Particle Identification and RICH

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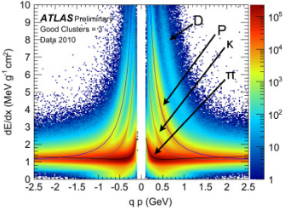
15/05/2025

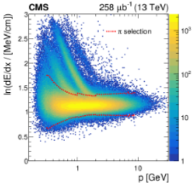
What is Particle Identification?

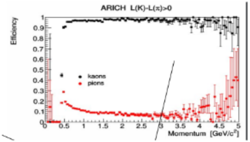
- We are strictly speaking about identifications of sub-atomic particles in the field of experimental particle physics.
- In our filed we have initial states colliding particles (both in fixed target and collider experiments) and final state particles. Particle Identification (PID) is relevant for both states.
- The devices (later we will call them PID detectors), that will be employed for PID purpose can use different technologies, algorithms, geometry etc...
- Essential idea will be to measure some properties of the particles to attribute its ID. Example, we can measure the charge of these particles, using a magnetic spectrometer and separate electrons from positrons, we can measure the energy deposited by a charge particles in a known material and size to estimate their dE/dx to identify the particles, etc.
- *There is* **NO** *unique technique for PID. Our experimental requirements dictate the choice of technologies, shape and essentially every tiny details*.

A few examples

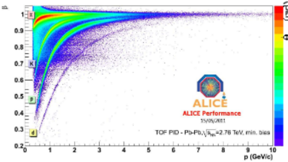
Here we see some snapshots on the momentum reach of different particle identification technologies.

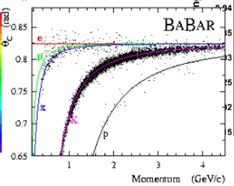


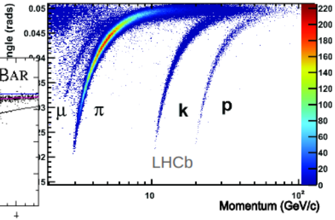




$$-\left\langle \frac{dE}{dx} \right\rangle = \frac{4\pi}{m_e c^2}\cdot\frac{nz^2}{\beta^2}\cdot\left(\frac{e^2}{4\pi\varepsilon_0}\right)^2\cdot\left[\ln\left(\frac{2m_e c^2\beta^2}{I\cdot(1-\beta^2)}\right)-\beta^2\right]$$

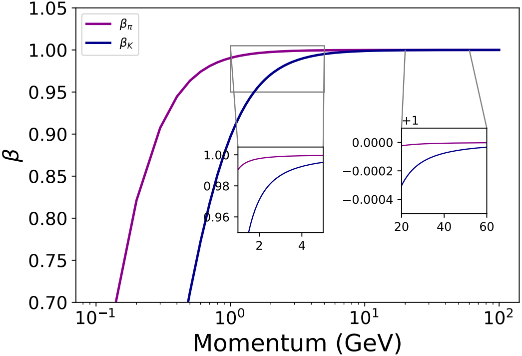






No technology is better than the other. It is simply the requirements and space constraints!

Relationship between Relativistic Speed and Momentum



- Dependence of relativistic speed (β) of a particle and its momentum. $\beta = \frac{p}{E}$.

A classical analogy: A camera, which zooms at an incredible level, without distortion.

How to do Particle Identification

- One common and intuitive technique can be to identify the mass of these particles. Every particle species has different invariant mass.
- Relativistic momentum is expressed as:

$$p = m\gamma\beta c$$
$$m = \frac{p}{\gamma\beta c} \tag{1}$$

- If in our experiment, we can measure the momentum of these particles and we can somehow measure their relativistic speed β, **independently**, we can determine their mass. How well can we measure the mass? Depends, on how well we can measure these two independent parameters.
- Determination of the mass can become complicated when particle is ultra-relativistic.

$$(\frac{\delta m}{m})^2 = (\gamma^2\frac{\delta\beta}{\beta})^2 + (\frac{\delta p}{p})^2$$

"Separation of speed allows separation of mass" I

$(\frac{\delta m}{m})^2 = (\gamma^2 \frac{\delta\beta}{\beta})^2 + (\frac{\delta p}{p})^2$ ...

- Imagine, we want to separate two particles of mass m_1 and m_2, of same momentum p. Their speed is different. Say, β_1 and β_2; the difference in speed is $\Delta\beta$. From equation 1, we can write down their squared mass difference

$$m_1^2 - m_2^2 = \frac{\Delta\beta(\beta_1 + \beta_2)}{c^2(\beta_1\beta_2)^2} p^2$$

- In ultra-relativistic world where β_1 & $\beta_2 \sim 1$, we can approximate:

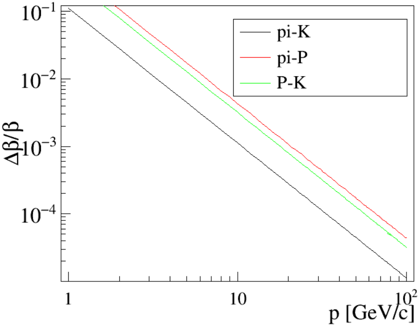
$$\frac{(\beta_1 + \beta_2)}{(\beta_1\beta_2)^2} = 2/\beta$$

$$\frac{\Delta\beta}{\beta} = \frac{(m_1^2 - m_2^2)c^2}{2p^2}$$

Think: What will be the $\Delta\beta/\beta$ for 2 GeV/c,10 GeV/c,40 GeV/c pions and kaons?

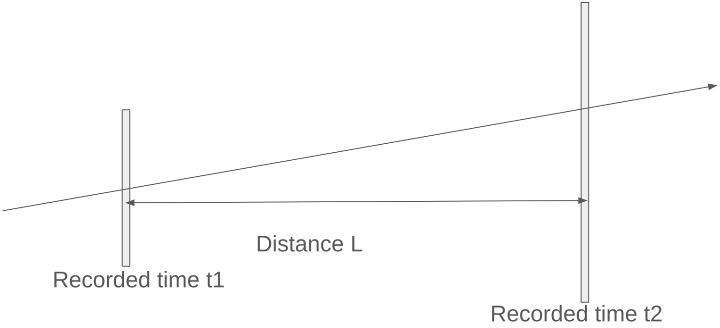
"Separation of speed allows separation of mass" II

- For pions and kaons at 2 GeV/c,10 GeV/c,40 GeV/c the differences in speed are around few 10^{-1}, 10^{-3} and 10^{-4}.
- These are just physical differences. To determine these differences with some statistical significance we need to be better than these values. Say by a factor of 2 (a.k.a 2σ separation).

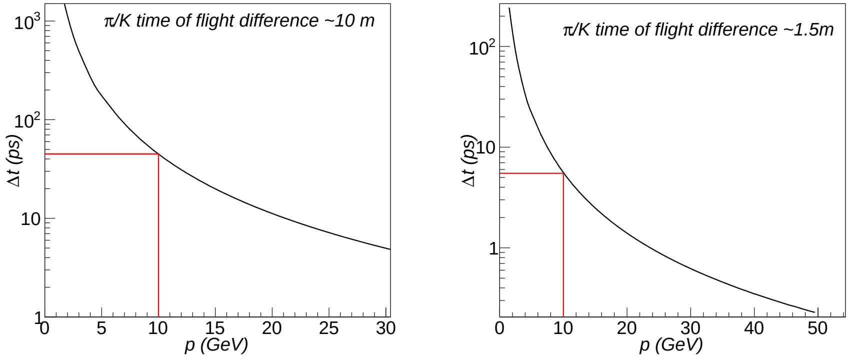


Think: How much time should they take to fly 1.5 m or 10 m path? It is realistic to measure such a difference?

The time of flight I



The time of flight II



- If we want at least 2-σ separation, we need 20 ps resolution (for 10 m) and few picosecond time resolution for 1.5 m time-of-flight detectors.
- Even for 10 m long flight path detector technology and related electronics are challenging. For smaller length, current technology does not support 10 GeV π/K separation using TOF! With 20 ps resolution, a 1.5 m TOF can work up to few GeV/c.

The time of flight III

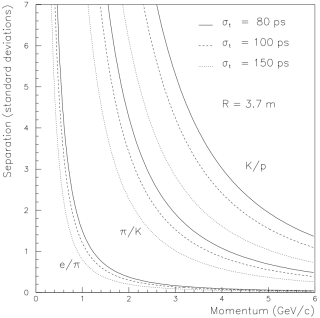


Figure: Time of Flight requirement for ALICE detector

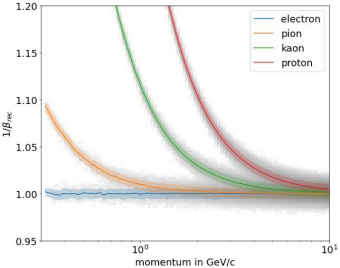
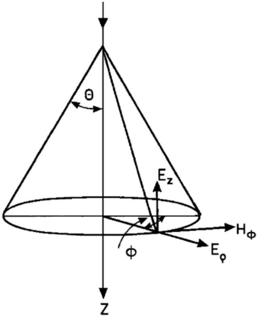


Figure: Simulation performance of the Forward time of flight detector at ePIC ($\lesssim$50 ps time resolution)

PID not by measuring something else : Exploiting Cherenkov radiation I

What is Cherenkov radiation?

It is a characteristic radiation emitted by *charged* particles, traveling through a *dielectric medium*, with a speed that is *faster* than the speed of light in that *medium.It is emitted with an specific angle, depending on the speed of the particle and the refractive index of the medium*. First observed by Pavel Cherenkov as a doctoral student of S. Vavilov in 1937 (even before the first PMTs came). Awarded 1957 Nobel prize in physics with Frank and Tamm.



$$cos\theta = \frac{1}{n\beta}$$

$$\beta = \frac{v}{c} = \frac{m\gamma vc}{m\gamma c^2} = \frac{pc}{E} = \frac{p}{E}; c = 1$$

$$cos\theta = \frac{\sqrt{p^2 + m^2}}{np}$$

$$m^2 = p^2(cos^2\theta - 1)$$

PID not by measuring something else : Exploiting Cherenkov radiation II

Note that we have a co-sinusoidal relationship, which indicates that $\frac{1}{n\beta}$ has an threshold. Also $0 < \beta < 1$ is. Therefore:

- $\exists$ a maximum Cherenkov angle when β is saturated. This angle is determined by the refractive index of the medium. Ex. C_2F_6 has nominal refractive index of 1.0008. From now on we will talk about (n-1). C_2F_6 has (n-1)$=$ 800 X $10^6 \equiv$ 800 part per million (ppm). The maximum Cherenkov angle is about 40 mrad.

- The threshold β allows to compute one the threshold momentum for a specific particle. In C_4F_{10} pions and kaons starts producing photons around 3 GeV and 9 GeV respectively. This threshold property is extremely powerful.

Can you guess the (n-1) of C_4F_{10} and thresholds of pions, kaons and protons for C_2F_6?

A physics example of using a Cherenkov counter I

Dirac's theory that every elementary particle has a specific ratio between their magnetic moment and angular momentum. This value should be exactly equal to **2**. This worked perfectly for electrons (with a little deviation, Feynman, Schwinger, Tomonaga and Dyson first understood why did that happen). Also, Dirac's theory predicted that these elementary particles should have their antiparticles. This again was true for electrons. So electron is a Dirac particle. What about protons?
Dirac was pretty sure that protons too are elementary (like many other theorists at that time). Otto Stern, (the same guy who discovered electrons have strange quantization ins space due to presence of an inhomogeneous magnetic field. As if electrons are behaving like a tiny magnets; the electron spin quantum number!), discovered that proton has very different value from Dirac's 2! What does it signify?
In 1955, at California Berkley Bevatron (GeV is BeV; Because, Giga is Billion) Chamberlin, Segre, Weignad and a young researcher name Ypsillantis, went on to check if protons have their anti-particles and they found that they do have one!

A physics example of using a Cherenkov counter II

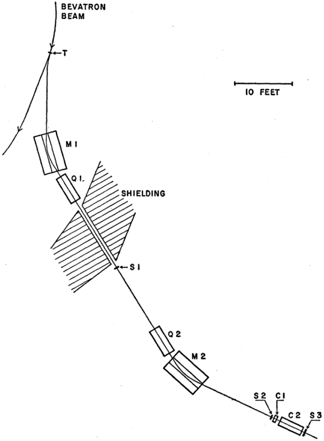


FIG. 1. Diagram of experimental arrangement. For details see Table I.

- The S1,S2,S3 are ordinary scintillators, they sit before and after a magnet M2 (this is analyzing the momentum), and the out coming particles have momentum around 1.19 GeV. But the out coming particles are overwhelmed by pions. What should be the minimum beam energy to produce such out coming particles? (It is a fixed target experiment with a target that is proton enriched.)
- S1 and S2, provided the time of flight. They were roughly 12 m apart. Estimate how much time pions and protons will take to travel this distance?
- To eliminate any wrong counting Cherenkov counter C1, was used in a threshold mode (aka Veto mode), the C1 rejected all particles below a $\beta = 0.79$. Which refractive index should it have?
- Counter C2, eliminated further wrong coincidences. It allowed particles only $0.75 < \beta < 0.78$. These types of Cherenkov counters are called **differential Cherenkov counters**. This Counter is actually identifying particles with proton mass. How can one select β values only in a window? Can you imagine a design technique that helps? Guess the refractive index!

A physics example of using a Cherenkov counter III

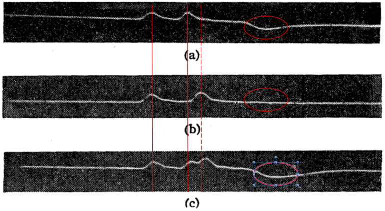
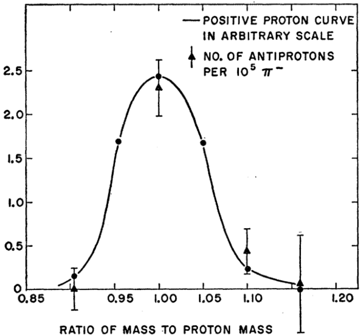
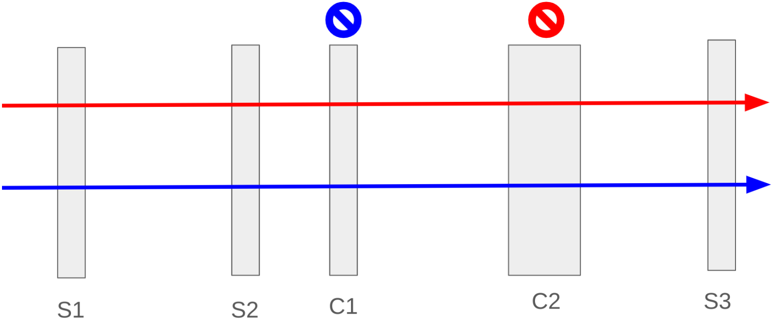


FIG. 2. Oscilloscope traces showing from left to right pulses from $S1$, $S2$, and $C1$. (a) meson, (b) antiproton, (c) accidental event.



A physics example of using a Cherenkov counter IV



A physics example of using a Cherenkov counter V

The differential counter (how can one select a velocity range?)

Figure: Marshall's design

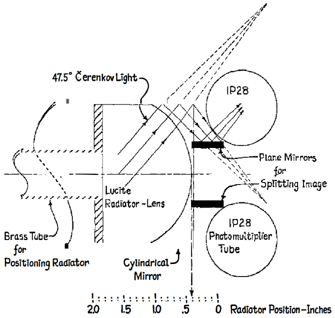


FIG. 7. Focusing counter with small sensitive area used by Marshall for analysis of meson beams. Radiator in this counter is integral with the lens.

Figure: C2 of Chamberlin et al.

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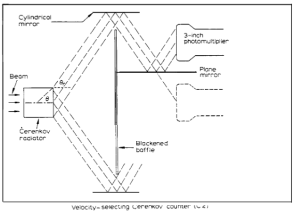


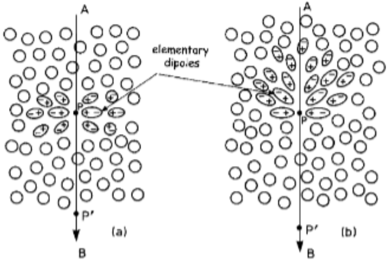
Fig. 7. View of the velocity-selecting Čerenkov counter.

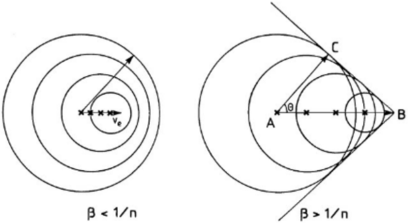
Both threshold and differential Cherenkov counters have drawbacks! It is limited in phase-space!

How can we overcome this?**But before that, let's see why does Cherenkov radiation happen in the first place! It will help us to improve the design!!**

Cherenkov radiation: microscopic view!

ALL ABOUT SYMMETRY BREAKING!

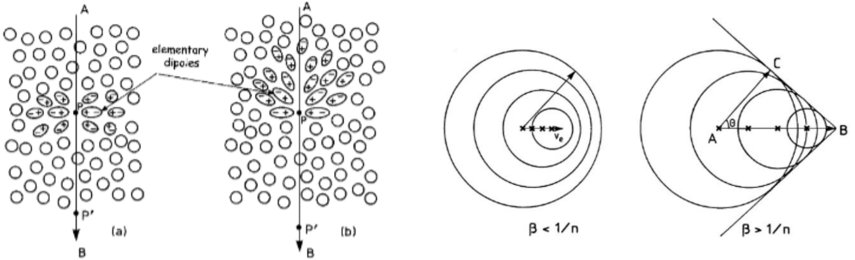




- Polarization of medium depends on the Electric field and the refractive index. $\vec{P_\omega} = (n^2 - 1)\vec{E_\omega}$. We intuitively understand it depends on refractive index. What other intuition we get from this equation?
- Frank and Tamm came with detailed theoretical description of the process. Essentially solving the dynamics of the polarization.
- Solution of the dynamics is essentially a solving a Bessel equation. $\frac{\partial^2 u(\rho)}{\partial \rho^2} + \frac{1}{\rho}\frac{\partial u(\rho)}{\partial \rho} + s^2 = 0$; $u(\rho)$ is the amplitude of the vector potential; $s^2 = \frac{\omega^2}{v^2}(\beta^2 n^2 - 1)$. There is another intuition here. Find it out!

Cherenkov radiation: microscopic view!

ALL ABOUT SYMMETRY BREAKING!



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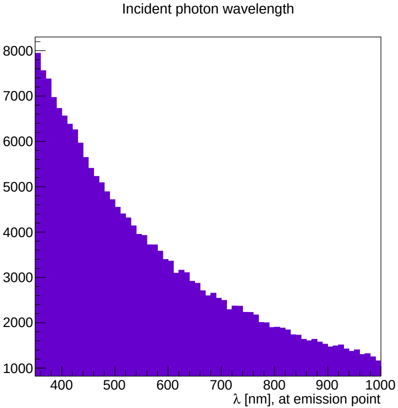
- The vector potential will only have physical solutions, if $\beta n > 1$; $\vec{A_Z} = -\frac{Ze}{c}\hat{z}\int_0^{+\infty} \frac{exp[i\omega(t - z/v) - i(s\rho - \frac{\pi}{4})]}{\sqrt{(2\pi s\rho)}}$
- This physical vector potential allows us to get the electric and magnetic field and most importantly the Poyenting vector. If we integrate the Poyenting vector, we get the total amount of radiation (W).
- $\frac{dW}{dl} = \frac{Z^2 e^2}{c^2}\int \left(1 - \frac{1}{\beta^2 n^2}\right)\omega d\omega$. Frank and Tamm Formula!

Importance of Frank and Tamm Formula

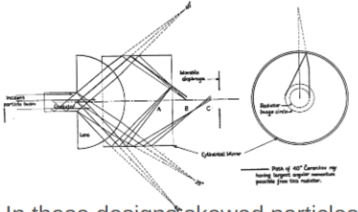
$$\frac{dW}{dl} = \frac{Z^2 e^2}{c^2} \int \left(1 - \frac{1}{\beta^2 n^2}\right) \omega d\omega \ ...$$

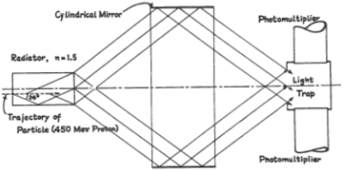
The Frank and Tamm Formula tells us how many photons will be emitted by the charged particle in the medium.

- If we have radiator length L, then number of emitted photons in the wavelength interval $d\lambda$ is $N = L\kappa \int \left(1 - \frac{1}{\beta^2 n^2}\right) \frac{d\lambda}{\lambda^2}$; we know that $(2\pi\omega\lambda = c/n(\lambda))$ and all the constant terms are inside κ. **More photons are produced in smaller wavelength**.
- This already tells us, we need photon sensors efficient to identify photons in smaller wavelengths.



RICH detector: Image Formation I





In these designs skewed particles does not focus! Limited phase-space!!

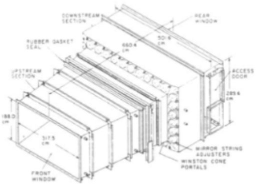
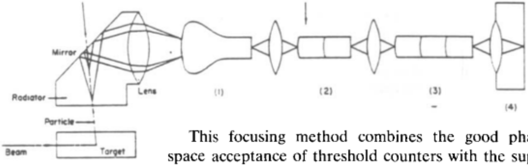
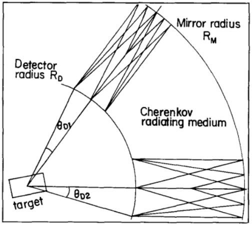


Fig. 5. The threshold Cherenkov counter C2 of the Fermilab experiment E691.



This focusing method combines the good phase space acceptance of threshold counters with the superior β resolution of differential counters. In its original form, proposed by Roberts [31] in 1960, it had a focusing lens which produced a Cherenkov ring on the surface of an image intensifier, as shown in Fig. 6. The

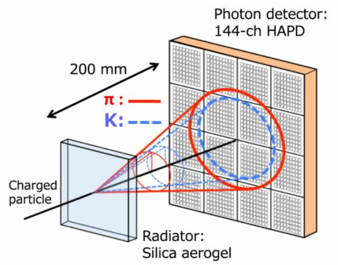
RICH detector: Image Formation II

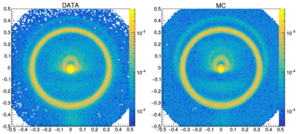


- Image formation is the central idea of a RICH detector as the name suggests: Ring Imaging CHerenkov Counter.
- The image of a ring (projection of a cone is a ring) can be used for particle identification and the diameter of the ring image is proportional to the Cherenkov angle. A pattern recognition of a ring, by means of Identifying the ring photons can even enhance the performance. Each photon of the ring is then a potential sample for PID.
- Image can be formed either by focusing (mirror based focusing) or in a proximity focusing (no focusing) RICH.

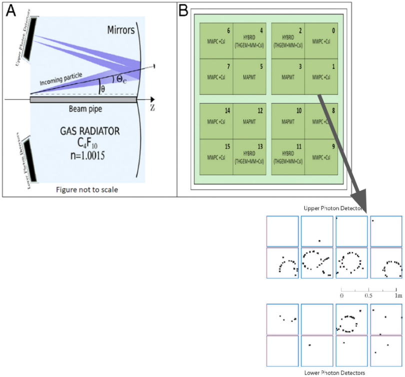
RICH detector: Image Formation III

A proximity focusing RICH





A mirror focused RICH



Importance of number of detected photons I

We can determine the Cherenkov angle for each detected single photon. If our single photon resolution is $\sigma\theta$, then the resolution on the ring angle is $\sigma_{\theta_c} = \frac{\sigma_\theta}{\sqrt{N}}$, where N is the number of detected **signal** photons. But, this is an approximate. You have to be careful, that your sensor can add some spurious hits and that will also dilute your resolution and also other correlated error coming from the spectrometer can add inaccuracy to the ring resolution. In such cases, you need to add such contribution in quadrature.
Our β resolution depends on the accuracy of Cherenkov angle (σ_{θ_c}) and accuracy of the refractive index.

$$(\frac{\sigma_\beta}{\beta})^2 = (tan\theta_c\theta_c)^2 + (\frac{\Delta n}{n})^2$$

The upper limit of our momentum up to which we can do n_σ separation critically depends on number of detected photons, single photo-electron resolution and the nominal value of the Cherenkov Angle.

$$\beta_1 - \beta_2 = \frac{\Delta m^2 \beta}{2p^2}$$

$$n(cos\theta_1 - cos\theta_2) = n\ 2sin(\frac{\theta_1 + \theta_2}{2})sin(\frac{\theta_2 - \theta_1}{2}) = n\ 2sin\theta\frac{\Delta\theta}{2} \sim \ldots$$

$$p^2 \sim \frac{\Delta m^2 \beta}{2nsin\theta\Delta\theta} \rightarrow p^2 \sim \frac{\Delta m^2 \beta^2}{2n\beta sin\theta\Delta\theta} \rightarrow p^2 \sim \frac{\Delta m^2}{2tan\theta\Delta\theta} \rightarrow p^2 \sim \frac{\Delta m^2}{2tan\theta n_\sigma \sigma_{\theta_C}} \rightarrow p^2 \sim \frac{\Delta m^2\sqrt{N_d}}{2tan\theta n_\sigma \sigma_\theta}$$

$$p_{up} \sim \left(\frac{\Delta m^2\sqrt{N_d}}{2tan\theta n_\sigma \sigma_\theta}\right)^{1/2}$$

Assumption: $\beta_1 \sim \beta_2 \sim 1 \rightarrow \beta^2 \sim \beta \sim 1$. They are interchangeable.
Therefore, having larger number of detected photons and minimization of the inaccuracies in detection of single photon Cherenkov angle is key to design an efficient RICH.

Importance of number of detected photons II

How many number of Photons can we detect in the first place?
The number of detected photons depends on several factors.

- The quantum efficiency of the sensor (QE).
- The efficiency with which a single photo-electron is detected (ϵ).
- Altogether one can consider a Photon Detection Efficiency (PDE).
- The overall transparency of the radiator (T).
- In case of mirror focused RICH the reflectance of the mirrors (R).

Importance of number of detected photons III

Considering these conditions and using the Frank and Tamm Relation our expected number of detected photons (or to be more technically correct photo-electrons) is:

$$N_{pe} = N_0 L sin^2\theta$$
$$N_0 = 2\pi\alpha c \int \epsilon QE(\lambda)T(\lambda)R(\lambda)\frac{d\lambda}{\lambda^2}$$

This N_0 is called the figure of merit for the RICH detector. An efficient RICH should have try to make this number large.
The maximum number of detected photons (N_{pe}^{max}) is therefore:
$N_{pe}^{max} = N_0 L sin^2\theta^{max}$. However, θ^{max} corresponds to saturated particles, means $\beta \rightarrow 1$. We can write from Cherenkov equation $sin^2\theta^{max} = 1 - \beta_{th}^2 = \frac{1}{\gamma_{th}^2}$.
Calculate!

Importance of number of detected photons IV

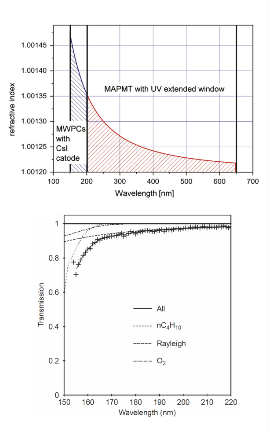
We can therefore estimate the number of detected photons from the ratio.

$$\frac{N_{pe}}{N_{pe}^{max}} = \frac{sin^2\theta}{sin^2\theta^{max}}$$
$$\simeq \frac{\theta}{\theta^{max}} \simeq (1 - \frac{p_{th}^2}{p^2})$$

This is a important consideration for selection of the RICH radiator.

- **Number of detected photons and maximum number of detected photons depend on the ratio of $\frac{p_{th}^2}{p^2}$. Independent of mass hypothesis.**
- **Therefore, if the threshold is at a smaller momentum, the saturation of both Cherenkov angle and the number of photons happen at a smaller momentum.**
- **The Cherenkov angles saturate faster than the number of detected photons for same value of $\frac{p}{p_{th}}$. If the number of detected photons is 64% of the maximum number of detected photons, the ring angle is already 80% of the maximum Cherenkov angle. For example, one way to handle this is to improve granularity. Pitch of readouts should therefore be optimize. $\sigma_{space} = \frac{pitch}{\sqrt{12}}$ (growing cost, larger probability of cross-talk etc...), one can also try to select radiator with lesser Chromaticity, improve foacalization etc ... However, there is a limit which controls the best resolution we can obtain from the detected single photon. So improving number of photons is a MUST!!**

Importance of number of detected photons V



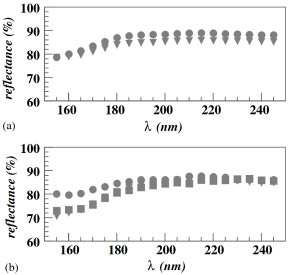


Fig. 3. (a) Mean value of the reflectance measured for the 126 mirror units at the centre (dots) and at the edge (triangles). (b) Reflectance of one mirror unit immediately after production (dots), after one year (squares) and after two years (triangles) permanence in RICH vessel.

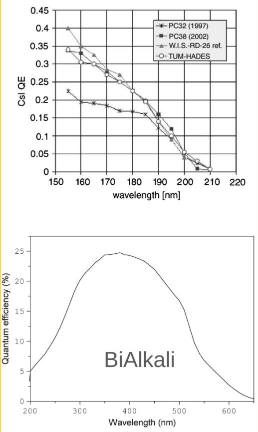
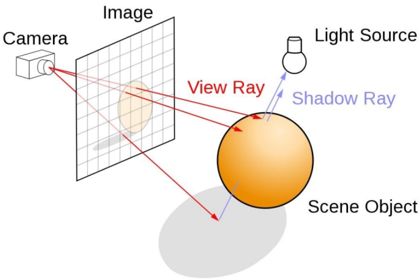
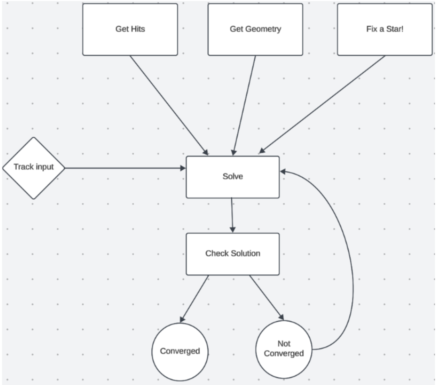


Figure: Example of optimization of different components of COMPASS/AMBER RICH just for one thing! More and more photons!

Inverse ray tracing: The concept I





Cherenkov angle reconstruction

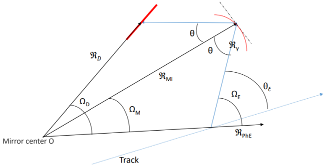
Let us know talk about, Cherenkov angle reconstruction for a focusing RICH.
What we know:

- We know where we have detected the photons. The hit coordinates.
- We know from the tracking, at which angle the track has entered and exited the RICH, this allows us to guess the possible points for the photon emission. For an ideal focusing RICH, the emission point uncertainty is zero. We can choose the midpoint for simplicity.
- We know what are our mirror parameters (Radius, center of sphere etc..)

What we DON'T know:

- At what angle the photon has impinged on the mirror surface and where exactly has it impinged.

And this is exactly what we want to know and estimate the Cherenkov angle.



- We know the angles Ω_D and angles Ω_M.
- We know the lengths $\mathcal{R}_\mathcal{D}$, $\mathcal{R}_\mathcal{M}$ and $\mathcal{R}_{phE}$.
- We just have to apply a sine law for similar triangles to have an estimate of the reflection angle θ.
- Given that $\Omega_D - \Omega_M - \theta$ is a very small number, we can determine the angle Ω_E in an iterative method.
- Once we know Ω_E, we can determine the photon vector (ν).
- The projection of ν on track vector **P** is the **reconstructed Cherenkov angle**.

The *advantage* is that we reconstruct the angle from pure geometry. Hence no dependence or assumption on refractive index or mass-hypothesis. But...

Cherenkov angle reconstruction

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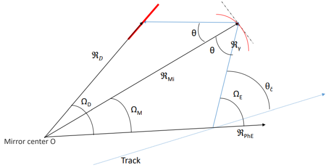

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The *advantage* is that we reconstruct the angle from pure geometry. Hence no dependence or assumption on refractive index or mass-hypothesis.
The *concern* is that we reconstruct the angle from pure geometry. A mistake in the geometry and you need to find a PhD student. The advantage of these kind of tuning studies is that the entire microscopic feature of the RICH technology will be clear!

Important considerations for a RICH I

Choice of the radiator:

- **NO OTHER LIGHT!!!** Intensity of generated Cherenkov photons is lower than scintillation. Therefore, during the radiator selection, we must take care that the amount of scintillation light is not significant. In COMPASS RICH-1 C_4F_{10} is used as a radiator with negligible scintillation.

  Question: CF_4 is estimated to have factor 40 more scintillation yield. But, LHCb is successfully using CF_4 for one of their RICH detectors. Can you guess what have they done? Hint: In gaseous ionization detectors sometimes a tiny fraction of a gas other than the ionizing gas is added. For a very specific purpose.

- The radiator generates these Cherenkov photons. Therefore, it should produce sufficient photons that can be detected. There should not be any absorption bands that absorbs photons of interesting wavelength range.
- The lighter the radiator material, the smaller the amount of generated photons. This can be compensated by employing larger radiator length.
- We have to make sure, that the gas is transparent in the wavelength range of interest.

Important considerations for a RICH II

- With all these criteria for high momentum PID using Cherenkov radiation we have very few gases left that can be used as a radiator.

Optical Boundaries and mirrors (if used): The Cherenkov photons are linearly polarized. Therefore, any optical media (filters, windows etc) present between the generation point and the sensor will have a finite reflection probability. We have to estimate carefully such losses. We also have to be careful that the materials are isotropic to polarized light.
The mirrors provide good reflectivity in the wavelength region of interest. Their reflective quality does not degrade over time. Proper choice of protective coating. The roughness should be very small otherwise it will introduce dispersion of light. For COMPASS roughness RMS is about a nanometer. Simulation study essential to determine the requirement. Check G4 on dielectric-metal interfaces on how to make surface rough.
The spot diameter (spot diameter D) should be very small for COMPASS it is about few mm.A focusing mirror makes all parallel light into a point (An infinite source is a point source and light beam from an infinite source is parallel). Therefore the mirror should contain all light power (95% is all!) at its focal length! A lot of details should be taken care during the coating of the mirrors.

Important considerations for a RICH III

The sensors (and readout electronics):

- Already from Frank and Tamm equation, we know that Cherenkov photon yield in the lower wavelength region is higher. We need high photon detection efficiency in the lower wavelength region.
- The sensor has high gain and high signal to noise ratio.
- Less dead areas and Intrinsically fast. This also brings us to design a fast electronics with low electronic noise.

In Case you are bored!

- Cherenkov radiation is a velocity dependent process. NOT momentum dependent. Therefore we can identify different masses.
- Cherenkov radiation has a threshold momentum and saturation angle. Both depends on the refractive index of the radiator material.
- Each photon is an independent source of particle identification, with a given resolution.
- If we can have more of these independent sources, our accuracy improves. Hence, we always fight for more photons.
- Longer radiator gives more photons. In case you can get a long radiator get a better sensor.

Let's look at ePIC I

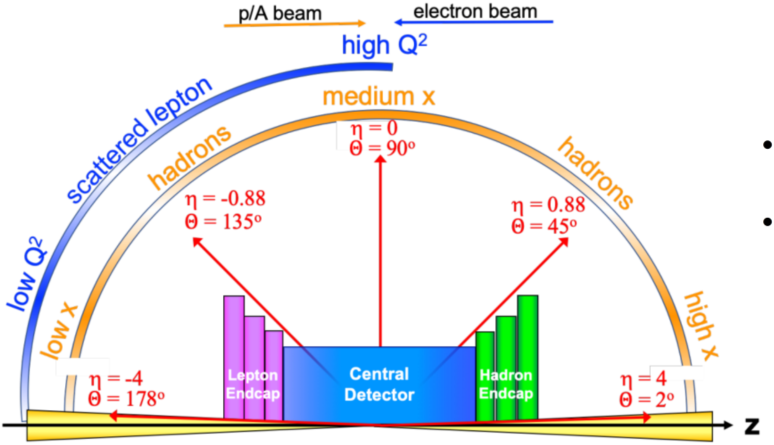
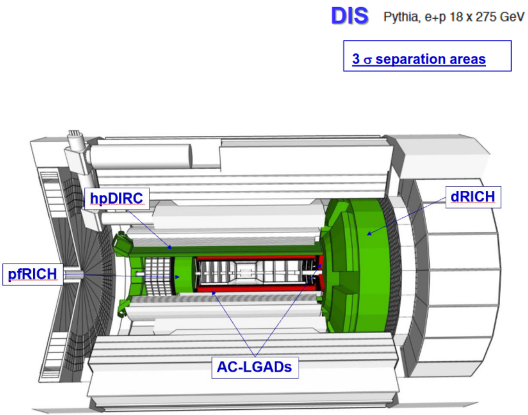
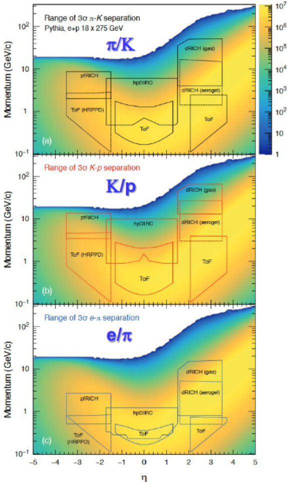


Figure 8.1: A schematic showing how hadrons and the scattered lepton for different $x - Q^2$ are distributed over the detector rapidity coverage.

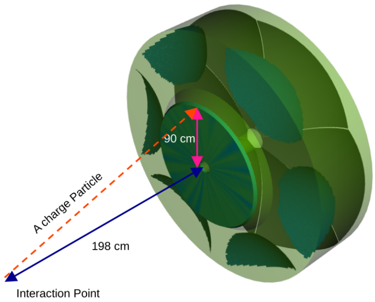
-
-

Let's look at ePIC II

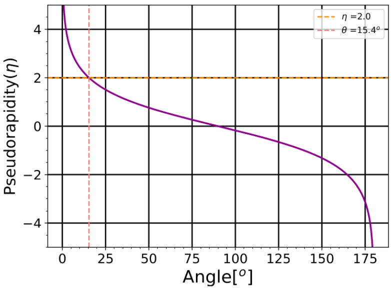




Let's look at ePIC III



Minimum Pseudo rapidity ~ Maximum angle :
arctangent (90/198) ~ 25 degrees ~ 420 mrad!



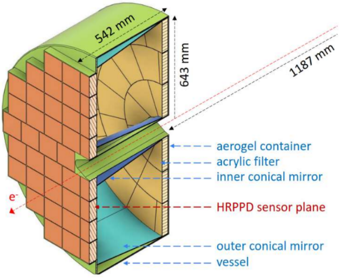
$$y = \ln\left(\frac{E + p_z c}{E - p_z c}\right)$$

$$\eta = -\ln\tan\left(\frac{\theta}{2}\right)$$

- Rapidity is tells us the angle between the XY plane and the direction of emission of a product of the collision.
- Can often be difficult to measure.
- We introduce pseudorapidity. A measure of the particle's angle wrt to beam axis.

PID Detectors in ePIC I

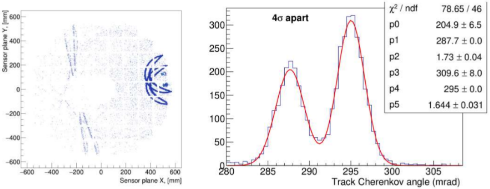
pfRICH:



Serves as Time of Flight using HRPPD sensors!

e-endcap RICH for ePIC detector

- A classical proximity focusing RICH
- Pseudorapidity coverage: $-3.5 < \eta < -1.5$
- Uniform performance in the whole $\{\eta,\phi\}$ range
- π/K separation above 3σ up to ~ 9.0 GeV/c and ~10-20ps t_0 reference with a ~100% geometric efficiency in one detector



Sophisticated chi-squared analysis capable of performing efficient pid with complicated event topologies.

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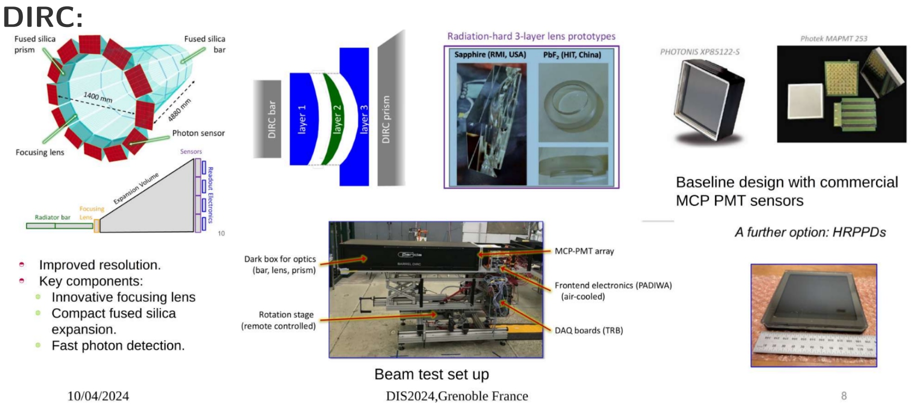
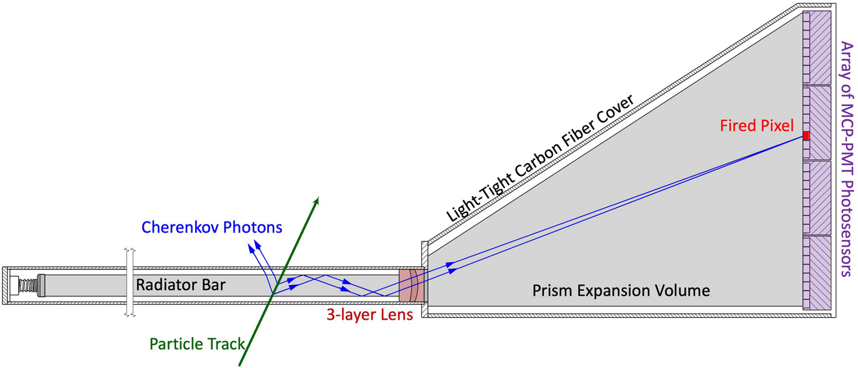
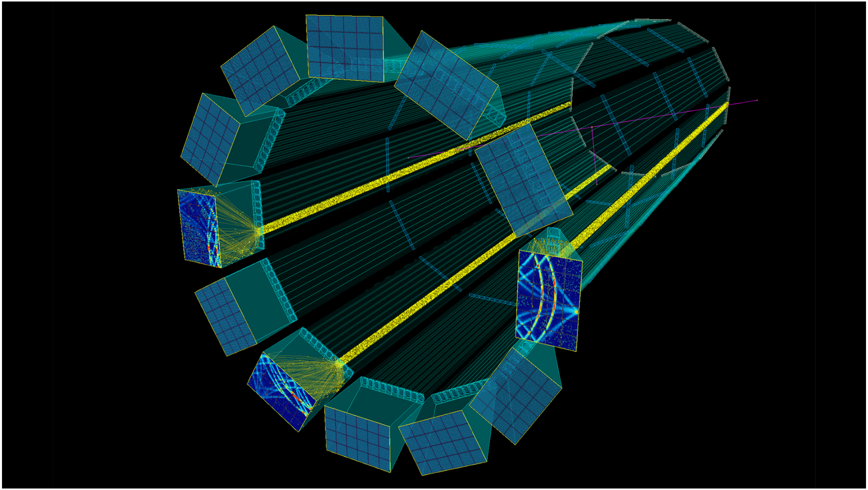
PID Detectors in ePIC II



PID Detectors in ePIC III

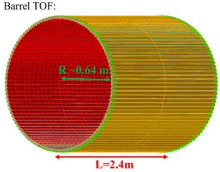


PID Detectors in ePIC IV

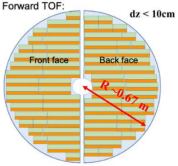


PID Detectors in ePIC V

TOF:

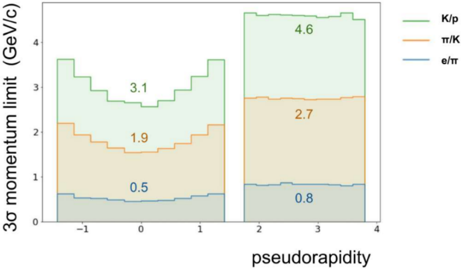


500 umX1cm strips
(1%X0)



500 umX500um pixels
(~3%X0)

	PID coverage (π/K)
Forward (1.5<η<3.5)	$0.15 < p < 2.5$ GeV/c
Barrel (|η|<1.4)	$0.15 < p_T < 1.5$ GeV/c



- ✔ Advanced geometric description in simulation,
- ✔ Physics performance studies,
- ✔ dedicated R&D with photosensors and
- ✔ readout commonality with pfRICH in readout ASIC

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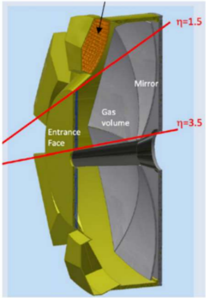
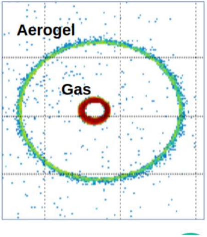
PID Detectors in ePIC VI

dRICH:





- Requirements:
  - **Wide acceptance** (+- 300 mrad/ 1.5<η≤3.5)
  - **High momentum coverage** up to 50 GeV/c π-K
    - Dual radiator (**aerogel (n ~1.02)**+ **C_2F_6 gas (n~1.0008)**)
- **Compact geometry:** short radiator space available
  - Smaller number of detected photons → Critical optical tuning and control over background hits.
- **Large sensor surface to be covered in magnetic field.**
  - Limited choice of photon-sensor (**SiPM as a cost effective solution**)
- Simulation contains: **6 identical sectors**
  - **Spherical mirror with radius 220 cm**
  - **SiPM sensors with realistic PDE and additional 70% safety factor.**
  - **Realistic parameters** for **aerogel** and **C_2F_6**

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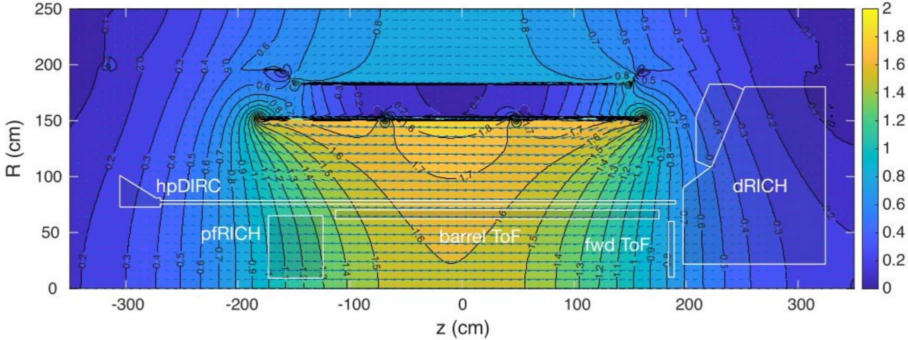
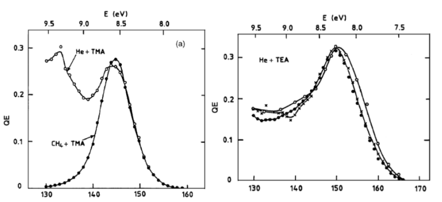
The Solenoid magnetic field



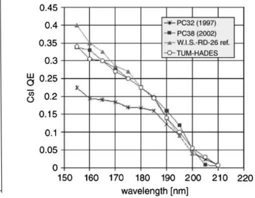
The presence of magnetic field dictates the choice of the photon sensors.

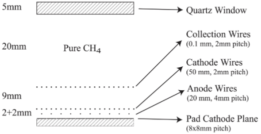
Evolution of photon detectors: my personal views I



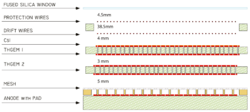
First generation photo converter. Gaseous phase has low ionization threshold (5.5 eV). Measured QE is good! Low vapour pressure→ very long photon free path→ Slow RICH

Revolution! Fast RICH With Solid Photo Converter! Delicate! Water contamination, ion bombardment kills

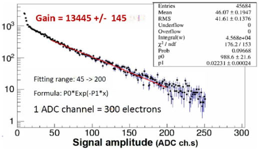


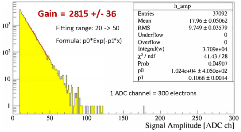


Open geometry



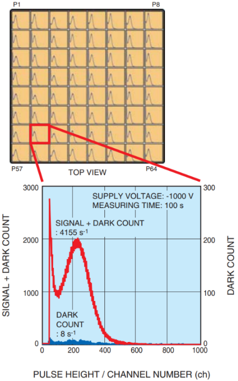
Closed geometry





Evolution of photon detectors: my personal views II

Figure 5: Single photon counting (Example)



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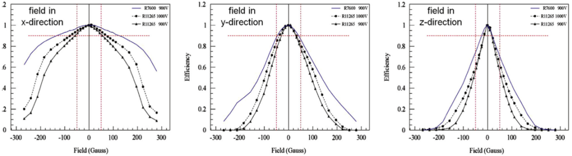
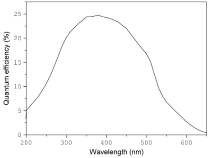
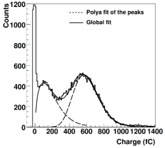
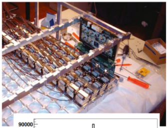
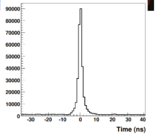
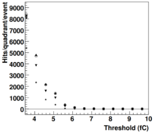












MaPMTs are fast, noise-free efficient photon detectors (Outside magnetic field)

Evolution of photon detectors: my personal views III

S. Eisenhardt / Nuclear Instruments and Methods in Physics Research A 565 (2006) 234–240 239

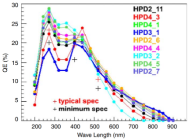


Fig. 12. Quantum efficiency of nine pre-series HPDs.

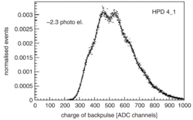


Fig. 13. A typical backpulse spectrum of signals of photo-electrons hitting the anode, measured on the bias supply line.

Hybrid Photon detectors worked great for LHCb. High dark count rate and to operate in higher luminosity made them to upgrade with MaPMTs

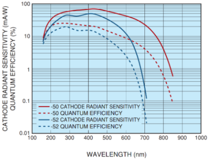
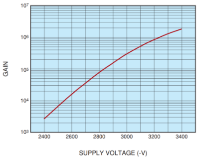
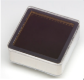
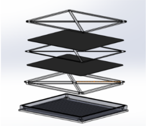


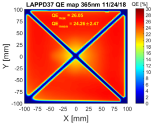
Figure 2: Typical gain

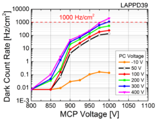


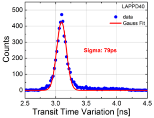
Commercial MCPs are fast, low noise, much better tolerant to magnetic field than classical PMTs. (Small read, expensive)

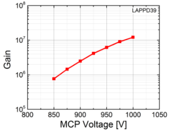






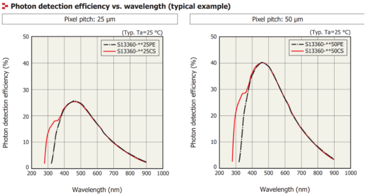


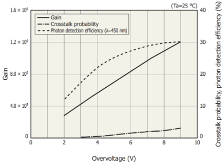


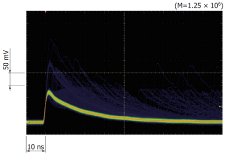


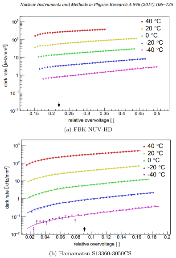
Large area MCP PMTs, high rate capability, high gain, low dark count... (novel technology, needs validation)

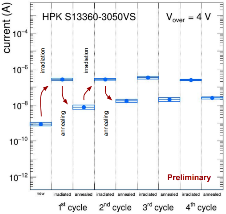
Evolution of photon detectors: my personal views IV

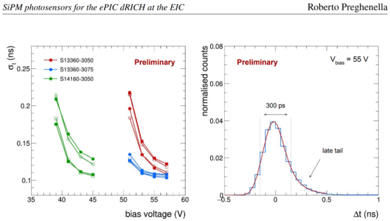










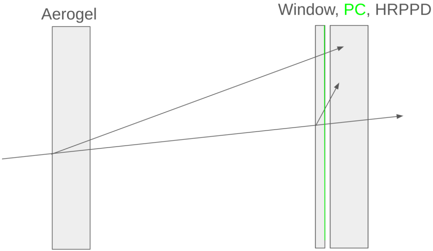


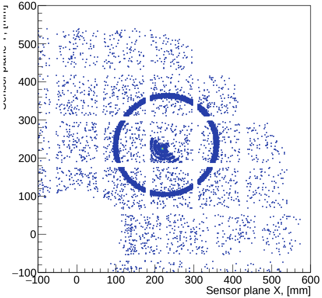
SiPM new generation photon detector, high gain, magnetic field insensitive, high PDE.
High dark count (needs to be cooled down), Sensitive irradiation (annealing method helps)

Why is the knowledge of photon detectors central to RICH simulations?

Evolution of photon detectors: my personal views V

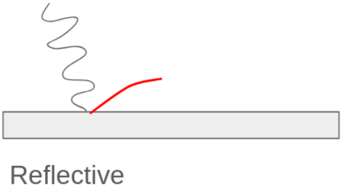
- Need to have a-priori knowledge on the photon sensors to estimate number of detected photons.
- Any abnormal input for photon detector parameters may lead to un-physical observables (this is in general true for other components as well, less critical).
- The largest effect on the number of photons comes from the photon sensor.

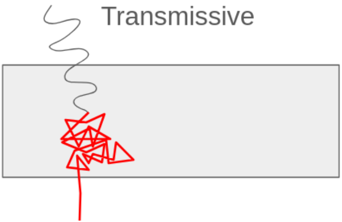




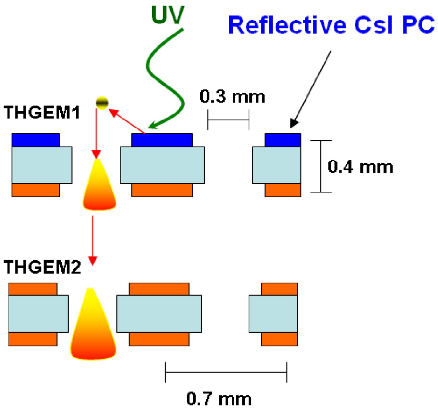
Principle of Photon Detectors I

- The MCPs convert a primary electron into many secondaries. The ratio of secondary to primary electrons are called the 'Gain' of the MCP.
- So we have to get an electron from the Cherenkov photon. How? Does Einstein tell you anything?
- A photoconverter (aka photcathode) does this job! Photocathode can be of two types: a) Reflective and b) Transmissive.





Principle of Photon Detectors II



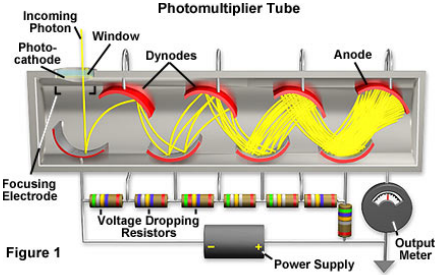
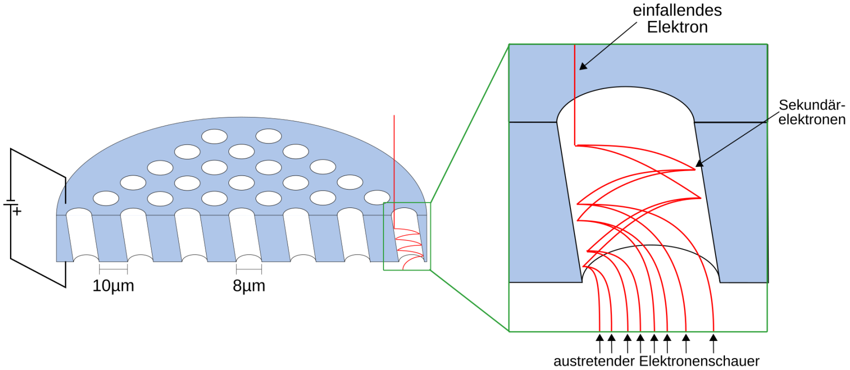
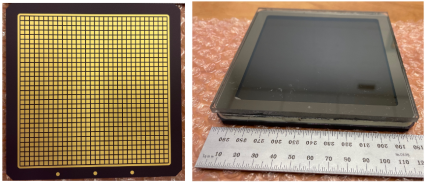


Figure 1

Principle of Photon Detectors III



Principle of Photon Detectors IV



1024 ~3.2mm pads

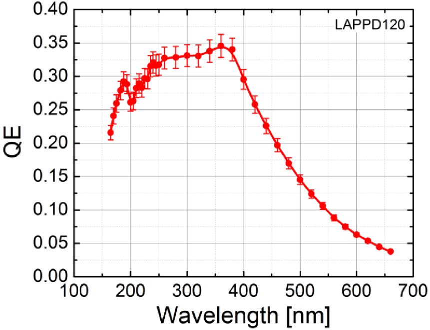
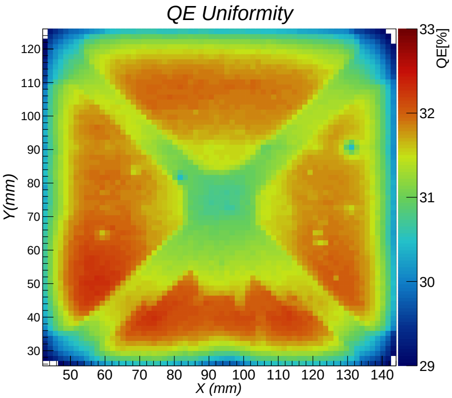


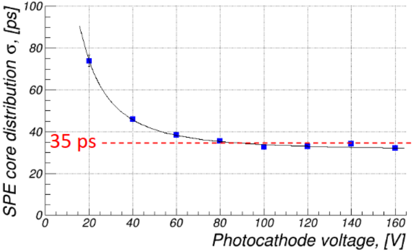
Figure: Non uniformity of QE means Non uniformity in RICH performance.

Principle of Photon Detectors V



Principle of Photon Detectors VI

- The HRPPD sensors used in the pfRICH will also be used as a timing detector.
- MCP PMTs are fast detectors.
- Cherenkov photons are instantaneous unlike scintillation.
- The idea is to utilize the Cherenkov photons generated in the quartz window and exploit their timing.



Principle of Photon Detectors VII

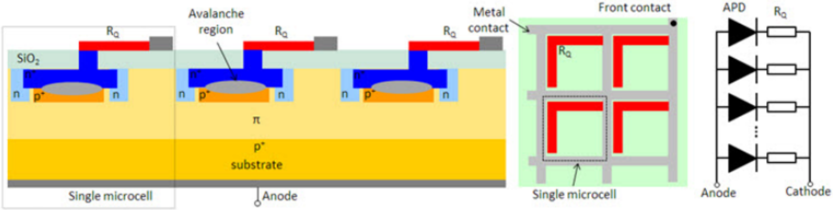


Figure 1. This figure depicts a typical structure of a SiPM. It does not correspond to the actual structure of the Hamamatsu product.

Principle of Photon Detectors VIII

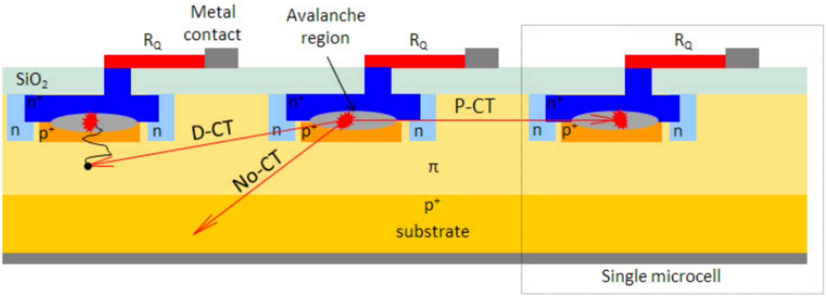
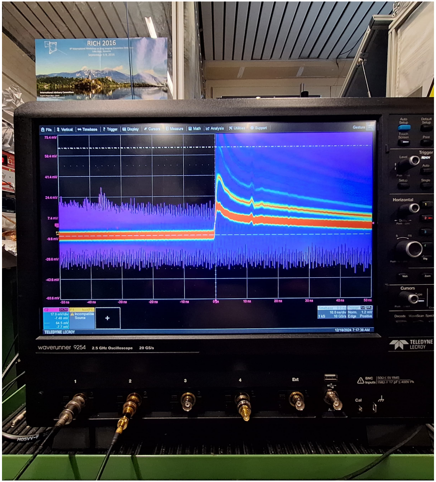


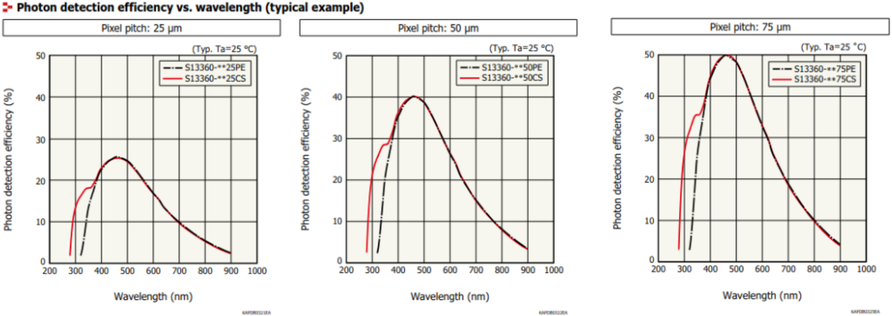
Figure 11. This diagram depicts the mechanism for the prompt (P-CT), delayed (D-CT), and no (No-CT) crosstalk. (It also shows a typical structure of a SiPM, but it does not correspond to the actual structure of the Hamamatsu product.)

Principle of Photon Detectors IX



Photon Detection Efficiency:

Principle of Photon Detectors X



The power of refractive index I

Note the central values and the widths!

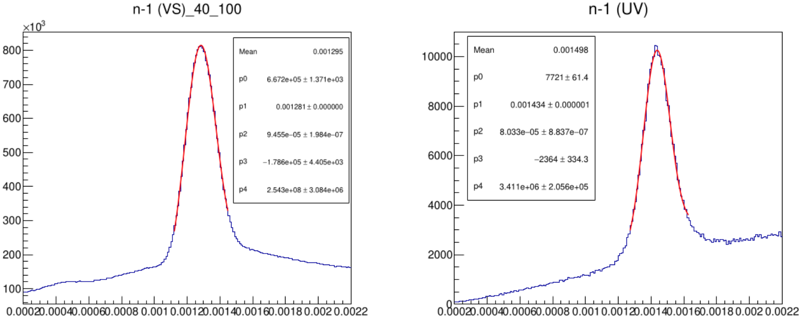


Figure: Example of refractive index extracted by using each single photon detected in MAPMTs(VS) and the gaseous detectors (UV)

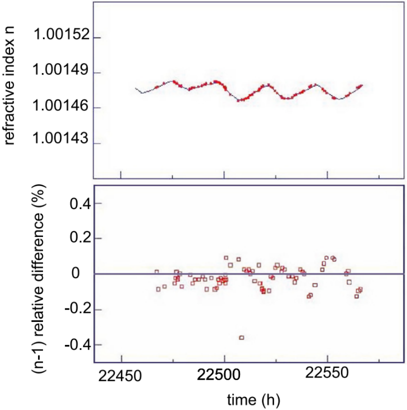
The power of refractive index II

The refractive index of the radiator gas is independent of everything. It depends on temperature and pressure of the radiator.

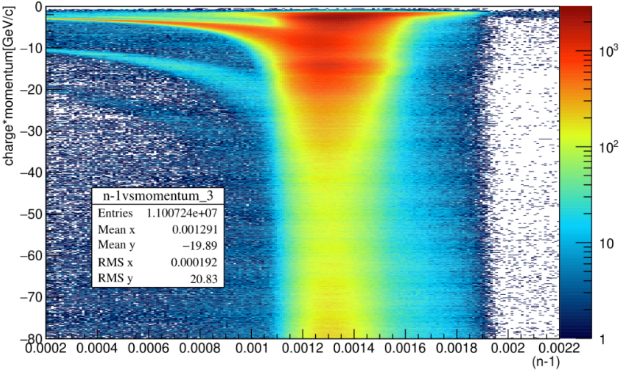
$$\frac{n^2-1}{n^2+2} \propto \frac{p(atm)}{T(K)}$$

A precise knowledge of refractive index is central for estimating the mass of the particle. But, we can play the opposite trick. We assume a mass hypothesis and can extract the refractive index of the radiator from each single photon. If, we obtain a meaningful distribution of the refractive index then we can claim the RICH is tuned.

Similar to the Cherekov angle the refractive index can be plotted as a function of the momentum.



The power of refractive index III



$$(n-1) = \frac{\sqrt{p^2 + m_\pi^2}}{\cos\theta . p} - 1$$

Similar to the saturation of the Cherenkov angle, the refractive index saturates (towards its nominal value). Steeper derivative of Cherenkov angle in the lower momentum and wrong mass hypothesis lead to wrong central value!

The power of refractive index IV

why is refractive index so powerful?

$$\tan\theta_{sat} \simeq \theta_{sat} = \frac{r}{f}$$

$$Also, \cos\theta_{sat} = \frac{1}{(n-1)+1}; \beta \rightarrow 1$$

$$1 - \frac{\theta_{sat}^2}{2} = 1 - (n-1)$$

$$\theta_{sat} = \sqrt{2(n-1)}$$

$$\therefore \frac{r}{f} \simeq \theta_{sat}$$

$$\frac{\delta(r)}{r} = \frac{\delta(n-1)}{2(n-1)}$$

Therefore, 1% error in ring radius would cause 26 ppm change in the refractive index if we assume nominal (n-1) is 1300 ppm. This is much more visible. In COMPASS for example a saturated ring has a radius of $\sim$ 16 cm in the MaPMTs.

The power of refractive index V

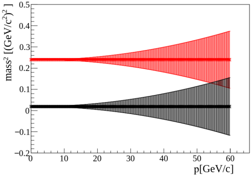
How precisely, can we measure the refractive index from the data?

$$\cos\theta = \frac{1}{n}; \beta \to \ 1;$$
$$1 - \frac{\theta^2}{2} = 1 - (n-1)$$
$$\theta\sigma_\theta = \sigma_{(n-1)}$$
$$\sigma_{(n-1)} = (\sigma_\theta)(\sqrt{2(n-1)})$$

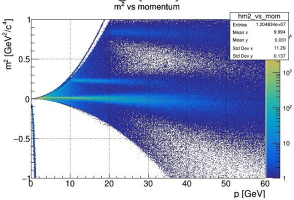
If we assume a nominal refractive index of 1300 ppm in the visible range and in some MaPMTs detectors we have single photon resolution of about 2 mrad. How much would be the spread of the (n-1) histogram?

Reconstructed Mass from the RICH: A hint towards PID I

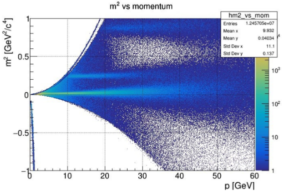
$$\left(\frac{\sigma_{m^2}}{m^2}\right)^2 = \left(2m^2\frac{\sigma p}{p}\right)^2 + \left(p^2\frac{2\theta_C\sigma_{\theta_C}}{(n-1)-1}\right)^2 + \left([2p^2-(p\theta_C)^2]\frac{\sigma_{(n-1)}}{[(n-1)-1]^2}\right)^2$$



Wrong (n-1)

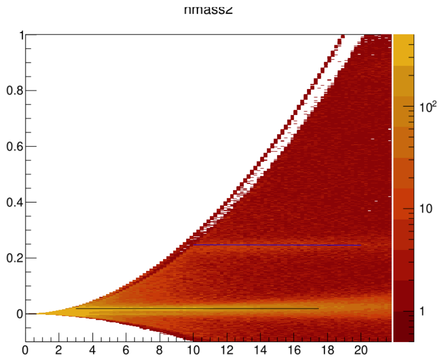


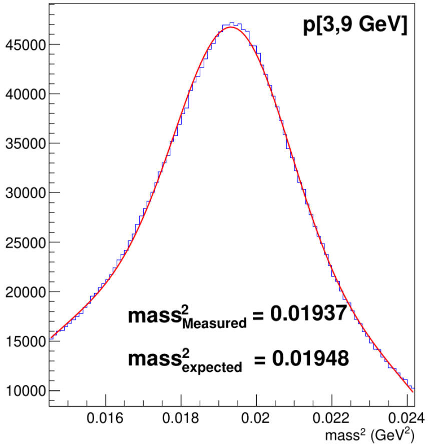
Better tuned (n-1)



- The squared mass has an error, that goes in quadrature with momentum, symmetrically.
- At saturation, our θ_{sat} is identical to 2(n-1), but over larger number of events, we do have cases where the difference gives a negative value the spread.
- Central idea is that the squared mass should be as straight as possible with momentum. Let's zoom it.
- Impact of refractive index is one of the two major contributors. What is the other one?

Reconstructed Mass from the RICH: A hint towards PID II





Few words on PID Algorithms I

COMPASS/Amber RICH has two inbuilt PID algorithms:

- Ring χ^2 based PID:

  $$\frac{\chi^2_M}{\nu} = 1/\nu \sum_{j=1}^{N_{rPh}} \frac{(\theta_j - \Theta_M^{UV})^2}{\sigma_{\theta j}}$$

- Likelihood based PID (track-by-track basis):

  $$\mathcal{L}_{\mathcal{M}} = exp(-(S_M + B)) \prod_{j=1}^{n} p_M$$

  $S_M = \int_C s_M \; d\theta \; d\phi$; $B = \int_C b \; d\theta \; d\phi$;
  un-normalized probability $p_M = s_M + b$

- Both methods should have ideally consistent performance.
- Ring χ^2, takes an average information of all the ring photons. Hence, we scale everything to UV refractive index.
- Likelihood method does take care of individual photon information over a large surface (70 mrad). Treats UV and VS refractive index properly.

Few words on PID Algorithms II

Some more details on Likelihood:

- An apple is more likely to be a fruit than a car. How do we know? We define parameters to define a car and a fruit; for example weight, taste, smell (when fresh or rotten), lifetime etc... We take several apples (the more the better) and test (based our observables or sampling values) them on these parameters. The closer we are to either of the hypothesis (car or fruit), the more likely apple favors one of the two. **(Take it with grain of salt, and refrain yourself from using it in Physics conferences!!)**
- We have set of parameters l_k and sampling variable θ_i; Likelihood $L = \prod_{i=1}^{N} p(\theta_i, l_k); \int p(\theta_i, l_k) = 1$. This is a normalized probability.

Few words on PID Algorithms III

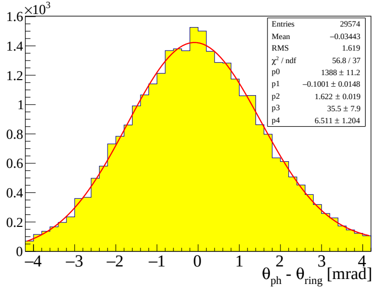
- Our sample size (the number of detected photons N) varies for each track. We have to relax the normalization condition. For us $\int P(\theta, l_k) = N(l_k)$. The number of detected photons will be governed by a Poisson Statistics. The observed value of this sample size for a track is not therefore a good estimation. We have to obtain it from a fit. This tells us why the characterization of photon detectors is fundamentally important.
- A simple replacement of $p(\theta_i, l_k)$ with $P(\theta, l_k)$ is not possible. why?.
- In case we have just one ring like concentration of hits; we can remedy this "why?", we not only check the observed events (photons) were observed at $(\theta_1, \theta_2 ... \theta_m)$ but not anywhere else. We take a 70 mrad circular patch (fiducial region; to sound posh) around the reflected track centre and count all the registered hits. With an extremely important assumption: the bins at which we scan this patch is negligibly tiny. We don't have a more than one events in that bin. How to account double hits? Let's give it some 'time'. **How would you extend this to a dual Ring scenario?**

Few words on PID Algorithms IV

- Then: Probability of 0 and 1 event is:
  $P_0 = e^{-\Delta\theta P(\theta)}$; $P_1 = \Delta\theta P(\theta) e^{-\Delta\theta P(\theta)}$.
- Physically, extended likelihood is an combined probability:
  $\mathcal{L} = \prod_i \Delta\theta P(\theta_i) \prod_j e^{-\Delta\theta P(\theta_j)}$; If we take a limit $\Delta\Theta \to d\theta$ we have
  $\mathcal{L} = \left[\prod_i P(\theta_i)\right] e^{-N}$; or in logarithmic form $ln(\mathcal{L}) = \sum_i P(\theta_i) - N$
- It is now, to find out a maximization of the extended Likelihood. The increasing normalization will increase the first term but will decrease the second. A very simple solution to this can be obtained again by using the Poisson statistics. If we have the total number of events (N) and we have observed n events following a Poisson Statistics, then essentially our likelihood is: $\mathcal{L} = \prod_{i=1}^{n} P(\theta_i) \frac{e^{-N}}{n!}$. And this is the form we adopt in COMPASS/AMBER RICH likelihood computation. Let us just plugin the relevant numbers now!

Few words on PID Algorithms V

- We have n number of detected photons inside a large fiducial region. With reconstructed θ_i values. Each of these photons, give an estimate on how far or close they stand wrt a mass hypothesis. We know, in which of the two detector types the photons were detected,hence the correct refractive index. Expected theta Cherenkov is calculated for that hypothesis. Note, that a-priori we don't know how our probability distribution should look like and how much is the spread. The detector Characterization give us an estimate. Both the shape and the spread. For us, it is Gaussian as we have seen.

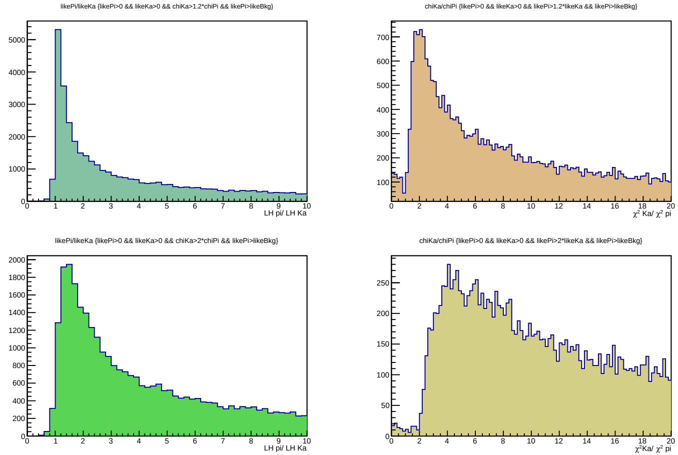


- This gives us a signal term

$$s_M = \frac{S_0}{\sigma_{\theta j}\sqrt{2\pi}} exp(-\frac{1}{2}\frac{(\theta_j - \Theta_M)^2}{\sigma^2_{\theta j}})\epsilon(\theta j, \phi j)$$

- We treat each detected photon hits has a non-zero background probability. This is computed from the background map over the large number of physics events. Assuming the chance to see a signal is small. And only few hits that has a very large signal contribution will give a likelihood value favoring a mass hypothesis. Otherwise the background hypothesis will dominate.

Consistent nature of χ^2 and Likelihood PID



We are seeing the COMPASS RICH data from 2022 physics run. A small sample of all particles provided signal, have good consistencies for both PID algorithm methods.

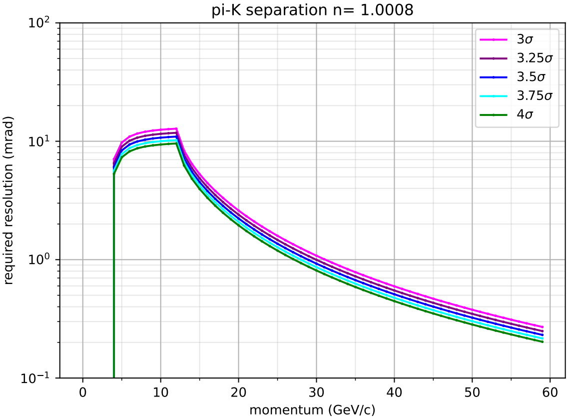
About to Wrap up: Example of dRICH simulation studies I

What are the parameters that determine the single photon Cherenkov angle resolution?

$$\sigma^2_{theta} = \sigma^2_{mag} + \sigma^2_{em} + \sigma^2_{Chrom} + \sigma^2_{pix}$$

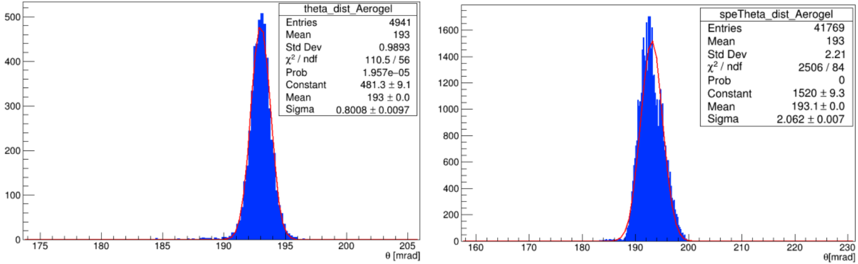
- Presence of the magnetic field but adding uncertainty to track position inside radiator.
- Emission point uncertainty.
- Chromaticity.
- Pixelization.

About to Wrap up: Example of dRICH simulation studies II



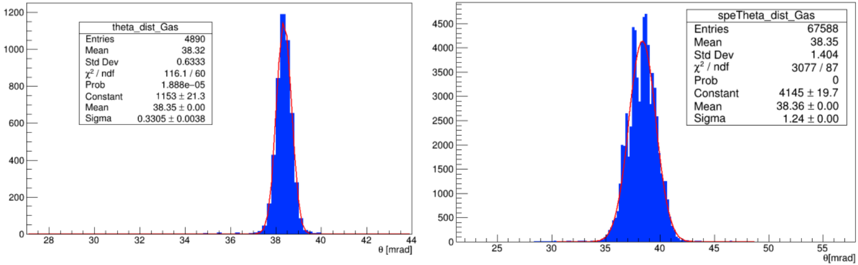
If considering all the contributions, we estimate that our single photon resolution is 1.4 mrad. How many number of photons should we detect to reach three sigma separation between pions and kaons at 50 GeV/c?

About to Wrap up: Example of dRICH simulation studies III

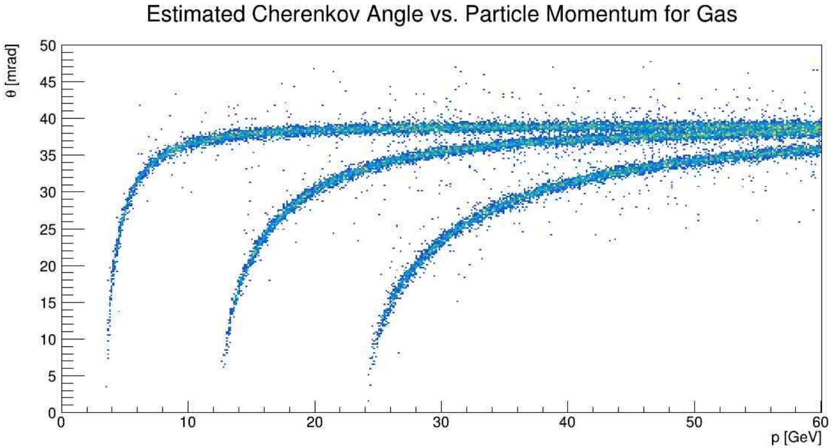


dRICH Aerogel angle

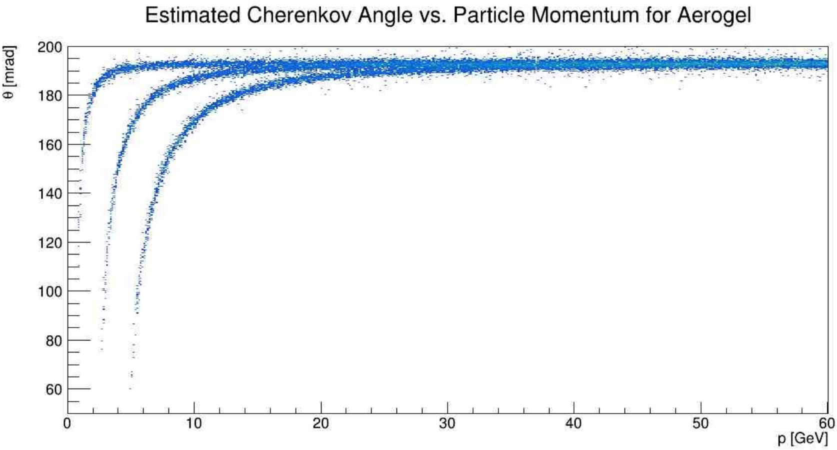
About to Wrap up: Example of dRICH simulation studies IV



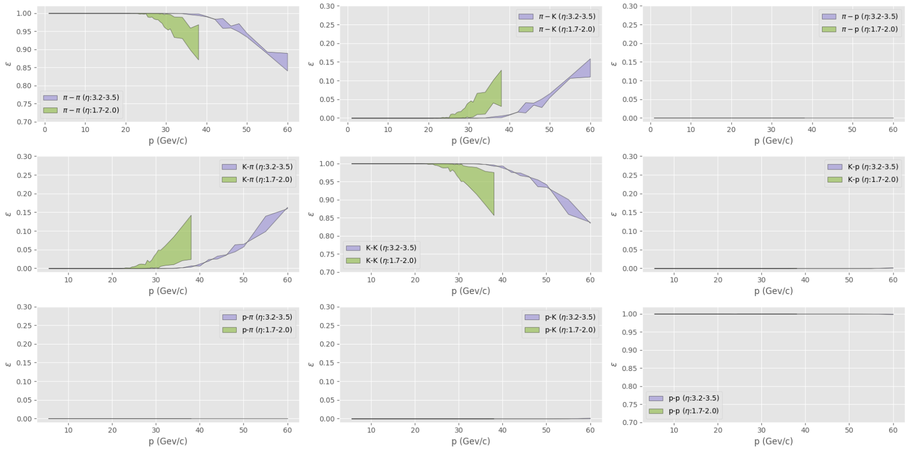
About to Wrap up: Example of dRICH simulation studies V



About to Wrap up: Example of dRICH simulation studies VI

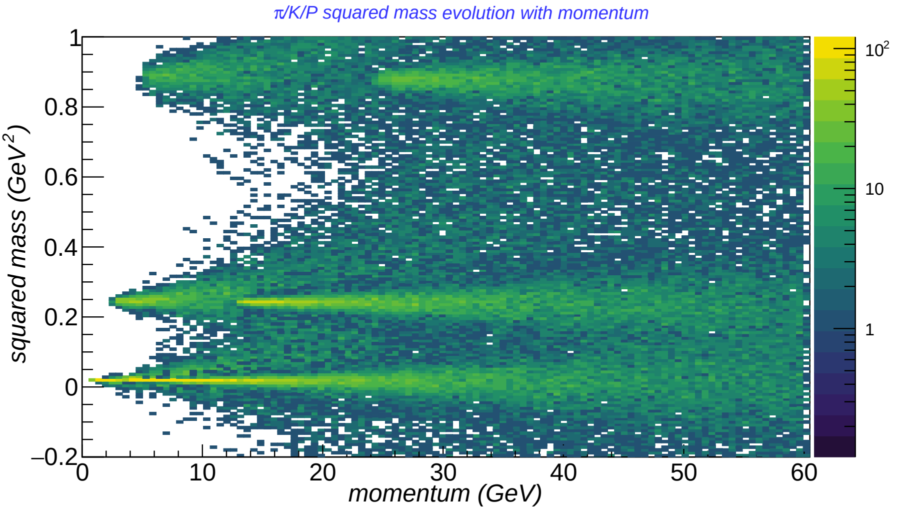


About to Wrap up: Example of dRICH simulation studies VII



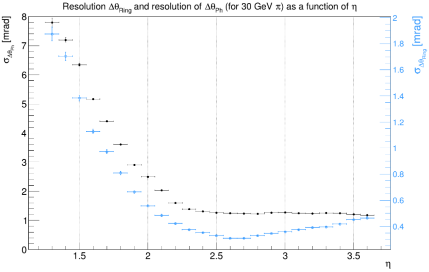
caveat: There is no likelihood estimation implemented in ePIC dRICH. This is a statistical estimate using simulation.
Some other features can be studied too...

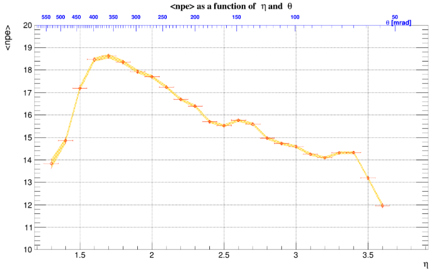
About to Wrap up: Example of dRICH simulation studies VIII



About to Wrap up: Example of dRICH simulation studies IX

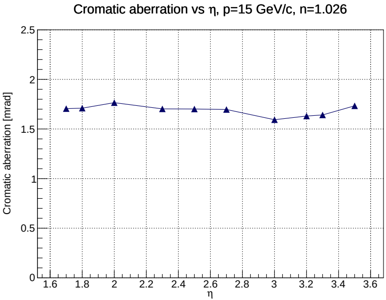
Even some microscopic features...

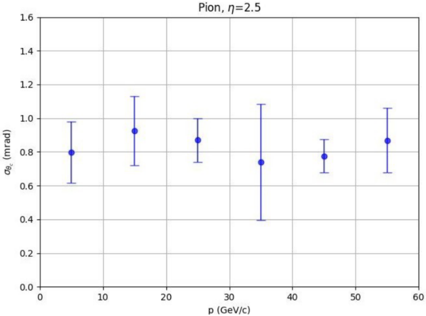




$$\sigma_{ring} = \frac{\sigma_{photon}}{\sqrt{N_s}} \oplus B$$

About to Wrap up: Example of dRICH simulation studies X





Let's wrap up I

- I am not a teacher, I am researcher working with different RICH technologies since a few years, in simulation, characterization, analysis and hardware aspects. Therefore, my course could have been overwhelming! My sincere apologies.
- I tried to convince that in current technological advancement, in high angular acceptance with a broadband momentum coverage RICH technology is extremely efficient for PID. I tried to put down most of the equations relevant. They are not fully detailed, but you can work on them.
- RICH (particular high momentum RICH) is a complex due to uncompromising demand on velocity resolution. It can be multi-component detector technology. Each component requires specific expertise and contemporary advancements are ongoing.
- Higher number of photons is a key parameter for RICH technology, the most demanding aspect of imaging!

Let's wrap up II

- MonteCarlo simulation for RICH detectors are fascinating, but requires cautious monitoring of several aspects and details coming from a-priori knowledge. ePIC PID systems provide opportunity to work on simulation studies and reconstruction software development with cutting edge software frameworks for extremely complicated RICH geometries and actually there are more than one RICH technology present. Simulations are being implemented with the recent most hardware choices available. Sophisticated reconstruction algorithm are being developed. (**Highly challenging and most importantly FUN!!!**.)

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10. Some I forgot, please point me to the plots, I will pass the reference...