Cherenkov and Transition Radiation Detectors

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CERN

Acknowledgement: I make use of a lot of material provided by

- Peter Krizan, JSI, Ljubljana (Cherenkov)
- Christoph Rembser, CERN (Transition Radiation)

Thanks!

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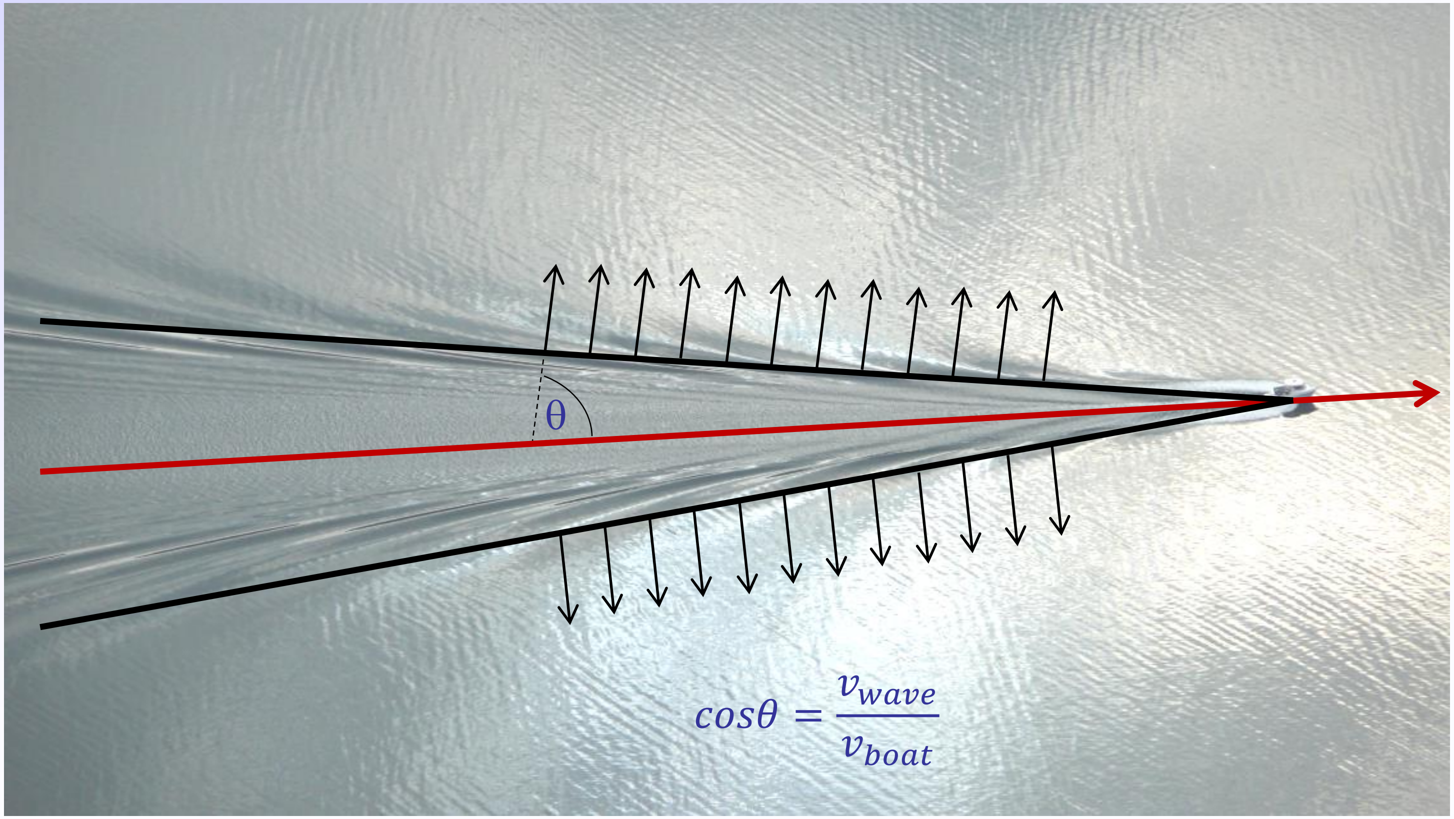
Outline

- Cherenkov radiation
- Short introduction to photodetectors
- Cherenkov detectors
- Transition radiation
- Transition radiation detectors

Cherenkov Radiation

A charged particle, moving through a medium at a speed which is larger than the speed of light in the medium, produces Cherenkov light.

Classical analogue: fast boat on water



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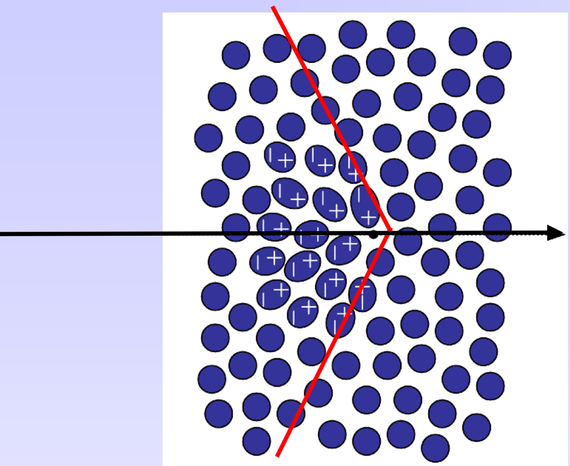
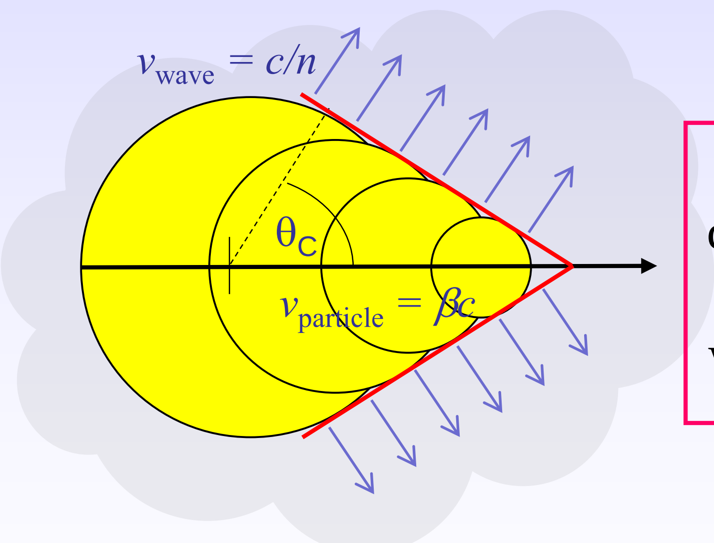


The dielectric medium is polarized by the passing particle.
↘ "the radiator"

A coherent wave front forms if

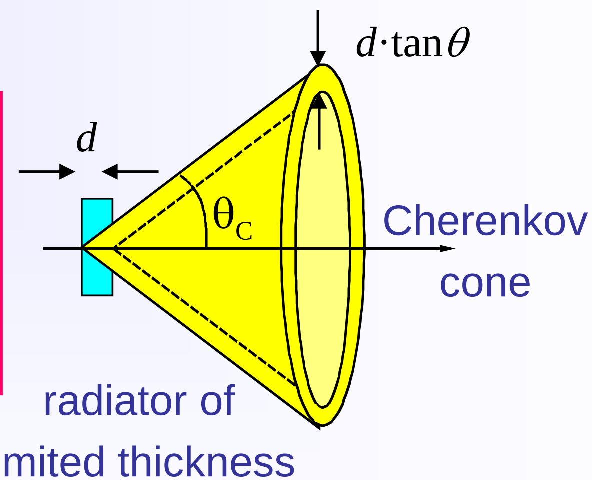
$$v_{\text{particle}} \geq c_{\text{medium}} = \frac{c}{n}$$

$$\beta_{\text{particle}} \geq \frac{1}{n} \qquad (n = \text{refr. index})$$



$$\cos\theta_C = \frac{v_{\text{wave}}}{v_{\text{particle}}} = \frac{1}{n\beta}$$

with $n = n(\lambda) \geq 1$



$$\beta_{thr} = \frac{1}{n} \rightarrow \theta_C \approx 0$$ Cherenkov threshold

$$\theta_{\max} = \arccos\frac{1}{n}$$ 'saturated' angle (β=1)

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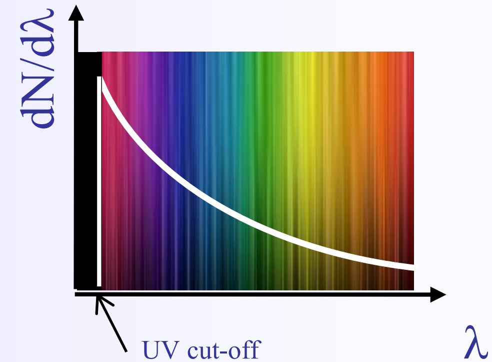
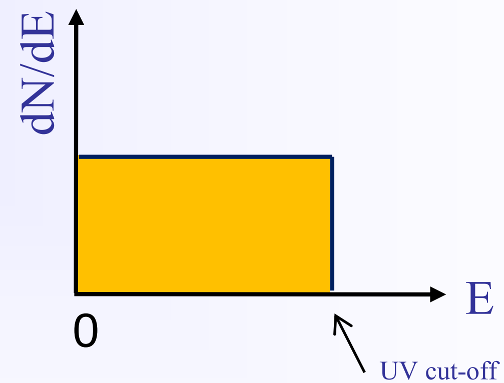
Number of emitted photons per unit length and unit wavelength/energy interval

$$\frac{d^2N}{dx\,d\lambda} = \frac{2\pi z^2\alpha}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2}\right) = \frac{2\pi z^2\alpha}{\lambda^2}\sin^2\theta_C$$



$$\frac{d^2N}{dx\,d\lambda} \propto \frac{1}{\lambda^2} \quad \text{with} \quad \lambda = \frac{c}{f} = \frac{hc}{E} \qquad \frac{d^2N}{dx\,dE} = const.$$



$$\frac{dN_\gamma}{dx} = \frac{\alpha}{\hbar c}\sin^2\theta \cdot \Delta E = \frac{370}{eV \cdot cm}\sin^2\theta \cdot \Delta E$$

Cherenkov effect is a weak light source.

There are only a few tens or hundreds of photons produced per cm.

Cherenkov detectors

medium	n	θ_{max} (deg.)	N_{ph} (eV^{-1} cm^{-1})
air*	1.000283	1.36	0.208
isobutane*	1.00127	2.89	0.941
water	1.33	41.2	160.8
quartz	1.46	46.7	196.4
aerogel	1.03	13.86	0.12

*NTP

- Energy loss by Cherenkov radiation small compared to ionization (≈0.1%)
- Cherenkov effect is a very weak light source

→ need highly sensitive photodetectors

Number of **detected** photo electrons $N_{p.e.} = L \sin^2\theta \underbrace{\frac{\alpha}{\hbar c} \int_{E_1}^{E_2} \varepsilon_Q(E) \prod_i \varepsilon_i(E)\, dE}$

$$N_0 = 370 \cdot eV^{-1} \cdot cm^{-1} \langle \varepsilon_{total} \rangle \Delta E$$

$\Delta E = E_2 - E_1$ is the width of the sensitive range of the photodetector (photomultiplier, photosensitive gas detector...)

N_0 is also called figure of merit (~ performance of the photodetector)

Example: for a detector with $\langle \varepsilon_{total} \rangle \cdot \Delta E = 0.2 \cdot 1\, eV$ $\quad L = 1\, cm$

and a Cherenkov angle of $\theta_C = 30^\circ$

one expects $N_{p.e.} = 18$ photo electrons

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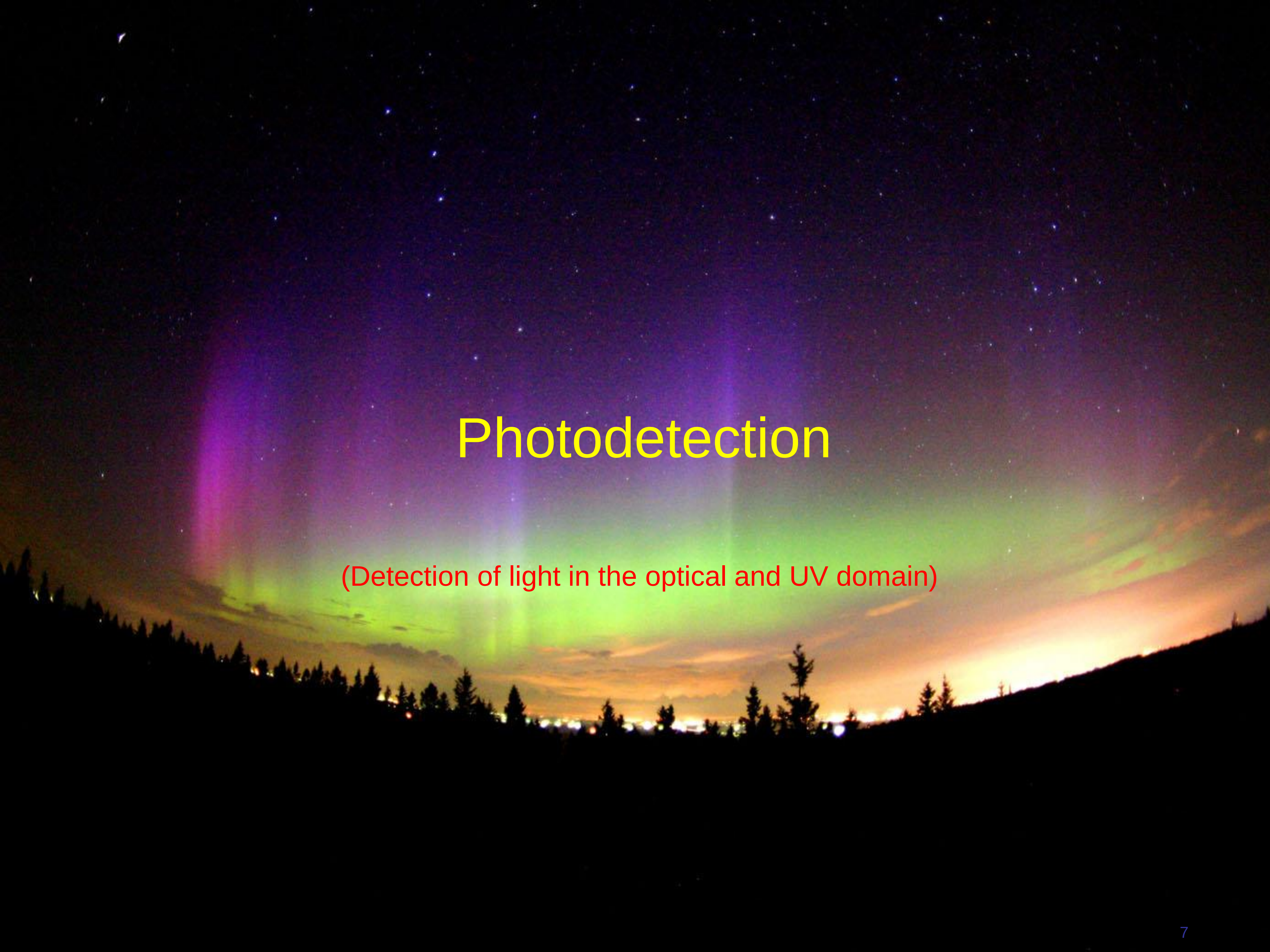


Photodetection

(Detection of light in the optical and UV domain)

Basics of photon detection

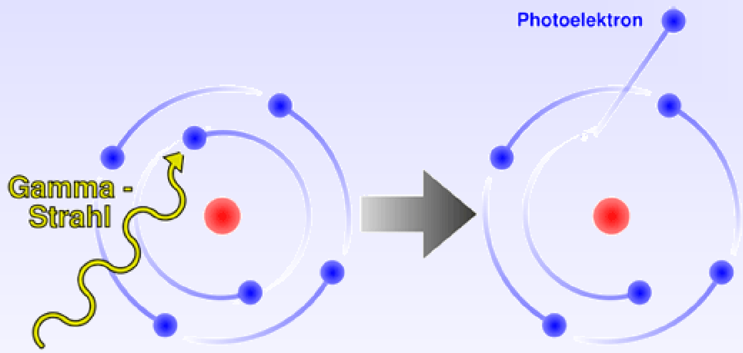
Purpose:

Convert light into detectable electronic signal

(we are not covering photographic emulsions!)

Principle:

Use photoelectric effect to 'convert' photons (γ) to photoelectrons (pe)



Details depend on the type of the photosensitive material (see below).

Photon detection involves often materials like K, Na, Rb, Cs (alkali metals) . They have the smallest electronegativity → highest tendency to release electrons.

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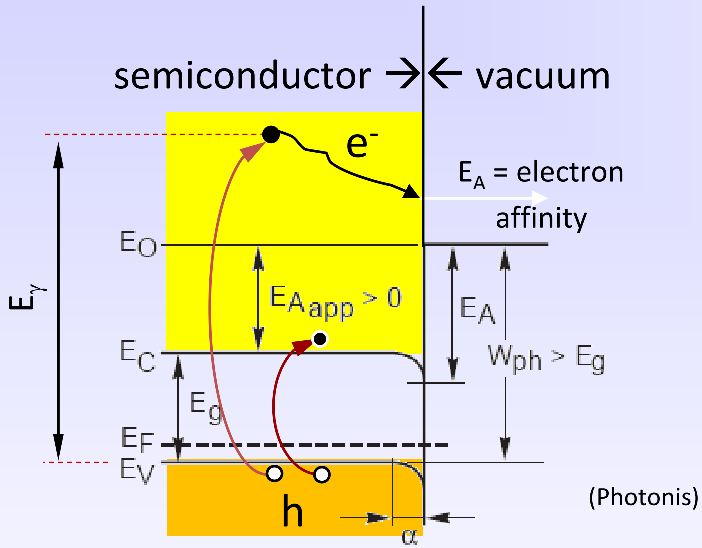
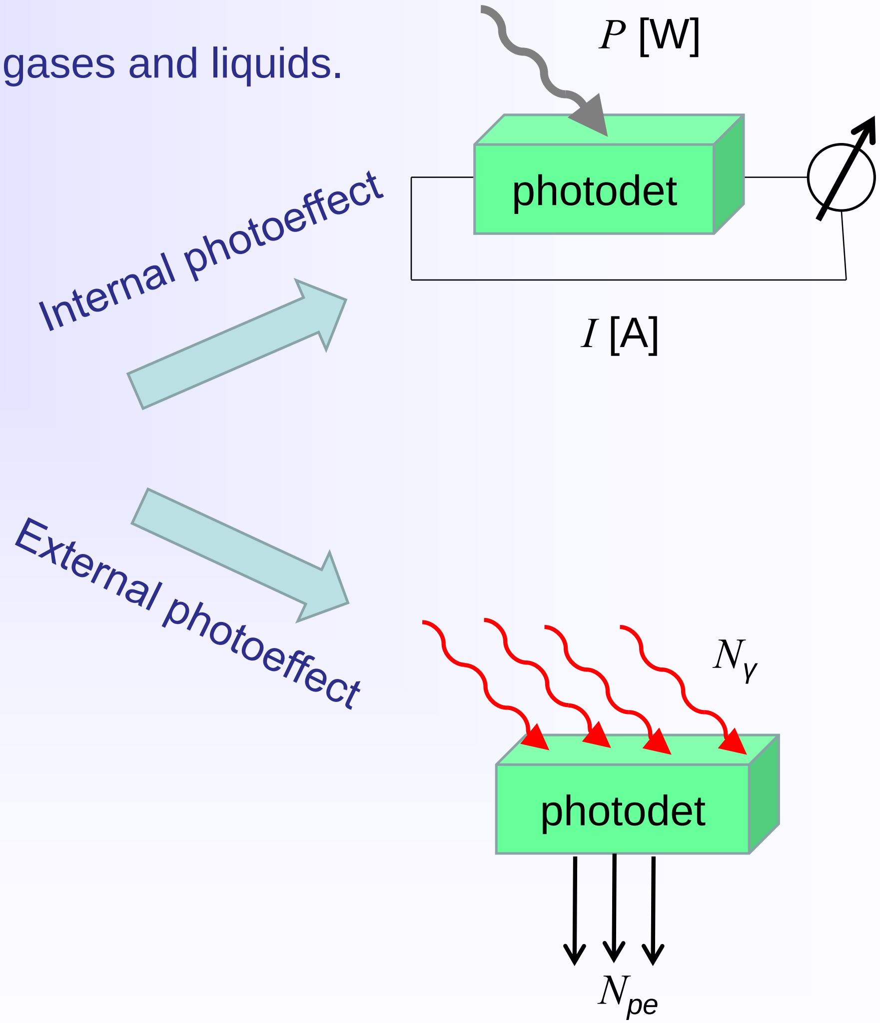
Basics of photodetection

Many solid photosensitive materials are semiconductors …

but photoeffect can also be observed from gases and liquids.





Internal photoeffect: $E_\gamma > E_g$

External photoeffect: $E_\gamma > E_g + E_A$

Basics of photon detection

Requirements on photodetectors

- High sensitivity, usually expressed as: quantum efficiency $QE(\%) = \frac{N_{pe}}{N_\gamma}$

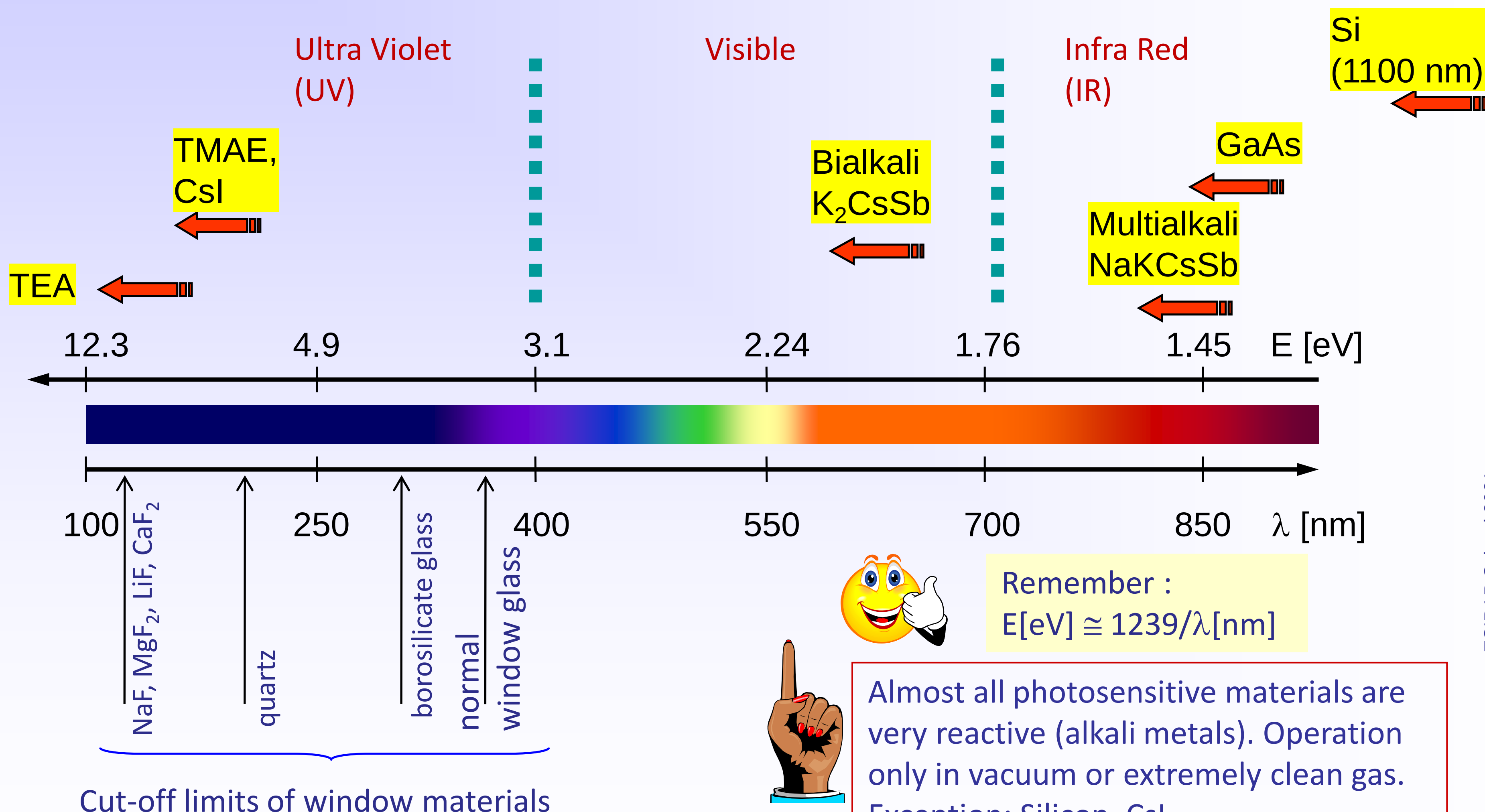
  or radiant sensitivity *S* (mA/W), with $QE(\%) \approx 124 \cdot \frac{S(mA/W)}{\lambda(nm)}$

QE can be >100% (for high energetic photons) !

- Good Linearity: Output signal ~ light intensity, over a large dynamic range (critical e.g. in calorimetry (energy measurement).
- Fast Time response: Signal is produced instantaneously (within ns), low jitter (<ns), no afterpulses
- Low intrinsic noise. A noise-free detector doesn’t exist. Thermally created photoelectrons represent the lower limit for the noise rate ~ $A_o T^2 \exp(-eW_{ph}/kT)$. In many detector types, noise is dominated by other sources.
- + many more (size, fill factor, radiation hardness, cost, tolerance/immunity to B-fields…)

Frequently used photosensitive materials / photocathodes

begin of arrow indicates threshold



Remember :
$E[eV] \cong 1239/\lambda[nm]$

Almost all photosensitive materials are very reactive (alkali metals). Operation only in vacuum or extremely clean gas. Exception: Silicon, CsI.

Photo-multiplier tubes (PMT's)

Basic principle:

Photo-emission from photo-cathode

Secondary emission from N dynodes:

- dynode gain $g \approx$ 3-50 (function of incoming electron energy E);
- total gain M:

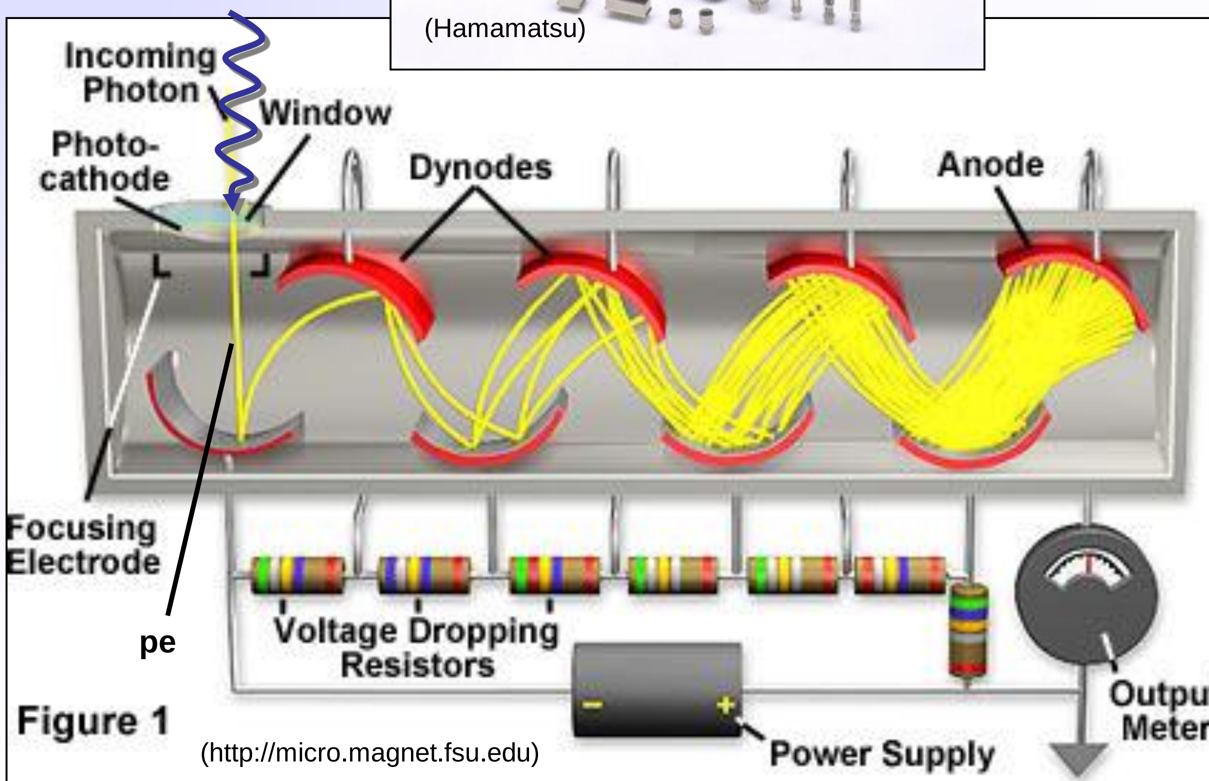
$$M = \prod_{i=1}^{N} g_i$$

Example:

- 10 dynodes with g = 4
- $M = 4^{10} \approx 10^6$

Very sensitive to magnetic fields, even to earth magnetic field (30-60 μT = 0.3-0.6 Gauss).
→ Shielding required (mu-metal).

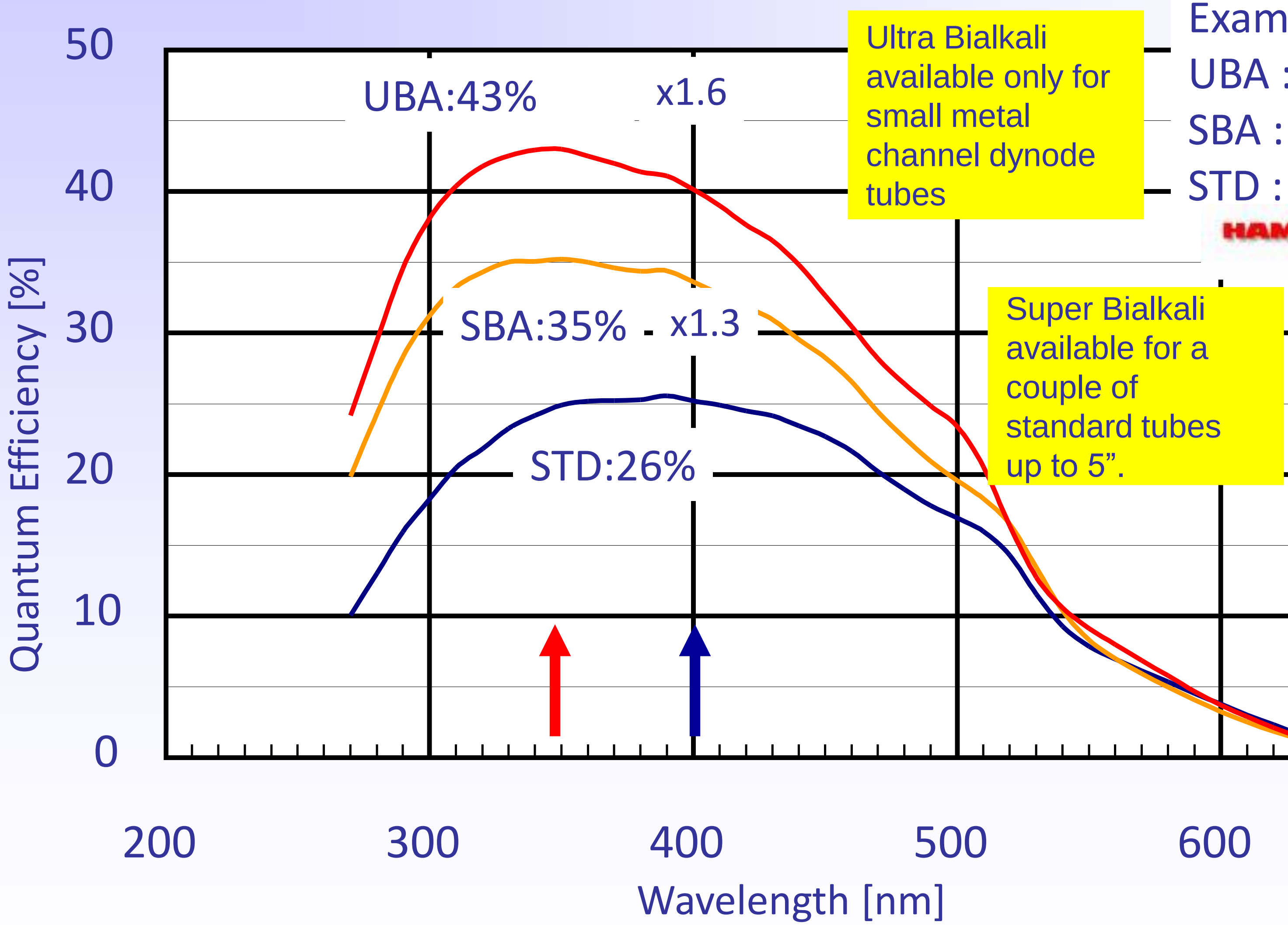
(Hamamatsu)



(http://micro.magnet.fsu.edu)

Latest generation of high performance photocathodes

QE Comparison of semitransparent bialkali QE



Example Data for
UBA : R7600-200
SBA : R7600-100
STD : R7600

HAMAMATSU

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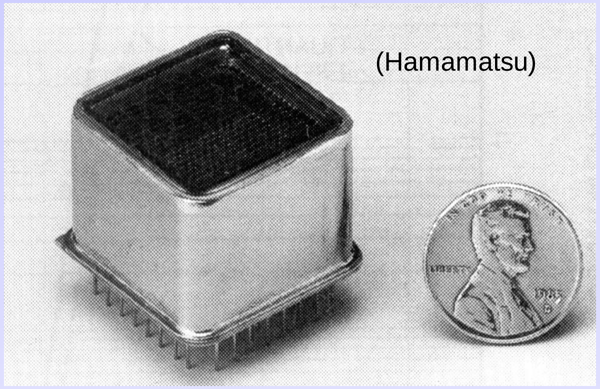
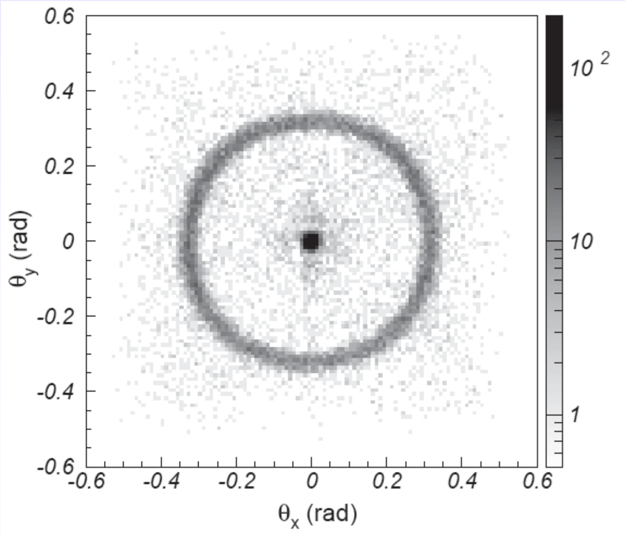
Multi-anode and flat-panel PMT's



Multi-anode PMT (Hamamatsu)

- Up to 8 × 8 channels (2 × 2 mm^2 each);
- Size: 28 × 28 mm^2;
- Bialkali PC: QE ≈ 25 - 45% @ λ_{max} = 400 nm;
- Gain ≈ 3 10^5;
- Gain uniformity typ. 1 : 2.5;
- Cross-talk typ. 2%

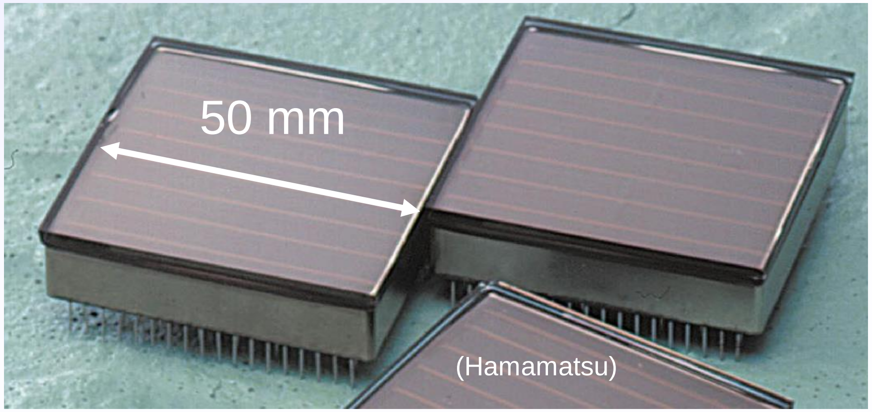
Cherenkov rings from 3 GeV/c π^- through aerogel



(T. Matsumoto et al., NIMA **521** (2004) 367)

Flat-panel (Hamamatsu H8500):

- 8 x 8 channels (5.8 x 5.8 mm2 each)
- Excellent surface coverage (89%)



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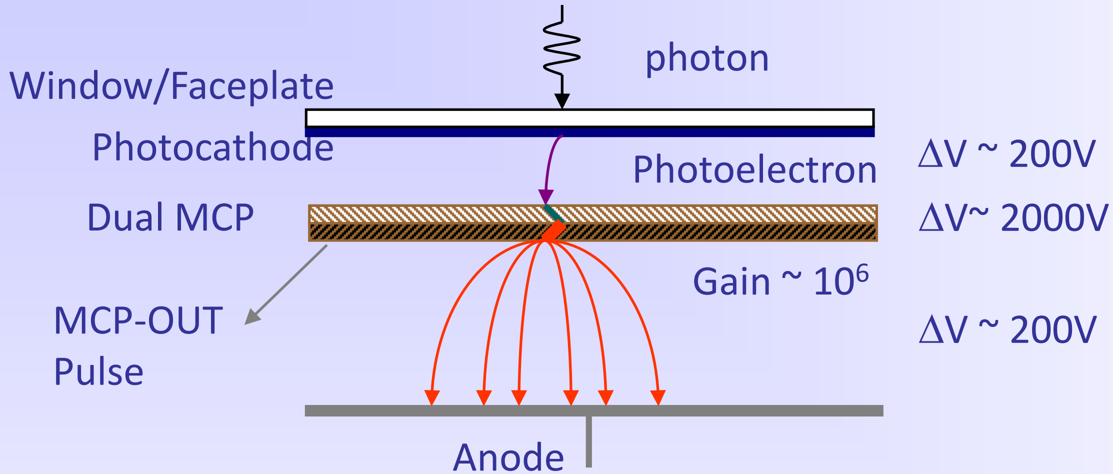
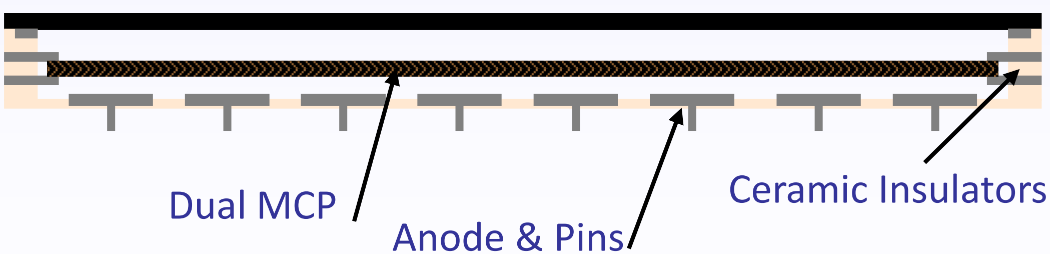
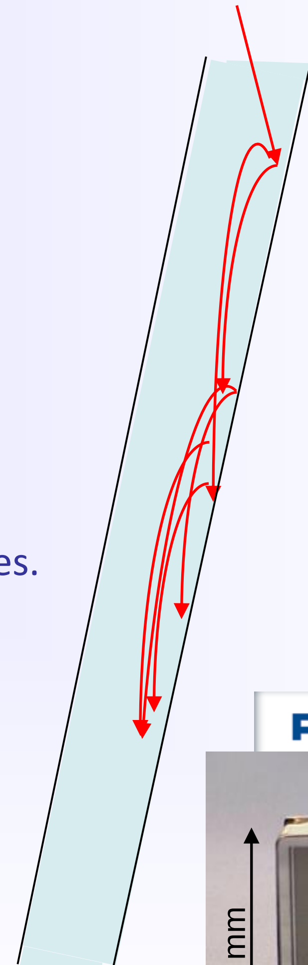
Micro Channel Plate (MCP) based PMTs



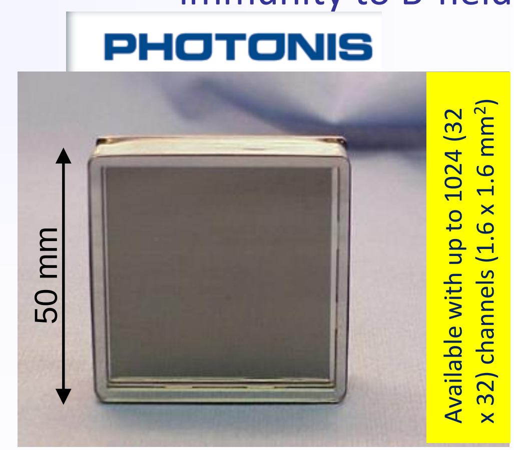
MCPs are usually based on glass disks, with lots of aligned pores. The surface of the pores are metal coated.

Gain stage and detection are decoupled → lots of potential and freedom for MA-PMTs: Anode can be easily segmented in application specific way.





- Typical secondary yield is 2
- For 40:1 L:D there are typically 10 strikes (2^{10} ~ 10^3 gain per single plate)
- Pore sizes range from <10 to 25 μm.
- Small distances → small TTS and good immunity to B-field



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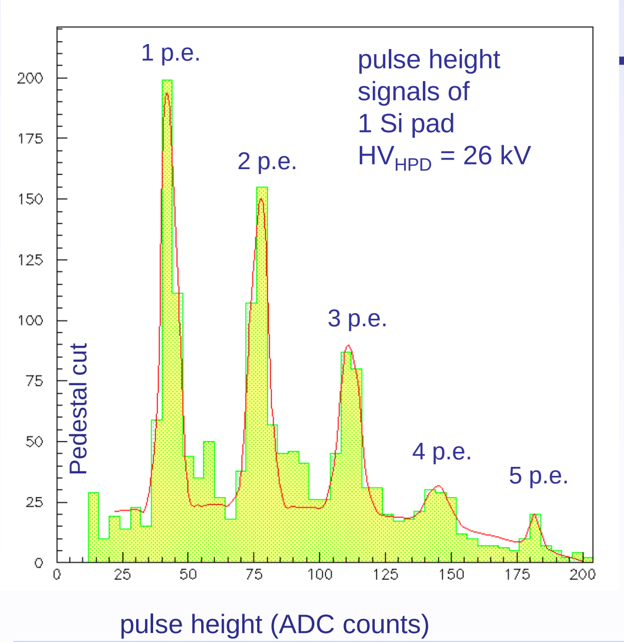
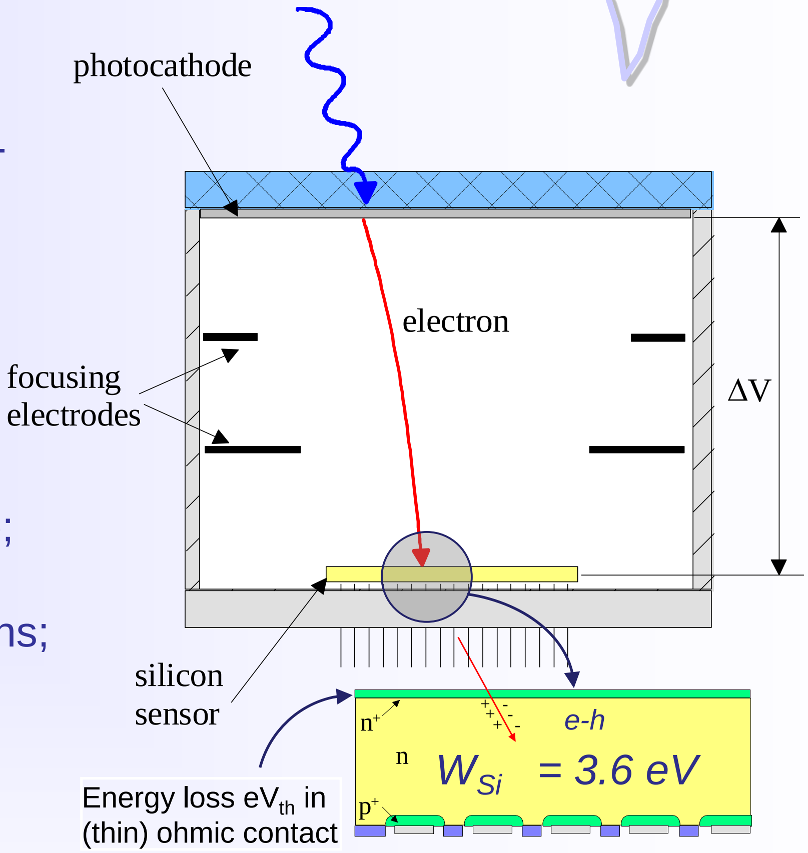
Hybrid Photon Detectors (HPD's)

Basic principle:

- Combination of vacuum photon detectors and solid-state technology;
- Optical window, (semitransparent) photo-cathode;
- Electron optics (optional: demagnification)
- Charge Gain: achieved *in one step* by energy dissipation of keV pe's in solid-state detector anode;



➔ low gain fluctuations;



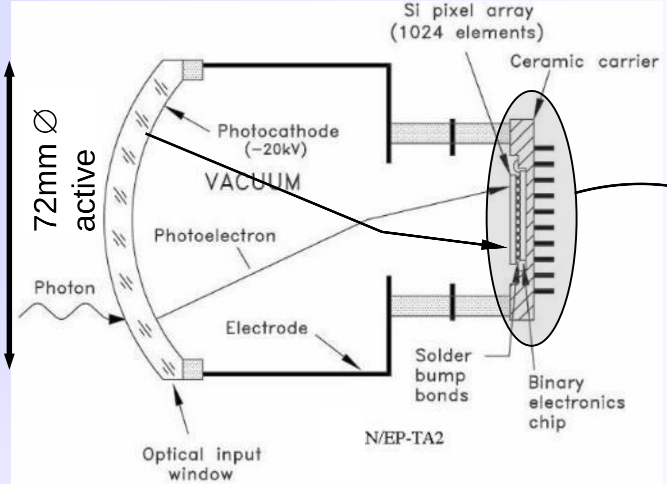
$$M = \frac{e(\Delta V - Vth)}{W_{Si}}$$

ΔV = 20 kV
→ M ~ 5000

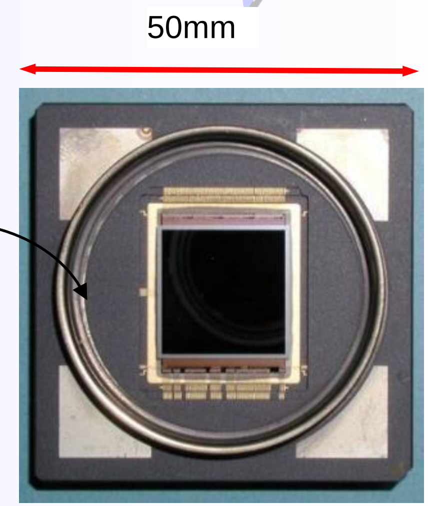
$$\sigma_M = \sqrt{F \times M}$$

F = Fano factor
F_{Si} ~ 0.1

Pixel-HPD's for LHCb RICH detectors

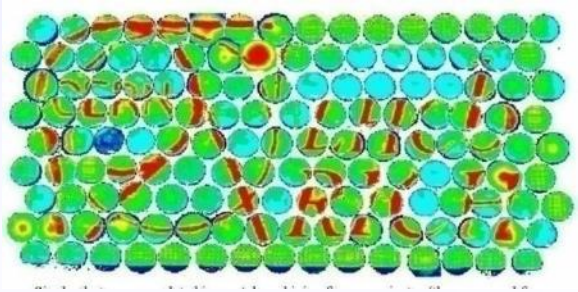


T. Gys, NIM A 567 (2006) 176-179



Pixel-HPD anode

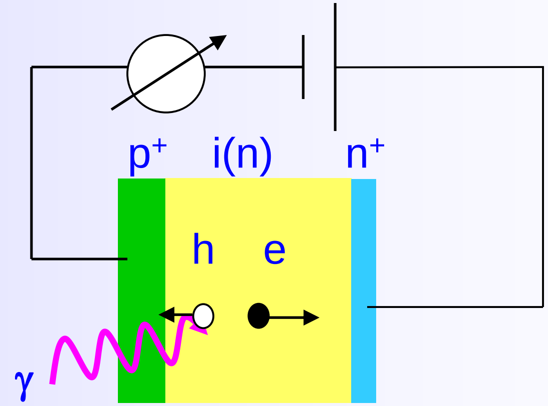
- Cross-focused electron optics
- pixel array sensor bump-bonded to binary electronic chip, developed at CERN
- 8192 pixels of 50 × 400 μm.
- specially developed high T° bump-bonding;
- Flip-chip assembly, tube encapsulation (multi-alkali PC) performed in industry (VTT, Photonis/DEP)

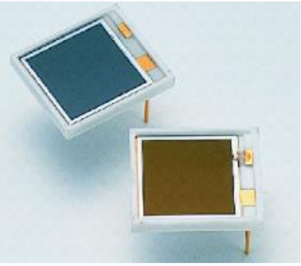


During commissioning: illumination of 144 tubes by beamer. In total : 484 tubes.

(Si) – Photodiodes (PIN diode)

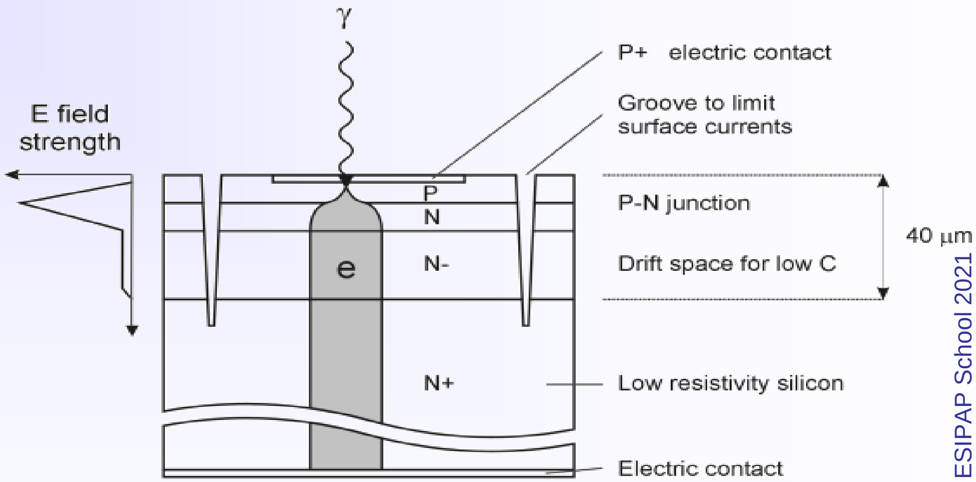
- P(I)N type
- p layer very thin (<1 μm), as visible light is rapidly absorbed by silicon
- High QE (80% @ $\lambda \approx 700$nm)
- Gain = 1



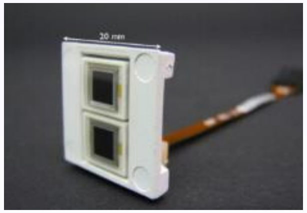


Avalanche photodiode (APD)

- High reverse bias voltage: typ. few 100 V
- Special doping profile → high internal field ($>10^5$ V/cm) → e and h avalanche multiplication
- Avalanche must stop due to statistical fluctuations.
- Gain: typ. O(100)
- Rel. high gain fluctuations (excess noise from the avalanche). CMS ECAL APD: ENF = 2 @G=50.
- Very high sensitivity on temp. and bias voltage ΔG = 3.1%/V and -2.4 %/K



Hamamatsu S8148.
(140.000 pieces used in CMS barrel ECAL).

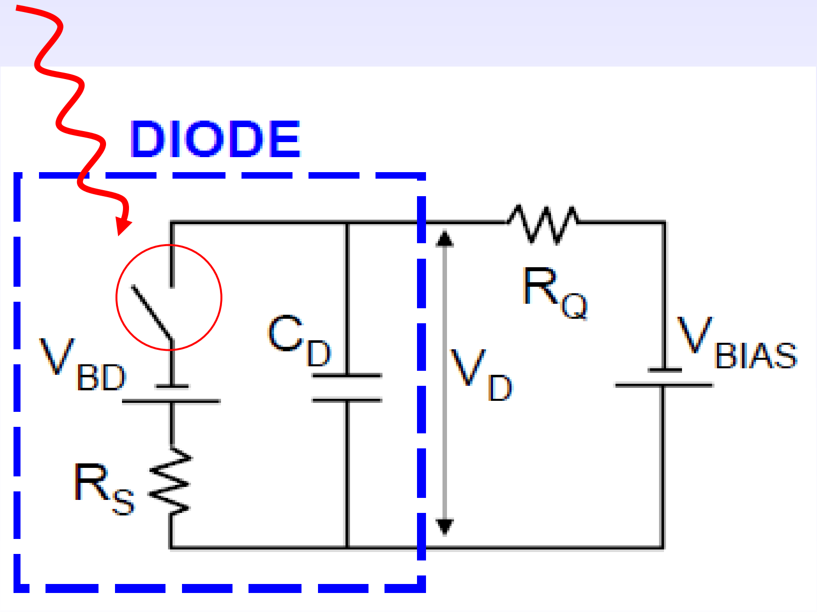


Solid-state … Geiger mode Avalanche Photodiode (G-APD)

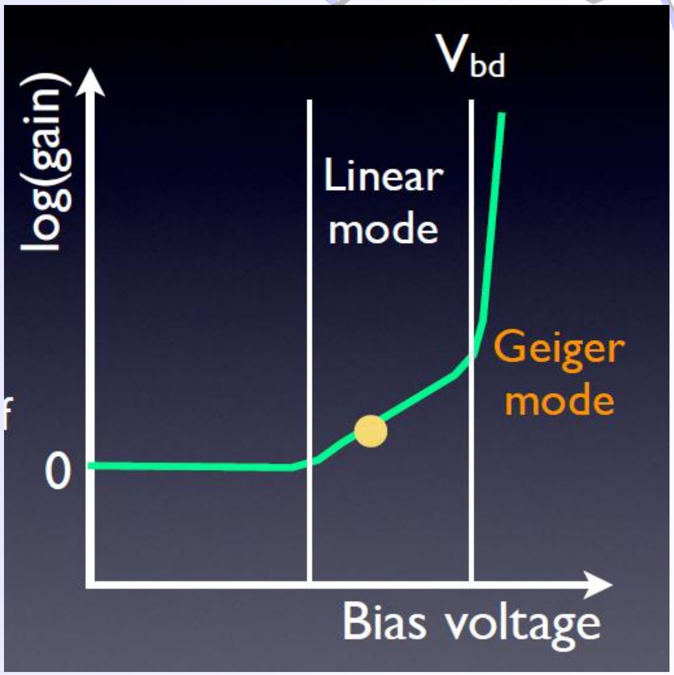
How to obtain higher gain (= single photon detection) without suffering from excessive noise ?

Operate APD cell in Geiger mode (= full discharge), however with (passive) quenching.

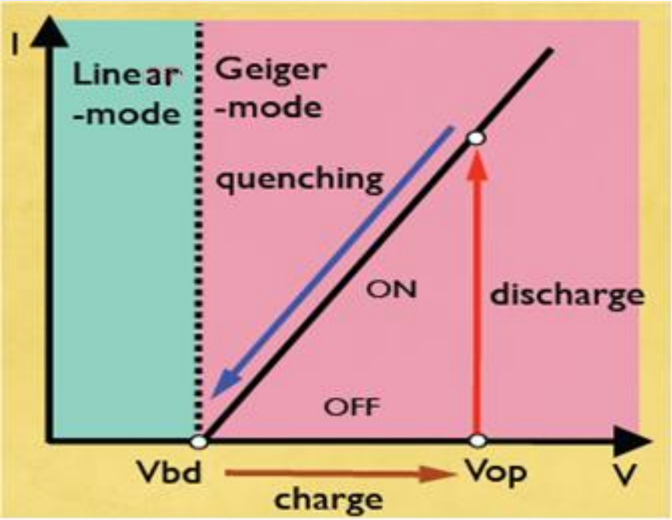
Photon conversion + avalanche short-circuits the diode.



J. Haba, RICH2007

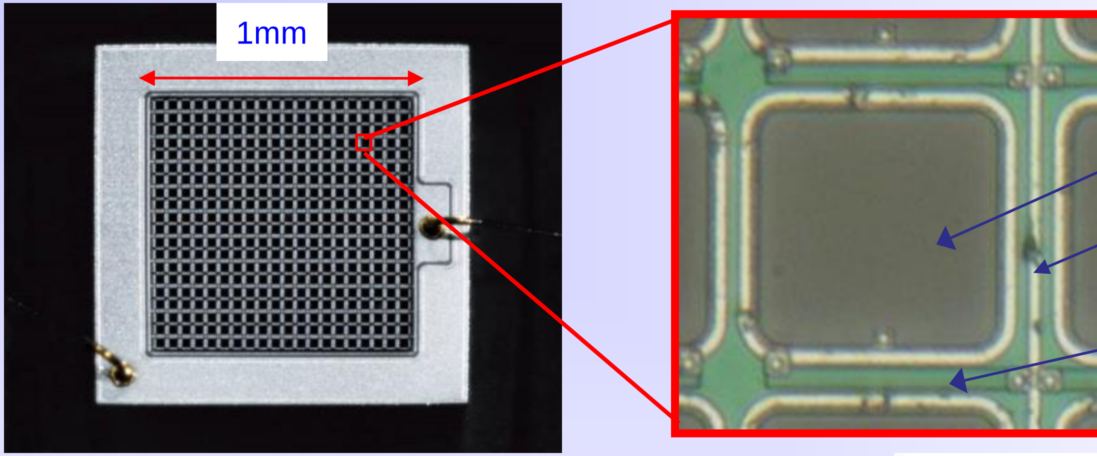


J. Haba, RICH2007



J. Haba, RICH2007

Multi pixel G-APD, called G-APD, MPPC, SiPM, …



100 – several 1000 pix / mm^2

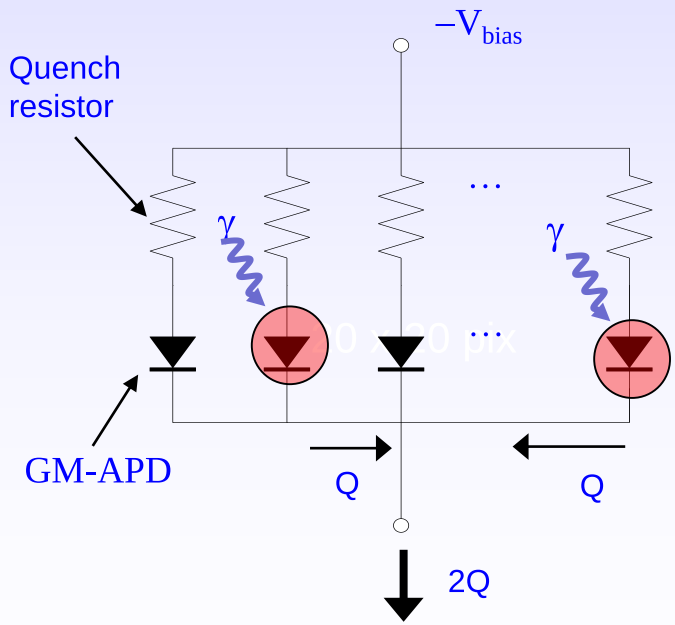
GM-APD

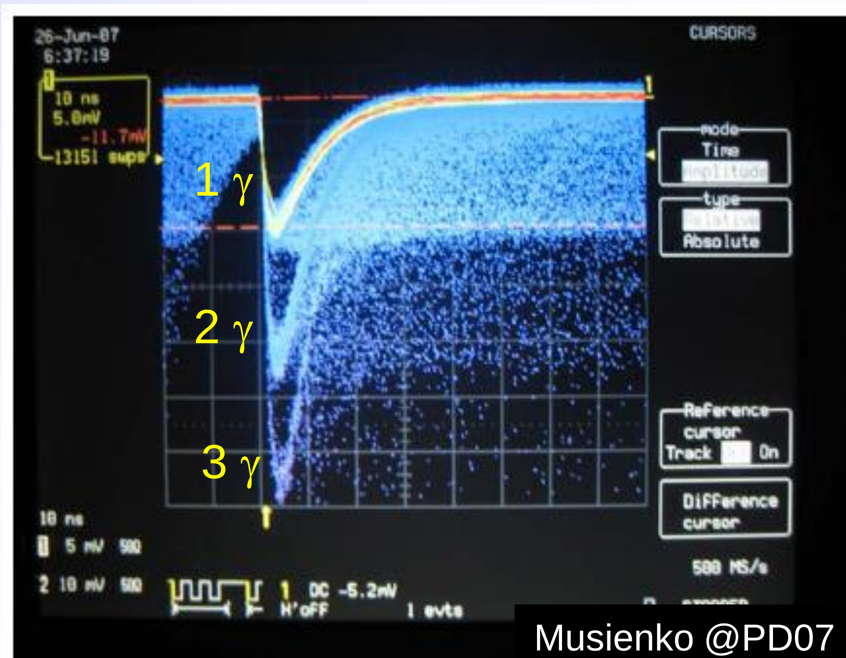
Bias bus

Quench resistor

Only part of surface is photosensitive!

Sizes up to 6×6 mm^2 now standard.





Quasi-analog detector allows photon counting with a clearly quantized signal

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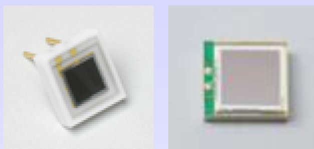
SiPM designs (just examples)

Hamamatsu HPK (http://jp.hamamatsu.com/)

25x25µm², 50x50µm², 100x100µm² pixel size

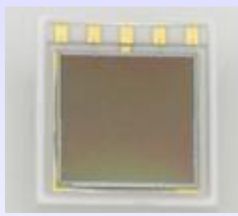
1x1mm²

3x3mm²



Arrays

1x4mm²
1x4 channels

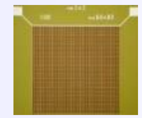


6x6 mm²
2x2 channels

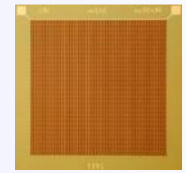
FBK-IRST

50x50µm² pixel size

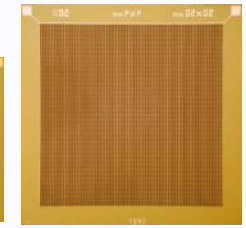
1x1mm²



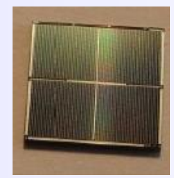
2x2mm²



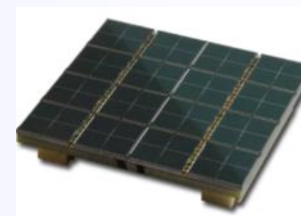
3x3mm²



4x4mm²



4x4mm²
2x2 channels



3x3 cm²
8x8 channels

SensL (http://sensl.com/)

20x20µm², 35x35µm², 50x50µm², 100x100µm² pixel size

3.16x3.16mm²
4x4 channels

3.16x3.16mm²
4x4 channels

6 x 6 cm²
16x16 channels

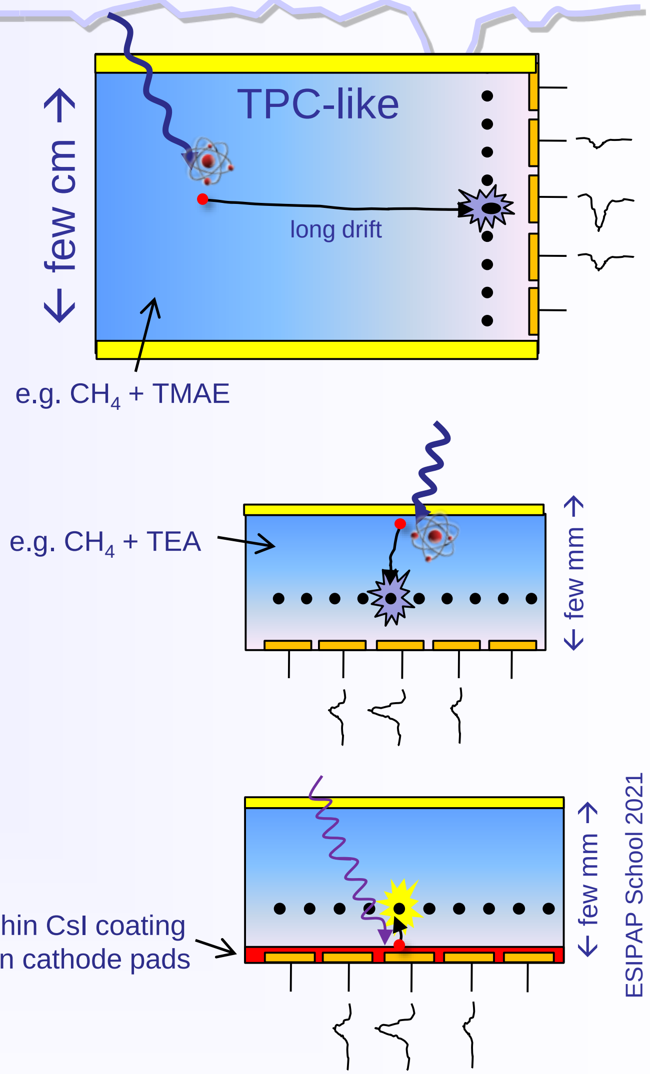
Gaseous Photodetectors

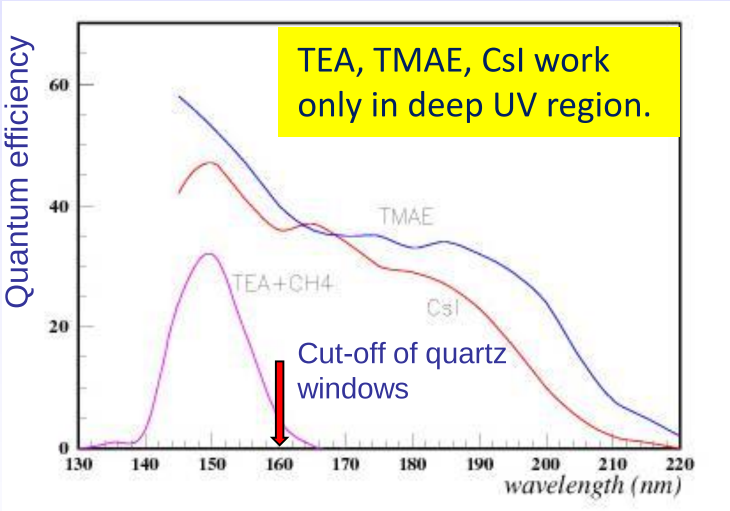
Principle:

A. Ionize photosensitive molecules, admixed to the counter gas: TMAE (λ_{abs} = O(cm), TEA (λ_{abs} = O(mm).

B. release photoelectron from a solid photocathode (CsI, bialkali...). λ_{abs} = 0.

In both cases free photoelectrons create Townsend avalanches → Gain



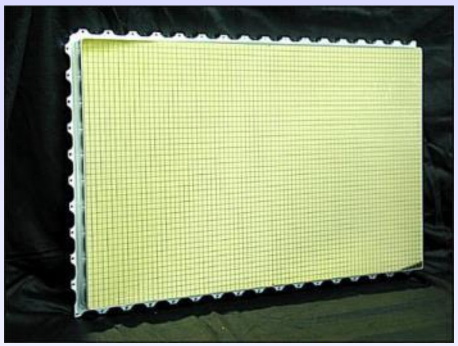


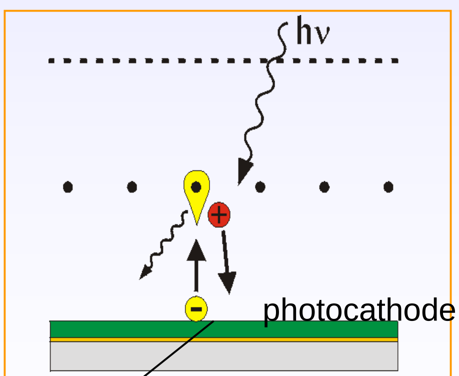
The dream: Bialkali works in visible domain, however requires VERY clean gases. Long term operation in a real detector not yet demonstrated.

- Challenges: How to achieve high gain (10^5) ? How to control ion feedback and light emission from avalanche? How to purify gas and keep it clean? How to control aging ?

Gaseous photodetectors: A few implementations...

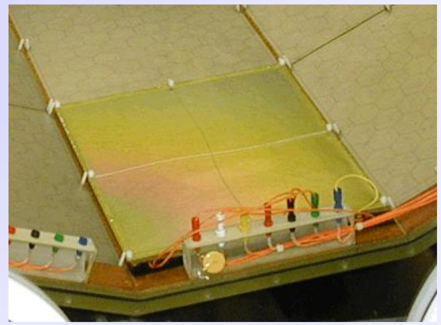
Proven technology:
Cherenkov detectors in ALICE, HADES, COMPASS, J-LAB…. Many m^2 of CsI photocathodes

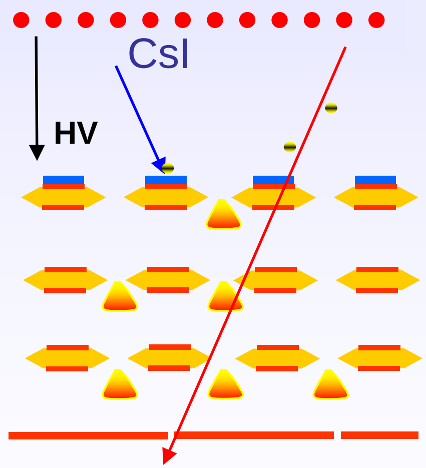




CsI on readout pads

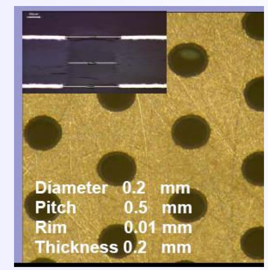
Micro Pattern Structures (GEM) + CsI
HBD (RICH) of PHENIX.

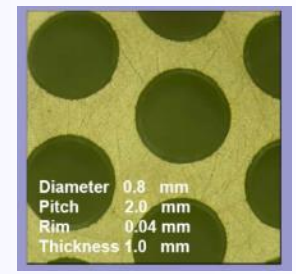


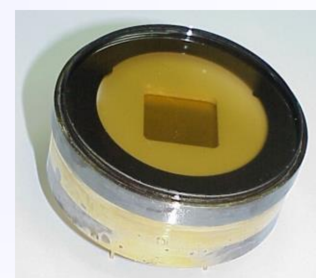


CsI on multi-GEM structure

R&D:
Thick GEM structures
Visible PC (bialkali)
Sealed gaseous devices







Sealed gaseous photodetector with bialkali PC. (Weizmann Inst., Israel)

Cherenkov detectors

Cherenkov detectors can exploit …

1 $N_{ph}(\beta)$ → Threshold detector. Do not measure θ_C

2 $\theta(\beta)$ → Ring Imaging Cherenkov detectors "RICH"
→ Detection of Internally reflected Cherenkov light "DIRC".
} Measure θ_C

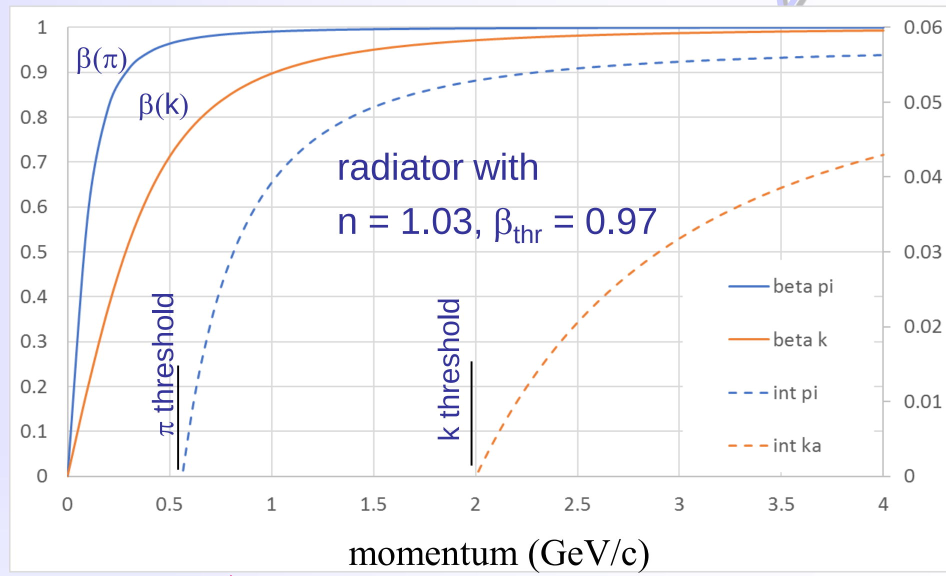
Knowing both the speed $\beta = v/c$ and the momentum p of the particle allows to derive the mass of the particle and hence identify it (e.g. π, K, p, d,…). Particle ID.

3 Prompt emission of Cherenkov light (different from scintillation) plus angular information → very fast timing detectors. TOP, TORCH

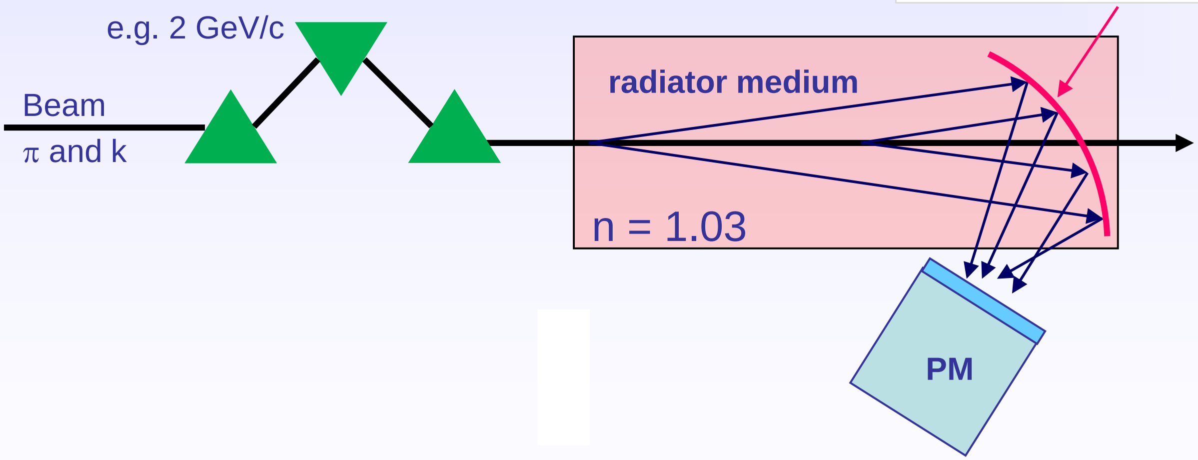
Cherenkov detectors

Threshold Cherenkov detectors

$$N_{ph} \approx 1 - \frac{1}{n^2 \beta^2} = 1 - \frac{1}{n^2} \cdot \left(1 + m^2 / p^2\right)$$

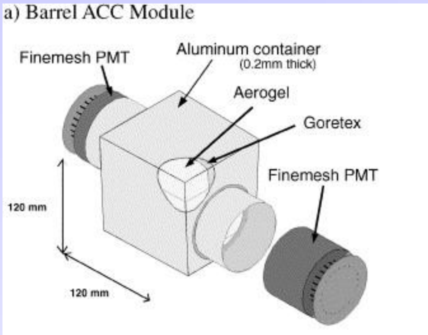


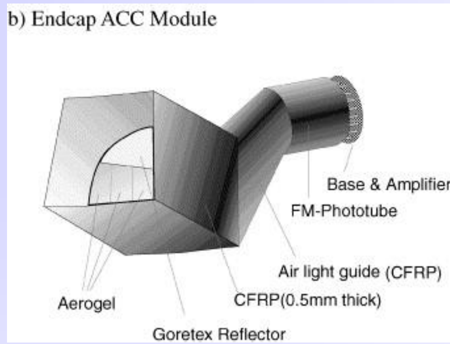
Often used in secondary beamlines (e.g. CERN PS, SPS) to tagg particle type

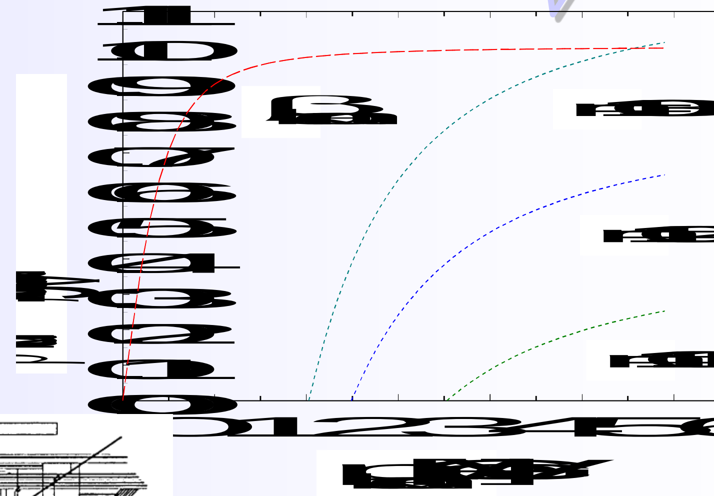


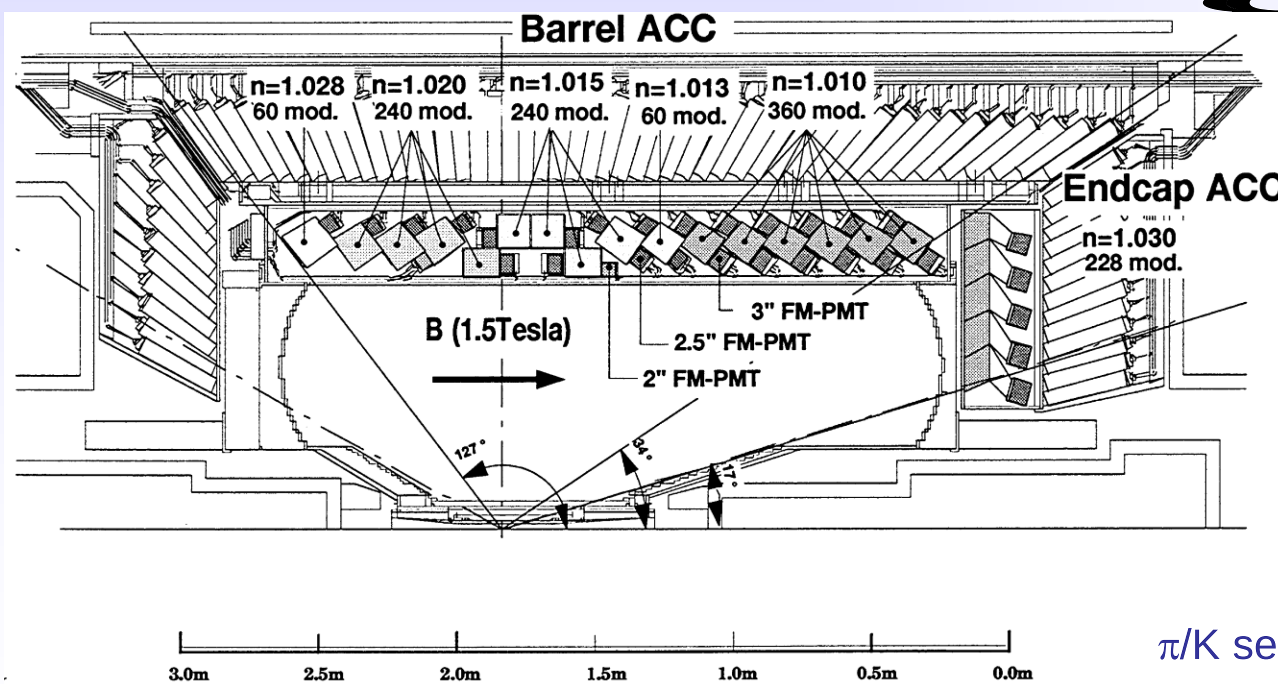
Principle of a simple in-beam threshold Cherenkov counter

BELLE threshold aerogel counters









- Almost 1200 independent detector modules in total.
- 6 different aerogels.

π/K separation up to 3.5 GeV/c

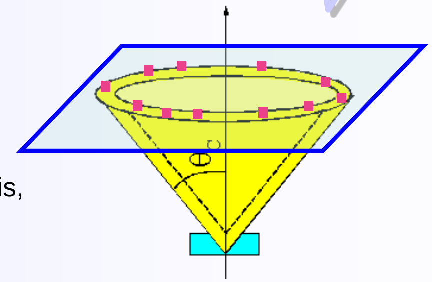
Ring Imaging Cherenkov detectors (RICH)

RICH detectors determine θ_C by intersecting the Cherenkov cone with a photosensitive plane

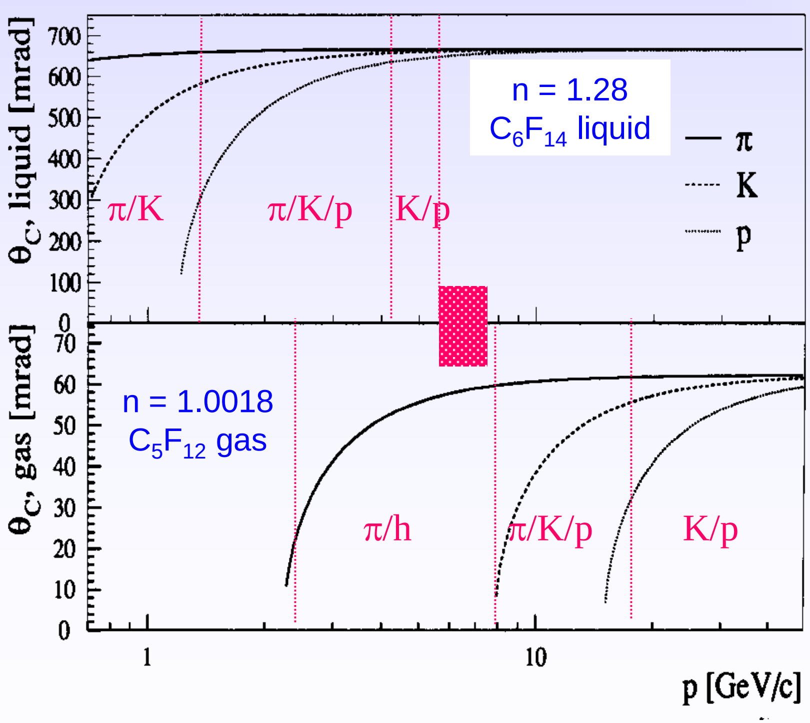
→ requires large area photosensitive detectors, e.g.

- wire chambers with photosensitive detector gas
- PMT arrays

(J. Seguinot, T. Ypsilantis, NIM 142 (1977) 377)



DELPHI



$$\theta_C = \arccos\left(\frac{1}{n\beta}\right) = \arccos\left(\frac{1}{n}\cdot\frac{E}{p}\right) = \arccos\left(\frac{1}{n}\cdot\frac{\sqrt{p^2+m^2}}{p}\right)$$

$$\cos\theta_C = \frac{1}{n\beta} \quad \rightarrow \quad \frac{\sigma_\beta}{\beta} = \tan\theta\cdot\sigma_\theta$$

Detect $N_{p.e.}$ photons (photoelectrons) →

$$\sigma_\theta \approx \frac{\sigma_\theta^{p.e.}}{\sqrt{N_{p.e.}}}$$

→ minimize $\sigma_\theta^{p.e.}$

→ maximize $N_{p.e.}$

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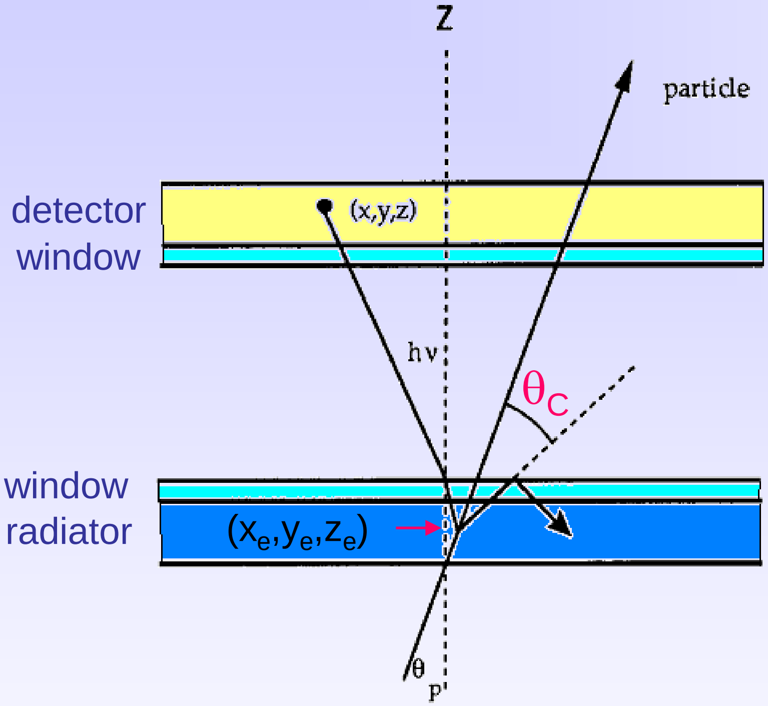
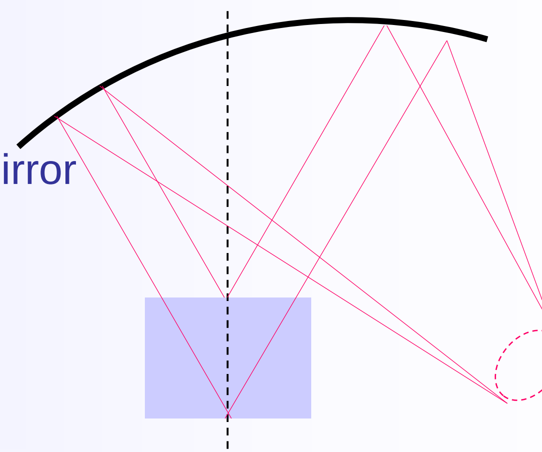
Reconstruction and resolution of Cherenkov angle

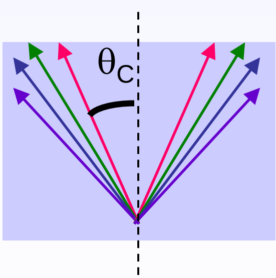


Determination of θ_C requires:

- space point of the detected photon (x,y,z)
  - photodetector granularity (σ_x, σ_y), depth of interaction (σ_z)
- emission point (x_e,y_e,z_e)
  - keep radiator thin or use focusing mirror
- particle direction θ_p, ϕ_p
  - RICH requires good tracker



- the chromatic error - an 'irreducible' error



$$n_{rad} = n(E)$$

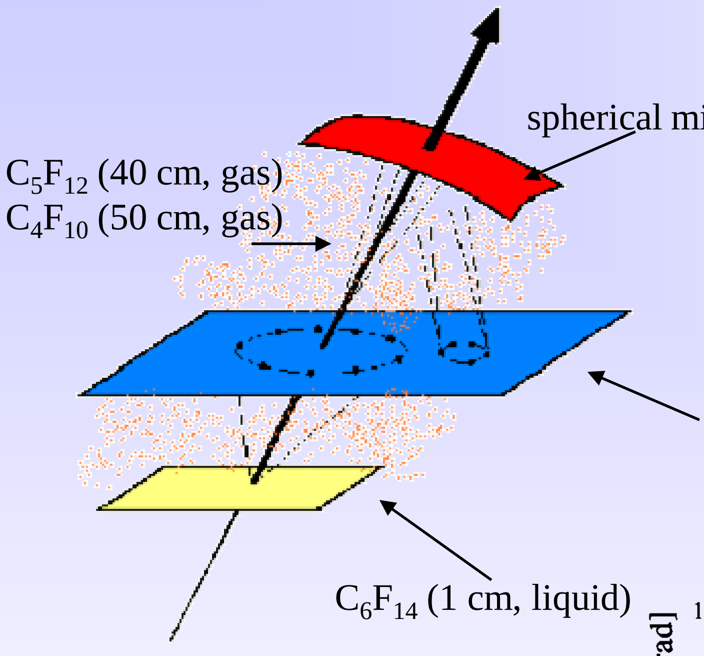
$$\sigma_\theta^c = \frac{1}{n\tan\theta}\sigma_n = \frac{1}{n\tan\theta}\frac{dn}{dE}\sigma_E$$

σ_E is related to the sensitivity range of the photodetector ΔE

$\Delta E \uparrow \rightarrow N_{pe} \uparrow$ good $\quad \sigma_E \uparrow$ bad

$\Delta E \downarrow \rightarrow N_{pe} \downarrow$ bad $\quad \sigma_E \downarrow$ good

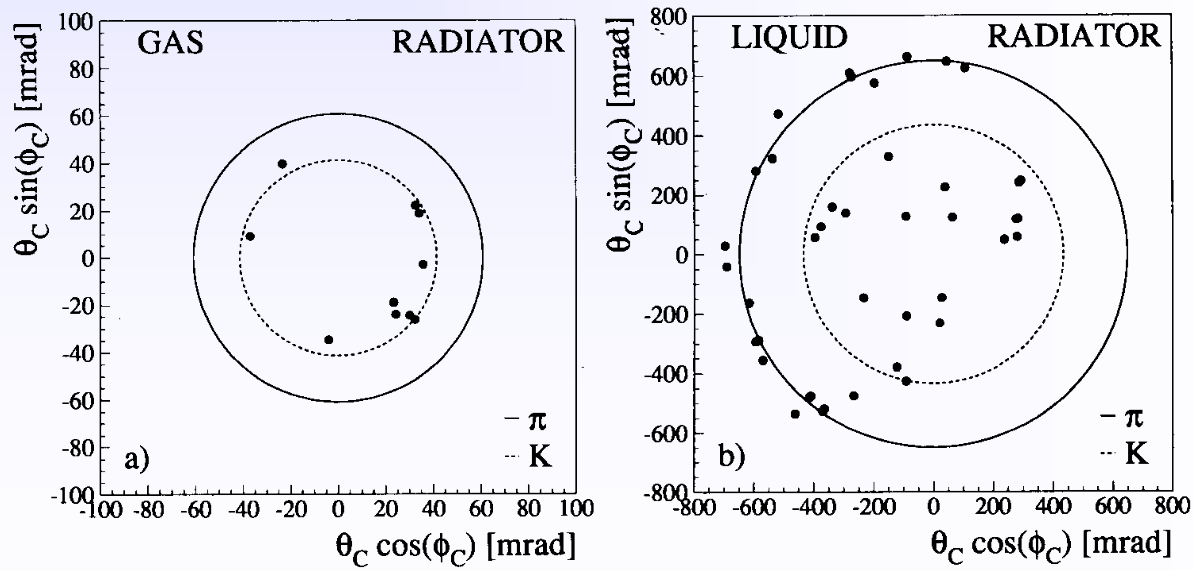
Ring Imaging Cherenkov detectors (RICH)



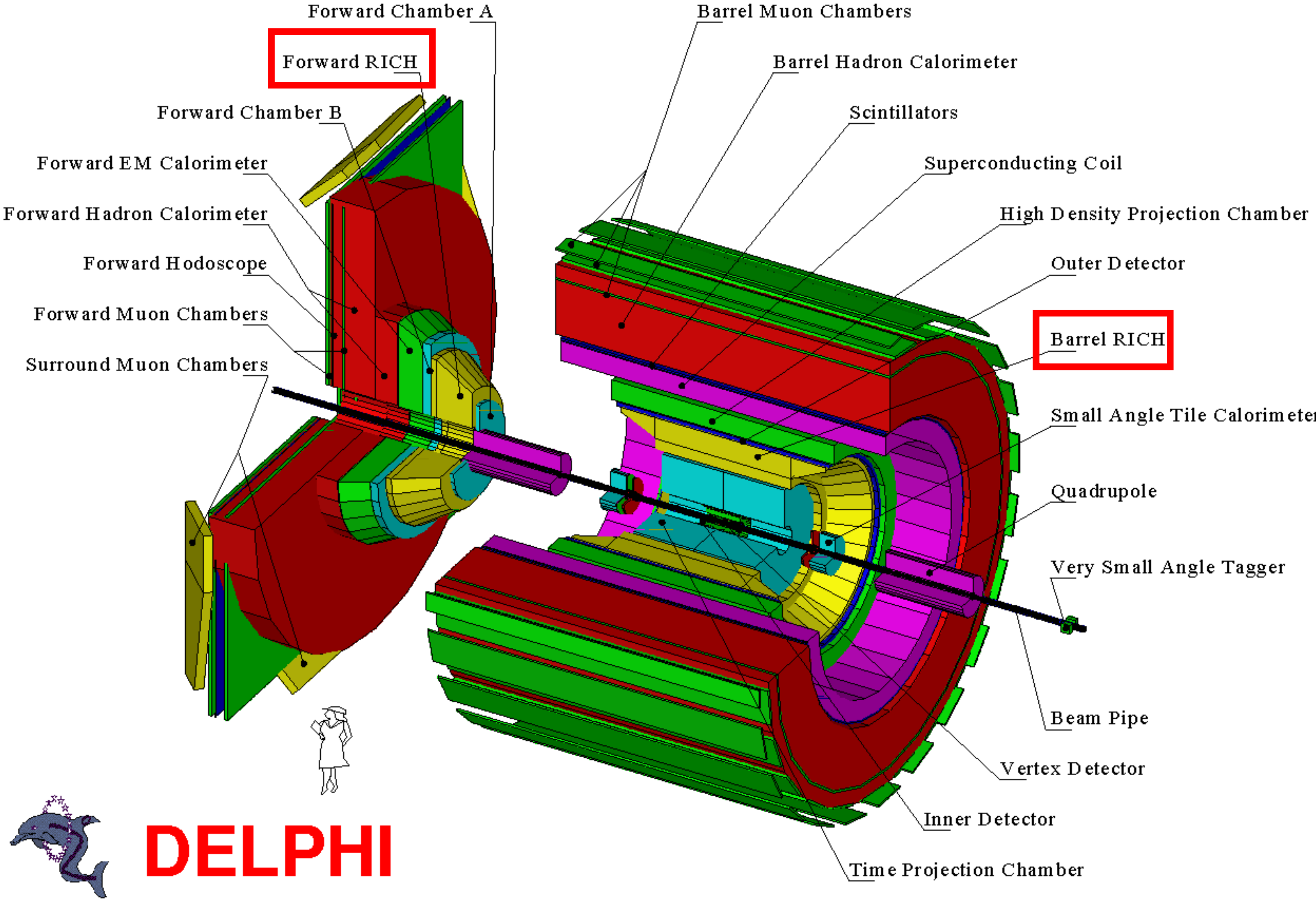
DELPHI and SLD:
A RICH with two radiators and a common photodetector plane
→ covers a large momentum range.
→ π/K/p separation 0.7 - 45 GeV/c:

(W. Adam et al. NIM A 371 (1996) 240)

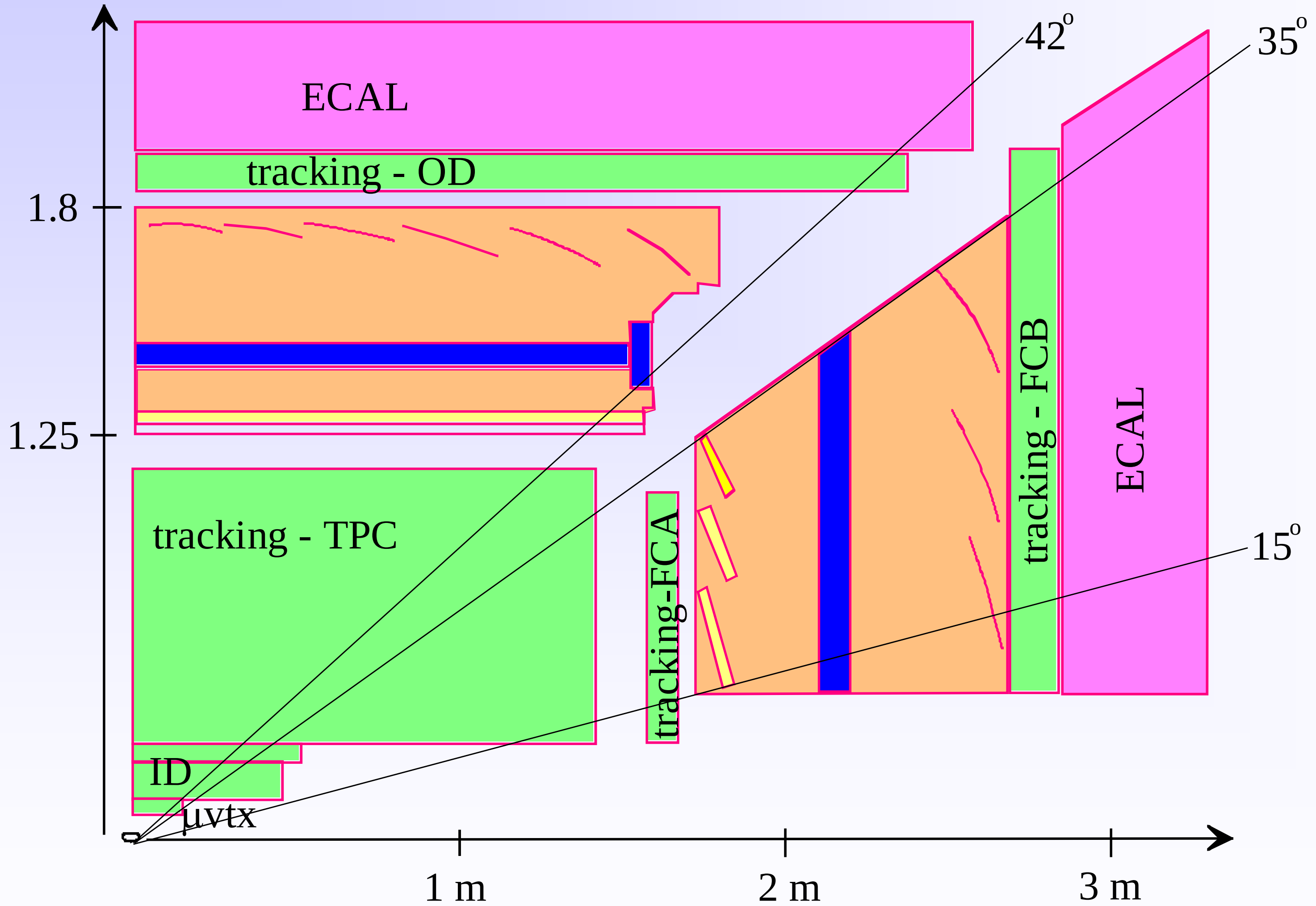
Generation 1



Two particles from a hadronic jet (Z-decay) in the DELPHI gas and liquid radiator.
Circles show hypotheses for π and K

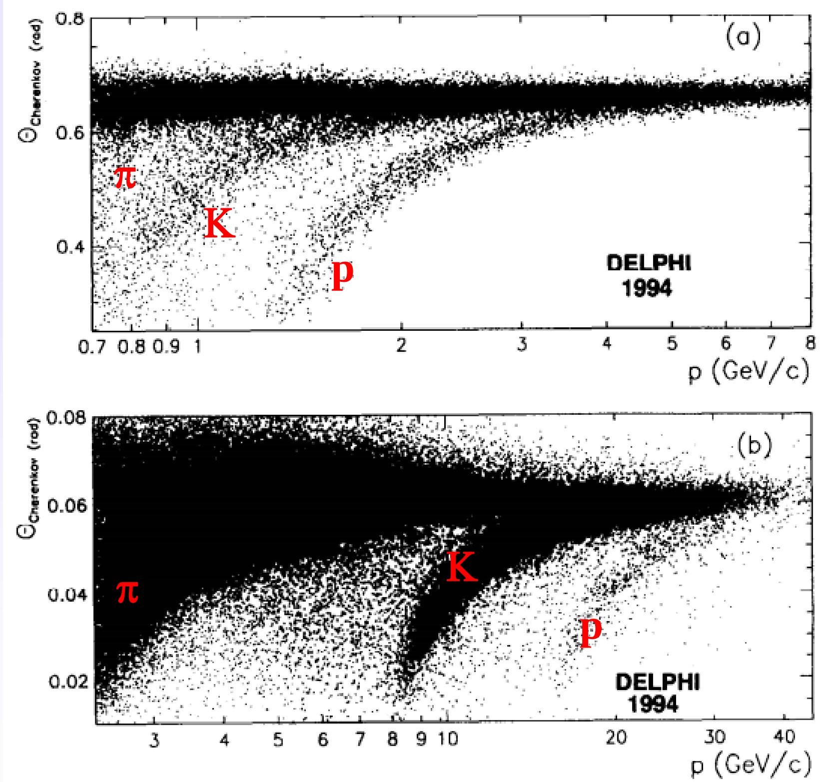

Forward Chamber A
Forward RICH
Forward Chamber B
Forward EM Calorimeter
Forward Hadron Calorimeter
Forward Hodoscope
Forward Muon Chambers
Surround Muon Chambers
Barrel Muon Chambers
Barrel Hadron Calorimeter
Scintillators
Superconducting Coil
High Density Projection Chamber
Outer Detector
Barrel RICH
Small Angle Tile Calorimeter
Quadrupole
Very Small Angle Tagger
Beam Pipe
Vertex Detector
Inner Detector
Time Projection Chamber
DELPHI

The RICH detectors are sandwiched between tracking detectors which provide precise particle track extrapolation



- The DELPHI RICHes were complex and delicate, and required 24/24h care, 365 days a year. It took years to make them work and perform.
- Working in the VUV posed strict requirements on purity of all liquids and gases.
- The windows were made of quartz. The whole detector was kept at 1030 mbar, 40°C the whole year.
- Materials were attacked by C_xF_y fluids. Leaks between radiator systems, shorts in the TPC drift field and many more things had to be taken care of.

But it finally worked!



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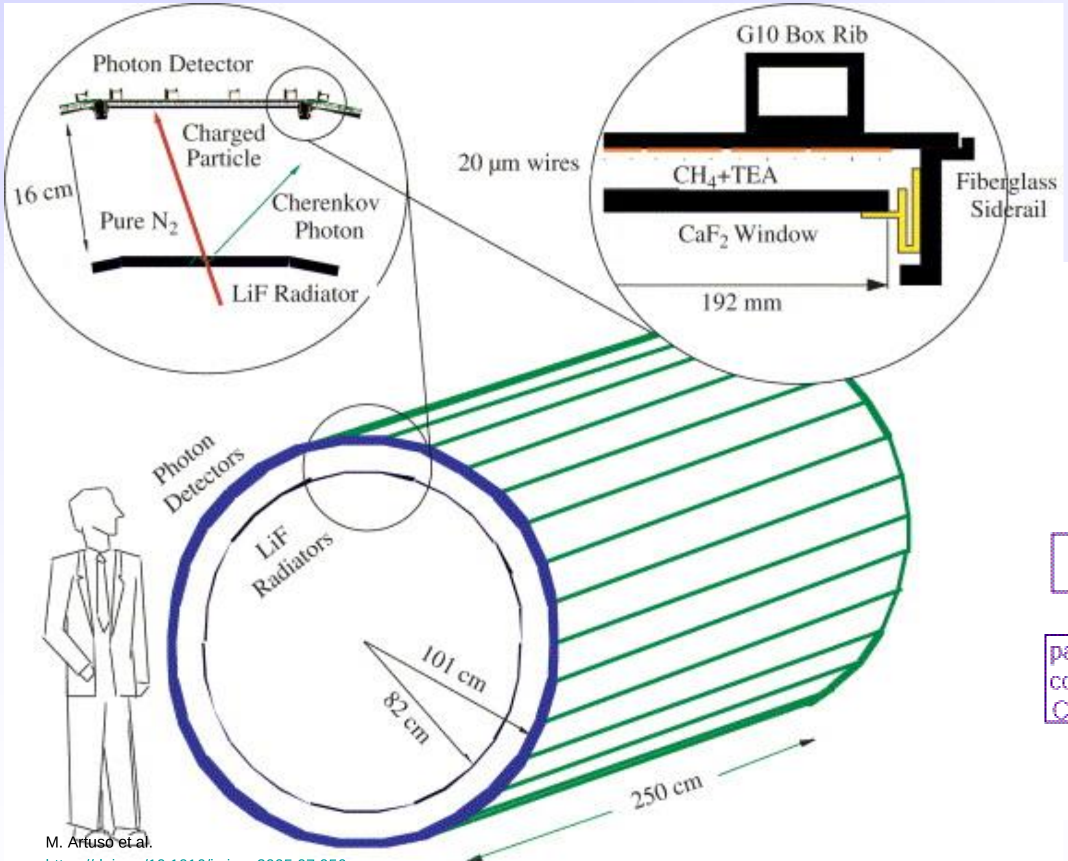
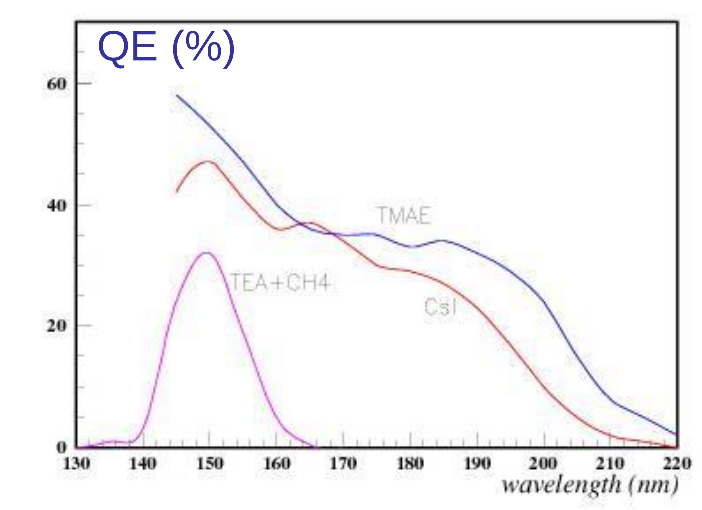
Fast RICH detectors

Generation 1.5

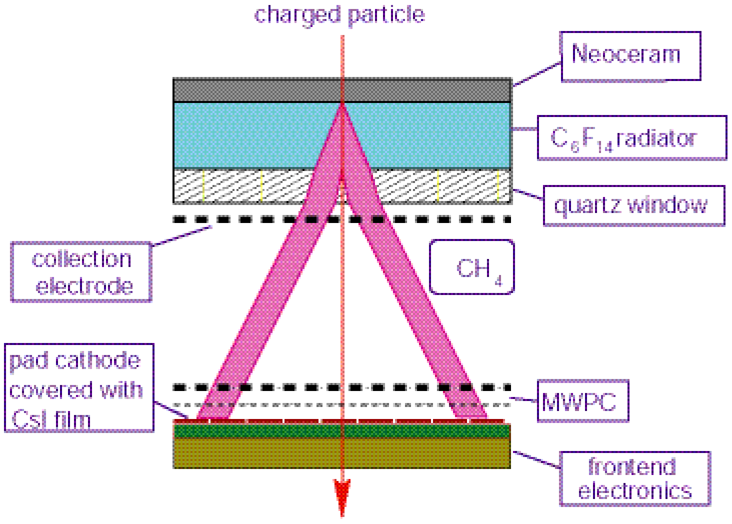
CLEO RICH @ CESR, Cornell



M. Artuso et al.
https://doi.org/10.1016/j.nima.2005.07.056



ALICE RICH @ LHC



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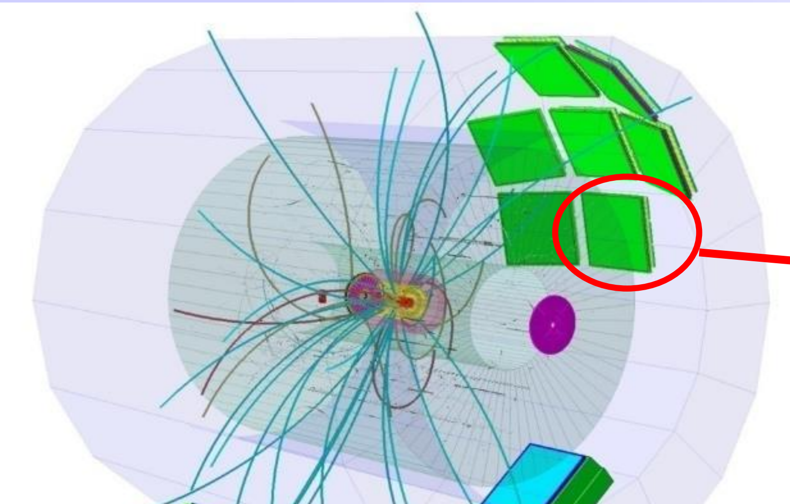
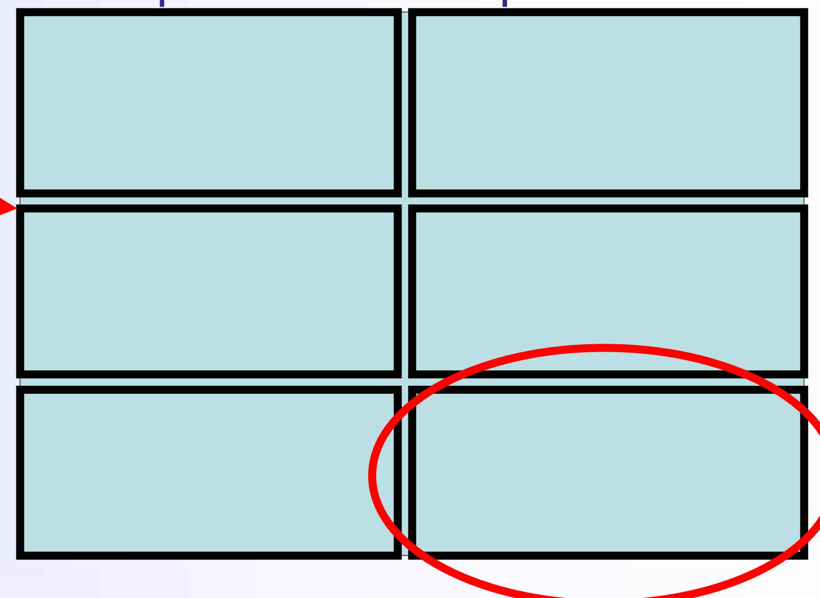
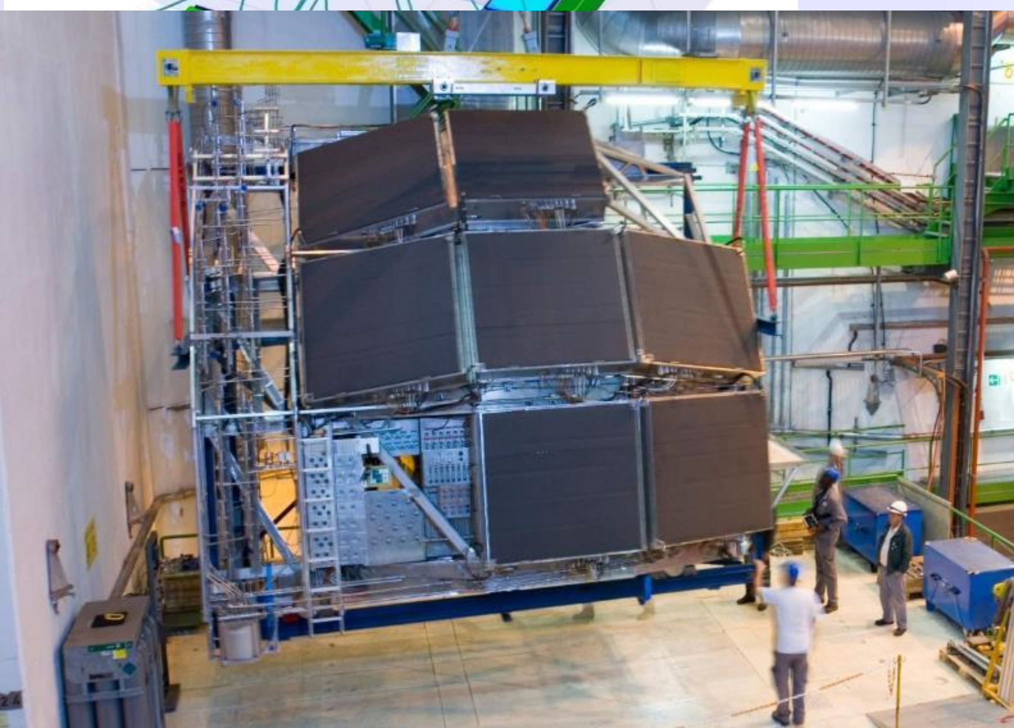
ALICE RICH = HMPID

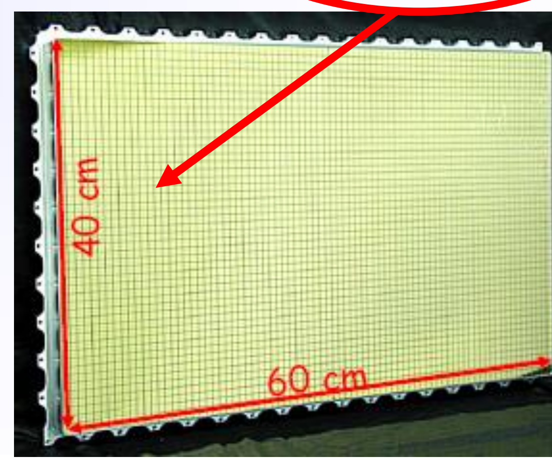


The largest scale (11 m²) application of CsI photo-cathodes in HEP!

Six photo-cathodes per module



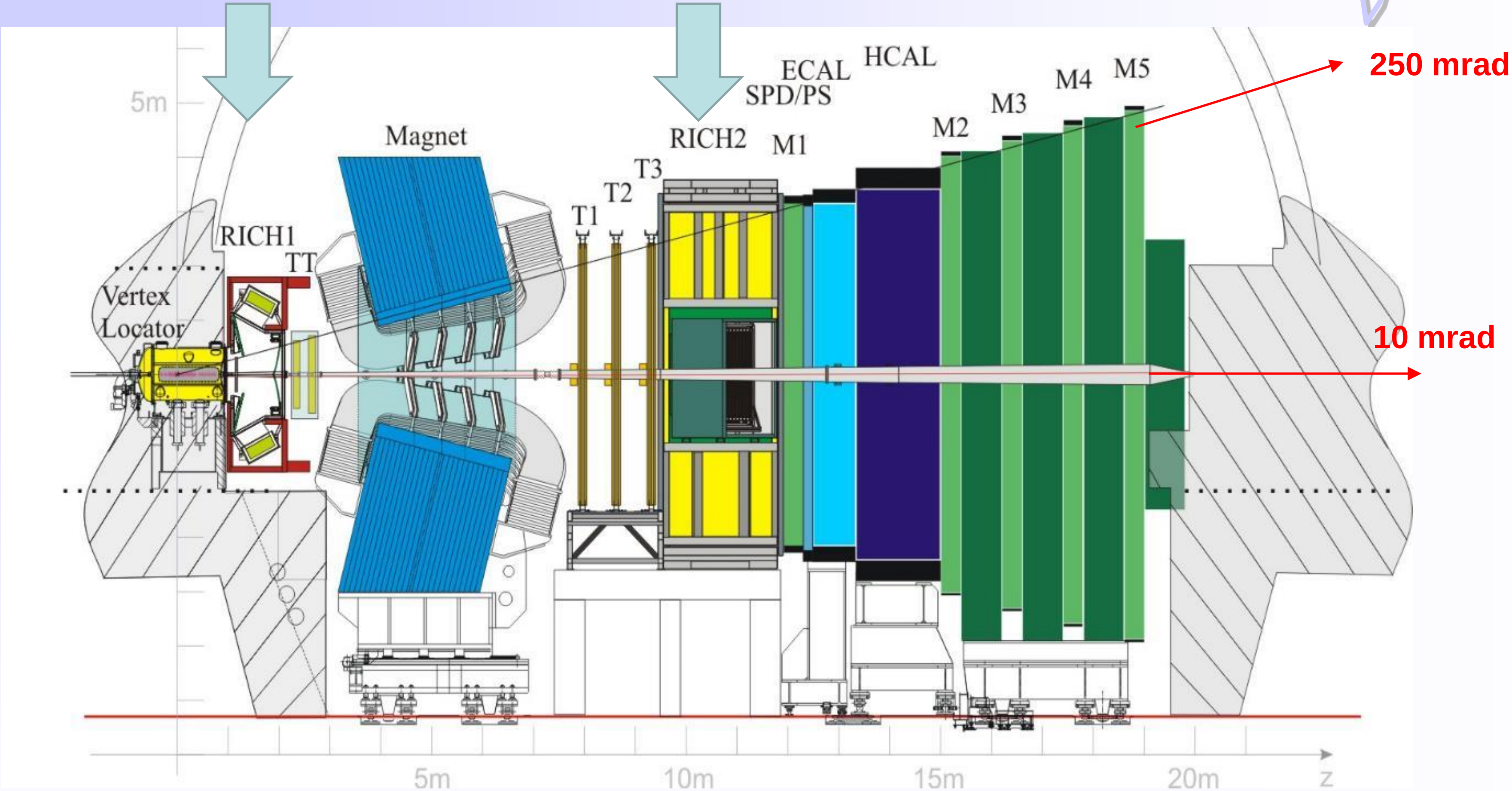




CsI photo-cathode is segmented in 0.8x0.84 cm pads

The LHCb RICH counters

Generation 2



Vertex reconstruction:
VELO

Trigger:
Muon Chambers
Calorimeters
Tracker

PID:
RICHes
Calorimeters
Muon Chambers

Kinematics:
Magnet
Tracker
Calorimeters

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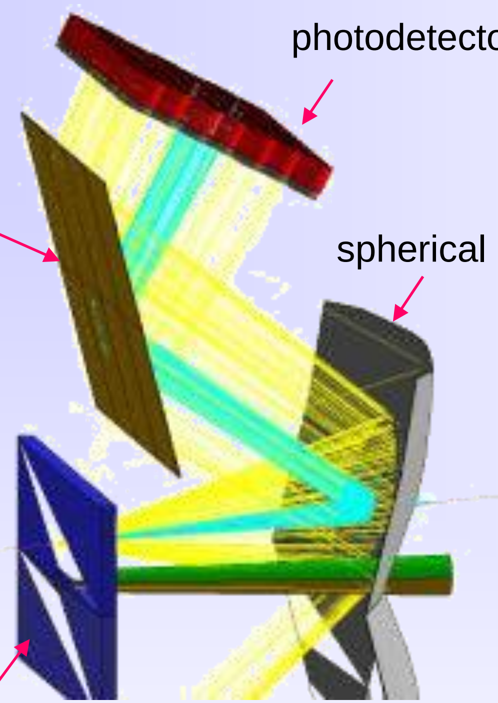
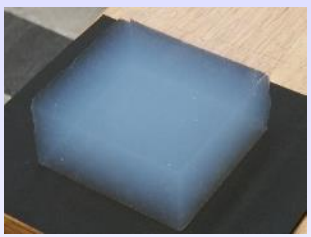
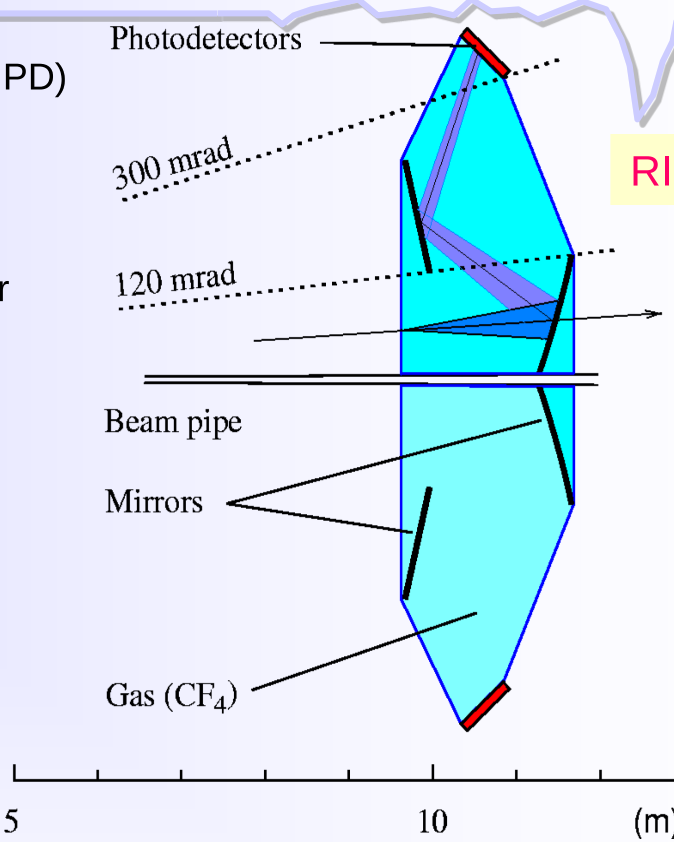
2 RICH detectors in LHCb

RICH 1





RICH 2

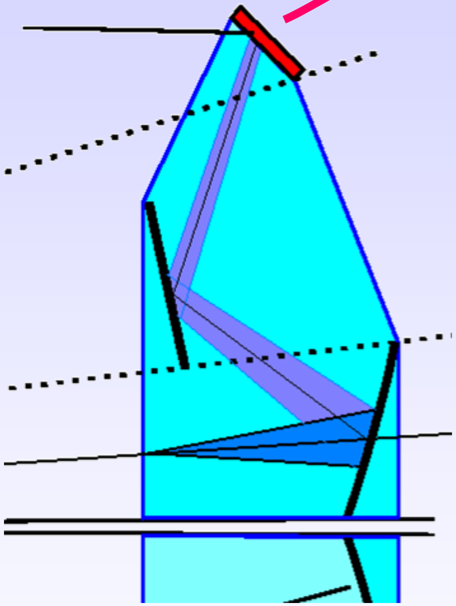


radiator	C_4F_{10}	aerogel
θ_C	3.03°	13.8°
n	1.0014	1.03
p_{thresh} (π)	2.6	0.6 GeV/c
$N_{p.e.}$	31	6.8
σ_θ	1.29	2.19 mrad
p (3σ)	56	13.5 GeV/c

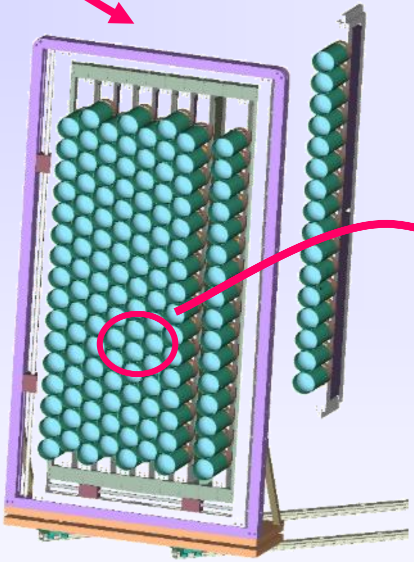
radiator	CF_4
θ_C	1.8°
n	1.0005
p_{thresh} (π)	4.4 GeV/c
$N_{p.e.}$	23
σ_θ	0.6 mrad
p (3σ)	98.5 GeV/c

2 RICH detectors in LHCb

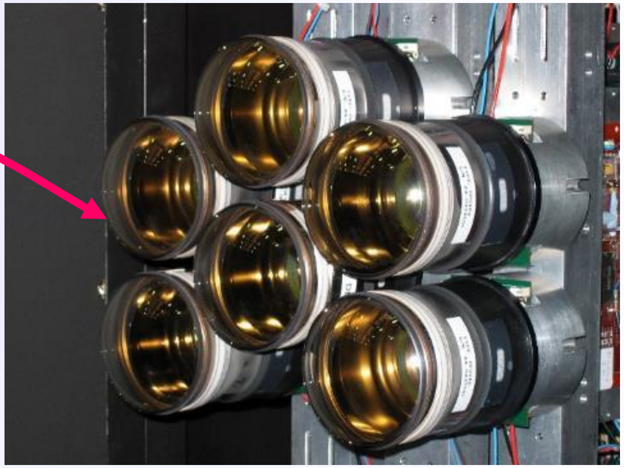
RICH 2



photodetector plane



beam test in 2004 with 6 HPDs



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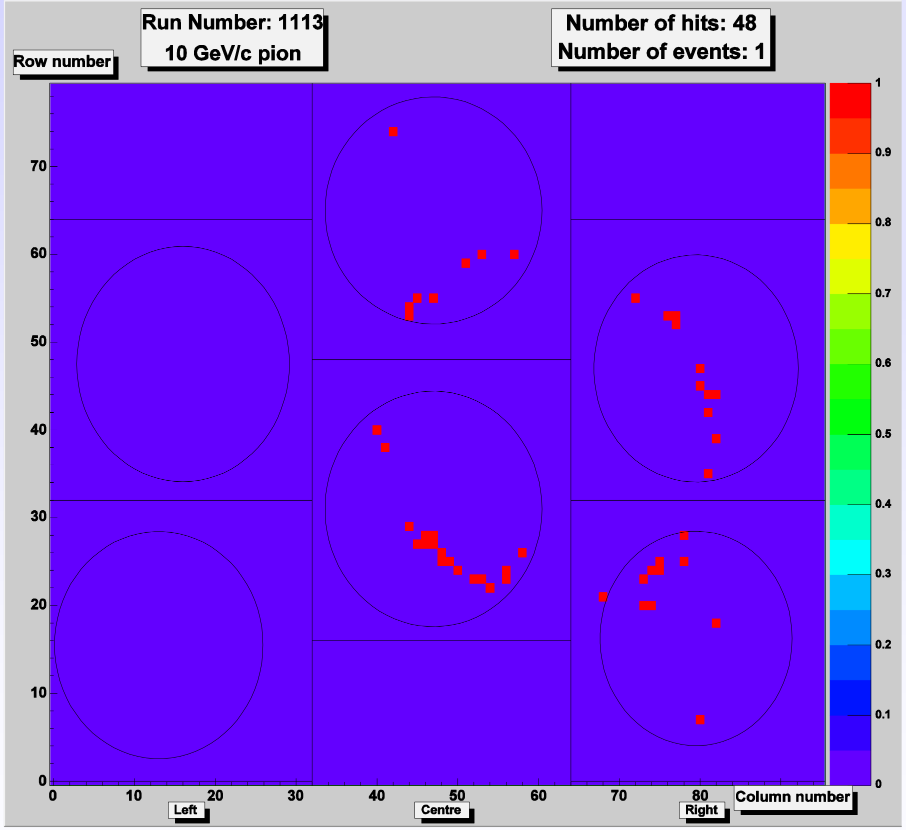
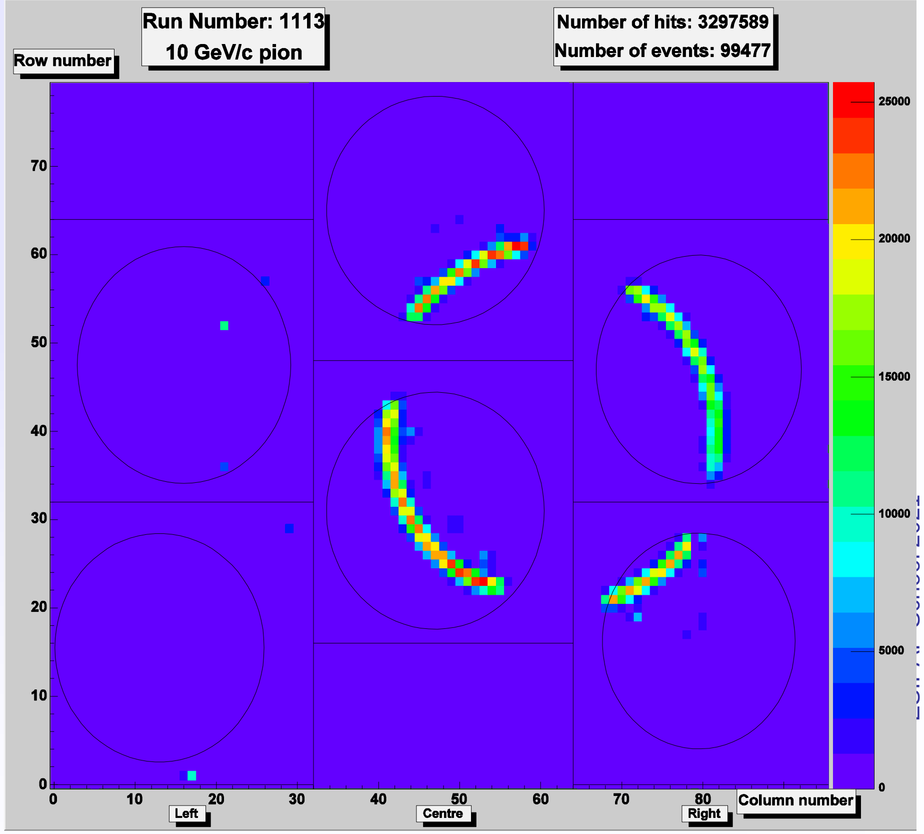
2 RICH detectors in LHCb

Beam test results with C_4F_{10} radiator gas (autumn 2004).

Single pion (10 GeV/c)

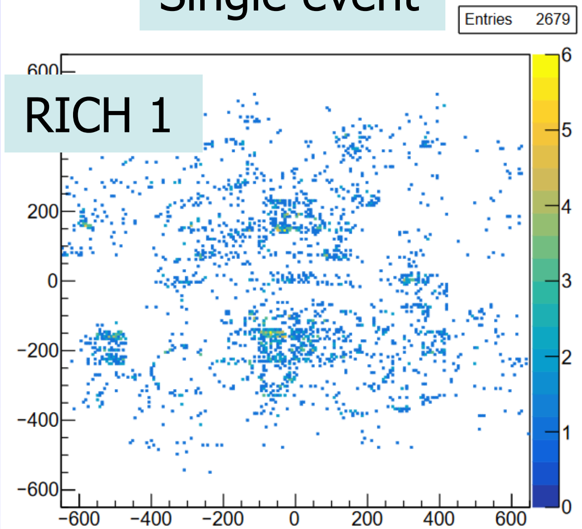


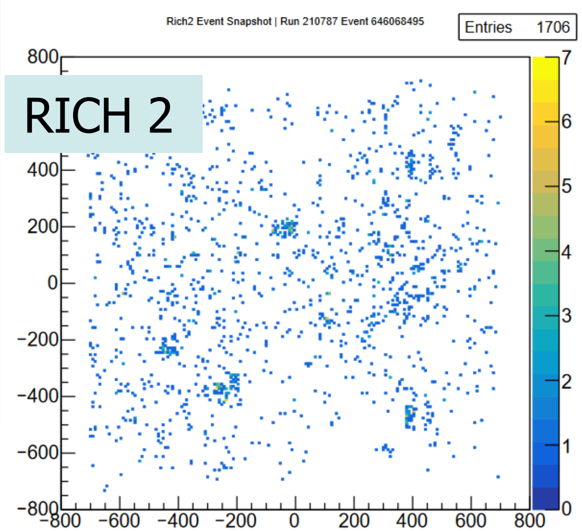
Superimposed events (100 k pions, 10 GeV/c)

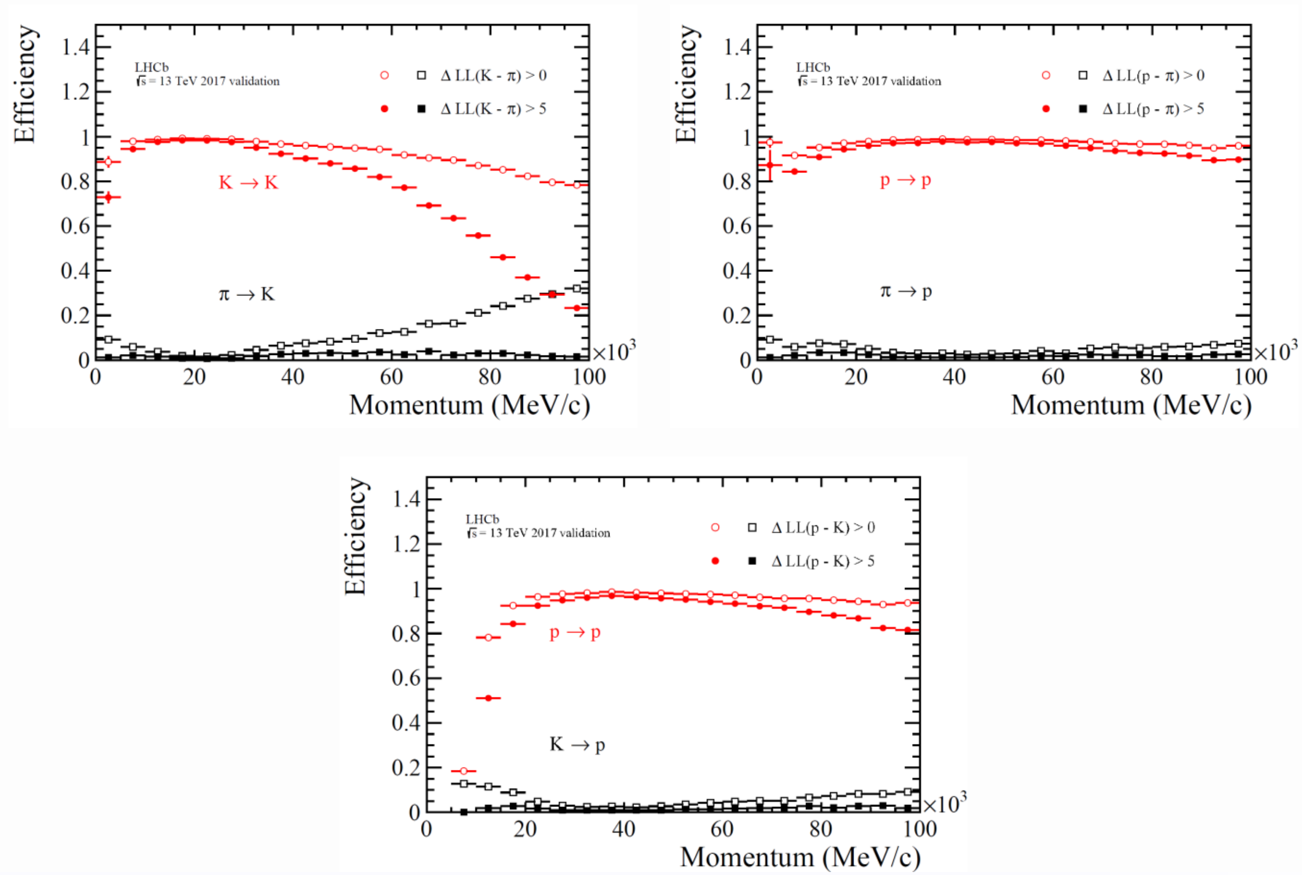


Performance of LHCb RICHes

Single event

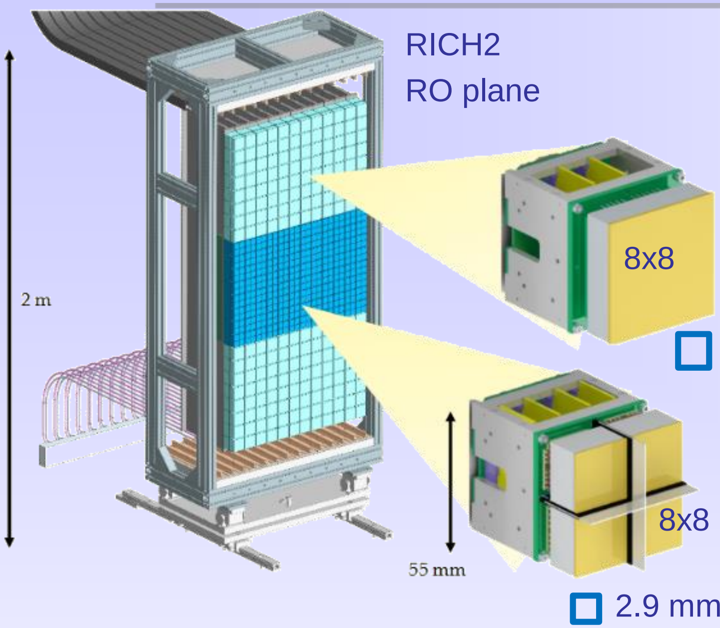


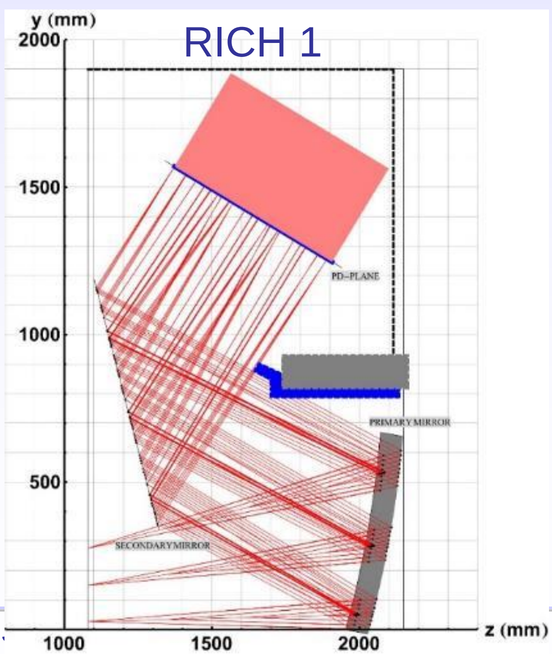


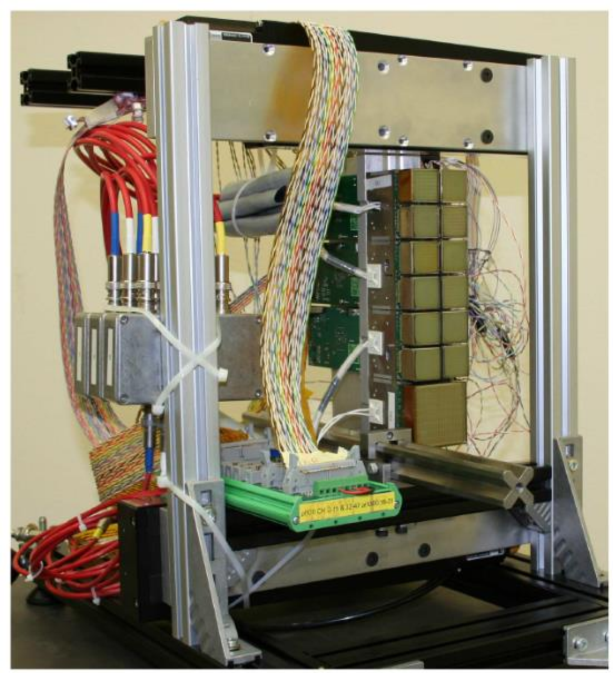


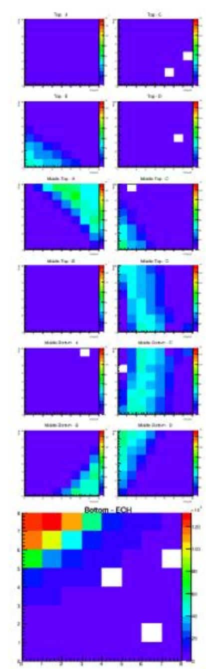
LHCb Upgrade (under way, LS2)

- New photon detectors: MaPMTs Hamamatsu R13743 (H12700) and R13742 (R11265)
- New electronics working at 40 MHz readout rate
- New optics layout for RICH 1 (no aerogel)









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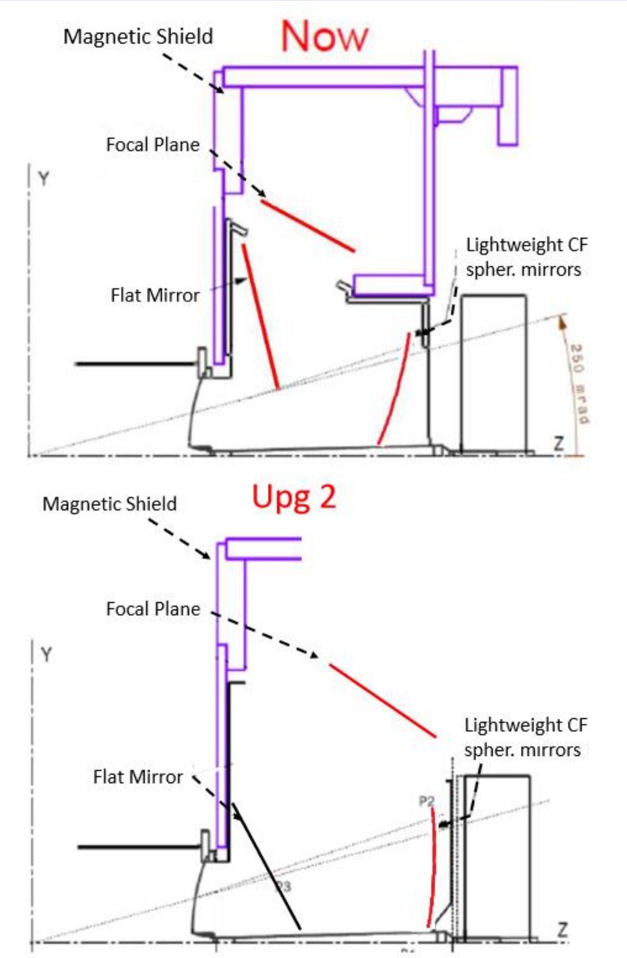
Future LHCb Upgrade (LS4!!)

Generation 3?



- Provide PID at p-p luminosity of 10^{34} in the forward region
- Aim to use **SiPM (cryo-cooled?) photodetectors**
- Need ultralight mirrors (in active region)
- Incremental improvements in:
  - Improve Cherenkov angle resolution
    - More photons in the green → lower chromatic error
  - Reduced event complexity with timing
  - Enhanced number of photons

Radiator	C_4F_{10}			CF_4	
Detector Version	RICH 1 Current (HPD)	RICH 1 UPG1	**RICH 1 UPG2**	RICH 2 UPG1	**RICH 2 UPG2**
Average Photoelectron Yield	30	40	**60–30**	22	**30**
Single Photon Errors (mrad)					
Chromatic	0.84	0.58	**0.24–0.12**	0.31	**0.1**
Pixel	0.9	0.44	**0.15**	0.20	**0.07**
Emission Point	0.8	0.37	**0.1**	0.27	**0.05**
Overall	1.47 ⇨	0.82 ⇨	**0.3–0.2**	0.46 ⇨	**0.13**

New optics

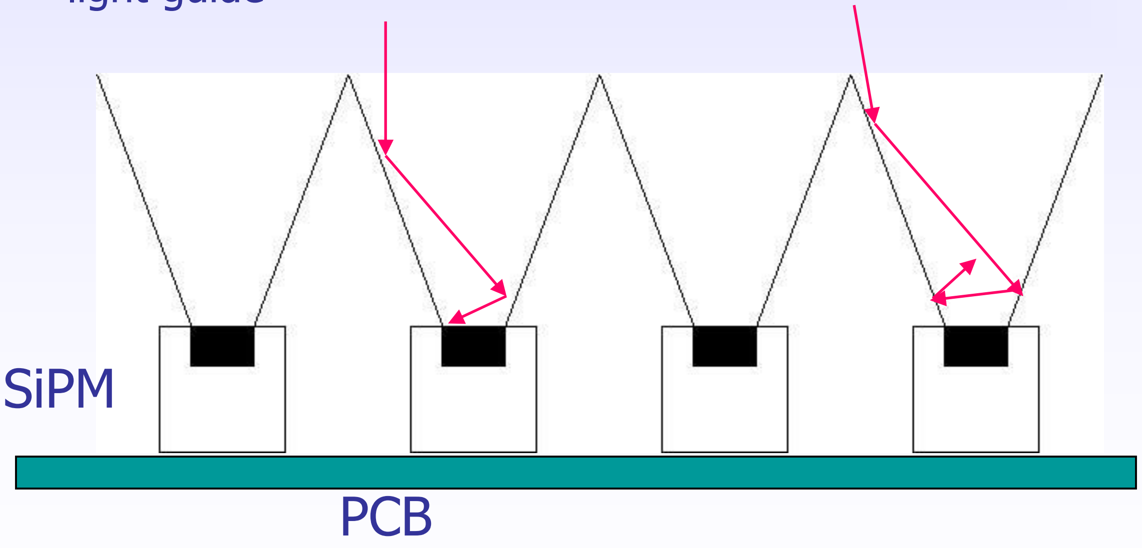
New optics

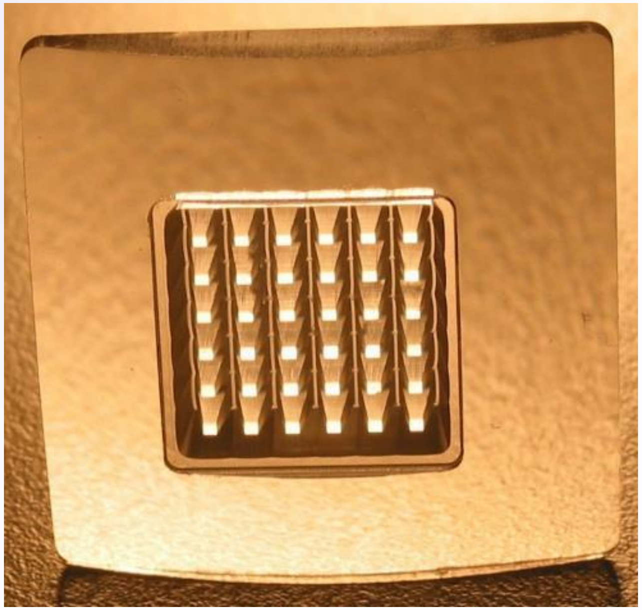
SiPM as photosensor for a RICH counter ?

Improve the signal to noise ratio:

- Reduce the noise by a narrow (<10ns) time window (Cherenkov light is prompt!)
- Increase the number of signal hits per single sensor by using light collectors
- Reduce the noise even further by cooling the SiPMs

E.g. light collector with reflective walls or plastic light guide





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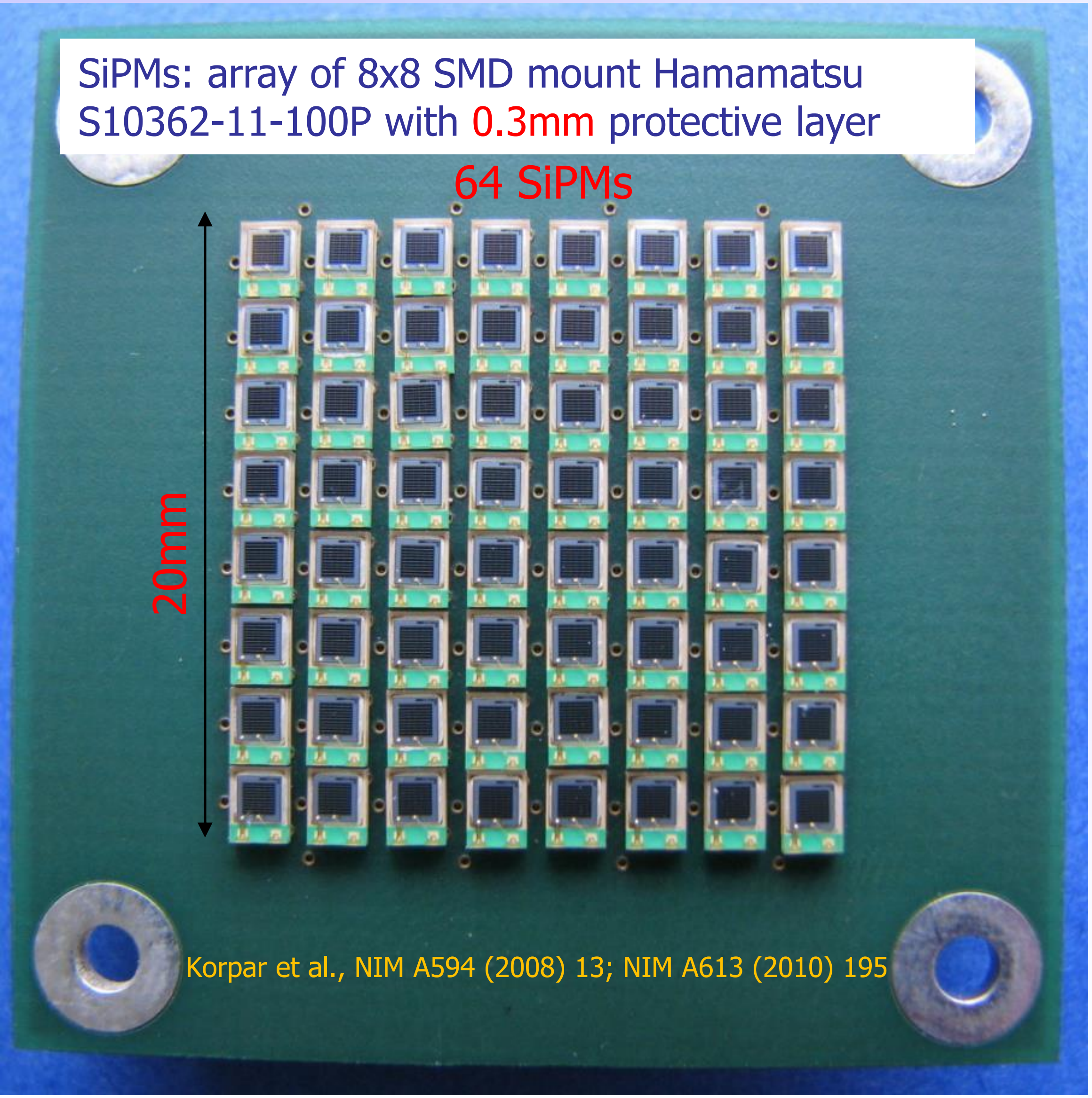
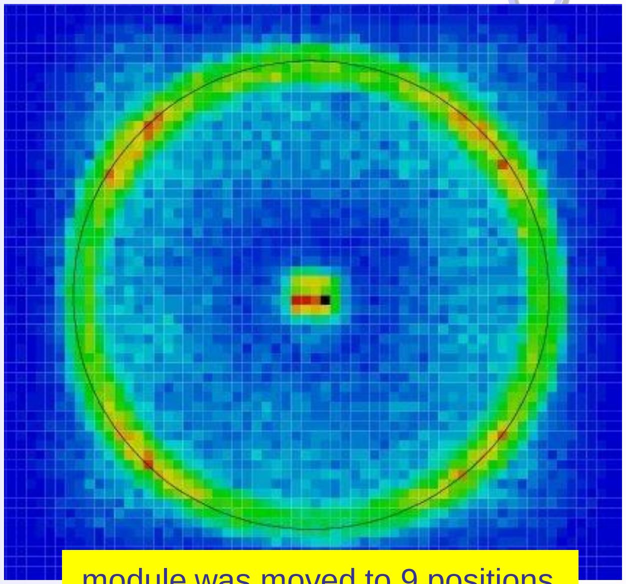
Photon detector with SiPMs and light guides

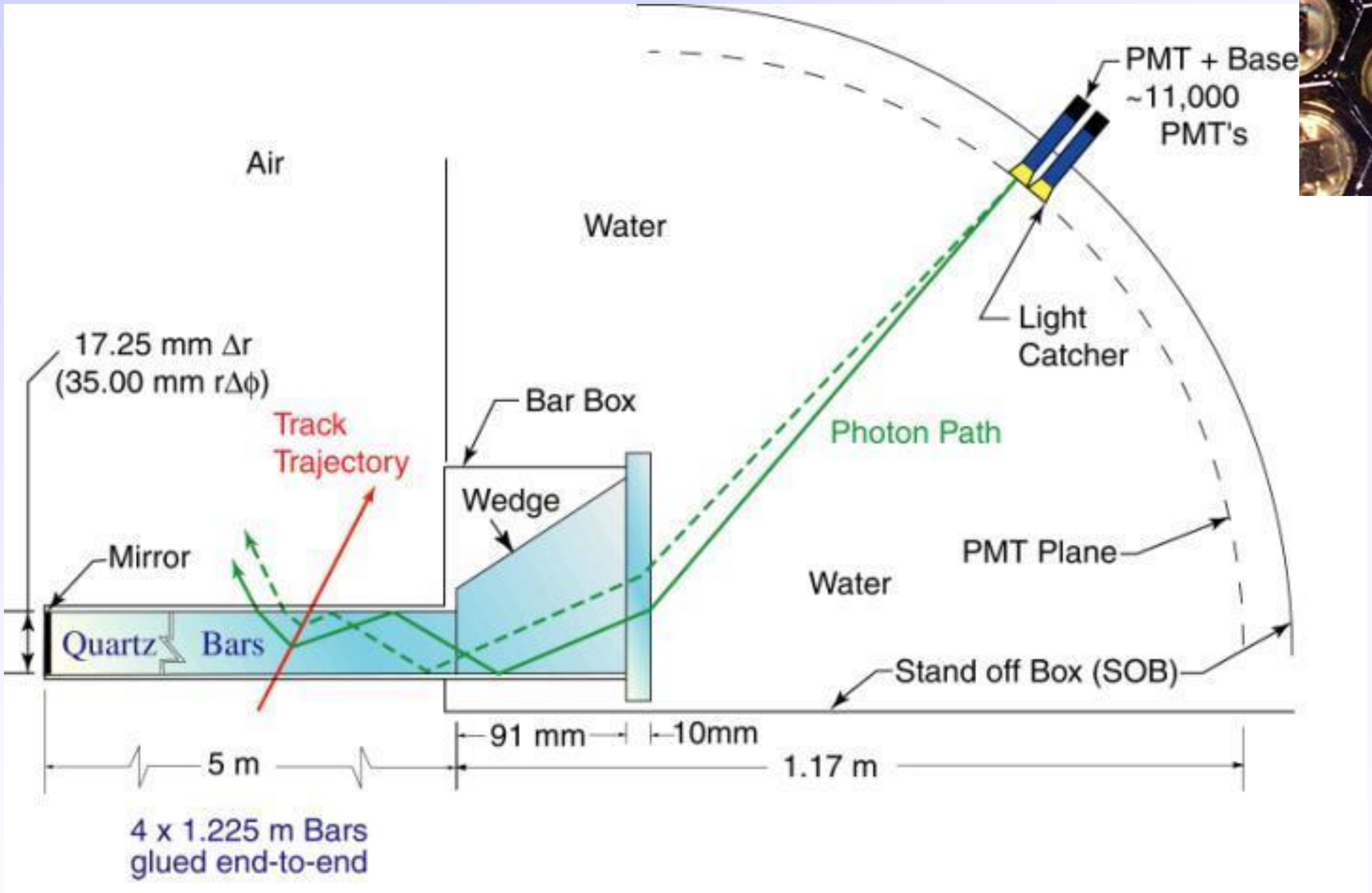


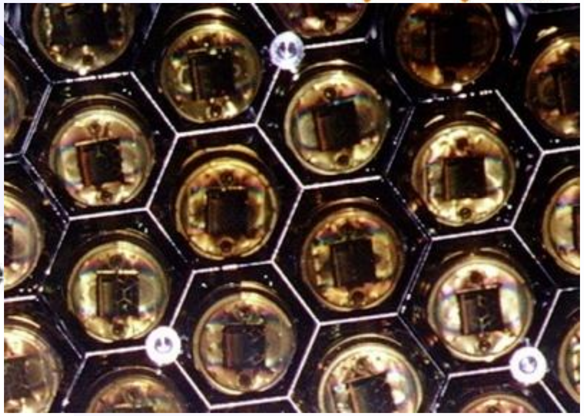


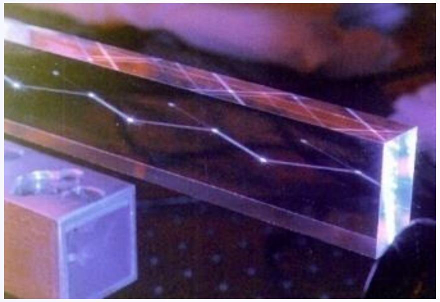
module was moved to 9 positions to cover the ring area. Save $$$!

DIRC @BaBar: Detection of Internally Reflected Cherenkov light

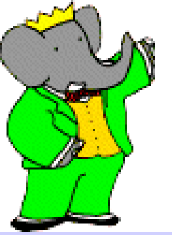
Use the internally reflected C-light, which would normally be lost!





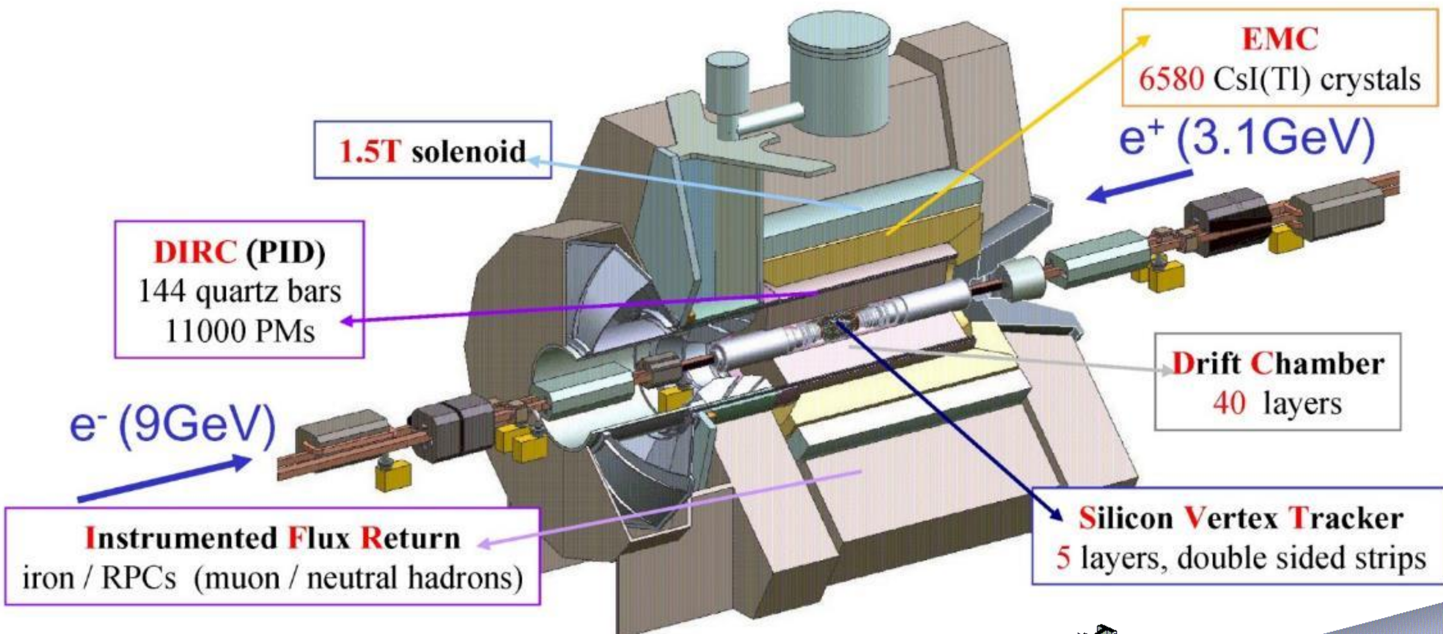


During propagation: angle of Cherenkov light is conserved, except of left/right and up/down ambiguities

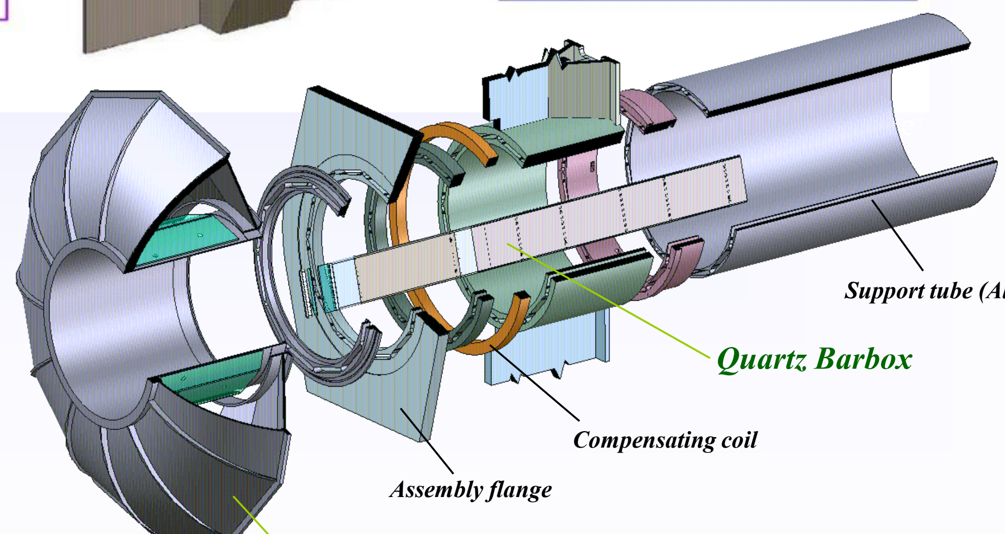


DIRC @ BaBar

BaBar spectrometer at PEP-II



Only radiator is in active volume of detector. Photodetectors & electronics do not disturb!



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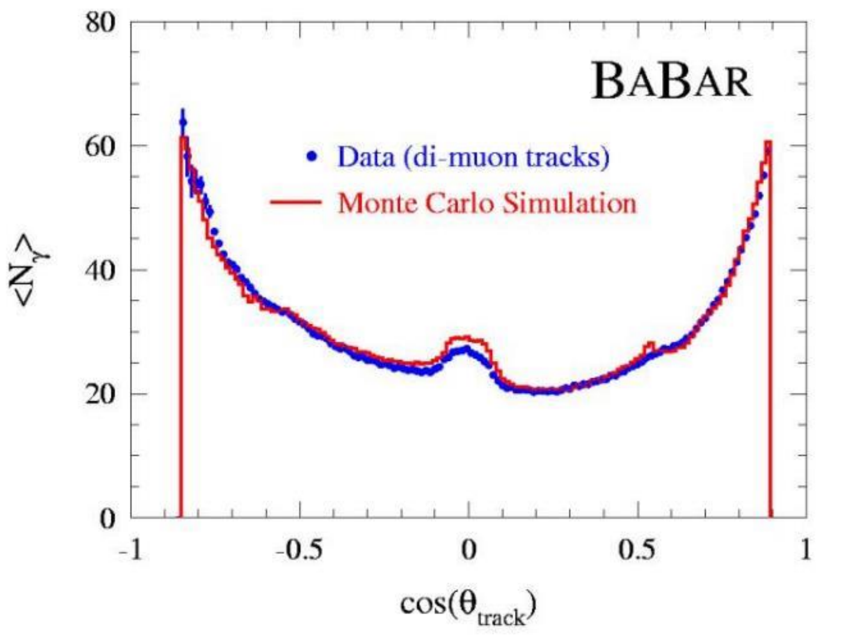
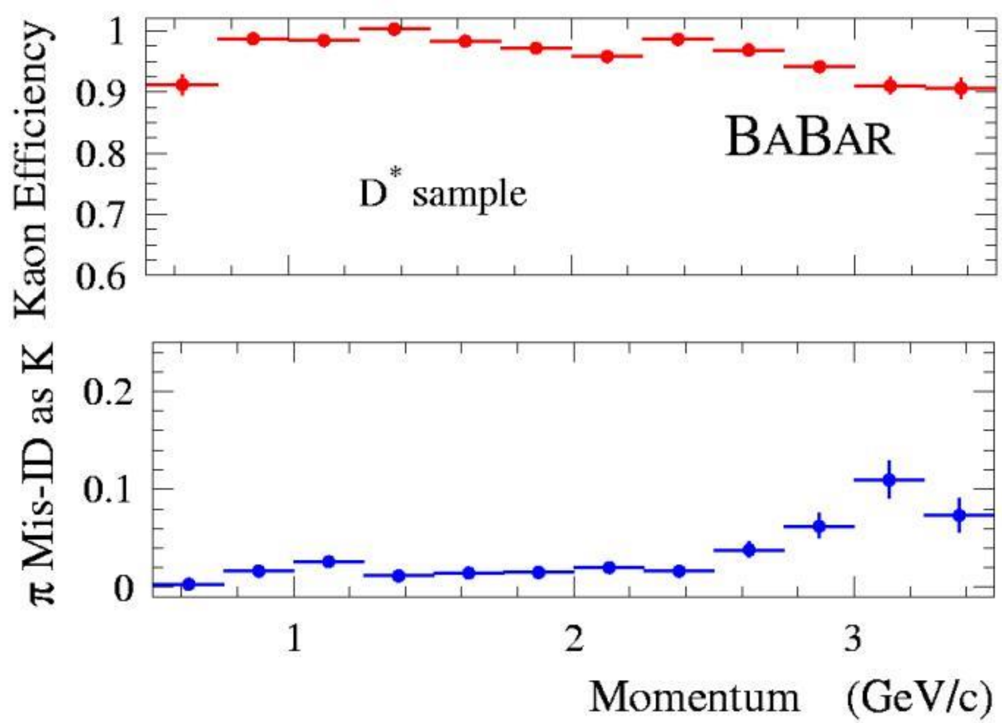
DIRC performance



← Lots of photons!

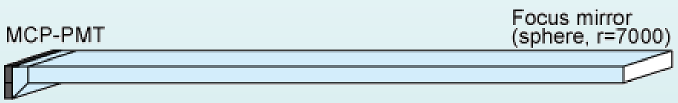
Excellent π/K separation



NIM A553 (2005) 317

Belle II Cherenkov detectors

Barrel PID: Time of Propagation Counter (TOP)



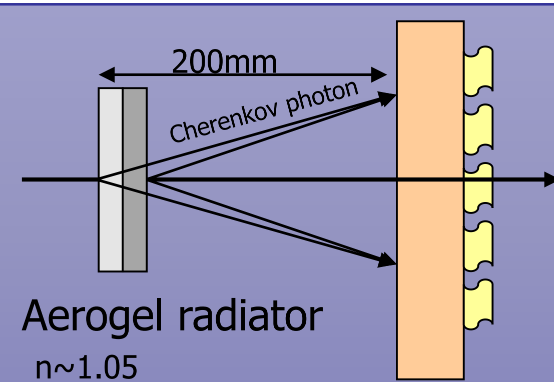
Quartz radiator

Focusing mirror

Small expansion block

Hamamatsu MCP-PMT (measure t, x and y)

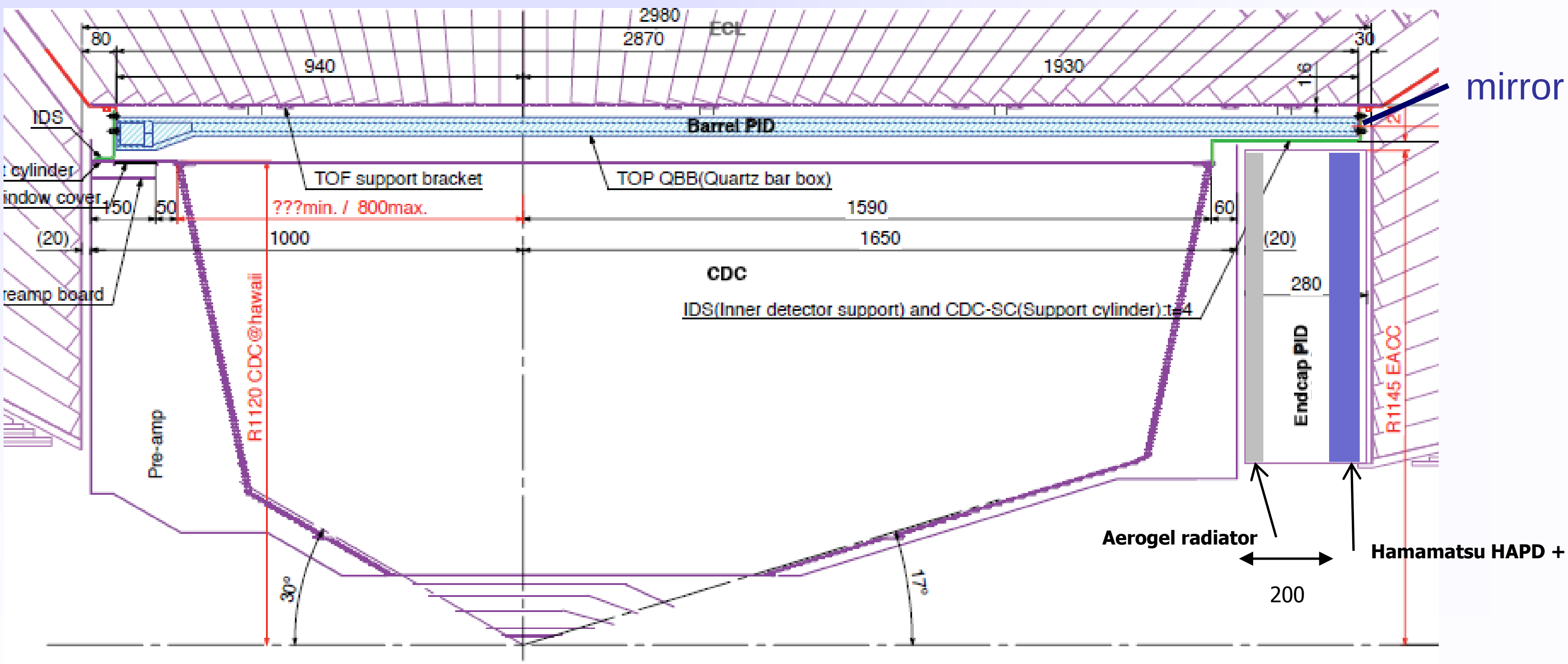
Endcap PID: Aerogel RICH (ARICH)



Aerogel radiator

n~1.05

Hamamatsu HAPD
+ new ASIC



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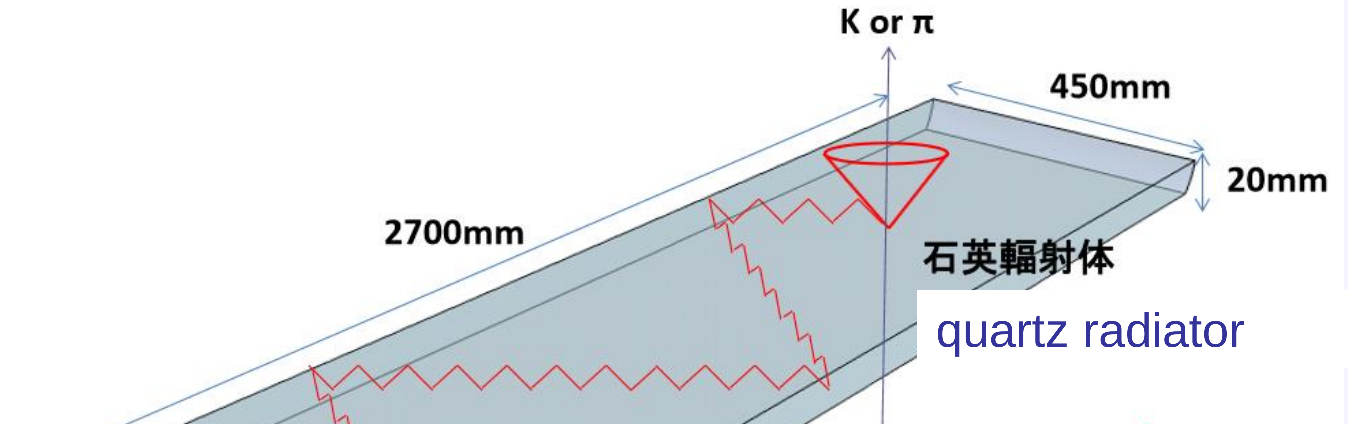
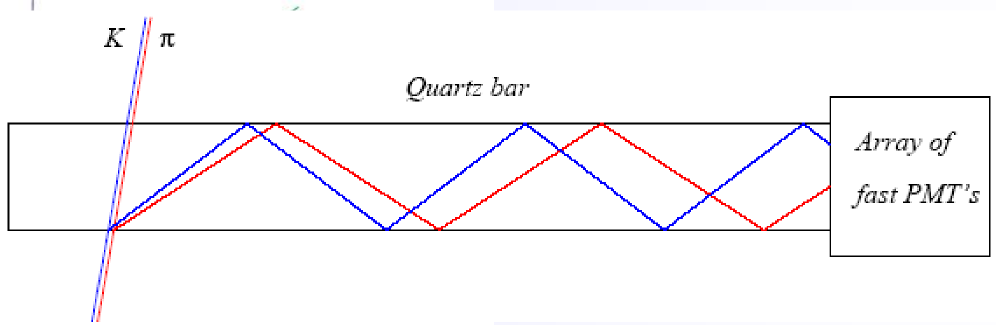
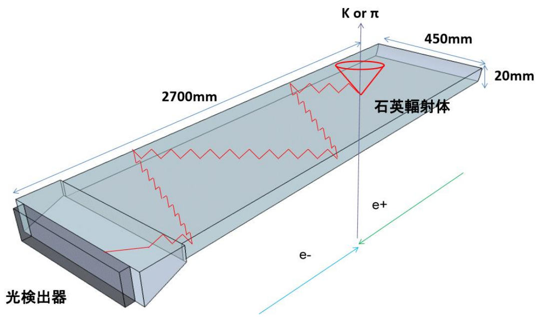
Time of propagation (TOP) counter





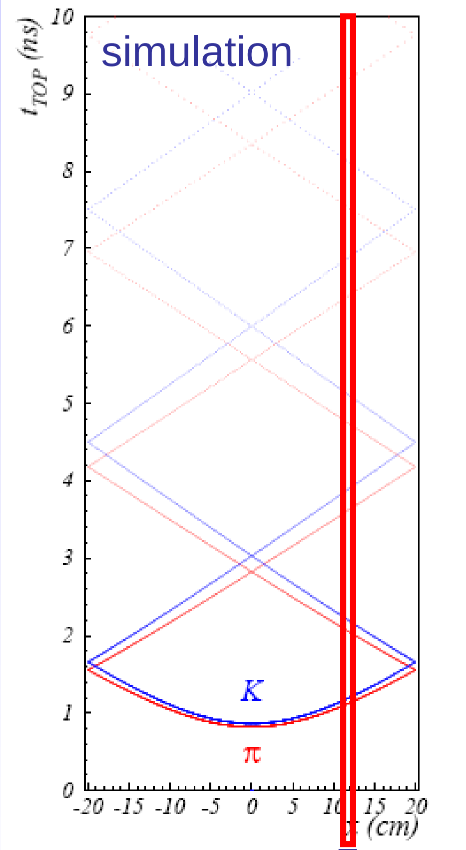
- Similar to the DIRC, Cherenkov ring imaging with precise time measurement.
- Reconstruct Cherenkov angle from two photon hit coordinates and the time of propagation of the photon
- Photon detector (MCP-PMT), pixels of ~5 x 5 mm^2, very fast multi-GHz sampling electronics
  - Excellent time resolution ~ 40 ps
  - Single photon sensitivity at 1.5 T

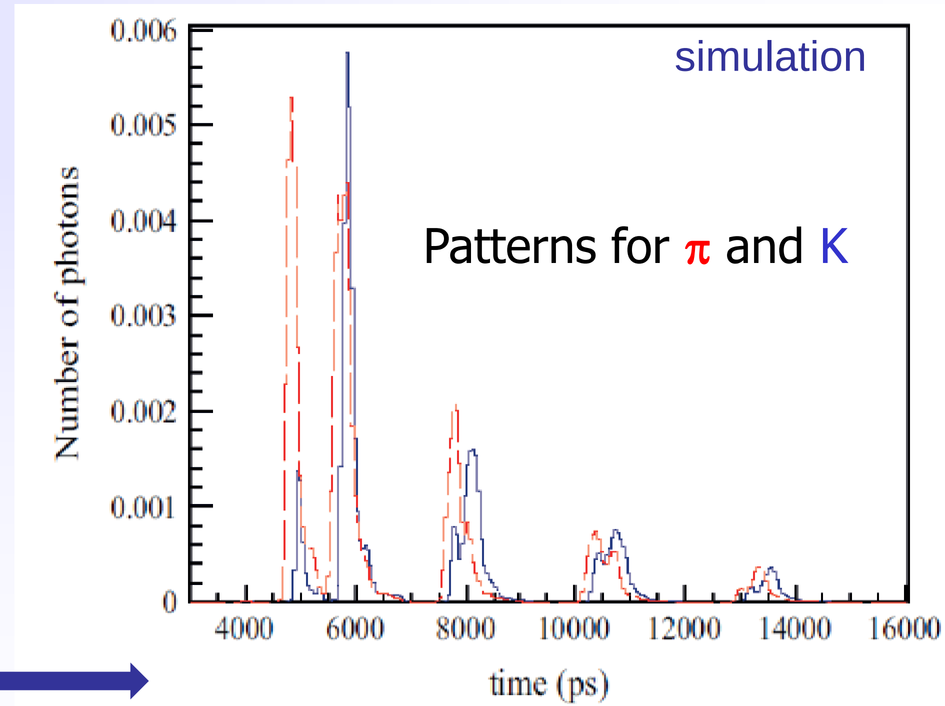


TOP 'image' reconstruction

Pattern in the coordinate-time space ('ring') of a pion and kaon hitting a quartz bar

Time distribution of signals recorded by one of the PMT channels (slice in x): different for π and K (~shifted in time)

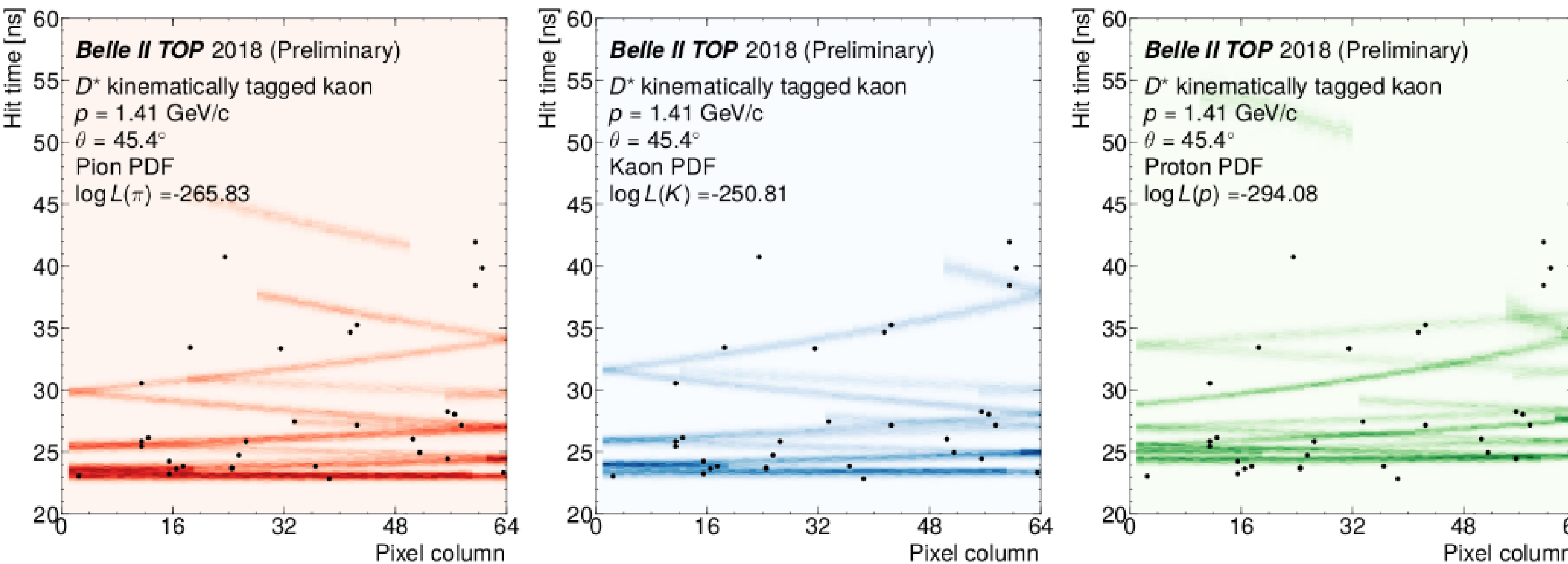




The name of the game: analytic expressions for the 2D likelihood functions
→M. Starič et al., NIMA A595 (2008) 252-255

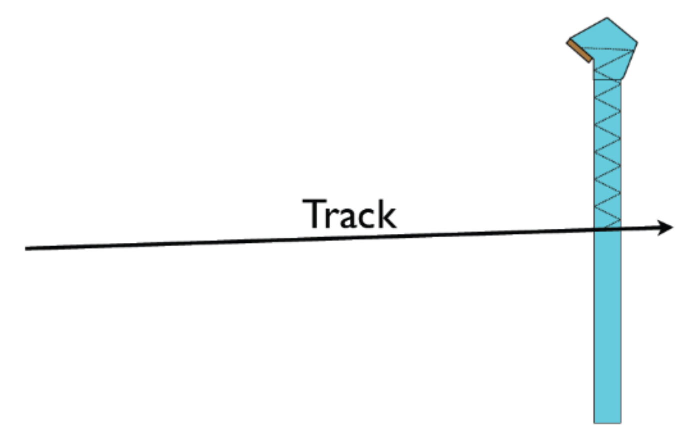
TOP first events

The early BELLE II data demonstrates that the TOP principle is working



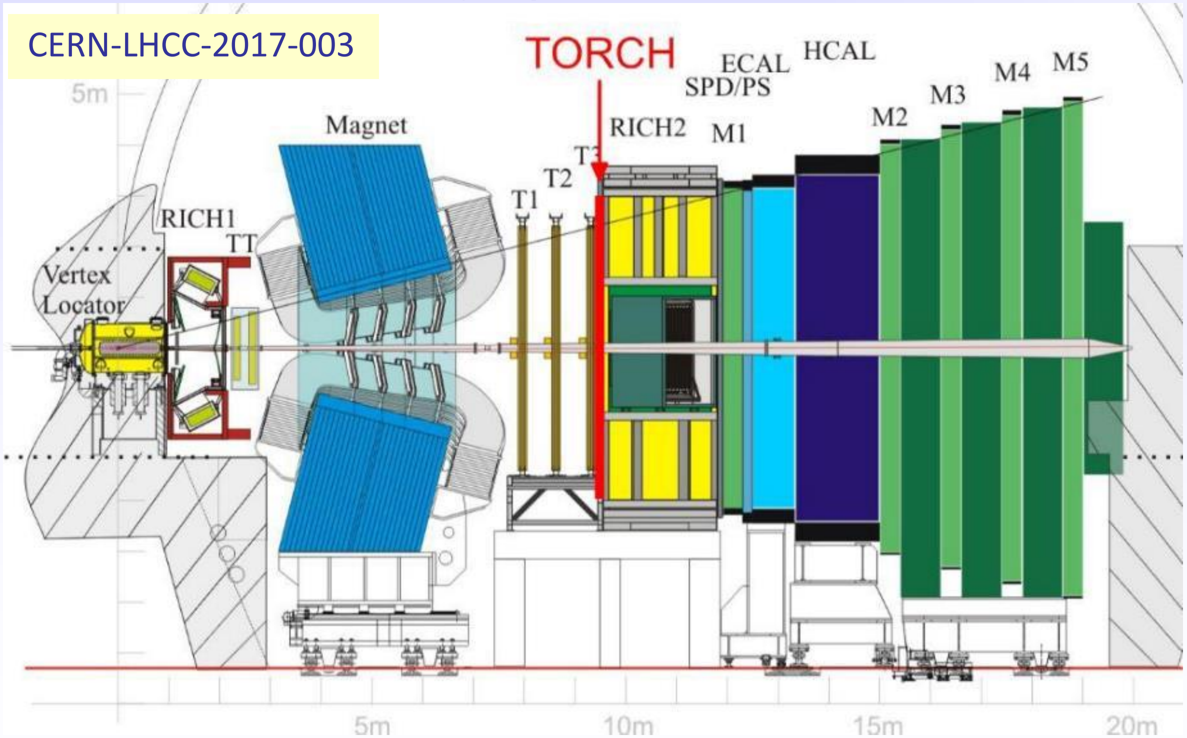
TORCH

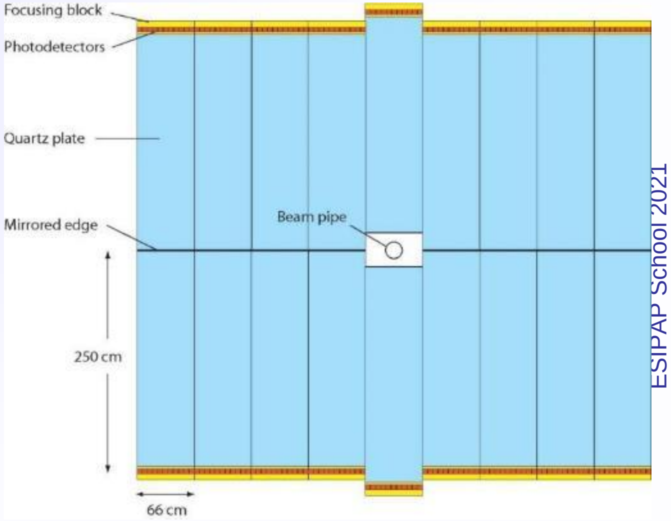
- A special type of Time-of-Propagation counter, part of a future LHCb upgrade.
- Aim for π,k,p separation, 2-10 GeV/c.
- At 10 GeV/c: Δt of π-k = 35 ps
- Can be achieved with 30 photons and 70 ps resolution for single photons.



– TORCH area 5 x 6 m^2
– 18 module system
– 11 MCPs per module

CERN-LHCC-2017-003





Just radiator in active volume

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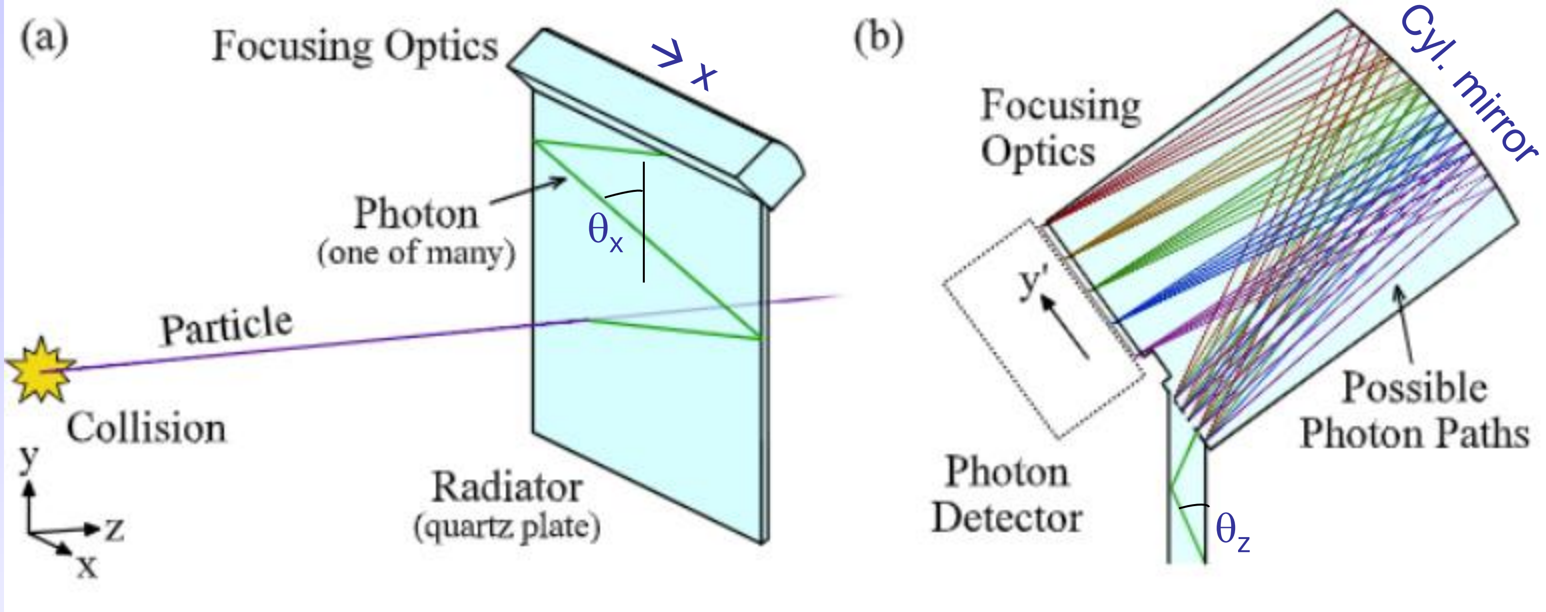
TORCH principle



Particle impact point known → θ_x can be derived from measurement of coordinate x on segmented MCP photodetector.

Cylindrical mirrored surface maps the photon angle θ_z to a y' position

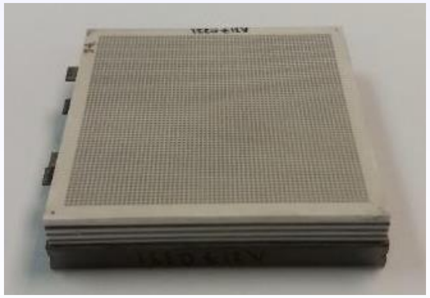
C-angle known

↓

Photon arrival time can be corrected for time of propagation

↓

Precise TOF information



Photek, custom development (64 x 64 pixels)

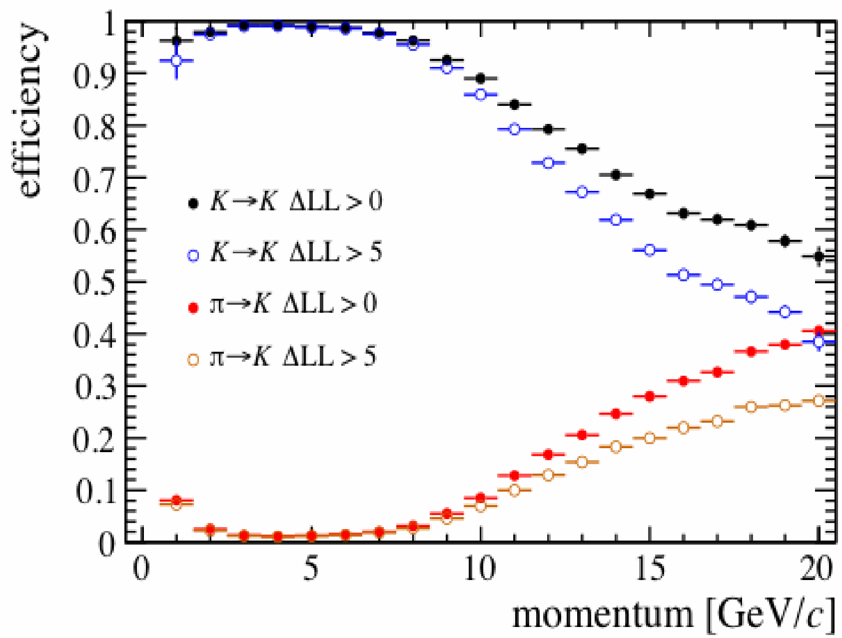
TORCH test beam results

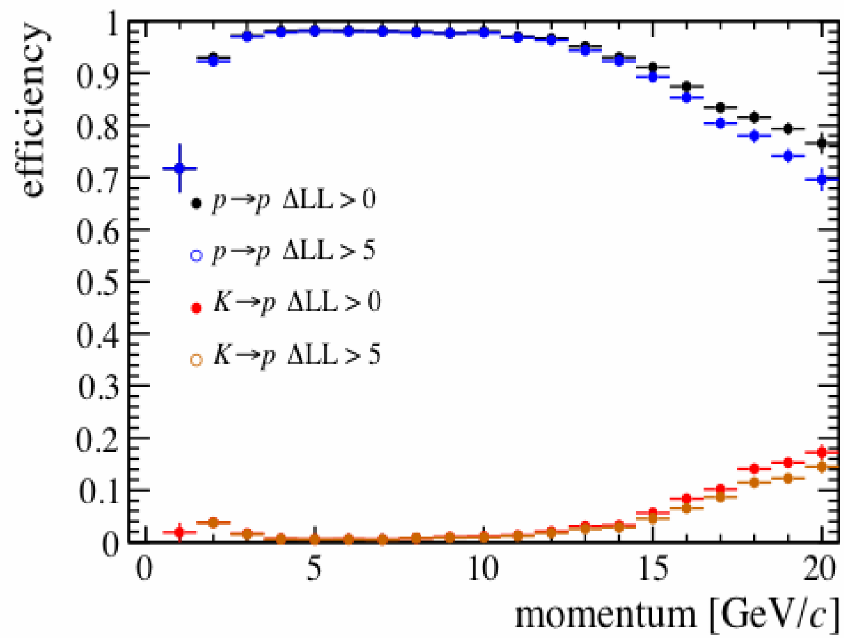
Test-beam campaigns (2017 & 2018):

- Single-photon time resolutions around 80 – 100 ps have been achieved
- Photon yields are measured to be within~10% and~30% of simulation, respectively

https://doi.org/10.1016/j.nima.2020.163671

Expected performance (simulation)





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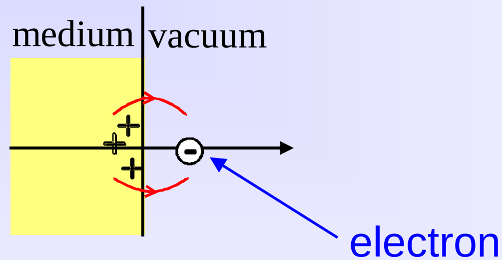
Particle ID by Transition radiation

(there is an excellent review article by B. Dolgoshein (NIM A 326 (1993) 434))

Transition Radiation was predicted by Ginzburg and Franck in 1946

TR is electromagnetic radiation, emitted when a charged particle traverses a medium with a discontinuous refractive index, e.g. the boundaries between vacuum and a dielectric layer.

A (too) simple picture



A correct relativistic treatment shows that…

(G. Garibian, Sov. Phys. JETP63 (1958) 1079)

- Radiated energy per medium/vacuum boundary

$$W = \frac{1}{3}\alpha\hbar\omega_p\gamma$$

$$W \propto \gamma$$

→ only high energetic $e^{\pm}$ emit TR of detectable intensity.
→ particle ID

Lorentz boost

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

$$\omega_p = \sqrt{\frac{N_e e^2}{\varepsilon_0 m_e}} \quad \left(\text{plasma frequency}\right)$$

$$\hbar\omega_p \approx 20\text{eV} \ \ (\text{plastic radiators})$$

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Particle ID by Transition radiation

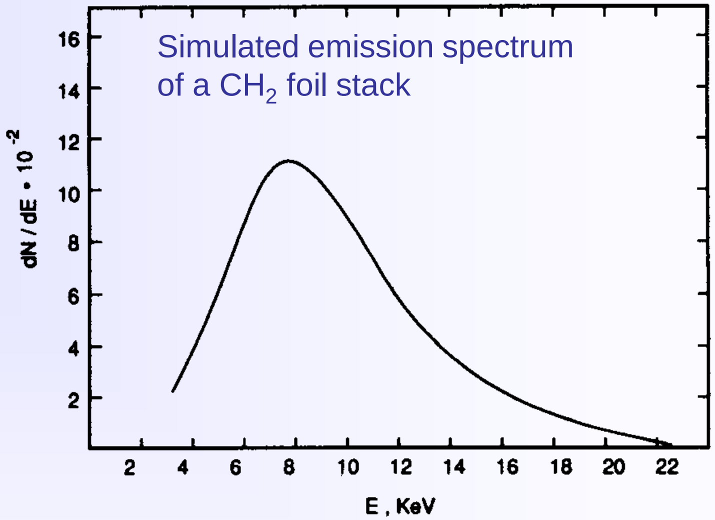
- Number of emitted photons / boundary is small $N_{ph} \approx \frac{W}{\hbar\omega} \propto \alpha \approx \frac{1}{137}$

→ Need many transitions → build a stack of many thin foils with gas gaps

- Emission spectrum of TR = f(material, γ)

Typical energy: $\hbar\omega \approx \frac{1}{4}\hbar\omega_p\gamma$

→ photons in the keV range



- X-rays are emitted with a sharp maximum at small angles $\theta \propto 1/\gamma$

→ TR stay close to track

- Particle must traverse a minimum distance, the so-called formation zone Z_f, in order to efficiently emit TR.

$$Z_f = \frac{2c}{\omega(\gamma^{-2} + \theta^2 + \xi^2)}, \quad \xi = \omega_p / \omega$$

Z_f depends on the material (ω_p), TR frequency (ω) and on γ.

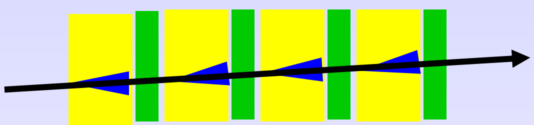
$Z_f(air)$ ~ mm, $Z_f(CH_2)$ ~ 20 μm → important consequences for design of TR radiator.

Particle ID by Transition radiation

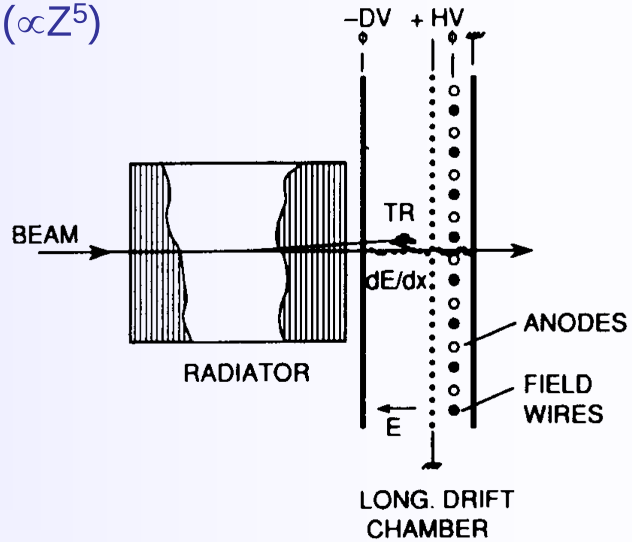
TR Radiators:

- stacks of thin foils made out of CH_2 (polyethylene), $C_5H_4O_2$ (Mylar)
- hydrocarbon foam and fiber materials

Low Z material preferred to keep re-absorption small ($\propto Z^5$)



alternating arrangement of radiators stacks and detectors
→ minimizes reabsorption

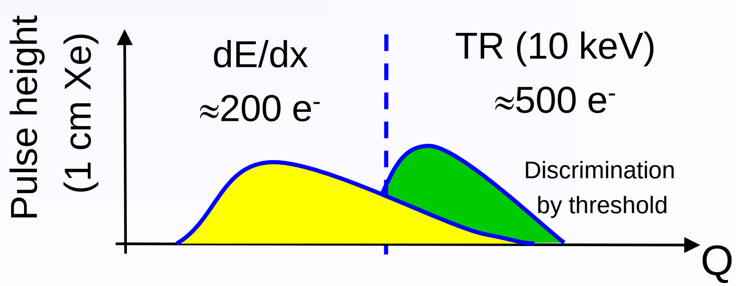


TR X-ray detectors:

- Detector should be sensitive for $3 \leq E_\gamma \leq 30$ keV.
- Mainly used: Gas detectors: MWPC, drift chamber, straw tubes…
- Detector gas: $\sigma_{\text{photo effect}} \propto Z^5$

  → gas with high Z required, e.g. Xenon (Z=54)
- Intrinsic problem: detector "sees" TR and dE/dx

Very Schematic!



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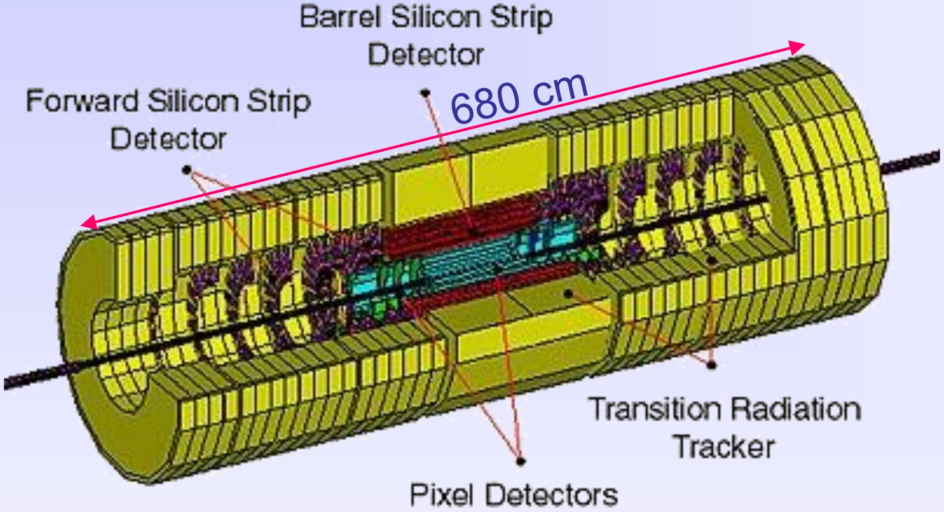
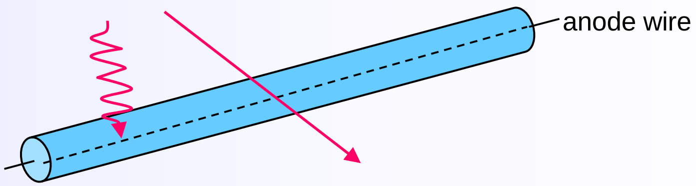
Particle ID by Transition radiation

The ATLAS Transition Radiation Tracker (TRT)



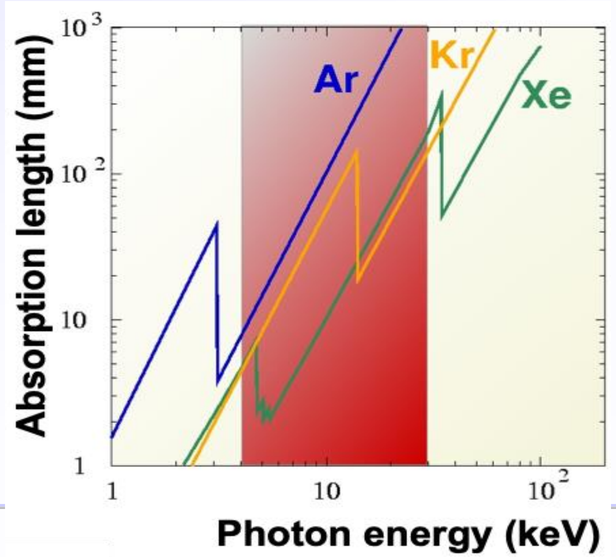
~300'000 straw tubes (d = 4mm)



Every straw is a mini drift tube. Measure drift time of electrons to anode wire

Active gas is $Xe/CO_2/O_2$ (70/27/3) operated at ~$2x10^4$ gas gain;

drift time ~ 40ns (fast!)



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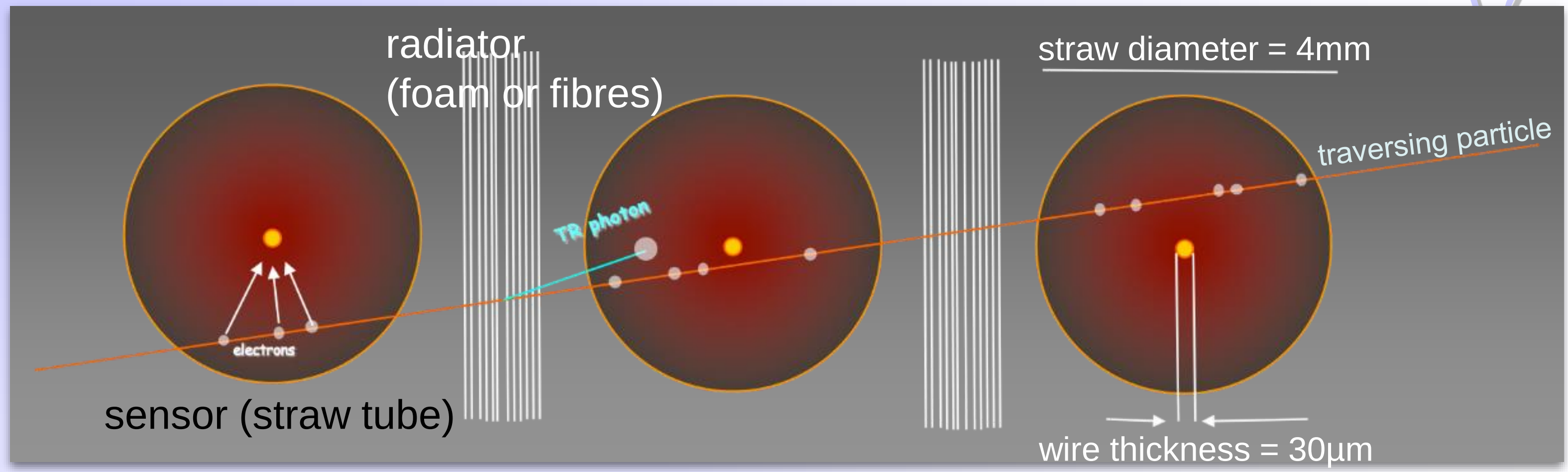
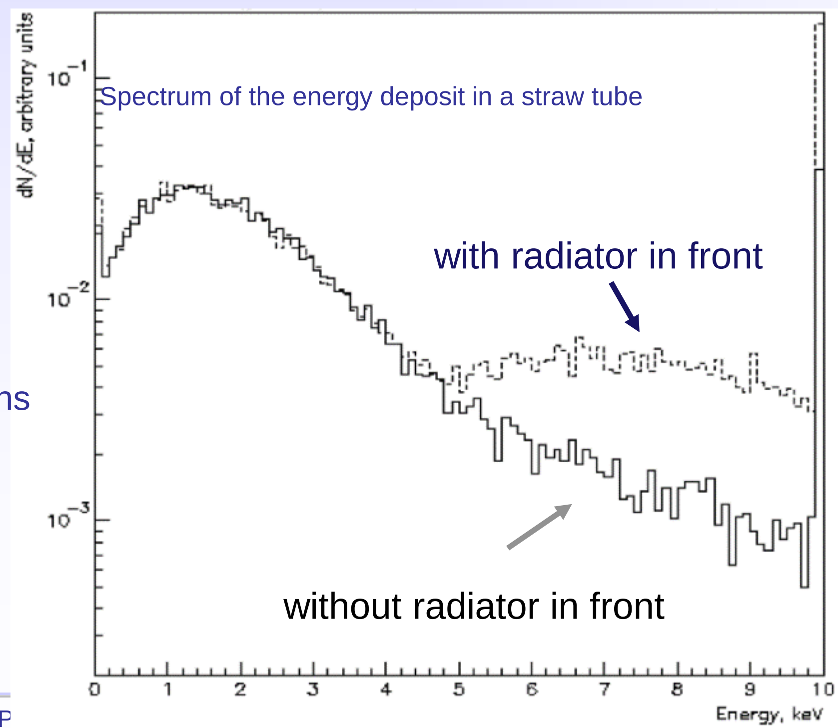
Basic principle



data test beam
20GeV electrons



Signal in straw is superposition of dE/dx and TR

Special challenges at the LHC

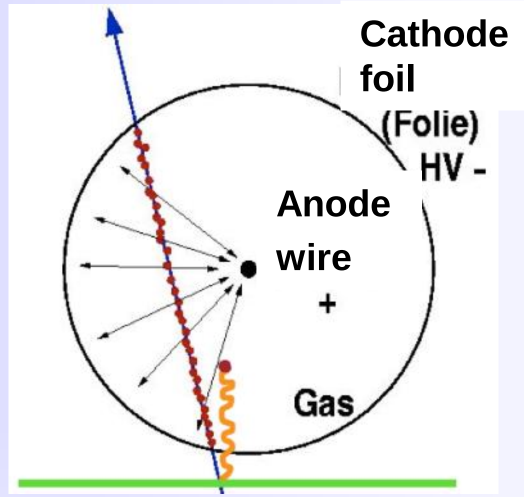
- Very high occupancy: up to 30% of straws receive a signal in a bunch crossing;
- Very high counting rate: up to 20 MHz/straw
- Short bunch crossing interval: 25 ns
- High spatial resolution needed ⇒ many measurement points (35/track);

radiator (foam or fibres)

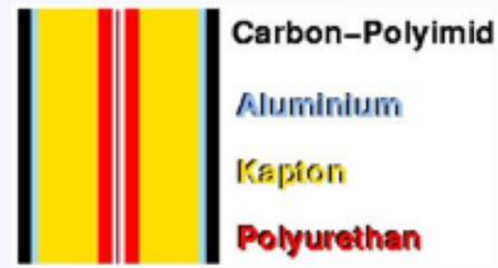
- Radiation environment: ~10 MRad and 10^{14} n/cm^2 year;
- Fast and chemically passive straw gas: otherwise ageing!
- Chemically resistant straw materials: operating straw acts like an electrochemical reactor
- Minimum amount of material (in radiation lengths)
- Extremely precise and robust mechanical structure of ~100μm/few m =~10^{-5};
- Temperature stable: cooling required.

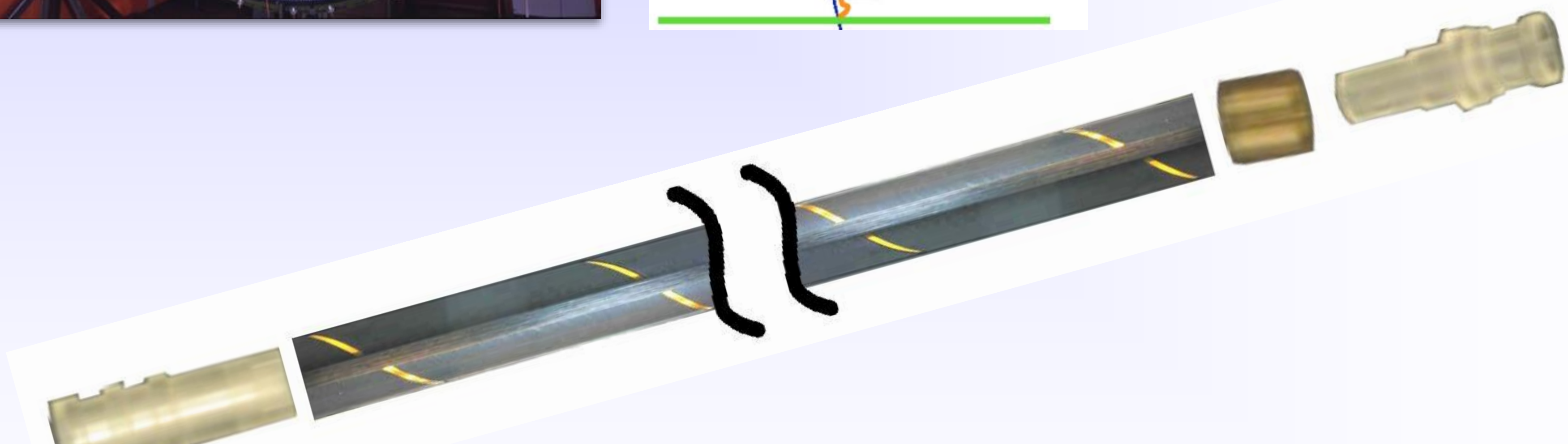
The sensor - a straw

straws in an end-cap wheel



layers of a straw wall

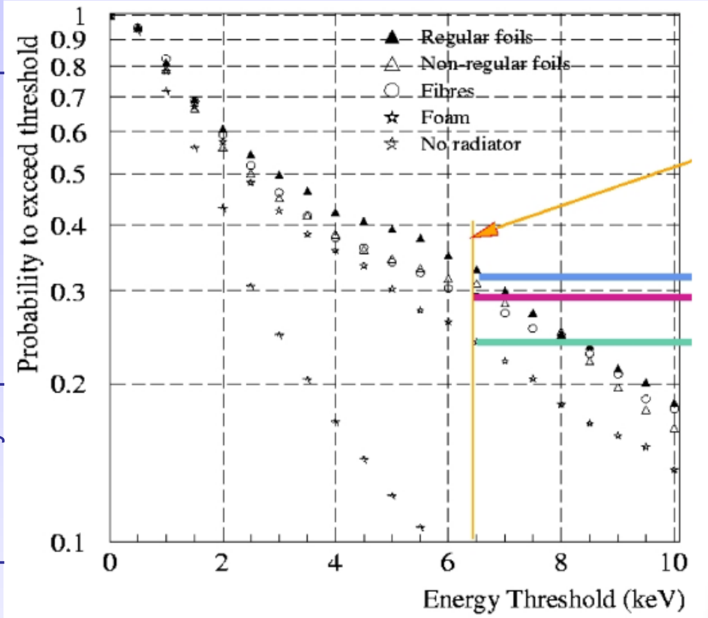




New for ATLAS: stiff straw, supported by **carbon fibre strips**, allows self supporting structures, thus reduced material inside the detector; Length: 144 cm in barrel, 39 cm in end-cap.

The radiator

~probability to produce detectable TR photon



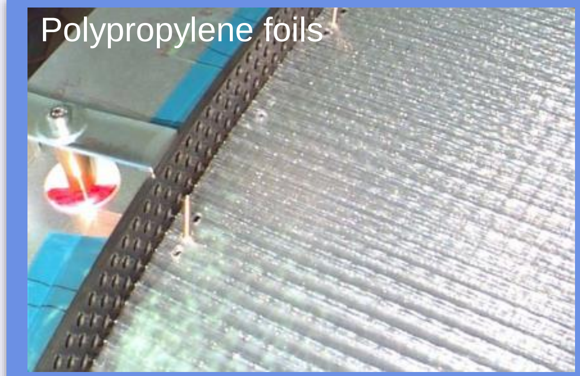
Optimal TR threshold (~6.5 keV)

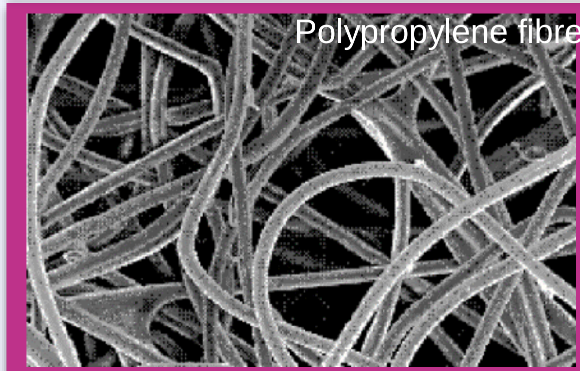
Regular foils (TRT end-caps)

Fibers (TRT barrel)

Foam (TRT barrel)

easy to build structures!

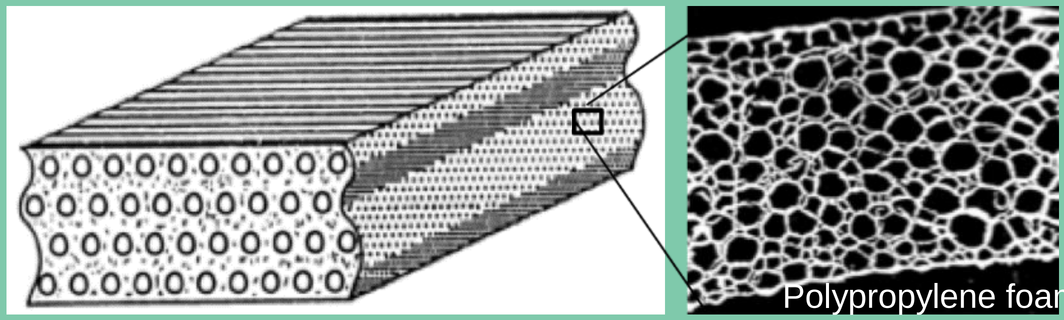




Choice of Radiator materials: ensure balance between TR-performance and simple construction.

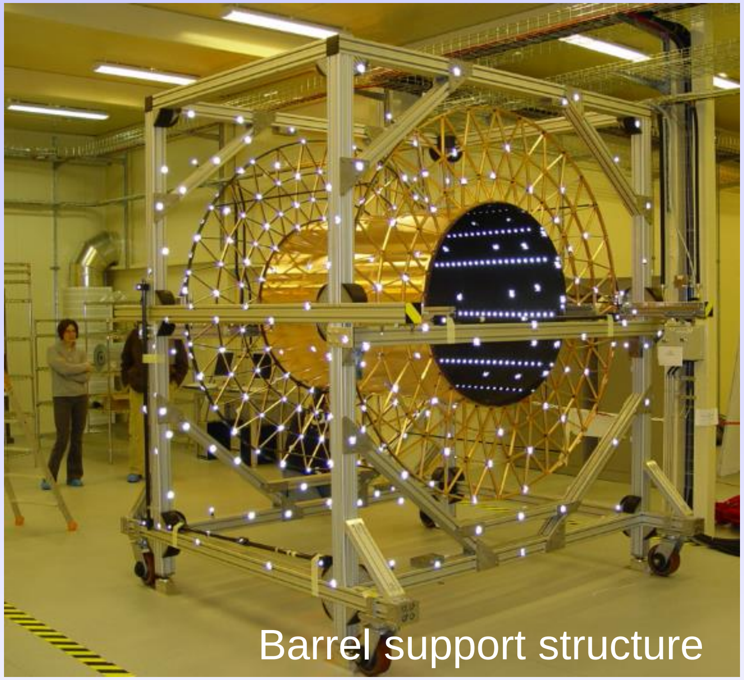
What was new about these foams?

No impurities from other material, always present in other type of foams



TRT barrel module production

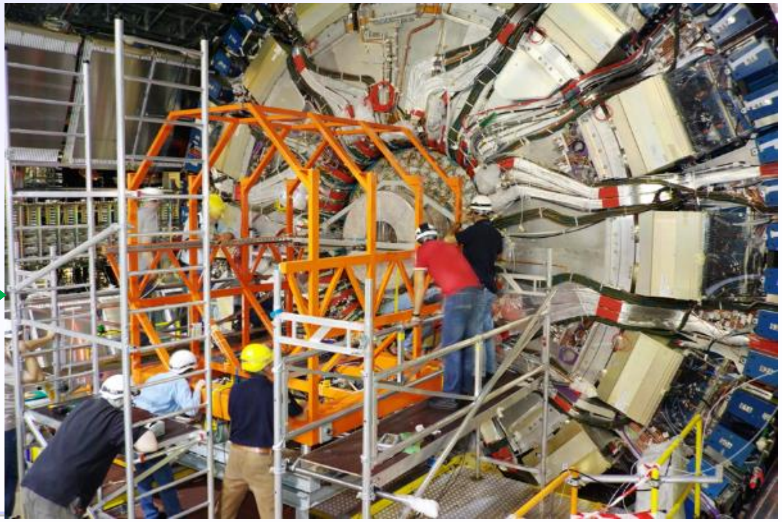
From modules to a complete barrel detector



inserting modules

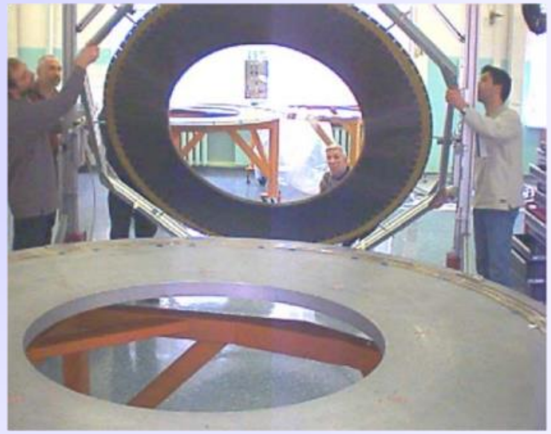
TRT Barrel detector (with semi conductor detector inserted)

insertion into ATLAS

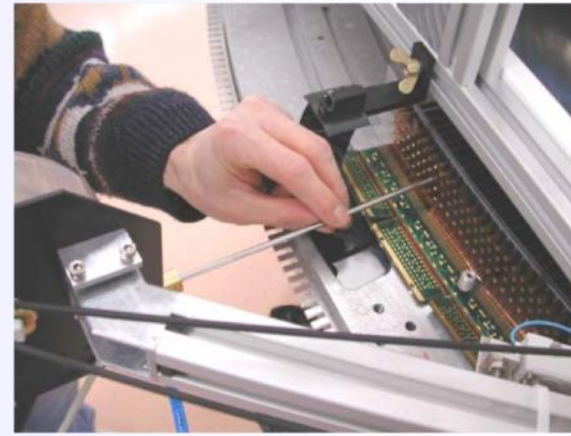


- assembly of a basic element, a wheel with 4 straw layers/planes

Installation of straws
(tests leak tightness)

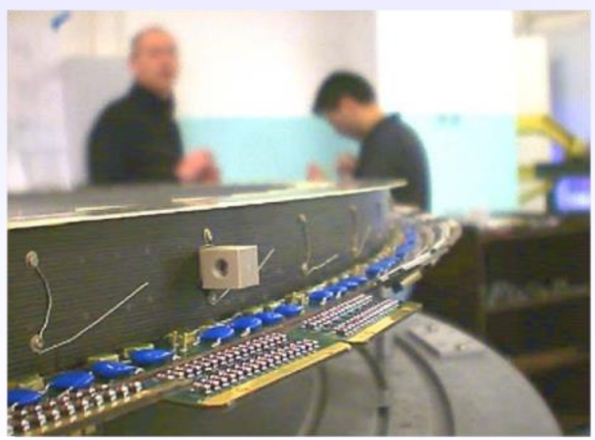


Transfer of wheel…

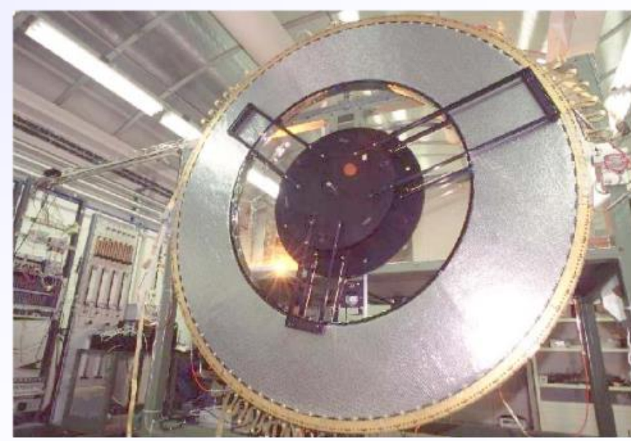


…to string wires

Fixating and connecting wires
(tests wire tension & HV)

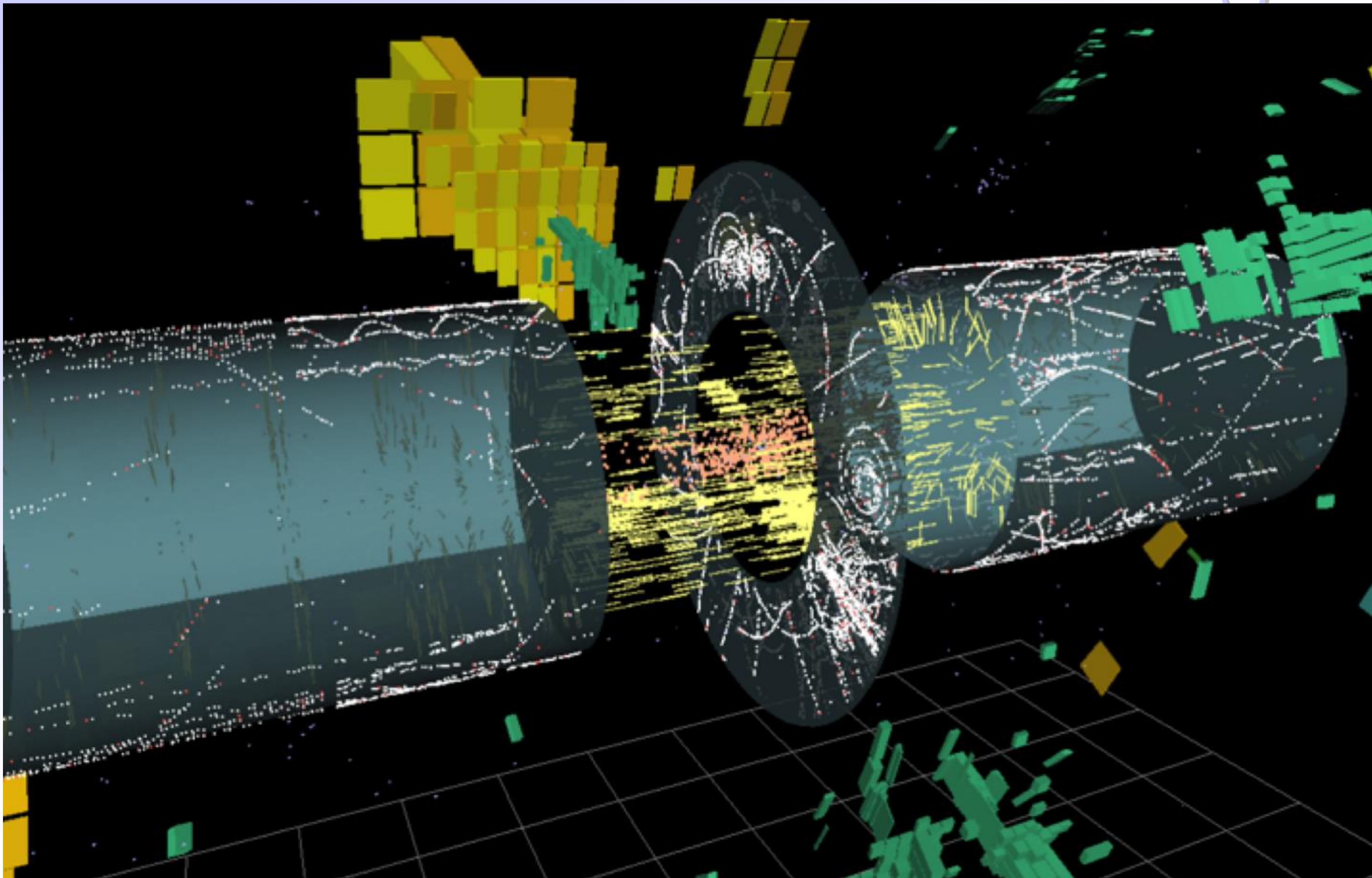


Sealing of wheel
(tests leak tightness & HV)



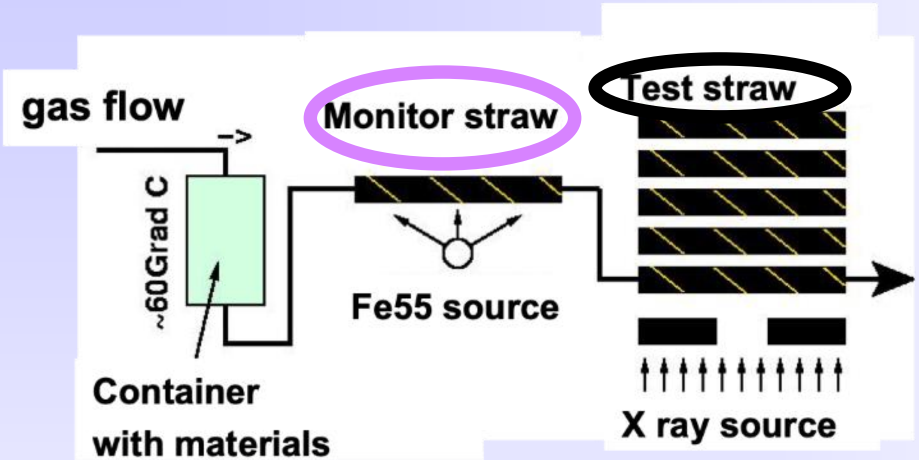
Final acceptance tests
(test wire centricity etc.)

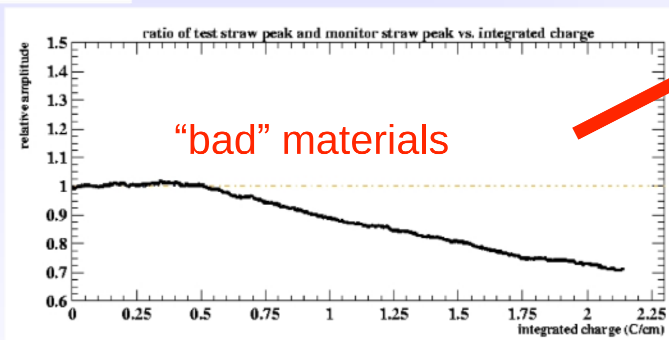
A TRT event display

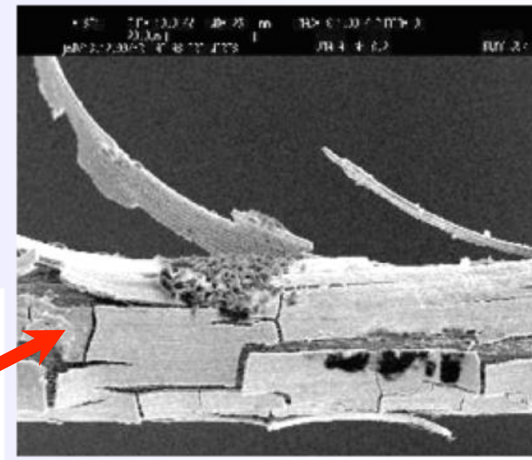


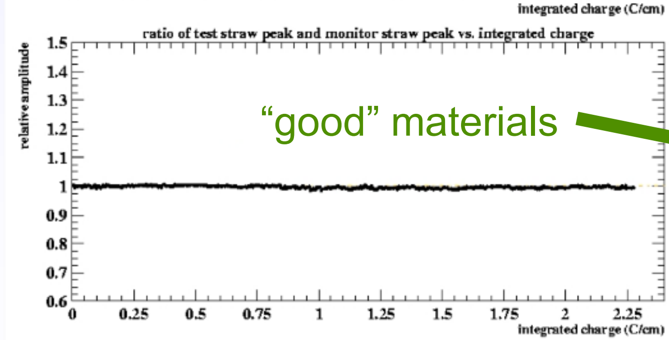
Example: tests for radiation hardness of TRT wires

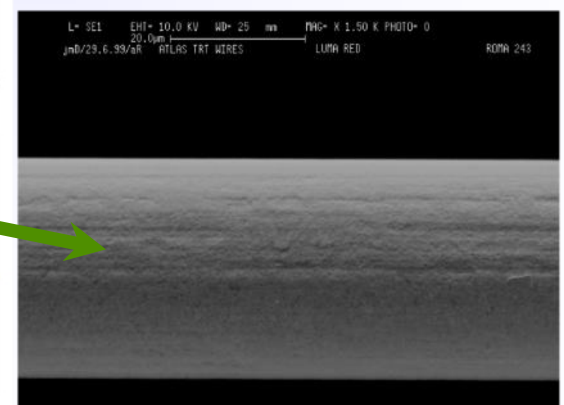
Mandatory in high radiation environments: test of all materials











Check ratio of height of signal amplitude for test straw (radiated) and monitor straw (not radiated)

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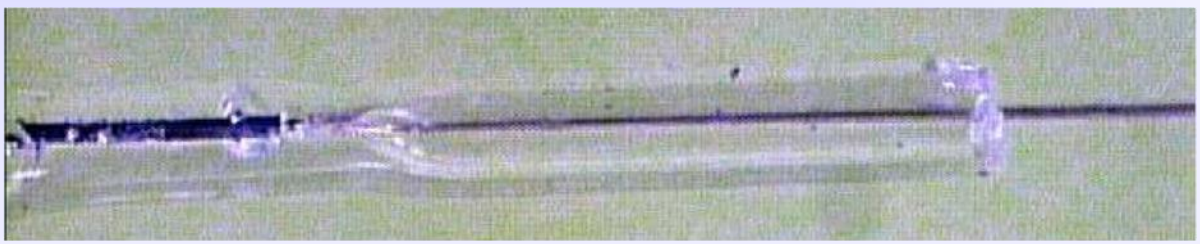
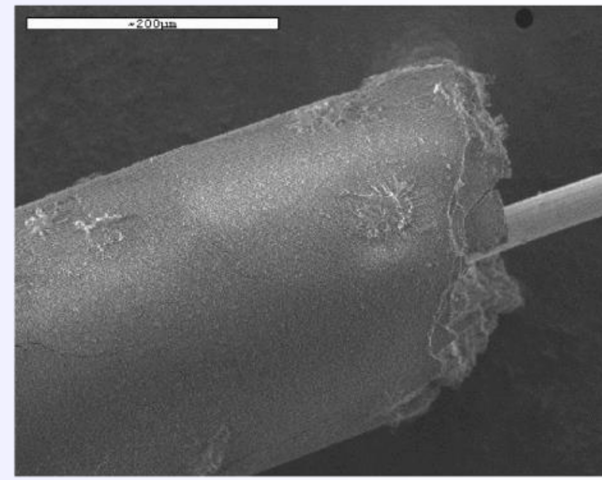
ATLAS TRT: bad surprise during assembly (2)

Original TRT gas mixture (70% Xe, 20% **CF_4**, 10% CO_2) was destroying the detector (2002)

- glass wire joints of barrel TRT "melting" with radiation 0.3-04 C/cm, less than 1 year nominal LHC operation
- Reason: hydrofluoric acid HF



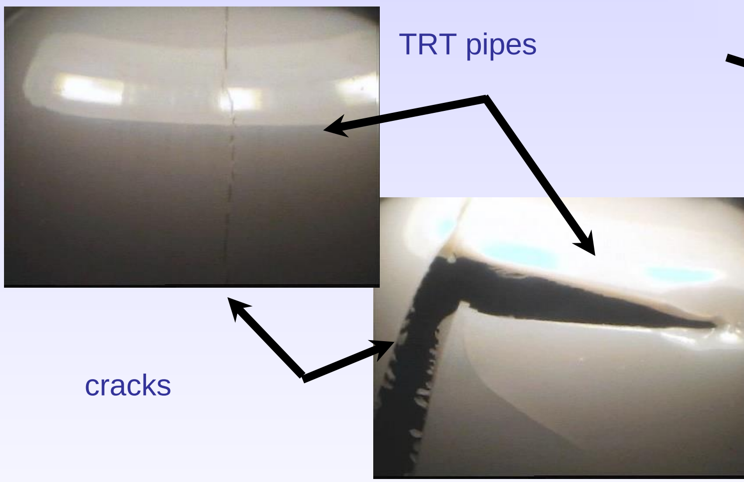


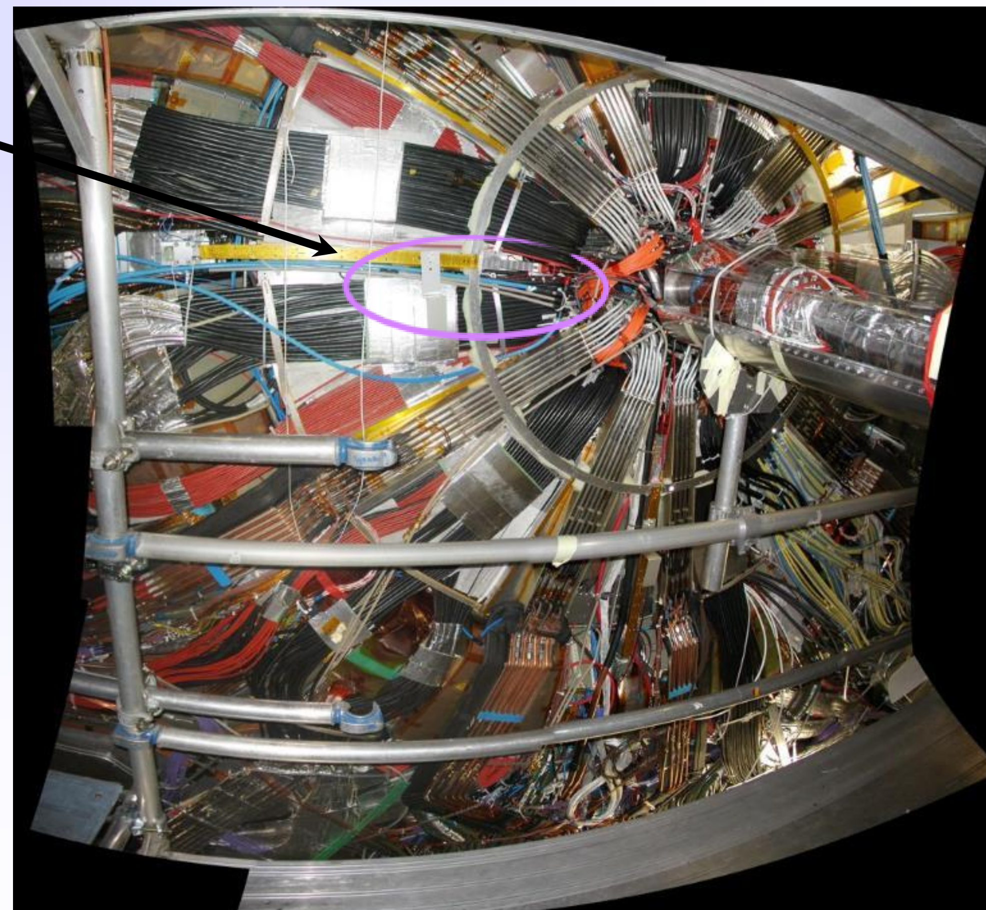
Within one year, a new mixture was developed: 70% Xe, 27% CO_2, 3% **O_2**

- O_2 very unusual, strong quencher ("eats" electrons)
- only works for TRT as straws have small diameter (we are very lucky! … for once)

ATLAS TRT: bad surprise during operation

- Cracks in outlet pipes of active gas developed in 2012
- gas losses: 150l/day instead of <0.5l/day up to 2011;
- reason: aggressive ozone produced when active gas mixture is radiated, ozone attacks plastic gas pipes (although plastic material has been validated - but material seem to have changed properties when being heated and bent....)
- no chance to fix leaks



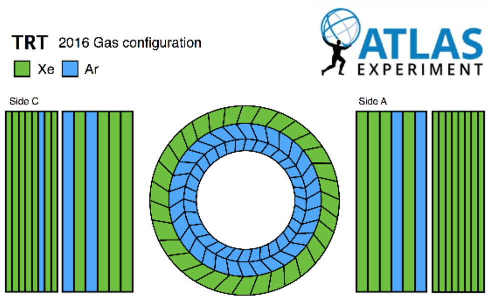


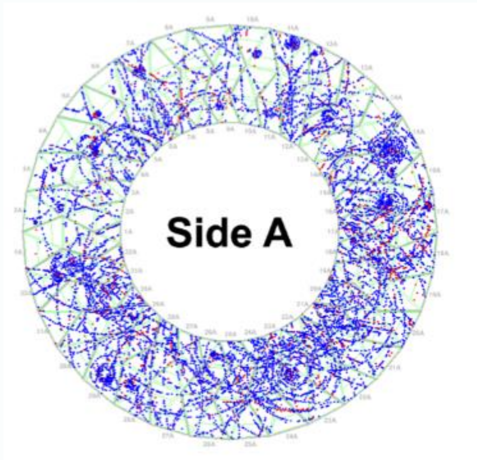
- Difficult to access!!!
- For effected region, switched to Argon based gas mixture in the straws.
- Reduce PID performance.

TRT Performance - Tracking

in 2016: already suffering from broken gas pipes

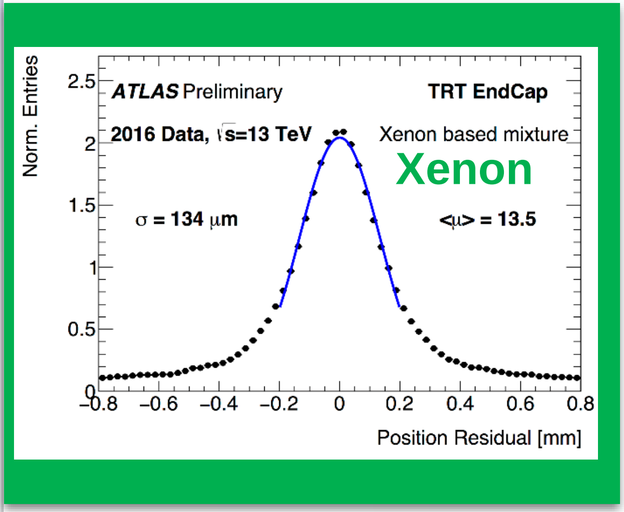
⇒ detector partially operated with Argon mixture

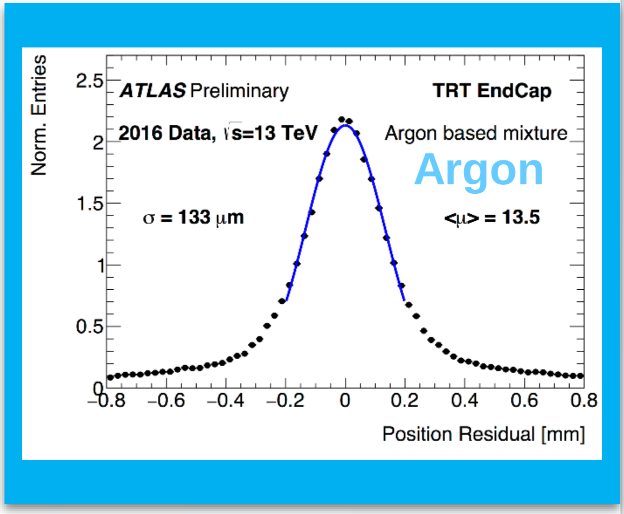


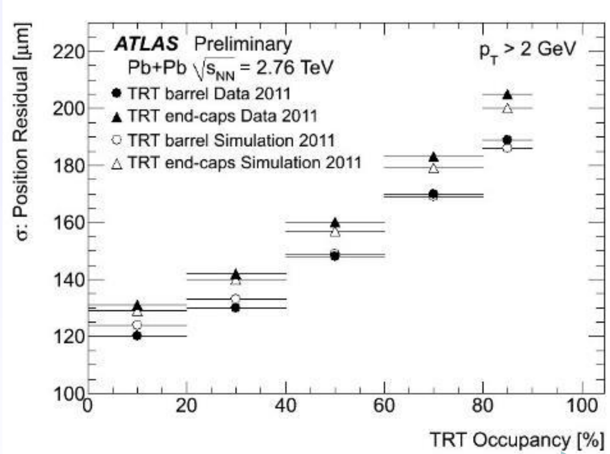


low occupancy (number of collisions per bunch crossing <μ> low)

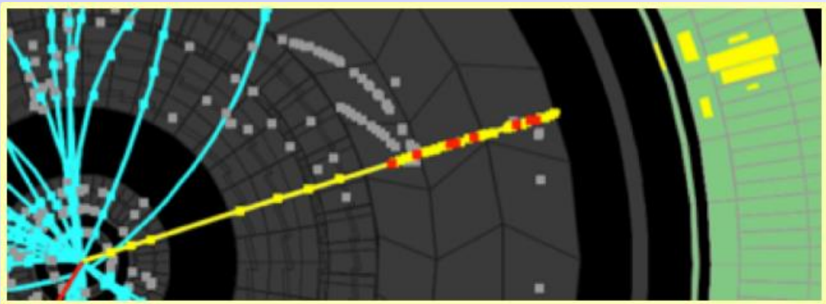
high occupancy (number of collisions per bunch crossing <μ> high, i.e. Heavy Ion Collisions)





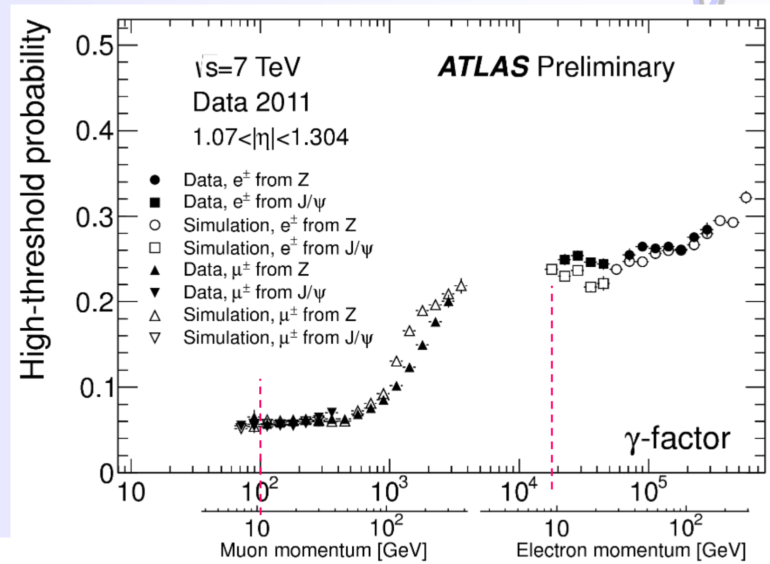


increasing occupancy



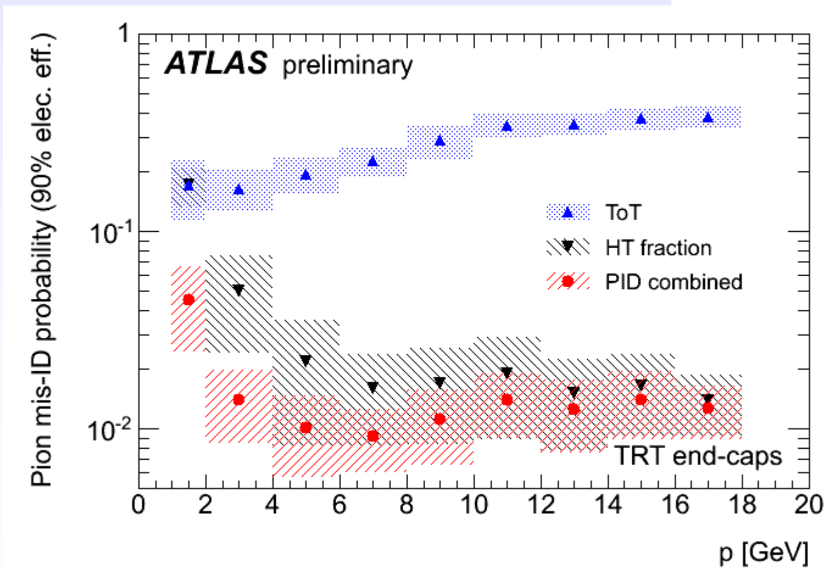
Event with an electron (yellow track):
hits with high signal (=TR, passing a high level HL threshold) are indicated in red

TR turn ON curve: HL probability VS gamma factor



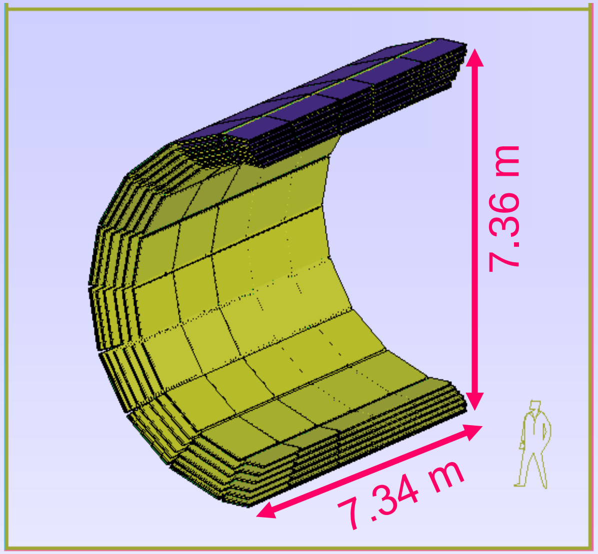
10 GeV μ vs 10 GeV e

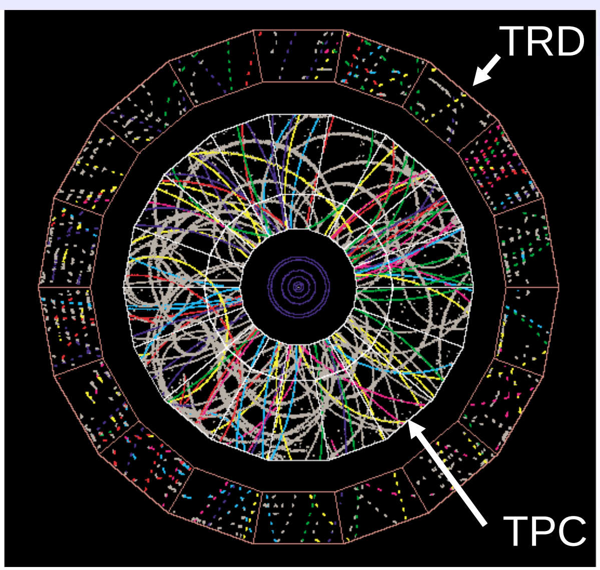
Typical Figure of Merit for a TR detector:



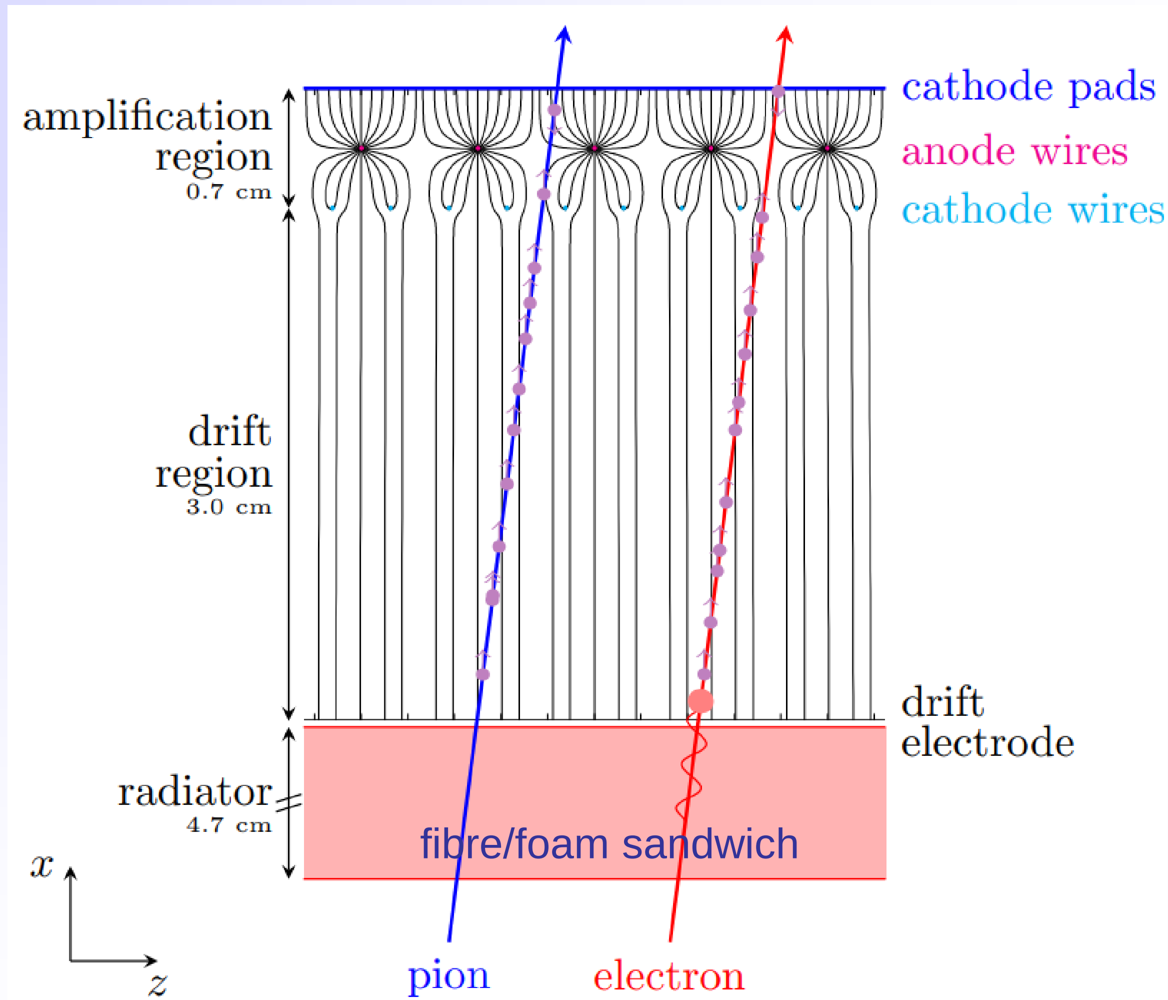
ALICE TRD

CERN-EP-2017-222





Time Expansion Chamber with Xe/CO_2 gas (85%-15%)



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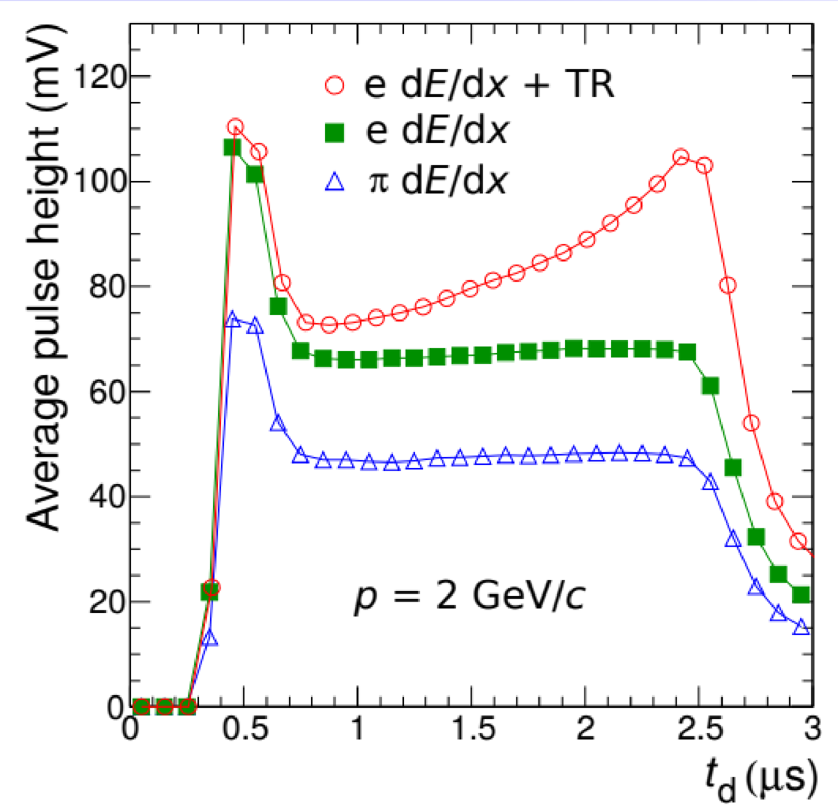
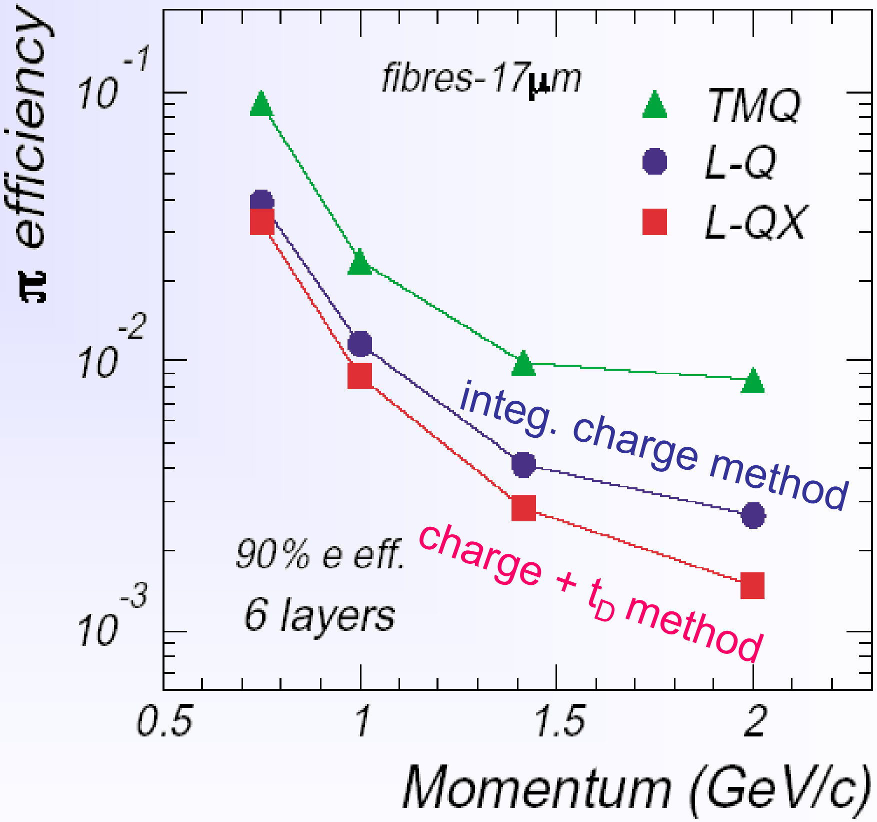
ALICE TRD performance

Pulse height vs drift time





TMQ = Truncated mean of charge

L-Q = Likelihood on charge

L-QX = 2D Likelihood on charge and x-coord.

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11 take home messages

- **Cherenkov radiation** is produced by a charged particle traversing a dielectric medium at a speed $v \geq c/n$ (threshold).
- Weak light source, visible and UV.
- Light intensity increases like $\sin^2\theta = 1 - (n^2\beta^2)^{-1}$ → saturated angle at $\beta \approx 1$
- Detection of C-light requires low-noise single photon sensitive photodetectors.
- Main applications are PID (π/k) by threshold, Ring Imaging or Time Of Propagation counters (incl. TORCH).

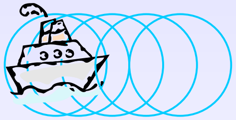
- **Transition radiation** is produced by a charged particle at the edge of a dielectric medium.
- Intensity scales with Lorentz boost γ. In HEP experiments, only $e^{\pm}$ reach high enough γ values (> 1000)
- Extremely weak light source, X-ray, O(10keV)
- Need many transitions → foil stacks, foams
- Detection by gas detector (drift chamber / tubes) operated with high-Z gas (Xe)
- Main application is tracking with $e^{\pm}$ enhancement.

BACK-UP MATERIAL

Propagating waves

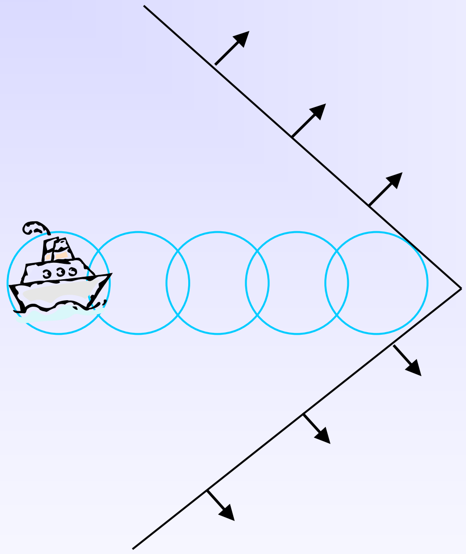
- A stationary boat bobbing up and down on a lake, producing waves

- Now the boat starts to move, but slower than the waves



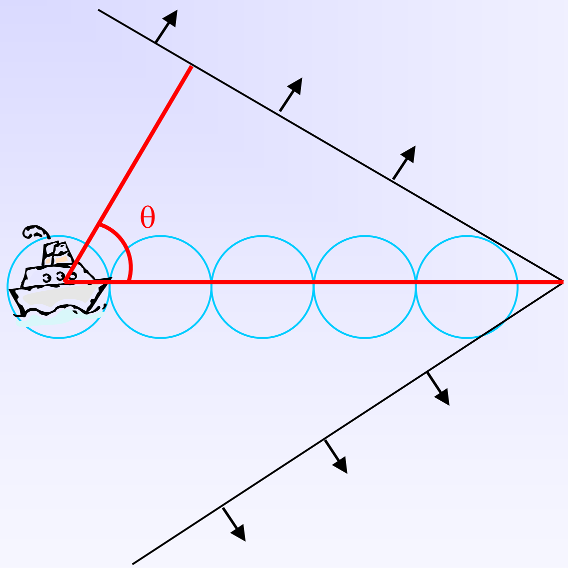
No coherent wavefront is formed

- Next the boat moves faster than the waves



A coherent wavefront is formed

- Finally the boat moves even faster



The angle of the coherent wavefront changes with the speed

$$\cos\theta = v_{wave} / v_{boat}$$

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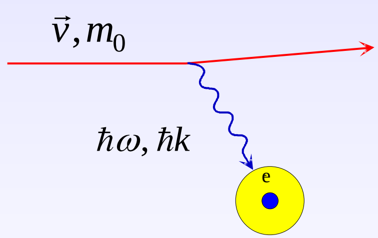
Reminder: Interaction of charged particles

Detection of charged particles

Particles can only be detected if they deposit energy in matter.
How do they lose energy in matter ?

Discrete collisions with the atomic electrons of the absorber material.



$$\left\langle \frac{dE}{dx} \right\rangle = -\int_0^\infty NE \frac{d\sigma}{dE} \hbar \, d\omega$$

N : electron density

$E = \hbar\omega$

$$\left(\omega = 2\pi f = 2\pi \cdot \frac{c}{\lambda} \right)$$

W.W.M. Allison, J.H. Cobb,
Ann. Rev. Nucl. Part. Sci. 1980. 30: 253-98

If $\hbar\omega, \hbar k$ are in the right range ⇨ ionization.

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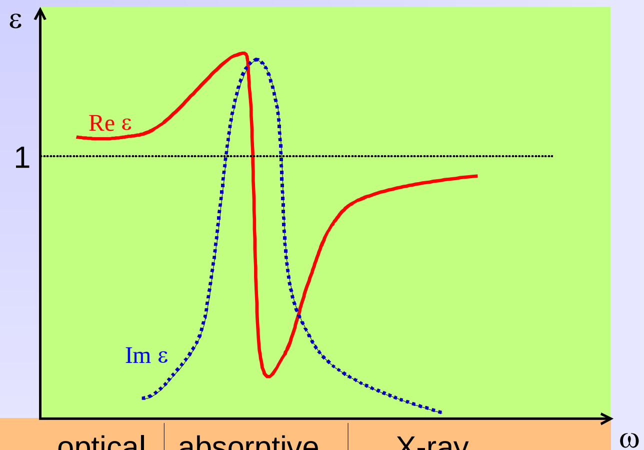
Interaction of charged particles



regime:	optical	absorptive	X-ray
effect:	Cherenkov radiation	ionisation	transition radiation
$E=\hbar\omega$	eV	O(10) eV	keV

Optical behaviour of medium is characterized by the complex dielectric constant ε

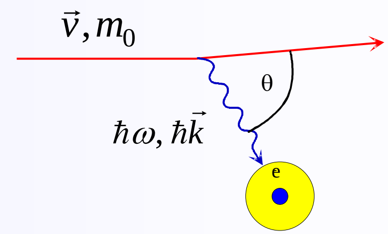
$\mathrm{Re}\sqrt{\varepsilon} = n$ Refractive index

$\mathrm{Im}\,\varepsilon = k$ Absorption parameter

Instead of ionizing an atom or exciting the matter, under certain conditions the photon can also escape from the medium.

⇨ Emission of **Cherenkov** and **Transition** radiation.
This emission of real photons contributes also to the energy loss.

A photon in a medium has to follow the dispersion relation



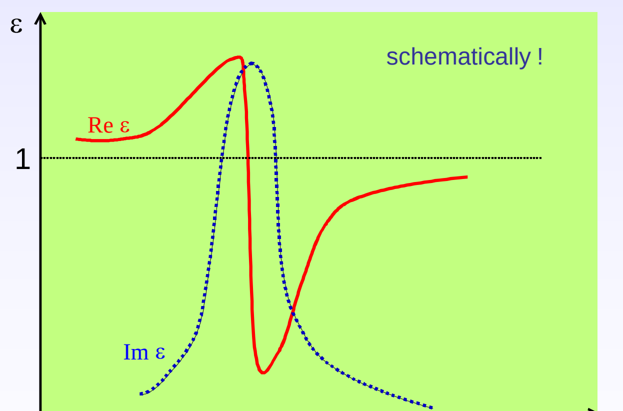
$$\omega = 2\pi f = 2\pi \frac{c/n}{\lambda} = k\frac{c}{n} \qquad \omega^2 - \frac{k^2c^2}{\varepsilon} = 0 \qquad \varepsilon = n^2$$

Assuming soft collisions + energy and momentum conservation
→ emission of real photons:

$$E = E' + \hbar\omega \quad \vec{p} = \vec{p}' + \hbar\vec{k}$$ … solve for ω

$$\omega \cong \vec{v}\cdot\vec{k} = v\cdot k\cos\theta$$

$$\rightarrow \quad \cos\theta = \frac{\omega}{vk} = \frac{kc}{n}\cdot\frac{1}{vk} = \frac{1}{n\beta}$$



regime:	optical	absorptive	X-ray
effect:	Cherenkov radiation	ionisation	transition radiation

Emission of photons if

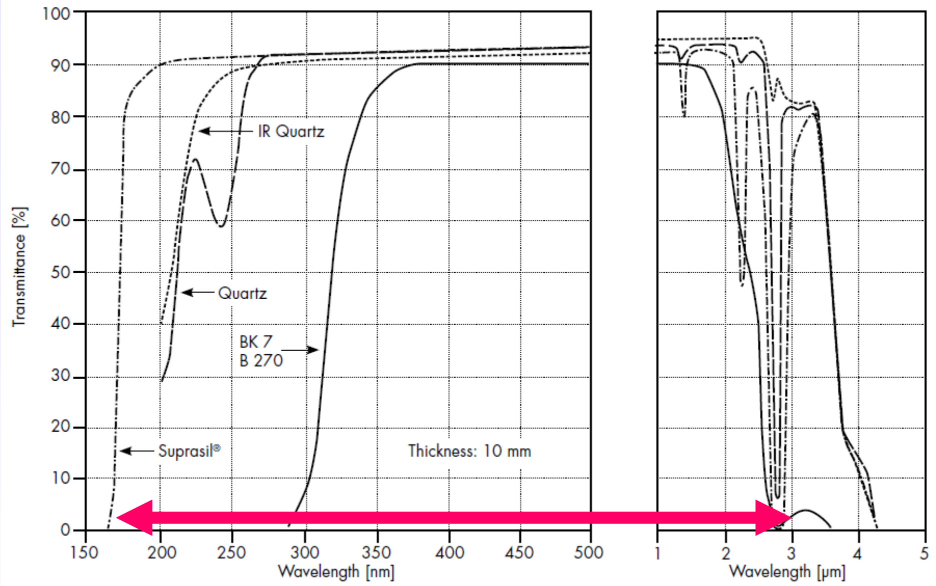
$$\beta = \frac{1}{n\cdot\cos\theta} \qquad \beta \geq 1/n \qquad v \geq c/n$$

A particle emits real photons in a dielectric medium if its speed $v = \beta\cdot c$ is greater than the speed of light in the medium c/n. ➔ **Cherenkov radiation.**

Estimate the energy loss by Cherenkov radiation in quartz

Private exercise

$$\frac{dN_\gamma}{dx} = \frac{\alpha}{\hbar c}\sin^2\theta \cdot \Delta E = \frac{370}{eV \cdot cm}\sin^2\theta \cdot \Delta E$$



$n_{quartz} \approx 1.46$

$\rightarrow \sin^2\theta = 1 - \cos^2\theta = 1 - 1/n^2 = 0.53$

$\lambda_{min} = 160$ nm $\rightarrow E_{max} \approx 1234 / \lambda \approx 7.7$ eV

$\lambda_{max} \approx 3$ µm $= 3000$ nm $\rightarrow E_{min} \approx 0$

$\Delta E = 7.7$ eV

$$\frac{dN_\gamma}{dx} = 370 \cdot 0.53 \cdot 7.7 = 1509 \text{ photons/cm}$$

$$\left.\frac{dE}{dx}\right|^{\text{Cherenkov}} = 1509 \cdot \langle E_\gamma \rangle = 5.8 \text{ keV/cm} \quad \longleftrightarrow \quad \left.\frac{dE}{dx}\right|^{\text{Ionization}} \approx \rho_{\text{quartz}} \cdot 2 \text{ MeV/g} \cdot \text{cm}^2 \approx 5 \text{ MeV/cm}$$

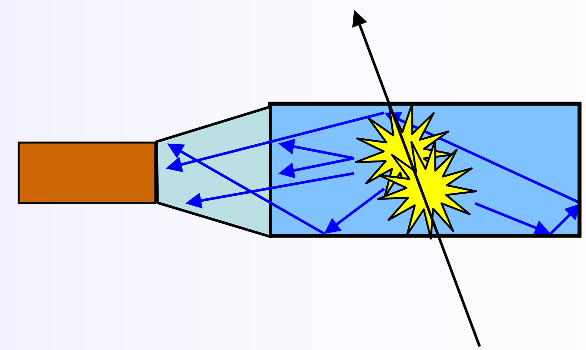
$\langle E_\gamma \rangle = \Delta E/2 = 3.85$ eV

Cherenkov effect is a weak but very useful light source.

The classical domains of application

- **Calorimetry**

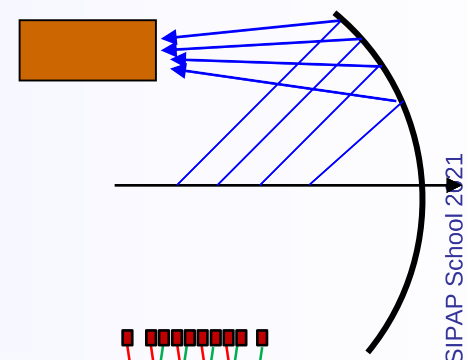
  Readout of organic and inorganic scintillators, lead glass, scint. or quartz fibres
  → Blue/VIS, usually 10s – 10000s of photons



- **Particle Identification**

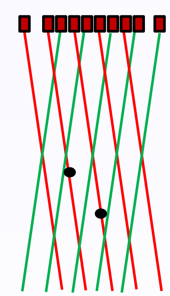
  Detection of Cherenkov light →UV/blue, single photons

  Time Of Flight → Usually readout of organic scintillators (not competitive at high momenta) or Cherenkov radiators



- **Tracking**

  Readout of scintillating fibres → blue/VIS, few photons



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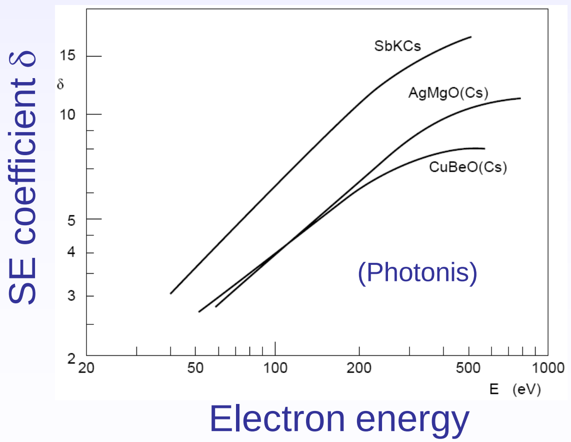
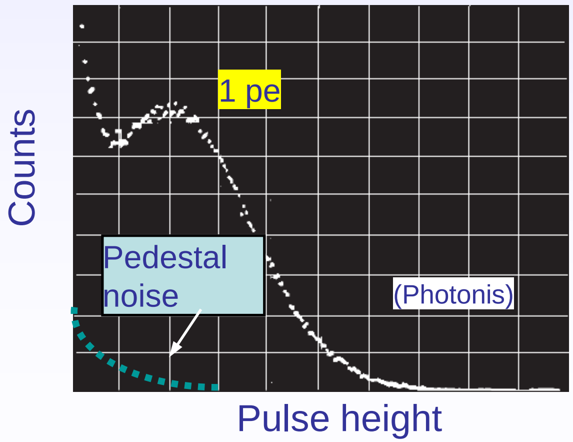
Gain fluctuations of PMT's

- Mainly determined by the fluctuations of the number of secondary electrons m_i emitted from the dynodes;
- Poisson distribution: $$P(n,m_i) = \frac{m_i^n e^{-m_i}}{n!}$$
- Standard deviation: $$\frac{\sigma_n}{m_i} = \frac{\sqrt{m_i}}{m_i} = \frac{1}{\sqrt{m_i}}$$

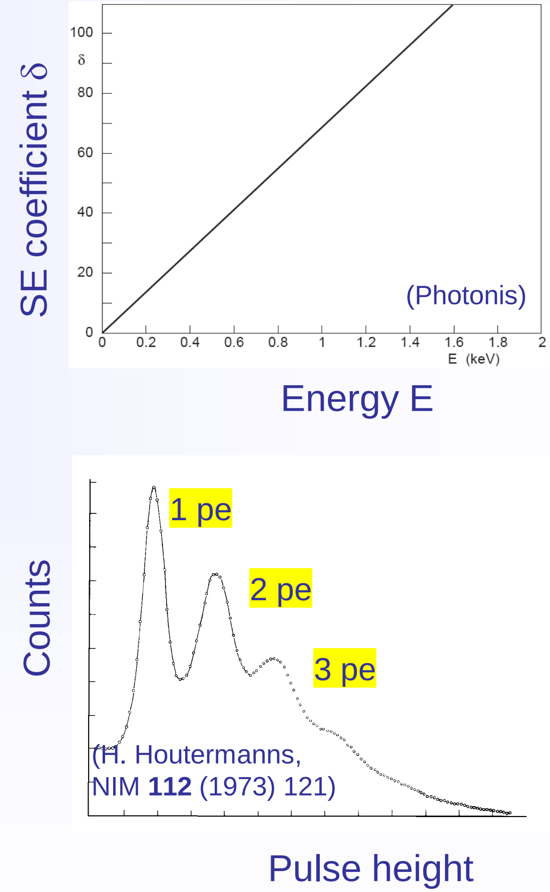
$\Rightarrow$ fluctuations dominated by 1st dynode gain $m_1 = \delta_1$

CuBe dynodes E_A>0





GaP(Cs) dynodes E_A<0



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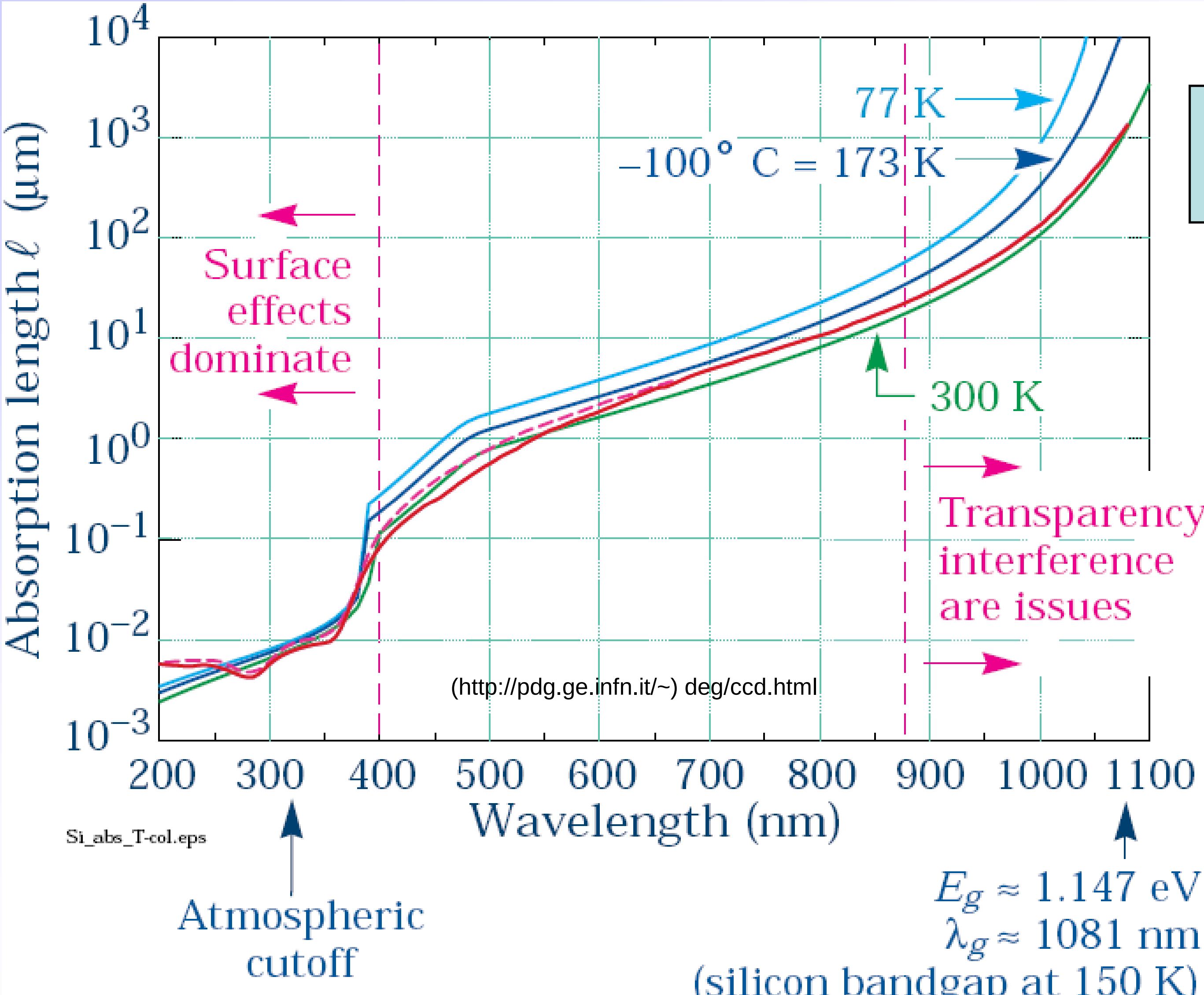
Light absorption in Silicon



At large λ, temperature effects become important

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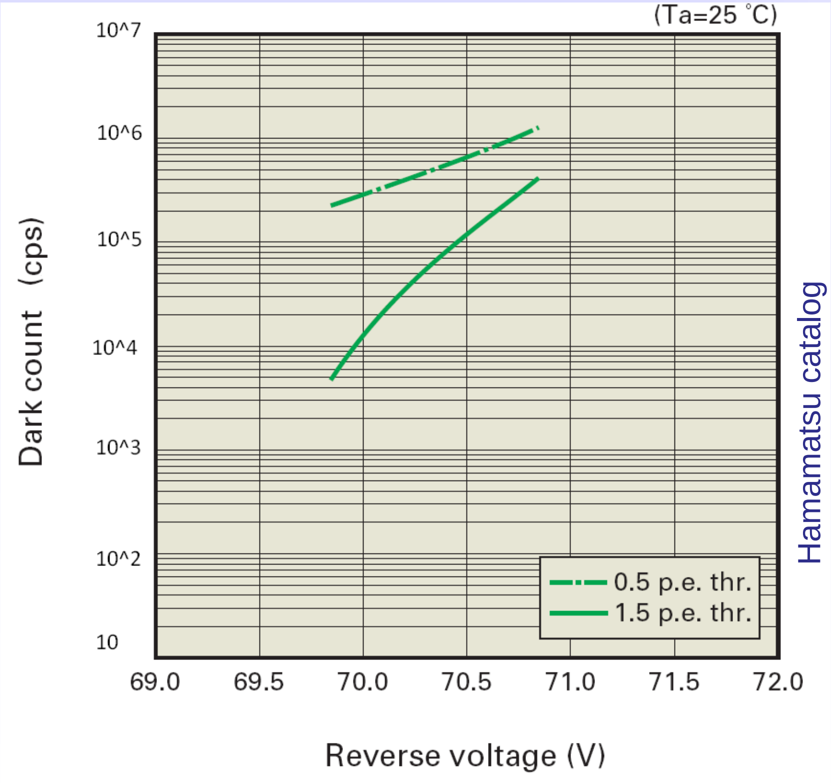
Multi pixel G-APD = G-APD, MPPC, SiPM, ...

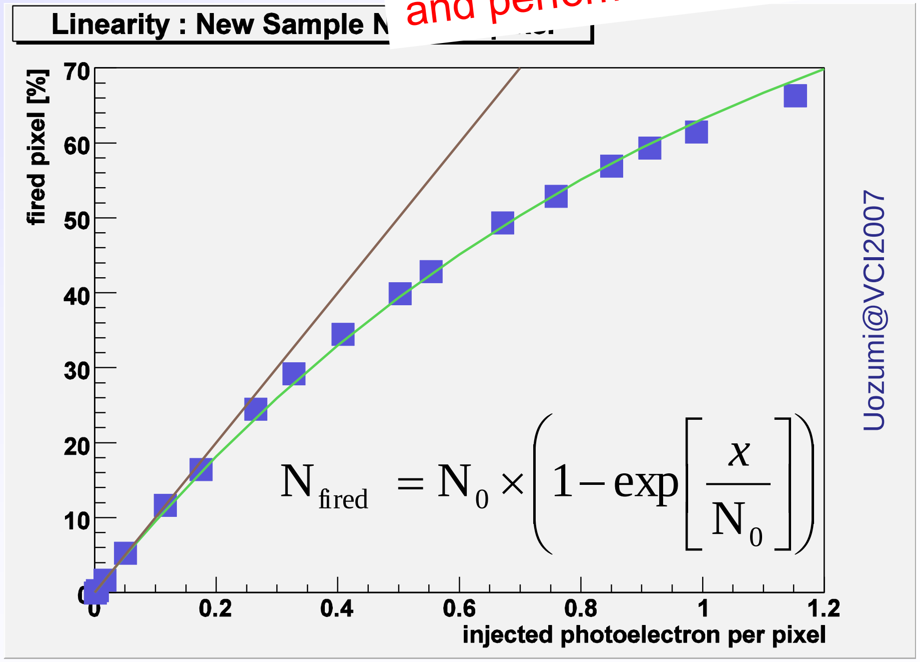
You cannot get "something for nothing"

- G-APD show dark noise rate in the O(100 kHz – MHz / mm^2) range.
- The gain is temperature dependent O(<5% /°K)
- The signal linearity is limited
- The price is (still too) high

~10 producers are now in the market. Continuous improvement in technology and performance.



Hamamatsu catalog



$$N_{fired} = N_0 \times \left(1 - \exp\left[\frac{x}{N_0}\right]\right)$$

Uozumi@VCI2007

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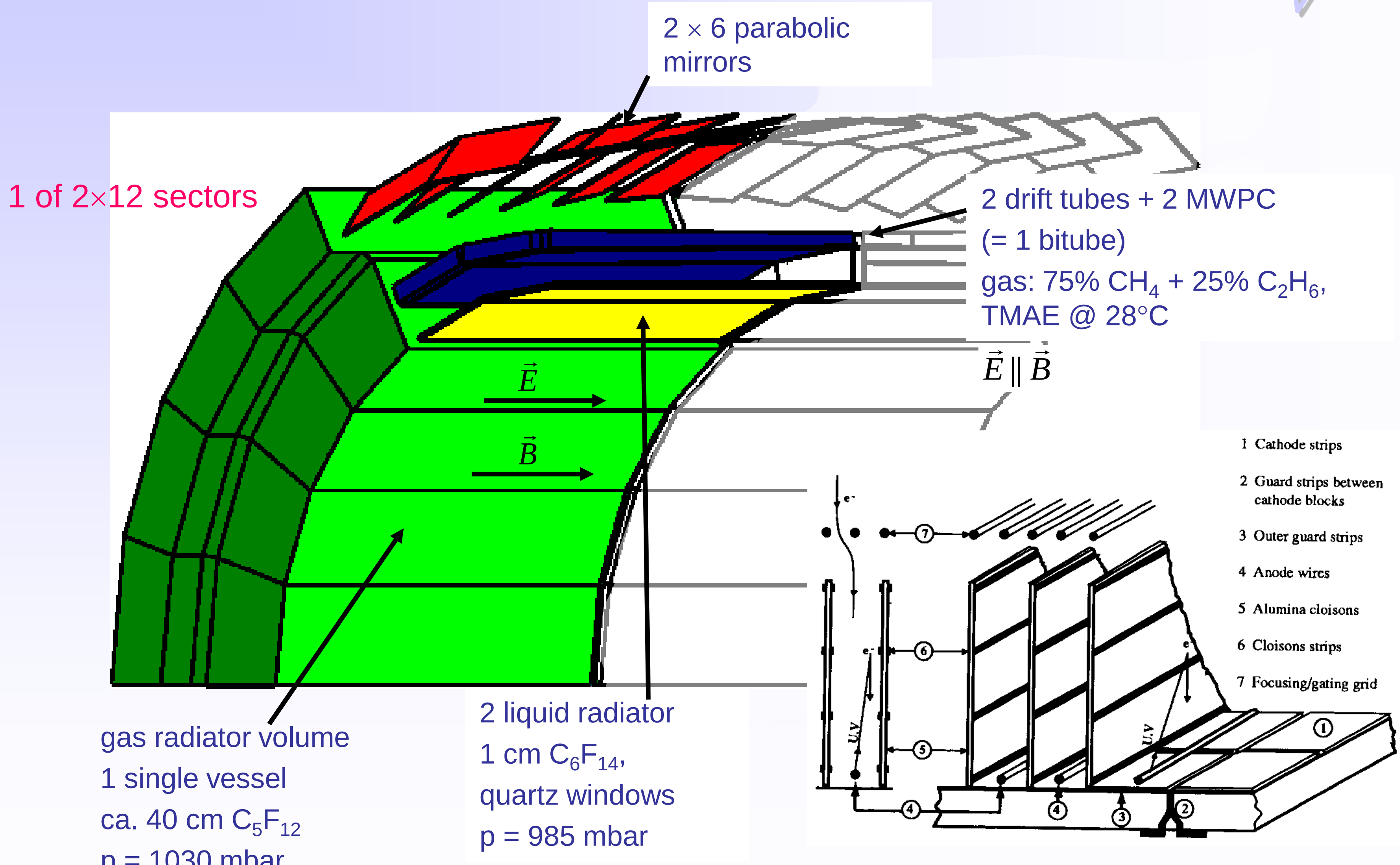

2 × 6 parabolic mirrors
1 of 2×12 sectors
2 drift tubes + 2 MWPC
(= 1 bitube)
gas: 75% CH_4 + 25% C_2H_6,
TMAE @ 28°C
$\vec{E} \parallel \vec{B}$
$\vec{E}$
$\vec{B}$
1 Cathode strips
2 Guard strips between cathode blocks
3 Outer guard strips
4 Anode wires
5 Alumina cloisons
6 Cloisons strips
7 Focusing/gating grid
gas radiator volume
1 single vessel
ca. 40 cm C_5F_{12}
p = 1030 mbar
2 liquid radiator
1 cm C_6F_{14},
quartz windows
p = 985 mbar

Forward RICH

1 of 2×12 sectors

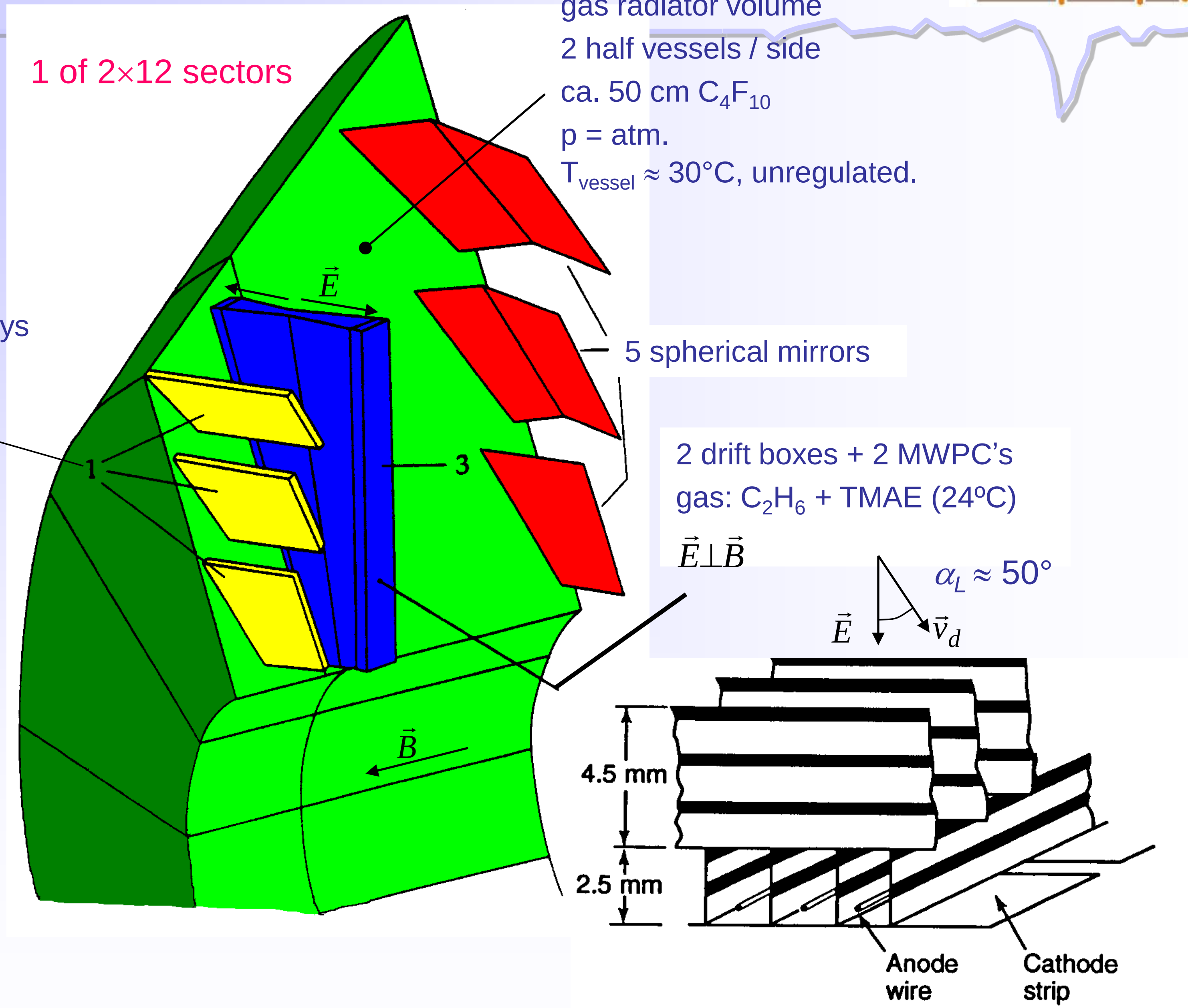
3 liquid radiator trays
1 cm C_6F_{14},
quartz windows
p = atm.

gas radiator volume
2 half vessels / side
ca. 50 cm C_4F_{10}
p = atm.
$T_{vessel} \approx 30°C$, unregulated.

5 spherical mirrors

2 drift boxes + 2 MWPC's
gas: C_2H_6 + TMAE (24ºC)
$\vec{E} \perp \vec{B}$

$\alpha_L \approx 50°$



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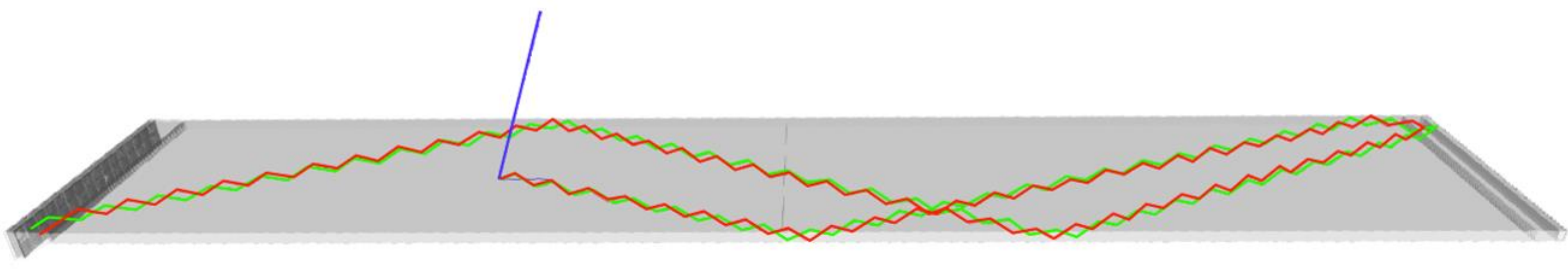
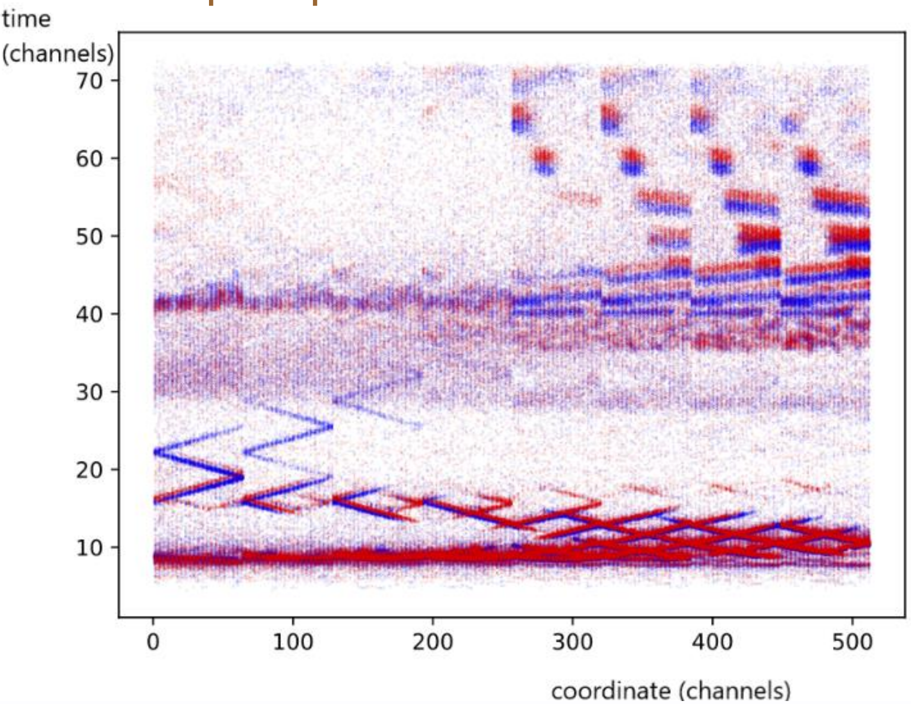
Separation of kaons and pions



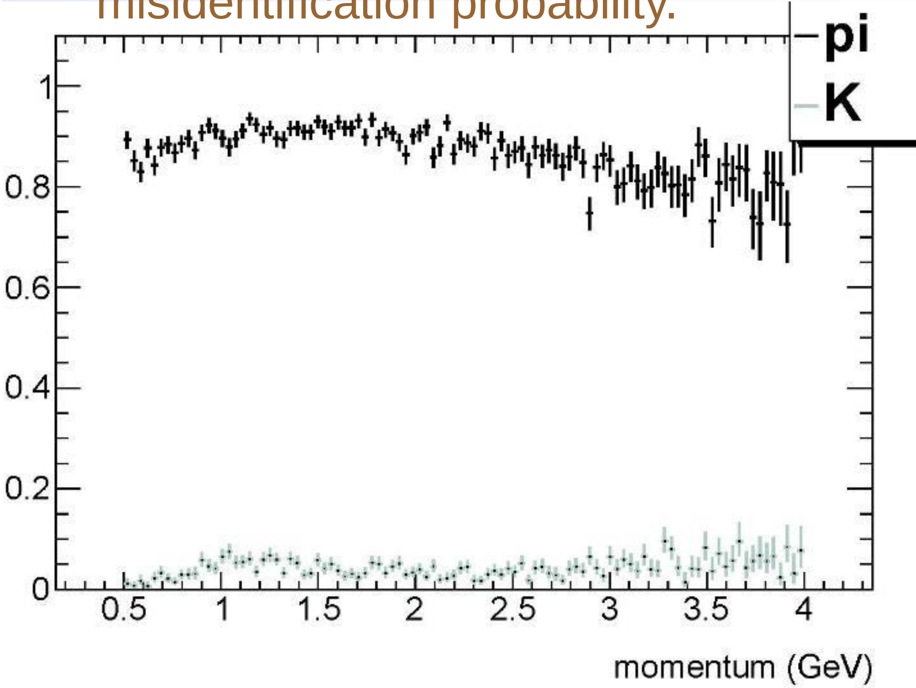
Pions vs kaons in TOP:

different patterns in the time vs PMT impact point coordinate



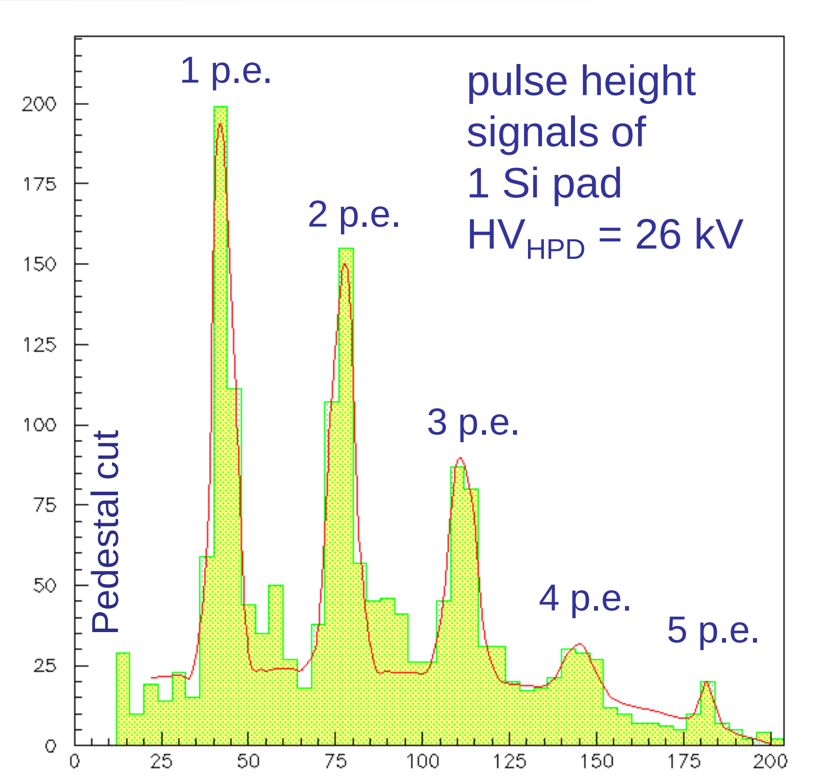
Pions vs kaons:

Expected PID efficiency and misidentification probability.



Hybrid Photon Detectors (HPD's)

10-inch prototype HPD (CERN)
for Air Shower Telescope CLUE.



pulse height (ADC counts)

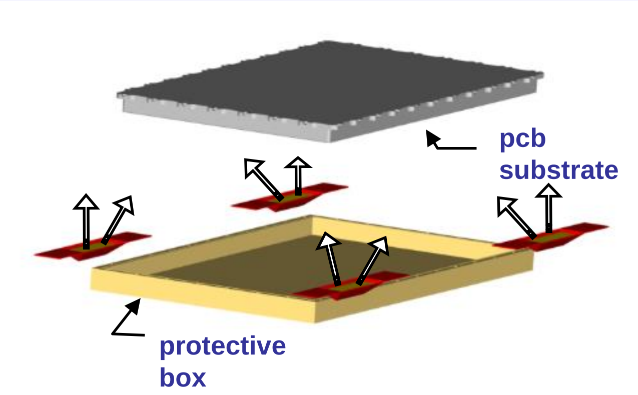
Photon counting. Continuum due to electron back scattering.

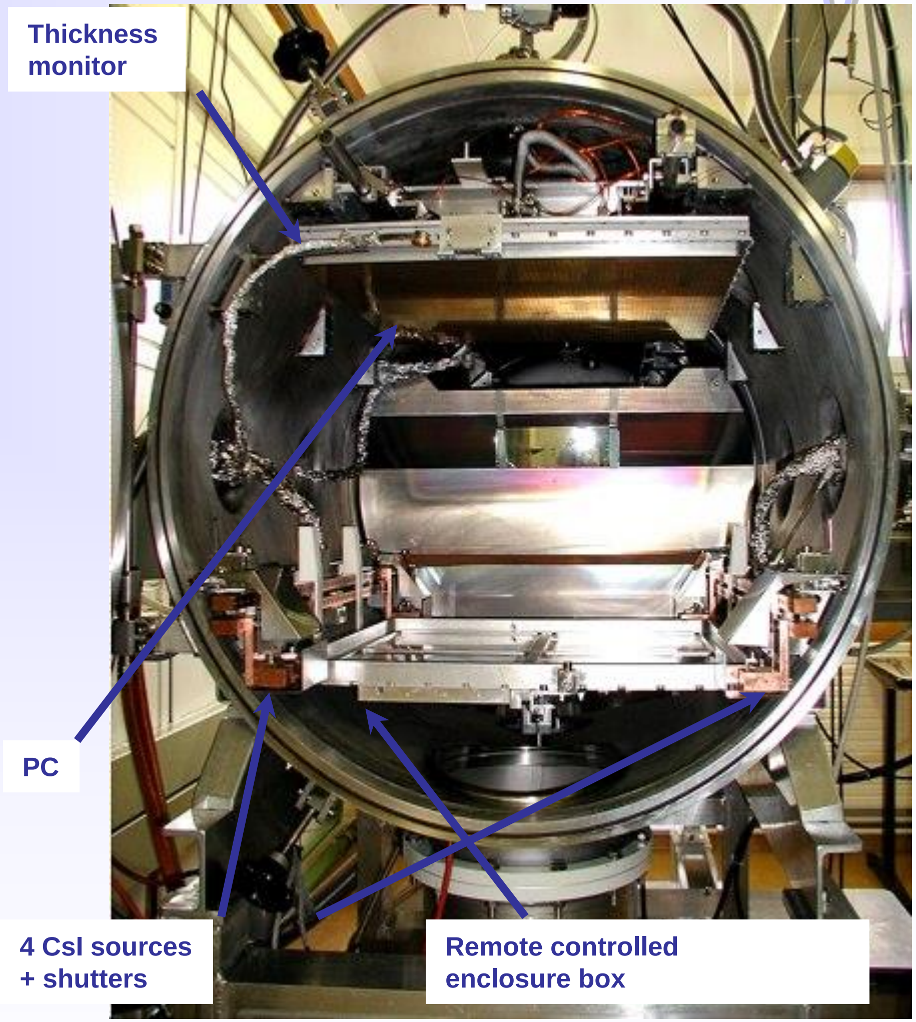
CERN CsI deposition plant

CsI photocathode produced with a well defined, several step procedure, with CsI vacuum deposition and subsequent heat conditioning.

CsI doesn't like water !!!

→ Assembly of cathode and wire chamber in a glove box.





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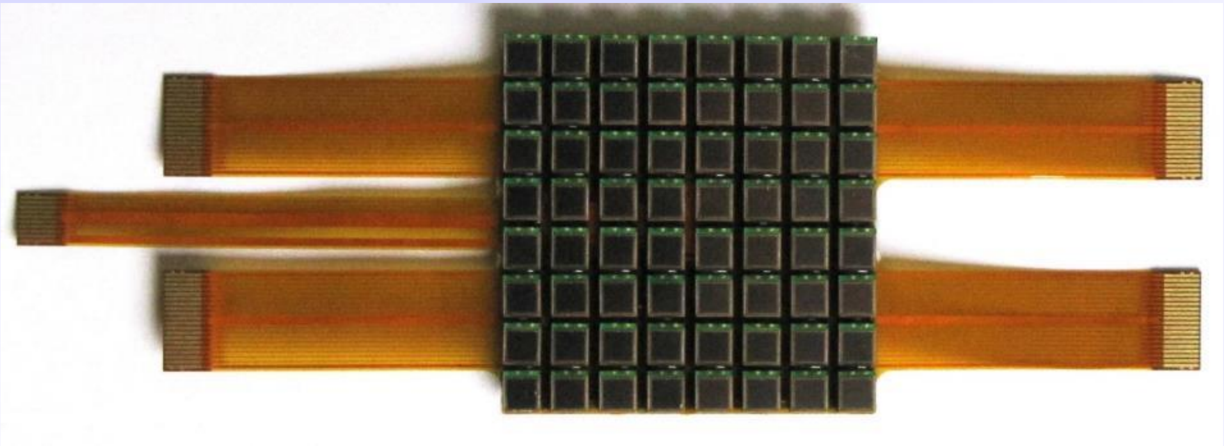
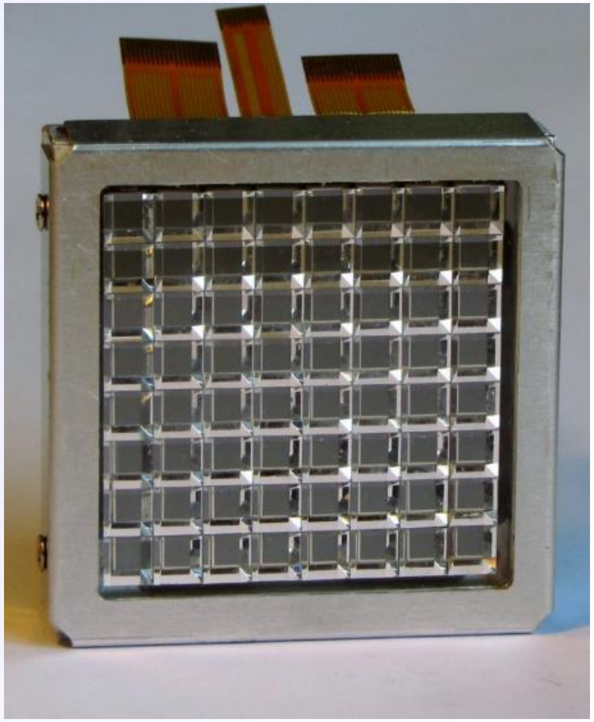
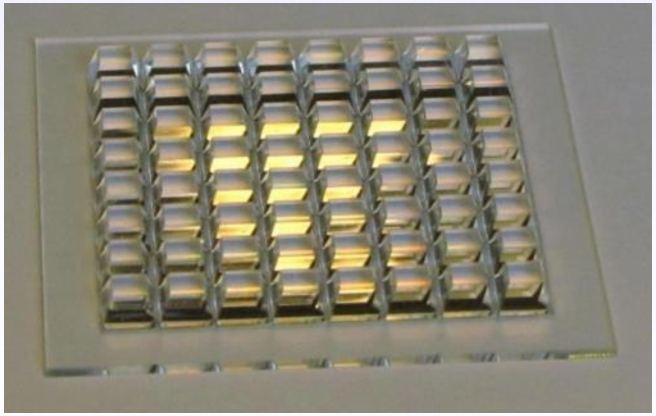
Next step: use arrays of SiPMs

Example: Hamamatsu MPPC S11834-3388DF

- 8x8 SiPM array, with 5x5 mm^2 SiPM channels
- Active area 3x3 mm^2
- + array of quartz light collectors



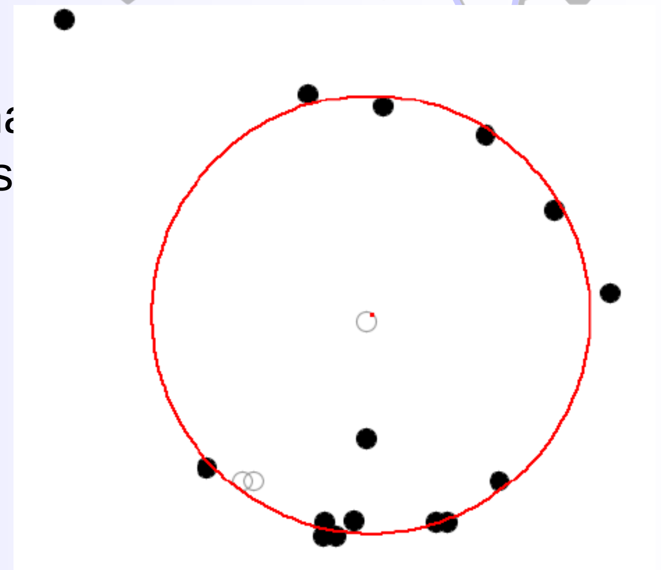




E. Tahirović et al., NIM A787 (2015) 203

Digital SiPM

Digital SiPM (Philips): instead of an analog sum of signa
from all cells of a single SiPM, use on board electronics
a digital sum + time stamp



Square matrix 20x20 cm²

- Sensors: DPC3200-22-44
- 3x3 modules = 6x6 tiles = 24x24 dies = 48x48 pixels in total
- 576 time channels
- 2304 amplitude (position) channels
- 4 levels of FPGA readout: tiles, modules, bus boards, test board

→ A.Y. Barnyakov et al., NIM A732 (2013) 352

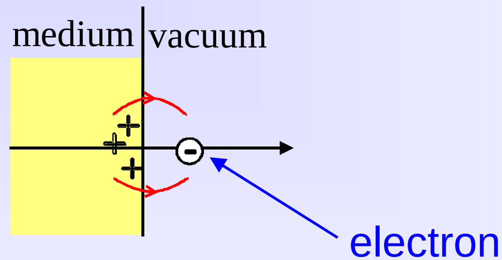
Particle ID by Transition radiation

(there is an excellent review article by B. Dolgoshein (NIM A 326 (1993) 434))

Transition Radiation was predicted by Ginzburg and Franck in 1946

TR is electromagnetic radiation emitted when a charged particle traverses a medium with a discontinuous refractive index, e.g. the boundaries between vacuum and a dielectric layer.

A (too) simple picture



A correct relativistic treatment shows that…

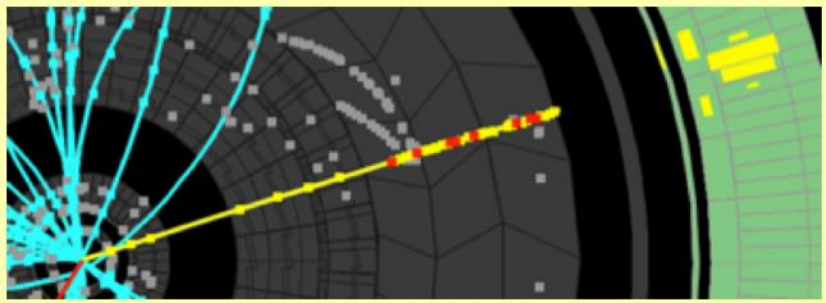
(G. Garibian, Sov. Phys. JETP63 (1958) 1079)

- Radiated energy per medium/vacuum boundary

$$W = \frac{1}{3}\alpha\hbar\omega_p\gamma \qquad \boxed{W \propto \gamma} \longrightarrow$$

only high energetic $e^{\pm}$ emit TR of detectable intensity.
→ particle ID

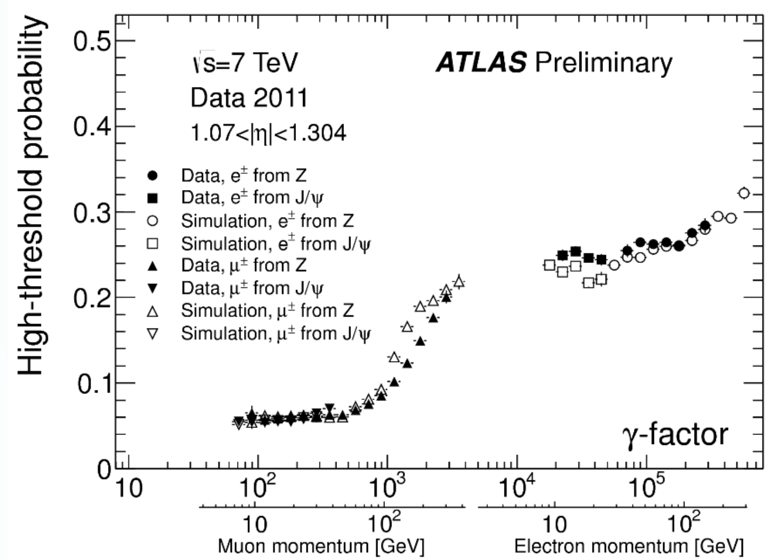
$$\omega_p = \sqrt{\frac{N_e e^2}{\varepsilon_0 m_e}} \qquad \begin{pmatrix}\text{plasma}\\ \text{frequency}\end{pmatrix} \qquad \hbar\omega_p \approx 20\text{eV} \;\; (\text{plastic radiators})$$

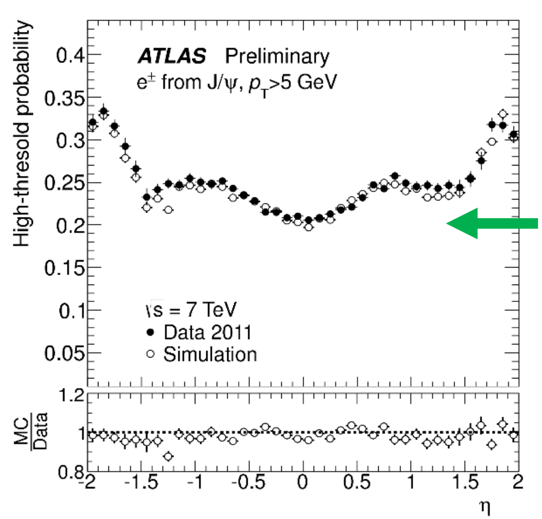


event with an electron (yellow track)

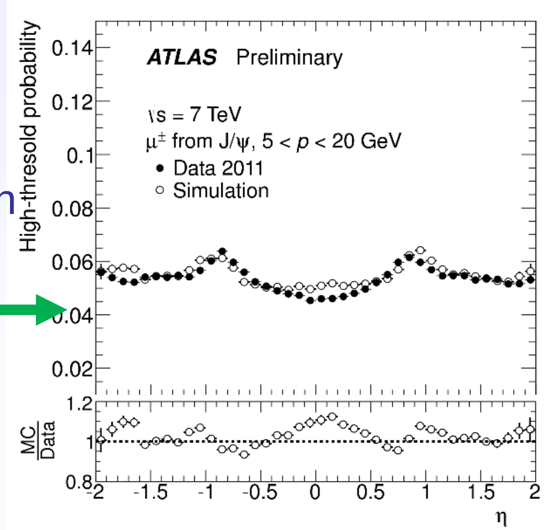
hits with high signal (=TR, passing a high level HL threshold) are indicated in red

TR turn ON curve: HL probability VS gamma factor



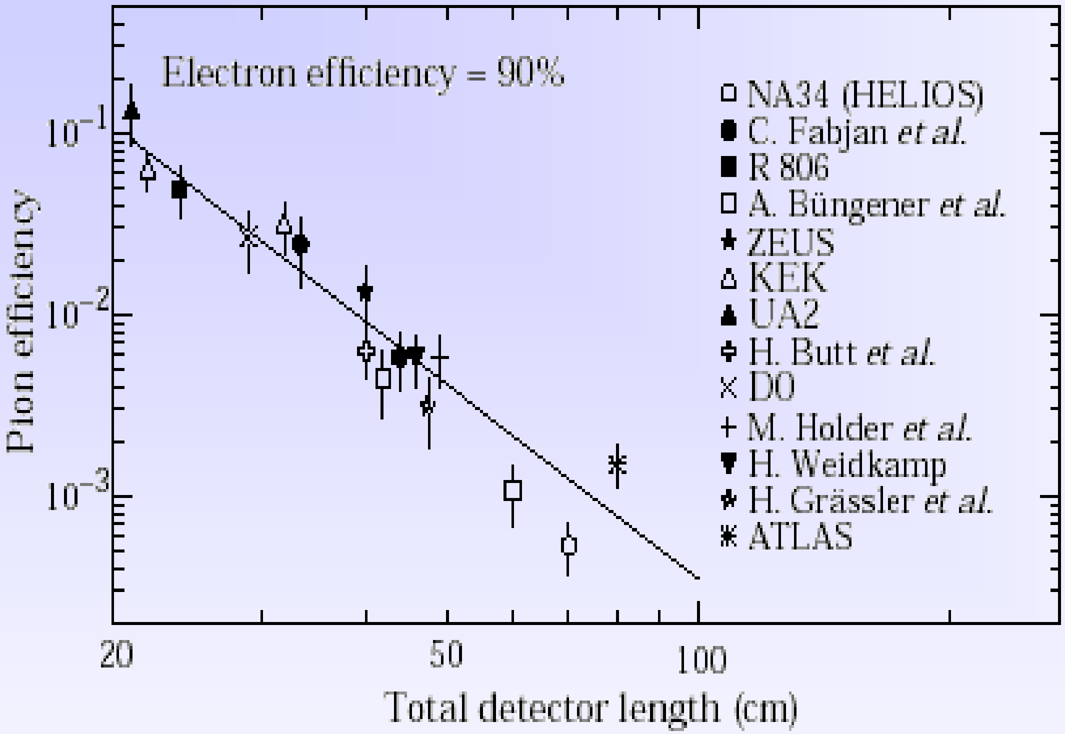


HL hit probability for electrons 4 times higher than for minimum ionising particles (muons)



ESIPAP School 2021

Particle ID by Transition radiation



Rejection Power : $R_{\pi/e} = \varepsilon_\pi / \varepsilon_e$ (90%)

one order of magnitude in Rejection Power is gained when the TRD length is increased by ~ 20 cm