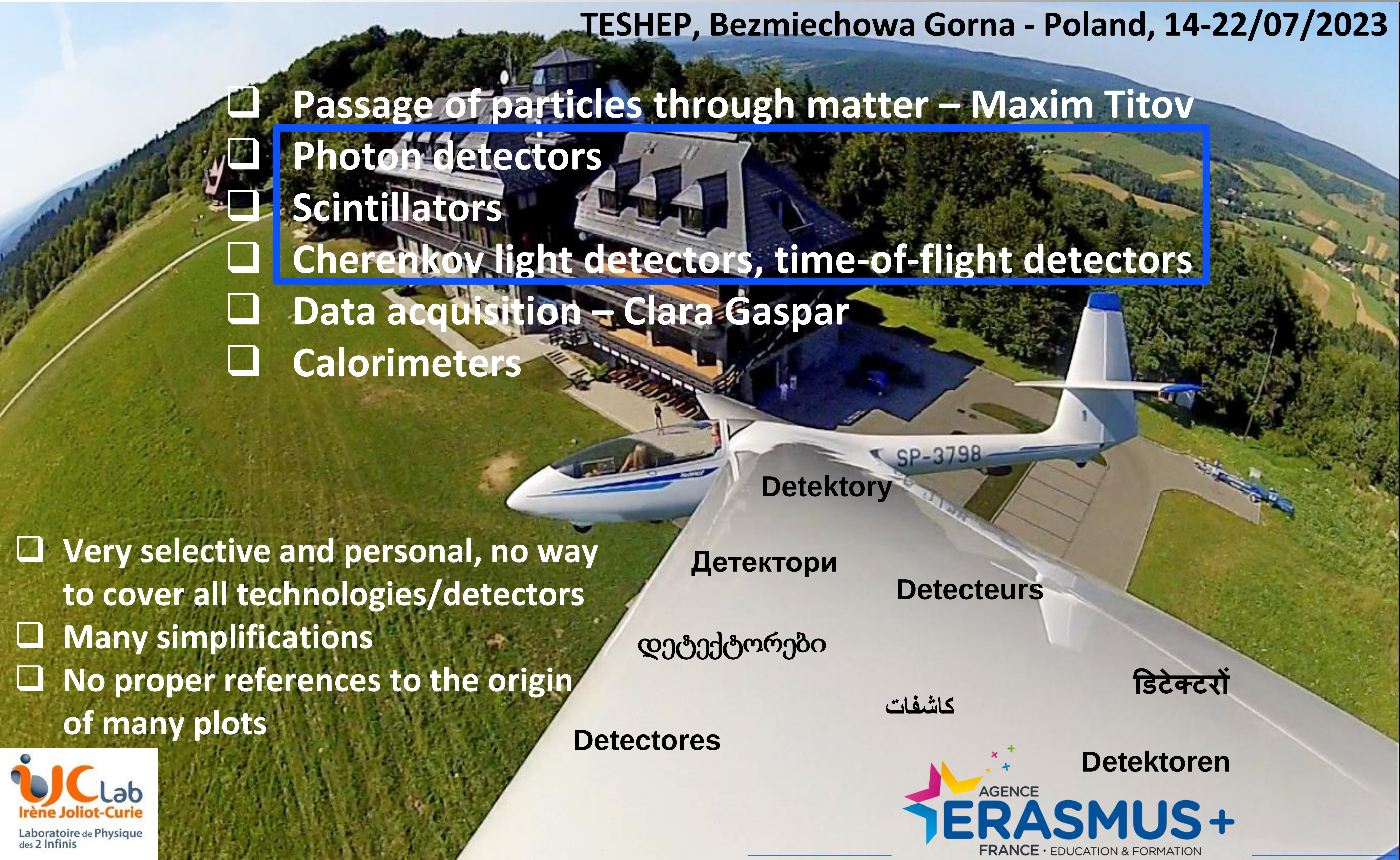
Detektory do fizyki wysokich energii

Sergey Barsuk, IJCLab Orsay, sergey.barsuk@ijclab.in2p3.fr

TESHEP, Bezmiechowa Gorna - Poland, 14-22/07/2023



- ☐ Passage of particles through matter – Maxim Titov
- ☐ Photon detectors
- ☐ Scintillators
- ☐ Cherenkov light detectors, time-of-flight detectors
- ☐ Data acquisition – Clara Gaspar
- ☐ Calorimeters

- ☐ Very selective and personal, no way to cover all technologies/detectors
- ☐ Many simplifications
- ☐ No proper references to the origin of many plots

Detektory

Детектори

Detecteurs

დეტექტორები

डिटेक्टरों

كاشفات

Detectores

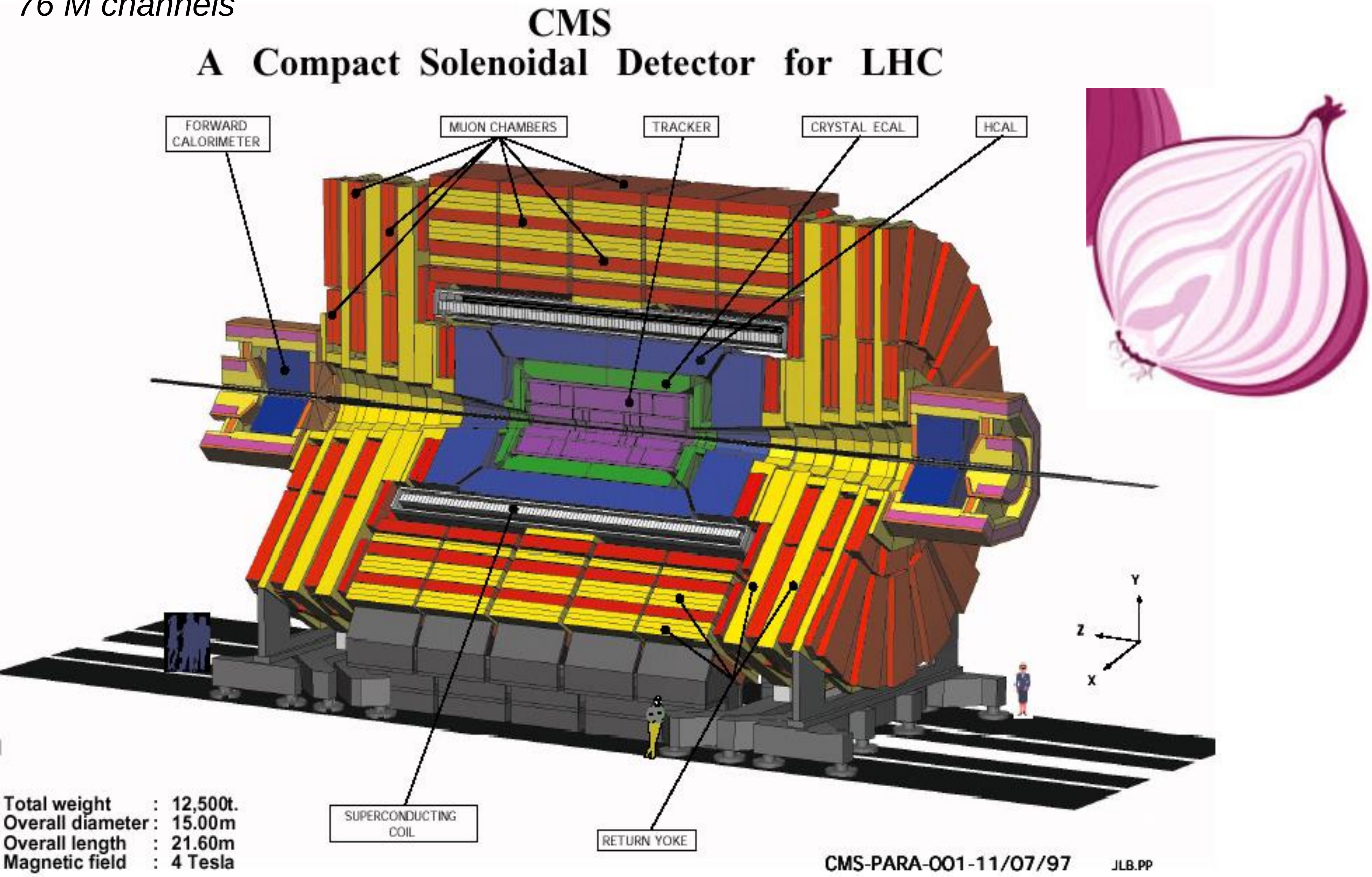
Detektoren

IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

AGENCE ERASMUS+ FRANCE · EDUCATION & FORMATION

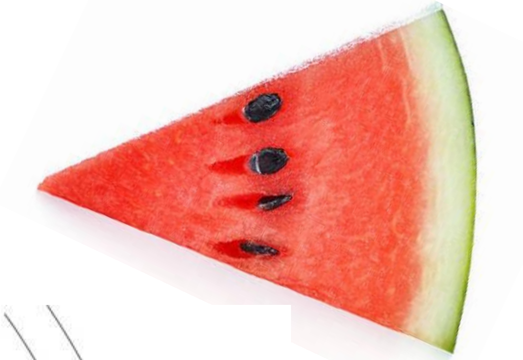
CMS – 4π “onion” detector

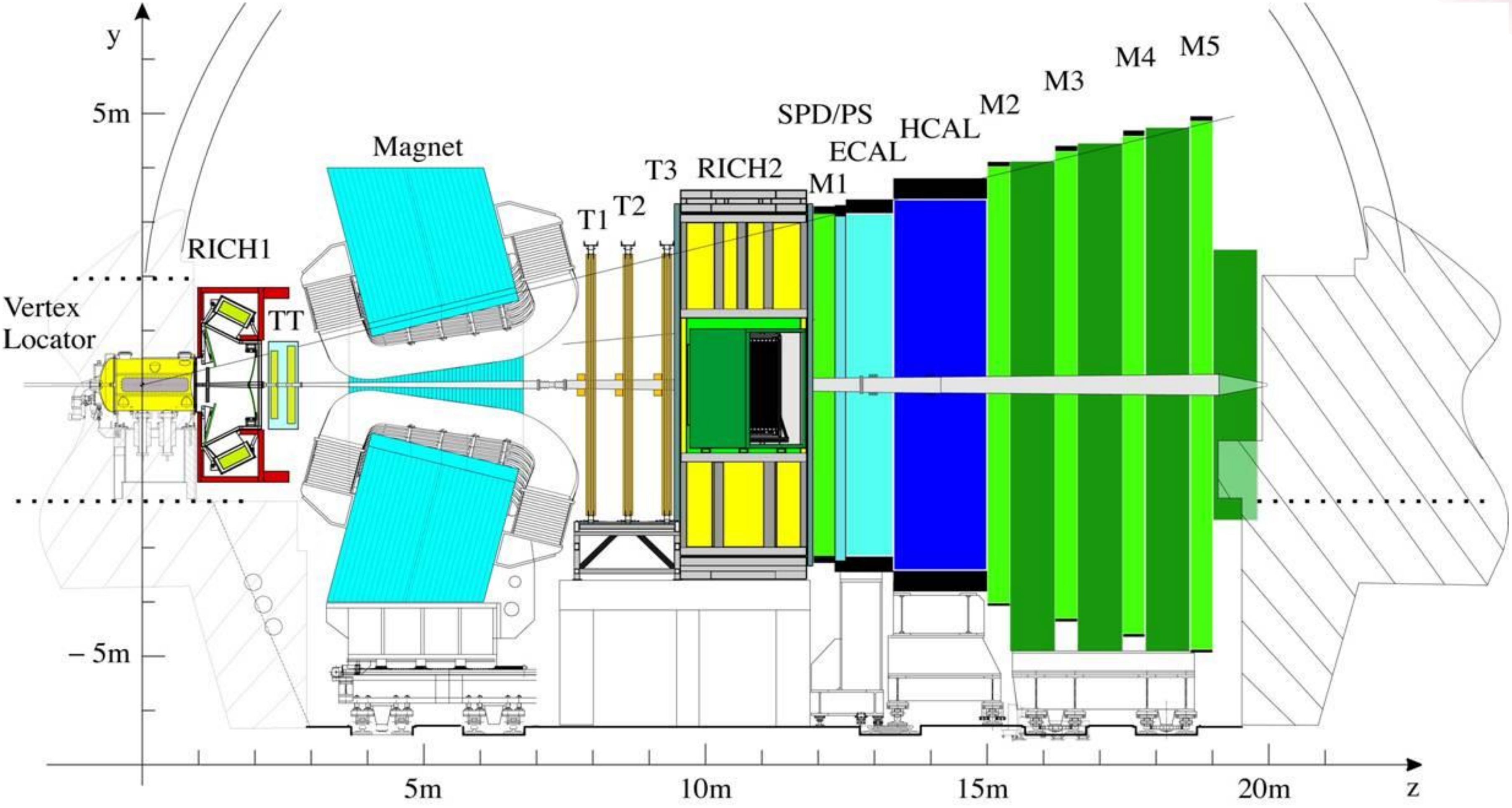
76 M channels



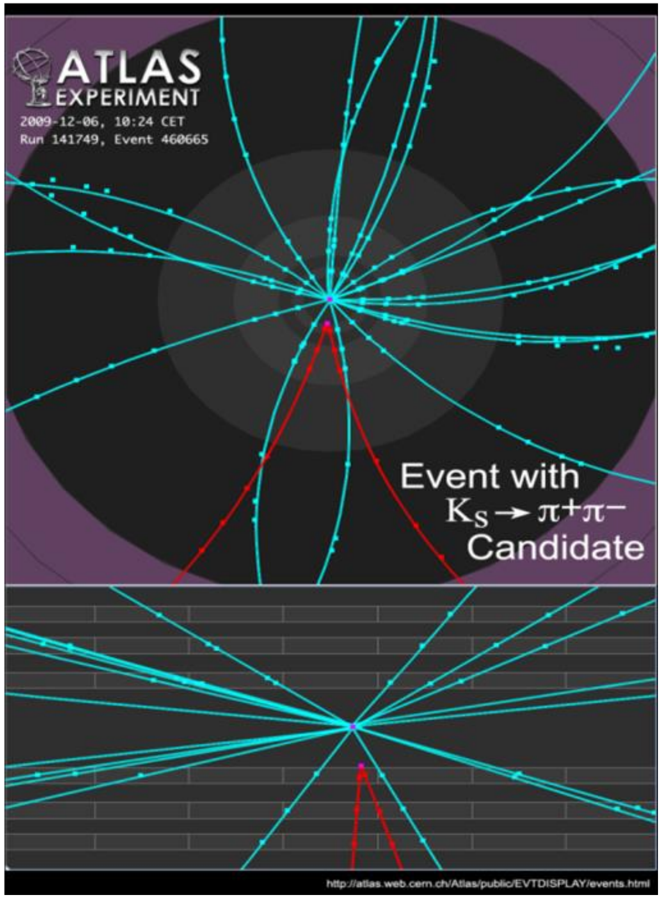
LHCb – forward “watermelon slice” detector

42 M channels





Non-destructive methods: charged particles → Tracking, PID



$K_S \rightarrow \pi^+\pi^-$ candidate as reconstructed in the Inner Tracker

Gaseous detectors

Measure: hit and/or drift time

Position resolution: ~ 50 μm → Tracks reconstruction

+ Magnetic field → Momentum

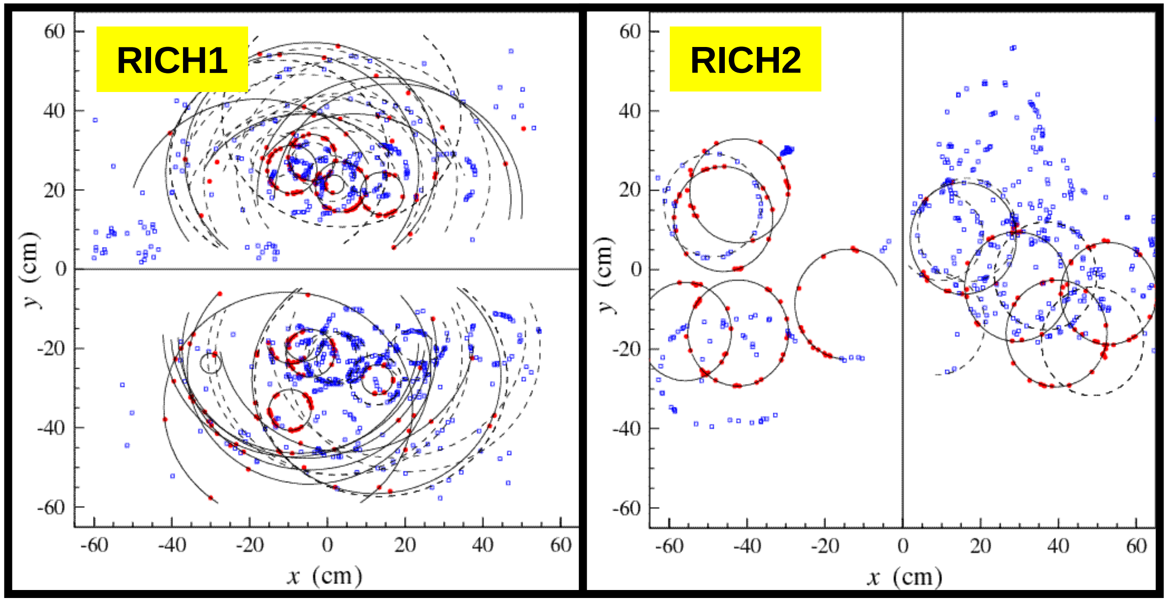
Measure also: energy loss dE/dx → Particle ID

Silicon detectors

Measure: hits and/or amplitude

Position resolution: ~ 5 μm → Tracks & Vertices reconstruction

Example: LHCb Ring Imaging CHerenkov detector RICH



Cherenkov detectors : Radiator + Cherenkov light measurement

Transition radiation detectors

Time-Of-Flight

Destructive methods

Calorimeters: electromagnetic and hadronic

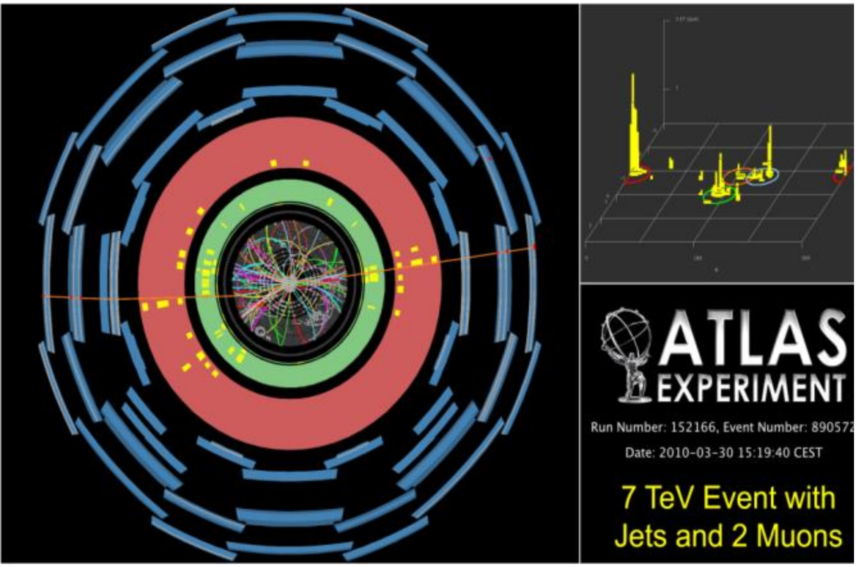
Measure: shower energy and/or shower shape

- ➔ Energy resolution
- ➔ Position resolution: ~few mm
- ➔ Particle ID

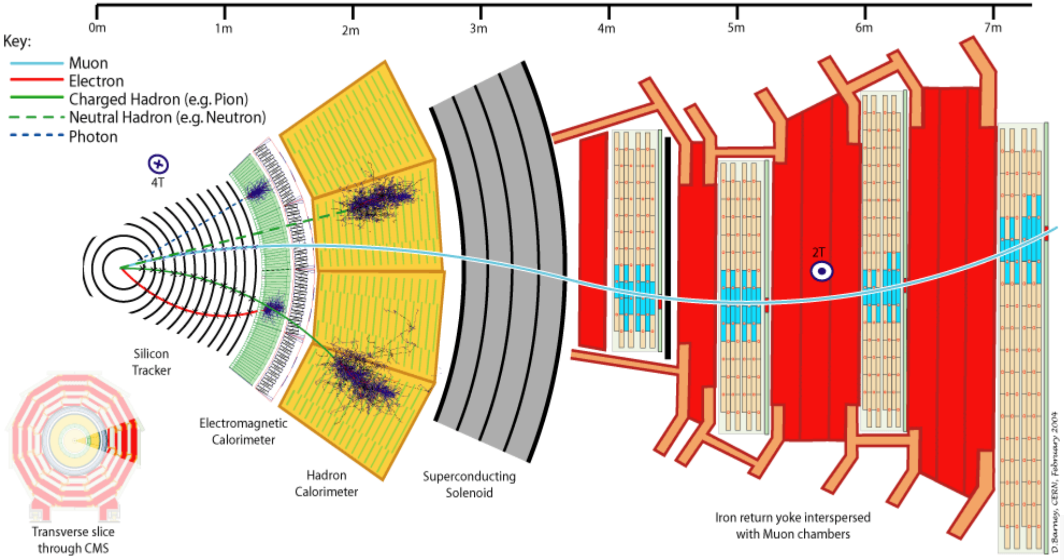
Muon detectors Measure: Muon track after absorber

➔ Particle ID

Muons in ATLAS



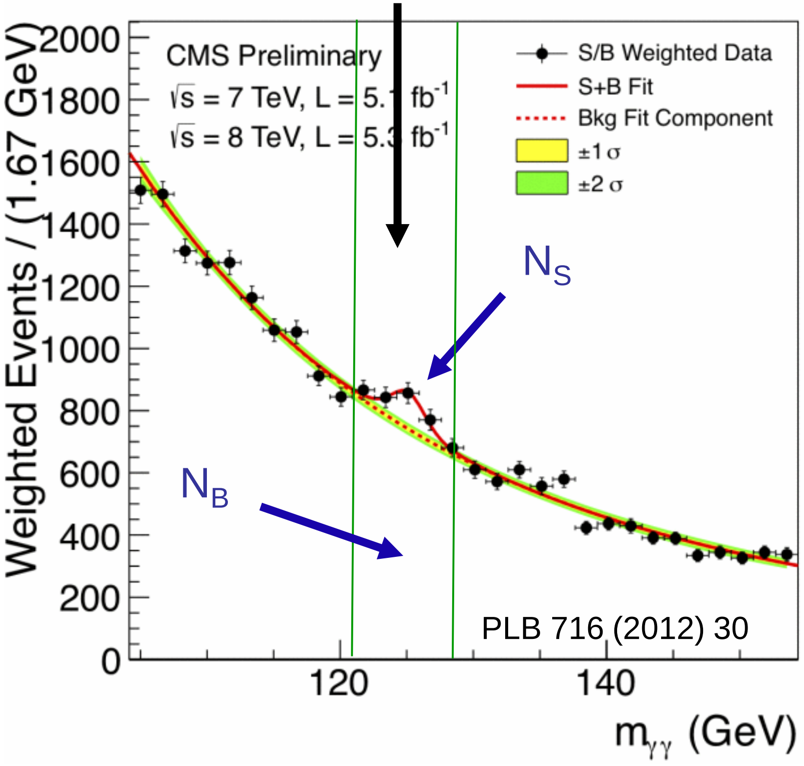
Muon in CMS



Signal over background: efficiency and resolution

- ❑ **Efficiency** ~ amount of signal and Intrinsic **detector resolution**, (simplified) effect on **H → γγ**
  - ❑ *Spatial resolution* → degrades mass resolution via momentum measurement; contributes to combinatorial background via picking up random tracks and via PID.
  - ❑ *Energy resolution* → degrades mass resolution via energy measurement; contributes to combinatorial background via PID.
  - ❑ *Time resolution* → degrades mass resolution via contribution to spatial resolution in tracking devices; contributes to combinatorial background via pile-up and via PID.

Is the excess due to the decay of a particle into two photons ?



PLB 716 (2012) 30

Statistical significance: $S = N_S / \sqrt{N_B}$

N_S (N_B) : Number of signal (background) events, estimated in the peak region

$$S \sim \varepsilon \sqrt{L / \sigma}$$

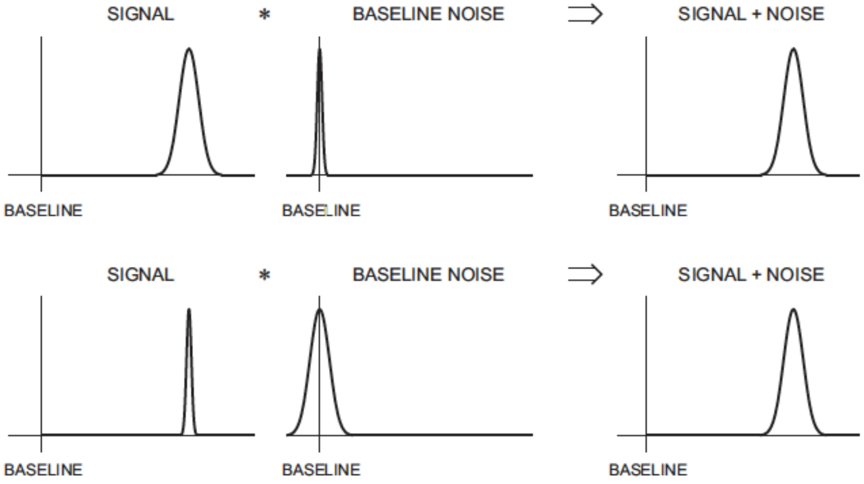
- ❑ <u>S > 5</u> → signal > <u>5 times</u> higher than the expected fluctuation on N_B
- ❑ Probability, that the background fluctuates by more than 5 standard deviations is 10^{-7}

→ Discovery

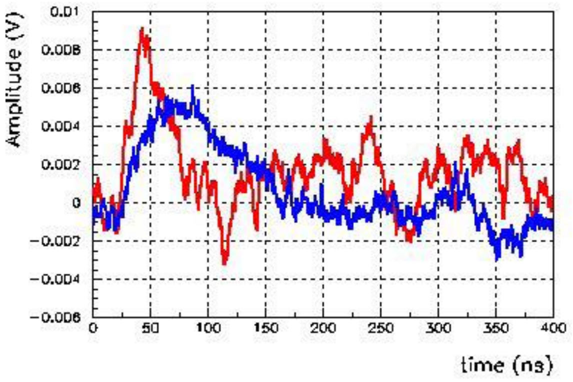
Signal over background: efficiency and resolution

- Signal treatment added to intrinsic detector resolution → **Read-out electronics**

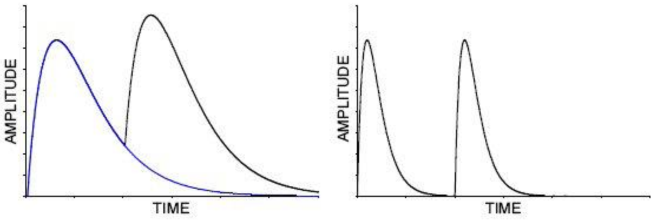
  - Every signal comes with its noise



- Realistic signal + noise shape



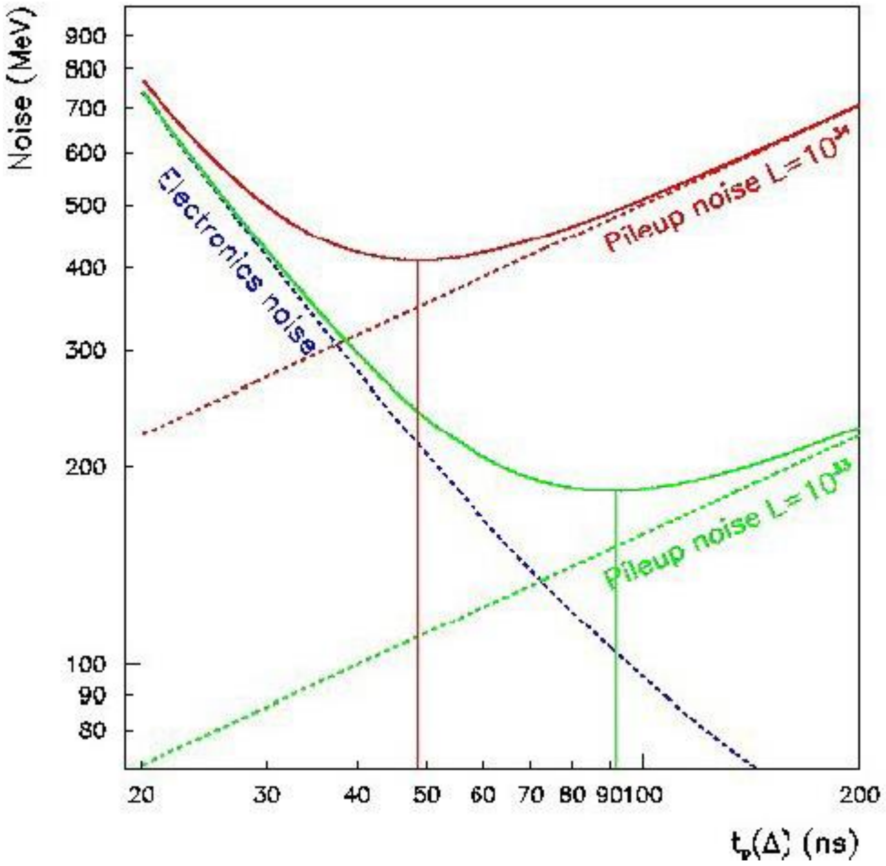
  - Reduce pile-up



After E. Garutti et al.

Signal over background: efficiency and resolution

- Signal treatment added to intrinsic detector resolution → **Read-out electronics**
  - Example: ATLAS LAr calorimeter
  - Ionization signal 500 ns ~ 20 LHC BXs
  - Fast shaper reduces signal to 5 LHC BXs → less pile-up but higher electronics noise
  - Choice of optimal timing varies with luminosity



After E. Garutti et al.

Photon detection

Examples above targeted reconstruction of **H → γγ**

Why: Photon detector applications

HEP, Nuclear physics, astrophysics:

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

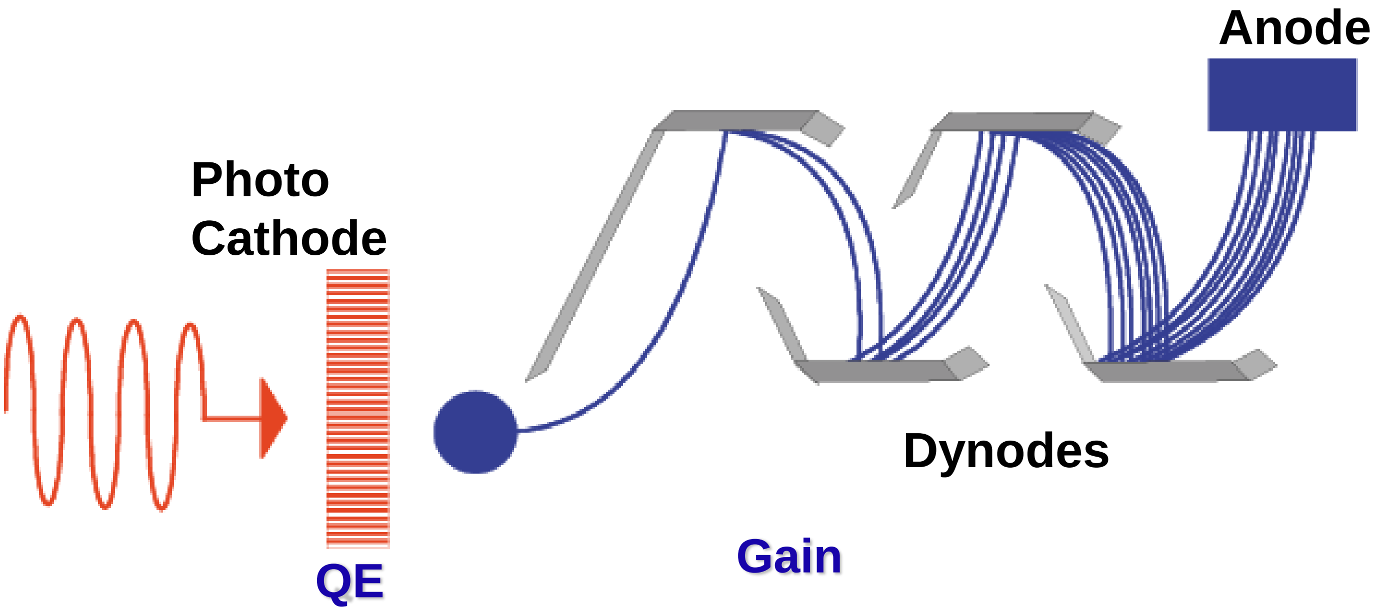
photons in ~visible range, λ = 100 nm … 1000 nm or E ~ few eV

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

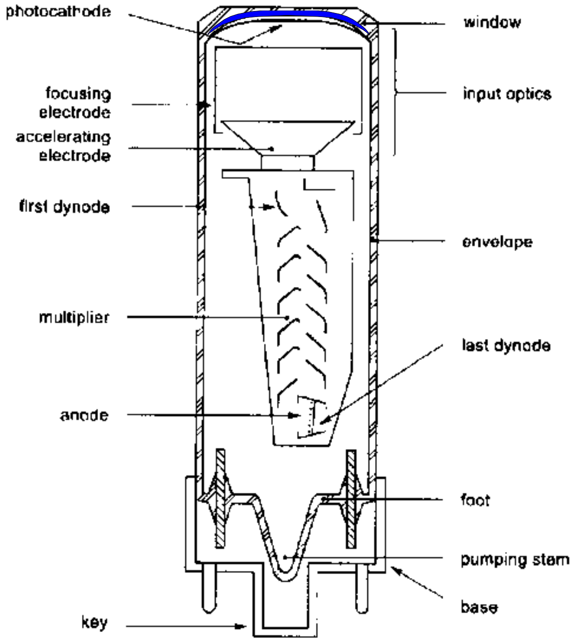
- → rare clean events (problem: noise, impurities etc)
- → busy events (problem: pileup from other particles, including photons)

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

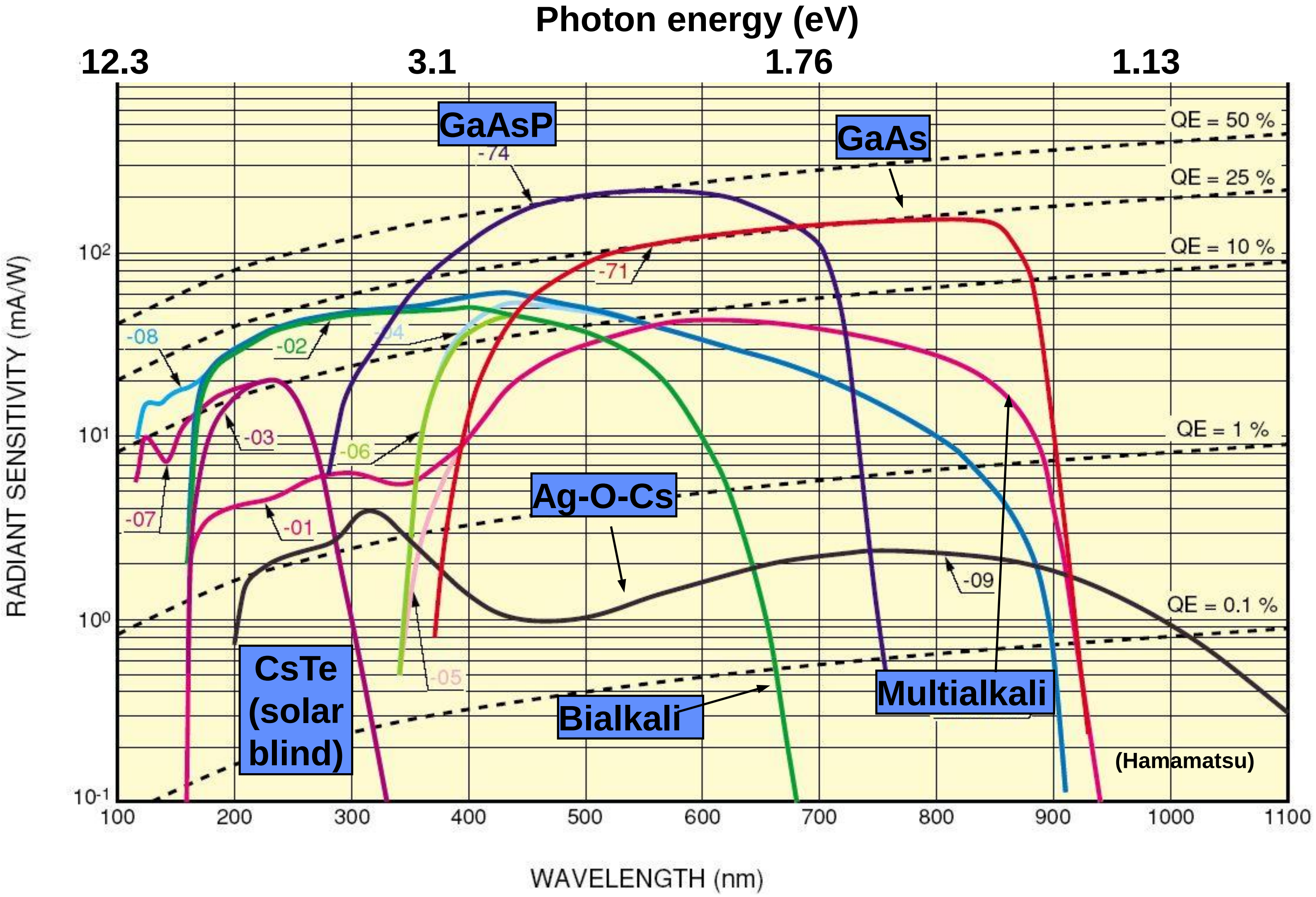


Choice of photocathode :

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

QE is a strong function of the photon wavelength

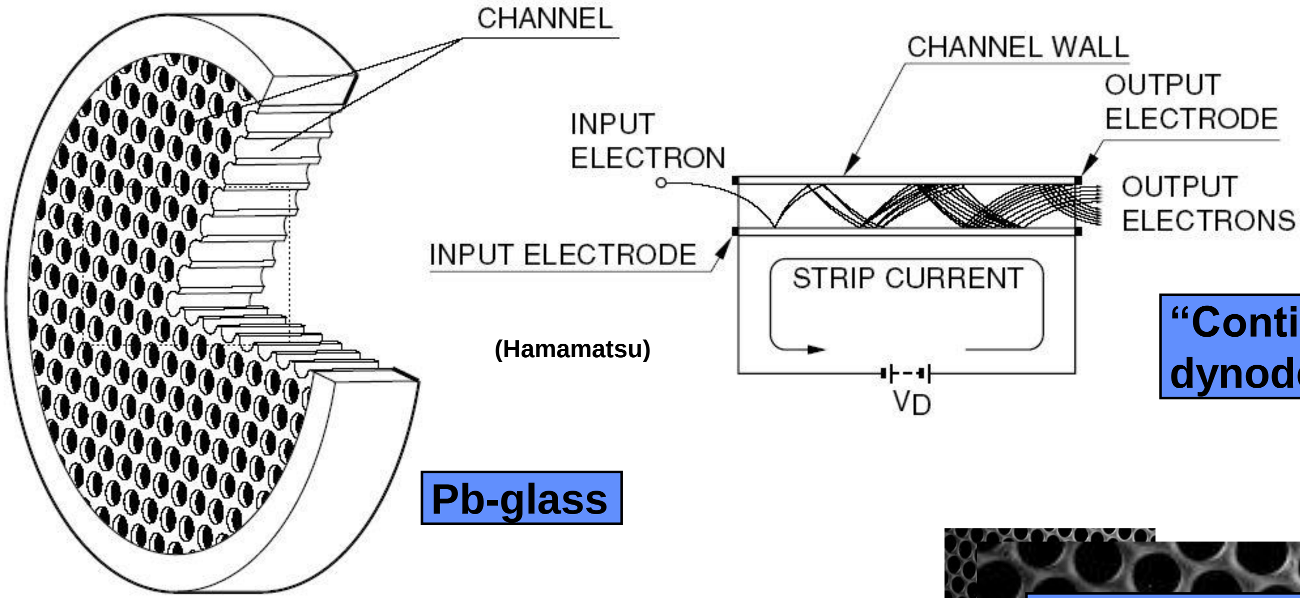
QE's of typical photo-cathodes



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

from T. Gys, Academic Training, 2005

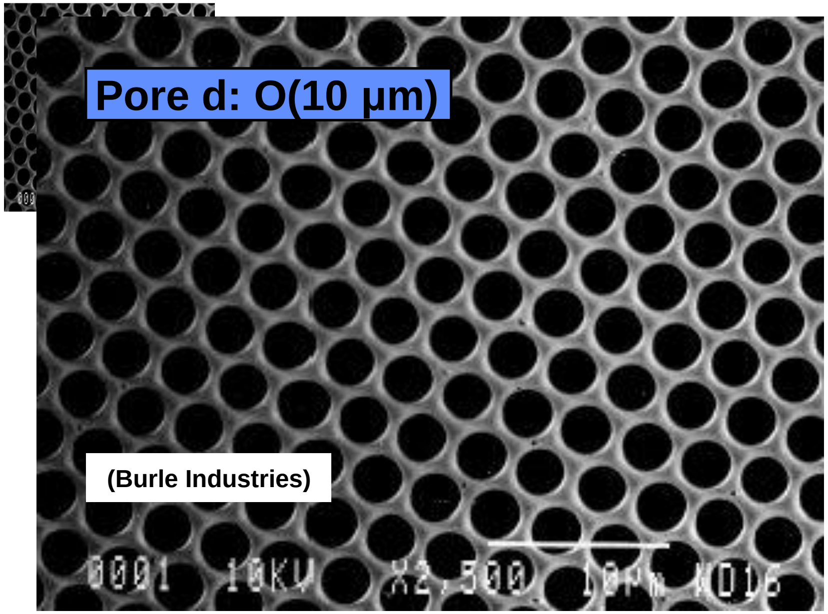
Vacuum photon detectors: Micro Channel Plate



(Hamamatsu)

“Continuous” dynode chain

Pb-glass



Pore d: O(10 μm)

(Burle Industries)

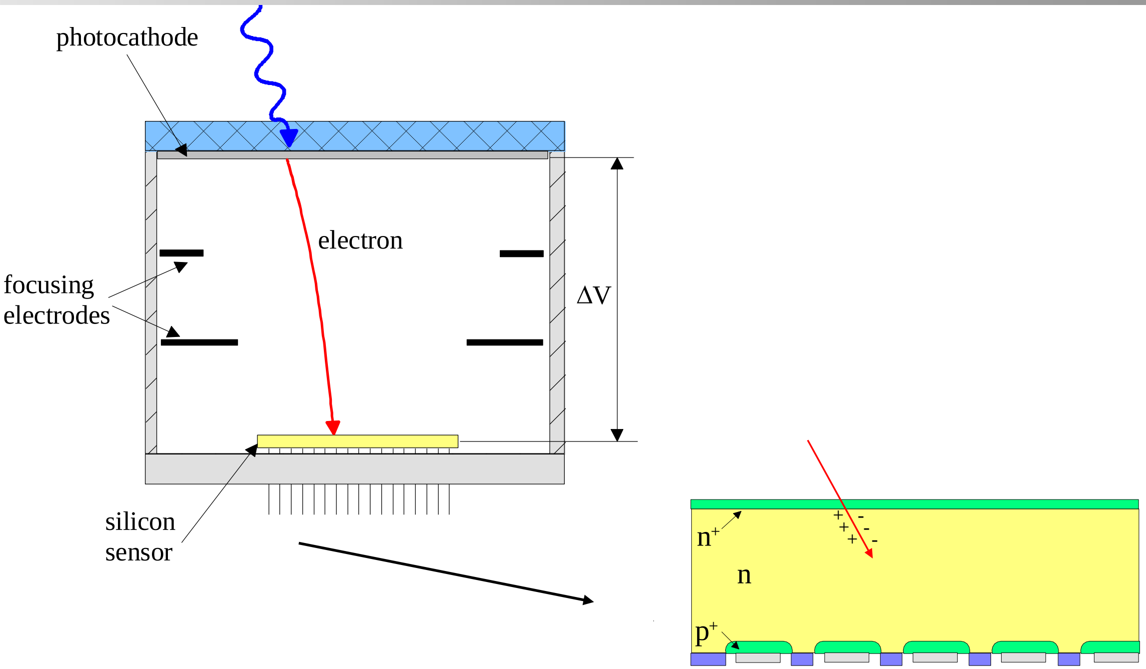
- ☐ **Gain fluctuations** can be minimized by operating in the saturation mode
- ☐ Kind of **2D PMT**:
  + high gain up to 5 x 10^4;
  + fast signal (transit time spread ~20 ps);
  + less sensitive to B-field (0.1 T);
  - limited lifetime (0.5 C/cm^2);
  - limited rate capability (mA/cm^2)

from T. Gys, Academic Training, 2005

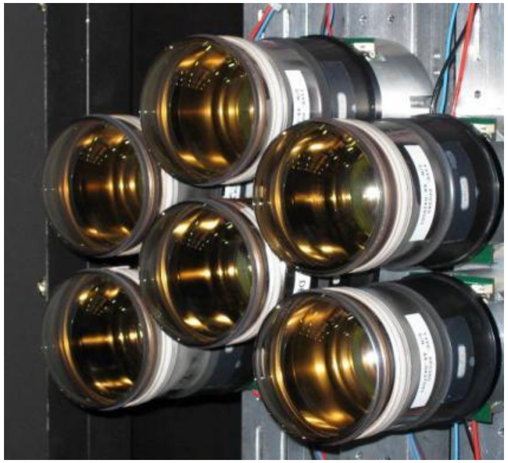
Vacuum photon detectors: HPD

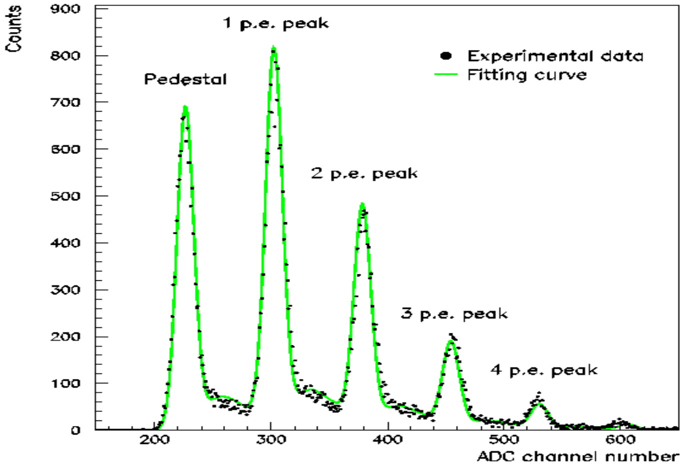
Photo Multiplier Tube
- dynodes and anode
+ silicon sensor

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

Solid-state photon detectors

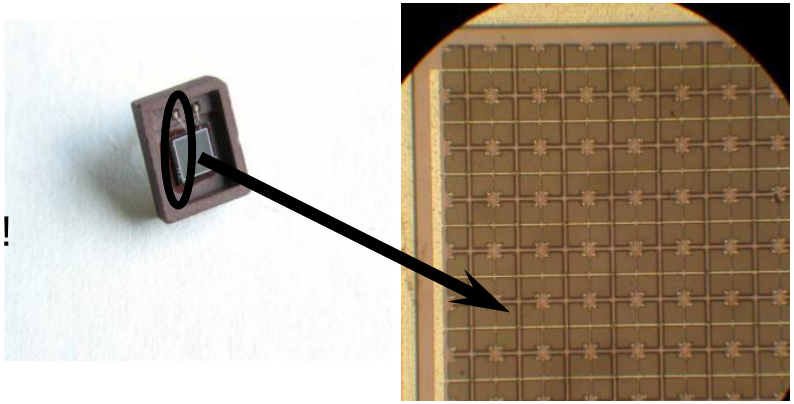
- **More compact, lightweight, tolerant to MF, cheaper, allow fine pixelization, ...**

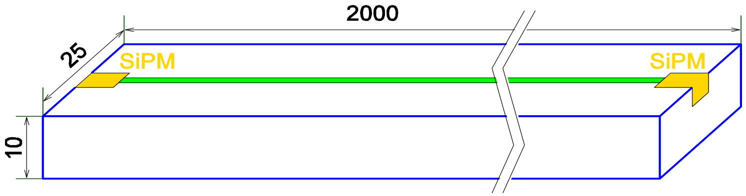
E.g.: **Silicium Photon Multiplier (SiPM)**

- 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

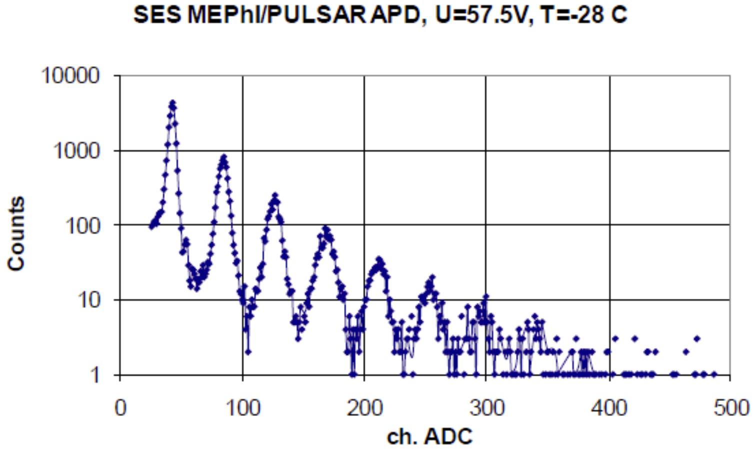
Signal is readout directly from SiPM w/o preamp and shaper !





- 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/cm^3
- ☐ 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 resolu**tion
- ☐ 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.

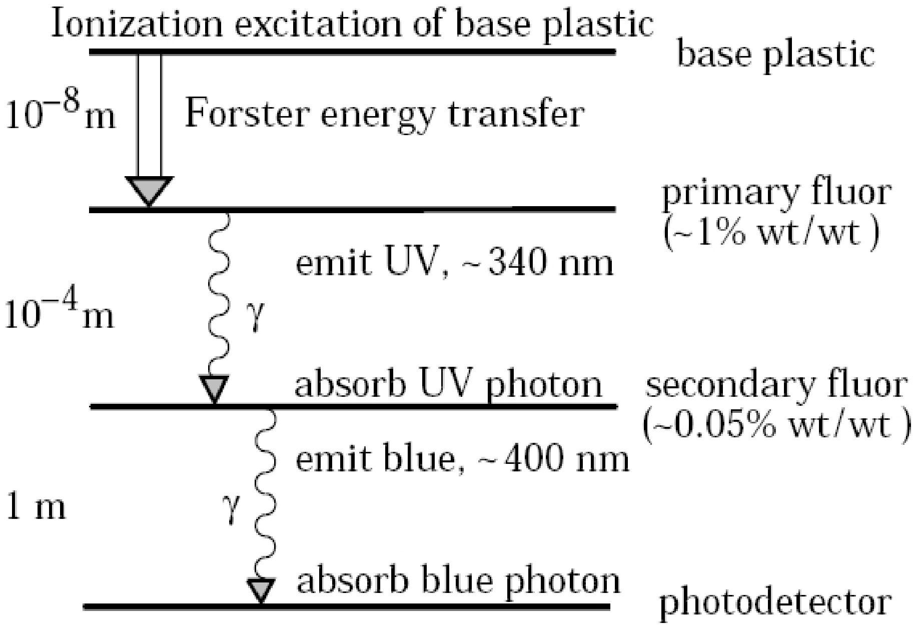


Figure 28.1: Cartoon of scintillation "ladder" depicting the operating mechanism of plastic scintillator. Approximate fluor concentrations and energy transfer distances for the separate sub-processes are shown.

- 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

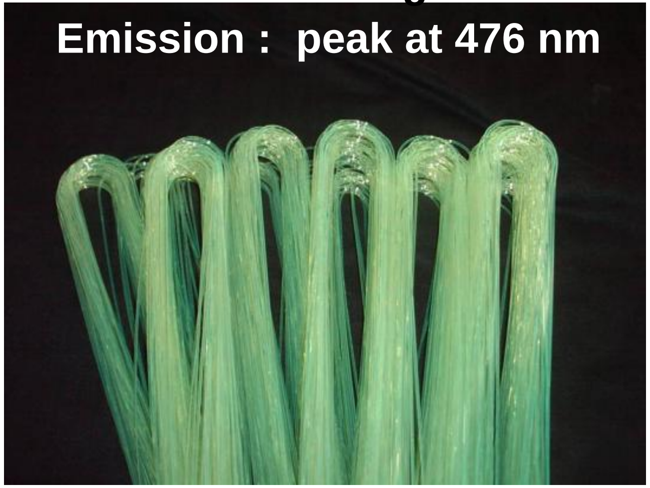
Optical fibers

WLS fibers: Y11 (Blue →) Green

Kuraray

Attenuation length : > 3.5 m

Emission : peak at 476 nm



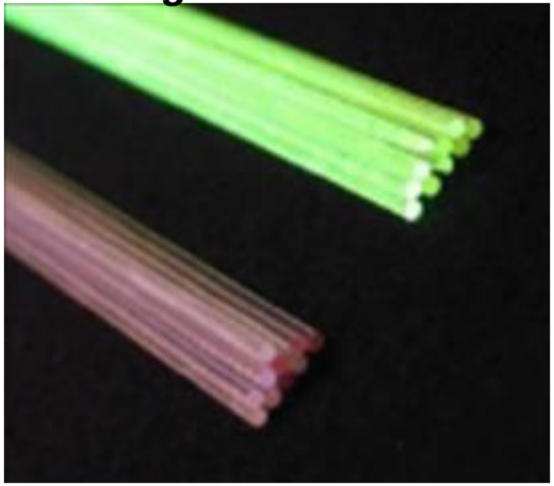
Clear transport fibers: PSM

> 10 m

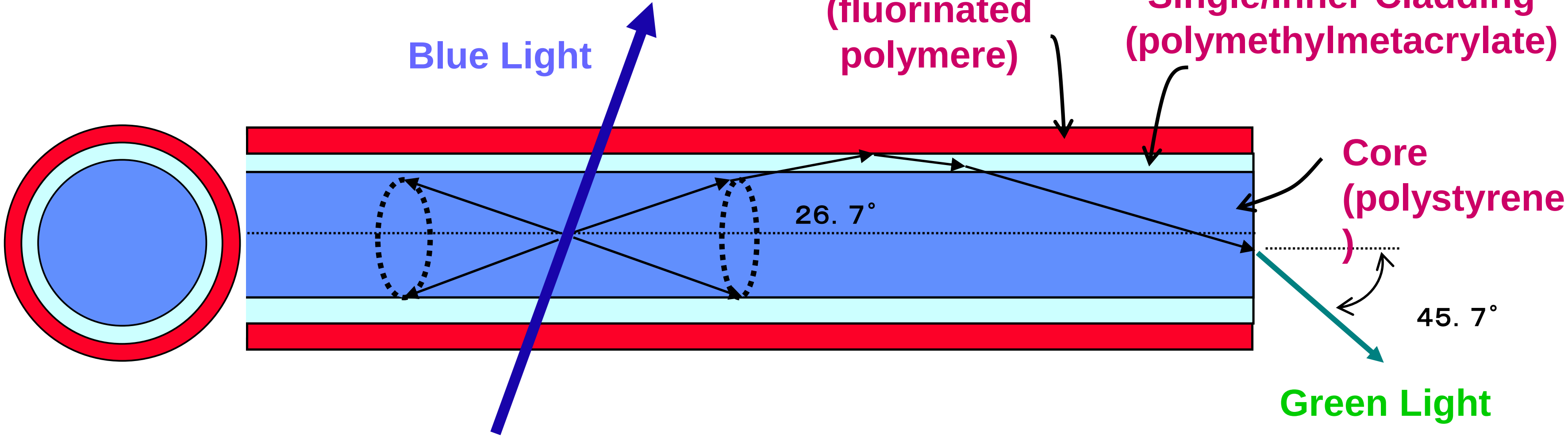
Crystals fibers: LuAG (Ce)

Fibercryst

Inorganic scintillator



Example: Y11 double cladding



→ 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

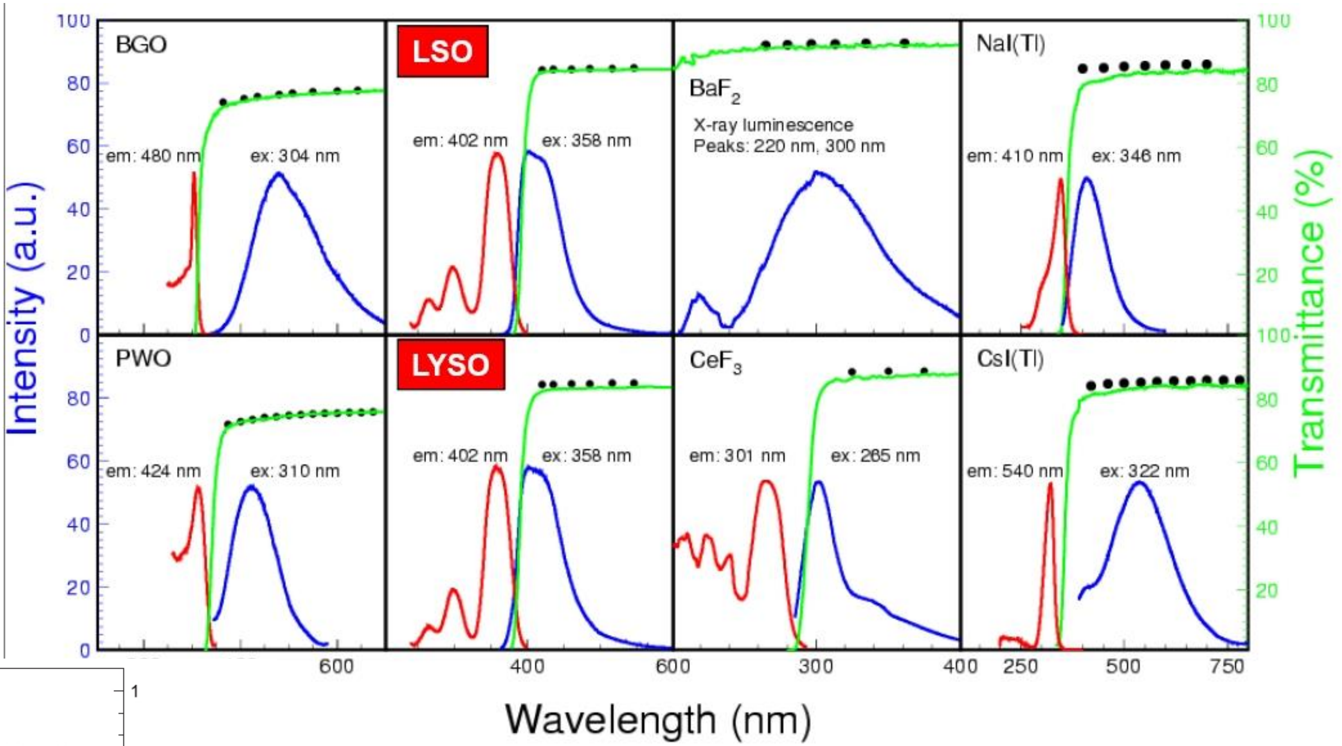
L3 BGO: 22 X_0

CMS PWO(Y): 25 X_0

Excitation, Emission, Transmission

R.-Y.Zhu

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



7

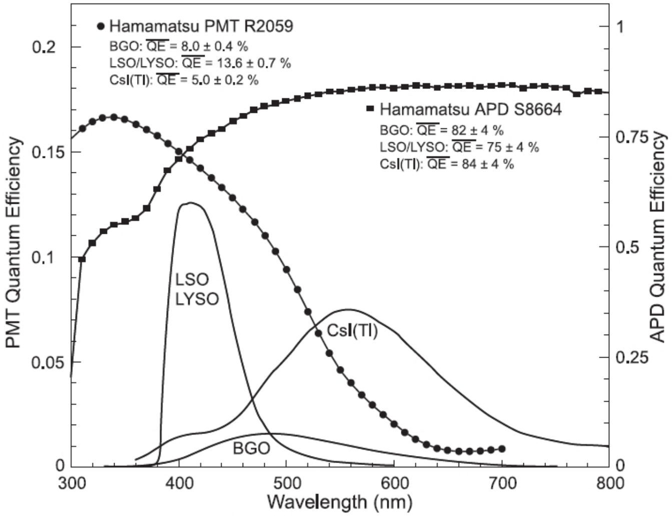


Figure 28.2: The quantum efficiencies of two photodetectors, a Hamamatsu R2059 PMT with bi-alkali cathode and a Hamamatsu S8664 avalanche photodiode (APD), are shown as a function of wavelength. Also shown in the figure are emission spectra of three crystal scintillators, BGO, LSO and CsI(Tl), and the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

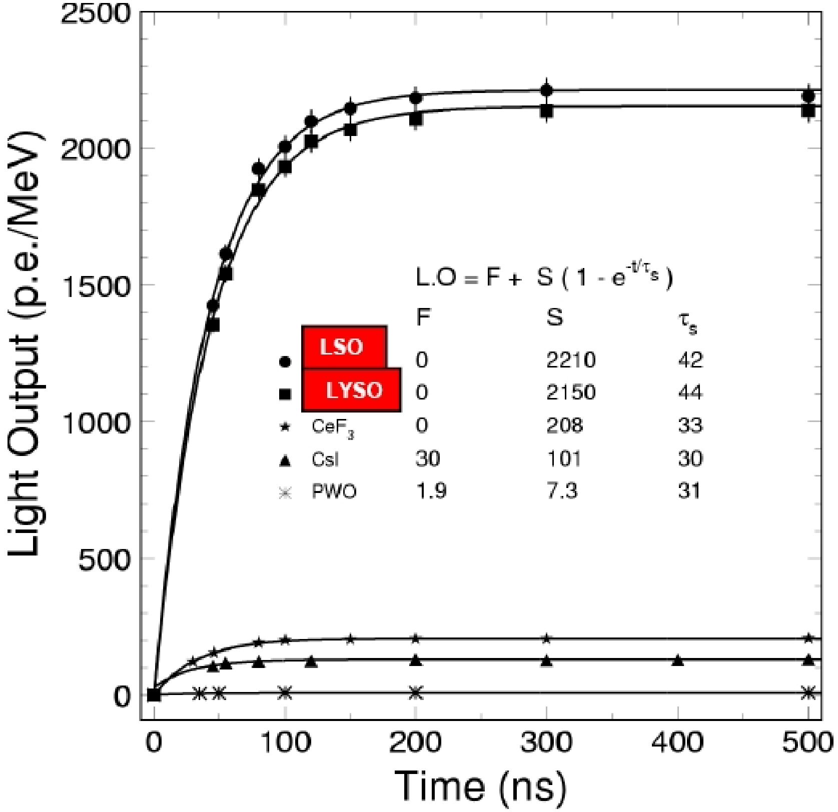
- ☐ Matching photon detector to the crystal emission spectra

Timing of the crystal signal

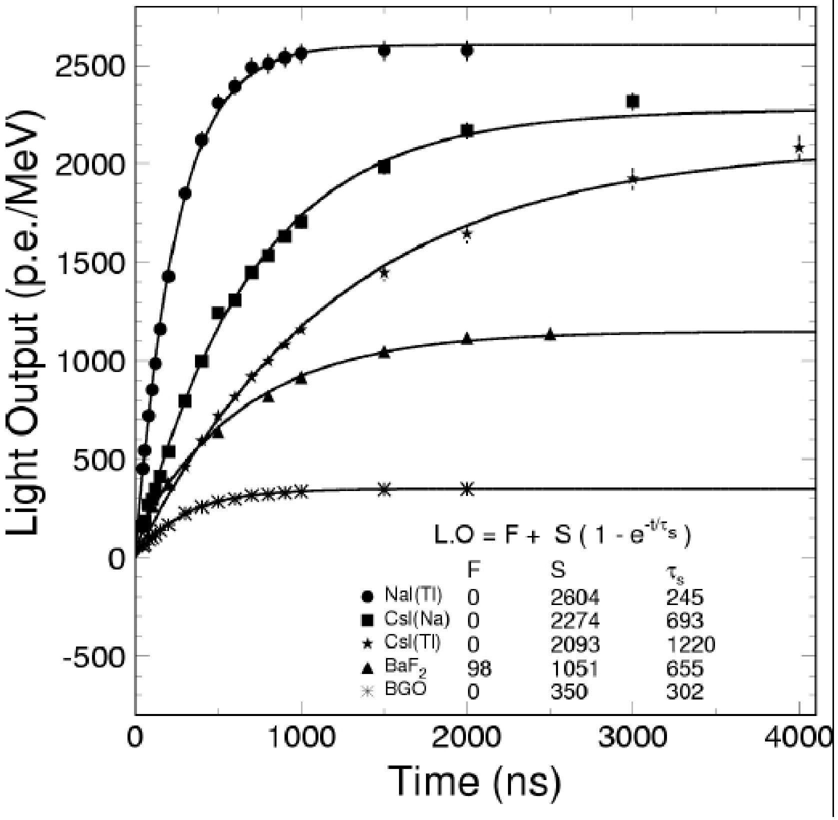
R.-Y.Zhu

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

Fast Crystal Scintillators

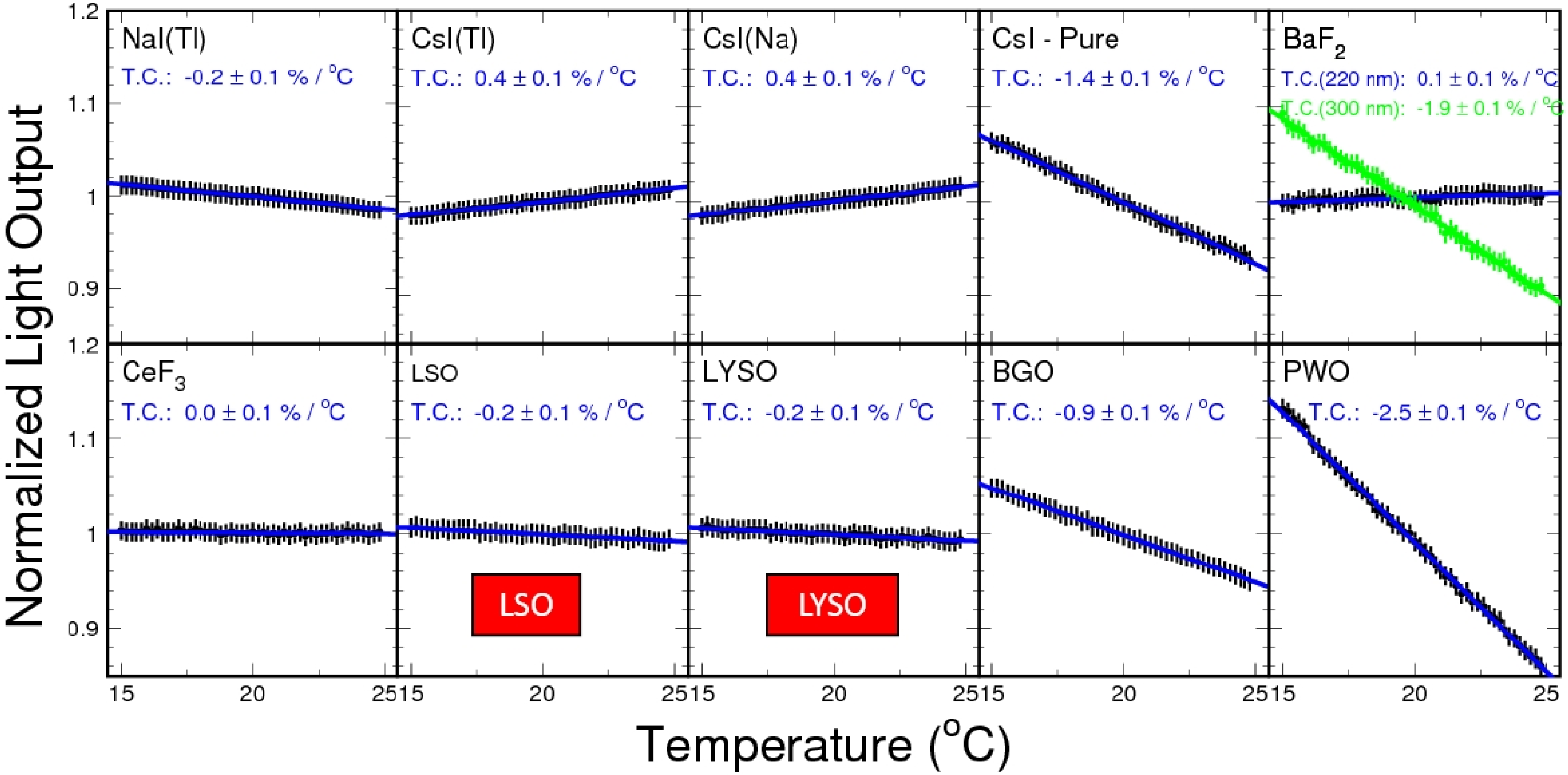


Slow Crystal Scintillators



Temperature dependence

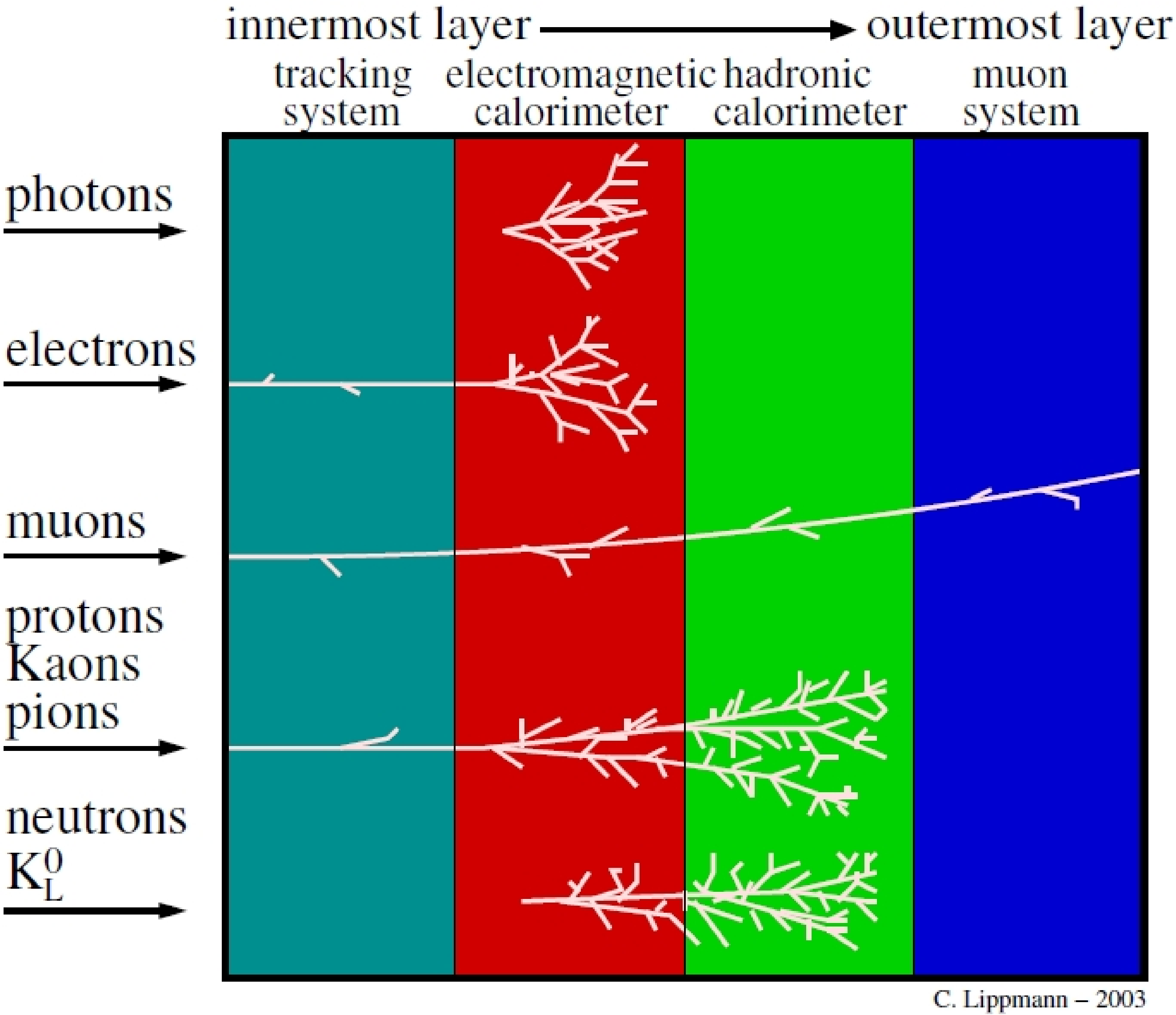
R.-Y.Zhu



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

Particle Identification, first glance

Particle Identification, first glance ID

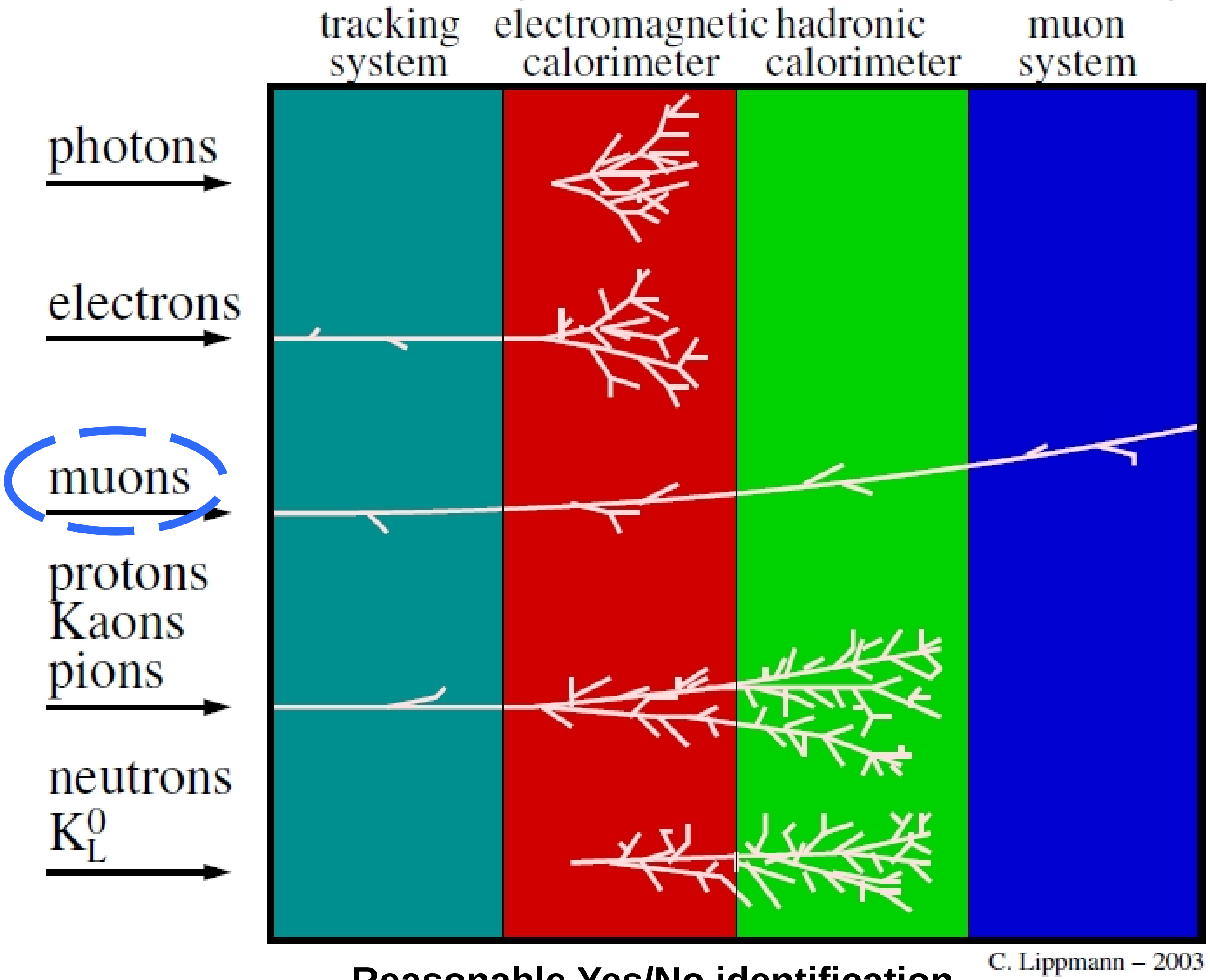


Reasonable Yes/No identification

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

Q: search for “true muon”

What is a background for muon identification ?

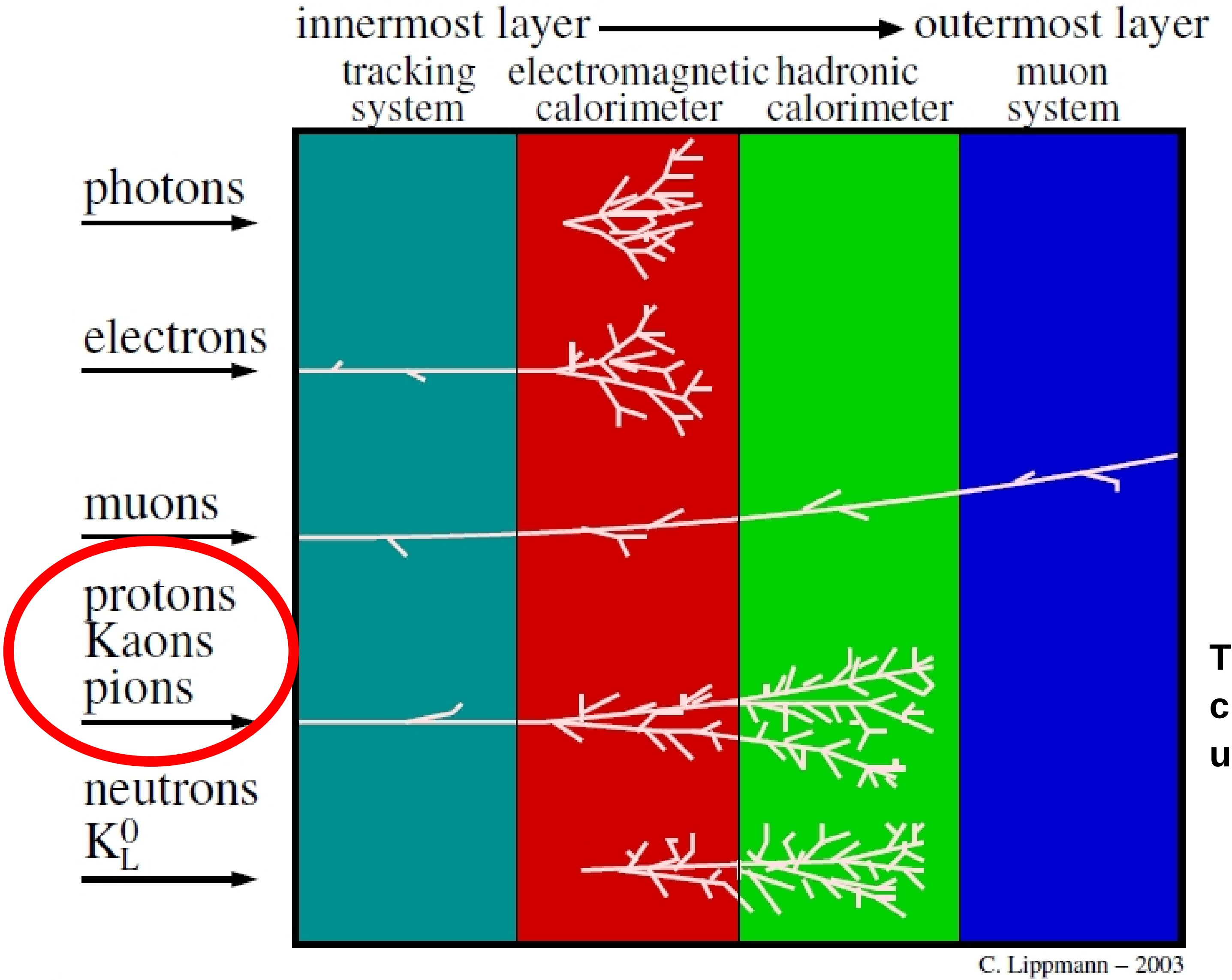


C. Lippmann – 2003

Reasonable Yes/No identification

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

Particle Identification, first glance ID



Try to distinguish charged hadrons using more tools !

Reasonable Yes/No identification

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

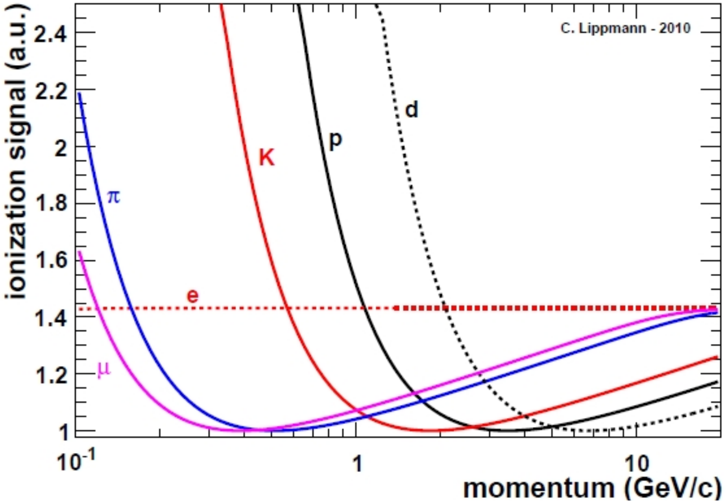
Charged particle identification

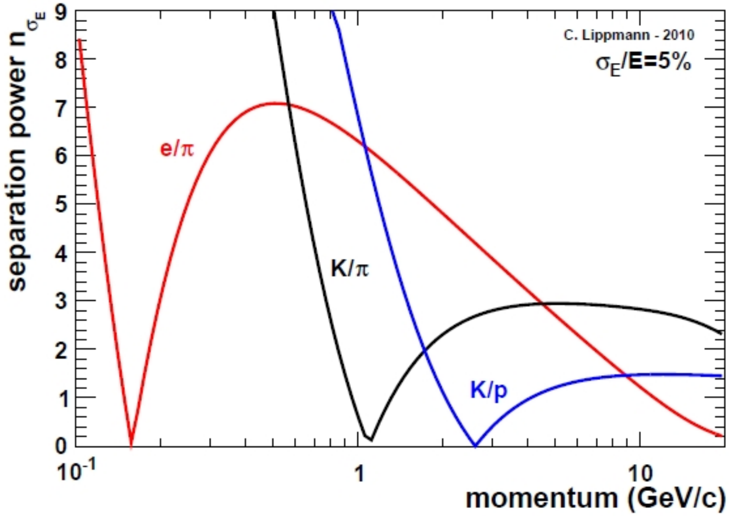
Typical separation power achievable in gaseous detector.

Assumed energy resolution : 5%

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

Often *simultaneous measurement of momentum and velocity for charged hadrons*





Cherenkov radiation detectors

- ❑ Charged particles ID over a range of momentum few hundred MeV/c - several hundred GeV/c

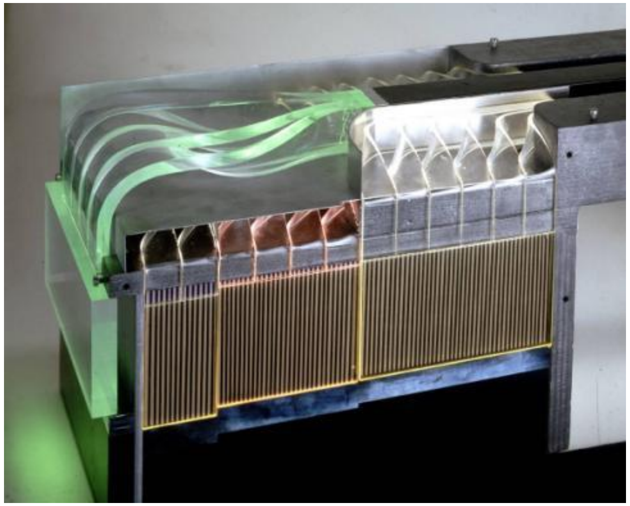
- ❑ A charged particle with velocity β=v/c greater than local velocity of light in a medium with refractive index n=n(λ) may emit light along a conical wave front.

- ❑ The angle of emission: $\cos\Theta_C = \frac{1}{\beta \cdot n}$

$\cos \theta_{max} = 1/n$

$\beta_{min} = 1/n$

Radiator
+
Photon detector



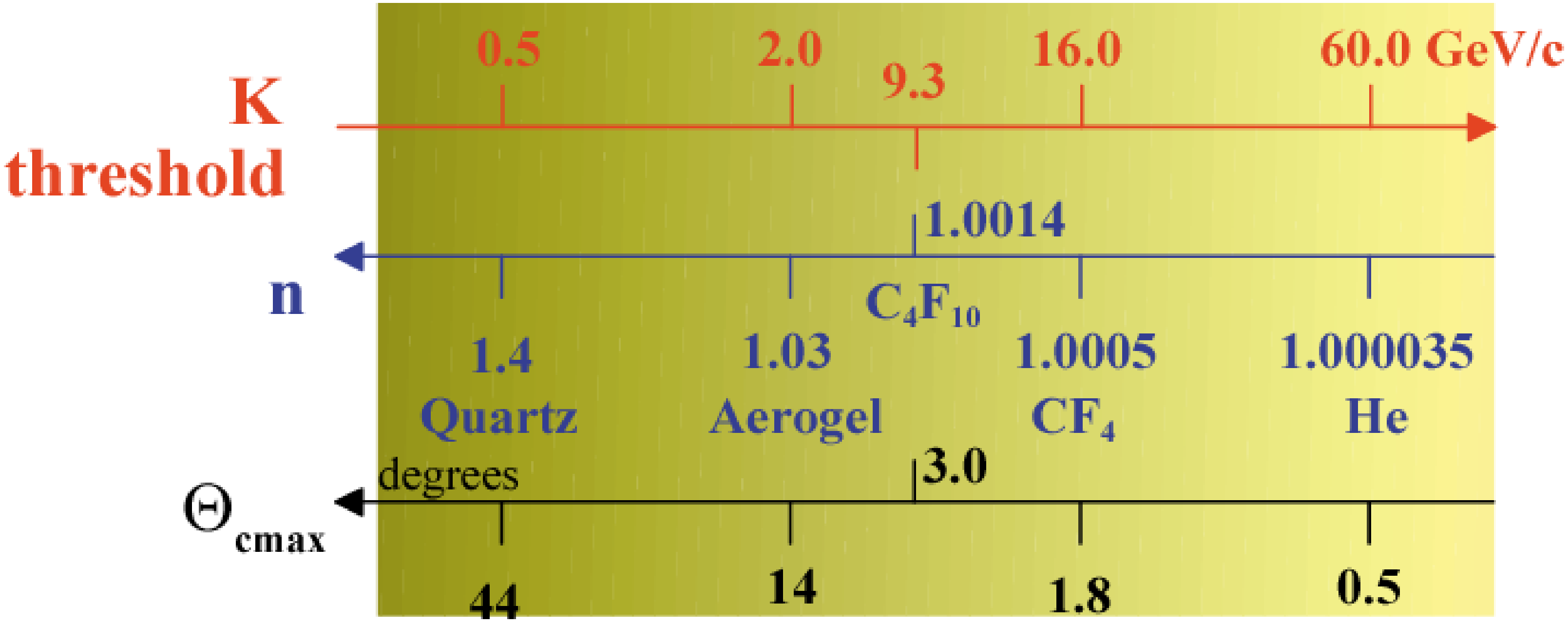
➔ Particle ID :

Threshold (detect Cherenkov light)

and

Imaging (measure Cherenkov angle) techniques

Threshold Cherenkov Detector: examples



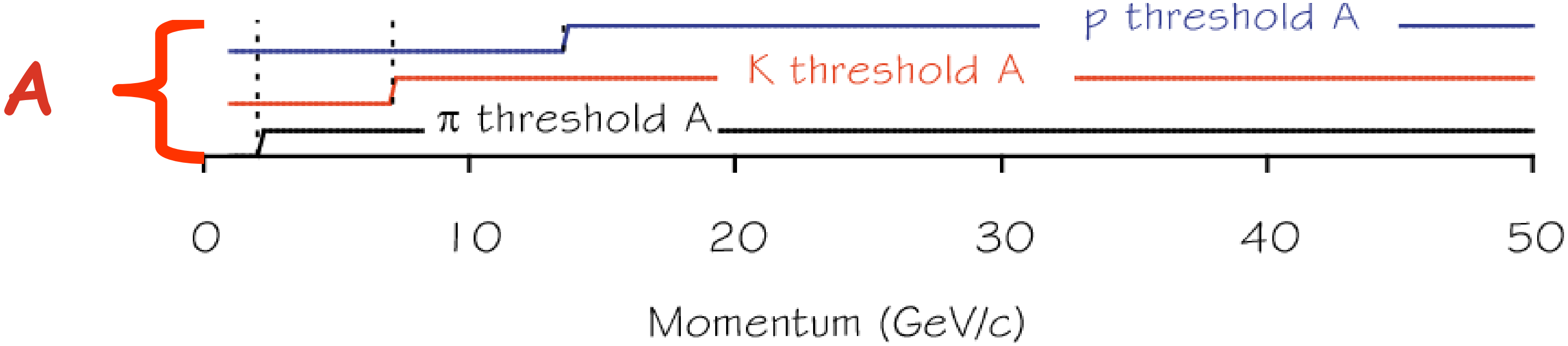
Threshold Cherenkov Detector: examples

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

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

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

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

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

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

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

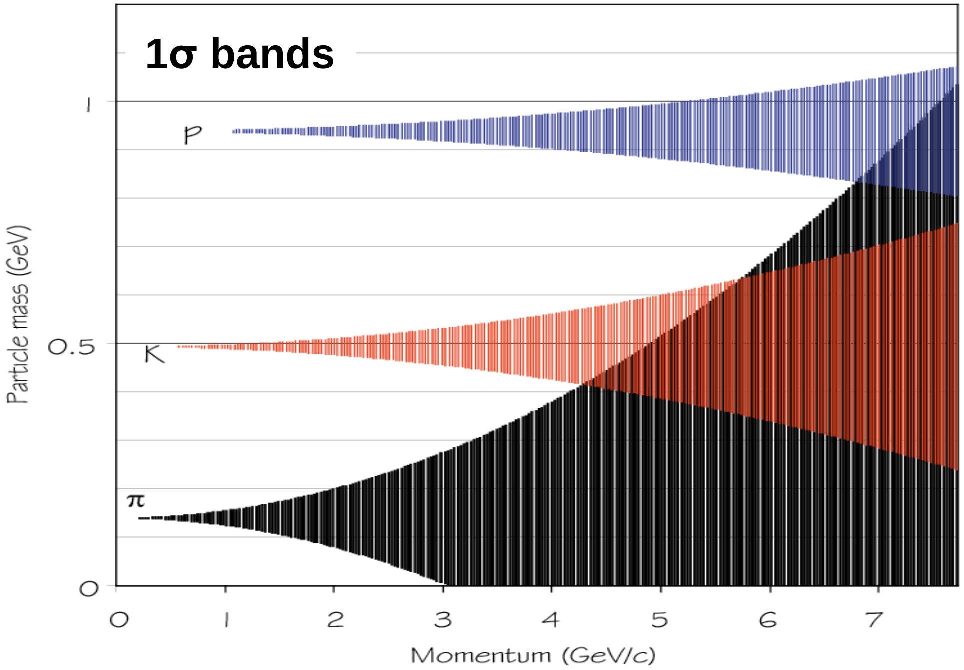
⇒

low chromaticity
high granularity
high packing density

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

set :
n = 1.333 (H$_2$O) → θ_{max} = 41.4 °, β_{min} = 0.75

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



Imaging technique: measure Cherenkov radiation angle

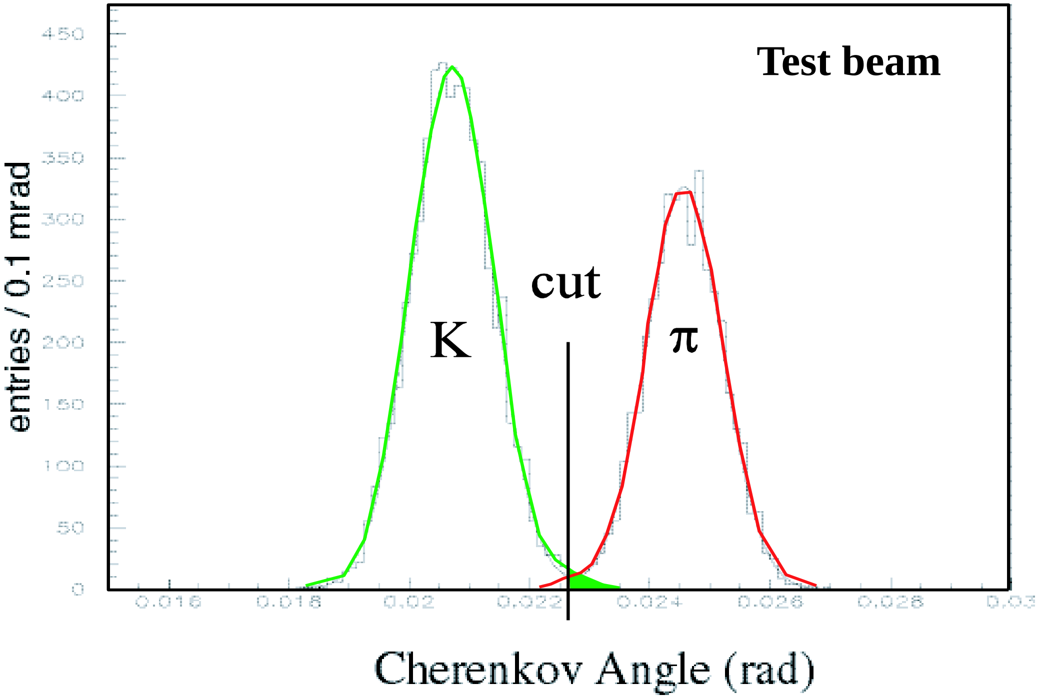
Separation power:

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

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

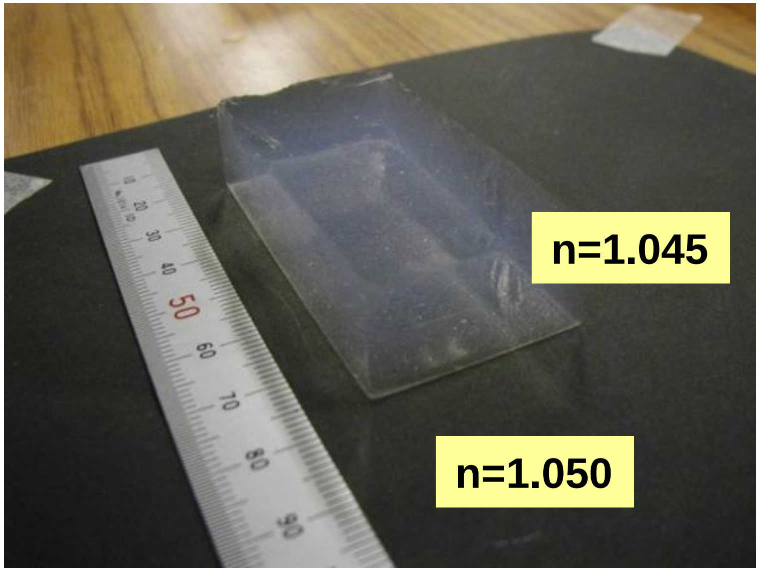
- Adjusting the position of the cut placed between the two peaks to identify a candidate as K or π gives a trade-off between *efficiency* and *misidentification*

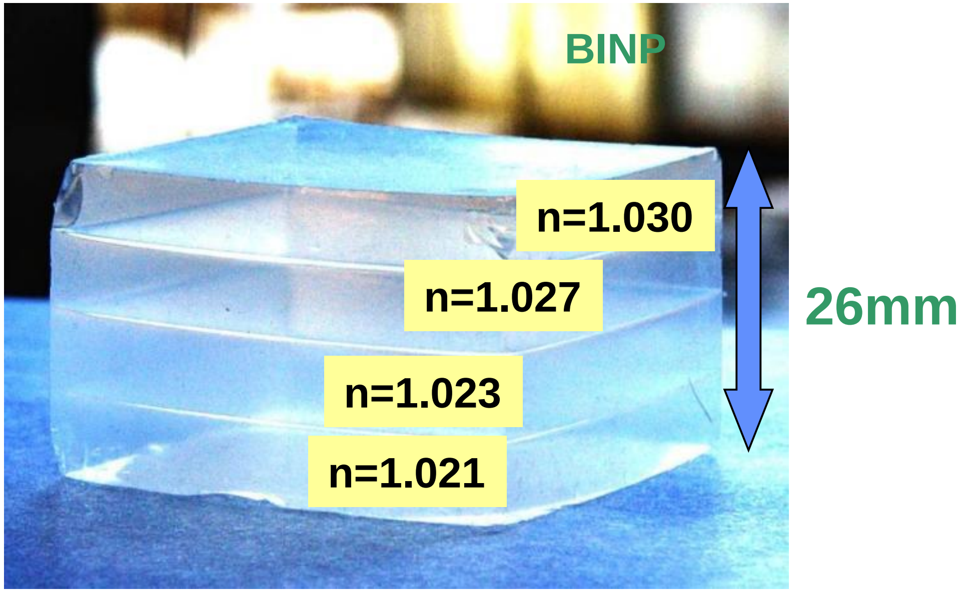


- The overall resolution determines how high in momentum particles can be distinguished, since the increase in Cherenkov angle *saturates,* so the radius for different *mass hypotheses* get closer together

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



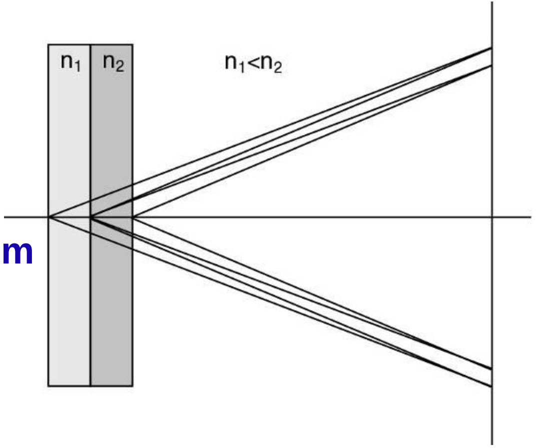


Aerogel is a manufactured material with the lowest density of any known solid. Derived from a gel in which the liquid component of the gel has been replaced with a gas.

Aerogel RICH for SuperBelle (R&D)

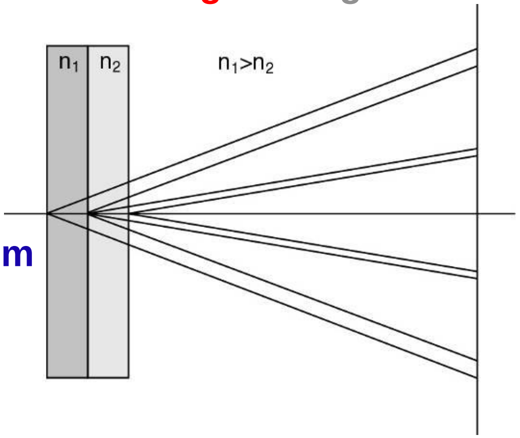
- ☐ Aerogel with multiple refractive indices increases Nph without degrading angular resolution

"focusing" configuration n1<n2

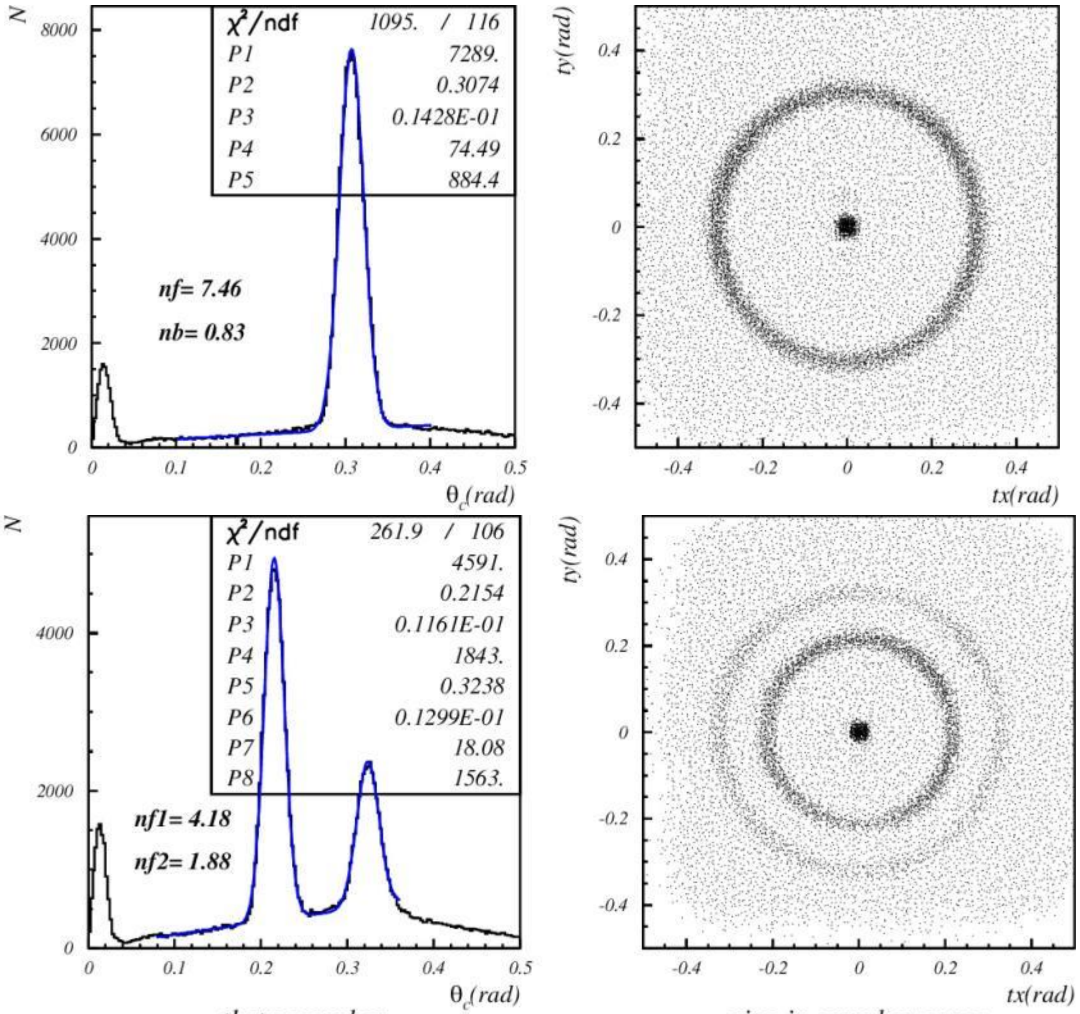


2+2cm

"defocusing" configuration n1>n2



2+2cm



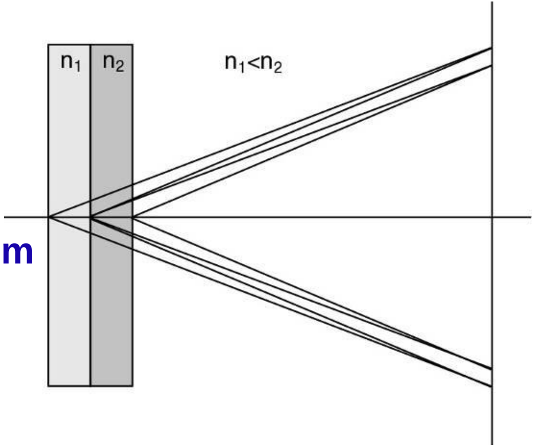
theta cerenkov

ring in cerenkov space

Aerogel RICH for SuperBelle (R&D)

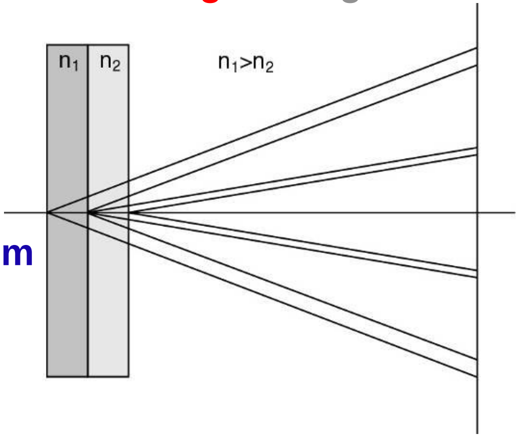
- ☐ Aerogel with multiple refractive indices increases Nph without degrading angular resolution

“focusing” **configuration n1<n2**

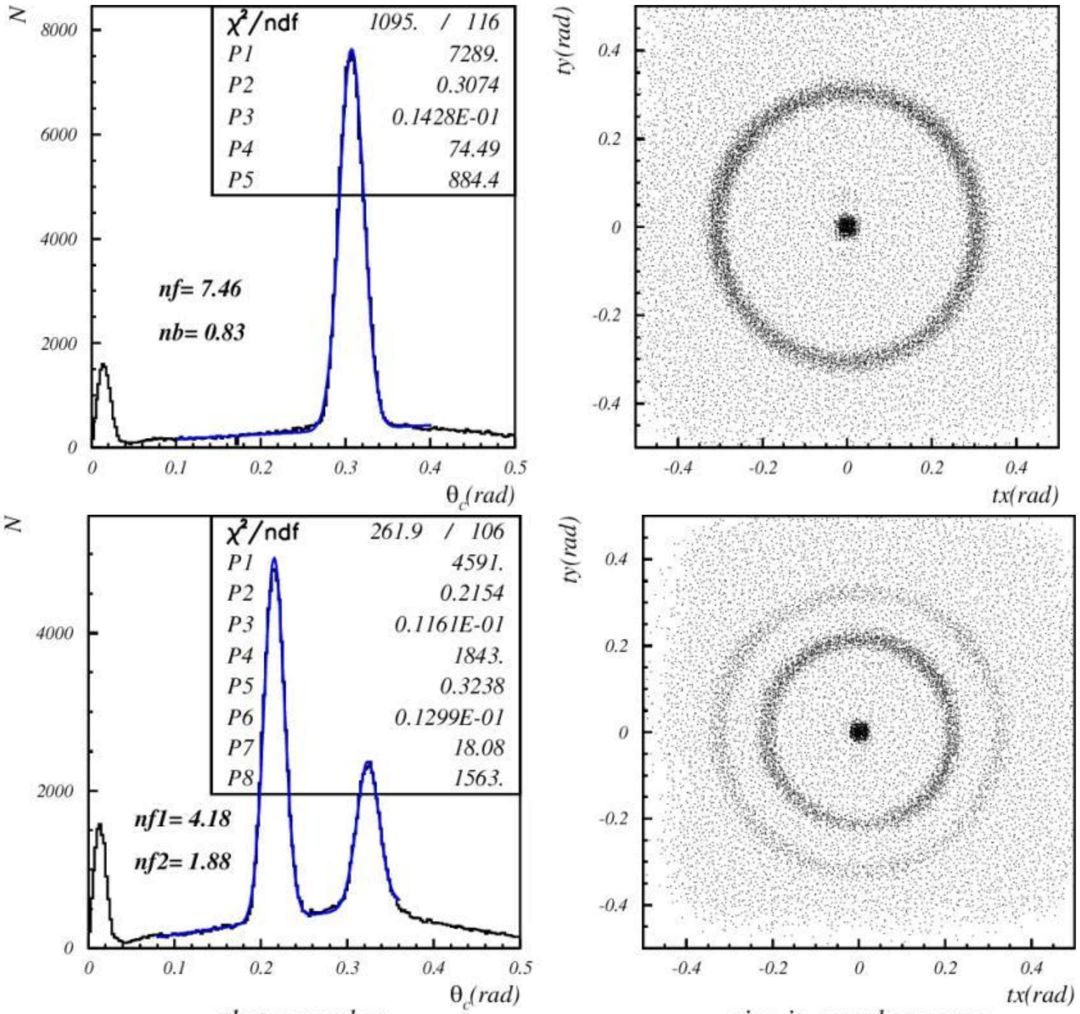


2+2cm

“defocusing” **configuration n1>n2**



2+2cm



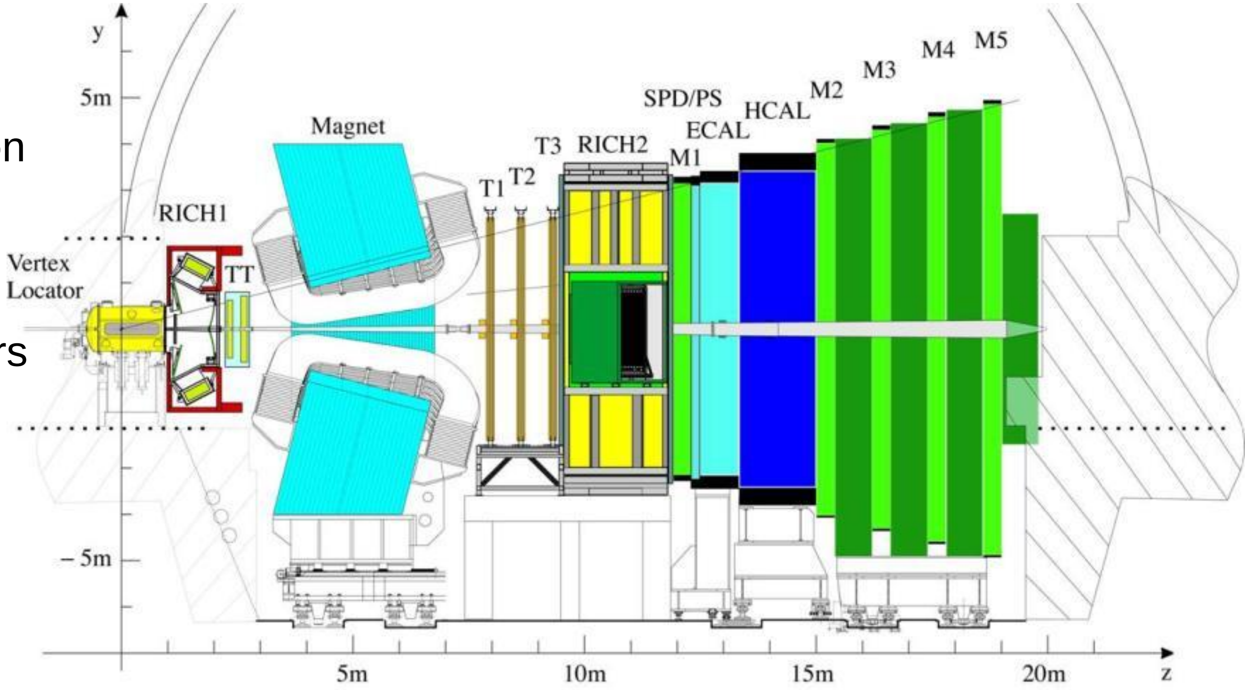
theta cerenkov *ring in cerenkov space*

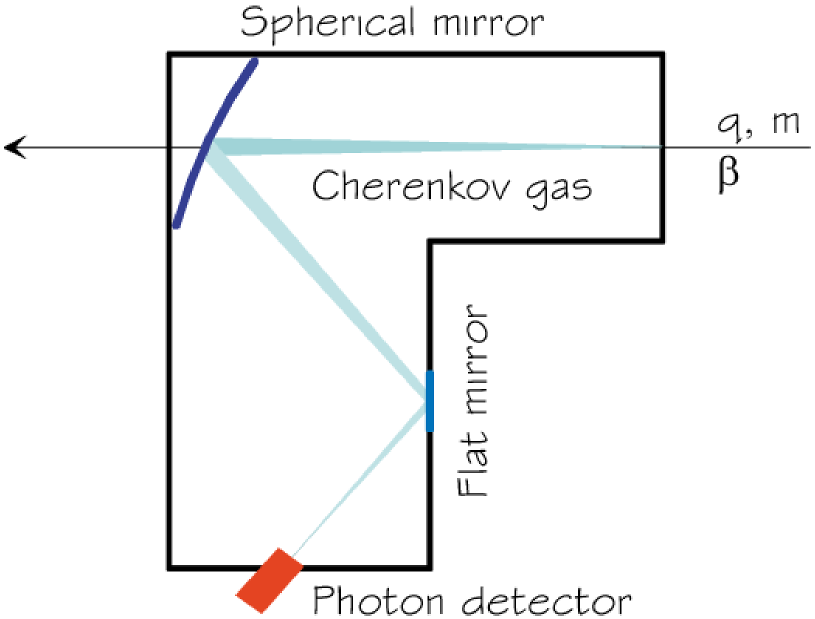
Q: Which configuration is better ?

LHCb: charged hadron identification with RICH detectors

Position photodetectors in tolerable radiation zone

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





(HPD)

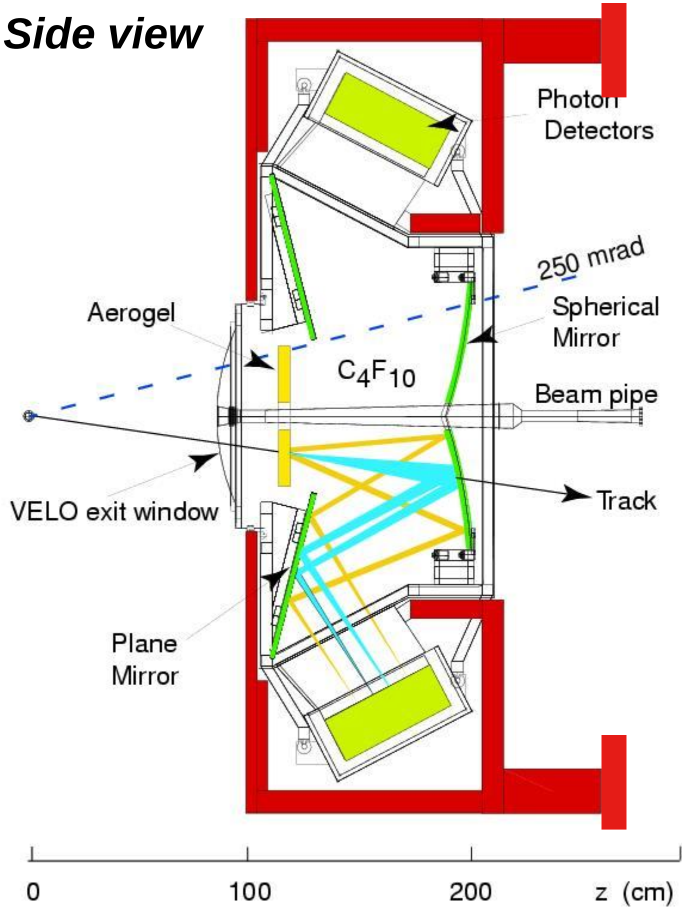
Keep few 10 mrad resolution

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

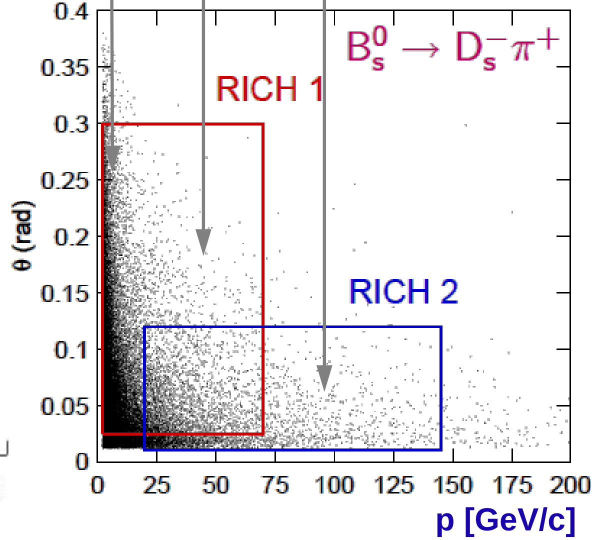
Acceptance 25-300 mrad



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

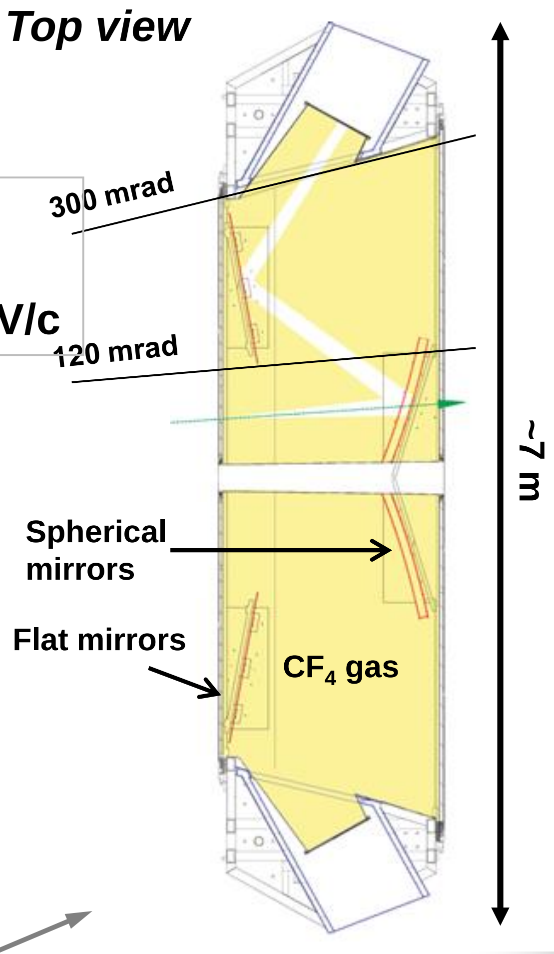
C_4F_{10}:
n=1.0014
Up to ~70 GeV/c

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



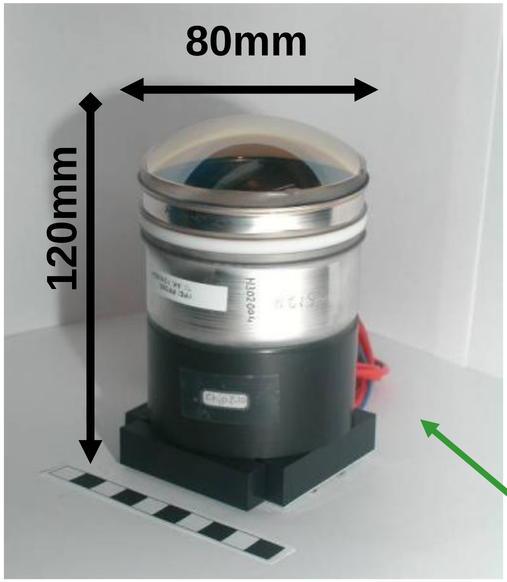
RICH 2

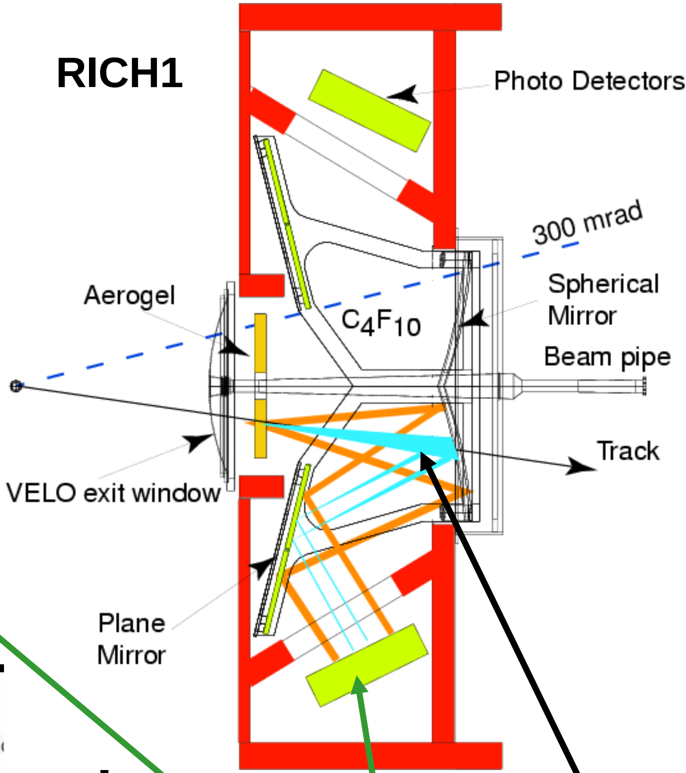
Acceptance 15-120 mrad

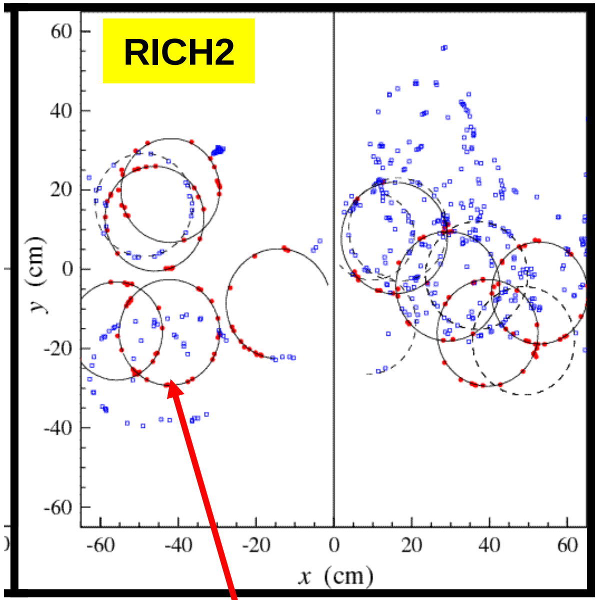


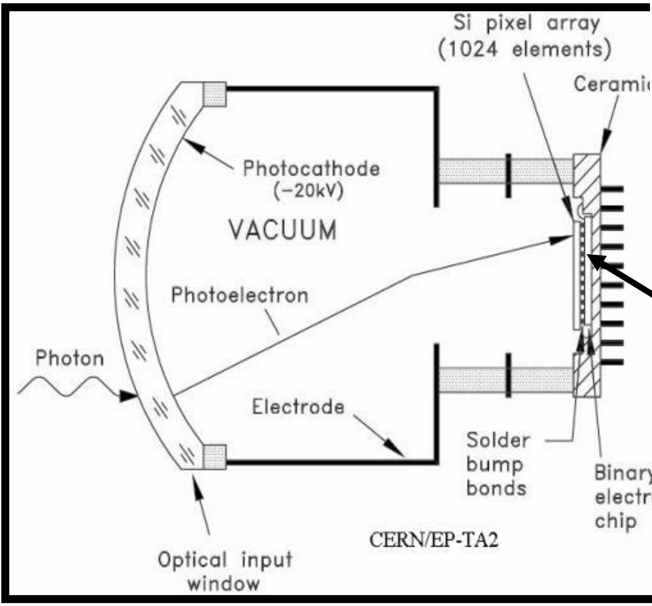
Note scale difference

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

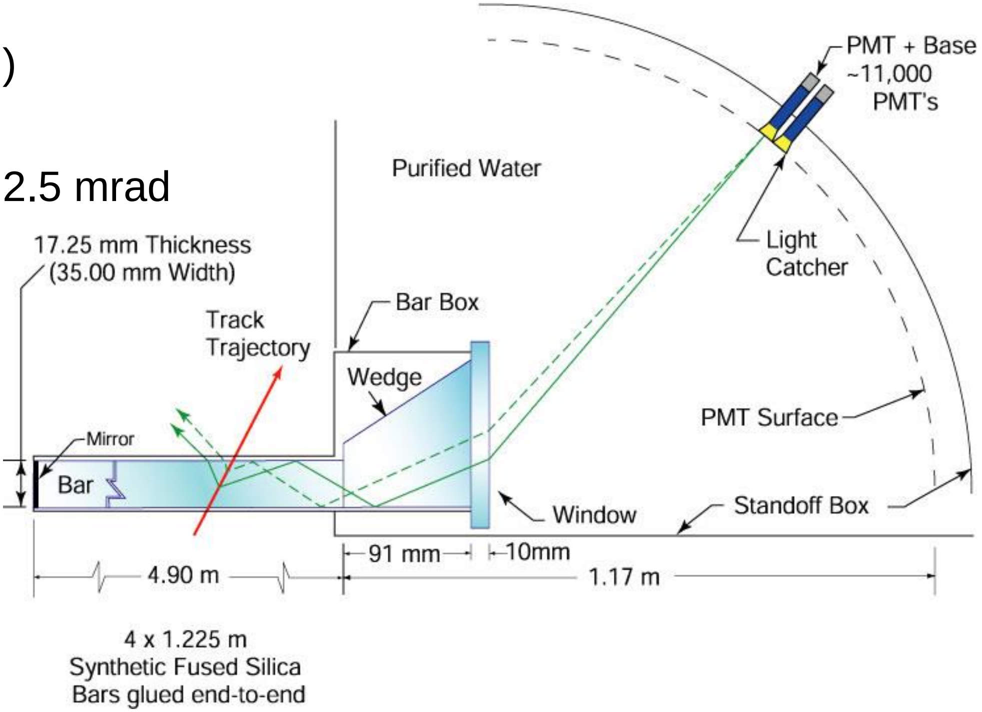
Fast focusing Detector of Internally Reflected Light (DIRC at BaBar)

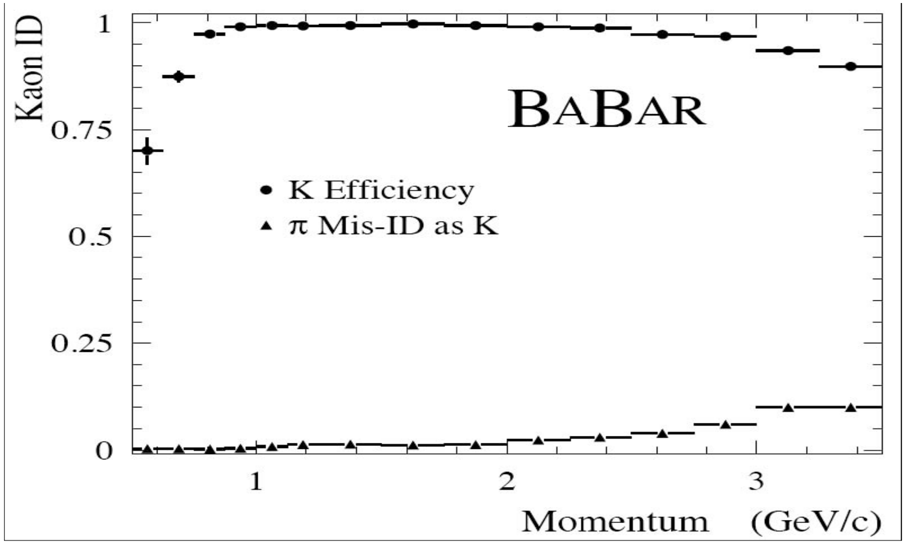
Secure escape of light towards photodetectors in 4π experiment

- 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





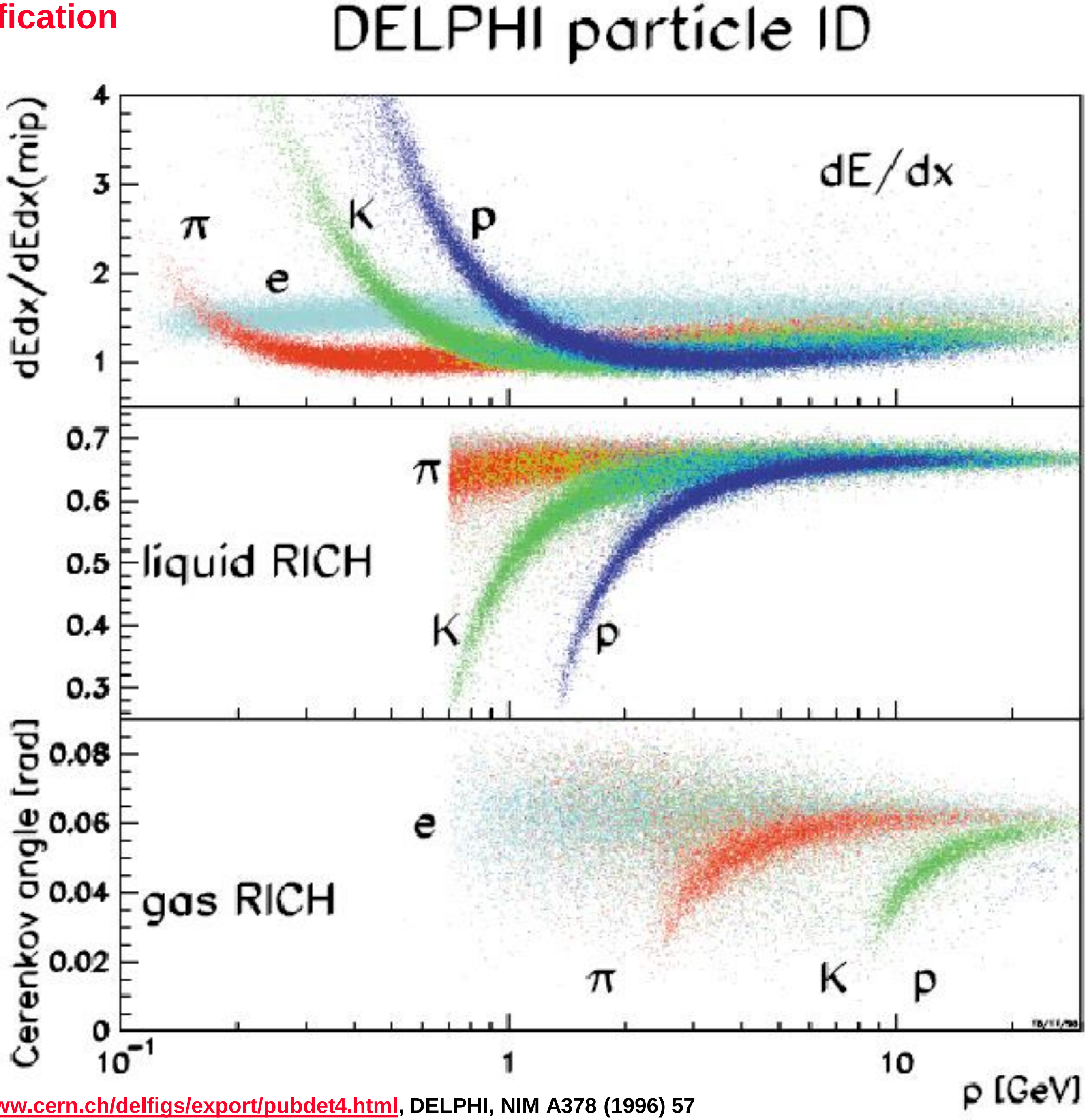
I. Adam et al.,
NIM A538 (2005) 281

Example: DELPHI **Particle Identification** with the

TPC

and

RICHes



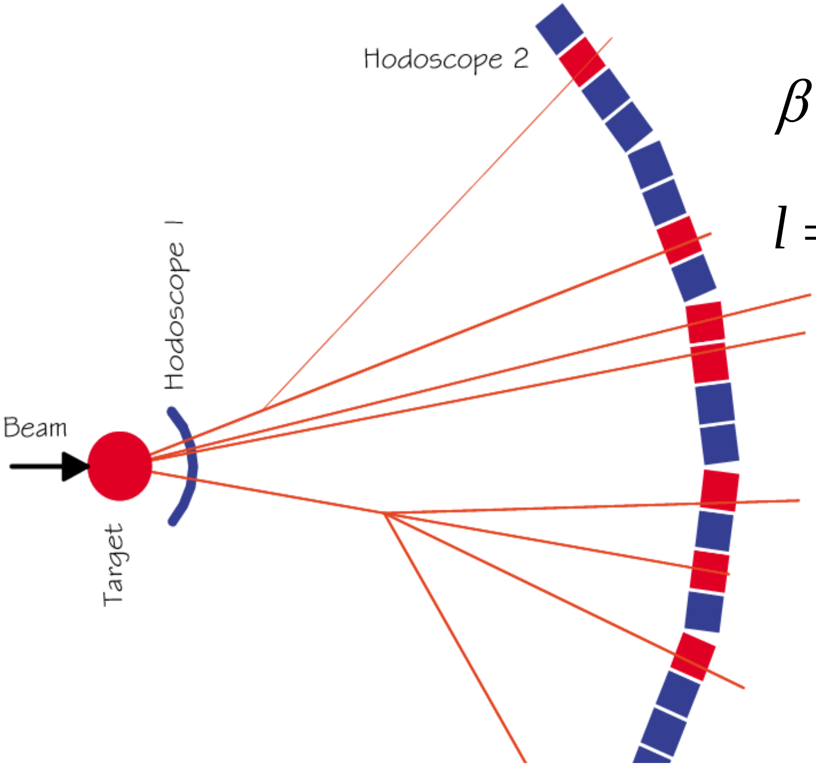
Can do it with data:

- p from Λ
- K from Φ
- π from K^0

http://delphiwww.cern.ch/delfigs/export/pubdet4.html, DELPHI, NIM A378 (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



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

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

→ **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 :

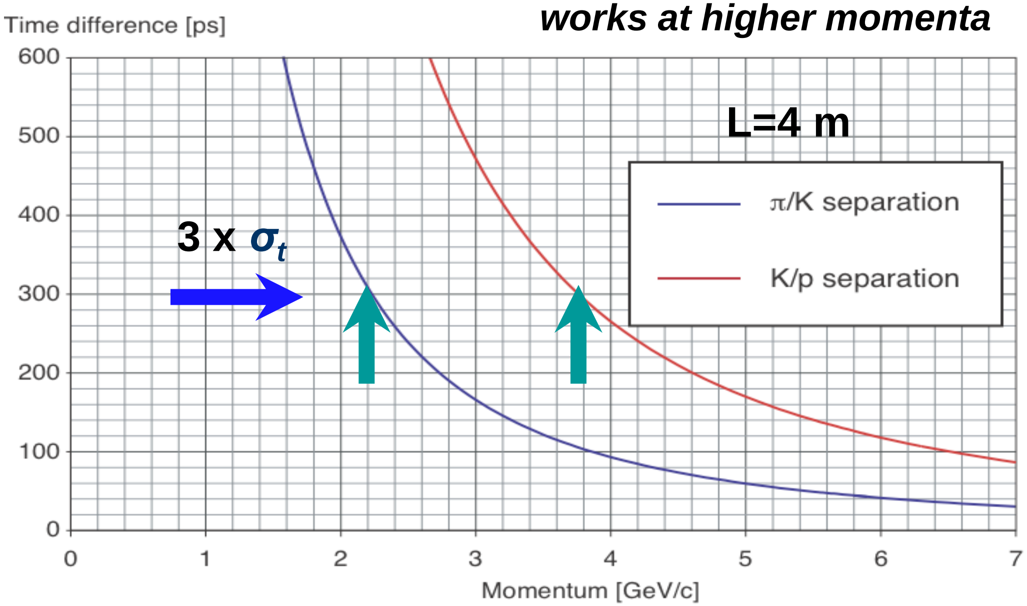
$$N_\sigma = \frac{|m_1^2 - m_2^2|}{2\, p^2\, \sigma_\theta \sqrt{n^2-1}}$$

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

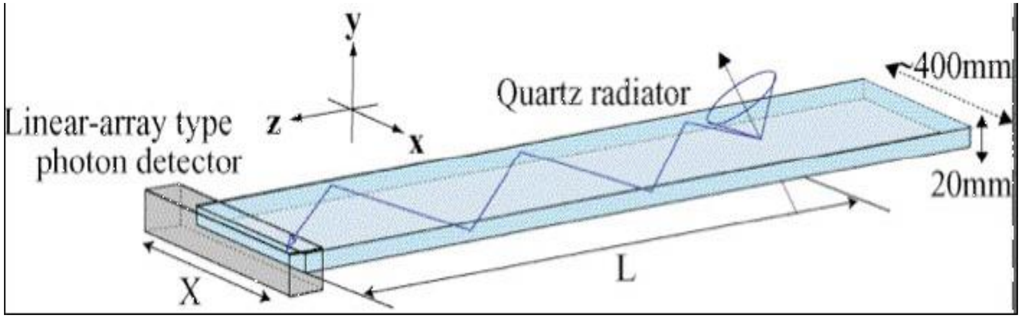
TOF based on fast gaseous counters

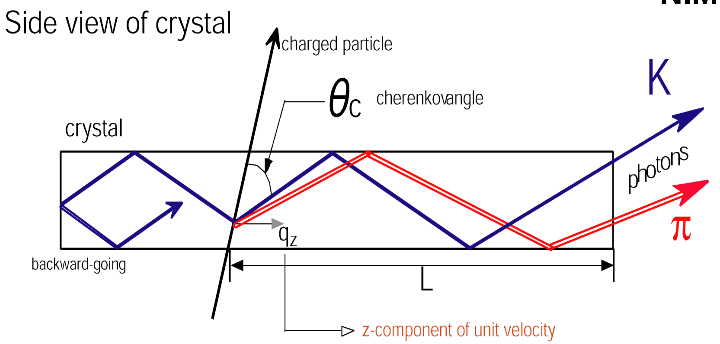
- ☐ Not sensitive to B
- ☐ Very good time resolutions
  → 30-50 ps
- ☐ Cost effective solution for large surfaces
- ☐ Capability at high rates

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

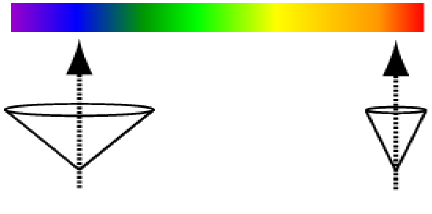
NIM A453 (2000) 331





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

t_K-t_π (3 GeV)=75 ps
for 1 m flight path



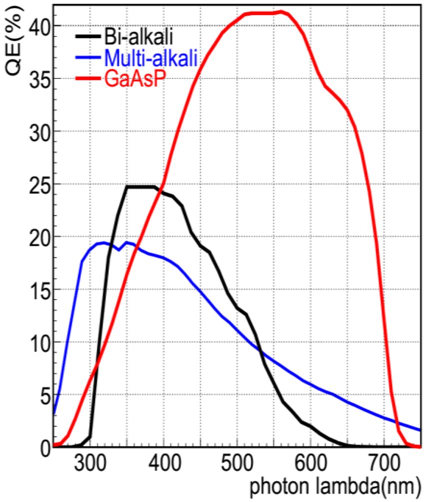
$\Delta\theta_c$~1.2 mrad

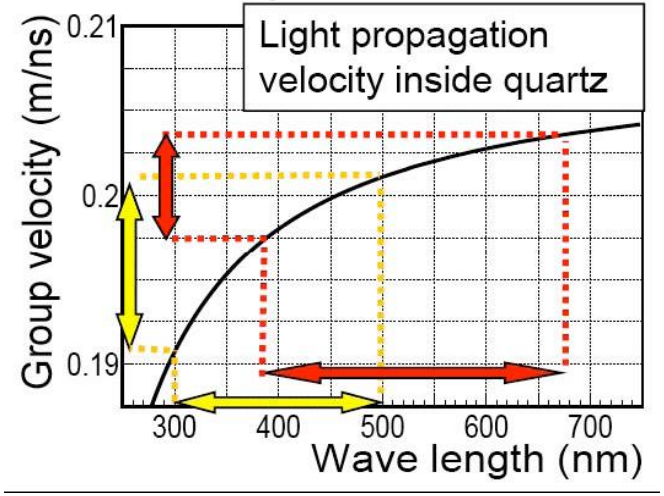
Chromatic
time
dispersion:
~ 100 ps

Requirements to MCP-PMT

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

Yellow: bialkali photocathode
Red: GaAsP photocathode





TOF from Cherenkov light: TOF + RICH → TORCH

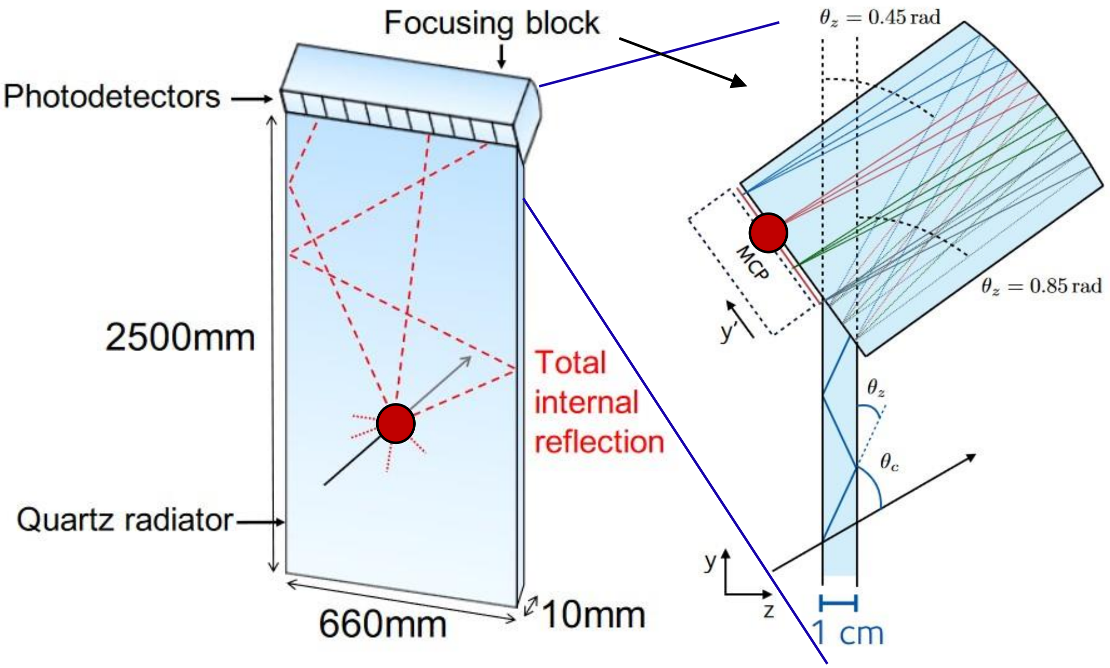
NIM A639 (2011) 173, NIM A1050 (2023) 168181

- ☐ Time Of internally Reflected CHerenkov light
- ☐ Charged particles ID for p = 2–20 GeV
- ☐ Flight path ~9.5 m, i.e. flight time difference of 35 ps between 10 GeV π and K
- ☐ Target time resolution per photon ~70 ps, i.e. 10−15 ps TOF resolution for 30 detected photons per charged particle
- ☐ Measure : particle entry position ; photon hit coordinate ; (unfolding multiple internal reflections of the photon)

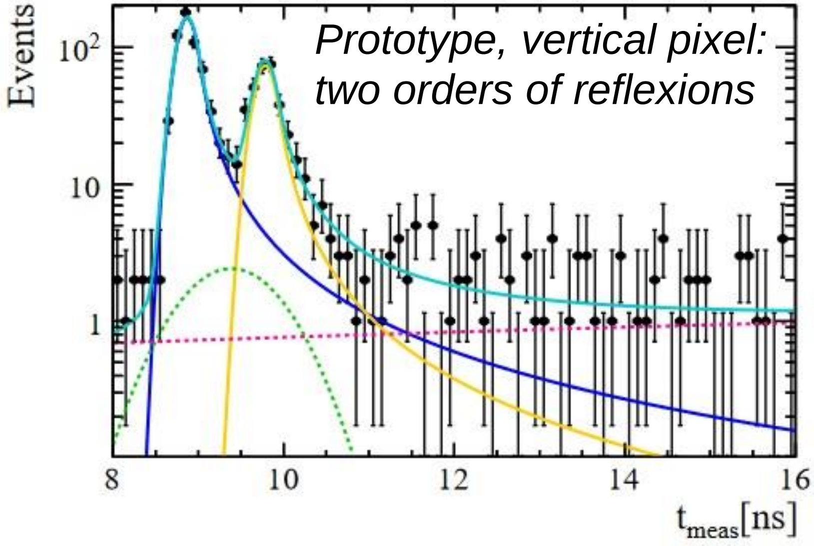
→ Cherenkov emission angle θ_C

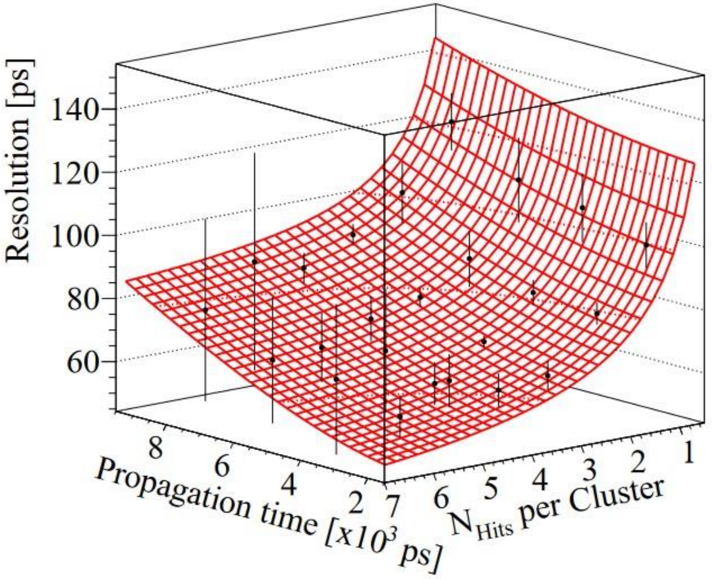
→ Photon (+ charged particle) path length

→ ***β***

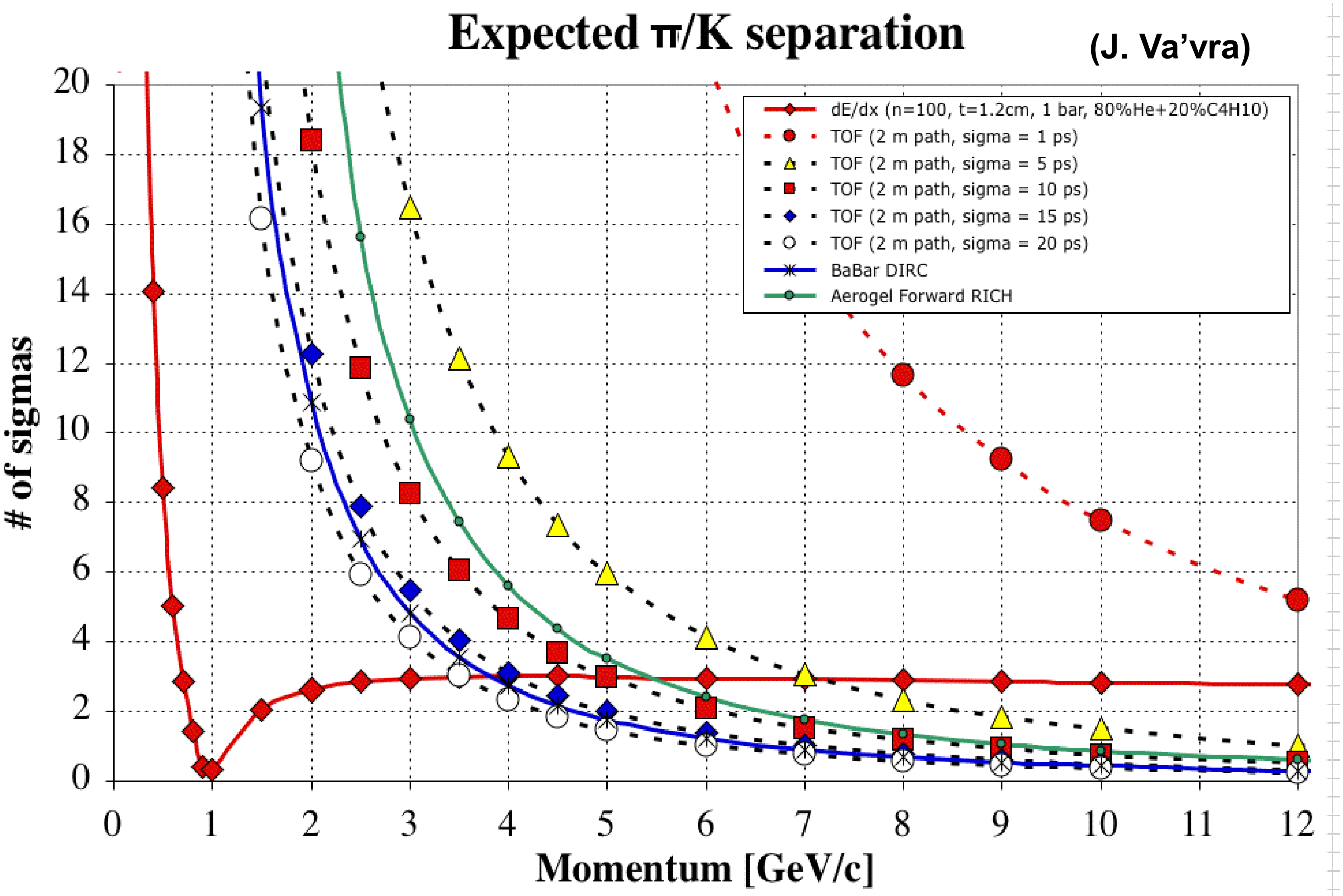


$$\sigma^2_{\mathrm{TORCH}} = \sigma_{\mathrm{prop}}(t_p)^2 + \sigma^2_{\mathrm{MCP}} + \sigma_{\mathrm{RO}}(N_{\mathrm{Hits}})^2$$

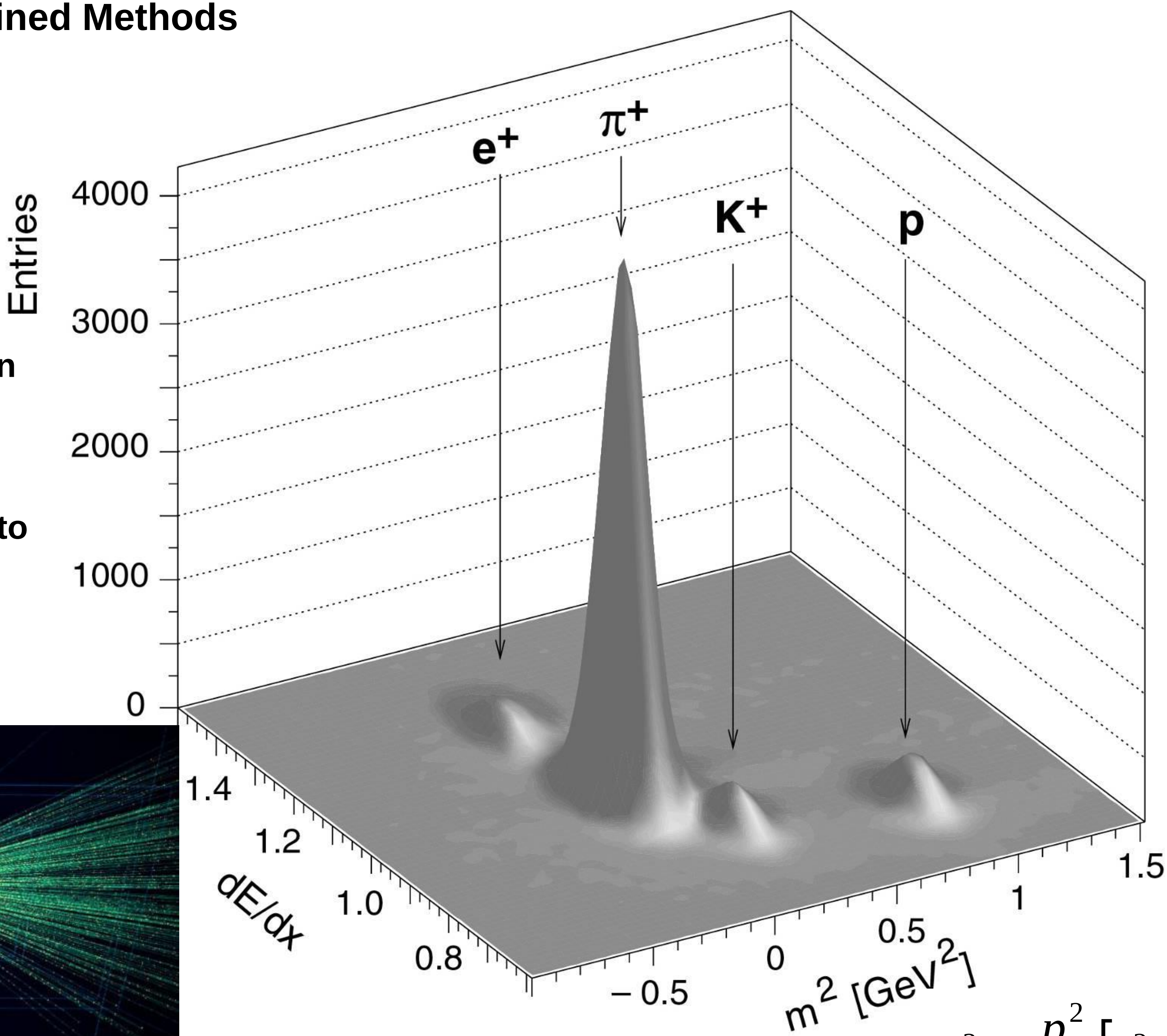

Prototype, vertical pixel: two orders of reflexions



Projected ps-TOF particle ID performance

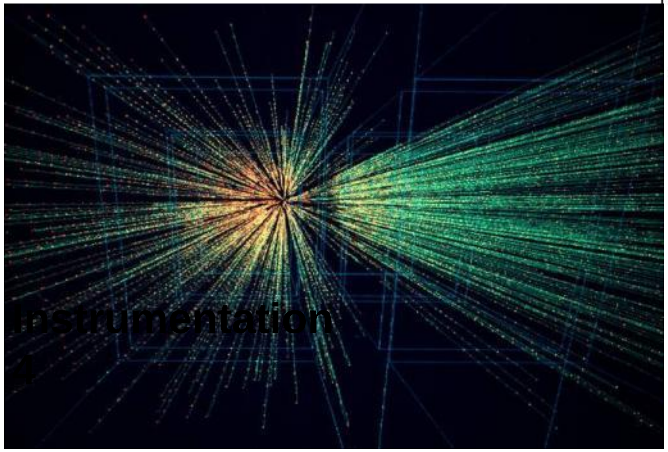


Particle ID: Combined Methods



<u>NA49</u>

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



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

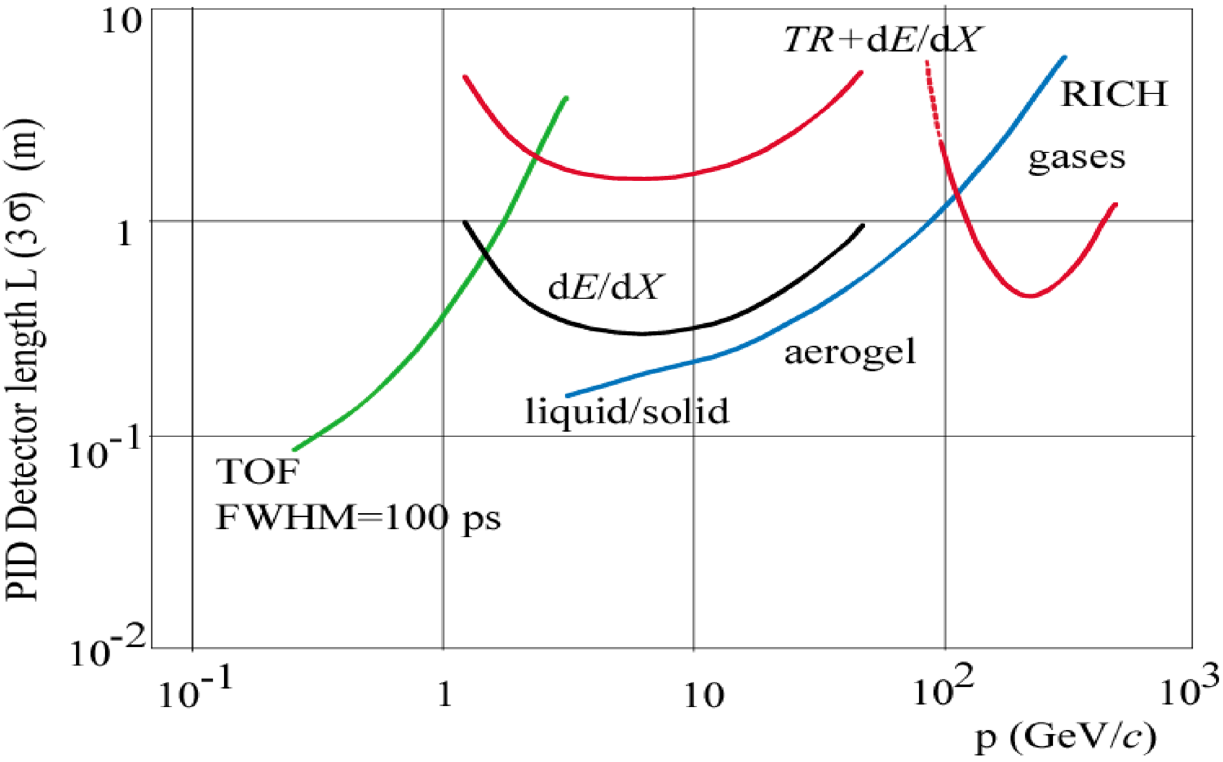
NA49, CERN-EP/99-001

Particle Identification: summary

- ☐ Wide variety of techniques for charged particles ID
- ☐ **Cherenkov detectors**
  Very powerful; tuning the choice of radiator
- ☐ **Ionization energy loss**
  Provided by existing tracking detectors
  Limited separation at low *p*
- ☐ **Time Of Flight**
  Excellent performance at low *p*
  Range of TOF momentum coverage will increase with faster photon detectors
- ☐ Transition radiation
  Electron identification
- ☐ Powerful **combined methods**

Pion-Kaon separation for different PID methods

The length of the detectors needed for 3σ separation



NIM A 433 (1999) 533

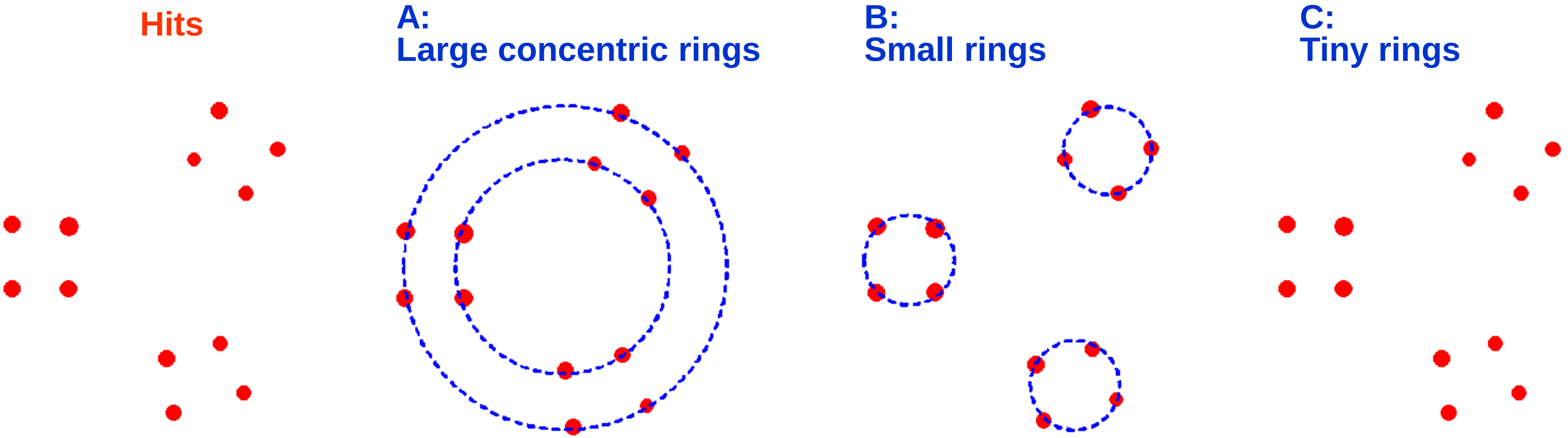
+ calorimetry for e, γ, π^o identification

+ muon detecting system

Quest: search for the rings

Photons ➔ Hits ➔ Rings

Ring reconstruction.


Hits

A:
Large concentric rings

B:
Small rings

C:
Tiny rings

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

=

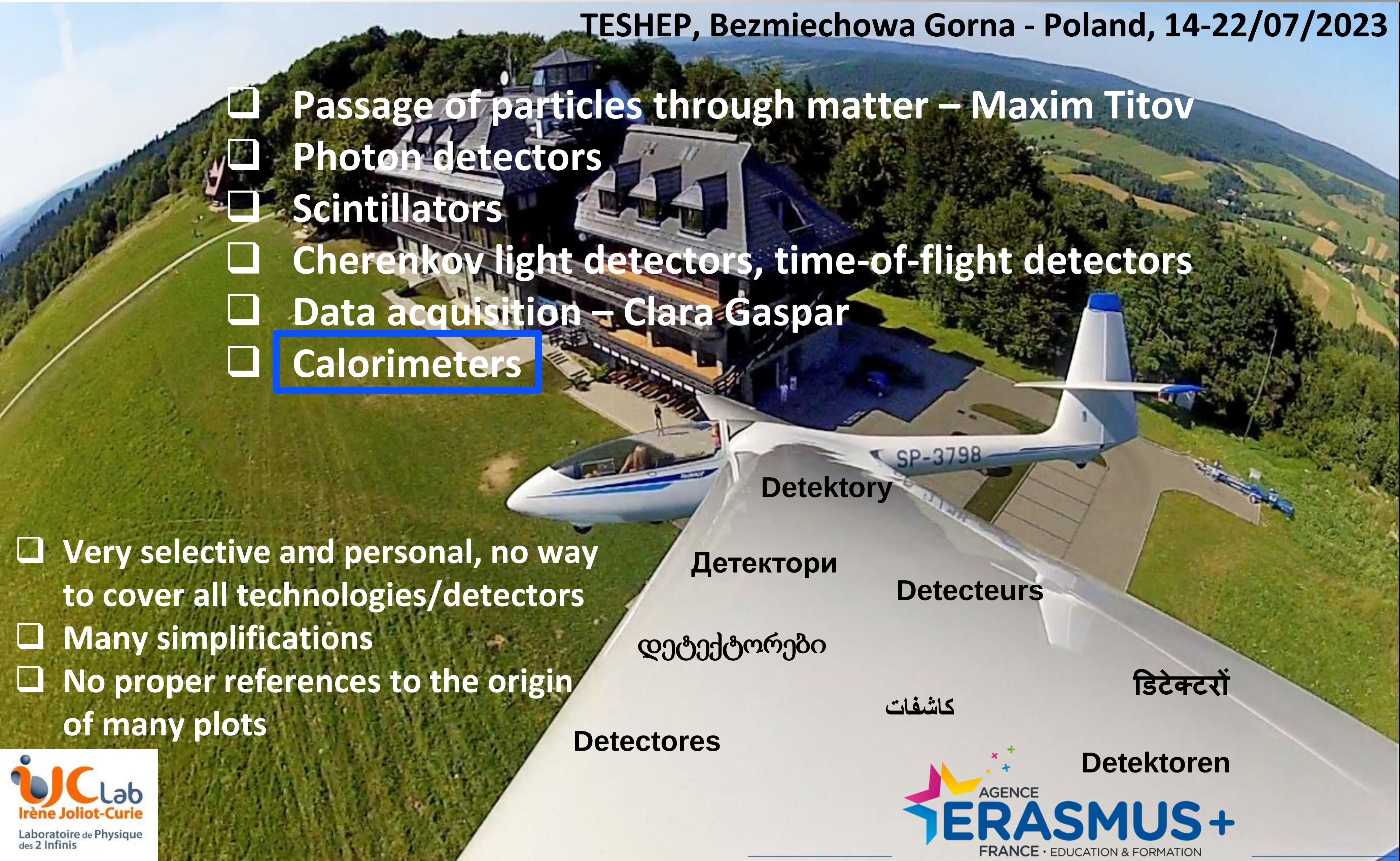
The answer *must* depend on the process which is believed to have lead to the dots being generated.

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

Detektory do fizyki wysokich energii

Sergey Barsuk, IJCLab Orsay, sergey.barsuk@ijclab.in2p3.fr

TESHEP, Bezmiechowa Gorna - Poland, 14-22/07/2023



- ☐ Passage of particles through matter – Maxim Titov
- ☐ Photon detectors
- ☐ Scintillators
- ☐ Cherenkov light detectors, time-of-flight detectors
- ☐ Data acquisition – Clara Gaspar
- ☐ Calorimeters

- ☐ Very selective and personal, no way to cover all technologies/detectors
- ☐ Many simplifications
- ☐ No proper references to the origin of many plots

Detektory

Детектори

Detecteurs

დეტექტორები

डिटेक्टरों

كاشفات

Detectores

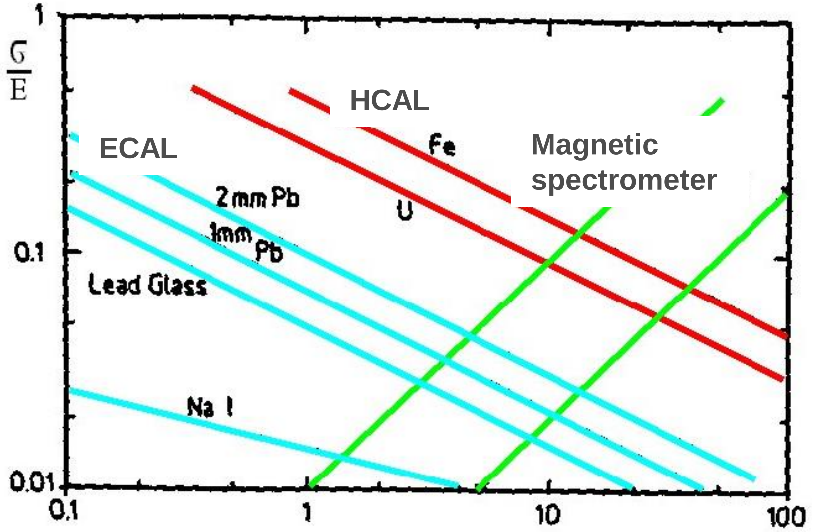
Detektoren

IJCLab
Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis

AGENCE ERASMUS+
FRANCE · EDUCATION & FORMATION

Calorimeters

- Measures **charged** (e, h) **+ neutral** (photons, n, K_L, …) particles; muons usually traverse calorimeters loosing small amounts of energy by ionization (MIP)
- Energy flow : **total (missing) energy**, jets, …
- Fast signal ➔ real time (**trigger**)
- Performance *improves* with *E*
  (unlike *p* measurement)

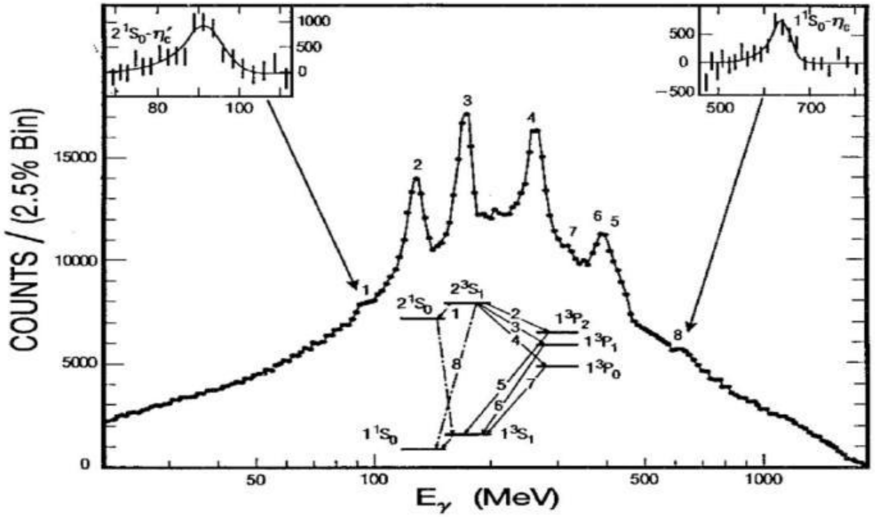


- Calorimeter yields :
  → Energy measurement
  → Position/angular measurement
  → Particle ID
  → Missing energy given full coverage of the acceptance

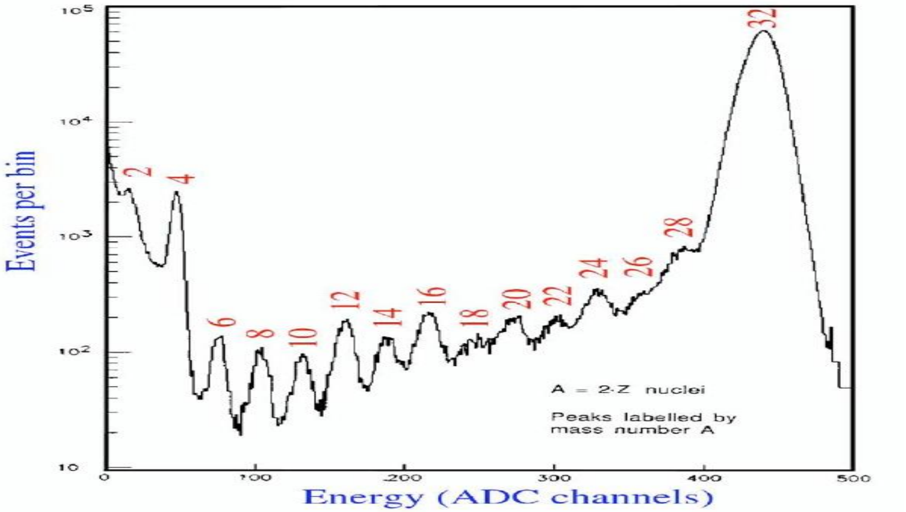
- Tricky: Uniformity of response, signal linearity, calibration : energy = f(measured signal), radiation resistance, hadronic shower fluctuations, … ➔ performance limited

Calorimetry canonical illustrations

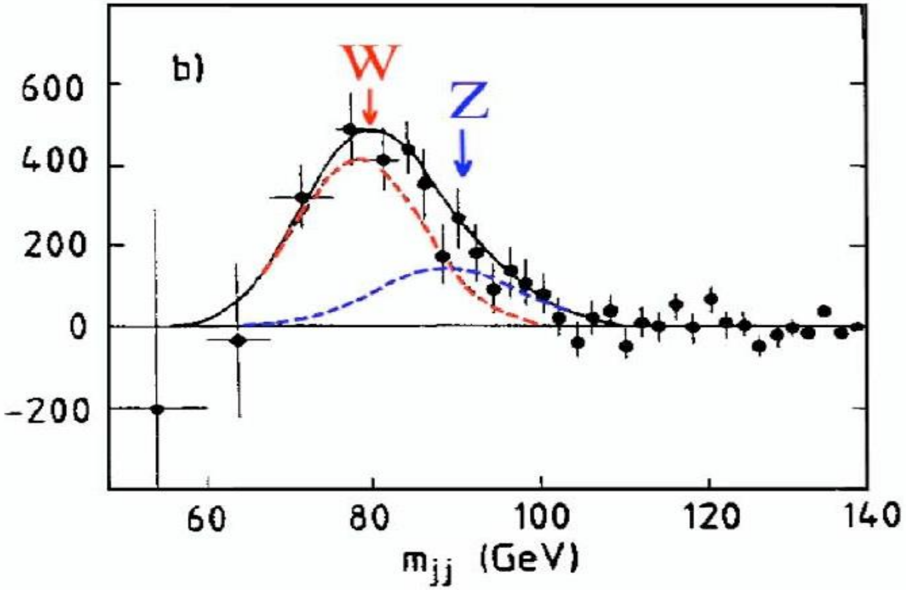
<u>EM energy resolution</u> charmonium spectroscopy (SPEAR)



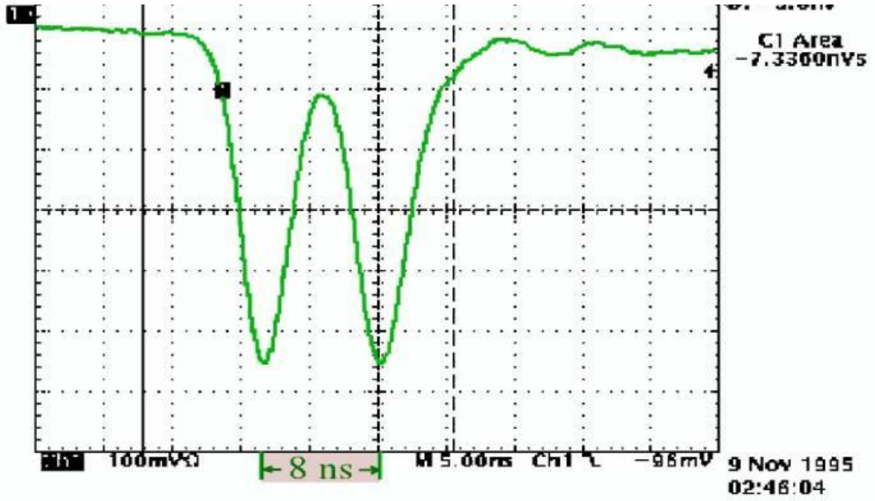
<u>H energy resolution</u> WA80 calorimeter – composition of *p*-selected CERN heavy ion beam



<u>H energy measurement</u> UA2 experiment, QCD bgrd subtracted



<u>Signal speed</u> two subsequent evts, NA50 Zero Degree Quartz Fiber calorimeter, CERN heavy ion beam



Calorimeters

- ☐ **Electromagnetic Calorimeters**
- ☐ **Hadronic Calorimeters**

Destructive method :
EM or hadronic showers measurement
by total absorption with signal ~ E

EM interaction : Xo ranges from 13.8 g/cm2 for Fe to 6.0 g/cm2 for U

H interaction : λ_I ranges from 132.1 g/cm2 for Fe to 209 g/cm2 for U

EM Calorimeters: MANY (15-30) Xo deep

H Calorimeters: many (5-8) λ_I deep

Energy resolution of EM calorimeter

Usually parameterized by
(stands also for hadron calorimeter) :

$$\boxed{\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}}$$

, E measured in GeV

a : intrinsic resolution or stochastic term

Simplified model :
Number of produced ions/e$^-$ pairs (or photon) N=E/w
Detectable signal (→E) is ∝ N (N quite large)

$$\frac{\sigma}{E} = \frac{\sigma_N}{N} = \frac{1}{\sqrt{N}} \approx \frac{a}{\sqrt{E}}$$

In **homogeneous** calorimeters, where all the energy is detected, resolution better than 1/√N by a factor √F because total energy does not fluctuate (F : fano factor)

Ge : 100 keV, w=2.96 eV → 475 eV while measured 180 eV F=0.13

Most of the time not all the released energy is measured (ionization or light, or dead material), only a **sampling fraction** fs measured

$$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \frac{1}{\sqrt{f_s}}$$

c : contribution of electronics noise
+ at LHC pile up noise…

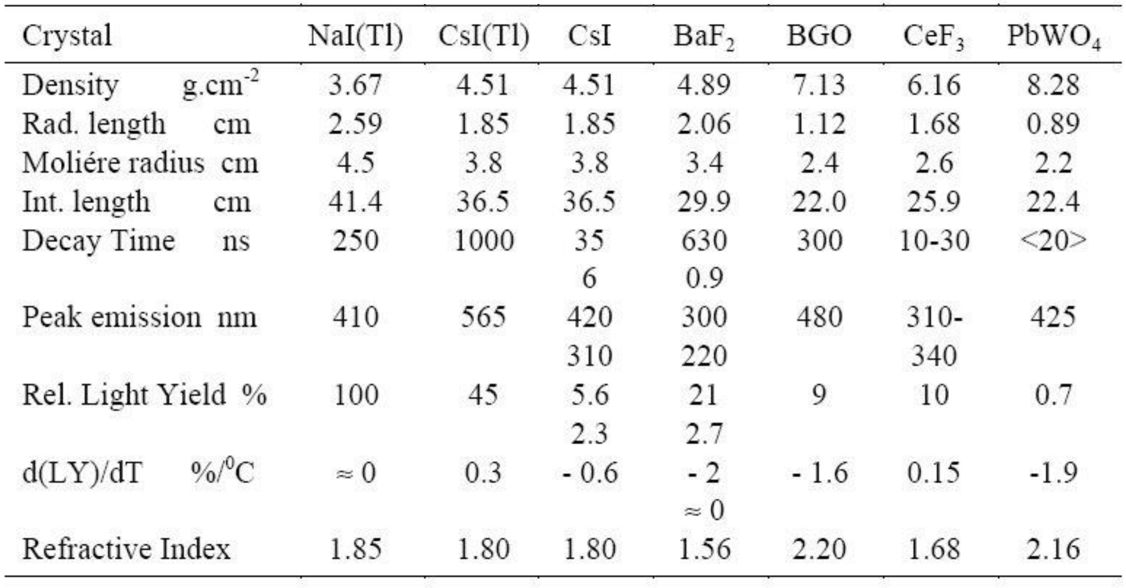
b : constant term, contains imperfections
response variation versus position (uniformity), time (stability), temperature, mis-calibration, radiation damage, ….

Homogeneous calorimeters

- *Same medium to generate the shower and the detectable signal*

Crystals

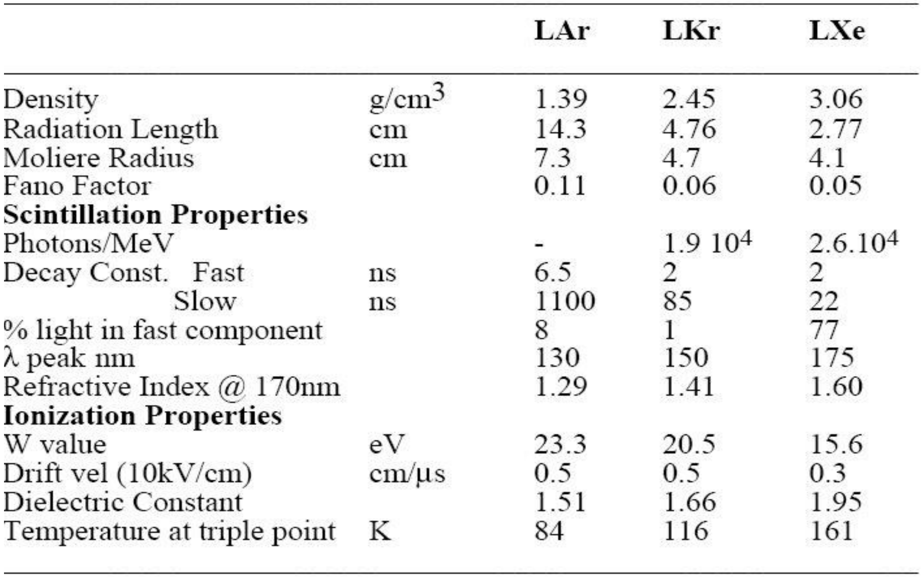
Babar/Belle/KteV L3 CMS



Crystal	NaI(Tl)	CsI(Tl)	CsI	BaF_2	BGO	CeF_3	$PbWO_4$
Density g.cm^{-2}	3.67	4.51	4.51	4.89	7.13	6.16	8.28
Rad. length cm	2.59	1.85	1.85	2.06	1.12	1.68	0.89
Moliére radius cm	4.5	3.8	3.8	3.4	2.4	2.6	2.2
Int. length cm	41.4	36.5	36.5	29.9	22.0	25.9	22.4
Decay Time ns	250	1000	35 6	630 0.9	300	10-30	<20>
Peak emission nm	410	565	420 310	300 220	480	310- 340	425
Rel. Light Yield %	100	45	5.6 2.3	21 2.7	9	10	0.7
d(LY)/dT %/^{0}C	≈ 0	0.3	- 0.6	- 2 ≈ 0	- 1.6	0.15	-1.9
Refractive Index	1.85	1.80	1.80	1.56	2.20	1.68	2.16

Noble liquids

ICARUS KEDR,NA48



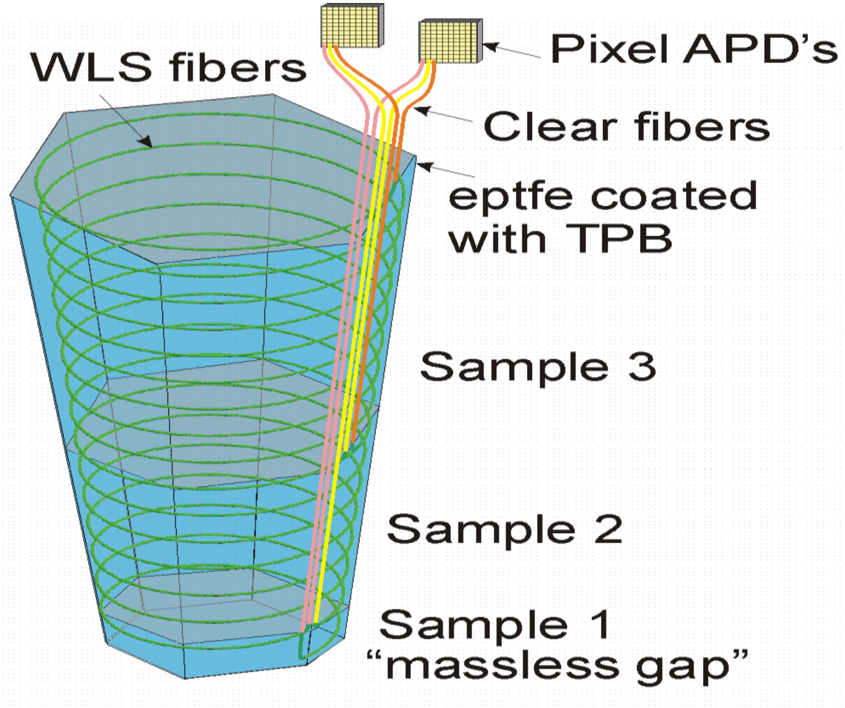
		LAr	LKr	LXe
Density	g/cm^3	1.39	2.45	3.06
Radiation Length	cm	14.3	4.76	2.77
Moliere Radius	cm	7.3	4.7	4.1
Fano Factor		0.11	0.06	0.05
Scintillation Properties				
Photons/MeV		-	1.9 10^4	2.6.10^4
Decay Const. Fast	ns	6.5	2	2
Slow	ns	1100	85	22
% light in fast component		8	1	77
λ peak nm		130	150	175
Refractive Index @ 170nm		1.29	1.41	1.60
Ionization Properties				
W value	eV	23.3	20.5	15.6
Drift vel (10kV/cm)	cm/μs	0.5	0.5	0.3
Dielectric Constant		1.51	1.66	1.95
Temperature at triple point	K	84	116	161

Cryogeny/purification !

Should use the best compromise / environment / physics
In general good energy resolution but less position resolution / PID because more difficult to have (longitudinal) segmentation

Noble liquids: LiXe

LiXe longitudinal segmentation (Hitlin et al.)



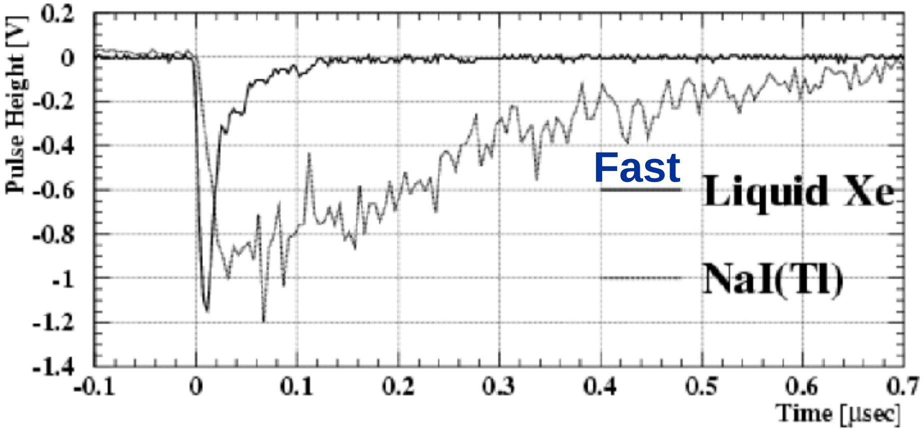
Detection of scintillation light

In Liquid Xenon **:** ~30000 γ/MeV at 175 nm.

Hexagonal cells of ~R_M=5cm

Depth=45cm ~16Xo

Longitudinal segmentation provided by WLS only in one segment



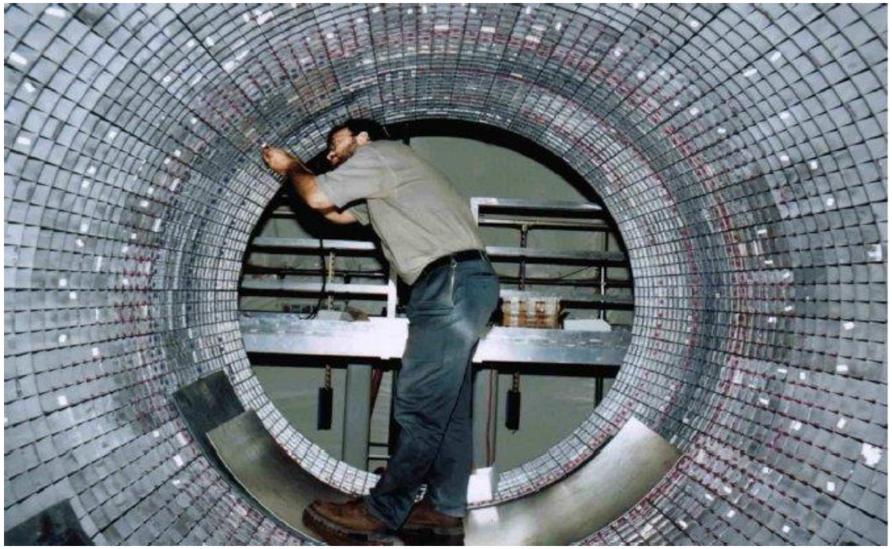
Homogeneous calorimeters with crystals: BaBar

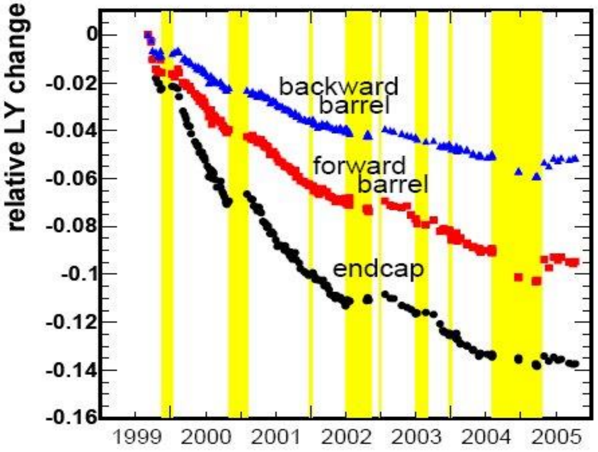
6580 crystals of CsI(Tl)
about 17 X_0

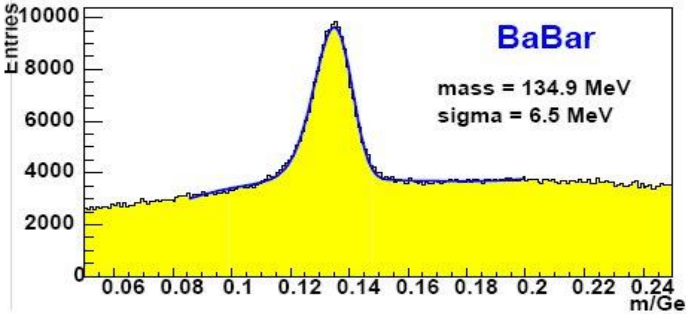
Photon energy between
20 MeV and 8 GeV

$$\frac{\sigma_E}{E} = \frac{(2.30 \pm 0.03 \pm 0.3)\%}{\sqrt[4]{E(\mathrm{GeV})}} \oplus (1.35 \pm 0.08 \pm 0.2)\%$$

$$\sigma_\theta = \sigma_\phi = \frac{(4.16 \pm 0.04)\,\mathrm{mrad}}{\sqrt{E(\mathrm{GeV})}}$$

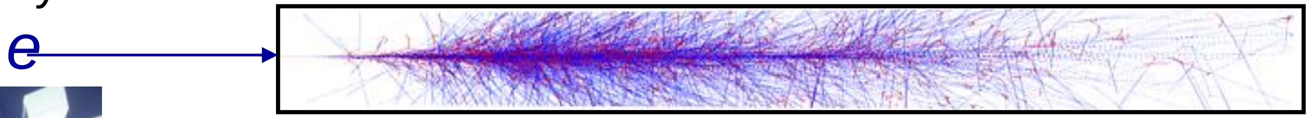


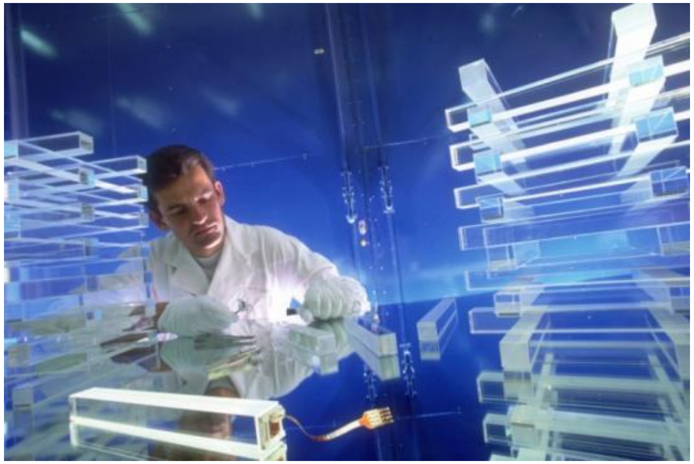


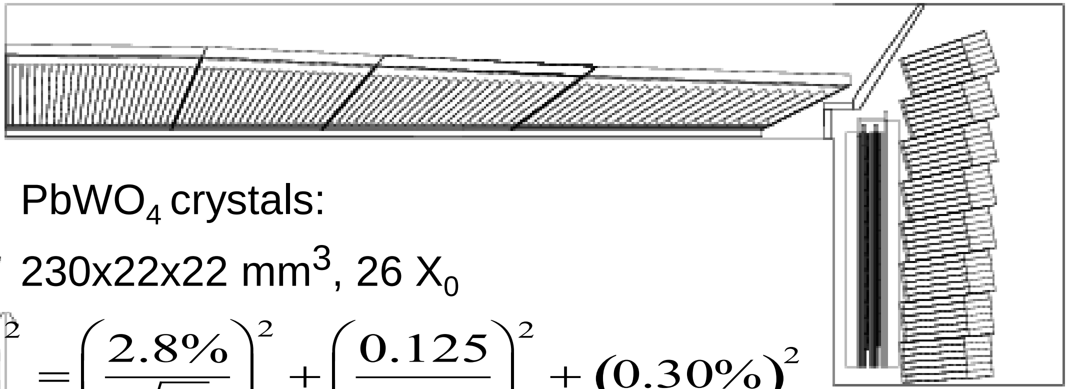


Homogeneous calorimeters with crystals: CMS EM calorimeter

❑ H → γγ : stress on EM calorimetry







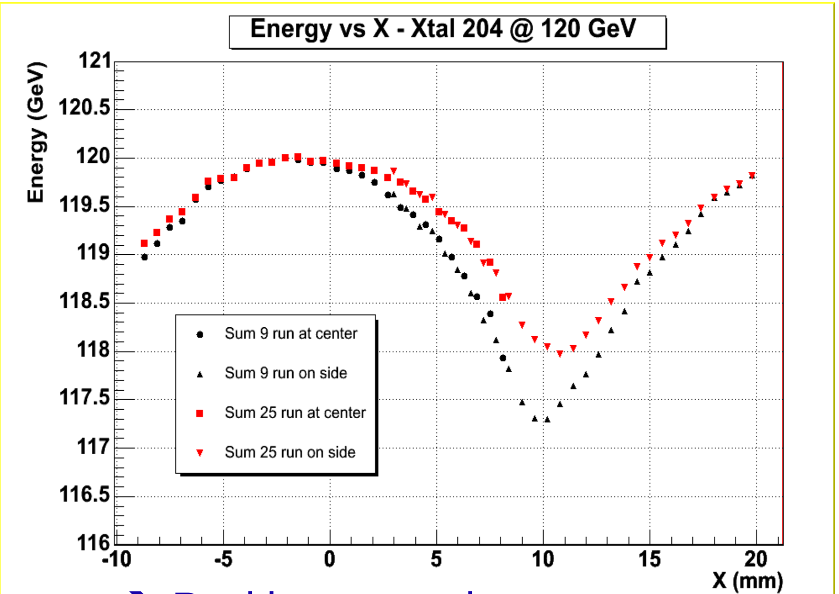
PbWO$_4$ crystals:

230x22x22 mm^3, 26 X$_0$

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{2.8\%}{\sqrt{E}}\right)^2 + \left(\frac{0.125}{E}\right)^2 + (0.30\%)^2$$

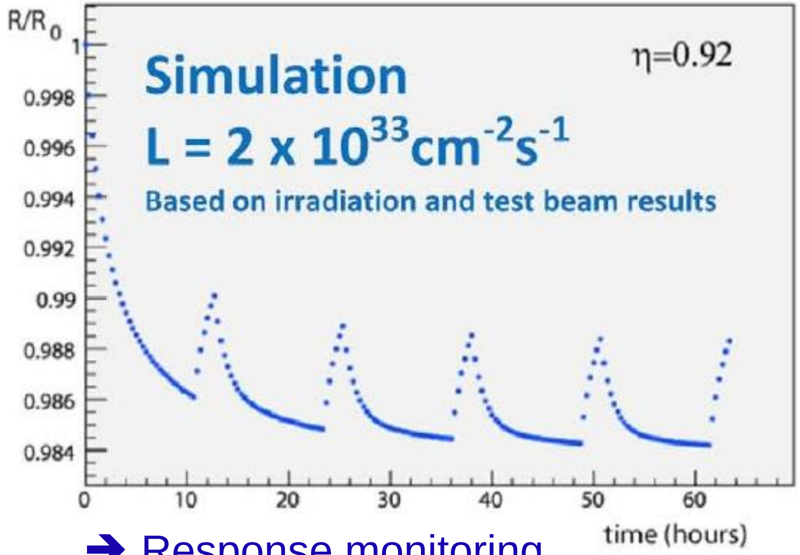
Stochastic **Noise** **Constant**

Response depends on the position



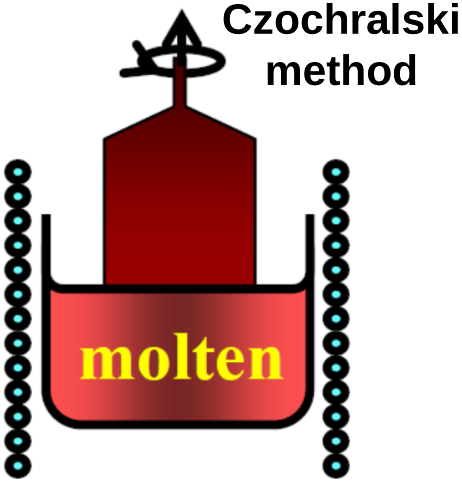
→ Position correction

Radiation damage of PbWO$_4$

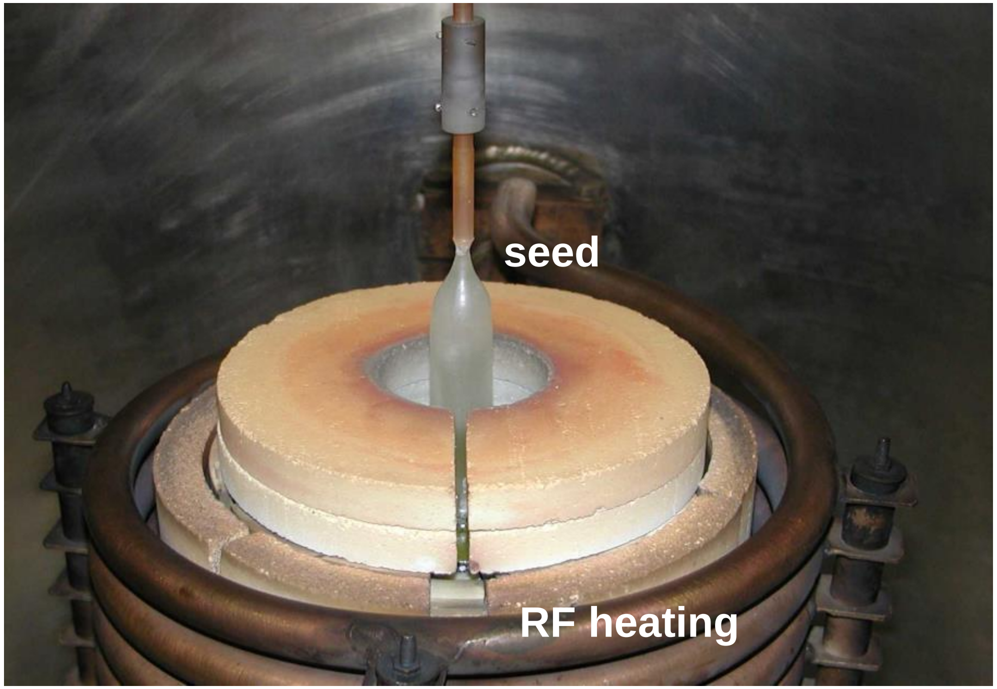


→ Response monitoring

Homogeneous calorimeter with crystals: CMS EM calorimeter



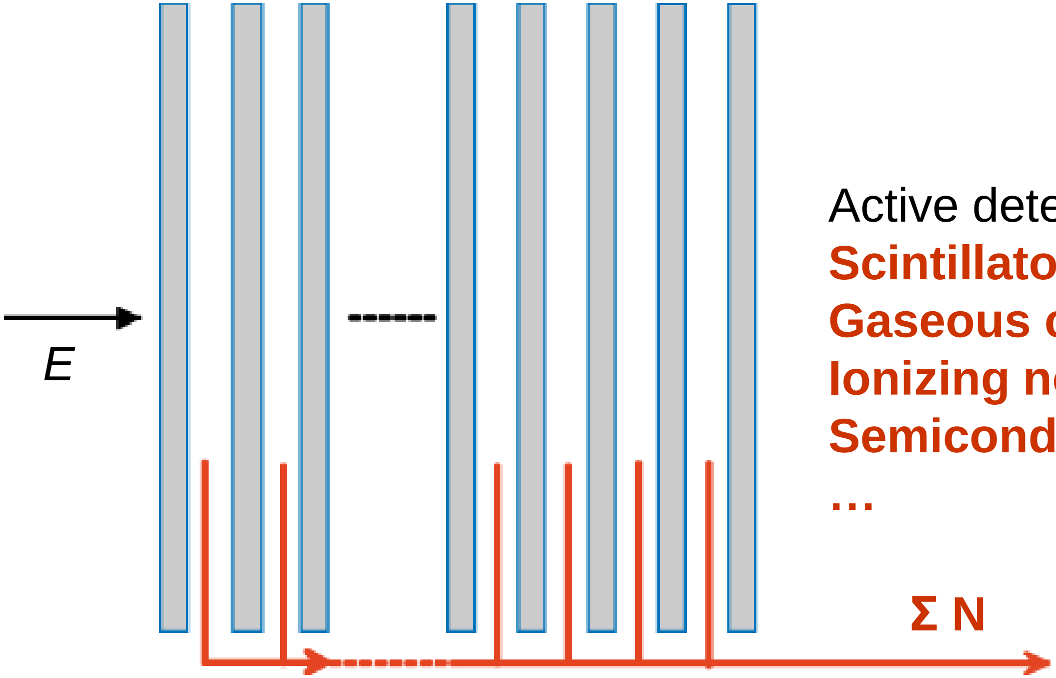
- A CMS $PbWO_4$ crystal ‘boule’ emerging from its 1123°C melt



Sampling Calorimeters

- ❑ Use a *different medium to generate the shower and to detect signal*: only a fraction of signal (f_s) sampled in the active detector → larger stochastic term

Intrinsic resolution goes from 1- 3 % for crystal or homogeneous noble liquids to 8-12% for sampling calorimeters.



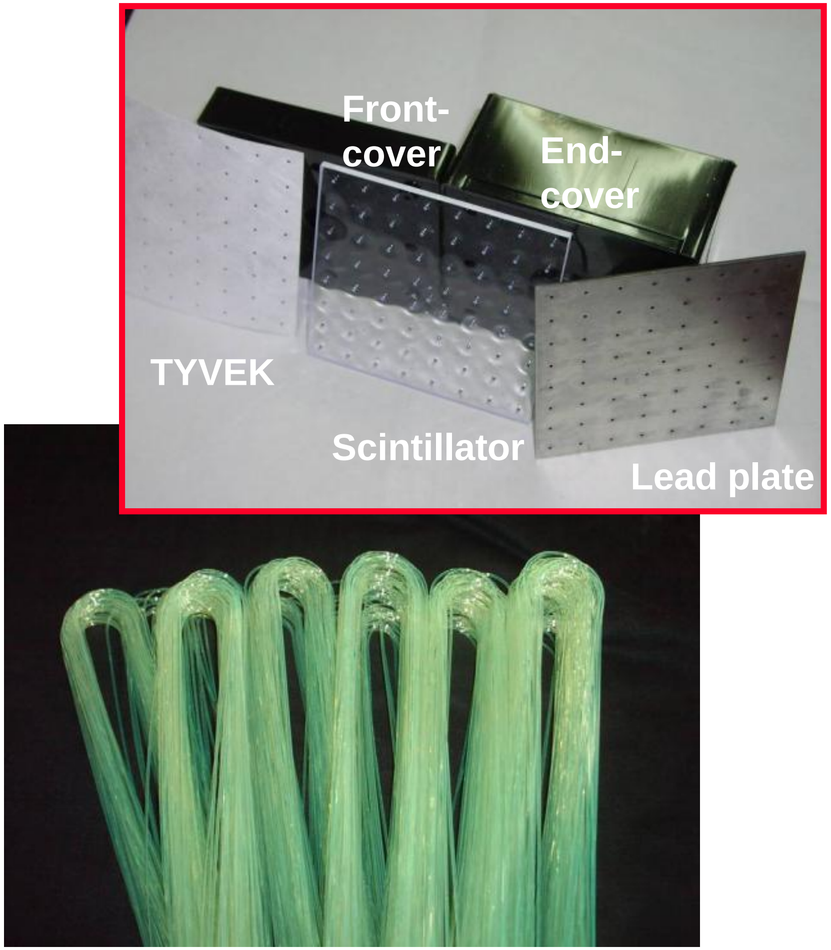
Particle absorption
and
Shower sampling
are separated

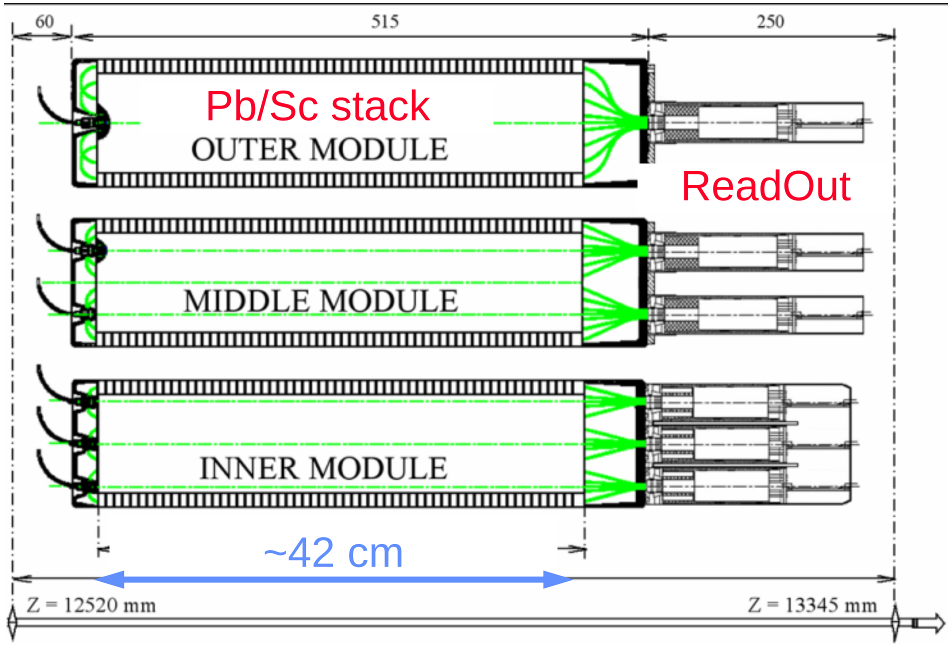
Active detector:
Scintillators
Gaseous chambers
Ionizing noble liquid
Semiconductors
…

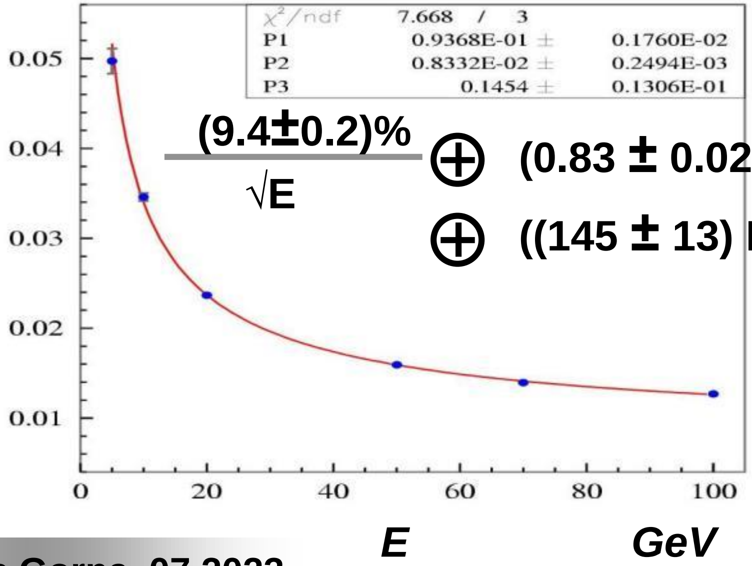
- ❑ Resolution is better, smaller is the detection gap and larger the sampling fraction (up to some limitations…). Easy for longitudinal segmentation

LHCb ECAL : Shashlyk type, 25Xo, R_M = 2.5cm

- 6000 detector cells
- Volume ratio Pb:Sc = 2:4 (mm)
- 25 X_o , 1.1 λ depth
- Light yield: ~3000 ph.e./GeV



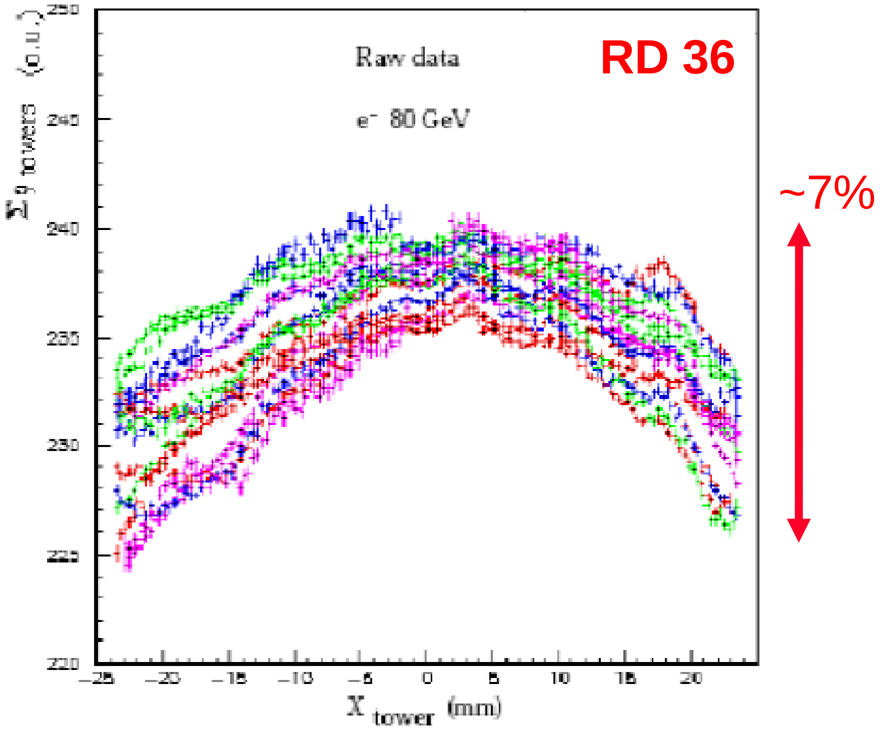




$$\frac{(9.4\pm0.2)\%}{\sqrt{E}} \oplus (0.83 \pm 0.02)\% \oplus ((145 \pm 13)\ \mathrm{MeV})/E$$

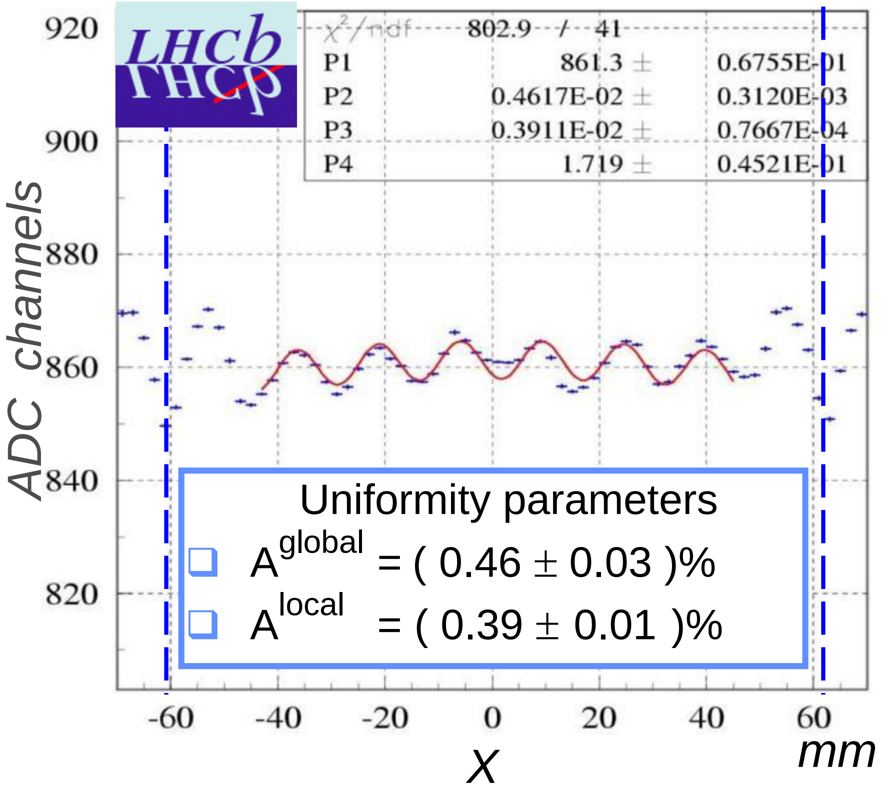
Lateral uniformity of response:

Transverse scan with 80 GeV electrons



Lateral scan of ECAL module with

50 *GeV* e⁻ beam



Uniformity parameters

☐ $A^{global} = (\ 0.46 \pm 0.03\ )\%$

☐ $A^{local} = (\ 0.39 \pm 0.01\ )\%$

Spread over the module (Max.-to-Min.):

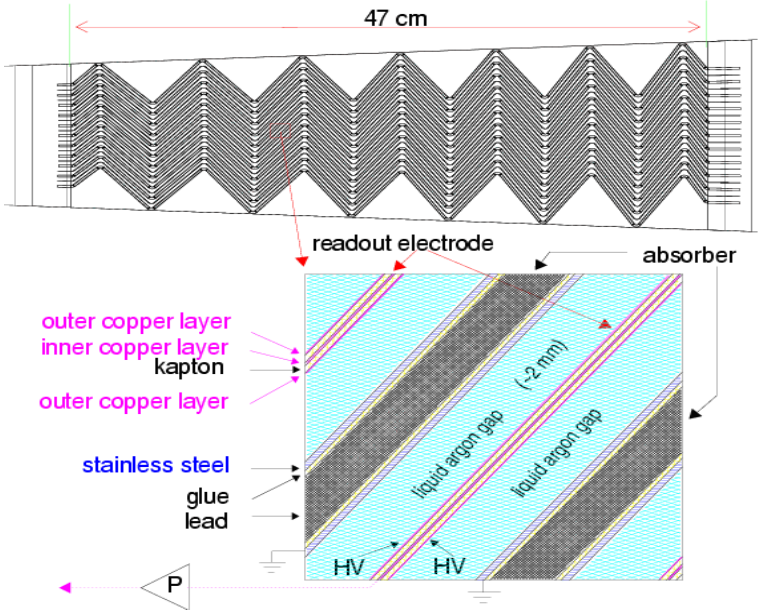
☐ ±1.3% for e-beam parallel to module axis

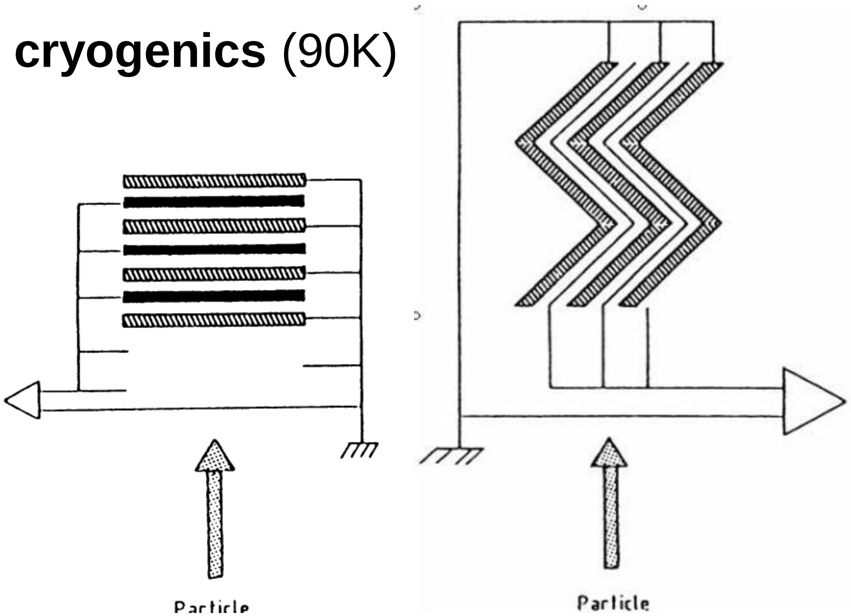
☐ ±0.6% for e-beam at 200 mrad

Alternative sampling geometry: ATLAS accordion ECAL

- ❑ Accordion geometry minimizes dead zones (no crack/dead space), reduces connection lines
- ❑ Readout board allows **fine segmentation** (azimuth, rapidity, longitudinal)

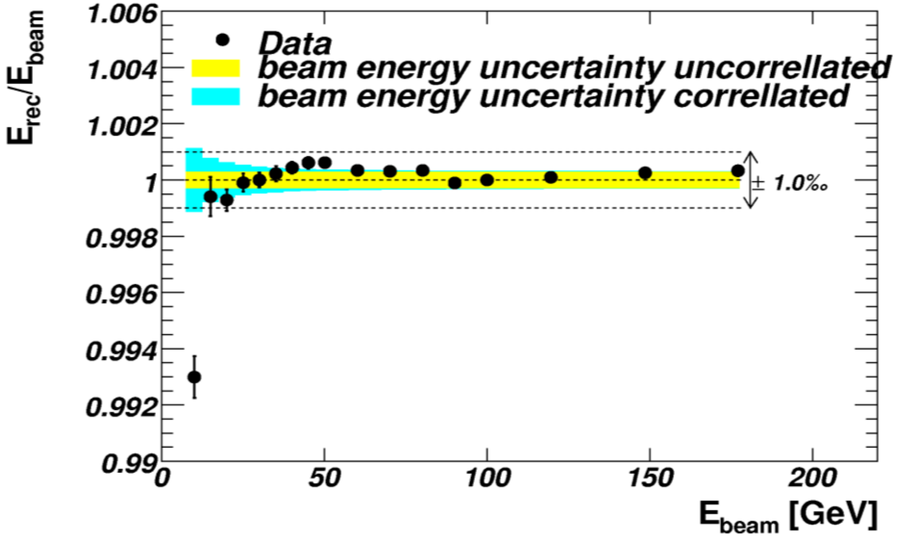
- ❑ **LAr not sensitive to radiation, stable in time, but cryogenics** (90K)
- ❑ 200000 channels





- ❑ Collect ionisation electrons with an electric field across 2.1 mm liquid Argon drift gap

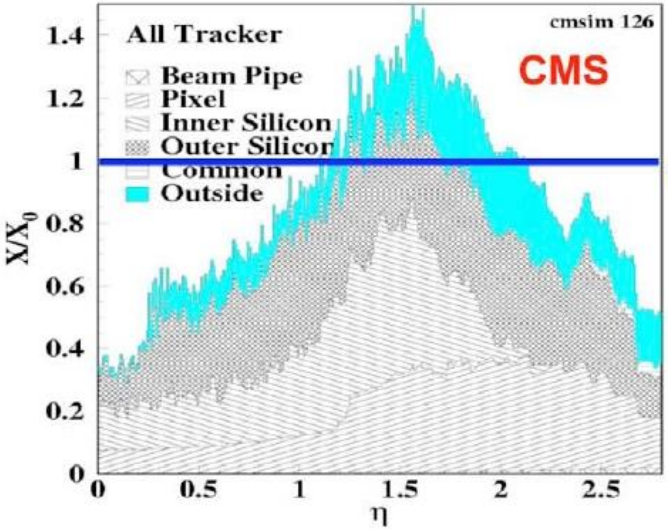
Energy linearity →
important parameter for precision measurement (W mass)



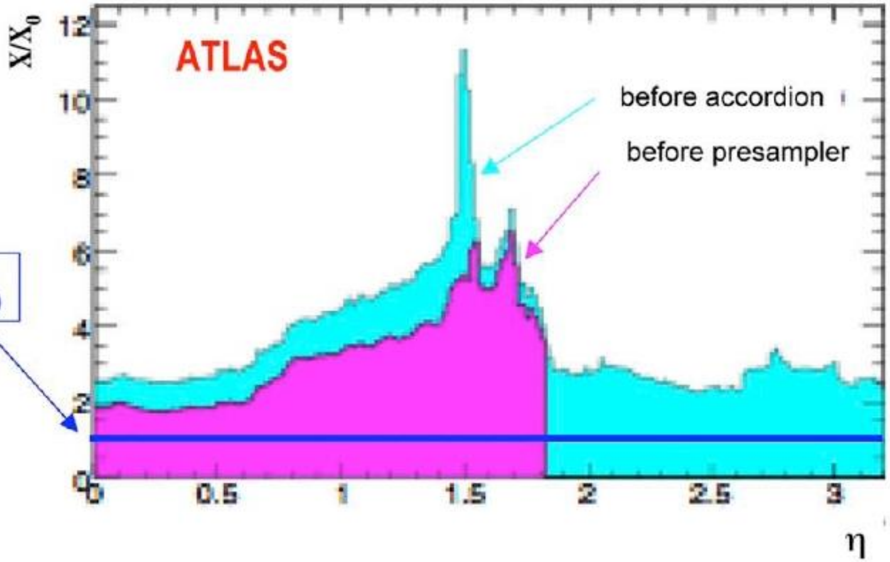
Enemy: material upstream the EM calorimeter

➔ Bremsstrahlung for electrons

➔ Pair production for photons



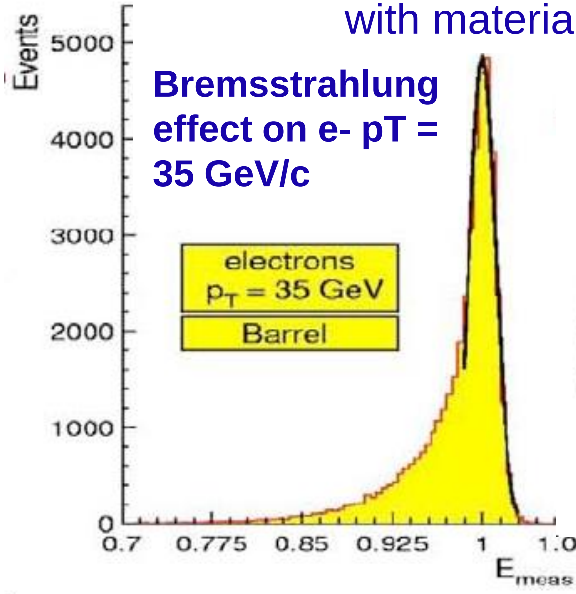
1 X_0

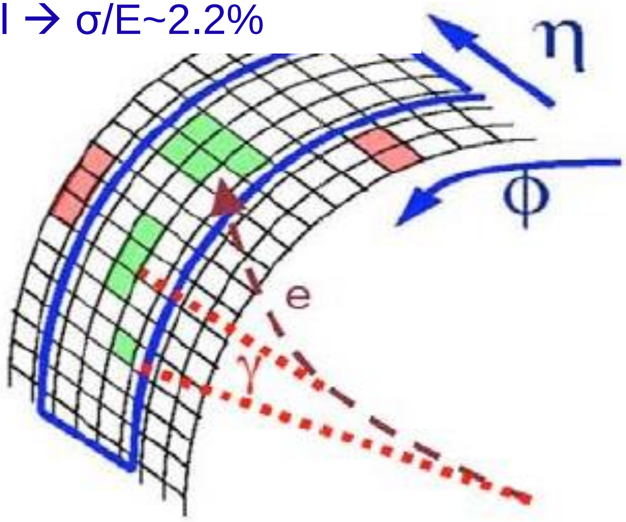


CMS : no material → σ/E~0.7%

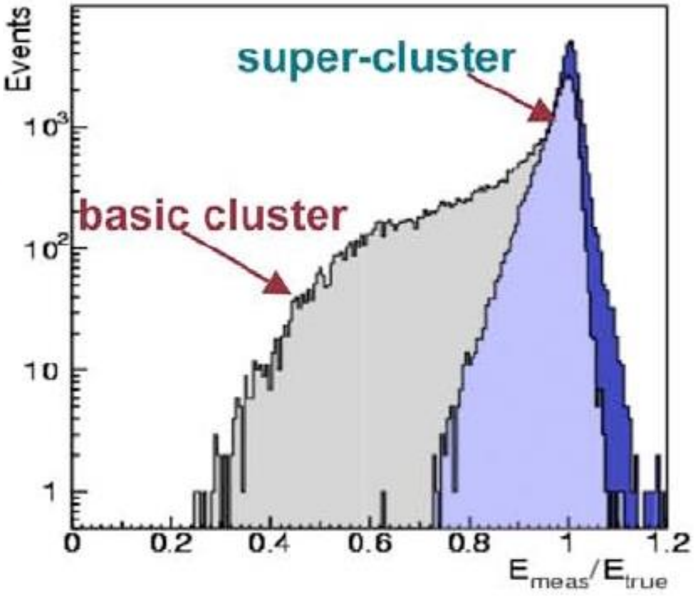
with material → σ/E~2.2%

Bremsstrahlung effect on e- pT = 35 GeV/c





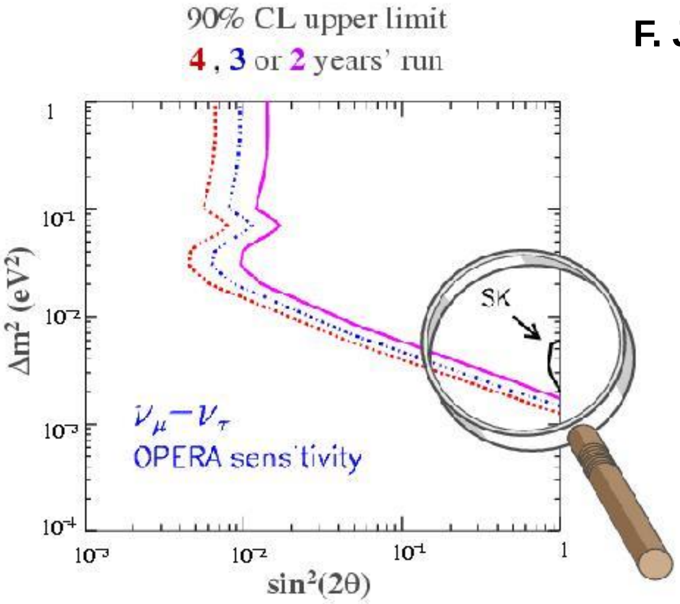
Recovery of Bremsstrahlung photon energy



ATLAS : use pre-shower, E1/E2 to recover lost energy

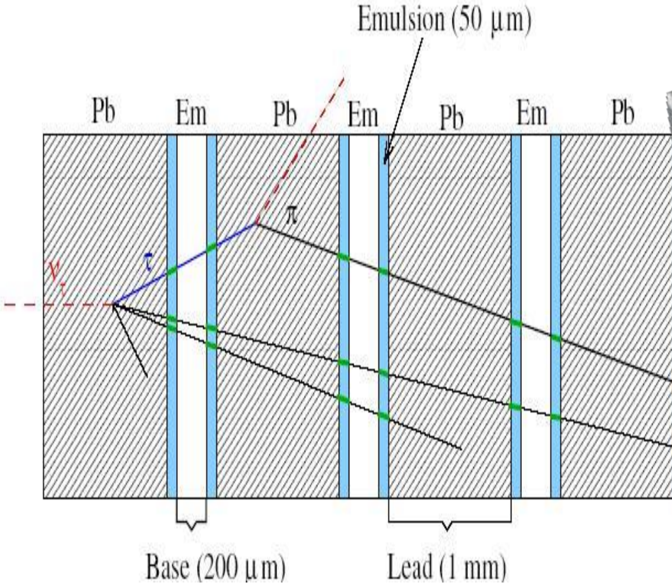
Example : EM shower reconstruction with emulsion films in

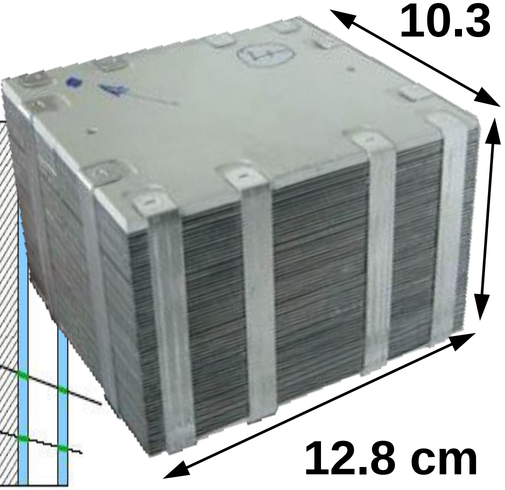
F. Juget



Appareance search of ν_μ <-> ν_τ oscillations in the parameter region indicated by S-K for the atmospheric neutrino deficit.

Principle: direct observation of τ decay topologies in ν_τ cc events





10.3 cm

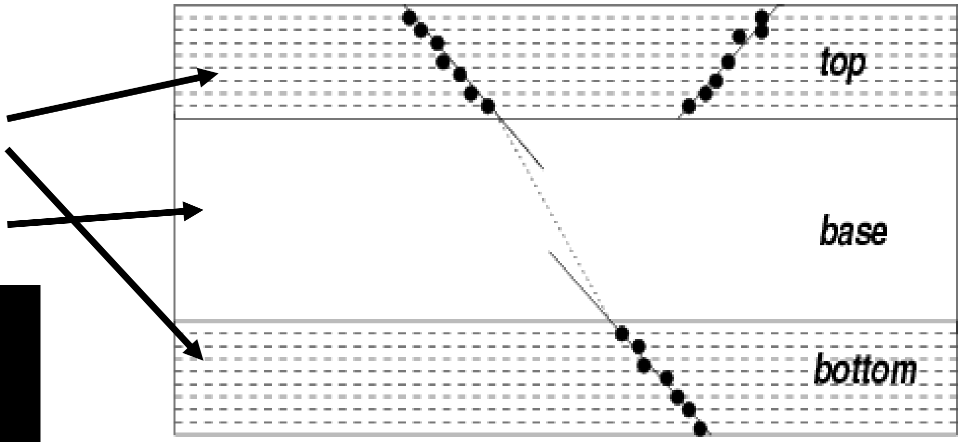
7.5 cm =10 X_0

12.8 cm

Basic unit: BRICK sandwich :
56 Pb sheets 1mm +
57 emulsion layers
(8.3kg)

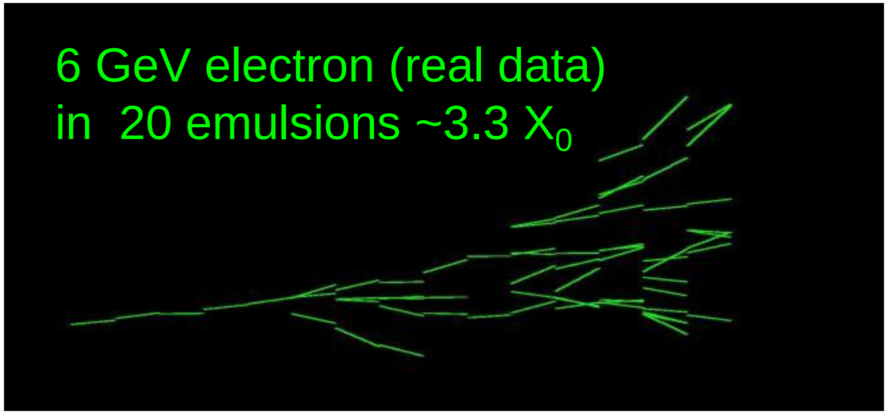
154 750 bricks → target mass: 1.35 ktons

Automated emulsion analysis

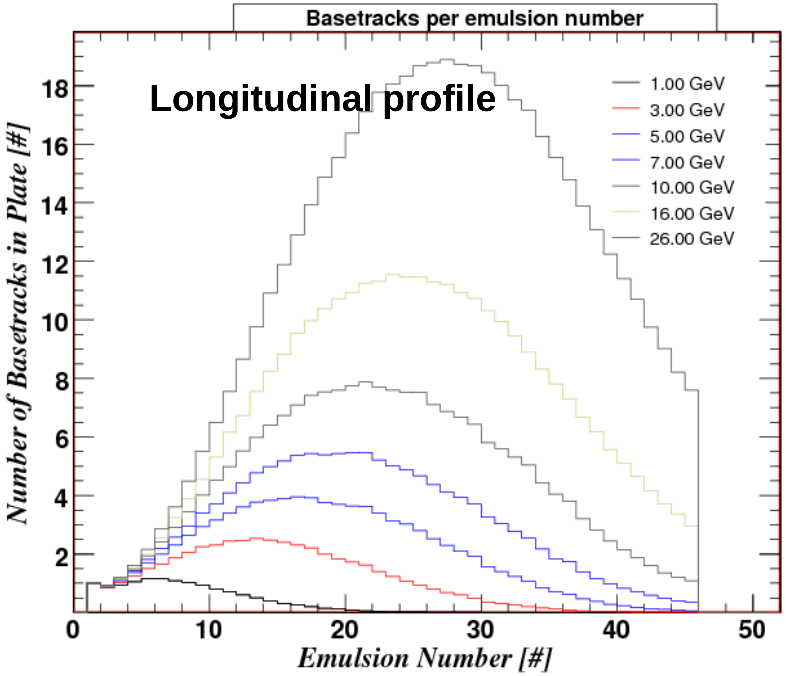


2 emulsion layers 50 μm

plastic base 200 μm

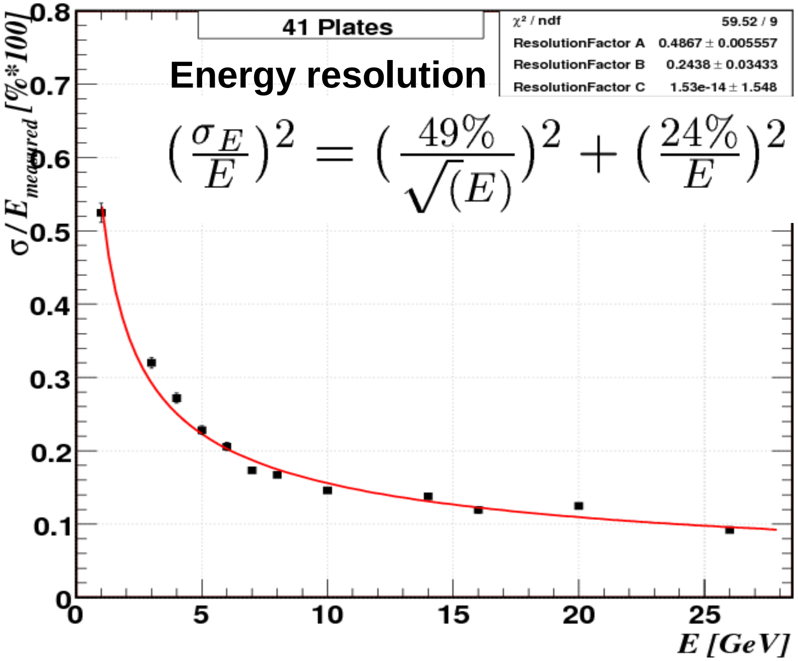


6 GeV electron (real data)
in 20 emulsions ~3.3 X_0



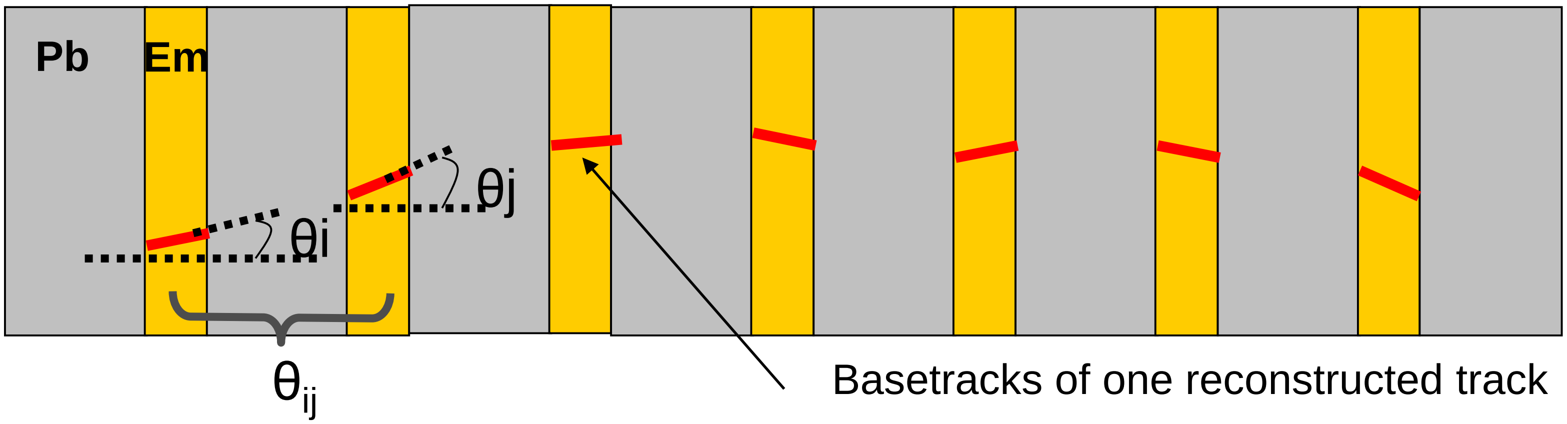
Resolution for 41 plates:

(25% at 5 GeV- 35% at 2 GeV)



$$\left(\frac{\sigma_E}{E}\right)^2 = \left(\frac{49\%}{\sqrt{(E)}}\right)^2 + \left(\frac{24\%}{E}\right)^2$$

Measurement of charged hadron momentum from multiple scattering in lead



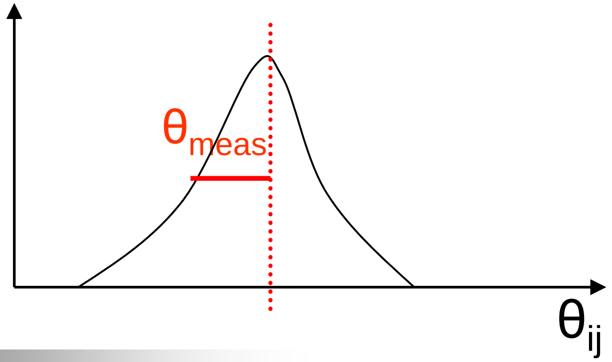
Basetracks of one reconstructed track

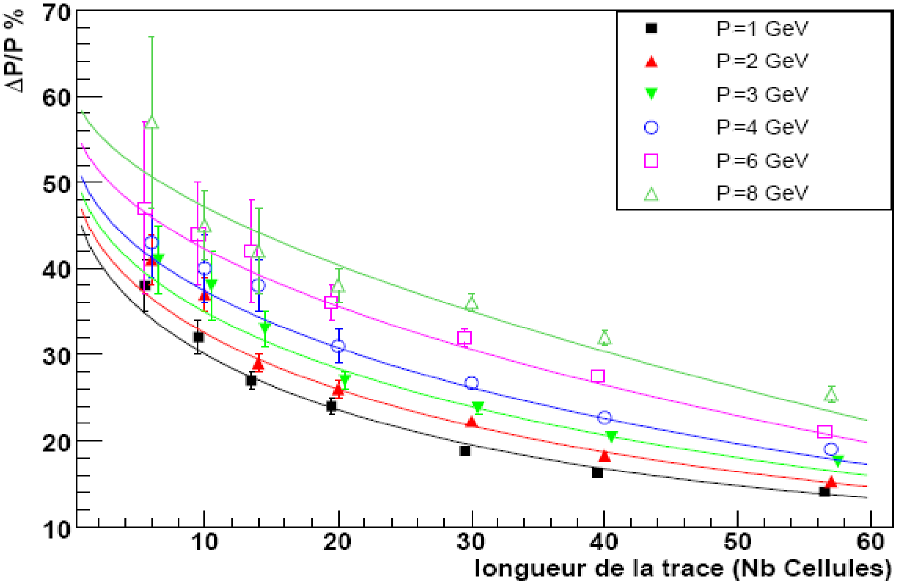
Principle : use angular differences θ_{ij} of particle tracks mesured in emulsions, due to multiple coulomb scattering in lead :

$$\theta^2_{meas} = \frac{13.6^2 * X}{X_0 * p^2} + \delta\theta^2$$

Resolution on basetracks, should be known or measured

RMS θ_{ij}



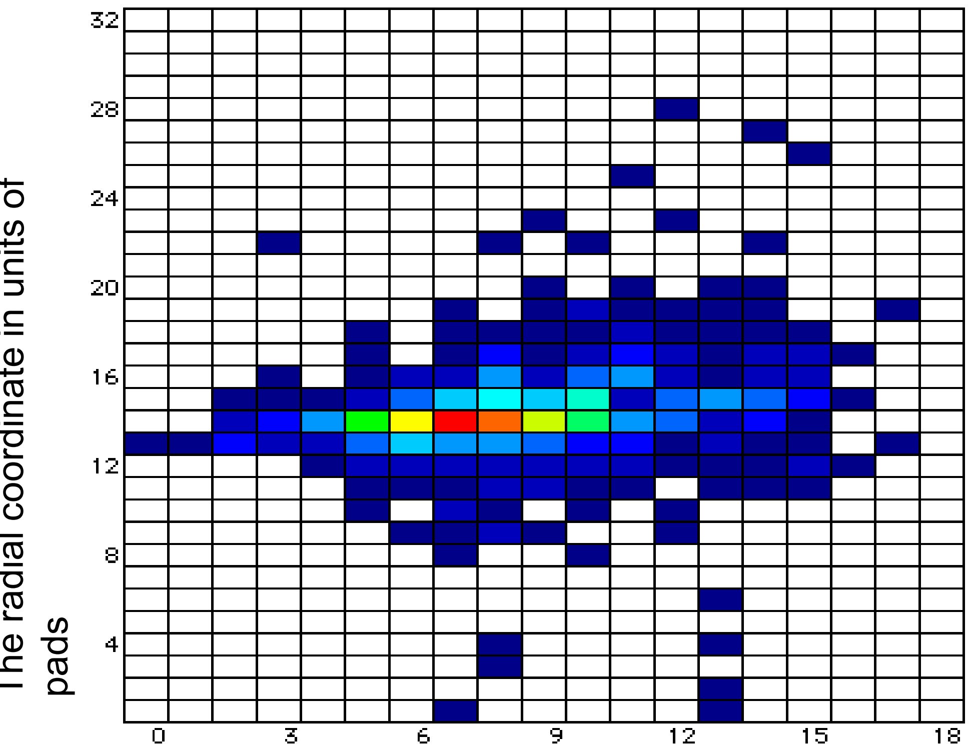


→ Momentum resolution is ~ 20%-30% at 2 GeV

How to limit fluctuations in sampling calorimeters

Something of the best we can do at the moment:
Silicon Tungsten calorimeter (if you can afford it)

Excellent space and energy resolution!



The depth within the calorimeter, numbered by detector layer

OPAL CERN-EP-99-13

SiW for ILC

Absorber : tungsten

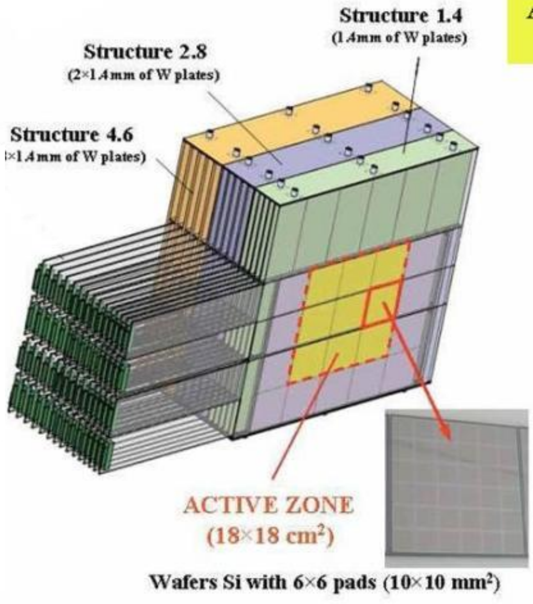
Active element : silicon

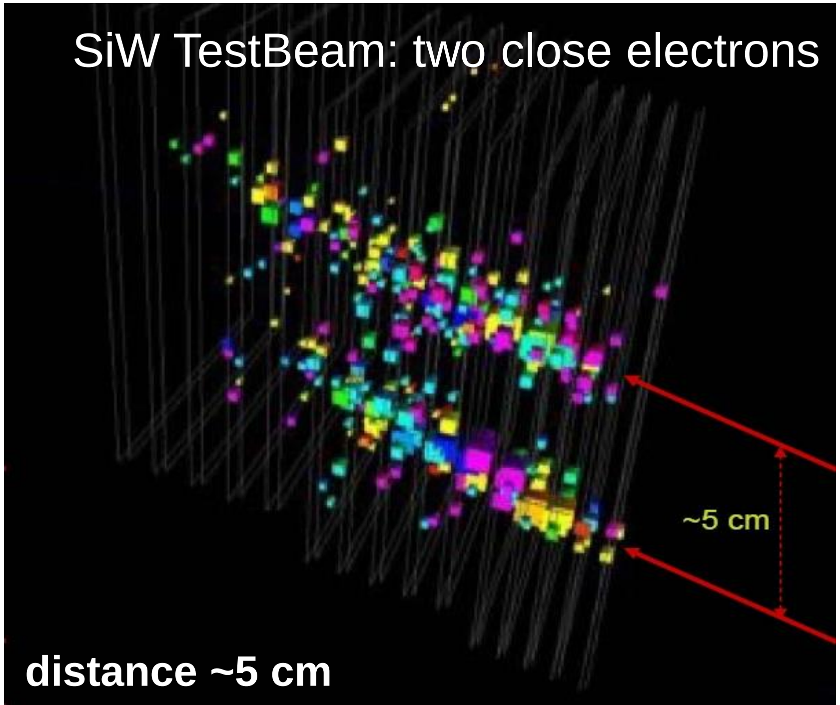
High sampling : 30 layers

High granularity : 1x1 cm^2 cells

Compact : ~ 20 cm depth for 24 Xo

Channels : 6471 (2006)




SiW TestBeam: two close electrons

distance ~5 cm

Example : A Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics

V. Bonvicini

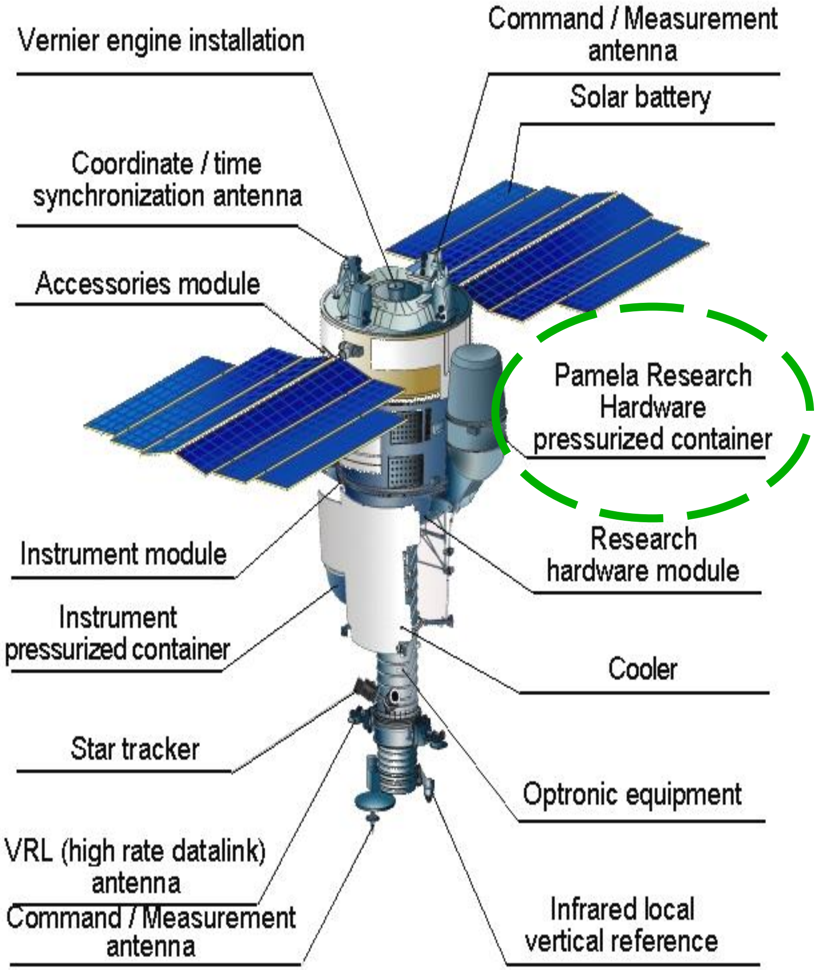
- ☐ Study antiparticles in cosmic rays
- ☐ Search for antimatter
- ☐ Search for dark matter
- ☐ Study cosmic-ray propagation
- ☐ Study solar physics and solar modulation
- ☐ Study the electron spectrum (local sources?)

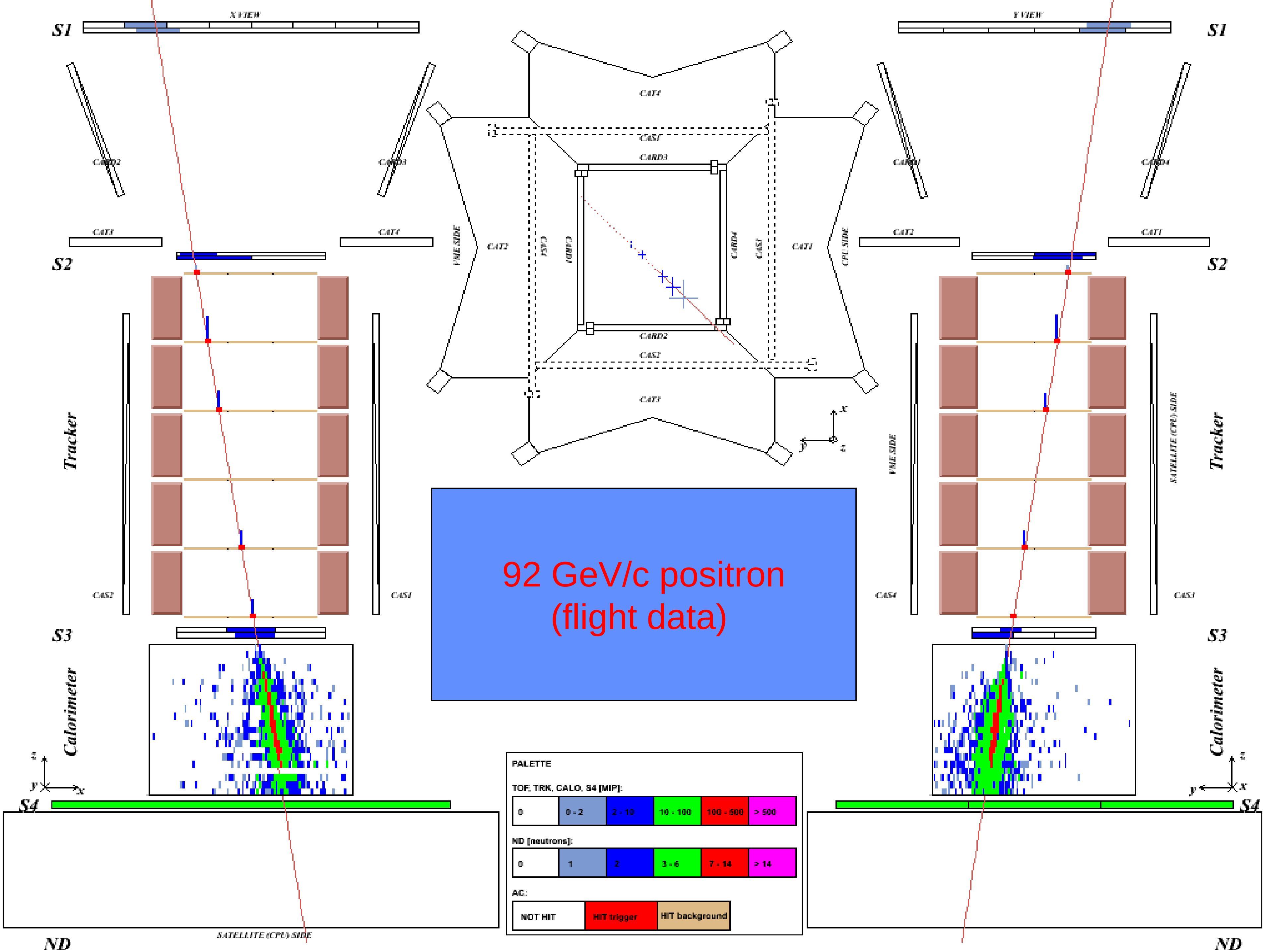
Si-W Imaging Calorimeter

- ☐ lepton/hadron discrimination
- ☐ $e^{+/-}$ energy measurement

- ☐ 22 W plates (2.6 mm / 0.74 X_0)
- ☐ 44 Si layers (X-Y), 380 μm thick
- ☐ Total depth: 16.3 X_0 / 0.6 λ_I

- ☐ p,e^+ selection efficiency ~ 90%
- ☐ p rejection factor ~ 10^5
- ☐ e rejection factor > 10^4
- ☐ Energy resolution ~ 5% @ 200 GeV





92 GeV/c positron
(flight data)

PALETTE

TOF, TRK, CALO, S4 [MIP]:

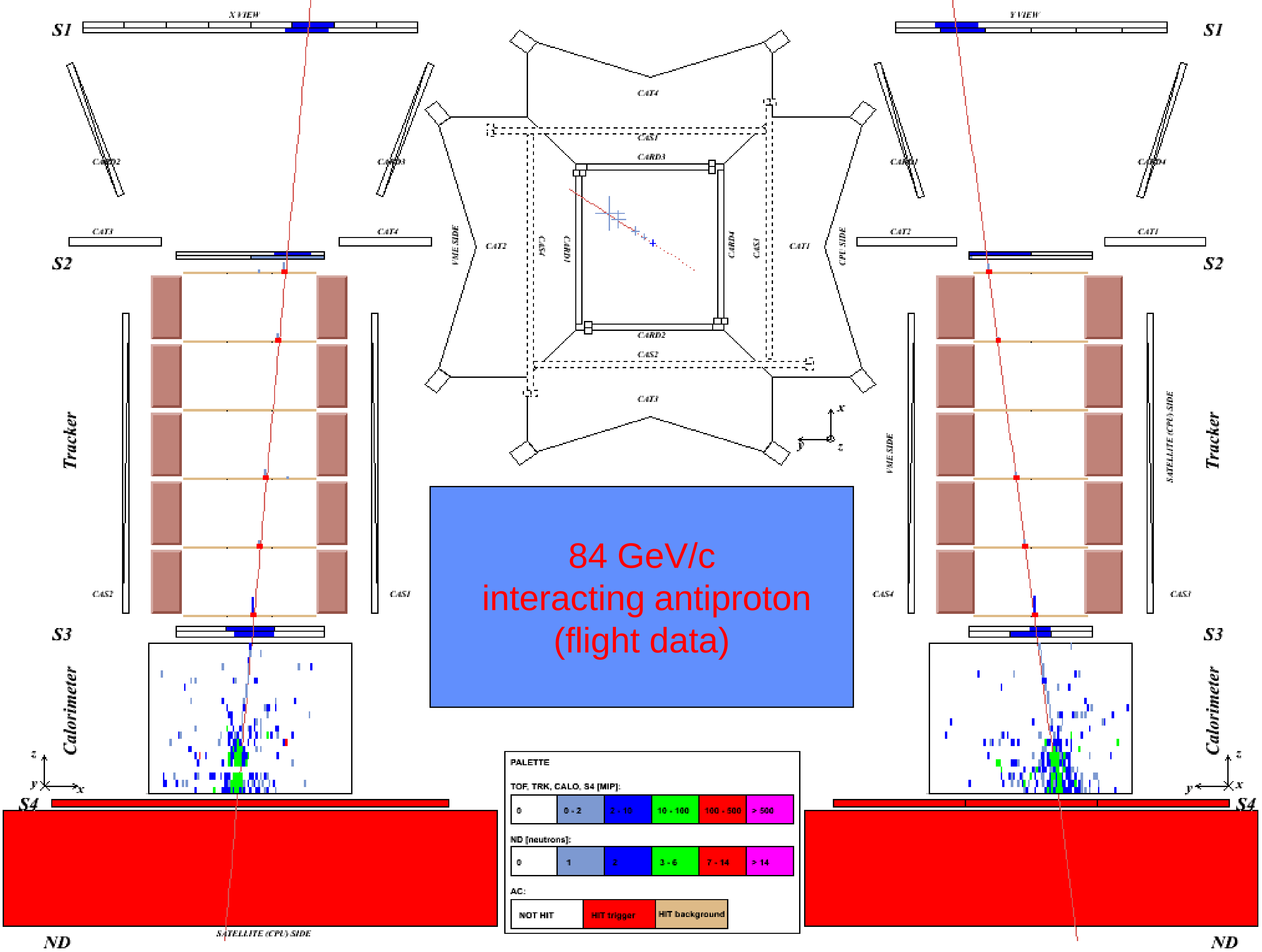
0	0 - 2	2 - 10	10 - 100	100 - 500	> 500

ND [neutrons]:

0	1	2	3 - 6	7 - 14	> 14

AC:

NOT HIT	HIT trigger	HIT background



84 GeV/c
interacting antiproton
(flight data)

PALETTE

TOF, TRK, CALO, S4 [MIP]:

0	0 - 2	2 - 10	10 - 100	100 - 500	> 500

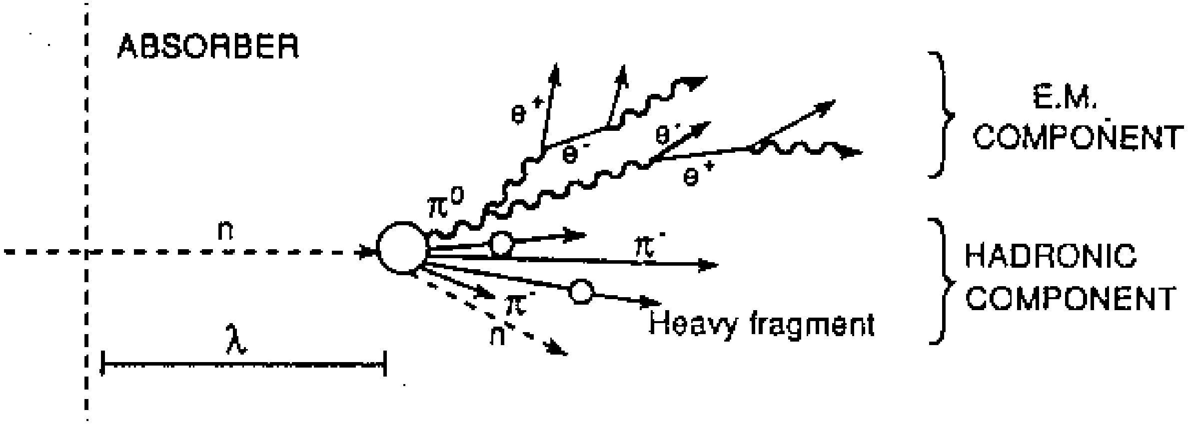
ND [neutrons]:

0	1	2	3 - 6	7 - 14	> 14

AC:

NOT HIT	HIT trigger	HIT background

Hadronic showers



- ☐ Visible energy:

$$E_{vis} = e\ E_{em} + \pi\ E_{ch} + n\ E_n + N\ E_{nucl}$$

- ☐ Each component has its own **sampling fraction,**

e/h ≠ 1

- ☐ **Large fluctuations** of shower content from an event to another

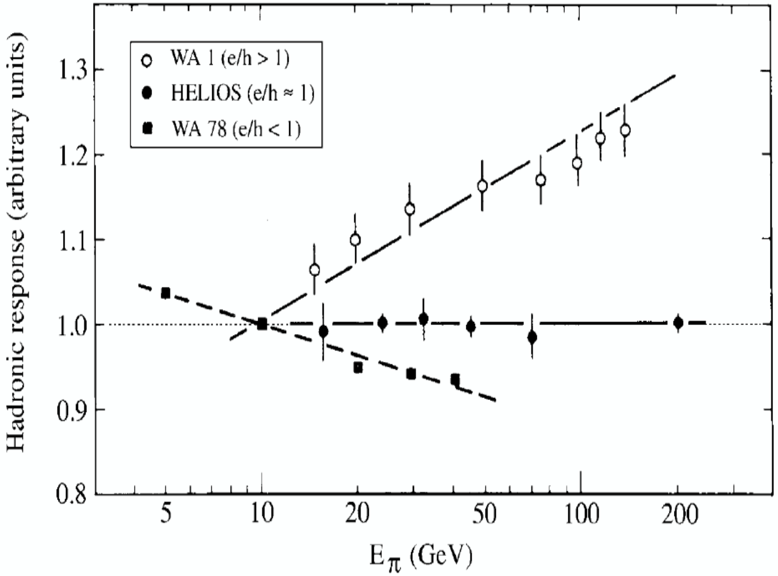
- ☐ Absorber in hadronic sampling calorimeter usually not Pb but Fe (Cu)

  Active layer : Sc (high sensitivity to neutrons), Lar

- ☐ **Resolution** worse than for EM showers

$$\frac{\sigma(E)}{E} \approx \frac{50-100\ \%}{\sqrt{E}} \oplus 3-5\% \,(\mathrm{E\ en\ GeV})$$

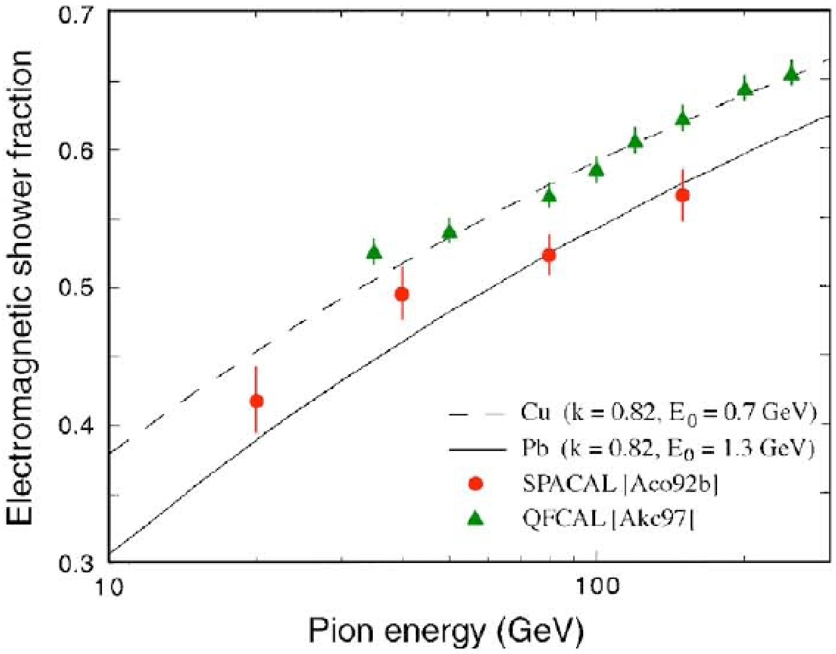
Response to EM different to hadron
→Non linearity



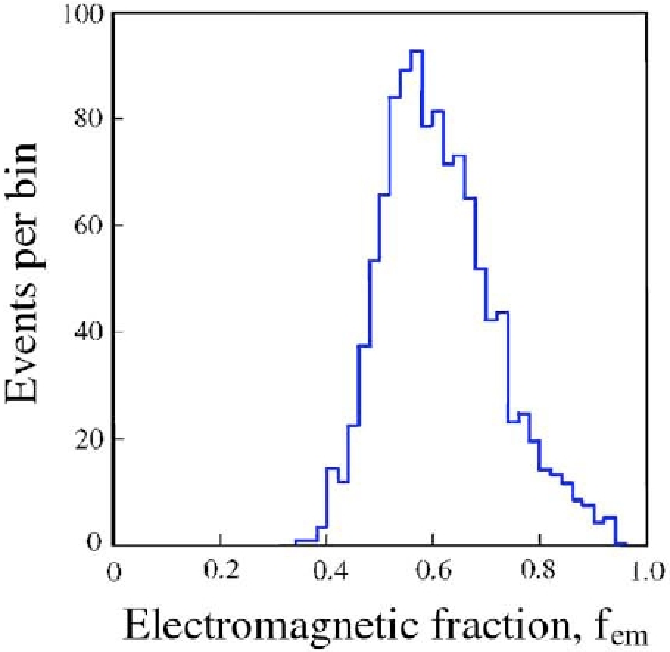
Compensation by HW or SW

Hadronic showers

- ❑ Event-to-event fluctuations large and non-Gaussian
- ❑ EM shower fraction $\langle f_{em} \rangle$ depends on shower energy and age



f_{em} large and energy dependent

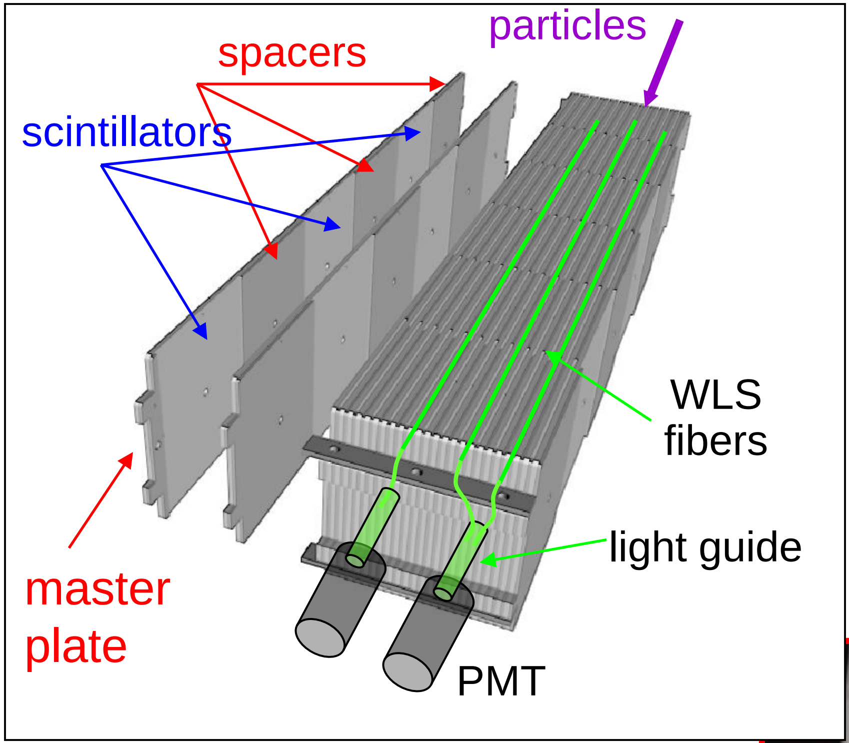


f_{em} fluctuations large and non-Poissonian

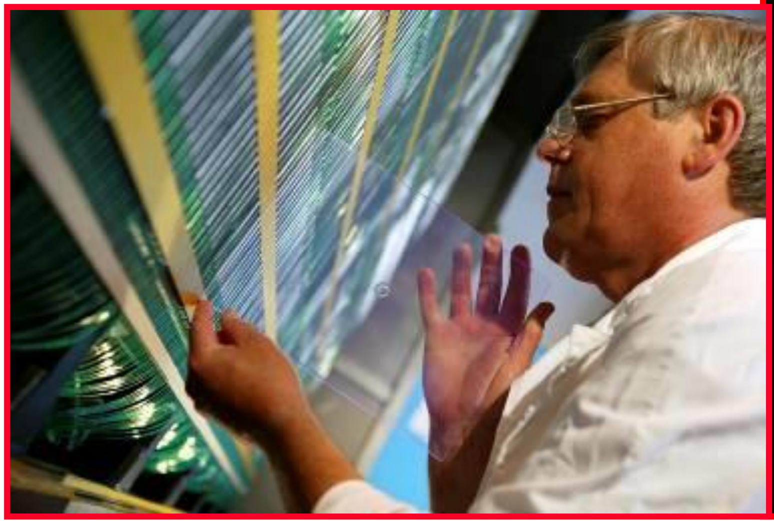
Essential for hadronic energy measurement:

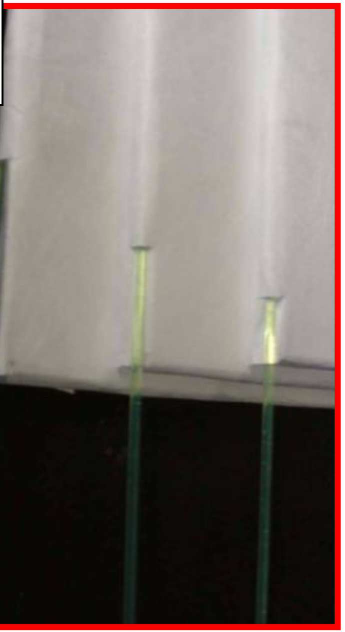
limit fluctuations and establish correct **energy scale**

Tile Calorimeter (ATLAS, LHCb)



Fiber-tile contact length adjusted to compensate light attenuation difference

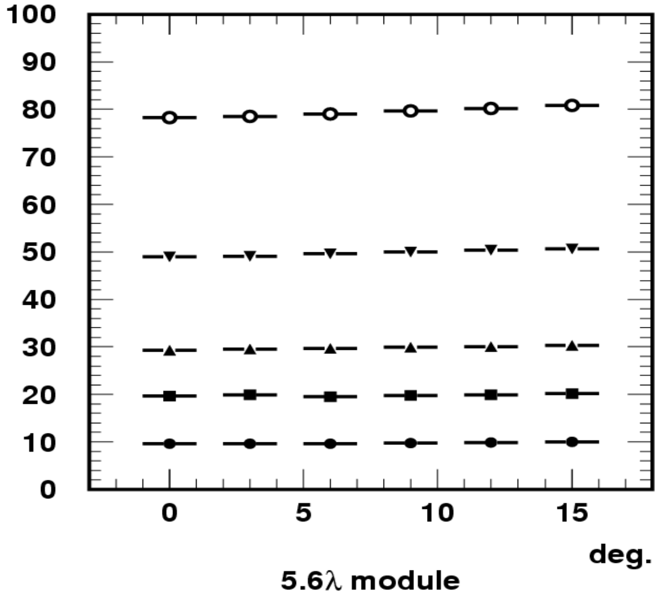




Energy resolution

$$\frac{\sigma}{E} = \frac{(69 \pm 5)\%}{\sqrt{E}} \oplus (9 \pm 2)\%$$

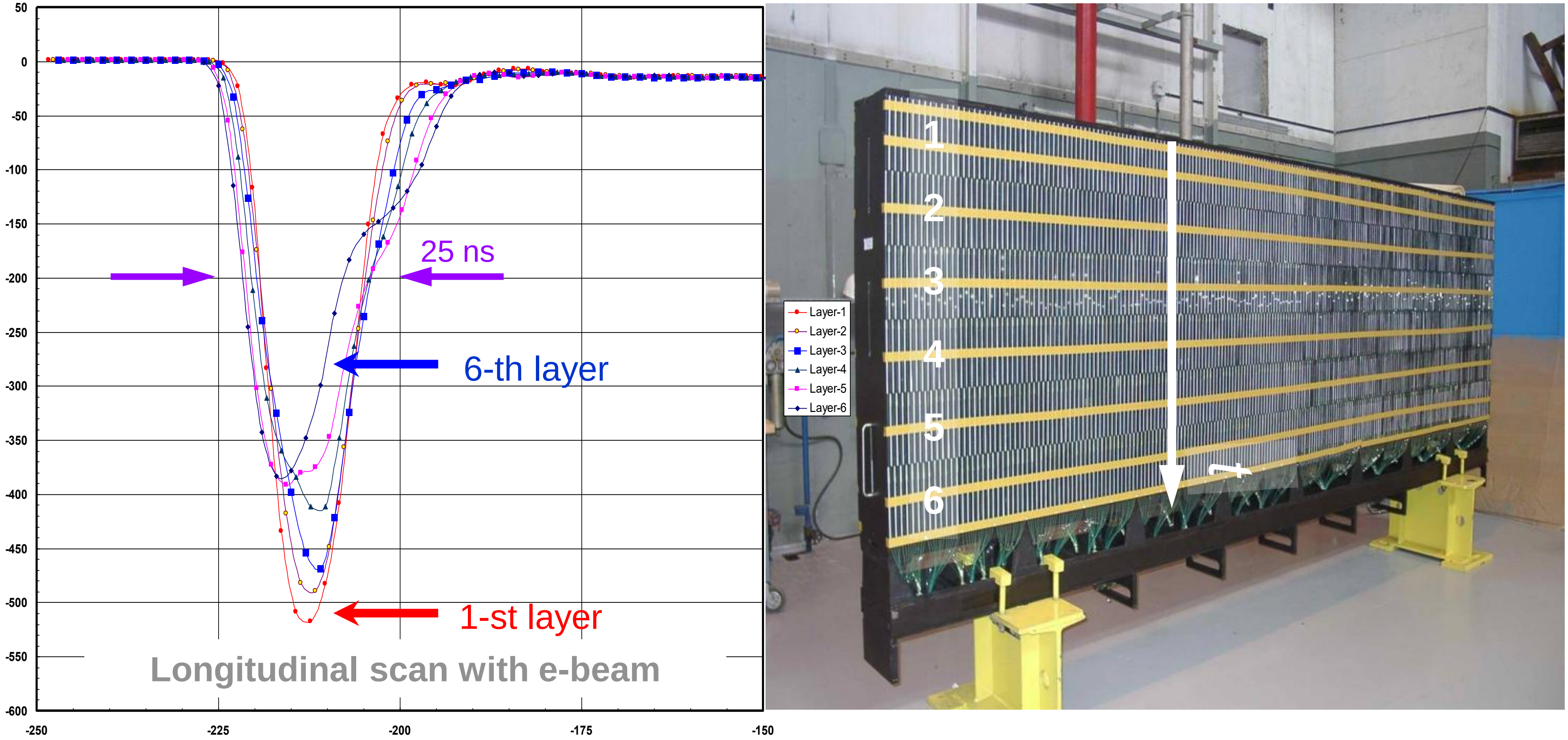
Angular dependence



~3% angular dependence at higher energies: shower not fully contained in **5.6 λ_I**

Signal timing

A pulse shape study on 30 GeV electron beam for 6 different layers in depth of the HCAL: 25 ns pulse shaping



Signal variations due to detector depth and mirrors at fiber ends

DREAM (Dual REAdout Module) – high resolution hadron calorimetry (Wigmans)

Idea : Improve resolution of hadron calorimetry using Cherenkov light

Hadron showers :

- ☐ EM component (π^o s)
- ☐ Non-EM component (mainly soft π)

} Response is different ($e/h \neq 1$)

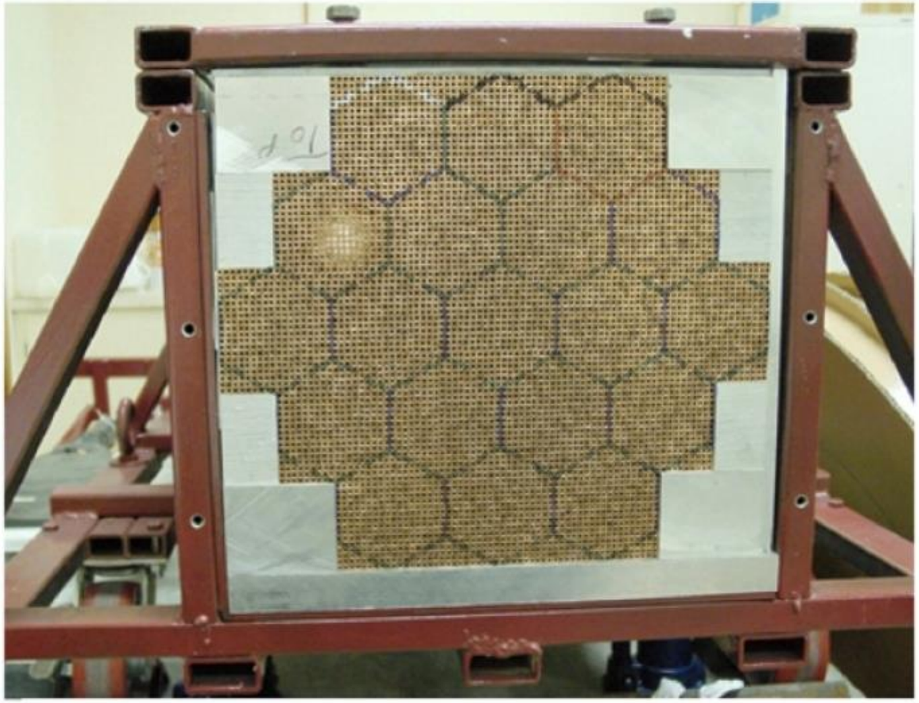
**Cherenkov light almost exclusively produced by EM component*

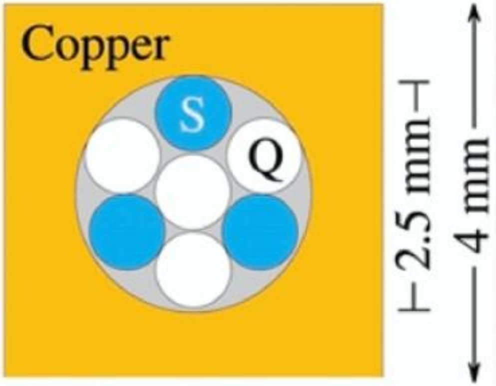
Recipe : determine f_{em} event by event by comparing Č and dE/dx signals ;
correct the response

e/h ratio is very different for Quartz and Scintillator measurements of energy

Use Quartz fibers to sample EM component (~only!),
in combination with Scintillating fibers

DREAM (Dual READout Module)

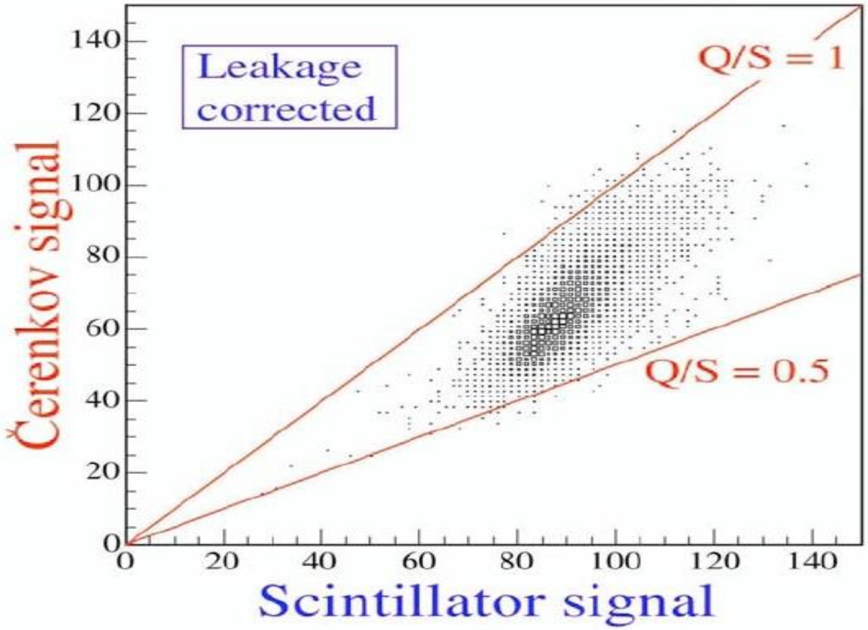


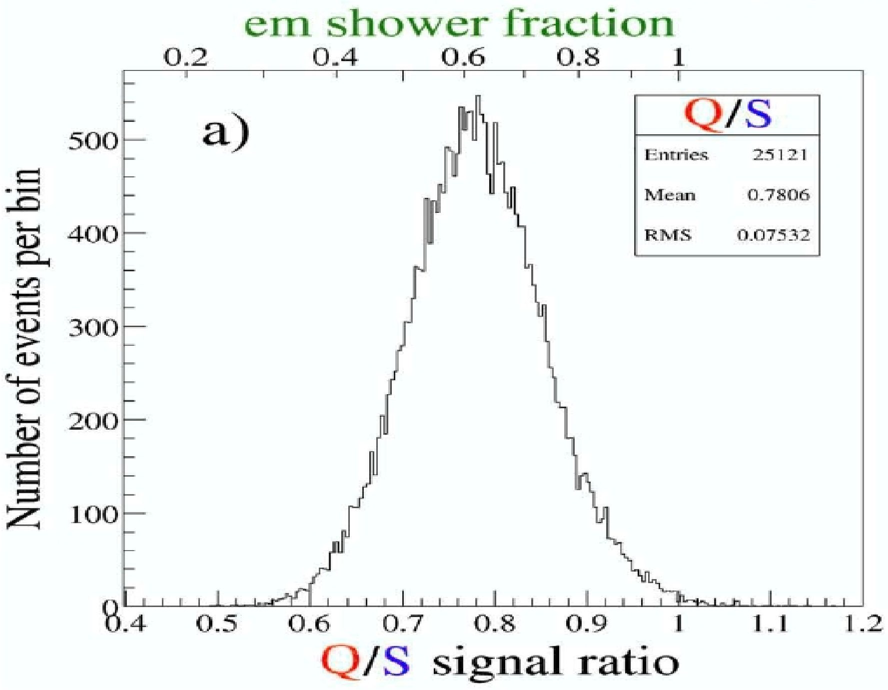


- *Some characteristics of the DREAM detector*
  - Depth 200 cm (10.0 λ_{int})
  - Effective radius 16.2 cm (0.81 λ_{int}, 8.0 ρ_M)
  - Mass instrumented volume 1030 kg
  - Number of fibers 35910, diameter 0.8 mm, total length ≈ 90 km
  - Hexagonal towers (19), each read out by 2 PMTs

DREAM Readout

Extraction of f_{em} and E : example





$$S = E\left[f_{\mathrm{em}} + \frac{1}{(e/h)_S}(1 - f_{\mathrm{em}})\right]$$

$$Q = E\left[f_{\mathrm{em}} + \frac{1}{(e/h)_Q}(1 - f_{\mathrm{em}})\right]$$

Cu/Sc **Cu/Q**

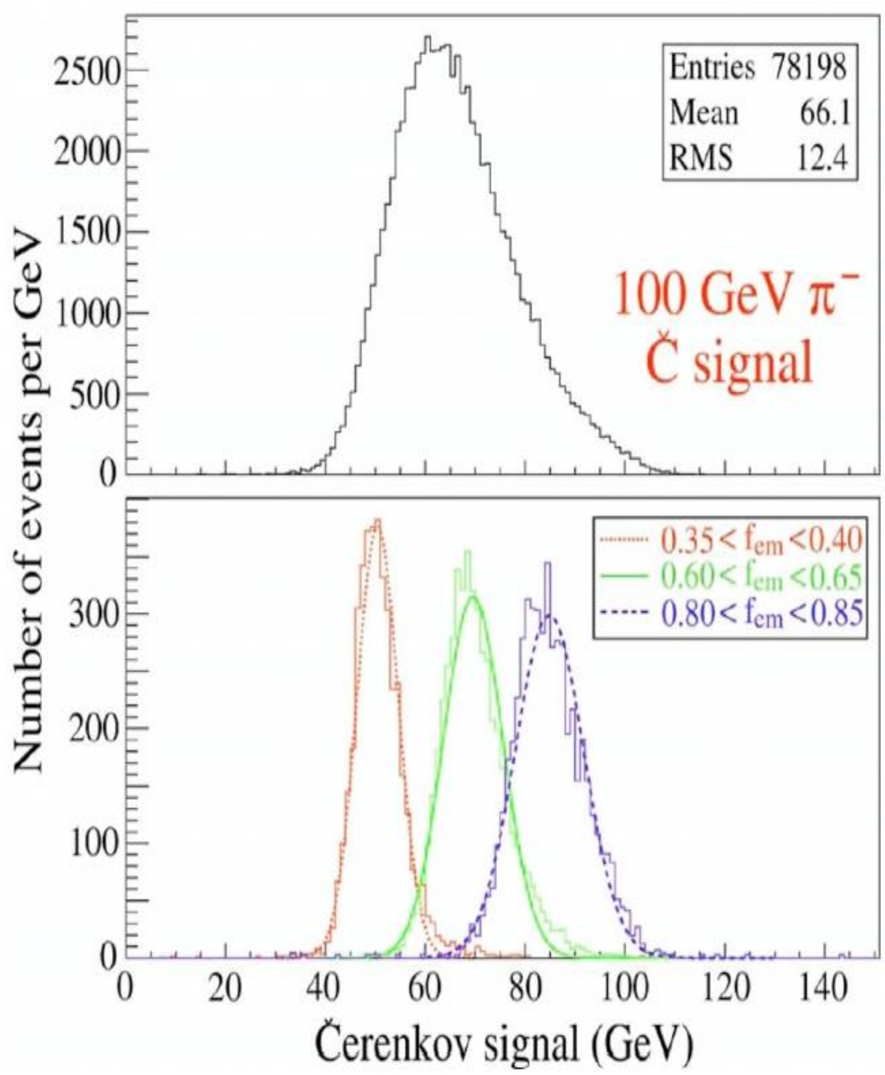
$e.g.$ If $e/h = 1.3\ (S),\ 4.7\ (Q)$

$$\boxed{\frac{Q}{S} = \frac{f_{\mathrm{em}} + 0.21\,(1 - f_{\mathrm{em}})}{f_{\mathrm{em}} + 0.77\,(1 - f_{\mathrm{em}})}}$$

$$\boxed{E = \frac{S - \chi Q}{1 - \chi}}$$

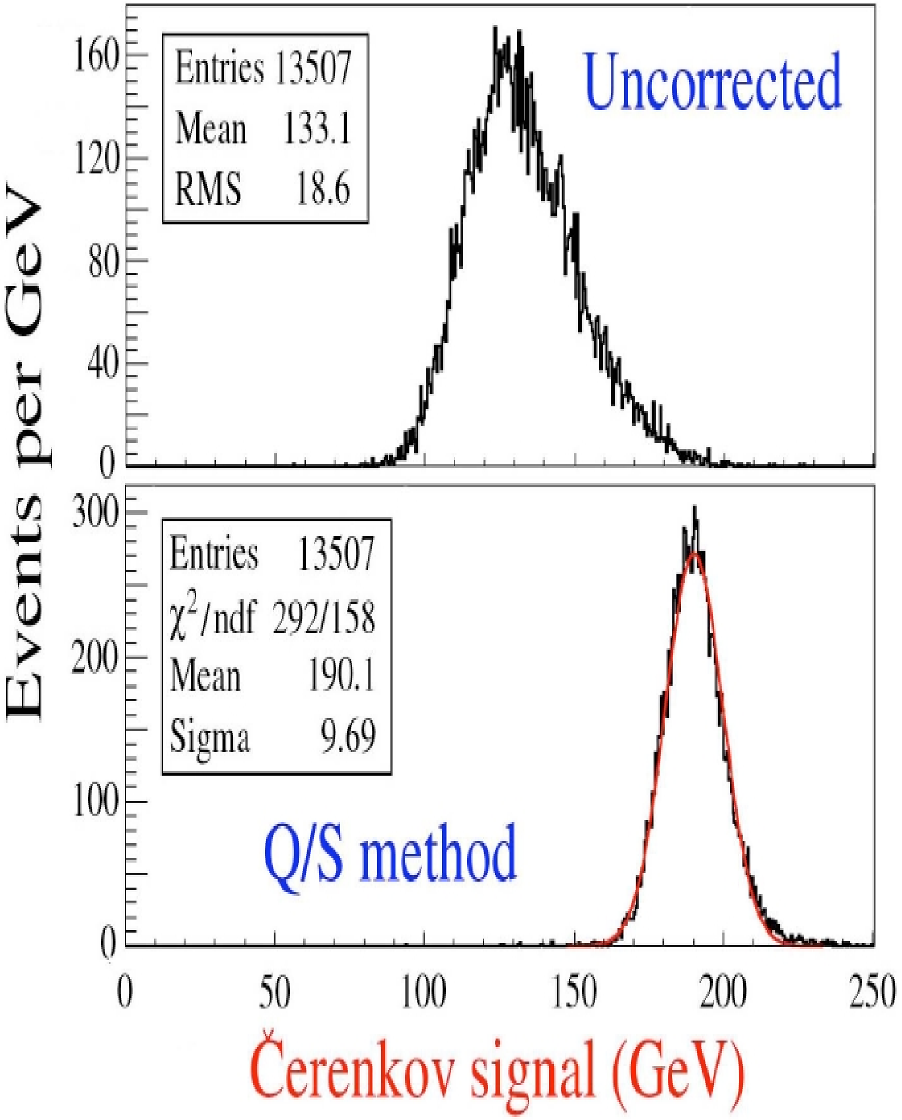
with $\chi = \frac{1 - (h/e)_S}{1 - (h/e)_Q} \sim 0.3$

Event selection based on f_{em}



NIM A537 (2005) 537

Corrections of 200 GeV "jets"



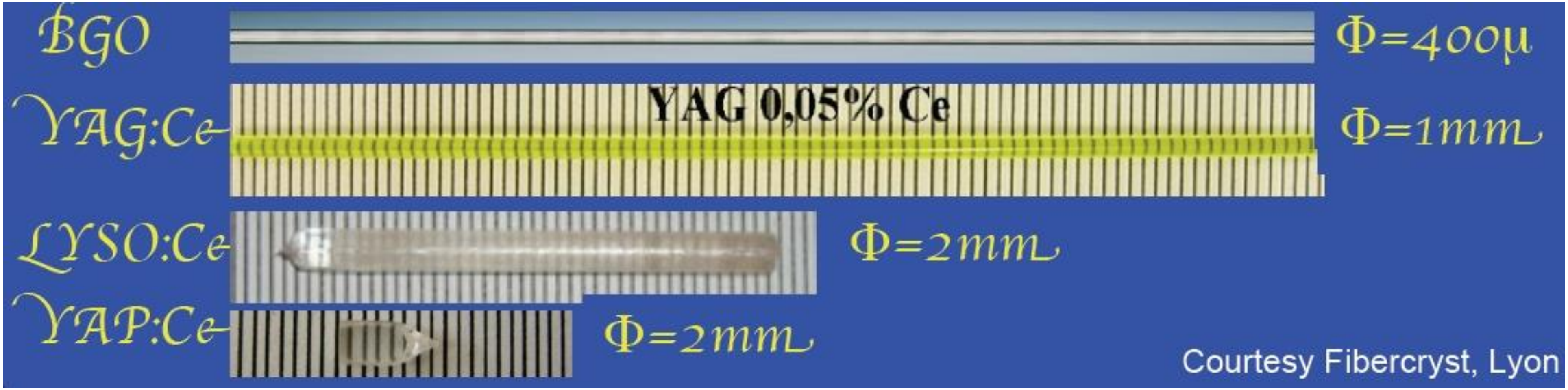
Meta-materials

P.Lecoq

- Scintillating cables made of heavy scintillating fibers of different composition to access different components of the shower

  → quasi-homogeneous calorimeter
- Fiber arrangement to obtain 3D imaging capability

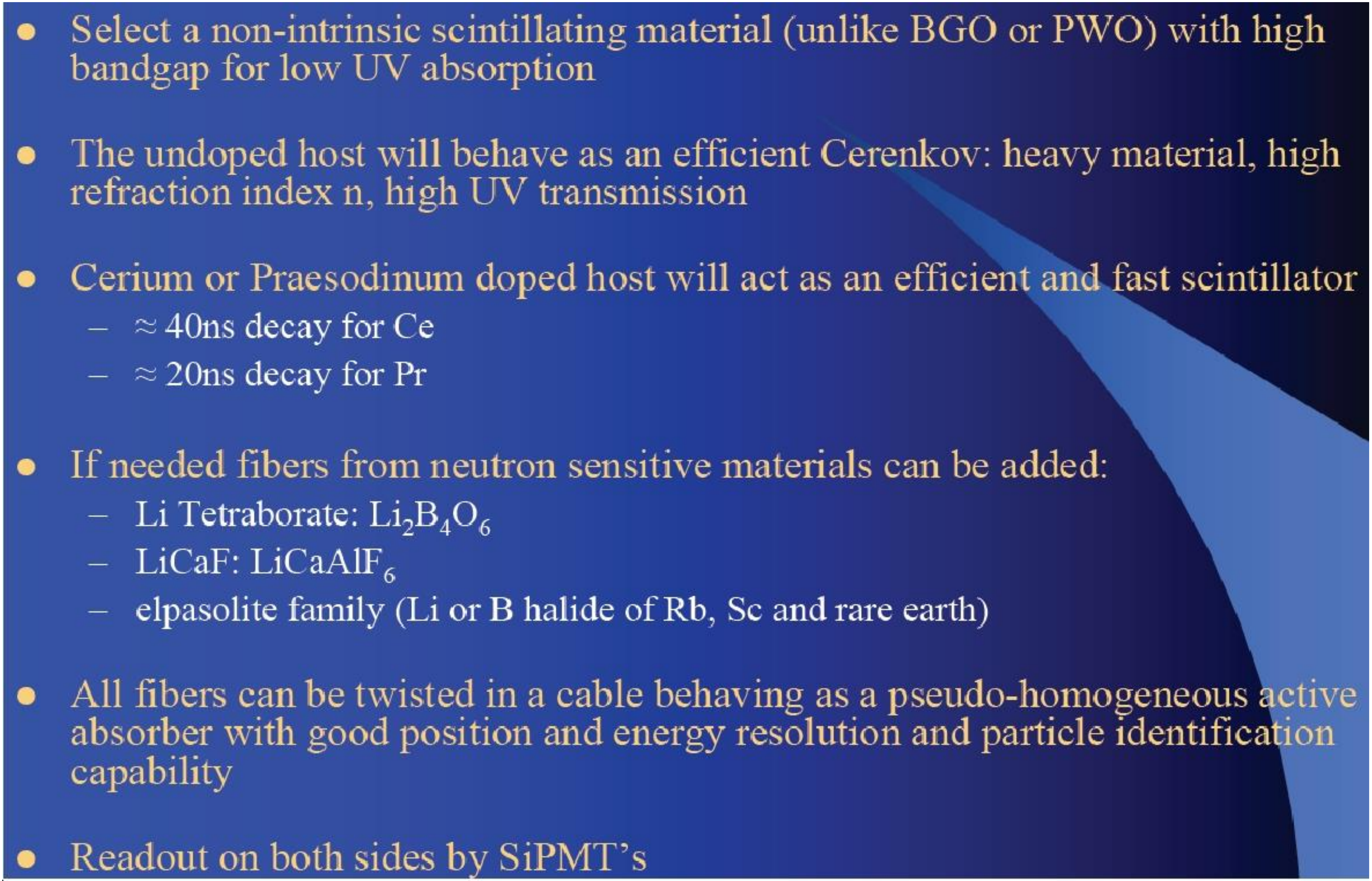
- Basic idea : produce “light guides” out of conventional scintillating materials



Courtesy Fibercryst, Lyon

Concept of meta-cable - 1

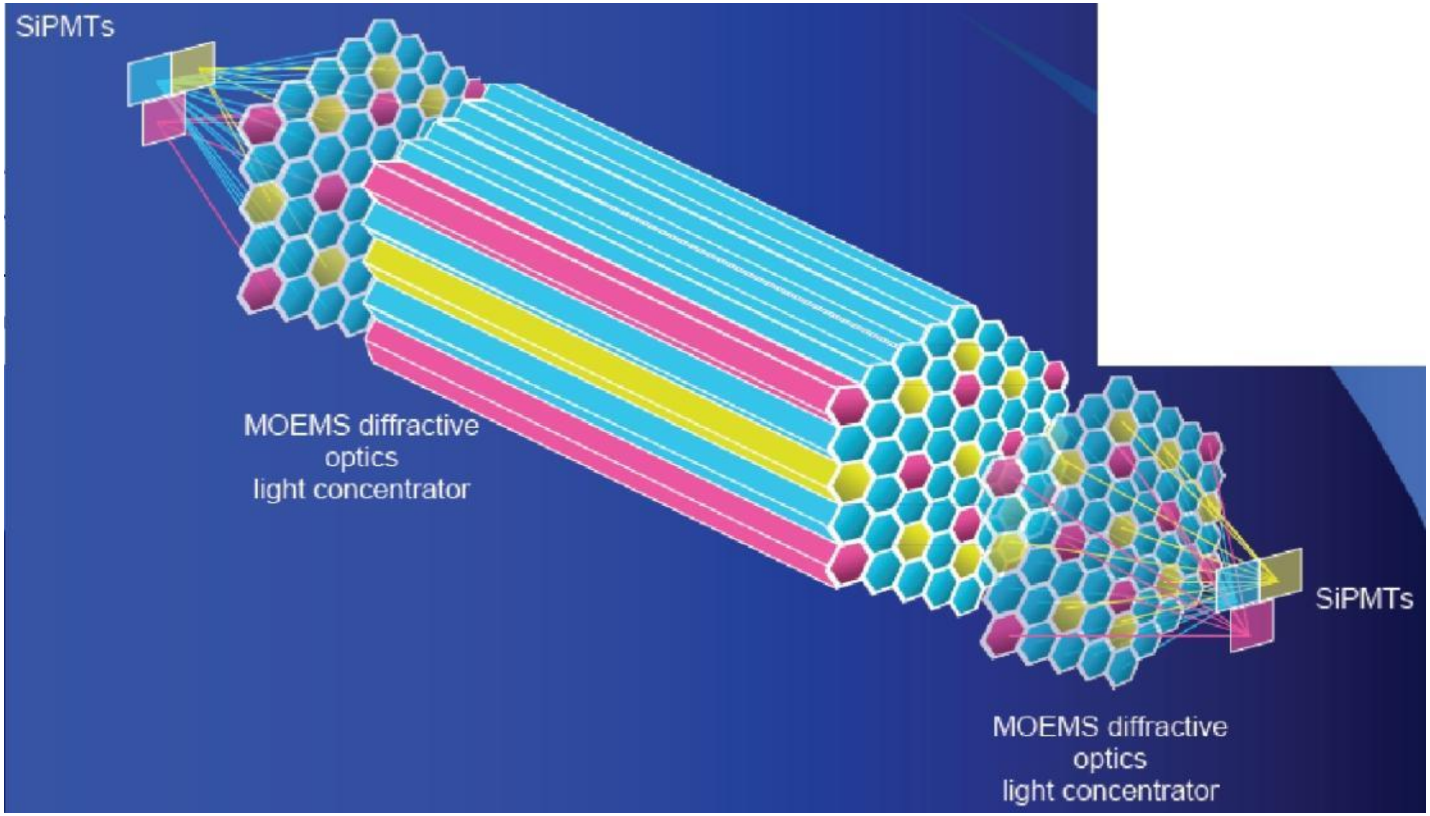
P.Lecoq



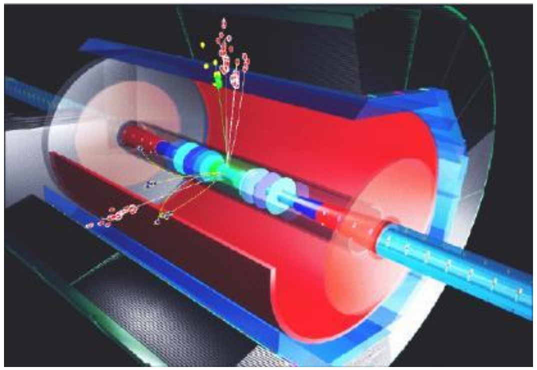
- Select a non-intrinsic scintillating material (unlike BGO or PWO) with high bandgap for low UV absorption
- The undoped host will behave as an efficient Cerenkov: heavy material, high refraction index n, high UV transmission
- Cerium or Praesodinum doped host will act as an efficient and fast scintillator
  - ≈ 40ns decay for Ce
  - ≈ 20ns decay for Pr
- If needed fibers from neutron sensitive materials can be added:
  - Li Tetraborate: $Li_2B_4O_6$
  - LiCaF: $LiCaAlF_6$
  - elpasolite family (Li or B halide of Rb, Sc and rare earth)
- All fibers can be twisted in a cable behaving as a pseudo-homogeneous active absorber with good position and energy resolution and particle identification capability
- Readout on both sides by SiPMT's

Concept of meta-cable - 2

P.Lecoq



Calorimetry for future experiments: jets



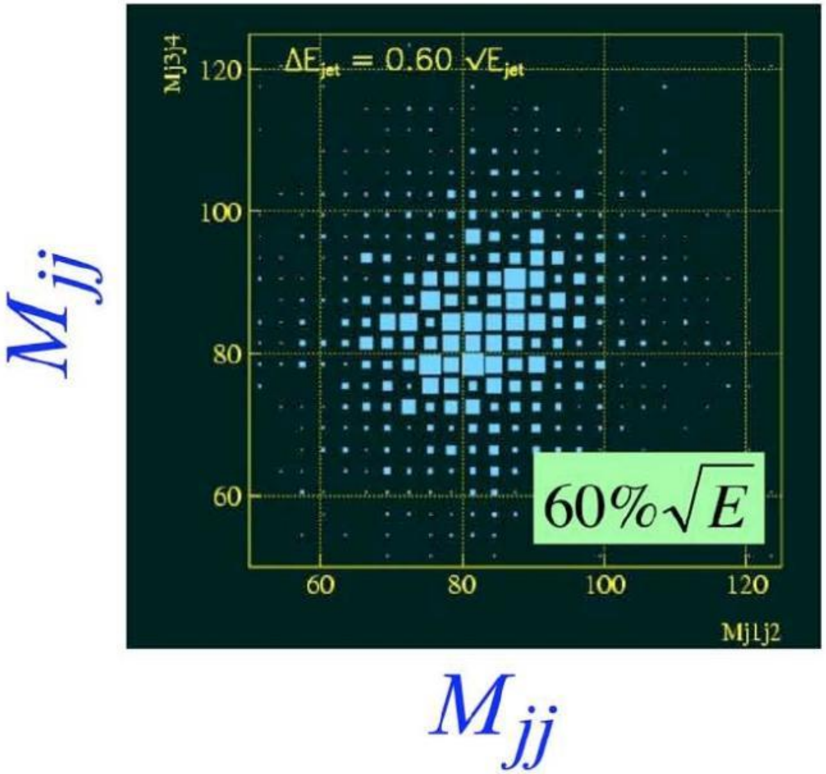
Goal : separate jets from WW and ZZ events

Final states with several bosons (W,Z,H) → multi-jet spectroscopy → hadronic energy resolution important

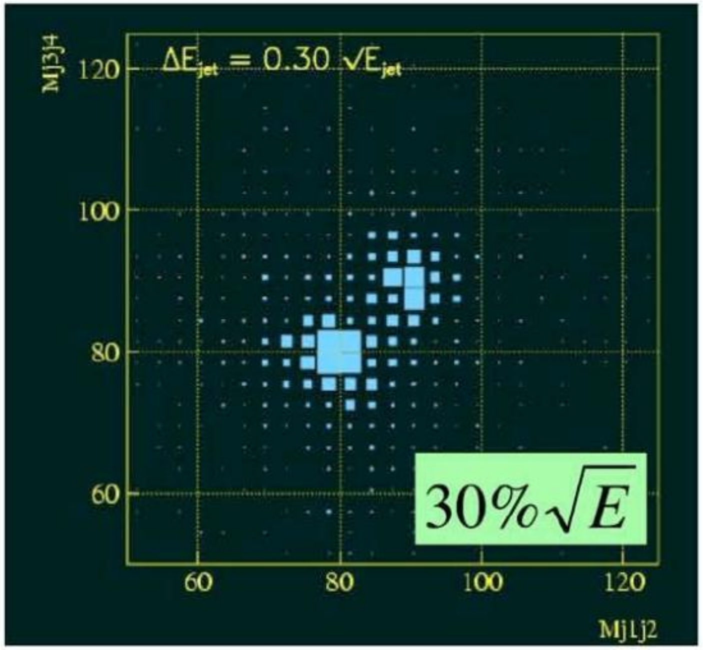
H → γγ completed at LHC ; add H → jet jet

- ➔ Hadronic energy resolution
- ➔ Granularity to resolve dijets

LEP-like



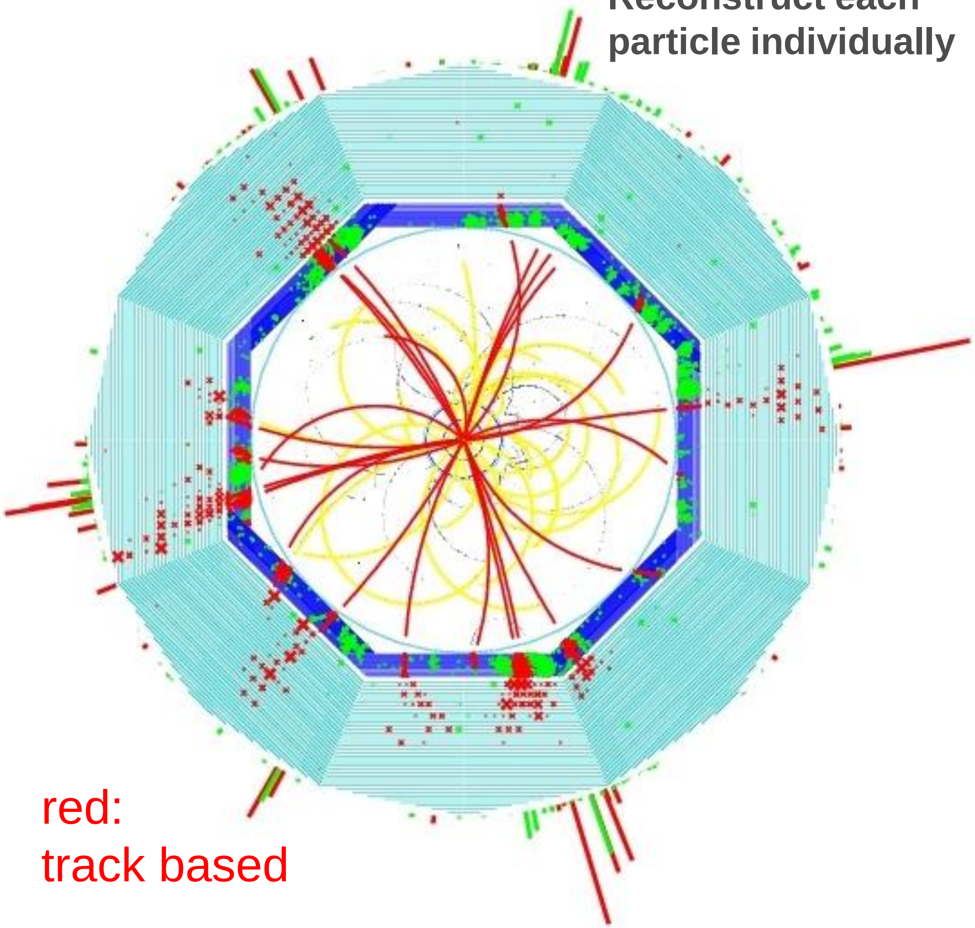
$m_Z – m_W > 3\sigma$: LC design goal



Particle Flow Analysis (Energy Flow Method)

- ☐ *Combine tracking, particle ID and calorimeter information*

- ☐ **Charged particles** : ~65% of jet energy
  However if only charged jet
  components are measured :
  $(\sigma/E)_{jet}$ = 25 .. 30%
  (independent of E_{jet})
  → Calorimetry essential
- ☐ **Photons** (→ ECAL) : ~25% of jet
  energy
- ☐ **Neutral hadrons** (→ ECAL+HCAL) :
  ~10% of jet energy
- ☐ *Problem: shower overlap*
  → Deconvolute contribution
  from showering charged particles
  to avoid double counting



Reconstruct each particle individually

red:
track based

green:
calorimeter based

ZHH → qqbbbb

Particle Flow Analysis (Energy Flow Method)

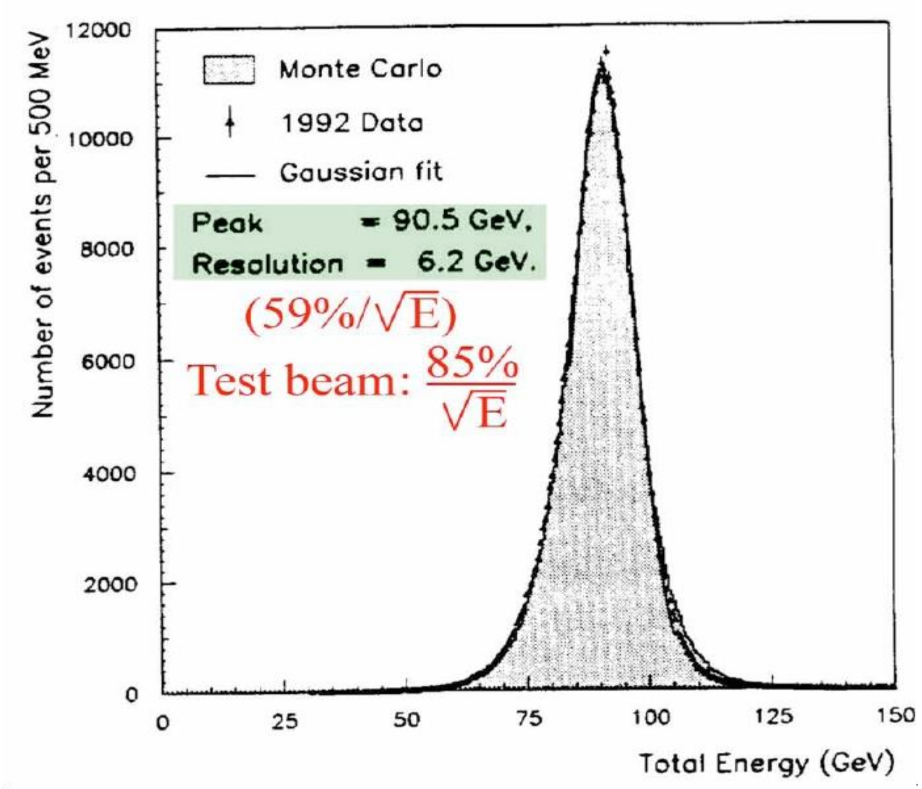
PFA at LEP : ALEPH

NIM A360 (1995) 481

PFA at Tevatron : CDF

Note CDF5005 (2000)

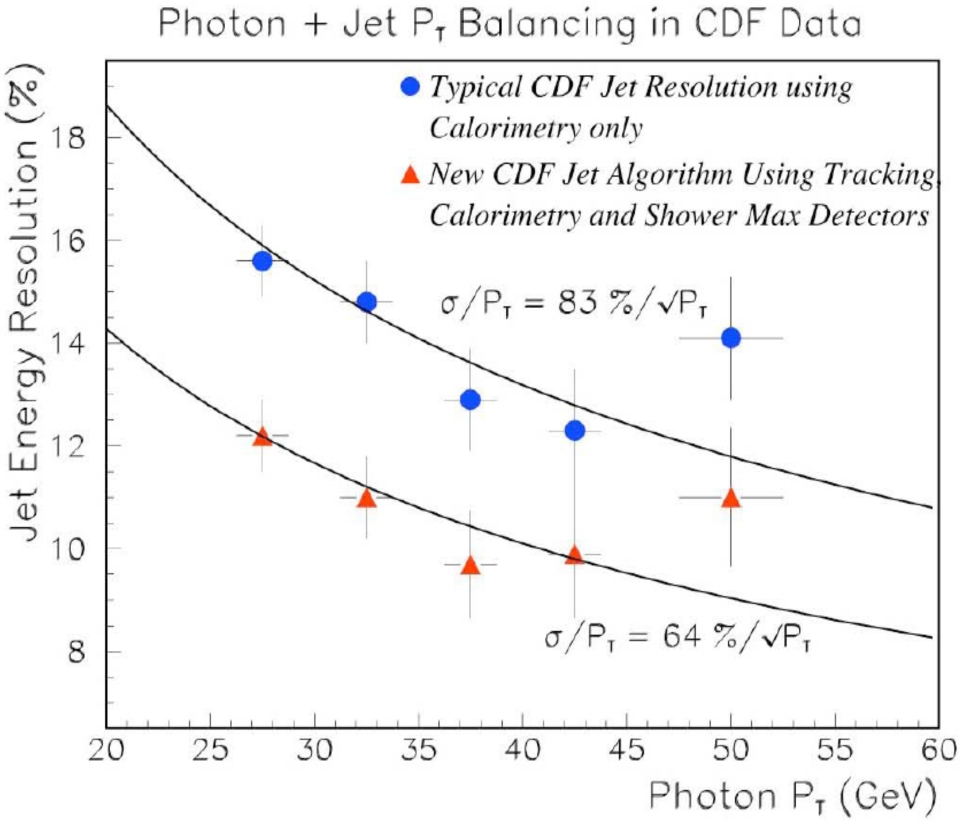
Reconstruct hadronic event structure using particle ID and software compensation



$(59\%/\sqrt{E})$

Test beam: $\frac{85\%}{\sqrt{E}}$

Central detector resolution



$$E_{\text{jet}} = E_{\text{charged}} + E_{\text{photons}} + E_{\text{neut. had.}}$$

$$\sigma^2_{E\text{jet}} = \sigma^2_{E\text{charged}} + \sigma^2_{E\text{photons}} + \sigma^2_{E\text{neut.had.}} + \sigma^2_{\text{confusion}}$$

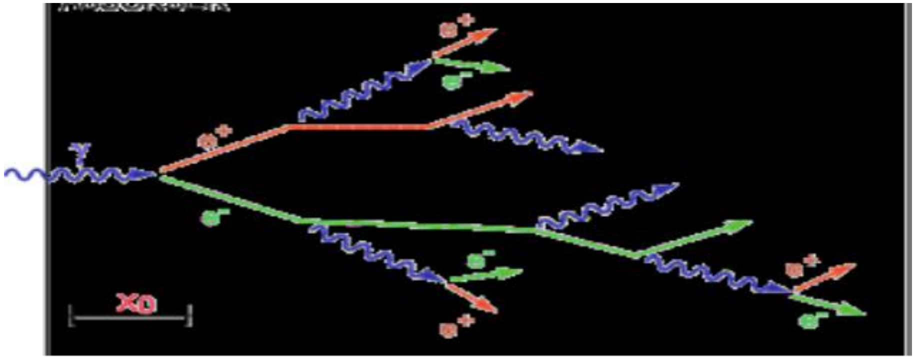
“Confusions” at high particle densities:

- Misinterpret detached fragment as neutral ➔ double-counting
- Erroneously absorb neutral in charged shower ➔ losses

➔ PFLOW can give worse results than pure calorimetry

Q: EM showers

Two electromagnetic showers are initiated **by an electron** and **by a photon**.
Which shower will penetrate deeper in the calorimeter ?



EM shower development

Probability of pair creation in 1 X_0 is $e^{-7/9}$, mean free path of a photon before creating a e^+e^- pair is $\Lambda_{pair} = 9/7\ X_0$

Q: search for “accompanied electrons”

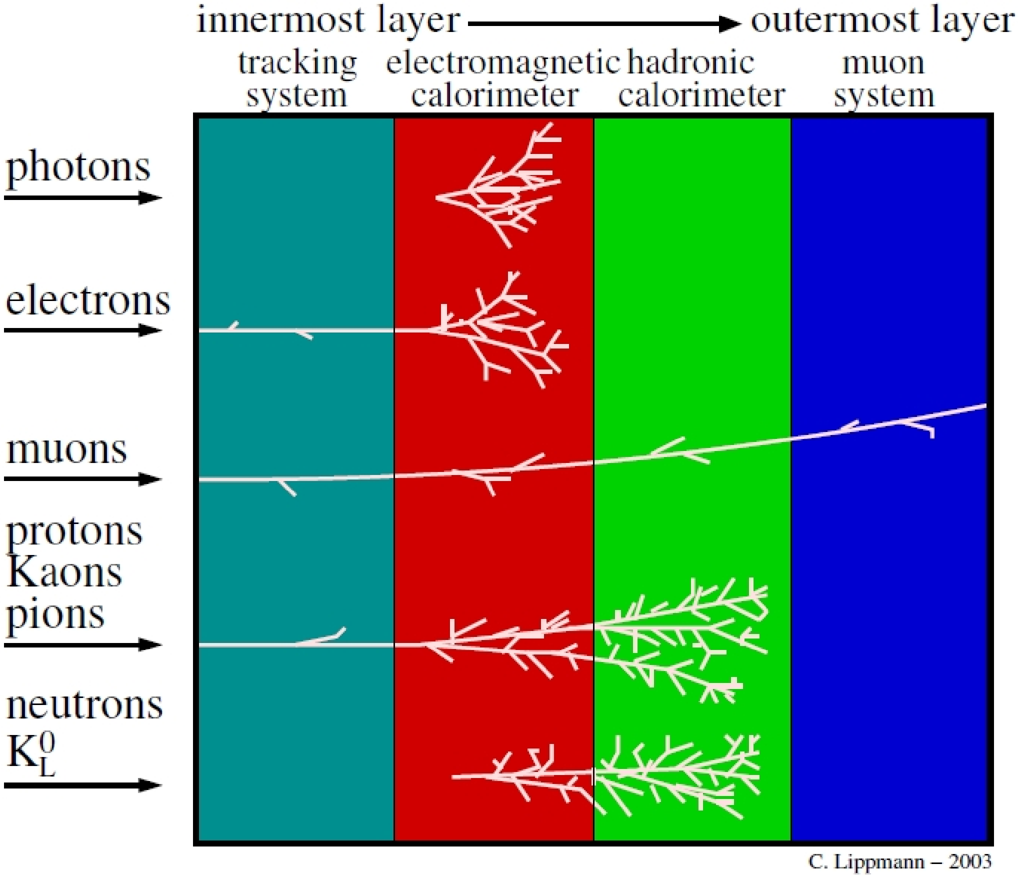
How to distinguish

a single electron

and

a combination of electron and photon

entering electromagnetic calorimeter close to each other ?



C. Lippmann – 2003

Q: calorimeter depth

Why different depth for electromagnetic and hadronic calorimeters ?

EM Calorimeters: MANY (15-30) Xo deep

H Calorimeters: many (5-8) λ_I deep