Instrumentation for high energy physics

LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

Sergey Barsuk, LAL Orsay, sergey.barsuk@lal.in2p3.fr

- Passage of particles through matter
- Photon detectors
- Scintillators
- Cherenkov light detectors, time-of-flight detectors
- Calorimeters
- Tracking detectors: silicon and gaseous detectors, introduction

- Very selective and personal, no way to cover all technologies/detectors
- Many simplifications, avoid formalism where possible
- No proper references to the origin for many plots

TESHEP, Poltava - Ukraine, 13-20/07/2018

Полтавський краєзнавчий музей

Why: Photon detector applications

HEP, Nuclear physics, astrophysics:

- → Scintillation (Calorimetry, Tracker, (also in the trigger), …)
  - → Organic scintillators
  - → Inorganic scintillators
- → Cherenkov and Transition radiation
- → Light from astronomical observations

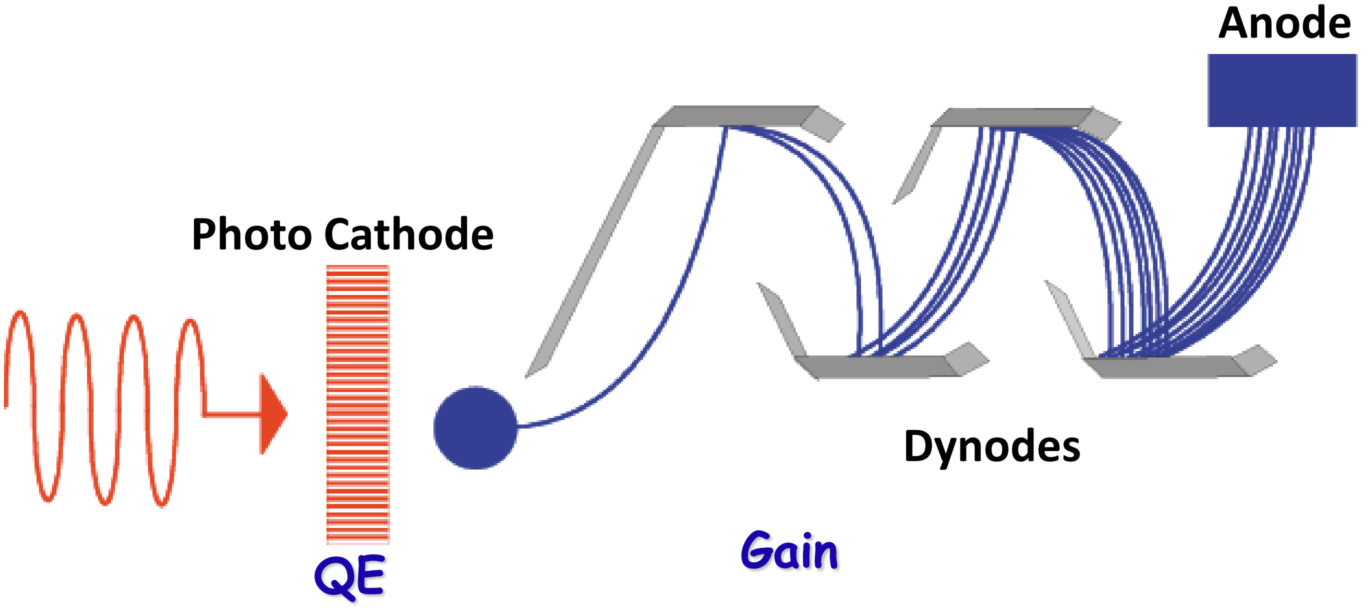
photons in ~visible range, λ = 100 nm … 1000 nm or E ~ few eV

What: photons as a particle or for imaging, in quite different environment

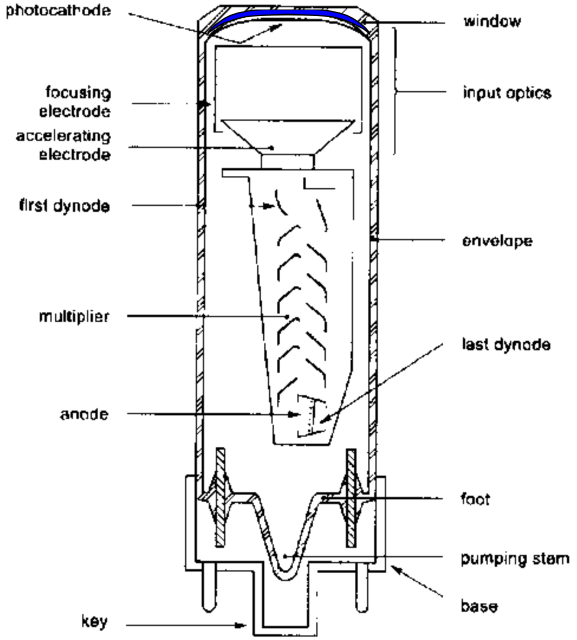
- → rare clean events (problem: noise, impurities etc)
- → busy events (problem: pileup from other particles, including photons)

How to: photons detection techniques

Vacuum photon detectors: Photo Multiplier Tube



- Photon-to-Electron Converting Photo-Cathode
- Dynodes with secondary electron emission
- Typical gain ~10^6.
  Transient time spread ~200 ps
- Sensitive to magnetic field
- Choice of Photo-Cathode: high QE
  for the wavelength of incoming light !
- Concerns: dynamic range, time dependence of response, rate capability

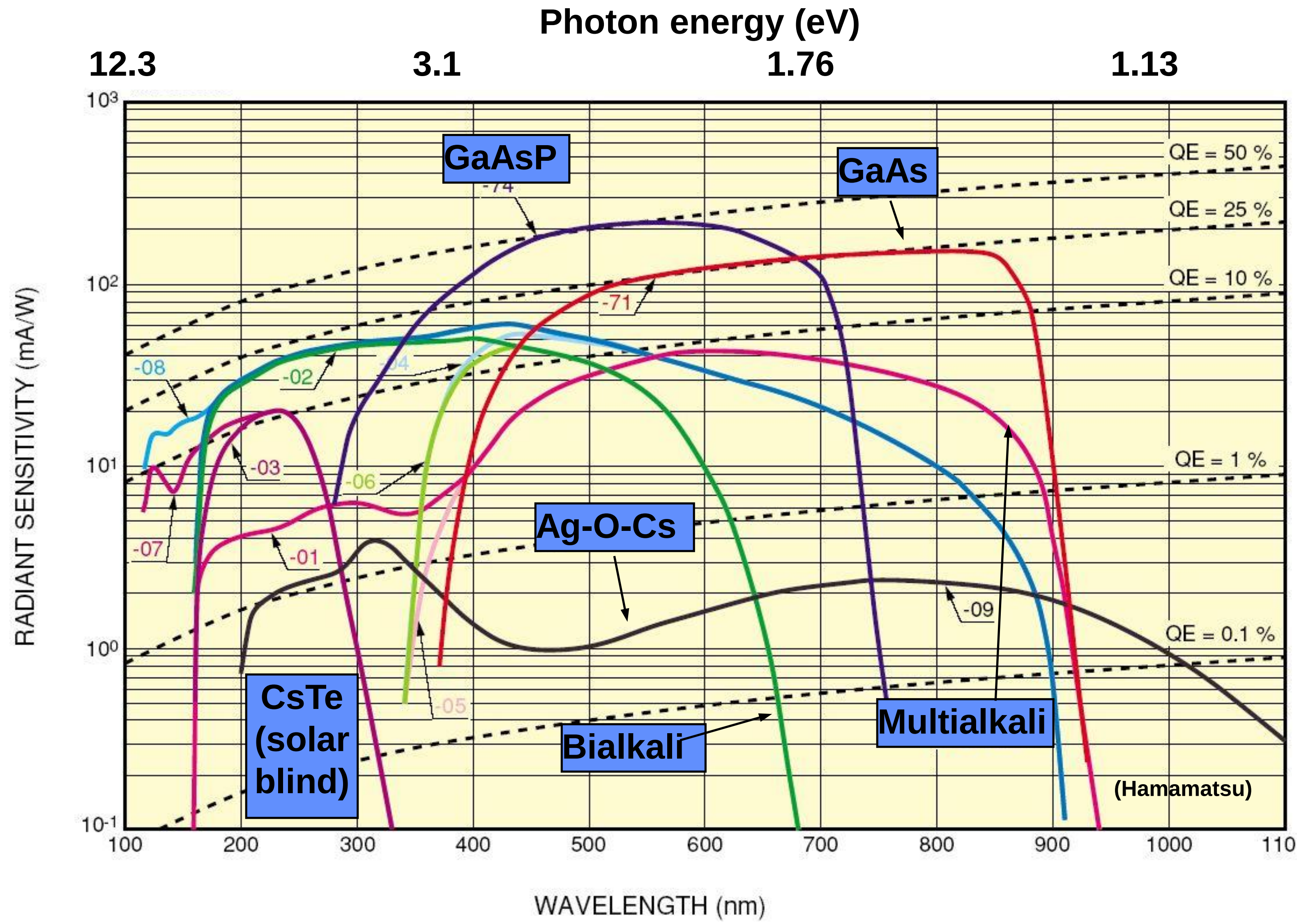


Choice of photocathode :

- Optimize for incoming light, e.g. choose high QE,
- Reliability according to working conditions
- …

QE is a strong function of the photon wavelength

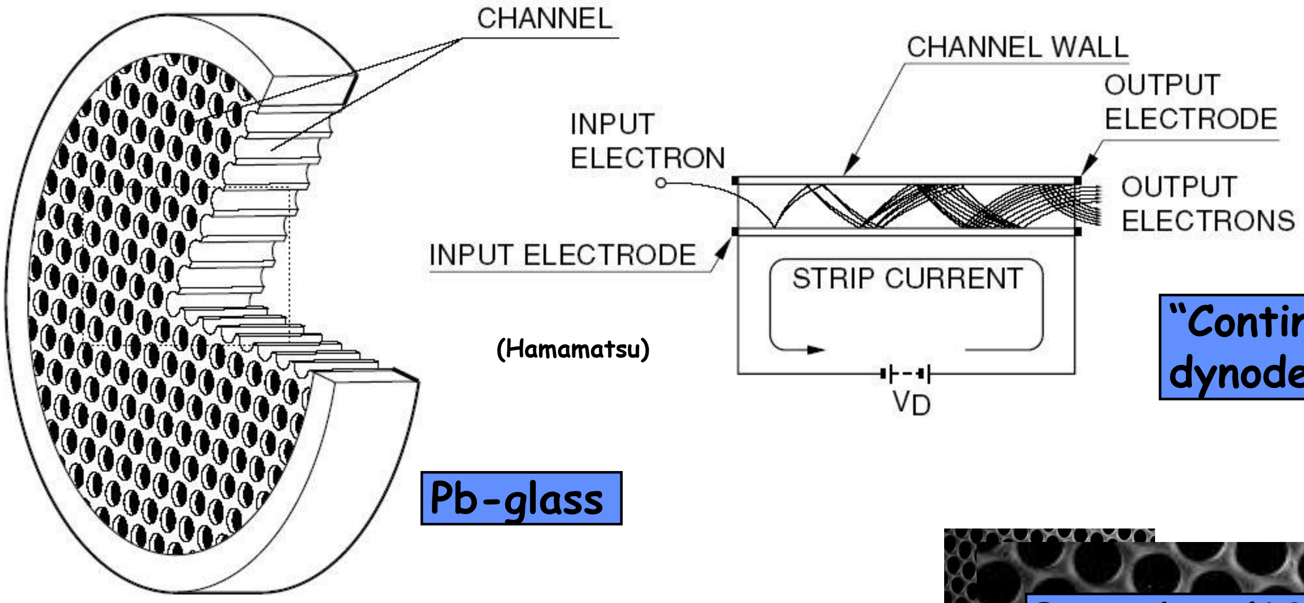
QE's of typical photo-cathodes



Bialkali: SbKCs, SbRbCs **Multialkali:** $SbNa_2KCs$ (alkali metals have low work function)

from T. Gys, Academic Training, 2005

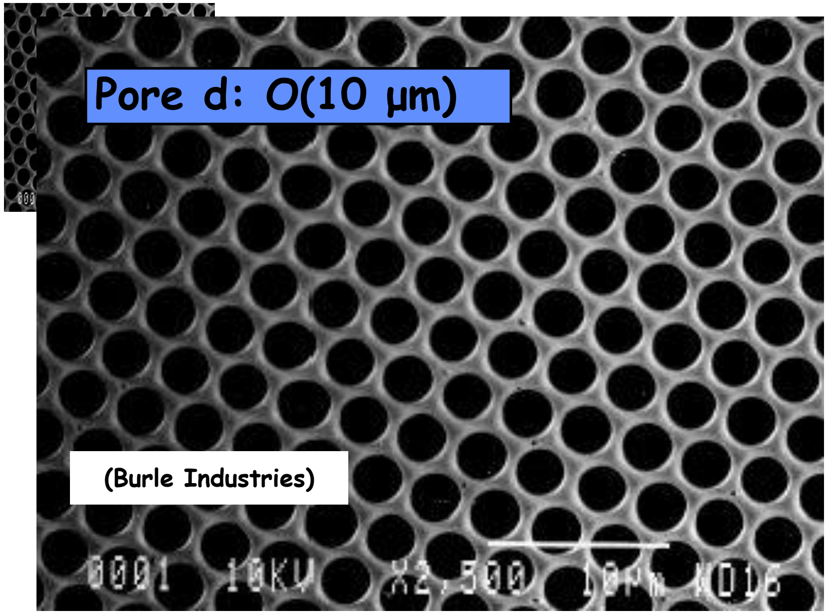
Vacuum photon detectors: Micro Channel Plate



(Hamamatsu)

“Continuous” dynode chain

Pb-glass



Pore d: O(10 μm)

(Burle Industries)

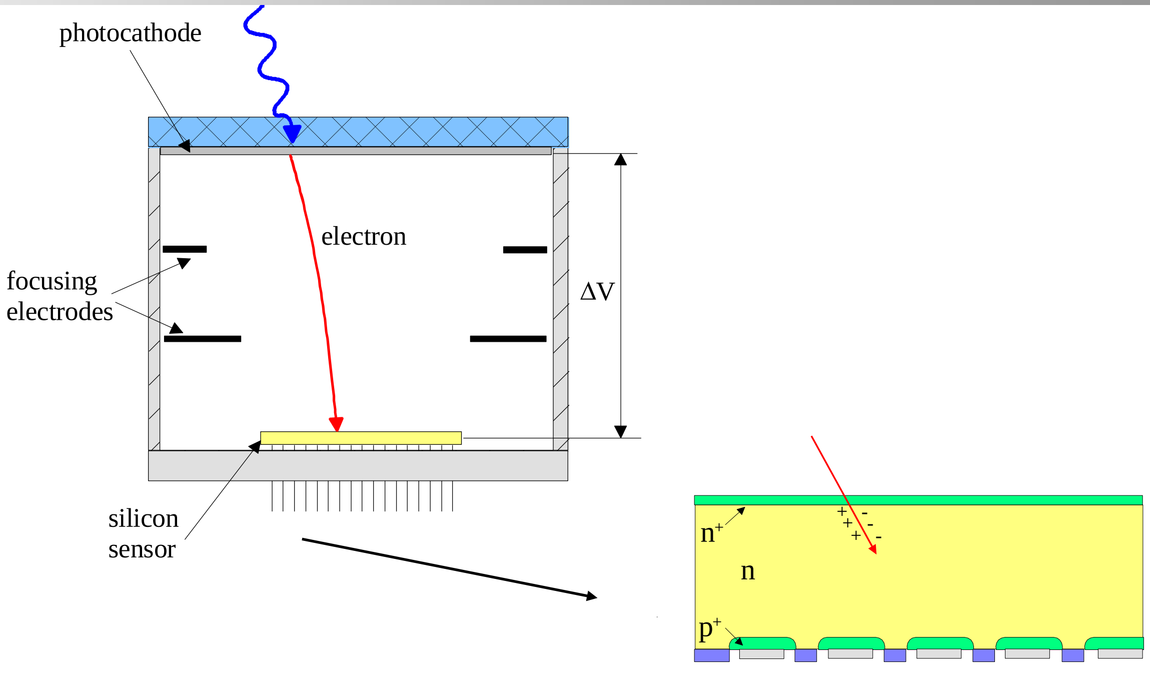
- ❑ **Gain fluctuations** can be minimized by operating in the saturation mode
- ❑ Kind of **2D PMT**:
  - \+ high gain up to 5 x 10^4;
  - \+ fast signal (transit time spread ~20 ps);
  - \+ less sensitive to B-field (0.1 T);
  - \- limited lifetime (0.5 C/cm^2);
  - \- limited rate capability (mA/cm^2)

from T. Gys, Academic Training, 2005

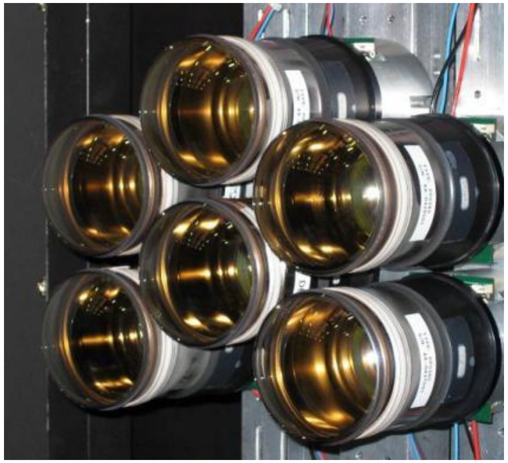
Vacuum photon detectors: HPD

Photo Multiplier Tube
\- dynodes and anode
\+ silicon sensor

Hybrid Photo Detector



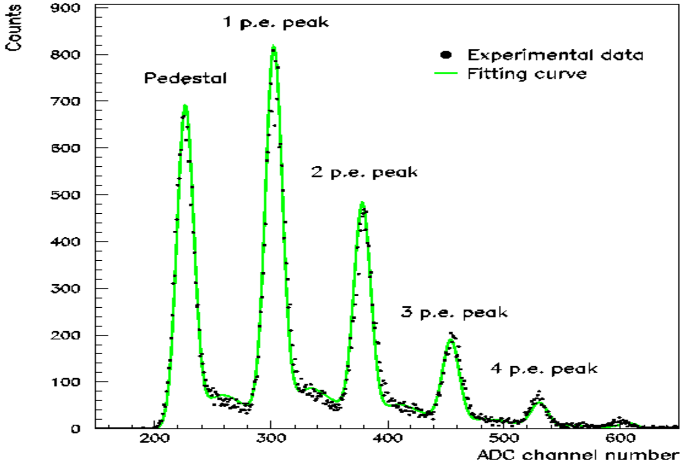
LHCb



- It takes 3.6 eV to create an electron-hole pair in silicon.

Using an accelerating voltage 20 kV → ~ **5000 electron-hole pairs, amplification in 1 step** → Good energy resolution

- But : High voltage, ion feedback → requires good vacuum

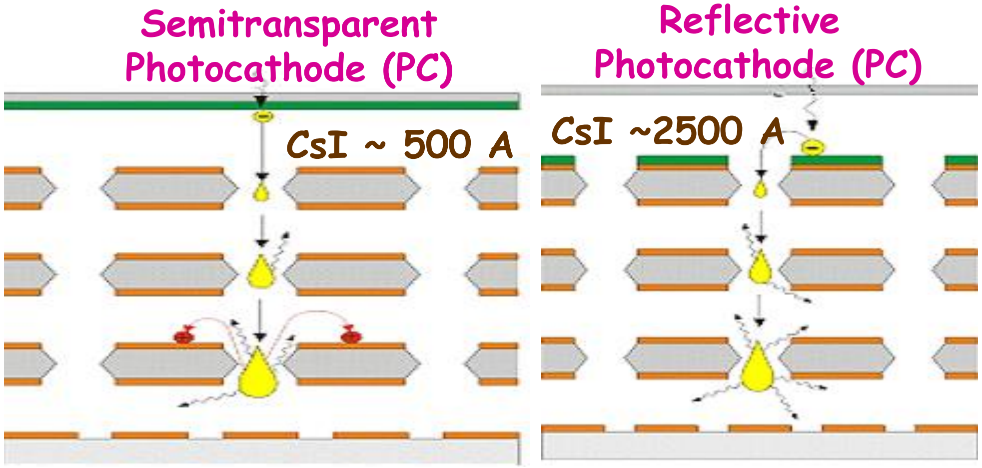


Gaseous photon detectors

- ❑ **GEM Gaseous Photomultipliers** (GEM+CsI photocathode) to detect single photoelectrons: photoelectron initiates avalanche in a high field region (also MWPC, Micromegas, …)

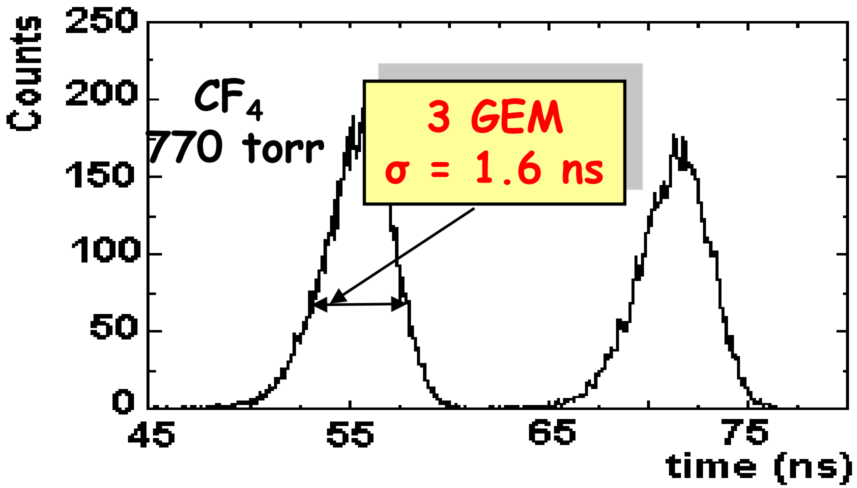
Multi-GEM Gaseous Photomultipliers:

- ❑ Largely reduced photon feedback (can operate in pure noble gas & CF_4)
- ❑ Fast signals [ns] → good timing
- ❑ Excellent localization response
- ❑ Able to operate at cryogenic T


Semitransparent Photocathode (PC)

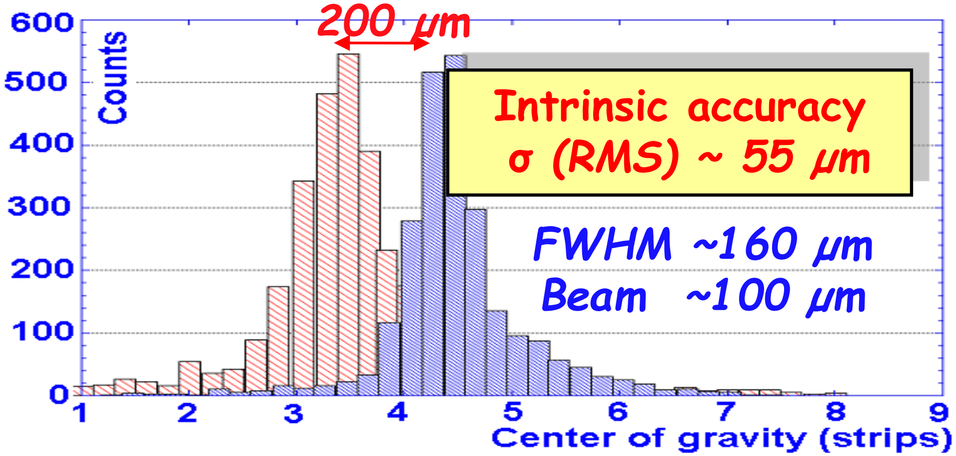
Reflective Photocathode (PC)

Single Photon Time Resolution:


CF_4
770 torr

3 GEM
σ = 1.6 ns

Single Photon Position Accuracy:


Intrinsic accuracy
σ (RMS) ~ 55 µm

FWHM ~160 µm
Beam ~100 µm

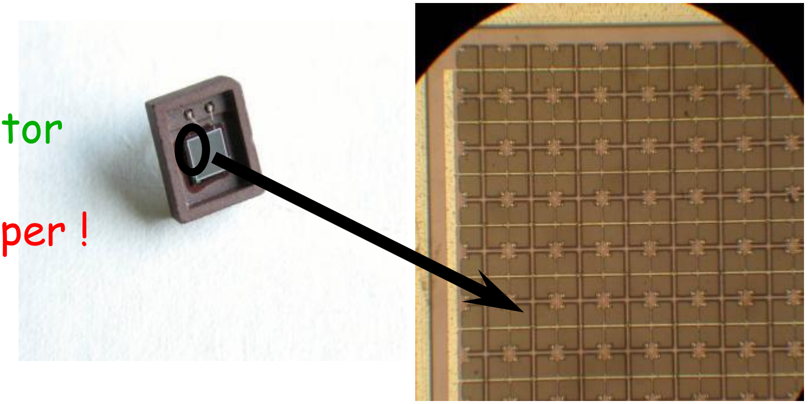
E.Nappi, NIMA471 (2001) 18; T. Meinschad et al, NIM A535 (2004) 324; D.Mormann et al., NIMA504 (2003) 93

Solid-state photon detectors

- **More compact, lightweight, tolerant to MF, cheaper, allow fine pixelization, ...**

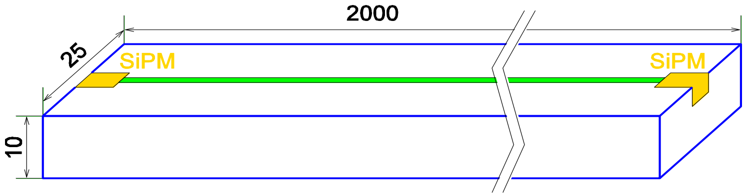
E.g.: **Silicium Photon Multiplier (SiPM)**

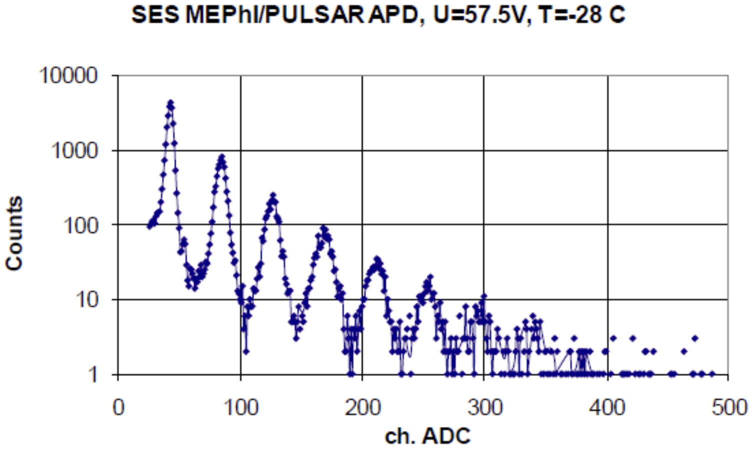
- Fully solid state photon detector, large array of tiny avalanche photodiods
- p-n junction under large reverse-bias voltage, packed over a small area and operated in a limited Geiger mode above breakdown voltage ➔ detectable electrical response from low-intensity optical signals, down to single photons
- Binary output, linearity achieved by summing cell outputs



SiPM 3x3 mm^2 attached directly to BICRON-418 scintillator 3x3x40 mm^3

Signal is readout directly from SiPM w/o preamp and shaper !





- Sensitive area : 3x3 mm2 # of pixels: 5625
- Pixel size: 30 µm x 30 µm
- Depletion region: ~1 µm
- SiPM noise (FWHM): room temperature 5-8 electrons
  -50 C 0.4 electrons

Scintillators : organic scintillators

- Ionization, produced by charged particles, to generate optical photons (usually, blue or green wavelength regions)
- Typical densities : 1.0 .. 1.2 g/cm3
- Typical yield : 1 photon / 100 eV energy deposit
- *Overlap between absorption and emission spectra in complex molecules*
- *Avoid re-absorption → increase Stocks' shift (distance between major absorption and emission peaks)*

- Decay time ~ns range ; Rise time faster !
  - High LY + fast response ➔ possibility of sub-ns timing resolution
- Fraction of light in the decay "tail" can depend on the exciting particle
  - Pulse shape discrimination ➔ particle ID
- Hydrogen content
    - Sensitive to proton recoils from neutrons

- Easy fabrication into desired shapes, low cost
    - Became common detector component
    - In form of scintillating fibers widely used in tracking and calorimetry
- Concerns: aging and handling, attenuation length, afterglow, radiation damage, …

Organic scintillators

Scintillation mechanism

- Scintillation: small part (~3%) of deposited energy is released by excited molecules as optical photons;
- Fluorescence: initial excitation by absorption of a photon, then de-excitation by emission of longer wavelength photon.

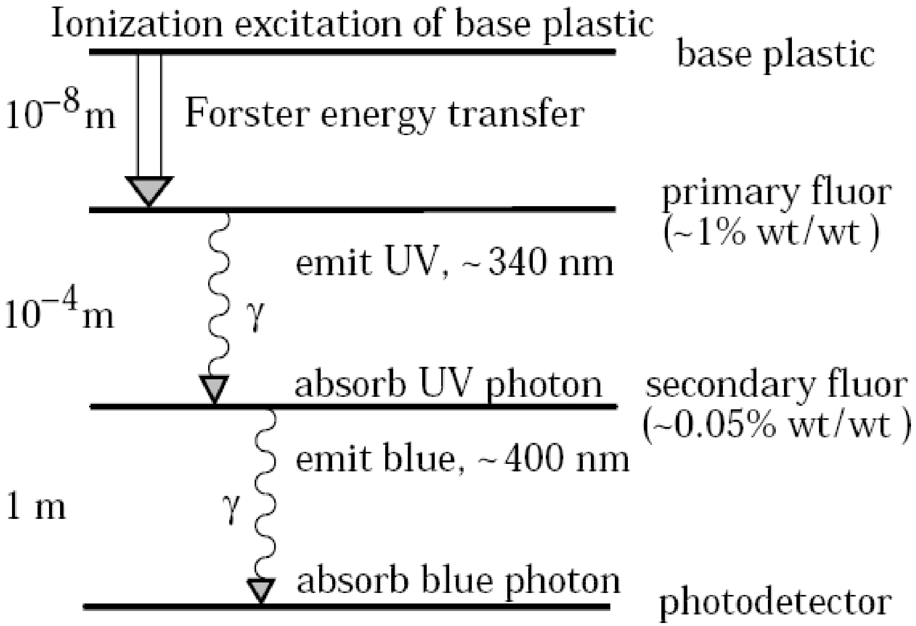


Figure 28.1: Cartoon of scintillation "ladder" depicting the operating mechanism of plastic scintillator. Approximate fluor concentrations and energy transfer distances for the separate sub-processes are shown.

- UV photons with short att. length ~few mm
- Efficiently re-radiates photons at wavelength, where base is more transparent;
- Shortens decay time
- Adjusts emission wavelength and/or attenuation length

Organic scintillators: illustrative number

Signal from a 10 GeV muon in 1 cm thick plastic scintillator ($\gamma = 1$) ?

Muons can be considered as a MIP with 2 MeV/(g/cm^2)
→ 2 MeV in 1 cm scintillator
→ For 2 MeV energy deposit, estimate total number of photons as 2 MeV / 100 eV = 2×10^4

Though, final result will depend on the scintillator optical properties, collection and transport efficiency and QE of PMT

Optical fibers: scintillating, wave-length shifting and clear

WLS fibers: Y11 (Blue →) Green

Kuraray

Attenuation length : > 3.5 m

Emission : peak at 476 nm

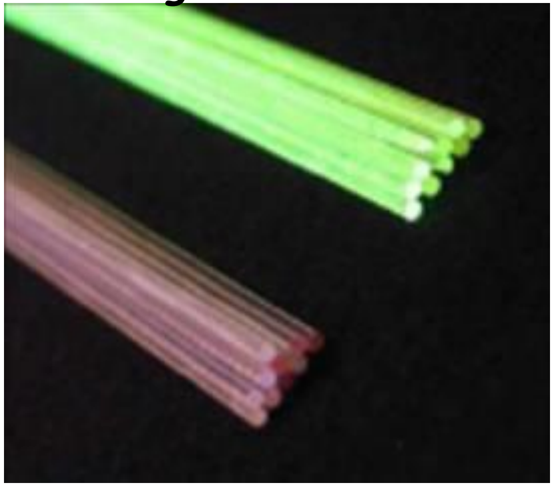
Clear transport fibers: PSM

> 10 m

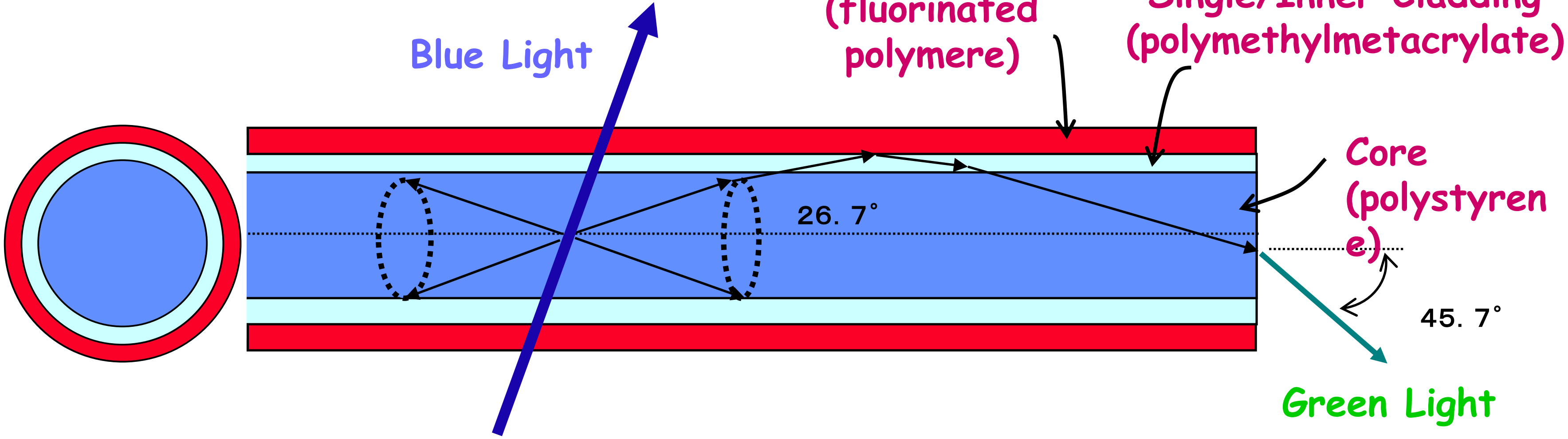
Crystals fibers: LuAG (Ce)

Fibercryst

Inorganic scintillator



<u>Example: Y11 double cladding</u>



Blue Light

Outer Cladding (fluorinated polymere)

Single/Inner Cladding (polymethylmetacrylate)

Core (polystyrene)

26. 7°

45. 7°

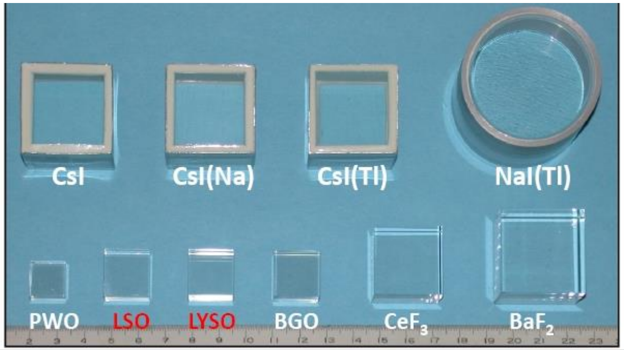
Green Light

→ Light collection in complex geometries

Scintillators : inorganic scintillators

- Higher density (4-8 g/cm^3) and high effective atomic number
  - ➔ high stopping power
  - ➔ high effective conversion efficiency for electrons or photons
- Applications
  - ➔ total absorption ECAL (opposite to sampling ECAL)
  - ➔ gamma rays detectors in wide energy range
- Mechanism: **energy deposited in crystal by ionization**, either directly by charged particles, or by conversion of photons into electrons or positrons, which subsequently produce ionization. This **energy is transferred to luminescent centers**, which then radiate **scintillation photons**.
- Often compromise between light yield, decay time, temperature stability, radiation resistance …

Crystals for HEP calorimeters

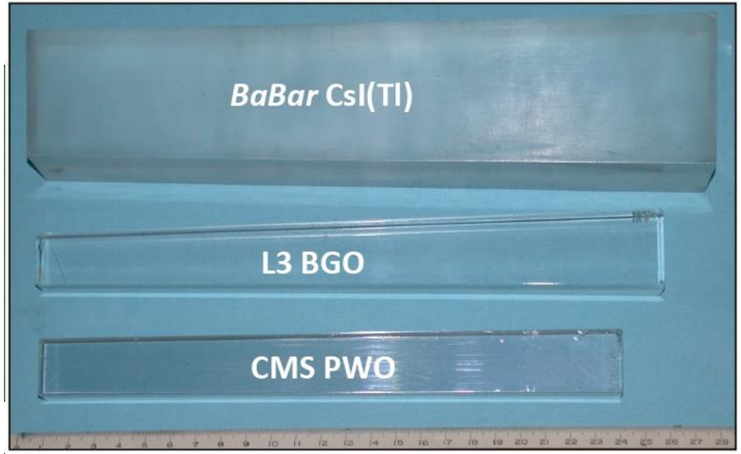


1.5 X$_0$ Cubic Samples:

Hygroscopic Halides

Non-hygroscopic

R.-Y.Zhu



Full Size Crystals:

BaBar CsI(Tl): 16 X$_0$

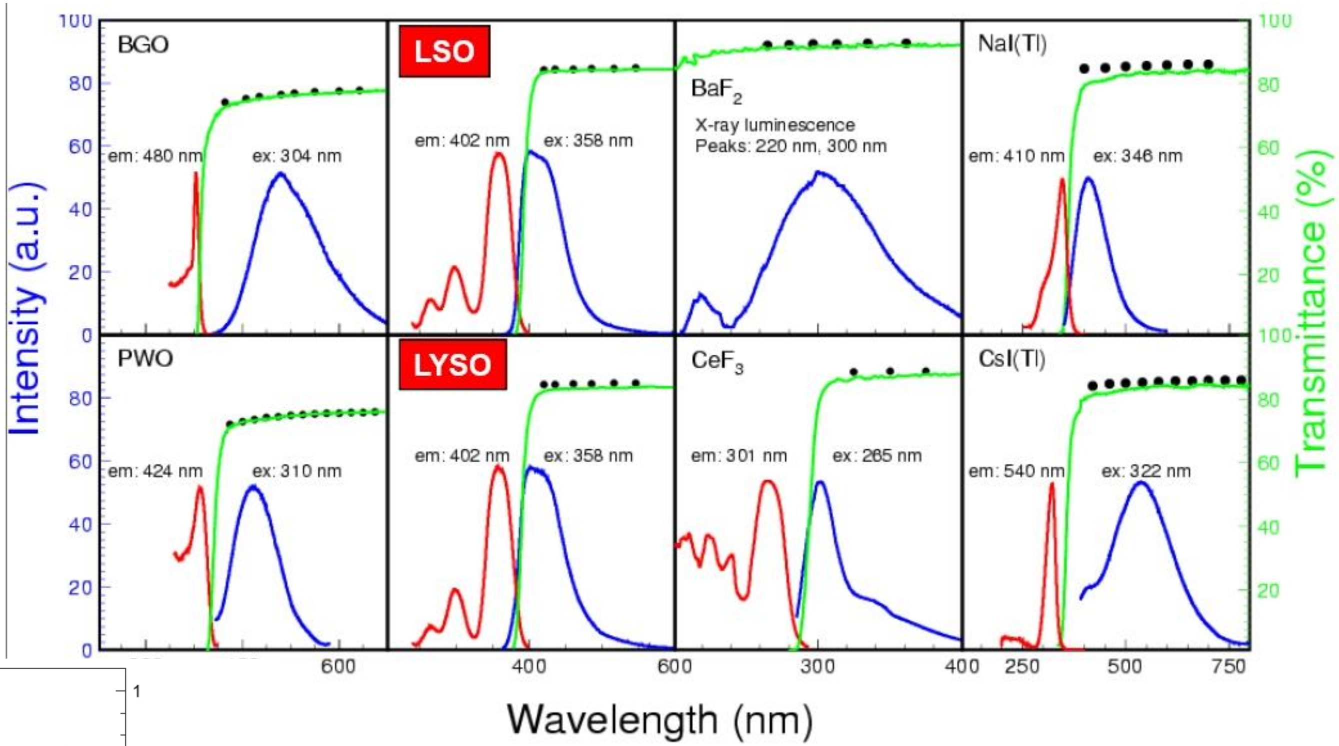
L3 BGO: 22 X$_0$

CMS PWO(Y): 25 X$_0$

Excitation, Emission, Transmission

R.-Y.Zhu

- LYSO (LSO) – Gerium doped Lutenium (Yttrium) Orthosilicate



7

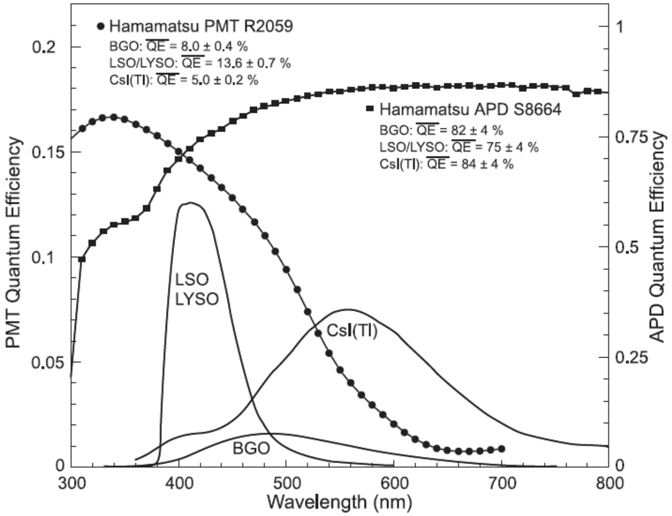


Figure 28.2: The quantum efficiencies of two photodetectors, a Hamamatsu R2059 PMT with bi-alkali cathode and a Hamamatsu S8664 avalanche photodiode (APD), are shown as a function of wavelength. Also shown in the figure are emission spectra of three crystal scintillators, BGO, LSO and CsI(Tl), and the numerical values of the emission weighted quantum efficiency. The area under each emission spectrum is proportional to crystal's light yield.

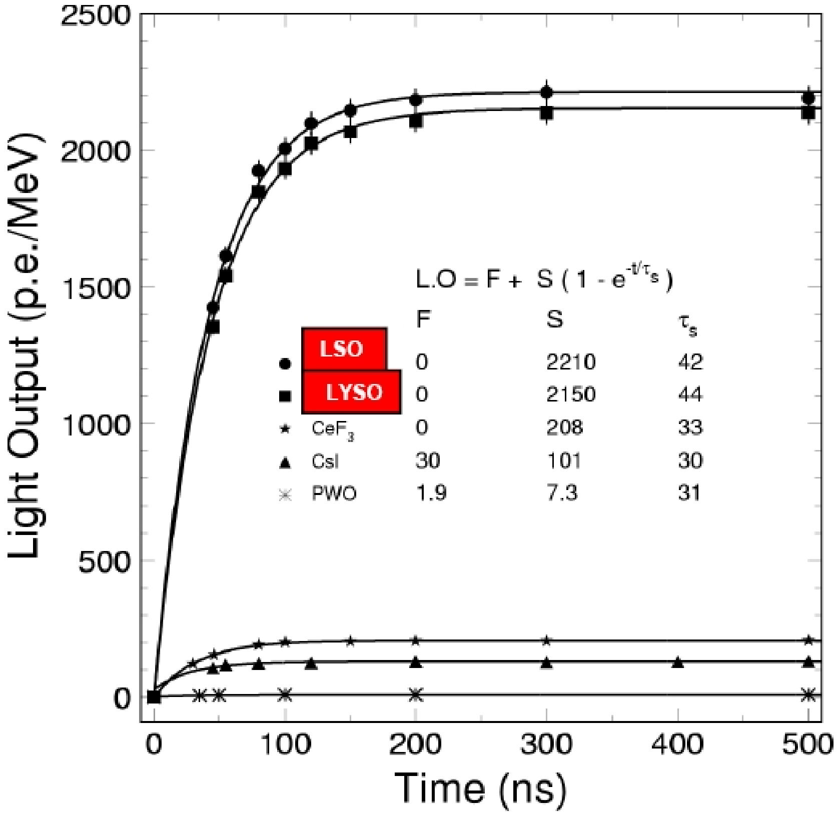
- Matching photon detector to the crystal emission spectra

Timing of the crystal signal

R.-Y.Zhu

Measured with Philips XP2254B PMT (multi-alkali cathode)
p.e./MeV: LSO/LYSO is 6 & 230 times of BGO & PWO respectively

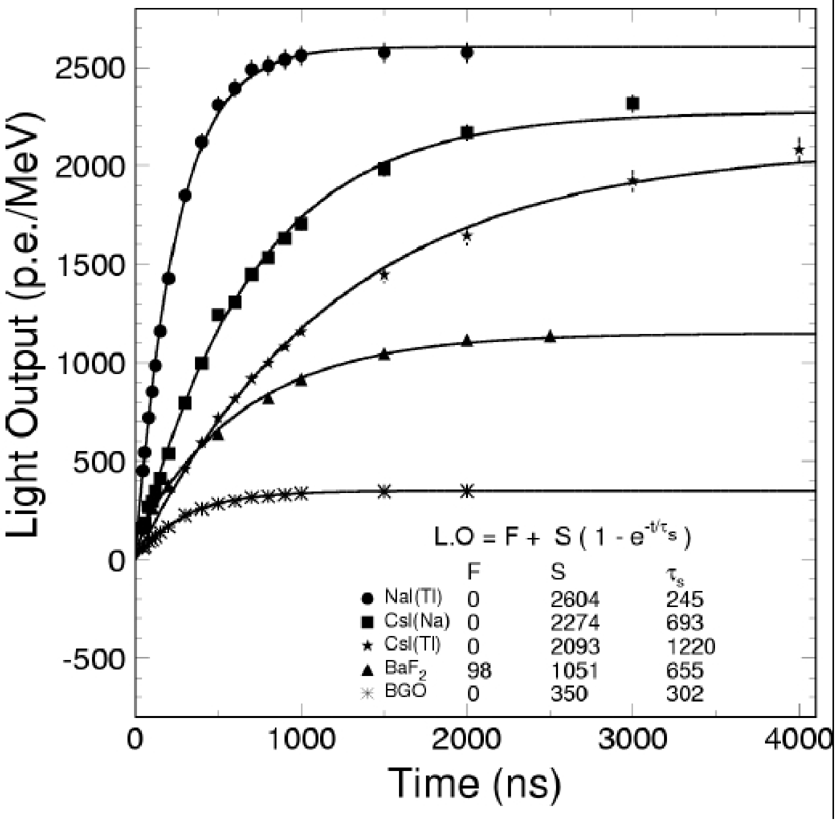
Fast Crystal Scintillators



$L.O = F + S(1 - e^{-t/\tau_s})$

	F	S	τ_s
● LSO	0	2210	42
■ LYSO	0	2150	44
★ CeF_3	0	208	33
▲ CsI	30	101	30
✳ PWO	1.9	7.3	31

Slow Crystal Scintillators

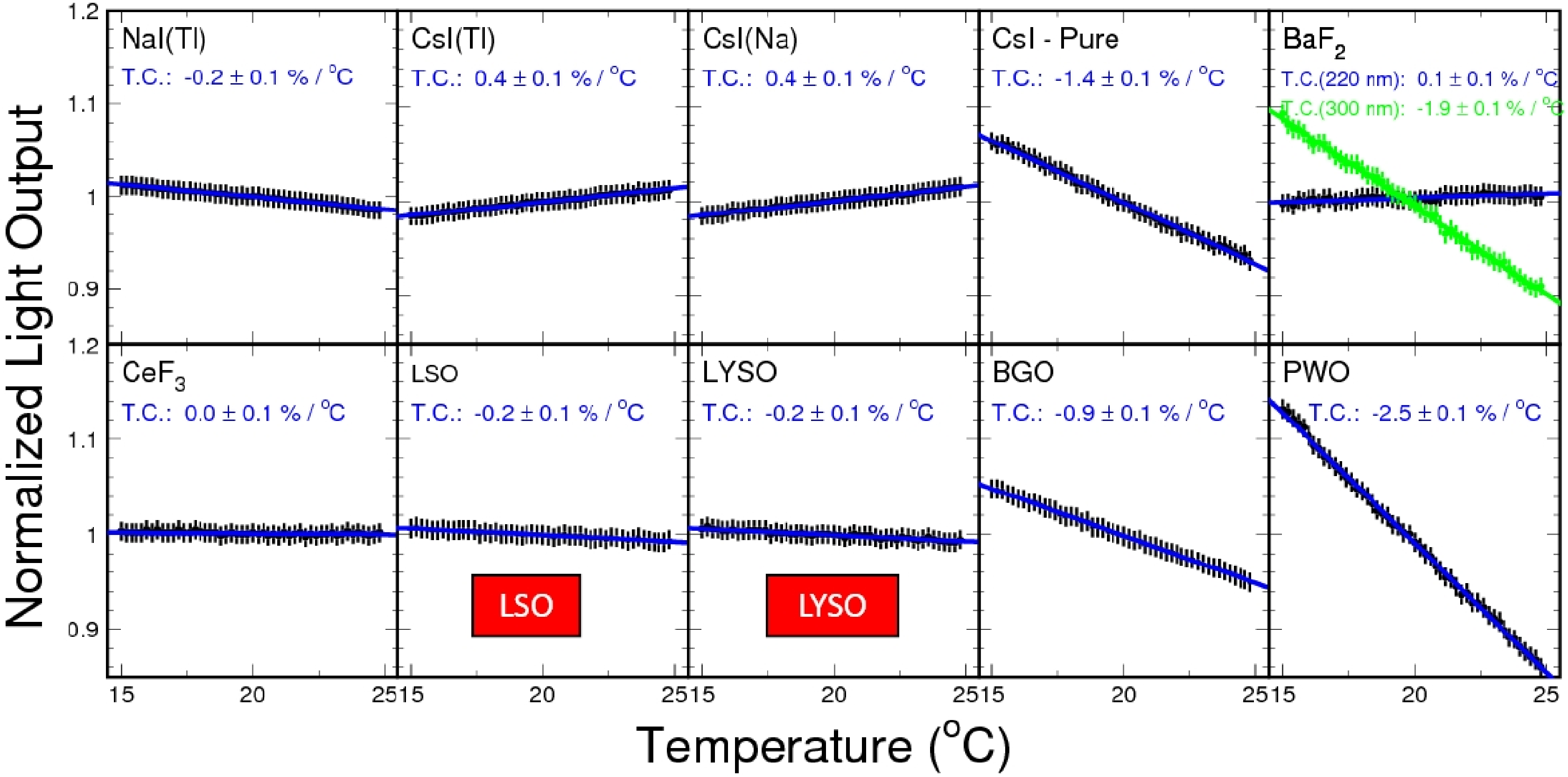


$L.O = F + S(1 - e^{-t/\tau_s})$

	F	S	τ_s
● NaI(Tl)	0	2604	245
■ CsI(Na)	0	2274	693
★ CsI(Tl)	0	2093	1220
▲ BaF_2	98	1051	655
✳ BGO	0	350	302

Temperature dependence

R.-Y.Zhu

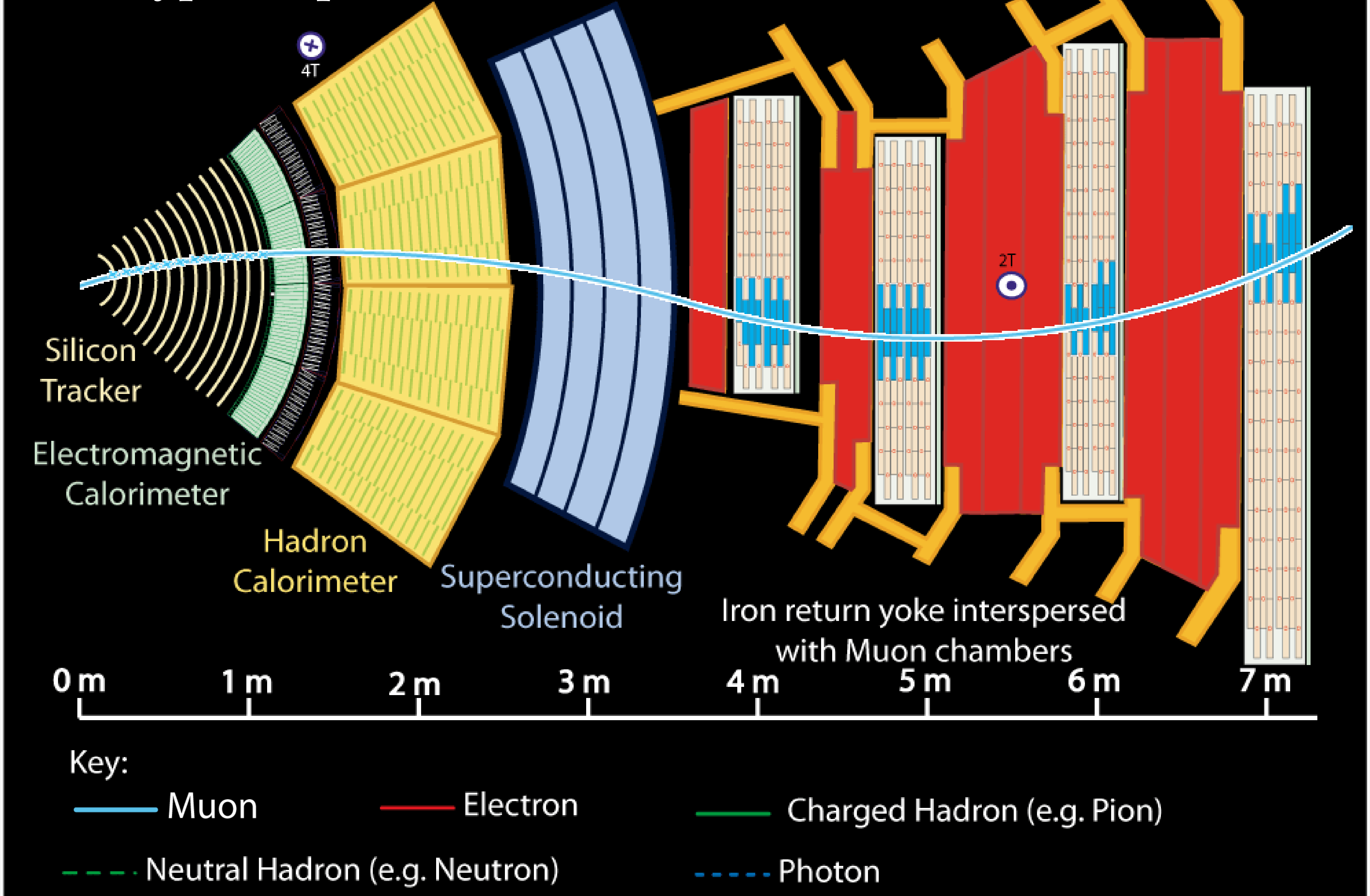


❑ **Scintillating materials are most widely used in calorimetry**

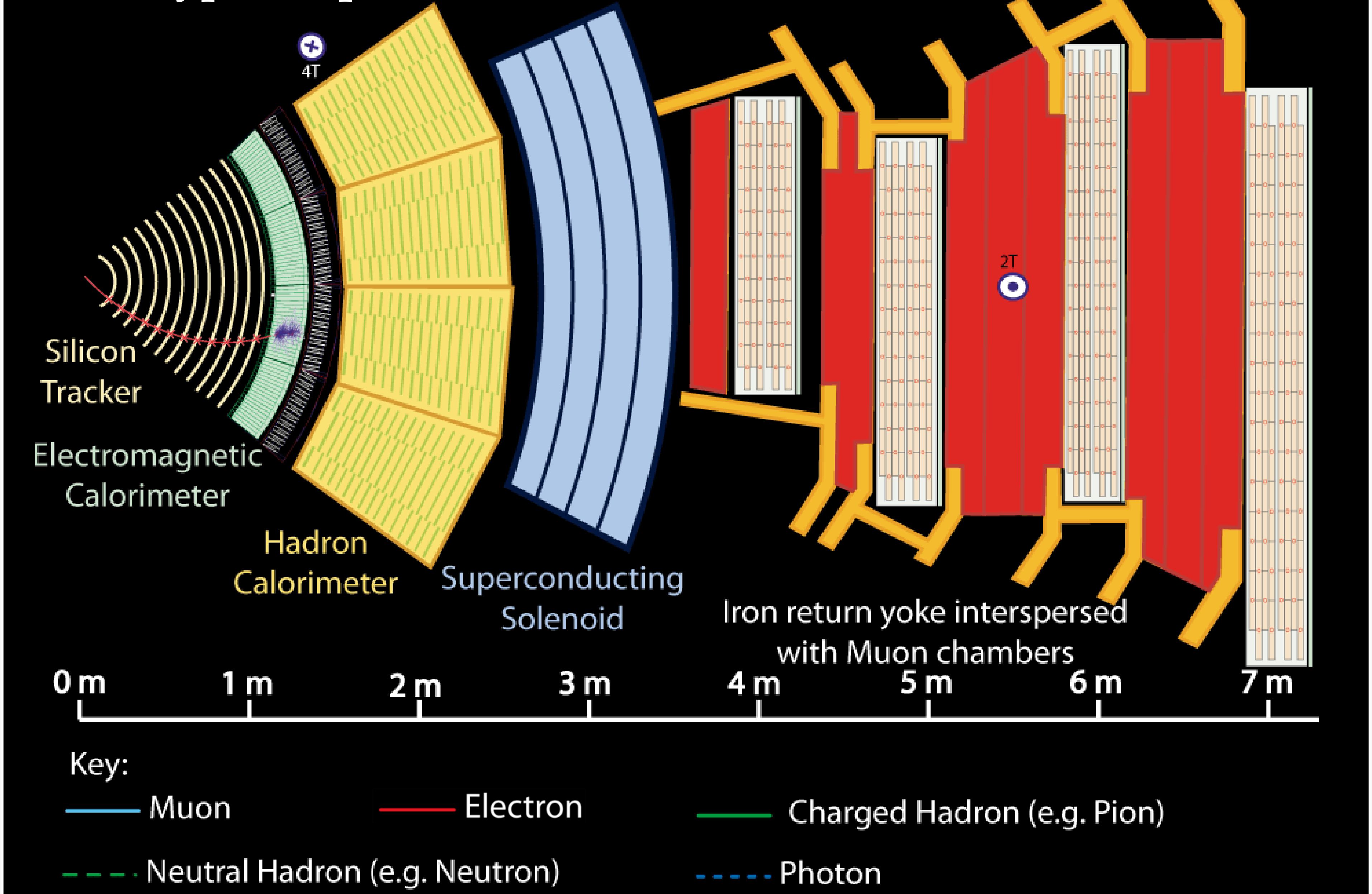
➔ **see next lecture.**

Particle Identification, first glance

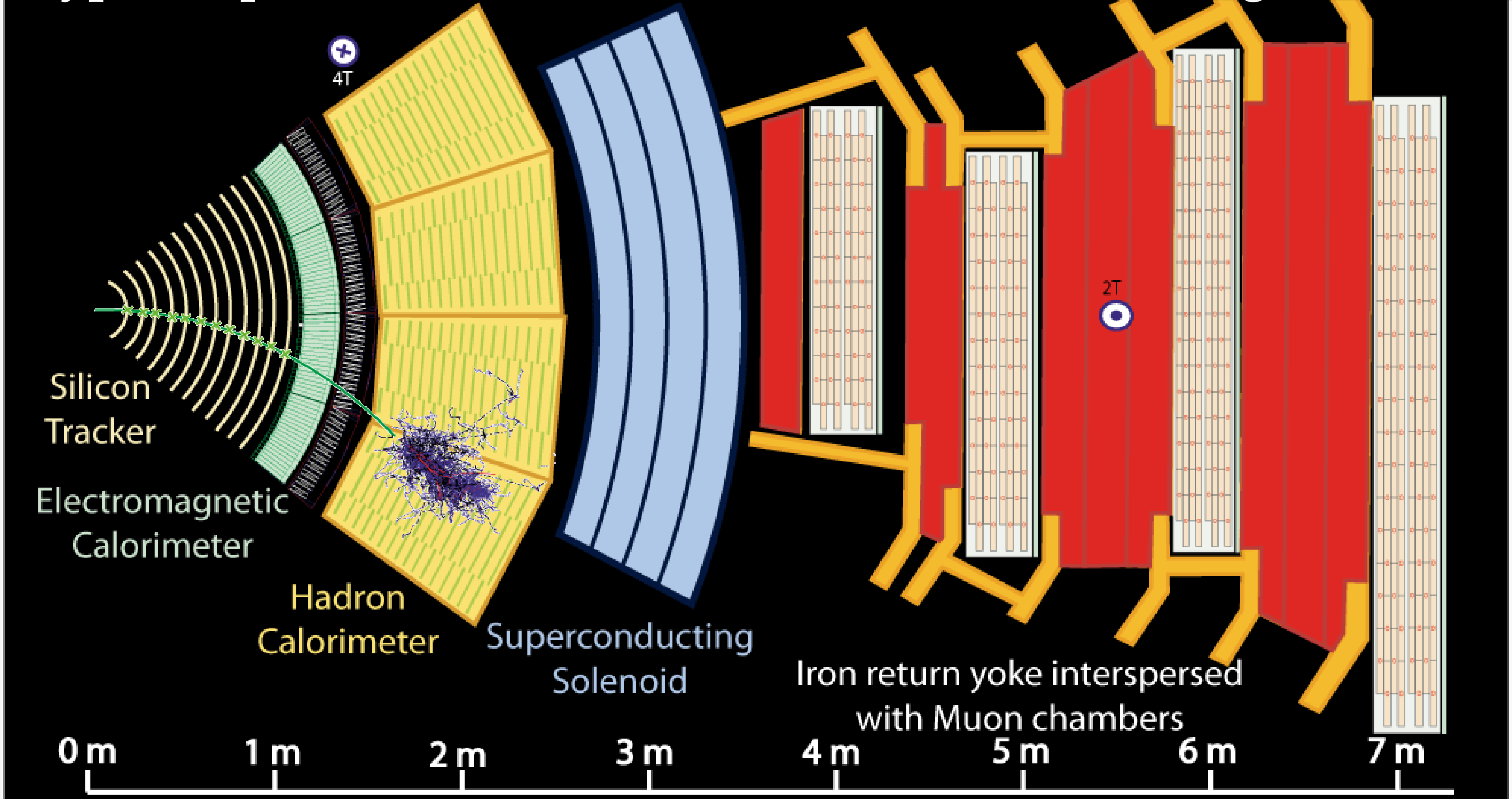
5 types of particles detected in the HEP Detector: Muon



5 types of particles detected in the HEP detector: Electron



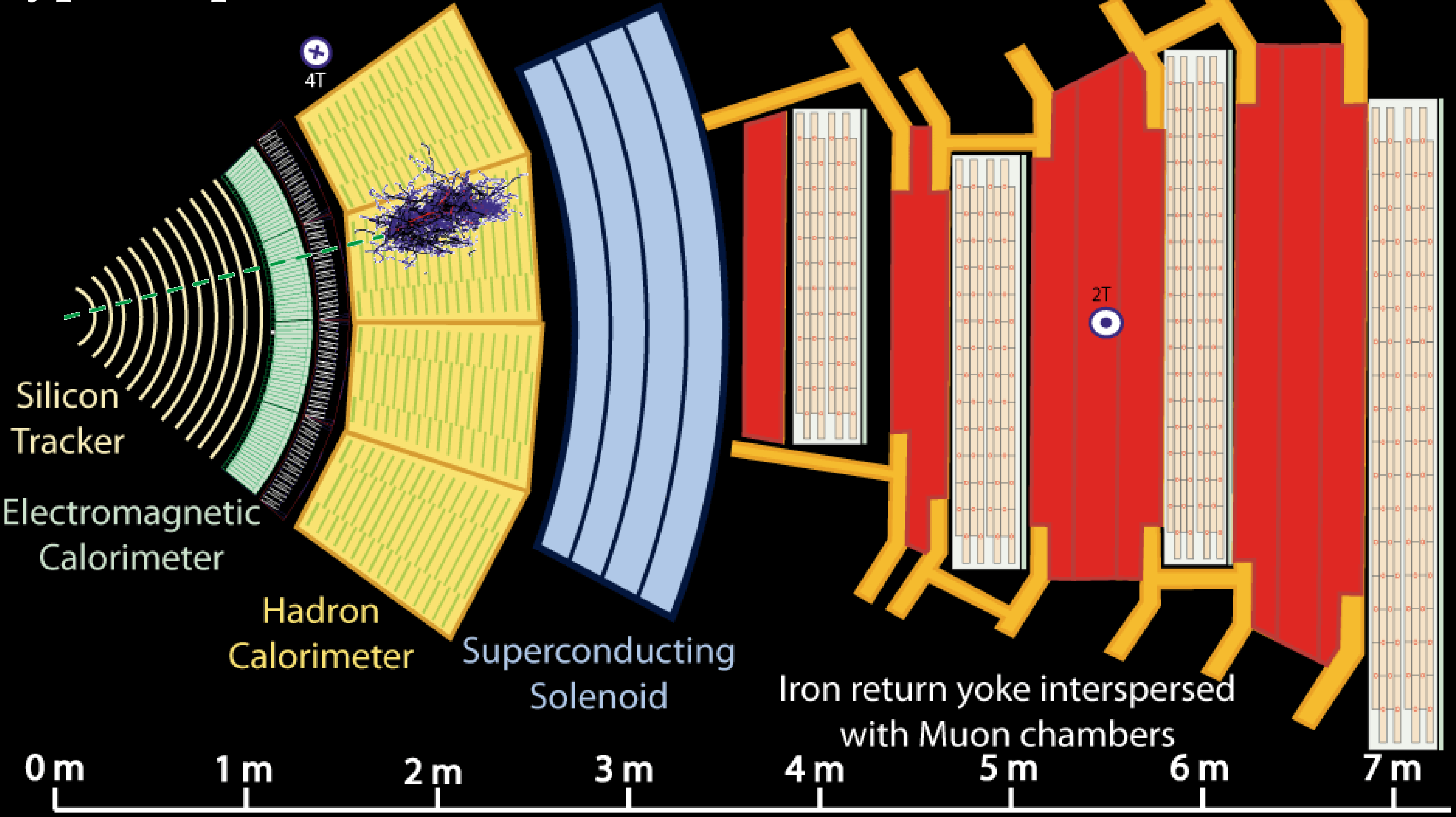
5 types of particles detected in the HEP detector: Charged Hadron



Key:

- Muon
- Electron
- Charged Hadron (e.g. Pion)
- Neutral Hadron (e.g. Neutron)
- Photon

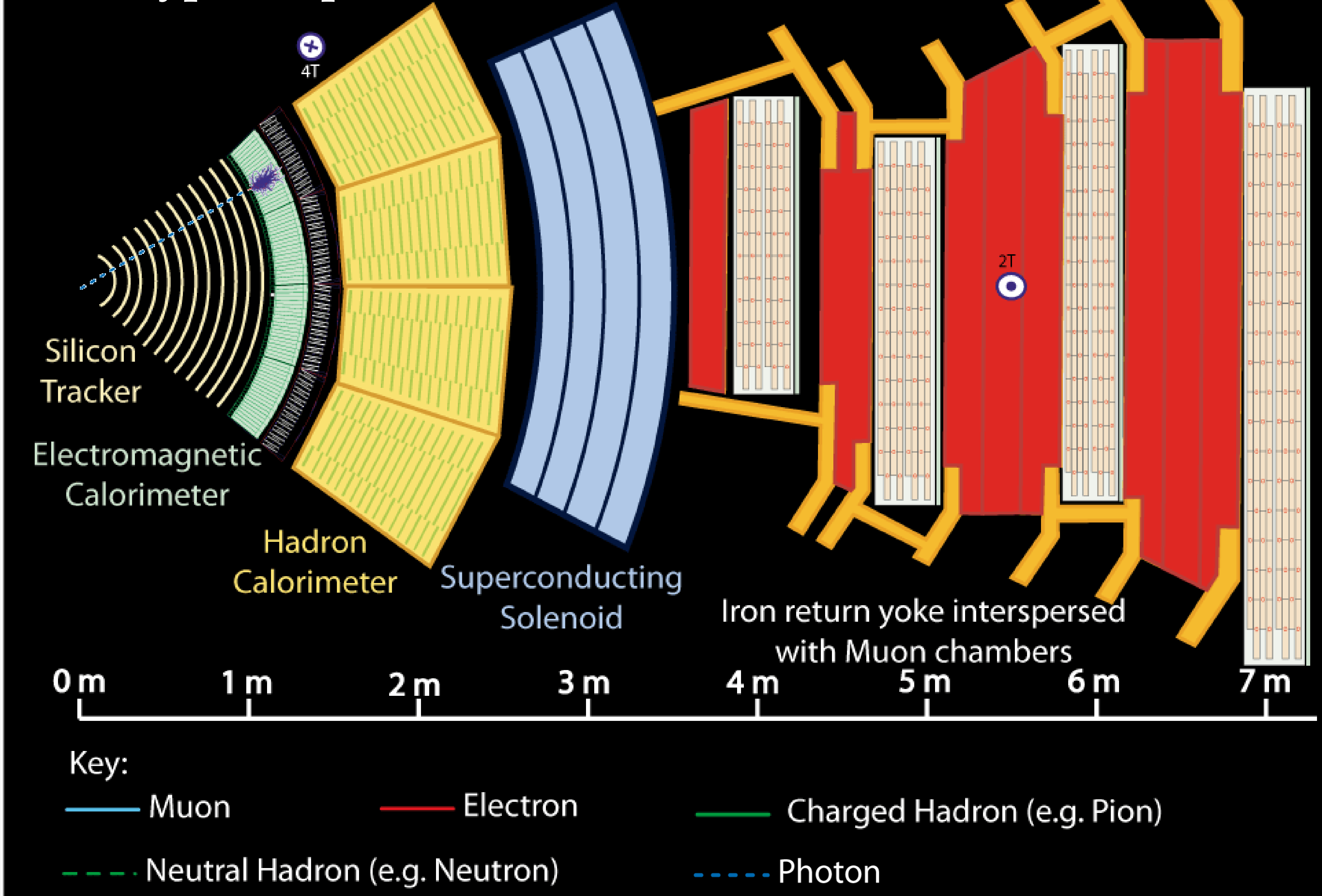
5 types of particles detected in the HEP detector: Neutral Hadron



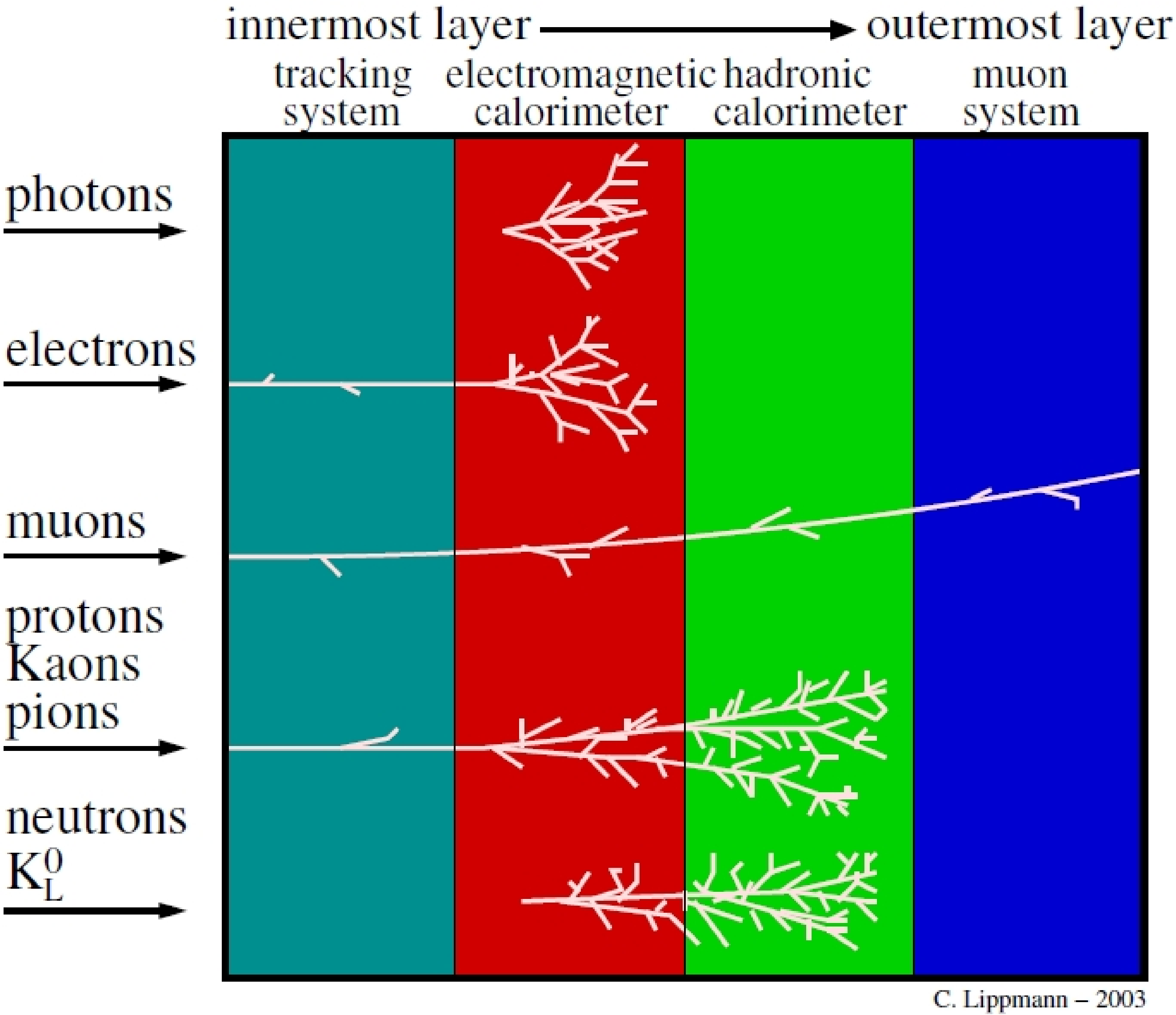
Key:

- Muon
- Electron
- Charged Hadron (e.g. Pion)
- Neutral Hadron (e.g. Neutron)
- Photon

5 types of particles detected in the HEP Detector: Photon



Particle Identification, first glance ID

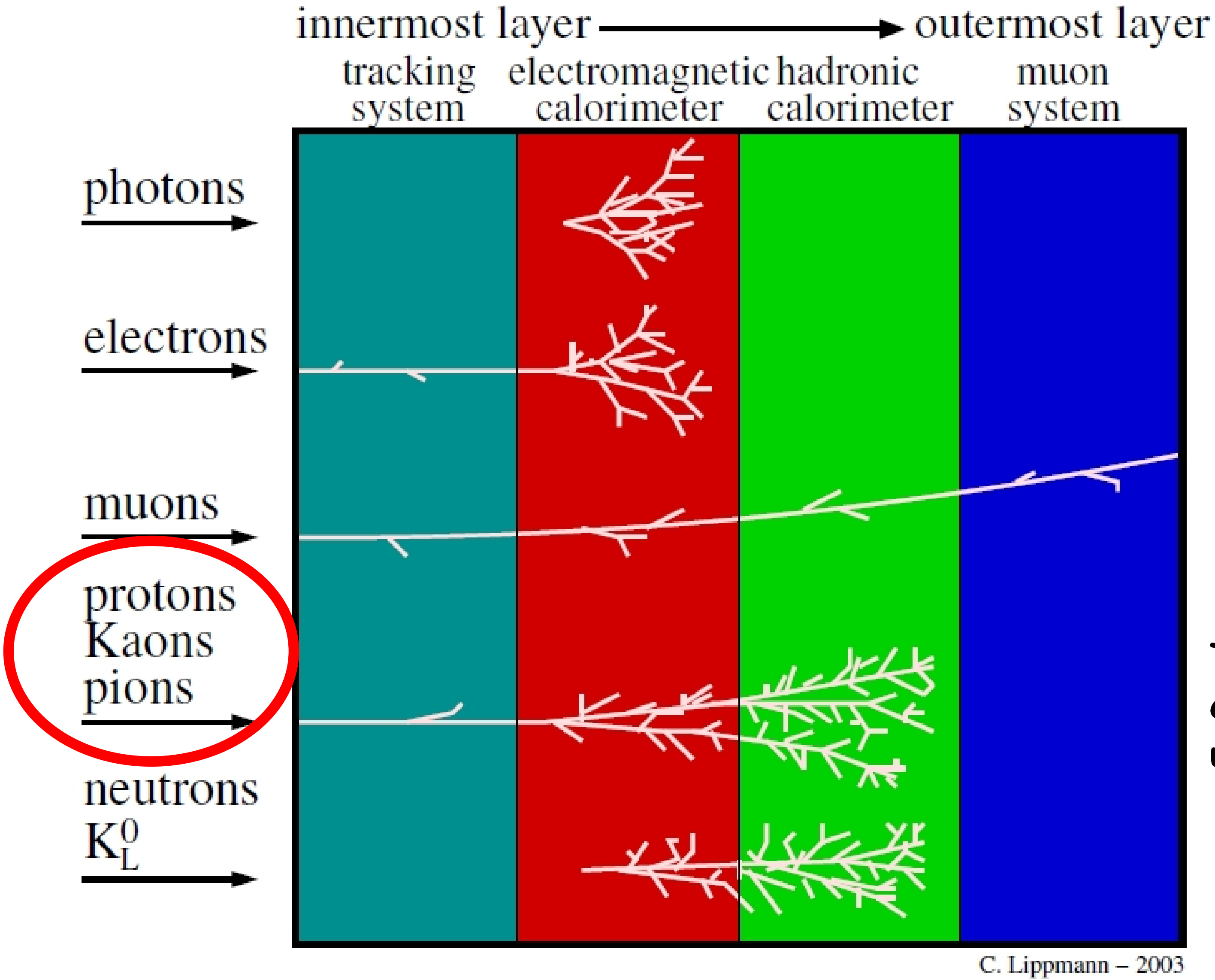


C. Lippmann – 2003

Reasonable Yes/No identification

… complicated by various backgrounds, depending on detector occupancy/granularity/efficiency/precision/noise/…

Particle Identification, first glance ID



C. Lippmann – 2003

Try to distinguish charged hadrons using more tools !

Reasonable Yes/No identification

… complicated by various backgrounds, depending on detector occupancy/granularity/efficiency/precision/noise/…

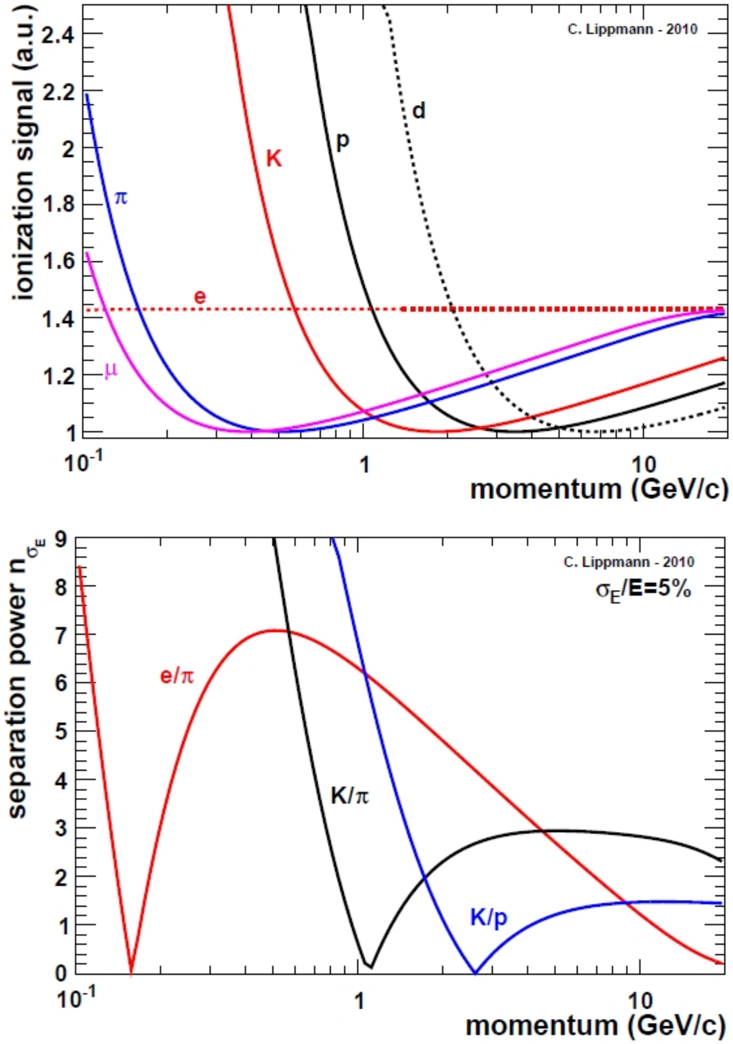
Particle Identification

Simultaneous measurement of momentum and velocity for charged hadrons

- ➔ Ionization, dE/dx
- ➔ Cherenkov light
- ➔ *Transition radiation*
- ➔ Time-of-flight measurement

Typical separation power achievable in gaseous detector.

Assumed energy resolution : 5%.



Cherenkov radiation detectors

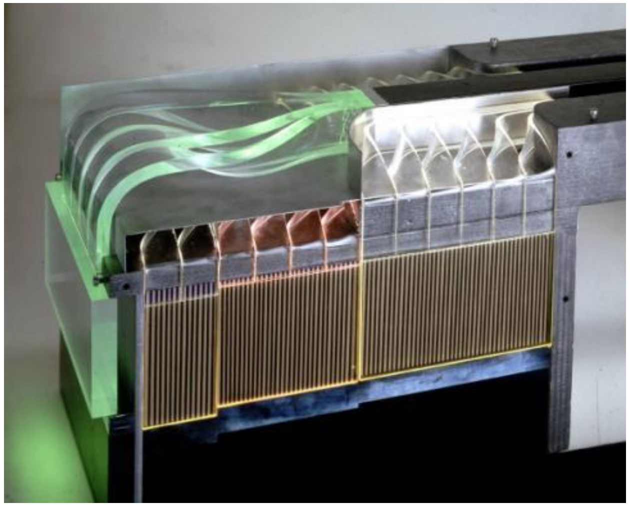
- ☐ Unique tool to identify charged particles with a high separation power over a range of momentum from few hundred MeV/c up to several hundred GeV/c

- ☐ A charged particle with velocity $\beta = v/c$ greater than local velocity of light in a medium with refractive index $n = n(\lambda)$ may emit light along a conical wave front.

- ☐ The angle of emission is given by:

$$\cos\Theta_C = \frac{1}{\beta \cdot n}$$

$$\boxed{\begin{aligned} \cos\theta_{max} &= 1/n \\ \beta_{min} &= 1/n \end{aligned}}$$

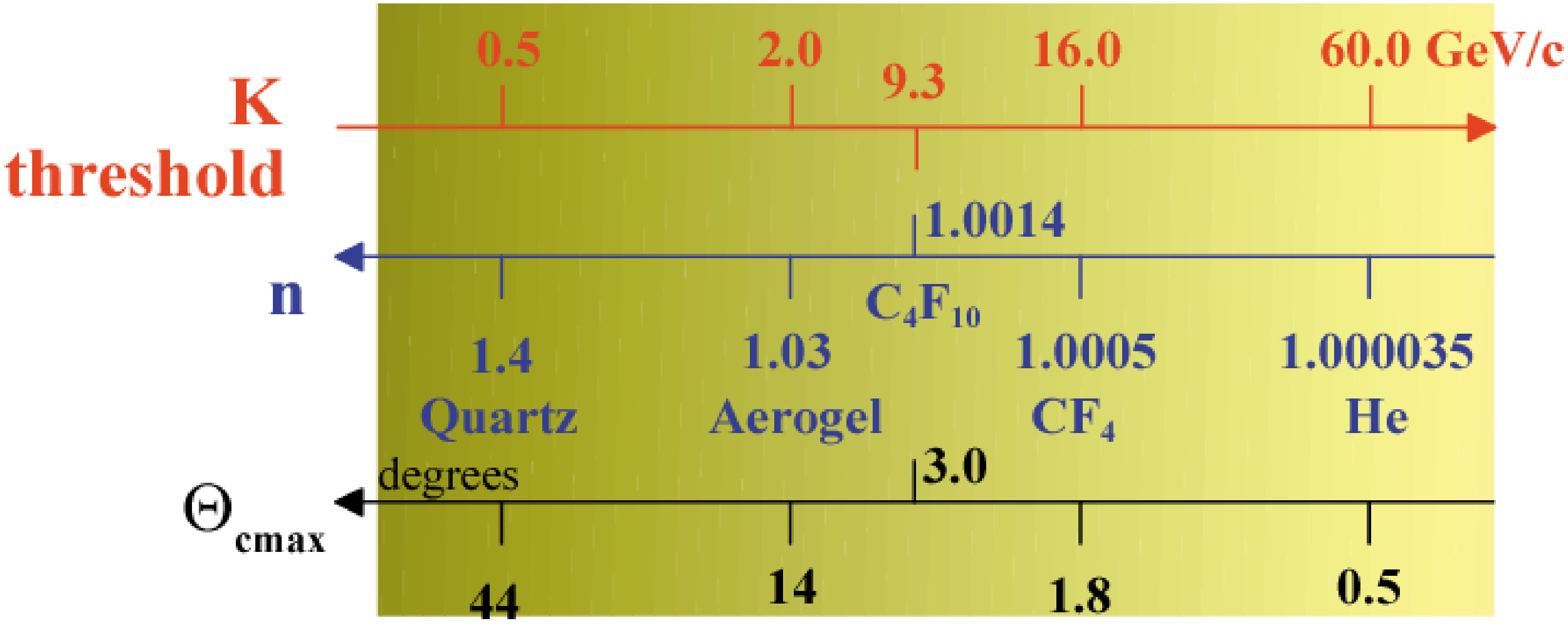


Radiator
+
Photon detector

➔ Particle ID : Threshold (detect Cherenkov light) and Imaging (measure Cherenkov angle) techniques

➔ Fast particle counters, tracking detectors, performing complete event reconstruction, ...

Threshold Cherenkov Detector: examples



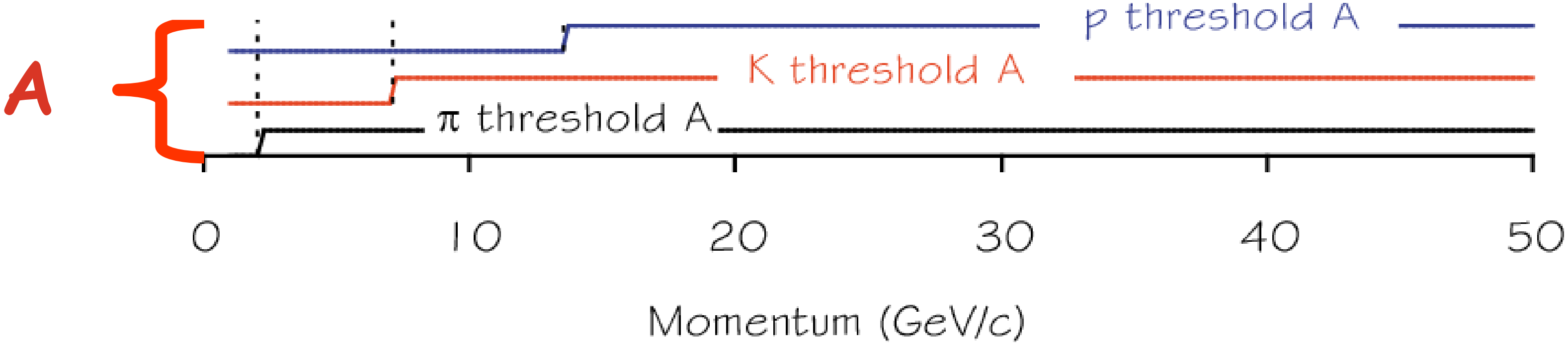
Threshold Cherenkov Detector: examples

To get a wider momentum range for particle identification, use more than one radiator.

Assume

A radiator: $n = 1.0024$

Positive particle identification:



Imaging Cherenkov Detector

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

$$m = \frac{p}{\beta\gamma}$$

$$\rightarrow \quad m = \frac{p}{\beta\gamma} = p\sqrt{n^2\cos^2\theta_c - 1}$$

$$\frac{\Delta m}{m} = \sqrt{\left(\frac{\Delta p}{p}\right)^2 + \left(\gamma^2 \cdot tg\theta \cdot \Delta\theta\right)^2}$$

$$\sigma_\theta^2 = \sum_i \Delta\theta_i^{\,2} \Rightarrow \sigma_{\theta_c} = \frac{\sigma_\theta}{\sqrt{N_{p.e.}}}$$

- ➔ **minimize** σ_θ
- ➔ **maximize** $N_{p.e.}$

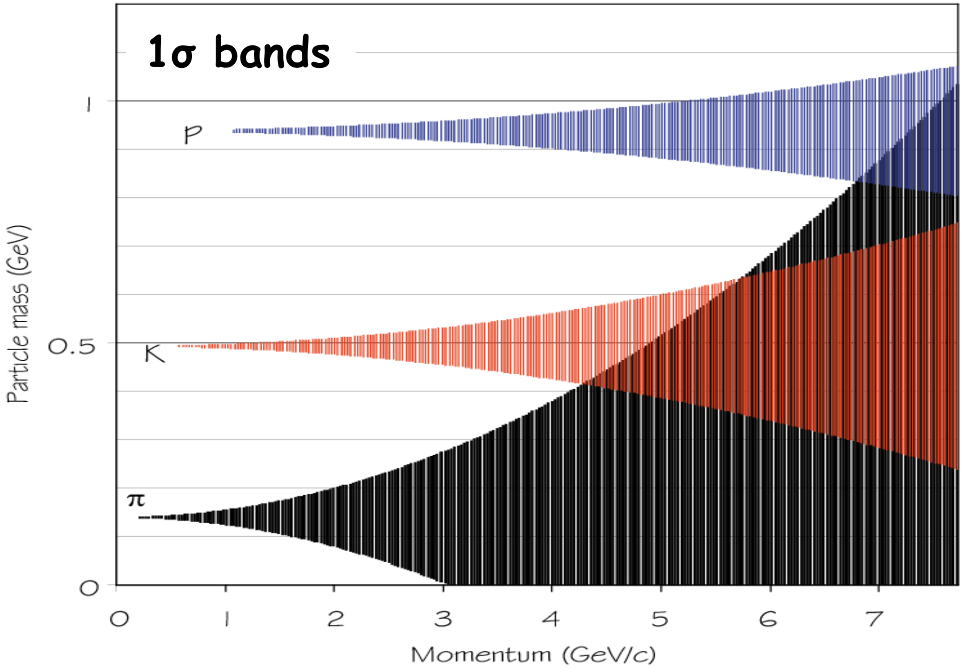
➡

low chromaticity
high granularity
high packing density

Goal: detect the maximum number of photons with the best angular resolution

set :
n = 1.333 (H_2O) → θ_{max} = 41.4 °, β_{min} = 0.75

$\Delta p/p^2$	$5 \cdot 10^{-4}$
$\Delta\theta$	15 mrad
L	1 cm



Imaging technique: measure Cherenkov radiation angle

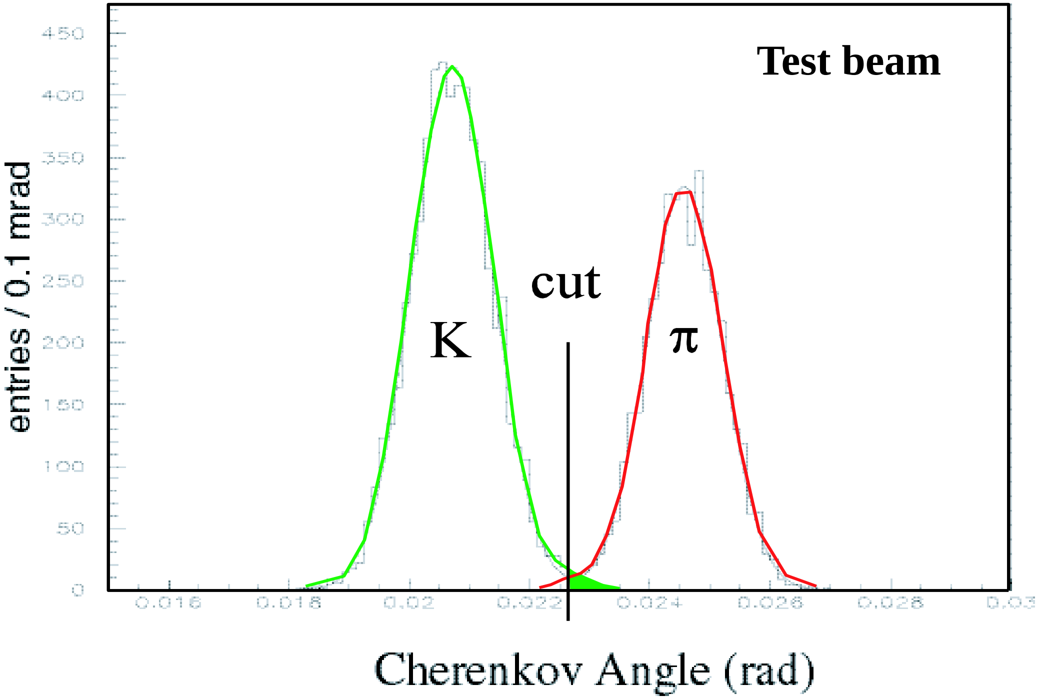
Separation power:

$$\theta_2 - \theta_1 = n\sigma_{\theta_c}$$

- Separating K and π, illustration from a test beam
- ~ Gaussian response, σ_θ ~ 0.7 mrad
  Peaks are separated by 4 mrad = 6 σ_θ

Generally: $$N_\sigma = \frac{|m_1^2 - m_2^2|}{2\,p^2\,\sigma_\theta\,\sqrt{n^2-1}}$$

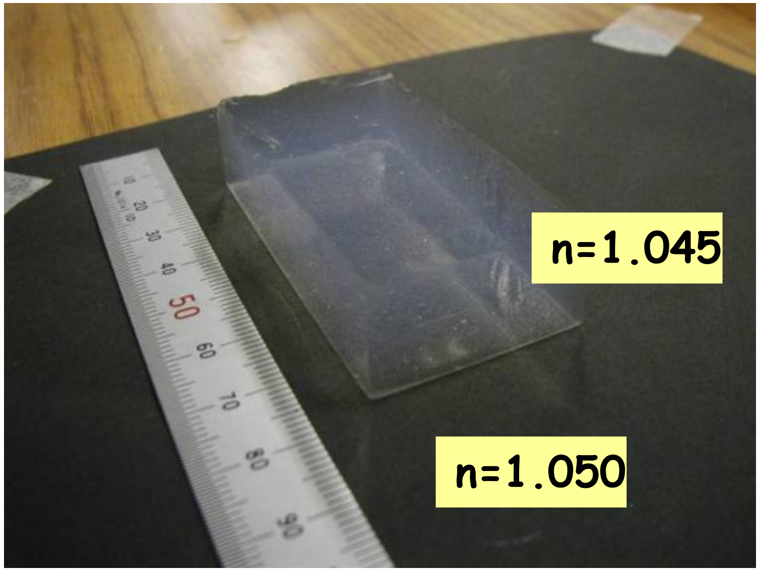
- Adjusting the position of the cut placed between the two peaks to identify a candidate as K or π gives a trade-off between *efficiency* and *misidentification*

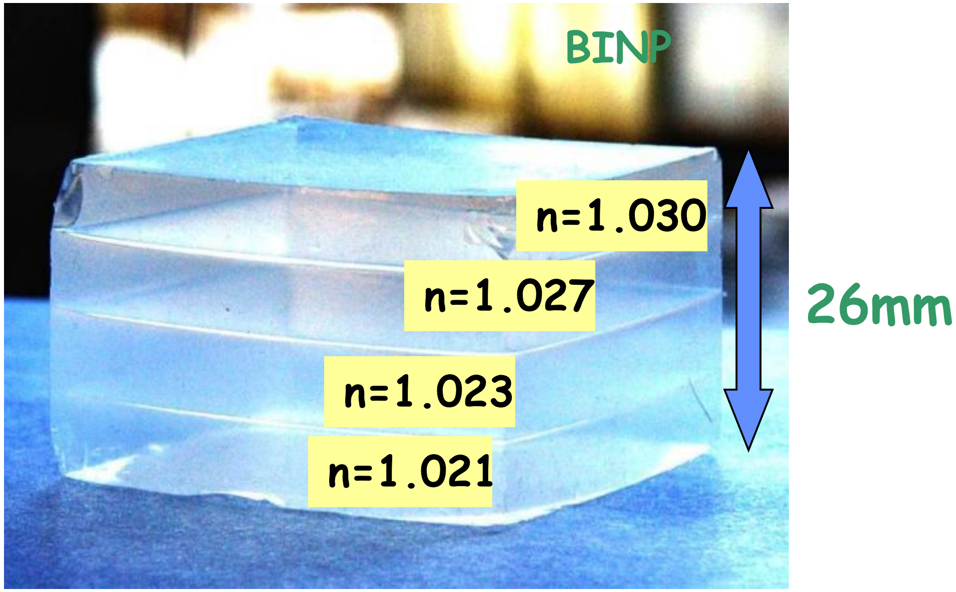


- The overall resolution determines how high in momentum particles can be distinguished, since the increase in Cherenkov angle *saturates*, so the radius for different *mass hypotheses* get closer together

Adjust precisely the value of refractive index n: Silica aerogels with different n (1.007 - 1.13)

Aerogel with layers of different n attached directly at molecular level



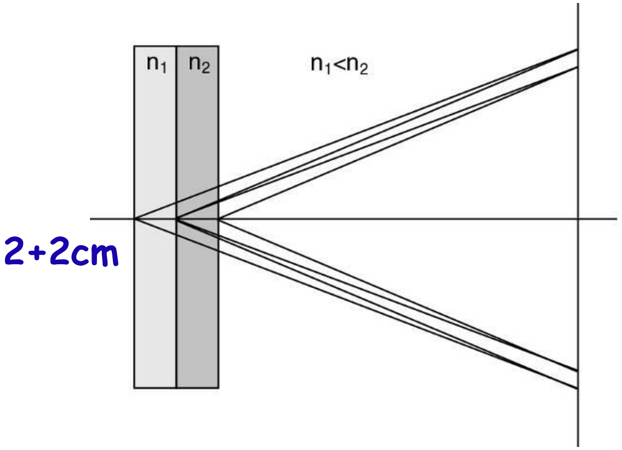


Aerogel is a manufactured material with the lowest density of any known solid. Derived from a gel in which the liquid component of the gel has been replaced with a gas.

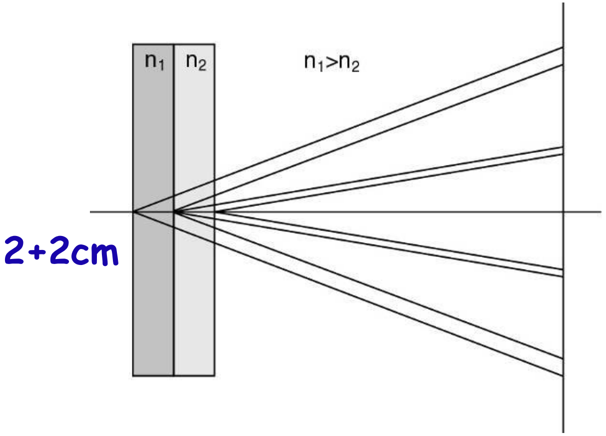
Aerogel RICH for SuperBelle (R&D)

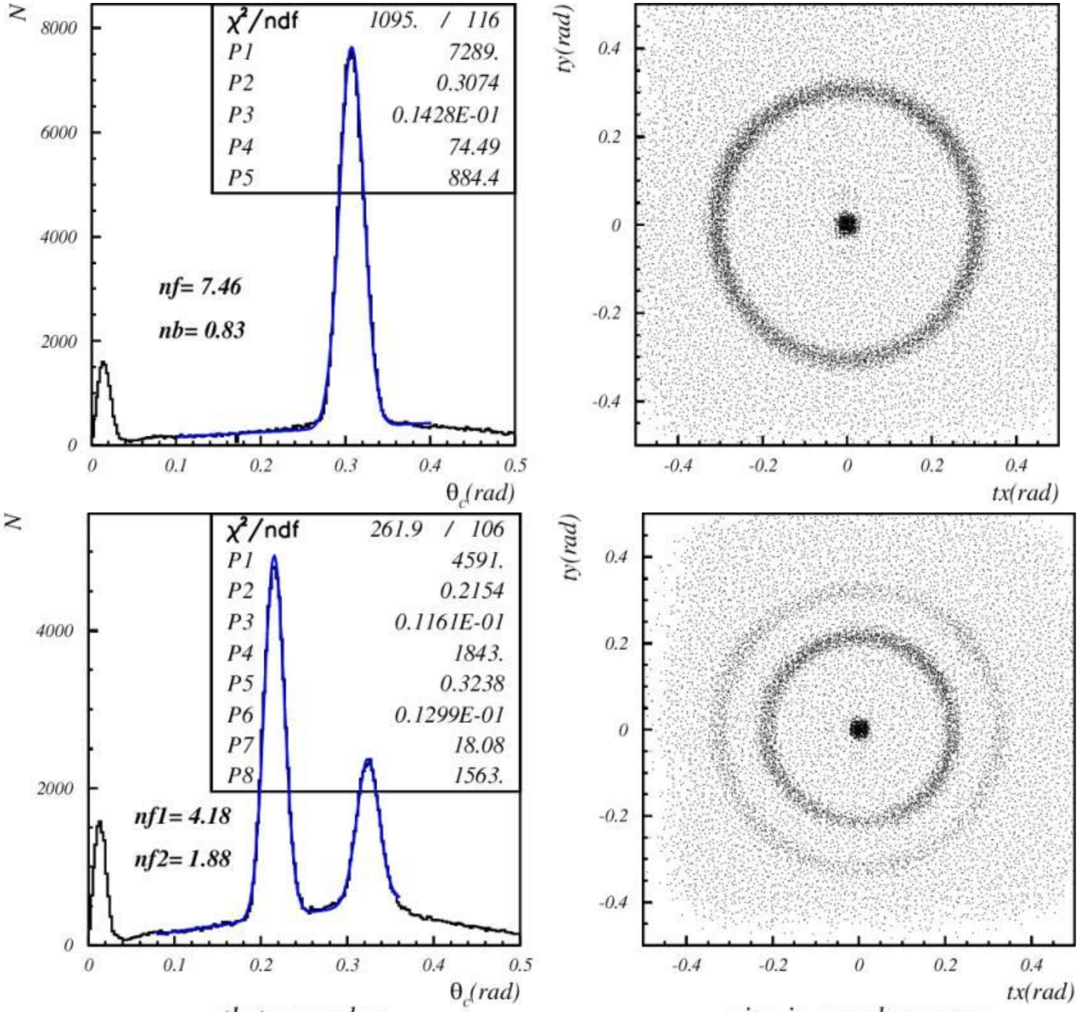
Aerogel with multiple refractive indices increases Nph without degrading angular resolution

"**focusing**" configuration n1<n2



"**defocusing**" configuration n1>n2





theta cerenkov

ring in cerenkov space

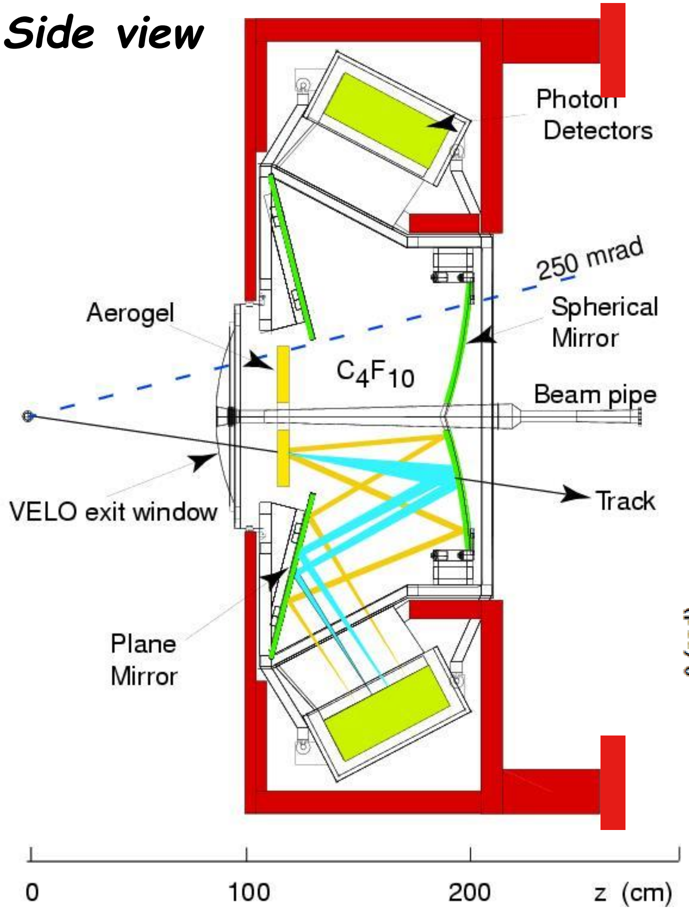
LHCb: charged hadron identification with RICH detectors

2 Ring Imaging Cherenkov Detectors (RICH): 3 Radiators, photons from Cerenkov cone focused onto rings recorded by Hybrid Photon Detector (HPD) arrays, out of acceptance

RICH 1

Acceptance 25-300 mrad

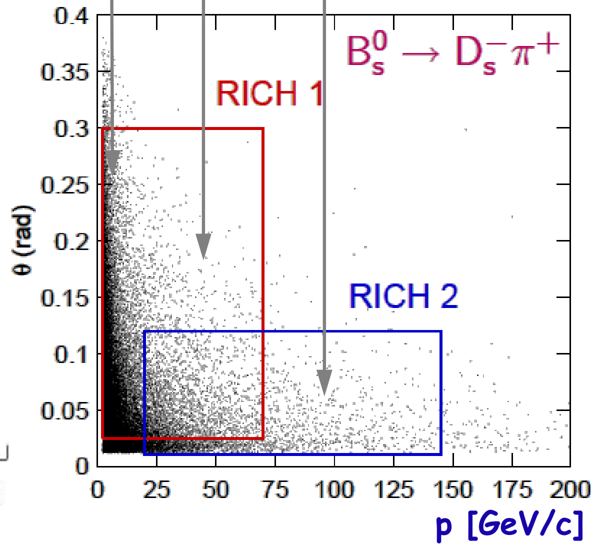
Side view



Silica Aerogel:
n=1.03
1-10 GeV/c

C_4F_{10}:
n=1.0014
Up to ~70 GeV/c

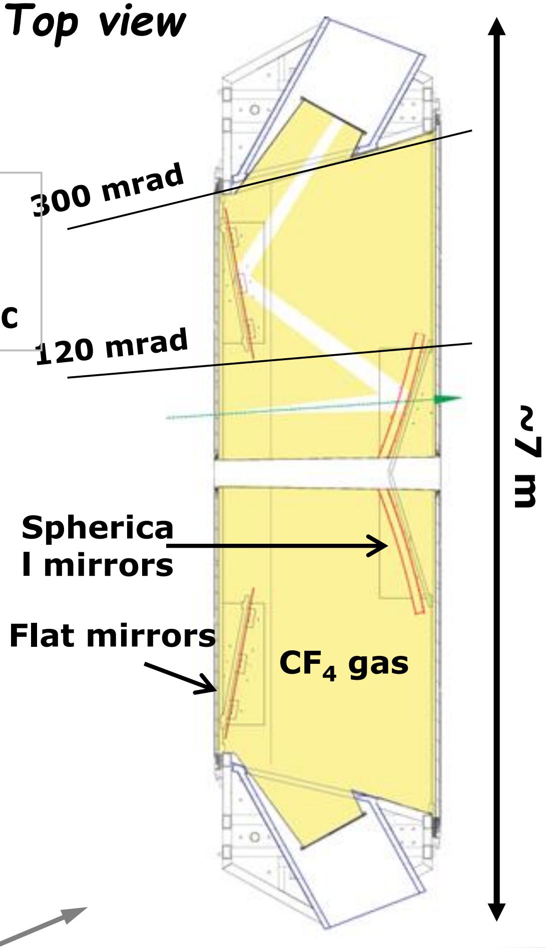
CF_4:
n=1.0005
Up to ~100 GeV/c



RICH 2

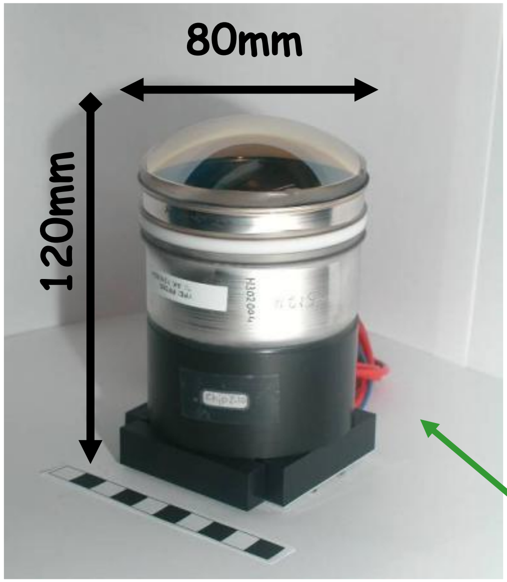
Acceptance 15-120 mrad

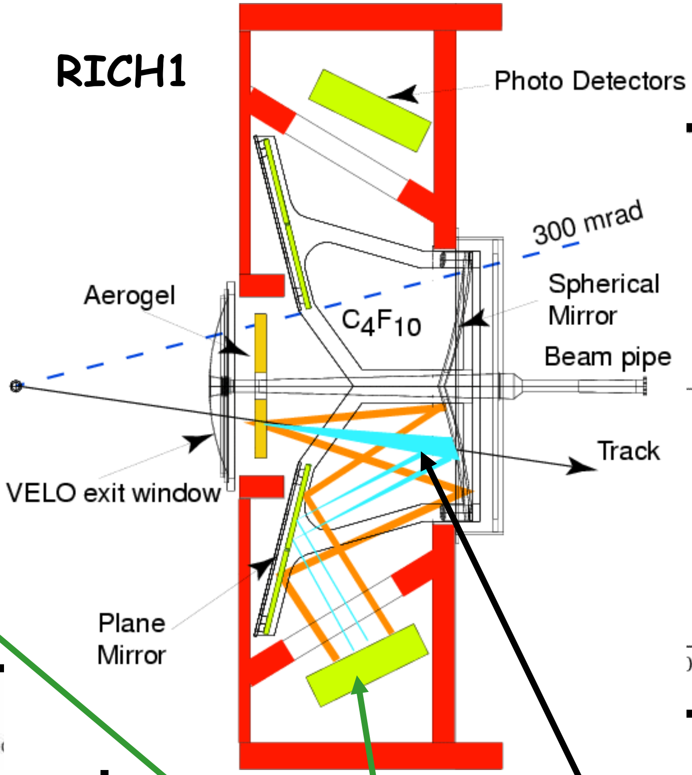
Top view

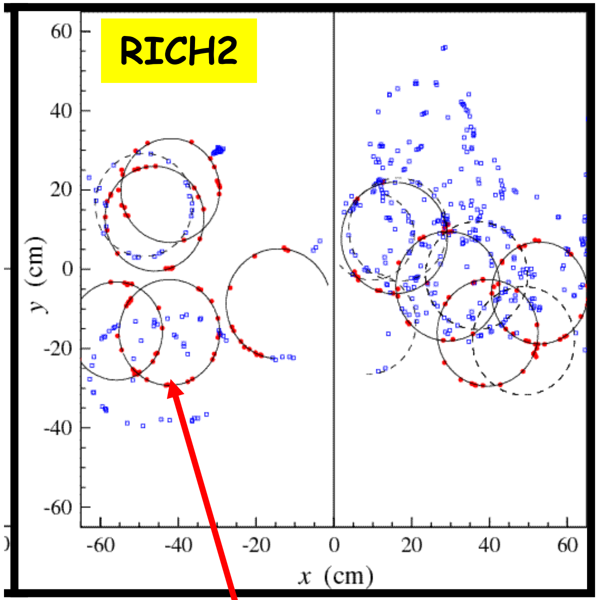


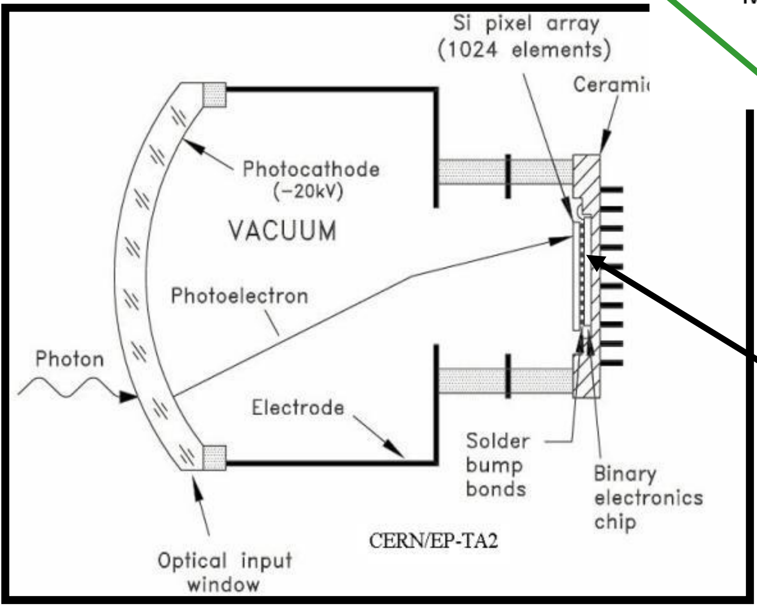
Note scale difference

LHCb: charged hadron identification with RICH detectors









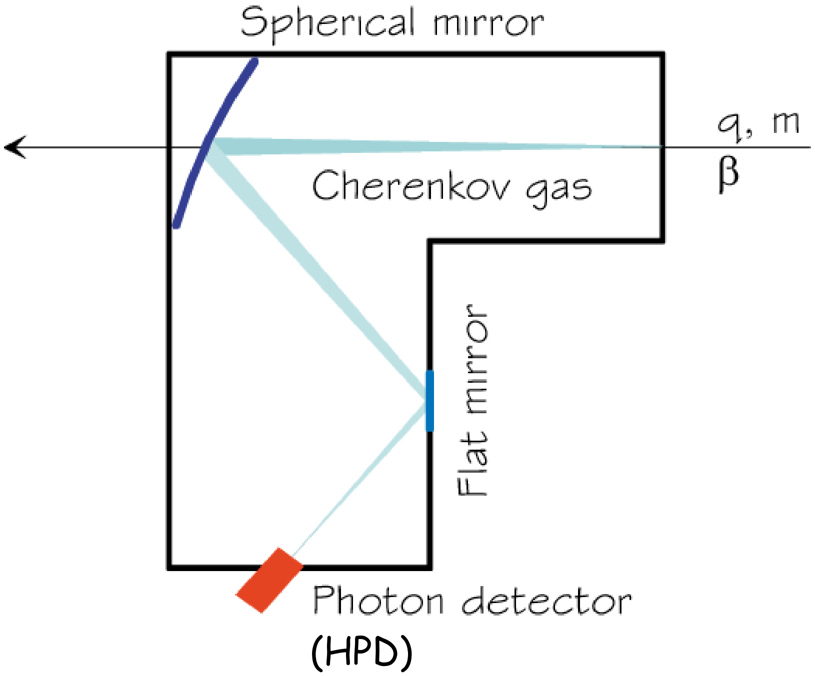
Photons from Cerenkov cone
focused onto rings
recorded by

Hybrid Photo Diodes arrays, out of acceptance.
Each containing a 1024 Si pixel array.

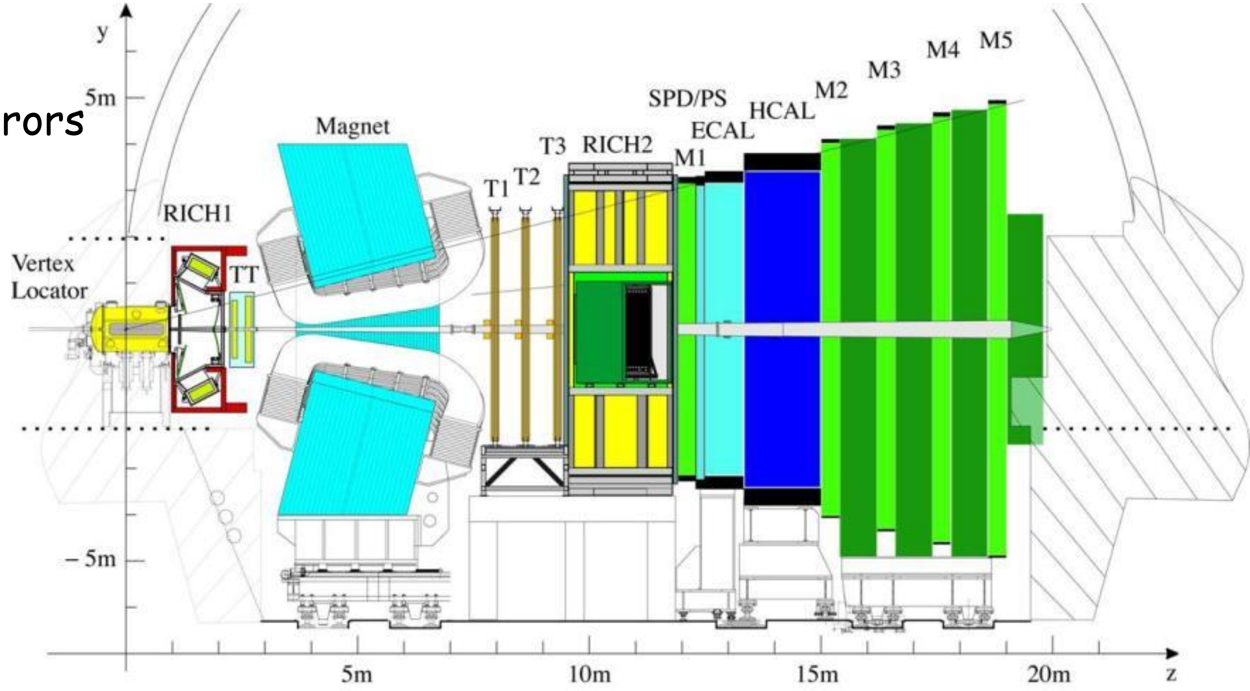
RICH1: Aerogel and C_4F_{10} RICH2: CF_4

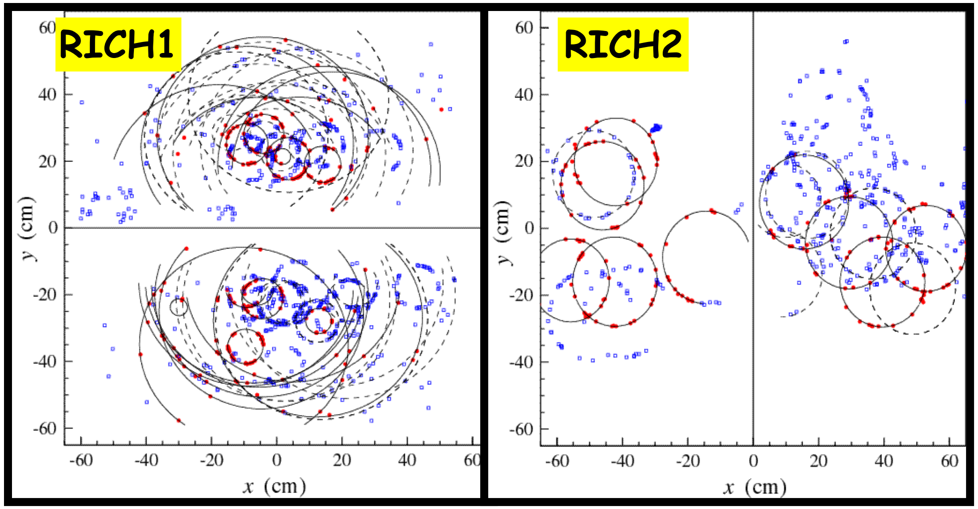
Position photodetectors in tolerable radiation zone

- ➔ Guide the light outside hot area
- ➔ System of large, precise, minimum material and radiation hard mirrors



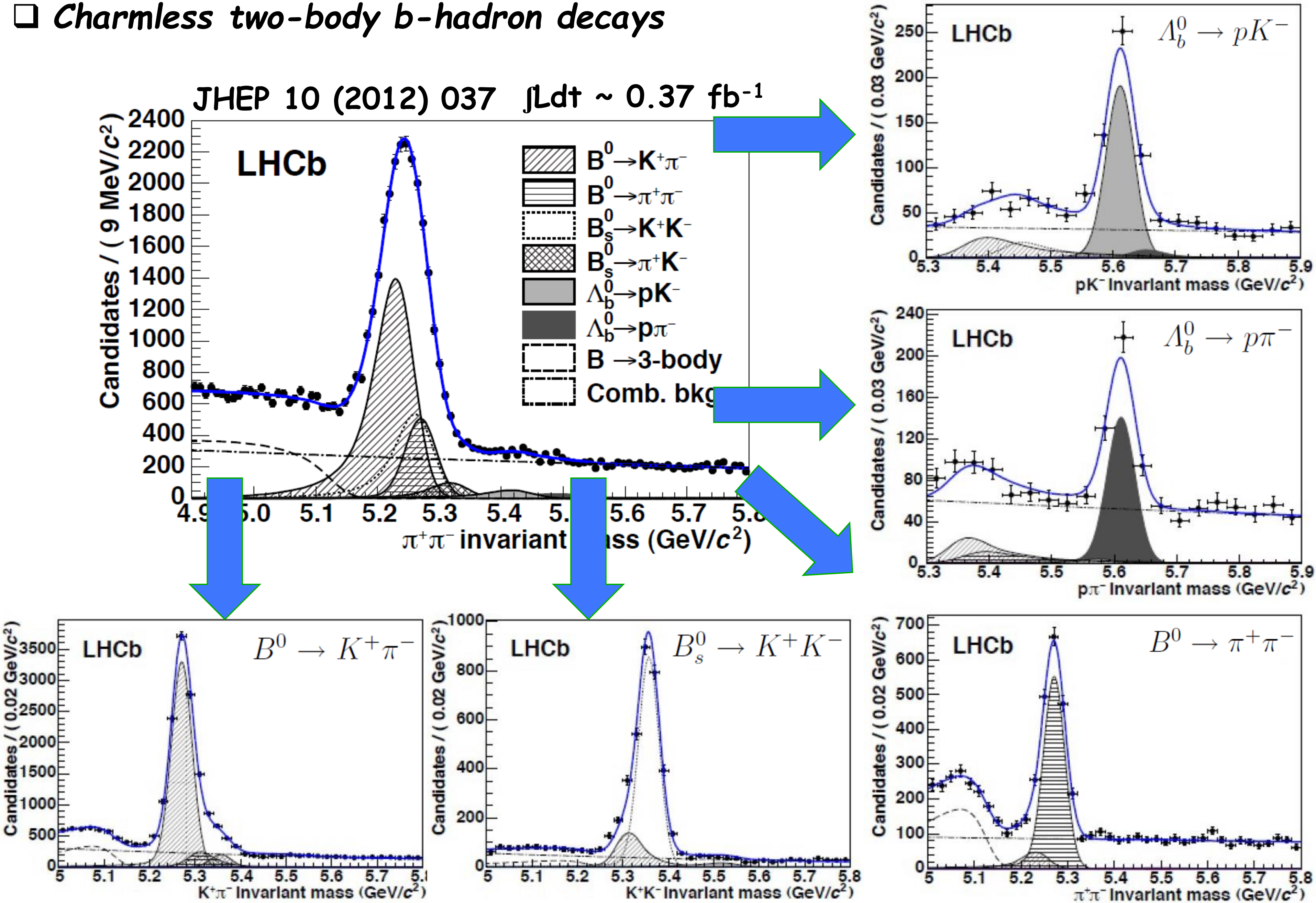
Keep few 10 mrad resolution !





LHCb: charged hadron identification with RICH detectors

- ☐ ***Charmless two-body b-hadron decays***



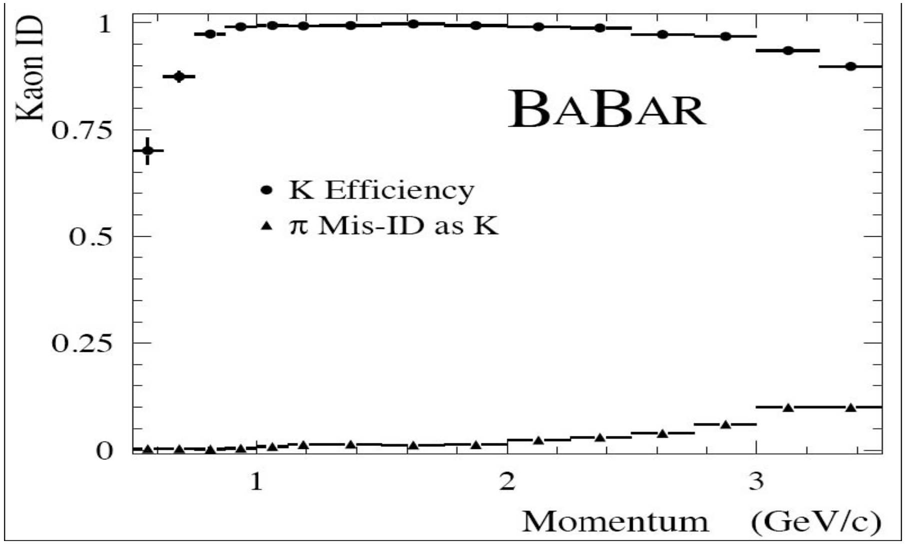
JHEP 10 (2012) 037 ∫Ldt ~ 0.37 fb^{-1}

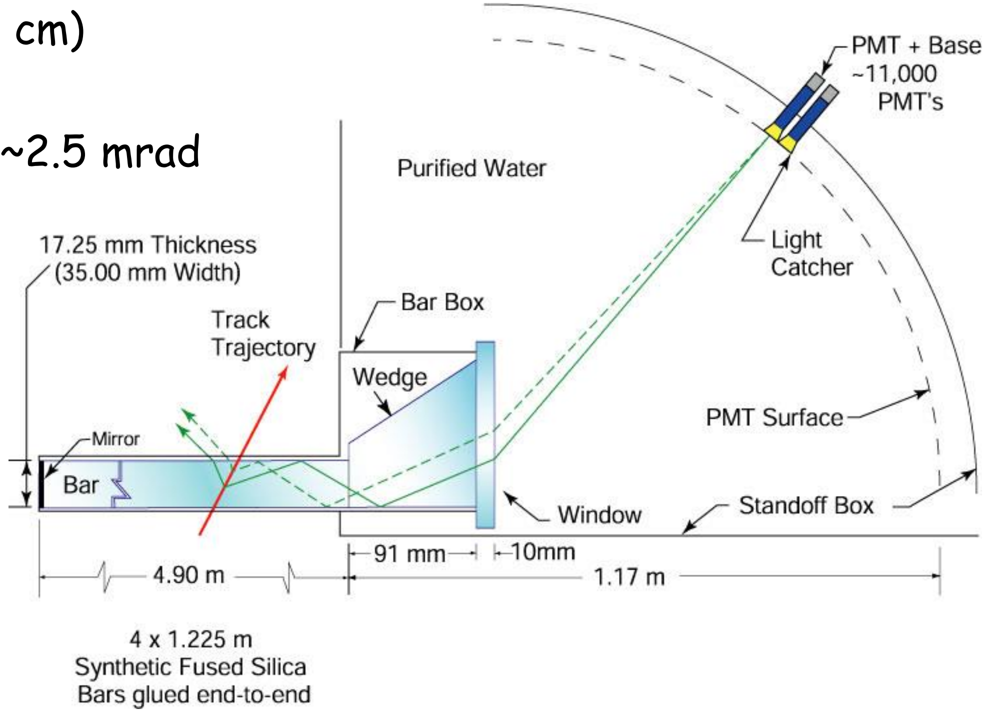
Fast focusing Detector of Internally Reflected Light (DIRC at BaBar)

Secure escape of light towards photodetectors in 4π experiment

- Detector of Internally Reflected Cherenkov light (BaBar experiment) uses **quartz as the radiator and as a light guide**
- Light trapped inside quartz bars by *total internal reflection* → takes little radial space
- TIR preserves the angles of the photons, detection at end of bars using PM array

- 144 fused silica radiator bars (1.7 x 3.5 x 490 cm)
- 11000 PMTs
- Cherenkov polar angle measurement precision ~2.5 mrad
- Good K/π separation up to ~3.5 GeV





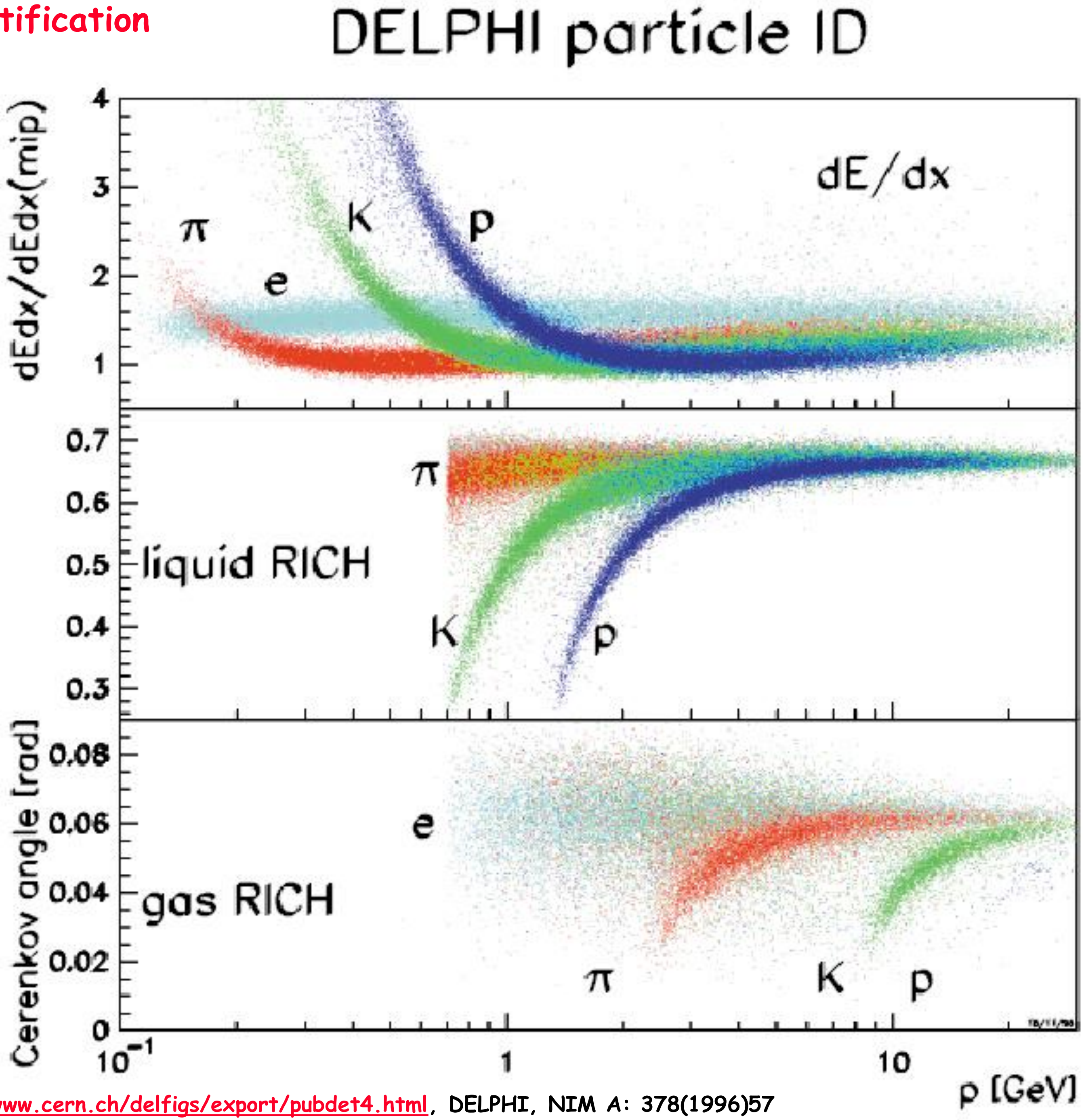
I. Adam et al.,
Nucl.Inst.&Meth., A 538 (2005) 281-357

Example: DELPHI **Particle Identification** with the

TPC

and

RICHes



Can do it with data:

p from Λ

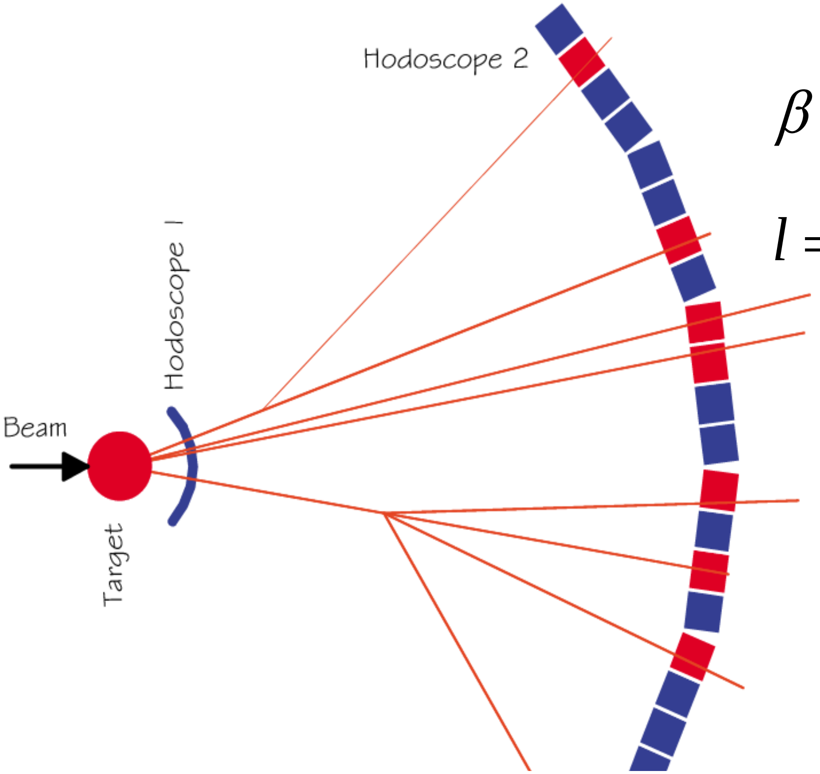
K from Φ

π from K^0

http://delphiwww.cern.ch/delfigs/export/pubdet4.html, DELPHI, NIM A: 378(1996)57

Time-of-Flight (TOF): measurement

- ☐ Traditional approach to TOF uses scintillator hodoscopes
- ☐ Organic scintillators yield light on a timescale of ~100 ps (Inorganic are slower)
- ☐ Resolution improves if light yield increased, as can average over the detected photons arrival times



$$\left.\begin{array}{l}\beta\cdot\gamma=\dfrac{p}{m}\\ l=v\cdot t\end{array}\right\}\ m^2=\frac{p^2}{l^2}\left[c^2t^2-l^2\right]$$

$$\left(\frac{\Delta m}{m}\right)^2=\left(\frac{\Delta p}{p}\right)^2+\gamma^2\left[\left(\frac{\Delta t}{t}\right)^2+\left(\frac{\Delta l}{l}\right)^2\right]$$

→ **Time-to-Digital Converter (TDC) resolution**

- ☐ Can simplify by using time of beam crossing to provide the "start" signal
- ☐ Due to magnetic field, tracks are not straight lines
  → use tracking to determine actual path length
- ☐ Multiple tracks would give rise to ambiguous solutions
  → detector is segmented according to the expected track multiplicity

TOF: limits to performance

Particle separation power (TOF) :

$$n_{\sigma_t,1-2} = \frac{\Delta t_{1-2}}{\sigma_t} = \frac{L}{c\sigma_t}\left(\frac{1}{\beta_1}-\frac{1}{\beta_2}\right) \approx \frac{Lc}{2p^2\sigma_t}\left(m_1^2-m_2^2\right)$$

Cf. RICH separation power :

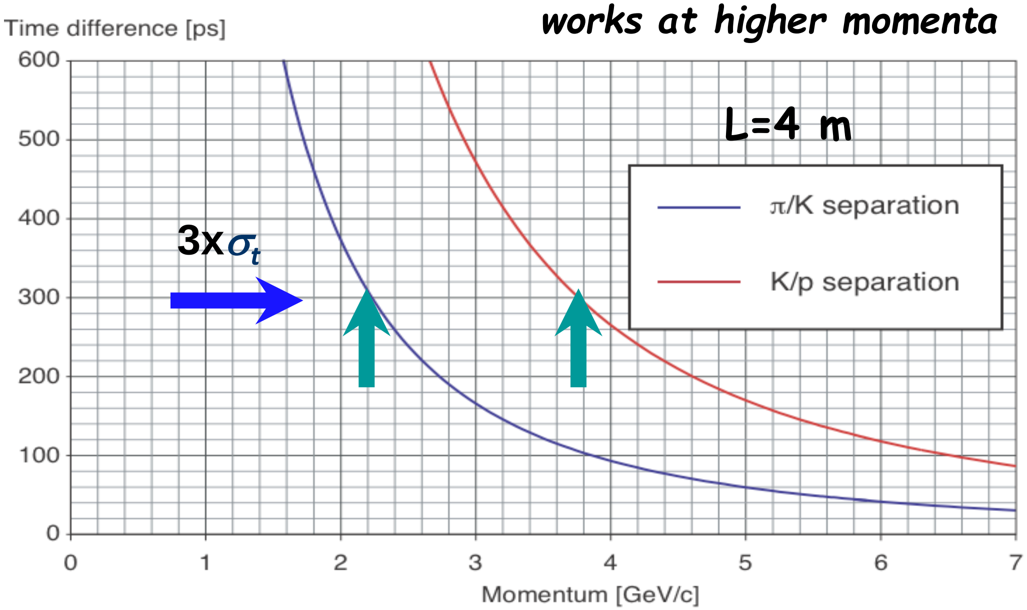
$$N_\sigma = \frac{|m_1^2 - m_2^2|}{2\ p^2\ \sigma_\theta \sqrt{n^2-1}}$$

works at higher momenta

Example:
L= 4 m
σ_t= 100 ps

→ π/K up to 2.2 GeV/c
→ K/p up to 3.7 GeV/c

For momenta above some GeV/c particle discrimination is almost lost !



Conventional TOF (scintillator + PMTs)

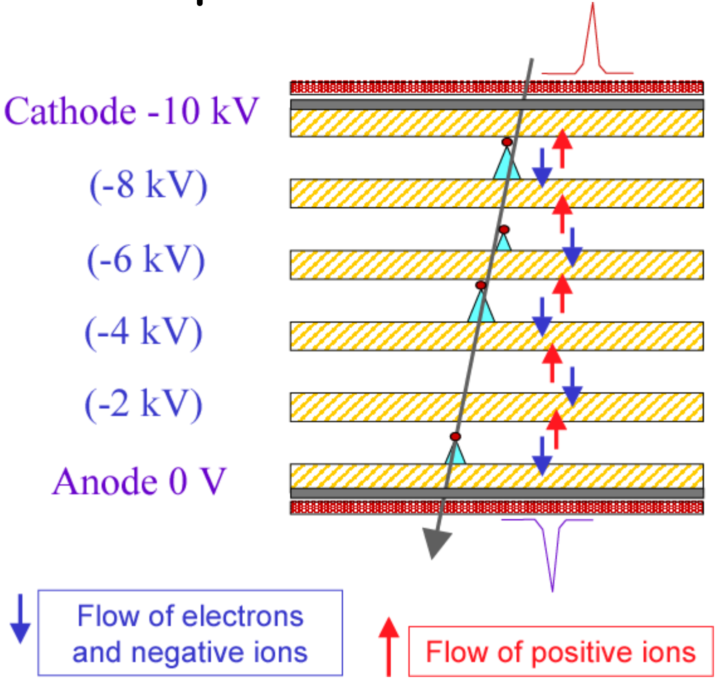
- ☐ Well proven technology
- ☐ Good time resolutions -> 50-100 ps (r/o at both ends of the scintillator bar)

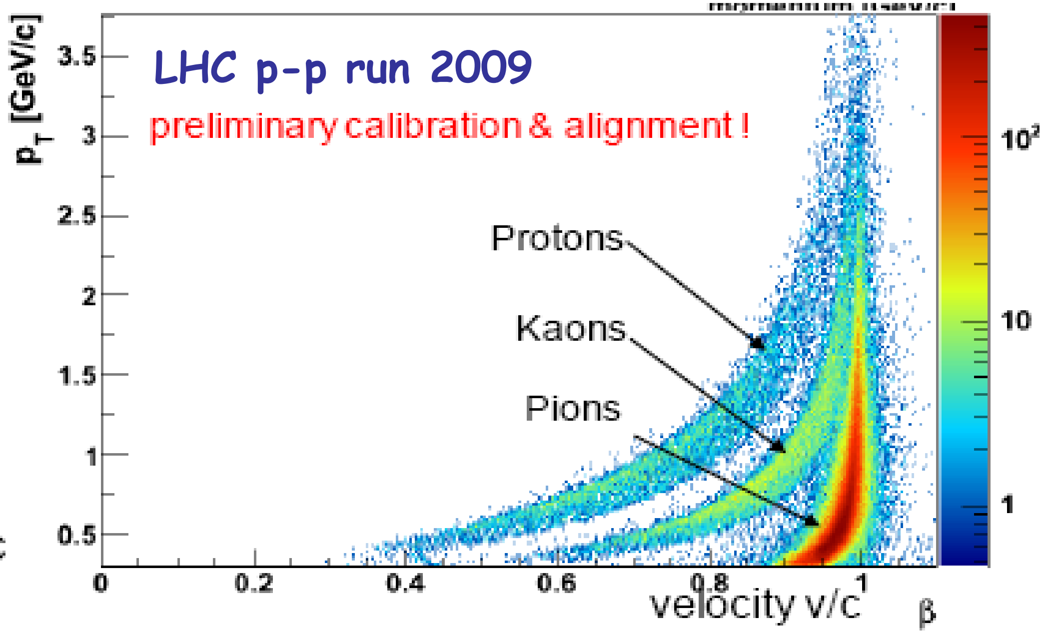
- ☐ Sensitive to B
- ☐ Expensive

TOF based on fast gaseous counters

- ☐ Not sensitive to B
- ☐ Very good time resolutions → 30-50 ps
- ☐ Cost effective solution for large surfaces
- ☐ Capability at high rates

Example:
use of MultiGap Resistive Plate Chambers



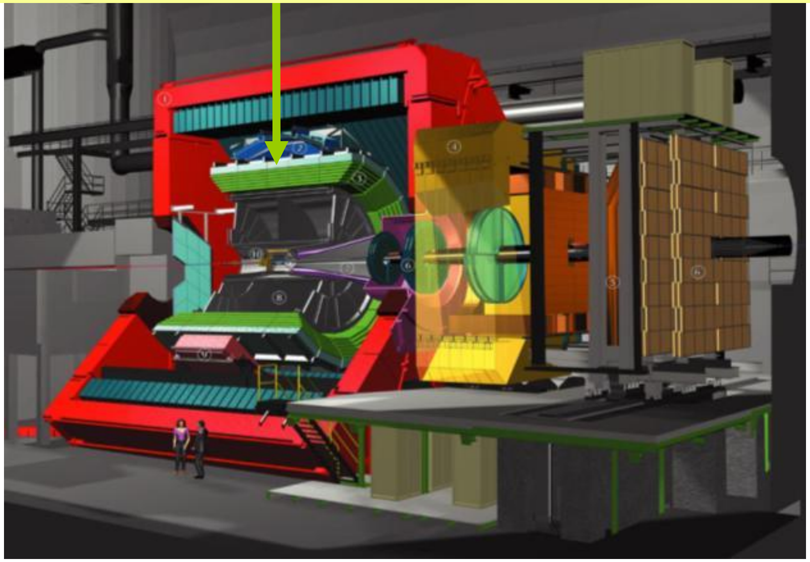

LHC p-p run 2009

preliminary calibration & alignment !

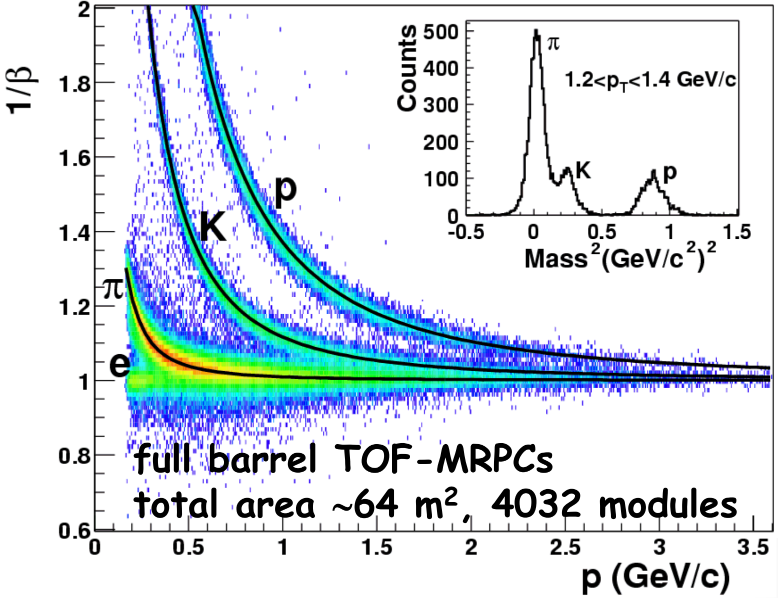
Example: ALICE and STAR MRPC TOFs

Barrel with radius of 3.7 m, divided into 18 sectors

1674 strips in total, 160 m² and 160,000 channels



STAR experiment at RHIC



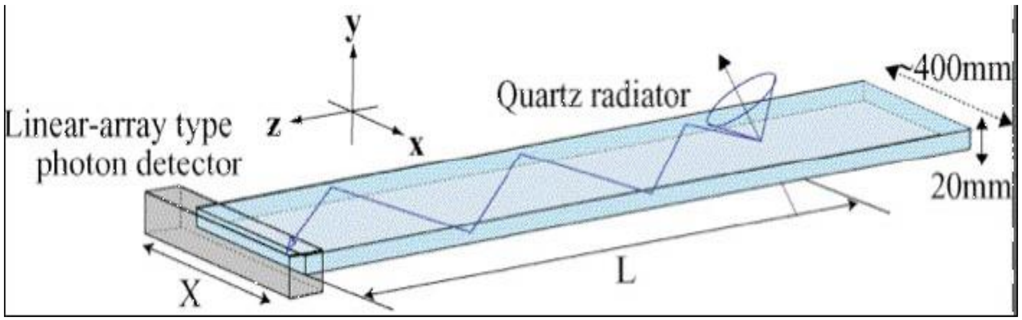
full barrel TOF-MRPCs

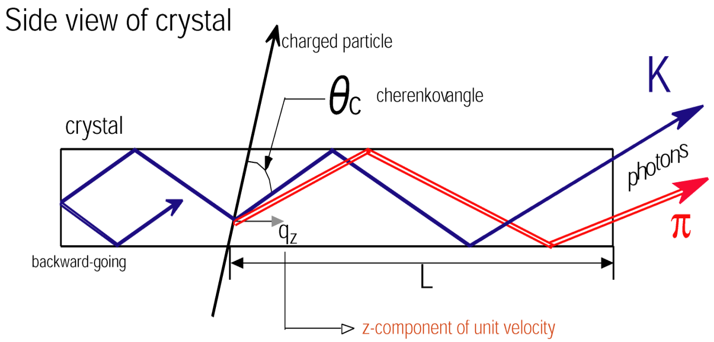
total area ~64 m², 4032 modules

Time Of Propagation (TOP) detector

Combine Time-Of-Propagation (TOP) of Cherenkov photons to a bar-end and their emission angles at the bar-end ➔ ring image information

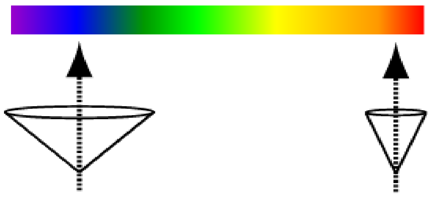
NIM A453(2000)331





$$TOP = \frac{L\cdot n_g(\lambda)}{c\cdot q_z}$$

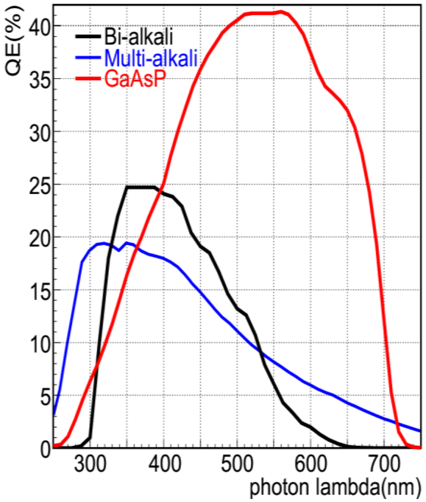
$t_K - t_\pi$(3 GeV/c)=75 ps for 1 m flight path

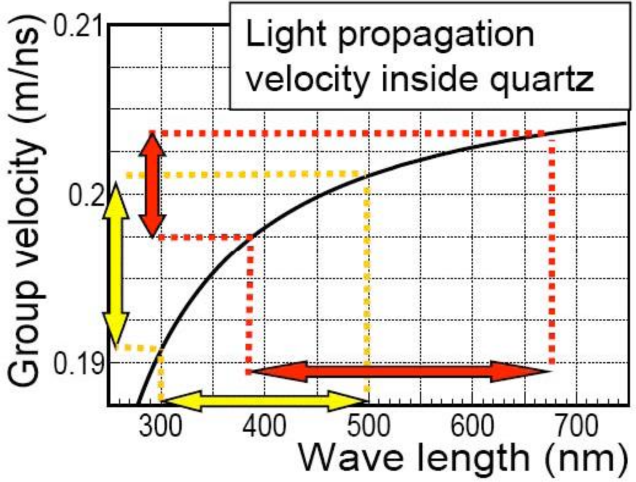


$\Delta\theta_c$~1.2mrad

Chromatic time dispersion: ~ 100 ps

Yellow: bialkali photocathode
Red: GaAsP photocathode





Requirements to MCP-PMT

- **high QE ;**
- **longer wavelengths,**
  (group velocity spread is smaller)

Time resolution ~35 ps for single p.e.

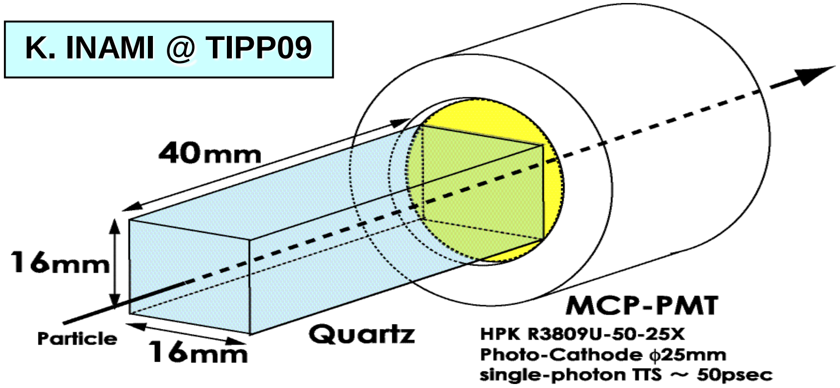
Further improvements: add photons reflected from the other side of the quartz bar, add TOF to the quartz bar information, …

TOF from Cherenkov light: R&D

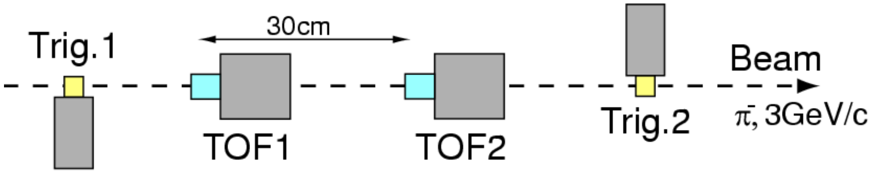
Y.Enari NIM A547 (2005) 490
K.Inami NIM A560 (2006) 303

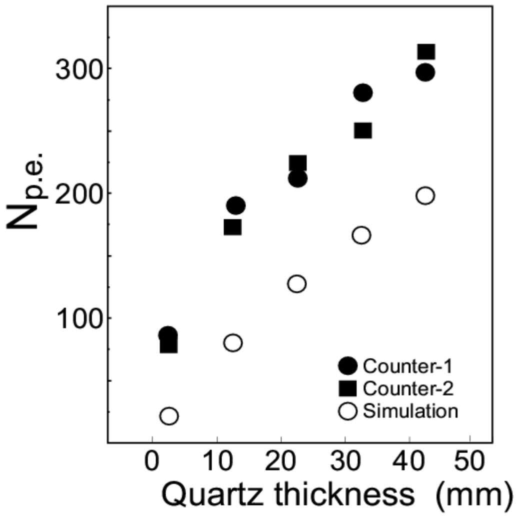
Exploit Cherenkov light

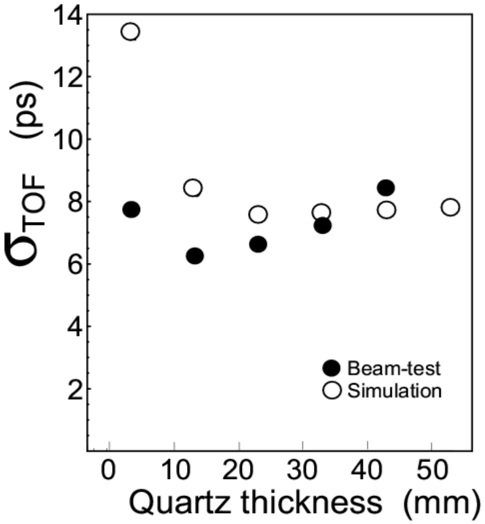
- ☐ Produced promptly
- ☐ Almost no time jitter (directionality)
- ➔ TORCH (TOF + RICH) concept

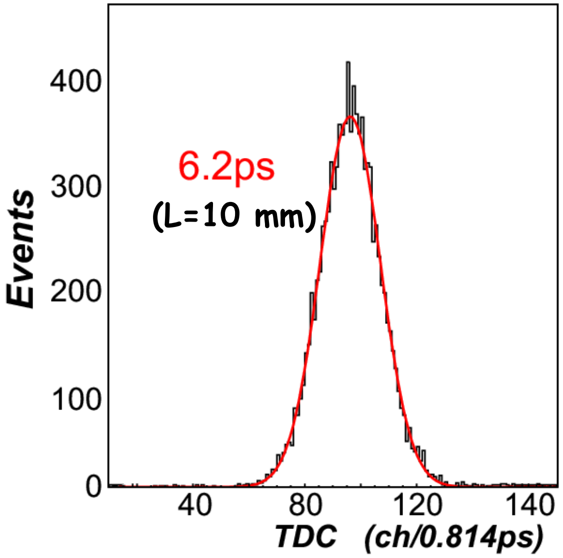


K. INAMI @ TIPP09

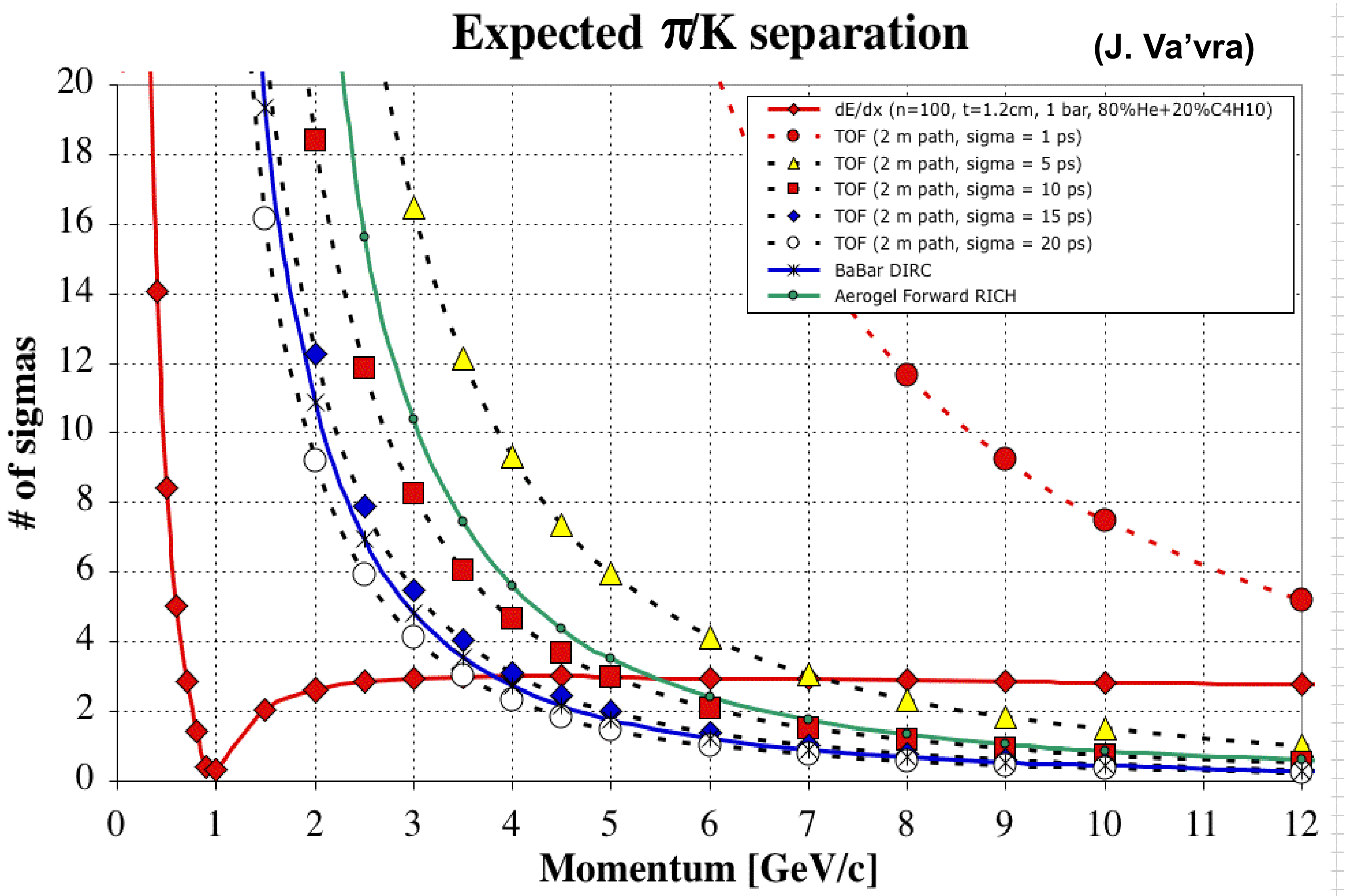








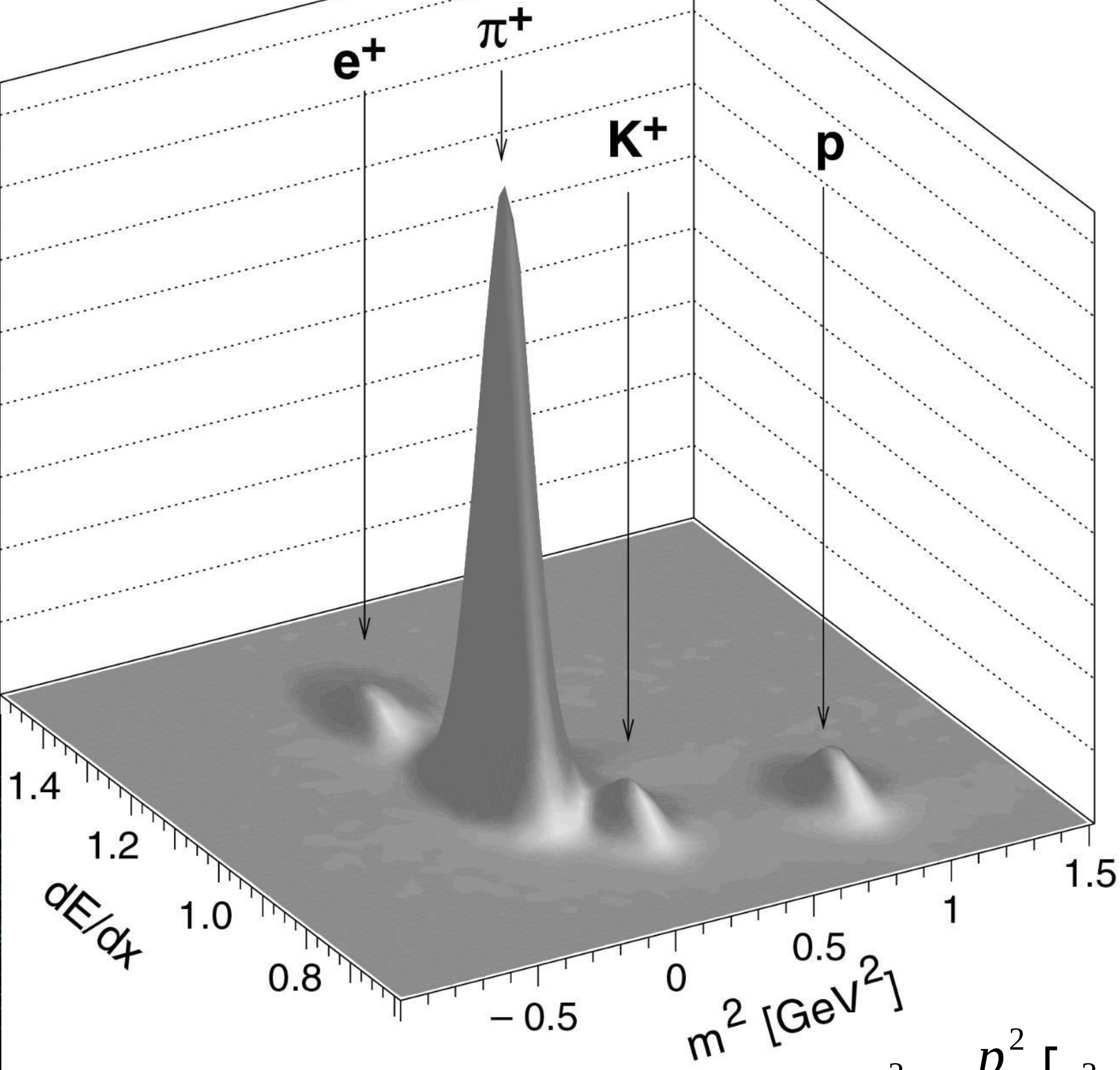
Projected ps-TOF particle ID performance

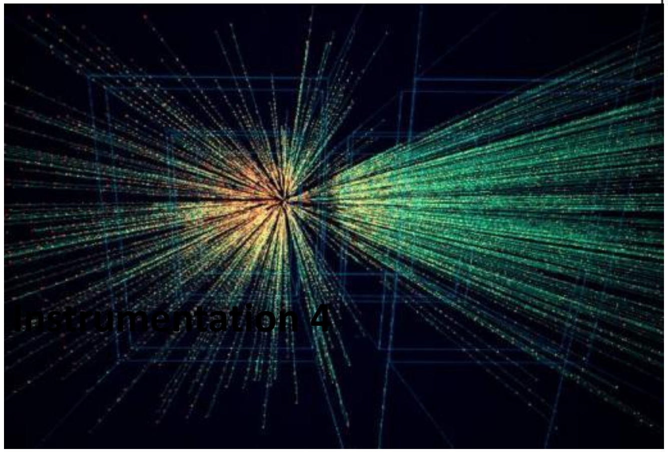


Particle ID: Combined Methods

NA49

Particle identification by simultaneous *dE/dX* and TOF measurement in the momentum range 5 to 6 GeV/*c* for central Pb+Pb collision





$$m^2 = \frac{p^2}{l^2}\left[c^2t^2 - l^2\right]$$

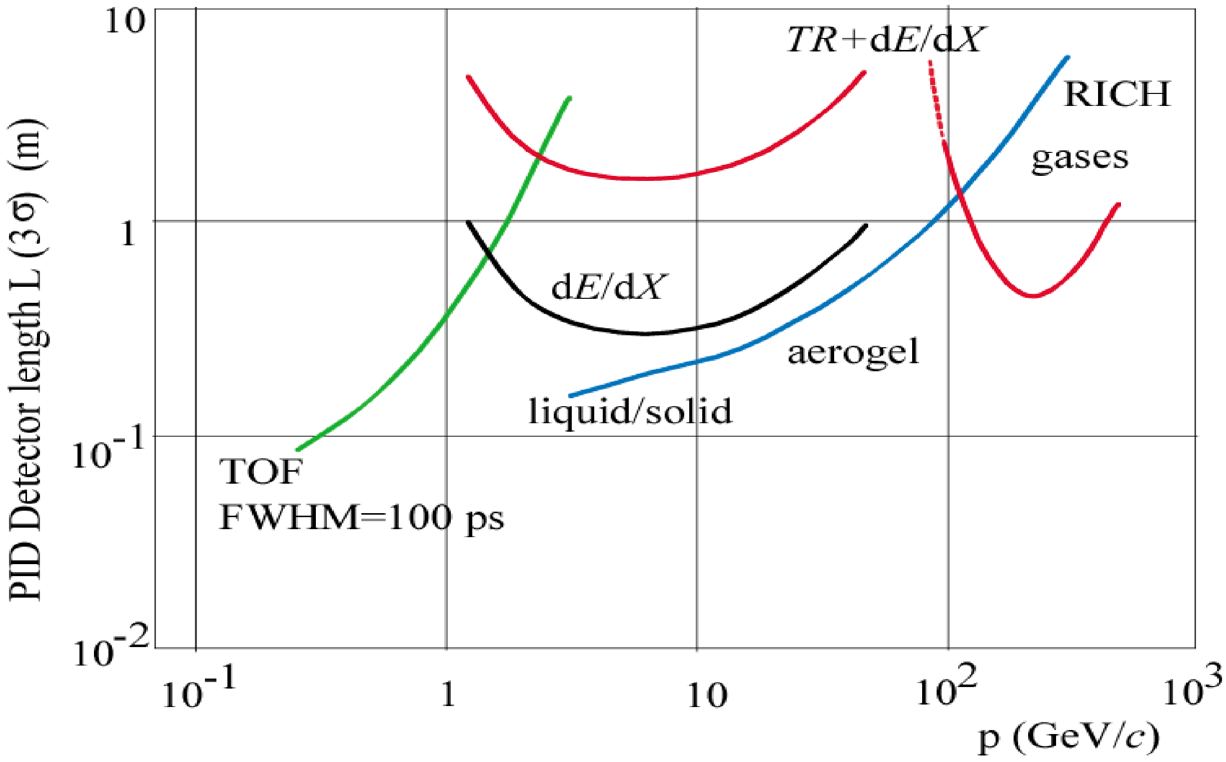
NA49, CERN-EP/99-001

Particle Identification: summary

- ☐ There is a wide variety of techniques for identifying charged particles
- ☐ **Cherenkov detectors** are in widespread use. Very powerful, tuning the choice of radiator
- ☐ **Ionization energy loss** is provided by existing tracking detectors but usually gives limited separation, at low *p*
- ☐ **Time Of Flight** provides excellent performance at low momentum
  With the development of faster photon detectors, the range of TOF momentum coverage should increase
- ☐ **Transition radiation** is useful in particular for electron identification

Pion-Kaon separation for different PID methods.

The length of the detectors needed for 3σ separation.



Dolgoshein, NIM A 433 (1999)

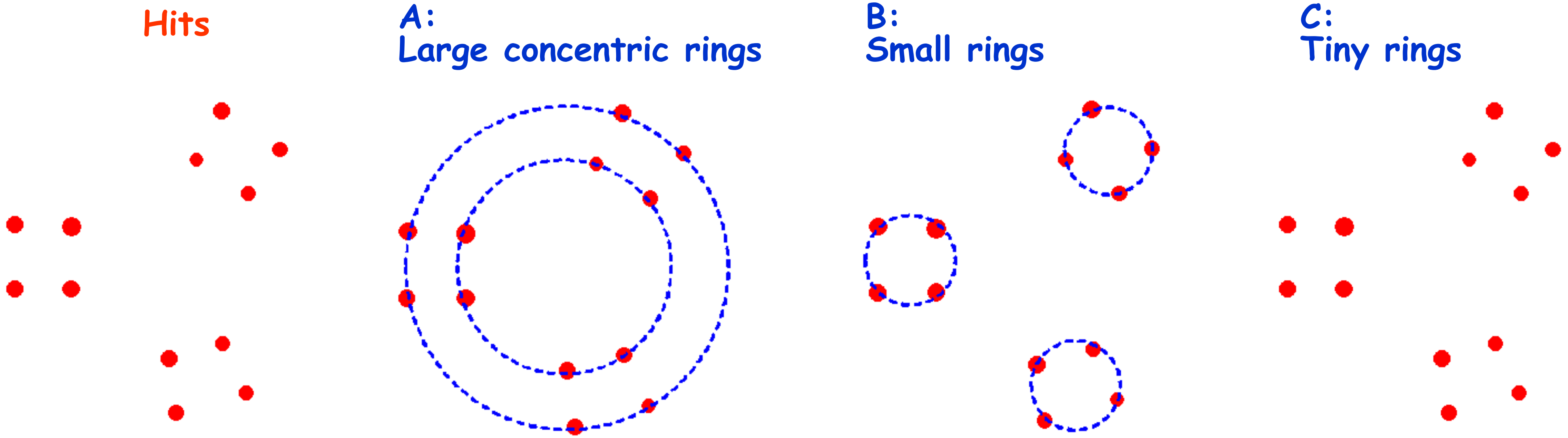
+ calorimetry for e, γ, π^0 identification

+ muon detecting system

Q: search for the rings

Photons → Hits → Rings

Ring reconstruction.



The answer *must* depend on what rings we expect to see.

=

The answer *must* depend on the process which is believed to have lead to the dots being generated.

C.G. Lester, NIM 560(2006)621