DREAM-like approach to calorimetry

Gabriella Gaudio
INFN – Sezione di Pavia

FRASCATI DETECTOR SCHOOL
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Hadronic showers

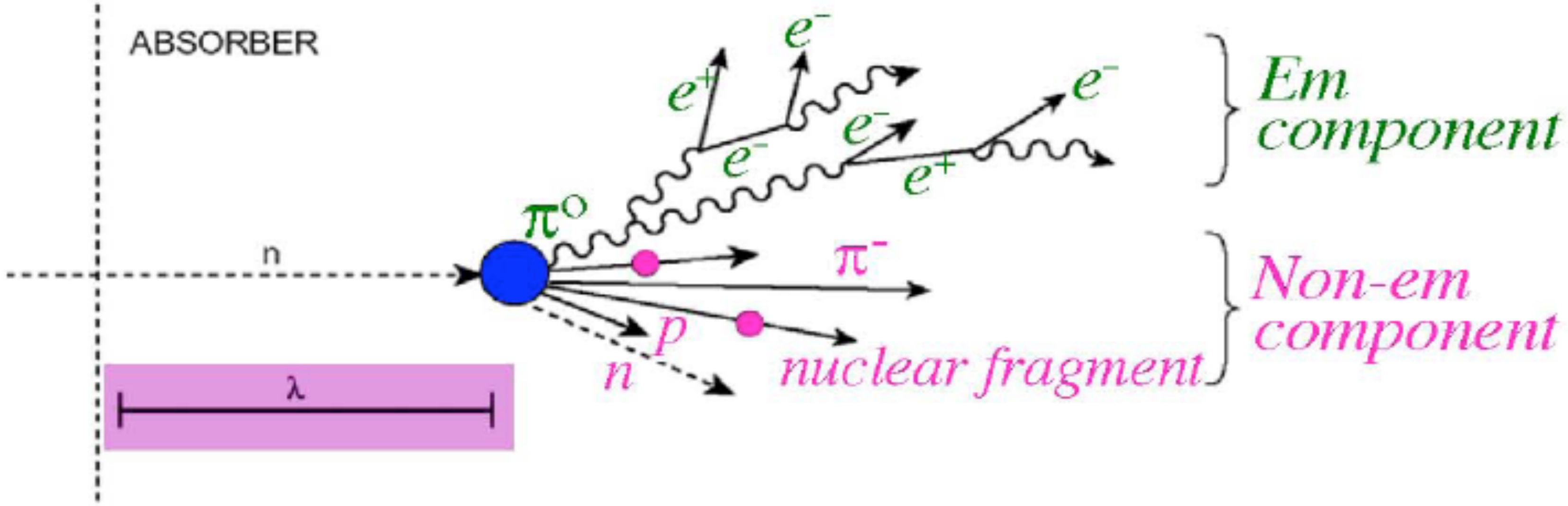
Hadronic showers consist of two components:

Electromagnetic (em) (π^0, η, γ) and non-em components

- The calorimeter response to these two components is typically very different
- Hadronic showers are characterized by very large fluctuations due the energy sharing between these two components

1. f_{em} varies event-by-event (fluctuation in calorimetry response) and grows with energy (non linearity)
2. fluctuation in the amount of invisible energy

electrons positrons, photons, π^0



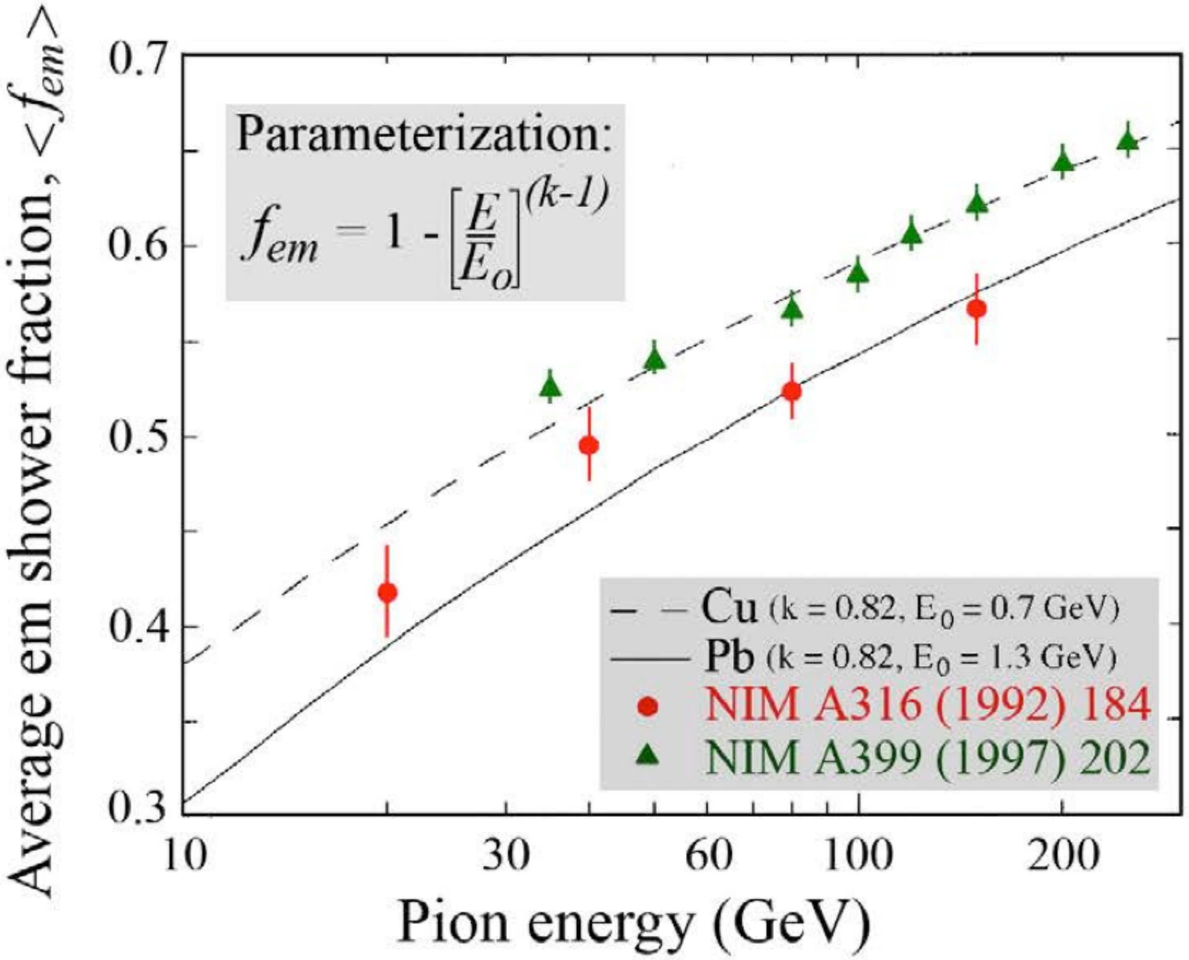
Charged hadrons (π,k…), nuclear fragments, neutrons, neutrinos, breakup of nuclei (invisible energy)

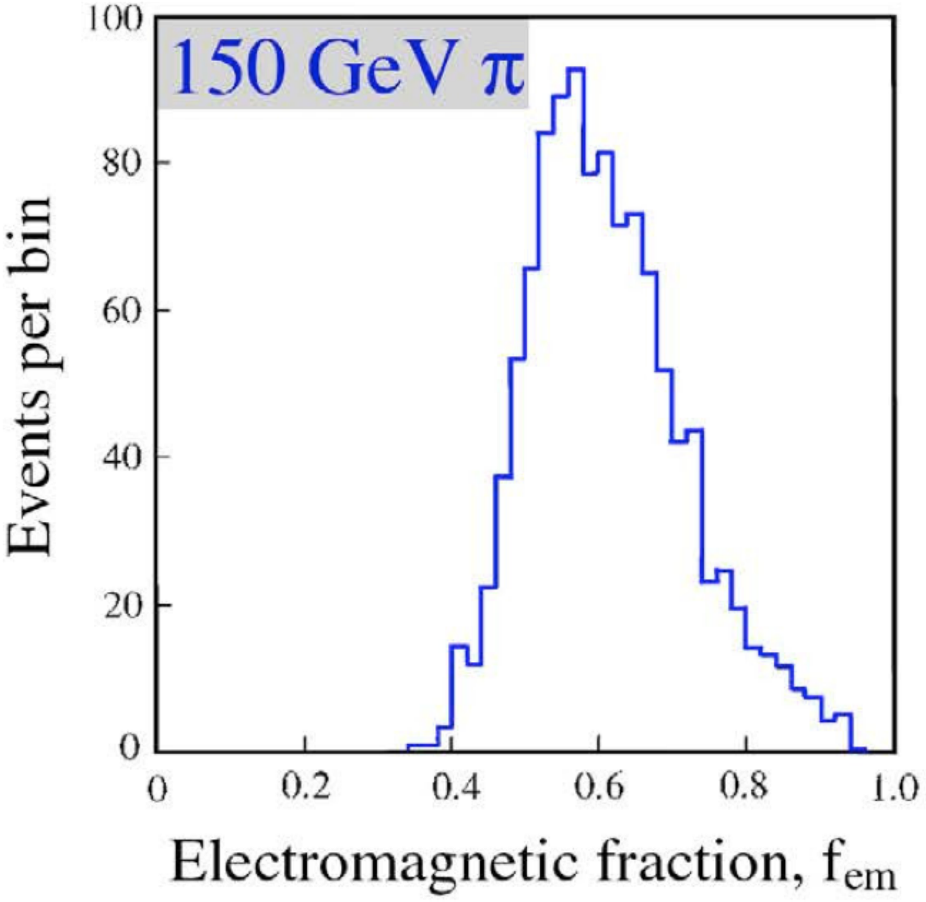
The electromagnetic fraction

- π_0 decays into 2 photons start an electromagnetic shower (f_{em})
  - f_{em} grows with energy → *non-linearity*
  - f_{em} varies event-by-event → *fluctuation in calorimetry response*

$$\langle f_{em} \rangle = 1 - \left(E / E_0 \right)^{(k-1)}$$

E_0 = average energy to produce a π^0
(k-1) related to average multiplicity



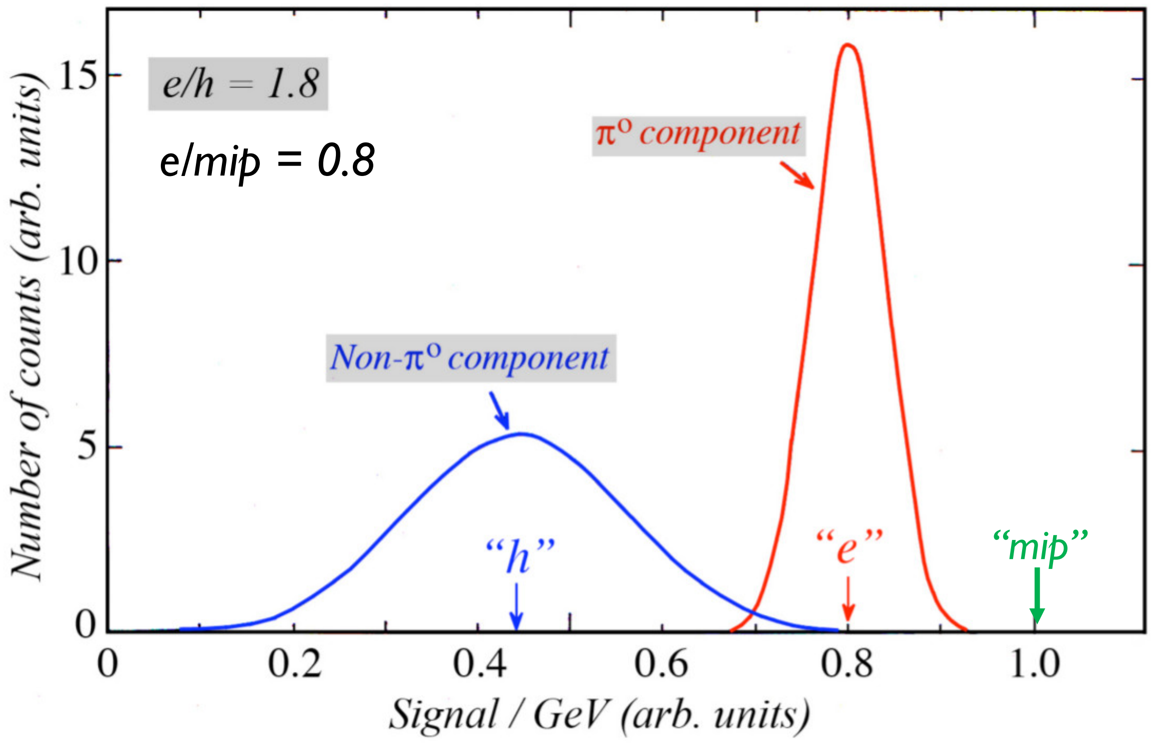


Calorimeter Response

The detector response to the em (e) and non-em (h) components is NOT the same

This effect is quantified by the e/h ratio

In this example, only 1/1.8 ≈ 56% of non-πo energy is accounted in the signal



Take care:

The e/h ratio is a detector characteristic (typically, for crystals is ~2, for sampling calorimeters is in range 1-1.8), nevertheless:

1) e/π depends on energy (*fem depends on E and shower "age"*)
2) fem different for π, K, p → response depends of particle type

What compensation does and does not for you

- Compensation does not guarantee high resolution
  - Fluctuations in f_{em} are eliminated, but others may be very large
- Compensation has some drawbacks
  - High Z absorber required → small e/mip → non linearity
  - Small sampling fraction required → em resolution limited

$$\frac{\sigma}{E} = 2.7\% \frac{\sqrt{d/f_{sampl}}}{\sqrt{E}}$$

  - Relies on neutrons → calorimeter signals have to be integrated over large volume and time. SPACAL's $30\%/\sqrt{E}$ needed 15 tonnes and 50 ns. Not always possible in practice
- High-resolution electromagnetic and high-resolution hadronic calorimetry are mutually exclusive:
  - Good jet energy resolution ⇒ Compensation ⇒ very small sampling fraction (~ 3%) ⇒ poor electron/photon resolution
  - Good electromagnetic resolution ⇒ high sampling fraction (100% Crystals, 20% LAr) ⇒ large non compensation ⇒ poor jet resolution

Principles of Dual Readout Calorimetry

Simultaneous measurement on event-by-event basis of elm fraction of hadron showers

Cherenkov light C	only produced by relativistic particles, dominated by electromagnetic shower component
Scintillation light S	measure dE/dx

$$S = [\ f_{em} + (\mathrm{h/e})_{s} \times (1 - f_{em})\ ] \times E$$
$$C = [\ f_{em} + (\mathrm{h/e})_{c} \times (1 - f_{em})\ ] \times E$$

e/h ratio of the C (S) calorimeter structure (measured)

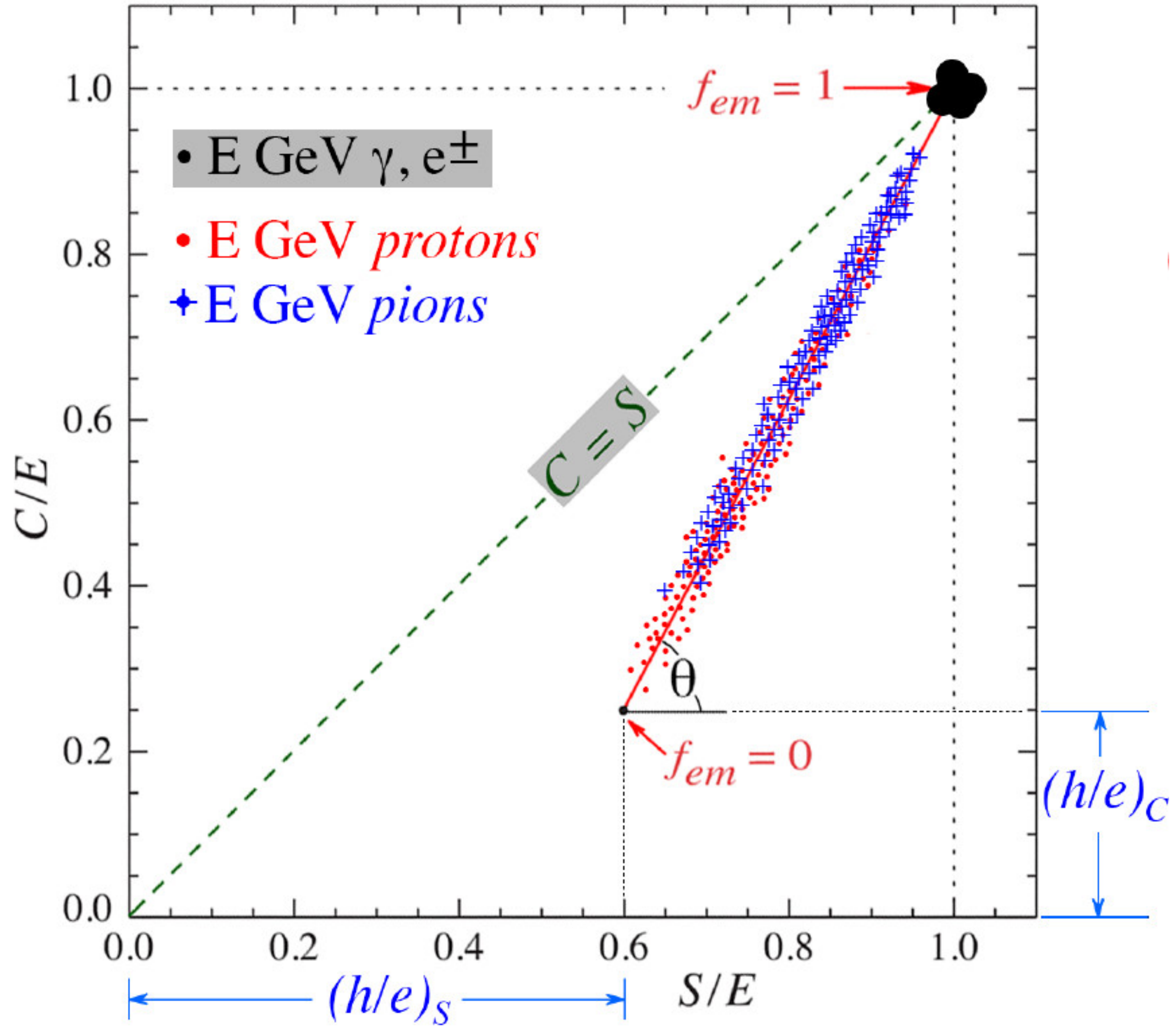
$$c = (h/e)_C$$
$$s = (h/e)_S$$

It is possible to evaluate $f = \dfrac{c - s(C/S)}{(C/S)(1-s) - (1-c)}$ and $E = \dfrac{S - \lambda C}{1 - \lambda}$

Principles of Dual Readout Calorimetry

$$S/E = f_{em} + (h/e)_s \times (1 - f_{em})$$

$$C/E = f_{em} + (h/e)_c \times (1 - f_{em})$$



$$cotg\,\theta = \frac{1-(h/e)_S}{1-(h/e)_C} = \chi$$

Θ, χ independent of both

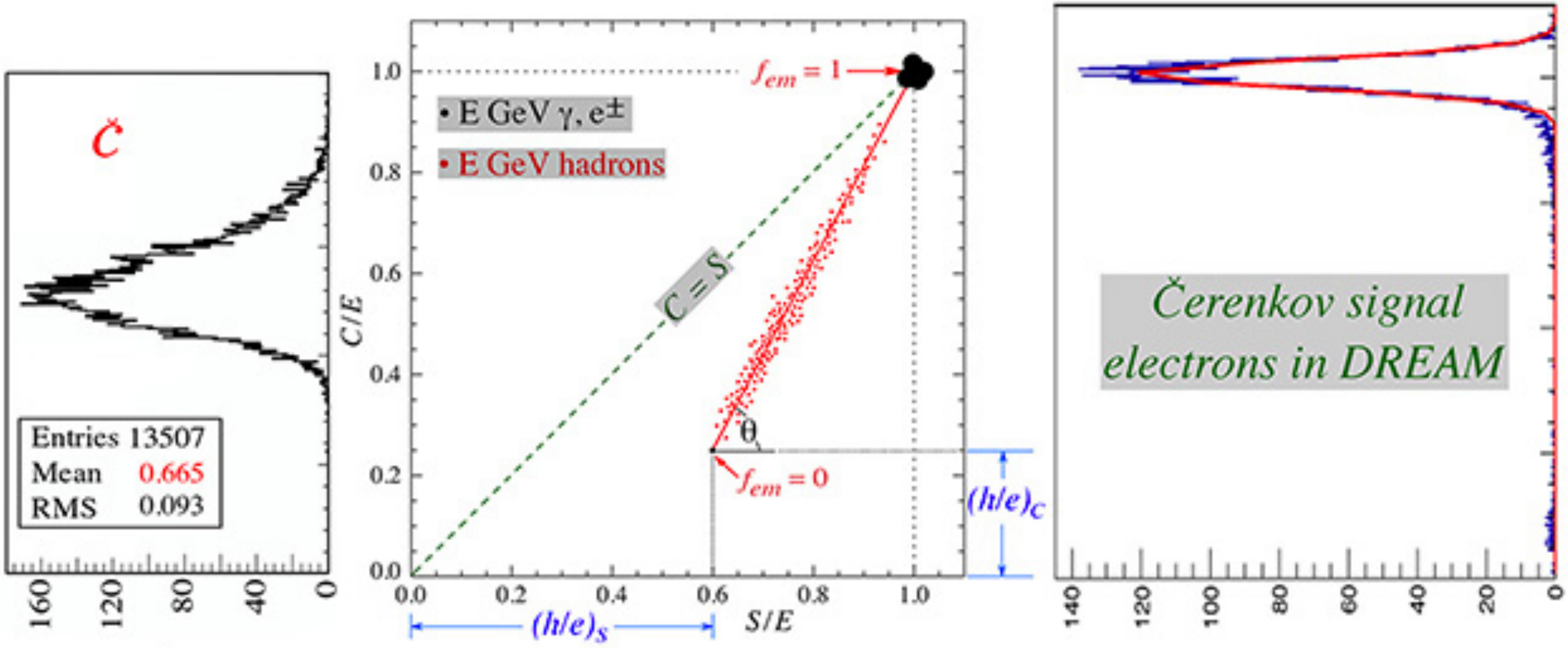
- energy
- type of hadron

$$E = \frac{S - \chi C}{1 - \chi}$$

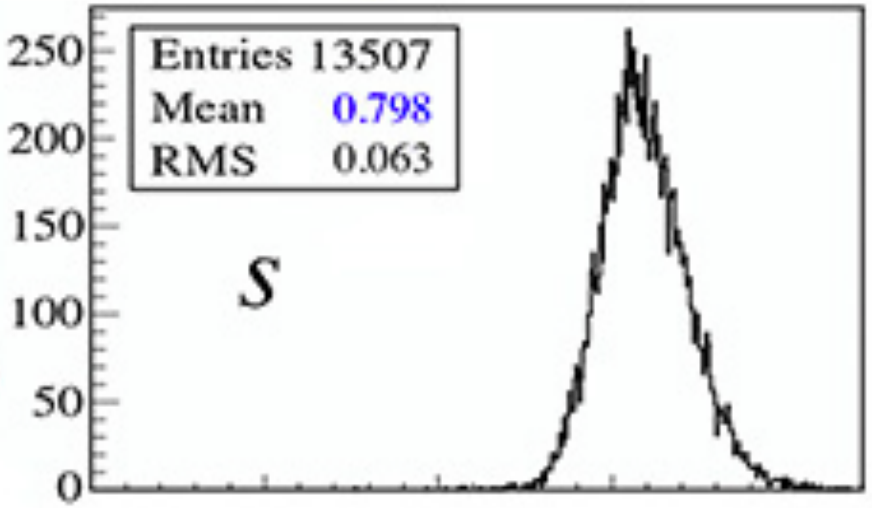
is universally valid

Calorimeter calibration done with electrons

Before Correction

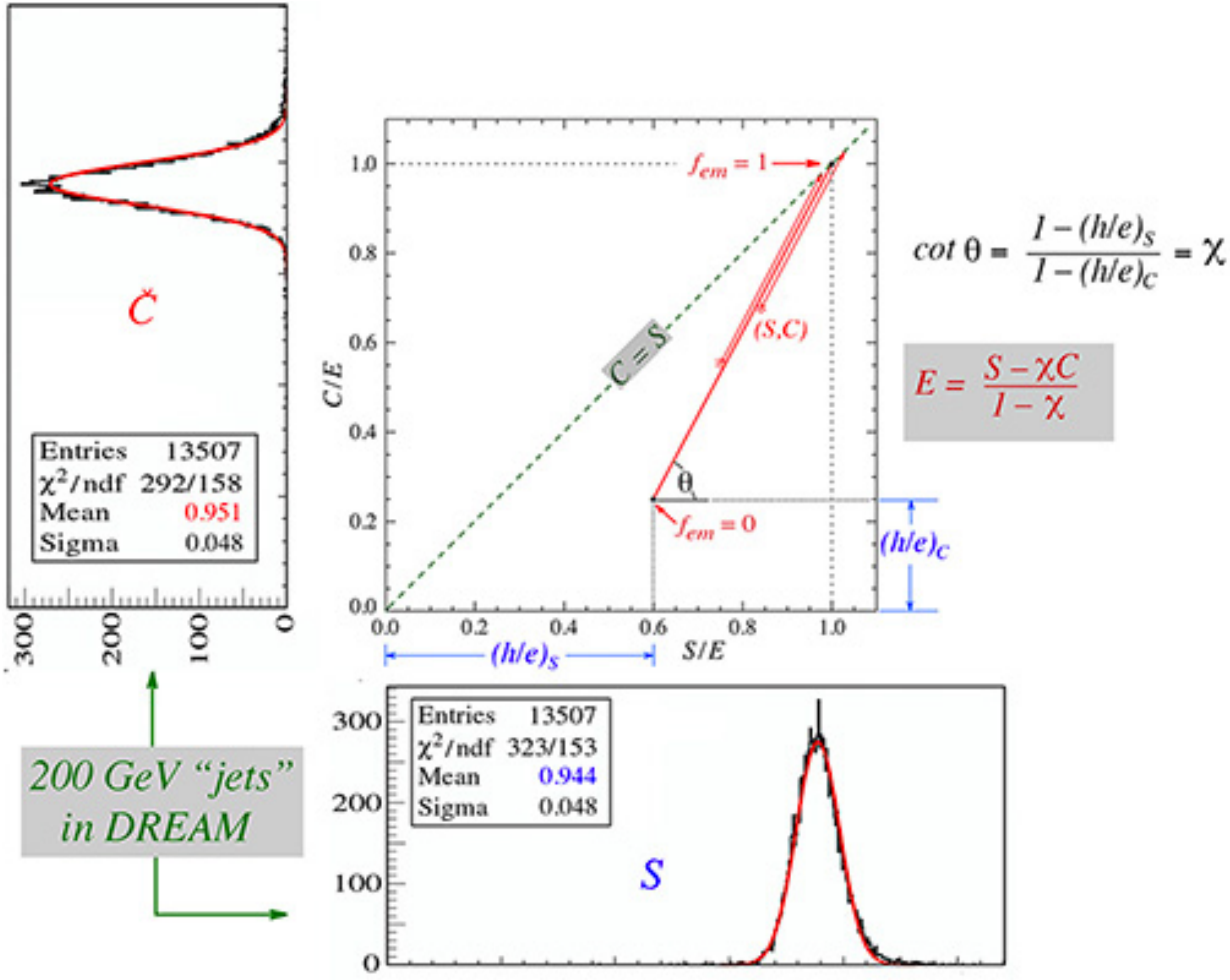


200 GeV "jets" in DREAM



- Calculate C/S ratio event-by-event
- Calculate fem
- Obtain corrected C and S and Energy which one would obtain if fem=1 (em scale calibration)

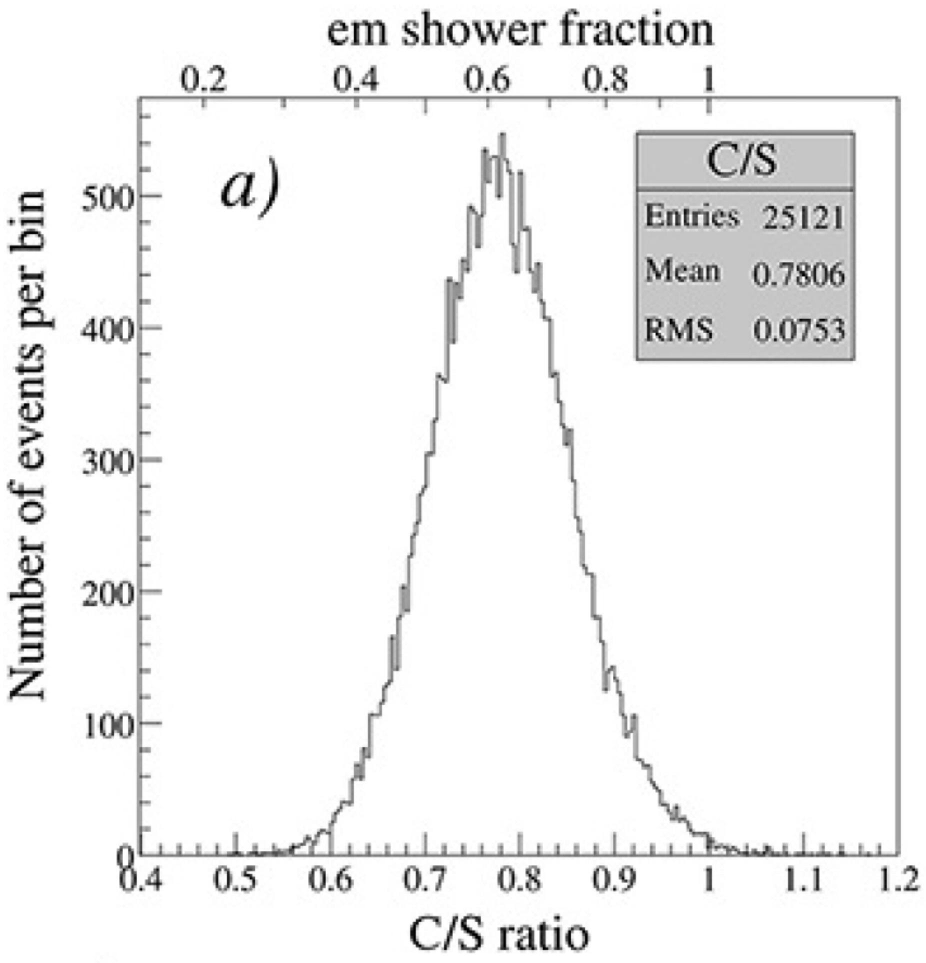
After Dual Readout approach



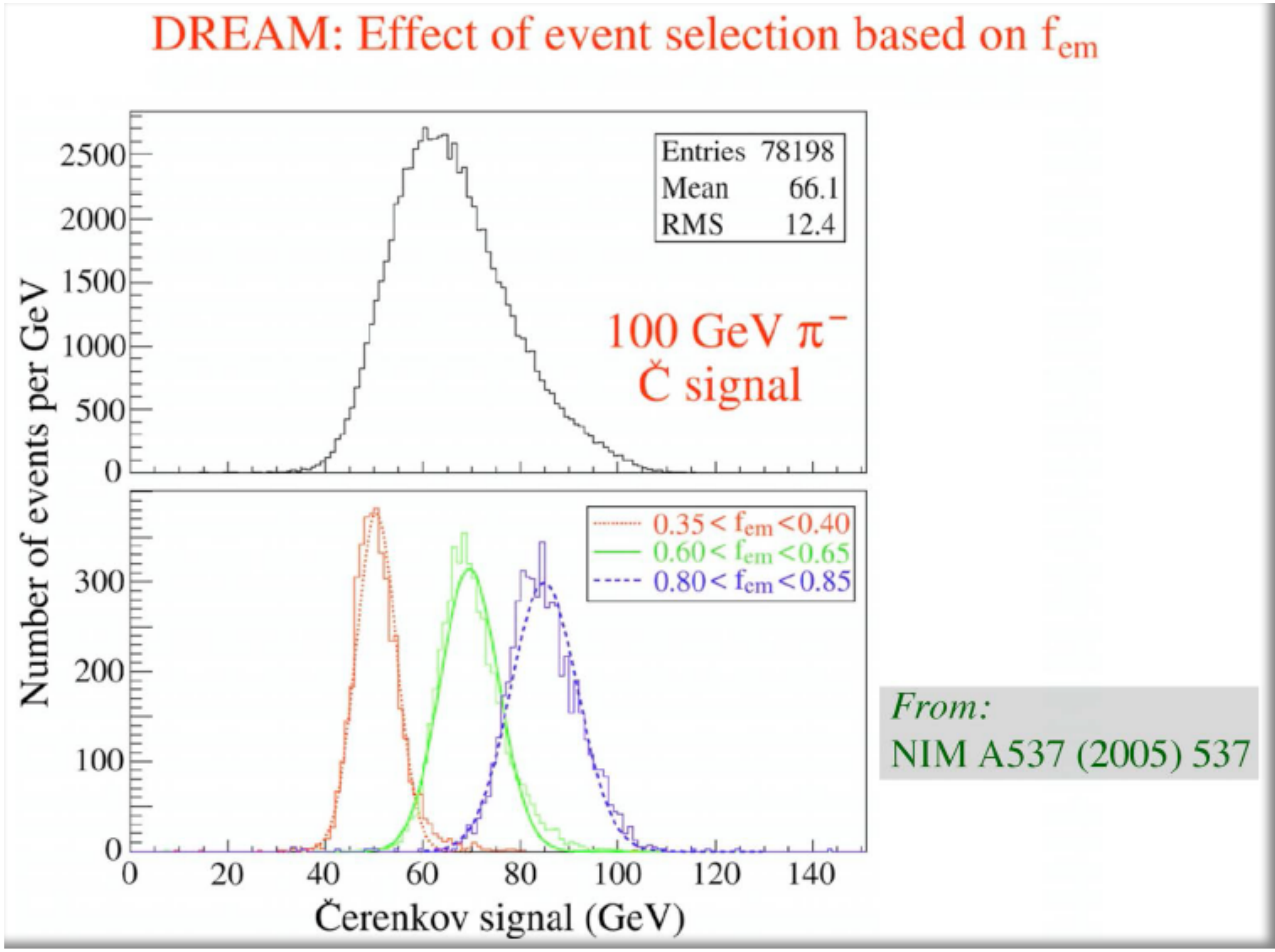
$$\cot\theta = \frac{1-(h/e)_S}{1-(h/e)_C} = \chi$$

$$E = \frac{S-\chi C}{1-\chi}$$

E.M. Fraction Fluctuation

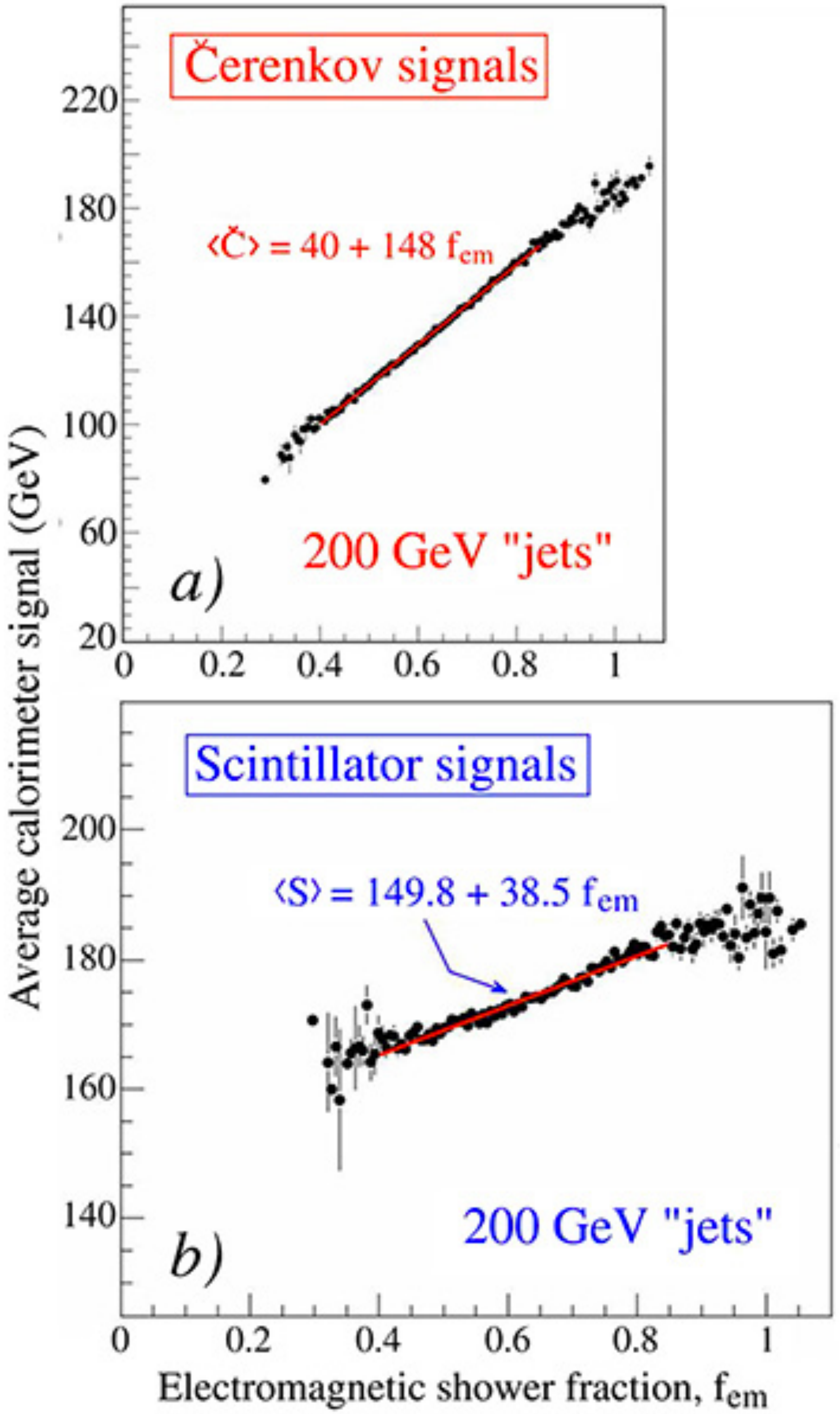


$$f = \frac{c - s(C/S)}{(C/S)(1-s) - (1-c)}$$


DREAM: Effect of event selection based on f_{em}

From:
NIM A537 (2005) 537

Measuring h/e



$$C/E = f_{em} + (h/e)_c \times (1 - f_{em})$$
$$S/E = f_{em} + (h/e)_s \times (1 - f_{em})$$

$$C = E \times [(h/e)_C + f_{em}(1 - (h/e)_C)]$$
$$S = E \times [(h/e)_S + f_{em}(1 - (h/e)_S)]$$

From the linear fit it is possible to determine the (e/h) values for both calorimeter structure (scintillation and Cherenkov)

Invisible Energy

- In nuclear reactions some energy has to be provided (binding energy) to free protons and neutrons.
- This energy doesn't result in a measurable signal (*invisible energy*)
- Invisible energy accounts on average for about 30-40% of non-em shower energy

Large event-by-event fluctuations limit resolution

Correlation between invisible energy and kinetic energy carried by released nucleons

Evaporation nucleons: soft spectrum, mostly neutrons (2-3 MeV)

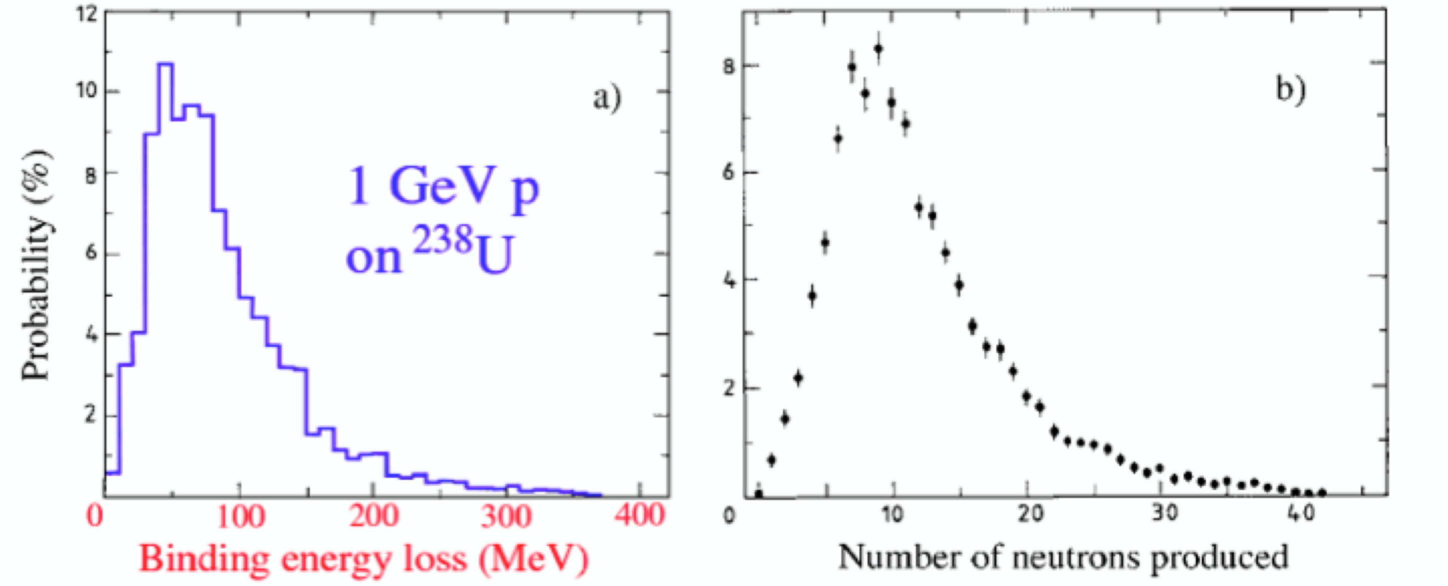
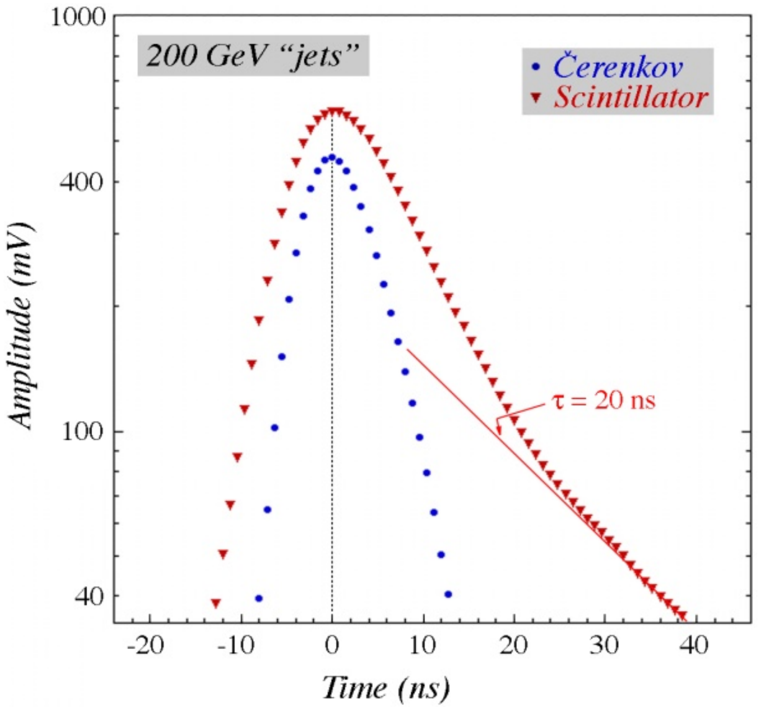


FIG. 4.43. The nuclear binding energy lost in spallation reactions induced by 1 GeV protons on ^{238}U nuclei (*a*), and the number of neutrons produced in such reactions (*b*). From [Wig 87].

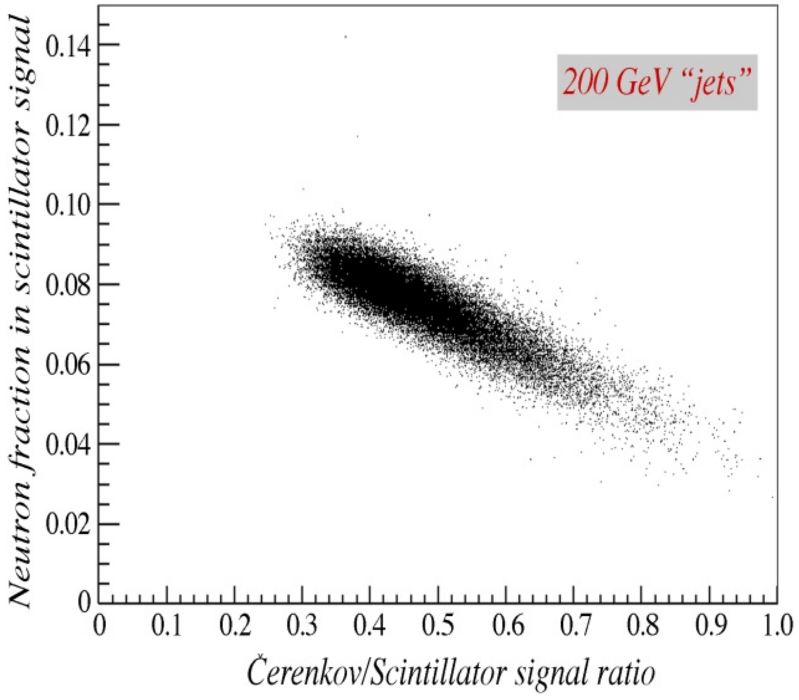
Invisible Energy

Measurement of the kinetic energy of neutrons which is correlated to nuclear binding energy loss (invisible energy) from time structure of the signal (*NIM A 598 (2009) 422)*

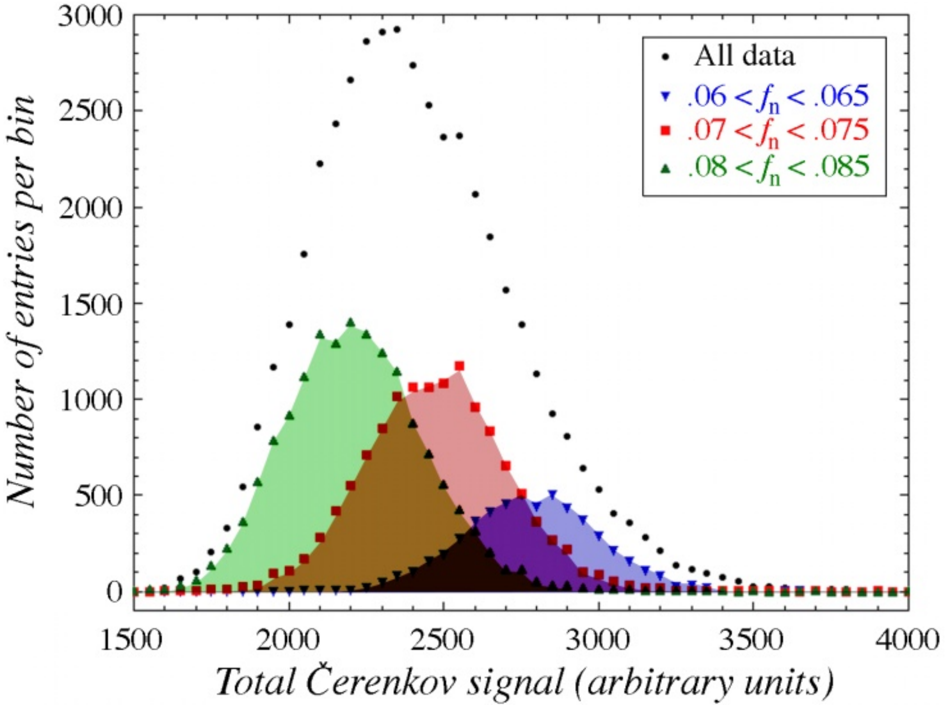
Time structure of DREAM signal.
Tail absent in em showers



N fraction anti-correlated
to f_{em} (C/S)



Probing the tot. signal distribution with
N fraction



Dual Readout R&D

Homogeneous Calorimeter	**Sampling Calorimeter**
Possibility to solve light yield and sampling fluctuation problem. Need to separate C and S light.	Two types of fibers, either sensitive to Cherenkov and Scintillation Separated by construction

RD52 coll

2007-11 **Crystals DRC**

Single Xtals, prove of principles

- $PbWO_4$ + Pr, Mo doped $PbWO_4$
- BGO
- BSO

NIM A 638 (2011) 47
NIM A 640 (2011) 91
NIM A 621 (2010) 212
NIM A 604 (2009) 512
NIM A 593 (2008) 530
NIM A 595 (2008) 359

Matrixes + DREAM, em section

- $PbWO_4$
- Doped $PbWO_4$
- BGO

NIM A 598 (2009) 710
NIM A 686 (2012) 125
NIM A 610 (2009) 488
NIM A 584 (2008) 273

DREAM coll

2003 - 11 ***DREAM Cu-fiber***

NIM A 533 (2005) 305
NIM A 536 (2005) 29
NIM A 537 (2005) 537
NIM A 548 (2005) 336
NIM A 550 (2005) 185
NIM A 581 (2007) 643
NIM A 598 (2009) 422

RD52 coll

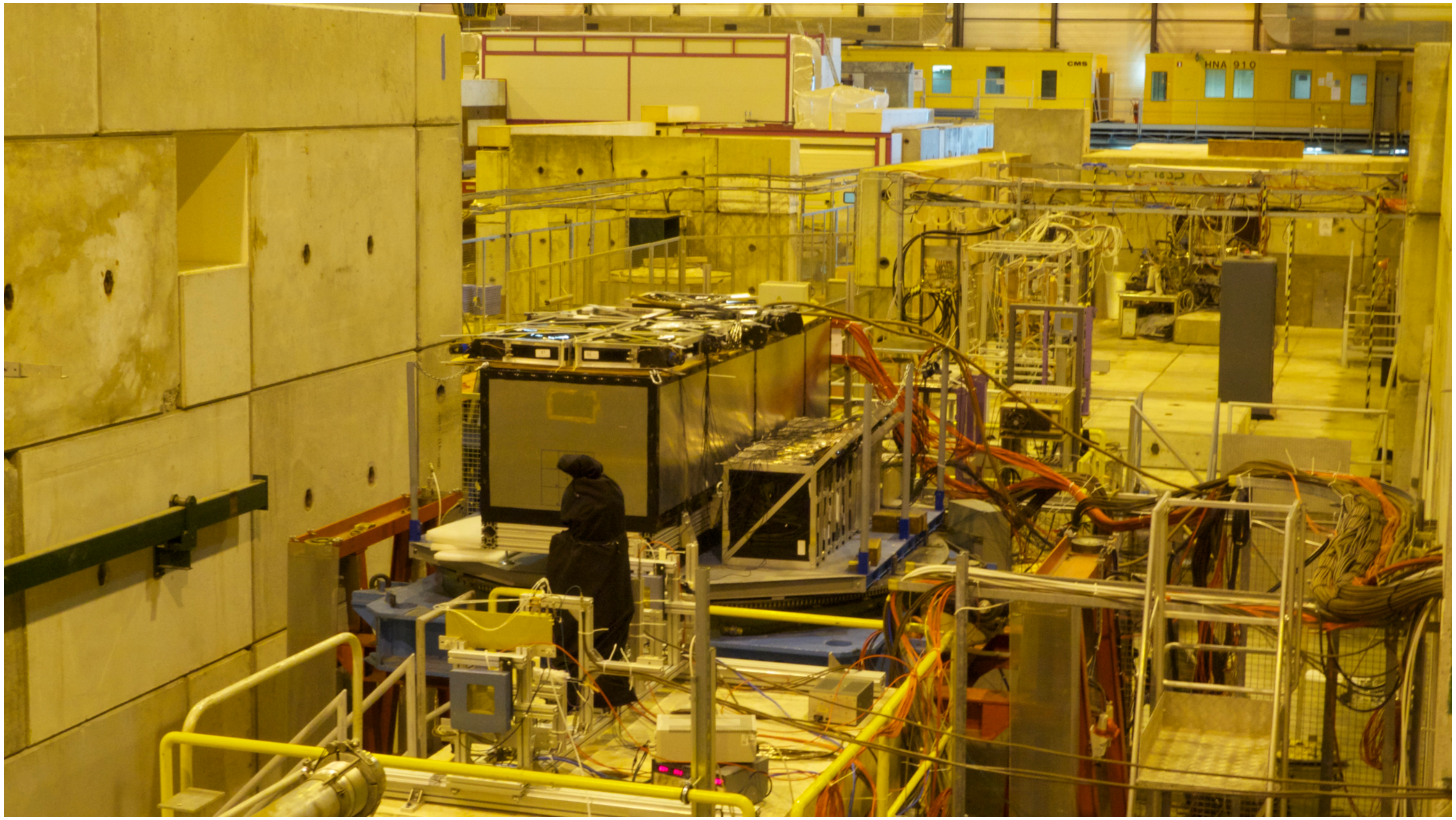
2010 ***Pb - Tile DRC***

INST 9, (2014) C05009

2012- 16 ***Cu, Pb Fiber DRC***

NIM A 762 (2014) 110
NIM A 735 (2014) 120
NIM A 735 (2014) 130
NIM A 808 (2016) 41

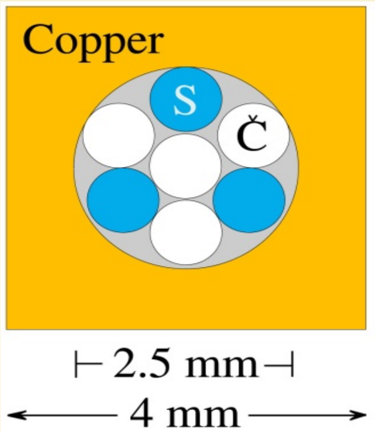
Dual readout with sampling fiber calorimeters

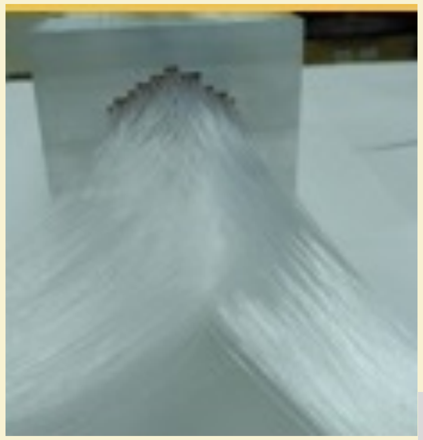


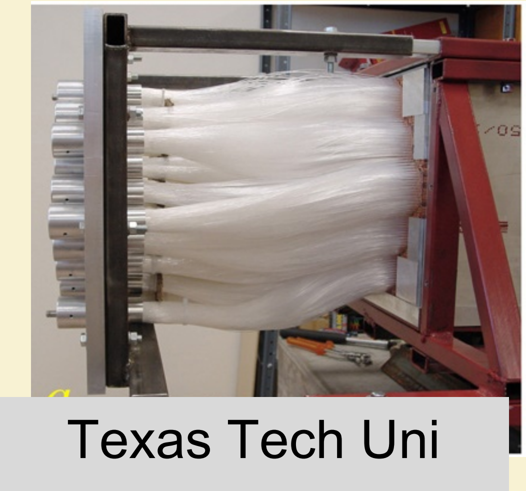
The dual readout fiber calorimeters

2003
DREAM

Copper
2m long, 16.2 cm wide
19 towers, 2 PMT each
Sampling fraction: 2%



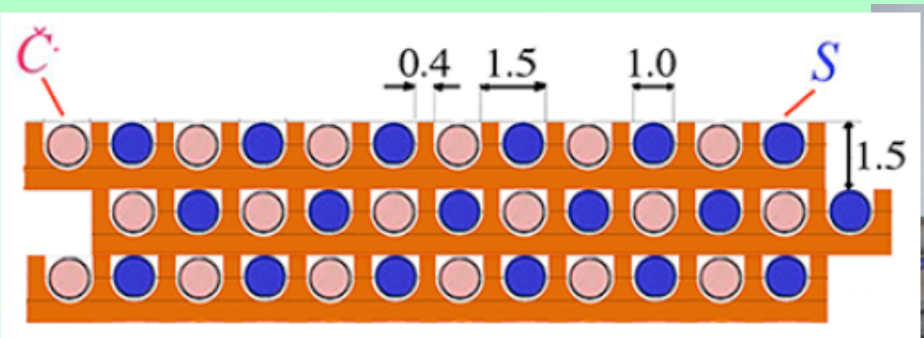



Texas Tech Uni

2012
RD52

Copper, 2 modules

Each module: $9.3 * 9.3 * 250\ \text{cm}^3$
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: 4.5%, 10 λ_{int}

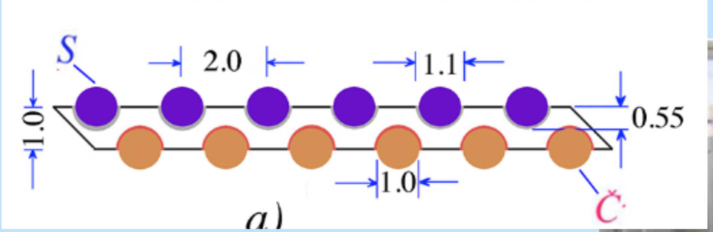


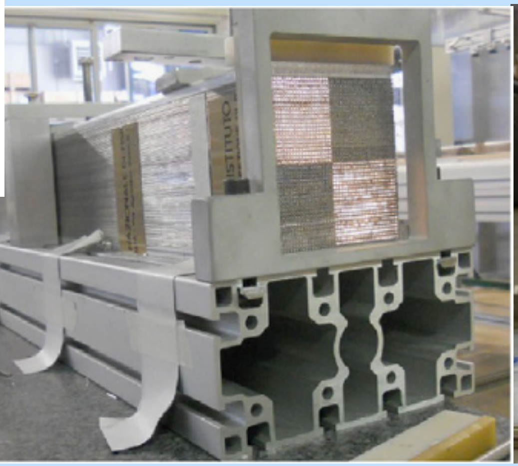

INFN Pisa

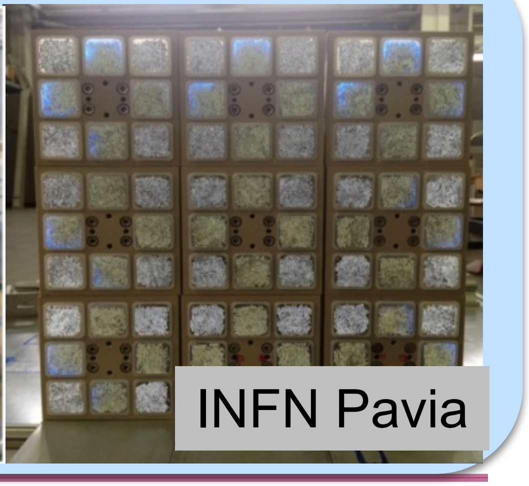
2012
RD52

Lead, 9 modules

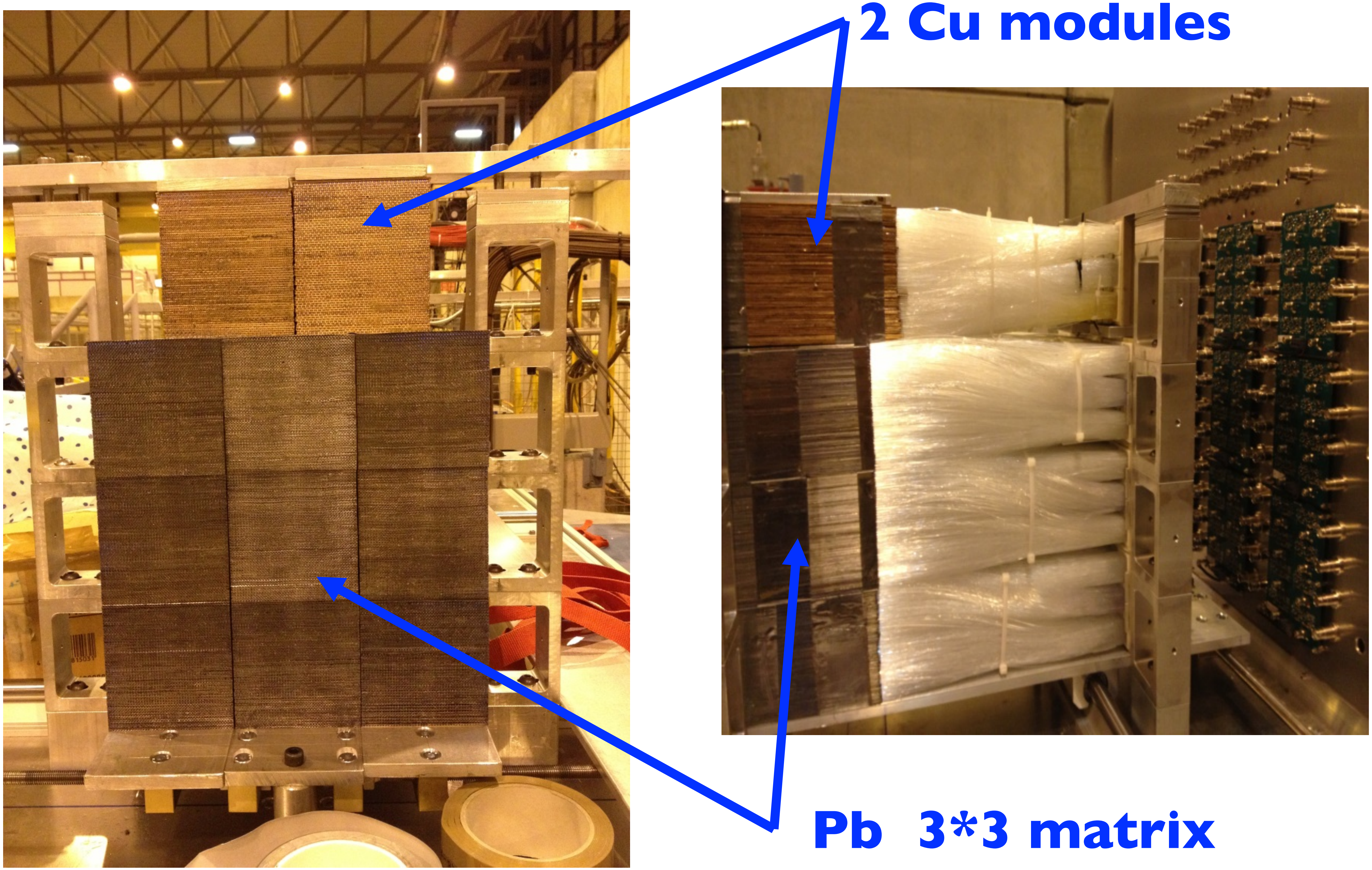
Each module: $9.3 * 9.3 * 250\ \text{cm}^3$
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: 5%, 10 λ_{int}






INFN Pavia

The dual readout fiber calorimeters



2 Cu modules

Pb 3*3 matrix

Why copper rather than lead?

1) Detector mass

2) Čerenkov light yield

3) Linearity, and thus resolution for jet detection

Detector mass

Hadronic shower development governed by nuclear interaction length, λ_{int}

Lead: λ_{int} *= 170 mm,* ρ *= 11.3 g/cm*^{3}

Copper: λ_{int} *= 151 mm,* ρ *= 8.96 g/cm*^{3}

What is the mass of a calorimeter of 10 x 3 x 3 λ_{int}^3 *?*

Lead: 4996 kg
Copper: 2776 kg

Čerenkov light yield

Čerenkov light is almost exclusively produced by the em shower components in hadron absorption

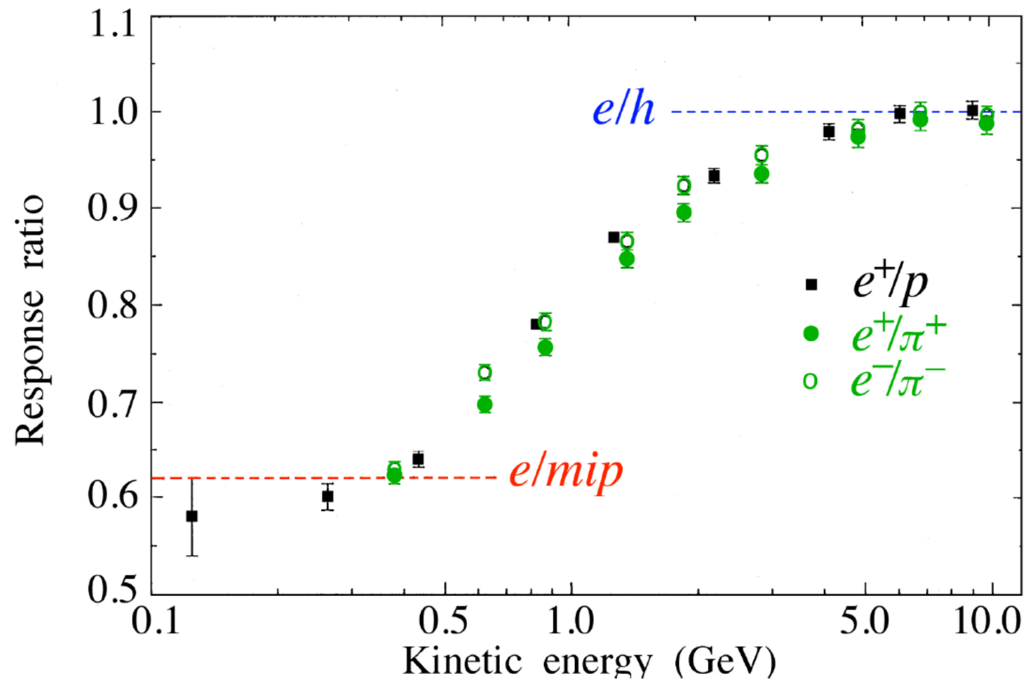
Lead: e/mip = 0.6

Copper: e/mip = 0.9

For a structure with a given sampling fraction, we get 50% more Čerenkov photons per GeV deposited energy

This will directly affect the hadronic energy resolution, since Čerenkov light yield is a major limiting factor

Non-linearity at low energy in calorimeters with high-Z absorber. Important for jet detection



RD52 fiber calorimeters results

Electromagnetic performance:

- Resolution: 5-10%/sqrt(E)
- Linearity: within 1%
- Electromagnetic shower profile

Hadronic performance:

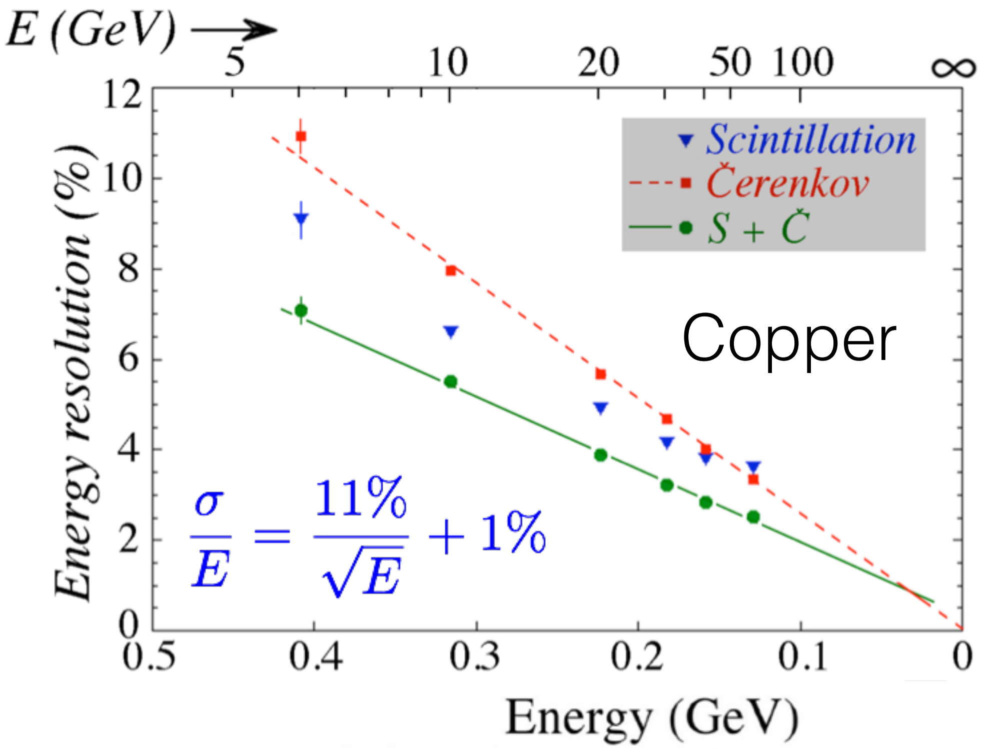
- Resolution: 53%/sqrt(E)
- Linearity: within 1%

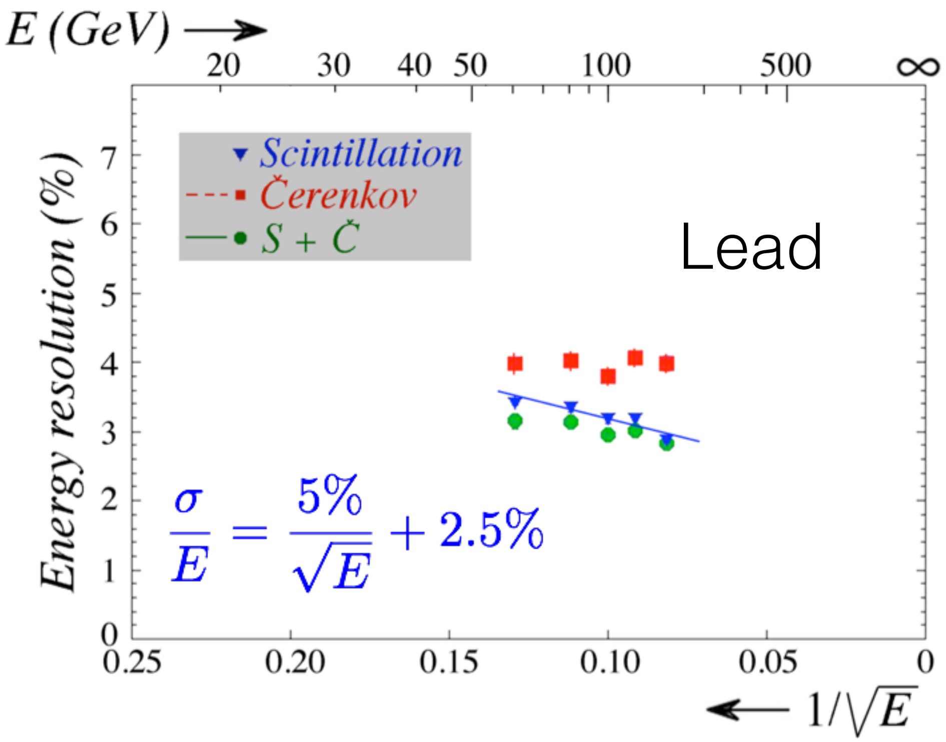
Other performance:

- Particle identification
- Time structure & light attenuation correction

Electromagnetic and hadronic resolution

Electromagnetic Resolution

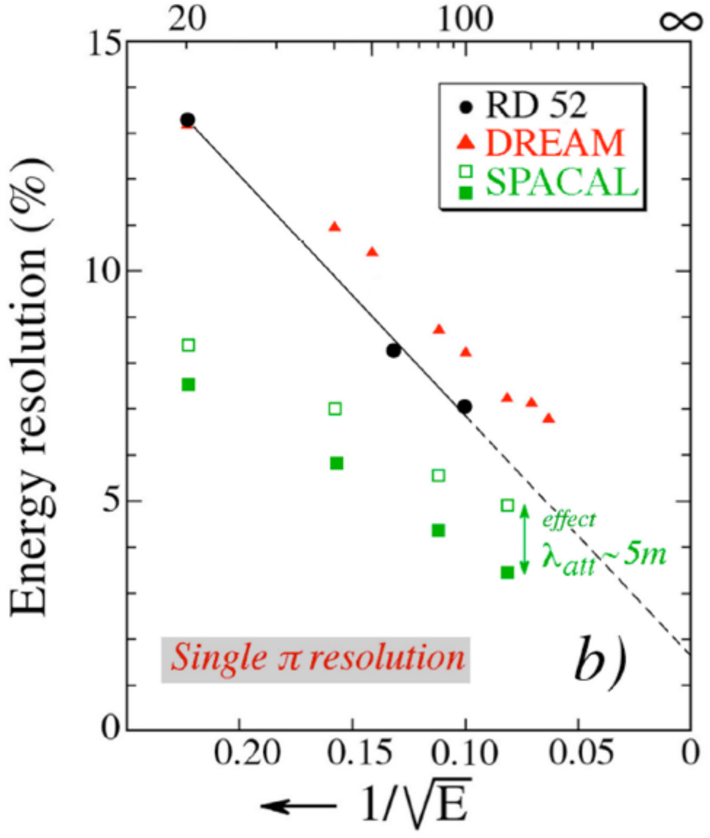


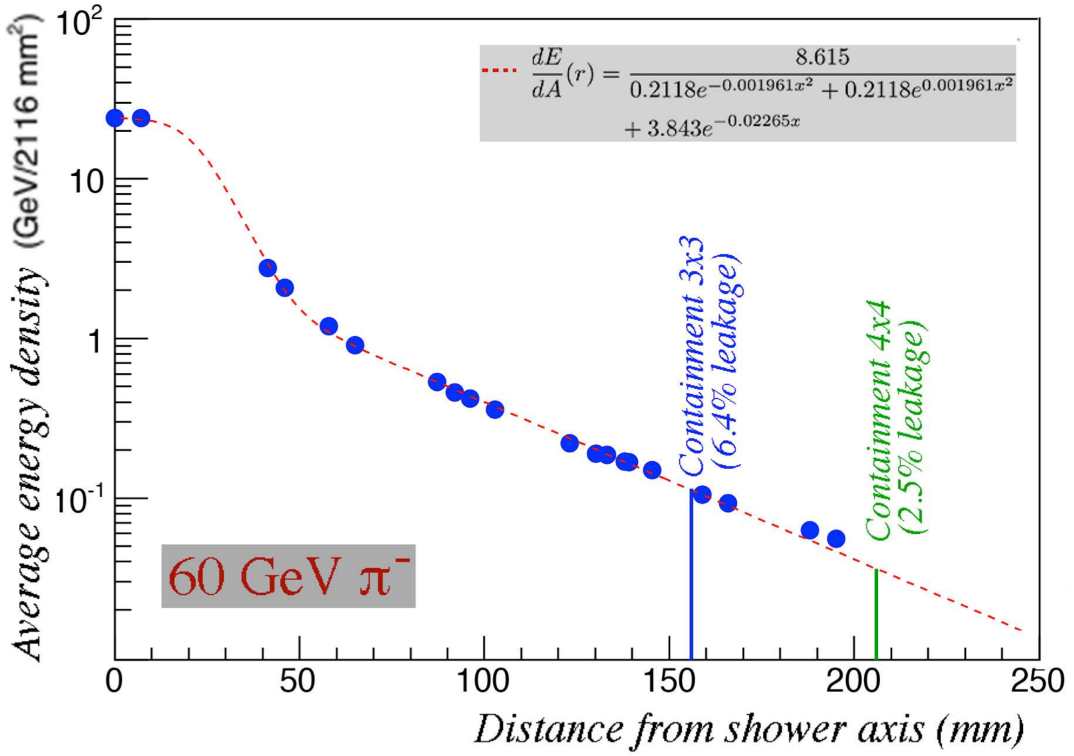


Hadronic Resolution
(Pb Module)

$$\frac{\sigma}{E} = \frac{53\%}{\sqrt{E}} + 1.7\%$$

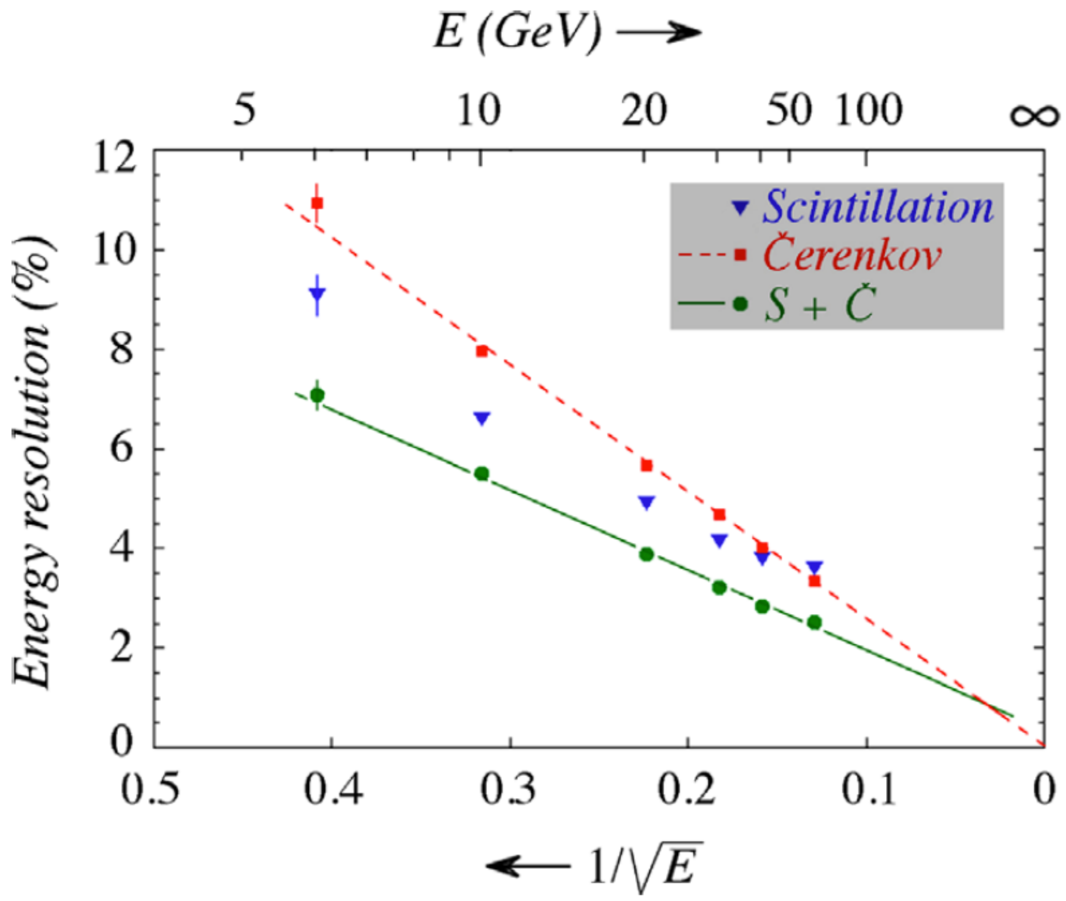
To include corrections on:
- light attenuation
- lateral leakage

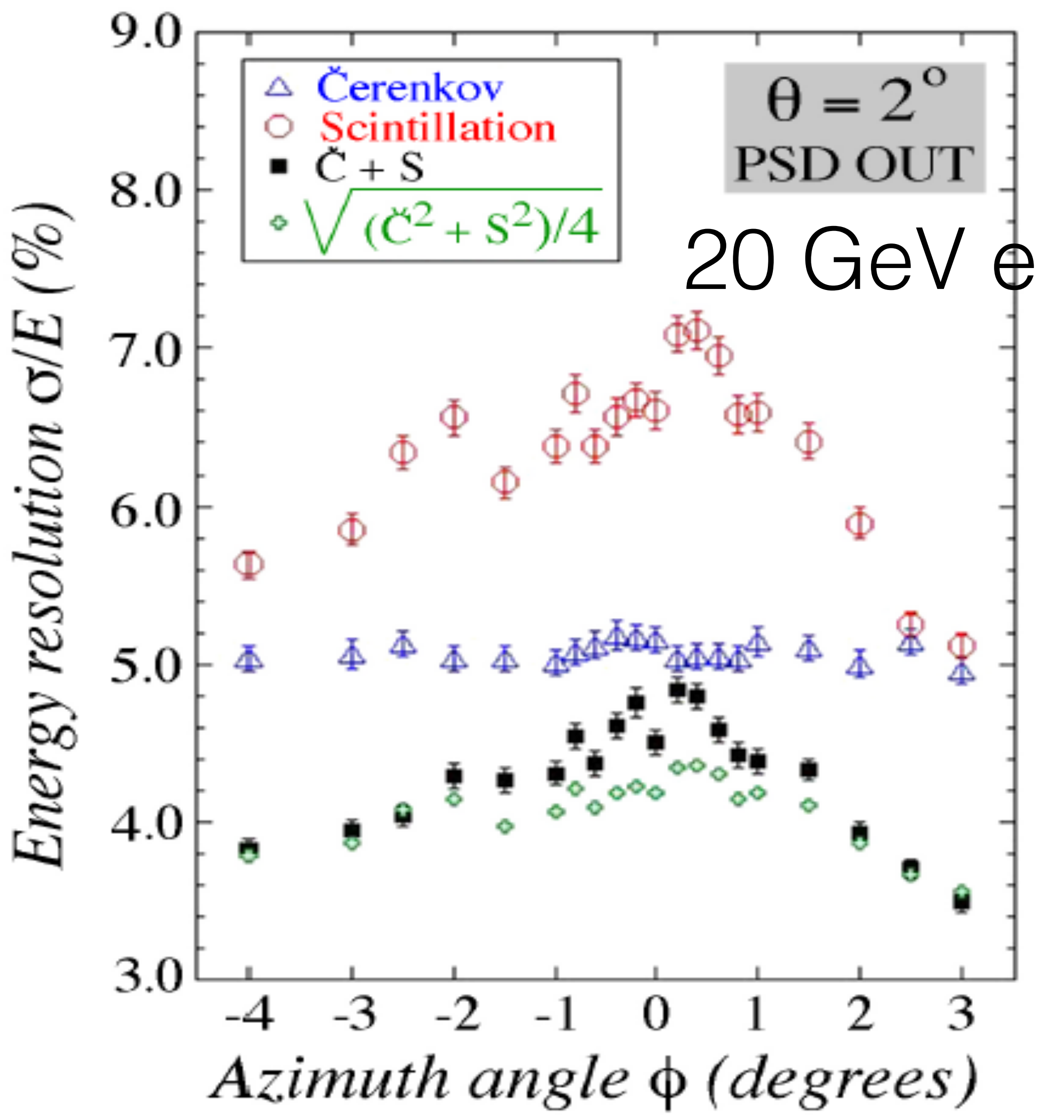




EM performance in DR sampling calo

C and S independent: sample different parts of the shower, possible to add the two signals



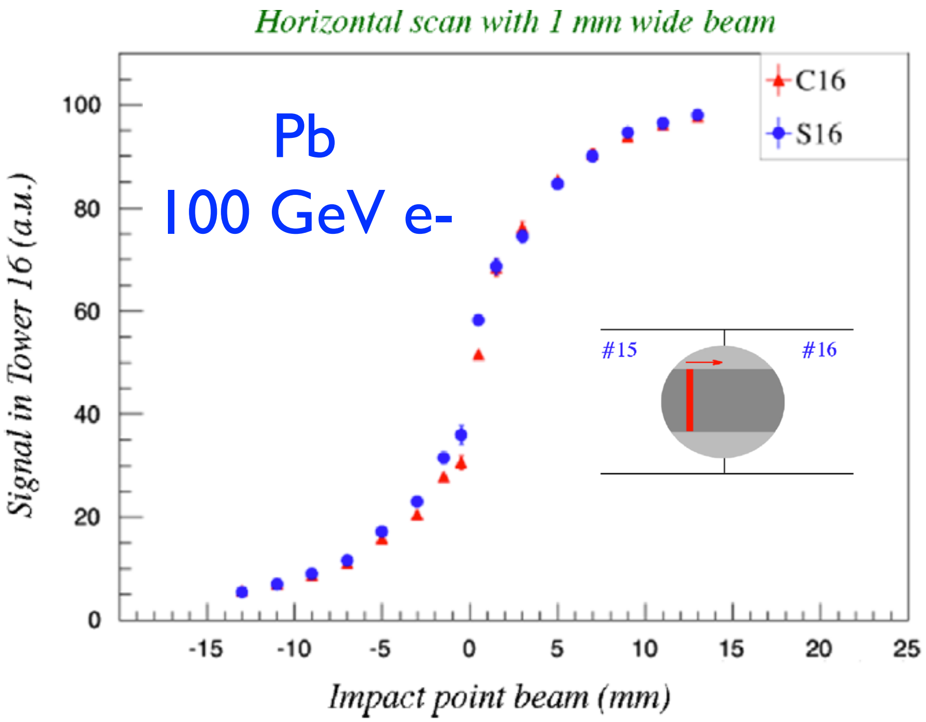


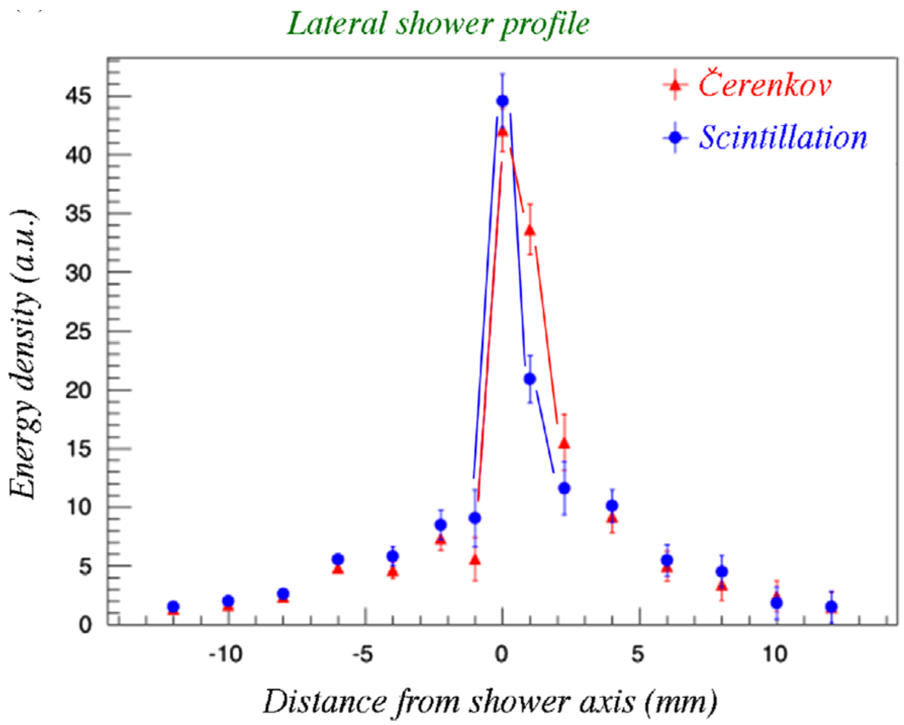
Constant term due to fluctuation in interaction point (only S). Disappears for larger angles

Early part of the shower do not contribute to the C signal: C light produce by particle travelling in the same direction of fibers fall outside numerical aperture of the fiber

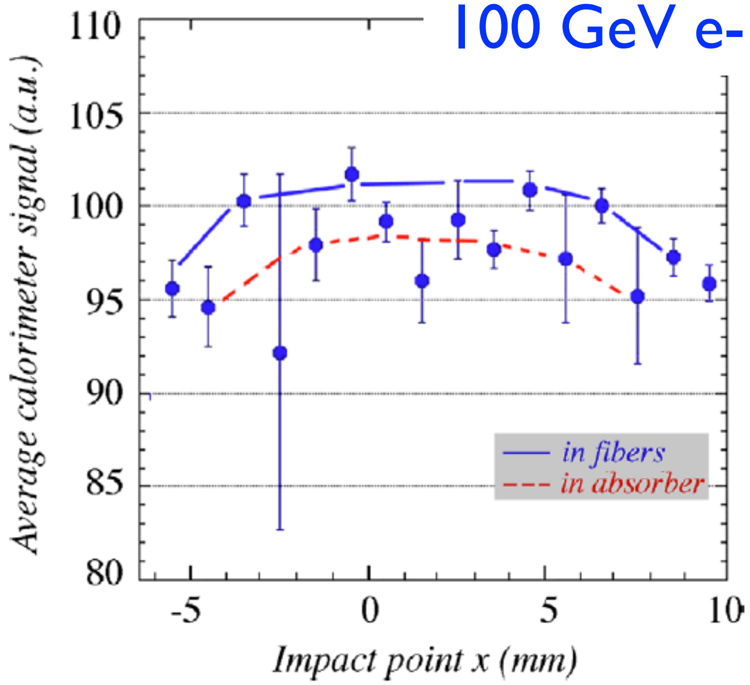
EM performance RD52 calo

Radial shower profile and response uniformity

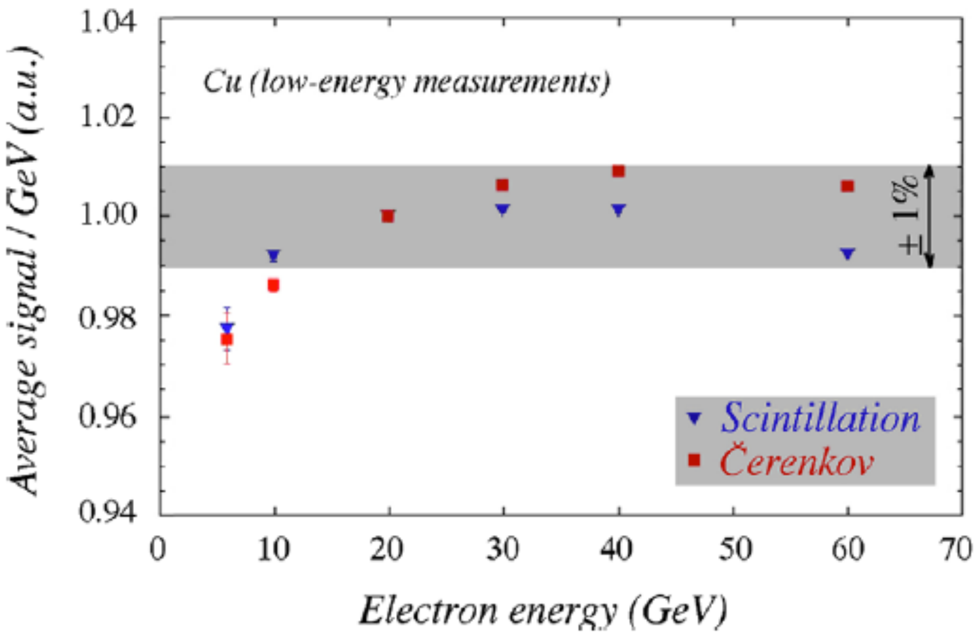


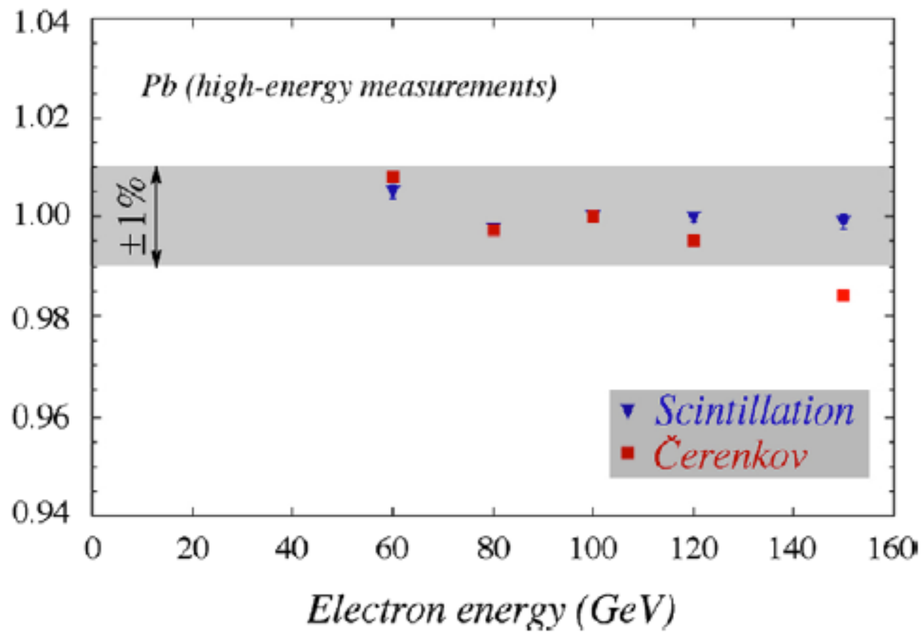


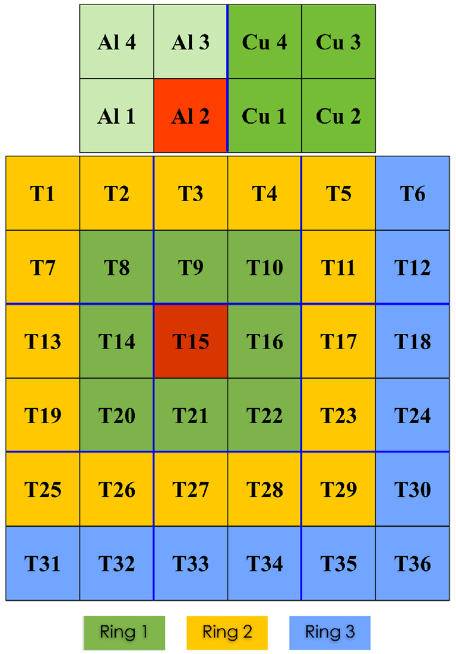
Pb – S signal
100 GeV e-



Signal linearity







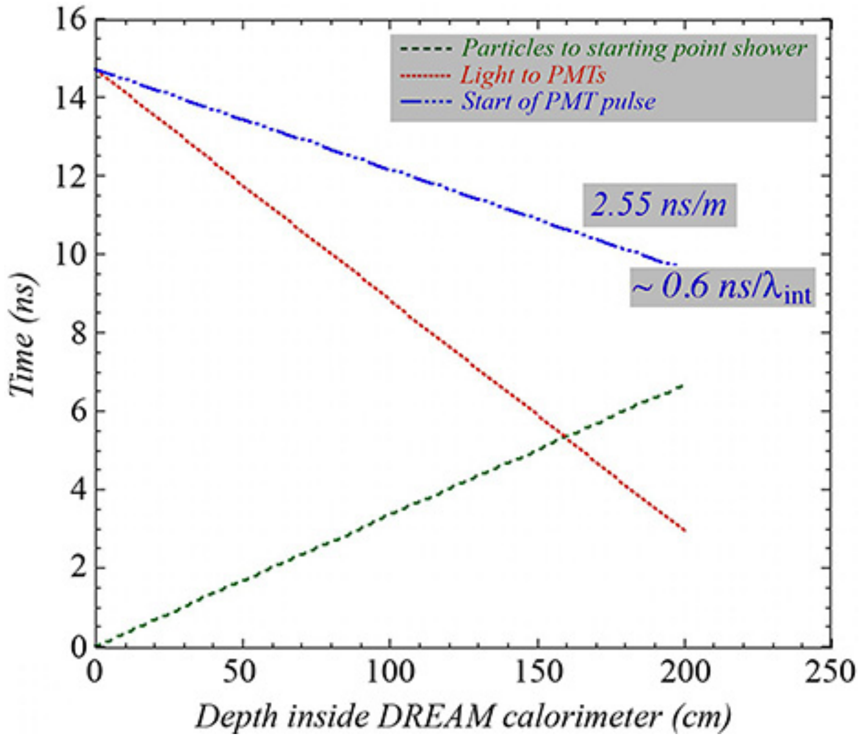
	Al 4	Al 3	Cu 4	Cu 3	
	Al 1	Al 2	Cu 1	Cu 2	
T1	T2	T3	T4	T5	T6
T7	T8	T9	T10	T11	T12
T13	T14	T15	T16	T17	T18
T19	T20	T21	T22	T23	T24
T25	T26	T27	T28	T29	T30
T31	T32	T33	T34	T35	T36

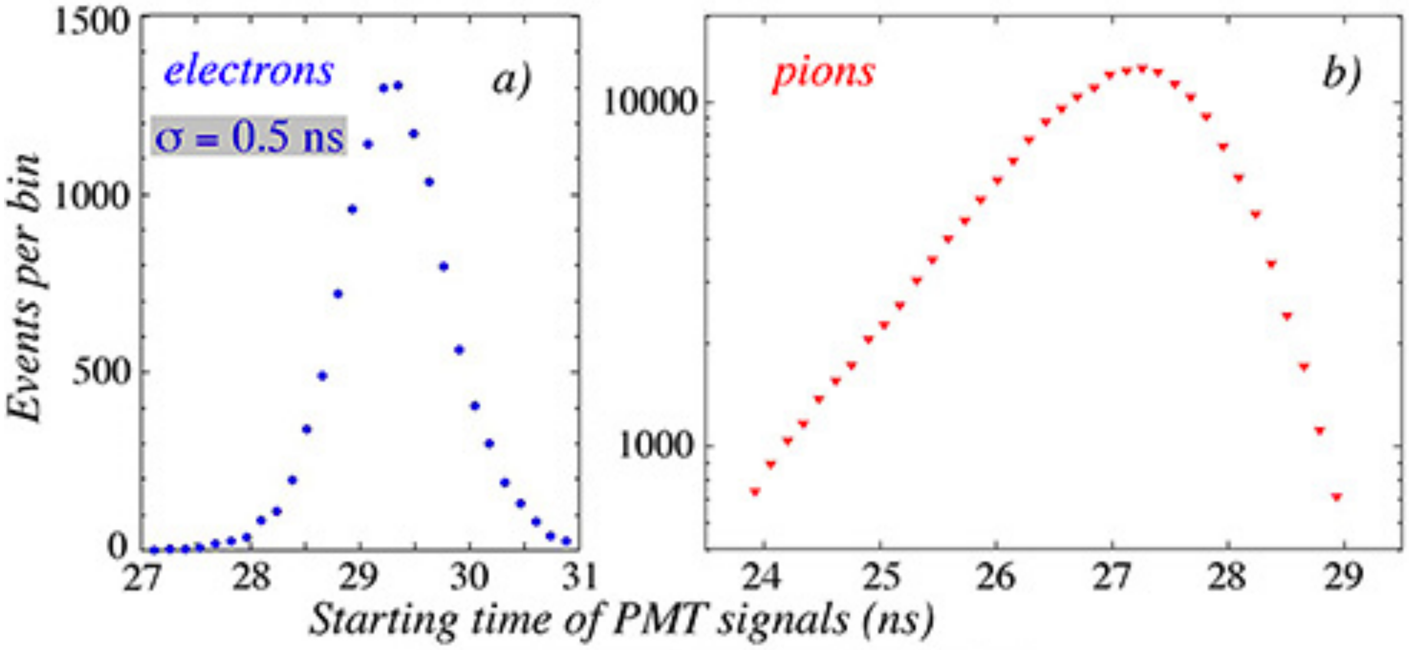
Ring 1 Ring 2 Ring 3

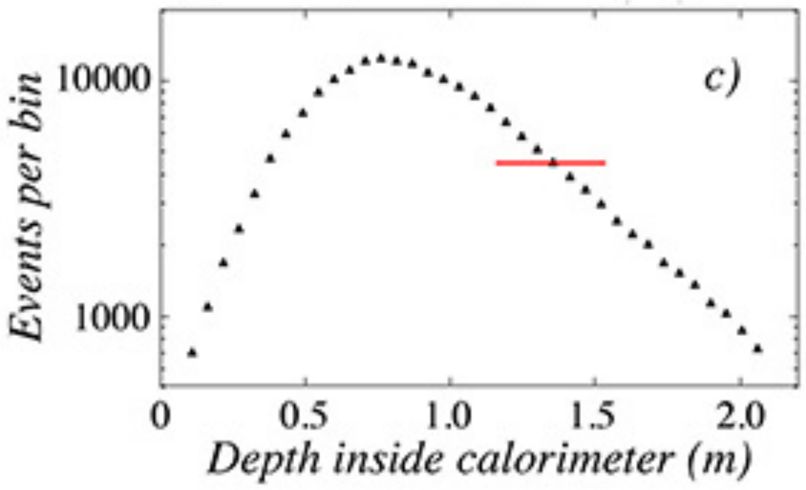
Light attenuation and longitudinal profile

Depth at which light is produced in had shower fluctuate at the level of a λ_{int} (~25 cm in RD52 calo)

Costant term (~ 1%) due to light attenuation (8m per Scintillation and 20m for Cherenkov)







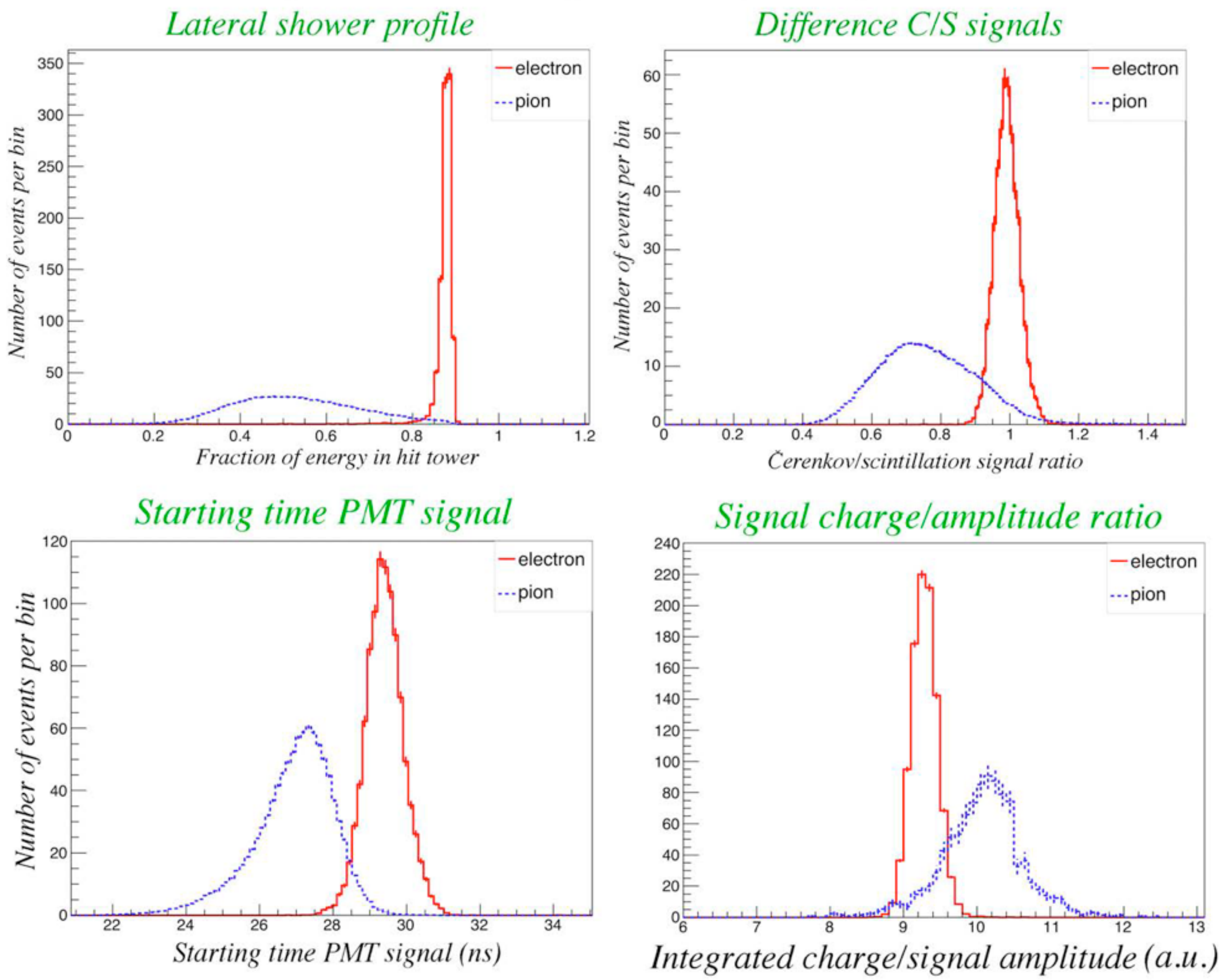
Particles travel ~ c

Light in media travel at c/n

Using PMT signal starting time it is possible to correct for light attenuation effect

Particle ID in sampling dual readout calorimeter

Methods to distinguish e/π in longitudinally unsegmented calorimeter


Lateral shower profile

Difference C/S signals

Starting time PMT signal

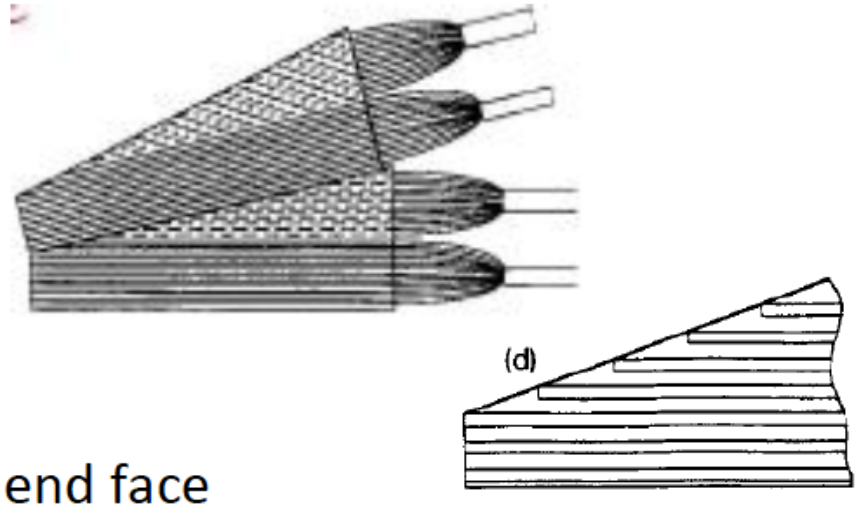
Signal charge/amplitude ratio

Combination of cuts: >99% electron efficiency, <0.2% pion mis-ID

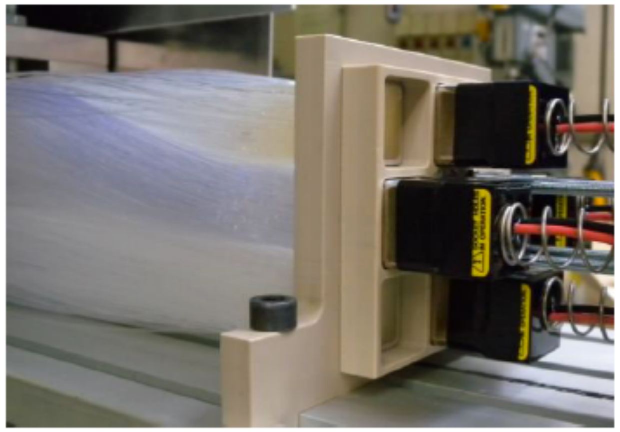
From RD52 experiment to 4π calorimeter

Best solution found: Copper Dual Readout (em + had) fiber calorimeter , high fiber filling fraction, not longitudinally segmented, read out with fast electronics (< ns).

Suggestions on **what needs to be done**..



- Projective geometry *(NIM A337 (1994) 326- 341)*
- Use of SiPm → two advantages:
  - Get rid of the "fiber forest", readout closer to the end face
  - transversal segmentation as small as needed
- Rad hardness Cherenkov clear fibers (Cherenkov l.y. could become worse .. in case use quarts, but more expensive)
- Industrial production of grooved Copper
- Custom fast electronics
- …



Fiber bunches + PMT →

SiPM matrix directly coupled to end of detector

Proposal for Future Accelerator

Growing interest in Dual Readout Calorimetry for Future Accelerators

CepC – FCCee

Participating in the Conceptual Design Report (CDR)

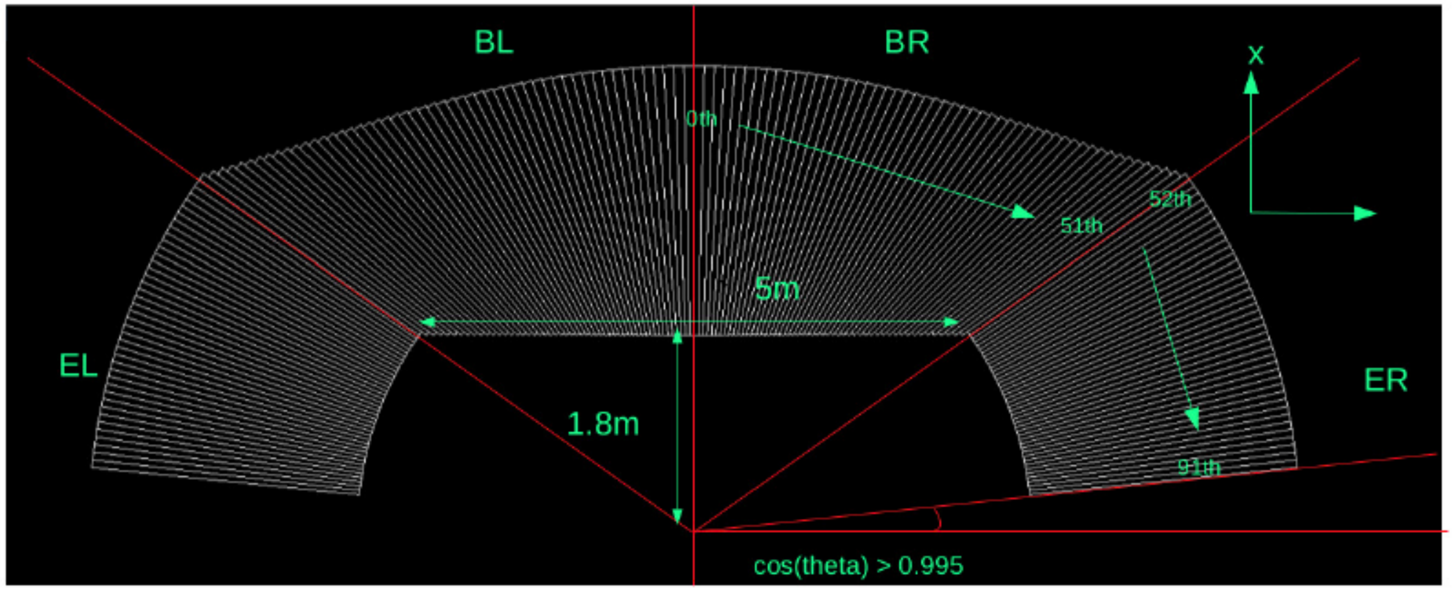


Figure 6: A possible 4π solution (called ”wedge” geometry).

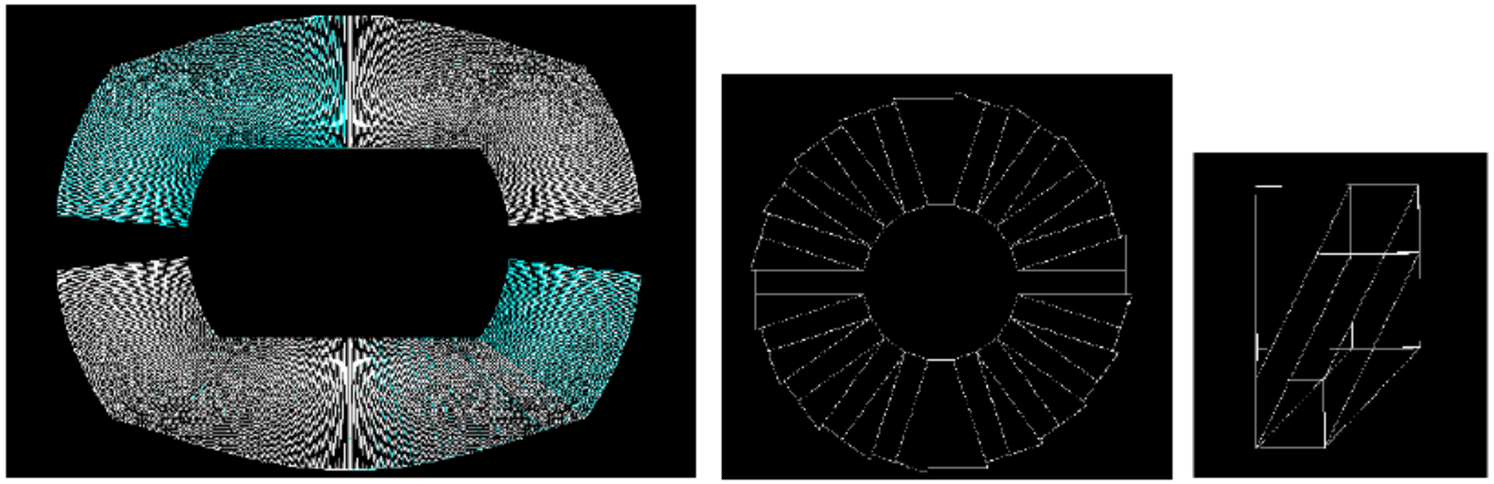


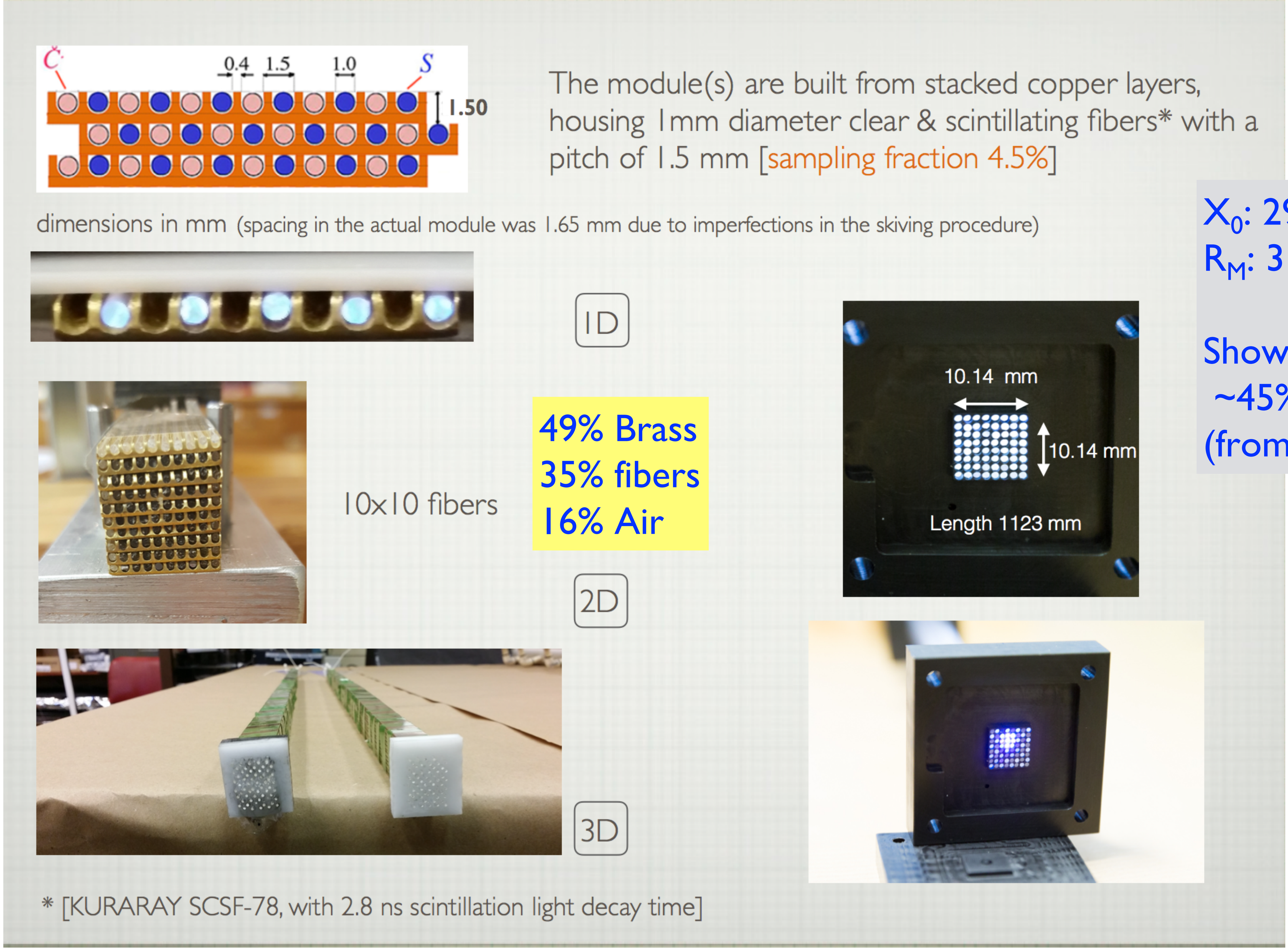
Figure 7: An alternative 4π solution (called ”wing” geometry).

PMT vs SiPM readout

- *SiPM advantages:*
  - *compact readout (no fibres sticking out)*
  - *longitudinal segmentation possible*
  - *operation in magnetic field*
  - *larger light yield (# of Čerenkov p.e. limits resolution)*
  - *very high readout granularity → particle flow "friendly"*

- *SiPM (potential) disadvantages:*
  - *signal saturation (digital light detector)*
  - *cross talk between Čerenkov and scintillation signals*
  - *dynamic range*
  - *instrumental effects (stability, afterpulsing, ...)*

Dual Readout calo - SiPM readout



The module(s) are built from stacked copper layers, housing 1mm diameter clear & scintillating fibers* with a pitch of 1.5 mm [sampling fraction 4.5%]

dimensions in mm (spacing in the actual module was 1.65 mm due to imperfections in the skiving procedure)

10x10 fibers

49% Brass
35% fibers
16% Air

* [KURARAY SCSF-78, with 2.8 ns scintillation light decay time]

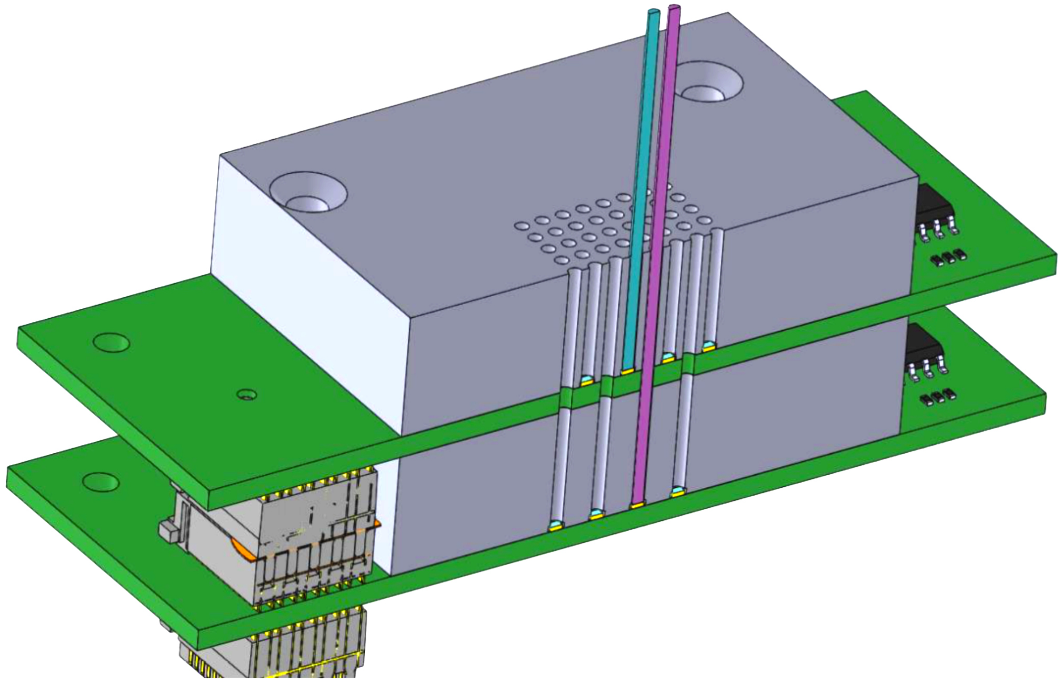
X_0: 29 mm
R_M: 31 mm

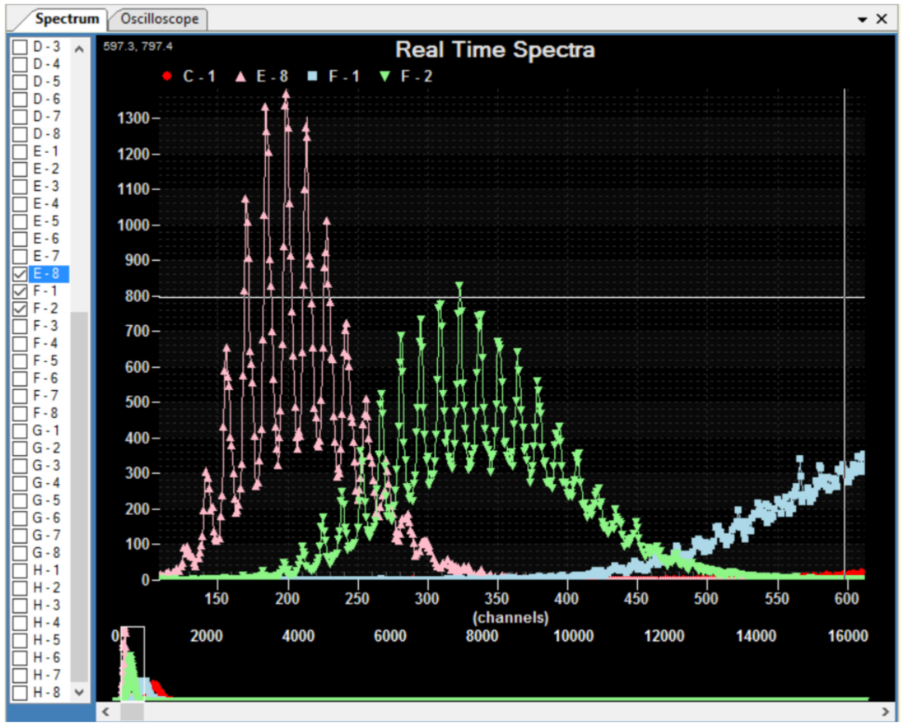
Shower containment:
~45%
(from simulations)

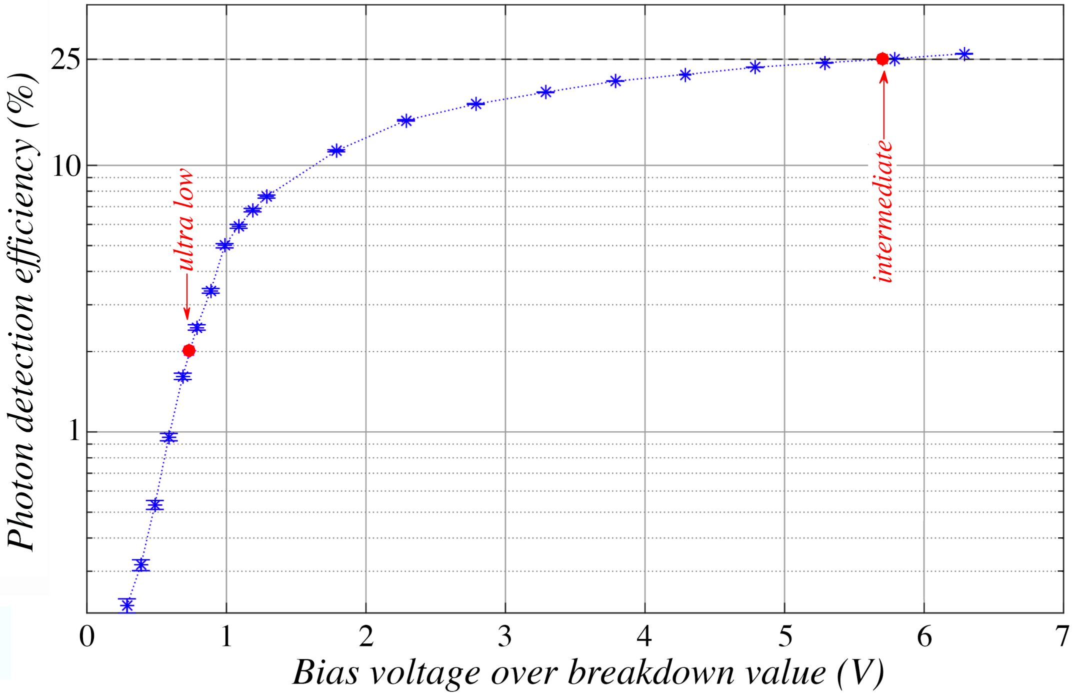
Dual Readout calo - SiPM readout

HAMAMATSU S13615-1025	
Sensitive area	1×1 mm^2
Cell pitch	25 μm
No. of pixels	1584
Peak Photon Detection Efficiency	25%
Breakdown voltage V_{br}	53 V
Recommended operational voltage V_{op}	V_{br} + 5V
Gain at V_{op}	7×10^5
Dark Count Rate at V_{op}	50 kps
Optical Crosstalk at V_{op}	1%

1584 cell/sensor



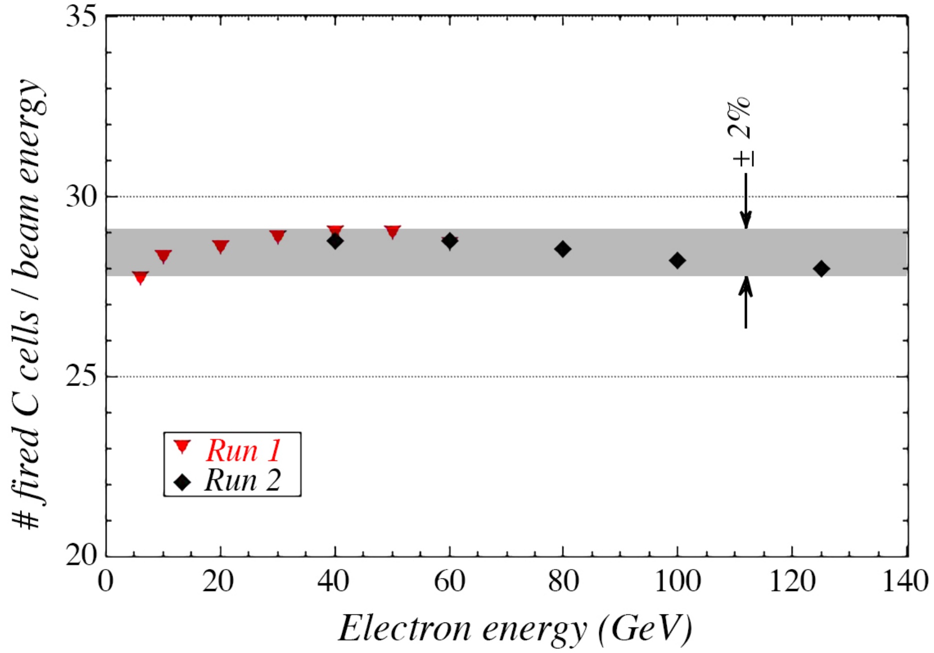




Results for SiPM - dual readout calorimeter

Cherenkov

Light yield:



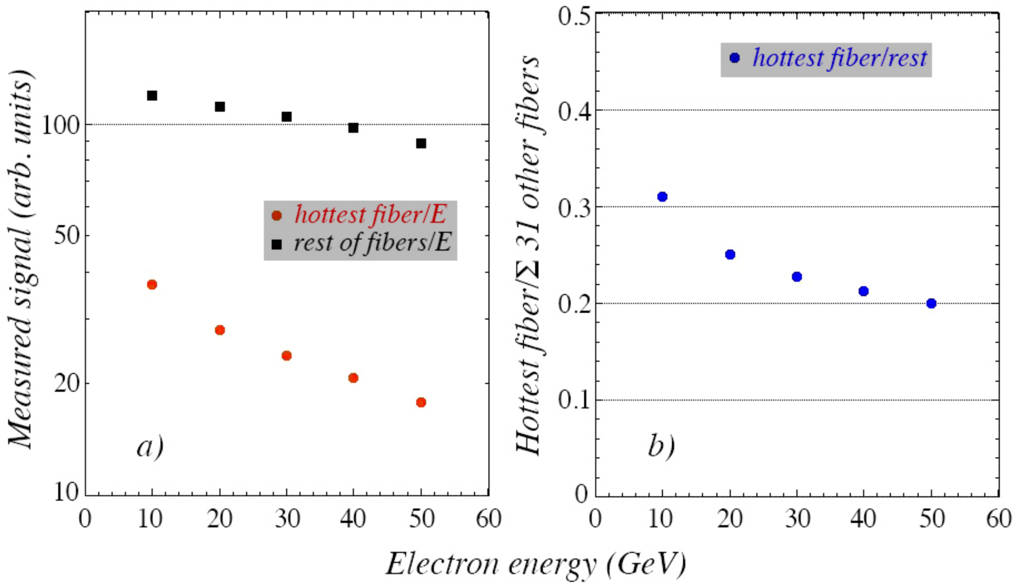
- Correction for shower containment (45%)
- Correction for cross-talk

54 Cpe/GeV

- RD52 calo measured 30 Cpe/GeV
- Improve photostatistic → Reduce contribution to resolution

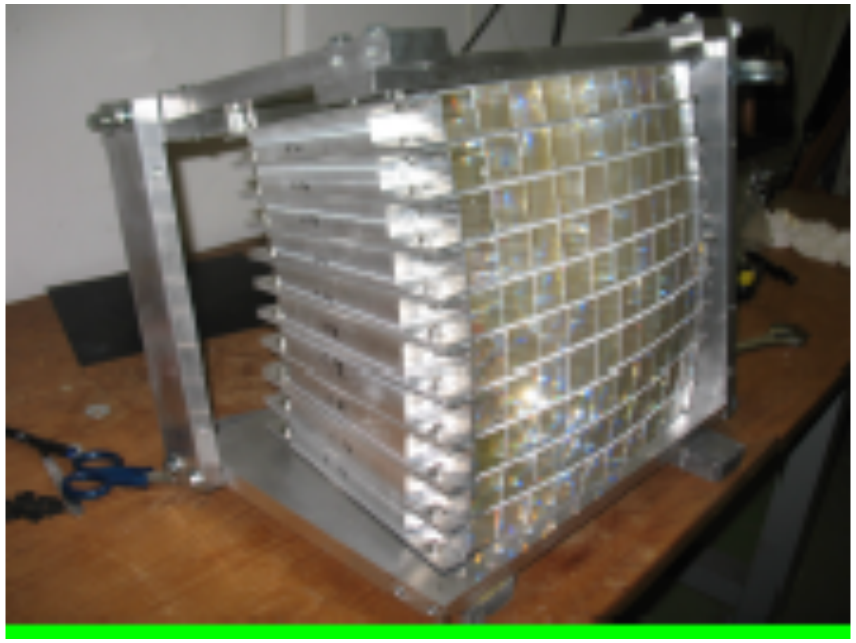
Scintillation

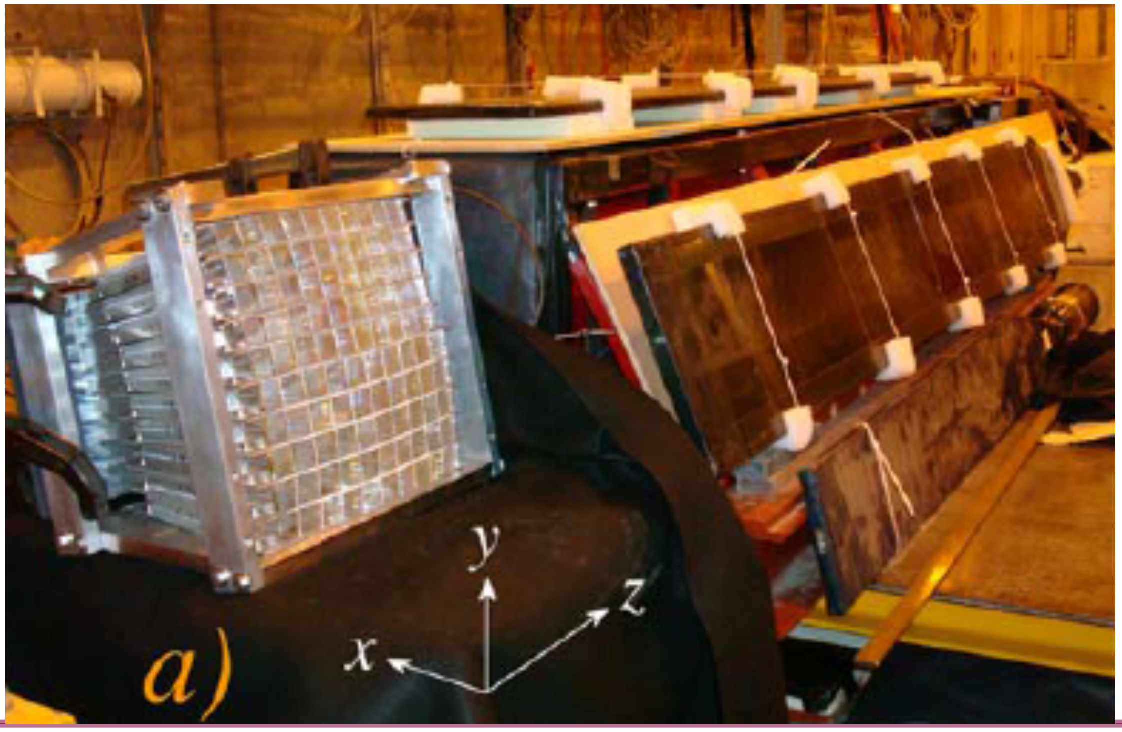
Signal Saturation:

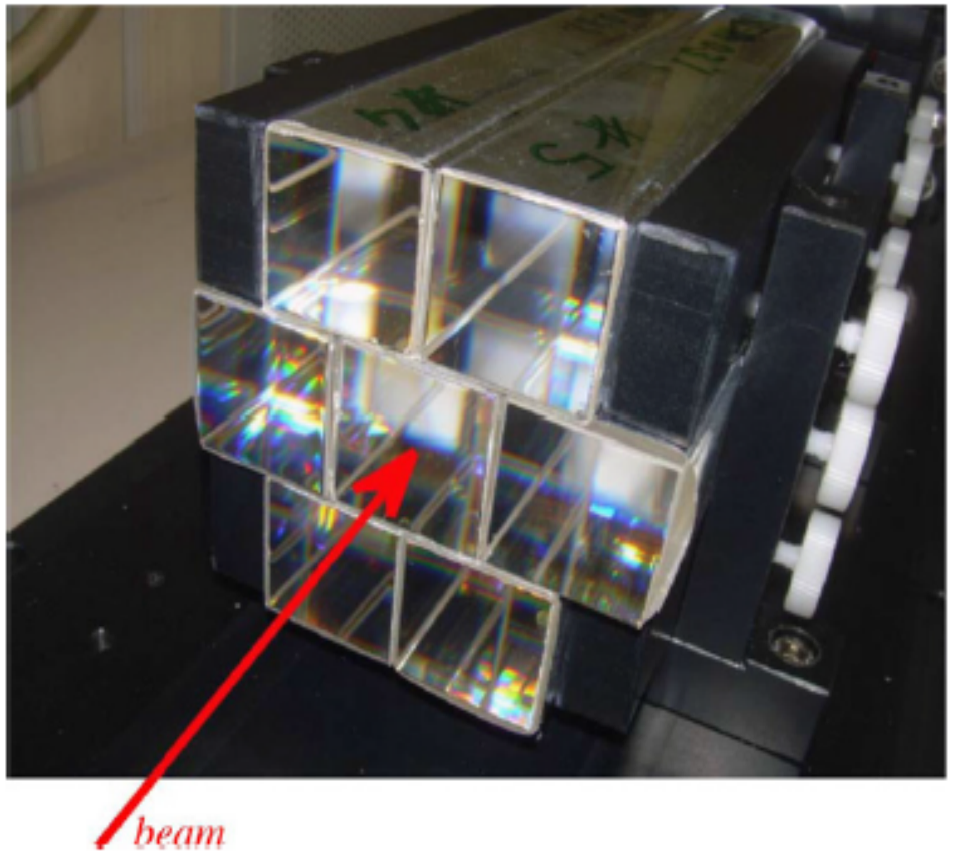


- Light yield 3200 Spe/GeV
- Correction for PDE allow to improve on the saturation. Still remain in the hottest cells
- Signal reduction needed to save linearity

Dual readout with homogeneous materials (Crystals)







Dual Readout method in homogeneous calorimeter

Motivations:

- high density scintillating crystal widely used in particle physics experiment: ensure excellent energy resolution for electromagnetic showers

- calorimeters with a crystal EM compartment usually have a poor had. resolution due to
  - fluctuation of the starting point of the hadronic shower in the EM section
  - different response to the em and non-em component of the shower in the two calorimeters

Dual readout applied to an hybrid system:

Measuring fem on an event-by-event basis allows to correct for such fluctuations and allows to eliminate the main reasons for poor hadronic resolution

Dual Readout method in homogeneous calorimeter

Properties	Čerenkov	Scintillation
Angular distribution	Light emitted at a characteristic angle by the shower particles that generate it $\cos\theta = 1/(n\beta)$	Light emission is isotropic: excited molecules have no memory of the direction of the particle that excited them
Time structure	Instantaneous, short signal duration	Light emission is characterized by one or several time constants. Long tails are not unusual (slow component)
Optical spectra	$\frac{dN_C}{d\lambda} = \frac{k}{\lambda^2}$	Strongly dependent on the crystal type, usually concentrated in a (narrow) wavelength range
Polarization	polarized	not polarized

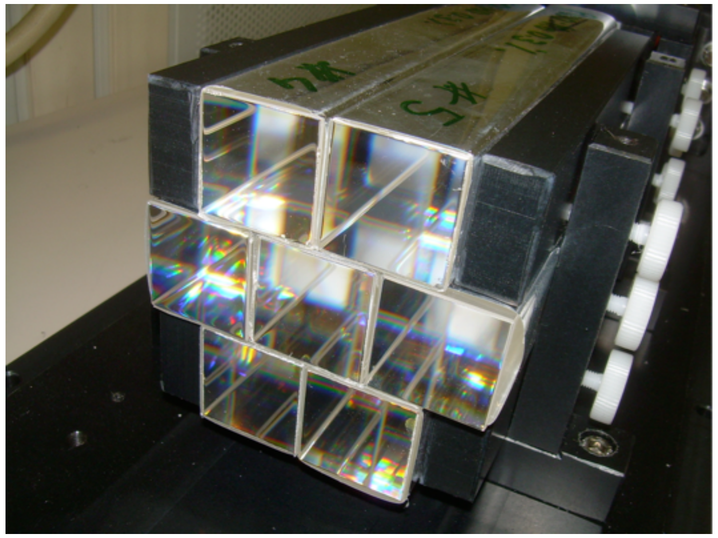
Dual Readout method in homogeneous calorimeter

Requirements for using crystals in dual readout based calorimeter:

Good Čerenkov vs Scintillation separation

Response uniformity

High light yield (to reduce contribution of p.e. fluctuation to the resolution)

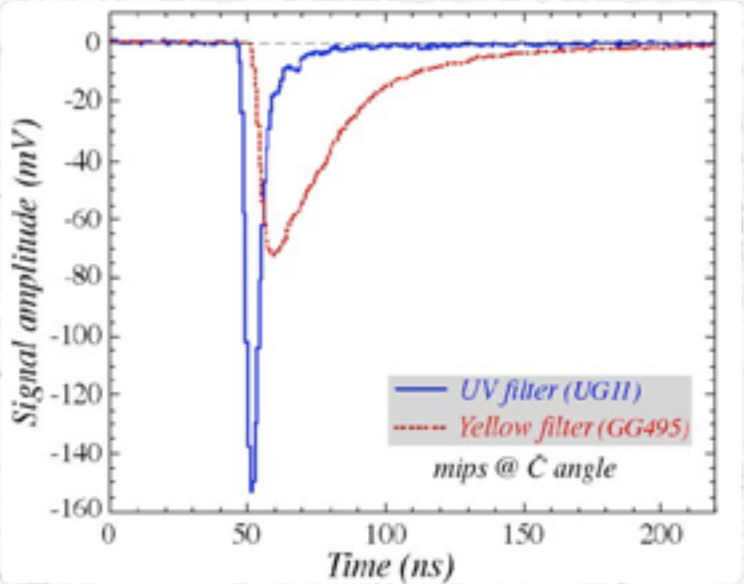


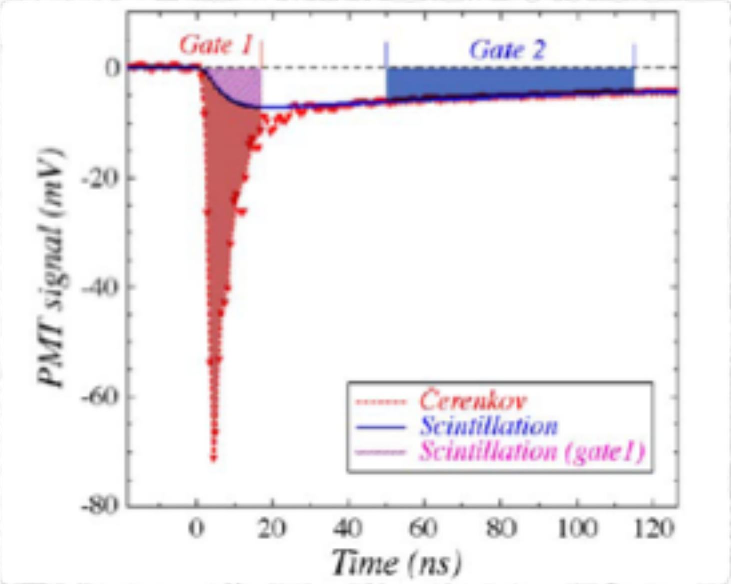
Separation can be achieved by:

- ✴ optical filters: exploit different spectral region of Č and S
- ✴ time integration: exploit different time structure of Č and S

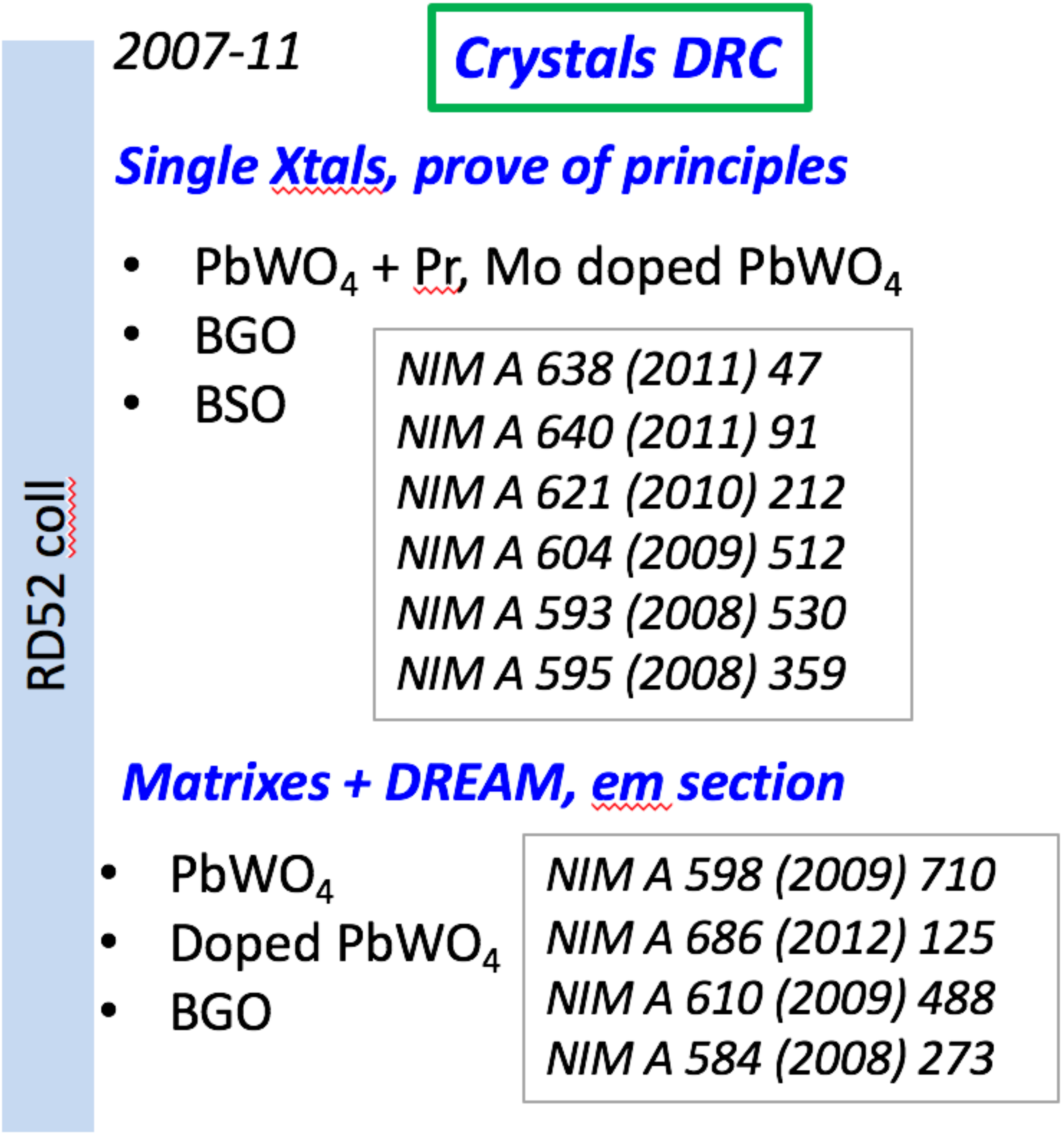
In order to have the best possible separation a crystal must have a scintillation emission:

- ✴ in a wavelength region far from the Cherenkov one
- ✴ with a decay time of order of hundreds of nanoseconds
- ✴ not too bright to get a good C/S ratio (<50% BGO emission)





Dual Readout method in homogeneous calorimeter



RD52 coll

2007-11

Crystals DRC

Single Xtals, prove of principles

- $PbWO_4$ + Pr, Mo doped $PbWO_4$
- BGO
- BSO

NIM A 638 (2011) 47
NIM A 640 (2011) 91
NIM A 621 (2010) 212
NIM A 604 (2009) 512
NIM A 593 (2008) 530
NIM A 595 (2008) 359

Matrixes + DREAM, em section

- $PbWO_4$
- Doped $PbWO_4$
- BGO

NIM A 598 (2009) 710
NIM A 686 (2012) 125
NIM A 610 (2009) 488
NIM A 584 (2008) 273

Conclusion from testing homogeneous DRC

Consideration before testing

ADVANTAGES:	**FORESEEN DISADVANTAGES:**
• No sampling fluctuations • simpler calibration	• No sensitivity to neutrons • high cost • rad hardness

Additional outcomes from performed tests:

To separate the C and S component, crystals have to be *readout in non conventional way*

→ results not good as the ones obtained by standard EM calorimetry

Extraction of pure C and S signals implies

- *To sacrifice a large fraction of available C photons* (optical filters)
- *C photons are attenuated by crystal UV self absorption*

Crystal + optical filters don't offer a benefit in term of C light yield in dual readout calorimetry (comparable with the one measured with the RD52 fiber calorimeter)

Further studies on dual readout method

LuAG and Ce:LuAG

Jinst, Vol. 6, Oct. 2011

Studies on sampling and homogeneous dual readout calorimetry with meta-crystals

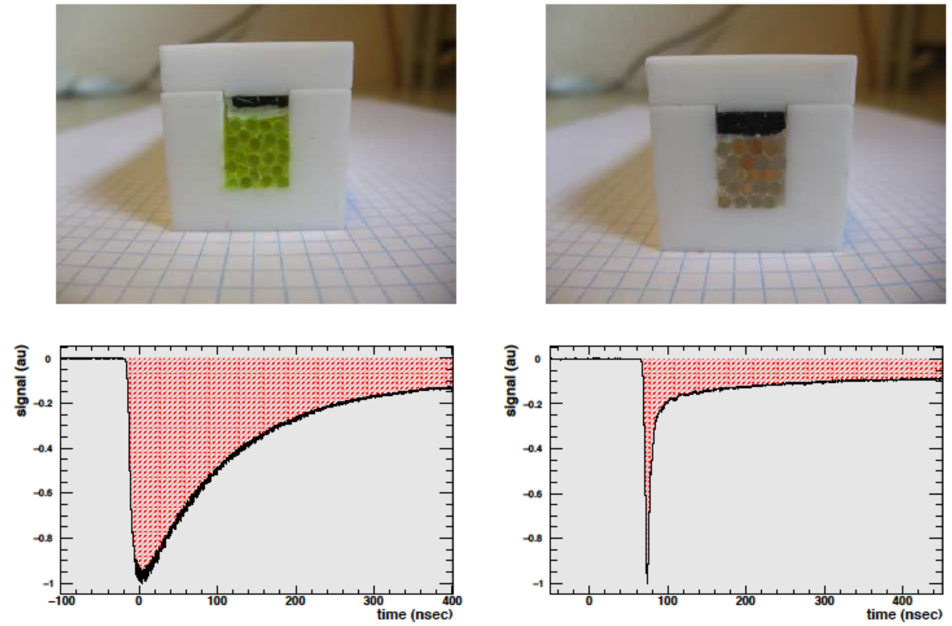
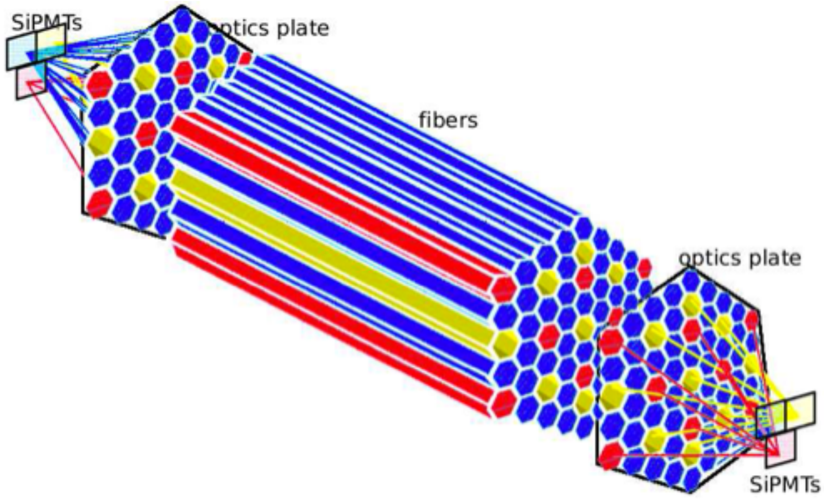


Figure 5. Bundles of Ce doped (top left) and undoped (top right) LuAG fibers and corresponding typical signal pulses recorded (bottom row). Each fiber measures 2 mm in diameter and 80 mm in length.



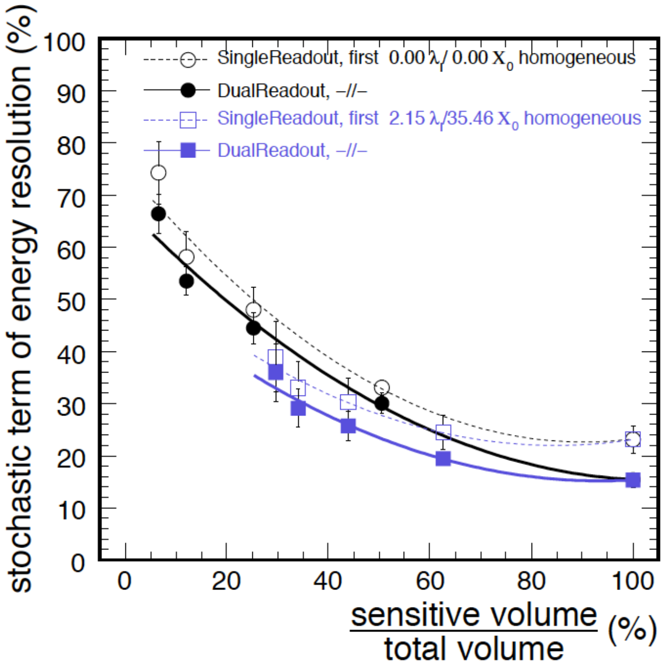


Figure 11. Simulated performance, in terms of the energy resolution's stochastic term, of $4.3 \times 4.3 \times 8.6\ \lambda_I^3$ single or dual readout calorimeters with various sampling configurations of ionisation and Cherenkov signal readout.

Backup slides

Aims of Dual Readout Project

- Address the factors which limit the resolution of hadron calorimeter to reach the theoretical resolution limit
  - Calibration of the calorimeter can be done with electrons
  - High resolution EM and HAD calorimetry
  - Can comply with the requirements for Future collider physics
- Study and eliminate/reduce dominant source of fluctuation

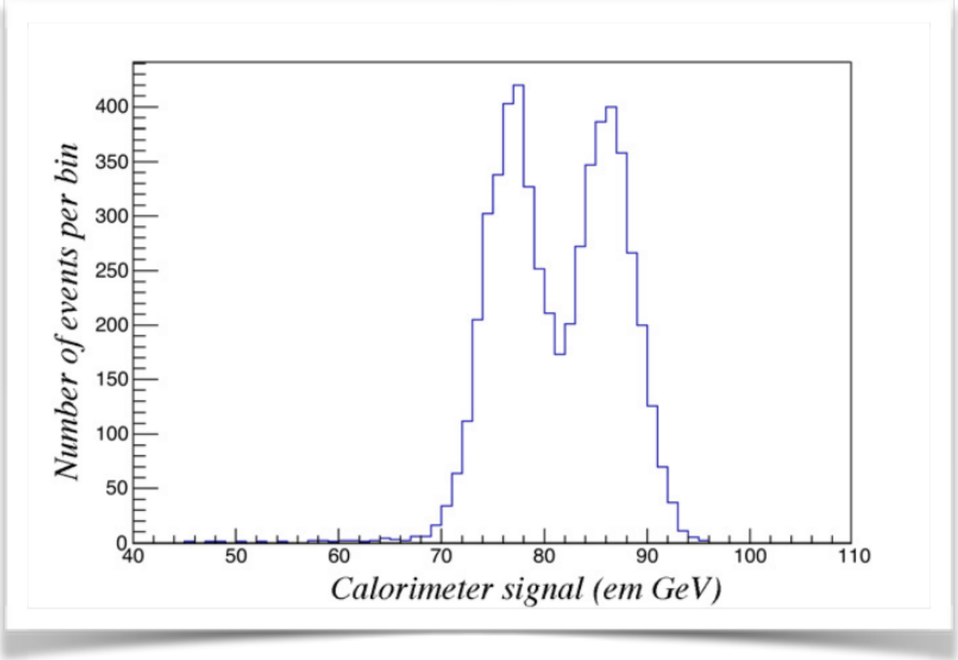
This research activity has been/is carried on by the RD52 experiment @CERN
http://highenergy.phys.ttu.edu/dream/index.html

Dual Readout Sampling Calorimeters

Features of dual readout calorimeters:

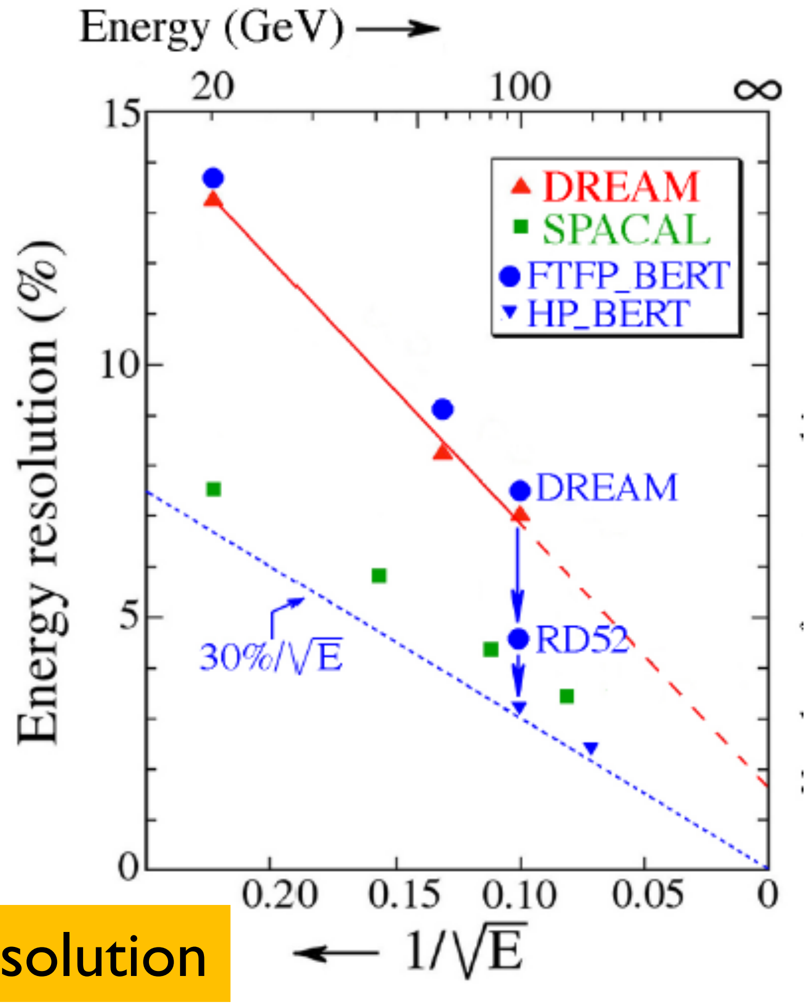
- Compensation achieved without construction constraints
- Calibration of an hadron calorimeter with electrons.
- No intercalibration between sectors
- High resolution EM and HAD calorimetry

DREAM method simulated with GEANT4



The response curve for a mixture of hadrons with energies corresponding to the W and Z masses (GEANT4 simulation)

NIM. A762 (2014) 100



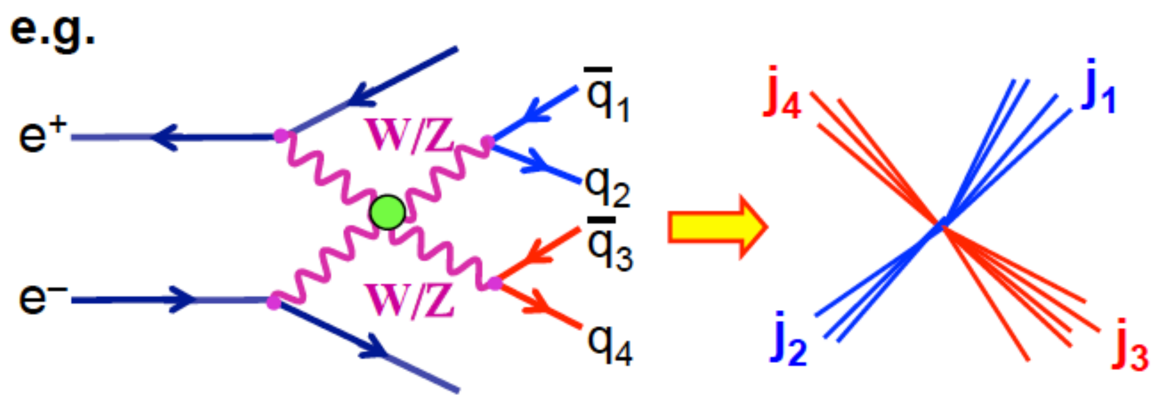
Hadronic E resolution

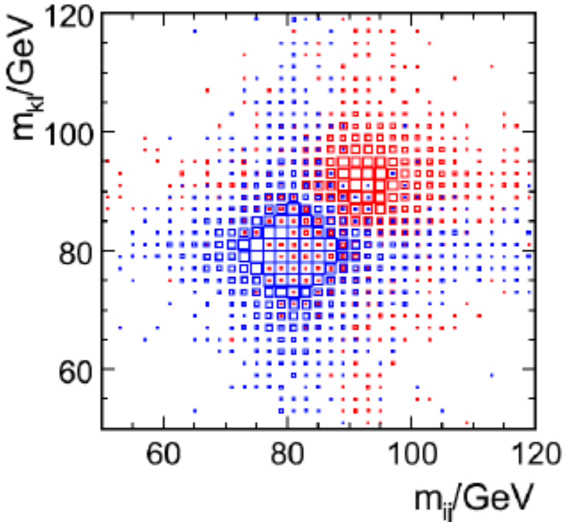
High resolution Calorimetry

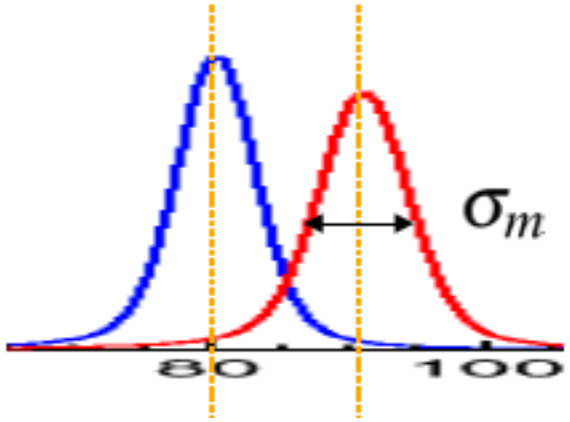
For future colliders, jet energy resolution will be a determinant factor of understanding high energy physics.

Required to have best possible di-jet mass resolution for narrow resonance observation

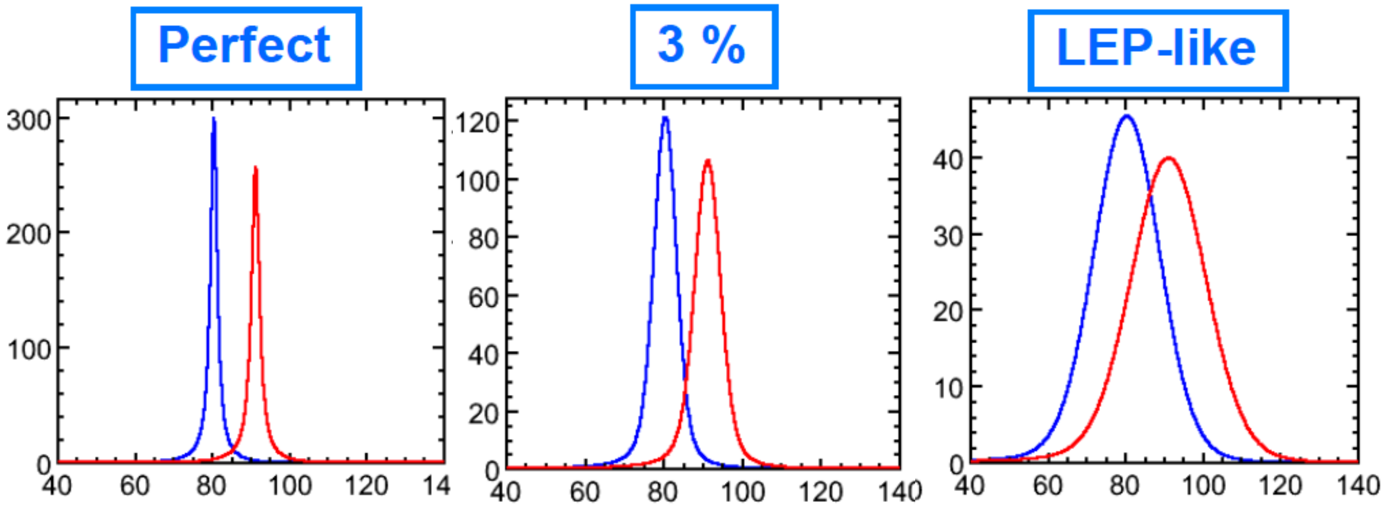
At very least one need to distinguish W/Z hadronic decays







$$\text{W/Z sep} = (m_Z - m_W)/\sigma_m$$



Jet E res.	W/Z sep
perfect	**3.1 σ**
2%	**2.9 σ**
3%	**2.6 σ**
4%	**2.3 σ**
5%	**2.0 σ**
10%	**1.1 σ**

W/Z sep: 3σ

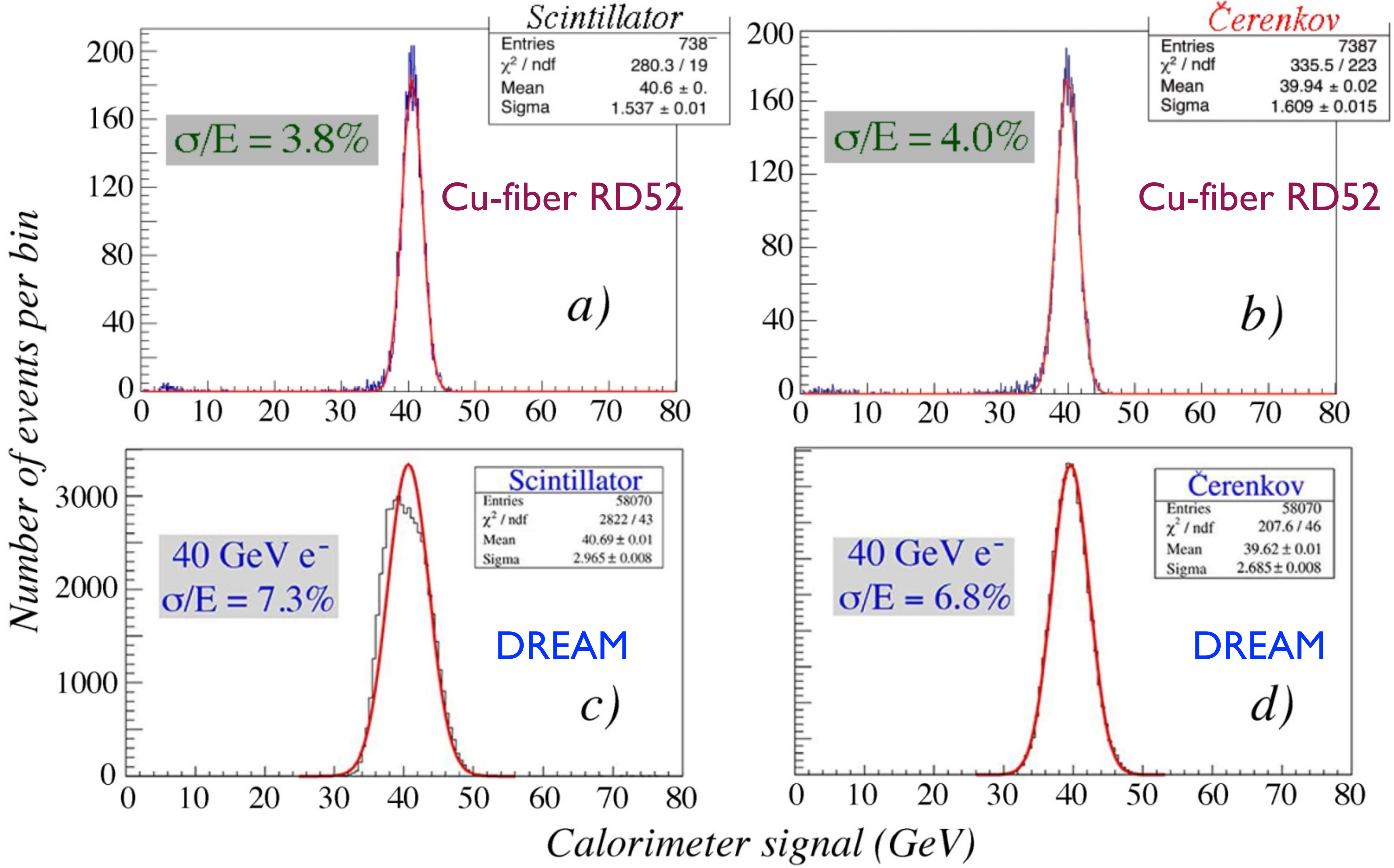
$$\frac{\sigma}{E} \sim \frac{30\%}{\sqrt(E)}$$

NIM A 735 (2014) 130

EM performance RD52 Cu calo

Em performance strongly improved with the new RD52 Cu-fiber prototype.

Better sampling fraction



Cu-fiber RD52

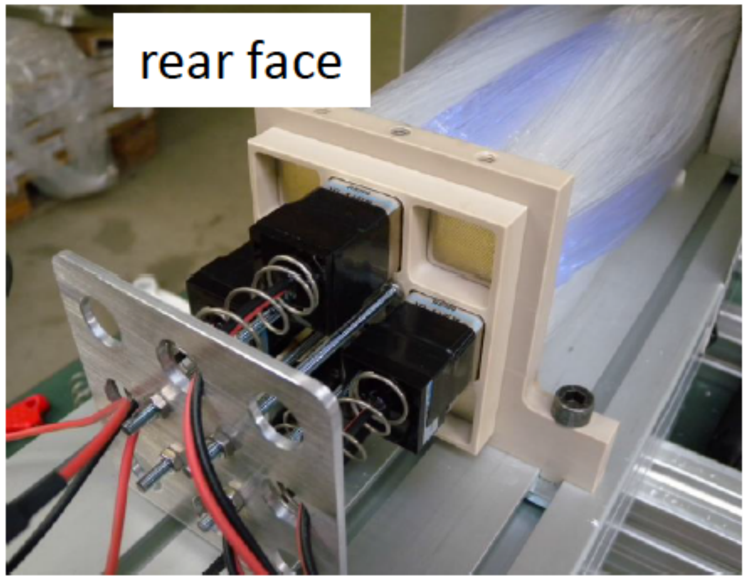
Cu-fiber RD52

DREAM

DREAM

Pb-fiber module construction

Pb fabrication:
Cold extrusion (industry, Italy), both sides.
Assembling in INFN Pavia, no glue used



Pb-fiber module construction

Cu-fiber module construction

We have investigated many techniques in order to make grooves in Cu:

- **Extrusion** (technique used for RD52 Pb, and for DREAM, not easy for RD52 Cu pattern)

not possible with this pattern, because aspect ratio and Cu too hard
Trials done in AMES lab (USA), not good depth control

- **Rolling** not enough precision obtained

Impossible with one face pattern
Somehow done for two sides pattern but but not good uniformity

- **Saw scraping with rotating calibrated disks** (like PISA prototype)

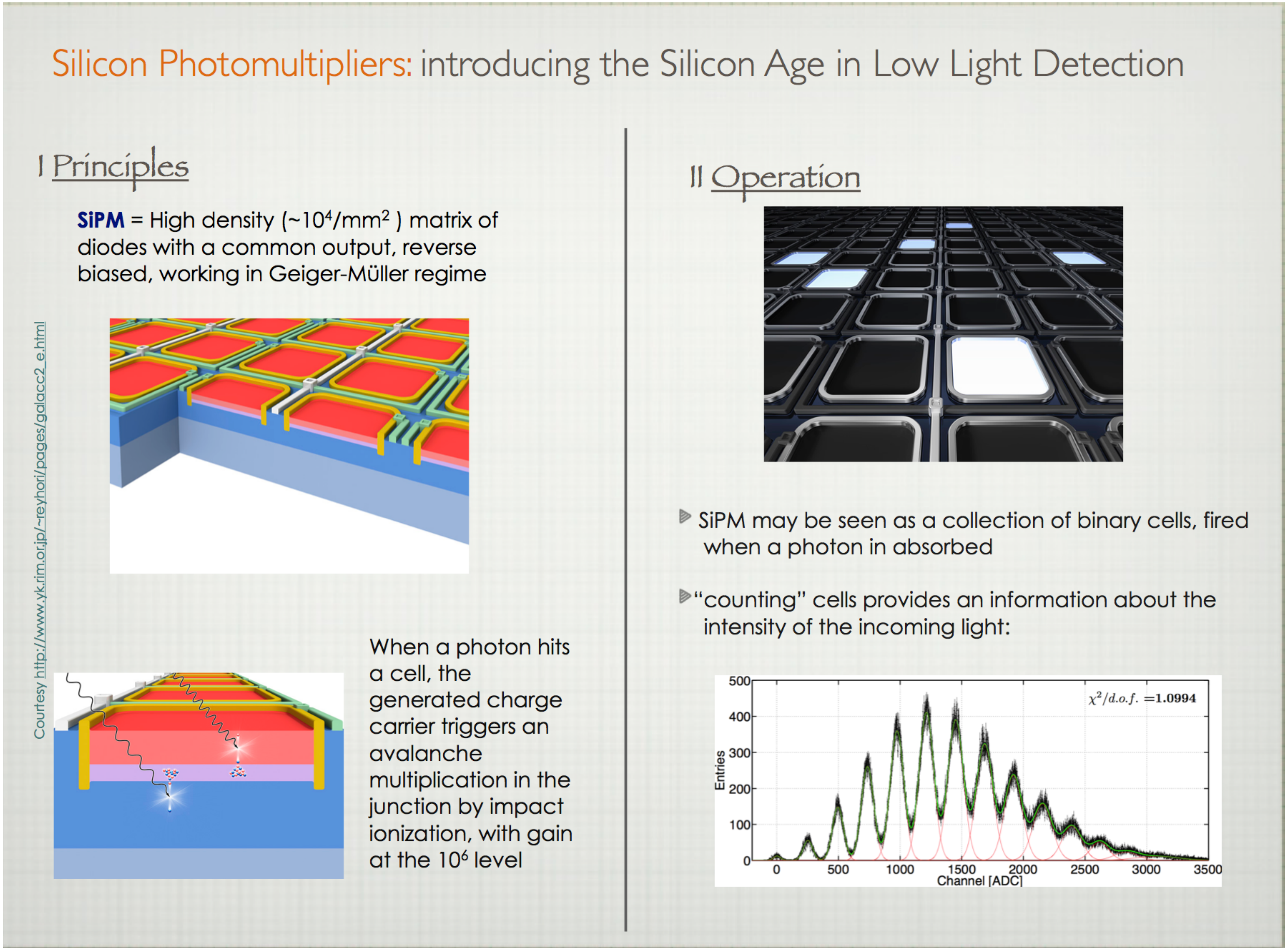
time consuming for big production

- **Water jet**
- **Chemical milling**

PROMIZING, INDUSTRIALLY COMPATIBLE

+ Final rolling for fine adjustments

Silicon Photo Multiplier (SiPM)



Silicon Photomultipliers: introducing the Silicon Age in Low Light Detection

I Principles

SiPM = High density (~10^4/mm^2) matrix of diodes with a common output, reverse biased, working in Geiger-Müller regime

Courtesy http://www.yk.rim.or.jp/~reyhori/pages/galacc2_e.html

When a photon hits a cell, the generated charge carrier triggers an avalanche multiplication in the junction by impact ionization, with gain at the 10^6 level

II Operation

- SiPM may be seen as a collection of binary cells, fired when a photon in absorbed
- "counting" cells provides an information about the intensity of the incoming light: