Literature Review

Particle Identification in Modern Cherenkov Detectors

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Abstract

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 ...... Persistent challenges include ...... We conclude by outlining promising future developments for ......

Keywords: Particle Identification, Cherenkov Detectors, DIRC, RICH, PANDA, EIC, GSI

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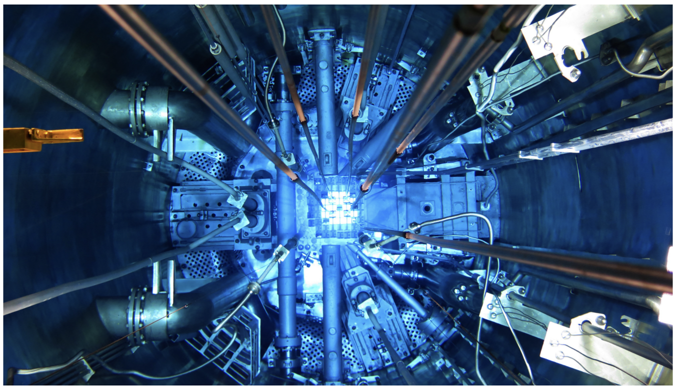

Figure 1: **Cherenkov radiation in a nuclear reactor pool.** The characteristic glow is indicative of relativistic electrons moving through the water. (Photo: IAEA)

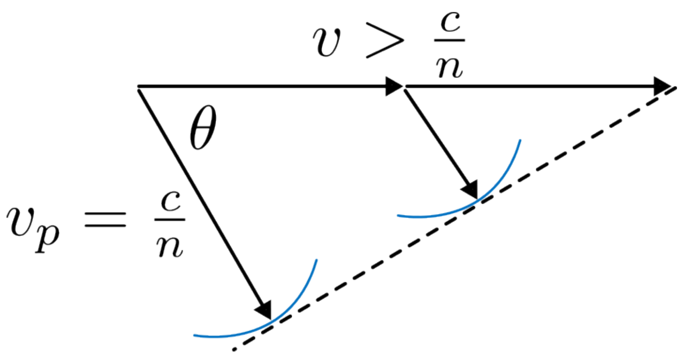

Figure 2: **Schematic of a Cherenkov cone.** A particle travels through a medium with velocity v. Photons are emitted at the phase velocity v_p and angle θ to the path of travel of the particle, giving the characteristic blue shock cone.

1. Introduction

2. Theoretical Foundations

2.1. 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 Čherenkov 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 2, 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 3. 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.

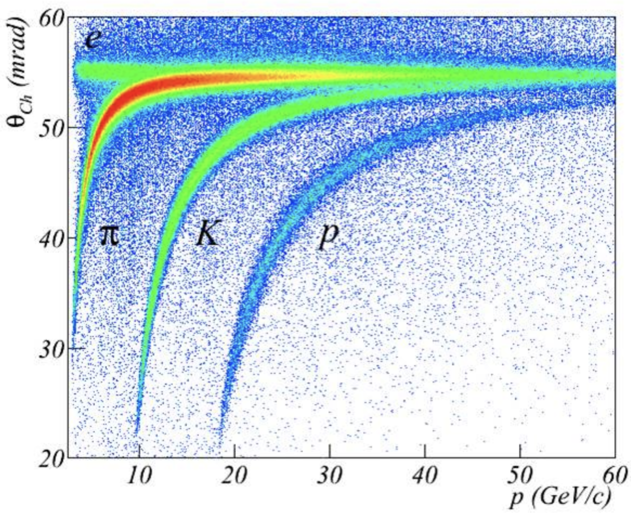

Figure 3: **Cherenkov spectroscopy of the COMPASS RICH-1 detector at CERN.** There are clear curves for different particle species. These curves can be determined mathematically using (1) and relativistic dynamics. (Photo: [3])

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 $E = N\hbar\omega$, 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.

2.2. 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 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 3.

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.

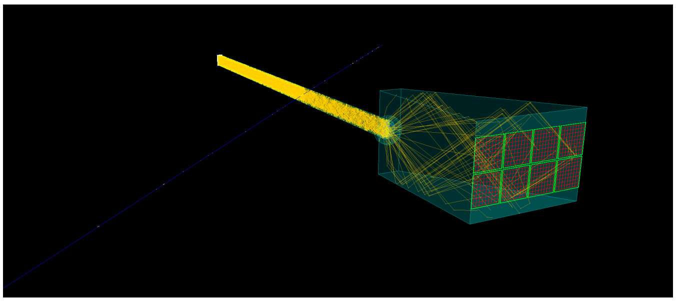

Figure 4: **Simulated event display of PANDA Barrel DIRC.** The blue track is a charged particle incident on the detector, and the yellow tracks are all Cherenkov photons. There is a mirror at the far end of the radiator bar, causing all photons to eventually reach the detector array.

2.3. Optical Detector 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 4 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.

2.4. 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

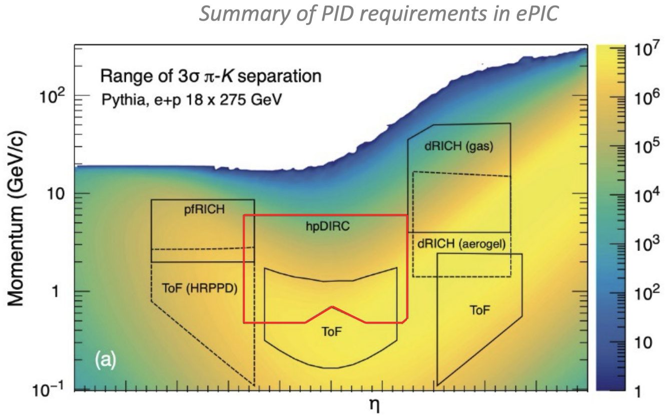

Figure 5: **The ePIC PID requirements.** The pfRICH, hpDIRC and dRICH are all Cherenkov based detectors that are expected to perform 3σ pion and kaon separation at momenta between around 1 and 10 GeV. Here, η represents the pseudorapidity. (Photo: Greg Kalicy, ePIC Collaboration [5])

used to provide hadron PID across essentially all high momentum ranges, as shown in Fig 5. 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.

2.5. Statistical Event Reconstruction Methods

The problem of event reconstruction is to determine what happened inside the detector based on the data obtained from the photo-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].

i want to put something about our time imaging algorithm here... help me roman! :D

In general, likelihood methods serve many detector assemblies well. However, they are in essence a brute-force method, and as such plagued by the usual computation limitations. One potential new-age solution is the use of machine learning. 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. This has already seen encouraging results on Geant4 simulated data for the Hyper-Kaminokande experiment [7].

3. Photomultipliers

3.1. 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 [8]. This amplified electron signal is then incident on an anode plate, where the signal is read as an analogue voltage.

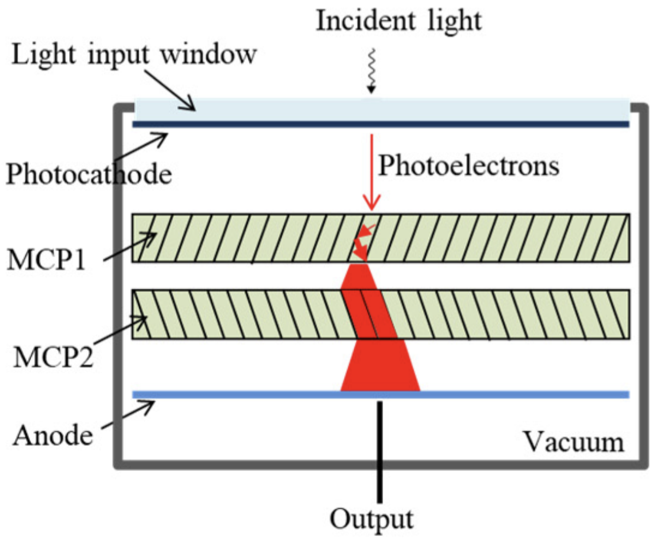

Figure 6: **Cross section of a traditional MCP-PMT.** Due to the proximity of the anode and the photocathode, we are able to determine where the incident photon hit on the photocathode. MCP-PMTs are used in an incredible range of fields, from blood tests, to spectroscopy, to radar jamming. (Photo: [9])

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 [10].

- 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 time resolution of the MCP-PMT is often measured with the entire data acquisition system (DAQ) included, and modern photodetectors are pushing 100ps time resolution. This is a measure of how quickly a hit is detected after a laser pulse directly on the detector. 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 DAQ not being able to distinguish clear hits. The PANDA Barrel asks for a photoelectron rate capability of 500 kHz/cm^2 [10].

- 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 here. 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.

3.2. 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 [11] provides an excellent in depth description of SiPMs.

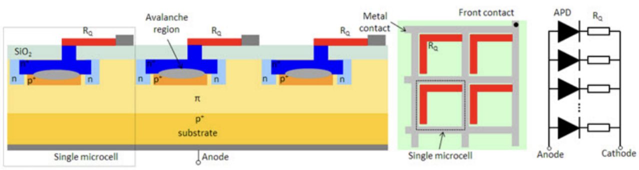

Figure 7: **Cross section of SiPM.** SiPMs are externally biased such that each avalanche photodiode (APD) is at breakdown voltage, allowing for electron avalanches. The gain from an SiPM roughly matches that of a MCP-PMT at 10^5 - 10^6. (Photo: Hamamatsu [12])

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.

3.3. LAPPDs might get cut

Large Area Picosecond Photodetectors (LAPPDs) are modern MCP-PMTs that harness many advances in machining and materials technology. Advances in glass manufacturing allow for borosilicate glass tiles to form large area vacuum housings for sensitive layers. Atomic layer deposition (ALD) allows for extremely precise tailoring of MCPs compared to traditional methods of manufacturing [13]. They feature good dark count rates (100 Hz/cm^2), an impressive timing resolution (50 ps), an improved spatial resolution, and a great QE [14].

3.4. HRPPDs might get cut

4. Photon Optics might get cut

4.1. Lenses & Reflections

4.2. Laser Calibration

5. Ring Imaging Cherenkov Detectors (RICH)

Ring Imaging Cherenkov Detectors 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 8 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.

5.1. Radiators

Different RICH experiments use different radiator materials. Common choices include aerogel such as in the Belle II ARICH [15], gaseous radiators such as in the old LHCb RICH [16] and (although in mostly retired detectors) liquids such as in the barrel CRID at SLAC [17].

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.

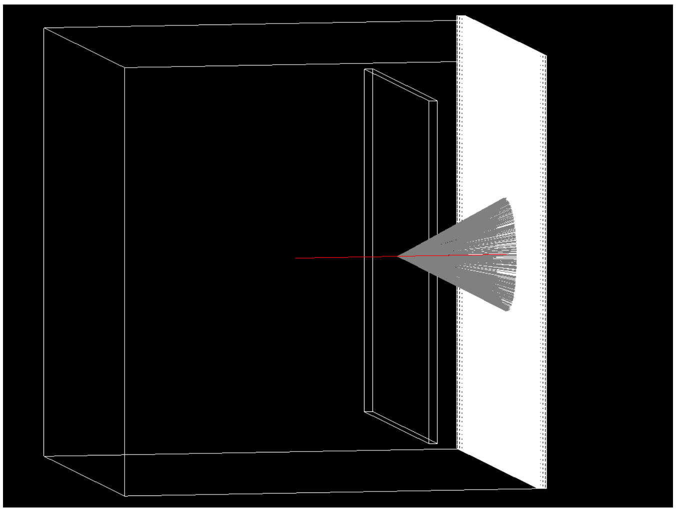

Figure 8: **Geant4 simulation of the simplified RICH detector.** The particle track (red) is incident on some material with a refractive index n, called the radiator. In this case, an aerogel radiator is simulated. The resulting Cherenkov photons (gray) emitted in a cone are incident on a square array 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.

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 [18]. Naturally though complexity comes at a cost, especially in the case of finely engineered components such as Cherenkov radiators.

5.2. RICH 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 9. More photons means better angular resolution, better event reconstruction and therefore more interesting physics. That's the idea anyway.

5.3. 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. Ensuring that the detector can be serviced and maintained is also a key consideration, especially for large scale experiments that may run for decades. 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 magneto-sensitive. These mechanical and integration challenges are often underappreciated, but are imperative to the success of a detector.

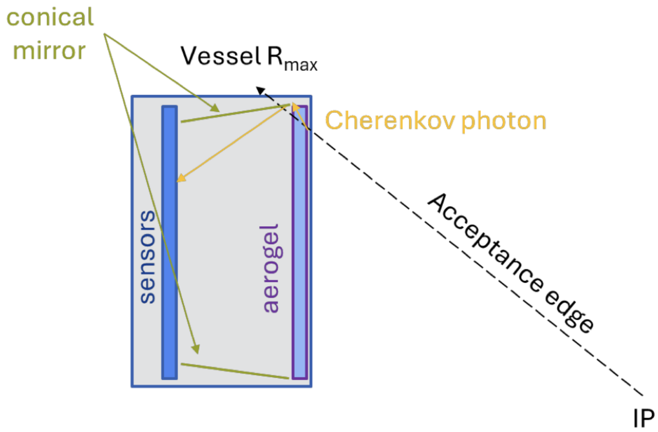

Figure 9: **Schematic cross section of the pfRICH.** The conical mirrors (green) near the edge of the vessel mean that Cherenkov photons can be detected from steeper angles than would be traditionally possible. (Photo: Brian Page, eIPC Collaboration [19])

6. Detection of Internally Reflected Cherenkov Light (DIRC)

7. Neutrino Identification with Cherenkov Detectors might get cut

7.1. Atmospheric Muons

7.2. Water Cherenkov Detectors

8. Applications at Future Facilities

8.1. PANDA DIRC at FAIR

8.2. hpDIRC at ePIC Brookhaven

8.3. Other Proposed Far Future Detectors might get cut

9. Current Challenges & Limitations

9.1. ML PID

Machine learning (ML) techniques are becoming increasingly prevalent in particle physics as the need for fast and accurate data analysis grows. As detector arrays become larger, so does the volume of data produced. Traditional

PID methods, such as likelihood-based event reconstruction as discussed in §2.5 can become computationally expensive and time-consuming. ML algorithms when trained have the possibility to skip all of the intermediate steps and directly classify particles from raw detector data. This is particularly useful in high-rate environments and is also applicable to non-Cherenkov detectors.

The way that raw data is presented to the ML algorithm is crucial. Often we will see hit patterns from photodetector arrays represented as 2D images, with pixel intensities represented by colour scales. This makes convolutional neural networks (CNNs) a reasonable choice for ML PID, as CNNs are well suited to image processing tasks. Other algorithms such as dense neural networks (DNNs) and normalising flows [20] are also being explored.

9.2. High Rate Environments

9.3. Radiation Damage

9.4. Budget Constraints

10. Emerging Technologies

10.1. HRPPDs

10.2. Advanced Optics

10.3. New Materials

11. Summary

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