Physics with Year Abroad, Literature Review: Particle Identification in Modern Cherenkov Detectors

Daniel Markhoff

School of Physics and Astronomy, University of Edinburgh, Edinburgh, UK and GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany

(Dated: 24 December 2025)

With major detector assemblies lining up for construction at high-energy facilities such as EIC and FAIR, technologies for particle identification are becoming ever more relevant. This review motivates the theory of the field, introduces the technologies behind modern Cherenkov detectors, and discusses the implementation of these detectors into upcoming experiments. Emphasis is placed on event reconstruction techniques and the challenges presented by cutting-edge physics programmes. Persistent challenges include . . . We conclude by outlining promising future developments for Cherenkov detectors.

CONTENTS

I. INTRODUCTION

Modern high energy physics experiments rely on the performance of the detector systems to accurately study collision events. Cherenkov based detectors will play a central role in the upcoming generation of experiments. Improving the capabilities of these detectors is the work of thousands of physicists and engineers around the world.

This review aims to provide an introduction to the field of Cherenkov specific systems for particle identification (PID). We will cover the basic principles of Cherenkov radiation, the design and operation of the two main types of Cherenkov detectors, and briefly over the latest advancements in technology.

We will begin with an overview of the necessary theoretical background in §II, and then introduce photomultipliers, the ever-so important devices that detect photons in §III. Following this, we will delve into the three main types of Cherenkov detectors in §IV.A, §IV.B, and §V, where over the chapters we will discuss their designs, principles of operation, and differences. Finally, we will explore the implementation of these detectors in upcoming experiments in §VI, and conclude with a discussion of some open research in §VII.

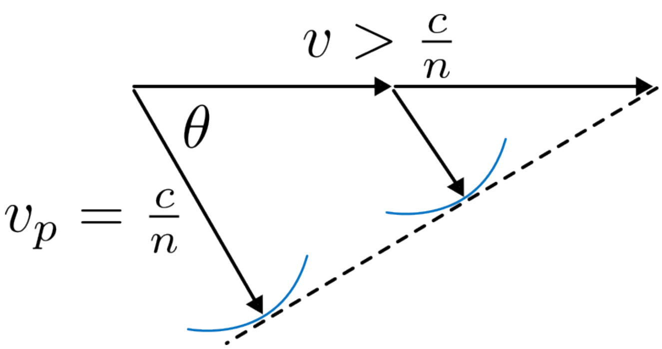

FIG. 1 **Schematic of a Cherenkov cone.** A particle travels through a medium with velocity v. Photons are emitted at the phase velocity v_p and angle θ to the path of travel of the particle, giving the characteristic blue shock cone.

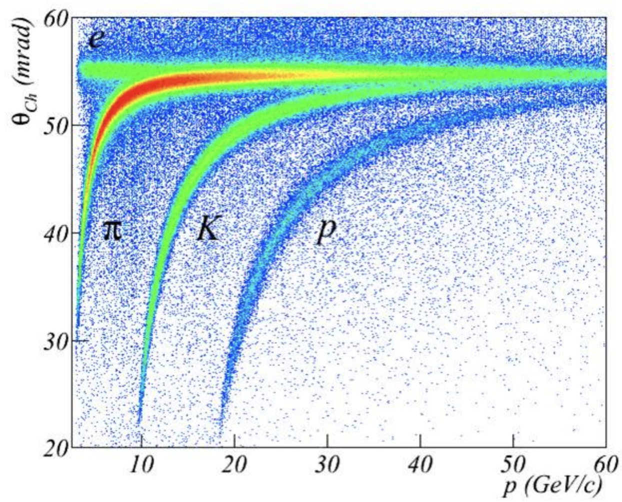

FIG. 2 **Cherenkov spectroscopy of the COMPASS RICH-1 detector at CERN.** There are clear curves for different particle species. These curves can be determined mathematically using (1) and relativistic dynamics[3].

II. THEORETICAL FOUNDATIONS

II.A. Cherenkov Radiation

Cherenkov radiation is a phenomenon that occurs when a charged particle travels through a dielectric medium with refractive index $n(\lambda)$ at a speed greater than the phase velocity in that medium. This effect was first observed by Pavel Cherenkov in 1934[1] and later explained theoretically by Ilya Frank and Igor Tamm[2].

From Maxwell's equations arises that electromagnetic propagation with wavelength λ will have its phase velocity modified by the medium it is travelling through. This leads to the idea of refractive index $n(\lambda) = c/v$, defined as the ratio between the speed of light in vacuum c and the phase velocity v in the medium. The condition for Cherenkov radiation to occur is then given by $v > c/n$.

The Cherenkov radiation itself propagates at the phase velocity of the medium. As such, the radiation forms a conical wavefront with characteristic angle θ, similar to how shock cones are formed by supersonic aircraft. The angle θ can be derived from simple geometric considerations shown in Fig 1, yielding the following:

$$\cos\theta = \frac{v_p}{v} = \frac{c}{nv} \tag{1}$$

The main principle behind a Cherenkov detector is to measure the angle θ of the emitted photons, which can then be used to determine the velocity v of the charged particle. With an associated momentum measurement from a forward tracking detector, the mass of the particle can be inferred, allowing for spectroscopy. This velocity spectroscopy for various particle species is shown in Fig 2. It can be seen that pions, for example, will produce a larger Cherenkov angle than kaons or pions at the same momentum, due to them being less massive.

The energy dE emitted per unit length is given by the Frank-Tamm formula, which can be expressed as

$$\frac{dE}{dx} = \frac{q^2}{4\pi}\int_{v>\frac{c}{n(\omega)}} \mu(\omega)\omega\left(1 - \frac{c^2}{v^2 n^2(\omega)}\right) d\omega \tag{2}$$

for a particle with charge q and frequency ω, moving through a medium with permeability μ and refractive index $n(\omega)$. The integral is taken over all frequencies where the Cherenkov condition $v = c/n(\omega)$ is met. By changing variables to wavelength λ and using that $E = Nh\omega$, one can show that the number of photons N emitted per unit length is inversely proportional to the square of the wavelength. This explains the characteristic blue of Cherenkov radiation, as shorter wavelength (blue light) photons are emitted more.

II.B. Relativistic Kinematics

Relativistic kinematics is the study of the motion of particles at near-light speeds. The purposes of this review do not require an exhaustive treatment of the subject, but a few key concepts pertaining to Cherenkov radiation and detector physics are summarised.

The famous energy-mass relation is written as:

$$E^2 = p^2c^2 + m_0^2c^4 \tag{3}$$

for a particle with energy E, momentum p and rest mass m_0. The Lorentz factor arises from considering the four-velocity, and defines a mapping between the rest frame of the particle (the frame in which the particle's velocity is zero) and the observer's frame. It is defined as:

$$\gamma = \frac{1}{\sqrt{1-\beta^2}} \tag{4}$$

where $\beta = v/c$ is the velocity of the particle as a fraction of the speed of light. We can use the Lorentz factor to transform Newtonian quantities into their relativistic

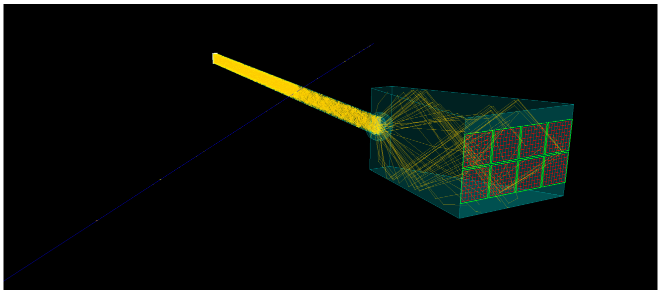

FIG. 3 **Simulated event display of PANDA Barrel DIRC.** The blue track is a charged particle incident on the detector, and the yellow tracks are all Cherenkov photons. There is a mirror at the far end of the radiator bar, causing all photons to eventually reach the detector array.

equivalents using the equations

$$p = \gamma m_0 v \tag{5}$$

$$E = \gamma m_0 c^2 \tag{6}$$

Using (5) and (6) we can rewrite the Cherenkov angle condition from (1) as

$$\cos\theta = \frac{c}{nv} = \frac{E}{npc} = \frac{\sqrt{p^2 + m^2c^2}}{np} \tag{7}$$

where one can clearer see how a combination of the Cherenkov angle and the momentum measurements can be used to infer the mass of the particle. This equation can be used to plot the theoretical curves for the experimental data in Fig 2.

Often in detector assemblies, the Cherenkov detectors will receive momentum measurements from forward detectors. Then, the statistics from the Cherenkov detectors are so impressive, that the detectors are usually able to decisively improve on the forward detector's measurements. This is especially true for DIRC detectors, which have an excellent angular resolution.

II.C. Optical and Imaging Theory

Cherenkov detectors rely heavily on the principles of optics to guide and detect emitted photons. Key concepts include Snell's law, total internal reflection, and the behaviour of light in various media. Fig 3 shows a simulated event display of PANDA's Barrel DIRC detector[4], illustrating how photons are internally reflected within the radiator bars and subsequently focused going into the trapezoidal expansion volume before being detected by the photodetector array.

One can imagine how important the optical properties and the geometry of the detector are to optimise things such as photon yield and angular resolution. All things told, the PANDA Barrel DIRC is actually a relatively rudimentary design compared to more recent simulations for EIC DIRC detectors, which employ more complex focusing optics to improve performance. This will be discussed further in § sec:photon-optics and § sec:applications-at-future-facilities.

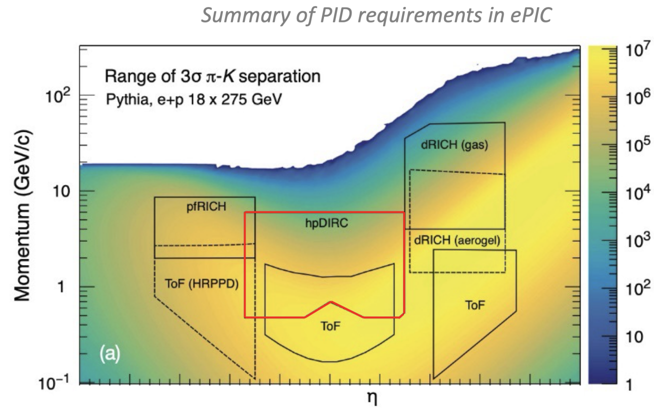

FIG. 4 **The ePIC PID requirements.** The pfRICH, hpDIRC and dRICH are all Cherenkov based detectors that are expected to perform 3σ pion and kaon separation at momenta between around 1 and 10 GeV, Here, η represents the pseudorapidity[5]

II.D. Particle Physics Motivation

Detector assemblies are becoming ever more complex out of necessity, as the continual push for higher precision measurements dominates the investigation into quantum chromodynamics. Many types of particle physics experiments require particle identification (PID) of hadrons such as pions, kaons and protons to observe rare processes or other heavy-ion collisions. These PID requirements often span across extensive momentum and solid angle ranges; Cherenkov detectors are excellent at fulfilling these requirements.

For example, at the upcoming ePIC experiment at the Electron-Ion Collider (EIC), Cherenkov methods will be used to provide hadron PID across essentially all high momentum ranges, as shown in Fig 4. These detector performance metrics will be crucial to the experiment's physics goals towards investigating things such as nucleon spin, sea quarks, and high energy gluon behaviour.

To summarise, hadron detection is extremely important for flavour tagging and thus event reconstruction in these QCD processes. That is why Cherenkov detectors are imperative components of cutting edge detector assemblies.

II.E. Statistical and Algorithmic Foundations of Event Reconstruction

The problem of event reconstruction in modern Cherenkov detectors is to determine what happened inside the detector based on the data obtained from the photon sensors. The most common current way of doing this is as a reverse ray-tracing problem. An algorithm iterates through the possible paths a photon can take through the detector, and evaluates a Gaussian likelihood under the hypothesis of each particle type[6]. This likelihood is built from the spatial and temporal residuals between the detected photon hits and the expected photon hits from the ray-tracing. For example, a Gaussian timing likelihood can be expressed as:

$$\mathcal{L}_h = \prod_{i=1}^{N} \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(t_i - \langle t_{i,h}\rangle)^2}{2\sigma^2}\right) \tag{8}$$

where t_i is the detected time of the i-th photon, $\langle t_{i,h}\rangle$ is the expected time of the i-th photon under hypothesis h, and σ is the timing resolution of the detector system. The hypothesis h can be for example a pion or a kaon. Note that many algorithms choose to use non-Gaussian likelihoods. By calculating the likelihood for each hypothesis, we can then form a log-likelihood ratio to determine which hypothesis is more probable:

$$\Delta \log \mathcal{L} = \log \mathcal{L}_{\text{kaon}} - \log \mathcal{L}_{\text{pion}} \tag{9}$$

This can be minimised across all detector hits to find the most probable particle type using various numerical methods. Variations on this spatial method include time-imaging[7], where the spatial information is largely ignored and instead the timing information is used to build probability density functions (PDFs) for each particle hypothesis. The detected photon times are then compared to these PDFs to form the likelihoods. Modern algorithms use a combination of spatial, temporal, and even angular information from other sub-detectors to build more robust likelihood functions.

In general, likelihood methods serve many detector assemblies well. However, they are in essence a brute-force method, held back by computation limitations. One potential new-age solution is the use of machine learning (ML). This aims to skip all of the setup and calculations surrounding the likelihood methods, and rather let a neural network learn how the detector reacts to certain particles, implicitly encoding all of the likelihood-like reasoning. This has already seen encouraging results on Geant4 simulated data for the Hyper-Kaminokande experiment[8] and for the PANDA Barrel DIRC[9].

III. PHOTON DETECTION TECHNOLOGIES

III.A. MCP-PMTs

Multichannel plate photomultipliers (MCP-PMTs) are devices that convert and amplify incoming photons into a measurable electrical signal. Photons incident on a photocathode emit electrons through the photoelectric effect. These electrons are difficult to measure as an electrical signal, so the number of electrons is amplified using a multichannel plate. These are thin wafers that contain thousands of μm capillaries. Via secondary emission, more electrons than are incident are produced[10]. This amplified electron signal is then incident on an anode plate, where the signal is read as an analogue voltage.

In detector physics we are interested in a few properties of MCP-PMTs. Firstly, the quantum efficiency (QE) of the photocathode is the probability of an incident photon producing a photoelectron. Around 20% are typical for modern MCP-PMTs. The requirements for the PANDA Barrel DIRC ask for a QE of 18% between 300–400nm[12].

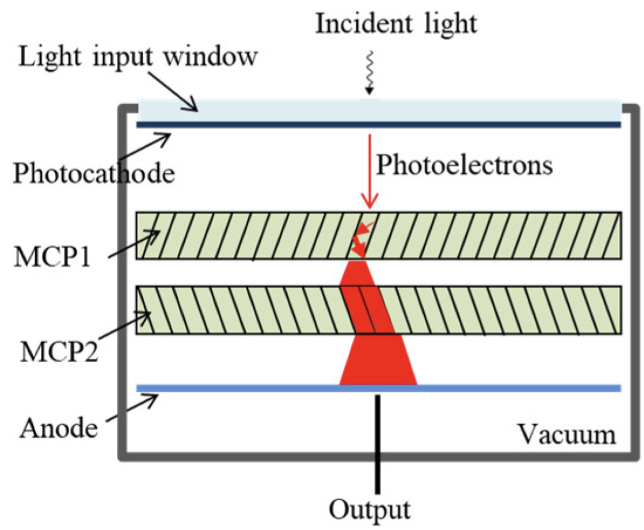

FIG. 5 **Cross section of a traditional MCP-PMT.** Due to the proximity of the anode and the photocathode, we are able to determine where the incident photon hit on the photocathode. MCP-PMTs are used in an incredible range of fields, from blood tests, to spectroscopy, to radar jamming[11].

Secondly, the consistency of accurate hits is of great interest. We want uniform gain across the entire MCP-PMT, and we do not want secondary electron emissions that cause faulty signals. The former is referred to as the gain behaviour, or gain uniformity. The latter, where we have erroneous secondary electron signals are called dark counts or afterpulsing depending on the cause. These are signals that are counted as a hit, but do not actually represent an incident Cherenkov photon.

Timing characteristics are also very important. The timing resolution of the MCP-PMT refers to the å uncertainty when the detector reports a single photon hit. Modern MCP-PMTs are pushing 15ps time resolution[13]. A lower timing resolution allows us to be more precise with event reconstruction. The timing resolution is also somewhat inversely correlated to the rate capability of the detector; this is a measure of how many incident photons the MCP-PMT can handle before becoming too saturated and therefore not being able to distinguish clear hits. The PANDA Barrel asks for a photoelectron rate capability of 500 kHz/cm^2[12].

Lastly, the lifetime of the MCP-PMT is of interest. If we are building detectors with price tags north of €100 million EUR, we want to make sure they last a good while. The main factors affecting MCP-PMT lifetime include overall exposure to photons, radiation damage and heat degradation/weathering. Minimising dark count rates and afterpulses is also crucial for MCP-PMT lifetime, as these add exposure and send electrons to places where they can cause chemical degradation.

MCP-PMT development is easily an entire thesis topic, so we will refrain from indulging more. However, it should be emphasised that this is a topic that is central to particle identification and detector physics; without MCP-PMTs, Cherenkov detectors are impossible.

III.B. SiPMs

Silicon photomultipliers (SiPMs) have been gaining traction recently due to developments in materials, leading to a great ease of manufacturing. They are tiny compared to an MCP-PMT, due to their use of 'microcells', each containing an avalanche photodiode (APD) and a quenching resistor, to stop the avalanche. The review[14] provides an excellent in depth description of SiPMs.

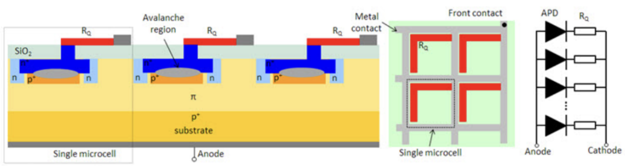

FIG. 6 **Cross section of SiPM.** SiPMs are externally biased such that each avalanche photodiode (APD) is at breakdown voltage, allowing for electron avalanches. The gain from an SiPM roughly matches that of a MCP-PMT at 10^5 - 10^6. (Photo: Hamamatsu[15])

SiPMs are much cheaper than MCP-PMTs and have a higher quantum efficiency, however suffer from a high dark count rate (erroneous hits) and do not have the same rate capability as MCP-PMTs. This has led to the explosion of SiPMs in fields like positron emission photography (PET) where precise timings are not so necessary, and where ruggedness and sturdiness is required. SiPMs also operate at a far lower voltage than MCP-PMTs and are not affected by magnetic fields, adding to their dependability.

IV. CHERENKOV IMAGING DETECTORS

IV.A. RICH

Ring Imaging Cherenkov Detectors (RICH) are a class of Cherenkov detectors that use a radiator at a known distance from a photodetector array to measure the Cherenkov angle of incident particles. Shown in Fig 7 is a simplified Geant4 simulation of a RICH detector.

The Cherenkov angles are emitted in a cone around the particle track, necessitating the ring shape; having near light speed particles directly incident on photodetectors is likely to be expensive. The outer radius of the ring is often encased in mirrors or lenses to trap Cherenkov photons and guide them towards the photodetector array. These optical elements are carefully manufactured to minimise chromatic dispersion and to maintain angular resolution.

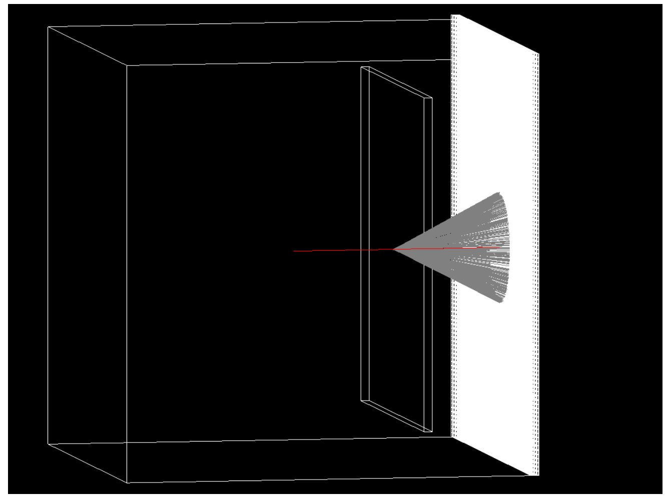

FIG. 7 **Geant4 simulation of the simplified RICH detector.** The particle track (red) is incident on some material with a refractive index n, called the radiator. In this case, an aerogel radiator is simulated. The resulting Cherenkov photons (gray) emitted in a cone are incident on a square array of sensitive photodetectors. In practice, the detector array is often a ring, and there are optics surrounding the device to guide photons towards the detector.

IV.A.1. Radiators

Different RICH experiments use different radiator materials. Common choices include aerogel such as in the Belle II ARICH[16], gaseous radiators such as in the old LHCb RICH[17] and (although in mostly retired detectors) liquids such as in the barrel CRID at SLAC[18].

Consider the Cherenkov angle condition from Eq 1. The radiator refractive index n is the key parameter that determines the choice of radiator, depending on expected beam momenta. Higher refractive indices are necessary for lower momentum particles, which is why we see older accelerator systems using liquid radiators with inherently higher refractive indices.

The refractive index is also wavelength dependent, which is a source of chromatic dispersion. This is an important consideration for radiator materials, as chromatic dispersion can degrade angular resolution. The refractive index also affects the number of Cherenkov photons produced, as per the Frank-Tamm formula in Eq 2. There are also tricks to play with the radiator design to improve photon yield, such as layering aerogel with different refractive indices without performance cost[19]. Naturally though complexity comes at a cost, especially in the case of finely engineered components such as Cherenkov radiators.

IV.A.2. Optics

Optical elements are often used in RICH detectors to increase photon yield. Lenses can be used to focus Cherenkov photons onto smaller photodetector areas, reducing cost and size. Mirrors can be used to reflect photons that would otherwise escape the detector. Other optical tricks such as the aforementioned layered radiator (also called proxy focusing) can be used to tighten the spread of the photon cone, allowing lower momentum charged particles to be measured.

As an applied example, the pfRICH at the forward section of the ePIC detector makes use of conical mirrors to increase the acceptance angle of particle tracks which can be seen in Fig 8. More photons means better angular resolution and therefore improved event reconstruction.

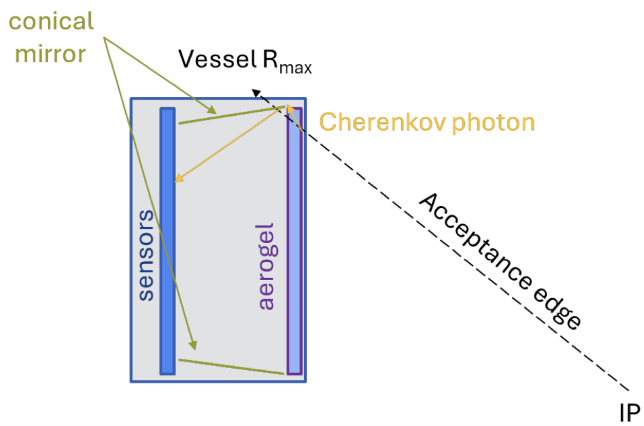

Fig. 8 **Schematic cross section of the pfRICH.** The conical mirrors (green) near the edge of the vessel mean that Cherenkov photons can be detected from steeper angles than would be traditionally possible[20]

IV.A.3. Mechanics & Integration

Modern detectors are large, complicated systems that enjoy premium real estate. Integrating a Cherenkov detector into such an array presents a unique set of mechanical and design challenges. Mechanical tolerances and alignment are crucial to maintaining accuracy. Optical elements must be precisely aligned and consistently calibrated throughout the detector lifetime, requiring robust mechanical support and space-hungry laser calibration systems. Careful thermal and radiation management are also necessary to ensure the longevity of photosensitive components. Consideration of the surrounding magnetic field from the solenoid used by the TOF detectors is also necessary, especially for PMTs which are magnetosensitive.

Ensuring that the detector can be serviced and maintained is also a key consideration, especially for large scale experiments that may run for decades. Some experiments are built on rails to allow the inner detectors (RICH, TOF, trackers etc.) the be slid out for maintenance. These mechanical and integration challenges are often underappreciated, but are imperative to the success of a detector.

IV.B. DIRC

Devices that detect internally reflected Cherenkov light are a type of Cherenkov detector, called DIRCs for short, circumvent the need for a separate radiator by using solid transparent bars, typically quartz, to both generate and guide Cherenkov photons to the photodetectors. Fig 3 already introduced in Section II.C showed a Geant4 simulation of the PANDA Barrel DIRC detector[4], but Fig 9 shows a more detailed rendering of the barrel detector itself.

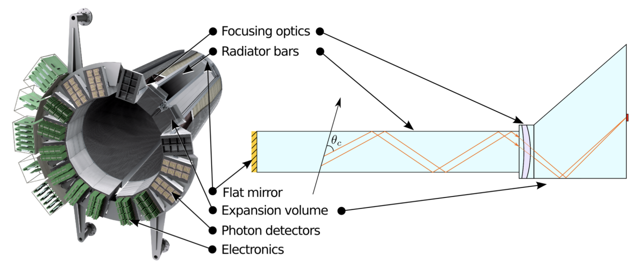

Fig. 9 **The PANDA Barrel DIRC along with an individual bar cross section.** 16 individual DIRC detectors are laid in a barrel-like arrangement, forming the very core of the detector array. Photons are internally reflected through the quartz bars.

The basic principle of DIRC operation is similar to that of other Cherenkov detectors; charged particles incident on a medium with refractive index $n > 1$ emit Cherenkov photons in a cone, and we try to measure the principle angle of this cone. However, in a DIRC detector the complexity arises from the optics of trapping and guiding the Cherenkov photons to a small array of photodetectors.

IV.B.1. Photon Transport via Internal Reflection

Similarly to photon transport in optical fibres, the Cherenkov photons produced in the quartz bars of a DIRC are trapped via total internal reflection as shown in Fig 9. The photons propagate to the end of the bar, where they are focused into an expansion volume, and then onto the photodetector array. The DIRC relies on photons internally reflecting hundreds of times with minimal loss, all while preserving the Cherenkov angle precision. The fused silica bars provide extremely smooth surfaces to facilitate this, with surface roughness possible on the order of angstroms[21].

The quartz bars are also UV transparent, allowing Cherenkov photons in the near-UV range to be detected, increasing the photon yield of the detector. Quartz is also known to be radiation hard, which will allow the detector to operate in the high radiation environments of modern accelerators without significant degradation over time[22]. The fused silica bars also have a near optimal refractive index of around 1.47 in the visible spectrum, giving large Cherenkov angles. Lower refractive indices would reduce the angle separation, harming PID performance, while higher refractive indices would increase chromatic dispersion, harming angular resolution.

IV.B.2. Chromatic Effects & Timing Resolution

Since Cherenkov photons are produced across a range of wavelengths, chromatic dispersion is unavoidable. Since the quartz bars are often meters long, blue photons often arrive 100s of picoseconds later than red photons. This is due to the wavelength dependence of the refractive index, which is around 1.50 for blue light and 1.47 for red light in quartz. However, dispersion can be corrected for if the photon arrival time is measured with sufficient precision, making it a crucial aspect of DIRC design.

Modern MCP-PMTs are able to achieve single photon timing resolutions on the order of 15–20ps[13]. Improvements in readout electronics and signal processing are also pushing timing resolutions lower[23]. These advancements allow photon timing to become a measurable observable, rather than just noise; detected photons provide x, y, t rather than just x, y. We can bake this information into our event reconstruction algorithms, simulating expected photon arrival times for bluer and redder photons separately, massively improving angular resolution.

These sorts of chromatic corrections via timing information lead to far more sophisticated event reconstruction than RICH systems. As discussed in Section II.E, statistical methods such as maximum likelihood estimation are extremely powerful. DIRC systems offer a unique double-edged sword; complex photon paths, internal reflections, and chromatic dispersion make analytical solutions near impossible, but the extremely detailed information available from precise timing measurements allow for robust statistical models such as time-imaging[7] and machine learning to shine.

IV.B.3. Reconstruction Methods & PID

While DIRC systems provide excellent PID performance in compact geometries, their reliance on time-based global likelihood reconstruction from chromatic effects can complicate hit–track association in high-multiplicity collider environments compared to spatially imaging RICH detectors. The aforementioned time-imaging reconstruction method builds up a PDF from expected photon arrival times for all detector array channels and particle types. Then, events to be classified can be compared to these PDFs on a maximum likelihood basis. The algorithm can be optimised using a lookup table of possible paths a photon could take to a specific channel, eliminating a few unnecessary computations. This allows more flexibility in focusing optics within the detector geometry, as possible paths can be analytically determined and placed in the lookup table. This improves photon yield and therefore PID performance, up to $4.8 \pm 0.1\ \sigma$[7]. However, from a software standpoint, the algorithm is unfriendly to parallelise due to heavy use of conditional logic. Parallel hardware prefers to perform the same operation on many different data points. This algorithm demands different operations depending on detector channel, timing, and hypothesis. As such, computation time becomes a problem for large datasets.

ML on the other hand is significantly easier to parallelise. Raw detector data is fed to the network on a per-event level and a sequence of fixed operations (mostly matrix multiplications) are performed. This inherently uses fewer CPU cycles per event when compared to time-imaging. The ML models are also easy to distribute onto modern hardware. Also since latency is predictable per event, as it is correlated to model size, data processing is unlikely to 'choke'; we are able to process batches of events at a time and can reliably expect all events to finish processing at around the same time. This is in contrast to variable latency such as in time-imaging reconstruction, where often batches are waiting on one particularly difficult event to finish processing before starting the next batch. These advantages make ML scaleable in a way that maximum likelihood algorithms are not.

Many different neural network architectures are being researched. This refers to the order and manner of the sequence of fixed operations that are done by the network. Dense networks consist of purely matrix multiplications, yet are seeing promising results[9]. More complicated networks such as normalising flows are closer to previous likelihood methods, but offer exact likelihood evaluation without iterative maximisation, combining the known strong performance of the time-imaging reconstruction method with the compute advantages of ML methods[24].

V. NEUTRINO IDENTIFICATION WITH CHERENKOV DETECTORS

While Cherenkov detectors can not directly detect neutrinos as they are neutral particles, neutrino events involving charged particles can be detected and reconstructed. However, since these interactions are rare and large in scale, the detector and radiator material must span an enormous volume. The simple solution to this is to use easy or natural materials such as water or ice. This presents a unique set of engineering challenges, such as waterproofing the detectors and synchronising timing across large distances. It is also very difficult to separate the weakly interacting neutrino events from other background. Different collaborations have taken unique approaches to these problems depending on their physics programmes.

V.A. Water Cherenkov Detectors (Super-K)

Water Cherenkov Detectors (WCDs) use large volumes of ultra-pure water as the radiator material. The Super-Kamiokande (Super-K) experiment in Japan 10 is a famous example of a WCD, using 50,000 tons of water surrounded by over 11,000 PMTs, buried under a kilometre of mountain to shield from natural radiation. The detector is used to study neutrinos at MeV-GeV energies from various sources, including the sun, atmosphere, supernovae, allowing us to study neutrino-specific phenomena[25], which before Super-K were largely unexplored.

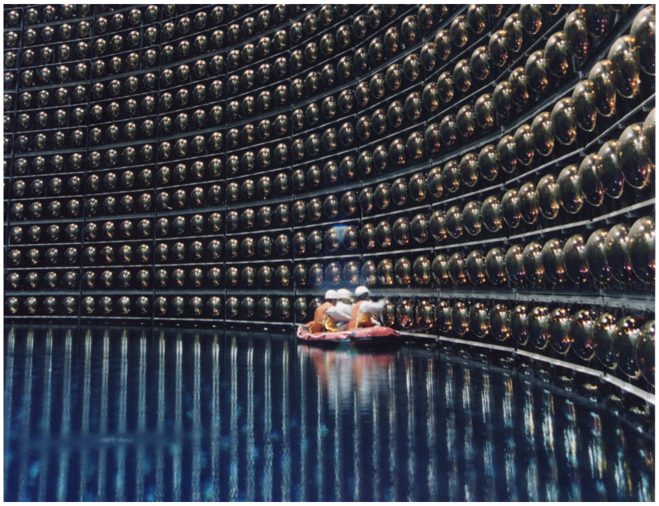

FIG. 10 **Inside the cylindrical water tank of Super-K.** Boats are used for the maintenance of water photodetectors. The detector is designed to identify neutrinos with MeV to GeV energies. (Photo: Kamioka Observatory, ICRR (Institute for Cosmic Ray Research), The University of Tokyo)

Super-K is squarely a precision detector for low energy neutrino physics. If we wish to study higher energy phenomena, such as cosmic neutrinos in the TeV-PeV range, we need to significantly increase the scale of the detector.

V.B. Cosmogenic Neutrinos

The IceCube Neutrino Observatory is a cubic kilometre scale Cherenkov detector buried deep in the Antarctic ice sheet. It uses over 5,000 photodetector modules arranged on 86 strings, deployed between 1.5 and 2.5 km deep. The detector is designed to identify high energy neutrinos from astrophysical sources. These neutrinos are filtered from low energy neutrinos and other background by using the entire Earth as a shield; events that come from the core of the Earth are almost certainly high energy neutrinos, as other particles would be absorbed.

Fig 11 depicts high energy cosmic neutrinos being formed through the Greisen–Zatsepin–Kuzmin (GZK) process, where ultra high energy (¿8 joules) cosmic rays, accelerated by natural sources like black holes, interact with the cosmic microwave background radiation to produce pions, which then decay into neutrinos.

Fig 12 shows such a cosmic event from IceCube, where a high energy neutrino has interacted with the ice to produce muons and subsequent Cherenkov radiation. The figure is to give a sense of the scale of the detectors and the event topologies involved. The thickness of the strings represents photon intensity, while the colours represent timing information, red being at the beginning of an event and green/blue being later in time.

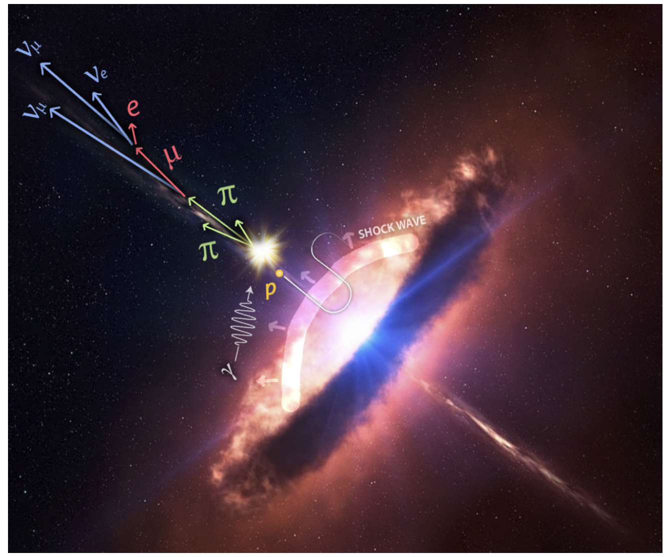

FIG. 11 **Cosmic neutrinos formed through the GZK process.** Protons accelerated by black holes are able to interact with the cosmic background, decaying through intermediary steps into various high energy neutrinos[26].

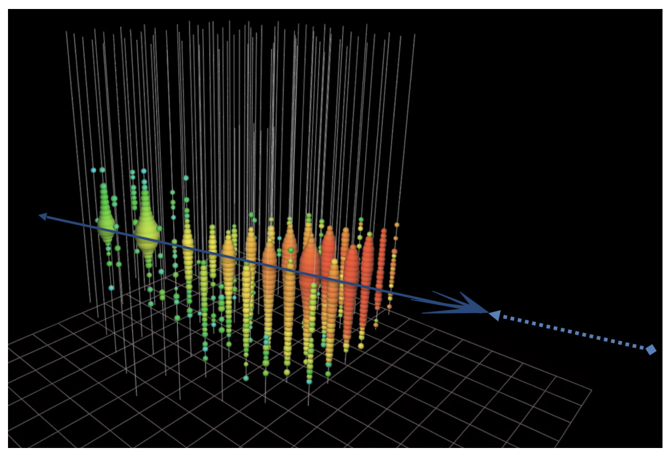

FIG. 12 **IceCube event display.** Multiple charged particle tracks can be distinguished. Maximum likelihood methods can be used to parse the muon tracks to identify neutrino interactions in the water[26].

Cherenkov detectors have proven to be invaluable tools in the current study of physics, but they also have a promising future. We will now look at some case studies of upcoming detectors.

VI. APPLICATIONS AT FUTURE FACILITIES

VI.A. PANDA DIRC at FAIR

VI.B. hpDIRC at ePIC Brookhaven

VI.C. Other Proposed Far Future Detectors

might get cut

VII. CURRENT CHALLENGES & LIMITATIONS

banana

VIII. CONCLUSION

IX. REFERENCES

[1] P. A. Cherenkov, "Visible Radiation Produced by Electrons Moving in a Medium with Velocities Exceeding that of Light," *Phys. Rev.*, vol. 52, pp. 378–379, Aug 1937.

[2] I. M. Frank and I. E. Tamm, "Coherent visible radiation of fast electrons passing through matter," *Compt. Rend. Acad. Sci. URSS*, vol. 14, no. 3, pp. 109–114, 1937.

[3] F. Tessarotto, P. Abbon, M. Alexeev, R. Birsa, P. Bordalo, F. Bradamante, A. Bressan *et al.*, "Long term experience and performance of COMPASS RICH-1," *Journal of Instrumentation*, vol. 9, p. C09011, 2014.

[4] B. Singh, W. Erni, B. Krusche, M. Steinacher, N. Walford, B. Liu, H. Liu *et al.*, "Technical design report for the $\overline{\mathrm{P}}$ANDA Barrel DIRC detector," *Journal of Physics G: Nuclear and Particle Physics*, vol. 46, no. 4, p. 045001, 2019.

[5] G. Kalicy, "The hpDIRC for the ePIC Experiment." Conference Session, 2025. XII International Workshop on Ring Imaging Cherenkov Detectors, Mainz, Germany.

[6] L. Šantelj, I. Adachi, R. Dolenec, K. Hataya, S. Iori, S. Iwata, H. Kakuno *et al.*, "Recent developments in software for the Belle II aerogel RICH," *Nucl. Instrum. Meth. A*, vol. 876, pp. 104–107, 2017.

[7] R. Dzhygadlo, A. Ali, A. Belias, A. Gerhardt, M. Krebs, D. Lehmann, K. Peters *et al.*, "Time imaging reconstruction for the PANDA barrel DIRC," *Journal of Instrumentation*, vol. 15, 2020.

[8] N. Prouse, P. de Perio, and W. Fedorko, "Machine Learning Techniques to Enhance Event Reconstruction in Water Cherenkov Detectors," *Phys. Sci. Forum*, vol. 8, no. 1, p. 63, 2023.

[9] D. Markhoff, R. Dzhygadlo, J. Schwiening, and Y. Wolf, "Application of FiLM Neural Networks for π/K Separation in the PANDA Barrel DIRC." Conference Session in Preparation, 2026.

[10] B. H, *Physics and Applications of Secondary Electron Emission.* McGraw-Hill Book Co., Inc., 1954.

[11] Z. Liu, H. Liu, P. Chen, K. Li, Y. Wei, L. He, X. Zhao *et al.*, "The Development of a Large-Area Microchannel Plate Photomultiplier Tube with a Gate Function," *Photonics*, vol. 12, no. 1, 2025.

[12] "Experience with series-produced MCP-PMTs for the PANDA Barrel DIRC." Conference Session, 2025. XII International Workshop on Ring Imaging Cherenkov Detectors, Mainz, Germany.

[13] A. Lyashenko, J. Agarwala, A. Asaturyan, M. Aviles, B. Azmoun, C. Chatterjee, S. Clarke *et al.*, "HRPPD photosensors for RICH detectors with a high resolution timing capability," *Nucl. Instrum. Meth. A*, vol. 1082, 2026.

[14] F. Acerbi and S. Gundacker, "Understanding and simulating SiPMs," *Nucl. Instrum. Meth. A*, vol. 926, pp. 16–35, 2019. Silicon Photomultipliers: Technology, Characterisation and Applications.

[15] S. Piatek and Hamamatsu, "What is an SiPM and how does it work?." Online, 2016. Accessed: 2025-11-21.

[16] T. Abe, I. Adachi, K. Adamczyk, S. Ahn, H. Aihara, K. Akai, M. Aloi *et al.*, "Belle II Technical Design Report," 2010.

[17] S. Amato, D. Carvalho, P. Colrain, T. Da Silva, J. R. T. De Mello, L. De Paula, M. Gandelman *et al.*, *LHCb RICH.* Technical design report. LHCb, Geneva: CERN, 2000.

[18] J. Va'vra, "Long-term operational experience with the barrel crid at sld," *Nucl. Instrum. Meth. A*, vol. 433, no. 1, pp. 59–70, 1999.

[19] T. Iijima, S. Korpar, I. Adachi, S. Fratina, T. Fukushima, A. Gorišek, H. Kawai *et al.*, "A novel type of proximity focusing rich counter with multiple refractive index aerogel radiator," *Nucl. Instrum. Meth. A*, vol. 548, no. 3, pp. 383–390, 2005.

[20] B. Page, "A Proximity Focusing RICH Detector for the ePIC Experiment at the EIC." Conference Session, 2025. XII International Workshop on Ring Imaging Cherenkov Detectors, Mainz, Germany.

[21] "Ultra-smooth surface with 0.4 Å roughness on fused silica,"

[22] M. Hoek, E. Bennet, D. Branford, E. Cowie, M. Düren, K. Föhl, D. Glazier *et al.*, "Radiation hardness study on fused silica," *Nucl. Instrum. Meth. A*, vol. 595, no. 1, pp. 190–193, 2008. RICH 2007.

[23] F. Keizer, "The FastRICH ASIC for the LHCb RICH enhancements," *Nucl. Instrum. Meth. A*, vol. 1067, p. 169664, 2024.

[24] C. Fanelli, J. Giroux, and J. Stevens, "Deep(er) reconstruction of imaging Cherenkov detectors with swin transformers and normalizing flow models," *Machine Learning: Science and Technology*, vol. 6, p. 015028, feb 2025.

[25] Y. Fukuda, T. Hayakawa, E. Ichihara, K. Inoue, K. Ishihara, H. Ishino, Y. Itow *et al.*, "Evidence for Oscillation of Atmospheric Neutrinos," *Phys. Rev. Lett.*, vol. 81, pp. 1562–1567, Aug 1998.

[26] F. Halzen, "Antarctic Ice and Ocean Water as Cherenkov Neutrino Detectors." Conference Session, 2025. XII International Workshop on Ring Imaging Cherenkov Detectors, Mainz, Germany.