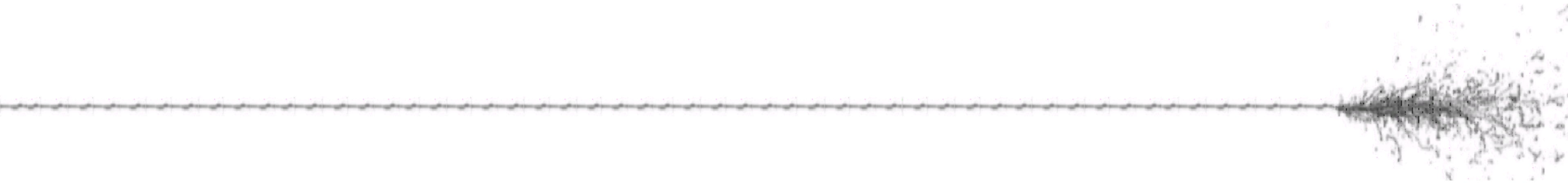
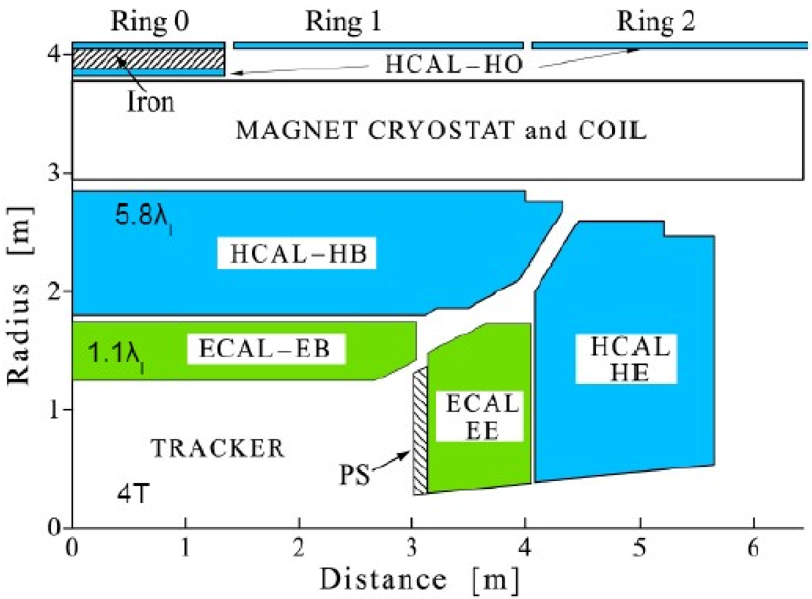


Calorimetry
- emerging technologies -

Erika Garutti
DESY

Jet energy resolution at LHC

CMS

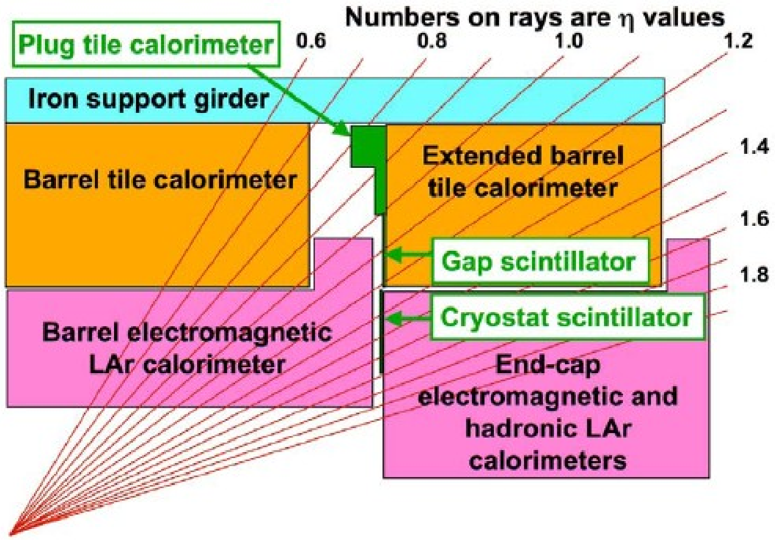


5 cm brass / 3.7 cm scint.
Embedded fibres, HPD readout

Expected jet resolution:

$$\frac{\sigma}{E} = \frac{125\%}{\sqrt{E}} \oplus \frac{5.6\ \text{GeV}}{E} \oplus 3.3\%$$

ATLAS



14 mm iron / 3 mm scint.
sci. fibres, read out by phototubes

Jet resolution with weighting:

$$\frac{\sigma}{E} = \frac{60\%}{\sqrt{E}} \oplus 3\%$$

Stochastic term for hadrons was ~93% and 42% respectively

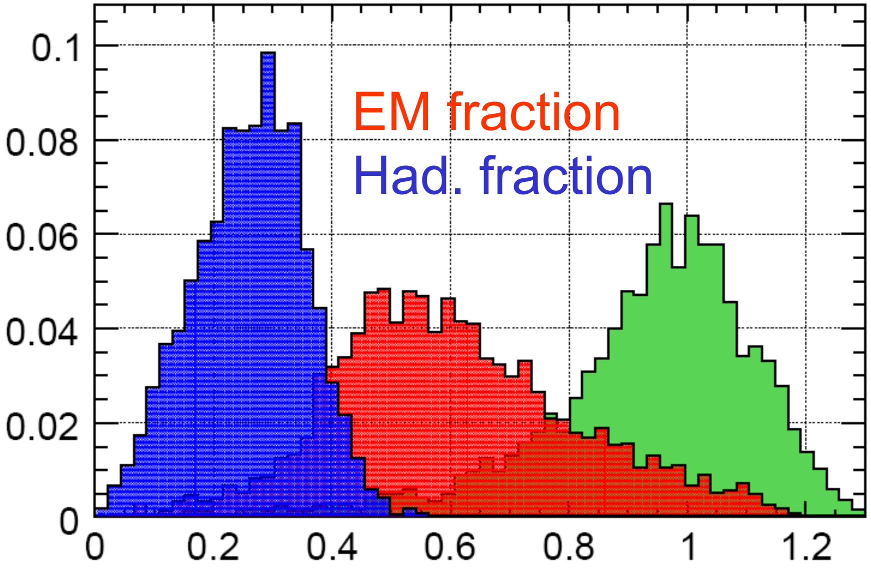
Dual readout calorimetry

Alternative approach to the problem of improving hadronic / jet energy resolution:

- measure the shower components in each event

➔ access the source of fluctuations:

- measuring f_{em} in each event removes the EM fluctuations
- ideally one wants to measure also f_n which is proportional to the binding energy to remove fluctuations in the invisible energy



Norm. 10 GeV pion

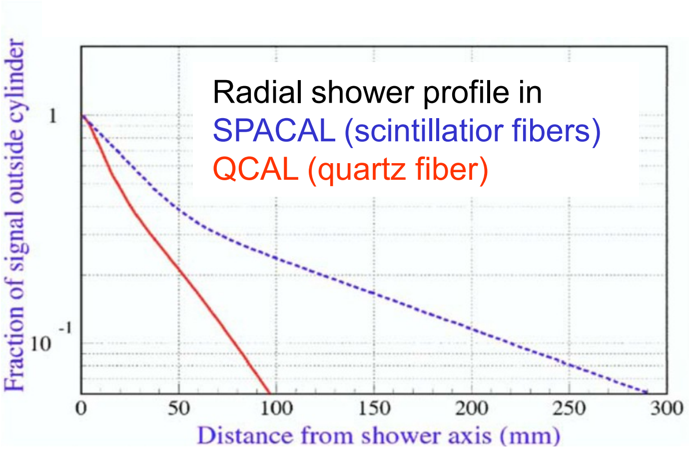
-Example: The DREAM calorimeter as a test of this approach

The Dual REAdout Method principle

Use Cerenkov light !!!

Quartz fibers (cherenkov emitter) are only sensitive to em shower component !

- ~80% of non-em energy deposited by non-relativistic particles
  $\Rightarrow$ e/h=5 (CMS-HF)
  $\Rightarrow$ radial profile of hadronic showers
- Hadronic component mainly spallation protons
  E_k ~ few hundred MeV $\Rightarrow$ non-relativistic
  $\Rightarrow$ no Cherenkov light
- Electron and positrons emit Cherenkov light
  up to a portion of MeV


Radial shower profile in
SPACAL (scintillatior fibers)
QCAL (quartz fiber)

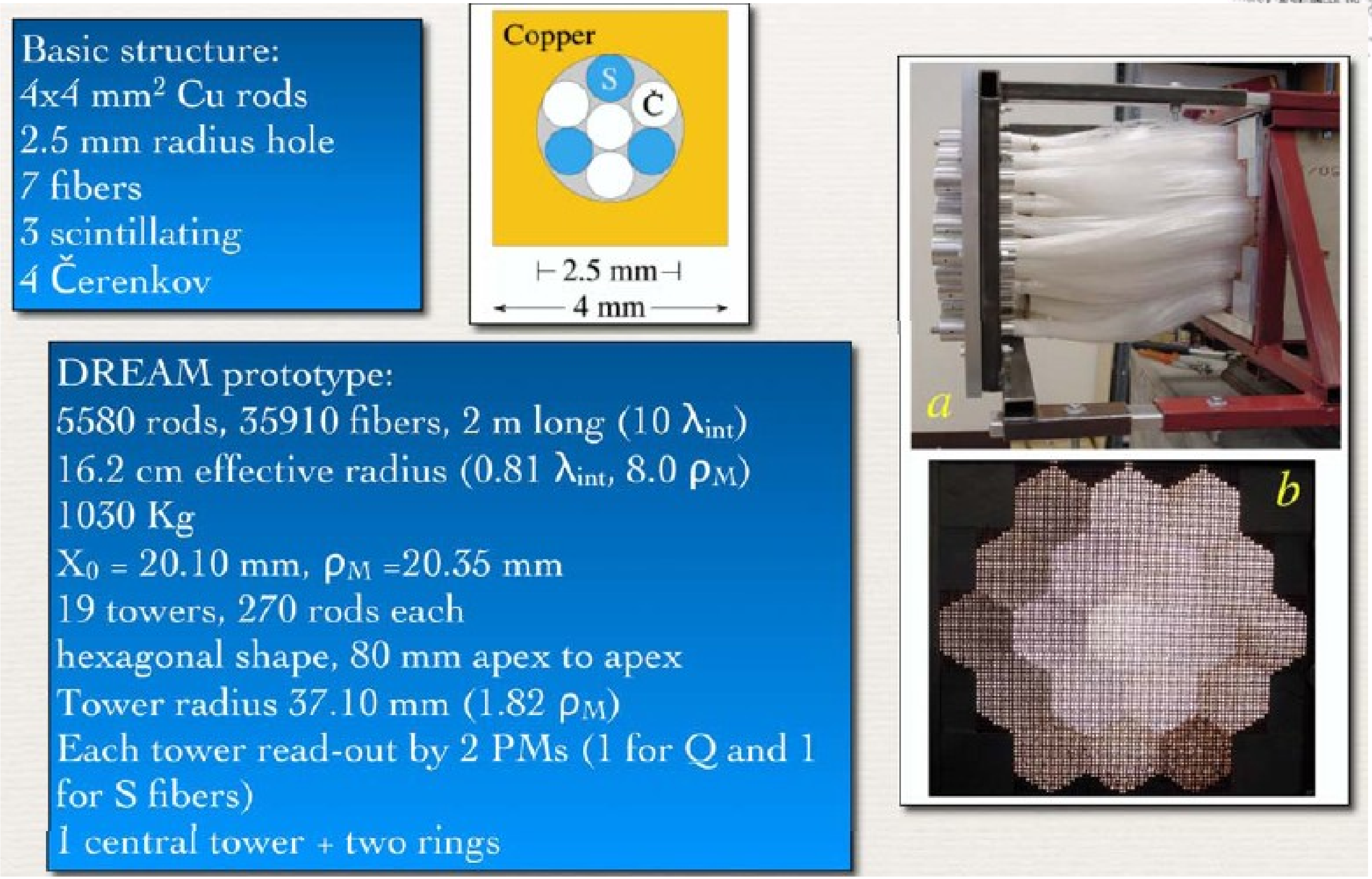
Use dual-readout system:

- Regular readout (scintillator, LAr, ...) measures visible energy
- Quartz fibers measure em shower component E_{em}

➔ Combining both results makes it possible to determine f_{em} and the energy E of the showering hadron

➔ Eliminates dominant source of fluctuations

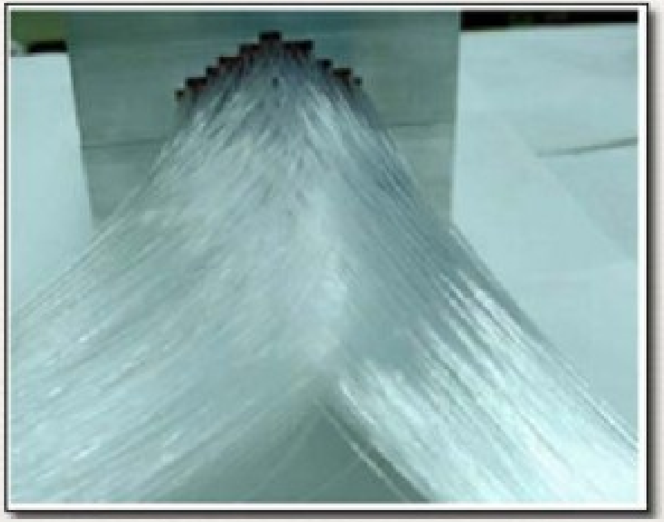
The DREAM prototype



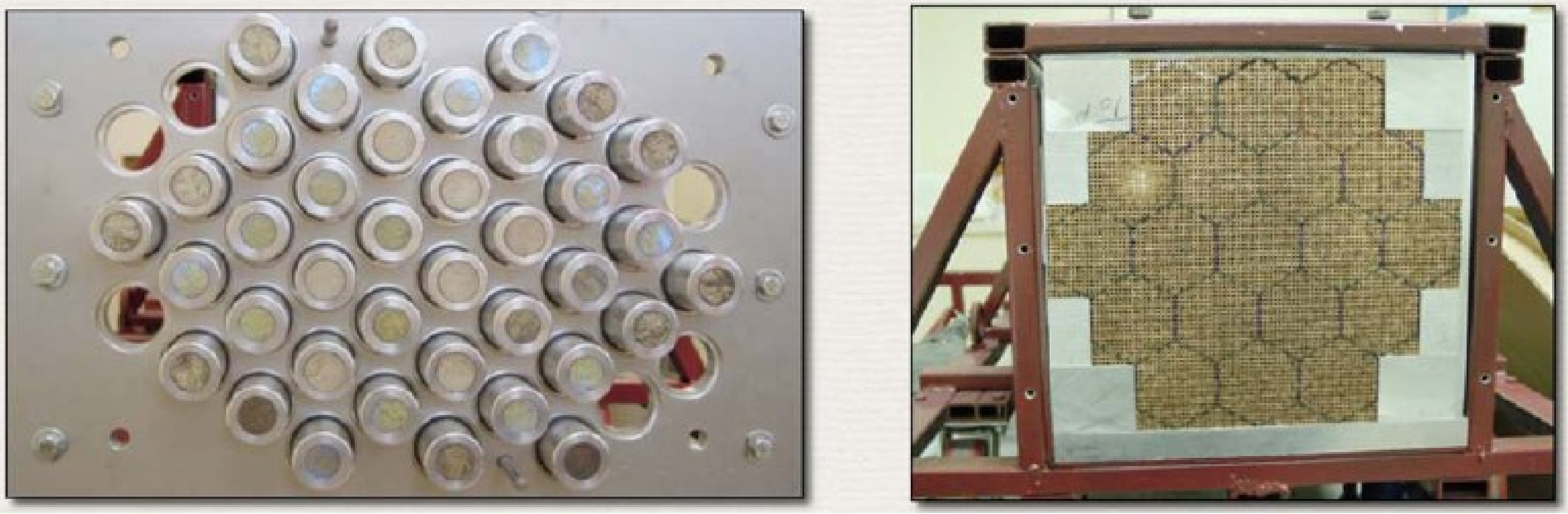
Basic structure:
4x4 mm^2 Cu rods
2.5 mm radius hole
7 fibers
3 scintillating
4 Čerenkov

DREAM prototype:
5580 rods, 35910 fibers, 2 m long (10 λ_{int})
16.2 cm effective radius (0.81 λ_{int}, 8.0 ρ_M)
1030 Kg
X_0 = 20.10 mm, ρ_M =20.35 mm
19 towers, 270 rods each
hexagonal shape, 80 mm apex to apex
Tower radius 37.10 mm (1.82 ρ_M)
Each tower read-out by 2 PMs (1 for Q and 1 for S fibers)
1 central tower + two rings

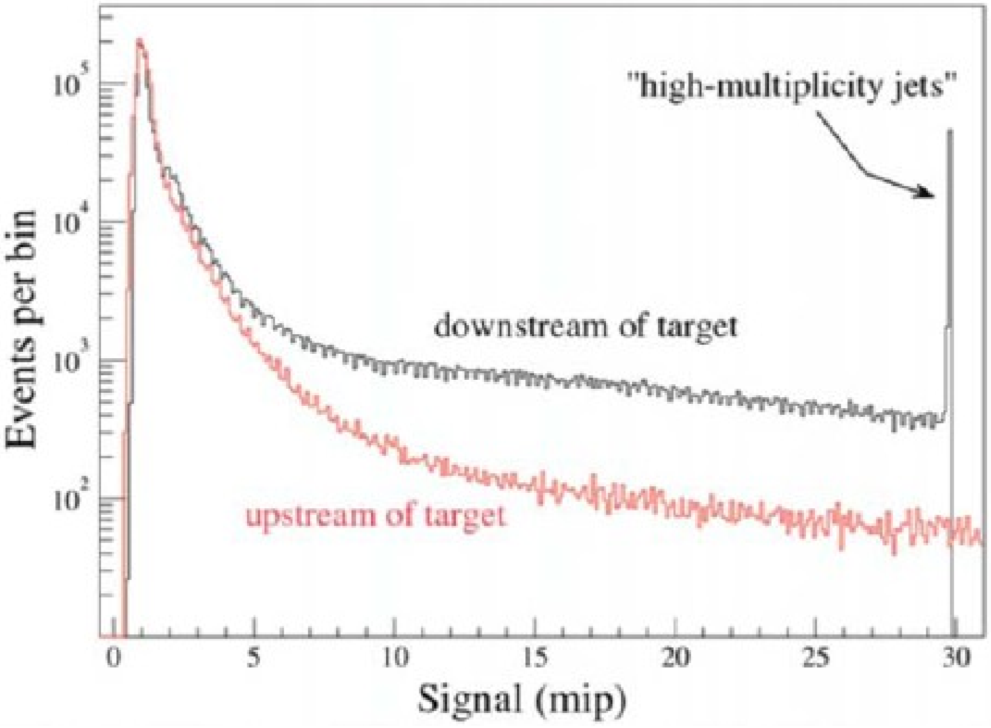
The DREAM prototype



DREAM prototype:
tested at the CERN H4 beam line
Data samples:
π from 20 to 300 GeV
"Jets" from 50 to 330 GeV
"Jets" mimicked by π interaction on 10 cm polyethylene target in front of the detector



Making “jets” at test beams



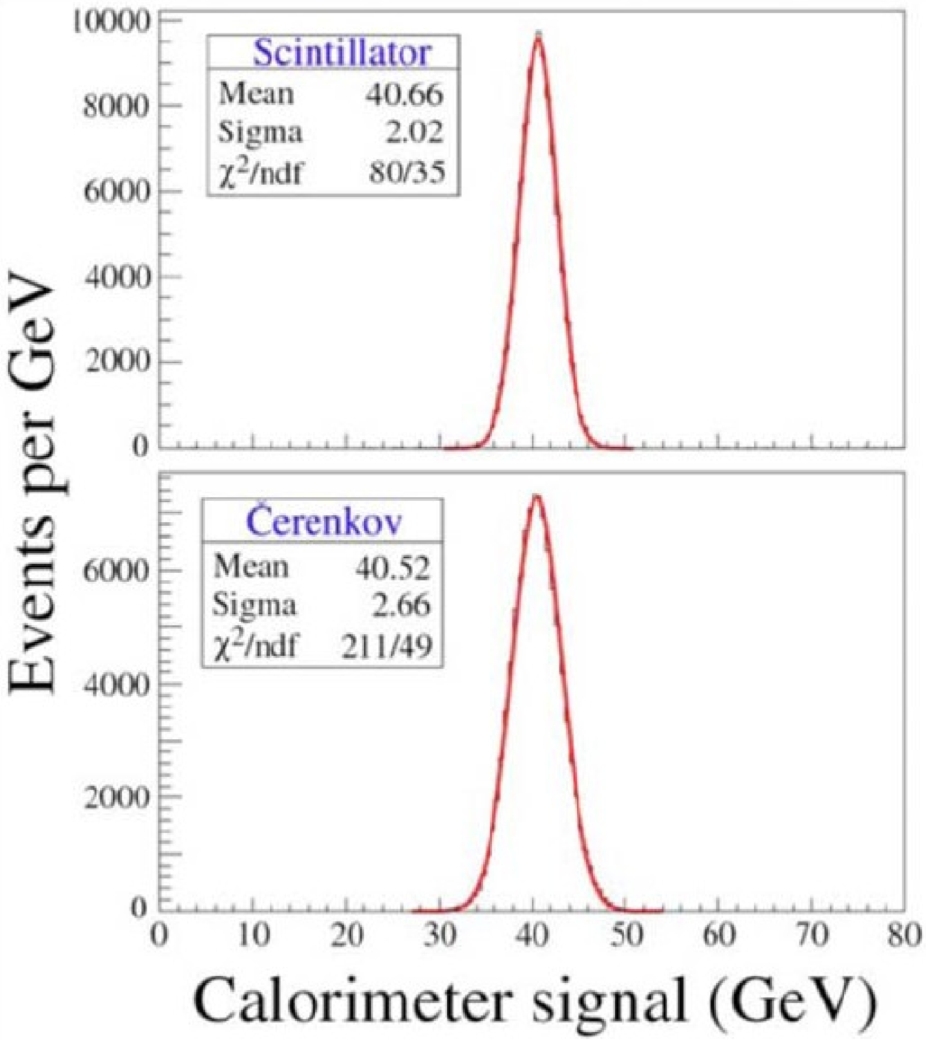
"JET" Measurements

Calibration with 40 GeV electrons

- Tilt 2° respect to the beam direction to avoid channelling effects

- Modest energy resolution for electrons (scintillator signal):

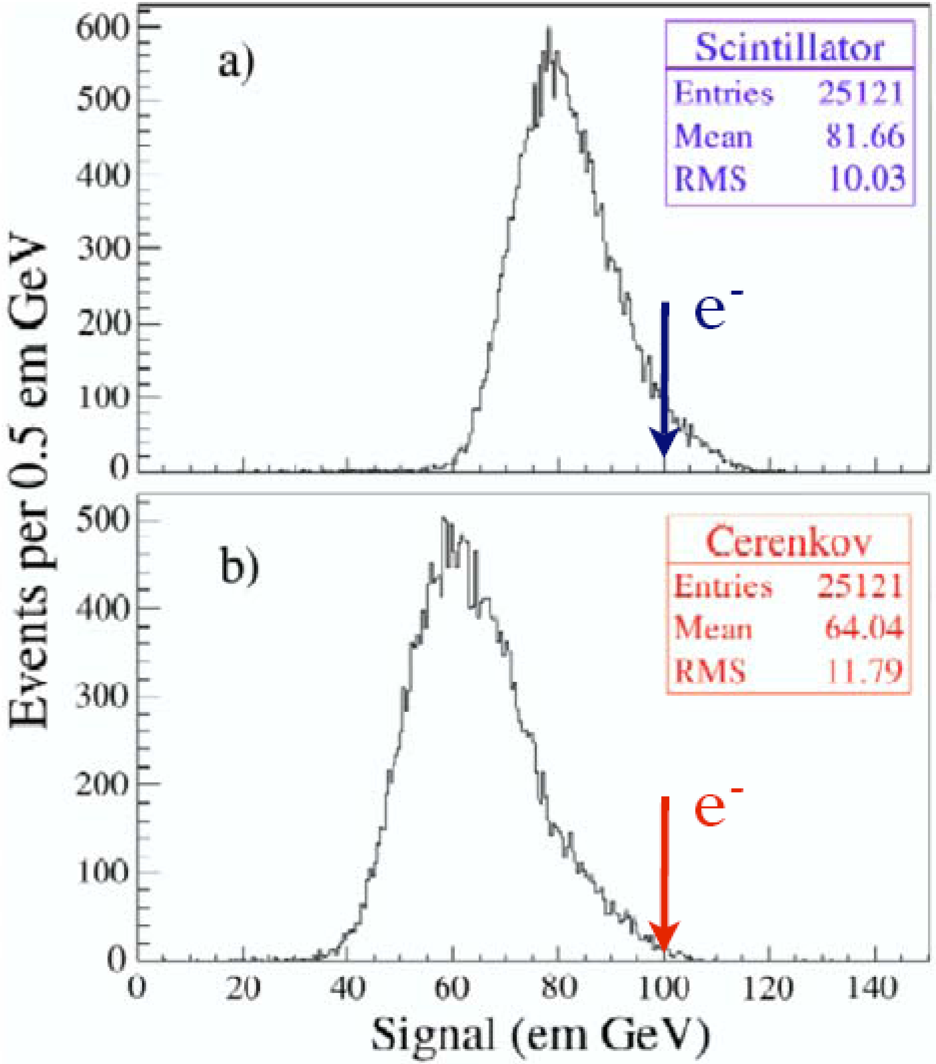
$\sigma/E = 20.5\%/\sqrt{E} + 1.5\%$



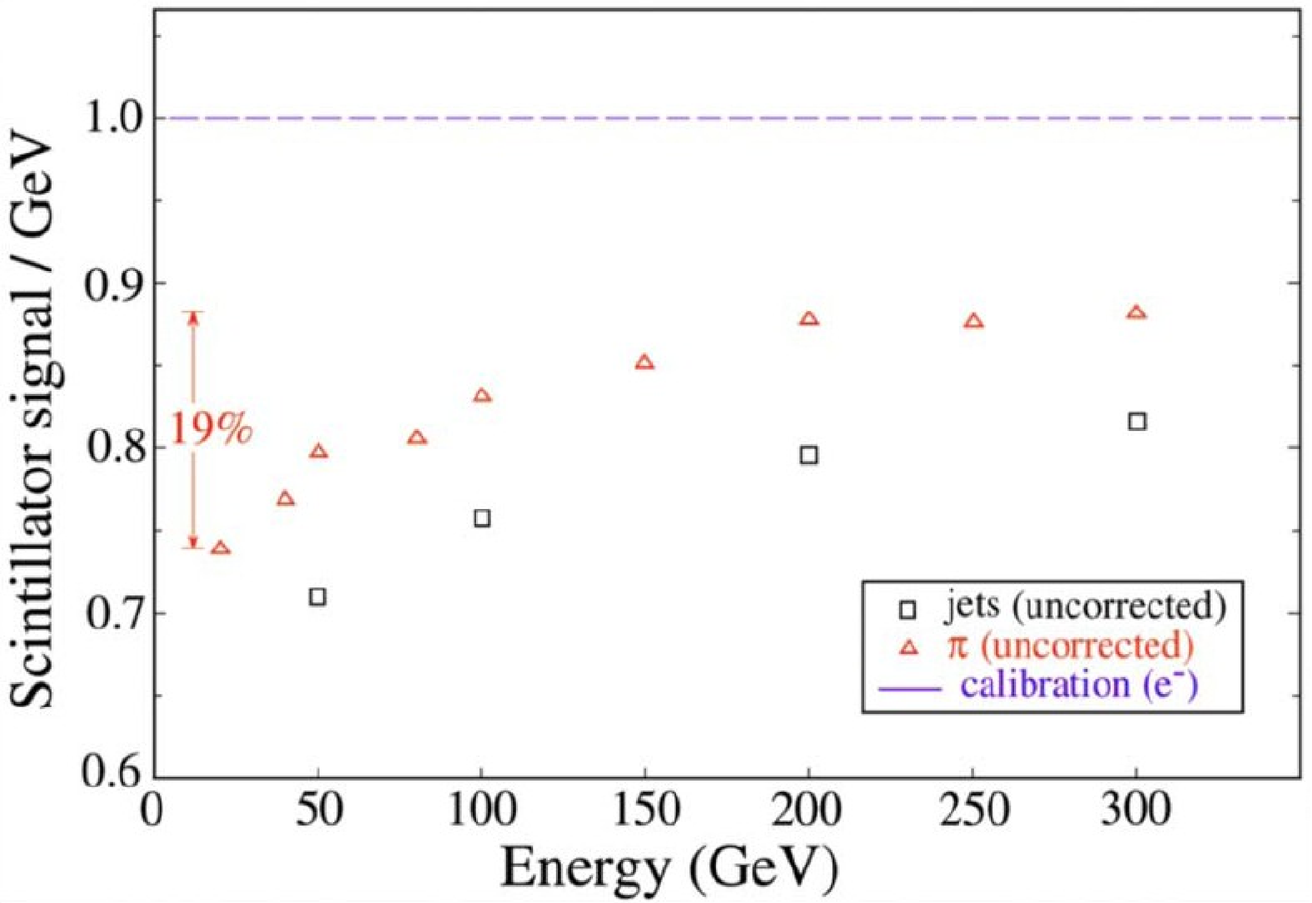
100 GeV single pions (raw signal)

Signal distribution:

- Asymmetric, broad, smaller signal than for e-
- Typical tails feature of a non-compensating calorimeter



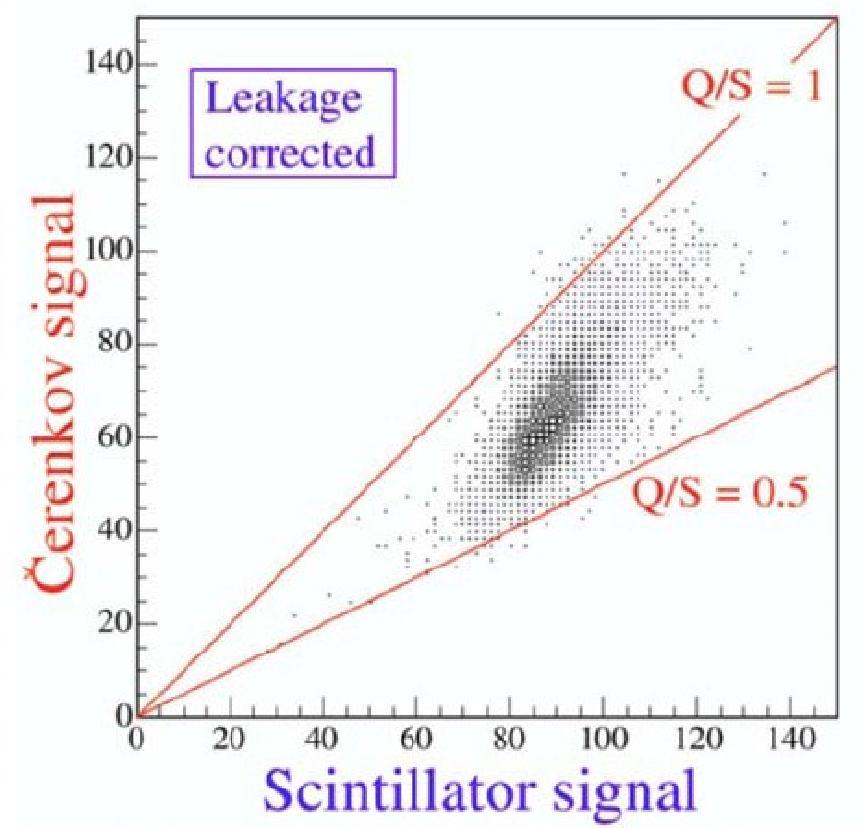
Hadronic response non-linearity



Hadron response is < 1 and ~20% non-linear

Similar non-linearity for jets

How to determine f_{em} and E



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

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

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

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

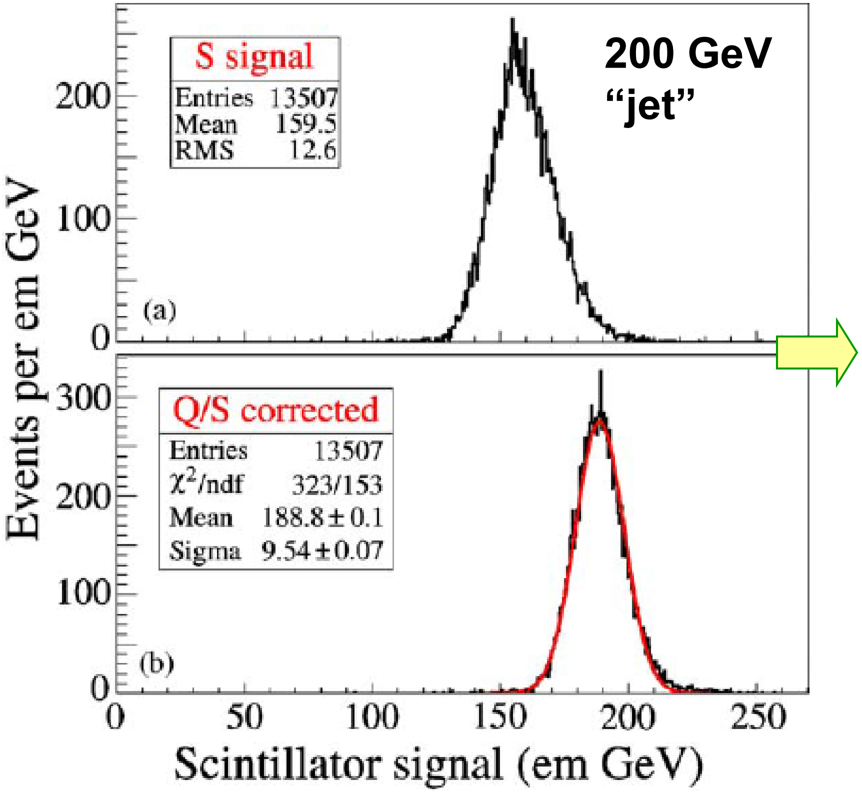
$$\boxed{E = \frac{S - \chi Q}{1 - \chi}}$$

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

Q/S<1 ➔ ~25% of the scintillator signal from pion showers is caused by non-relativistic particles, typically protons from spallation or elastic neutron scattering

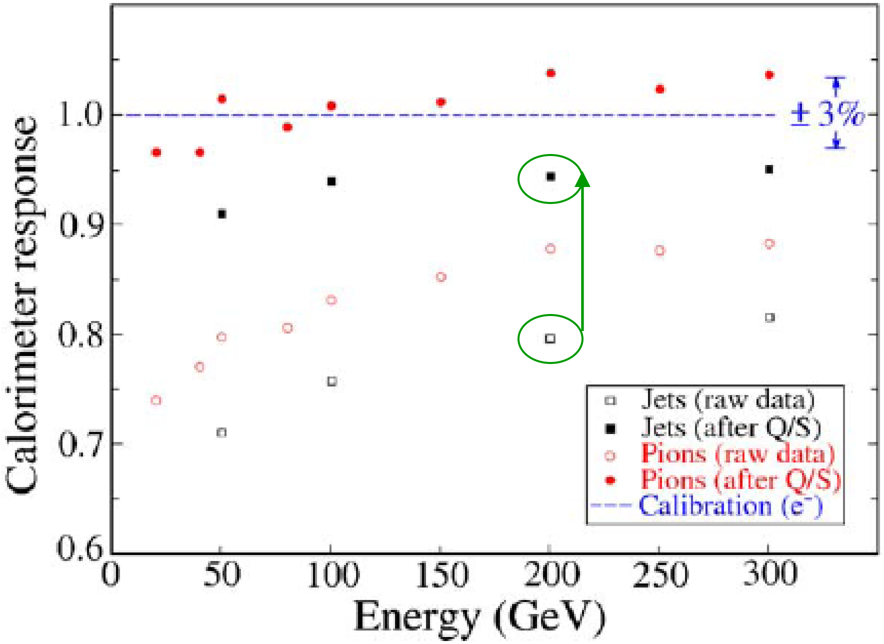
Reconstructed hadron energy

Scintillator signal before correction ➔ asymmetry due to non-compensation



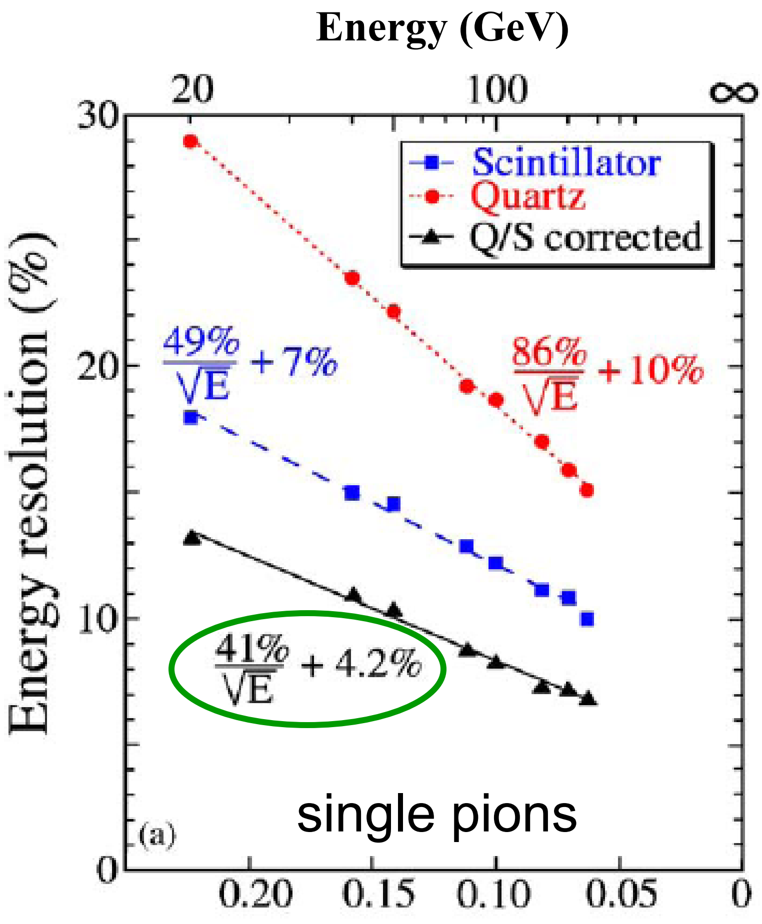
200 GeV
“jet”

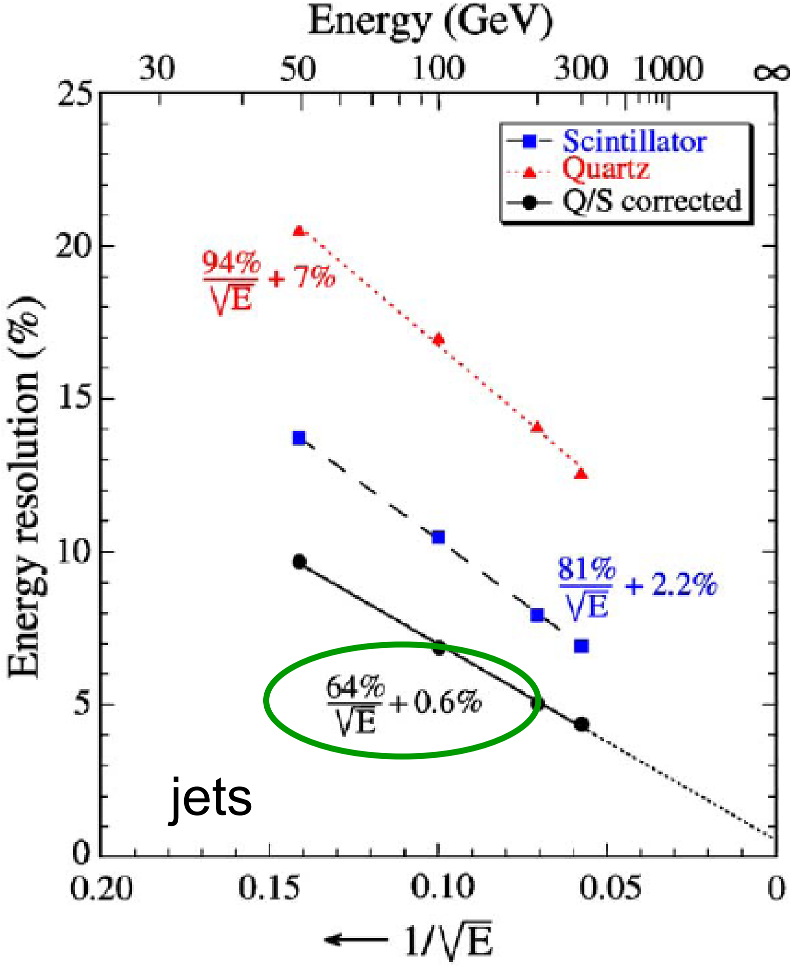
After Q/S method correction
➔ good Gaussian signal



Recovered linearity of response to pions and “jets”

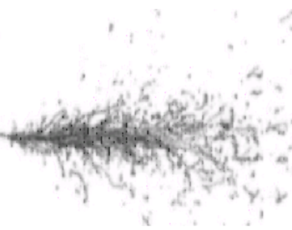
Energy resolution





Significant improvement in energy resolution especially for jets

DREAM conclusions and beyond



DREAM technique powerful to improve hadronic resolution:

- Correct hadronic energy reco. in an instrument calibrated with electrons
- Linearity for hadrons and jets
- Gaussian response functions
- Energy resolution scales with sqrt(E)
- $\sigma/E < 5\%$ for high-energy “jets”, in a detector with a mass of only 1 ton ! (dominated by fluctuations in shower leakage)

How to further improve:

- Increase Cherenkov light yield
  - DREAM: 8 p.e./GeV ➔ fluctuations contribute $35\%/\sqrt{E}$
- No reason why DREAM principle is limited to fiber calorimeters
  - Homogeneous detector ?!

  ⇒ Need to separate the light into its Č, S components
  - Sampling structure with alternating tiles of Č, S materials

Dual Readout with homogeneous material

Separation of Scintillation & Cherenkov light can be based on:

- Time structure of the signal
- Spectral difference
- Directionality of Cherenkov component

	Cherenkov	Scintillation
Time response	Prompt	Exponential decay
Light Spectrum	$\propto 1/\lambda^2$	Peak
Directionality	Cone: $\cos\theta_c=1/\beta n$	Isotropic

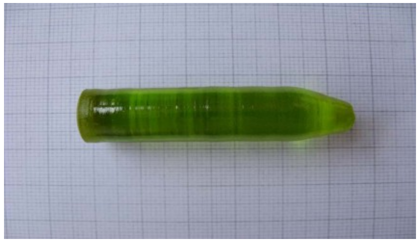
Tests performed at the SPS (CERN) by the DREAM collaboration with 2 kinds of crystals: **PbW0$_4$**, **BGO**

Crystal	LightYield % NaI(Tl)	Decay Time (ns)	Peak wavel.(nm)	Cutoff wavel.(nm)	Refr. Index	Density (g/cm³)
BGO	20	300	480	320	2.15	7.13
PWO	0.3	10	420	350	2.30	8.28

Disadvantages: BGO much brighter → C/S factor 100 smaller

Advantages: Scintillation spectrum peak at 480 nm → use filters Yellow for S, UV for C
Scint Decay time 300 ns (very different from prompt Cherenkov signal)

New crystals PbWO4 doped with different concentrations of
→ Praesodymium (peak 630 nm, τ~μs)
→ Molybdenum (500 nm, τ~30 ns) → seems to me more promising

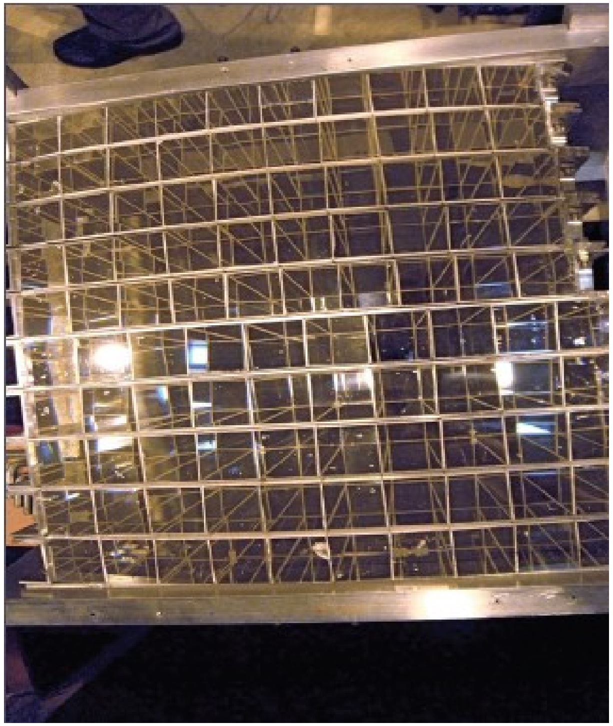


Cherenkov light in PbWo4 crystals

- Light yield typically 10 p.e./MeV (dependent on T, readout)
- Lead glass 0.5 - 1 p.e./MeV from Cherenkov effect (3 - 5%/√E)
  ➔ Expect substantial Č component in PbWO4 signals

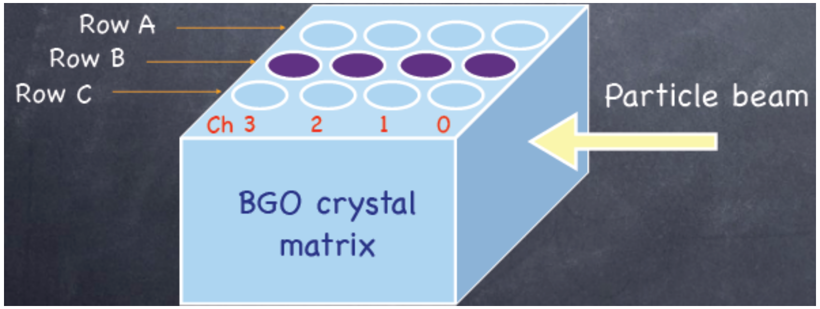
- How to detect/isolate Cherenkov component ?
  - Directionality of Cherenkov component
  - Time structure of signals
  - Spectral differences
  - Test doped Pb-glass with red / green scintillator

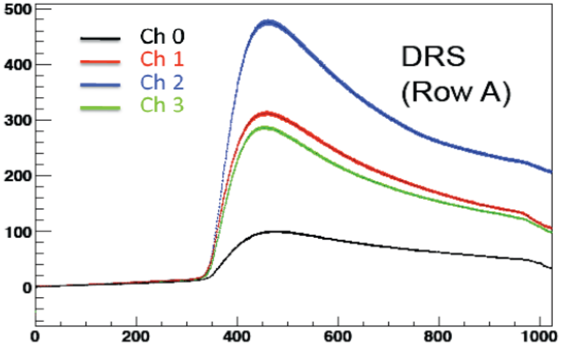
Dual readout with BGO crystals

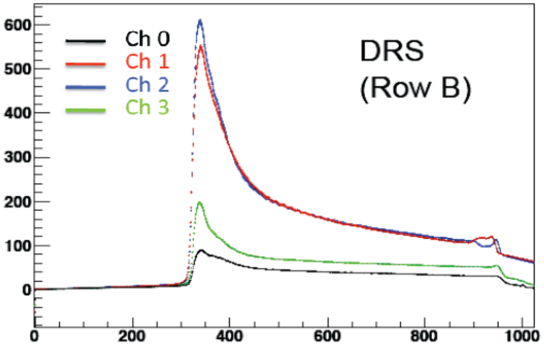


100 crystal BGO matrix was placed upstream of DREAM as the electromagnetic section

➔need longitudinal segmentation to resolve γ from π in jet





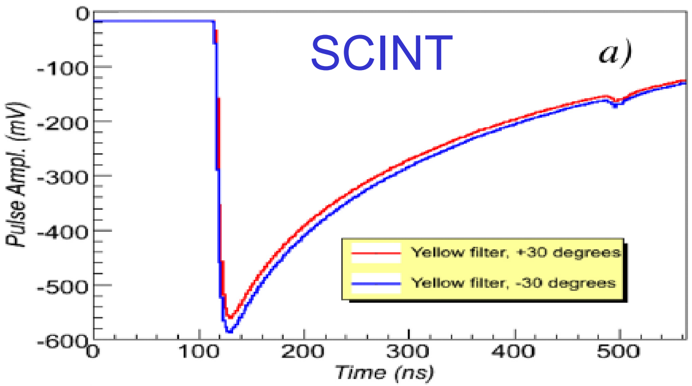


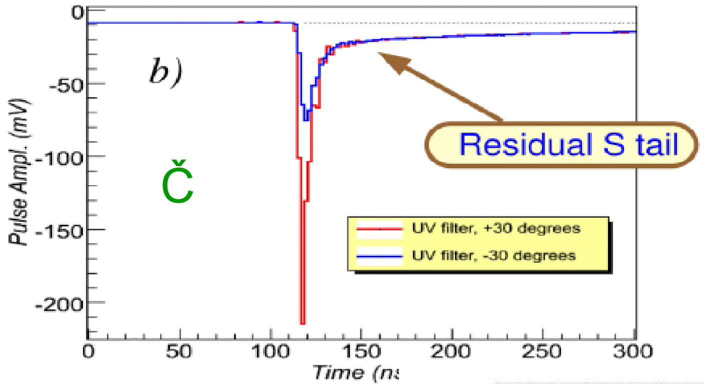
Use UV filters upstream of 4 PMTs to suppress the scintillation component

➔ PMTs with UV filter have an enhanced prompt peak due to the Cherenkov light

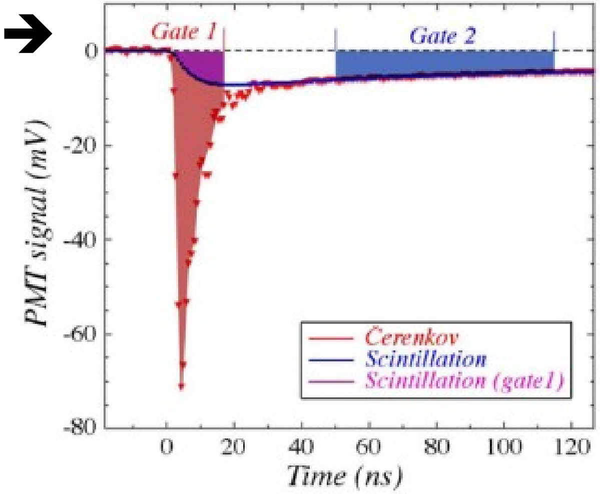
Cherenkov light measurements

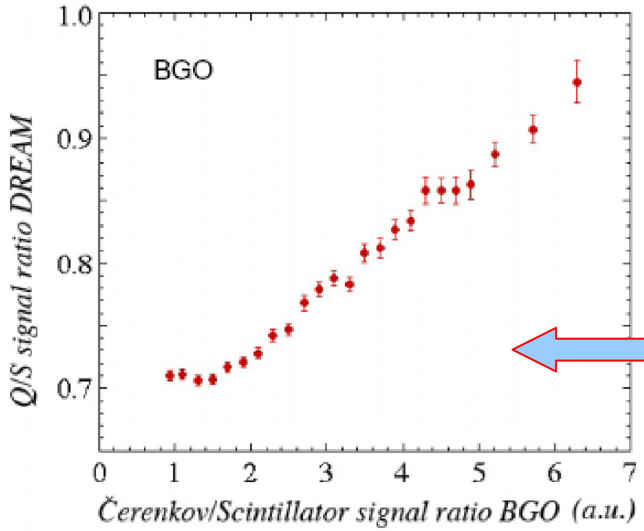
Average Time structure for 50 GeV electrons





C/S ratio event by event: integrate charge Q1 collected in the Gate1, and Q2 collected in Gate2 ➔



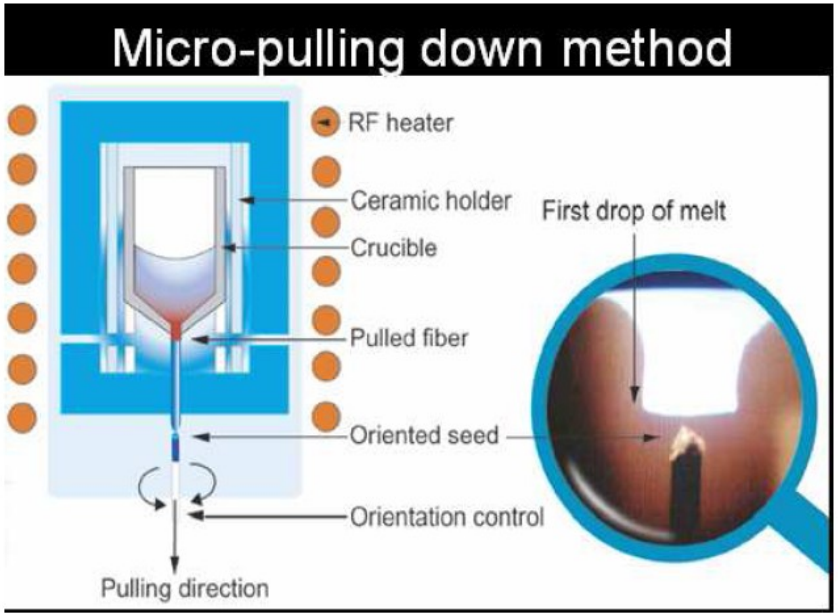


The variable C/S on BGO is able to measure the em component of the shower on the Calorimeter

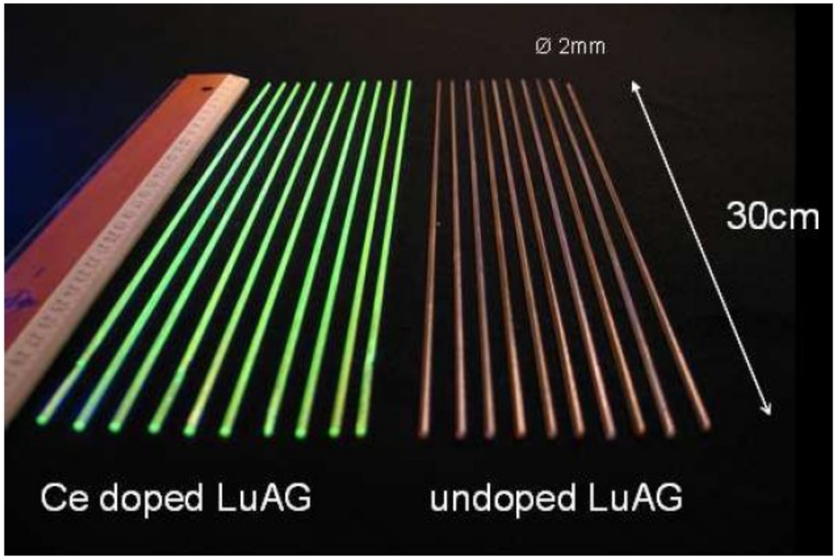
meta-materials, crystal fibers

Meta-material consisting of **undoped** and ***Ce doped*** heavy crystal bars of identical material. The undoped crystals behave as **Cherenkov radiators** while the doped crystals behave as ***scintillators***

➔ a candidate material is the Lutetium Aluminium Garnet (LuAG) crystal



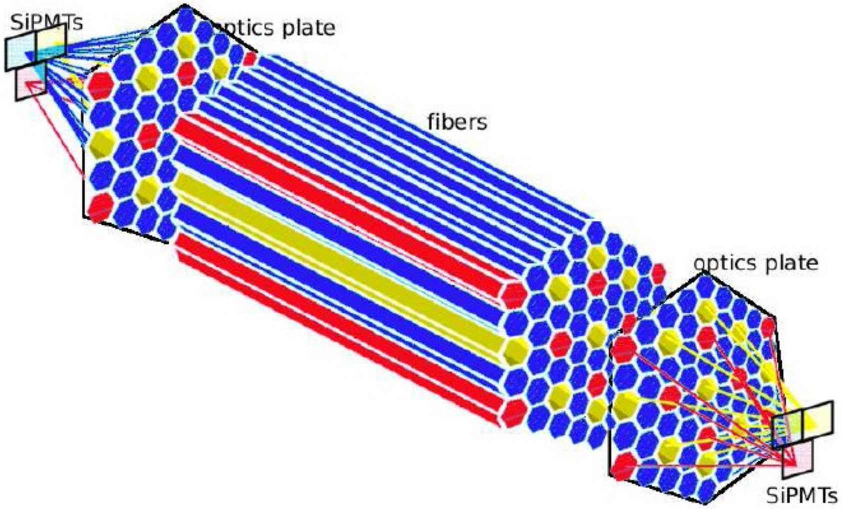
(courtesy of Fibercryst-Lyon, Cyberstar-Grenoble)



(20 fibers of diameter=2 mm, length=30 cm)

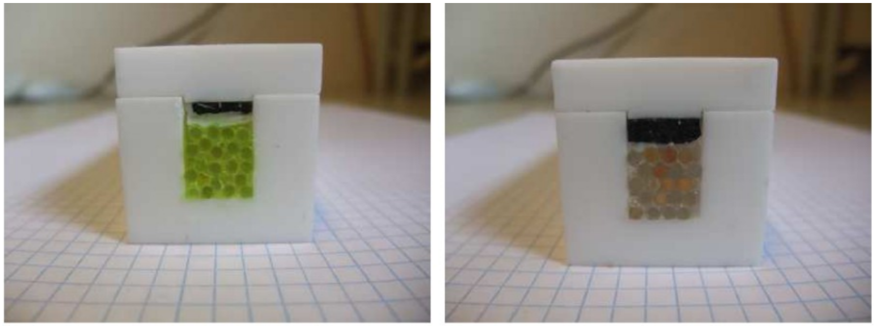
- fiber diameter between 0.3-3 mm, length up to 2 m
- pulling rate ranging from 0.1 to 0.5 mm/min
- capillary die can be non-cylindrical (e.g. square, hexagonal etc)

Design of a calorimeter readout unit

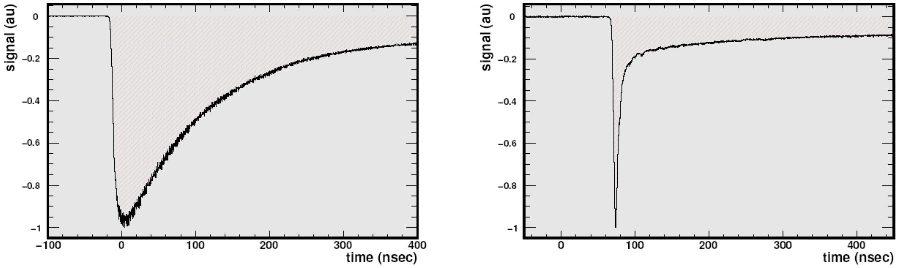


- a unit consists of a structured distribution of different types of fibers
- typical dimensions of a unit :
  d = 1-1.5 R_M; L = 20-25 X_0
- light from different types of fibers is directed to different SiPMTs by using diffractive optics light concentrators (micro-lenses) diffractive optics plate

Fiber bundles exposed to beam



(20 fibers of diameter=2 mm, length=80 mm) (20 fibers of diameter=2 mm, length=80 mm)

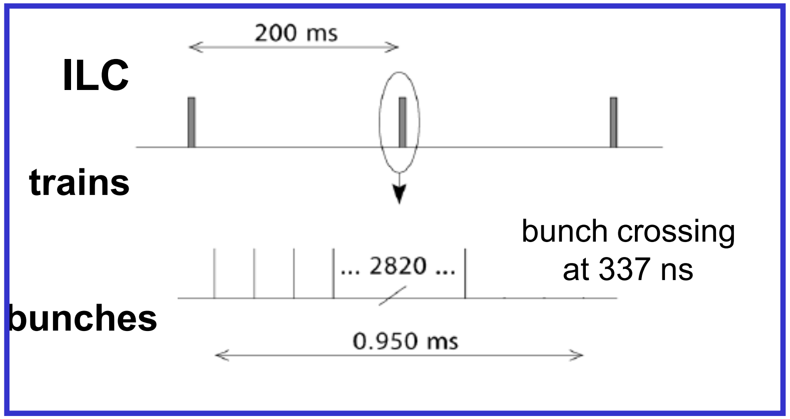


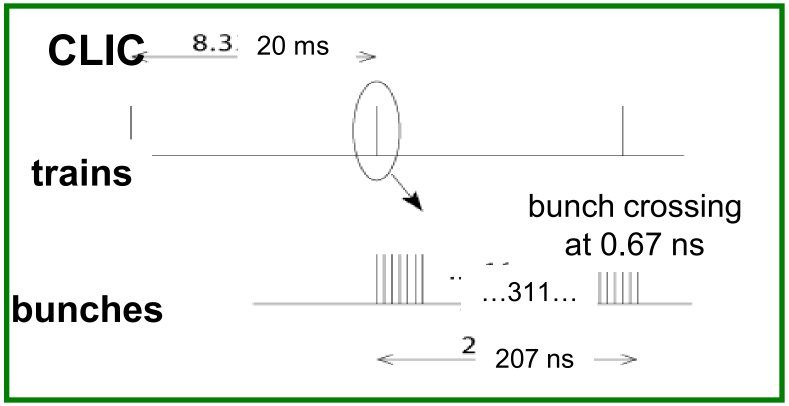
(scintillator) (Cherenkov radiator)

Ce doped LuAG **undoped LuAG**

expected difference in signal shape

Time resolution





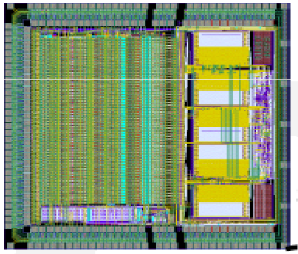
Time res. also relevant to study neutron component of hadronic showers

Beyond ILC ➔ CLIC
Higher gradient: 100 MV/m vs 35MV/m
Higher cms energy: 3 TeV vs 500 GeV

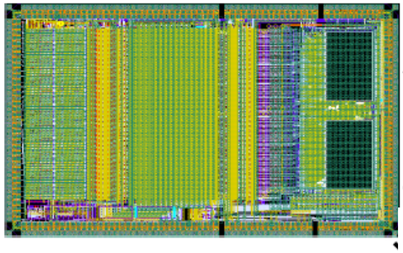
➔ Price to pay: 0.5 ns bunch crossing

Time stamp O(10ns) mandatory

TDC integrated in the “ROC” family of chips for future calorimeters
~ 1ns time resolution

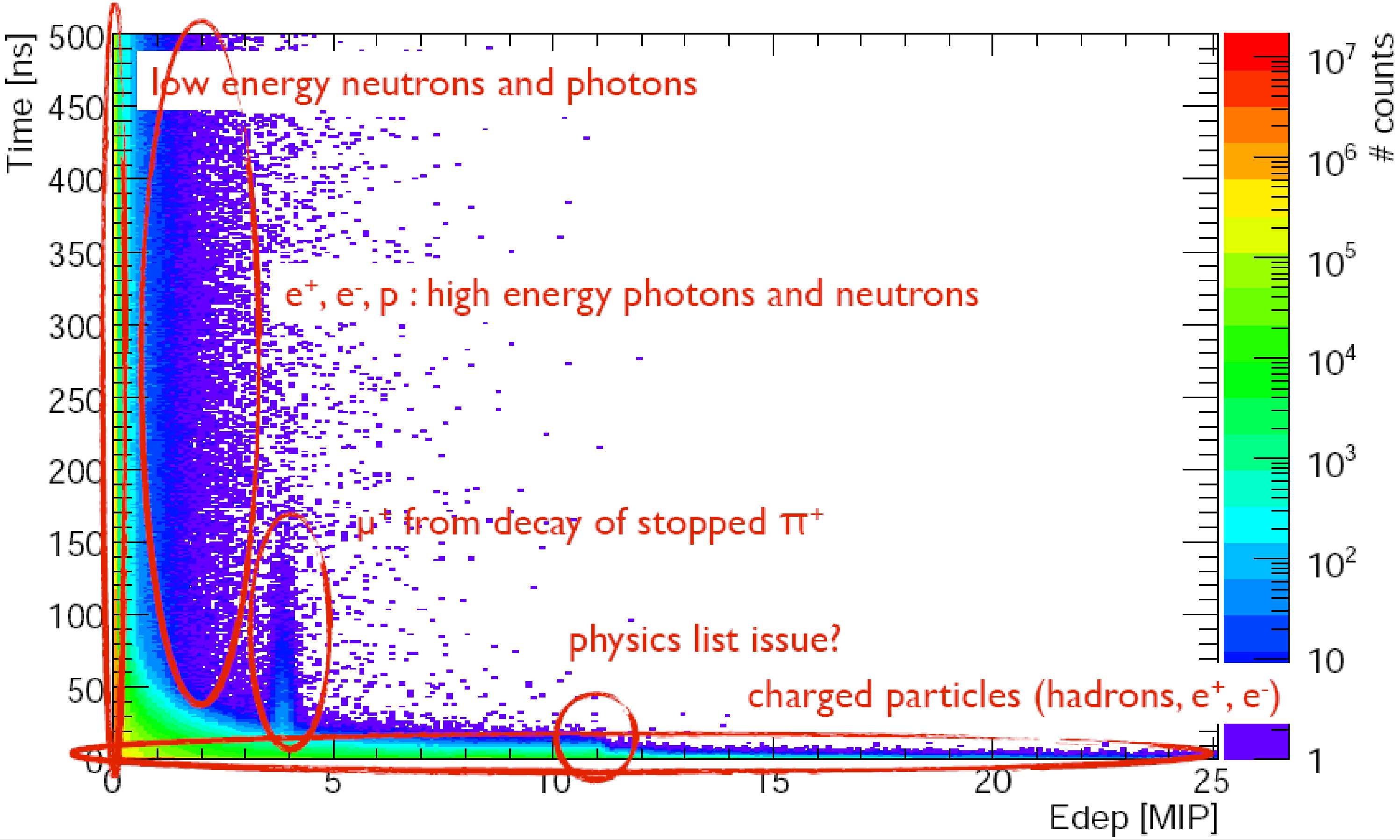


HARDROC
Digital HCAL
(RPC or µmegas)
64 ch. $16mm^2$



SPIROC
Analog HCAL
(SiPM)
36 ch. $32mm^2$
June 07

Time resolution



Time res. also relevant to study neutron component of hadronic showers

Next generation of calorimeters will be "4D imaging" calorimeters !!

sLHC & CLIC R&D

Calorimetry at sLHC ➔ radiation hard material

Exchange scintillator with quartz

Test of different quartz + WLS fiber geometries

Advantages of WLS fiber:

collect light to photo-detector

Improves homogeneity of tile

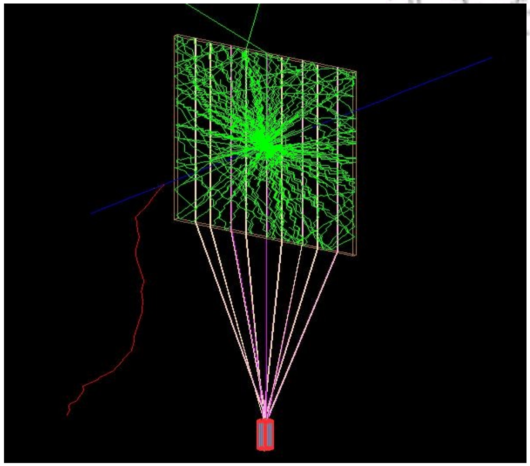
Disadvantages of WLS fiber:

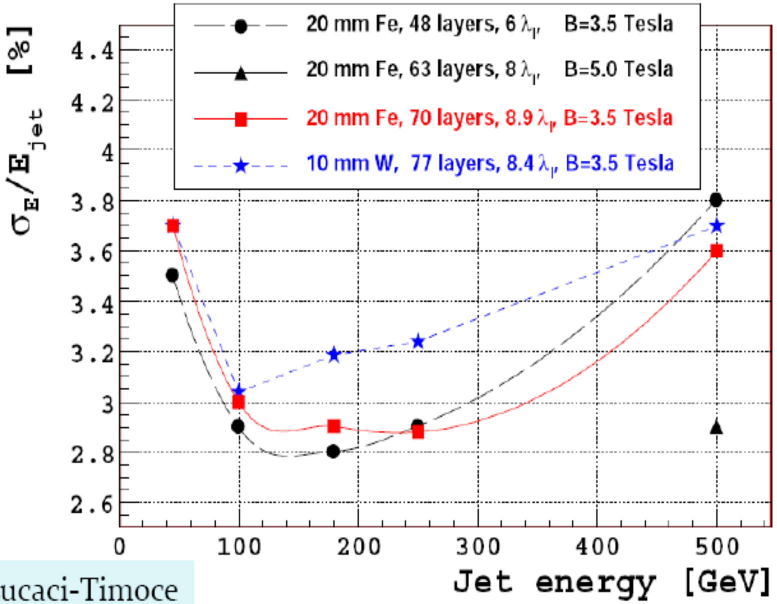
Degradation of fast Cherenkov signal (<1ns)
due to WLS fiber emission

Outlook on future R&D:

- Exploit fast Cherenkov signal + time resolution
- High granularity helps to reduce multiplicity/cell

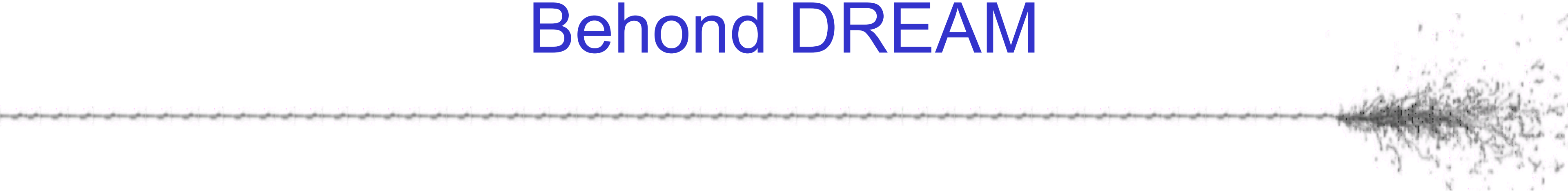
CLIC: move to Tungsten absorber





Lucaci-Timoce

Behond DREAM



For ultimate hadron calorimetry ($15\%/\sqrt{E}$)

➔ Measure E_{kin} (neutrons)

- correlated to nuclear binding energy loss (invisible energy)
- can be measured with third type of active material TREAM

➔ hydrogen enriched materials (not yet tested)

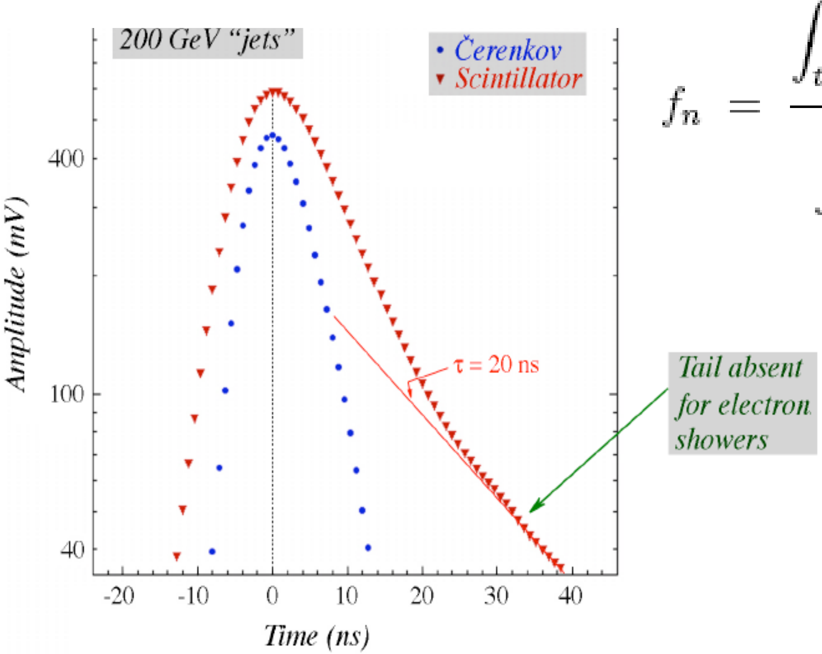
Measure Neutron Fraction

from the time structure of the signal

The neutron fraction is correlated to nuclear binding energy (invisible energy) ➔ next large source of fluctuations to attack

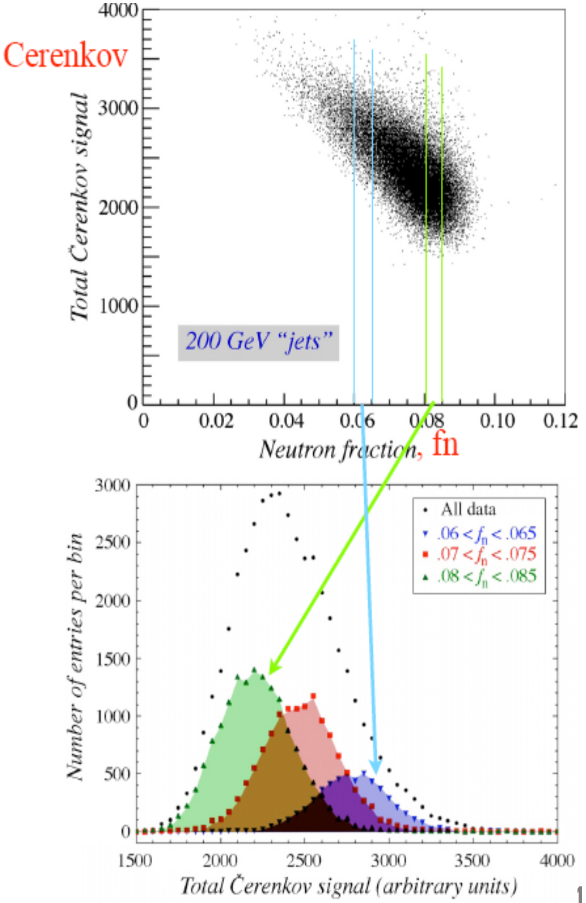
Neutron signal (f_n)= integral of scint signal over 20-40 ns

$$f_n = \frac{\int_{t=20\text{ns}}^{40\text{ns}} \sum_{i=2}^{19} S_i}{\int_{t=0}^{\infty} \sum_{i=1}^{19} S_i}$$

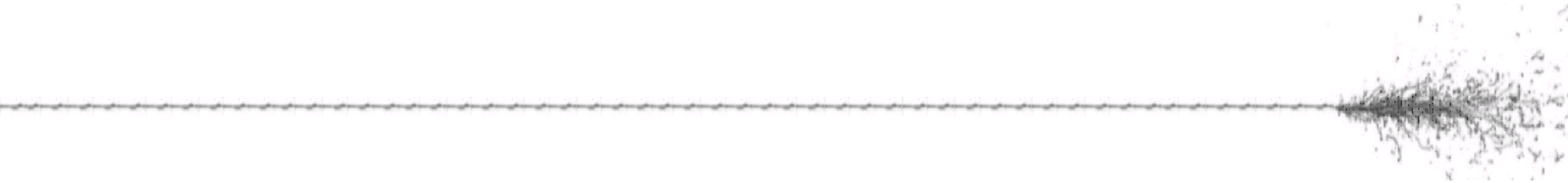


Tail absent for electron showers

f_n anticorrelated with C as aspected



The total C distribution can be decomposed into its constituent parts as a function of f_n



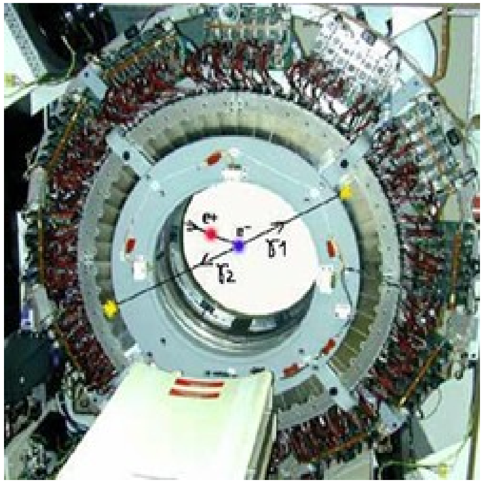
Calorimeters behind HEP

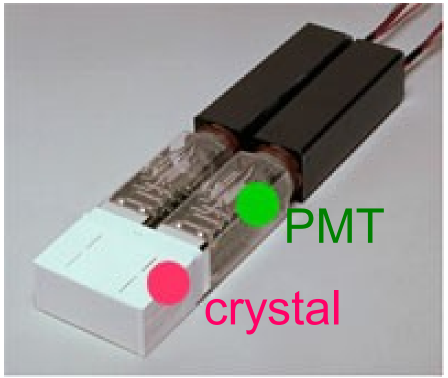
Positron Emission Tomography

How can a calorimeter save your life? ➔ PET

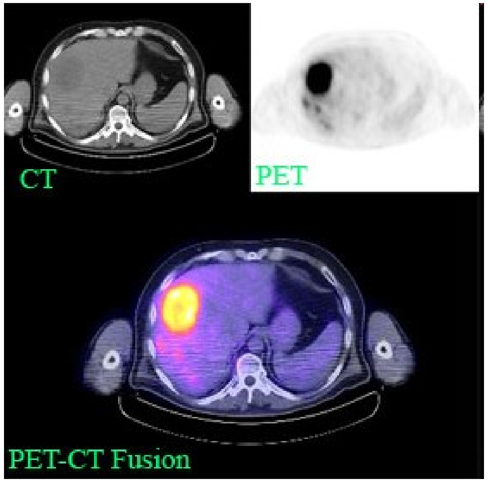
a commercial PET system
for hospital treatment

the same system without cover





basic unit of a PET:
crystal (LSO, BGO) + PMT



➔ Functional (metabolich) pictures of living organs in addition to Computer Tomography improves high resolution visualization of anatomic parts

Task: reconstruct 2 γ (511 keV) from annihilation of positron from a β-emitting tracer

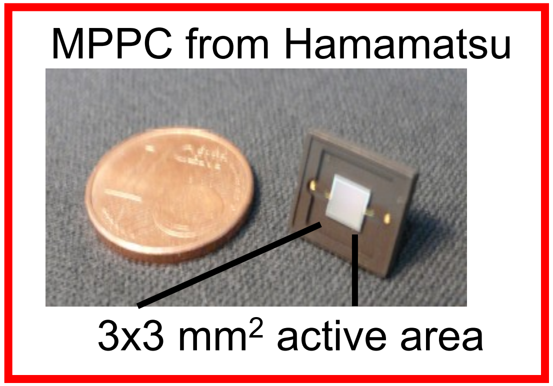
➔ calorimeter

New trends in PET calorimeters

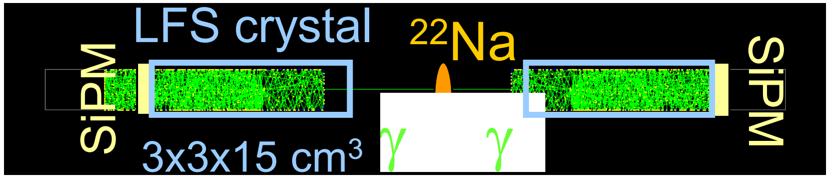
High granularity and small calorimeter cells improve space resolution

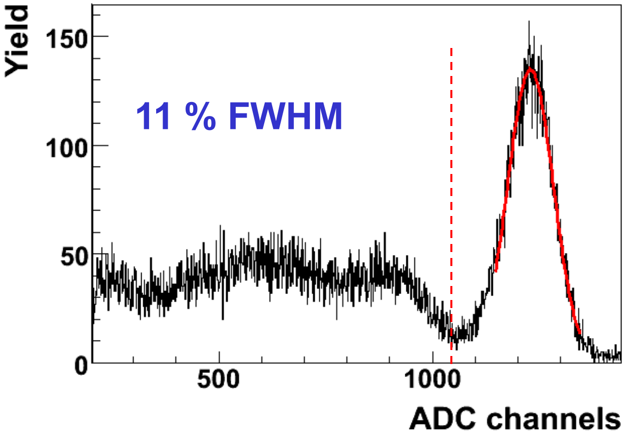
➔ Silicon Photomultiplier replace PMT

- compact system
- low HV & cost


MPPC from Hamamatsu

$3x3\ mm^2$ active area





- Good E res. ➔ reduce Compton bg.
- Good t res. ➔ reduce combinatorial bg.

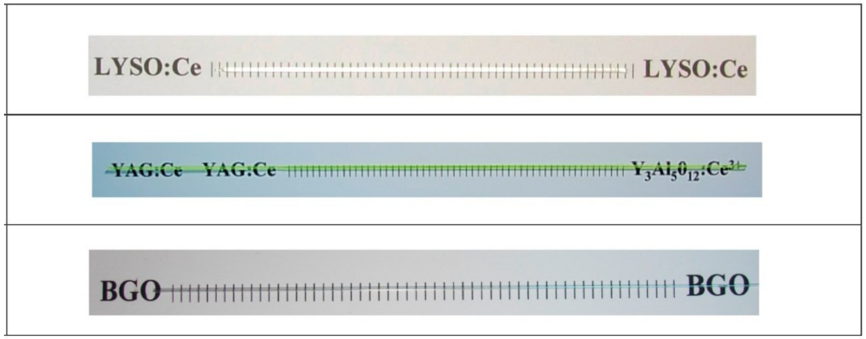
time resolution for coincidence of two channels ~250ps using SiPM readout and dedicated electronics possible

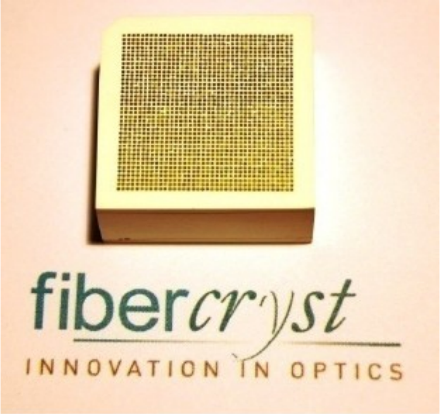
Technology frontier

new products

Extreme granularity

Fiber crystals: ∅ 350um – 3mm



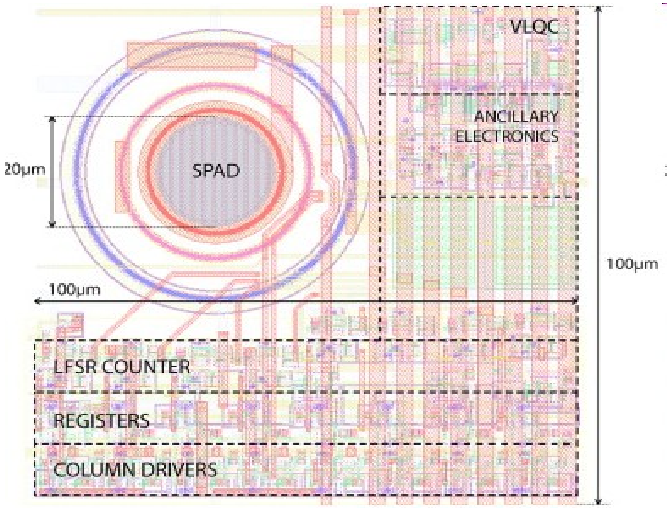


LuAG:Ce Array

Improve space resolution using smallest crystals individually read out

Extreme integration

new generation of Geiger-mode avalanche photo-detector: integrates SPAD on CMOS

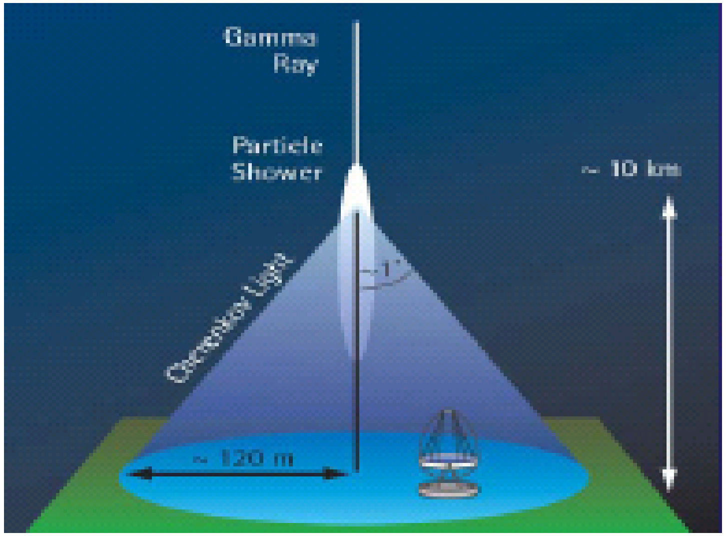


~50 um pixel SPADs arranged in arrays with individual pixel readout
- O(100ps) time resolution on single photon

E. Charbon et al., IEEE (ESSCIRC), Sep. 2009

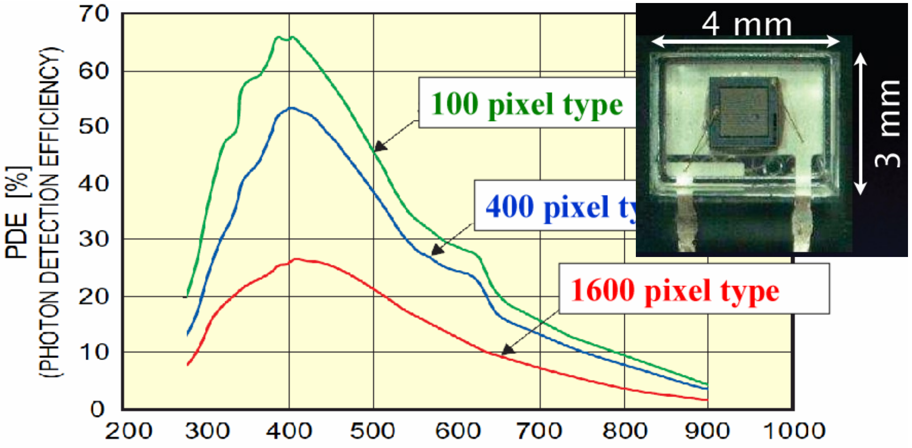
http://www.everyphotoncounts.com/arrays-linarray.php

Ground based Gamma Ray Astronomy



Gamma Ray induces electromagnetic cascade
➔ Relativistic particle shower in atmosphere
    ➔ Cherenkov light
    fast light flash (~ns)
    100 γ / m^2 (1 TeV Gamma Ray)

Next generation: **Cherenkov Array Telescope (CTA)**

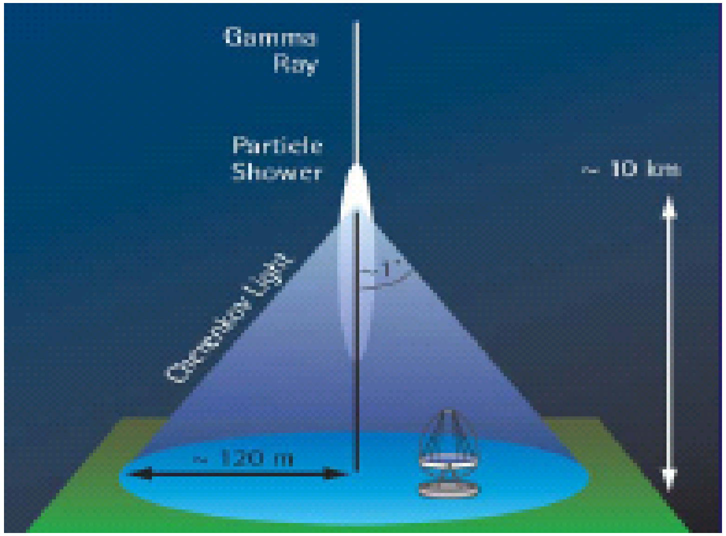


SiPM offer 60% PDE at 400nm
+ improvements with lower fill factor

CAMERA

- Expensive
- Camera composed of 1000 pixels ➔ use PMT for baseline (40% PDE)
- Fast timing response (~1ns) to cope with EAS Cherenkov flashes
- Electronics inside the camera
- Keep low weight

Ground based Gamma Ray Astronomy



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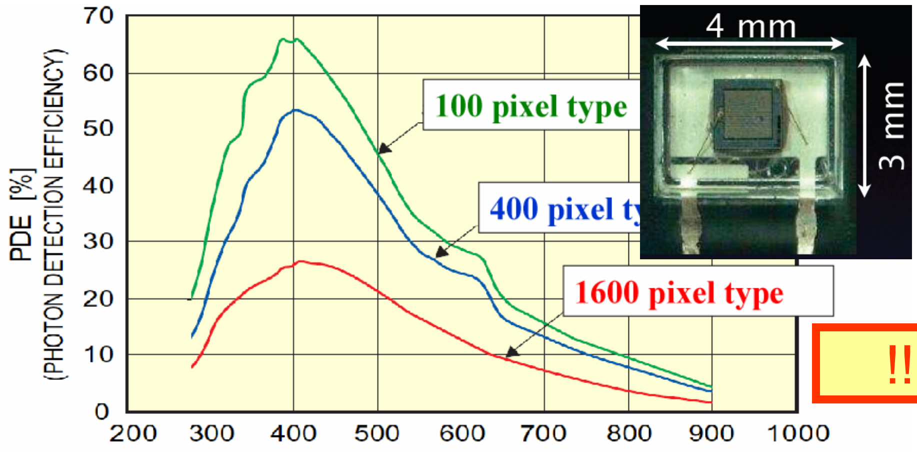
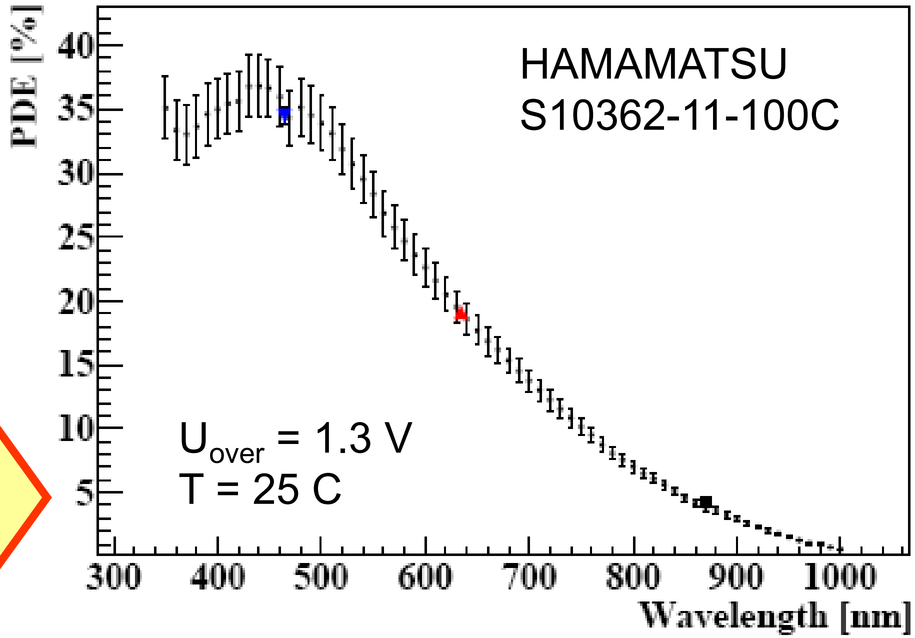


!!!



SiPM offer 60% PDE at 400nm
+ improvements with lower fill factor

P. Eckert et al, Nucl.Instrum.Meth.A620:217,2010

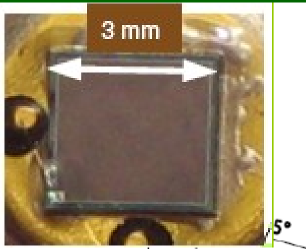
Positron Electron Balloon Spectrometer

Goal: Measure the cosmic ray positron fraction with a balloon borne spectrometer

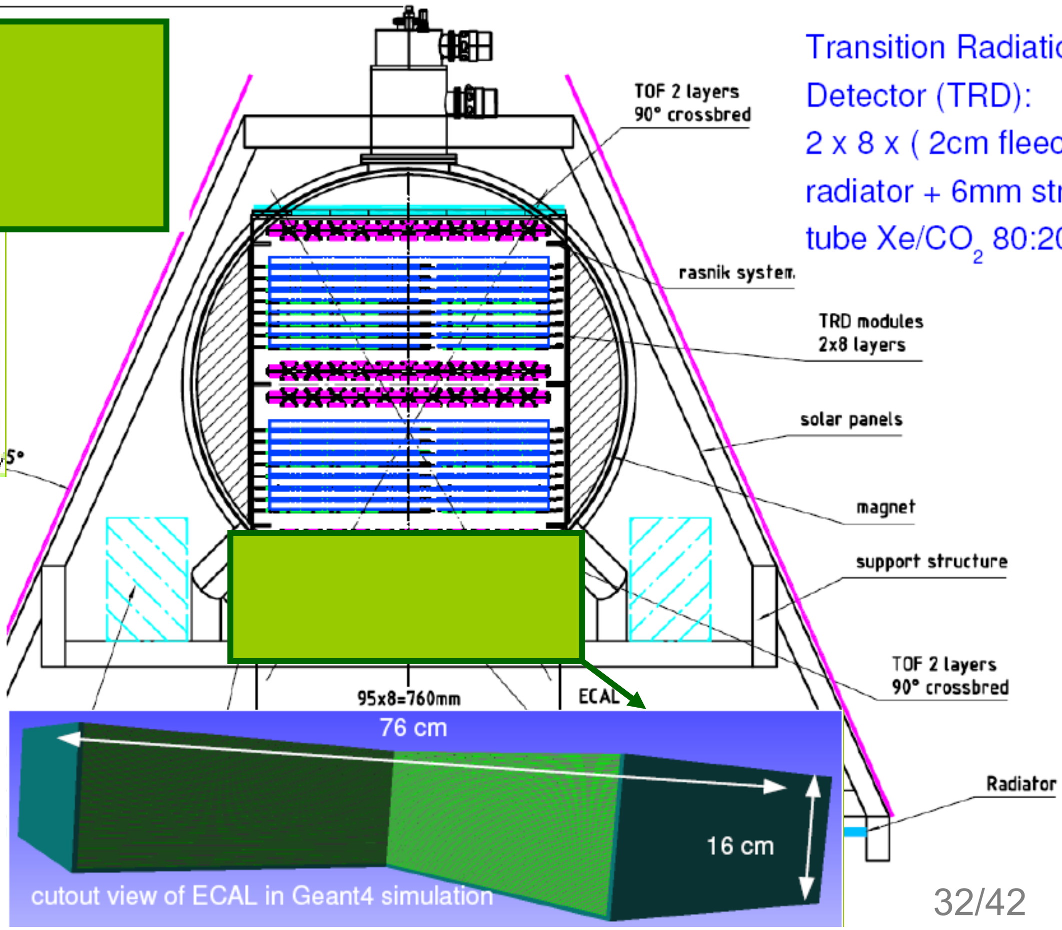
Motivation: Indirect search for dark matter

Requirements (calorimeter):

- Excellent proton suppression of O(10^6)
- Total payload weight < 2t
- Total power consumption < 1000W



Time-of-Flight system (TOF): 2 x 2 x 5 mm^3 scintillator, SiPM readout; trigger system!

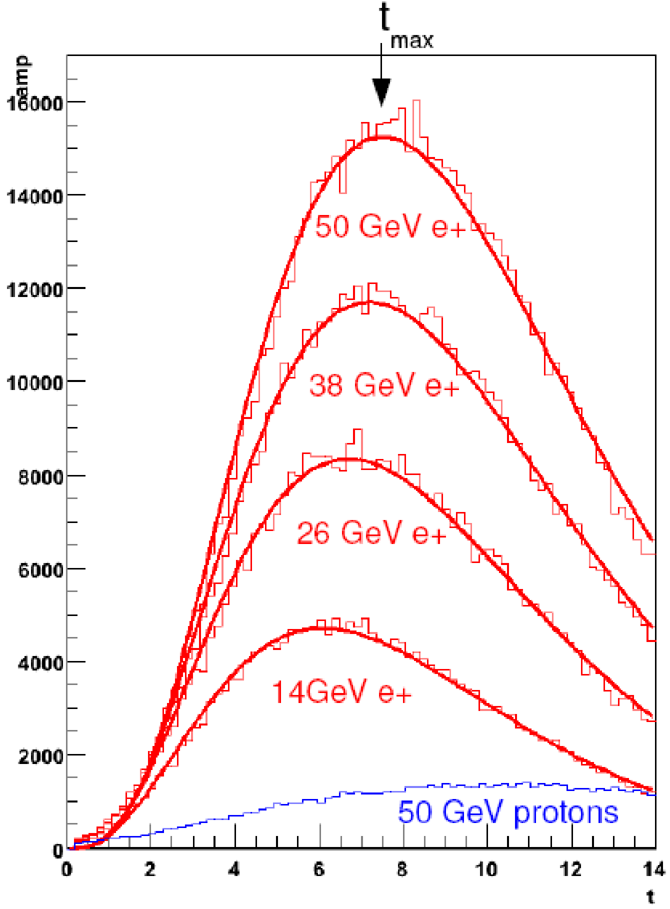


cutout view of ECAL in Geant4 simulation

Transition Radiation Detector (TRD): 2 x 8 x (2cm fleece radiator + 6mm straw tube Xe/CO_2 80:20)

Proton rejection

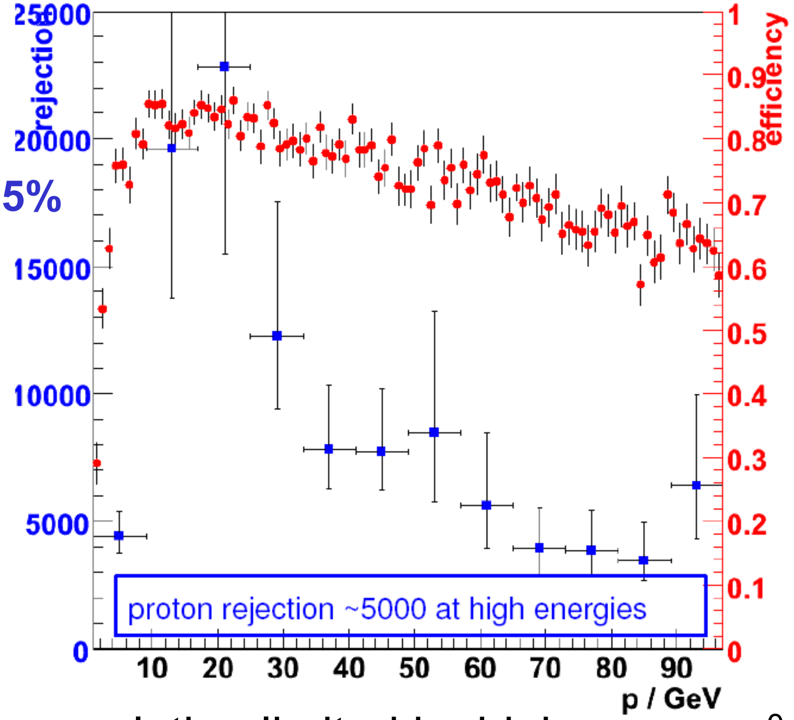
e/p separation based on different longitudinal shower shape at a given particle energy (spectrometer) ➔ extremely high granularity



$$\frac{dE}{dt} = E_0 \frac{b^{\alpha+1}}{\Gamma(\alpha+1)} t^{\alpha} e^{-bt} \qquad t=x/X_0$$

longitudinal shower profiles

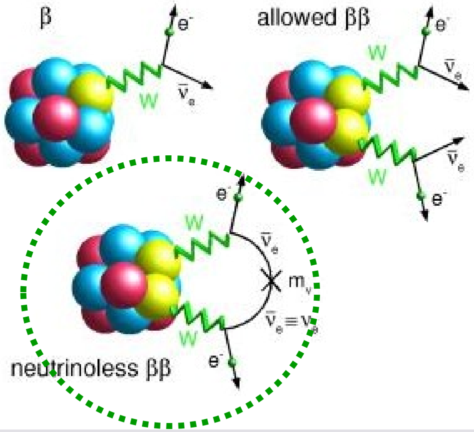
Simulated 40k positrons and 1700k protons



~ 65%

intrinsic resolution limited by high energy π^0 production ($p \rightarrow p\pi^0 X$) in front of or in first layers of ECAL

Calorimeter for ββ0ν search: The Bolometer

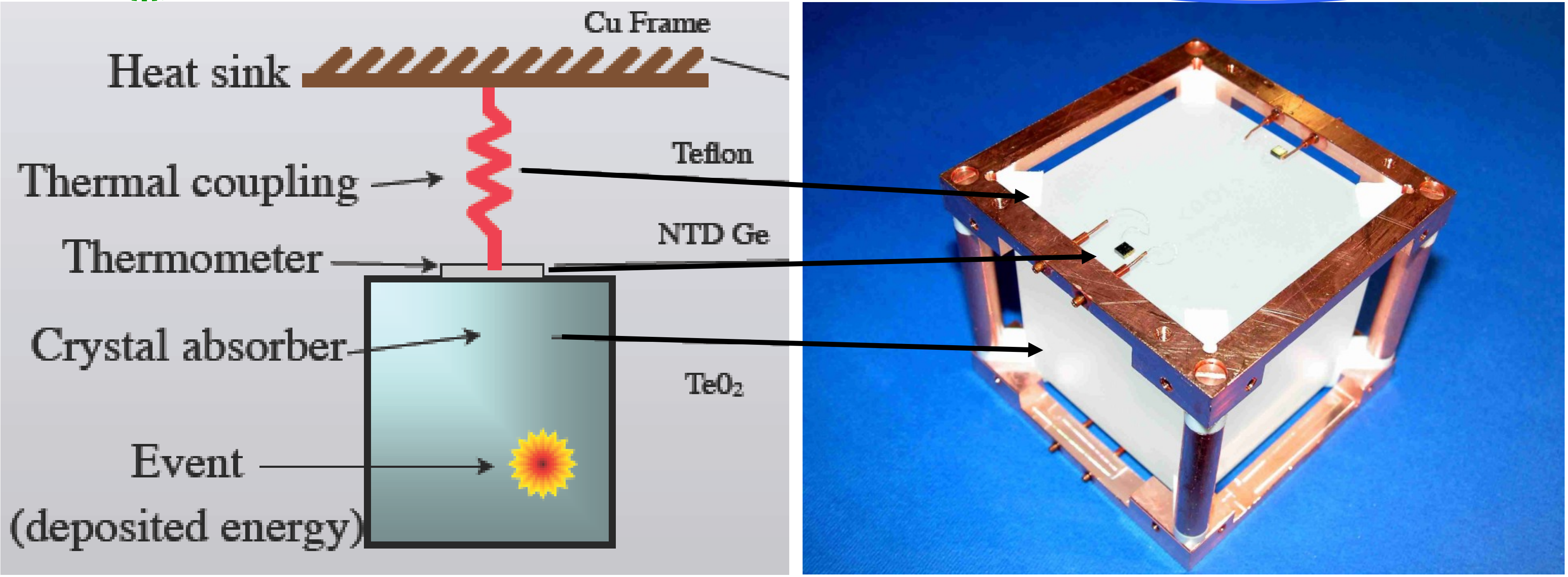


Bolometer operating principles:

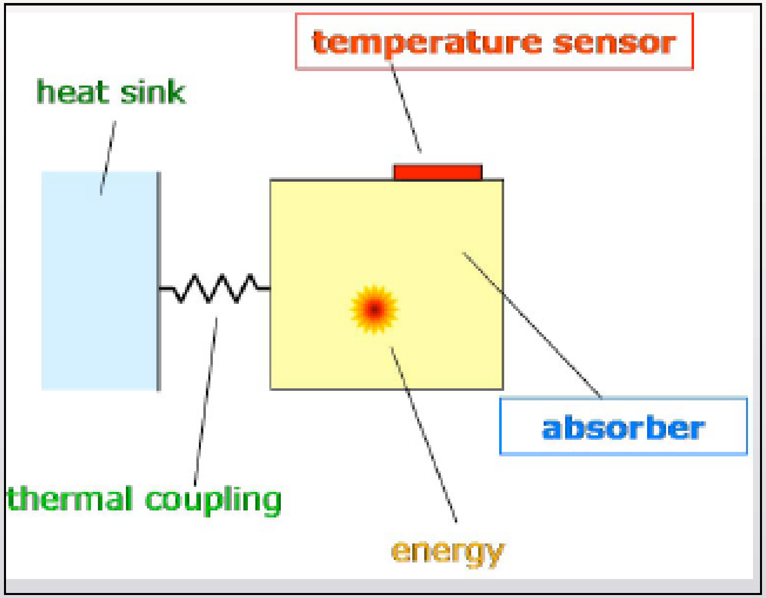
$$\boxed{\Delta T = E/C \cong 0.1 \text{ mK}}$$

→ **Low Temperature**

Absorber material TeO_2 low heat capacity large crystals available radiopure



Cryogenic bolometer



Heat sink: 8-10 mK

Weak thermal coupling (teflon holders):
$G = 4$ pW/mK

Thermister: NTD Ge-thermistor
$R \cong 100$ MΩ, $dR/dT \cong 100$ kΩ/μK

Crystal absorber: TeO_2 crystal
$C \cong 2$ nJ/K $\cong 1$ MeV / 0.1 mK

Temperature signal for E=1 MeV: ⟶ **$\Delta T = E/C \cong 0.1$ mK**

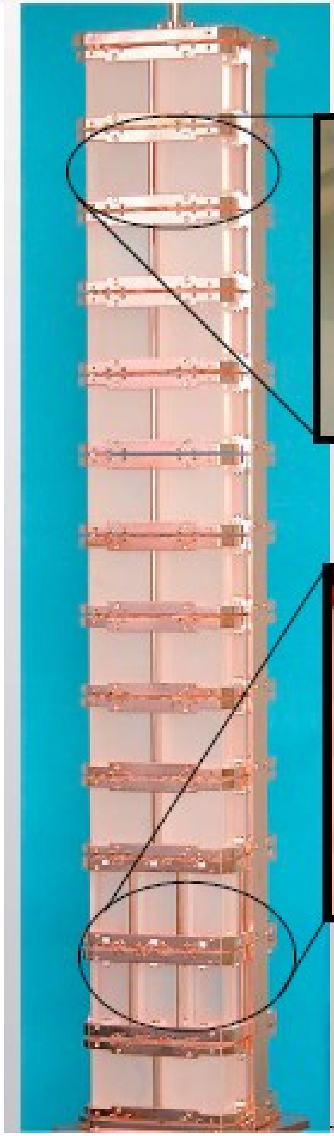
Signal size: $\Delta V = I \times dR/dT \times \Delta T$ ⟶ **1 mV/1 MeV**

Signal recovery time: $\tau = C/G$ ⟶ **0.5 s**

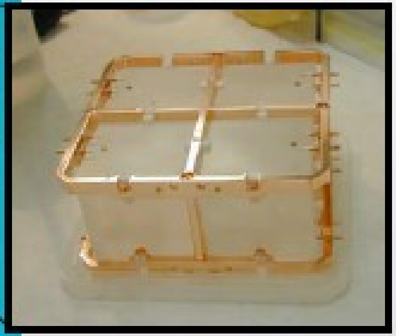
Noise over signal bandwidth (few Hz): ⟶ **$V_{rms} = 0.2$ μV**

Energy resolution (FWHM): ≅ 1 keV (in theory)

Cuoricino experiment @ Gran Sasso

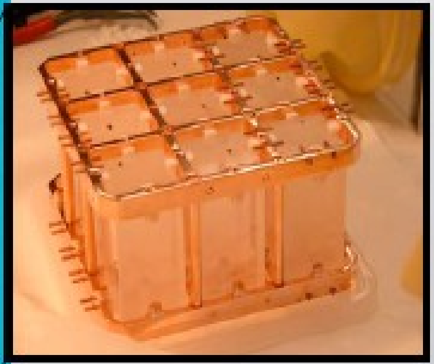


Currently the largest bolometer in the world



11 modules, 4 detector each,
crystal dimension: 5x5x5 cm^3
crystal mass: 750 g
44 x 0.79 = 34.76 kg of TeO_2

Encased in a lead shield, nitrogen box, neutron shield, and Faraday cage



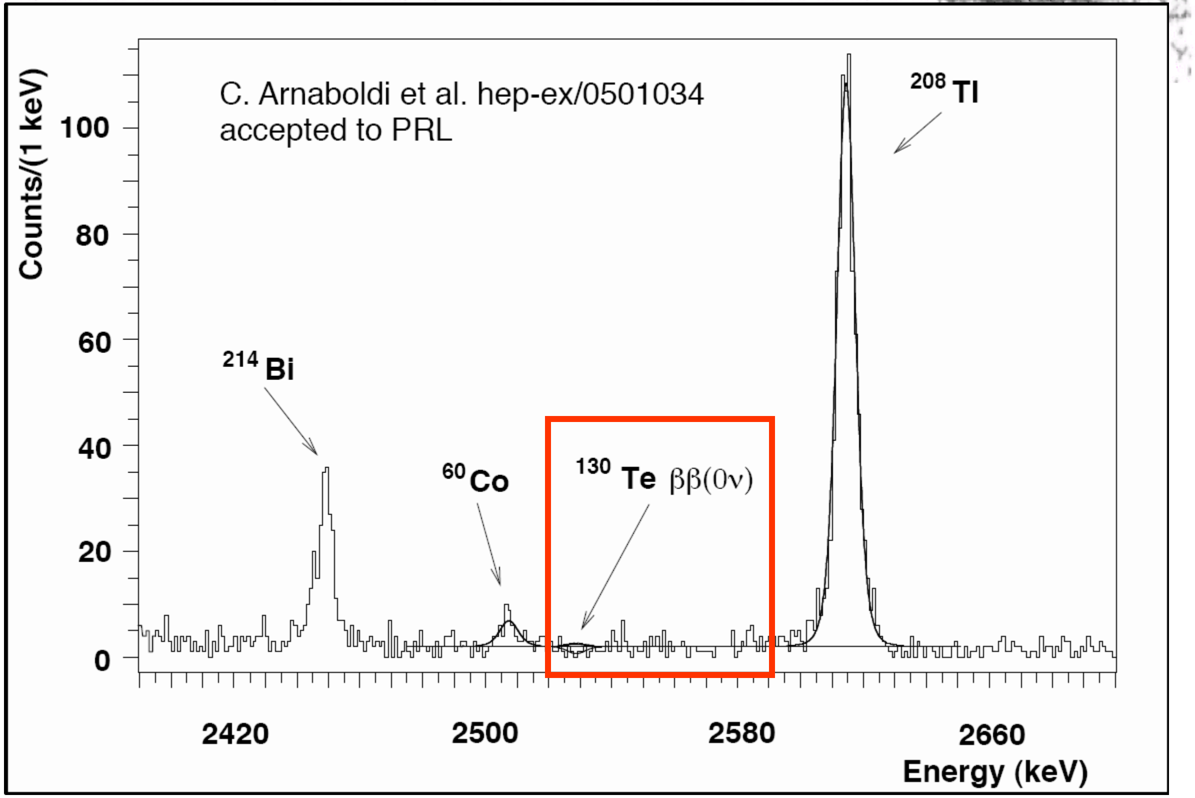
2 modules **x** 9 crystals each
crystal dimension: 3x3x6 cm^3
crystal mass: 330 g
18 x 0.33 = 5.94 kg of TeO_2

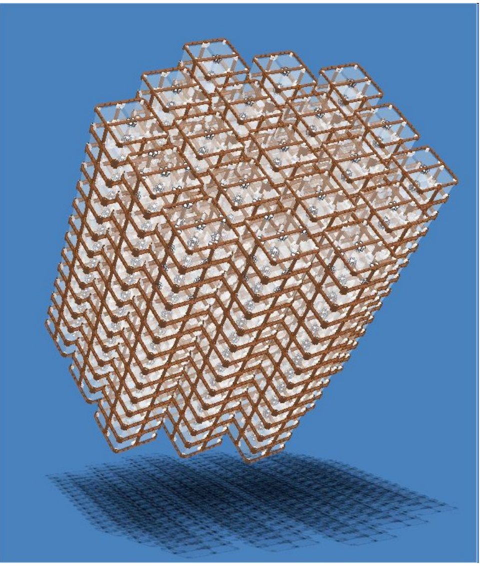
Total detector mass: 40.7 kg TeO_2 ⇒ **11.64 kg ^{130}Te**

Cuoricino limit on $\beta\beta 0\nu$

Resolution:
FWHM at 2615 keV
= 9.2 ± 0.5 keV

Background:
In the $\beta\beta 0\nu$ region
= 0.18 ± 0.01 counts/(keV kg y)





Results: no peak found

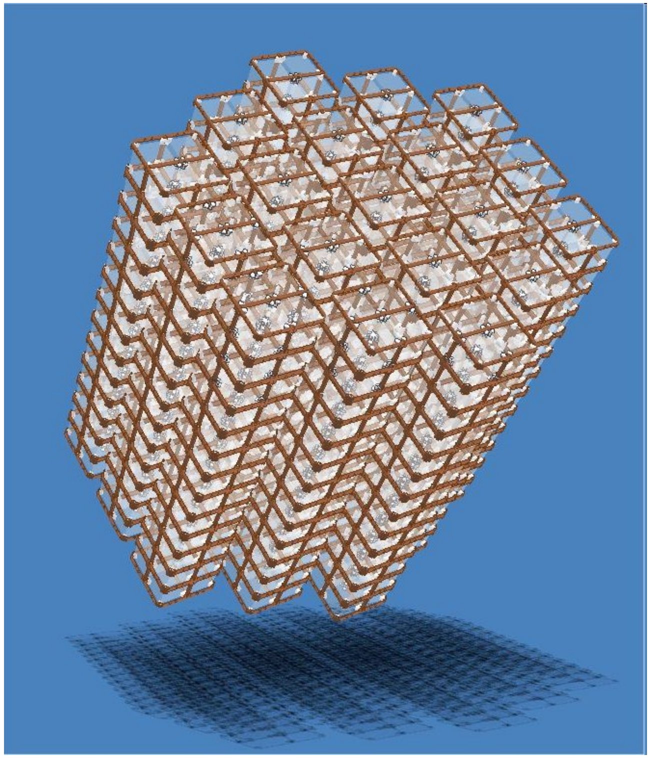
➔ $\tau^{0\nu}_{1/2} > 3.0 \times 10^{24}$ (at 90% C.L.)
$m_\nu < 0.2 – 0.98$ eV

CUORE will follow with: 988 TeO_2 bolometers cubes 5 cm^3 with a mass of 750 g each.

Next step: Cuore

Cryogenic Underground Observatory for Rare Events:

- Array of 988 TeO_2 crystals
- 19 Cuoricino-like towers suspended in a cylindrical structure
- 13 levels of 4 5x5x5 cm^3 crystals (750g each)
- ^{130}Te: 33.8% isotope abundance
- Time of construction: 4 years
- expected by 2010



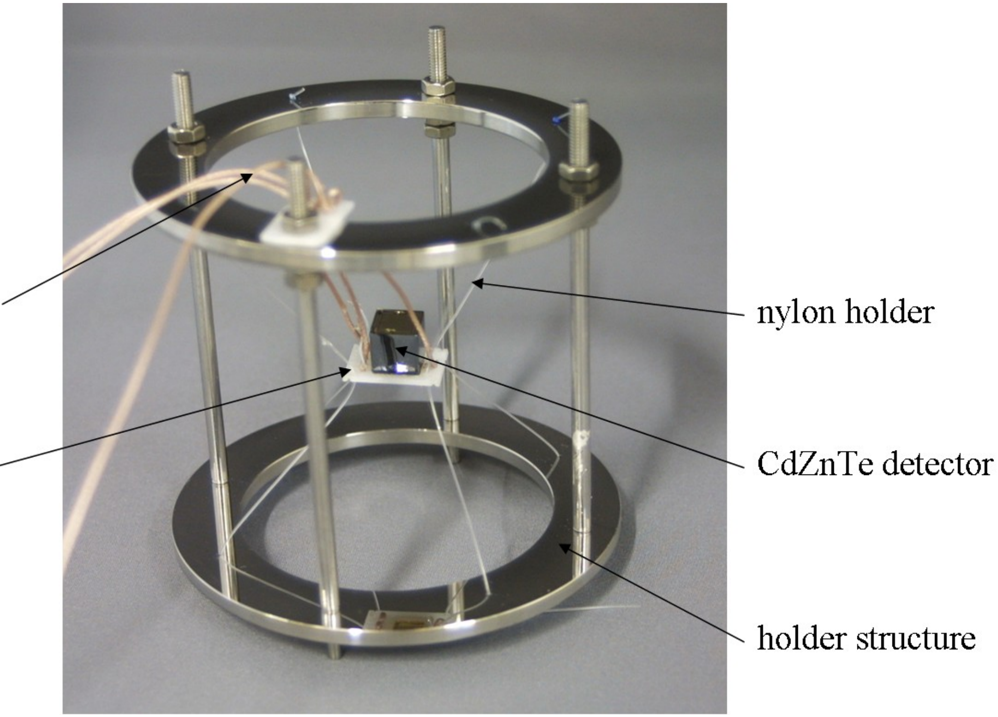
$$\boxed{750\ \text{kg}\ TeO_2\ \Rightarrow\ 200\ \text{kg}\ ^{130}Te}$$

With bolometry we are back to the original meaning of calorimetry !

New sensor materials: CdZnTe

New trends in $0\nu\beta\beta$ decay detectors

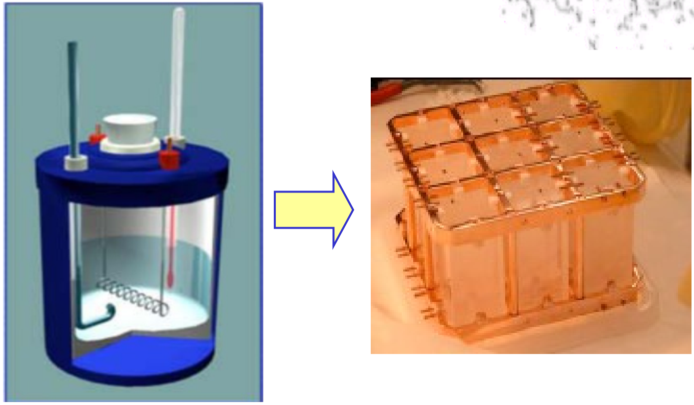
➔ The COBRA experiment



- detector based on CdZnTe semiconductor
- operated at room temperature
- high density of the crystal provides excellent stopping power
- detector array under design:

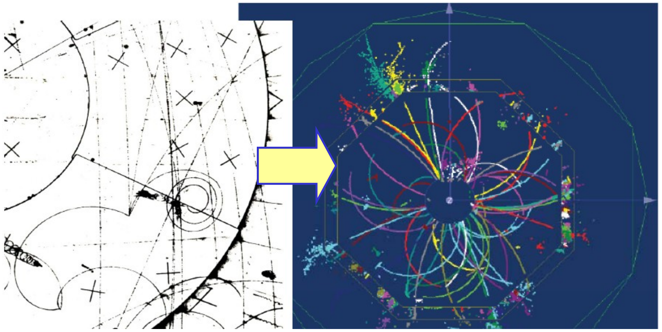
  ~6400 crystals
  of 1 cm^3 size (~6.5g)
  for a total of 400 kg

Conclusions



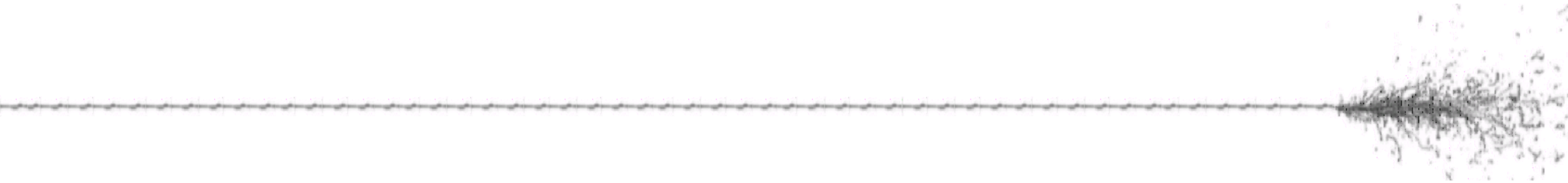
Calorimetry is a field developed over
more than a century,
still vital and in continuous evolution

Calorimetry at the technology frontier drives the development of
    new materials, new photo-detectors, new electronics, …, new analysis techniques, new ideas



Present key issues for calorimetry:

- Extreme segmentation (Imaging calorimeters)
- Extreme integration (maximum hermeticity)
- Compensation in limited volume (Pflow/ dual-readout)



Thank you all for your attention and participation during these lectures!

Acknowledgments

These slides are largely based on the work of:

The ATLAS collaboration	http://atlas.ch/
The CALICE collaboration	https://twiki.cern.ch/twiki/bin/view/CALICE/WebHome
The CMS collaboration	http://cms.ch/cms/index.html
The DREAM collaboration	