Photon Detectors

Silvia Gambetta
University of Edinburgh

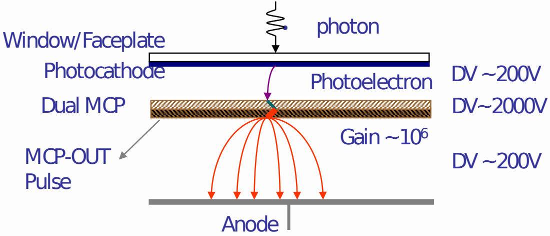
THE UNIVERSITY *of* EDINBURGH

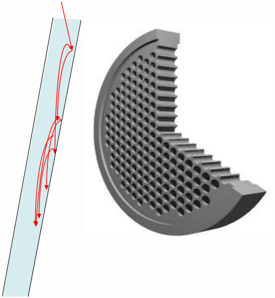
EURIZON detector school

eurizon
European network
for developing new horizons for RIs

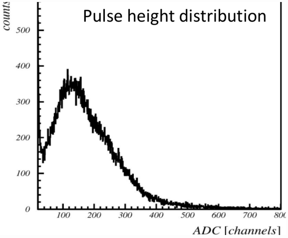
Micro Channel Plat PMT (MCP)

Similar to ordinary PMT but dynode structure is replaced by MCP: continuous dynode structure based on lead-glass disk with aligned pores (diameter = 6.5-25 μm, length = 400-1000 μm)

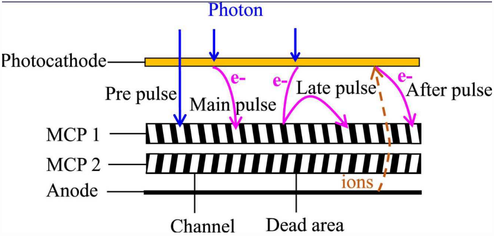




- $G \sim 10^6 - 10^7$, single photons (two MCP layers in Chevron configuration)
- Collection efficiency ~60%
- small thickness ⇒ small TTS ⇒ excellent intrinsic time resolution!
- very low sensitivity to magnetic field
- anode can be segmented according to application ⇒ position sensitive, easier to obtain finer granularity

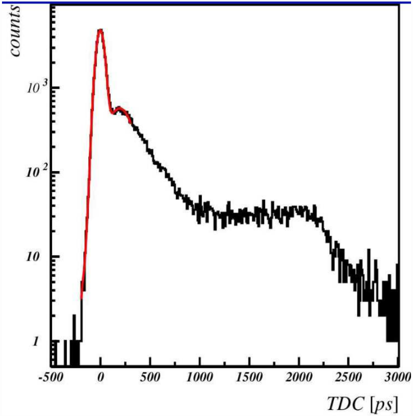


MCP PMT timing characteristics



Contributions to signal:

- Pre-pulse: no photon conversion in photocathode, SE in micro-channel, lower amplitude
- Main pulse: photon conversion in photocathode, SE in micro-channel, nominal amplitude
- Late pulse: after photoelectron backscattering and re-entry in micro-channel, $\sim$nom. amplitude
- After pulse (Ion Feed-Back): ionisation effects $\rightarrow$ Degradation of gain and quantum efficiency

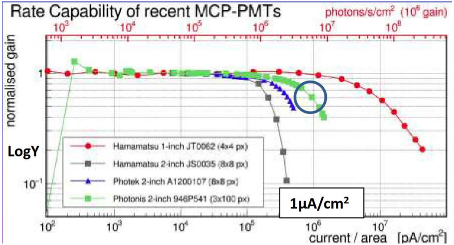


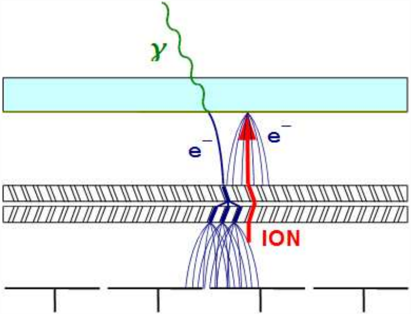
Typical single photon timing distribution with narrow main peak ($\sim$40 ps) and contribution from photoelectron back-scattering

MCPs limitations: ageing and rate capability

Ageing:

- during the amplification process atoms of residual gas get ionised → travel back toward the photocathode and produce secondary pulse
- ion bombardment damages the photocathode reducing QE
- thin Al foil (few μm) placed between MCPs blocks ion feedback but also about half of the electrons (Atomic Layer Deposition)



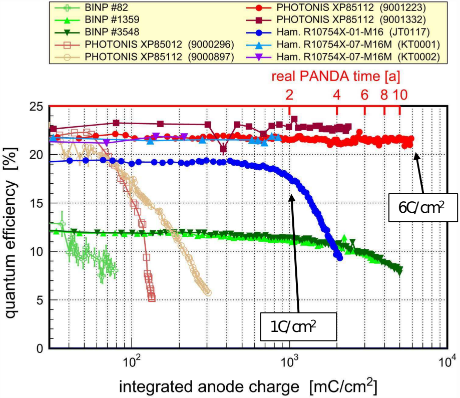


Rate capability:

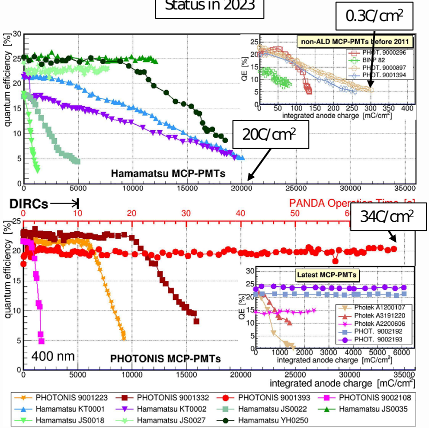
- Charge replenishment related to MCP R and C
- Maximum anode current ≤10% strip current
- typical saturation: 10MHz/cm2 ≈ 2μA/cm2 @ G=10^6 →the lower G the better

Evolution of the lifetime of MCPs

Status in 2014

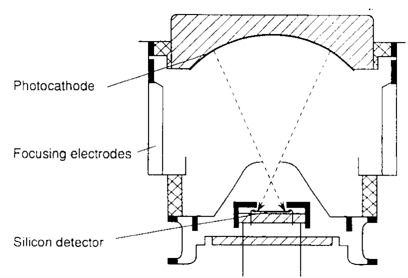


Status in 2023



Hybrid Photon Detectors (HPD)

- Combination of vacuum photon detector (image intensifier) and solid-state technologies
- Input: collection lens, (active) optical window, photocathode
- Gain: achieved in one step by energy dissipation of keV photo-electron in solid-state detector anode ⇒ low gain fluctuations
- Output: direct electronic signal



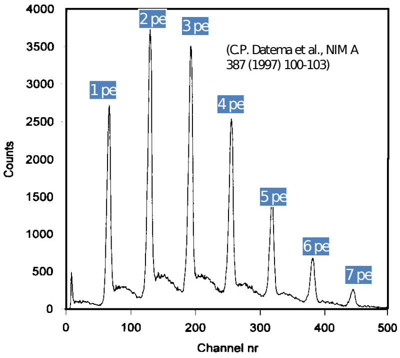
W_{Si} ~3.6 eV to create an electron-hole pair in silicon using an accelerating voltage 20 kV → ~5000 e-signal, enough to be detected using modern low-noise electronics encapsulation in the tube implies:

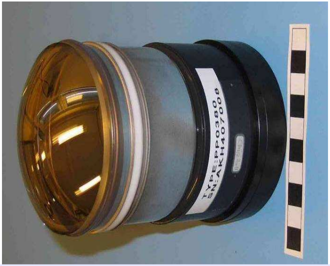
- compatibility with high vacuum technology (low out-gassing, high T bake-out cycles)
- internal (for speed and fine segmentation) or external connectivity to read-out electronics
- heat dissipation issues

⇒ complicated manufacturing procedure, very high HV needed for operations

HPD energy resolution

- negligible gain fluctuation
- excellent energy resolution: separation between photon peaks depending on electronics
- possibility of producing HPDs with bump-bonded electronics
- spatial resolution determined by silicon chip ⇒ excellent granularity
- very sensitive to magnetic field
- operation requires HV∼20 kV ⇒ challenging to implement
- complicated manufacturing: risk of damaging the vacuum

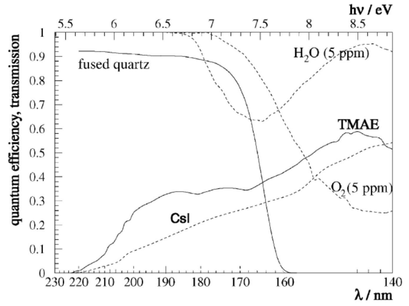




Gaseous Photon Detector

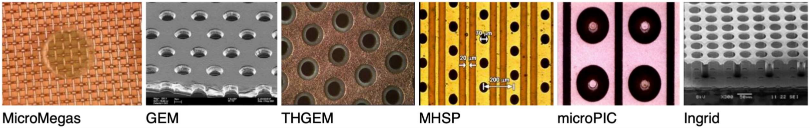
Gaseous Photon Detectors are a unique case in the family tree of photon detector: they are not commercially available

- Photon Detectors produced "in the house": a very cost-effective solution to cover very large areas
- they allow minimal material budget
- their operation is compatible with the presence of a magnetic field



a variety of techniques developed over the years:

- Multi-Wire Proportional Chamber PD: combine photo-ionising agent with MWPC
- Micro-Pattern Gaseous Detectors: exploit photolithographic structuring techniques to define precise, micrometer-scale structures on flat substrate as electron amplification devices



CsI Cathodes (High Momentum PID detector in Alice)

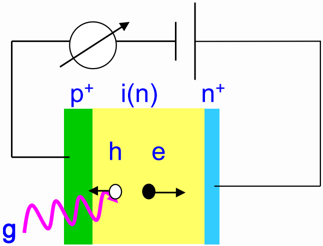
Main challenges

- reach a gain high enough ($\sim 10^5$)
- control of the Ion feedback and light emission from the avalanche process $\rightarrow$ control of ageing
- operationally: purify gas and keep it clean

Solid state photon detectors

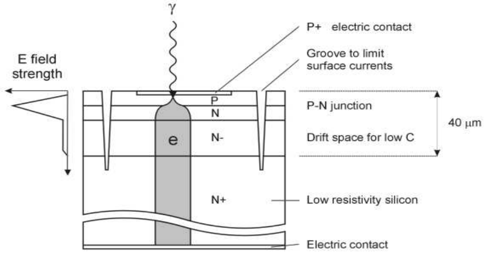
(Si) PIN diode

- P(I)N type
- p layer very thin ($< 1\mu$m) as visible light is rapidly absorbed by silicon
- High QE ($\lambda \approx 70\%$)
- Gain=1



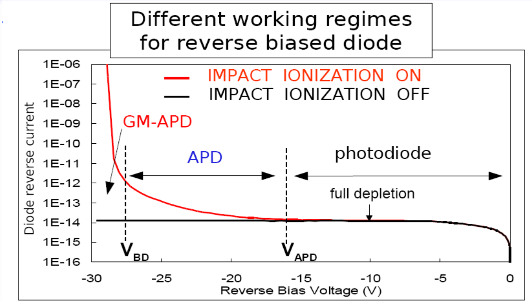
Avalanche photodiode (APD)

- high reverse bias voltage: typically few 100V
- special doping profile $\rightarrow$ photons create electron-hole pairs in the thin p-layer on top of the device and the electrons induce avalanche amplification in the high field at the p-n junction
- Gain$\approx$100, high gain fluctuations
- very high sensitivity to temperature and bias voltage



advantage: charge carriers are produced and detected within the same detector volume, unlike in vacuum-based or gas-chamber based light sensors
disadvantage: need several photons hitting the photon detector to generate a detectable signal above the noise level

How to enhance gain?



GM-APD

- $V_{bias} > V_{BD}$ ($V_{bias} - V_{BD}$ ~few volts)
- G$\to \infty$
- Geiger-mode operation (quenching resistor to stop avalanche)
- can operate at single photon level

APD

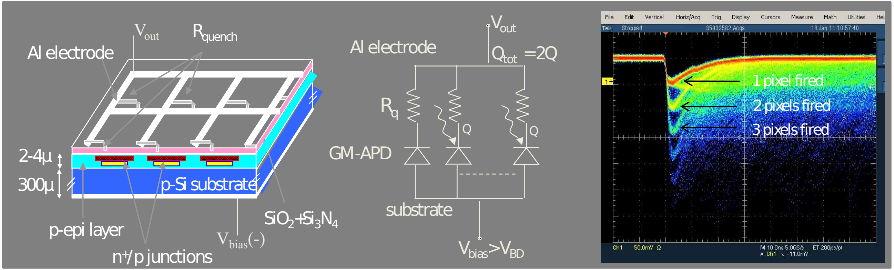
- $V_{APD} < V_{bias} < V_{BD}$
- G=(50-500)
- Linear-mode operation

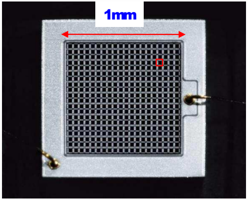
Photodiode

- $0 < V_{bias} < V_{APD}$ (few volts)
- G=1
- operate at high level (few hundreds of photons)

Silicon Photomultiplier (SiPM)

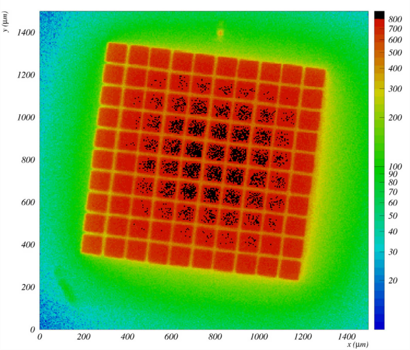
Matrix of n pixels connected in parallel on a common Si substrate. Each pixel is a GM-APD in series with a quenching resistor R_{quench}: an electron- hole pair produced by a photon in one of the micro-cells initiates the discharge and the micro-cell discharges until the voltage drops below the breakdown level, thus stopping the avalanche



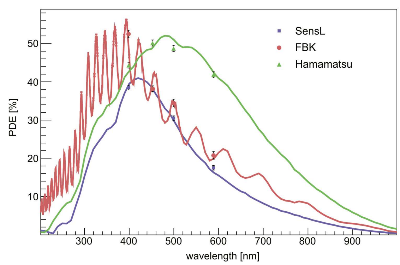


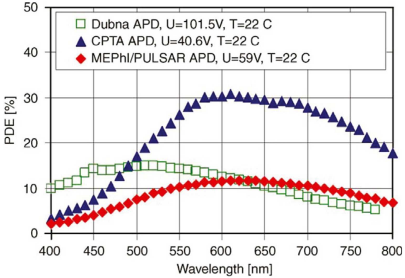
- micro cells of dimension 10-100μm
- counts incident photon by summing the pixels: output from SiPM $\sim$proportional to the number of hitting photons
- large detectable output for each incident photon $G \sim 10^6$

Photon Detection Efficiency



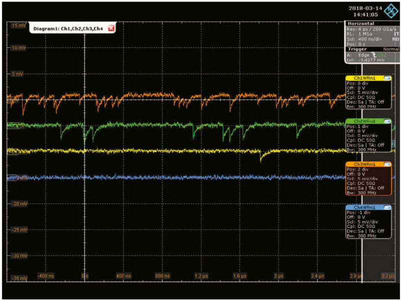
- intrinsic QE of silicon cell is excellent ($\sim 90\%$) in the green/red range thanks to absorption characteristic of silicon
- PDE takes into account geometrical efficiency: fill factor due to quenching resistors and trenches in SiPM $\Rightarrow \sim 40\%$
- trenches typically optimised to reduce optical cross talk between cells: secondary photons generated in the avalanche process through the ionisation and recombination of electrons and holes can induce a new avalanche in the neighbouring cell

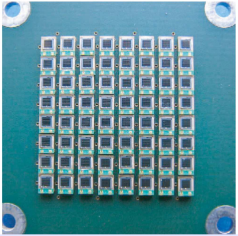


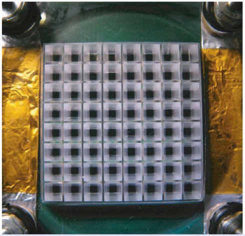


Dark Count Rate

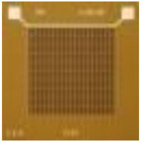
- high radiation environment induces defect in the silicon leading to high dark count rate and afterpulsing
- annealing can reduce the DCR: SiPM at temperatures between 175°C and 250°C
- studies on various model → one example
  - SiPM with DCR 200 Hz/mm^2 at -40°C
  - DCR reaching 700 kHz/mm^2 after 10^{11} $n_{1\ MeV\ eq}/cm^2$
  - rate reduced back to 40 kHz after annealing for 600 h up to 175°C
- promising results from annealing → can it be improved? can it be implemented in the experiment?

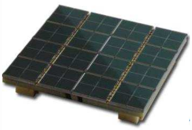






SiPM performance



Advantages:

- high gain: $10^5 - 10^6$ with low voltage (< 100V)
- low power consumption
- fast timing: $\sim 50 - 100$ps for single photons
- insensitive to magnetic field
- high photon detection efficiency $\sim$50%
- very compact, versatile geometry

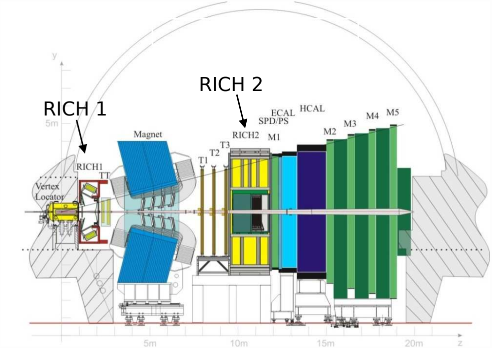
Drawbacks:

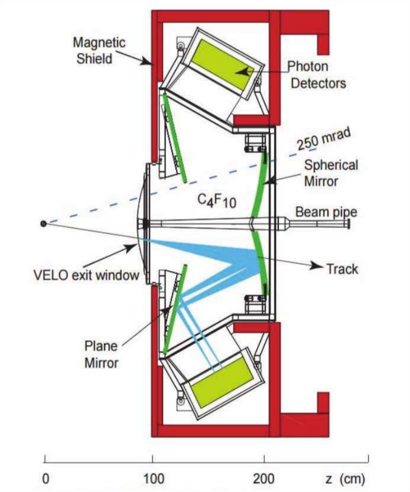
- high dark count rate at room temperature: 100kHz - 1MHz
- high dependence on temperature
- optical cross talk
- sensitive to radiation damage: DCR can reach 100MHz after irradiation $\Rightarrow$ need to operate at very low temperature

Example of applications with different types of photon detectors

LHCb RICH

- LHCb experiment at CERN built to study b- and c-hadrons physics
- two Ring Imaging Cherenkov Detectors installed: $\pi/K/p$ separation 2.6-100 GeV/c
- Cherenkov cones generated by charged particles passing through gas radiator are imaged as rings on photon detector plane

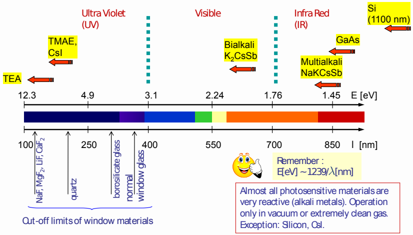


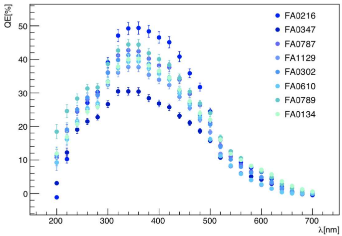


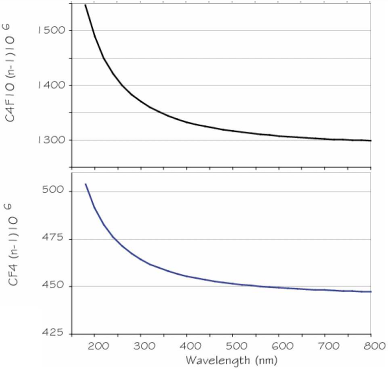
need to install position sensitive photon detector

Photon detectors

Larger Cherenkov photon yield towards the UV and the radiator dispersion drive the choice of the photocathode material





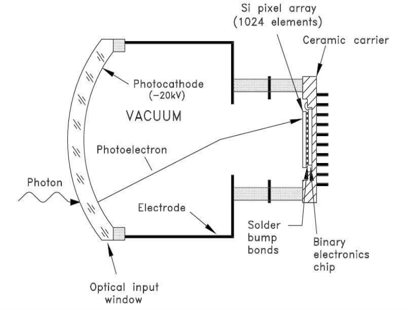


not only QE but also:

- granularity
- active area
- low dark counts (low noise)
- time response
- linearity

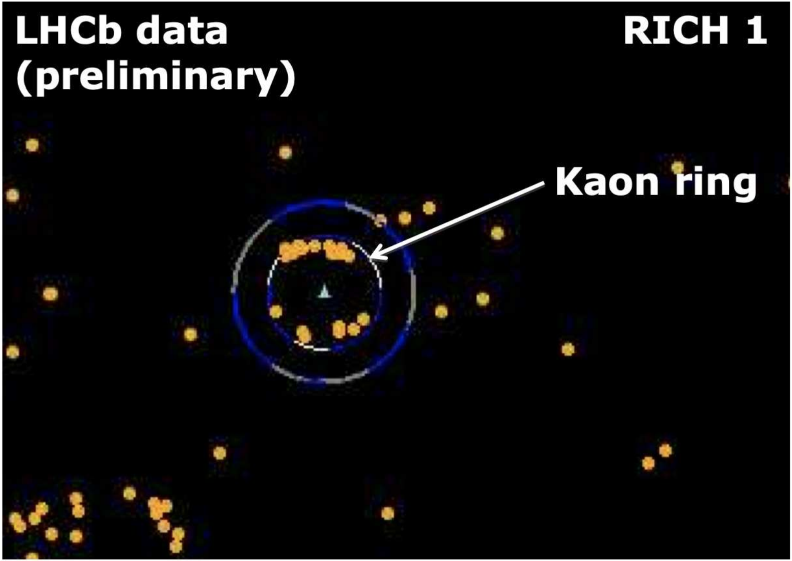
LHCb RICH

Pixel HPDs for former RICH (2009-2018) (QE=30% @300nm)



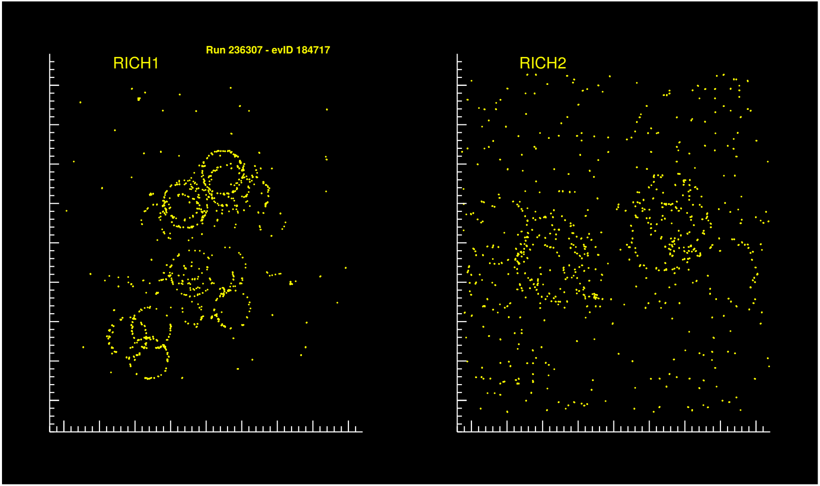
Multi-anode Photomultiplier Tubes for RICH upgrade (2022-) (QE=45% @400nm)

Pattern recognition



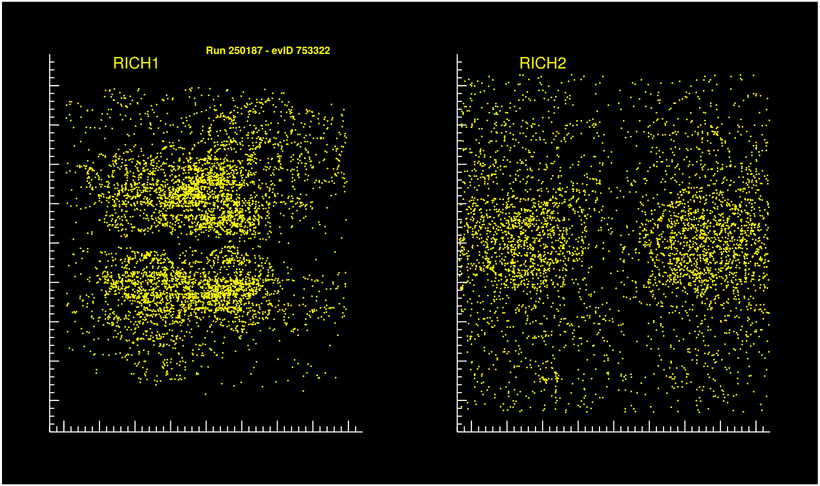
first generation

Pattern recognition



today

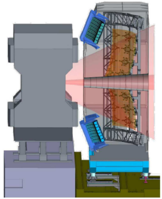
Pattern recognition

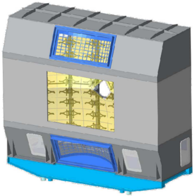


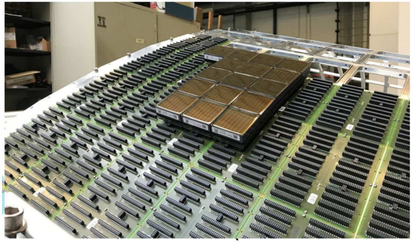
typical event in LHCb: can you find the rings? the importance of low noise and position sensitive photon detectors

The success of MaPMTs

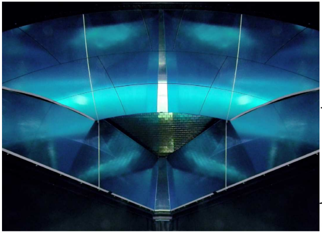
CBM
RICH gas detector: CO_2 as radiator

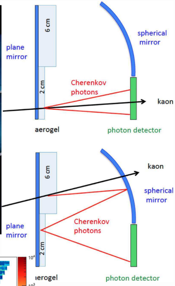


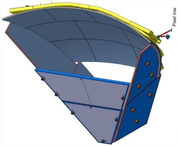


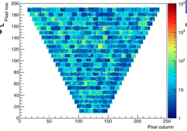


CLAS12
Aerogel RICH detector





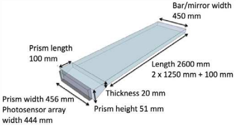


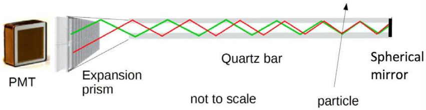


characterisation of the same MaPMT device for three different experiments in particle and nuclear physics: very robust and reliable position sensitive photon detector

Belle II Time Of Propagation

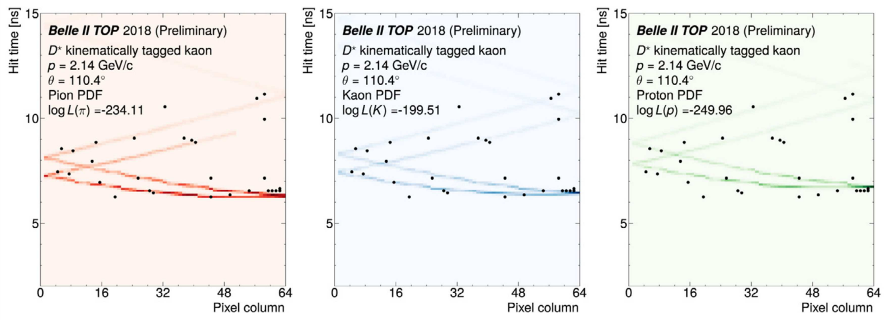
- π/K separation for 0.5-4 GeV/c





- measure time of arrival of Cherenkov photons with resolution better than 100 ps: Micro Channel Plate PMT (MCP-PMTs) developed to have TTS<50ps and resilient to magnetic field up to 1.5T

Identifying particles in a TOP

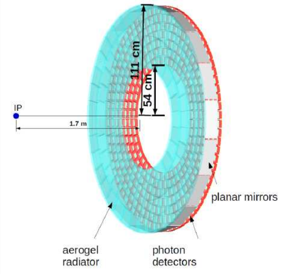


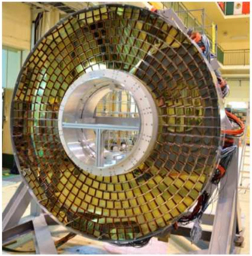
time-space distribution recorded by the Belle 2 TOP: different mass hypothesis superimposed

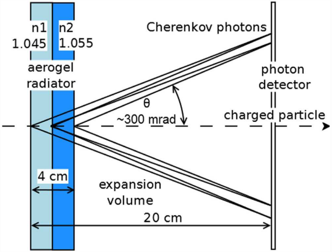
$\Rightarrow$ hits associated to a kaon candidate

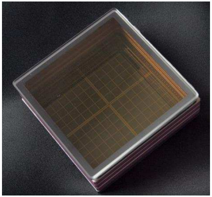
Aerogel: ARICH Belle2

- π/K separation for 1-4 GeV/c





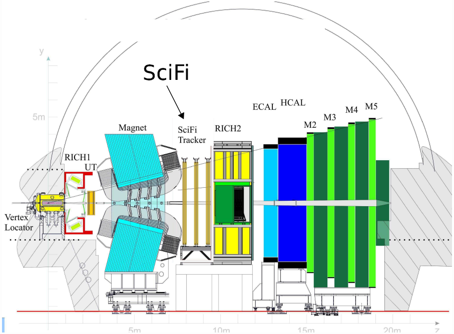


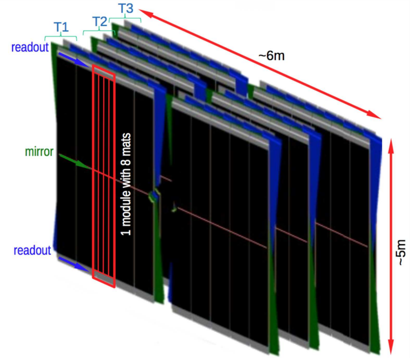


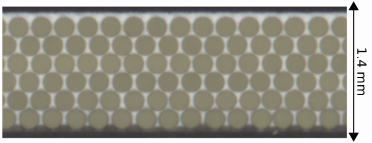
- two layer aerogel (n1=1.045, n2=1.055) coupled with Hybrid Avalanche Photo Detectors (HAPD) resilient to magnetic field up to 1.5T

LHCb SciFi

- scintillating fibre tracker installed in LHCb for upgrade (2022-)
- fibre mats composed by 6 layers of fibres with diameter of 250 μm
- mats 2.5m long
- need for high granularity photon detector to be coupled with fibres mats

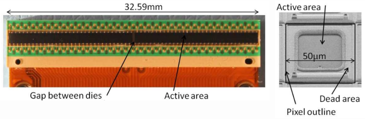


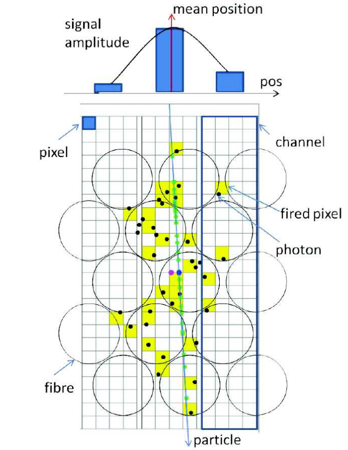




LHCb SciFi

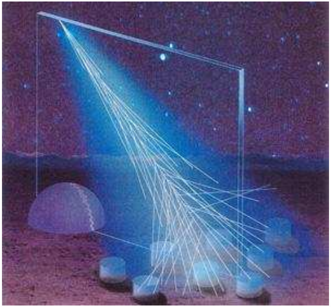
SiPM with 128 channels per array, operated at -50°C to limit DCR

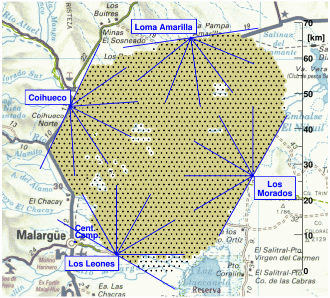




The Pierre Auger Observatory

detection of Ultra High Energy Cosmic Rays via Extensive Air Showers

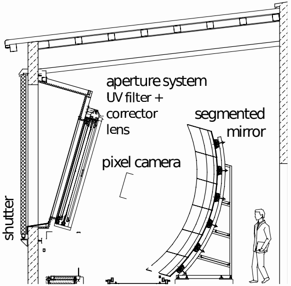


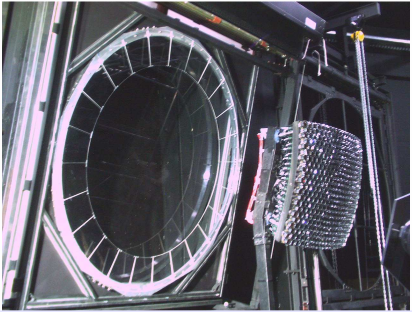


- 3000 km^2 in the Pampa Amarilla (Argentina)
- ∼1600 water Cherenkov tanks
- 4 fluorescence telescopes

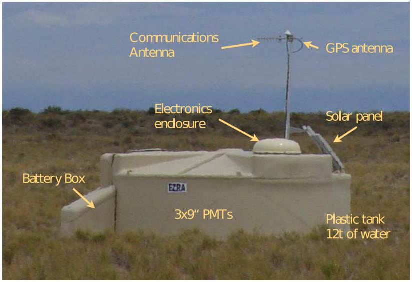
The Pierre Auger Observatory

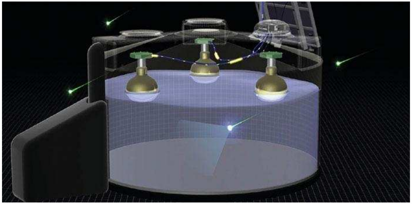
440 PMT per camera, hexagonal 40mm side: peak QE ∼ 29% @375nm



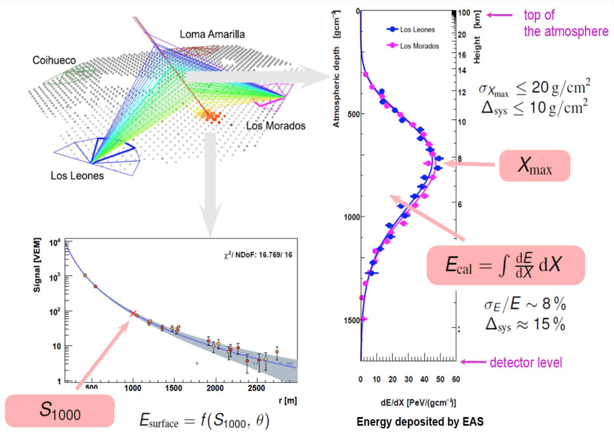


3 PMTs per tank (9"): QE ∼ 23% @400nm





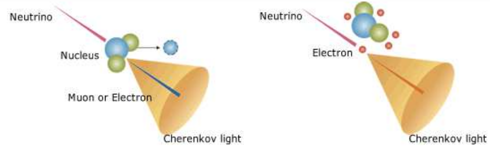
A hybrid event at Auger



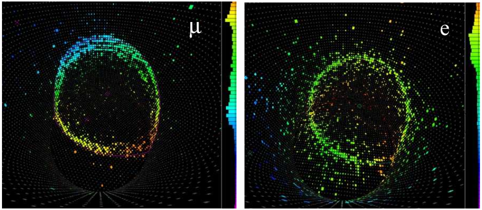
- hybrid events used to calibrate energy measurement of surface detector (100% duty cycle) and fluorescence detector (10% duty cycle)
- atmosphere used as a calorimeter:
    - measurement of the energy deposit: UHECR spectrum
    - measurement of the depth of maximum of the shower: mass of the primary
    - measurement of the arrival direction: look for the source

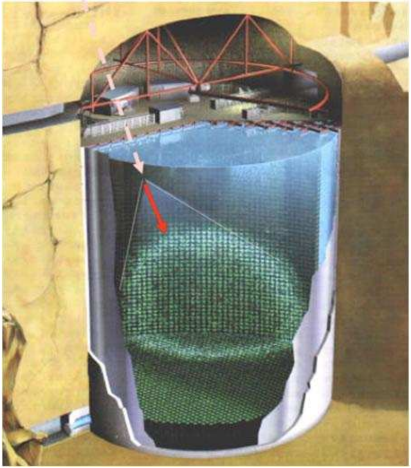
Super-Kamiokande

- Neutrino detector in Japan using water as the target and detector medium
- 1000m underground
- 50 kton of ultra pure water
- Cherenkov radiation used to identify electrons and muons
- PMT used to readout the signal



The generated charged particle emits the Cherenkov light.

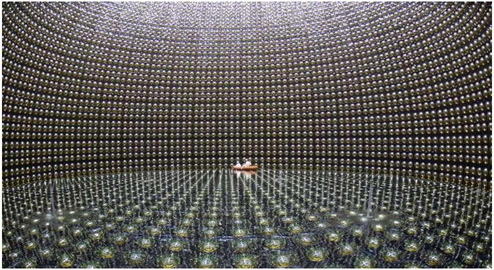


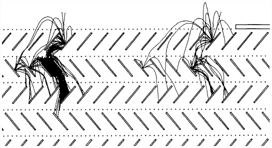


huge surface to be equipped with photon detectors

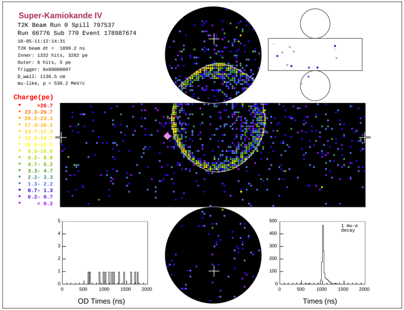
Super-Kamiokande

20 inch PMT developed by Hamamatsu ∼20 years ago: the biggest photon detector ever built (peak QE=22% @390nm)

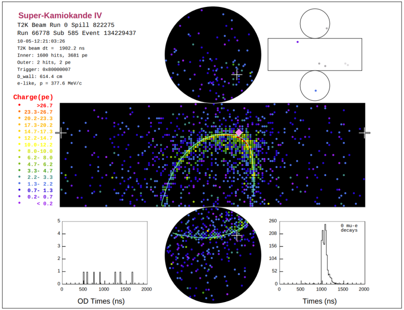




Events in Super-K



(a) muon-like event

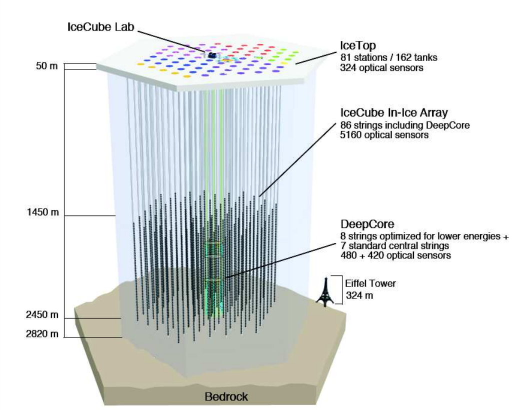


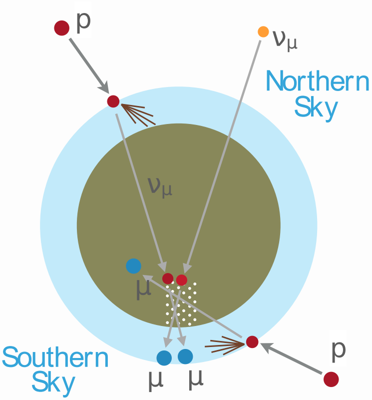
(b) electron-like event

- vertex is established from the timing of the PMT hits, and an initial track direction is calculated by searching for a well-defined edge in the PMT charge pattern
- search for Cherenkov ring candidates
- PID algorithm then classifies all the candidate rings observed as either muon-like or electron-like by comparing with MC

Ice-cube

- Neutrino experiment in the South Pole using ice as Cherenkov radiator
- instrumented volume: 1 km^3
- strings with 60 photon detectors 17 m apart deployed in ice

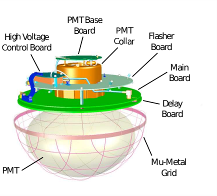




large volume to be instrumented in extreme conditions

Ice cube

10 inch PMT developed by Hamamatsu: peak QE=25%-34% @390nm



Ice Cube Gen2: Upgrade of photon detection system

Multi-PMT optical module (mDOM)

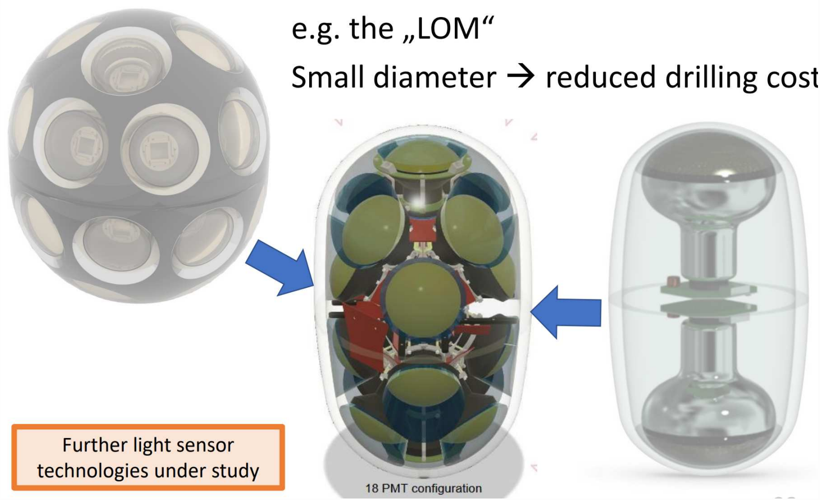
- 24 × 3” PMTs (Hamamatsu 12199-02)
- Based on KM3NeT design
- R&D and production by German groups

“D-Egg”

- Two 8” PMTs
- R&D and production by Japanese groups

Further light sensor technologies under study

Ice Cube Gen2: Upgrade of photon detection system



Summary

Many types of photon detectors developed over the years:

- sizes from 1x1 mm to 20inch diameter
- single channel or position sensitive
- single photon operation or multi-photons

- each application can need different device adapted to wavelength, speed, magnetic field conditions, ecc...
- just few examples shown in these slides
- constant R&D ongoing to develop new technologies

(Incomplete) References and credits

- Lecture notes from Stephan Eisenhardt MSc course
- N. Dinu, T. Gys, C. Joram, S. Korpar, Y. Musienko, V. Puill, D. Renker: "Photo-detection Principles, Performance and Limitations", Lectures from EDIT school 2011
- Text books: W.R. Leo, Techniques for Nuclear and Particle Physics Experiments
- RICH 2022 (2018) conference talks