ 1 & 2 & 3 & 4 \\ 1 & 2 & 3 & 4 \end{bmatrix}$$

And with this the loops can be omitted as shown in the following example,

```
def withBroadcast():
    a = np.random.randn(100)
    b = np.random.randn(100)
    x, y = np.broadcast_arrays(a[... , np.newaxis],
                               b[np.newaxis, ...])
    print (1-x)^2 + (2-y)^2 - 9
```

which prints a 4 by 4 array with the function evaluated for each combination of entries of x and y

$$\begin{bmatrix} -8 & -9 & -8 & -5 \\ -7 & -8 & -7 & -4 \\ -4 & -5 & -4 & -1 \\ 1 & 0 & 1 & 4 \end{bmatrix}$$

A runtime comparison shows

```
In [3]: %timeit withBroadcast()
10000 loops, best of 3: 76.8 us per loop
```

```
In [4]: %timeit noBroadcast()
100 loops, best of 3: 7.99 ms per loop
```

The version with broadcasting is 100 times faster than the double loop. And the memory consumption is moderate since the broadcasted entries are not new memory locations but just refer to the initial array.

Optimizations

It was claimed before that for each data point the weight for the whole grid has to be calculated. This is in fact not true. In the 2D case each grid point is a potential center for a circle only if it is not further away from a data point than the maximum ring radius R_T , so if a grid point is further away than R_T this calculation could be skipped. This could probably be done even smarter with the use of a sub grid so only points in the surrounding sub grids are considered of being possible centers rather than the whole grid.

Simple example: 2 circles without background

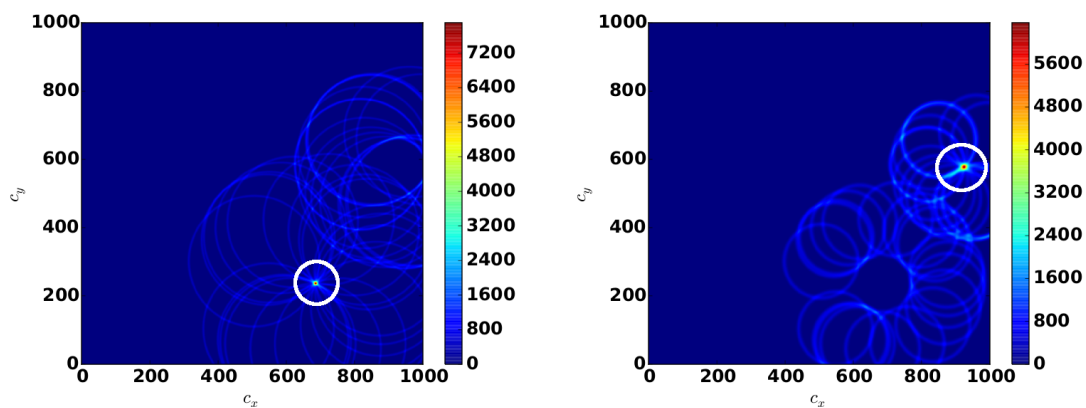


FIG. 3.3 – (Left) 2D weight matrix in the first iteration of the Hough transform algorithm. (Right) Second iteration of the 2D weight matrix of the Hough transform. Data points that satisfied the condition of being less than a certain distance ϵ away from the circle found in the first iteration are removed, leaving (hopefully) only data points available that belong to the second ring

3.1.3 3D: All parameters unknown

In this case all that is known are the data points and the algorithm has to retrieve both the centers and the radiuses of all rings. Moreover, the total number of rings is not necessarily known. The accumulator space is now three dimensional, two for the coordinates of the center and one for the radius. Similar to the 2D case, array broadcasting (see code snippet 3.4) is used to speed up the calculations of the weights. Furthermore, the algorithm has to decide itself whether or not all circles have been found a condition has to be set to decide when there are no more circles.

For deciding whether or not the algorithm has found all rings, a simple score threshold is used that whenever the highest score of the weight matrix is less than this threshold, the algorithm stops and it is assumed that all circles have been found. The threshold used in this thesis has been determined by trial and error and was set to a score of 3500. The pseudo code for calculating the weights and the threshold check is shown in 3.5. As in the 2D Hough transform, the algorithm has to remove data points that have contributed to the highest score. If this is not done, the algorithm will loop endlessly because always the same score will be found. Once the highest score has been found, the center coordinates and radius are extracted from the histogram and the algorithm calculates for every data point, if a data point lies on the circle given the extracted center and radius. If the data point lies within the distance of two times the bin width from the circle, it will be removed (see Code Snippet 3.6).

```

xbins = np.linspace(-0.5, 0.5, DIMENSION)
ybins = np.linspace(-0.5, 0.5, DIMENSION)
rbins = np.linspace(0, 0.5, R_DIMENSION)

x, y, r = np.broadcast_arrays(\
    xbins[np.newaxis, ..., np.newaxis], \
    ybins[np.newaxis, np.newaxis, ...], \
    rbins[..., np.newaxis, np.newaxis])

```

CODE SNIPPET 3.4 – Broadcasting of the 3 arrays x, y, r . With this 3 for-loops can be avoided improving speed and readability of the code.

The same scoring function as before is used, but this time it is a function of all three parameters $\eta(x, y, r)$:

$$\eta(x, y, r) = (x - d_x)^2 + (y - d_y)^2 - r^2 \quad (3.3)$$

where d_x and d_y are the coordinates of data points. Again,

$$w(\eta) = \frac{1}{\sqrt{2\pi\sigma}} \exp\left(\frac{-\eta^2}{2\sigma^2}\right). \quad (3.4)$$

Complexity

The complexity of this algorithm is of order $\mathcal{O}(m \times n \times u)$. As in the case of the 1D and 2D Hough transform, the accuracy depends on the binning. For the 3D Hough transform

```

while True:
    weights = np.zeros(\
        (R_DIMENSION, DIMENSION, DIMENSION))

    for x0,y0 in data['allPoints']:
        s = 0.001
        eta = (x-x0)**2 + (y-y0)**2 - r**2
        weights += 1./( sqrt( 2 * sconst.pi ) * s )*\
            np.exp( -( eta ** 2 ) / \
                ( 2 * s ** 2 ) )
    index = np.argmax( weights )
    rr,ii,jj = np.unravel_index( index,
        (R_DIMENSION, DIMENSION, DIMENSION))
    score = weights[rr][ii][jj]
    if score < THRESHOLD:
        break

```

CODE SNIPPET 3.5 – The while loop works as long as the highest found score is higher than THRESHOLD. If the score is lower than the threshold the loop breaks and the function returns the results that have been found.

```

circle['center'] = (xbins[ii], ybins[jj])
circle['radius'] = rbins[rr]
circles.append(circle)

used_xy += [tup for tup in data['allPoints'] if
    abs( ( tup[0] - circle['center'][0] ) ** 2 +
        ( tup[1] - circle['center'][1] ) ** 2 -
        circle['radius'] ** 2 ) < 2 * 0.001]
data['allPoints'][:] =
    [tup for tup in data['allPoints'] if
    abs( ( tup[0] - circle['center'][0] ) ** 2 +
        ( tup[1] - circle['center'][1] ) ** 2 -
        circle['radius'] ** 2 ) >= 2 * 0.001]

```

CODE SNIPPET 3.6 – In order to avoid finding the same ring over and over again, the algorithm has to remove points that belong to a found ring. If a data point lies within two times the bin width from a circle the algorithm considers that data point to be part of the corresponding ring and removes that data point from the list.

to match the resolution of the HPD of the LHCb RICH detector a binning of 400 bins in each of the two center coordinate parameters makes sense if the detector dimensions are $1\text{ m} \times 1\text{ m}$.

Optimisations

As for the 2D HT introducing a sub grid can be introduced for the x, y plane so only grid points within a predefined distance of a data point are used for calculating the score.

3.2 Combinatorial triplet Hough transform

A circle is uniquely defined by 3 points and its radius and the coordinates of its center can be calculated from the coordinates of these points. If there are 15 points lying on the same circle there are 455 possible combinations of triplets according to the binomial distribution,

$$\binom{N}{3} = \left(\frac{N!}{k!(N-k)!} \right).$$

Calculating the center and radius for these 455 triplets should result in the same center (x, y) and same radius r for all the triplets (effects of detector resolution and floating point inaccuracy not considered).

Having one random background hit in addition to the 15 points on the circle increases the number of triplets to 560. The triplets solely consisting of points on the circle still yield the same center and radius but the combinations that include a background hit will give different results and it is unlikely that two triplets that include the background point will yield the same center and radius. Here is an overview of the algorithm studied in this thesis.

1. Build all possible triplets of the data points.
2. For all triplets calculate the center and the radius of the potential circle.
3. Remove all triplets that yield a radius bigger than a pre-defined threshold.
4. Create a histogram with the distribution of r for the remaining triplets. Peaks in this histogram hint at the presence of a circle.
5. Scan the radius histogram for peaks and look at the 2D histogram of (x, y) for all triplets that belong to a given peak in the r distribution. If there is also a peak in the (x, y) histogram, the set of the points forming the triplets lie on a circle with a radius and center given by the positions of the peaks in the r and (x, y) histograms.

3.2.1 Generating the triplets

To generate the triplets, the python function `itertools.combinations()` from the `itertools` module is used. The input for this function is an iterable, in our case a list of tuples (each

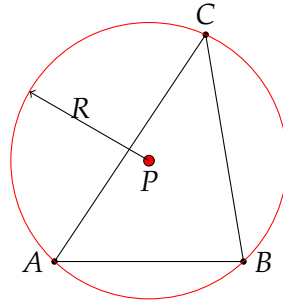


FIG. 3.4 – The circumradius (R) and the circumcenter (P) of a circle defined by three points (A, B, C).

tuple containing the x and y coordinate of a data point) which is used to create all possible combinations of triplets (of said tuples).

3.2.2 Calculating the Circle given 3 points

Let (A, B, C) be a triplet of points in a 2D plane and a, b, c the lengths of the sides opposite to the respective corner. The semiperimeter is defined as

$$s = \frac{a + b + c}{2}. \quad (3.5)$$

The radius R of the circumcircle of the triangle \overline{ABC} is:

$$R = \frac{abc}{4\sqrt{s(a+b-s)(a+c-s)(b+c-s)}} \quad (3.6)$$

and the barycentric coordinates of the circumcenter are:

$$\lambda_1 = a^2 \cdot (b^2 + c^2 - a^2) \quad (3.7)$$

$$\lambda_2 = b^2 \cdot (a^2 + c^2 - b^2) \quad (3.8)$$

$$\lambda_3 = c^2 \cdot (a^2 + b^2 - c^2) \quad (3.9)$$

Multiplying a matrix consisting of the column vectors of A, B, C ($A_x, A_y; B_x, B_y; C_x, C_y$) with a column vector of $\lambda_1, \lambda_2, \lambda_3$ and dividing the resulting vector by the sum of the barycentric coordinates (for normalization) yields the coordinate of the circumcenter of the triangle \overline{ABC}

$$\begin{pmatrix} A_x & B_x & C_x \\ A_y & B_y & C_y \end{pmatrix} \cdot \begin{pmatrix} \lambda_1 \\ \lambda_2 \\ \lambda_3 \end{pmatrix} = \begin{pmatrix} P'_x \\ P'_y \end{pmatrix} \quad (3.10)$$

$$\frac{\begin{pmatrix} P'_x \\ P'_y \end{pmatrix}}{\lambda_1 + \lambda_2 + \lambda_3} = \begin{pmatrix} P_x \\ P_y \end{pmatrix} = P \quad (3.11)$$

3.2.3 Ring finding

Once R and \mathbf{P} are calculated these values are stored as a pair in a tuple. A list is formed that holds all tuples (R, \mathbf{P}) for all triplets.

The next step is binning this data for R . For each bin in R , a list is created which contains the \mathbf{P} information for all (R, \mathbf{P}) tuples with R in this bin. This allows the algorithm when looking for a peak in the R histogram to access the values of \mathbf{P} for this R value.

Ring finding threshold

The algorithm applies a simple threshold on the number of associated points to decide whether a candidate is a ring or not. Assume just one ring with 10 points. From these 10 points, the algorithm creates 120 triplets $\binom{10}{3}$. For each of these triplets, the radius and the coordinates of the center are calculated. Since all triplets belong to the same ring the radius histogram has one peak at the value of the ring radius and the center histogram has one peak at the coordinates of the ring center. If the applied threshold is less or equal than 120, this ring will be found. So essentially we can decide how many points per ring are needed in order to be recognized as a ring and define the threshold as

$$\binom{\text{Number of Points}}{3} = \text{Threshold.} \quad (3.12)$$

This threshold is used for the radius and center finding of the algorithm.

Finding the radius

Once the radius histogram is filled, the algorithm looks for the index at which the maximum value of the histogram is stored. The algorithm then checks if the sum of the number of entries at this index and its the and right neighbours exceeds the radius threshold (which is a tuning parameter). If this is the case, the algorithm creates a list of the (x, y) coordinates for all tuples corresponding to this index and its left and right neighbours.

The code for extracting the radiuses with their center data is shown in Code Snippet 3.7. Assuming bin index i contains the highest score of the histogram. The code then adds the score from bin $i - 1$ and $i + 1$ to the maximum score and checks if the sum is bigger than the threshold. If that's the case the next step adds the center information stored in center to a separate list. The function then returns a list of radiuses that exceed the threshold and for each radius in the list there is a list of center data which is used to extract the center of the ring.

As long as the found maximum is bigger then the threshold the algorithm keeps looking for radiuses.

```

edges #x edges of the histogram
center #center data
while True:
    i = max(H)
    n = NUMBER_OF_R_BINS
    n_entries = sum(H[i-1 if i>0 else i:i+2
                    if i<n-1 else i+1])
    if n_entries < RADIUS_THRESHOLD:
        # there are less than THRESHOLD
        # entries in 3 bins
        break
    radiuses.append(edges[i])
    index_list = range(i-1 if i>0 else i,i+2
                      if i<n-1 else i+1)
    for index in index_list:
        if center[index]:
            center_list += center[index]
            H[index] = 0
    center_data.append(center_list)
return radiuses, center_data

```

CODE SNIPPET 3.7 – This code shows how the radius maxima are found and their respective center data is extracted. `n_entries` is the sum of the score of the maximum bin and its left and right neighbour. If the score exceeds the threshold the entries of these three bins are set to 0 and the radius value together with the center data are returned.

Finding the center

Using this list of center coordinates \mathbf{P} of a radius peak the algorithm now looks for a peak in the (x, y) plane of the \mathbf{P} histogram. If the sum of the number of entries in the peak and its four directly adjacent bins exceeds the center threshold, the radius and center coordinates are saved as a ring candidate. Code Snippet 3.8 shows the center extraction.

After this step the ring finding algorithm is done. The result for a typical event is shown in Figure 3.5. A cleaning step is now performed to remove duplicates. The algorithm compares all found circles and if the center coordinates and the radiuses of two circles are within a certain range these circles are considered to be duplicates and the one with the lower score is discarded. The range cuts were parameters that had to be tuned. If the range was too small then some duplicates were not detected. If the cut was too large, true rings were removed because they happened to be close to another ring. In Tables 4.6 and 4.7 the effects of different cuts can be seen.

3.2.4 Removing duplicates

The the main parameters for removing duplicates are used to decide whether a circle is a duplicate or not:

```

H #2d histogram with the center data
xedges
yedges
centers = []
n = NUMBER_OF_S_BINS
while True:
    i,j = max(H)
    score = sum(H[i-1 if i>0 else i:i+2
                if i<n else i+1,j]) +
            sum(H[i, j-1 if j>0 else
                j:j+2 if j+2 <= 3
                else j+1]) - H[i,j]
    if score < CENTER_THRESHOLD:
        break
    i_index = range(i-1 if i>0
                    else i,i+2 if i<n else i+1)
    j_index = range(j-1 if j>0
                    else j,j+2 if j<n else j+1)
    for ii in i_index:
        H[ii][j] = 0
    for jj in j_index:
        H[i][jj] = 0
    centers.append( {'center' : (xedges[i], yedges[j]),
                    'nEntries' : score } )

return centers

```

CODE SNIPPET 3.8 – H is the center histogram. After finding the index for the maximum value the values of the adjacent neighbours are also added to the score. If the score exceeds the center threshold the algorithm stores them as a center for a circle candidate and sets the used bins to 0.

- Distance between centers of pairs of rings
- Difference between radiuses of pairs of rings

Without cleaning up the algorithm finds a lot of duplicates. The reason for such duplicates can be background hits or a hits from another ring close to the actual ring. The triplets including one of these hits can shift the center or the radius of the ring they form just a little bit away from the true ring. As shown in Figure 3.6 indicated with an arrow there are peaks separated by one bin and thus the algorithm finds these peaks separately since only the directly adjacent neighbours are considered. It is possible that there are two rings with very similar radius but more often it is the same ring in addition with a background hit that lies close to the ring.

To decide whether or not a circle is a duplicate it is compared to all other found candidates and the distance of their centers and difference of their radiuses is compared.

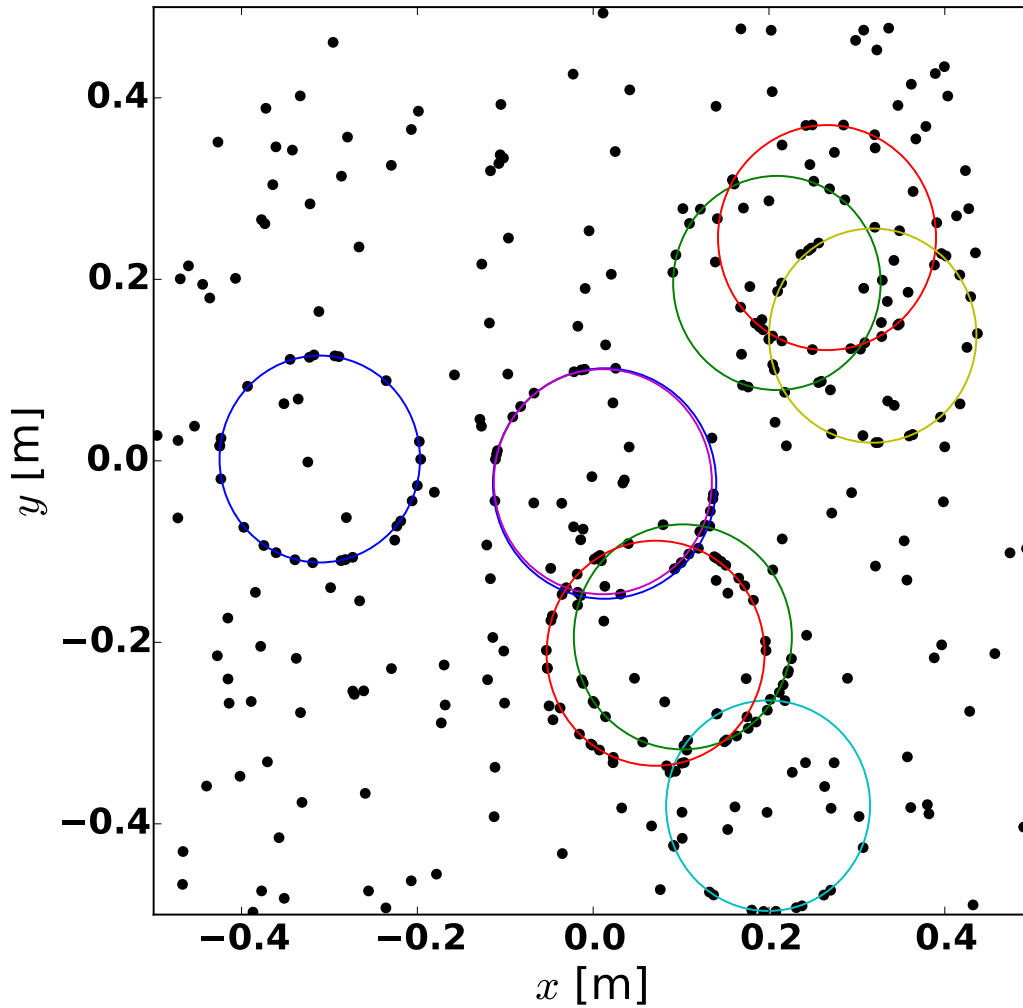


FIG. 3.5 – The result of the combinatorial triplet Hough transform before cleaning up duplicates. The blue and purple circles are basically the same ring.

$$\begin{aligned} |c_1 - c_2| &< \text{DUPLICATE_MAX_CENTER_DISTANCE} \\ |r_1 - r_2| &< \text{DUPLICATE_MAX_RADIUS_DISTANCE} \end{aligned} \quad (3.13)$$

where c_1 and c_2 are the center coordinates and r_1 and r_2 the radiuses of the circles.

However if there is no other circle within the threshold distances the circle is unique and will be added to a result list which at the end will be returned with all unique circles.

If the cut is too loose, there is a chance that a true ring gets discarded as a duplicate if its center and radius happens to be close to those of another ring.

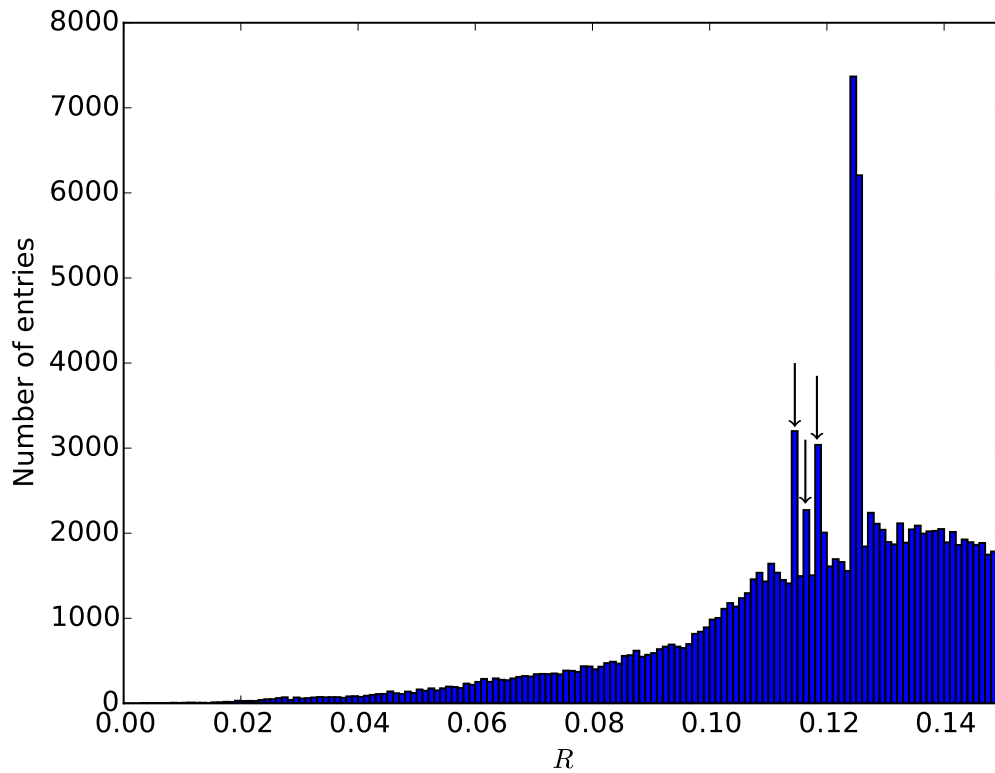


FIG. 3.6 – Two almost adjacent bins with a high score. Apart from the very clear peak of two bins next to each other at $r \approx 0.125$ with a score of 7000 and 6000 respectively, there are 3 smaller peaks separated around $r \approx 0.11 - 0.12$. The highest score is clearly visible. After the algorithm found this maximum and sets the bins to 0 the algorithm picks then the next maximas and its neighbours. But since there are several peaks separated by one bin means they are treated separately and this introduces a duplicate.

3.2.5 Combinatorics

The main drawback of this method is that the combinatorics increase with the number N of data points as $\binom{N}{3}$. For example, for 200 data points the number of triplets is

$$\binom{200}{3} = 1'313'400$$

and for 300 data points it is

$$\binom{300}{3} = 4'455'100.$$

The execution time of the algorithm is roughly of the order of $\mathcal{O}(N^3)$ which can be easily seen when taking the upper bound of $\binom{N}{3} \leq \frac{N^3}{3!}$ (see figure 3.7).

```

res = []
sorted_results = sorted( results, key=lambda k:
                        k['nEntries'], reverse=True)
while len(sorted_results):
    circle = sorted_results.pop()
    unique = True
    for dic in sorted_results:
        if (np.linalg.norm(np.array(circle['center']) -
                            np.array(dic['center']))) <
            DUPLICATE_MAX_CENTER_DISTANCE and\
            (abs(circle['radius'] - dic['radius']) <
             DUPLICATE_MAX_RADIUS_DISTANCE):
            unique = False
            break
    if unique:
        res.append(circle)
return res

```

CODE SNIPPET 3.9 – Pseudo code for removing possible duplicates from the circles found by the algorithm. First results are sorted by their number of entries in the histogram so the least relevant comes first. If for a given circle another circle exists with the same center and radius (within the cuts) then the circle is considered a duplicate and will be removed. `DUPLICATE_MAX_CENTER_DISTANCE` and `DUPLICATE_MAX_RADIUS_DISTANCE` are parameters that can be tuned

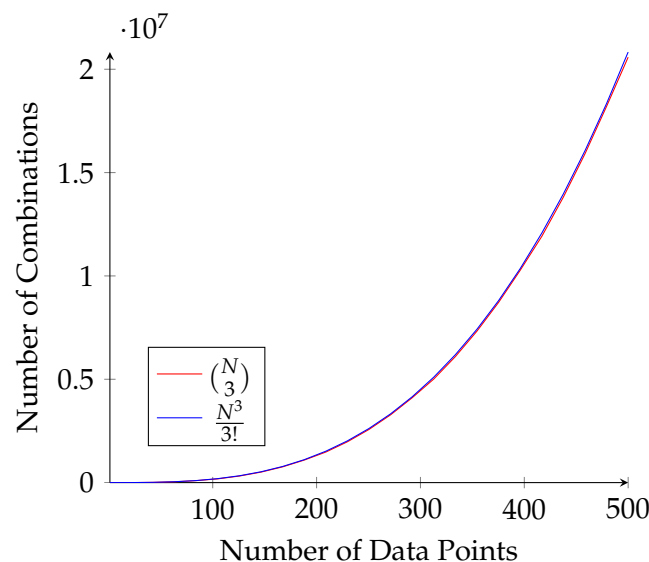


FIG. 3.7 – Scaling of the algorithm. Binomial growth $\binom{N}{3}$ compared with the approximation $\frac{N^3}{3!}$, where N is the number of data points.

Optimisation

The algorithm needs a threshold on the minimum height of the peak in the (x, y) and r histograms in order to decide if a candidate is a circle or not. The threshold is defined as the binomial coefficient $\binom{T}{3}$. If a ring has T points then there are $\binom{T}{3}$ possible triplets and the circle will be considered as a candidate. If a ring has less than T points then it will never be considered as a candidate.

In fact, not only processing the number of triplets created is a speed bump for the execution time but the time it takes to create the triplets scales with $\frac{N^3}{3!}$ as well. Reducing the number of triplets created will speed up the algorithm considerably.

This leads to the idea of splitting the original data set randomly into two lists. For each of these lists, all possible combinations of triplets are created separately and the two lists of triplets are then merged in one single list for further processing. In Figure 3.8 the difference in combinatorics between $\binom{N}{3}$ and $2 \cdot \binom{N/2}{3}$ can be seen.

The problem with this approach is the possible loss of efficiency, since the algorithm uses thresholds that define how many entries a bin in the (x, y) and the r histograms must have in order to be accepted as a candidate circle. These thresholds should be high enough such that triplets that contain noise points do not contribute significantly to the circle candidates but low enough that real circles with a low number of points can still be found.

For now we assume that we require a ring to have 10 hits which seems reasonable when looking at Figure 2.7 and considering the low probability that 10 random points form a circle. The question is what is probability of splitting points that belong to a specific circle in such way that at least one list yields enough triplets to reach these thresholds.

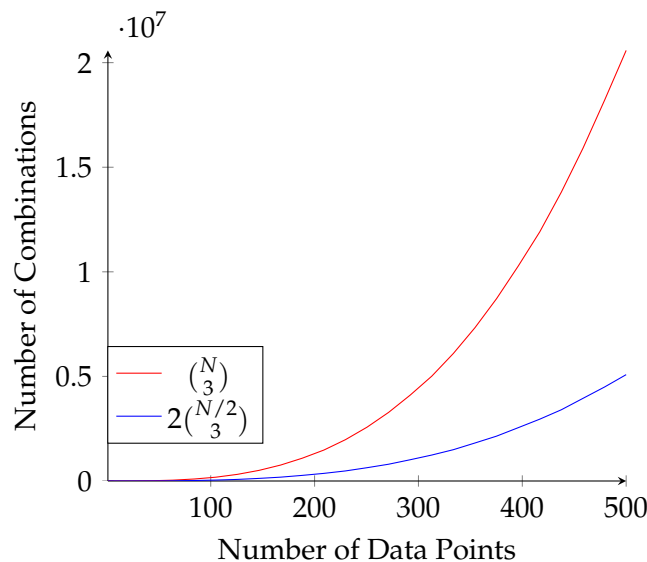


FIG. 3.8 – Number of combinations with $\binom{N}{3}$ compared to the number of combinations generated from $2 \cdot \binom{N/2}{3}$

In Figure 3.9 it can be seen that even if we split the lists there is a more than 50% chance that we lose no information for rings that have at least 13 points.

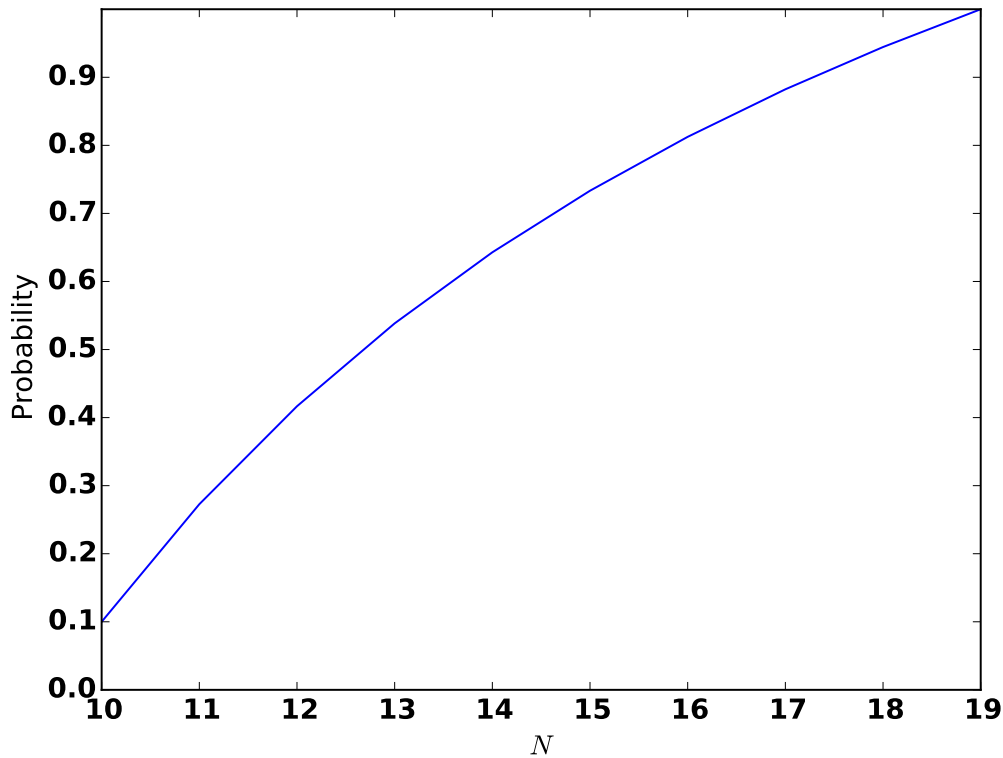


FIG. 3.9 – The probability when splitting randomly a list of N points into two that one of the two sublists contains more than 10 points.

Bin size dependency

In the conventional Hough transform the weight function is calculated with respect to the bin centers of the accumulator space. The larger the binning in the accumulator space is, the less accurate the calculations become. The number of bins is the main factor for the execution time of the algorithm. An advantage of this combinatorial approach lies in the fact that the parameters can be calculated accurately up to floating point precision and a histogram is only needed to group the results. A fine binning only marginally affects the execution time of the algorithm since the only operation done in the histogram is finding the maxima and this is only done a few times (stops when the found maximum is lower than the ring finding threshold).

3.2.6 Possible optimisation: average radius of random circles in a unit square

An interesting property of calculating the radius of circle candidates for triplets of random points that are distributed uniformly in the unit square is that they follow obey a certain distribution.

To prove this the average area \bar{X} of a triangle formed by three points randomly chosen from the unit square¹. Let $A = (A_x, A_y)$, $B = (B_x, B_y)$, $C = (C_x, C_y)$ be the vertices of the random triangle T . We consider the case where $A_y > B_y > C_y$ which takes $\frac{1}{6}$ of the total "volume" of the unit square. Fix A_y, B_y, C_y for the moment and we can write

$$B_y = (1 - t)A_y + t \cdot C_y, \quad 0 \leq t \leq 1.$$

The side AC of T intersects the horizontal level $y = B_y$ at the point $S = (s, B_y)$ with

$$s = s(A_x, C_x, t) = (1 - t)A_x + t \cdot C_x \quad (3.14)$$

The area X of T is then given by

$$X = \frac{1}{2} |B_x - s| \cdot (C_y - A_y)$$

We start integrate with respect to the six variables. The innermost integral is with respect to B_x and gives

$$\begin{aligned} X_1 &:= \int_0^1 X dB_x = \frac{1}{2} (C_y - A_y) \left(\int_0^s (s - B_x) dB_x + \int_s^1 (B_x - s) dB_x \right) \\ &= \frac{1}{4} (C_y - A_y) (1 + 2s + 2s^2). \end{aligned}$$

Next we integrate over B_y :

$$X_2 := \int_{A_y}^{C_y} X_1 dB_y = \frac{1}{4} (C_y - A_y)^2 \int_0^1 (1 - 2s + 2s^2) dt, \quad (3.15)$$

whereby s is given by Equation 3.14, and does not depend on A_y and C_y . It follows that the intregation factorizes into

$$X_3 := \frac{1}{4} \int_0^1 \int_{A_y}^{C_y} (C_y - A_y)^2 dC_y dA_y \times \int_0^1 \int_0^1 \int_0^1 (1 - 2s + 2s^2) dt dC_x dA_x$$

This gives

$$X_3 = \frac{1}{4} \cdot \frac{1}{12} \cdot \frac{11}{18} = \frac{11}{6 \cdot 144}$$

Generalizing the assumption at the beginning $A_y < B_y < C_y$, multiplying this result by 6 and obtain $\bar{X} = \frac{11}{144}$.

¹This proof is taken from has to be calculated[14]

From [15] it follows that the average area of a triangle in a unit circle is $\frac{3}{2\pi}$. Dividing this by the area of the unit circle gives the expected fraction of the area covered by a triangle in an arbitrary circle

$$\frac{\text{Expected area of a triangle in a unit circle}}{\text{Area of the unit circle}} = \frac{\frac{3}{2\pi}}{\underbrace{\pi r^2}_{r=1}} = \frac{3}{2\pi^2}$$

Finally the average area of a random circle in the unit square can then be obtained by dividing the average area of a triangle from the unit square by the expected area covered by a triangle in an arbitrary circle:

$$\frac{\frac{11}{144}}{\frac{3}{2\pi^2}} = \frac{11\pi^2}{216}$$

Finally this area should be equal to πR^2 where R is the average radius of a random circle in the unit cube

$$R\pi^2 = \frac{11\pi^2}{216}$$

$$R = \sqrt{\frac{11\pi}{216}} = 0.399986$$

Generating a data sample of randomly distributed points in the unit square and plotting the distribution of the radius calculated for this data set shows that there is indeed a peak around $R \approx 0.4$ as Figure 3.10 shows.

The idea behind this is to generate a data sample with only background hits and prepare the radius histogram. It could then be used to subtract from a real radius histogram to reduce the number of bins that have to be searched since most of the background should be gone. However, this has yet to be studied properly.

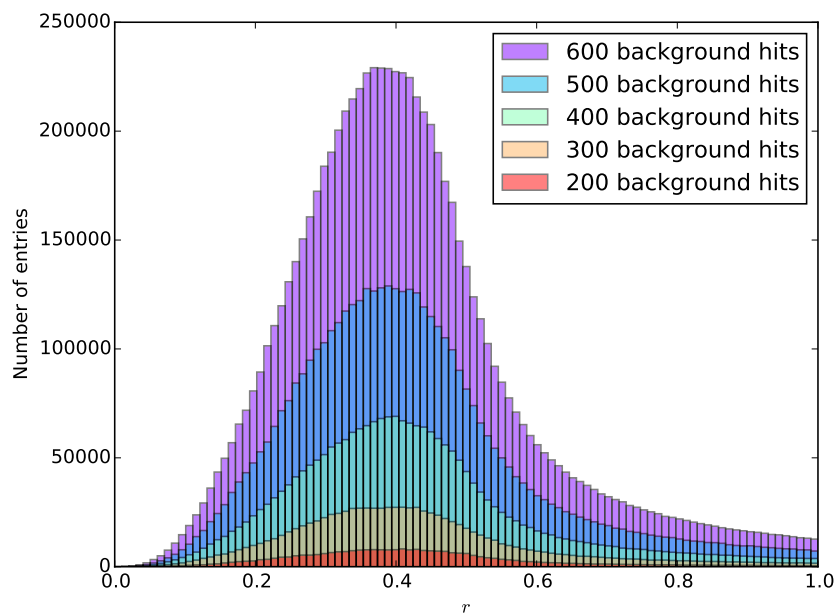


FIG. 3.10 – Radius distribution for uniformly generated background. Each data set contains only randomly generated background hits. The expected value of $R \approx 0.4$ is quite well represented for differently sized data sets

4 Results

In this section results for the conventional 1D, 2D and 3D Hough transform and for the combinatorial triplet Hough transform are presented. The 1D, 2D and 3D Hough transform were not pursued in depth. They are presented here as they offer a way of understanding how each extra dimension expands the algorithm and shows the problems that occur with each added dimension.

For the 1D, 2D and 3D Hough transform only a small set of events consisting of:

- 1 ring and 600 background hits
- 2 rings and 0 background hits
- 5 rings and 30 background hits
- 6 rings and 200 background hits (results only shown for 2D and 3D)

was Used . The number of points per ring and the distribution of the radiuses do not reflect the data obtained in *LHCb*.

For these conventional Hough transforms following data sets were tested

The number of points per ring ranges from 17–31 and the background hits are uniformly distributed in the unit square. The event with 1 ring and 600 background hits is meant to test how robust the algorithm is with a lot of background hits. The second test case is meant to test if the algorithm can handle two ring objects, the third is a mix between several rings and background and the last event is a special case where two rings lie have similar radiuses and are close to each other, potentially creating problems for the 2D and 3D algorithms where the center coordinates are unknown. In Figure 4.1 the real circles plotted from simulation parameters are shown for each of the events.

4.1 1D Hough transform results

The radius scores for the first three test events are shown in Figures 4.3 and 4.4. The radius score is a 1D plot of the weight function defined in Equation 3.2. The location of the highest score gives the value of the radius. Figure 4.2 shows the resulting circles in the (x, y) plane, using the known ring centers and the radiuses extracted by the algorithm. The numerical values of the highest and second highest score for each event are shown in Table 4.1. The highest and second highest score are well separated in each case, the algorithm has no problems to find any of the circles even with background. The fourth event was also tested for the 1D Hough transform but the results are not shown because they did not add anything that is not already covered with the first 3 events.

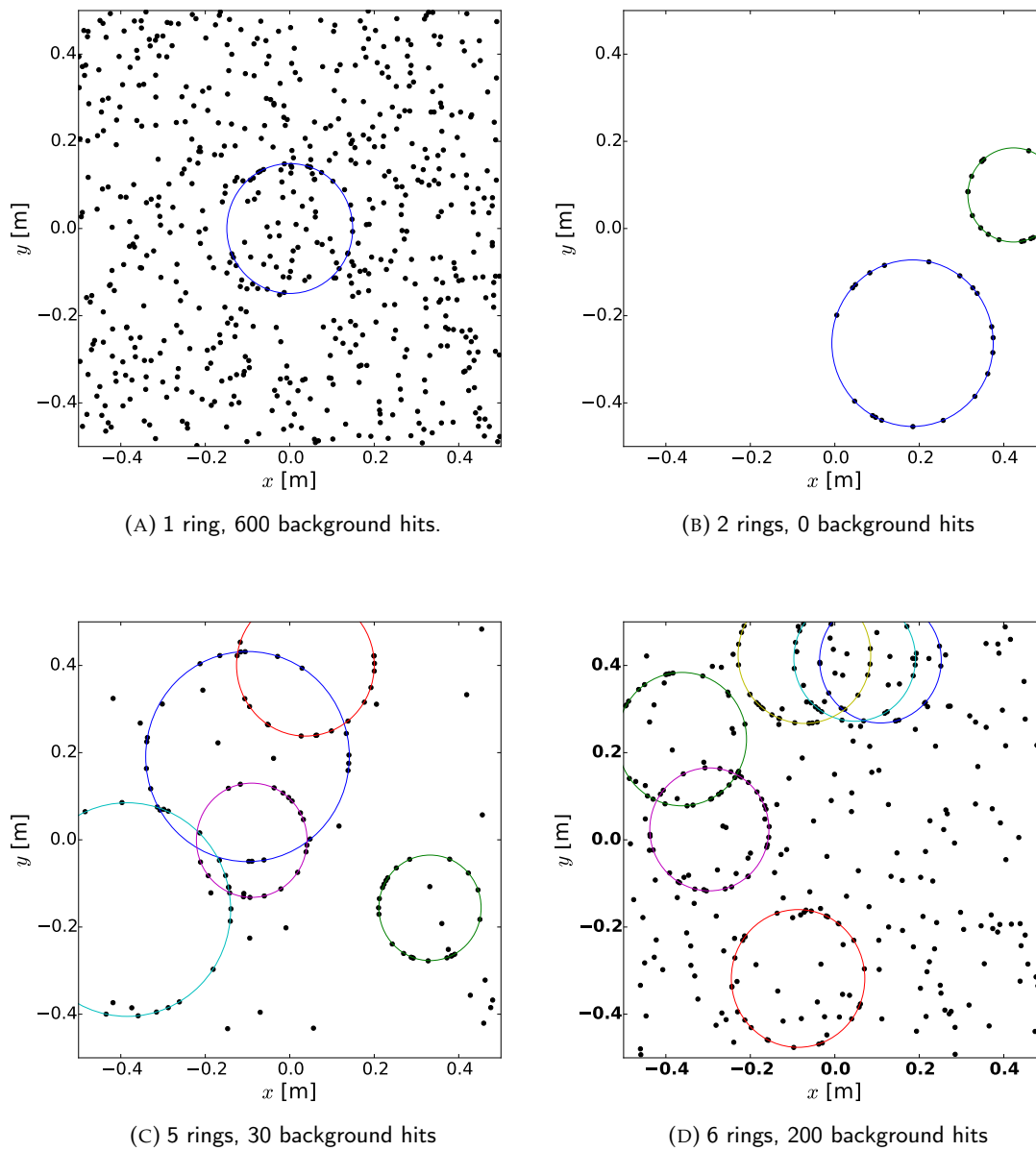


FIG. 4.1 – These are the test events as generated by the simulation.

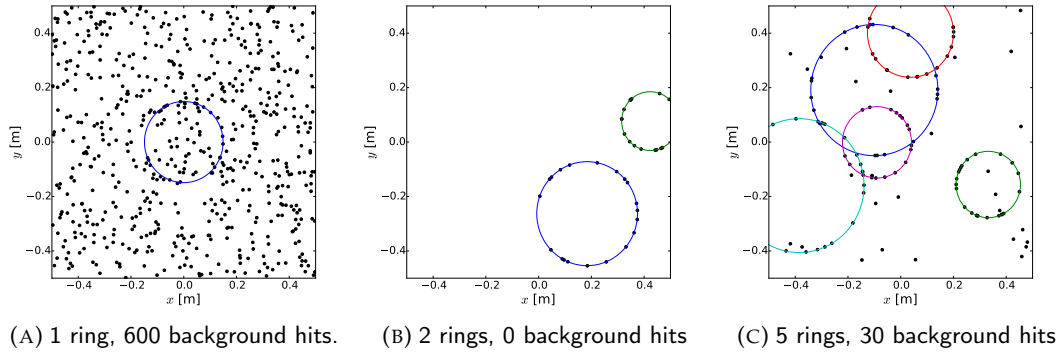


FIG. 4.2 – Circles found by the 1D Hough transform.

TAB. 4.1 – Highest and second highest radius scores for the three events. There is always a big difference between the highest score which determines the circle and the second highest score which is due to noise.

Event	Highest score	2nd highest score
1 circle 600 background hits	8'546	3'798
2 circle 0 background hits	7'904	828
	6'373	857
5 circle 30 background hits	7'519	1'401
	9'085	1'476
	6'758	1'341
	7'381	848
	7'410	1'498

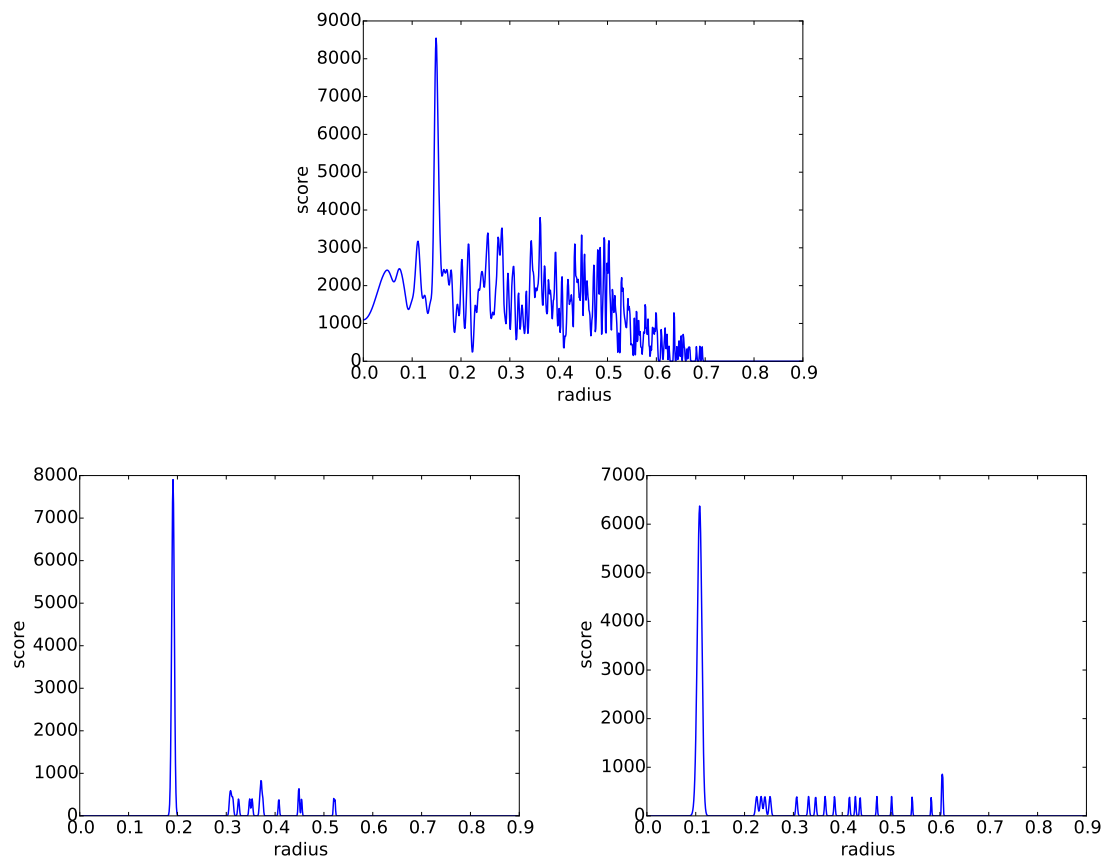


FIG. 4.3 – Radius scores for 1 ring and 600 background hits (top) and 2 rings with 0 background hits (bottom). For the event with only 1 ring and 600 background hits the scores from background hits for a given radius are higher than in the other events with less noise but the correct radius has still a distinct peak.

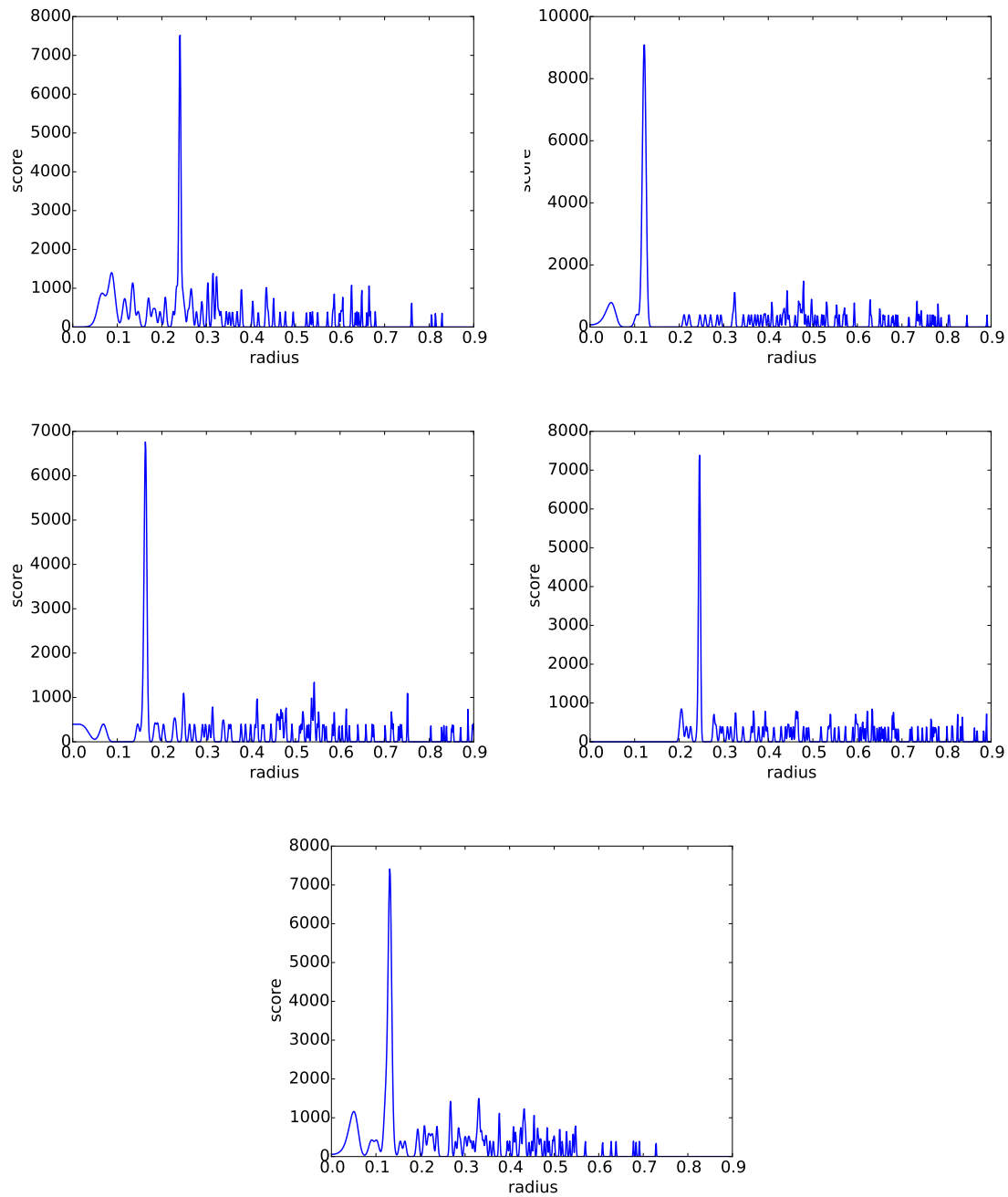


FIG. 4.4 – Radius scores for the 1D Hough transform for the 5 rings with 0 background.

TAB. 4.2 – 2D Radius scores for the different events.

Event	Highest score	2nd highest score
1 circle 600 background hits	8'720	5'778
2 circles 0 background hits	7'904 6'373	2'154 2'275
5 circles 30 background hits	7'488 9'095 6'892 6'498 6'721	4'489 3'717 2'387 2'373 1'953
6 circles 200 background hits	11'869 10'466 8'762 6'872 10'155 4'764	5'583 8'687 5'790 5'203 3'595 3'759

4.2 2D Hough transform

The 2D Hough transform uses again the weight function defined in Equation 3.2 to search for peaks with high score in the (x, y) plane for known ring radiuses. Instead of a 1D histogram it is now a two dimensional histogram in which the highscore has to be found. Figure 4.8 shows how a slice out of this plane looks like (similar to the 1D radius histogram).

The same events as for the 1D Hough transform were investigated. Additionally the results for the event with 6 rings and 200 background hits are shown.

In Figures 4.5 and 4.6 the circles found by the algorithm are shown and in Table 4.2 the highest and second highest score for each event are shown.

4.2.1 1 ring, 600 background hits

The ring was found by the algorithm. The highest and second highest score are well separated.

4.2.2 2 circles, 0 background hits

Both rings are found in this event. Two circles pose no problem unless the two rings have the same radius. If that is the case the algorithm will find the same circle twice unless there is a mechanism that avoids this. Assume the two rings have radius r and the algorithm calculates the weight matrix for the possible center coordinates. There will

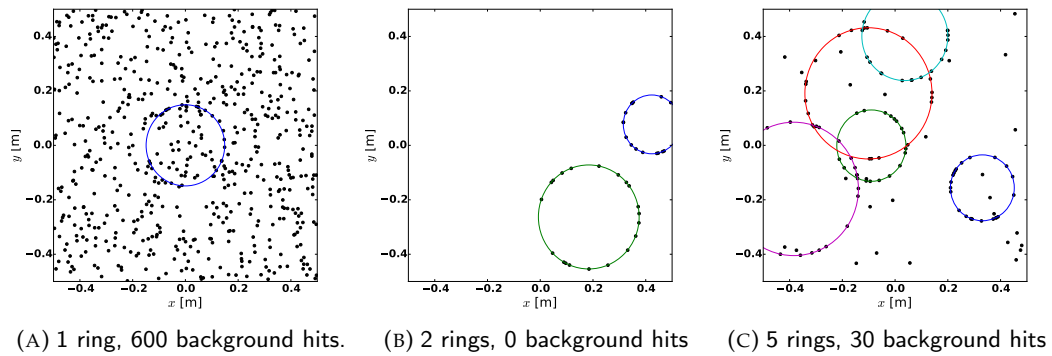


FIG. 4.5 – Circles found by the 2D Hough transform.

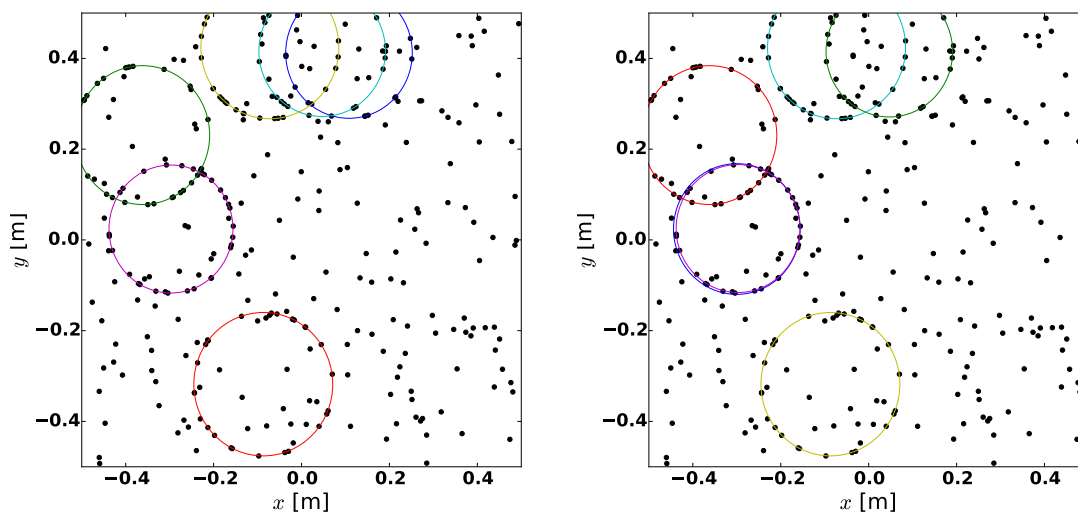


FIG. 4.6 – The rings generated by the simulation (left) and the rings found by the algorithm (right). The blue colored circle found by the algorithm is incorrect.

be two peaks, one for each ring. One peak will have a higher score and the algorithm extracts the coordinates of the peak. After that the algorithm searches the center for the second circle but since both circles have the same radius it will have the same scores again and find the first circle once more. Introducing a mechanism that removes points that were assigned to a circle solves this problem.

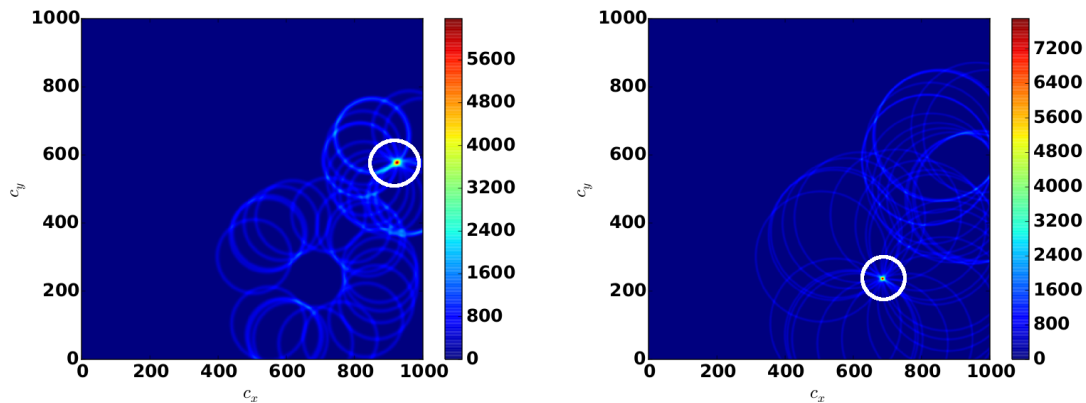


FIG. 4.7 – Center score for the 2D Hough transform for 2 rings with 0 background.

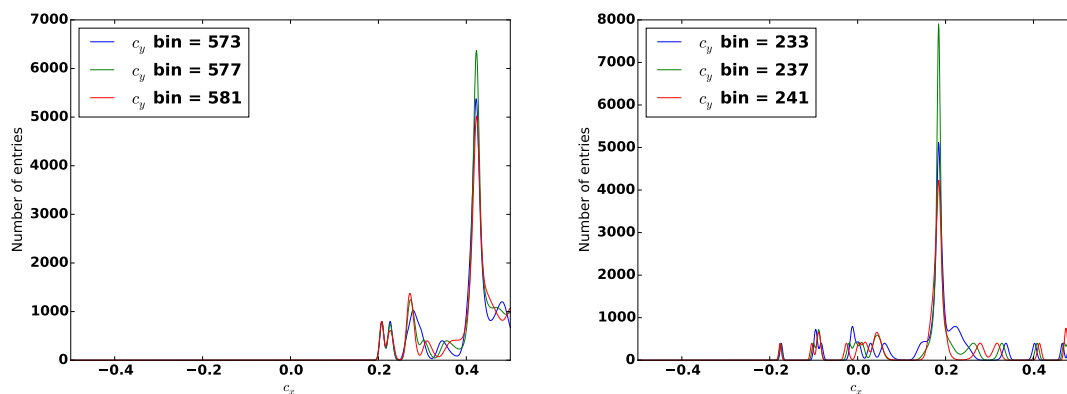


FIG. 4.8 – Horizontal slices (fixed c_y) around the maximum values out of the 2D histogram for the event with 2 circles and no background.

4.2.3 5 rings, 30 background hits

The algorithm had no problems finding all the circles. In Figure 4.9 the score histograms are shown.

4.2.4 6 circles, 200 background hits

As briefly discussed in the overview the algorithm does make mistakes as this event shows. 6 circles were generated with 200 background hits. The interesting part is not that amount of circles or the amount of background hits are the problem but the properties of

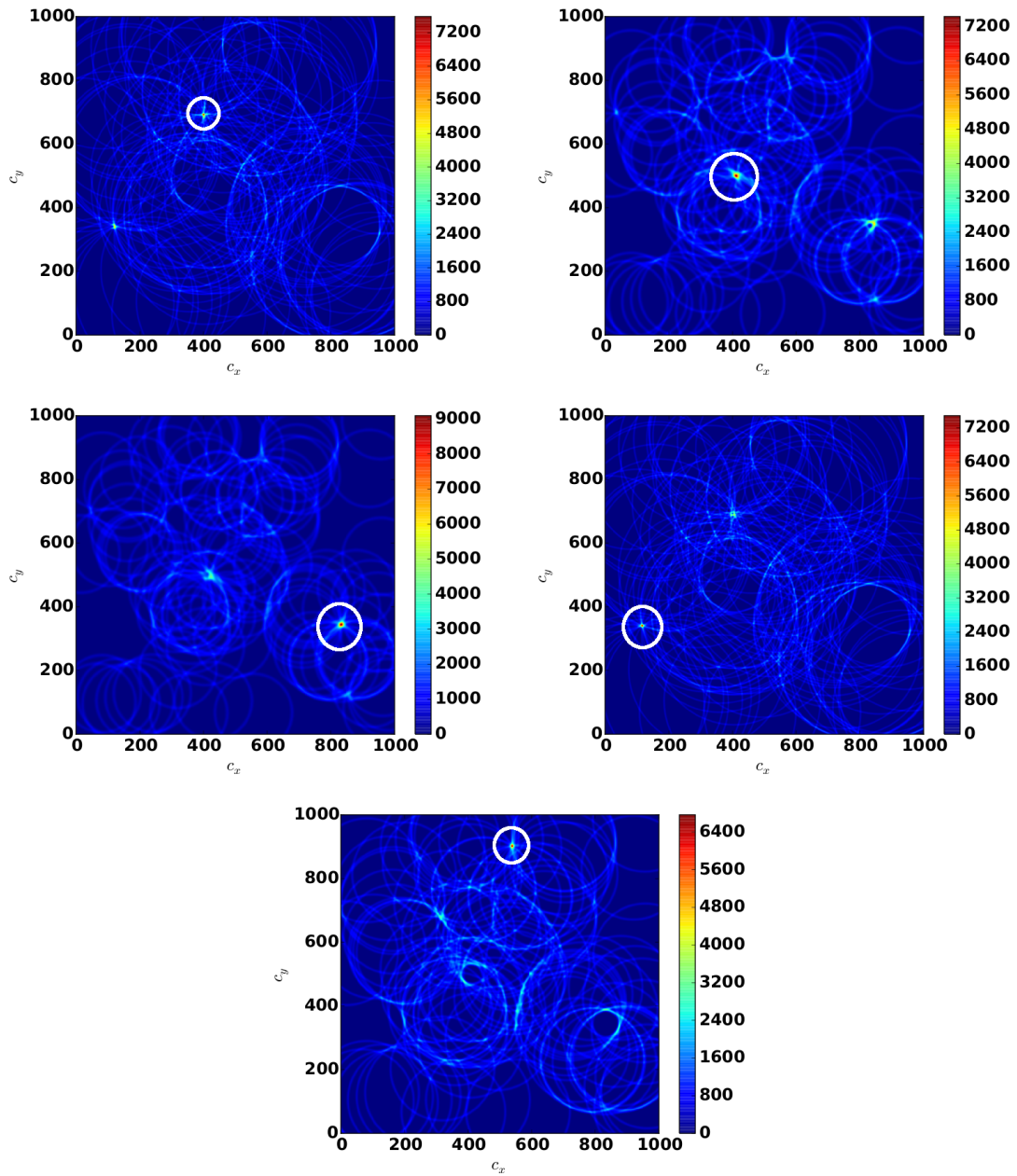


FIG. 4.9 – Scores in the (c_x, c_y) plane found by the 2D Hough transform for the event with 5 rings and 30 background hits.

the circles (center coordinate and radius). In this example there is a misidentification of a circle with points of another.

The reason for the wrong detection of the circle is quite simple. Two of the circles have very similar radiuses. The algorithm looks first for the blue circle (because that happens to be the way the centers are arranged in the list) and since so many points of the magenta circle lie so close together it is easy for the blue circle (who has a similar radius) to get a high score with these points, a higher score than it would get with its proper points. If the magenta points were more evenly distributed on the circle or if there were more blue points this probably would not happen but that is something that cannot be controlled.

Theoretically it is also possible that the magenta circle gets fitted to the blue points but since there are still enough magenta points left after the removal of the points assigned to the blue circle they still have the highest score with their own points and the blue circle goes unnoticed.

Also, if the magenta circle would be checked before blue then the algorithm would find the proper circles as well. So it actually can depend on the order in which the circles are searched.

A possible way to fix this particular problem seemed tuning the parameter of the weight function namely reducing the standard deviation.

$$w(\eta) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(\frac{-\eta^2}{2\sigma^2}\right)$$

Having a higher σ means that a point that is a bit off of the circle still contributes a considerable value to the total score. The smaller the σ is the sharper the peak. However if the peak is too sharp then the algorithm might discard possible results because they are just a bit off the circle and since the peak is so narrow they do not contribute at all to the total score.

Tests with this event have shown that varying the σ parameter was not the leading factor in finding the circle. Even with the smaller σ the algorithm often failed to find the right circles. However, changing the order of the radiuses in which they appear in the list caused the algorithm to find the right circles without changing the σ .

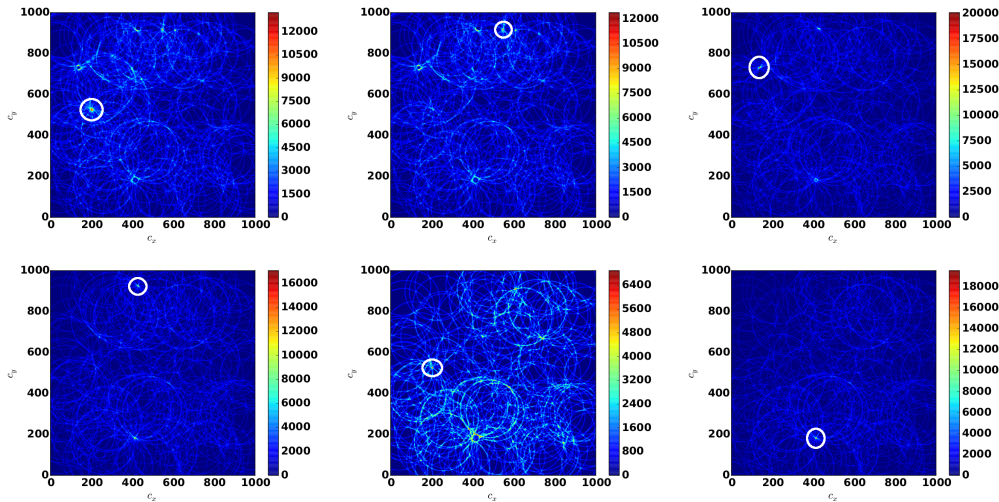


FIG. 4.10 – Scores in the (c_x, c_y) plane found by the algorithm for 6 circles with 200 background hits.

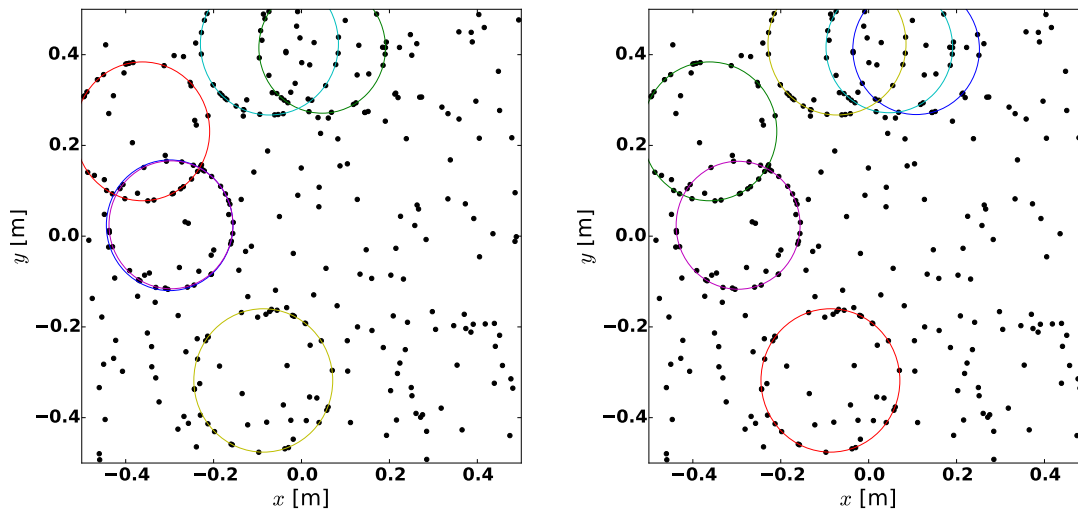


FIG. 4.11 – On the left side the wrong result obtained by the 2D Hough transform and the correct one on the right side

4.3 3D Hough transform Results

The 3D Hough transform has to deal with 3 unknown parameters: (x, y, r) , and the fact that the number of rings is unknown. As explained in Section 3.1.3, a threshold is needed to decide when the algorithm should stop finding a circle. This value depends heavily on the value of the parameter σ of the weight function. Here the σ was set to 0.001 and the threshold was set to 3500. This threshold was determined by looking at the scores of different circles with varying number of points per circle. After testing the algorithm for different events and comparing their scores this threshold found all the circles. Plots of the found circle for the four tested events are shown in Figure 4.12.

4.3.1 3D: Overview of the results

The 3D Hough transform algorithm solves three of the four events correctly. The event that failed was that with 1 circle and 600 background hits where the signal to noise ratio was too small for the algorithm to isolate the correct solution. In Table 4.3 the scores for the 10 highest scores are shown. The threshold was set to 3500. The obvious fix seems to set the threshold to a higher value (e.g. 6300) so the algorithm would not pick up any fake rings. However, with a threshold that high legit rings from other events would get lost. For a fixed threshold there will always be a case where rings get lost or fake rings get picked up. Quantitative study would require to process a larger amount of events which is not done here since the focus in this thesis is on the triplet approach. On the other hand the 3D Hough transform managed to solve the 6 circles with 200 background hits despite having less information. This is probably due to the fact that the 3D Hough transform finds the circles sorted by score and does not depend on the order in which circles are searched (remember, in the 2D case the radius is given and depending on which radius is given first we can solve it correctly or not).

TAB. 4.3 – The ten highest scores found by the 3D Hough transform for the event with 1 ring and 600 background hits.

8'122	6'256	5'672	5'654
5'373	5'290	5'047	5'000
4'727	4'647		

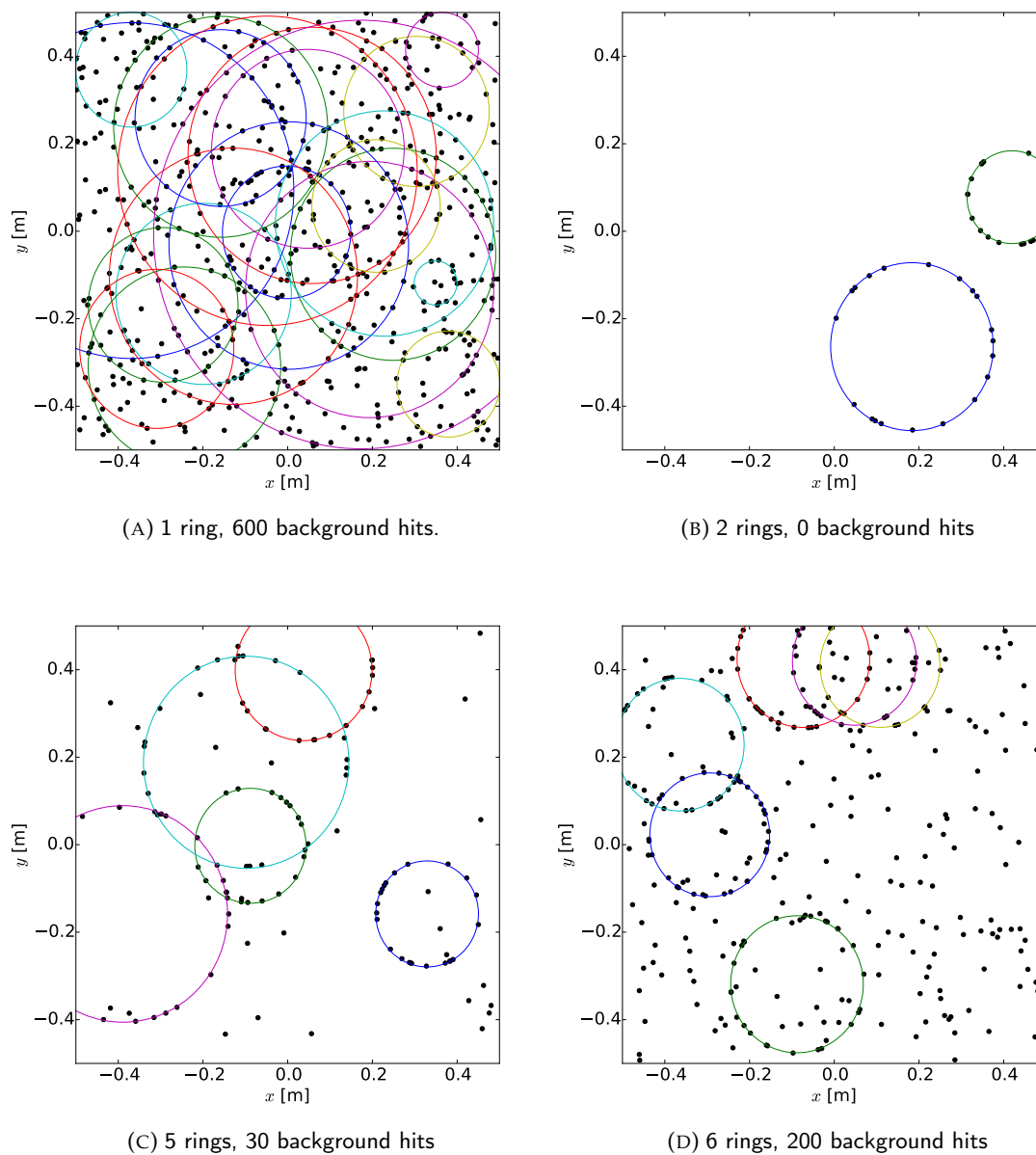


FIG. 4.12 – Circles found by the 3D Hough transform.

TAB. 4.4 – Highest scores and the first fake score for the 3D Hough transform.

	Scores fo the true rings	Highest fake ring score
1 circle 600 background hits	8'122	6'265
2 circles 0 background hits	7'332 5'601	No fakes found
5 circles 30 background hits	8'170 6'979 6'477 4'416 3'536	2'712
6 circles 200 background hits	10'269 9'050 8'505 8'258 5'836 3'944	3'485

TAB. 4.5 – Efficiency and ghost rate for different thresholds (radius and center cuts are fixed at 0.006). The ghost fraction explodes when the ring finding threshold is too low.

Threshold	ϵ	Missed	γ	Fakes
20	99.99%	7	183.22%	91573
35	99.98%	9	131.50%	65723
56	99.97%	16	9.07%	4533
84	99.92%	41	2.13%	1067
165	99.57%	214	0.13%	66
220	99.18%	410	0.05%	27
286	98.43%	784	0.01%	4

4.4 Combinatorial triplet Hough transform

This method was tested against a set of 10'000 events generated in a Monte-Carlo simulation with parameters (number of rings, number of points per ring, number of noise points) tuned to reproduce distributions measured in LHC*b*. The whole set was tested several times, with different thresholds for the radius and center histograms. Each of these runs used the method of splitting the data point list into two lists and building triplets from the sublists as discussed in 3.2.5. The results show that this choice yielded an efficiency above 98%. The performance was evaluated with an analysis script to measure the efficiency ϵ and ghost rate γ .

The efficiency is defined as

$$\epsilon = 1 - \frac{m}{T} \quad (4.1)$$

where m is the number of circles that were not found by the algorithm and T is the true number of rings from summed over all events. The ghost rate is defined as

$$\gamma = \frac{f}{T} \quad (4.2)$$

where f is the number of fake circles that were found by the algorithm but have no match in the test data and T again the total number of circles.

4.4.1 Ring finding threshold

In Table 4.5 the different efficiencies for the algorithm for different values of the threshold can be seen. Intuitively one expects the ghost rate to increase at low threshold since it is more likely for random combinations of triplets to pass the threshold. With increasing threshold the efficiency will drop when legit rings fall below the threshold.

4.4.2 Cuts for removing duplicates

Additional circles can get lost because they get identified as duplicate when they are in fact just another distinct circle in the vicinity of another circle. Duplicate circles that

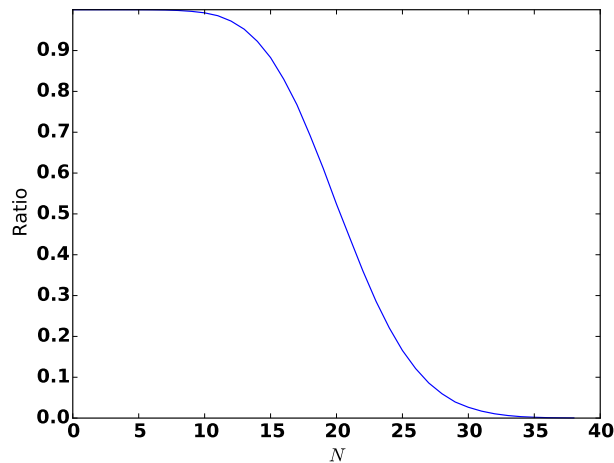


FIG. 4.13 – Reversed cumulative distribution of the points per circle. The plot shows the ratio of circles with more than N points over the total number of circles

are typically created with a major fraction of points of a circle and for example a single background hit that is just far enough off that the radius and center histogram show it as a distinct circle. In Code Snippet 3.9 the duplicate removal is shown. First all ring candidates are sorted ascending by number of entries they had in the center histogram. The first circle is then popped from the list and is compared to all the remaining circles in the list. If the circle is within the threshold distance (see Equations in 3.13) the circle is flagged as not unique and the comparison for the rest of the circles stop.

4.4.3 Comparing algorithm with the data

The parameters to evaluated the performance of the algorithm are:

- Distance between the center of a calculated ring and the corresponding true ring
- Difference between calculated radius and the true radius of a ring

They are used to decide whether or not the algorithm has found a circle. The reconstructed radius and center coordinates are compared with the true test in the test data. If a circle is within these bounds the circle will be considered as found. In a real application however, these parameters are useless because a priori there is no knowledge about the true circles.

Cut variation for a fixed ring finding threshold

In Tables 4.6 and 4.7 different cut parameters were tested and compared for the efficiency and ghost rate.

Tables 4.8 show all combinations of cuts for both radius and center ranging from 0.003 to 0.0012 in steps of 0.003 for different ring finding thresholds.

TAB. 4.6 – Efficiency and ghost rate for a fixed radius cut (0.003) and ring finding threshold (120) with varying center cut. The tighter the center cut is the more duplicate circles remain after the clean up.

C cut	ϵ	Missed	γ	Fakes
0.003	99.19%	405	0.17%	86
0.006	99.19%	407	0.12%	62
0.009	99.18%	409	0.12%	60
0.012	99.17%	415	0.12%	60

TAB. 4.7 – Reducing ghost rate for a fixed center cut (0.003) with varying center cut. The tighter the center cut is the more duplicate circles fail being detected by the removeDuplicate code shown above

R cut	ϵ	Missed	γ	Fakes
0.003	99.19%	405	0.17%	86
0.006	99.19%	405	0.15%	77
0.009	99.19%	405	0.15%	77
0.012	99.19%	405	0.15%	76

TAB. 4.8 – Results for all the cut combinations for radius and center cuts

Threshold = 35 (7 points for a circle)					
R cut	C cut	ϵ	Missed	γ	Fakes
0.003	0.003	99.99%	4	178.96%	89444
0.003	0.006	99.99%	6	151.62%	75777
0.003	0.009	99.98%	8	144.59%	72264
0.003	0.012	99.97%	13	140.88%	70408
0.006	0.003	99.99%	4	174.01%	86968
0.006	0.006	99.98%	9	131.50%	65723
0.006	0.009	99.96%	19	118.91%	59432
0.006	0.012	99.94%	28	113.54%	56745
0.009	0.003	99.99%	4	173.53%	86729
0.009	0.006	99.98%	12	130.54%	65244
0.009	0.009	99.95%	25	112.21%	56079
0.009	0.012	99.93%	36	103.50%	51727
0.012	0.003	99.99%	4	173.30%	86612
0.012	0.006	99.97%	15	130.26%	65103
0.012	0.009	99.94%	32	111.64%	55795
0.012	0.012	99.91%	47	99.85%	49902
Threshold = 56 (8 points for a circle)					
R cut	C cut	ϵ	Missed	γ	Fakes
0.003	0.003	99.98%	11	20.54%	10264

0.003	0.006	99.97%	13	14.52%	7255
0.003	0.009	99.97%	15	13.59%	6792
0.003	0.012	99.96%	21	13.24%	6616
0.006	0.003	99.98%	11	19.23%	9611
0.006	0.006	99.97%	16	9.07%	4533
0.006	0.009	99.95%	26	7.29%	3641
0.006	0.012	99.93%	35	6.82%	3409
0.009	0.003	99.98%	11	19.14%	9568
0.009	0.006	99.96%	19	8.91%	4454
0.009	0.009	99.94%	32	5.90%	2950
0.009	0.012	99.91%	43	4.94%	2467
0.012	0.003	99.98%	11	19.10%	9544
0.012	0.006	99.96%	22	8.87%	4432
0.012	0.009	99.92%	39	5.81%	2906
0.012	0.012	99.89%	54	4.29%	2143

Threshold = 84 (9 points for a circle)

<i>R cut</i>	<i>C cut</i>	ϵ	Missed	γ	Fakes
0.003	0.003	99.93%	36	5.82%	2911
0.003	0.006	99.92%	38	4.00%	1999
0.003	0.009	99.92%	40	3.80%	1900
0.003	0.012	99.91%	46	3.72%	1861
0.006	0.003	99.93%	36	5.37%	2682
0.006	0.006	99.92%	41	2.13%	1067
0.006	0.009	99.90%	51	1.66%	830
0.006	0.012	99.88%	60	1.57%	787
0.009	0.003	99.93%	36	5.34%	2671
0.009	0.006	99.91%	44	2.09%	1044
0.009	0.009	99.89%	57	1.27%	636
0.009	0.012	99.86%	68	1.07%	534
0.012	0.003	99.93%	36	5.33%	2665
0.012	0.006	99.91%	47	2.08%	1040
0.012	0.009	99.87%	64	1.25%	626
0.012	0.012	99.84%	79	0.88%	439

Threshold = 165 (11 points for a circle)

<i>R cut</i>	<i>C cut</i>	ϵ	Missed	γ	Fakes
0.003	0.003	99.58%	209	0.48%	238
0.003	0.006	99.58%	211	0.32%	162
0.003	0.009	99.57%	213	0.31%	156
0.003	0.012	99.56%	219	0.31%	155
0.006	0.003	99.58%	209	0.42%	209
0.006	0.006	99.57%	214	0.13%	66
0.006	0.009	99.55%	224	0.10%	50
0.006	0.012	99.53%	233	0.10%	49
0.009	0.003	99.58%	209	0.42%	209

0.009	0.006	99.57%	217	0.13%	64
0.009	0.009	99.54%	230	0.07%	34
0.009	0.012	99.52%	241	0.05%	26
0.012	0.003	99.58%	209	0.42%	208
0.012	0.006	99.56%	220	0.13%	64
0.012	0.009	99.53%	237	0.07%	34
0.012	0.012	99.50%	252	0.04%	18

Threshold = 220 (12 points for a circle)

<i>R cut</i>	<i>C cut</i>	ϵ	Missed	γ	Fakes
0.003	0.003	99.19%	405	0.17%	86
0.003	0.006	99.19%	407	0.12%	62
0.003	0.009	99.18%	409	0.12%	60
0.003	0.012	99.17%	415	0.12%	60
0.006	0.003	99.19%	405	0.15%	77
0.006	0.006	99.18%	410	0.05%	27
0.006	0.009	99.16%	420	0.04%	21
0.006	0.012	99.14%	429	0.04%	21
0.009	0.003	99.19%	405	0.15%	77
0.009	0.006	99.17%	413	0.05%	25
0.009	0.009	99.15%	426	0.02%	11
0.009	0.012	99.13%	437	0.02%	9
0.012	0.003	99.19%	405	0.15%	76
0.012	0.006	99.17%	416	0.05%	25
0.012	0.009	99.13%	433	0.02%	11
0.012	0.012	99.10%	448	0.01%	6

Threshold = 286 (13 points for a circle)

<i>R cut</i>	<i>C cut</i>	ϵ	Missed	γ	Fakes
0.003	0.003	98.44%	779	0.05%	25
0.003	0.006	98.44%	781	0.03%	17
0.003	0.009	98.43%	783	0.03%	16
0.003	0.012	98.42%	789	0.03%	16
0.006	0.003	98.44%	779	0.04%	21
0.006	0.006	98.43%	784	0.01%	4
0.006	0.009	98.41%	794	0.01%	3
0.006	0.012	98.39%	803	0.01%	3
0.009	0.003	98.44%	779	0.04%	21
0.009	0.006	98.43%	787	0.01%	4
0.009	0.009	98.40%	800	0.00%	2
0.009	0.012	98.38%	811	0.00%	2
0.012	0.003	98.44%	779	0.04%	21
0.012	0.006	98.42%	790	0.01%	4
0.012	0.009	98.39%	807	0.00%	2
0.012	0.012	98.36%	822	0.00%	2

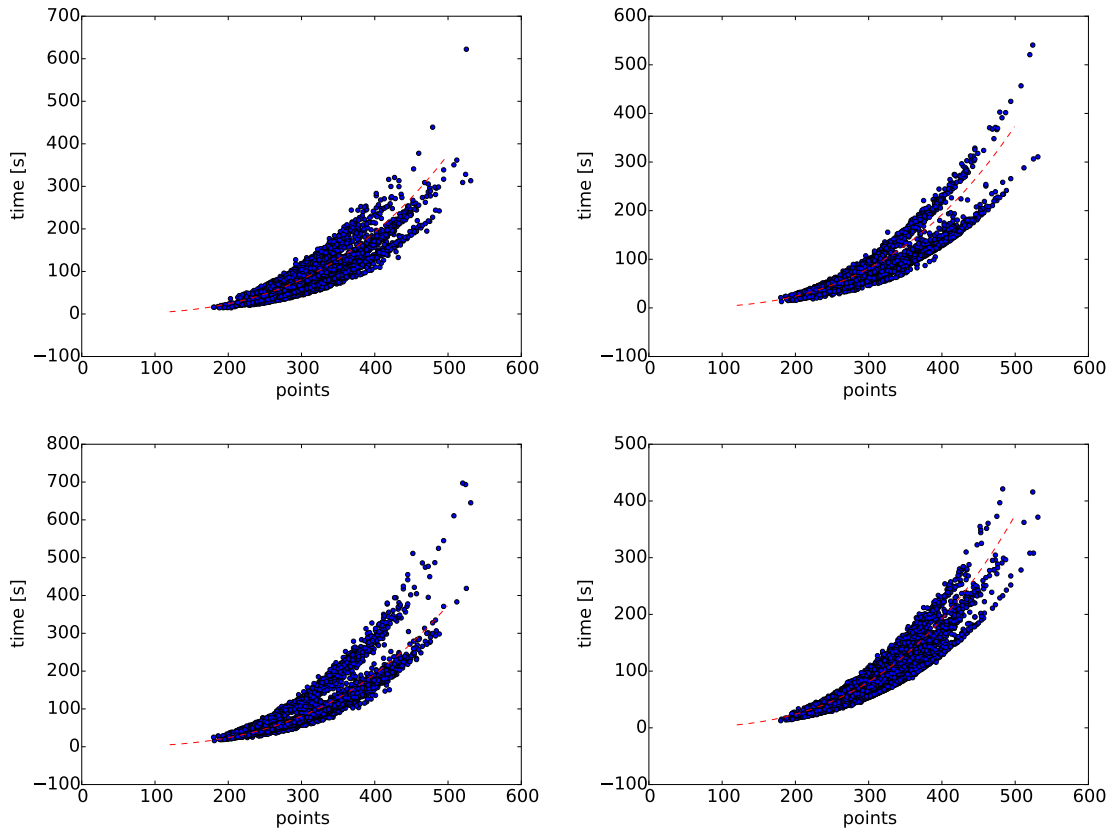


FIG. 4.14 – Runtimes of four different runs with different ring finding thresholds.

These results show that the most important parameter for changing the ghost rate is the ring finding threshold. If this threshold is too low, too many fake rings are found from random point combination that happen to lie close to a circle.

The main reason for missed rings is again the ring finding threshold since it limits the number of rings being found. Since the algorithm uses two split lists, the number of missed circles is even slightly higher due to the fact that sometimes the points of a circle can be split just in a way that the two lists do not contain enough points individually to create an accepted circle (see subsection 3.2.3).

4.4.4 Execution time

The execution time of the whole algorithm depends strongly on the number of data points. The runtime ranges from several seconds to several minutes as shown in Figure 4.14. The algorithm was run on the farm-ui cluster of the University of Zurich. The worknodes are not identical. This could explain why there is branching in the runtime when some nodes are slightly quicker than the other. The fit in the plot is $1.8e-5 \frac{N^3}{6}$ where N is the number of data points to show the dependency of the runtime on the points. The constant factor was determined by trial and error but is for all the plots the same.

5 Conclusions

This thesis studied different Hough transforms for ring detection in the LHC*b* detector. In a first approach a 1D Hough transform was used and then extended to two and three dimensions. As a fourth approach a new method based on triplets of hits was developed for the ring detection.

First of all it should be noted that especially the one, two and three dimensional Hough transforms were only superficially studied. Their study served more of an introduction into the Hough transform by adding extra dimensions for each case. The statements regarding these methods should always be considered with this in mind.

The 1D Hough transform assumes the number of rings and ring centers are known and searches for maximas in the r distribution for each rings. It is a very stable method having no trouble to find different rings in different kinds of set ups. Even high background does not seem to impede the efficiency of the method. It is also a faster than all the other approaches since it only has to search a one dimensional histogram.

The 2D Hough transform assumes the number of rings and radiuses are known and searches for maxima in the (x, y) distribution for each ring. It shows a good performance as well but it suffers from lower speed due to the increased complexity namely searching 2 dimension for the parameters instead of just one. Another problem is also the misidentification of rings based on the order in which they are searched for and possibly also the sensitivity of the weight function used to weigh the centers for a given data points and radius.

The 3D Hough transform does not make any assumptions on the number of rings or ring parameters. The main weakness of this method is the score threshold which tells the algorithm when to stop looking for a ring (the 1D and 2D transform did not have this problem since due to the information given it was known, how many rings there were). If the threshold is too low, too many fake rings can be formed by random combinations of (background) hits. - if it's too high a valid ring might get lost. The difficulty in defining a score threshold is that it is based on the scoring function 3.2. Depending on the σ chosen the scoring function can behave quite differently. A problem related to that is that the 3D Hough transform strongly depends on the bin size of the parameter space. The bins should not be large big or the algorithm becomes inaccurate because the scoring function uses inaccurate values. If the bins are too small, the algorithm takes forever due to the $\mathcal{O}(N^3)$ complexity. But the disadvantage can also have advantages because now the algorithm does not depend anymore on the order of which it looks for rings - it always picks the strongest candidates first and every subsequent candidate has a lower score until the score is so low that it's unlikely that it is a ring.

Finally the main part of this thesis discusses the combinatorial triplet Hough transform. It is based on the fact that 3 points define a ring. Given 3 points in a 2D space it is possi-

ble to calculate the center and radius of the ring on which these 3 points lie. Given a list of points a creating a list of all possible triplets can be used to find possible rings. The algorithm works very well and maintains a high efficiency with all tested parameters but suffers as the 3D Hough transform from a high runtime (up to several minutes). However given the high accuracy of the algorithm in determining the ring parameters makes this approach still very interesting and may offer potential for future investigations. The parameter with the largest impact is the ring finding threshold which defines how many points need to lie on a ring in order to qualify as a circle candidate. Choosing this threshold too low many fake circles appear and the ghost rate skyrockets. Setting this threshold too high means an inherent loss of efficiency from which the algorithm can never recover since circles with a point count lower than the threshold will never be considered as a candidate.

5.1 Outlook

As a next step the possibility of parallelising the algorithm should be considered. Once the two triplet lists are generated the radius and centers for these triplets can be calculated independently. Other options for optimisation would be improving the code. Some steps have already been done. For example instead of using the `np.linalg.norm` function of the numpy module (which has a high overhead see [16]) a simple norm function has been implemented. There was not enough time to test the speed improvement systematically but a profiling of one event showed an improvement of the speed from 188 s to 95 s. In general, the method where radius and center of triplets get calculated would be a good start to optimise the code since that's the place where the algorithm spends most of its time (shown by profiling the python script but not shown in this thesis).

Bibliography

- [1] Philipp Gloor. *New Approach for a Circle Hough Transform to Detect Cherenkov Rings in the LHCb RICH detector - Source Code*. Online. URL: <https://github.com/fibbo/CircleHoughTransform>.
- [2] Georges Aad et al. "The ATLAS experiment at the CERN large hadron collider". In: *Journal of Instrumentation* 3.8 (2008).
- [3] Kenneth Aamodt et al. "The ALICE experiment at the CERN LHC". In: *Journal of Instrumentation* 3.08 (2008), S08002.
- [4] A Augusto Alves Jr et al. "The LHCb detector at the LHC". In: *Journal of instrumentation* 3.08 (2008), S08005.
- [5] CMS Collaboration, R Adolphi, et al. "The CMS experiment at the CERN LHC". In: *Jinst* 3.08 (2008), S08004.
- [6] LHCb Collaboration. *The LHCb Detector*. Online. URL: <http://lhcb-public.web.cern.ch/lhcb-public/en/Detector/Detector-en.html>.
- [7] A. A. Alves Jr. et al. "Performance of the LHCb muon system". In: *JINST* 8 (2013), P02022. DOI: 10.1088/1748-0221/8/02/P02022. arXiv: 1211.1346 [physics.ins-det].
- [8] TDR LHCb. *RICH technical design report*. Tech. rep. CERN-LHCC-2000-037, 2000.
- [9] RICH LHCb. "Technical Design Report". In: *CERN/LHCC* 37 (2000), p. 2000.
- [10] Richard O. Duda and Peter E. Hart. "Use of the Hough Transformation to Detect Lines and Curves in Pictures". In: *Commun. ACM* 15.1 (Jan. 1972), pp. 11–15. ISSN: 0001-0782. DOI: 10.1145/361237.361242. URL: <http://doi.acm.org/10.1145/361237.361242>.
- [11] H.P.V.C. *Method and means for recognizing complex patterns*. US Patent 3,069,654. Dec. 1962. URL: <https://www.google.com/patents/US3069654>.
- [12] M. Adinolfi et al. "Performance of the LHCb RICH detector at the LHC". In: *Eur. Phys. J. C* 73 (Nov. 2012), p. 2431. DOI: 10.1140/epjc/s10052-013-2431-9. eprint: 1211.6759.
- [13] Roger Forty, LHCb Collaboration, et al. "RICH pattern recognition for LHCb". In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 433.1 (1999), pp. 257–261.
- [14] Christian Blatter. *The expected area of a triangle formed by three points randomly chosen from the unit square*. Online. Apr. 2015. URL: <http://math.stackexchange.com/questions/1236958/the-expected-area-of-a-triangle-formed-by-three-points-randomly-chosen-from-the>.
- [15] Eric W. Weisstein. *Circle Triangle Picking*. Online. URL: <http://mathworld.wolfram.com/CircleTrianglePicking.html>.

-
- [16] numpy. *Source code for numpy.linalg.norm*. Online. Apr. 2015. URL: <https://github.com/numpy/numpy/blob/v1.10.0/numpy/linalg/linalg.py#L1976-L2221>.