Dual readout calorimetry

general introduction and implications for CLIC

Lucie Linssen

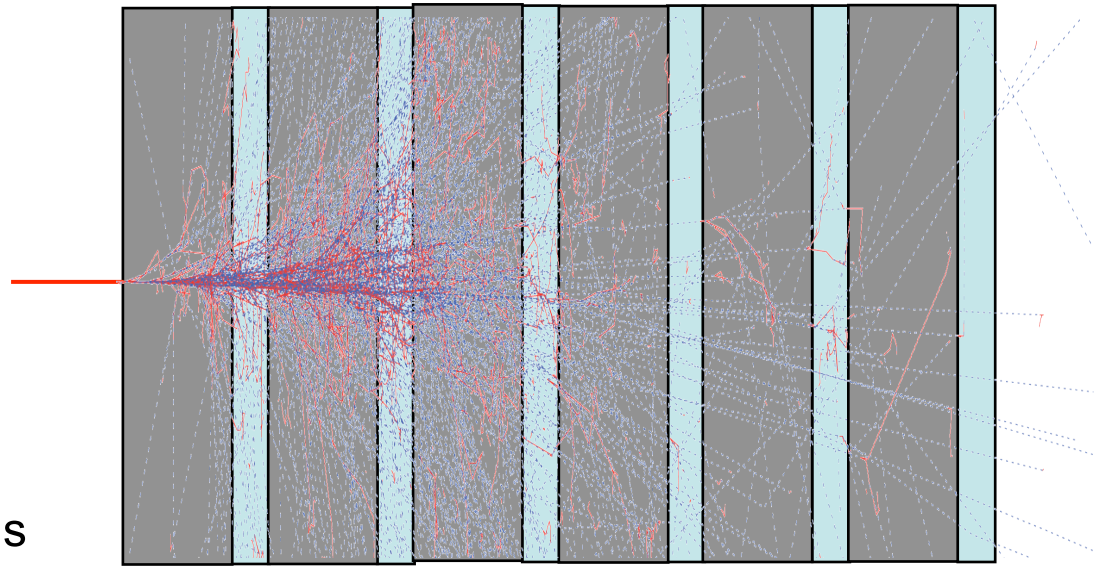
Why calorimetry?

- Measurement of individual charged and neutral particles
- Measurement of jets, mass reconstruction with jets
- Measurement of energy flow within an event
    - Transverse energy E_t, missing E_t

Important calorimetry features

- Energy resolution
- Position resolution (position and angle)
- Time resolution
- Particle Identification capability
- *Signal linearity, reliable calibration, gaussian signal distribution*

EM-shower, HAD-shower in a snapshot



Electromagnetic shower (EM):

Particles in shower: electrons, photons

Processes: bremsstrahlung, pair production

Shower depth: ~ 23 X_0 (100 GeV)

Shower width: ~ 5 ρ_M

Hadronic shower component (HAD):

Particles in shower: all types, including slow neutrons

Processes: particle processes (em, hadronic), nuclear processes

Shower depth: ~ 7-9 Λ_{int}

Shower width: ~ 1.5-2 Λ_{int}

ILC calorimetry requirements

Requirements for ILC calorimetry are dominated by:

- **High-precision jet reconstruction (mass reconstruction with jets)**
- Mass reconstruction with leptons (incl. neutrinos)
- Good π^0 reconstruction (including 2γ vertexing)

Energy resolutions required
(for ILC, with similar values for CLIC):

Electrons, photons: typically $\sigma_E/E = 15\%/\sqrt{E}$ quoted

Single Hadrons: $\sigma_E/E = 60\%/\sqrt{E}$ ← actually, momentum resolution will be used instead

Jets: $\sigma_E/E = 30\%/\sqrt{E}$ (below 100 GeV), σ_E/E = 3-4% (above 100 GeV)

(with $\sigma_E/E = 60\%/\sqrt{E}$ => $\sigma_E/E = 30\%/\sqrt{E}$ giving factor 1/1.4 in luminosity for some crucial processes)

ILC jets go up to up to ~250 GeV in energy, CLIC jets up to ~700 GeV

Composition of ILC calorimeters (PFA based)

SiD concept

HCAL

R_{min} = 141 cm, R_{max} = 253 cm

40 layers of Steel/Gas (2.0 cm + 0.8 cm)

$\lambda = 5.1$, $X_0 = 46.5$

segmentation: 1.0 cm x 1.0 cm

ECAL

20 layers 2.5 mm Tungsten +

10 layers 5 mm Tungsten

30 gaps, 1.25 mm, Silicon pixel

$\lambda = 1$, $X_0 = 29$

Moliere radius 13 mm

ILD concept

HCAL

R_{min} = 206 cm, R_{max} = 333 cm

48 layers of Steel/Scint (2.0 cm + 0.5 cm)

$\lambda = 6.0$, $X_0 = 55{,}3$

segmentation: 3.0 cm x 3.0 cm

ECAL

20 layers Tungsten of 0.6 X_0 +

20 layers Tungsten of 1.2 X_0 +

Active material: Silicon or scintillator

$X_0 = 23$

Cell sizes 5*5 mm^2

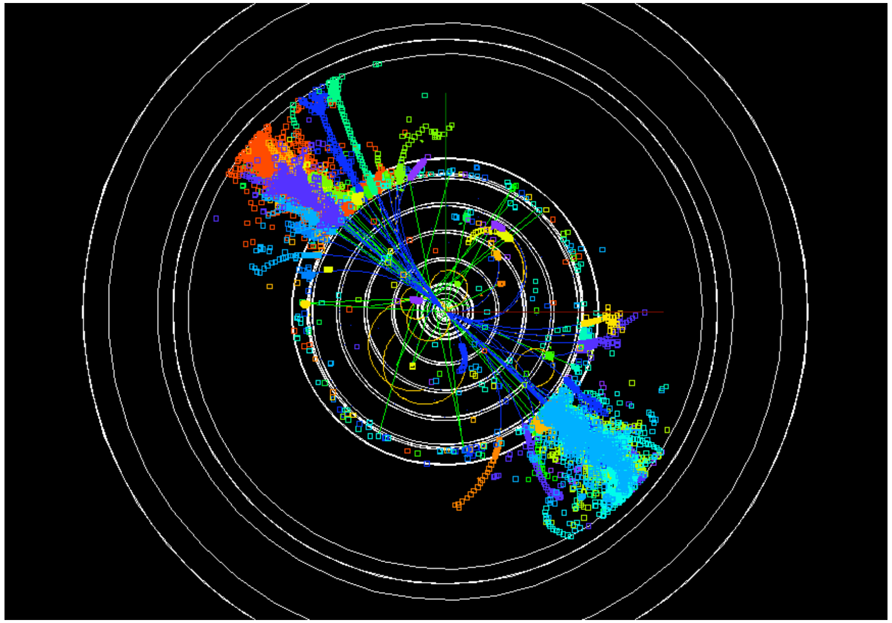
What is different for CLIC calorimetry (1)?

At CLIC particle/jet energies are higher than at ILC:

-- Need for a deep HCAL ($7\Lambda_i$ to $9\Lambda_i$, tbc)

-- Cannot increase coil radius too much => need heavy absorber

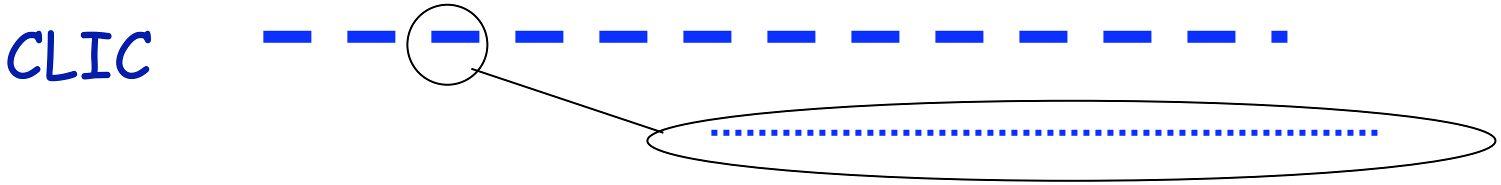
-- At higher energy jets are more compact => additional difficulty to separate particles within the jet



3 TeV e^+e^- event on SiD detector layout, illustrating the need for deeper calorimetry

What is different for CLIC calorimetry (2)?

Train repetition rate 50 Hz



CLIC:	1 train = 312 bunches	0.5 ns apart	50 Hz
ILC:	1 train = 2820 bunches	337 ns apart	5 Hz

Therefore:

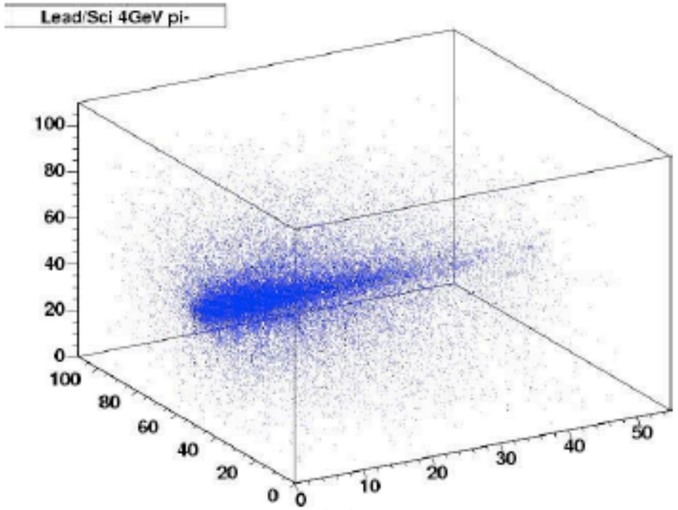
--- Overlapping background events can become a problem

--- Requires use of fast-responding detectors (e.g. no slow scintillation process)

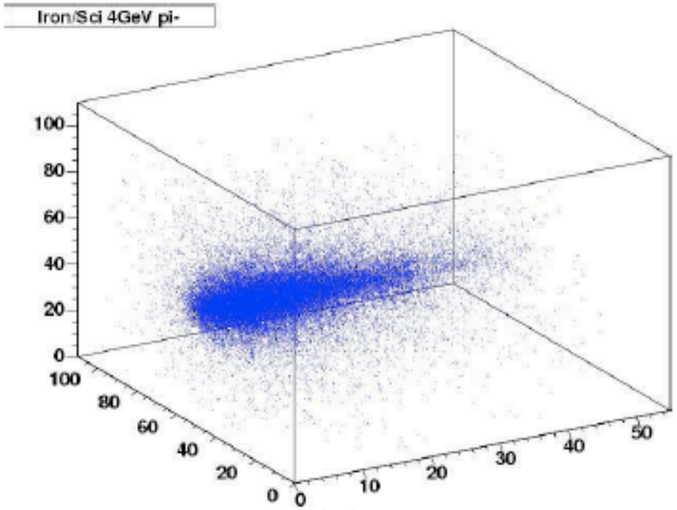
--- Detecting slow neutron shower components (with ~20 nsec decay lifetimes) may not be suitable (tbc)

Choice of materials and timing

Pb: Λi=17.1 cm, Xo=5.6 mm **Fe: Λi=16.8 cm, Xo=17.6 mm (+ scintillator)**



(a)

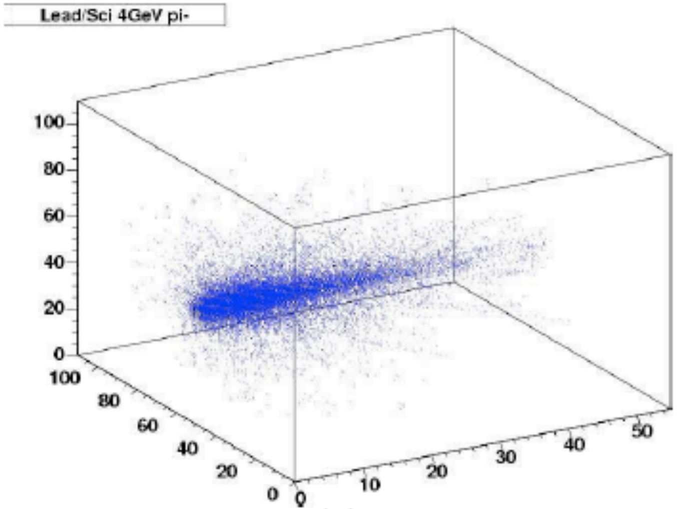


(b)

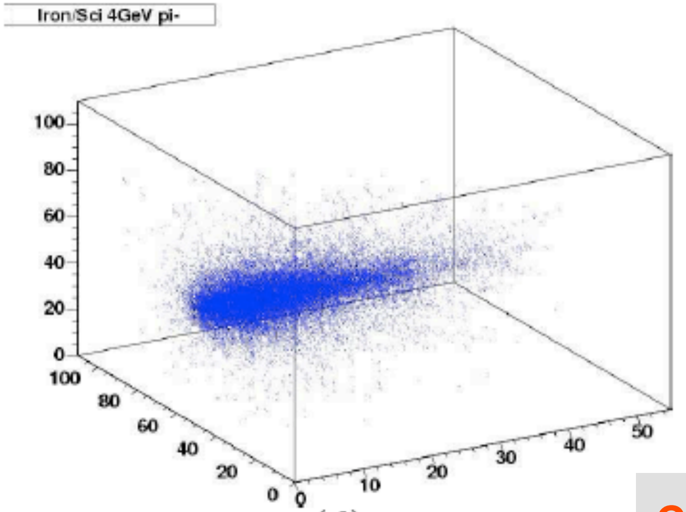
4 GeV pion

Geant4 simulation

No timing cut



(c)



(d)

With 5 ns timing cut

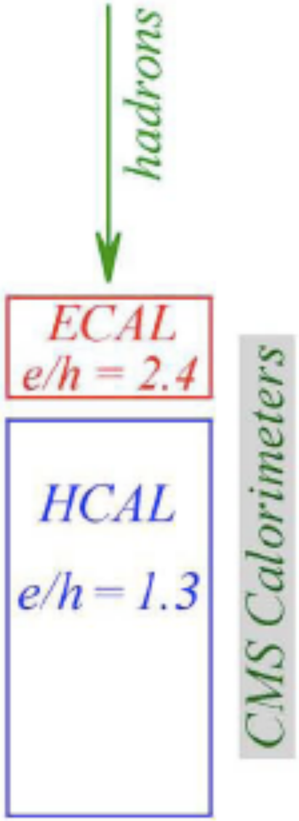
Courtesy, GLD concept

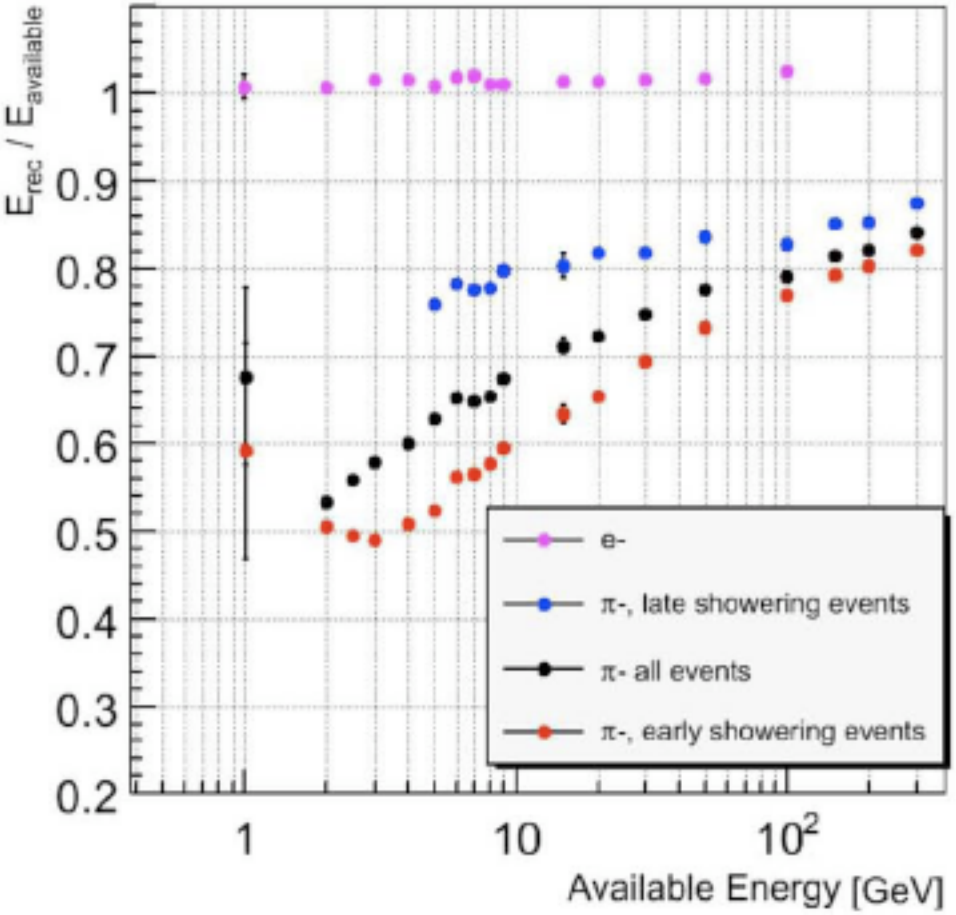
Richard Wigmans

e/h response ratio

The response of most calorimeters depends on the type of particle in the shower

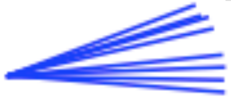
Example: CMS calorimetry ECAL e/h=2.4, HCAL, e/h=1.3



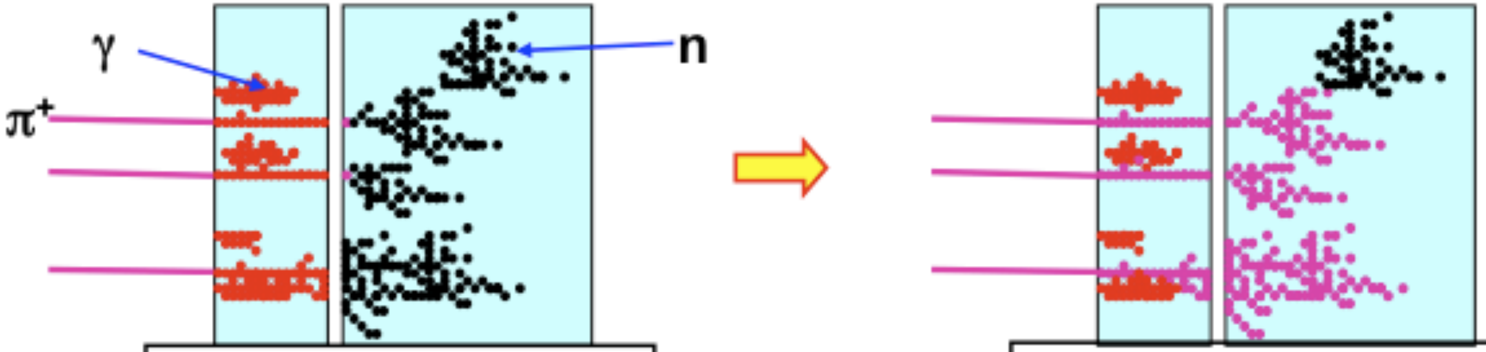


❷ The Particle Flow Paradigm

Mark Thomson



- **In a typical jet :**
  - 60 % of jet energy in charged hadrons
  - 30 % in photons (mainly from $\pi^0 \to \gamma\gamma$)
  - 10 % in neutral hadrons (mainly n and K_L)
- **Traditional calorimetric approach:**
  - Measure all components of jet energy in ECAL/HCAL !
  - ~70 % of energy measured in HCAL: $\sigma_\mathrm{E}/\mathrm{E} \approx 60\%/\sqrt{\mathrm{E(GeV)}}$
  - Intrinsically “poor” HCAL resolution limits jet energy resolution



$E_{JET} = E_{ECAL} + E_{HCAL}$

$E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$

- **Particle Flow Calorimetry paradigm:**
  - charged particles measured in tracker (essentially perfectly)
  - Photons in ECAL: $\sigma_\mathrm{E}/\mathrm{E} < 20\%/\sqrt{\mathrm{E(GeV)}}$
  - Neutral hadrons (ONLY) in HCAL
  - Only 10 % of jet energy from HCAL ⇨ much improved resolution

PFA for high-energy jets

Mark Thomson CLIC08
ILD detector description

- ★ Traditional calorimetry $\sigma_E/E \approx 60\%/\sqrt{E/\mathrm{GeV}}$
- ★ Does not degrade significantly with energy (but leakage will be important at CLIC)
- ★ Particle flow gives much better performance at "low" energies
  - very promising for **ILC**

<u>**What about at CLiC ?**</u>

- ★ PFA perf. degrades with energy
- ★ For **500 GeV jets**, current alg. and ILD concept:

$$\sigma_E/E \approx 85\%/\sqrt{E/\mathrm{GeV}}$$

- ★ Crank up field, HCAL depth…

$$\sigma_E/E \approx 65\%/\sqrt{E/\mathrm{GeV}}$$

- ★ **Algorithm not tuned for very high energy jets, so can probably do significantly better**

rms90 **PandoraPFA v03-β**

E_{JET}	$\sigma_E/E = \alpha/\sqrt{E_{jj}}$ $\lvert\cos\theta\rvert<0.7$	σ_E/E_j
45 GeV	23.8 %	3.5 %
100 GeV	29.1 %	2.9 %
180 GeV	37.7 %	2.8 %
250 GeV	45.6 %	2.9 %
500 GeV	84.1 %	3.7 %
500 GeV	64.3 %	3.0 %

63 layer HCAL (8 λ_I)
B = 5.0 Tesla

<u>**Conclude:**</u> for 500 GeV jets, PFA reconstruction not ruled out

Richard Wigmans

Dual (triple) readout method

Basic principle:

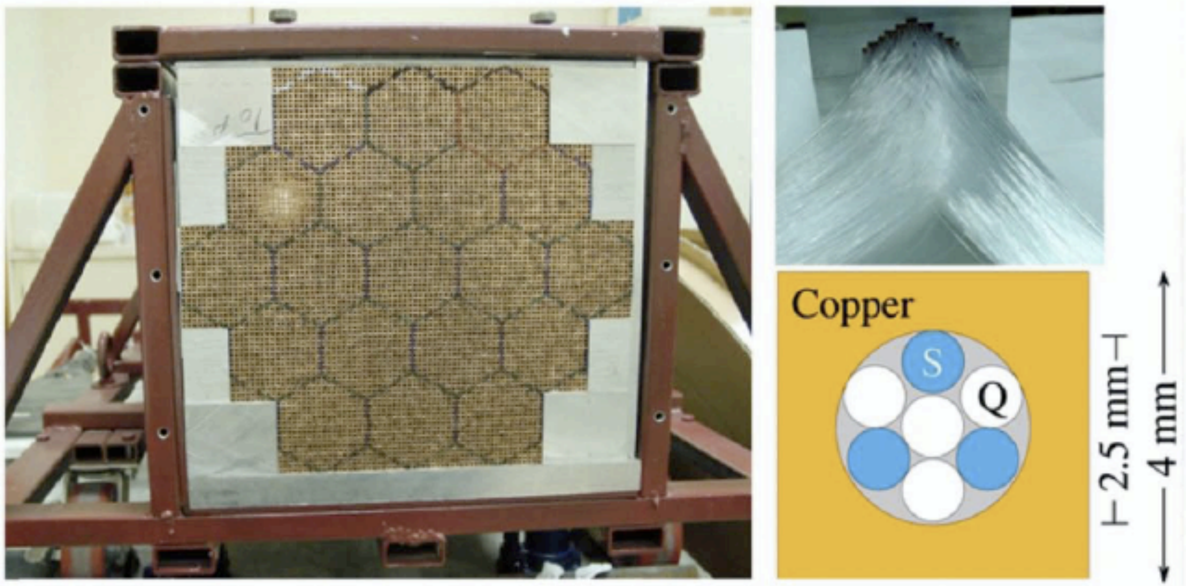
- Measure EM shower component separately
- Measure HAD shower component separately
- Measure Slow Neutron component separately

} **Dual** (first two) } **Triple** (all three)

EM-part=> electrons => highly relativistic => Cerenkov light emission

HAD-part=> “less” relativistic => Scintillation signal

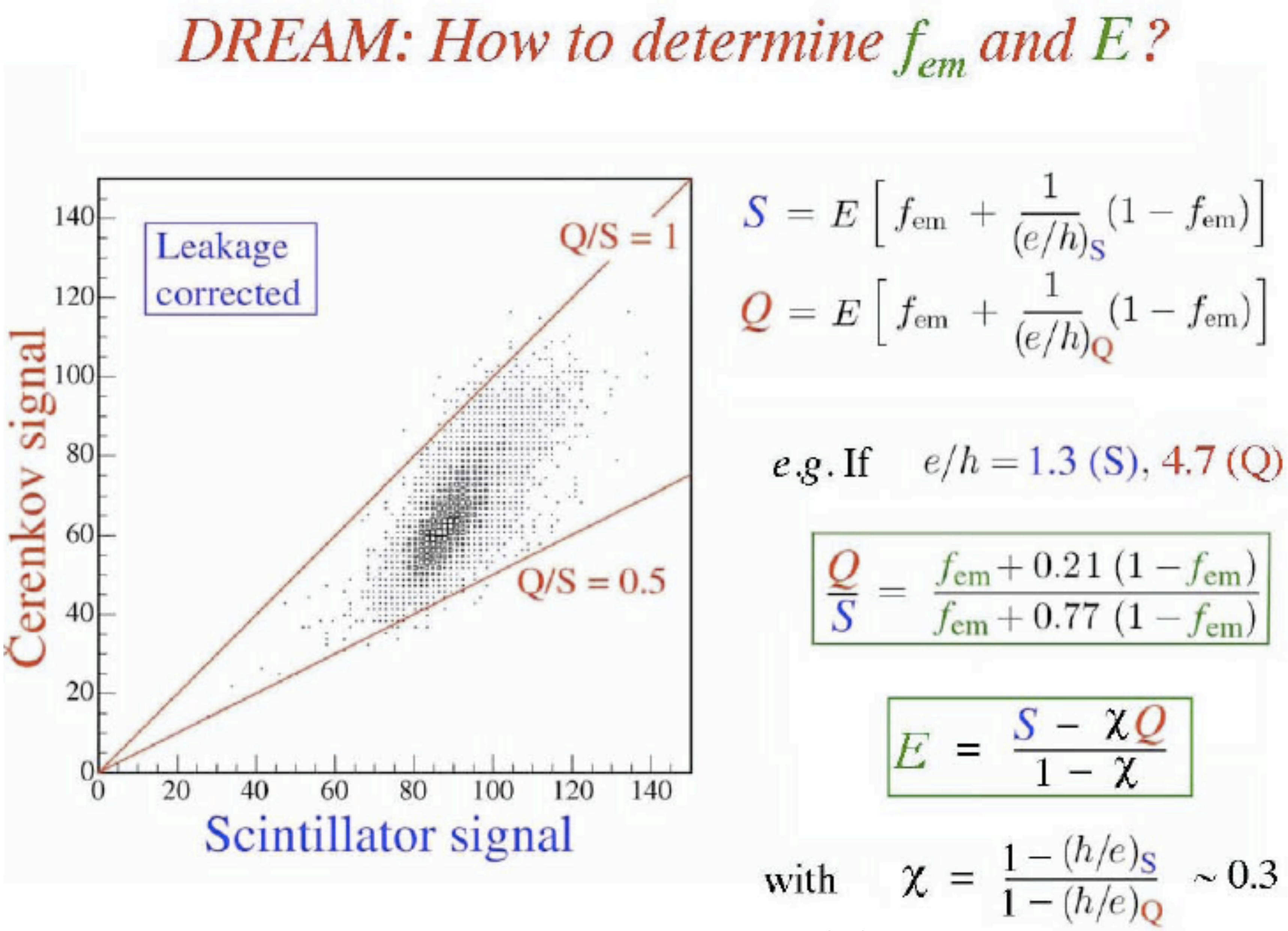
Slow neutrons => late fraction of the Scintillation signal



- *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

Application of dual read-out method

Richard Wigmans



DREAM: How to determine f_{em} and E?

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

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

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

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

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

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

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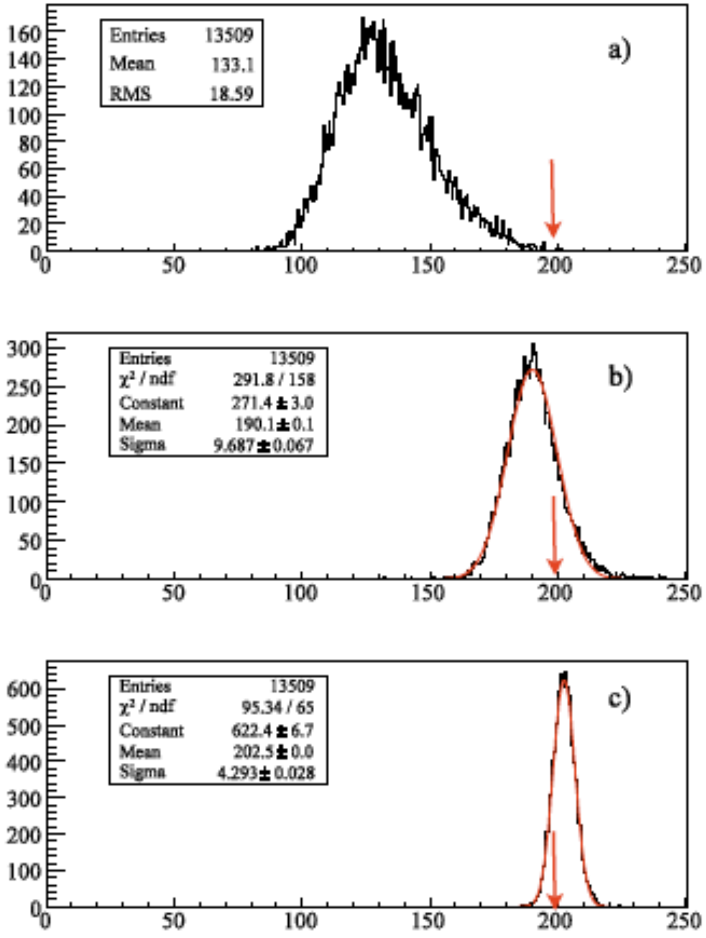
Dual readout method

DREAM data: 200 GeV π^- energy response



Scintillating (S) fibers only

Dual-readout of S and Cerenkov (C)

$$f_{EM} \propto (C/E_{shower} - 1/\eta_C)$$

(4% leakage + neutron BE loss fluctuations, and limited by photoelectron statistics in C)

Dual-readout of S and C:

$$f_{EM} \propto (C/E_{beam} - 1/\eta_C)$$

(suppresses leakage and BE fluctuations; too optimistic)

Data NIM A537 (2005) 537.

Triple => Neutron component of the shower

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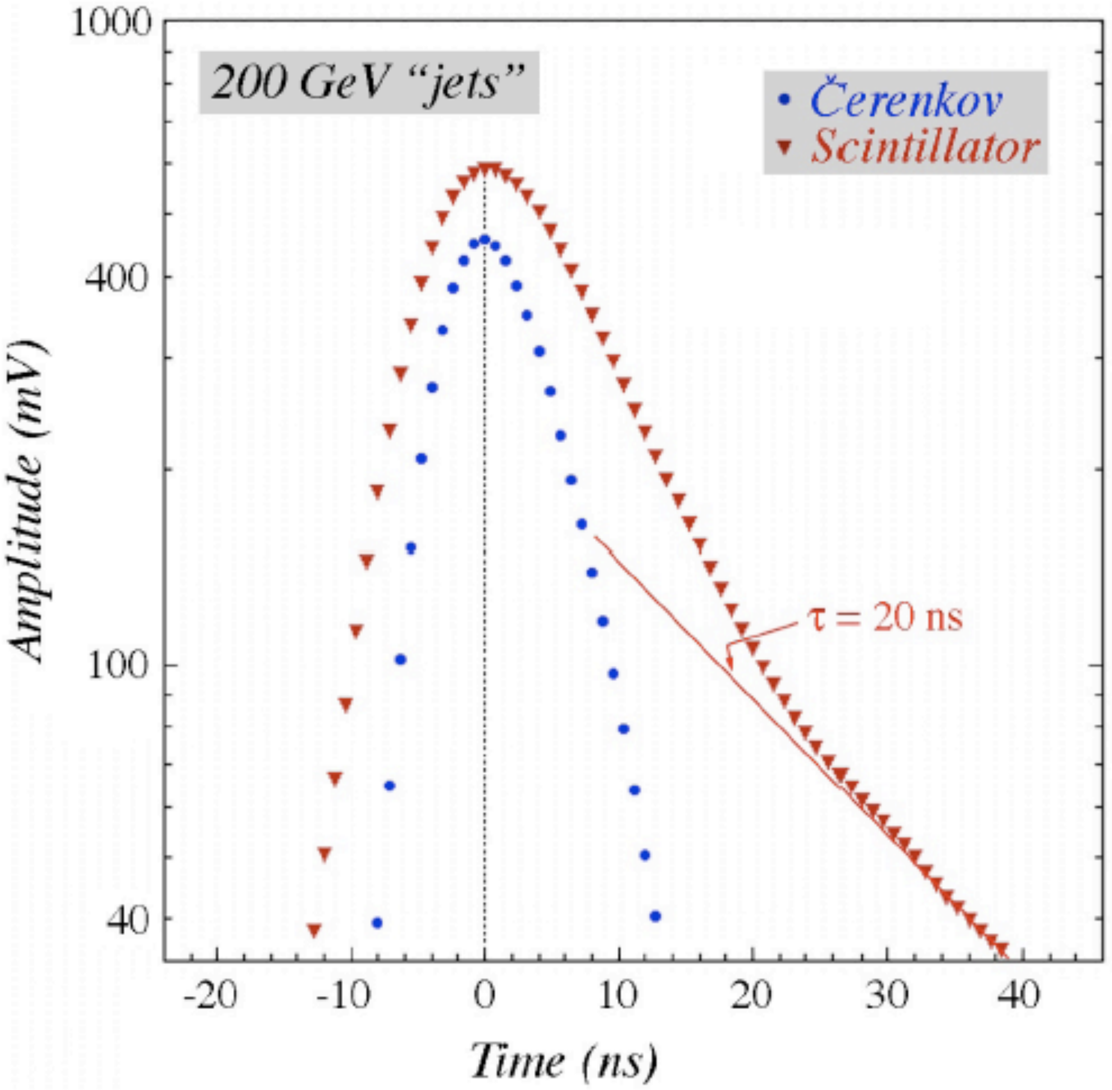


"neutron signal"
defined simply
as the integral of
the Scintillation
pulse over
20-40 ns

ILC calorimetry techniques

To improve HCAL precision new concepts/technologies are chosen:

- **Based on Particle Flow Algorithm**
  - Highly segmented (13-25 mm^2) ECAL (analog)
  - Very highly segmented ECAL (digital)
  - Highly segmented (1 cm^2) HCAL (digital)
  - Segmented HCAL (analog)
- **Based on Dual (Triple) readout**
  - Sampling calorimeter
    - Plastic fibres
    - Crystal fibres (<= materials studies)
  - Fully active calorimeter (EM part)
    - Crystal-based

Method and Engineering difficult, but conventional

Limited in energy-range to a few hundred GeV

Method and Engineering difficult and non-proven

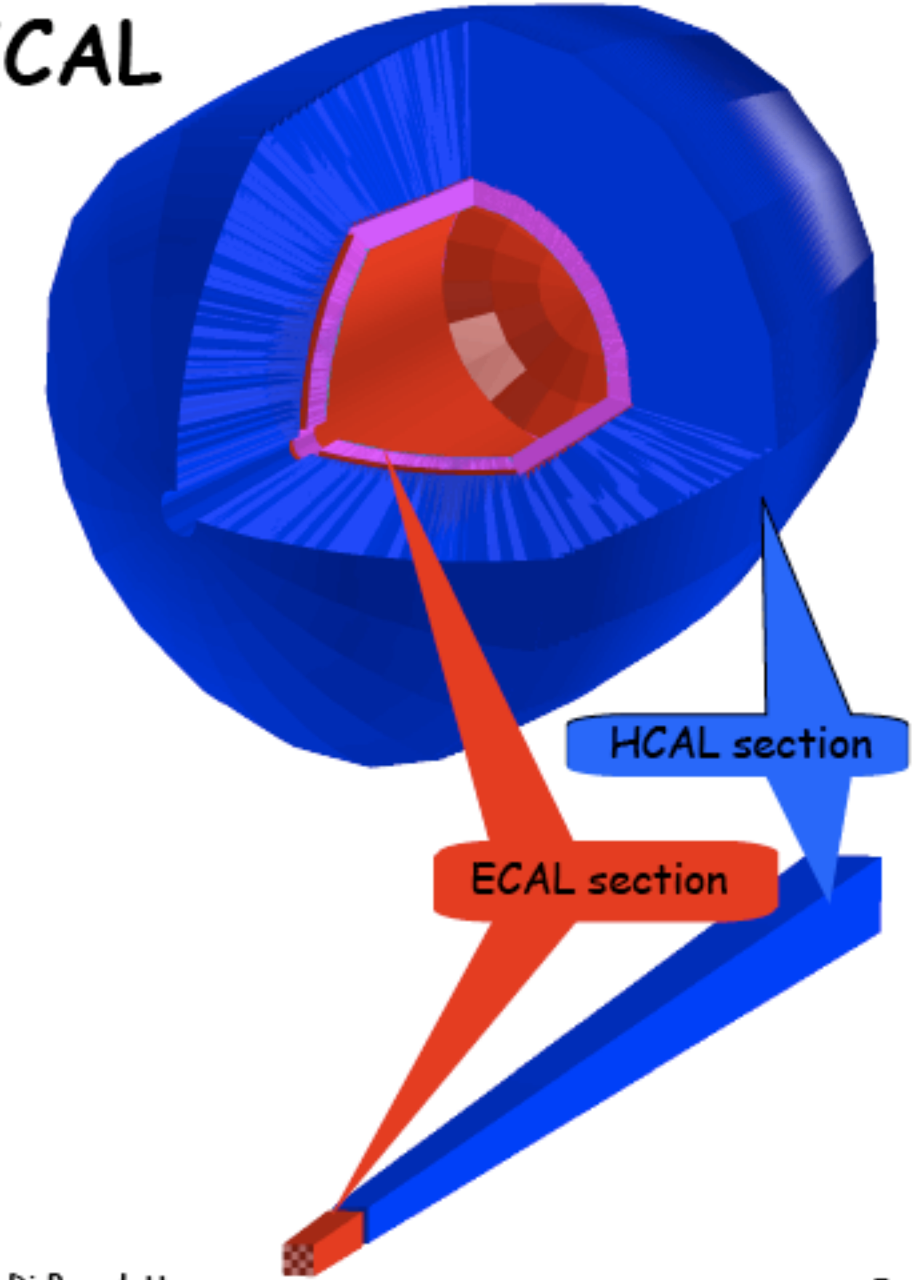
Not limited in energy range

Dual readout calorimetry research projects world-wide (incomplete and also overlapping)

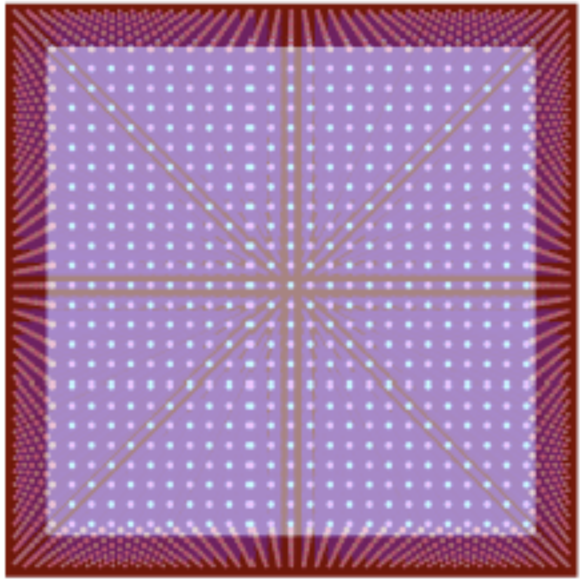
- DREAM collaboration (R.Wigmans et al.)
  - Dual readout beam tests, materials studies
- 4th concept (J. Hauptmann, C. Gatto et al.)
  - EMsection + HCAL section of full concept, mainly simulation studies
- Fermilab (A. Para et al.)
  - Crystals, light detection (SiPM), concept study
- CalTech (R-Y. Zu)
  - Properties of crystals
- CERN (P. Lecoq, E. Auffray-Hillemans)
  - Properties of: crystals, crystal fibres, metafibres
- ……..

The 4th Concept HCAL

- Cu + scintillating fibers
  + Čerenkov fibers
- ~1.4° tower aperture angle
- ~ 7.3 λ_{int} depth
- Fully projective geometry
- Azimuth coverage
  down to ~2.8°
- Barrel: 16384 towers
- Endcaps: 7450 towers

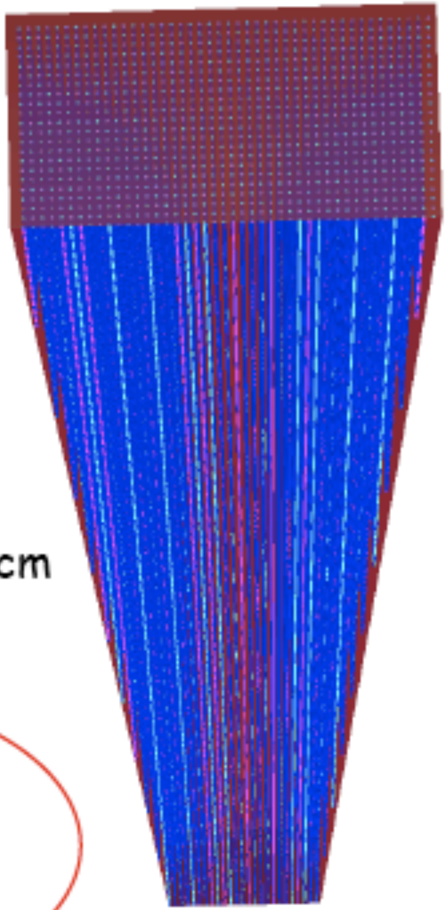


Hadronic Calorimeter Towers



Bottom view of single tower

Top tower size: ~ 8.1 × 8.1 cm²



Prospective view of clipped tower

Tower length: 150 cm

Bottom tower size: ~4.4 × 4.4 cm²

- 500 μm radius plastic fibers
- Fiber stepping ~2 mm
- Number of fibers inside each tower: ~1600 equally subdivided between Scintillating and Čerenkov
- Each tower works as two independent towers in the same volume

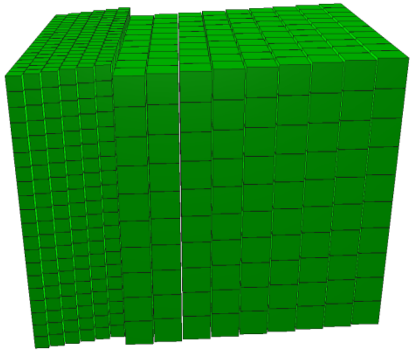
Quite the same absorber/fiber ratio as DREAM

Dual Readout Fibers Calorimeter

Adam Para, simulation studies

Conceptual Design of a High Resolution Calorimeter

- Six layers of 5 x 5 x 5 cm^3 crystals (EM section): 108,000 crystals
- three embedded silicon pixel layers (e/γ position, direction)
- 9 layers of 10 x 10 x 10 cm^3 crystals (hadronic section): 60,000 crystals
- 4(8?) SiPM per crystal. Half of the photodectors are 5x5 mm and have a low pass edge optical filters (Cherenkov)
  - No visible dead space.
  - 500,000(1,000,000?) photodetectors
- Total volume of crystals ~ 80-100 m^3.



Simulation result: $\sigma(E)/E = \sim 22\%/\sqrt{E}$ for jets

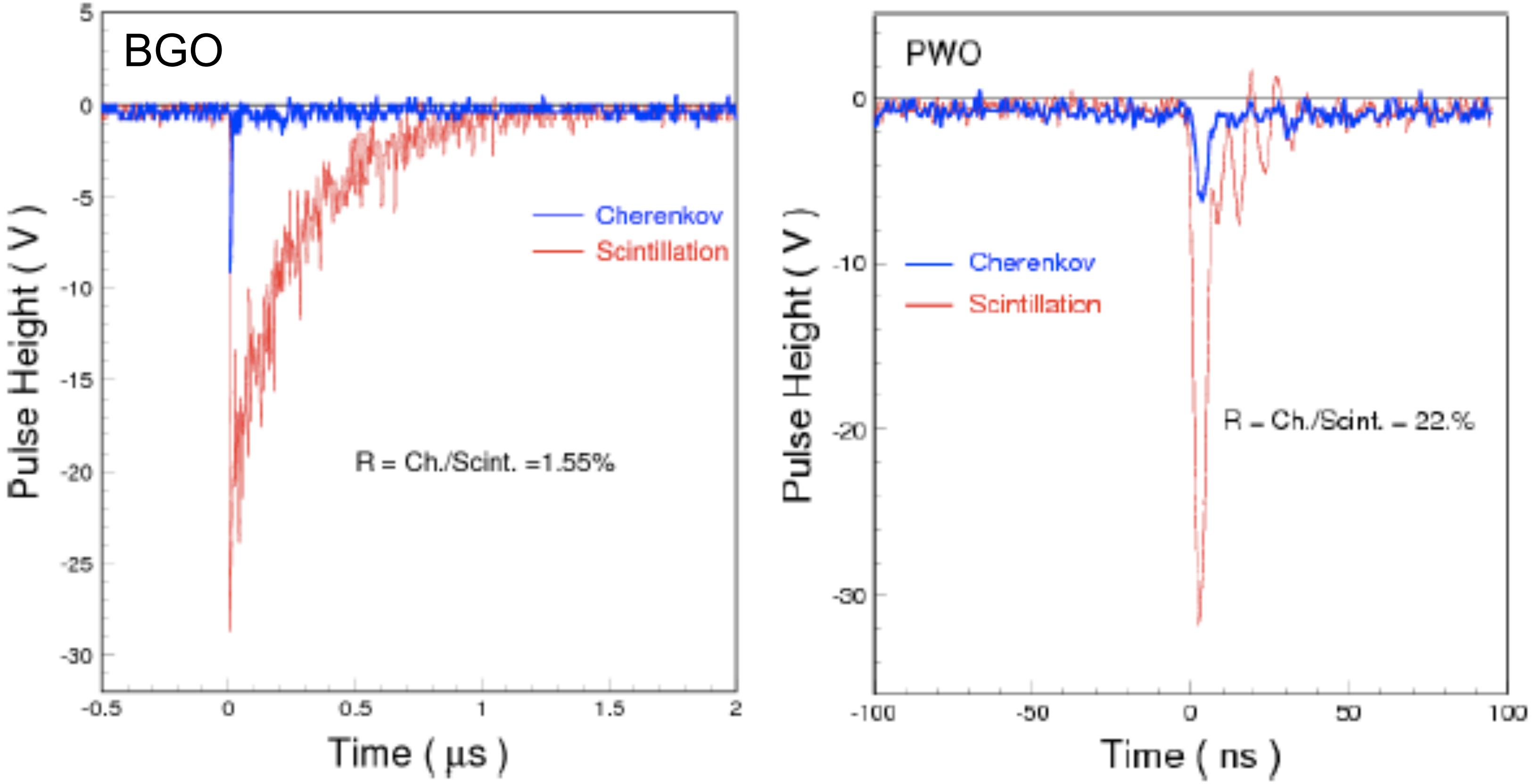
Good linearity for single particles, a bit less for jets

Vito Di Benedetto, Lecce, ILCRoot

Ren-Yuan Zhu, crystal measurements

Ratio of Cherenkov/Scintillation

1.6% for BGO and 22% for PWO with UG11/GG400 filter and R2059 PMT



Conclusions

- Dual (triple) readout is a promising scheme
- Its application is possible thanks to recent technology advances:
  - Compact photon-detectors, compatible with strong magnetic fields (e.g. SiPM)
  - Development of crystals and fibres with high density
- First beam tests indicate:
  - Excellent jet resolution
  - Good linearity over a large range
- Groups are becoming active in the field world-wide. Activities:
  - Scintillation/Cherenkov materials studies
  - Photon detector studies
  - Simulations
  - Proof-of-principle beam tests

- **What is missing?**
  - Work on a full engineering concept of a detector => convincing photon readout scheme, full hermetic and compact concept at a reasonable cost