Instrumentation for high energy physics

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- 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

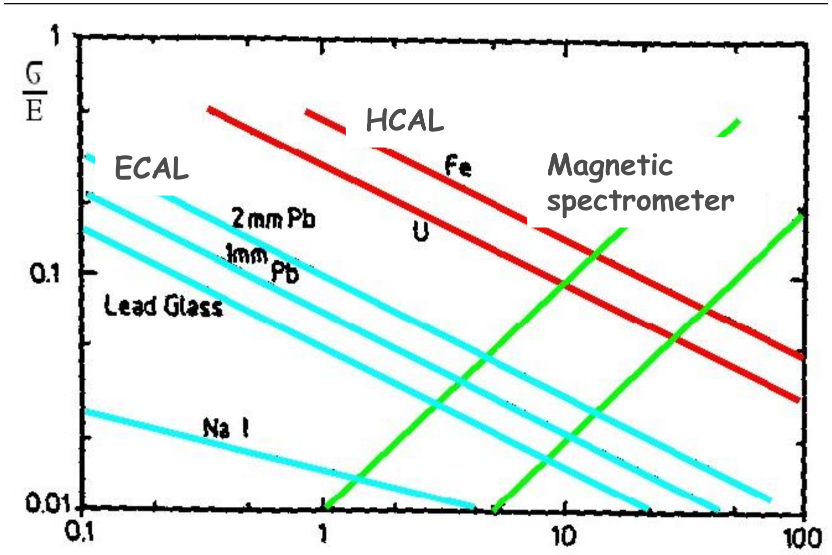
TESHEP, Poltava - Ukraine, 13-20/07/2018

Полтавський краєзнавчий музей

Calorimeters

- ☐ Measures charged (e, h) + **neutral** (photons, n, K_L, …) particles; muons usually traverse calorimeters loosing small amonts of energy by ionization
- ☐ 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

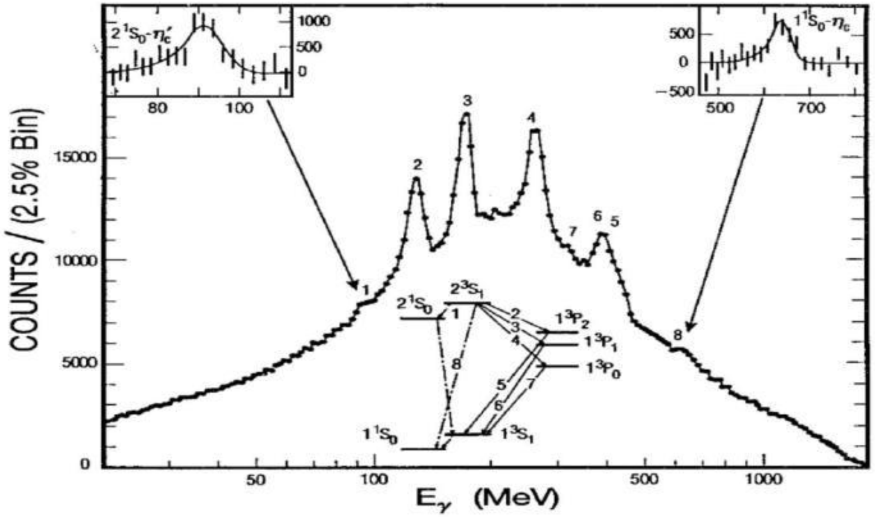
Tricky :

- ☐ Uniformity of response
- ☐ Signal linearity
- ☐ Calibration : Energy = f(Measured Signal)
- ☐ Radiation resistance
- ☐ Hadronic shower fluctuations
- ☐ …

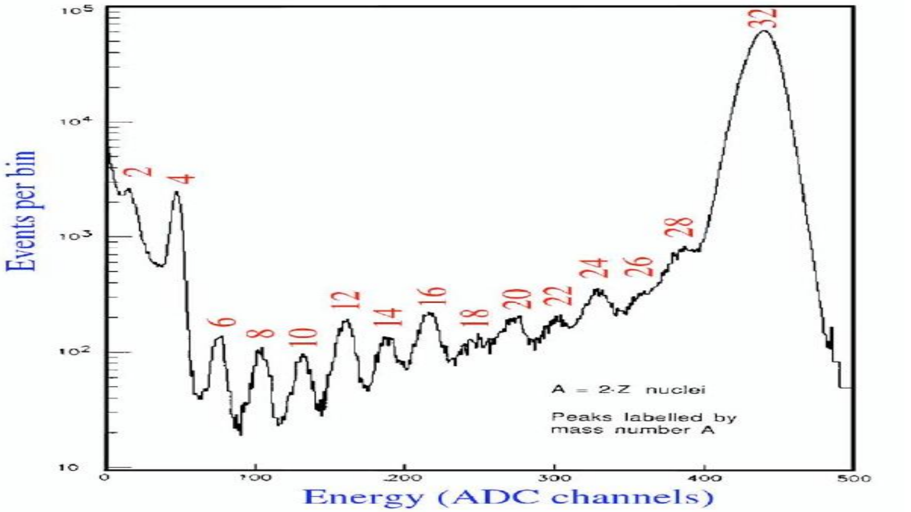
➔ Performance limited

Calorimetry canonical illustrations

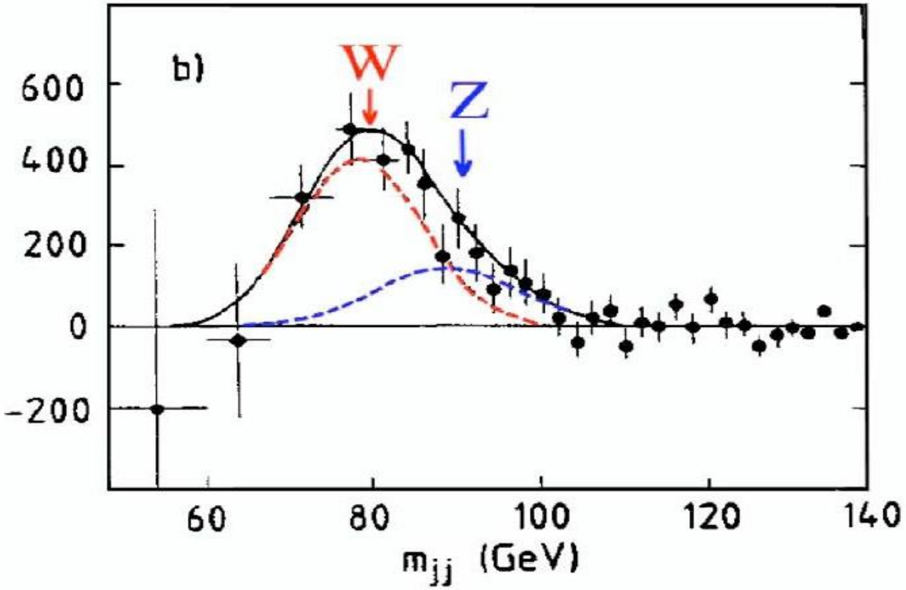
EM energy resolution charmonium spectroscopy (SPEAR)



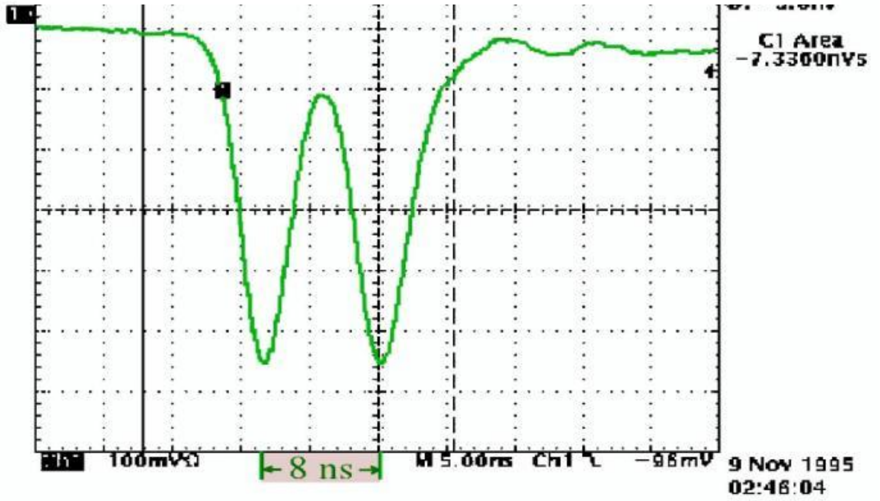
H energy resolution WA80 calorimeter – composition of *p*-selected CERN heavy ion beam



H energy measurement UA2 experiment, QCD bgrd subtracted



Signal speed 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 $\propto$ 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 $1/\sqrt{N}$ by a factor $\sqrt{F}$ 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…

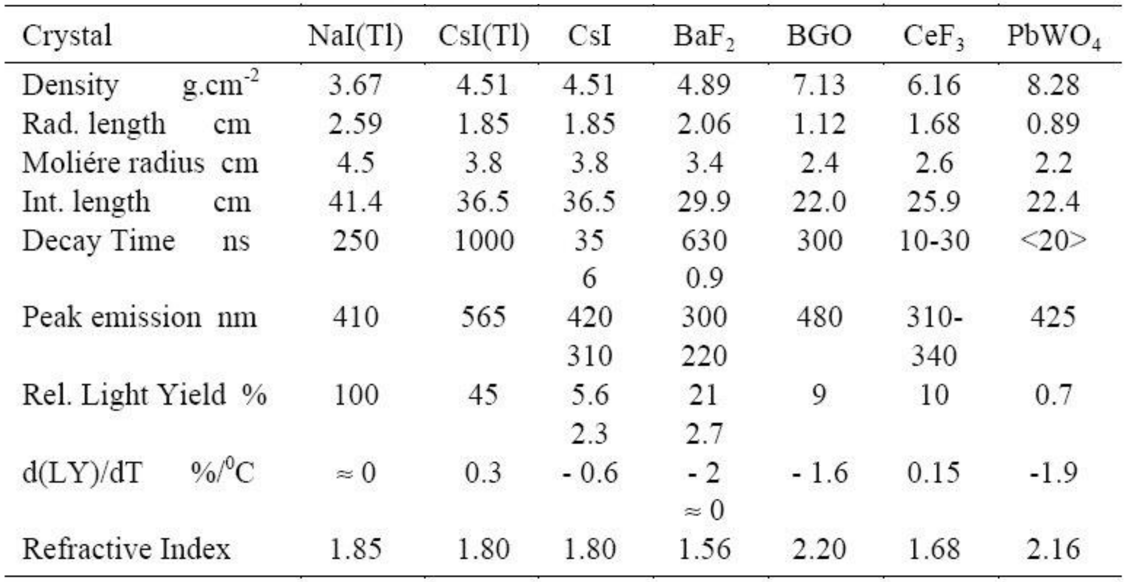
b : constant term, it contains all the imperfection
response variation versus position (uniformity), time (stability), temperature, mis-calibration, radiation damage, ….

Homogeneous calorimeters

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

Crystals

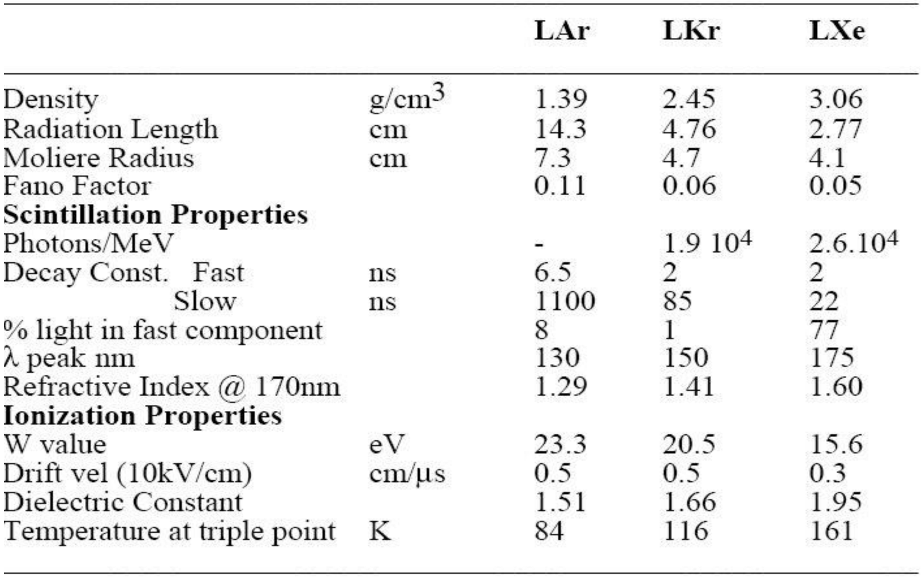
Babar/Belle/KteV L3 CMS



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

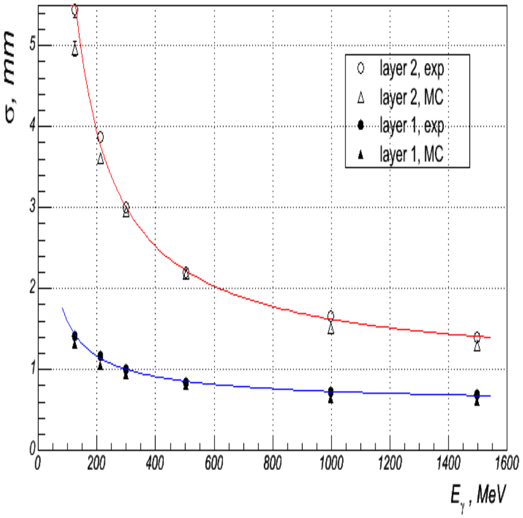
Cryogeny/purification !

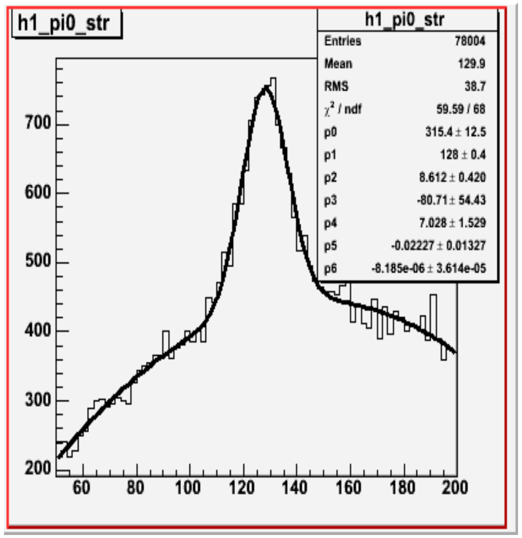
Should use the best compromise / environment / physics
In general good energy resolution but less position resolution / PID because more difficult to have segmentation (longitudinal…)

Noble liquids :

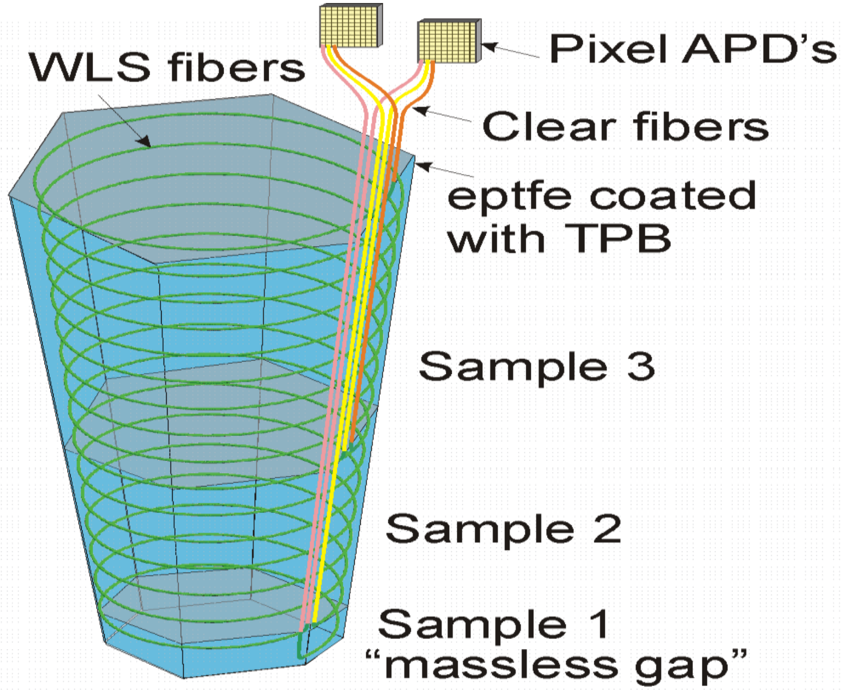
Large (11m^3) LiKr calorimeter at VEPP-4M

- Excellent space resolution ~1mm
- Excellent two photon separation
- Energy resolution ~ 3%/√E
- π^0 mass resolution ~10MeV will improve after calibration





LiXe longitudinal segmentation (Hitlin et al.), R&D



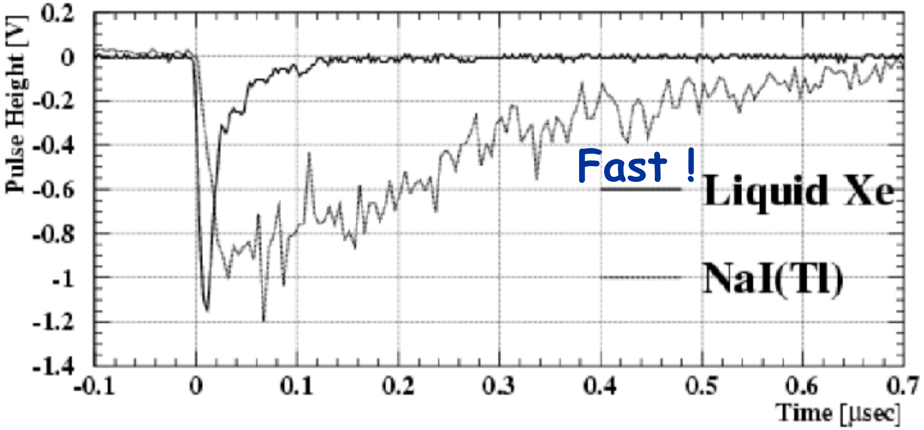
Detection of scintillation light

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



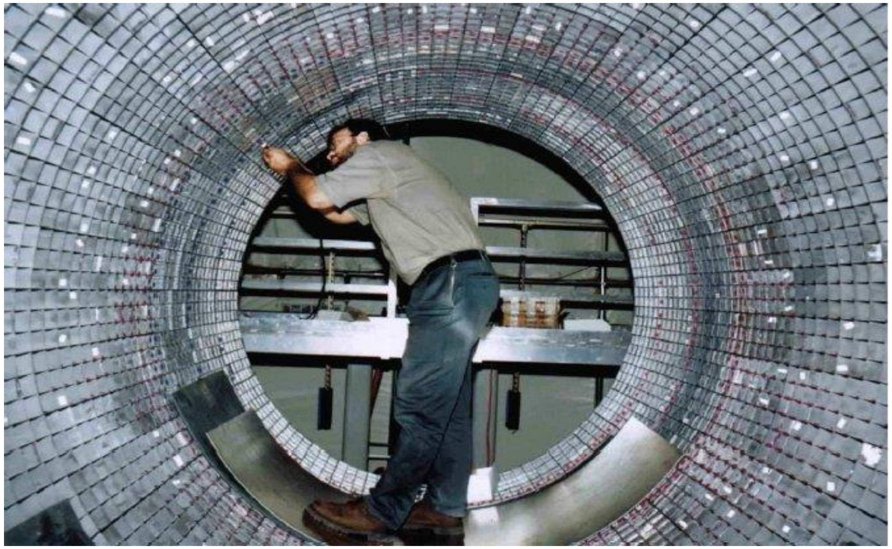
Examples of homogeneous calorimeter with crystals: BaBar

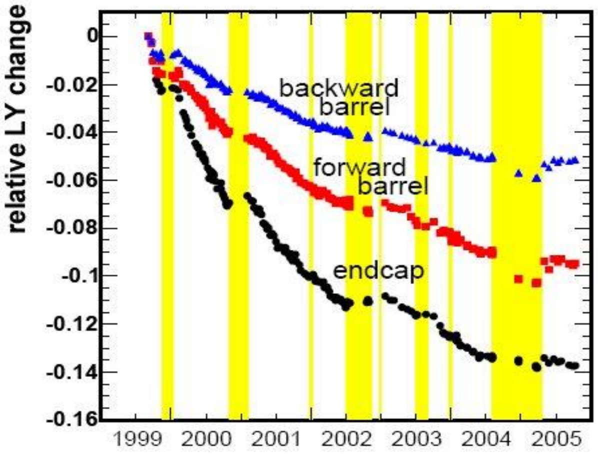
6580 crystals of CsI(Tl)
about 17 X_0

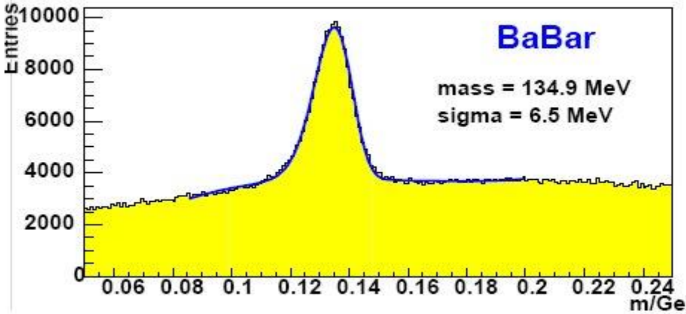
Photon energy between
20 MeV and 8 GeV

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

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

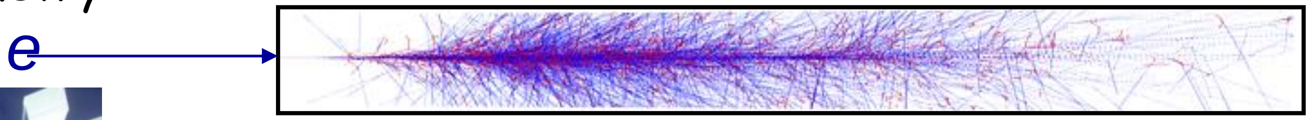


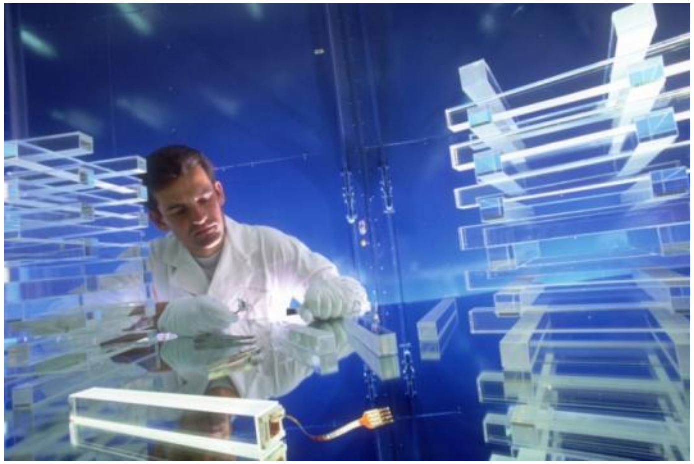


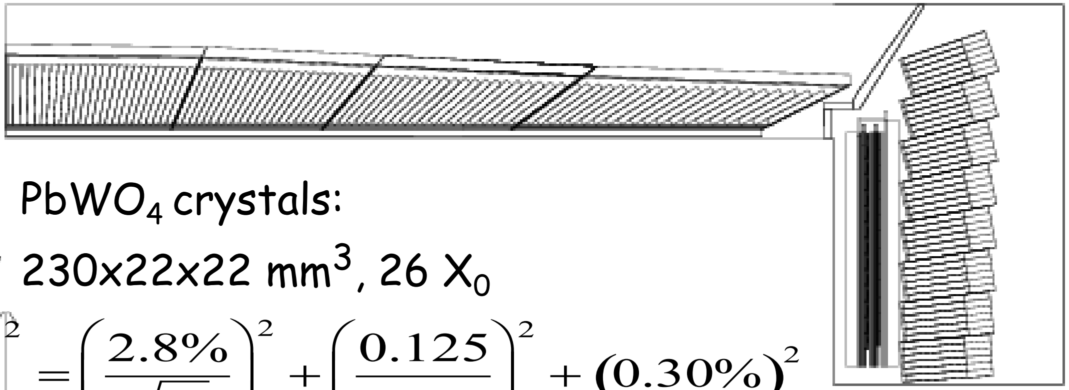


Examples of homogeneous calorimeter with crystals: CMS EM calorimeter

- H → γγ : stress on EM calorimetry







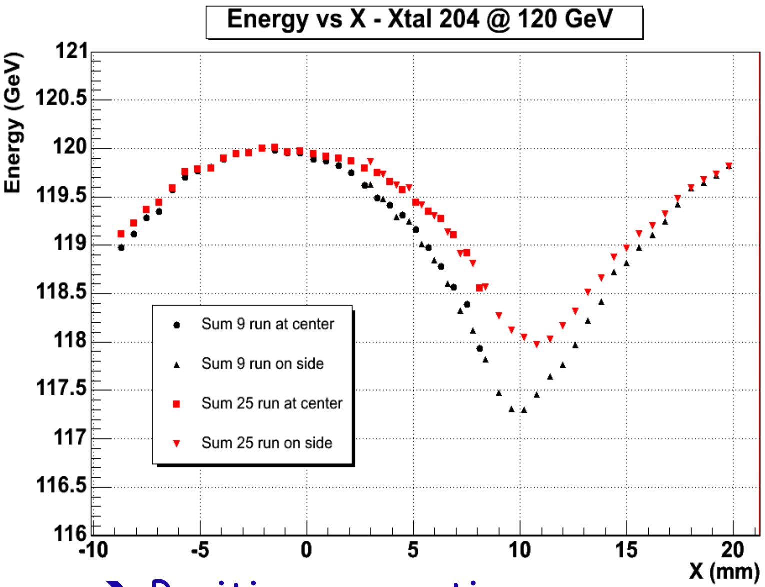
PbWO$_4$ crystals:

230x22x22 mm^3, 26 X$_0$

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

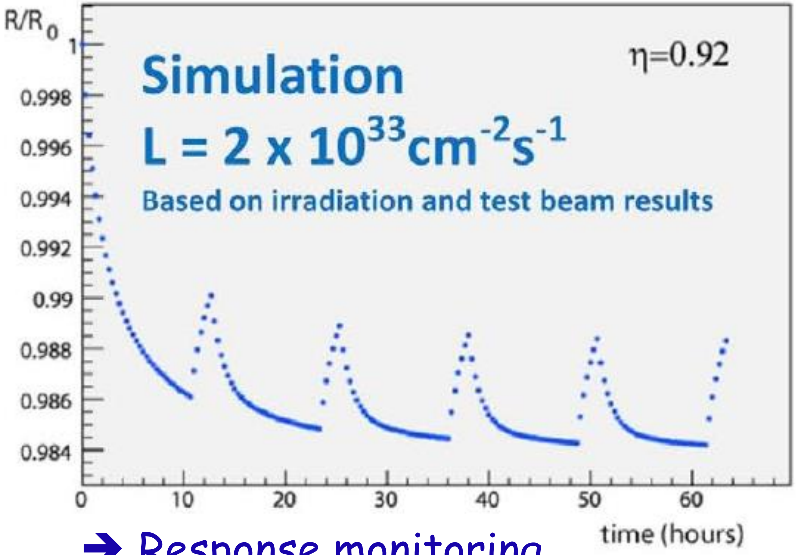
Stochastic **Noise** **Constant**

Response depends on the position



→ Position correction

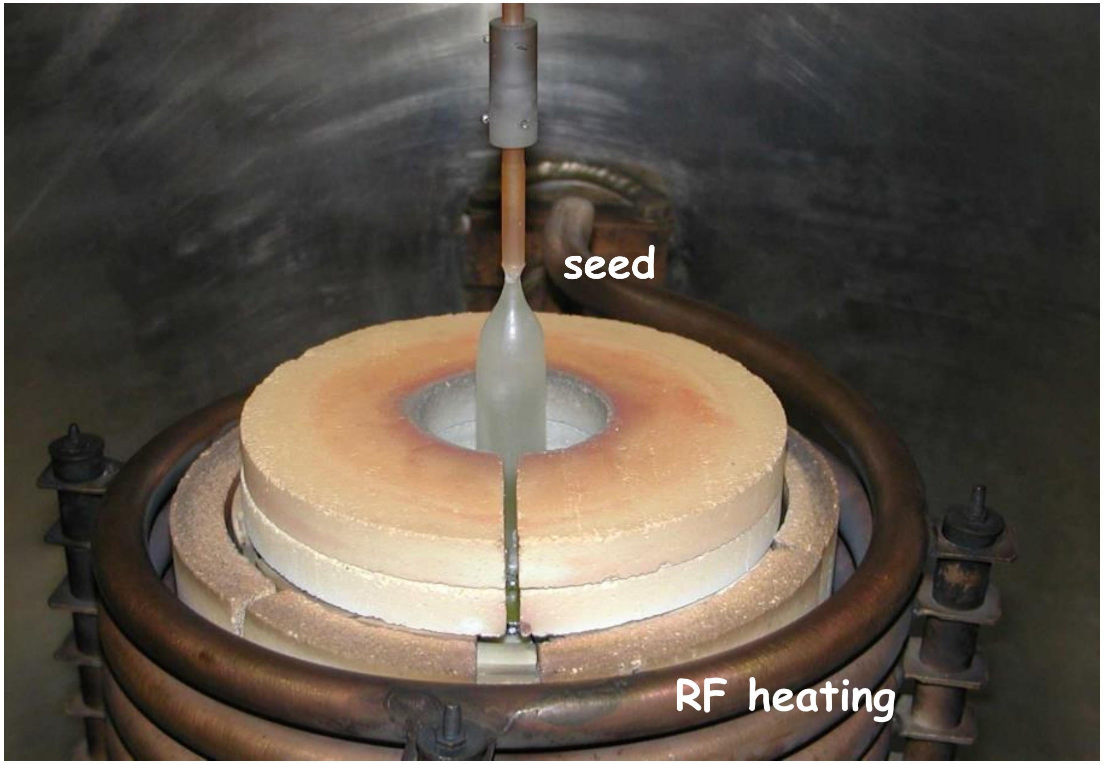
Radiation damage of PbWO$_4$



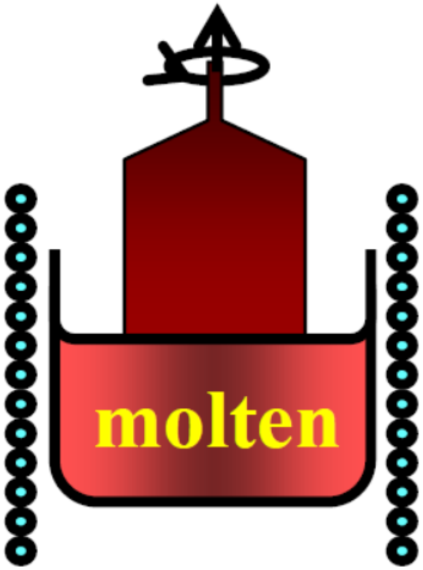
→ Response monitoring

Examples of homogeneous calorimeter with crystals: CMS EM calorimeter

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



Czochralski method

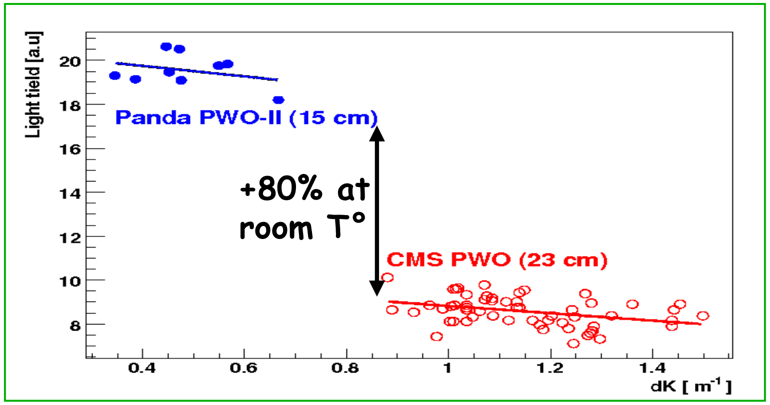


Example: further $PbWO_4$ crystals optimization for ECAL at PANDA experiment

Energies : from 10 MeV to 15 GeV

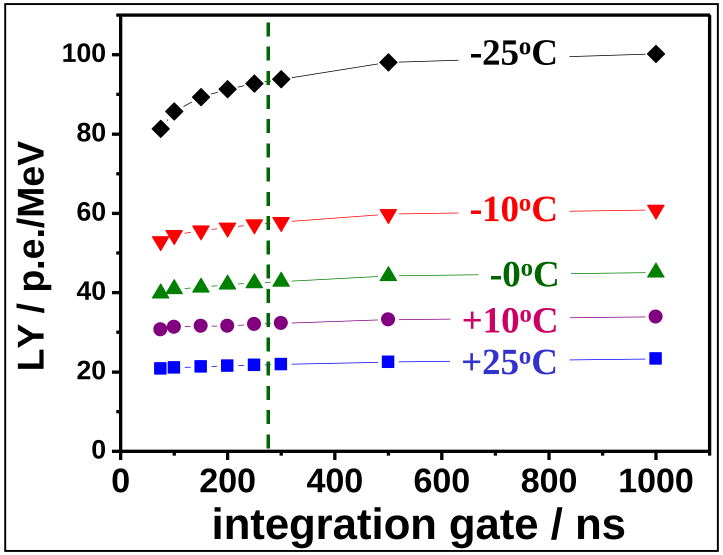
P.Rosier

- Optimization of the $PbWO_4$
  - reduction of defects (oxygen vacancies)
  - reduced concentration of La-, Y-Doping
  - better selection of raw material
  - optimization of production technology



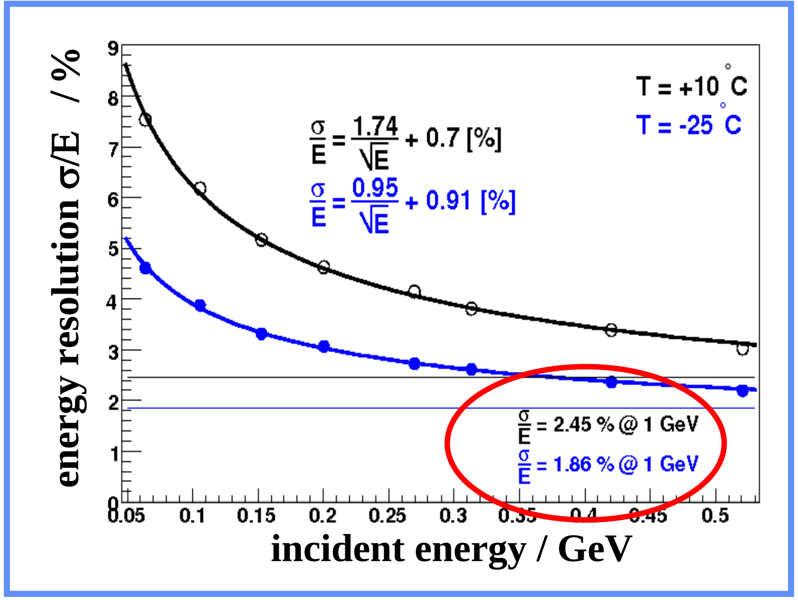
→ **Development of the PWO-II : Light yield increased**

4x lighter if cooled down



LY=92.2pe/MeV

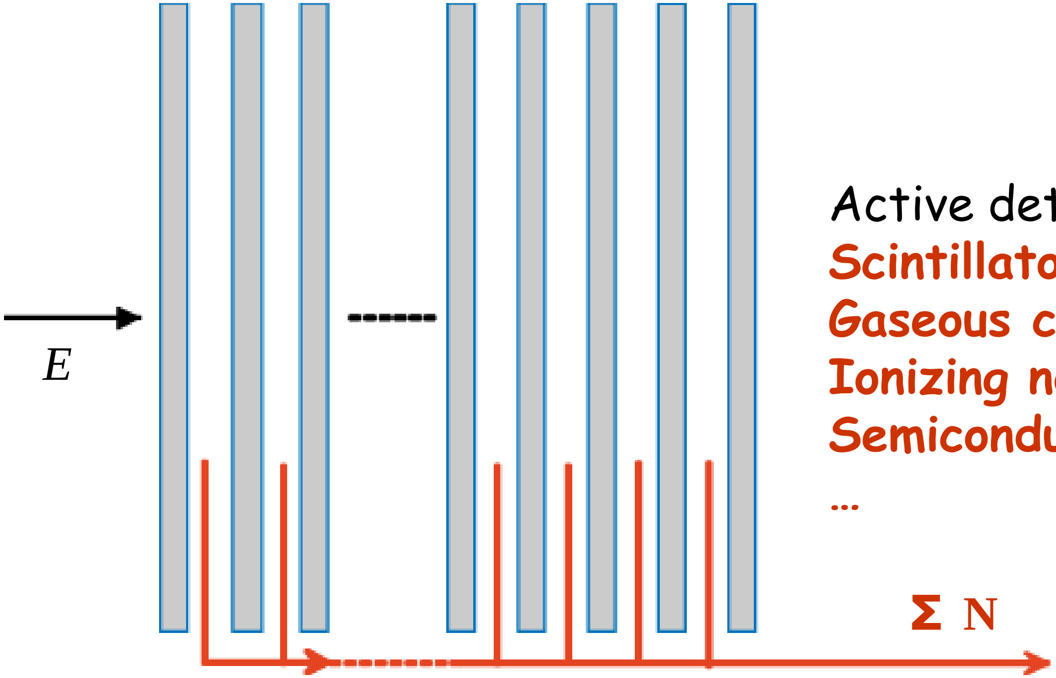
Response to high energy photons @MAMI, Mainz



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.



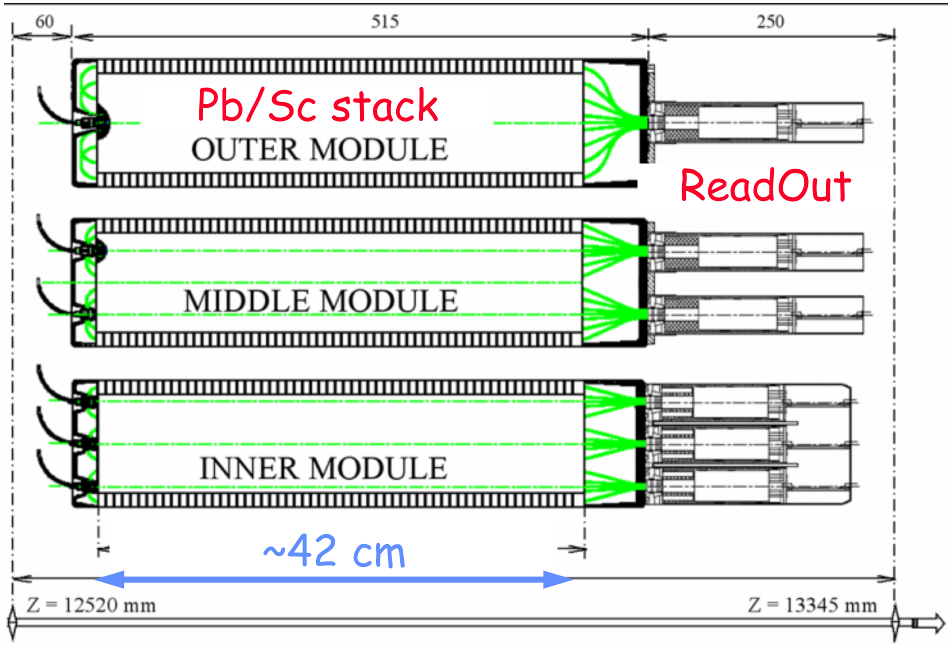
Particle absorption
and
Shower sampling
are separated.

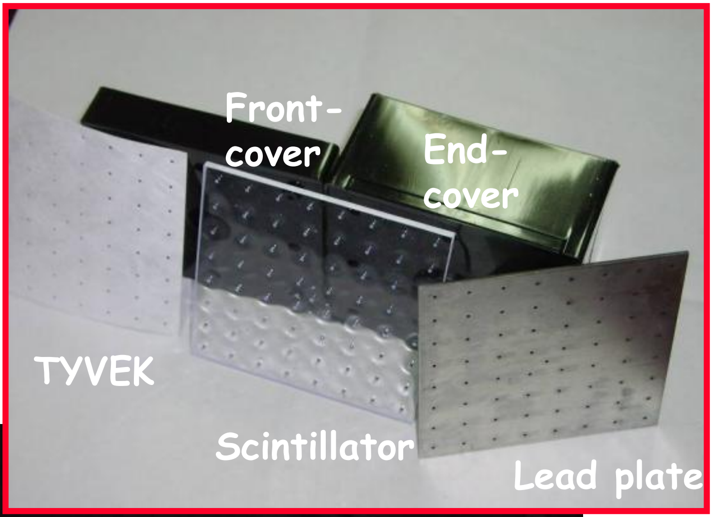
Active detector:
Scintillators
Gaseous chambers
Ionizing noble liquid
Semiconductors
…

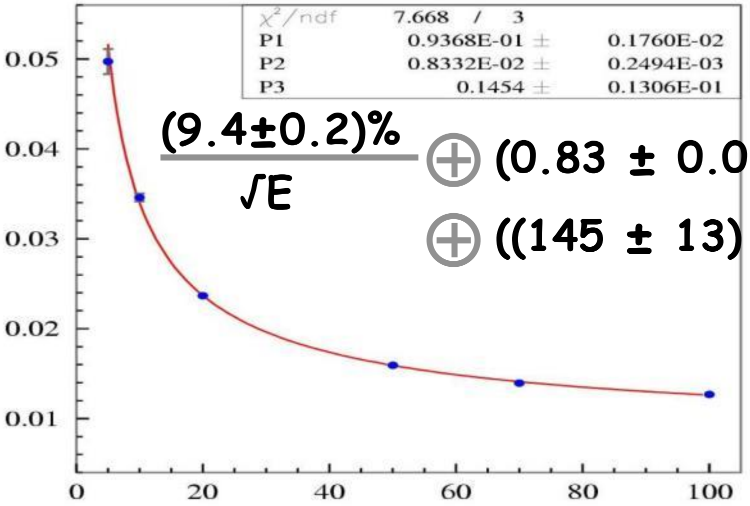
- ☐ Resolution is better, smaller is the detection gap and larger the sampling fraction (up to some limitations…). Easy for longitudinal segmentation

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

- ❑ 6016 detector cells/R-O channels
- ❑ Volume ratio Pb:Sc = 2:4 (mm)
- ❑ 25 X_0 , 1.1 λ depth
- ❑ Light yield: ~3000 ph.e./GeV



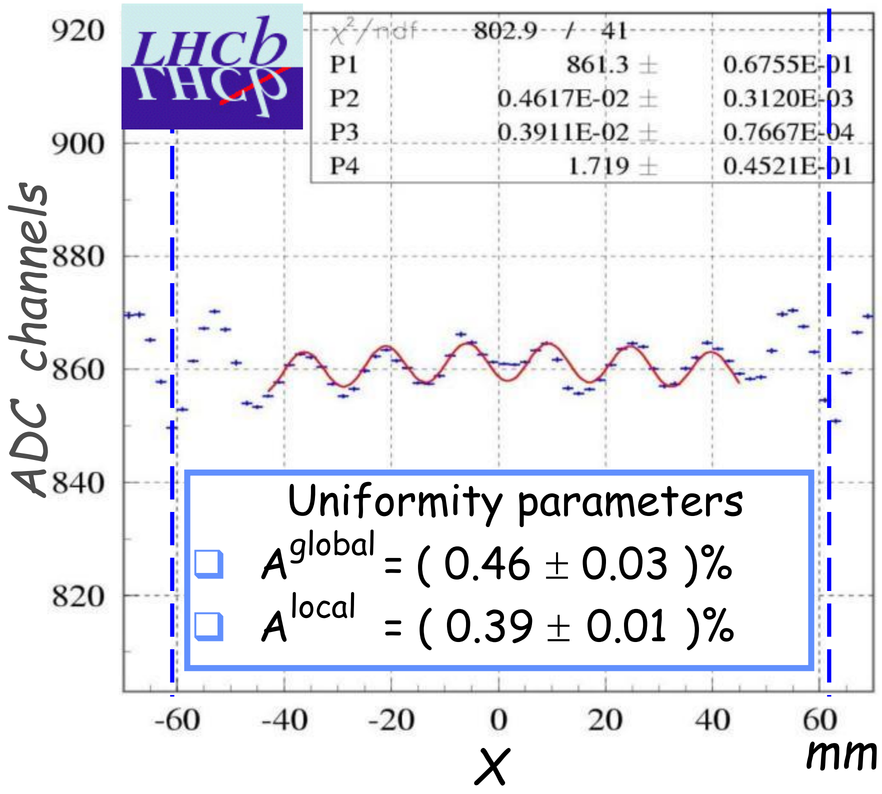




$$\frac{(9.4\pm0.2)\%}{\sqrt{E}} \oplus (0.83 \pm 0.02)\% \oplus ((145 \pm 13)\ \mathrm{MeV})/E$$

Lateral uniformity of response:

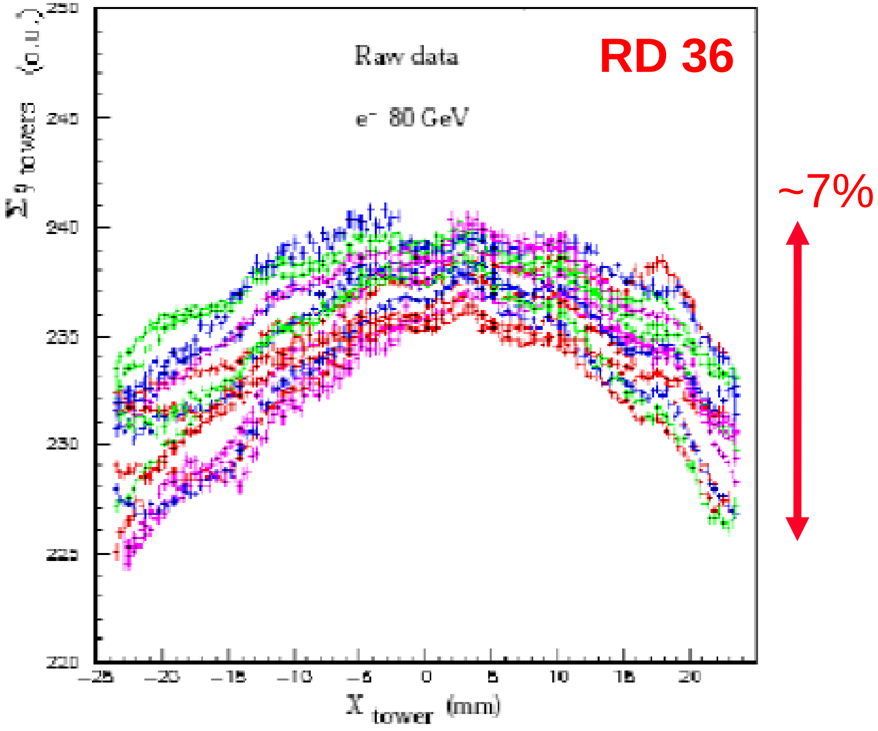
Lateral scan of ECAL module with
50 GeV e^- beam



Uniformity parameters

- ☐ A^{global} = (0.46 ± 0.03)%
- ☐ A^{local} = (0.39 ± 0.01)%

Transverse scan with 80 GeV electrons

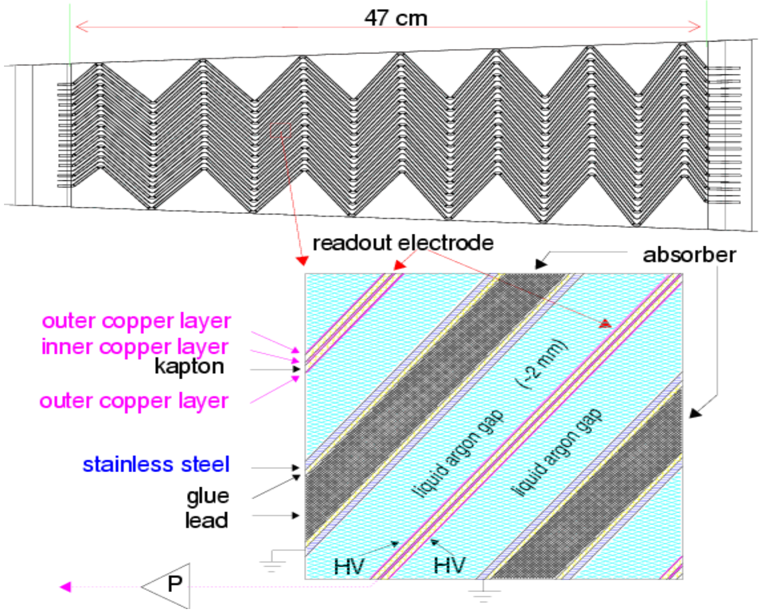


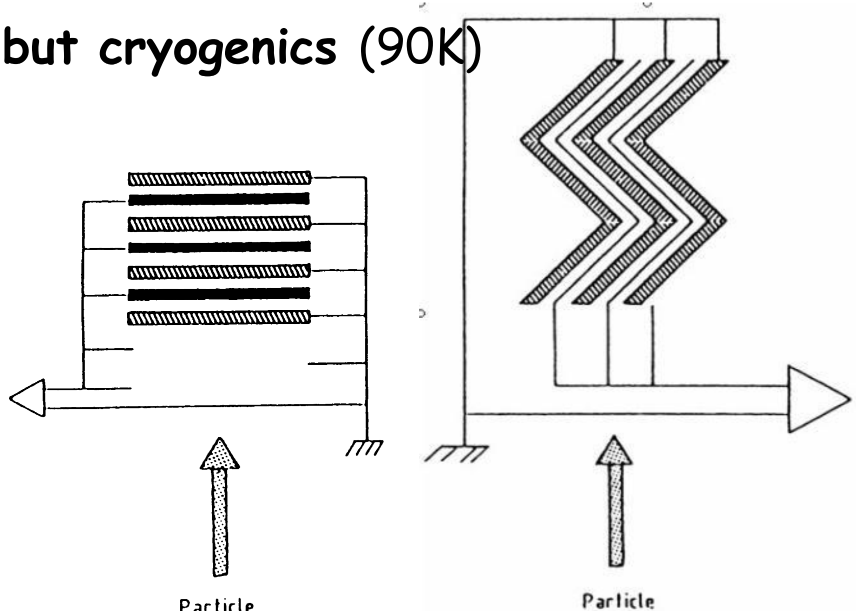
Spread over the module (Max.-to-Min.):

- ☐ ±1.3% for e-beam parallel to module axis
- ☐ ±0.6% for e-beam at 200 mrad

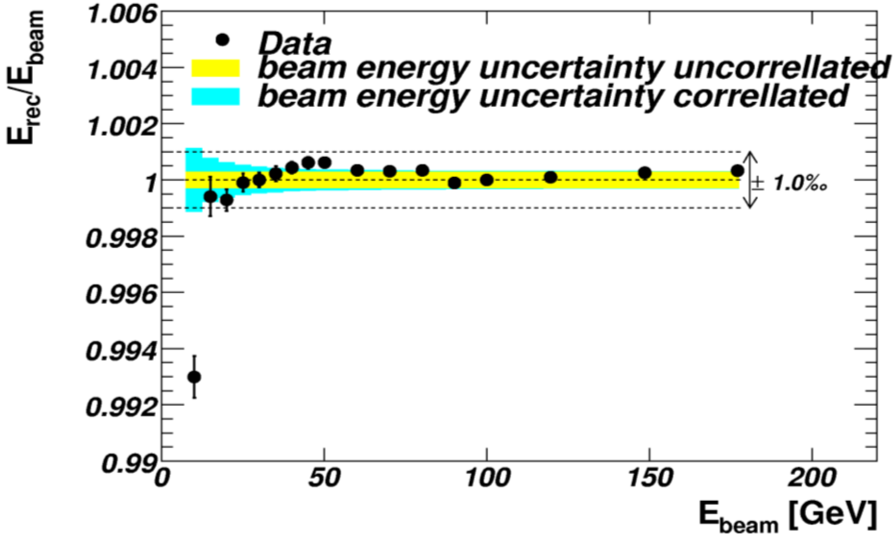
New sampling geometry: ATLAS accordion (ECAL)

- 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





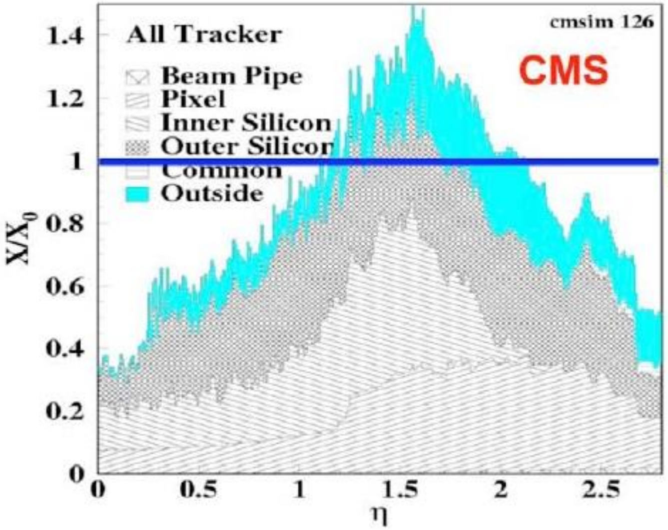
- Collect ionisation electrons with an electric field across 2.1 mm liquid Argon drift gap



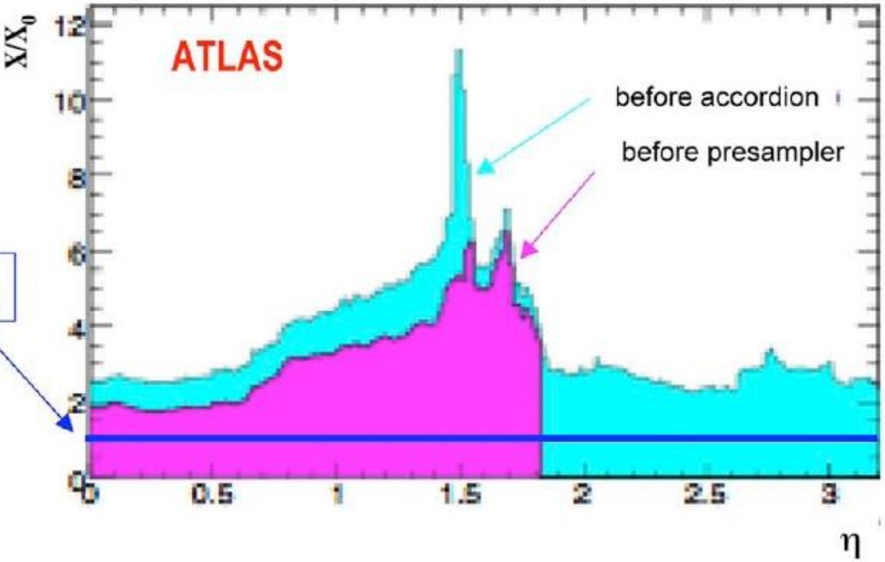
Energy linearity → important parameter for precision measurement (W mass)

Enemy: material upstream the EM calorimeter

➔ Bremsstrahlung for electrons
➔ Pair production for photons

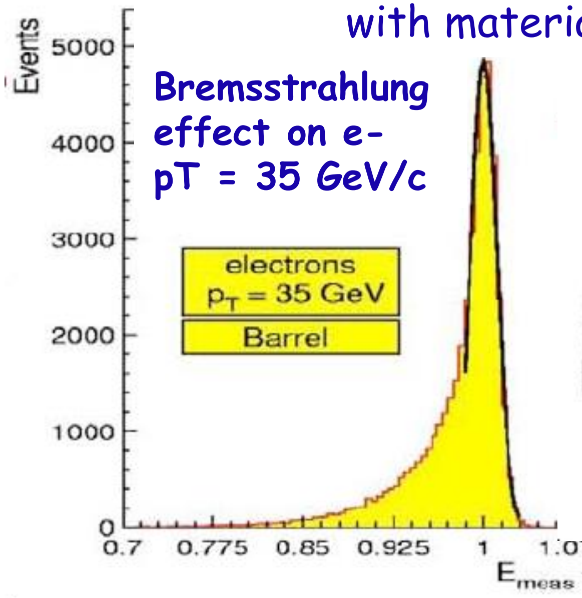


1 X_0

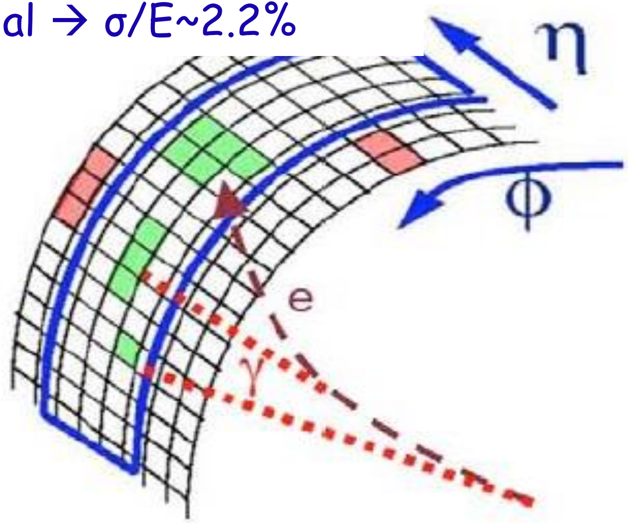


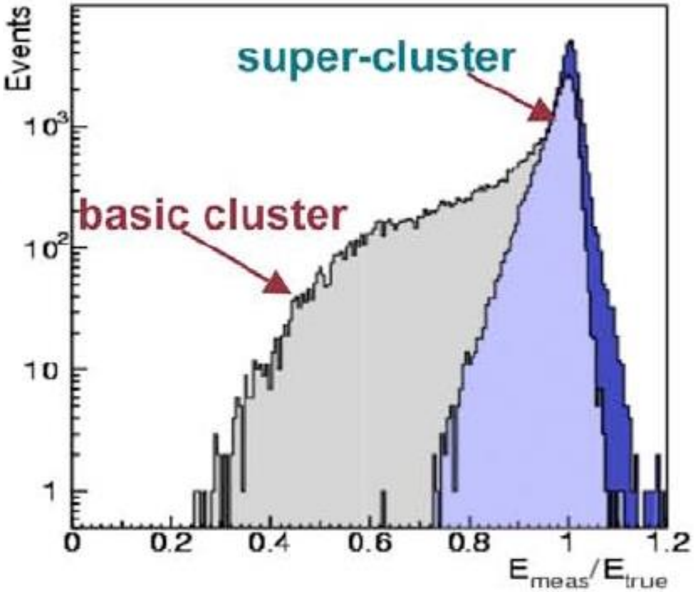
CMS : no material → $\sigma/E \sim 0.7\%$
with material → $\sigma/E \sim 2.2\%$

Bremsstrahlung effect on e- pT = 35 GeV/c

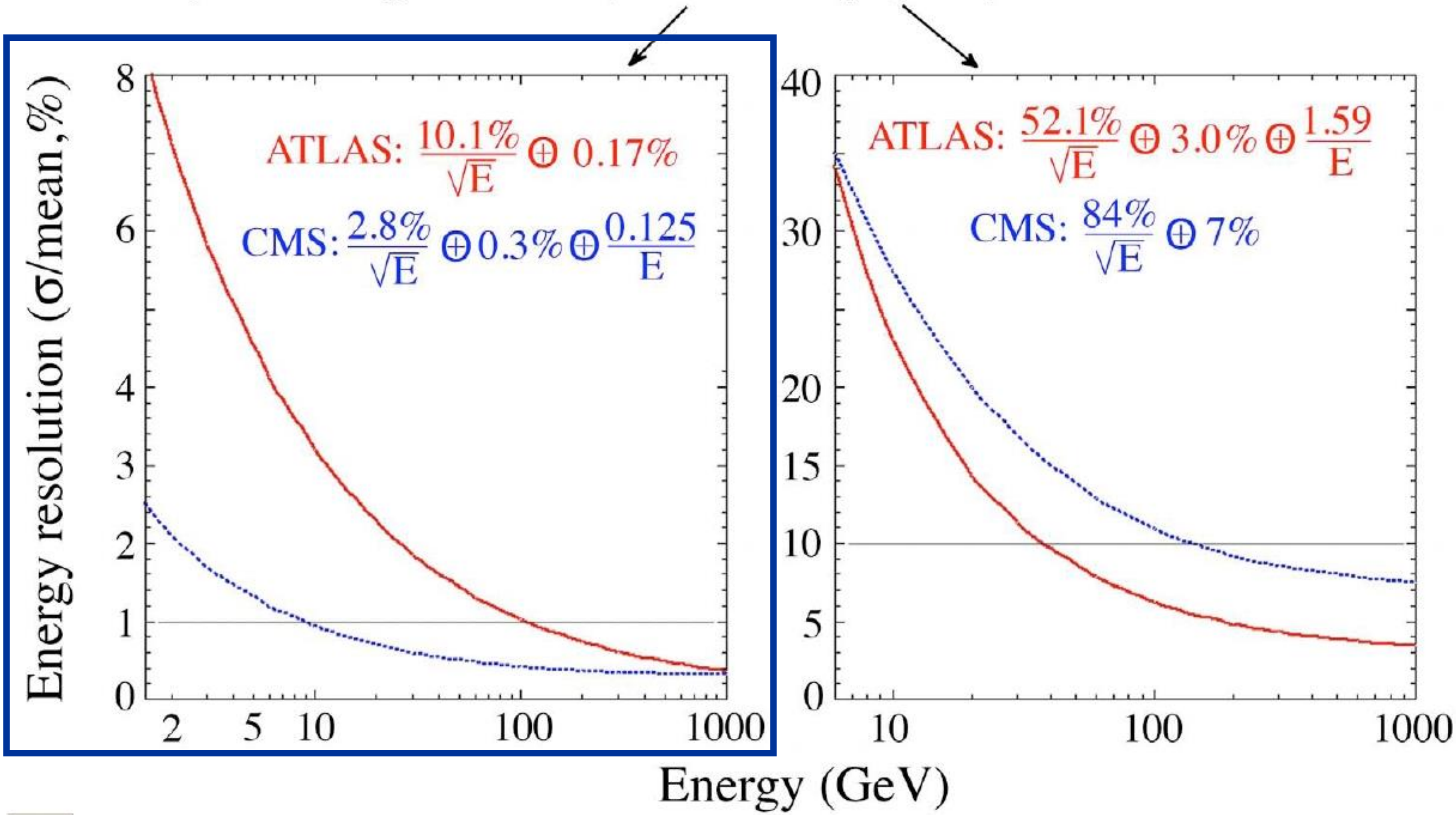


Recovery of Bremsstrahlung photon energy





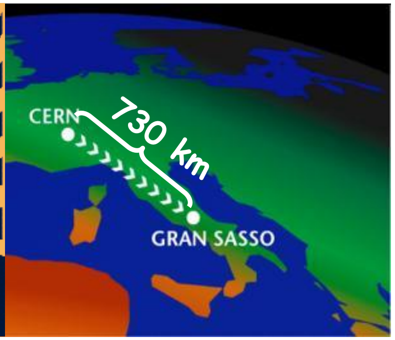
ATLAS : use pre-shower, E1/E2 to recover lost energy



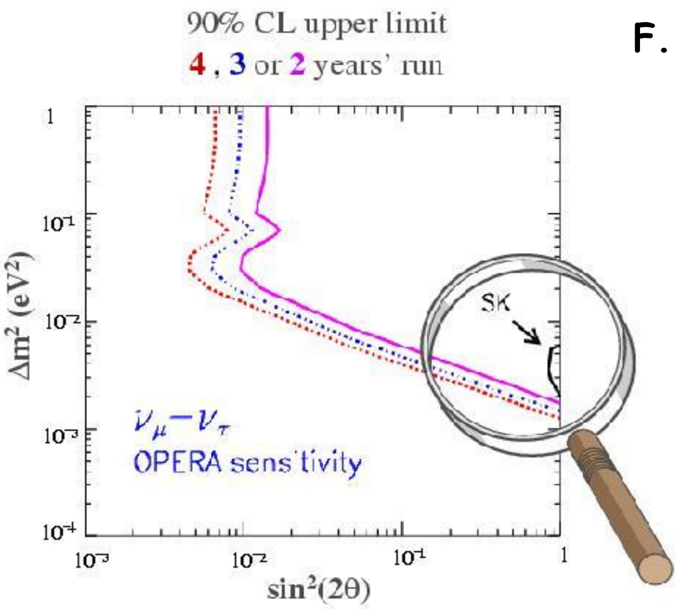
Reported energy resolution (electrons, single pions)

+ CALIBRATION !

Example : EM shower reconstruction with emulsion films in

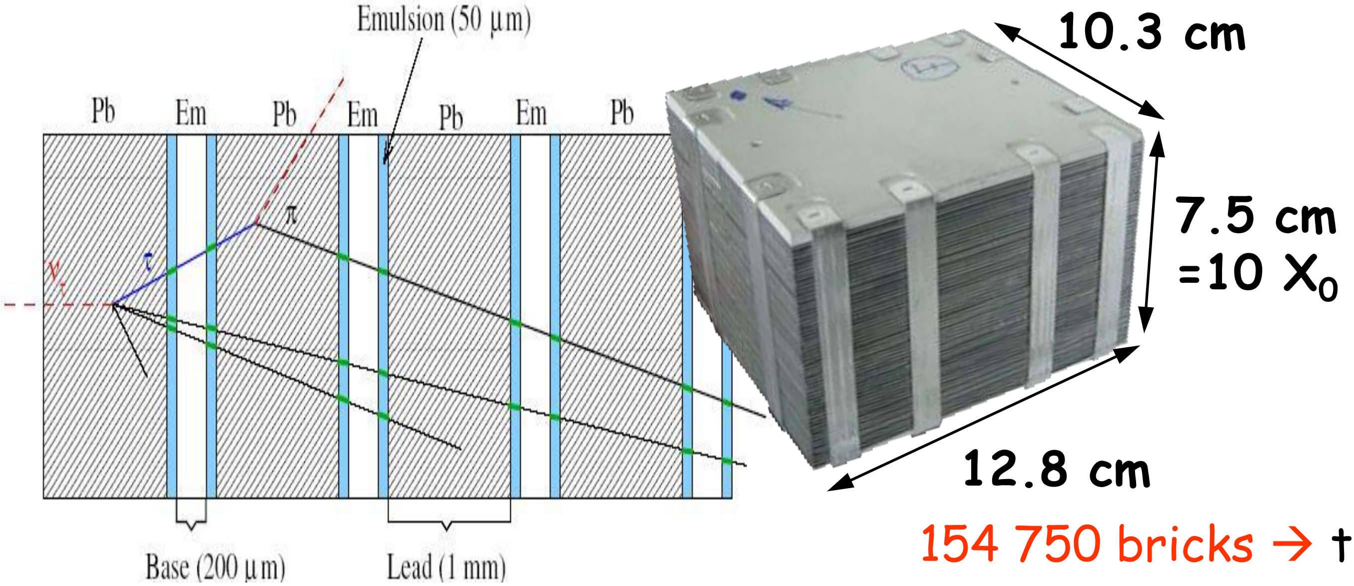


F. Juget



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



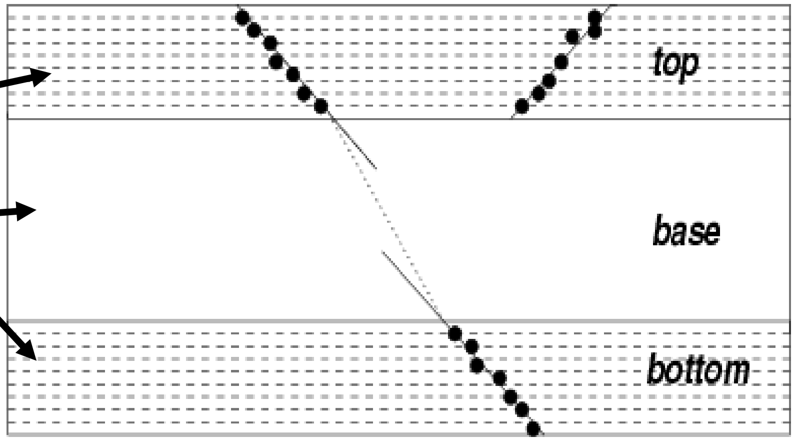
Basic unit: BRICK
sandwich :
56 Pb sheets 1mm +
57 emulsion layers
(8.3kg)

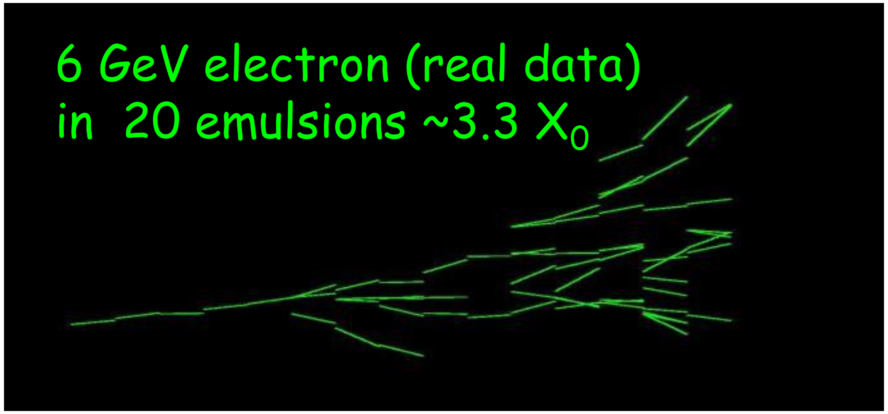
154 750 bricks → target mass: 1.35 ktons

Automated emulsion analysis

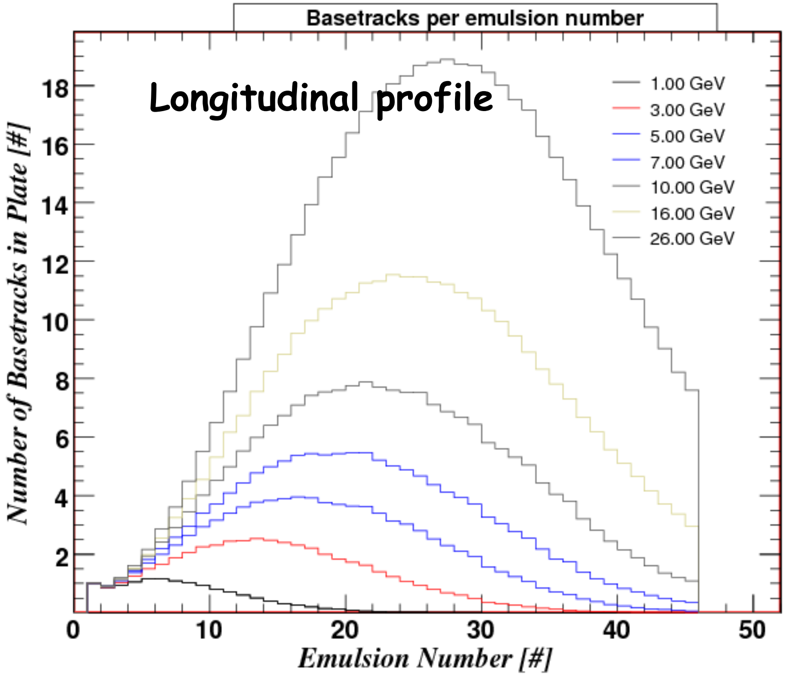
2 emulsion layers 50 μm

plastic base 200 μm



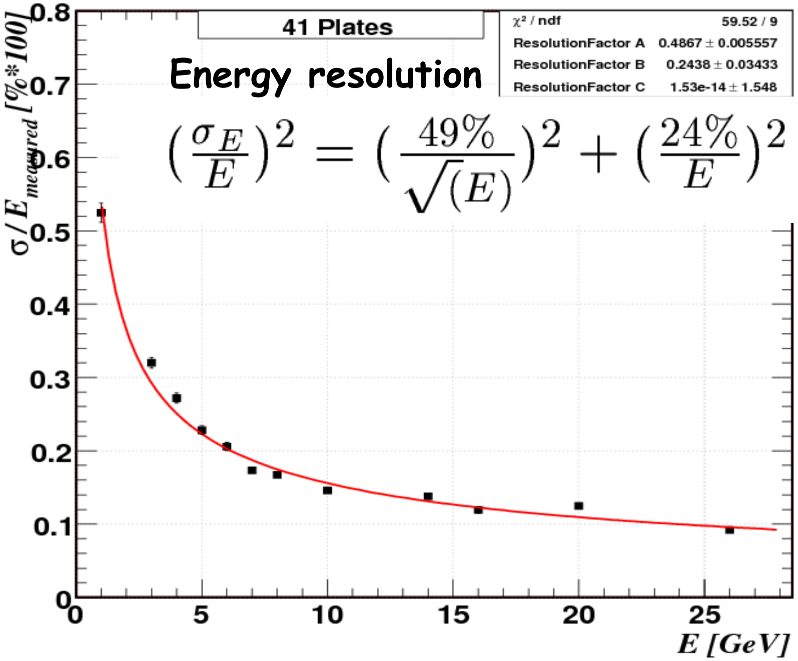


6 GeV electron (real data)
in 20 emulsions ~3.3 X_0



Resolution for 41 plates:

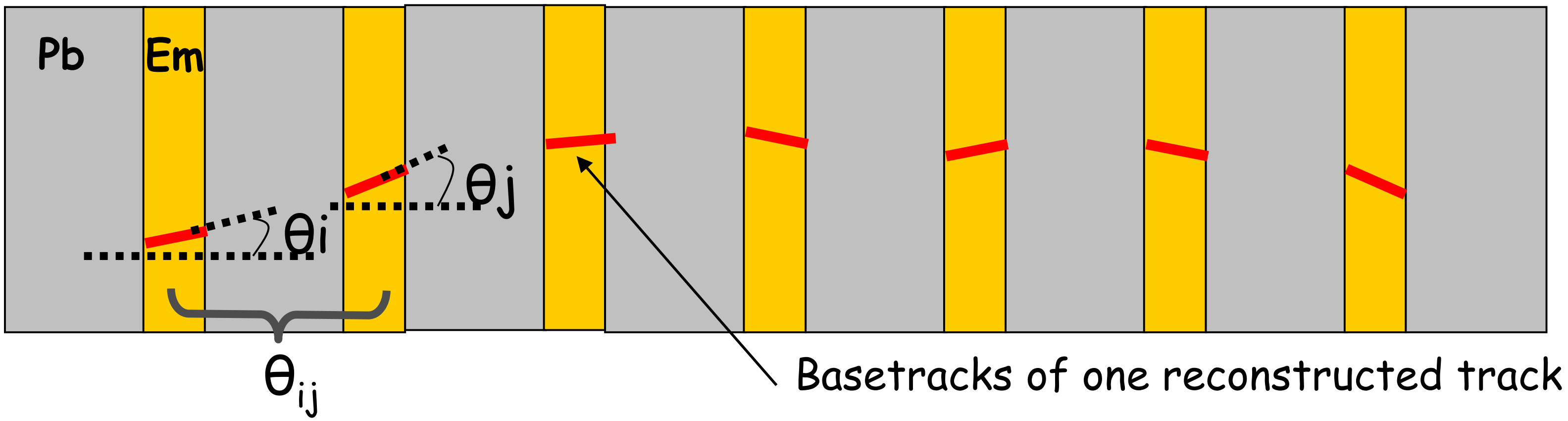
(25% at 5 GeV- 35% at 2 GeV)



Energy resolution

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

Measurement of charged hadron momentum from multiple scattering in lead



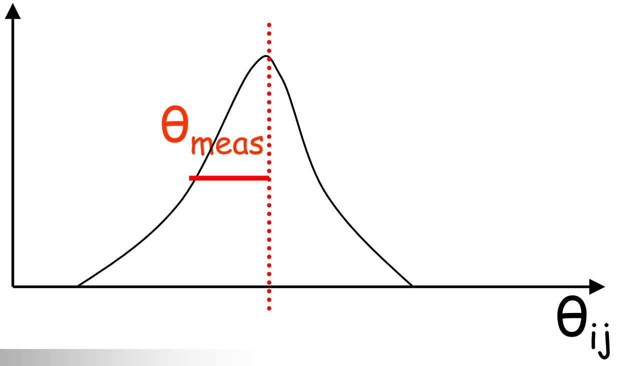
Basetracks of one reconstructed track

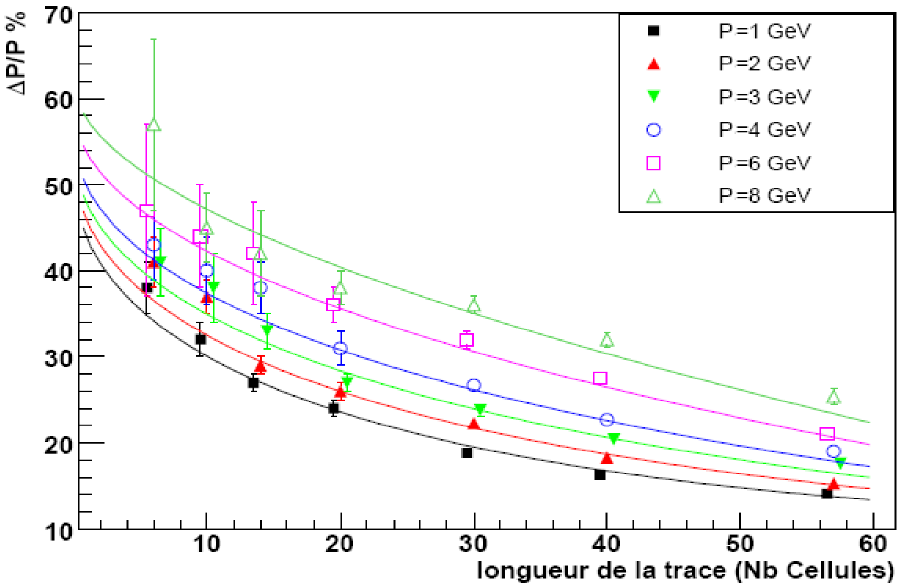
Principle : use angular differences θ_{ij} of particle tracks mesured in emulsions, due to multiple coulomb scattering in lead :

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

RMS θ_{ij}

Resolution on basetracks, should be known or measured



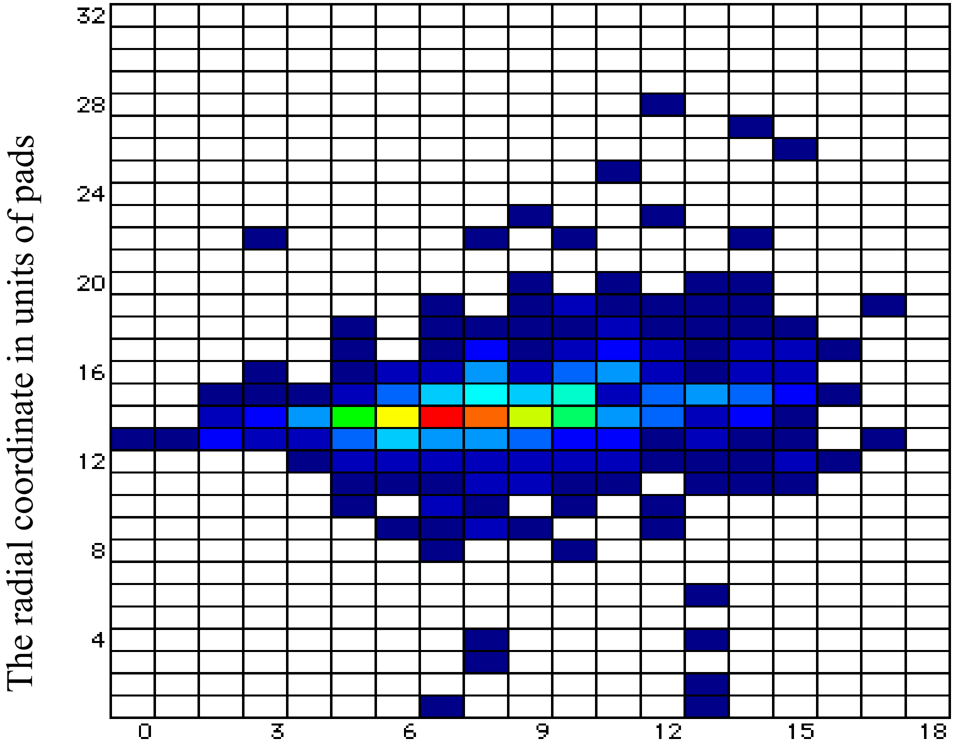


→ Momentum resolution is ~ 20%-30% at 2 GeV

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

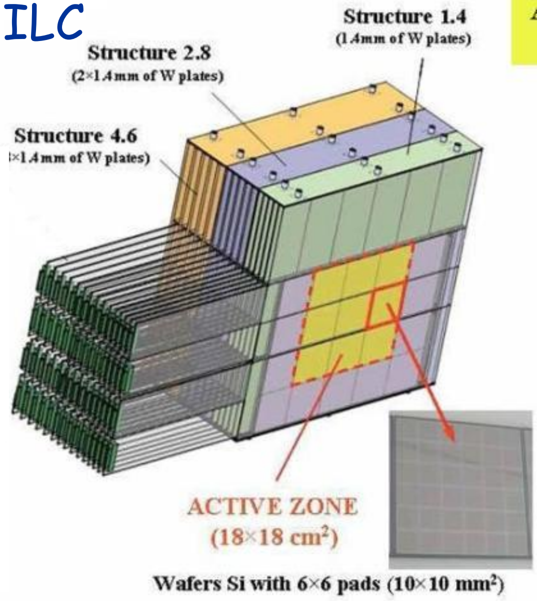
Active element : silicon

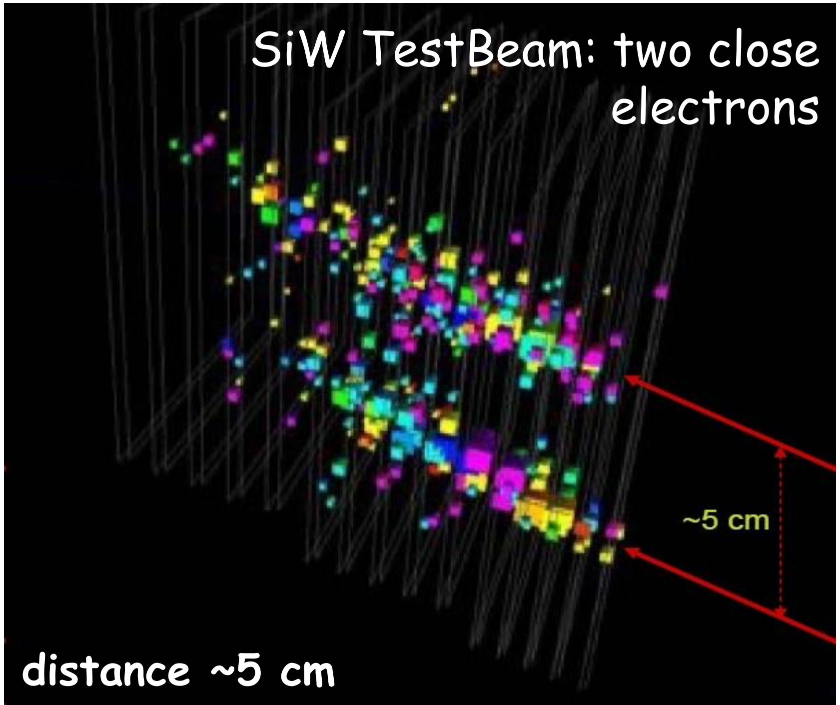
High sampling : 30 layers

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

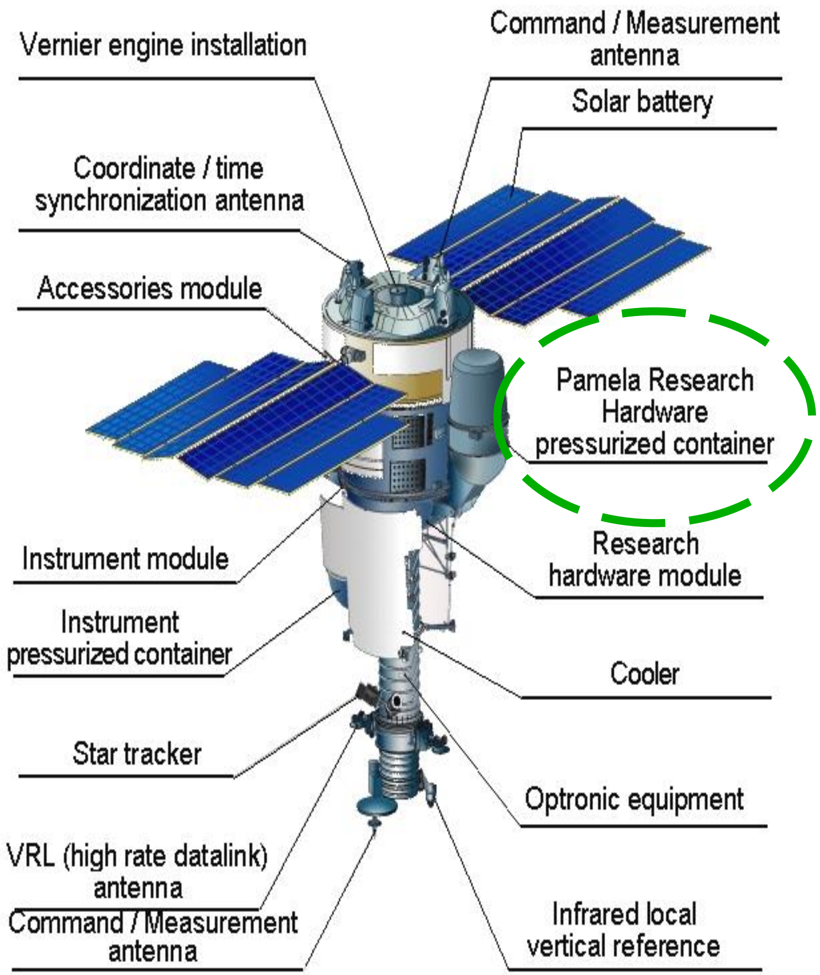
- Study antiparticles in cosmic rays
- Search for antimatter
- Search for dark matter
- Study cosmic-ray propagation
- Study solar physics and solar modulation
- Study the electron spectrum (local sources?)

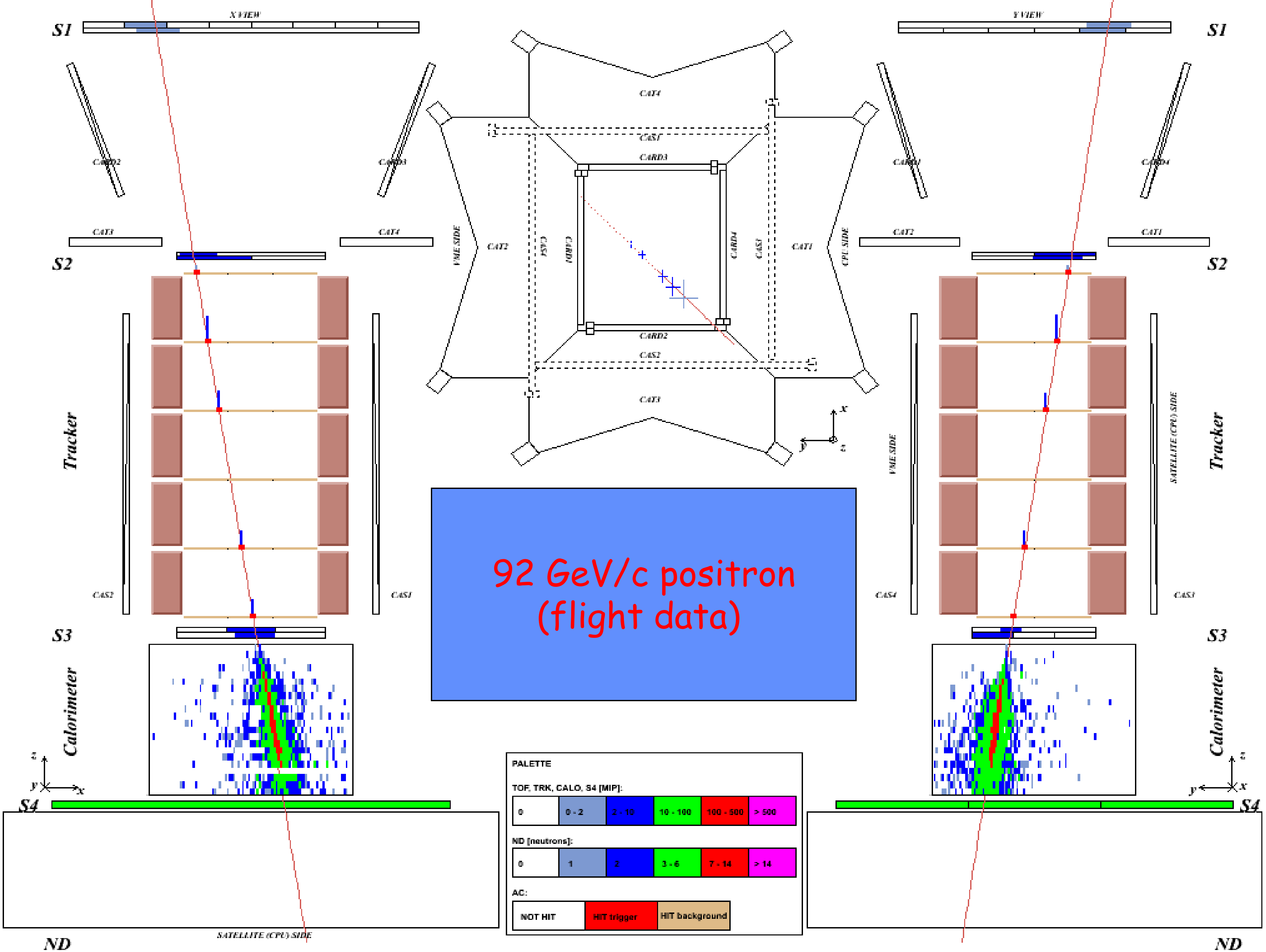
Si-W Imaging Calorimeter

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

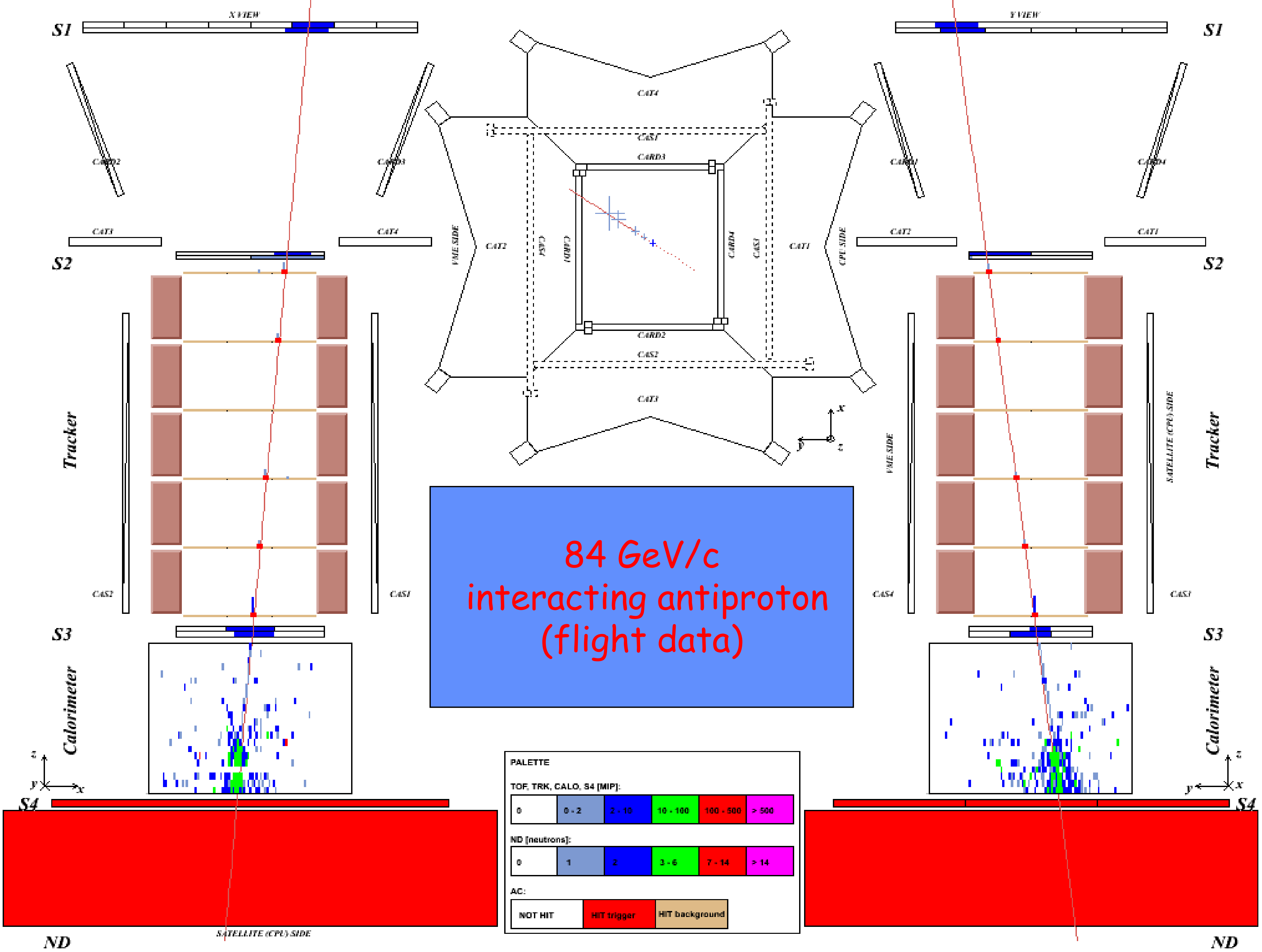
- 22 W plates (2.6 mm / 0.74 X_0)
- 44 Si layers (X-Y), 380 μm thick
- Total depth: 16.3 X_0 / 0.6 λ_I

- 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)



84 GeV/c
interacting antiproton
(flight data)

PALETTE

TOF, TRK, CALO, S4 [MIP]:

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

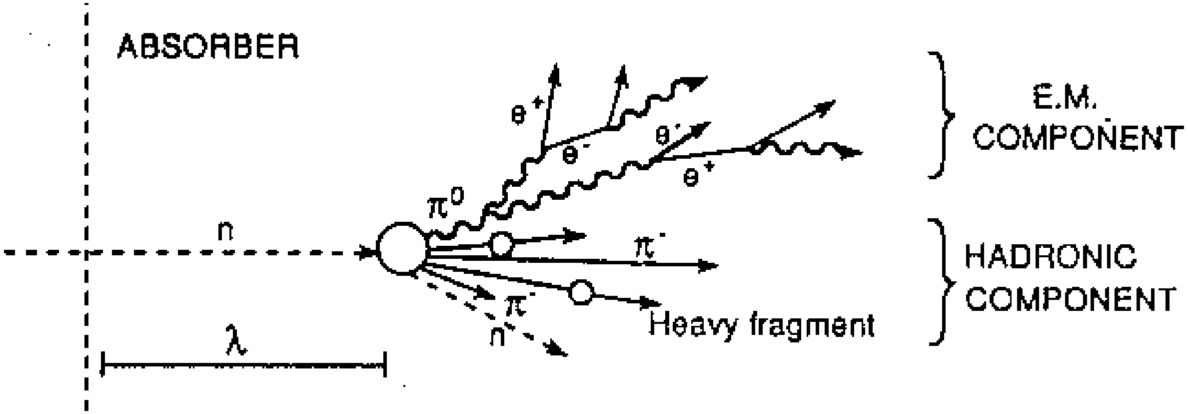
ND [neutrons]:

0	1	2	3 - 6	7 - 14	> 14

AC:

NOT HIT	HIT trigger	HIT background

Hadronic showers



Very large fluctuation from an event to another
→ resolution worse than for EM showers

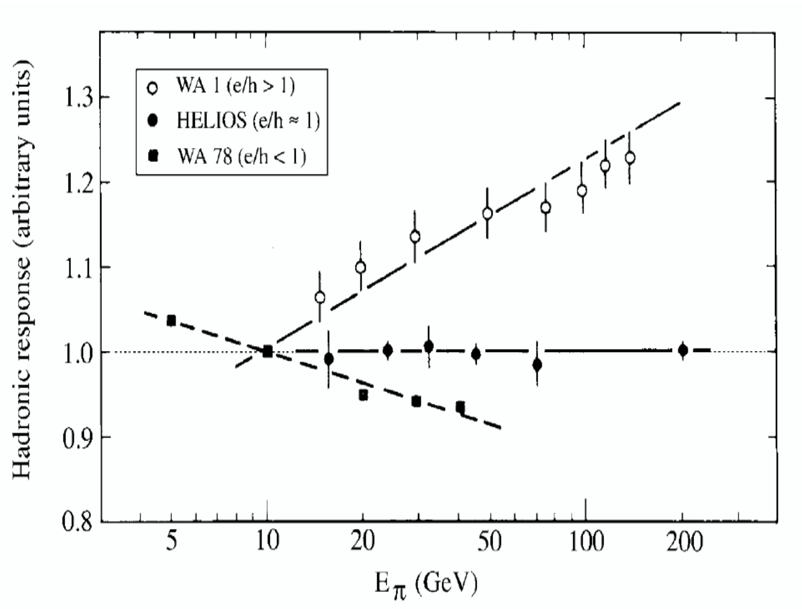
$$E_{vis} = e\ E_{em} + \pi\ E_{ch} + n\ E_n + N\ E_{nucl}$$

Each component has its own sampling fraction
Stochastic term contains sampling term of calorimeter (as in EM) + intrinsic shower fluctuation generally much larger

Absorber in hadronic sampling calorimeter usually not Pb but Fe (Cu)
Active layer : Sc (high sensitivity to neutrons), LAr

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

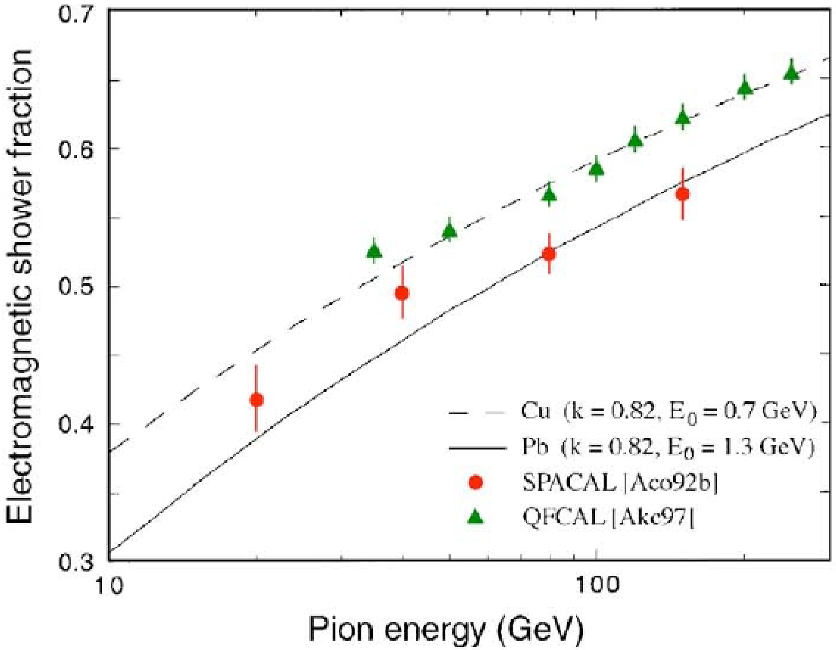
Response to EM different to hadron
→Non linearity



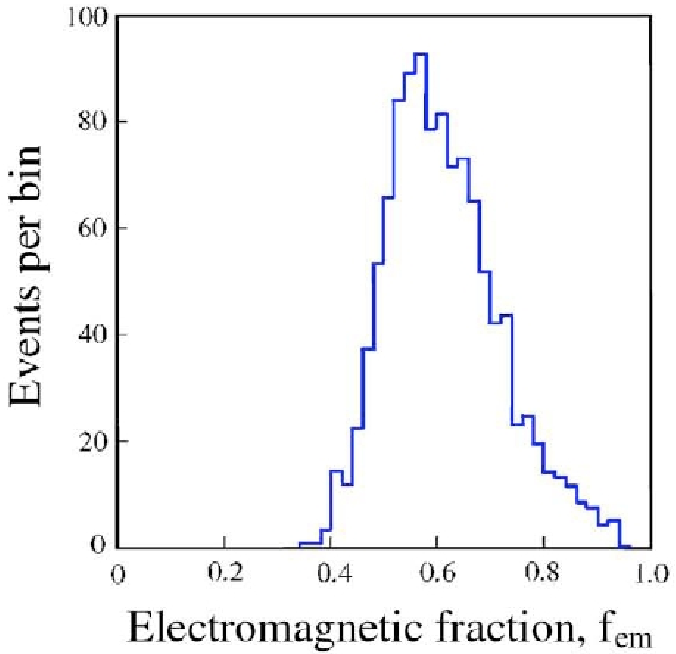
Compensation by HW or SW

Essential for hadronic energy measurement :

- Limit fluctuations :
  - EM shower fraction f_{em}
    - e/h ≠ 1 ;
    - Event-to-event fluctuations large and non-Gaussian ;
    - $\langle f_{em} \rangle$ depends on shower energy and age ;
  - Visible energy (nuclear binding energy losses) ;
- Establish correct energy scale .

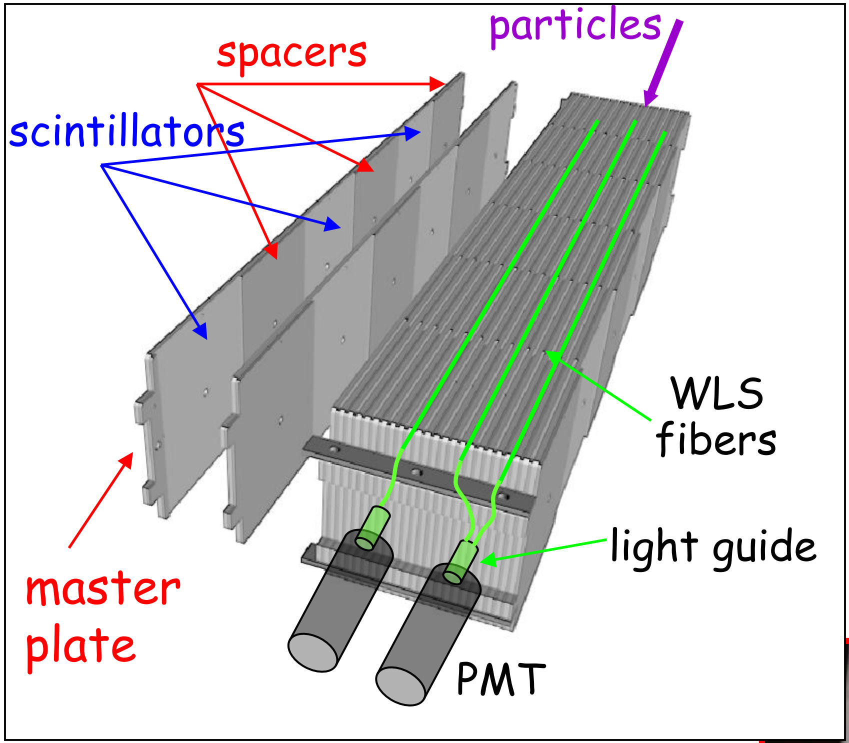


f_{em} large and energy dependent

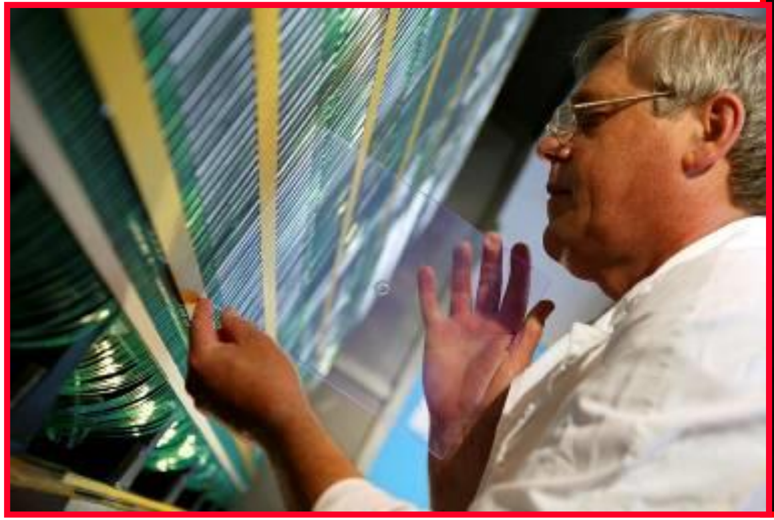


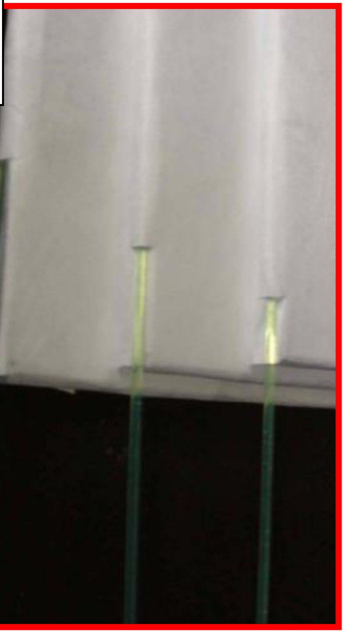
f_{em} fluctuations large and non-Poissonian

Tile Calorimeter (ATLAS, LHCb)



Fiber-tile contact length adjusted to compensate light attenuation difference

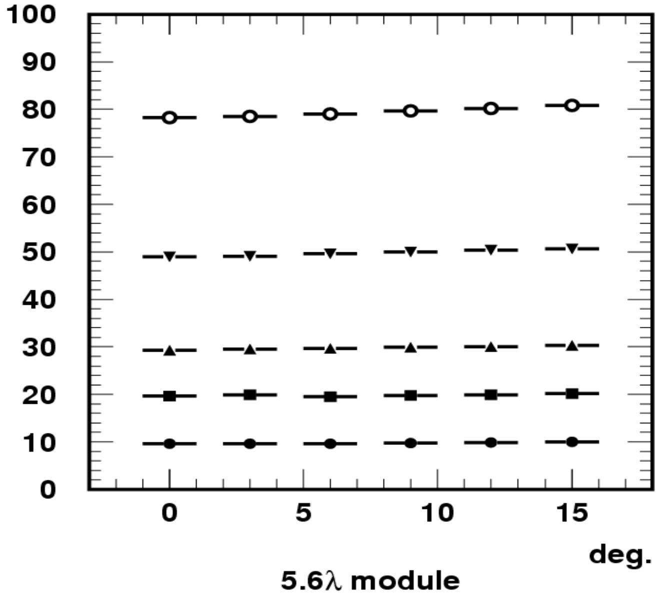




Energy resolution

$$\frac{\sigma}{E} = \frac{(69\pm5)\%}{\sqrt{E}} \oplus (9\pm2)\%$$

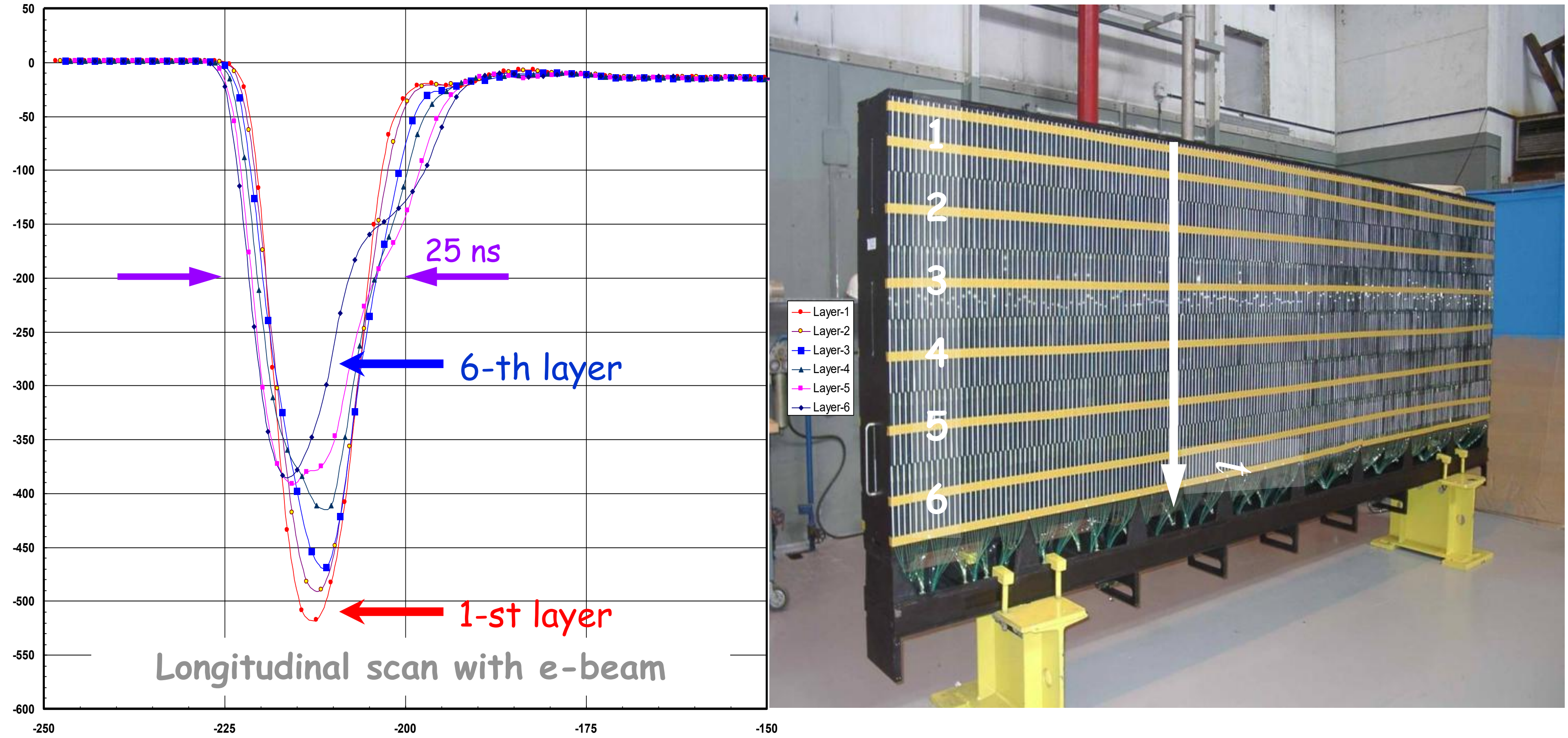
Angular dependence



~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^0 s)
- ☐ Non-EM component (mainly soft π)

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

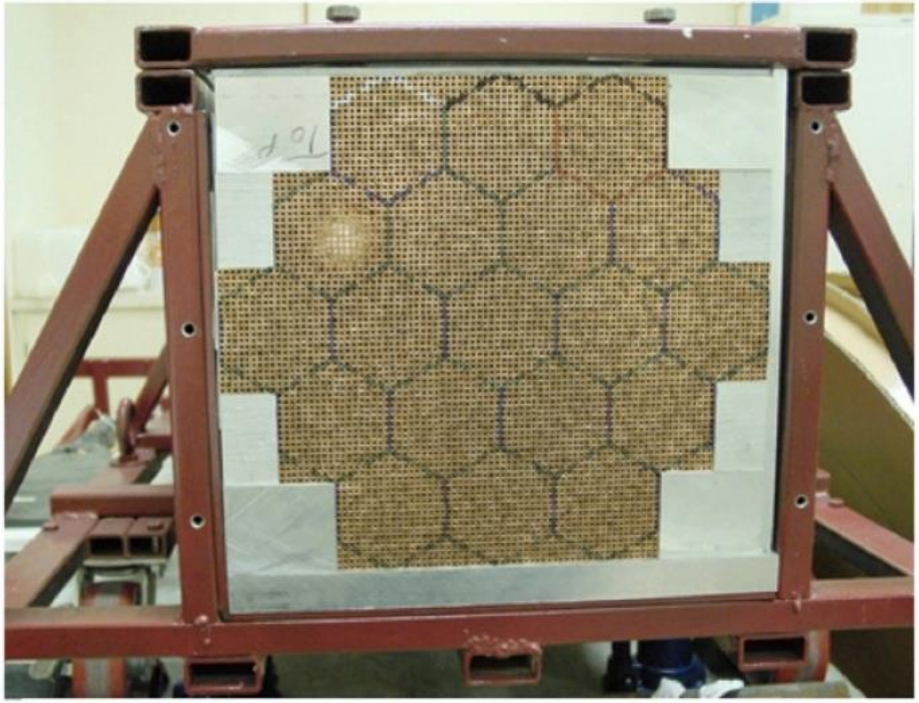
**Cherenkov light almost exclusively produced by EM component*

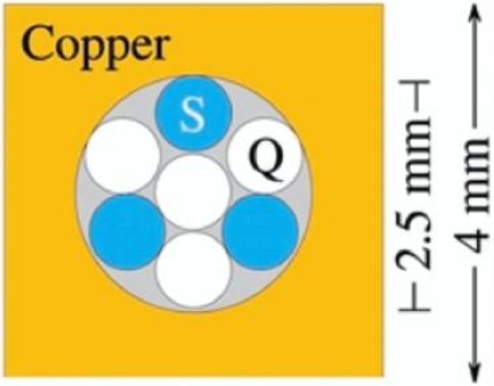
Recipe : determine f_{em} event by event by comparing Č and dE/dx signals ; correct the response

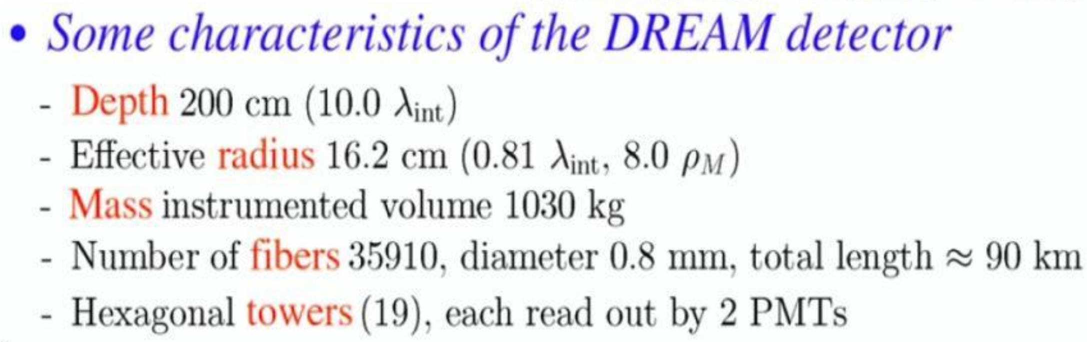
e/h ratio is very different for Quartz and Scintillator measurements of energy

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

DREAM (Dual READout Module)

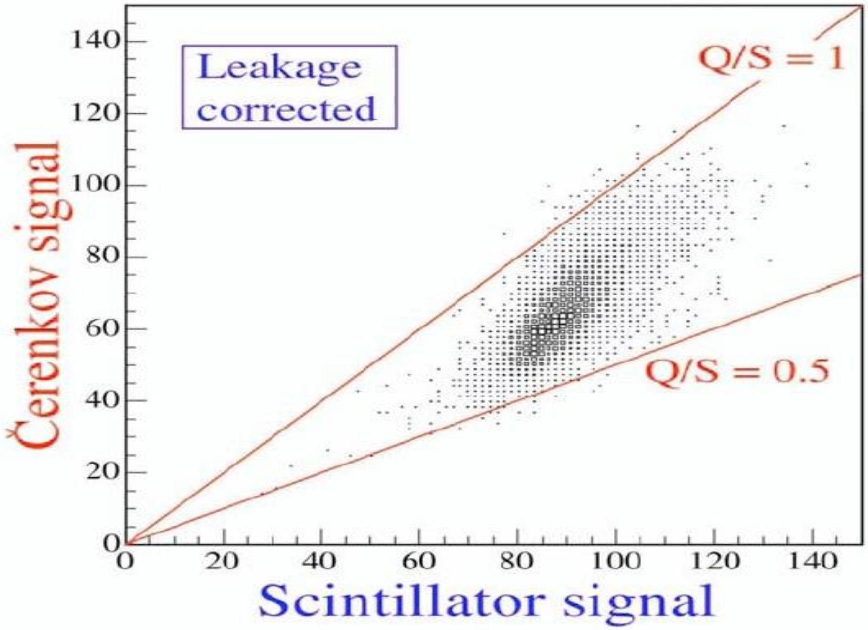


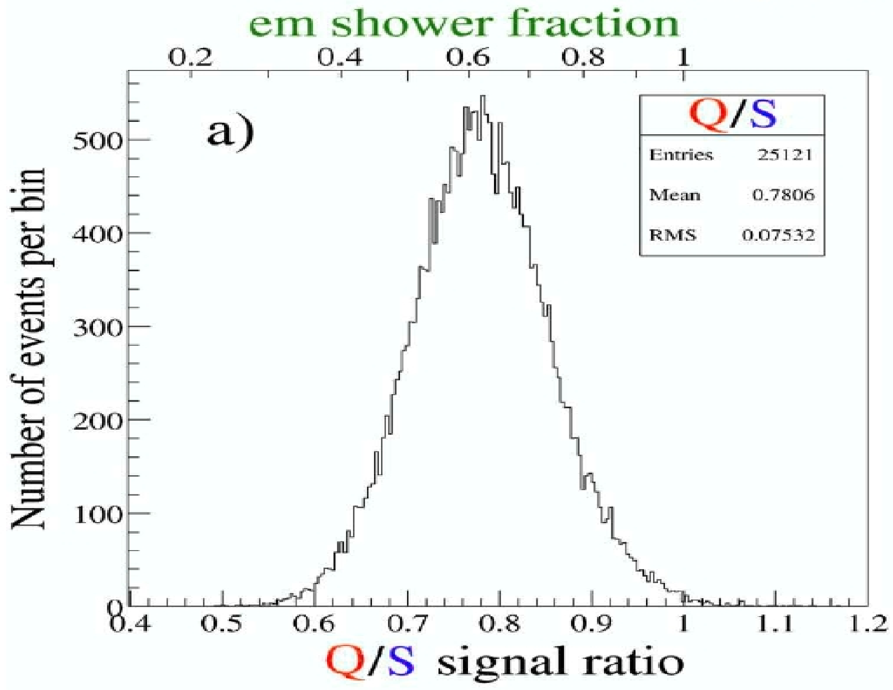




- *Some characteristics of the DREAM detector*
  - Depth 200 cm (10.0 λ_{int})
  - Effective radius 16.2 cm (0.81 λ_{int}, 8.0 ρ_M)
  - Mass instrumented volume 1030 kg
  - Number of fibers 35910, diameter 0.8 mm, total length ≈ 90 km
  - Hexagonal towers (19), each read out by 2 PMTs

DREAM Readout





Extraction of f_{em} and E : example

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

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

Cu/Sc **Cu/Q**

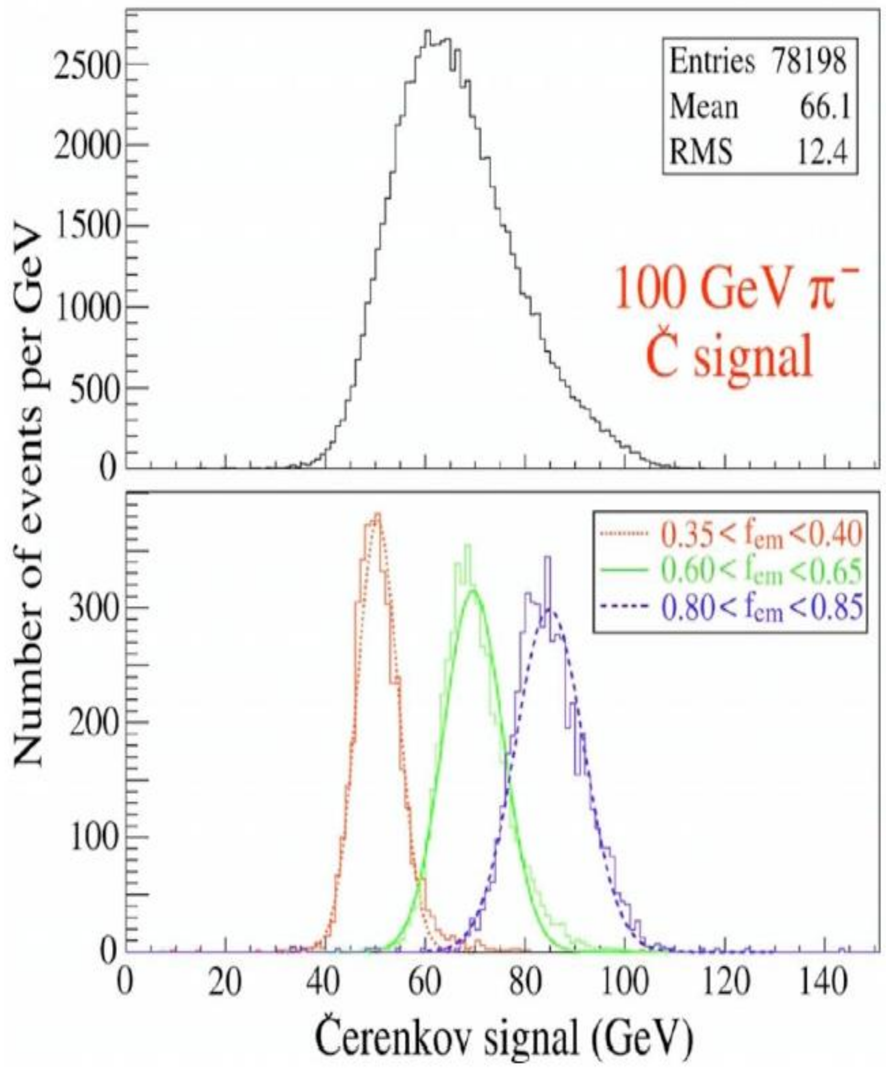
$$e.g.\ \text{If} \quad e/h = 1.3\ (S),\ 4.7\ (Q)$$

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

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

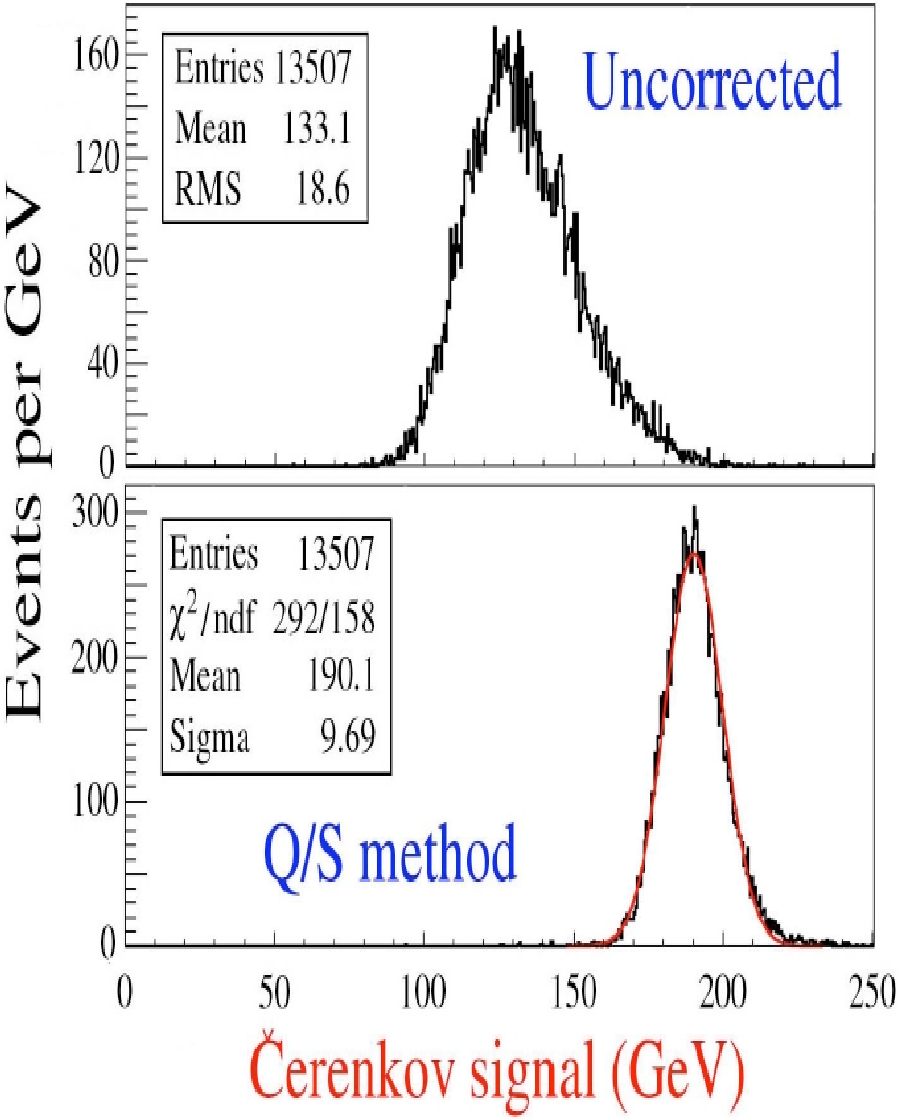
$$\text{with} \quad \chi = \frac{1 - (h/e)_S}{1 - (h/e)_Q} \sim 0.3$$

Event selection based on f_{em}



NIM A537 (2005) 537

Corrections of 200 GeV "jets"



Meta-materials

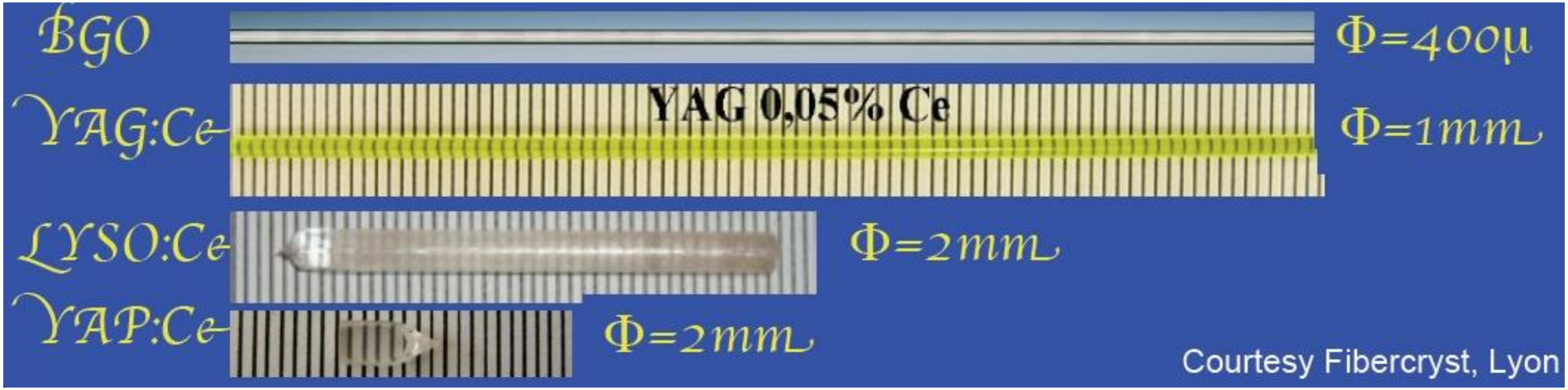
P.Lecoq

- ☐ 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

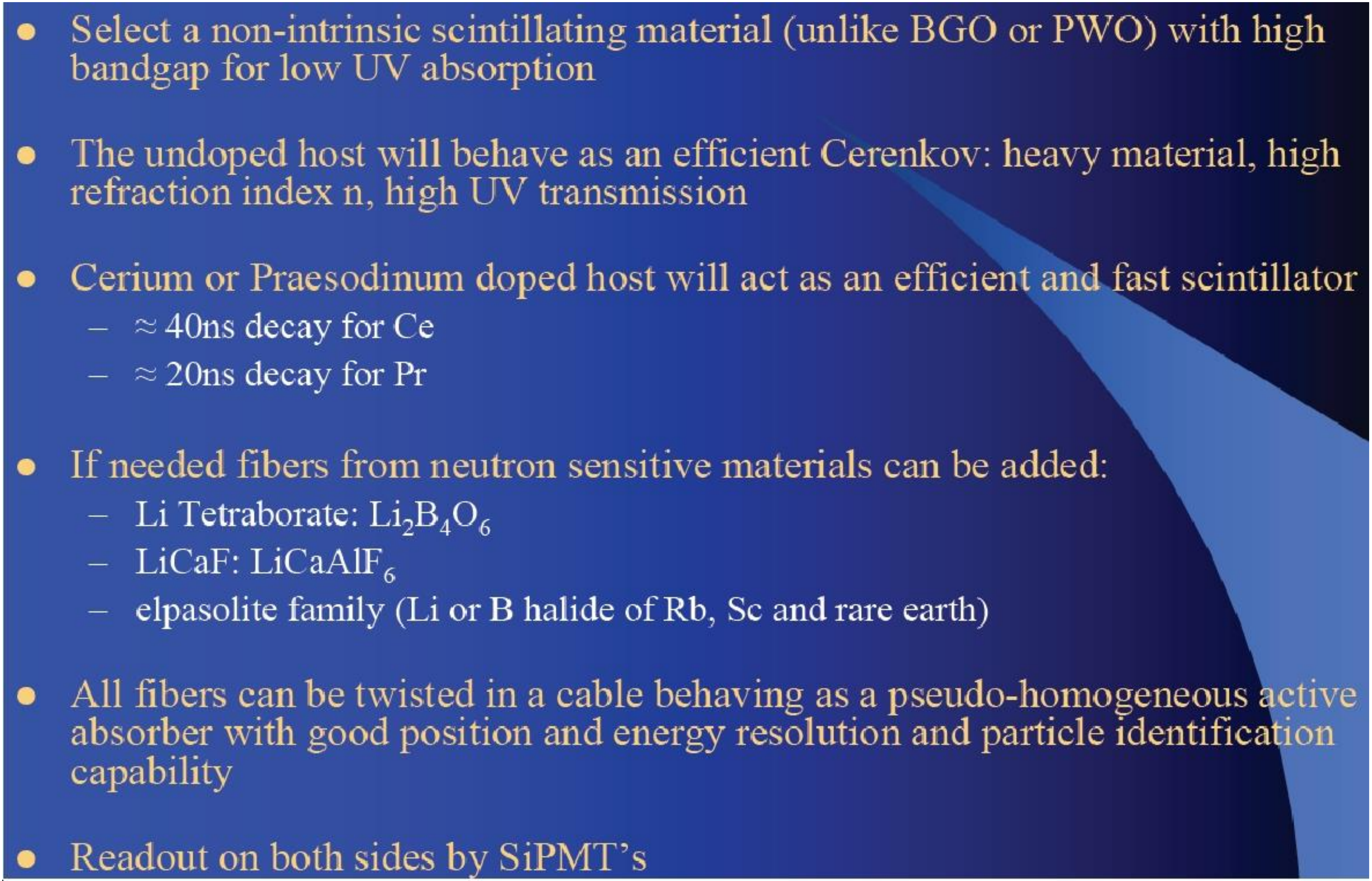
- ☐ Basic idea : produce "light guides" out of conventional scintillating materials



Courtesy Fibercryst, Lyon

Concept of meta-cable - 1

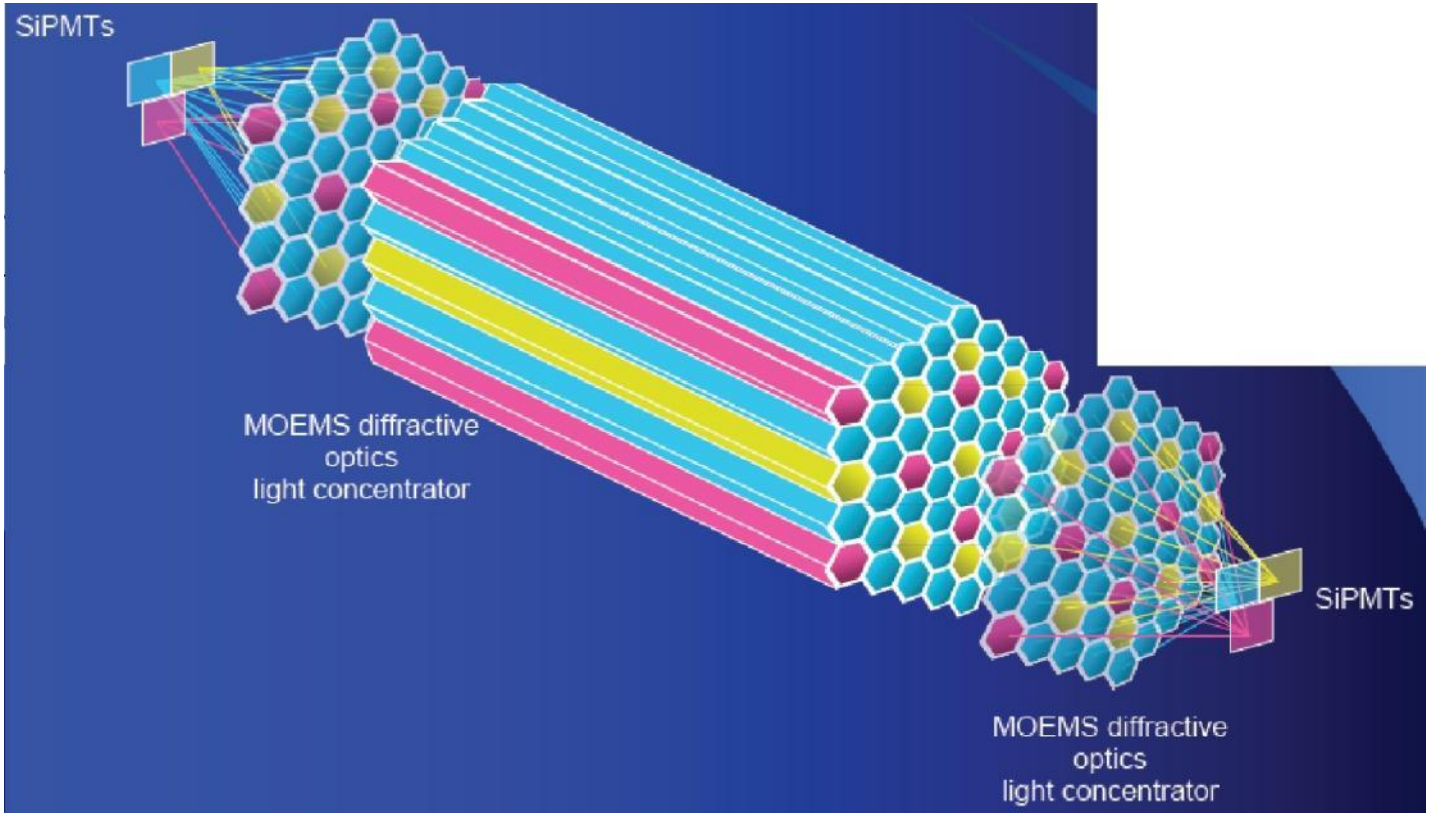
P.Lecoq



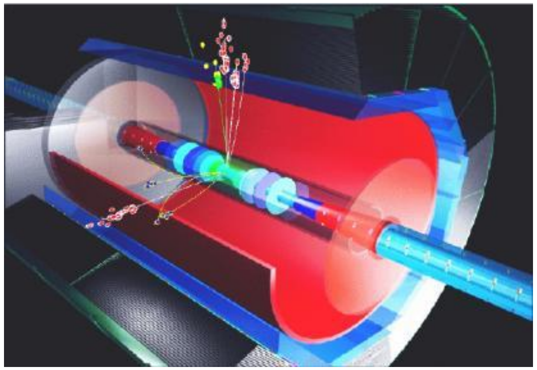
- Select a non-intrinsic scintillating material (unlike BGO or PWO) with high bandgap for low UV absorption
- The undoped host will behave as an efficient Cerenkov: heavy material, high refraction index n, high UV transmission
- Cerium or Praesodinum doped host will act as an efficient and fast scintillator
  - ≈ 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 ILC/CLIC/SLHC/…: jets



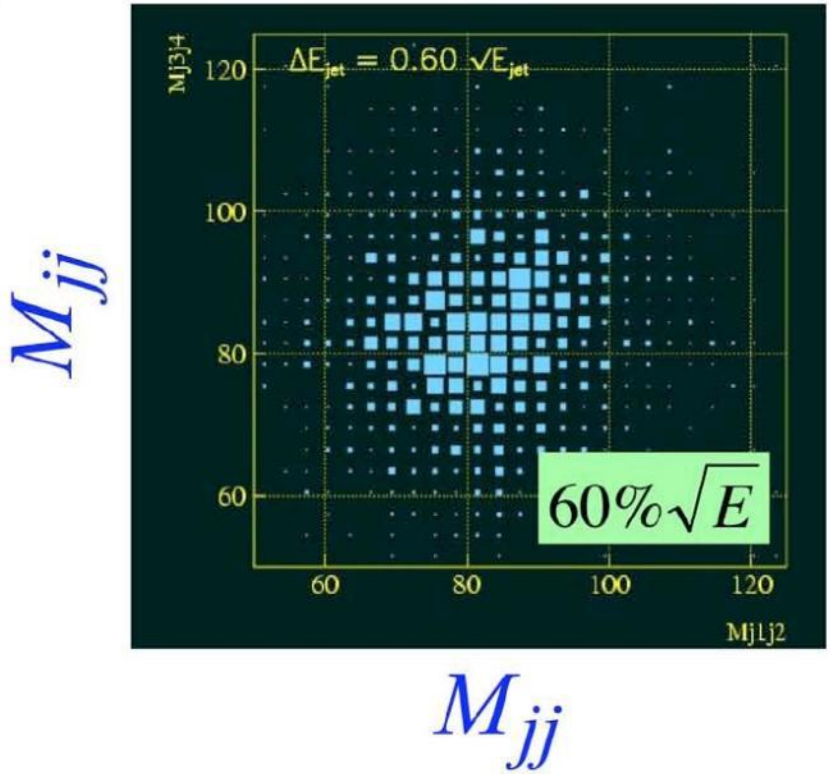
Goal : separate jets from WW and ZZ events

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

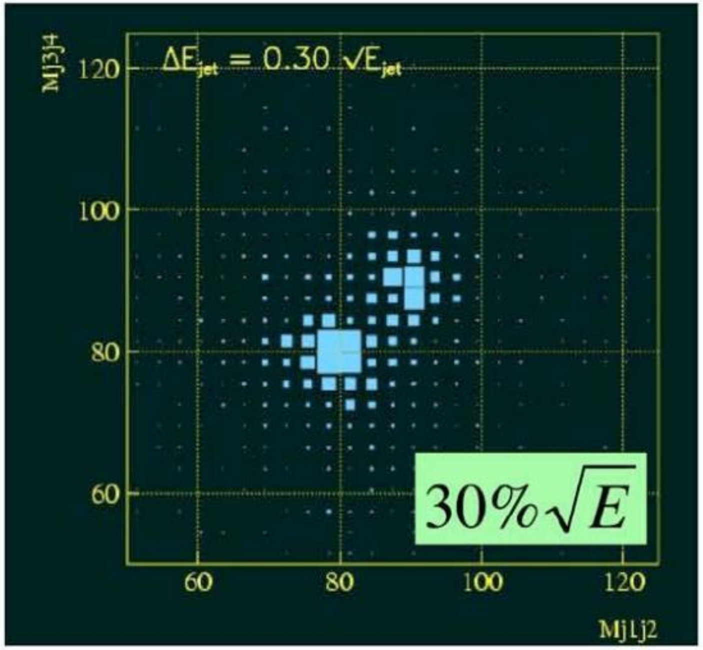
H → γγ completed at LHC ; add H → jet jet

- ➔ Hadronic energy resolution
- ➔ Granularity to resolve dijets

LEP-like



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

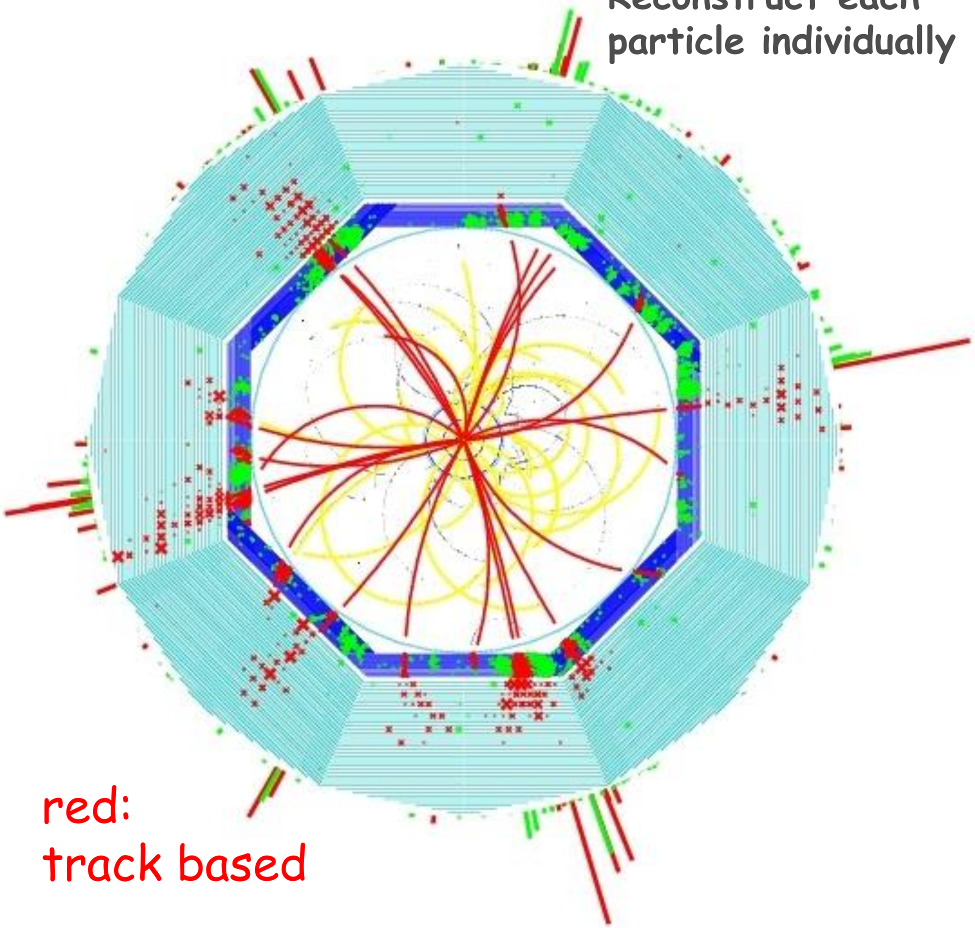


Particle Flow Analysis (Energy Flow Method)

- ☐ *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

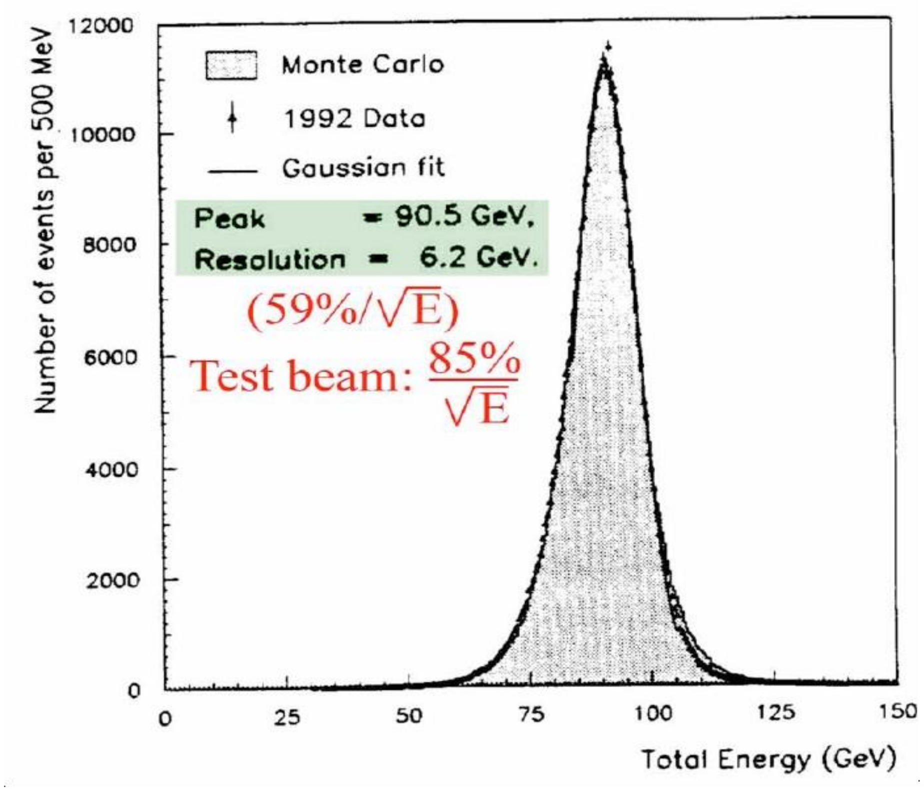
green:
calorimeter based

ZHH → qqbbbb

Particle Flow Analysis (Energy Flow Method)

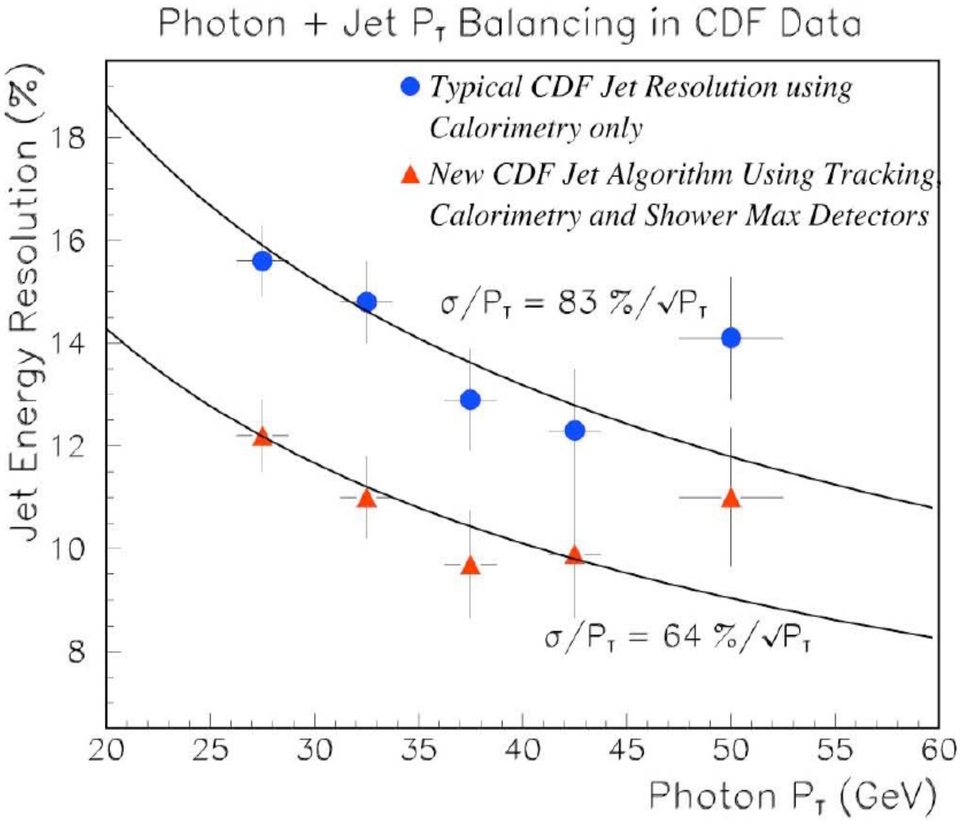
PFA at LEP : ALEPH NIM A360 (1995) 481

Reconstruct hadronic event structure using particle ID and software compensation



PFA at Tevatron : CDF Note CDF5005 (2000)

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: search for "accompanied electrons"

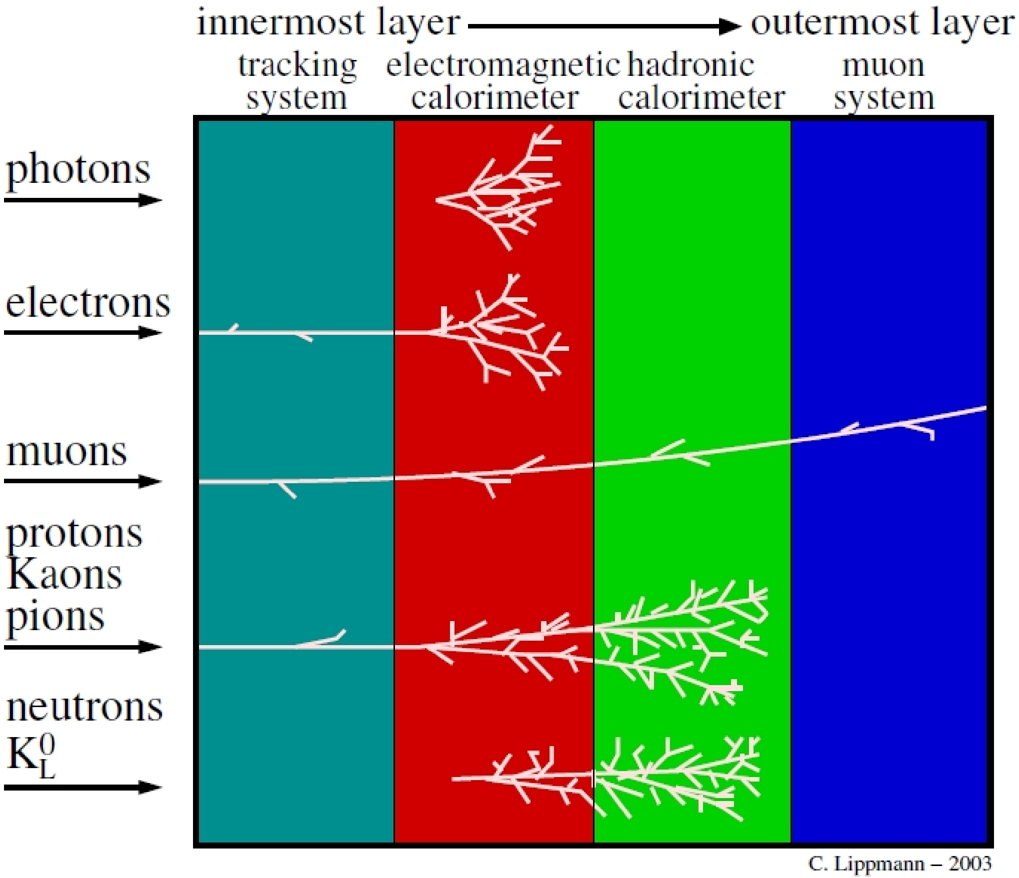
How to distinguish

a single electron

and

a combination of electron and photon

entering electromagnetic calorimeter close to each other ?



C. Lippmann – 2003