Double readout calorimeter at FCC-ee

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INFN – Sezione di Pavia

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

RD52 DREAM

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

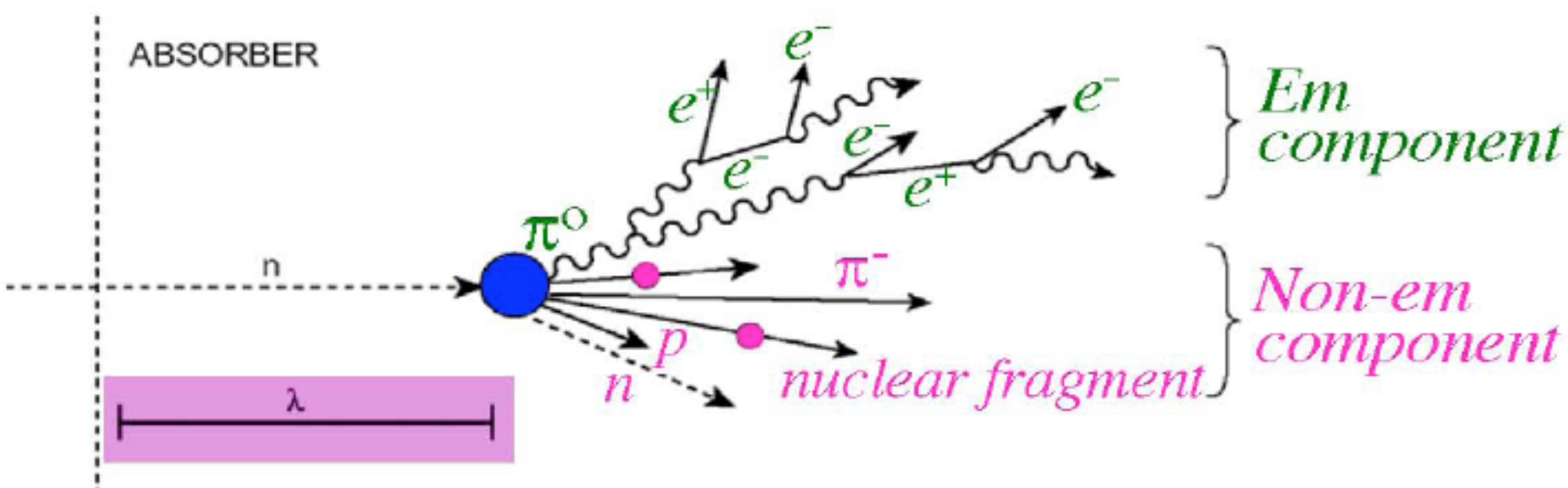
Principle of the Dual Readout method

Hadronic showers consist of two components:

em (π^0) 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. the 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)

1 - E.M. Fraction Fluctuation

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

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

$$C = [f + c(1-f)]E$$
$$S = [f + s(1-f)]E$$

where

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

It is possible to evaluate

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

and

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

$$\lambda = \frac{1-s}{1-c}$$

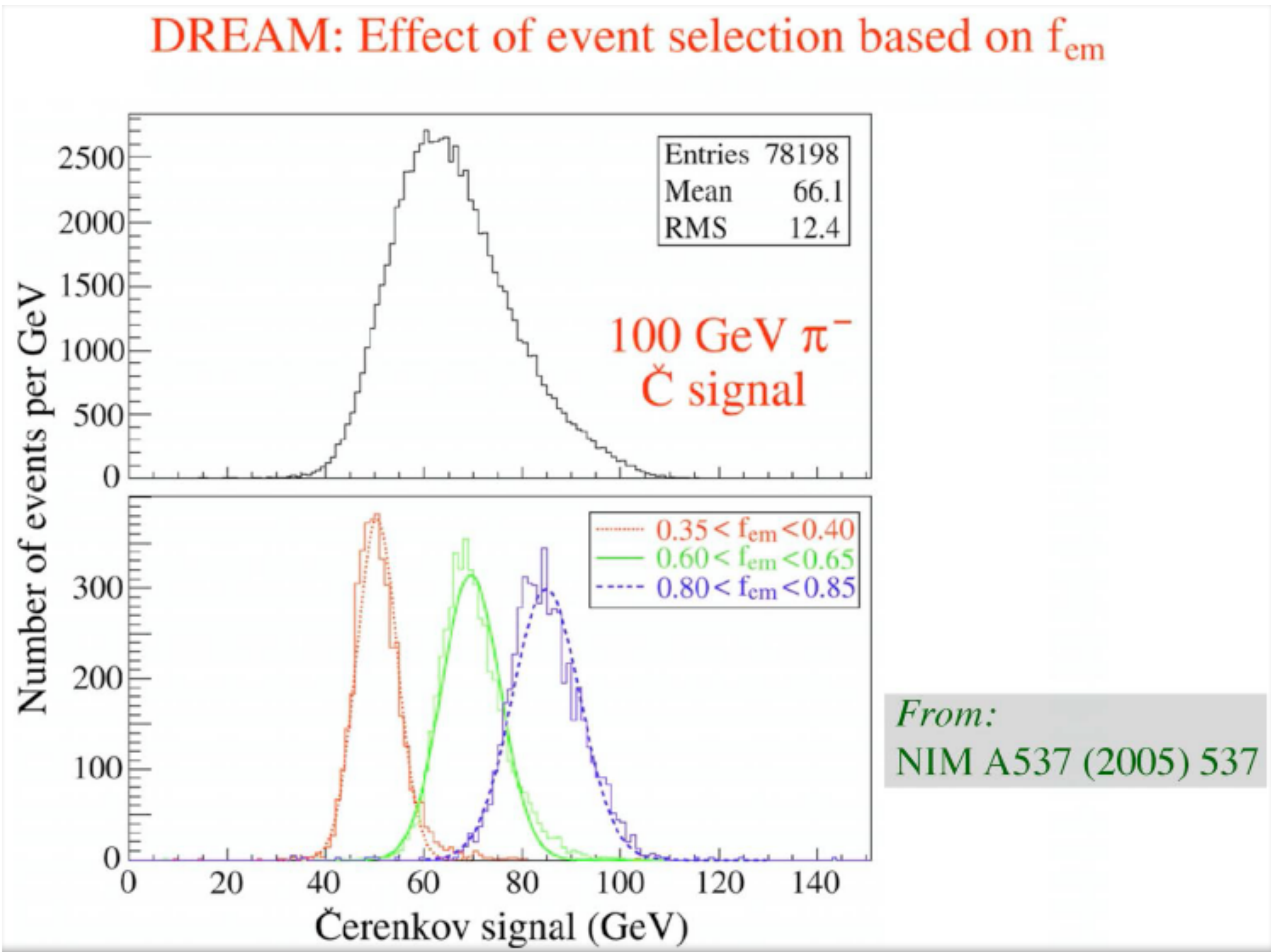
can be measured on beam of Energy E_0

$$\lambda = \frac{E_0 - S}{E_0 - C}$$

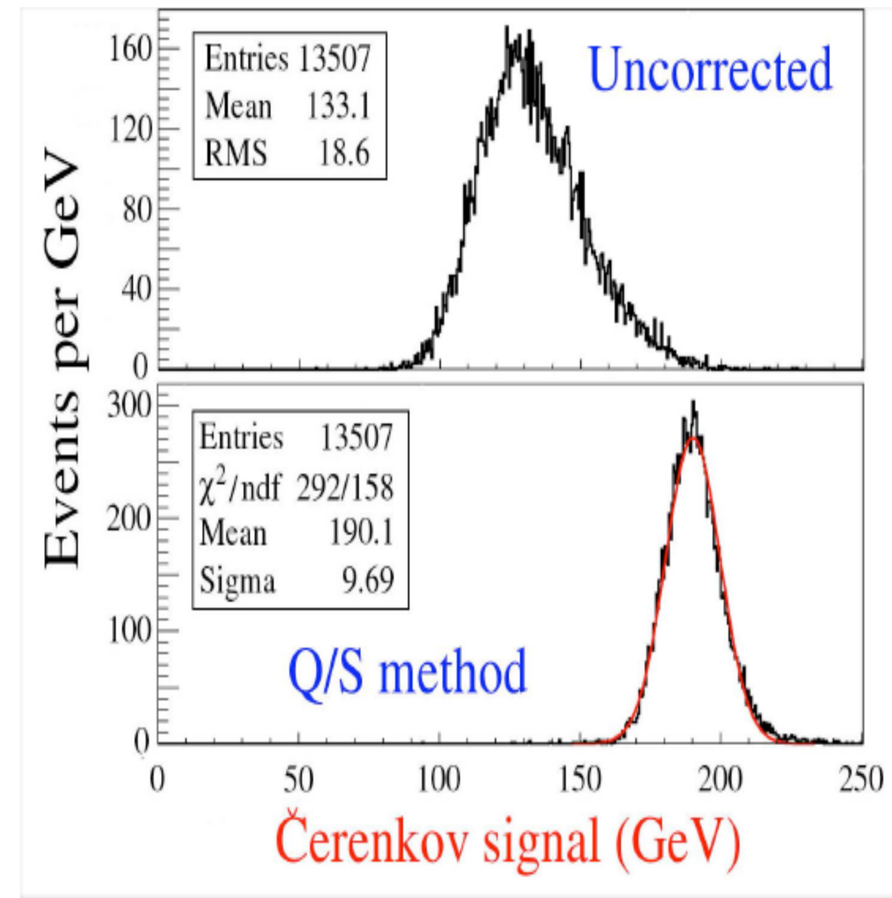
can be extracted from a linear fit of C vs S

$$S = (1-\lambda)E_0 + \lambda C$$

1 - E.M. Fraction Fluctuation



200 GeV "jets"



1 – E.M. Fraction Fluctuation

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

2 - 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)

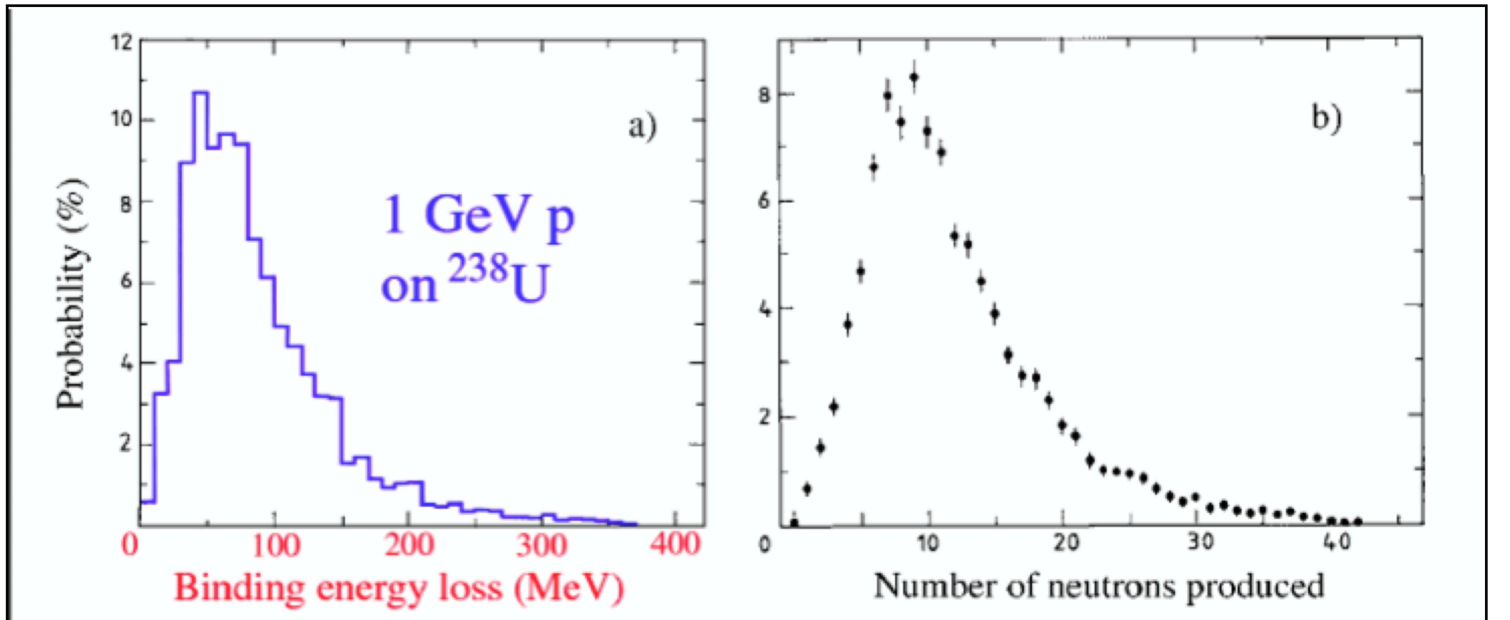
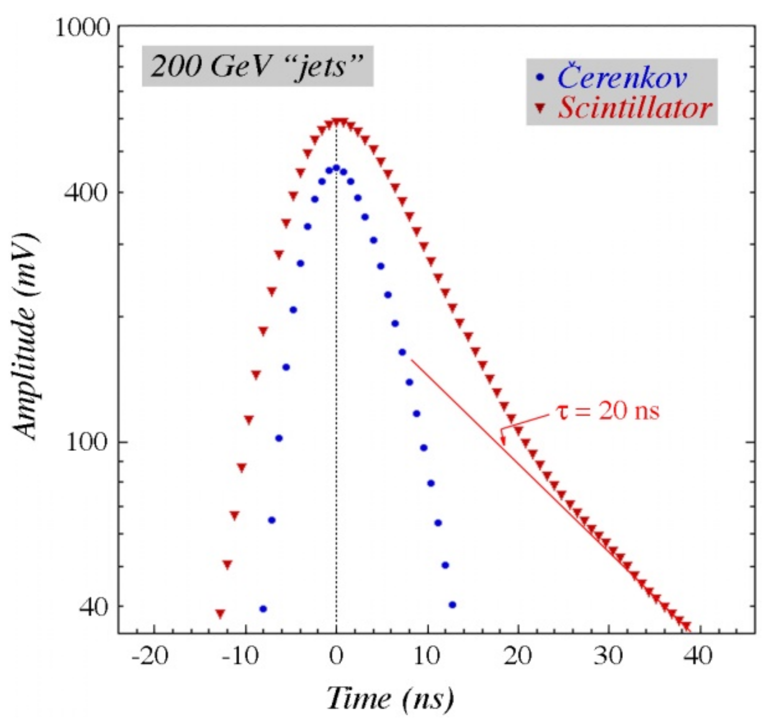


FIG. 4.43. The nuclear binding energy lost in spallation reactions induced by 1 GeV protons on ^{238}U nuclei (a), and the number of neutrons produced in such reactions (b). From [Wig 87].

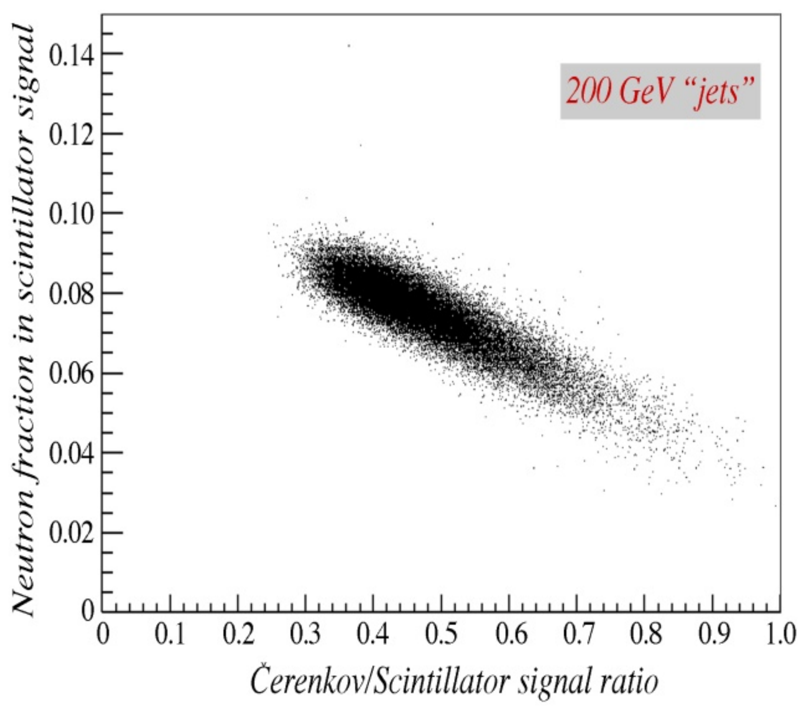
2 - Invisible Energy

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*)

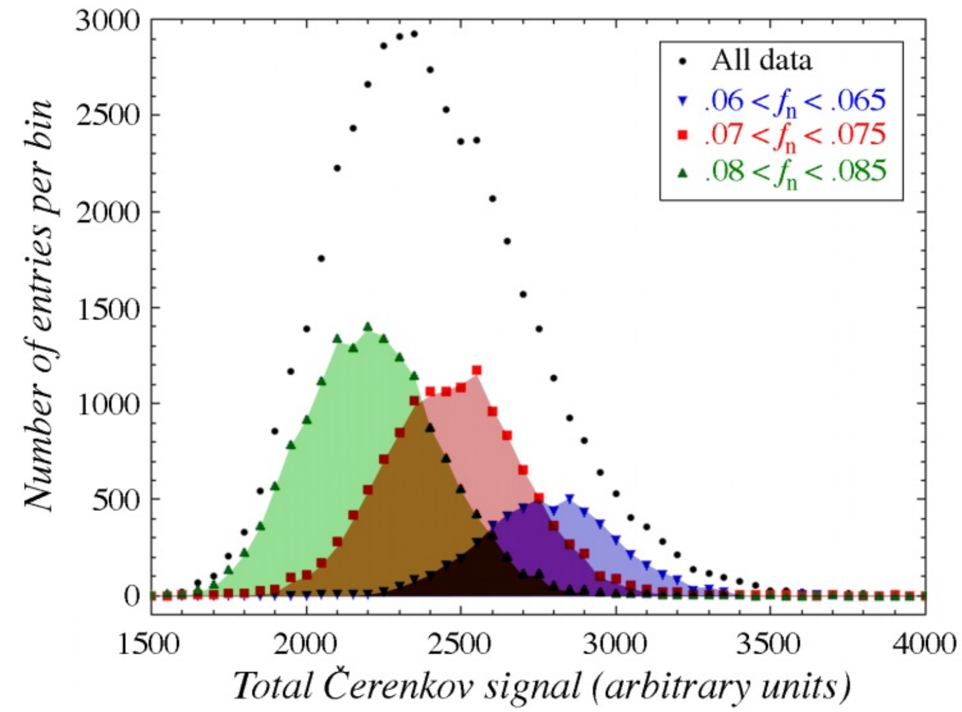
Time structure of DREAM signal. Tail absent in em showers



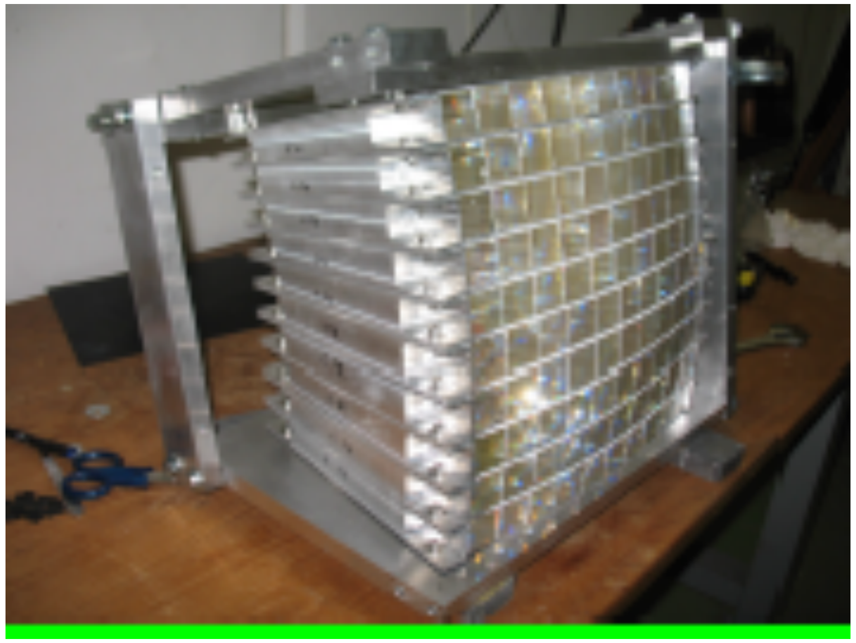
N fraction anti-correlated to f_{em} (C/S)

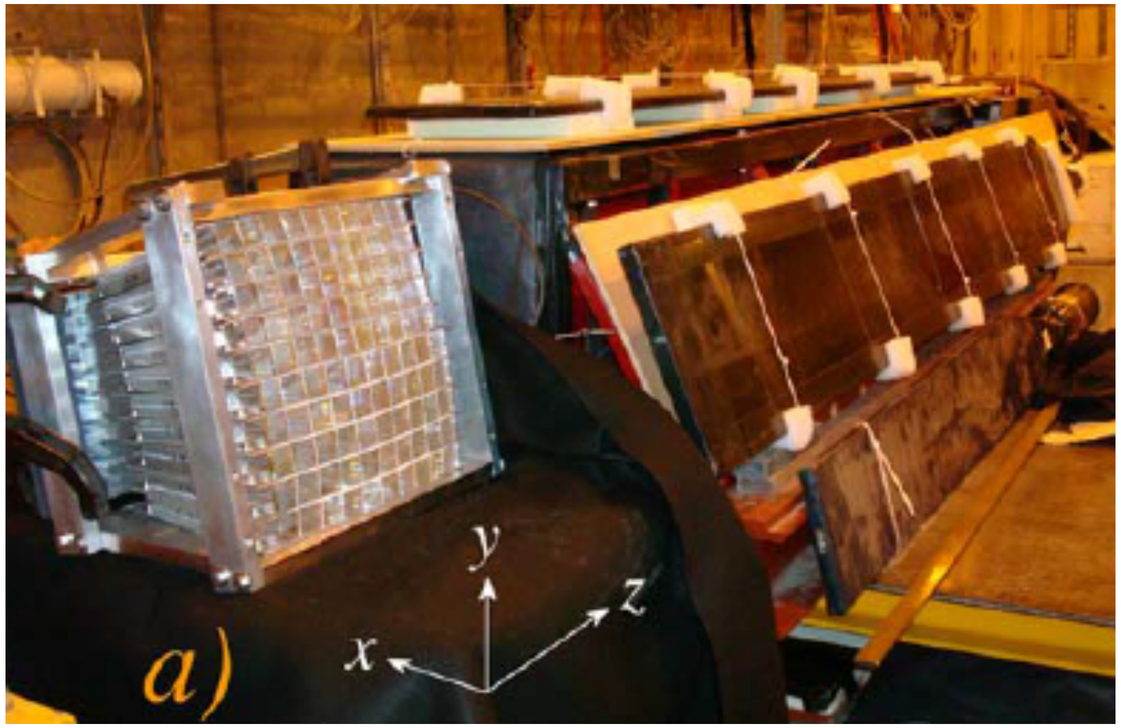


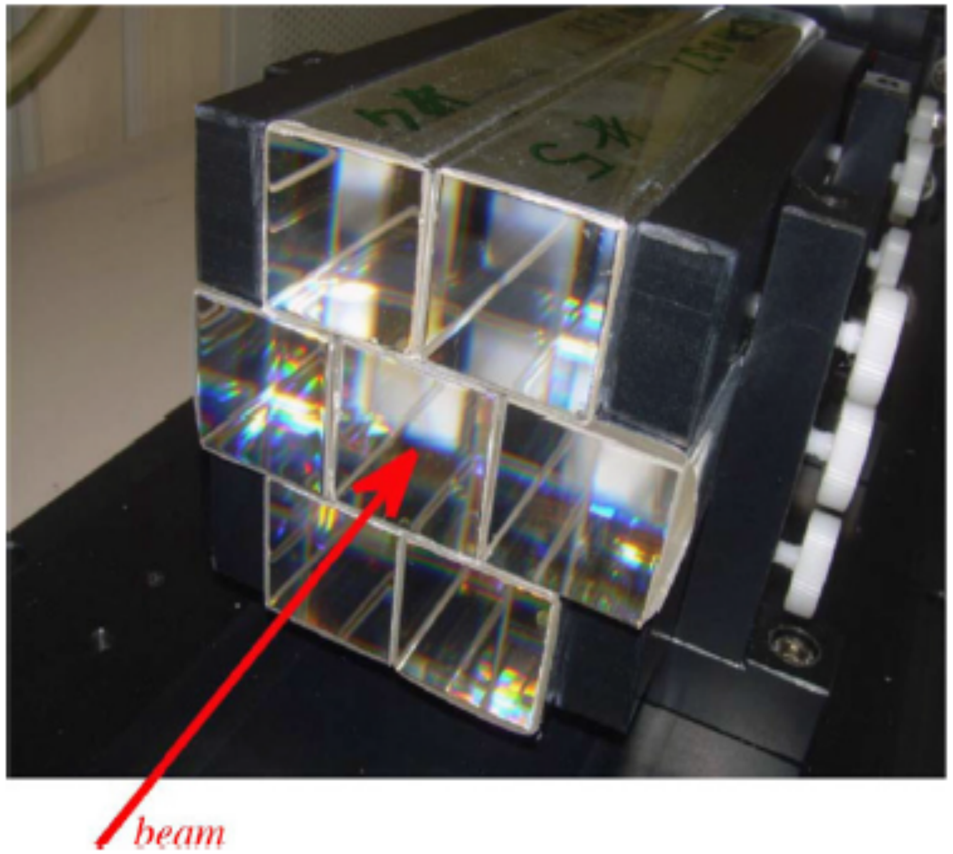
Probing the tot. signal distribution with N fraction



Dual readout 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:

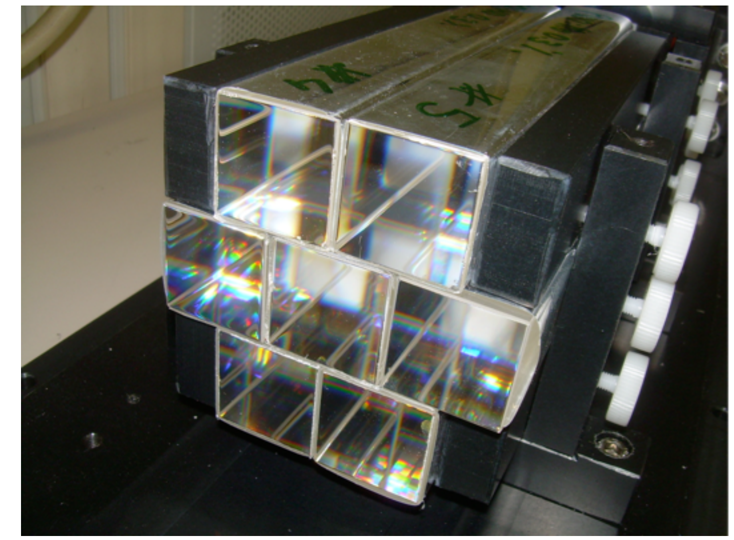
Measuring fem on an event-by-event basis allows to correct for such fluctuations and allows to eliminate the main reasons for poor hadronic resolution

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

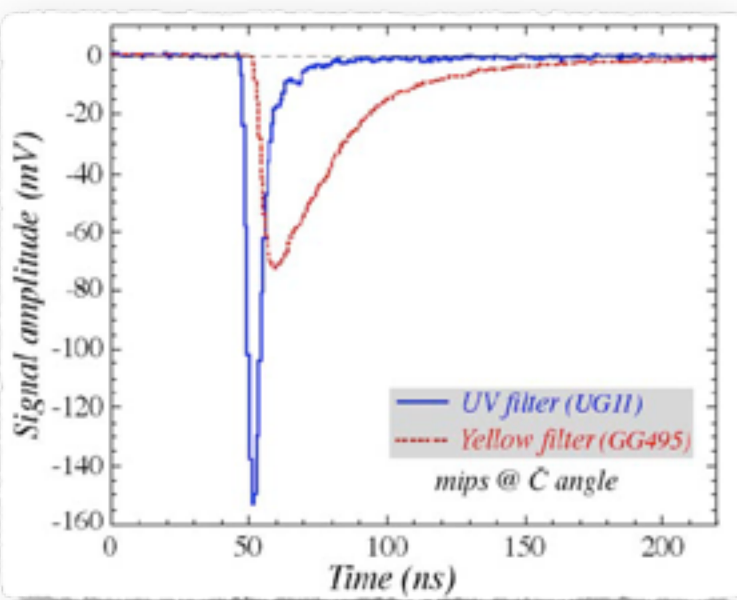
Requirements for using crystals in dual readout based calorimeter:

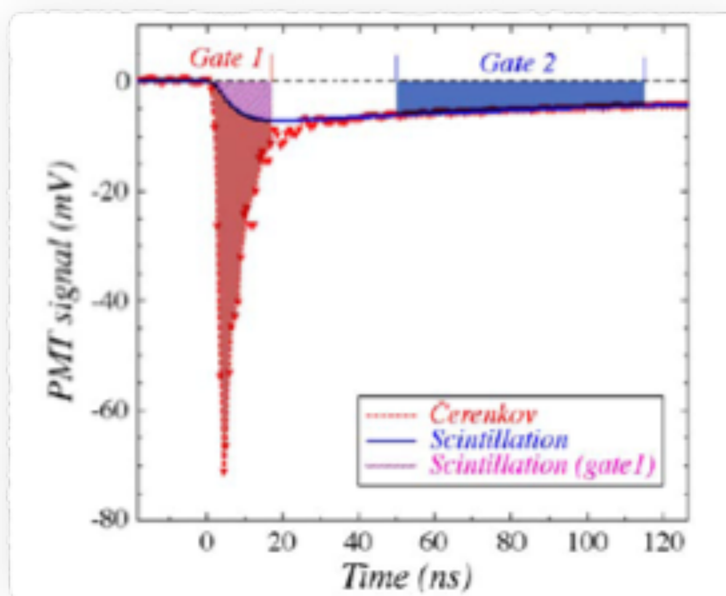
- Good Čerenkov vs Scintillation separation
- Response uniformity
- High light yield (to reduce contribution of p.e. fluctuation to the resolution)



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 $PbWO_4$
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- BSO

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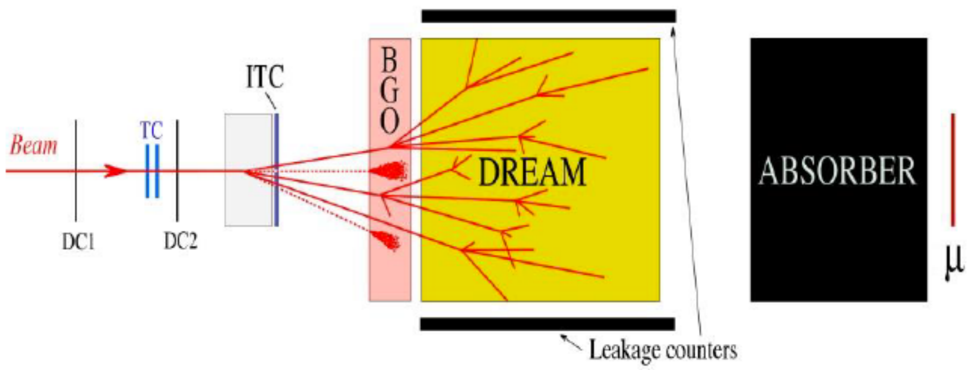
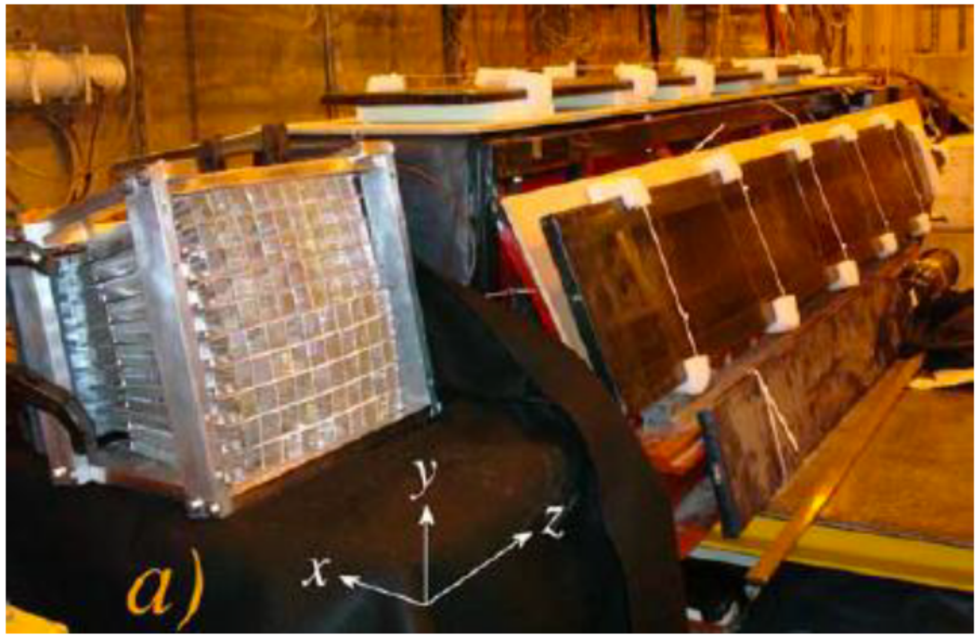
Crystal matrix + fiber sampling calo

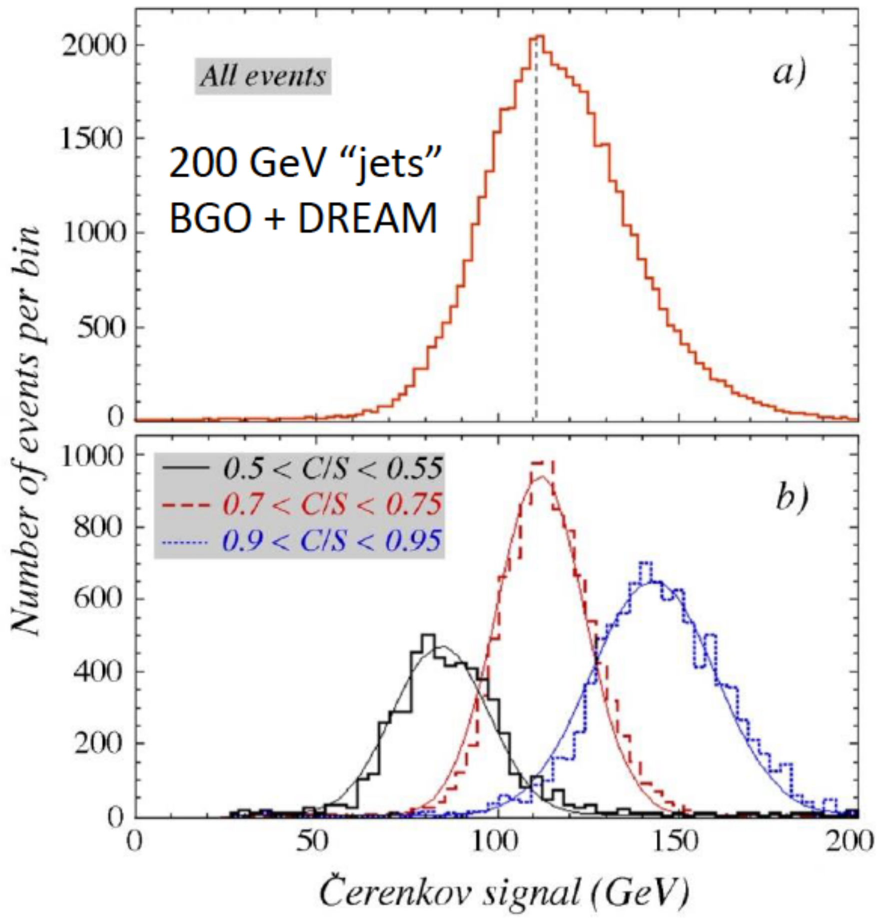
NIMA 598 (2009) 710, NIM A 610 (2009) 488

Purpose of these tests: to see to what extent the dual readout principle (that worked so well to improve the hadronic performance of the DREAM in stand alone) are applicable when most of the shower is deposited in a crystal calorimeter section

Performed tests: $PbWO_4$ matrix, BGO single Xtal, BGO matrix from L3 experiment (100 crystals) read first with 4 and then with 16 PMT

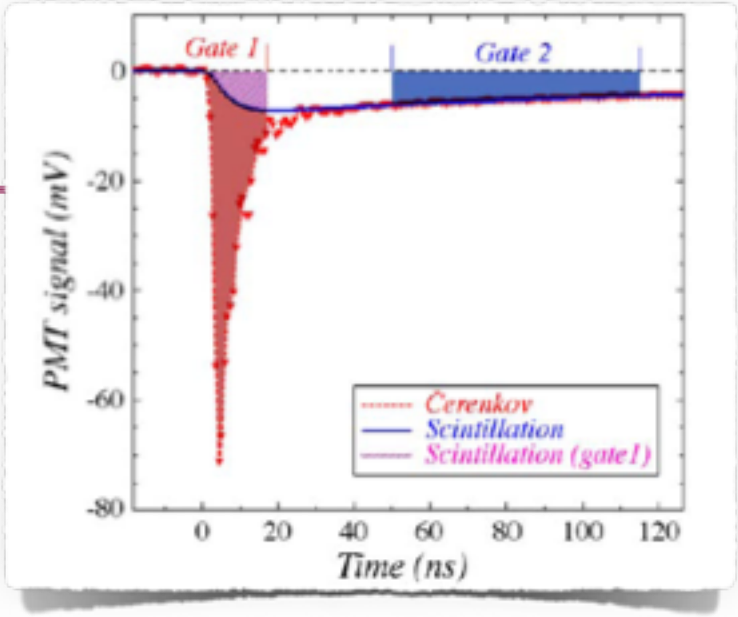






The dual-readout principle also worked well for this hybrid calorimeter system.

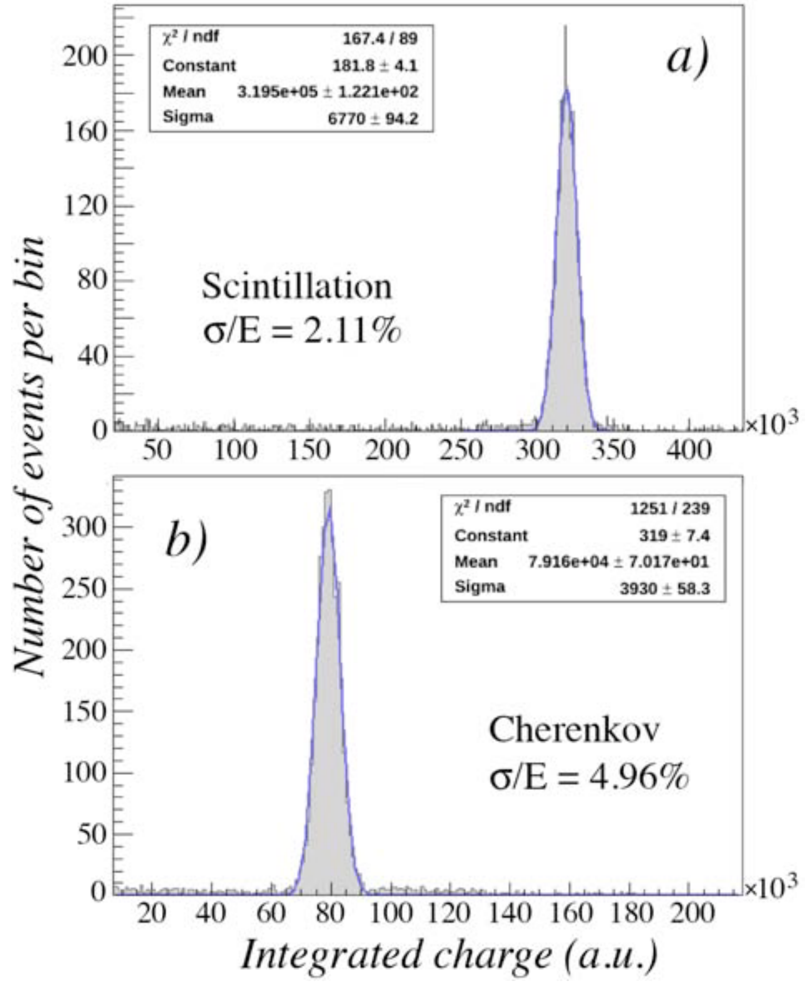
BGO Matrix results



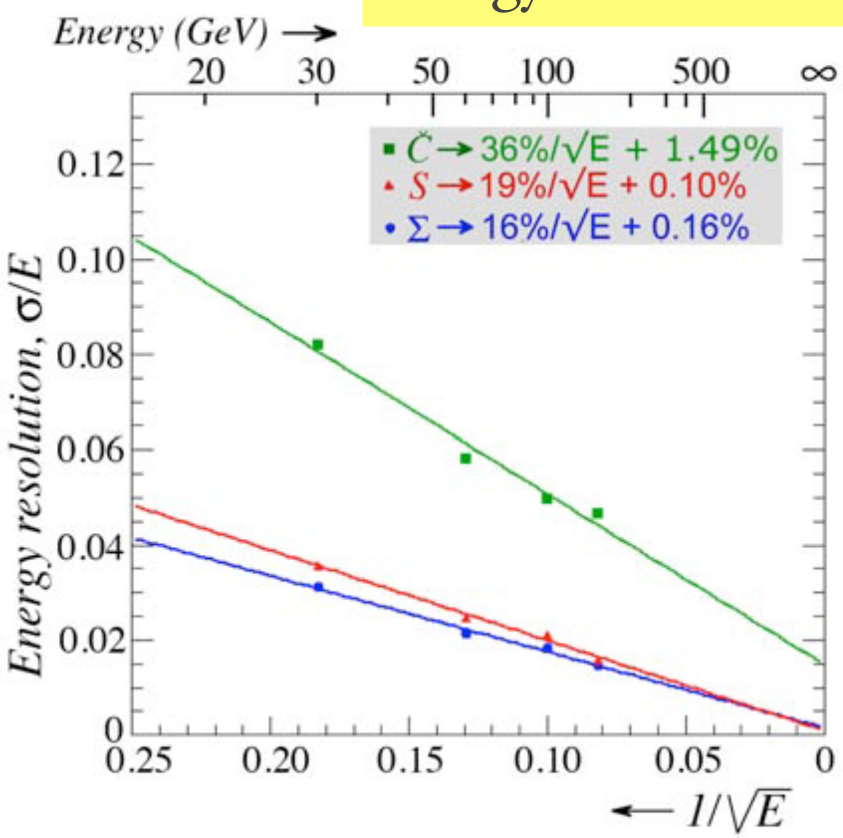
Resolution obtained from distribution of integrated charge

- Čerenkov energy resolution shows a constant term of about 1.5%
- good linearity (within ± 3%)
- Čerenkov light yield about 6 p.e./GeV

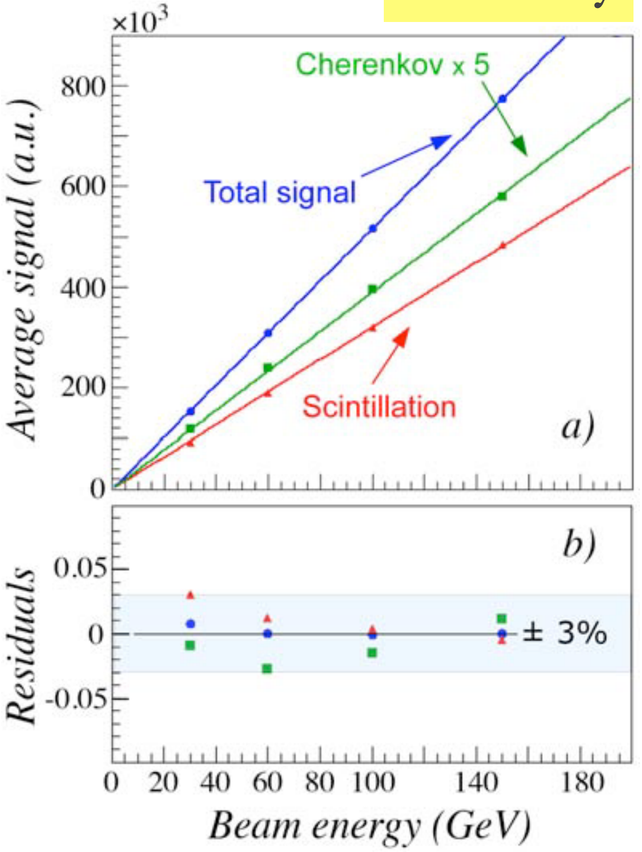
100 GeV electron



Energy Resolution

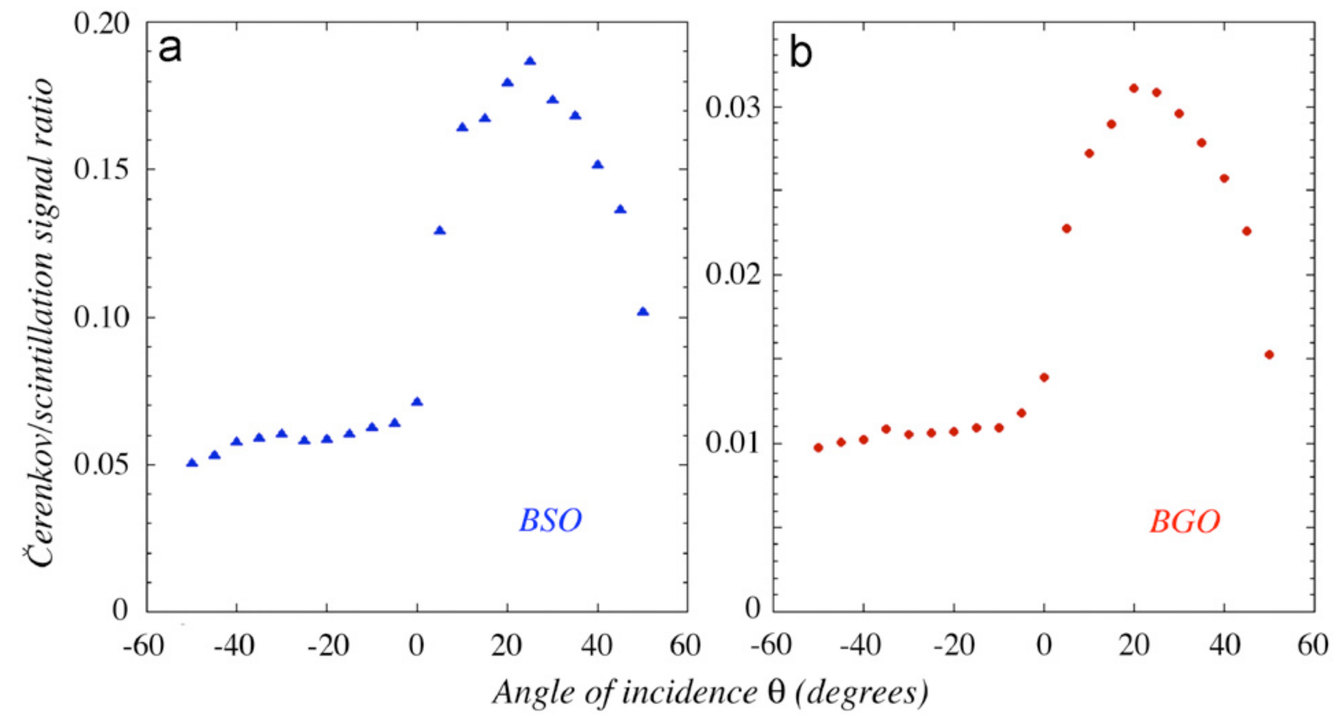


Linearity

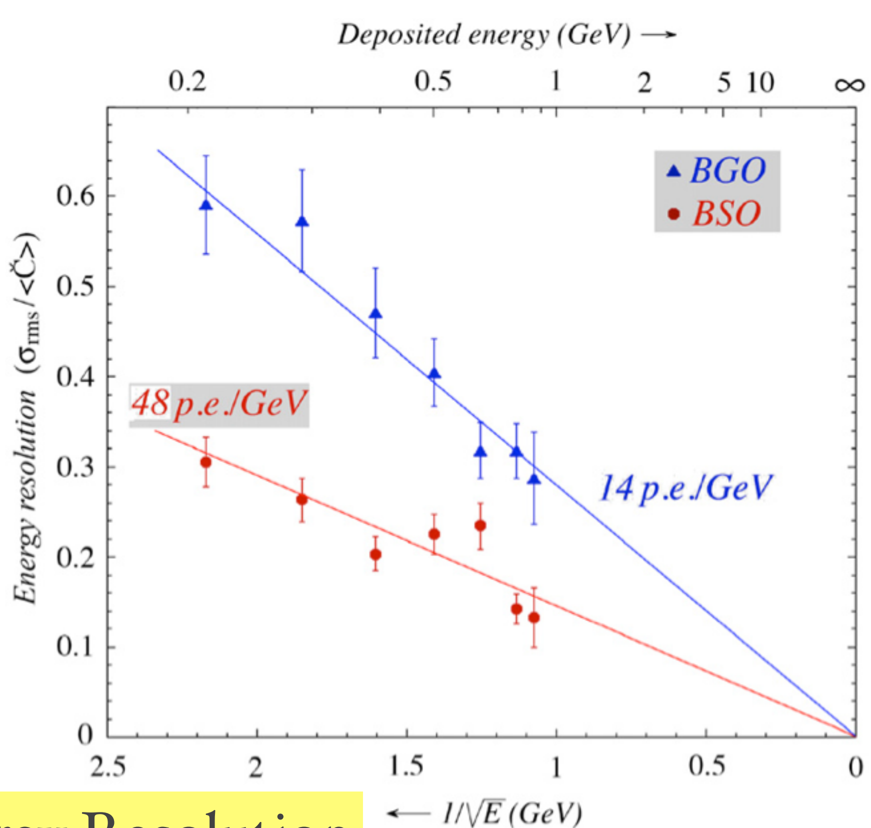


BGO vs BSO for dual readout use

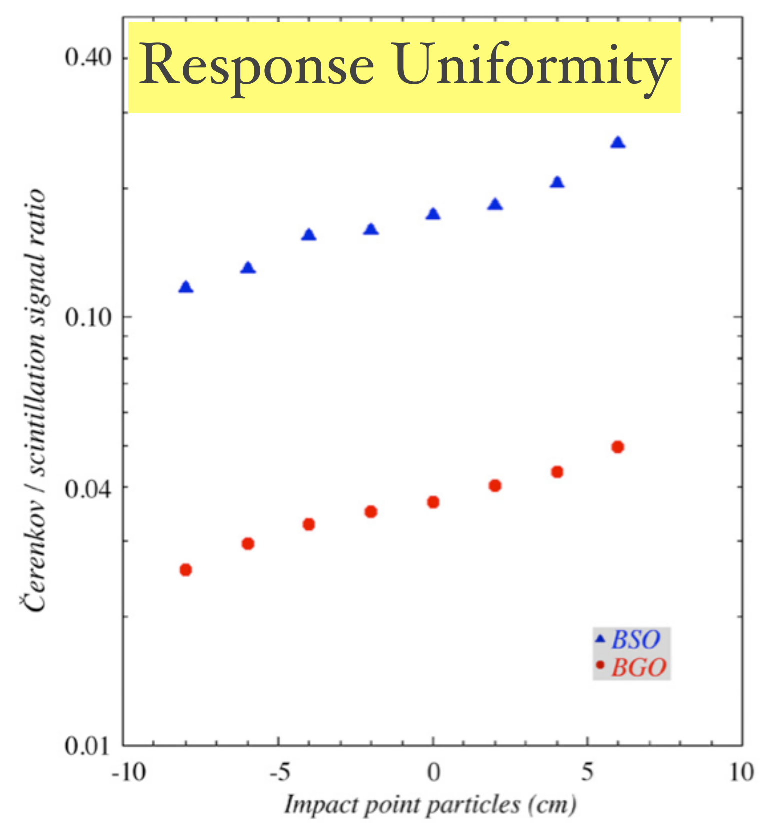
Crystal	Density (g cm^{-3})	Radiation length (mm)	Decay constant (ns)	Peak emission (nm)	Refractive index *n*	Relative light output
BSO	6.80	11.5	~ 100	480	2.06	0.04
BGO	7.13	11.2	~ 300	480	2.15	0.15



purity of the $\check{C}$ signal obtained with filters: separation power better by a factor of 6



Energy Resolution



- $\check{C}$ light yield: p.e. detected per unit deposited energy 2-3 times larger in BSO
- light attenuation length for $\check{C}$ light: mostly the same in both crystals

Mo:$PbWO_4$ matrix results

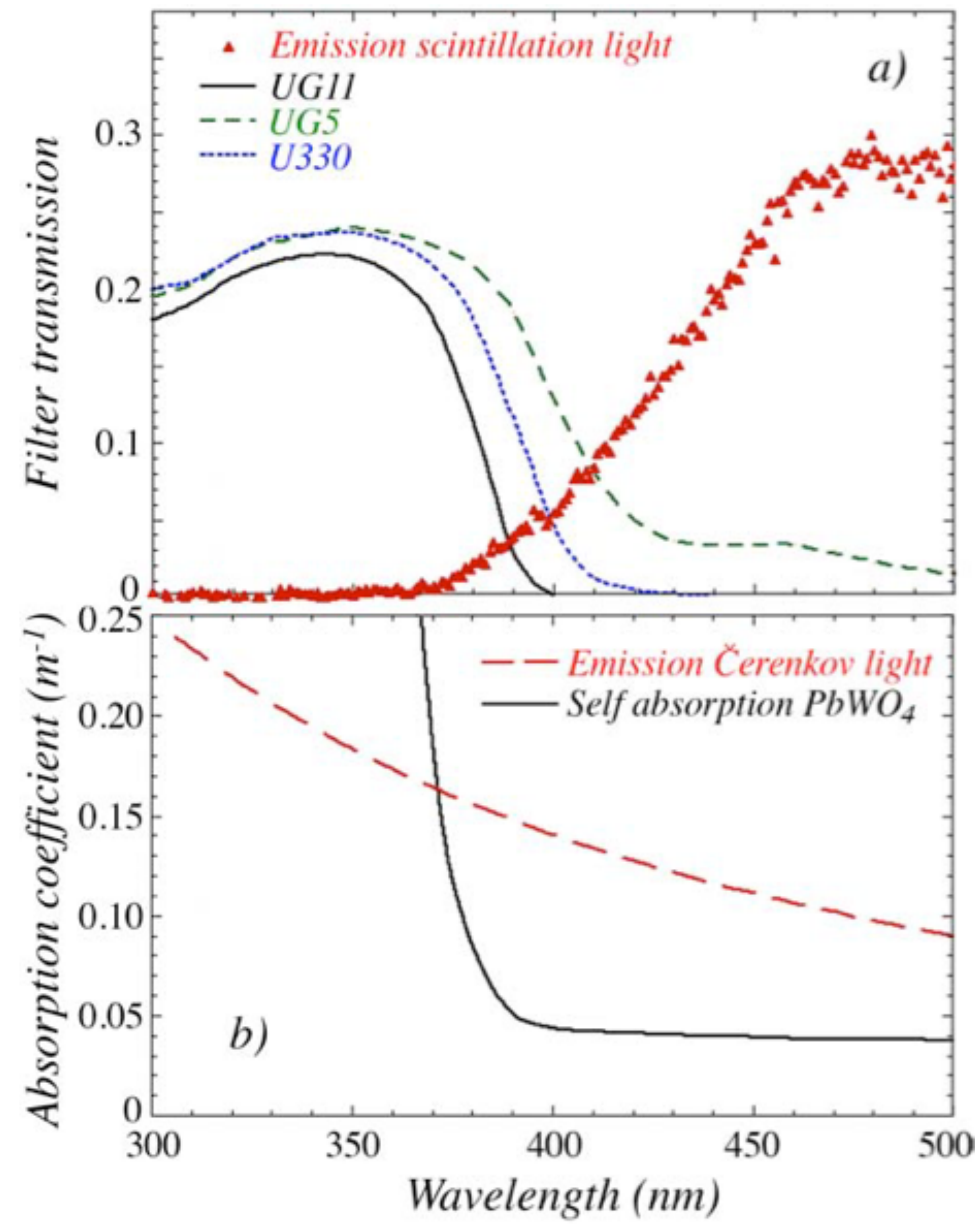
Molybdenum doping causes:

★ shift of the S spectra to higher λ wrt undoped crystal
★ longer S decay time (50 ns)
★ shift of the absorption cut-off to higher λ

This allows to obtain a ***very good C/S separation*** using filters.

Very narrow window where C light can be collected results in ***strong light attenuation***

Different filter combinations were used during the $PbWO_4$ matrix test, each optimizing one aspect of the readout



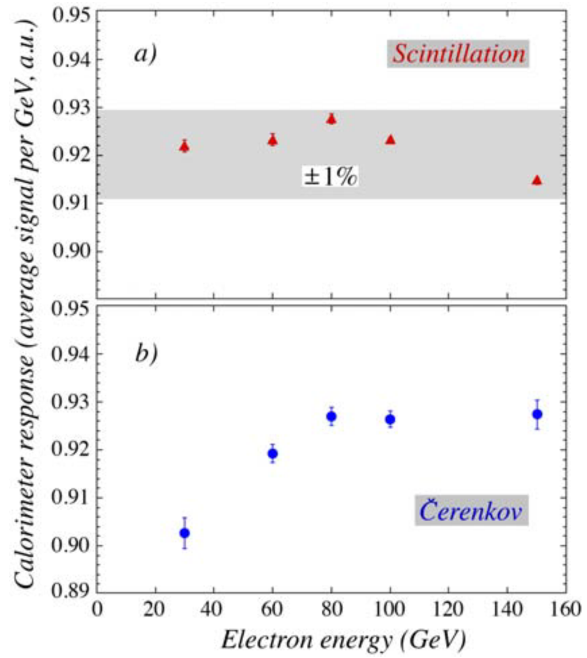
Mo:PbWO$_4$ matrix results

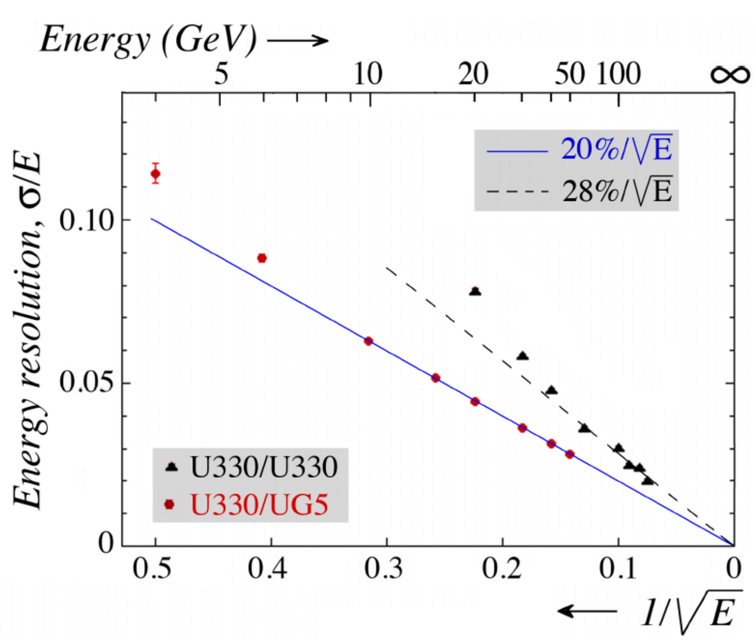
Cherenkov

Upstream GG495 (yellow), downstream U330:

good for S: measured resolution: ~ 1% for 100 GeV e-

poor for Č due to self absorption. Strong non linearity





U330 both sides

good for Č (sum of two sides)

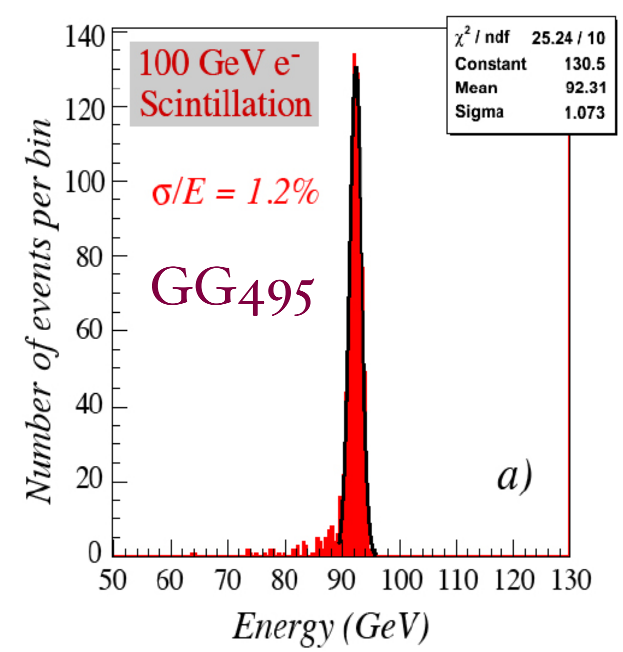
almost no S signal

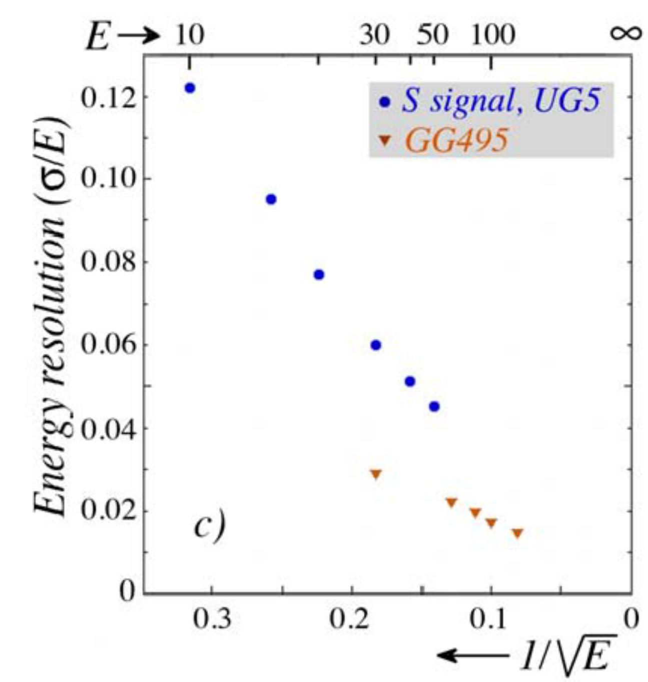
Scintillation

Optimal resolution for Scintillation light reached using yellow filter (large photo-statistic)

If one uses UV+UV filter configuration to improve the Čerenkov resolution

- scintillation signal has to be obtained from integration of the tail of the signal (largely reducing the p.e. photostatistic)





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*

Chrystal + 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

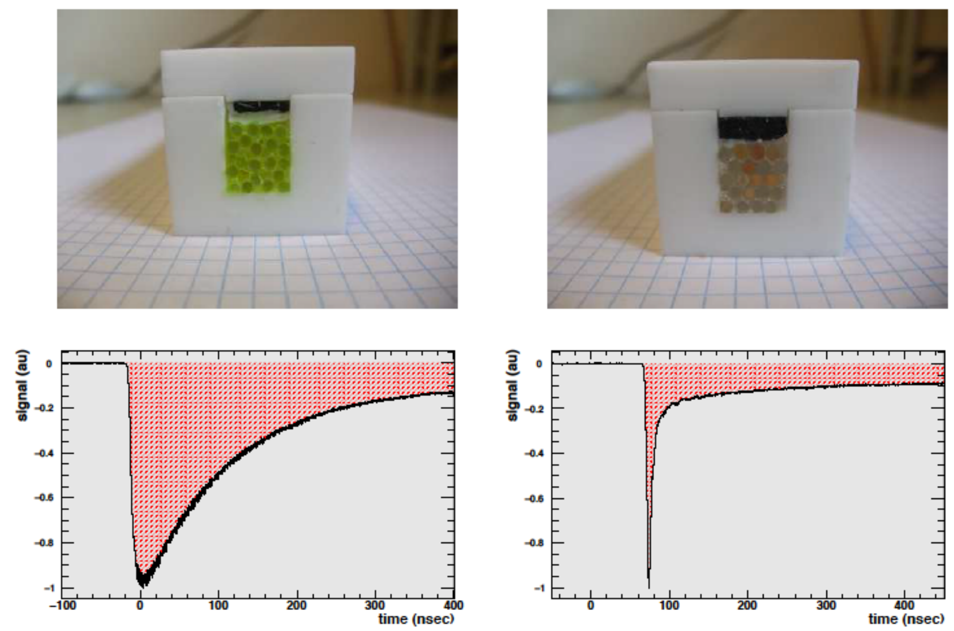
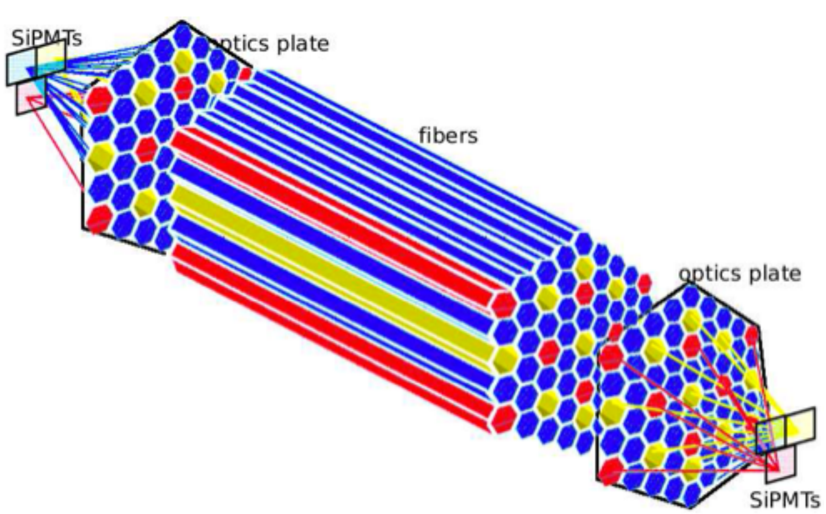


Figure 5. Bundles of Ce doped (top left) and undoped (top right) LuAG fibers and corresponding typical signal pulses recorded (bottom row). Each fiber measures 2 mm in diameter and 80 mm in length.



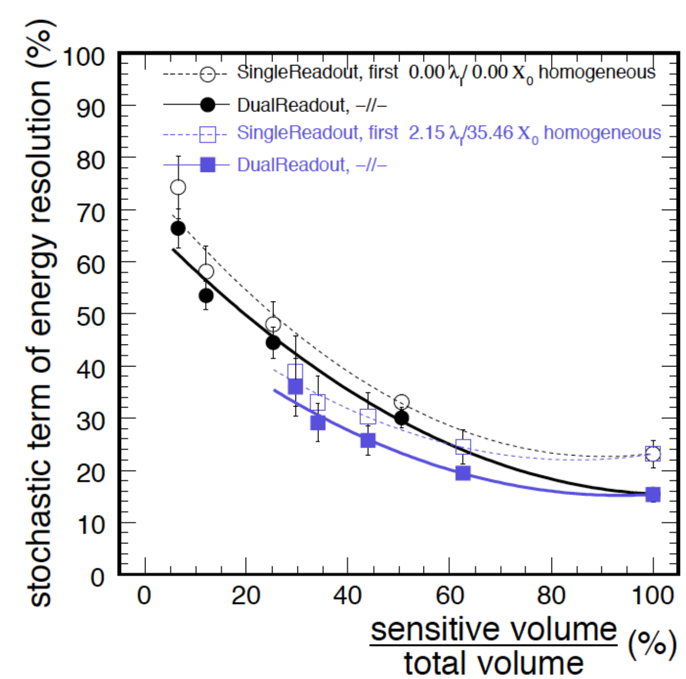
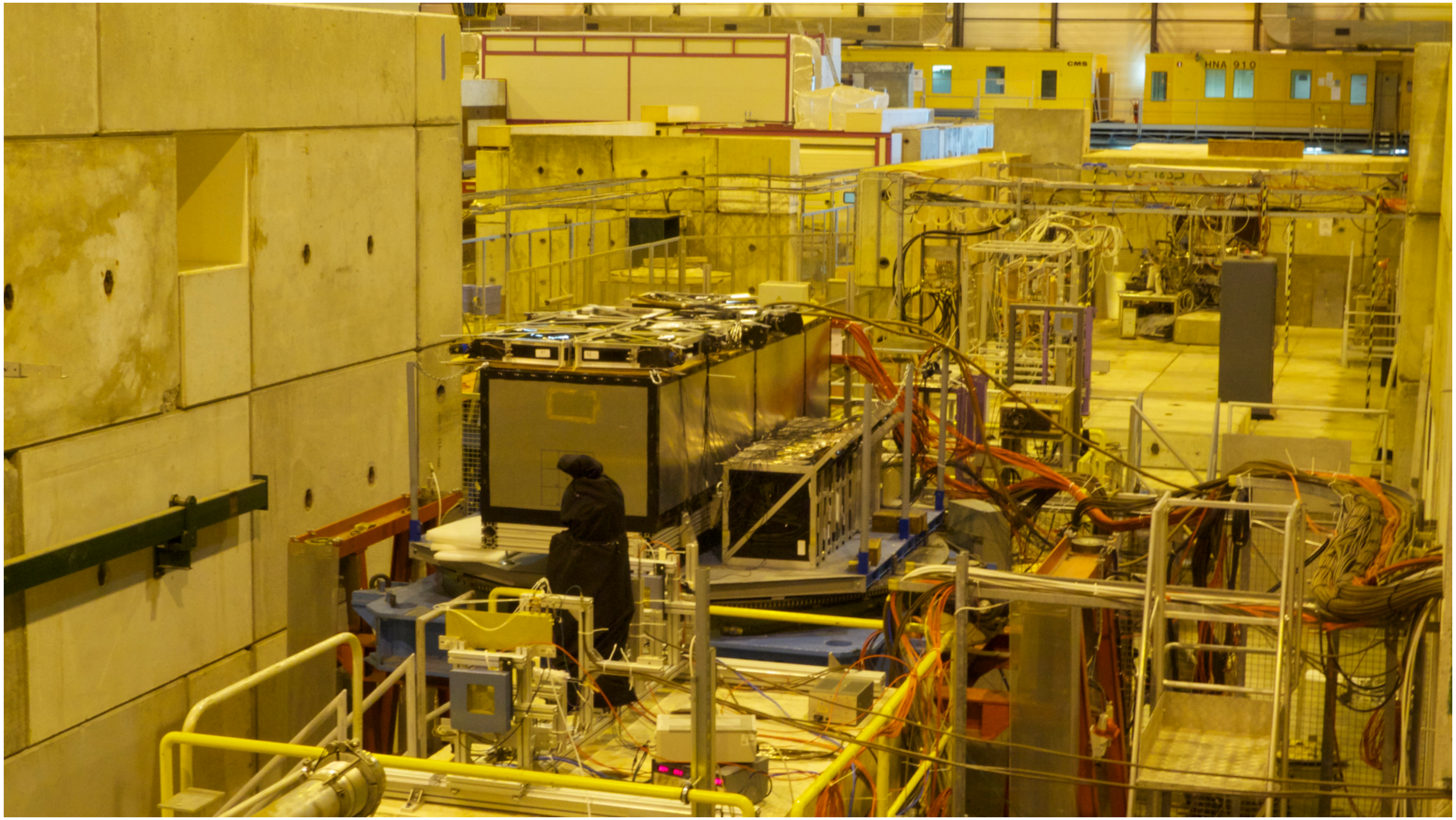


Figure 11. Simulated performance, in terms of the energy resolution's stochastic term, of $4.3\times4.3\times8.6\,\lambda_I^3$ single or dual readout calorimeters with various sampling configurations of ionisation and Cherenkov signal readout.

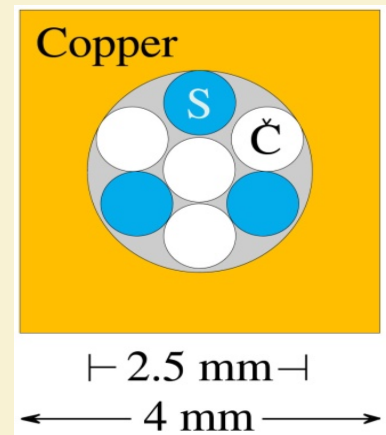
Dual readout with sampling fiber calorimeters

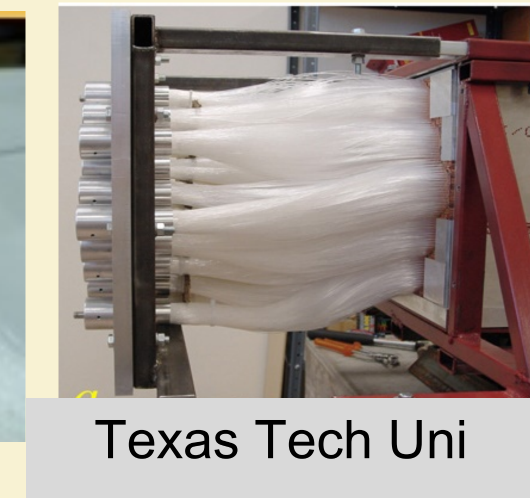


The dual readout fiber calorimeters

2003
DREAM

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

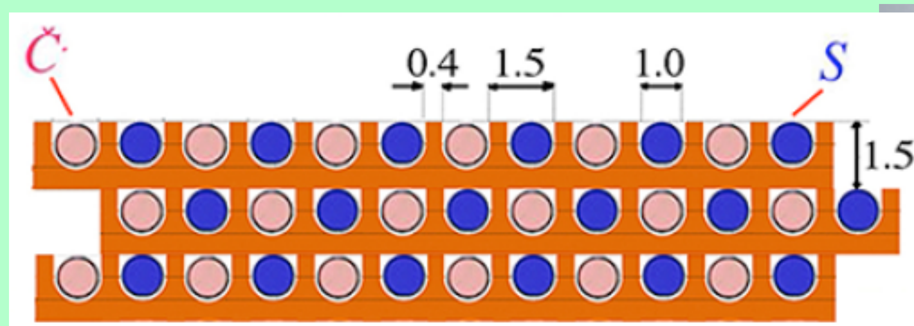




2012
RD52

Copper, 2 modules

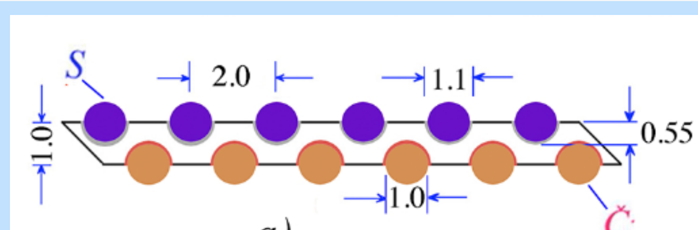
Each module: 9.3 * 9.3 * 250 cm^3
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: 4.5%, 10 λ_{int}

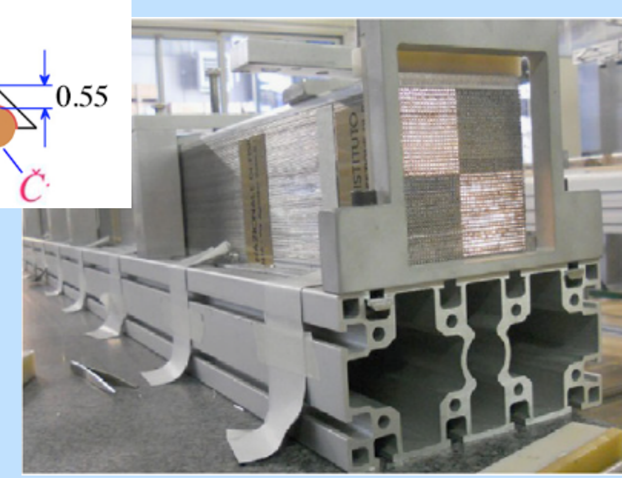


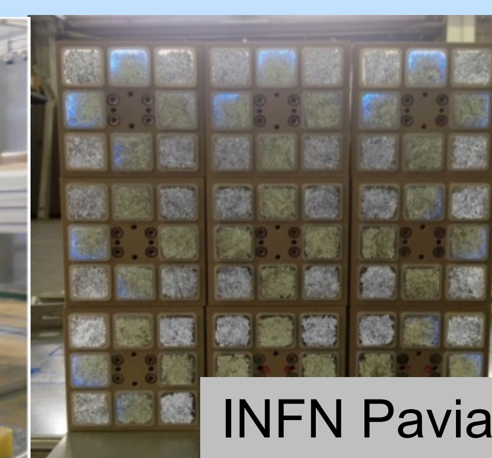
2012
RD52

Lead, 9 modules

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

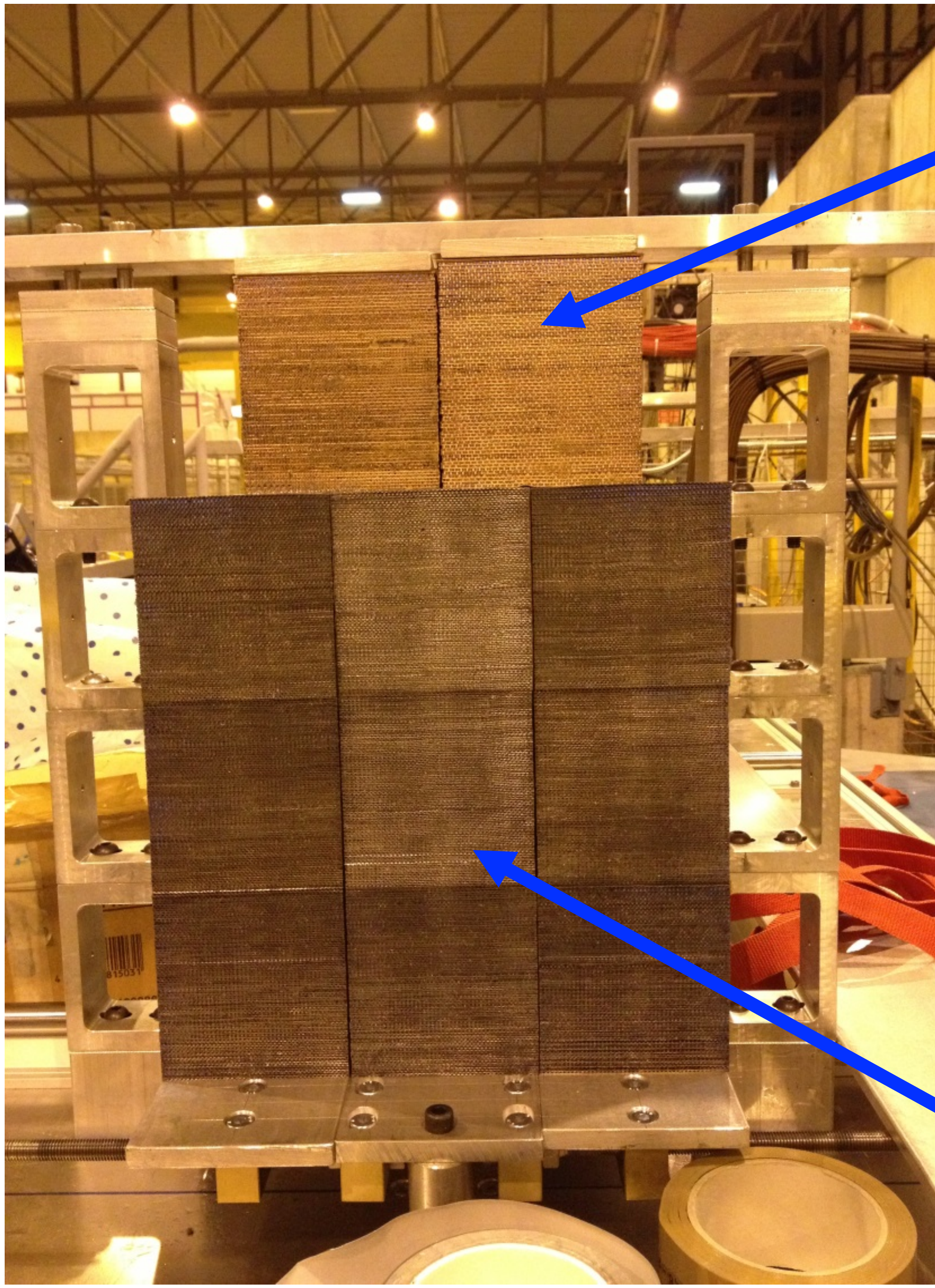






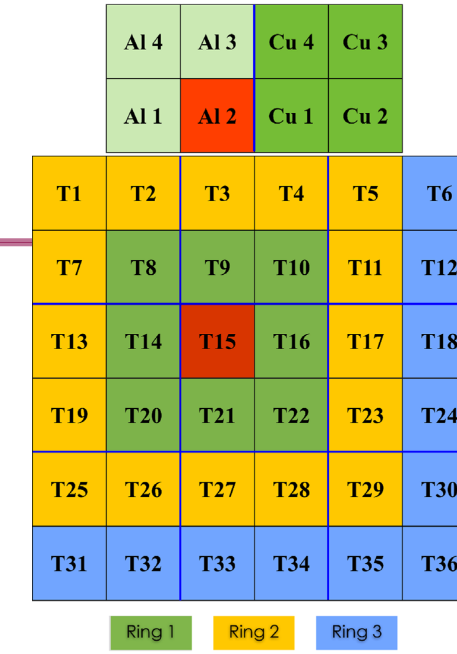
The dual readout fiber calorimeters

2 Cu modules

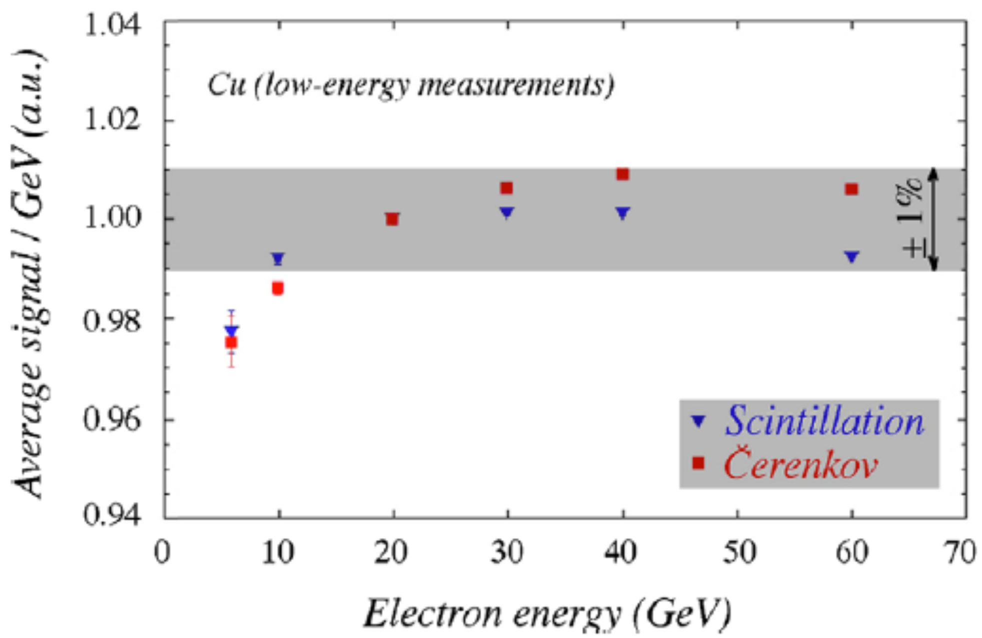


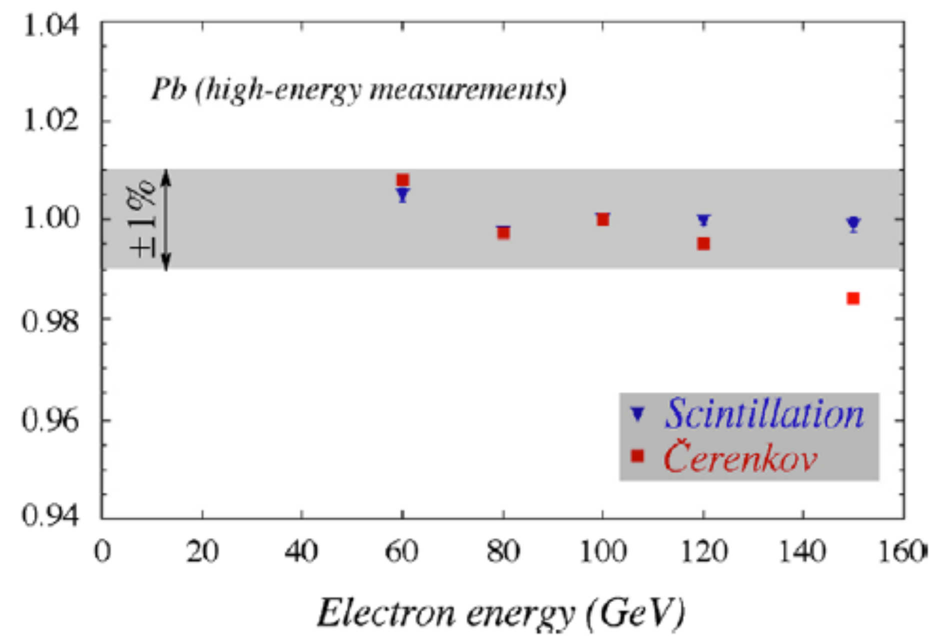
Pb 3*3 matrix

EM performance RD52 calo

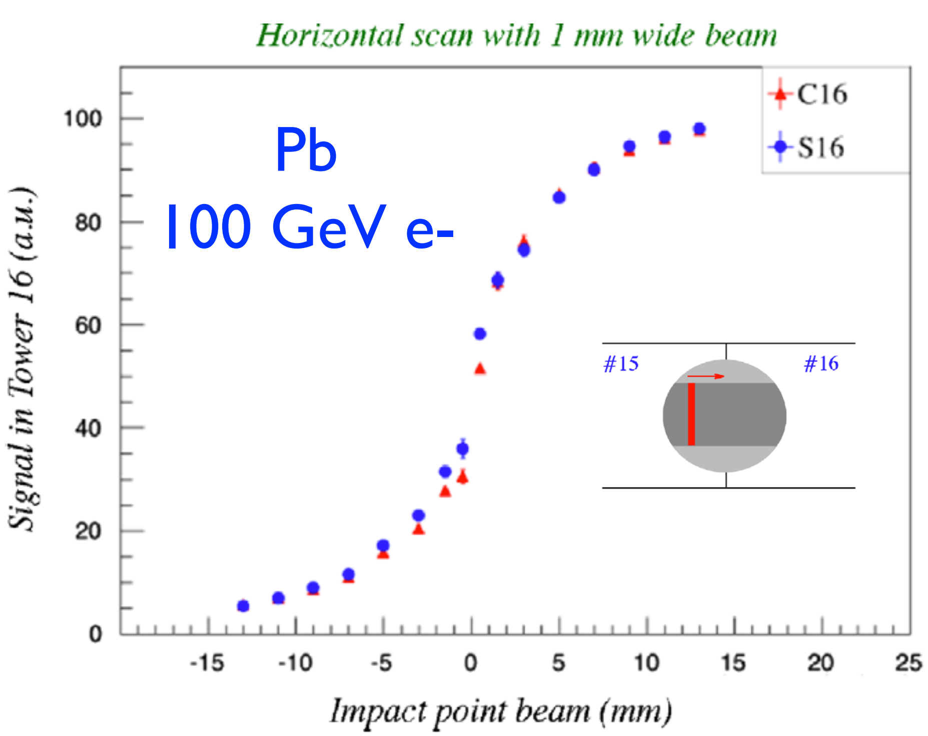


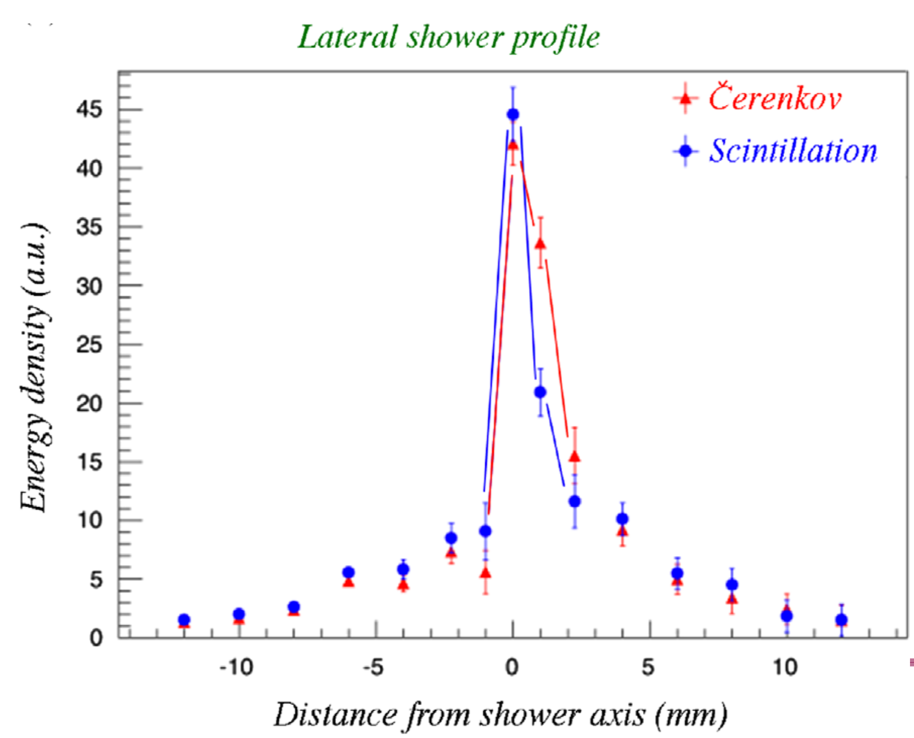
Signal linearity

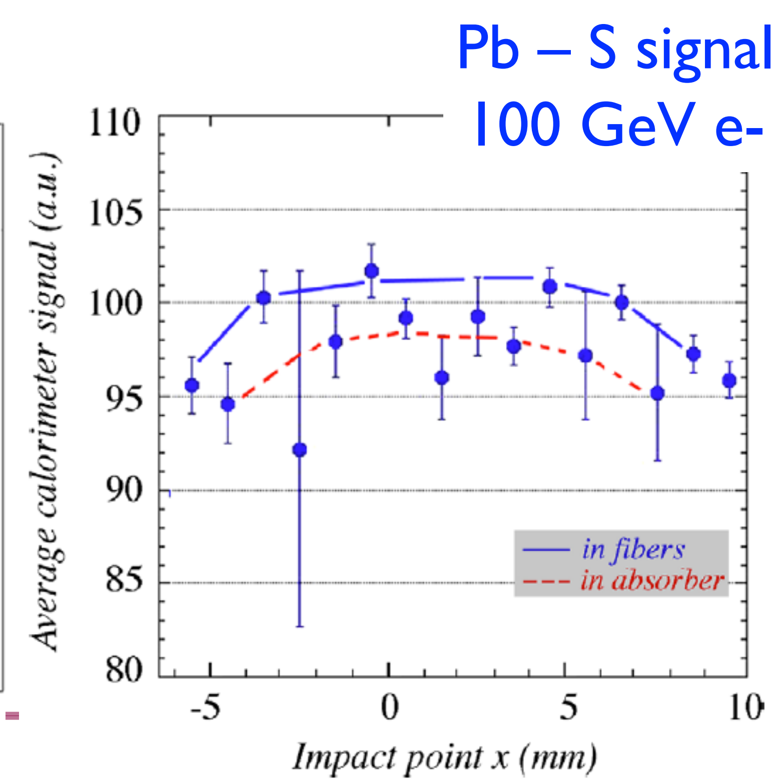




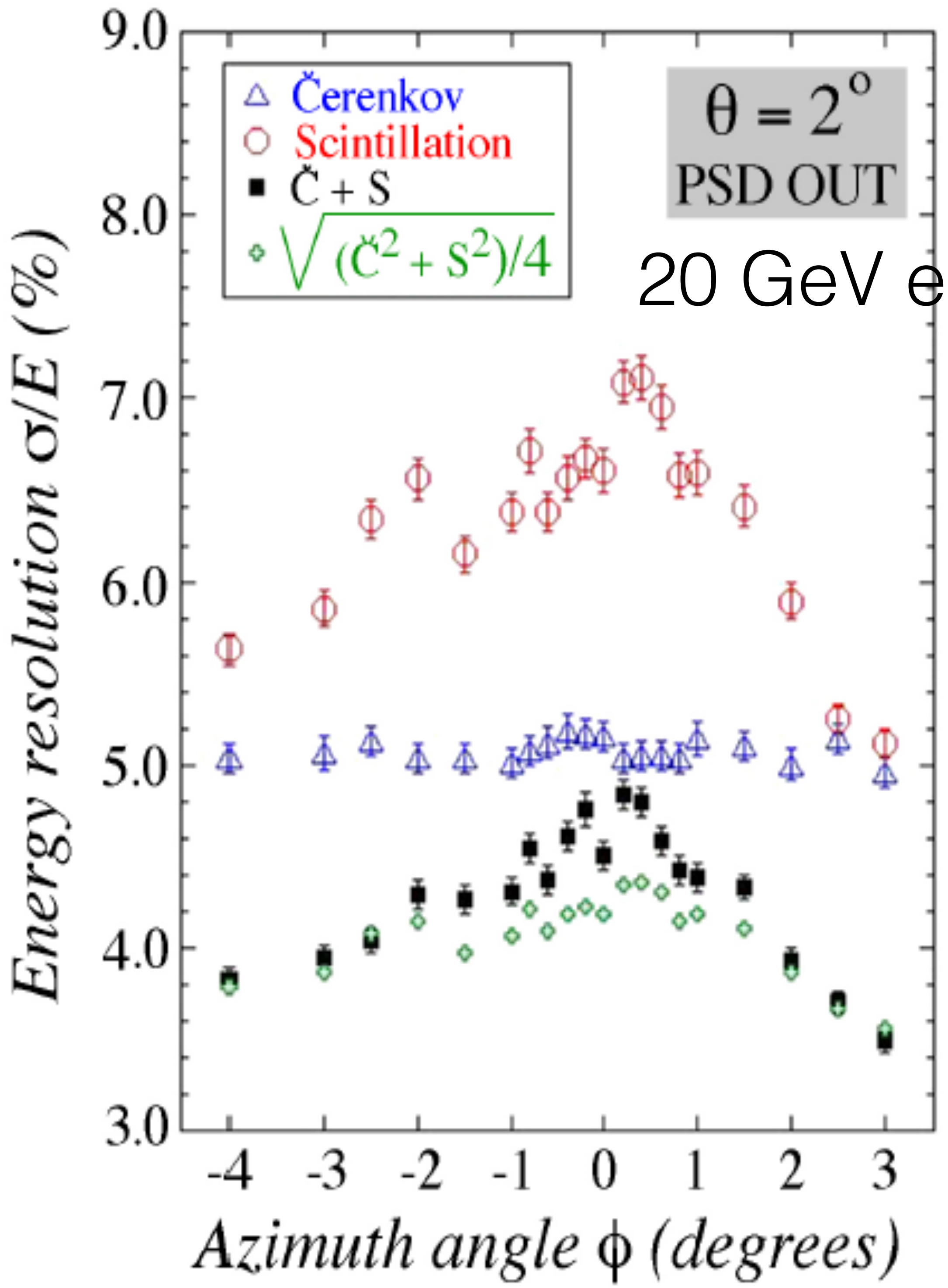
Radial shower profile and response uniformity







Small angle EM performance RD52 Cu calo



Fluctuations on different impact point

Em showers very narrow at the beginning;
Sampling fraction depends on the impact point
(fiber or dead material)

If particles enter at an
angle the dependence disappears

Effect NOT seen in Cherenkov signals
since early part of the shower do not
contribute to the signal (outside
numerical aperture C fibers)

S, C: sample INDEPENDENTLY
the em showers

→ We can sum their contributions
→ em energy resolution improves
by a factor √2

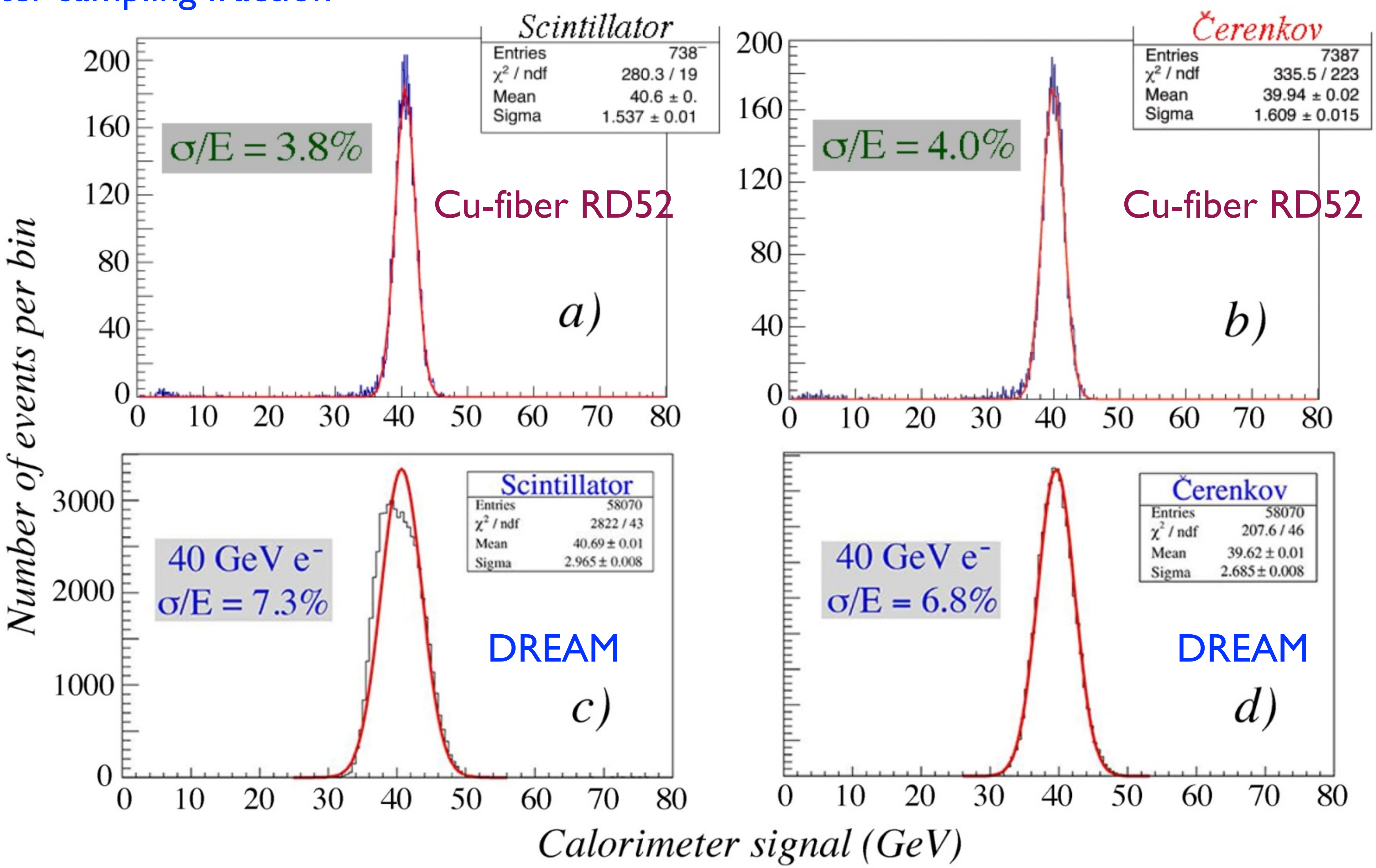
Estimated Cherenkov l.y. > 30 p.e./GeV

NIM A 735 (2014) 130

EM performance RD52 Cu calo

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

Better sampling fraction



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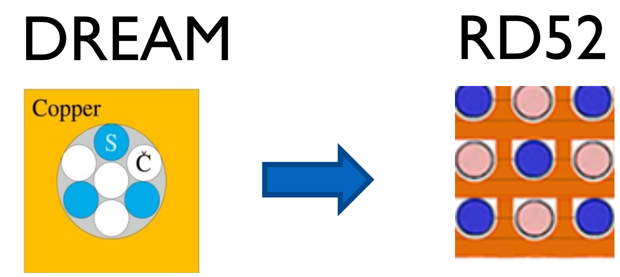
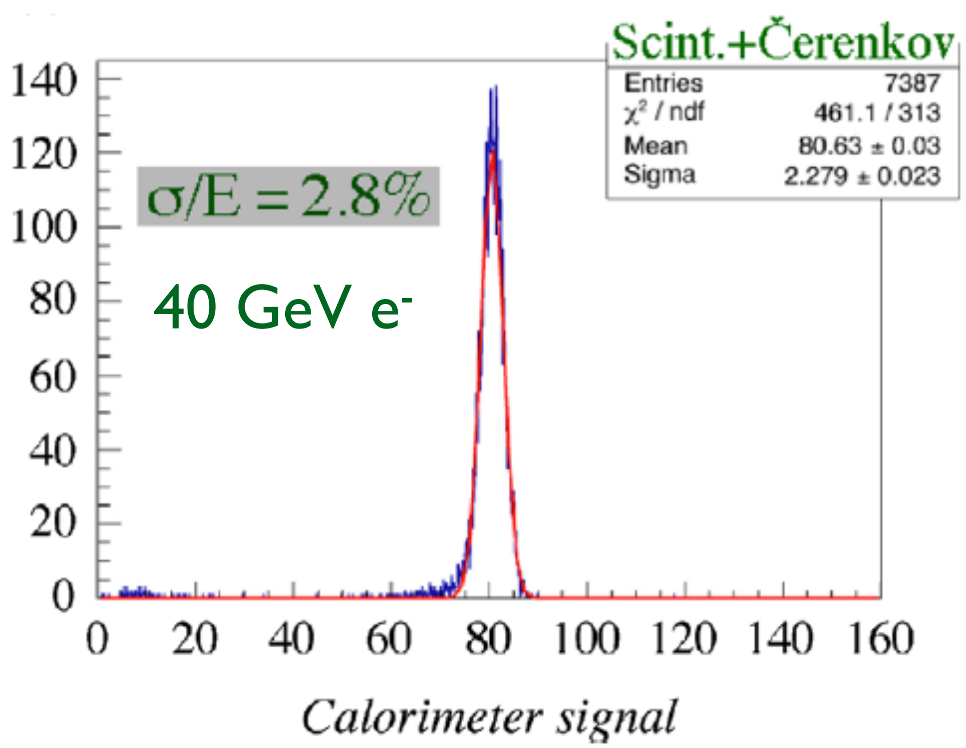
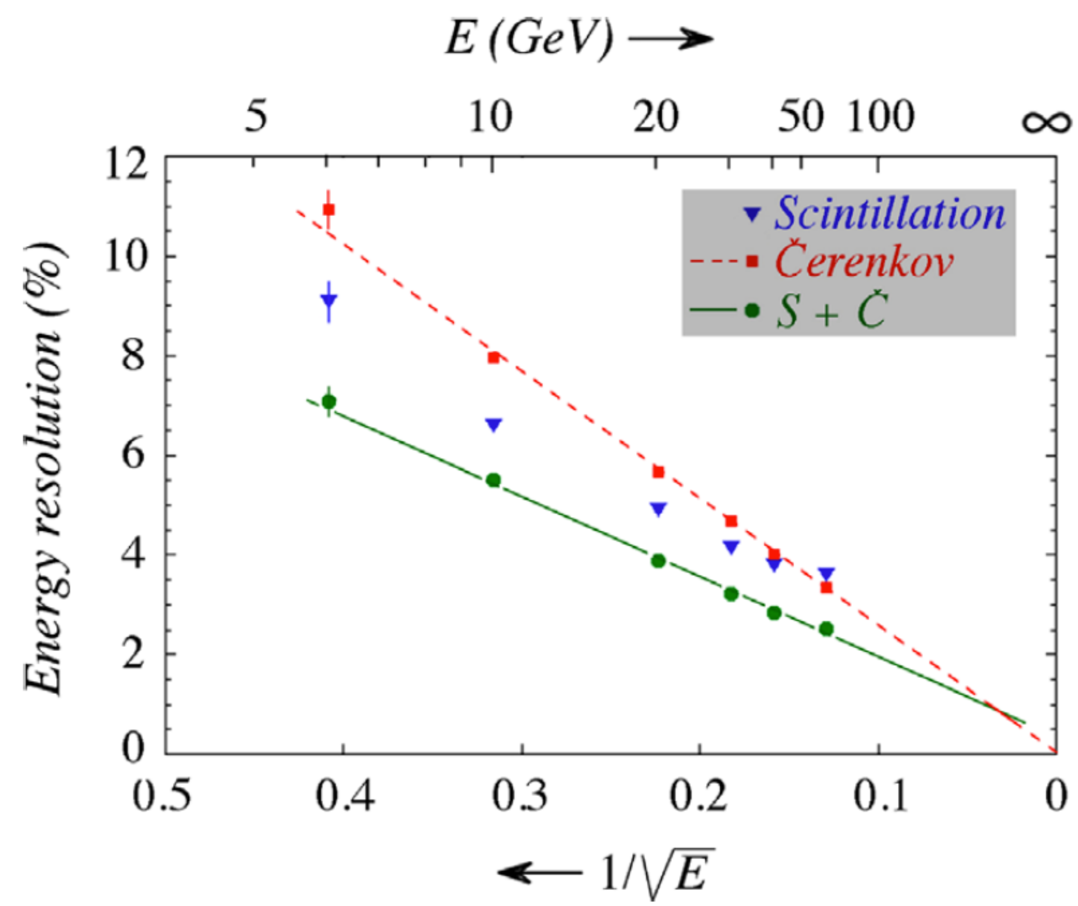
EM performance RD52 Cu calo

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



Improvement in resolution (doubled sampling fraction) if combining C and S independent signals

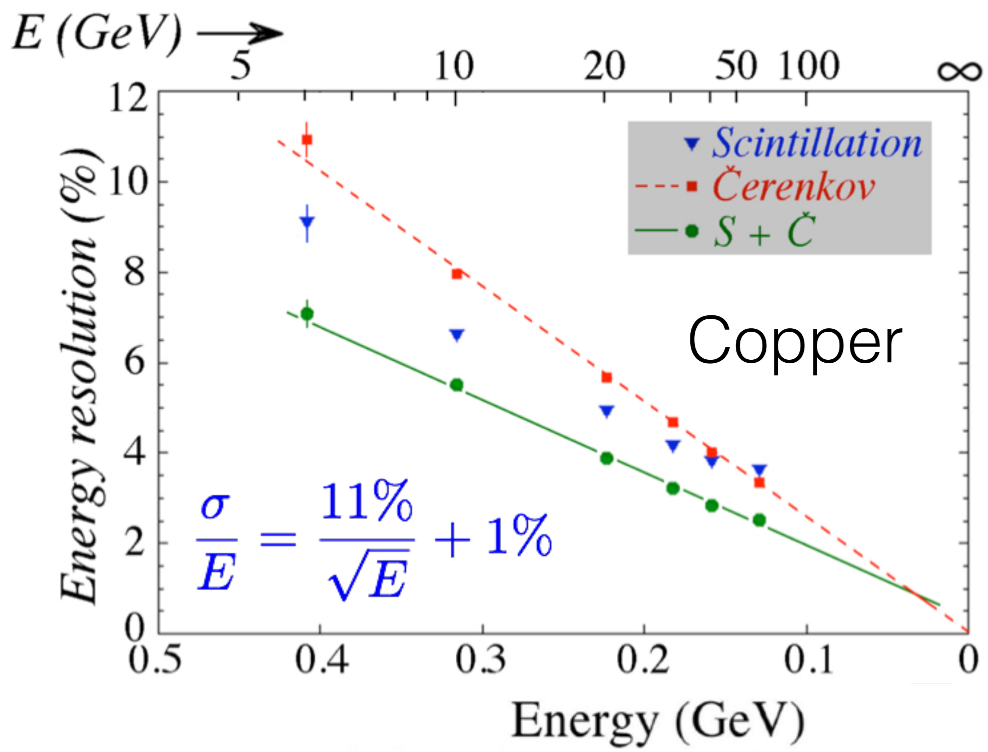


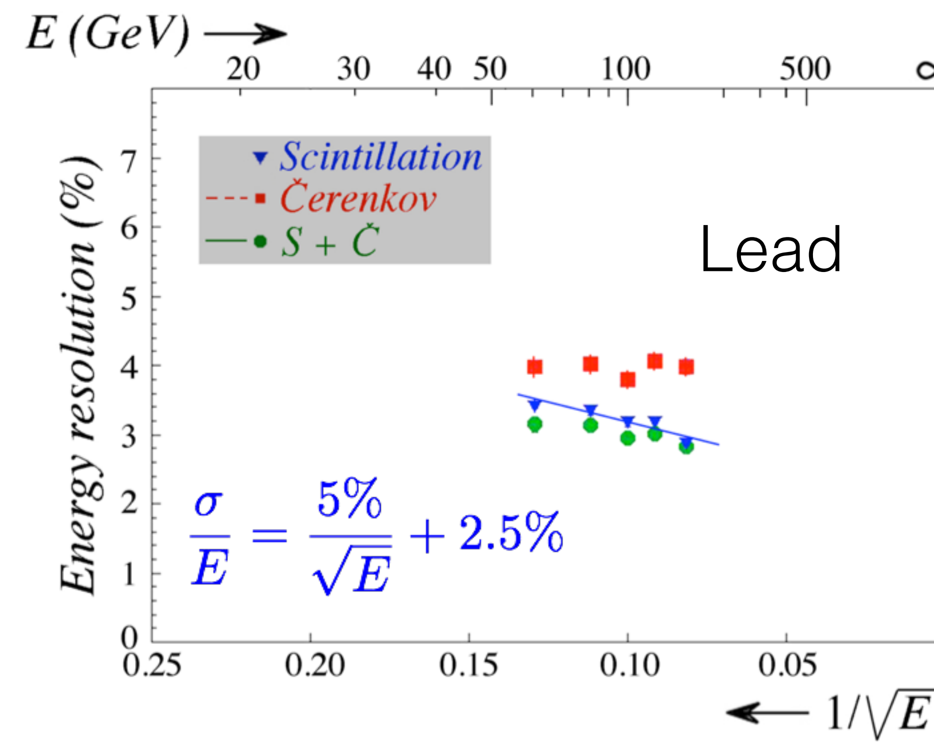


Constant term due to fluctuation in interaction point (only S). Disappears for larger angles

Dual Readout method in sampling calorimeter

Electromagnetic Resolution

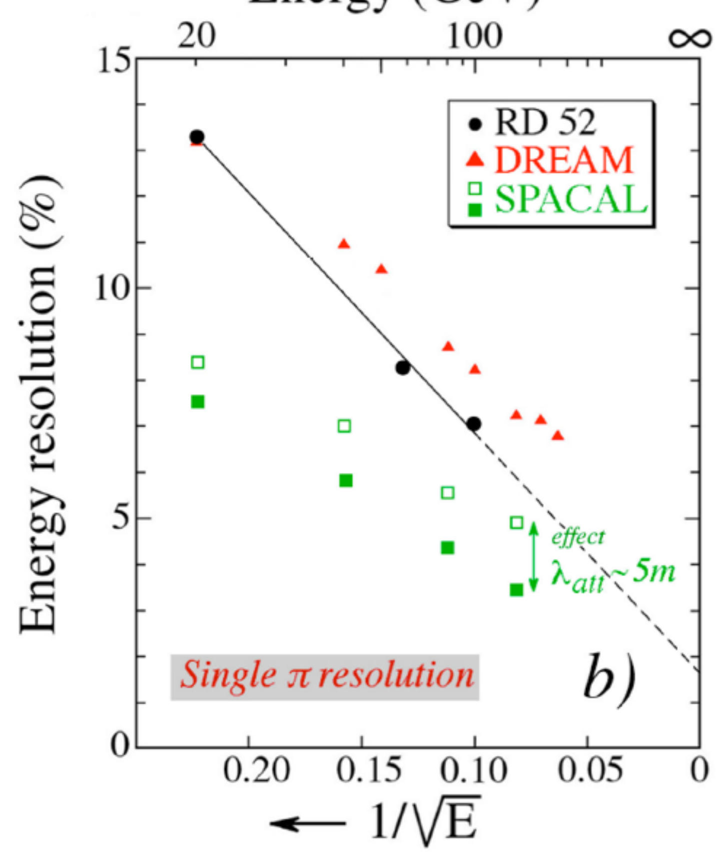


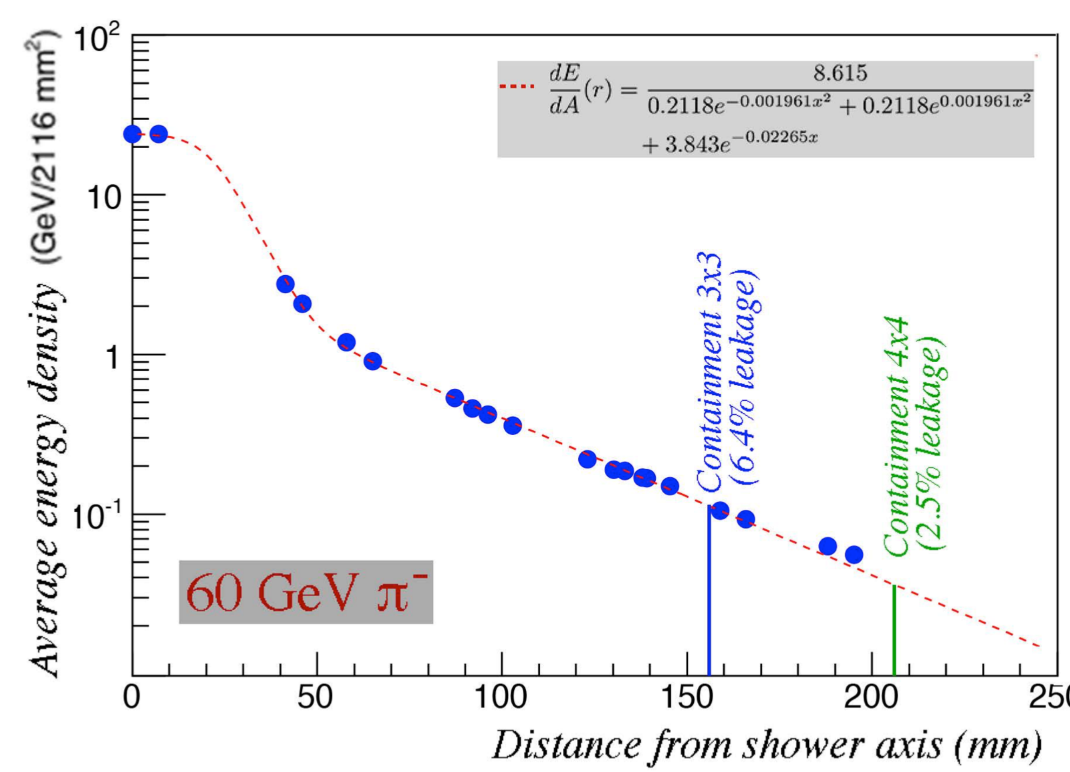


Hadronic Resolution (Pb Module)

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

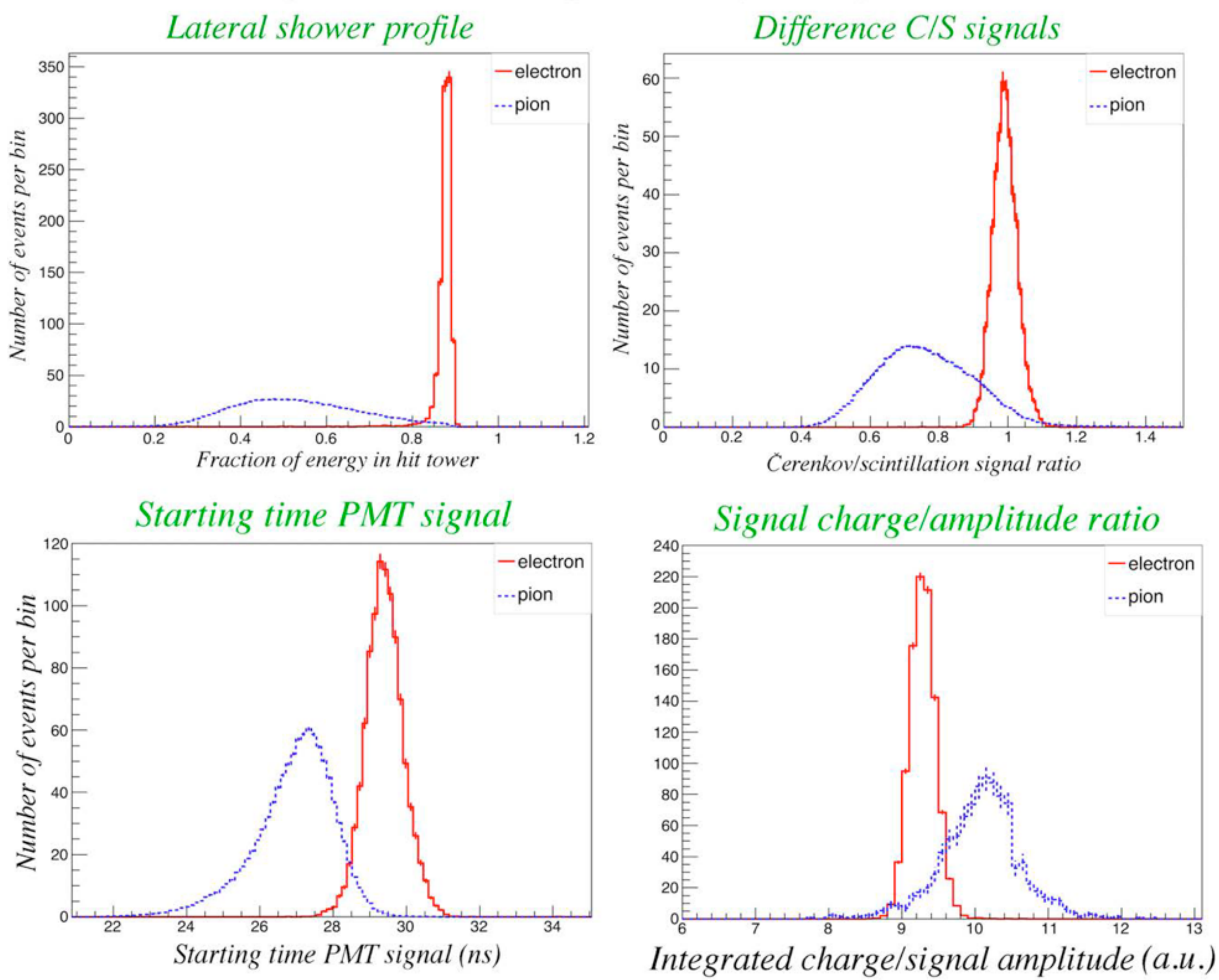
To include corrections on:
- light attenuation
- lateral leakage





Particle ID in sampling dual readout calorimeter

Methods to distinguish e/π in longitudinally unsegmented calorimeter



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

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: $\lambda_{int} = 170$ *mm*, $\rho = 11.3$ *g/cm*^{3}

Copper: $\lambda_{int} = 151$ *mm*, $\rho = 8.96$ *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

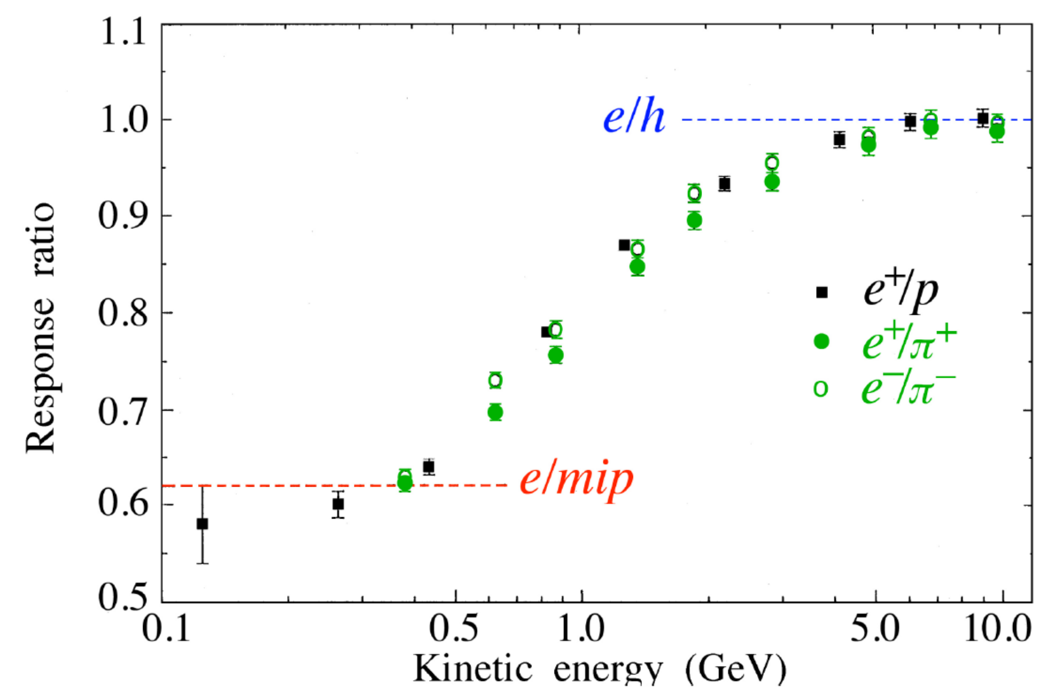
Lead: *e/mip = 0.6*

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



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

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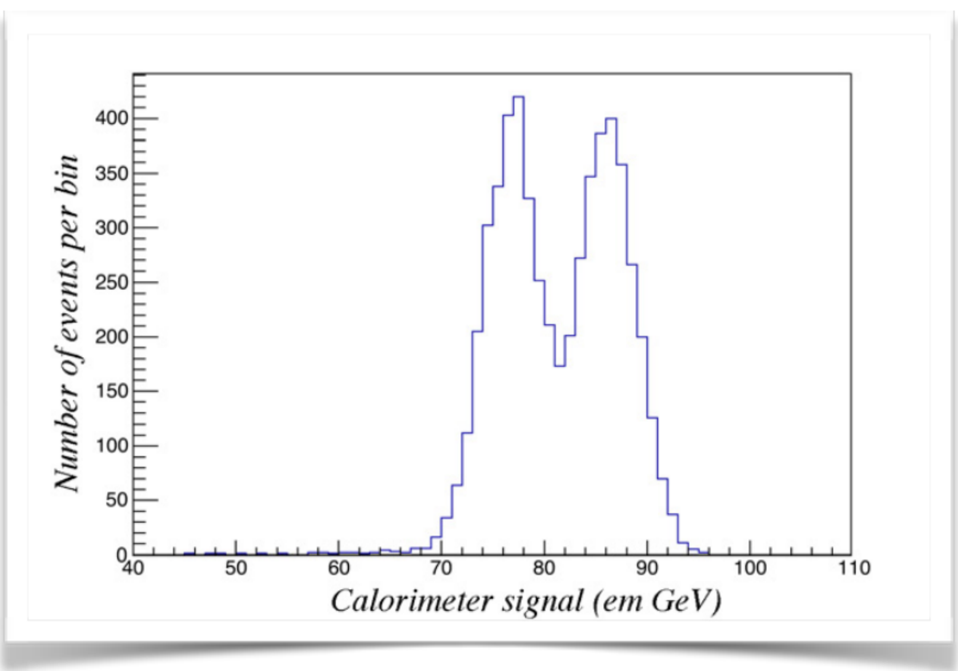
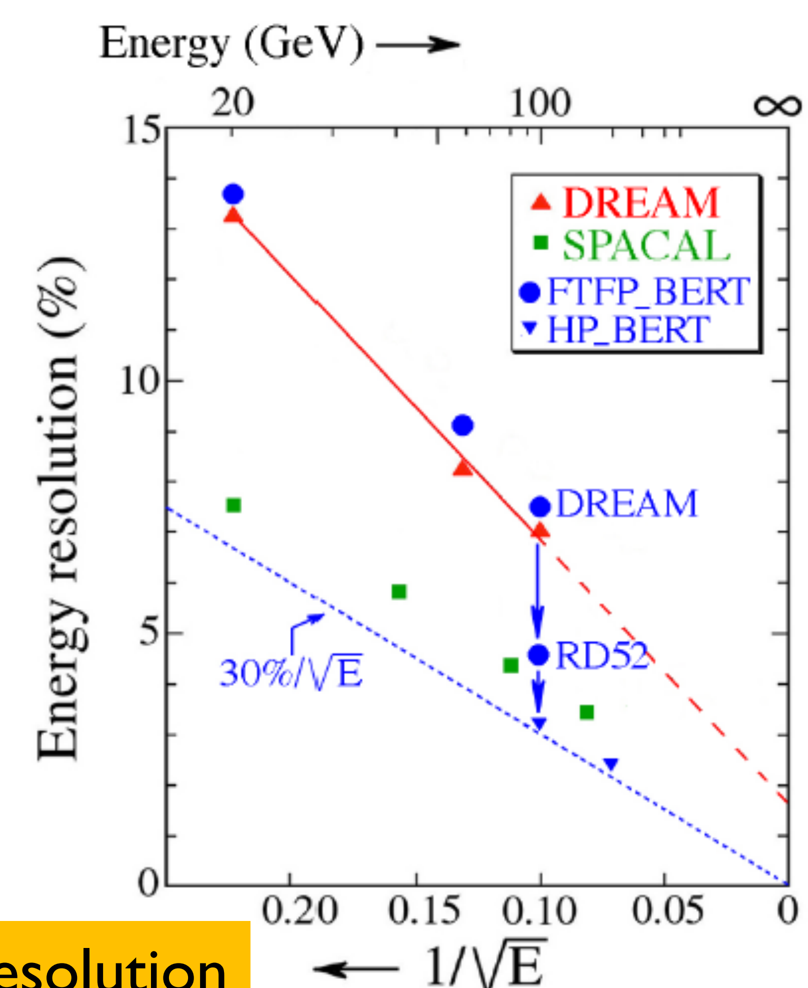


The response curve for a mixture of hadrons with energies corresponding to the W and Z masses (GEANT4 simulation)



Hadronic E resolution

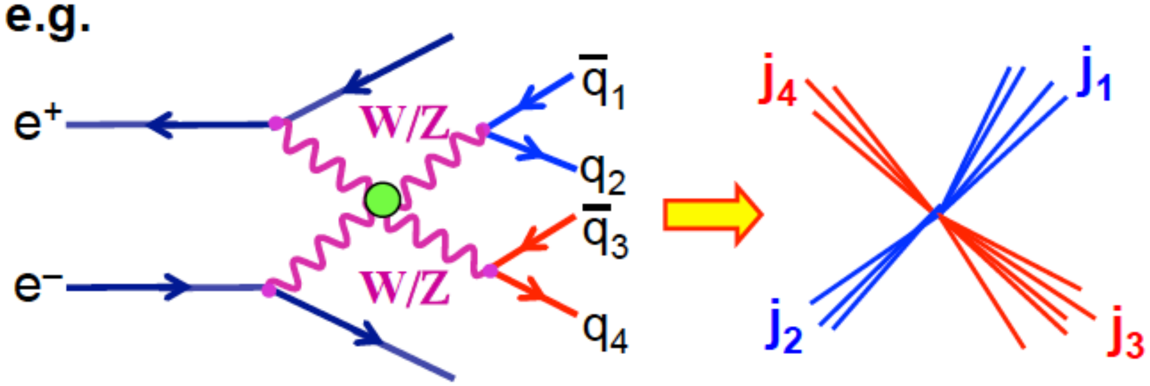
High resolution Calorimetry

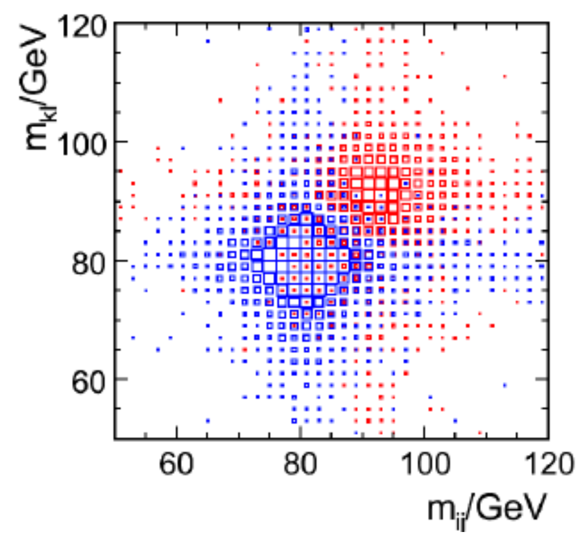
For future colliders, jet energy resolution will be a determinant factor of understanding high energy physics.

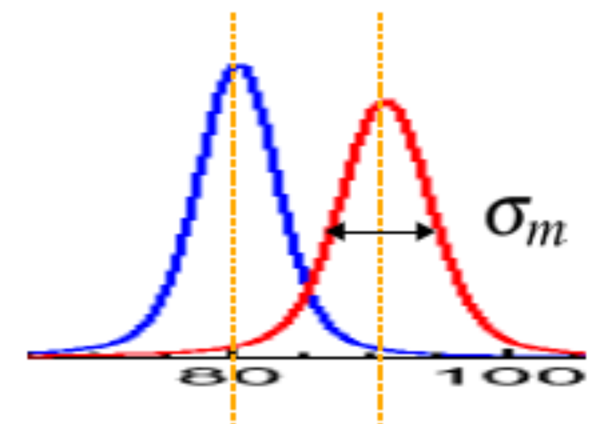
Required to have best possible di-jet mass resolution for narrow resonance observation

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

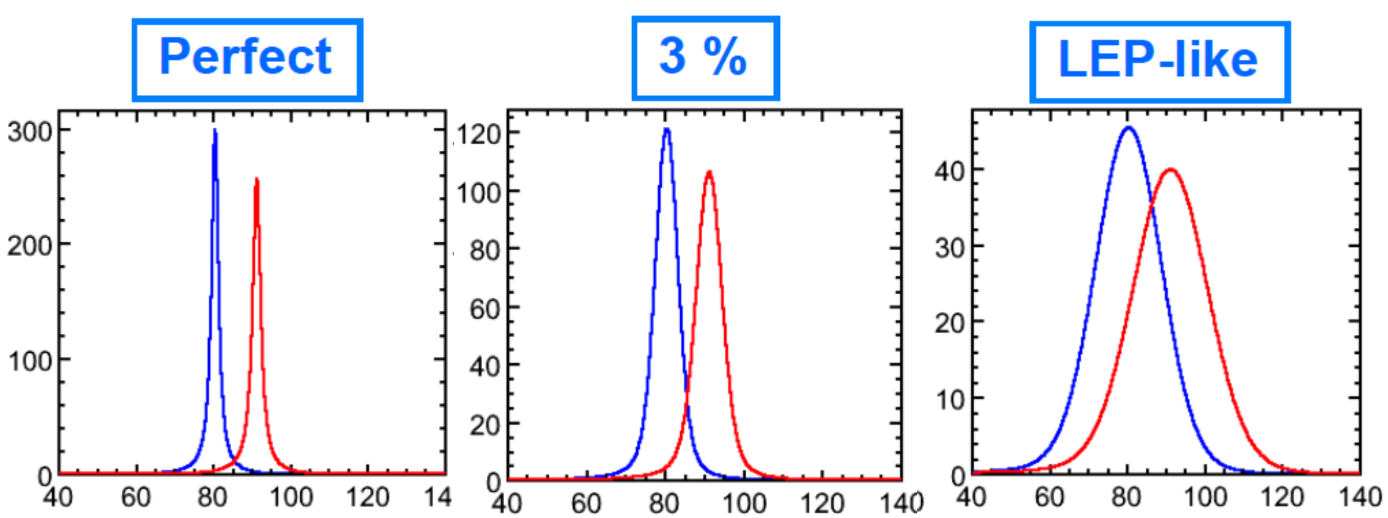
e.g.







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



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

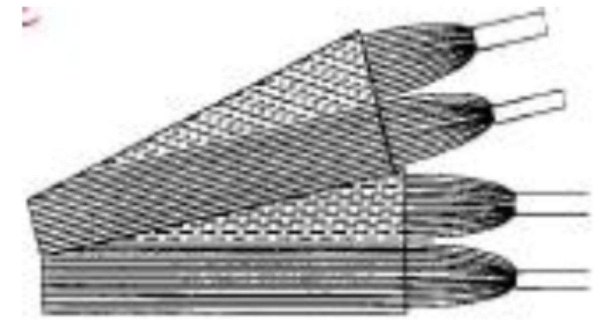
$$\frac{\sigma}{E} \sim \frac{30\%}{\sqrt(E)}$$

From RD52 experiment to 4π calorimeter

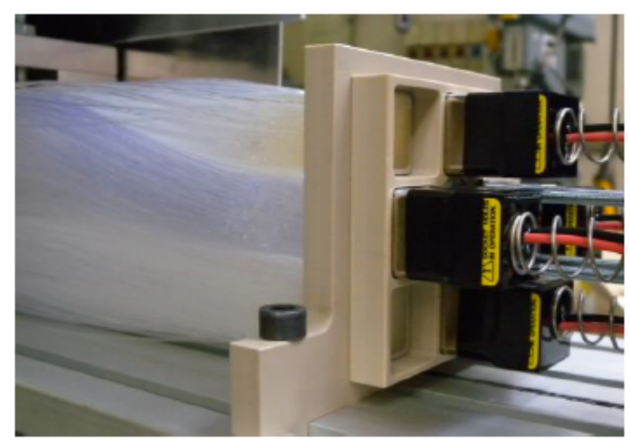
Best solution found: Copper Dual Readout (em + had) fiber calorimeter , high fiber filling fraction, not longitudinally segmented, read out with fast electronics (< ns).

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
- ...



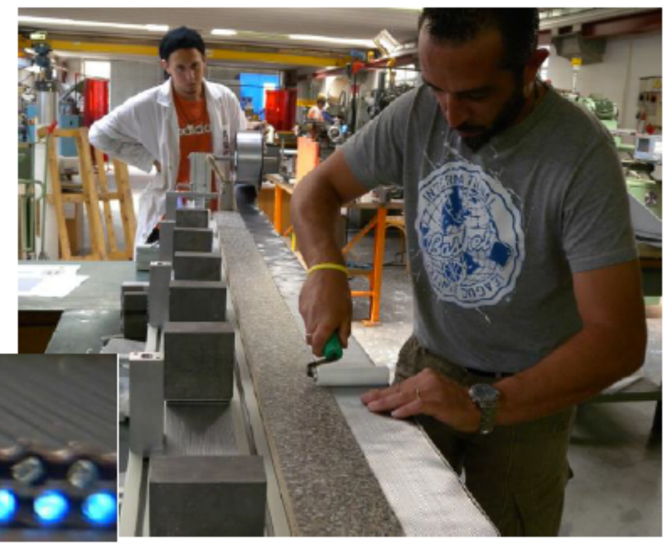
Fiber bunches + PMT →

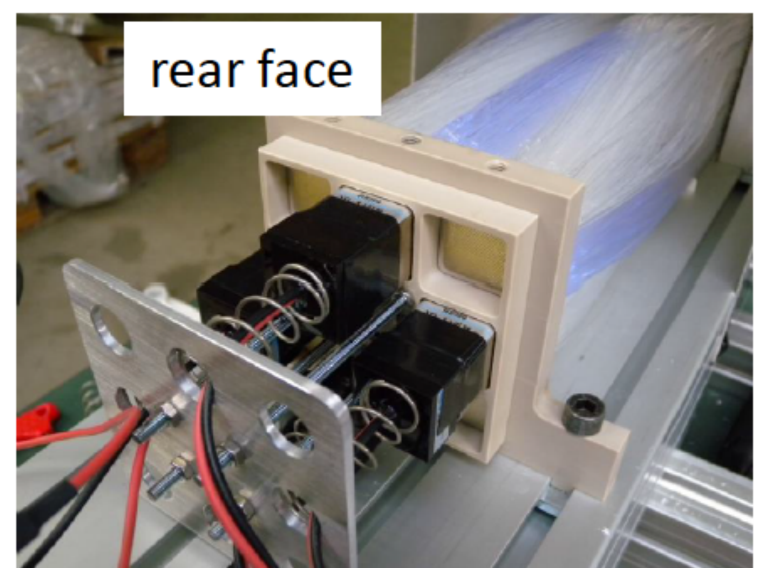
SiPM matrix directly coupled to end of detector

Backup slides

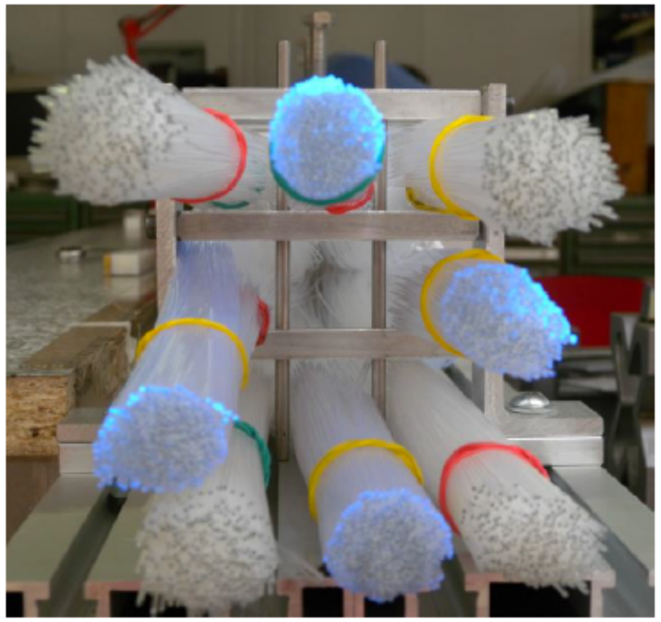
Pb-fiber module construction

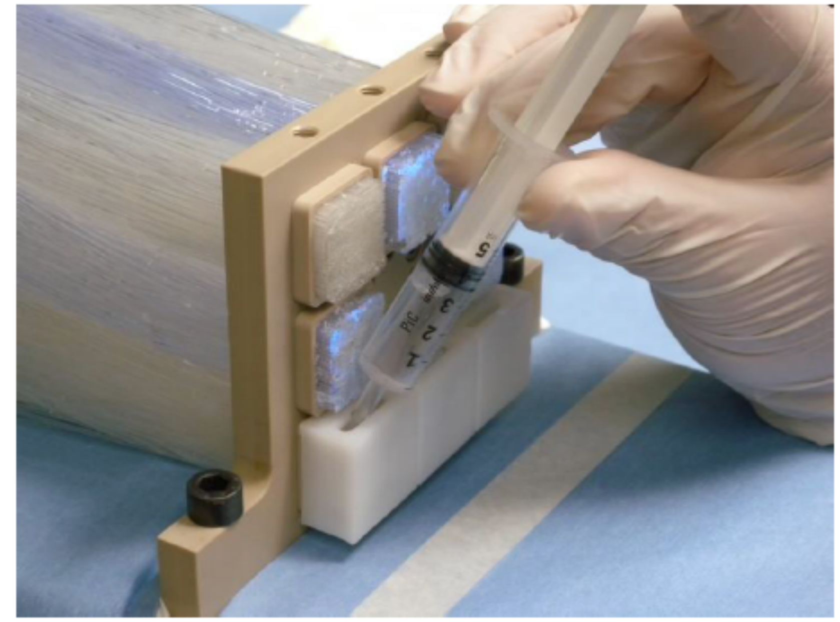
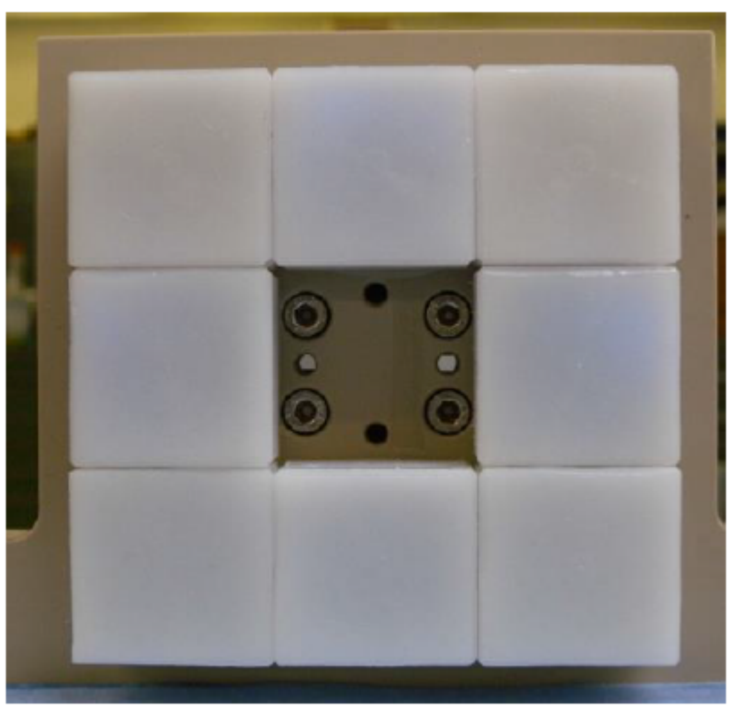
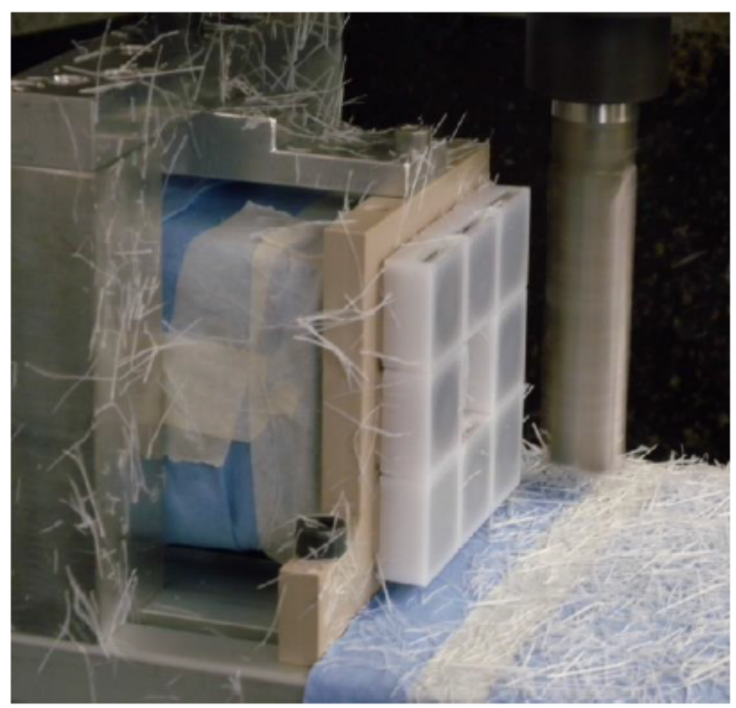
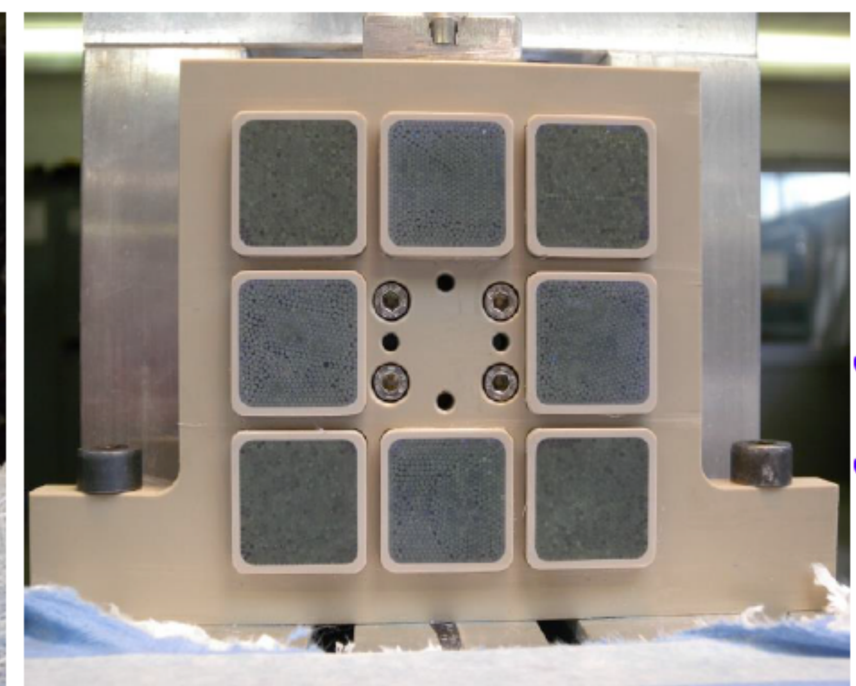
Pb fabrication:
Cold extrusion (industry, Italy), both sides.
Assembling in INFN Pavia, no glue used





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