Dual-Readout Calorimetry @ RD_FA

Roberto Ferrari

Bologna – July 4th, 2017

Outline

1) The idea

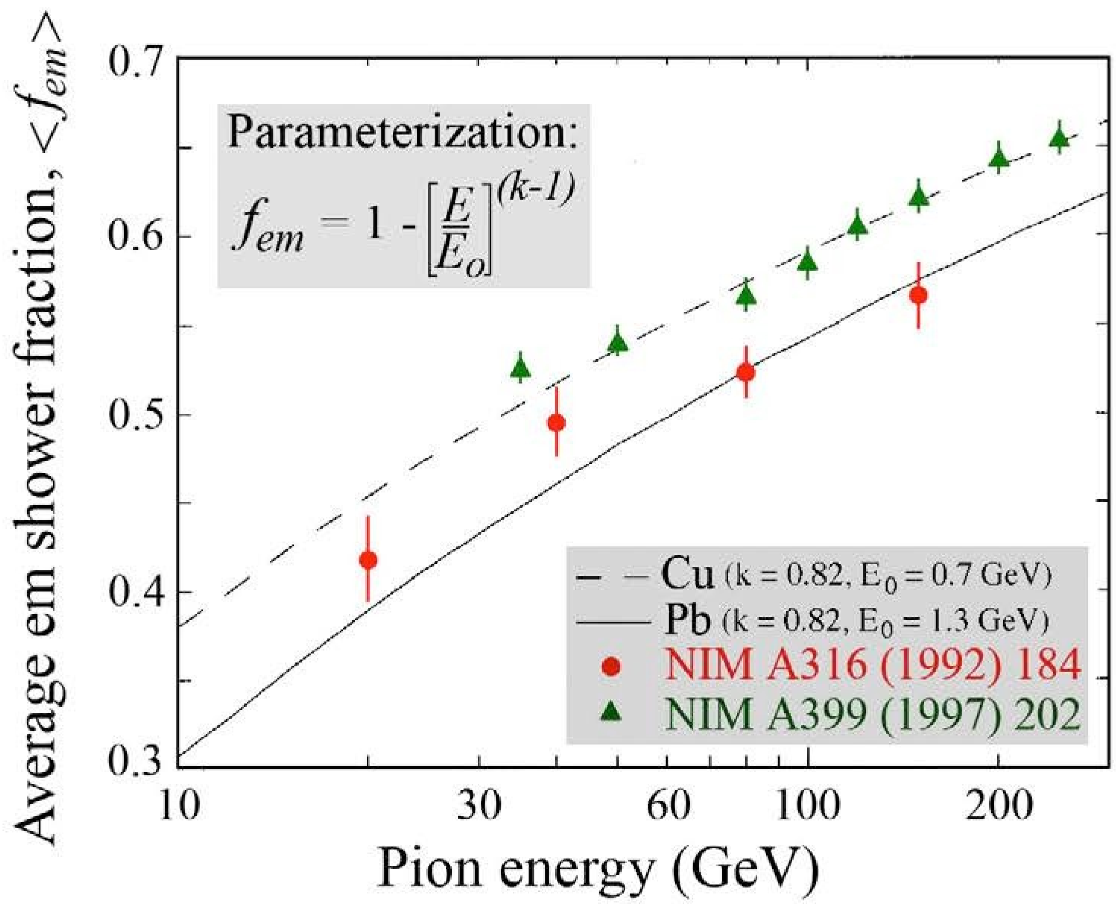
2) Where we are (RD52)

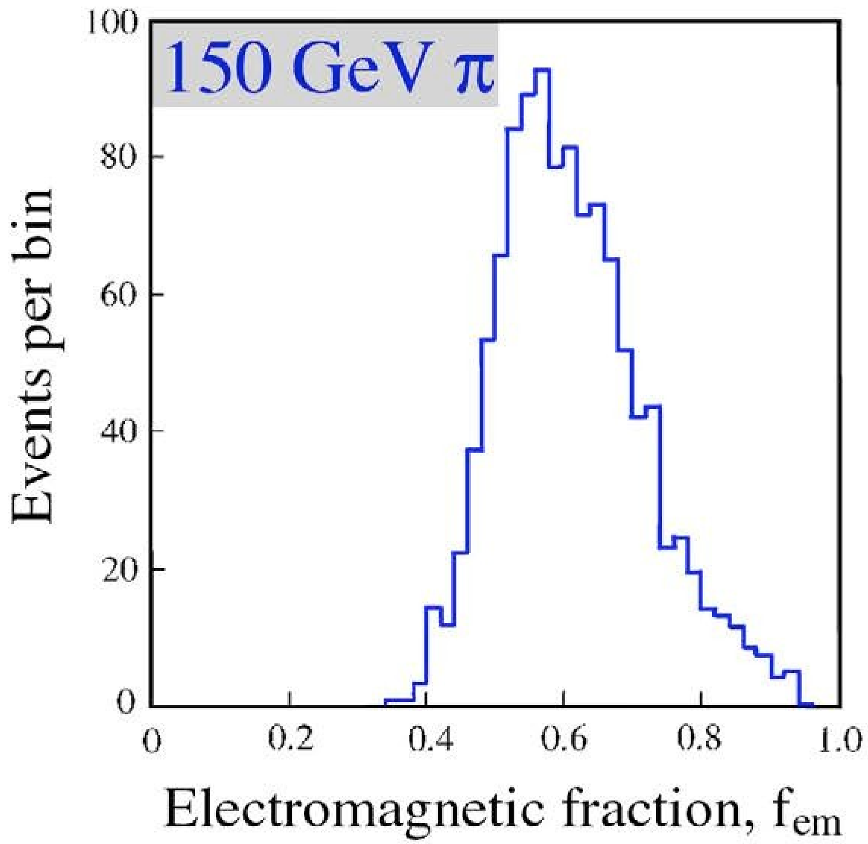
3) Open issues

4) Short- and middle-term planning

Electromagnetic Shower Fraction, f_{em}

i.e. the fraction of the shower energy deposited by π^os





The em fraction is, on average, *large and energy dependent*

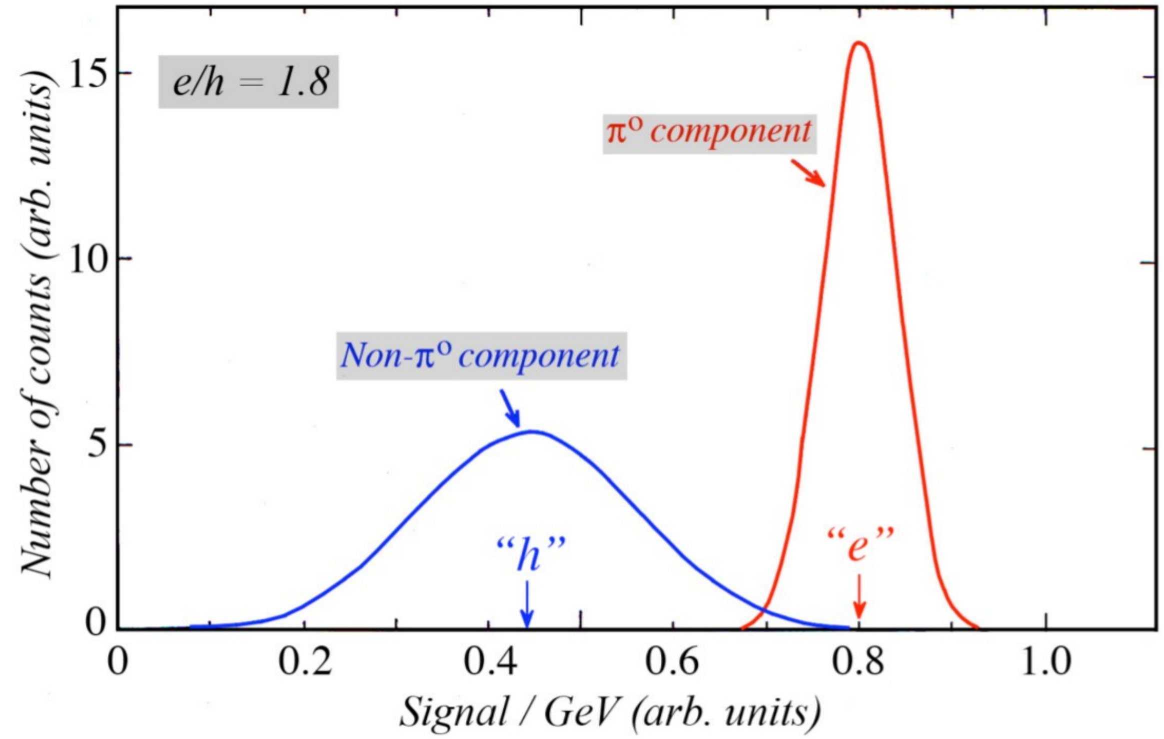
Fluctuations in f_{em} are *large and non-Poissonian*

Calorimeter Response

The detector response to the two components is NOT the same

This effect is quantified by the e/h ratio

In this example, only $1/1.8 \approx 56\%$ of non-π^o 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 (*f_{em} depends on E and shower "age")*

2) f_{em} different for π, K, p → response depends of particle type

Dual-Readout Sampling Calorimetry

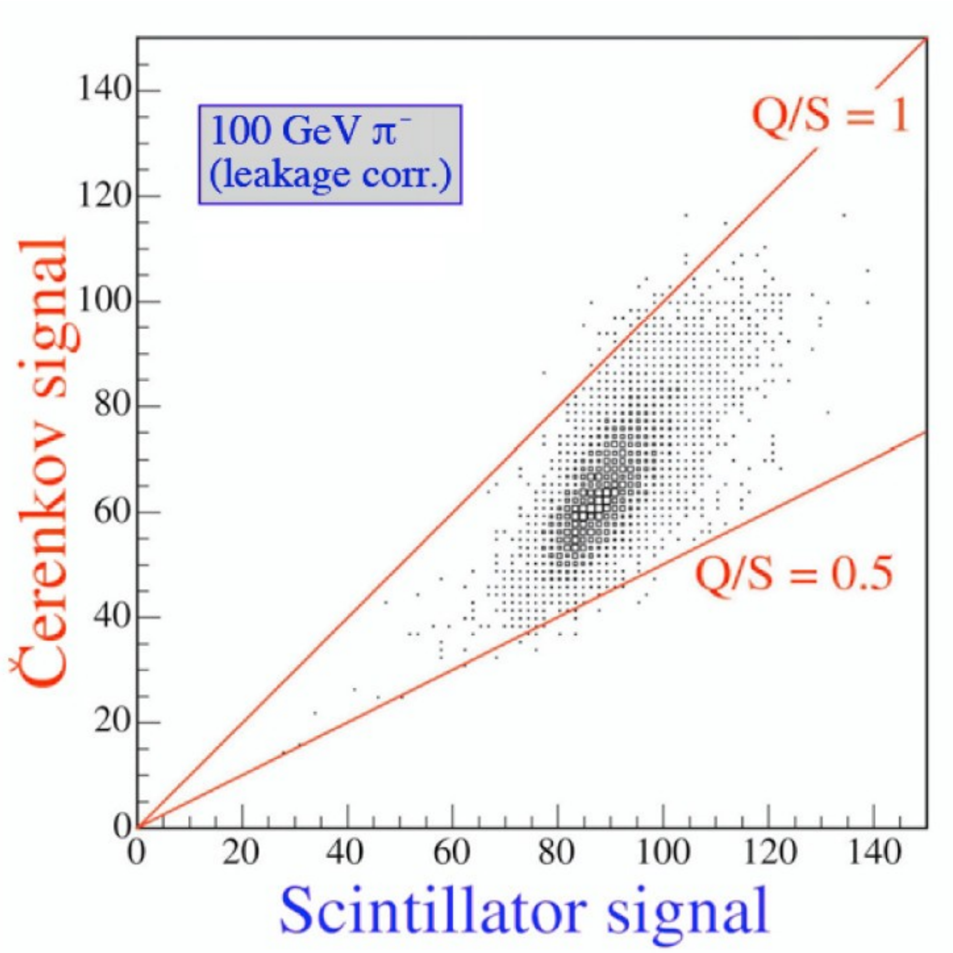
What: avoid spoiling em resolution in order to get e/h = 1 (i.e. keep e/h > 1) *BUT* measure f_{em} event-by-event

→ *eliminate effects of fluctuations in f_{em} on calorimeter performance*

How: exploit the fact that (e/h) values for a sampling calorimeter based on scintillation light or Čerenkov light are (very) different

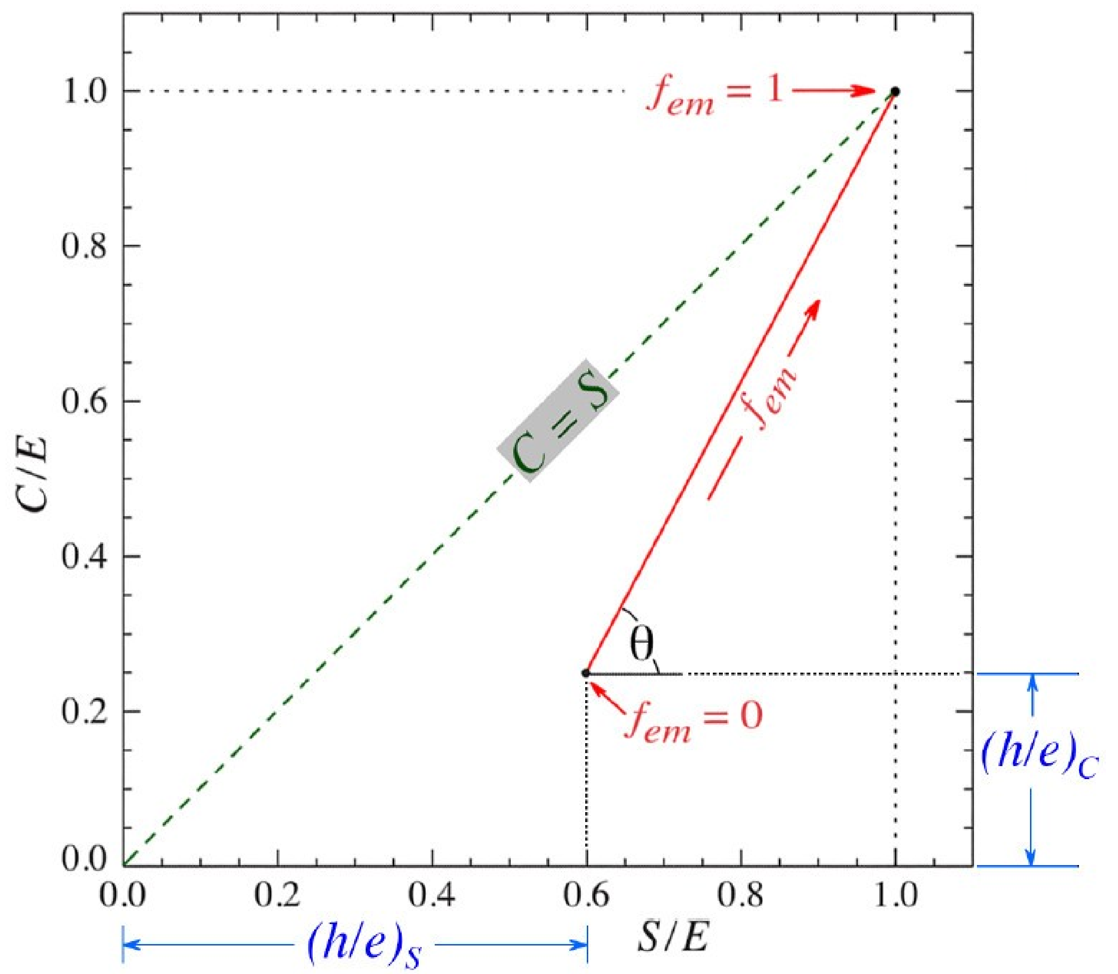
(e.g. protons contribute to S but not to Č signals)

Principles of Dual Readout Calorimetry



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

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

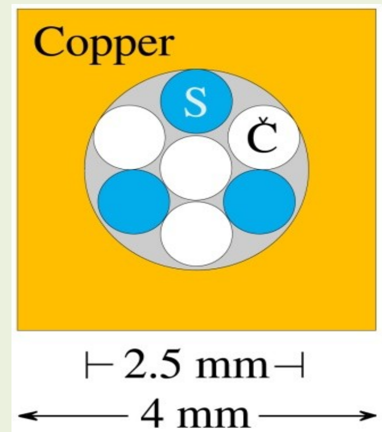


- Hadronic data points (S, C) are located around a straight (red) line

Dual-Readout w/ Sampling Fibre Calorimeters

2003
DREAM

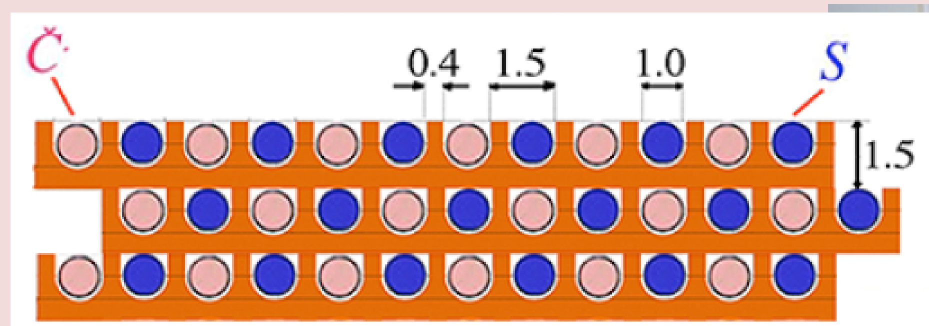
Copper
2m long, 16.2 cm wide
19 towers, 2 PMT each
Sampling fraction: 2%



2012
RD52

Copper, 2 modules

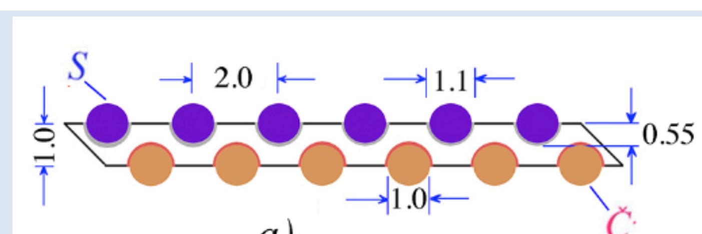
Each module: 9.3 * 9.3 * 250 cm^3
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: 4.5%, 10 λ_{int}

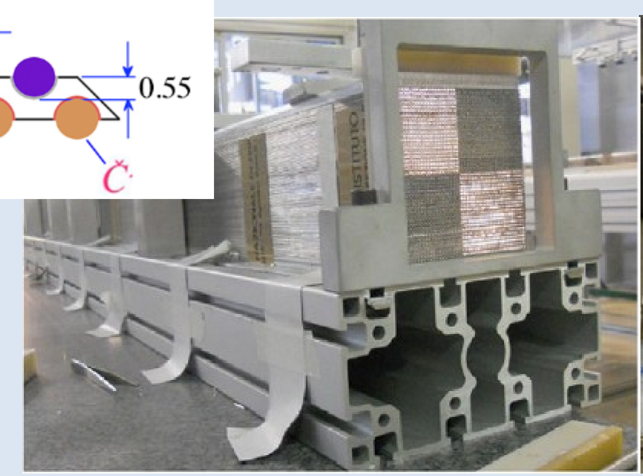


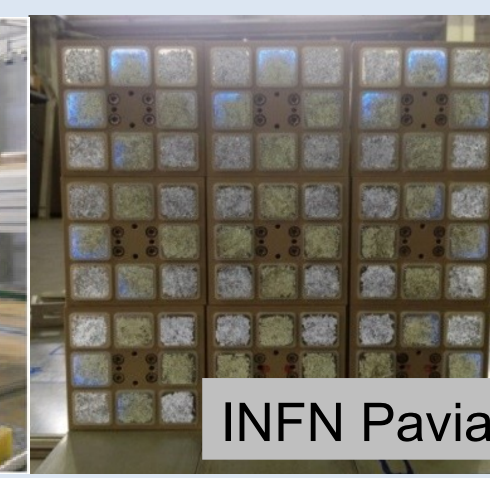
2012
RD52

Lead, 9 modules

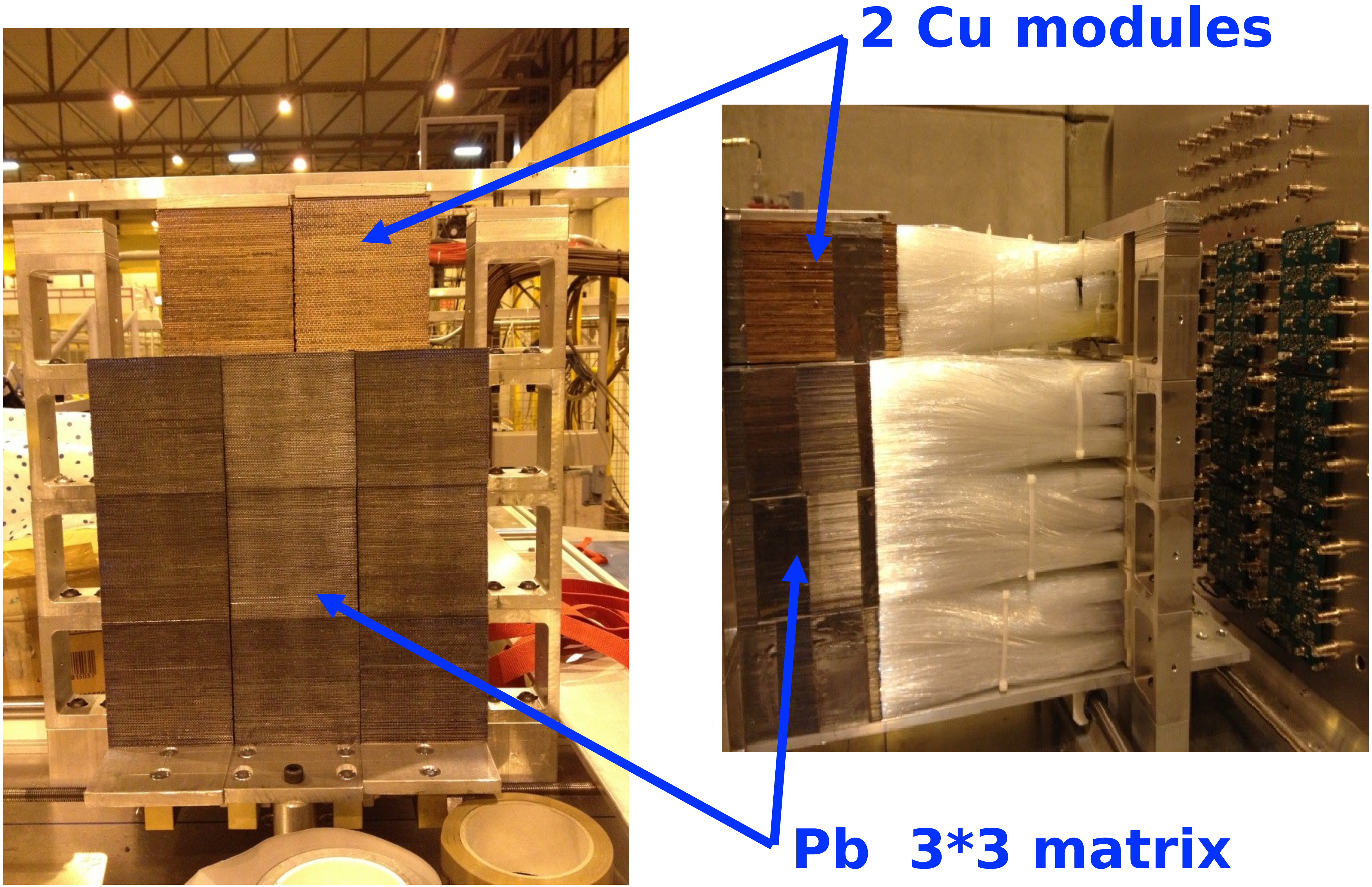
Each module: 9.3 * 9.3 * 250 cm^3
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: 5%, 10 λ_{int}







RD52 DR Fibre Calorimeters



Dual Readout at Work

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

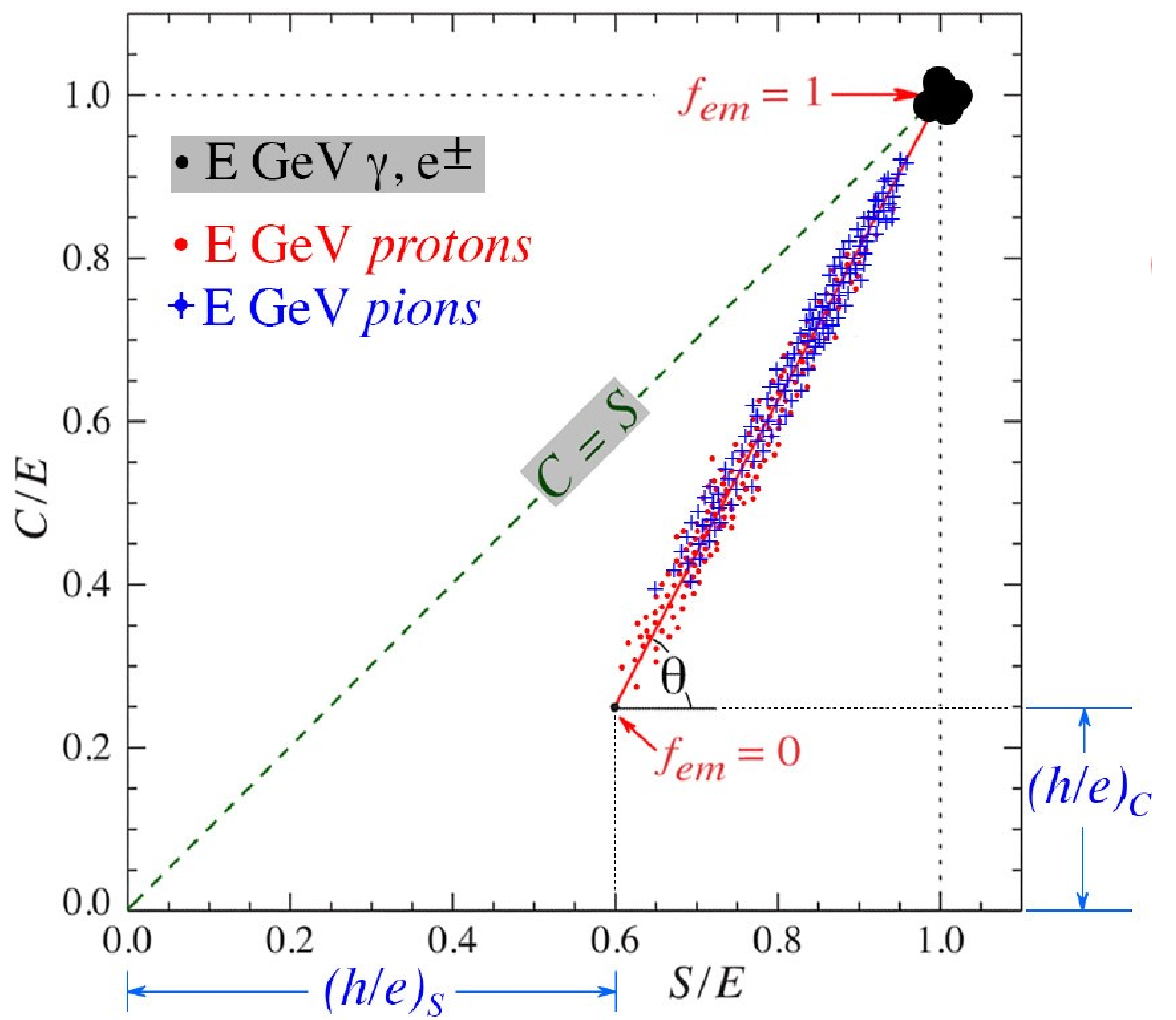
Θ, χ independent of both:

i) energy (!)

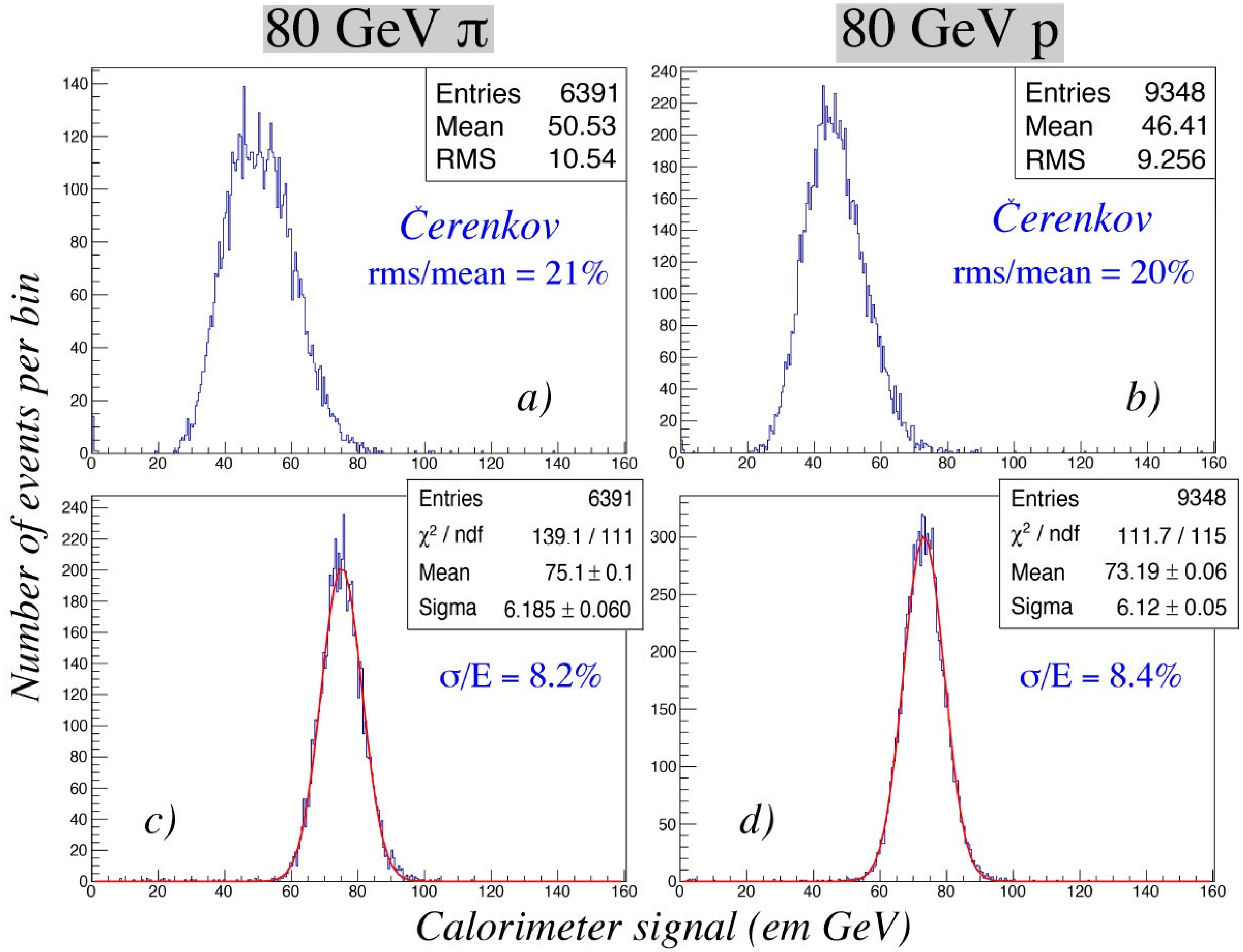
ii) type of hadron (!!)

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

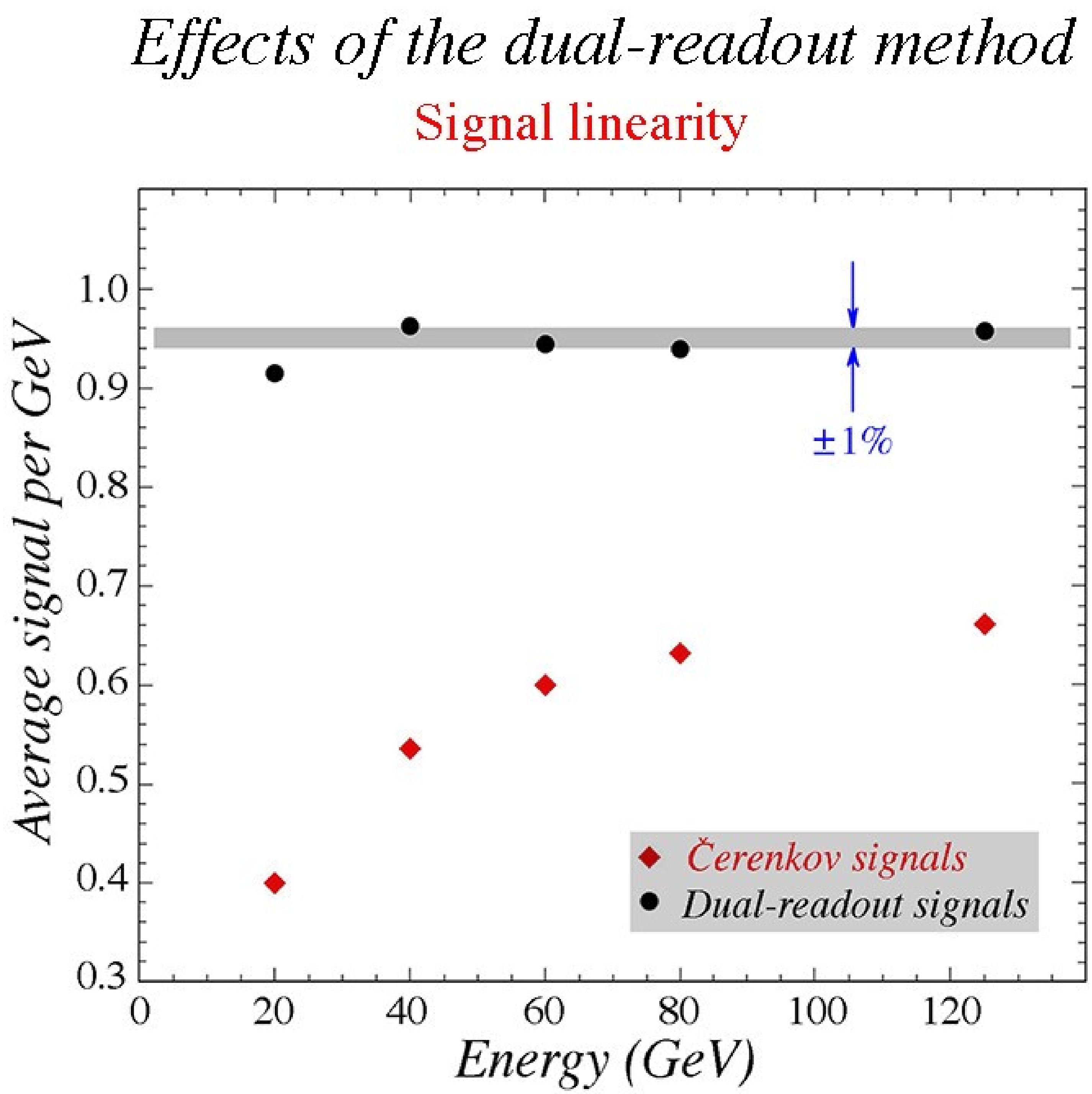
is universally valid



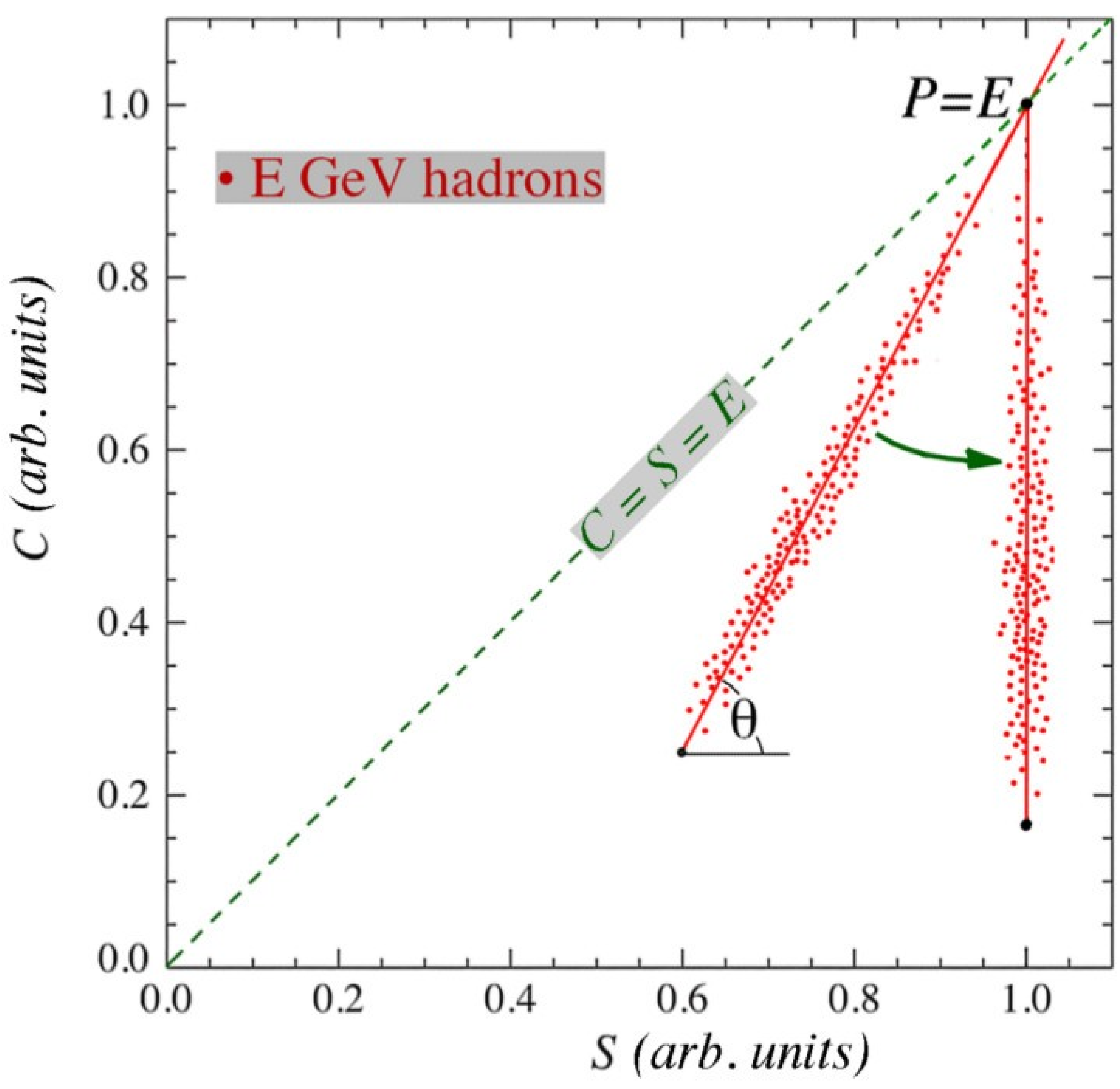
Dual Readout at Work (2)



Dual Readout at Work (3)



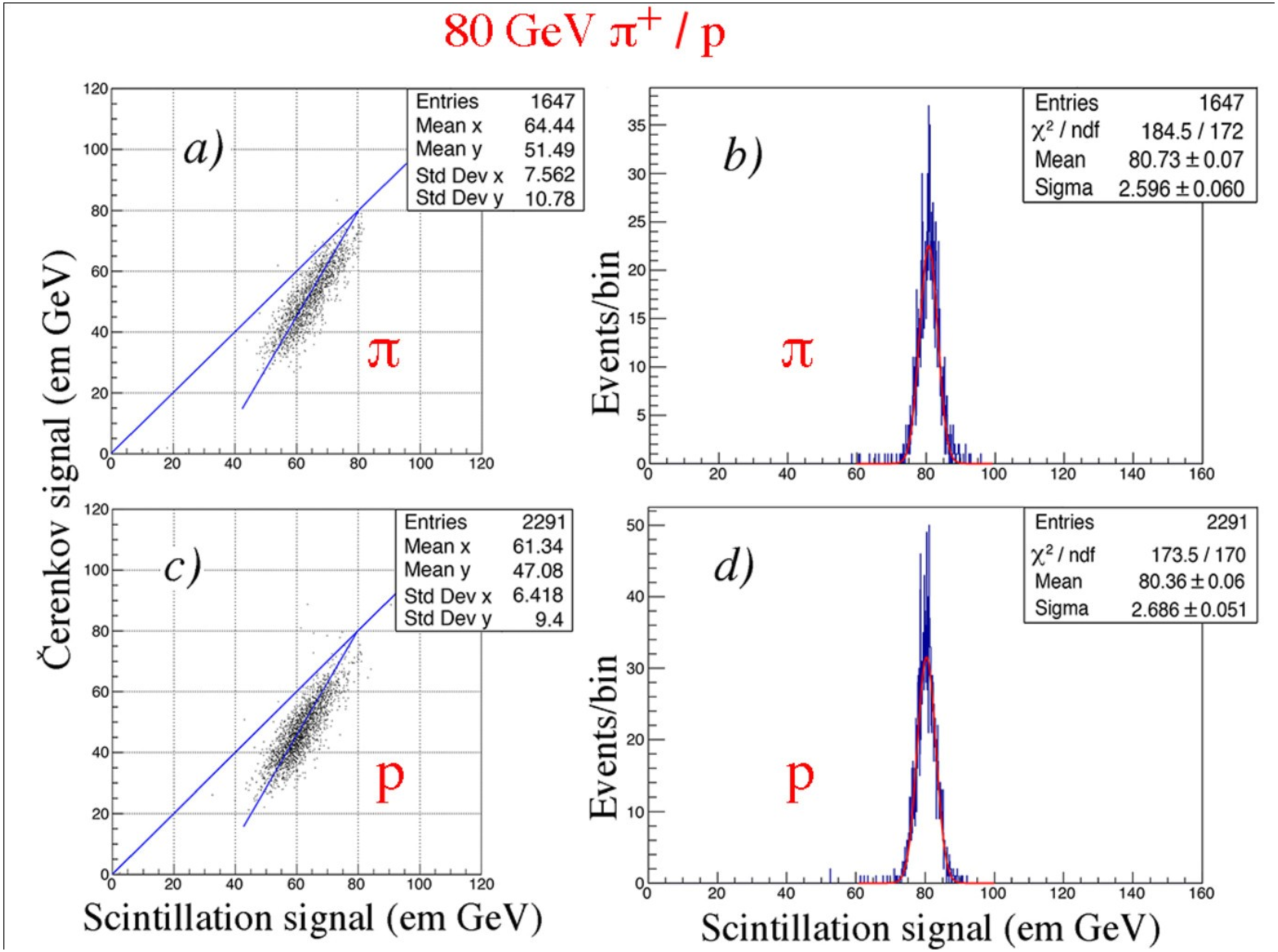
the Rotation Method



- *Fit experimental data with a straight line*
- *Determine coordinates of P (intersection with C=S line)*
- *Rotate data points about P over angle ($90^{\circ} - \theta$)*
- *Project data points on horizontal (S) axis*

θ is independent of E and particle type!!
→ Don't need this info!!

Applications of the Rotation Method

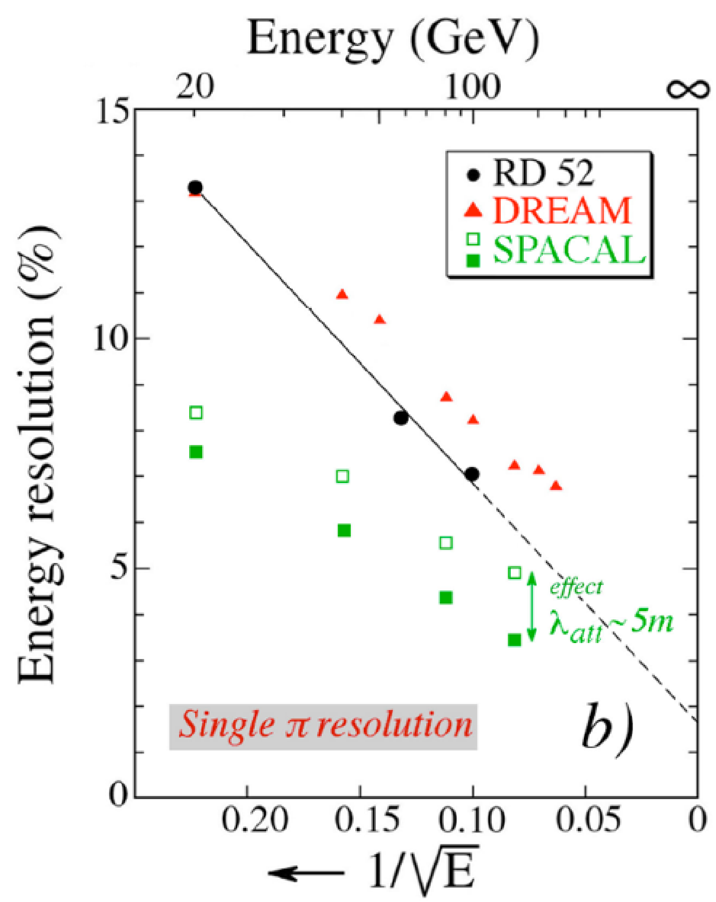


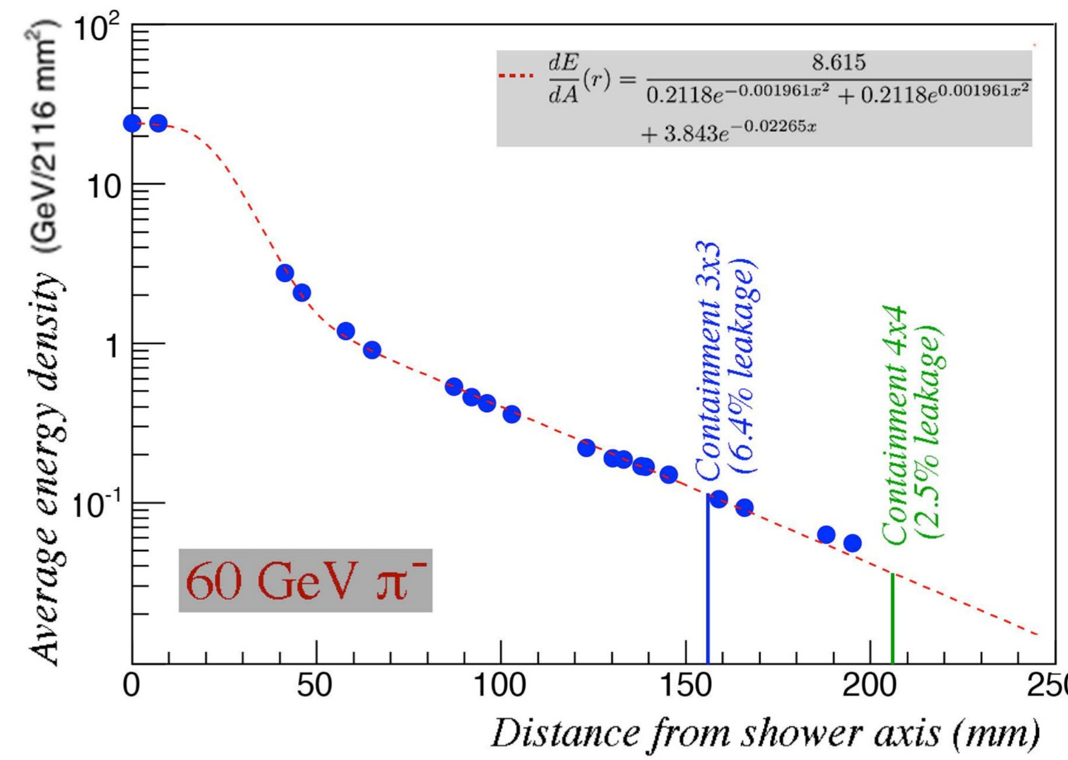
Single-Particle Hadronic Resolution

Hadronic Resolution
(Pb Module)

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

to be corrected for:
- light attenuation
- lateral leakage





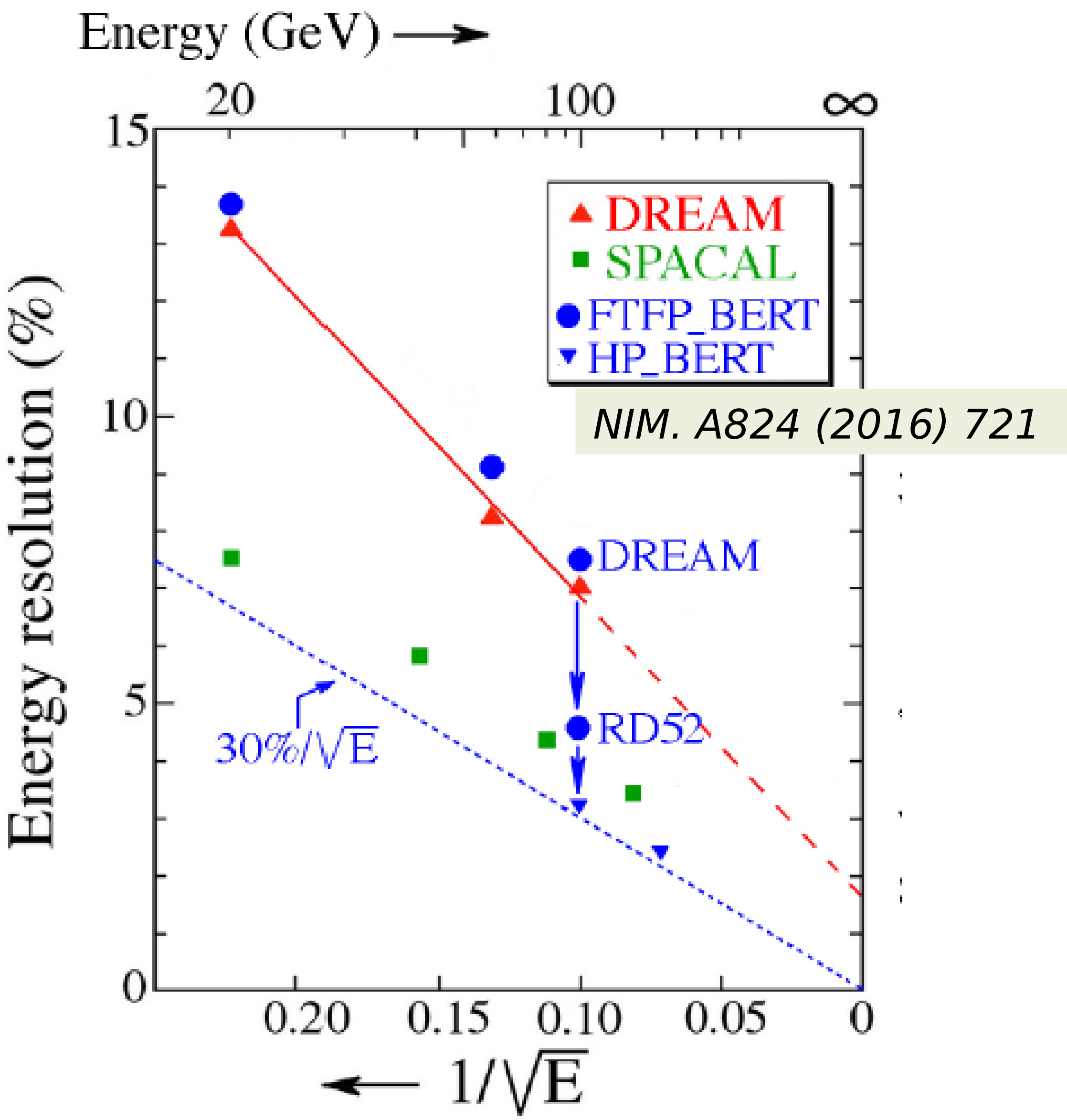
jet energy resolution ~ few % at ~100 GeV

(4th Concept Detector LOI quotes 30%/√E for jets)

Jet resolution should also be studied coupled w/ tracking information
(high granularity → "particle-flow friendly")

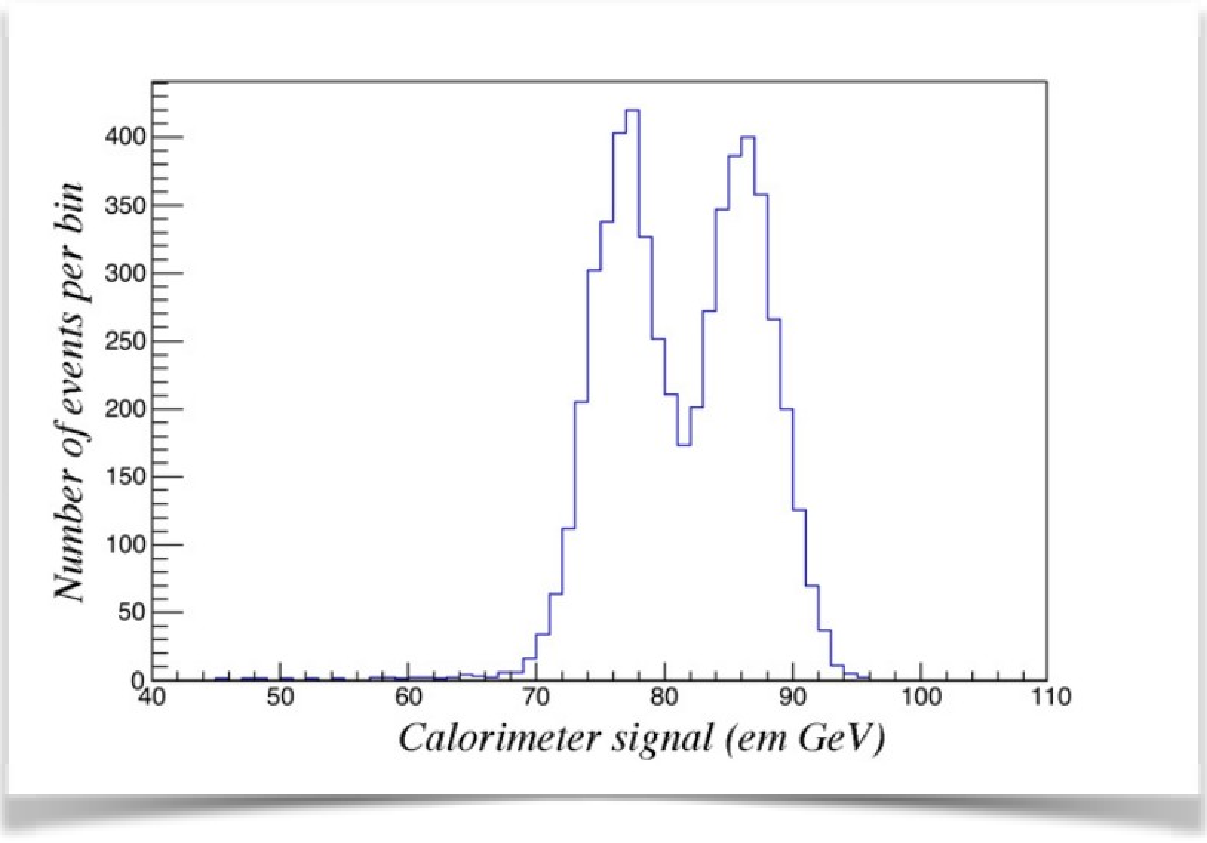
Geant4 Simulations

Hadronic Resolution



W/Z separation

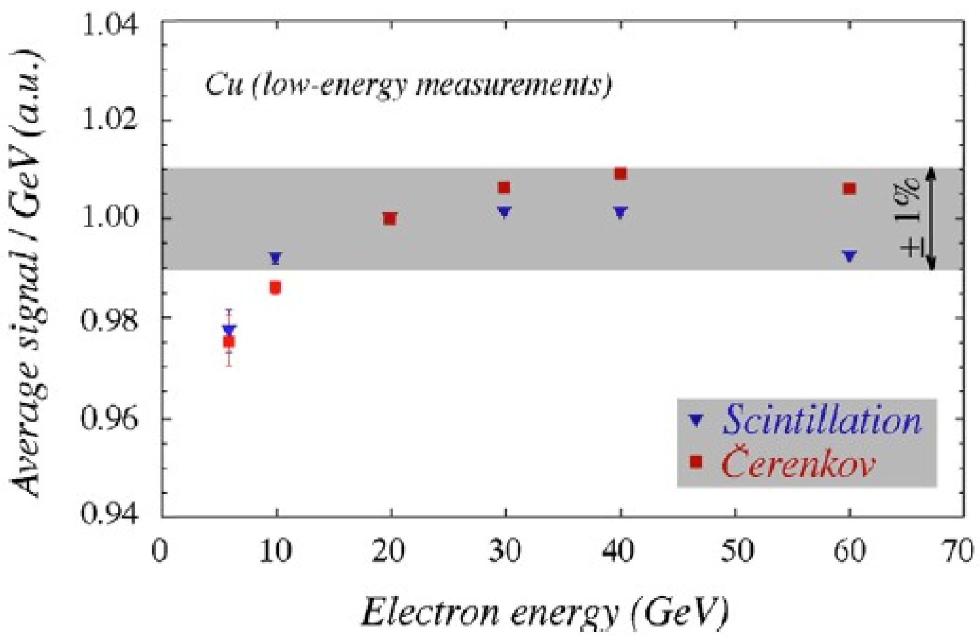
[H→WW / H→ZZ separation]

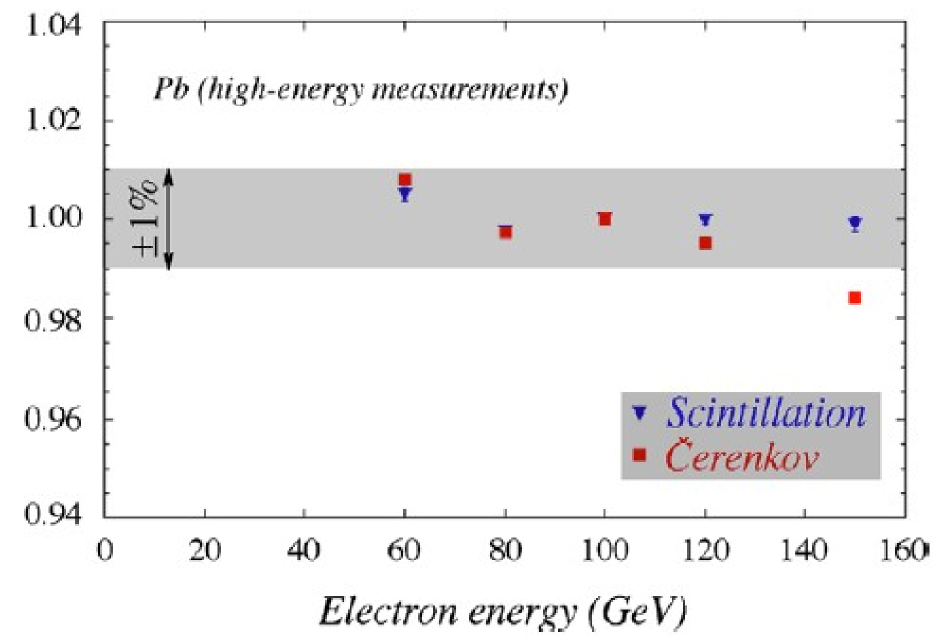


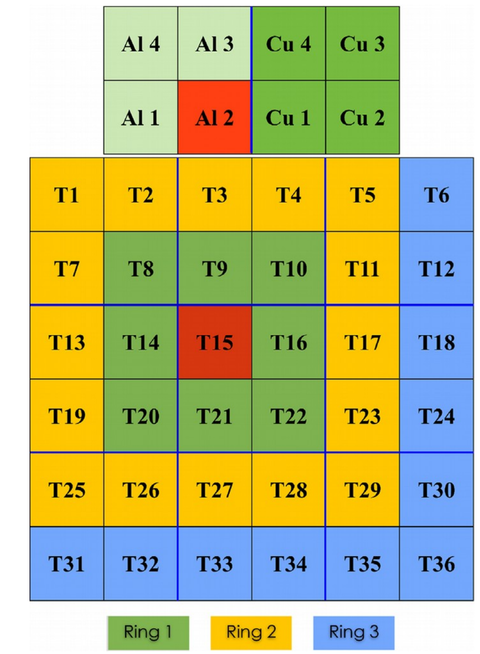
EM Performance of RD52 Calo.s

Signal linearity

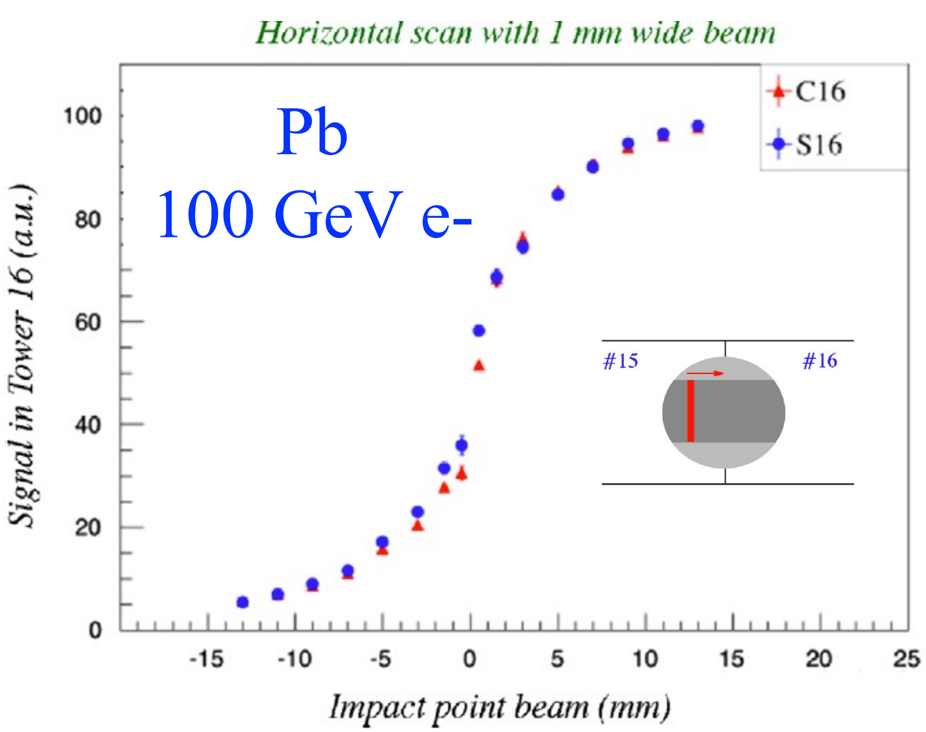
NIM A 735 (2014) 130

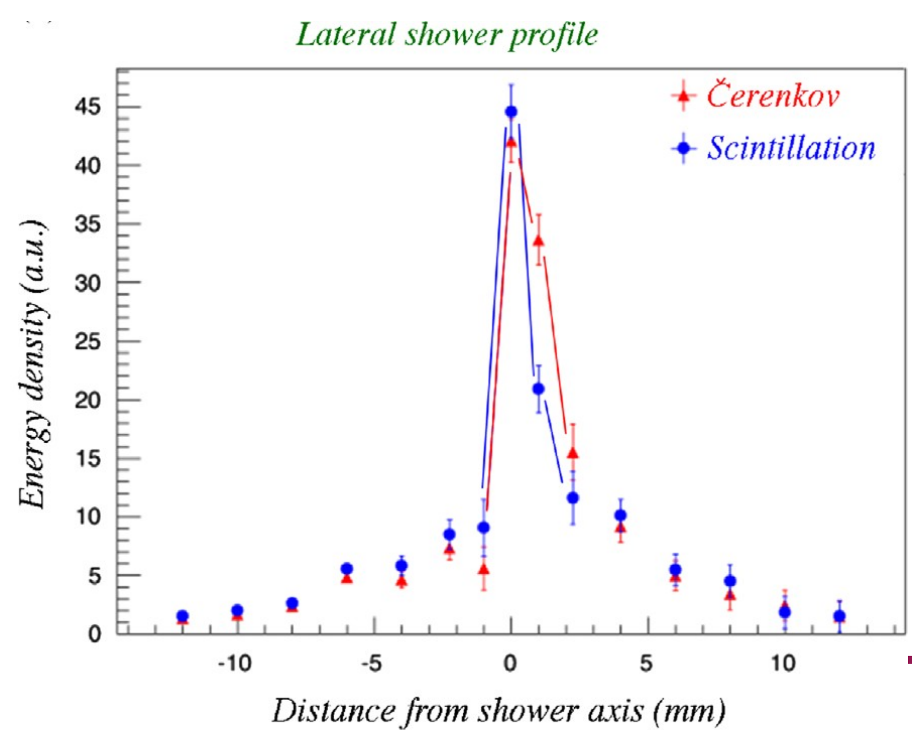


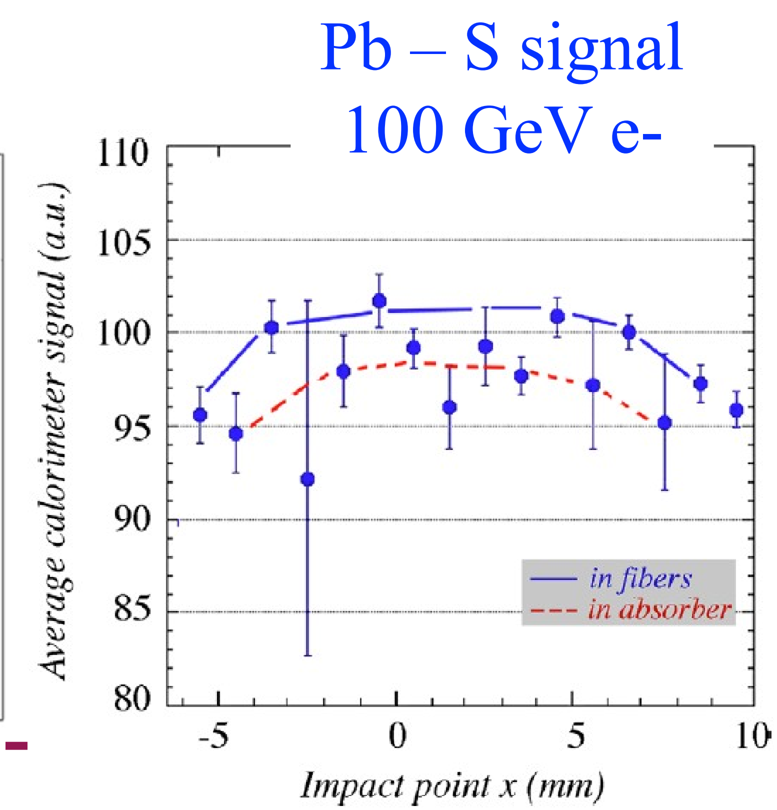




Radial shower profile and response uniformity



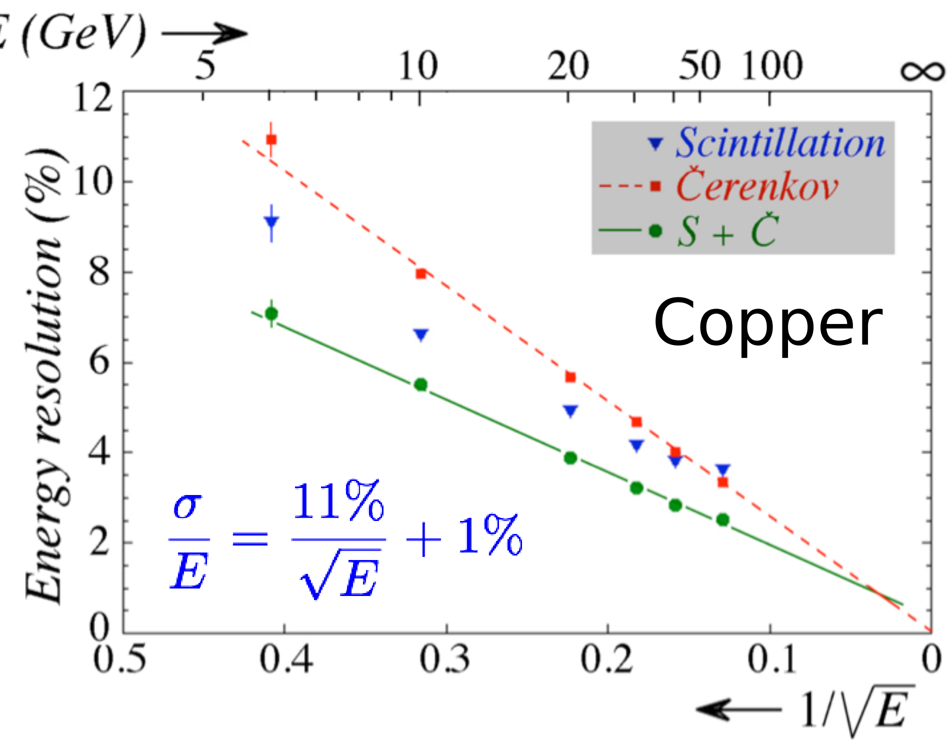


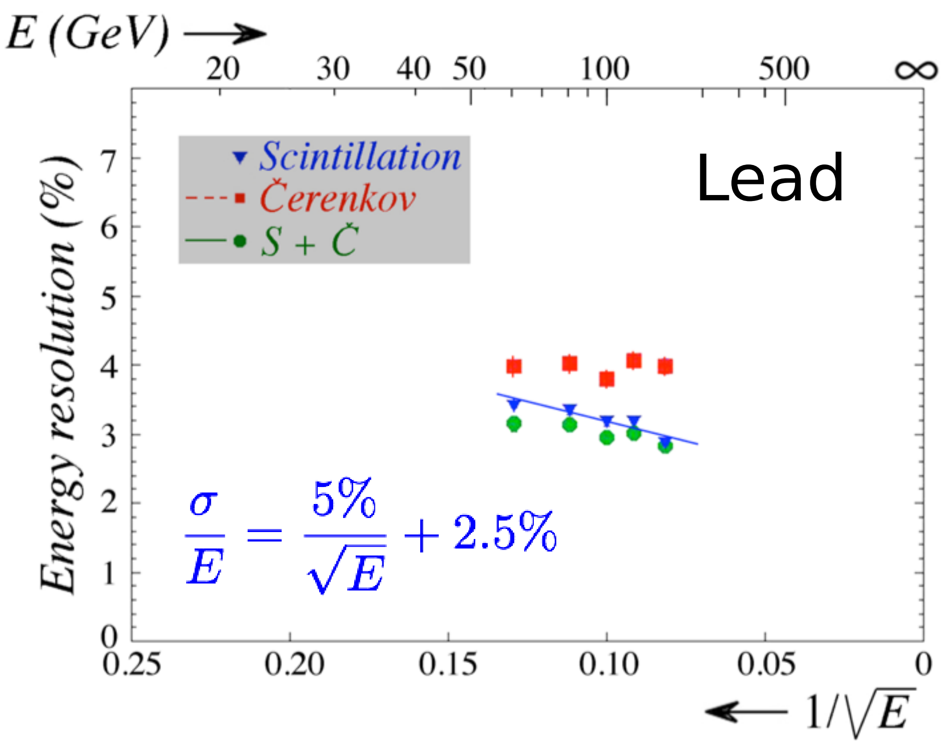


NIM A 735 (2014) 130

E.M. Resolution

~ 1% at 100 GeV

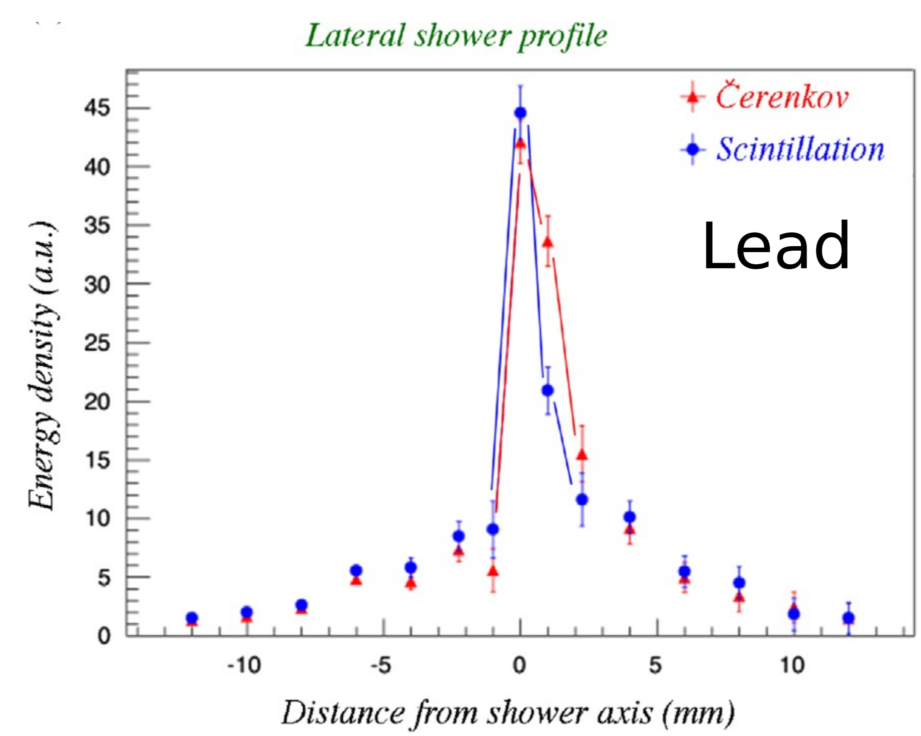




Improvement in resolution (doubled sampling fraction) while combining Č and S independent signals

Constant term due to fluctuations in interaction point (only S) → it disappears for larger angles

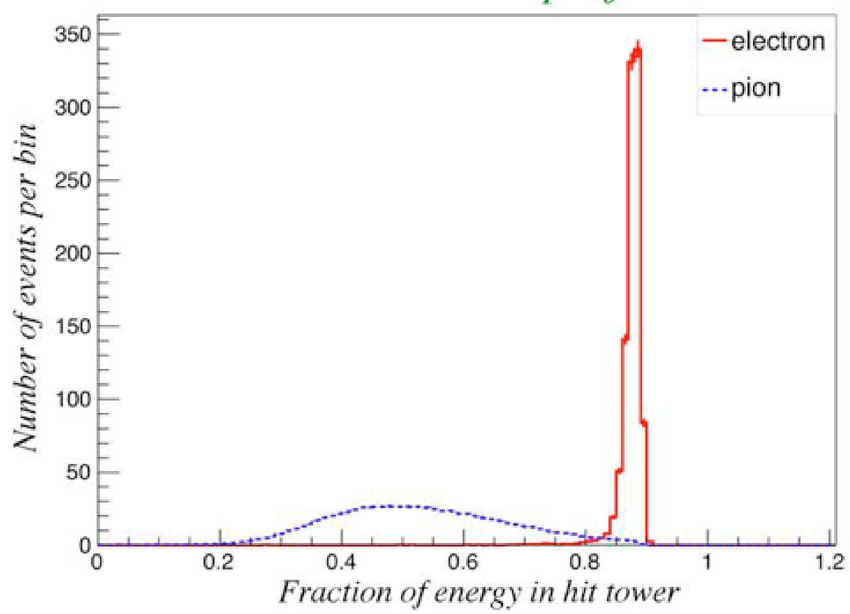
~ 2 GeV resolution on m_H in the γγ channel



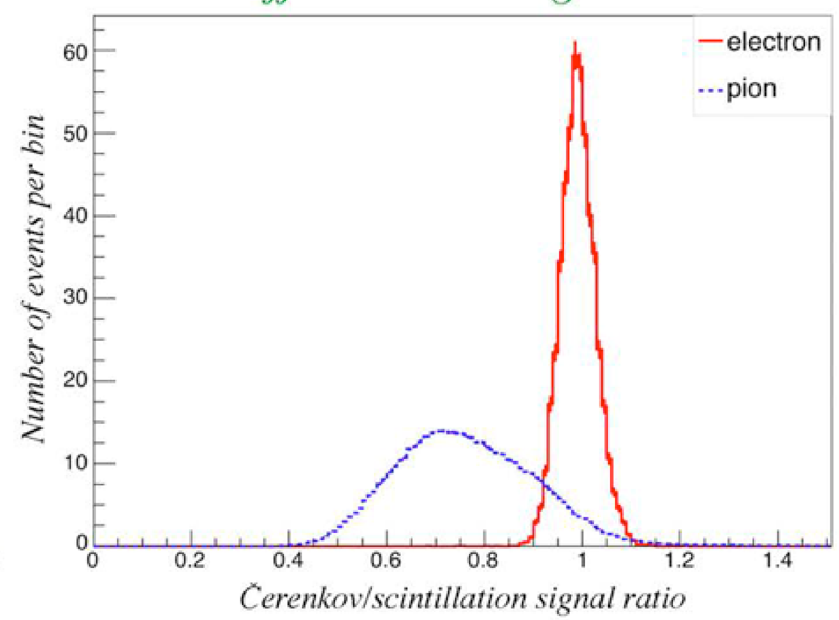
Particle ID (electron/hadron separation)

Methods to distinguish e/π in longitudinally unsegmented calorimeter

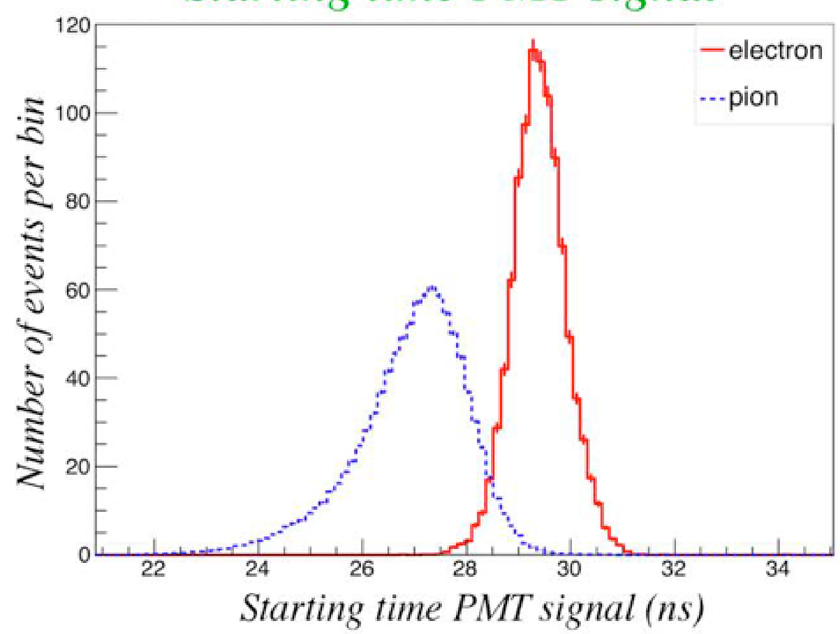
Lateral shower profile



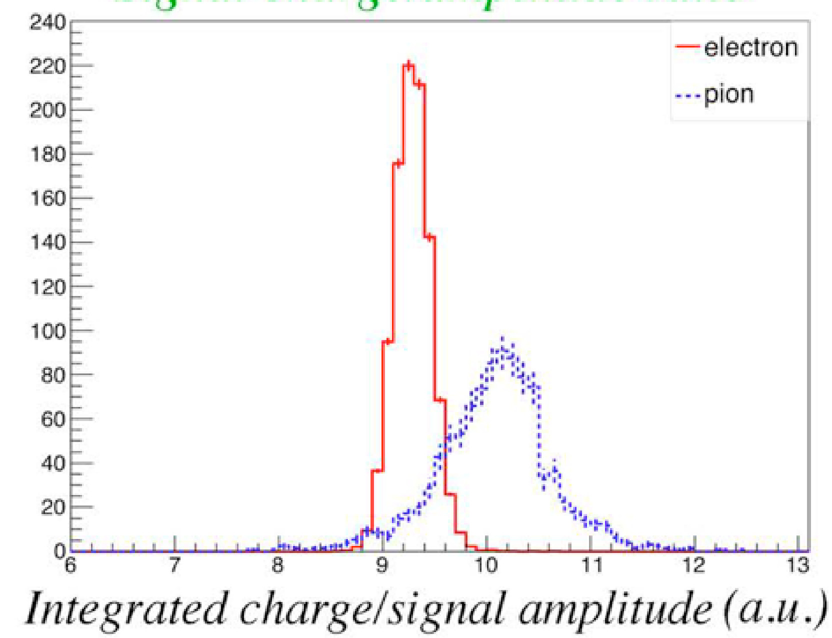
Difference C/S signals



Starting time PMT signal



Signal charge/amplitude ratio



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

Why Copper rather than Lead?

1) Detector mass

2) Cerenkov light yield (fem sampling)

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

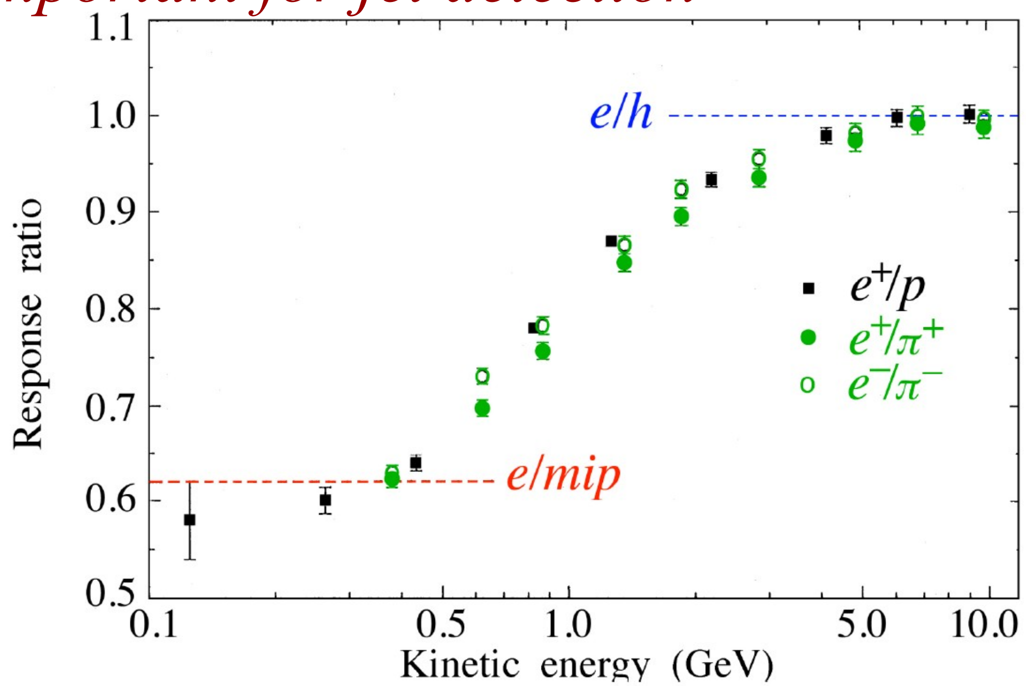
Lead: e/mip = 0.6

Copper: e/mip = 0.9

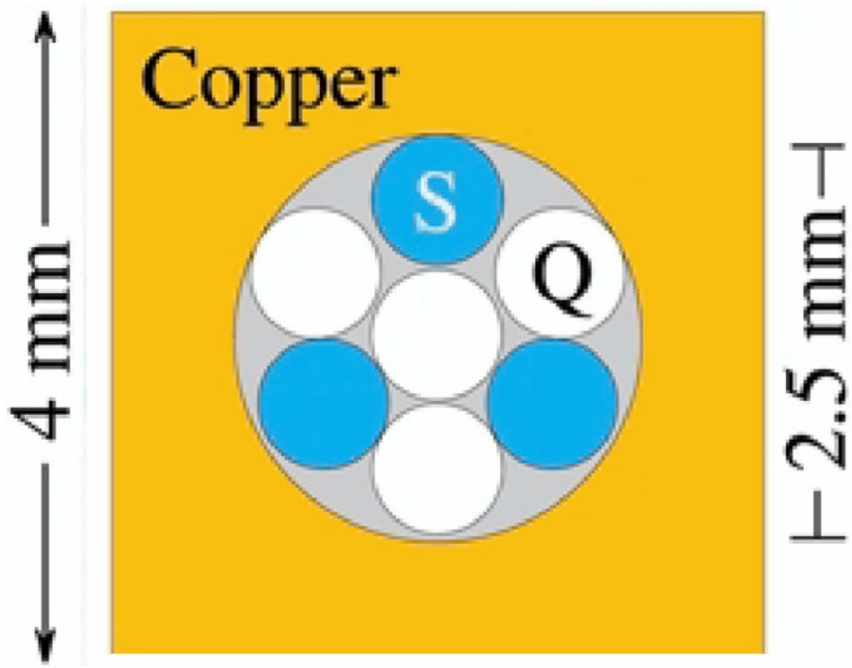
For a structure with a given sampling fraction, we get 50% more Čerenkov photons per GeV deposited energy

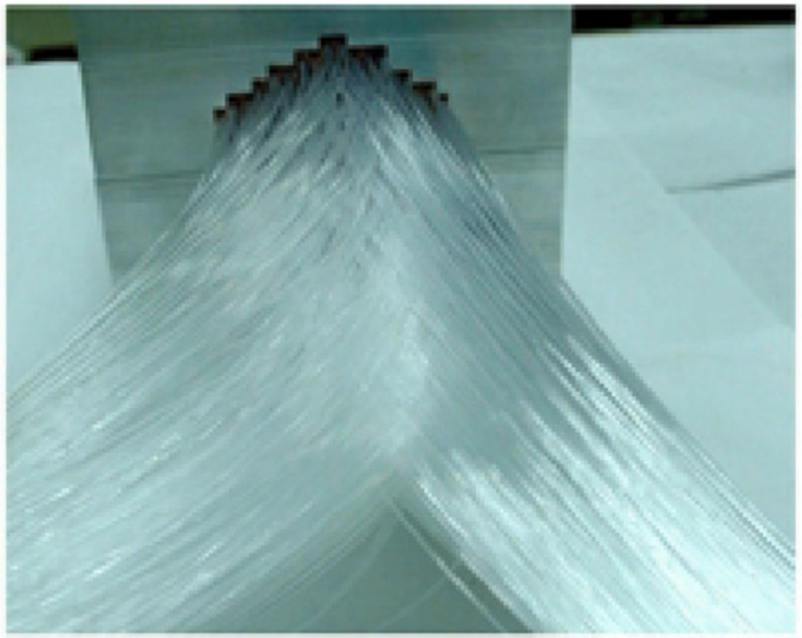
This will directly affect the hadronic energy resolution, since Čerenkov light yield is a major limiting factor

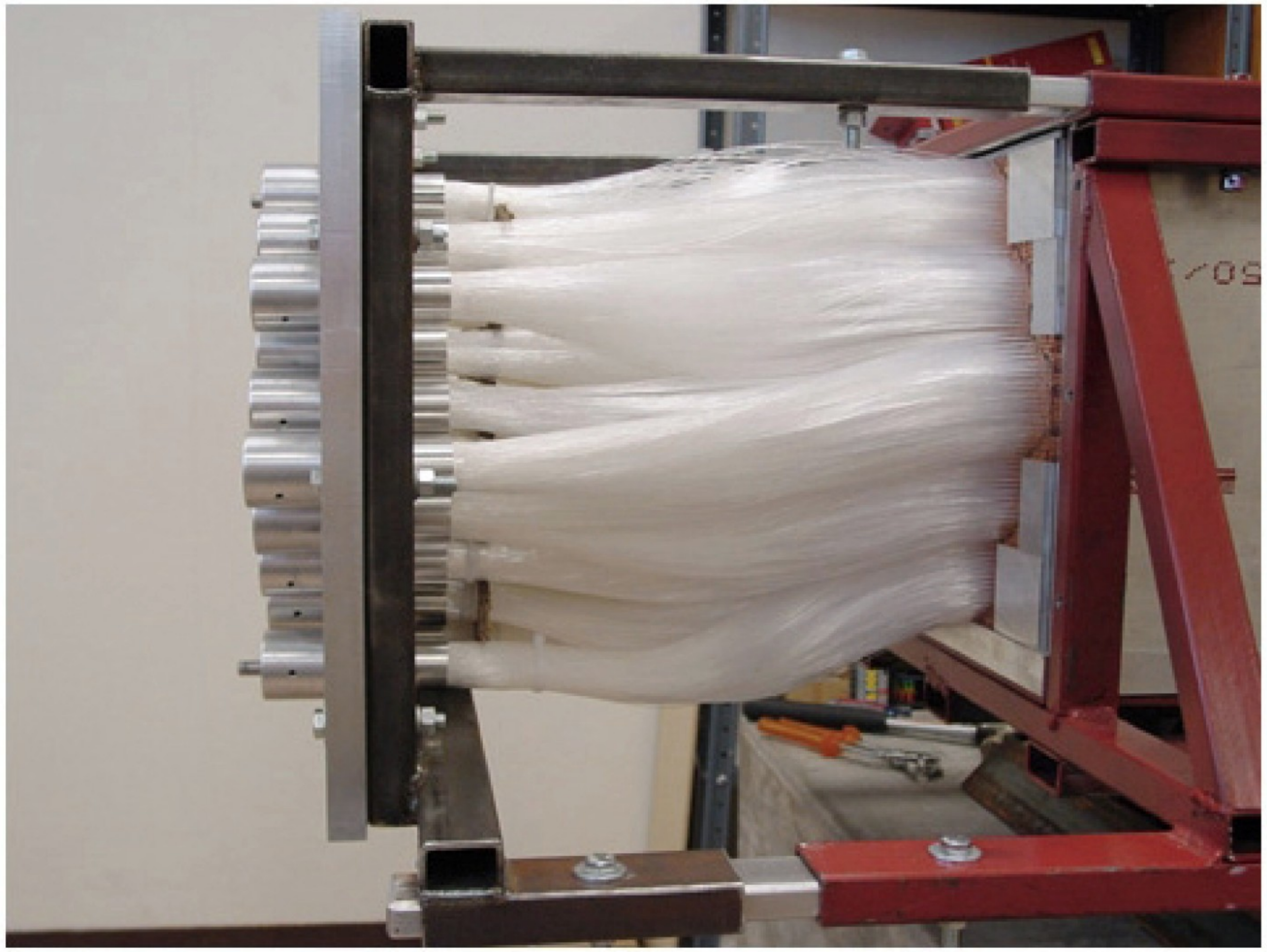
Non-linearity at low energy in calorimeters with high-Z absorber. Important for jet detection



The PMT readout of the DREAM calorimeter







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"*

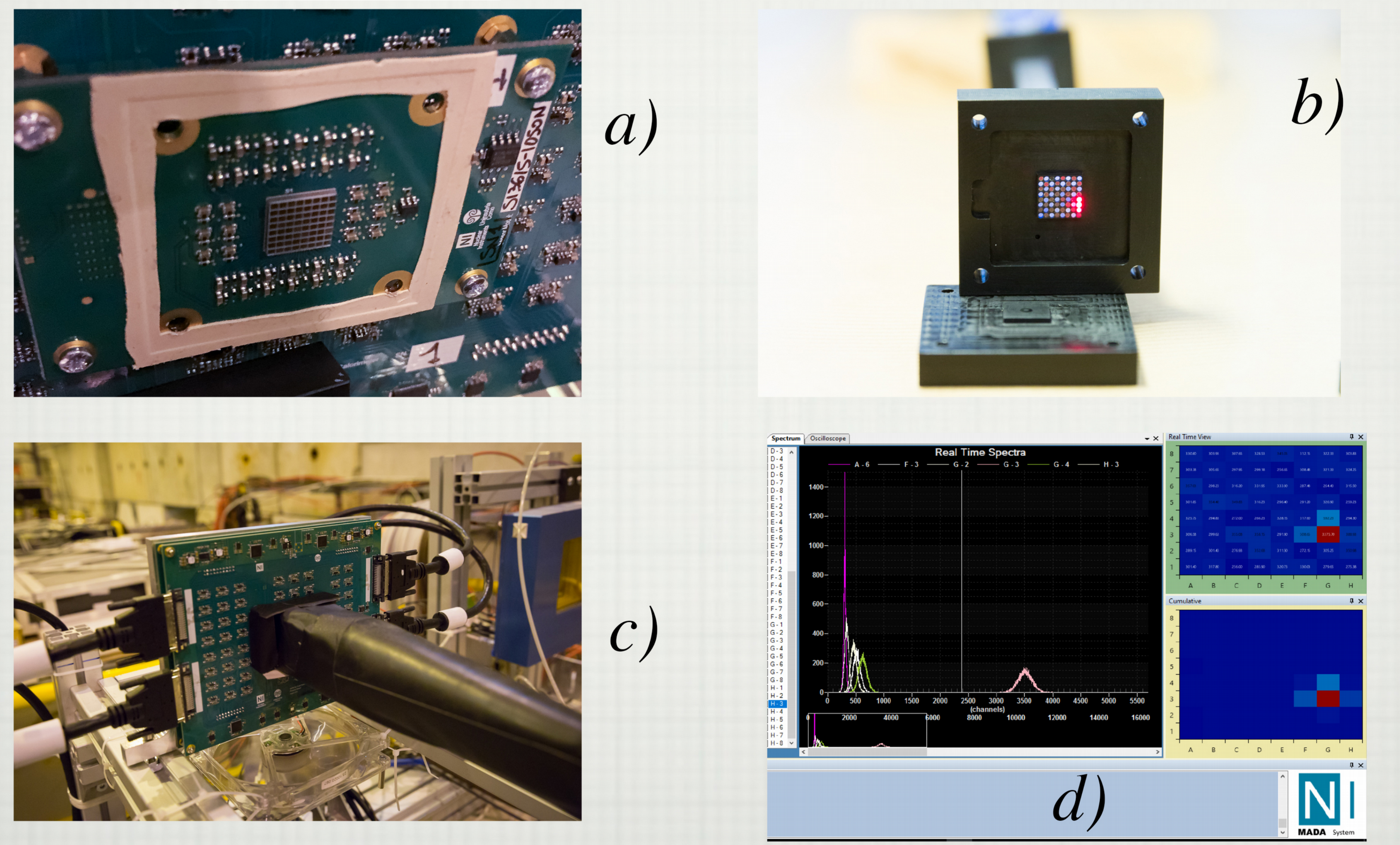
SiPM (potential) disadvantages:

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

First SiPM RD52 Readout

8 x 8 array of 1 mm^2 Hamamatsu SiPMs, 50 μm pixels (400/SiPM)

1 fiber per SiPM



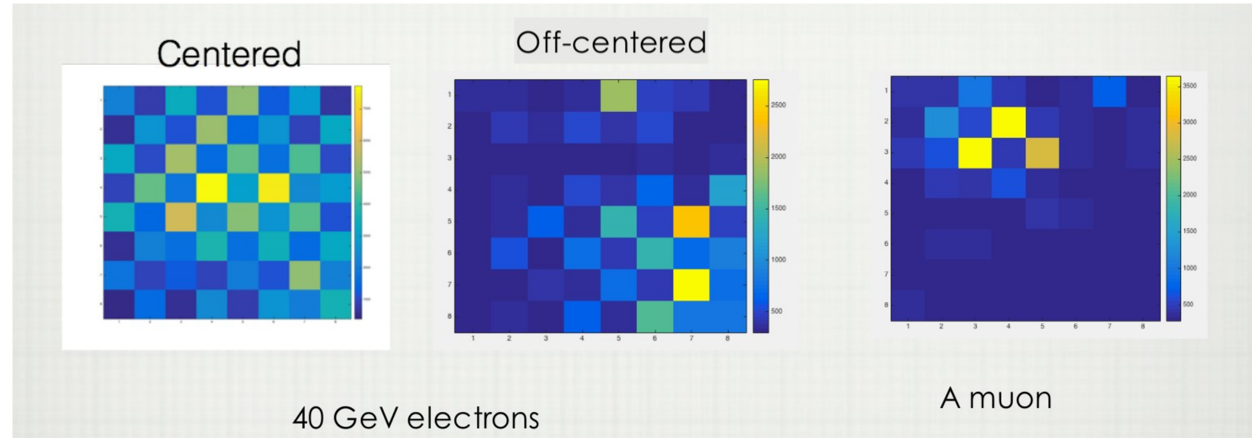
MODULE 1: *All channels equipped* (32 scintillating + 32 Čerenkov fibers)

MODULE 2: *Only Čerenkov fibers connected (32)*

First SiPM RD52 Readout

Event displays in 8x8 mm^2 regions →

Showering electrons deposit 50%
of their energy in this region



A short summary of the data taking conditions:

- two modules, both based on the array with 50 μm pitch cells:
  - module 1: both scintillating and Cherenkov fibres connected to the pixels of the array
  - module 2: Cherenkov fibers only were connected

driven by two main reasons:

- the saturation of the sensors connected to the scintillating fibres
- the study of the optical cross talk

- recorded data:

Module 1

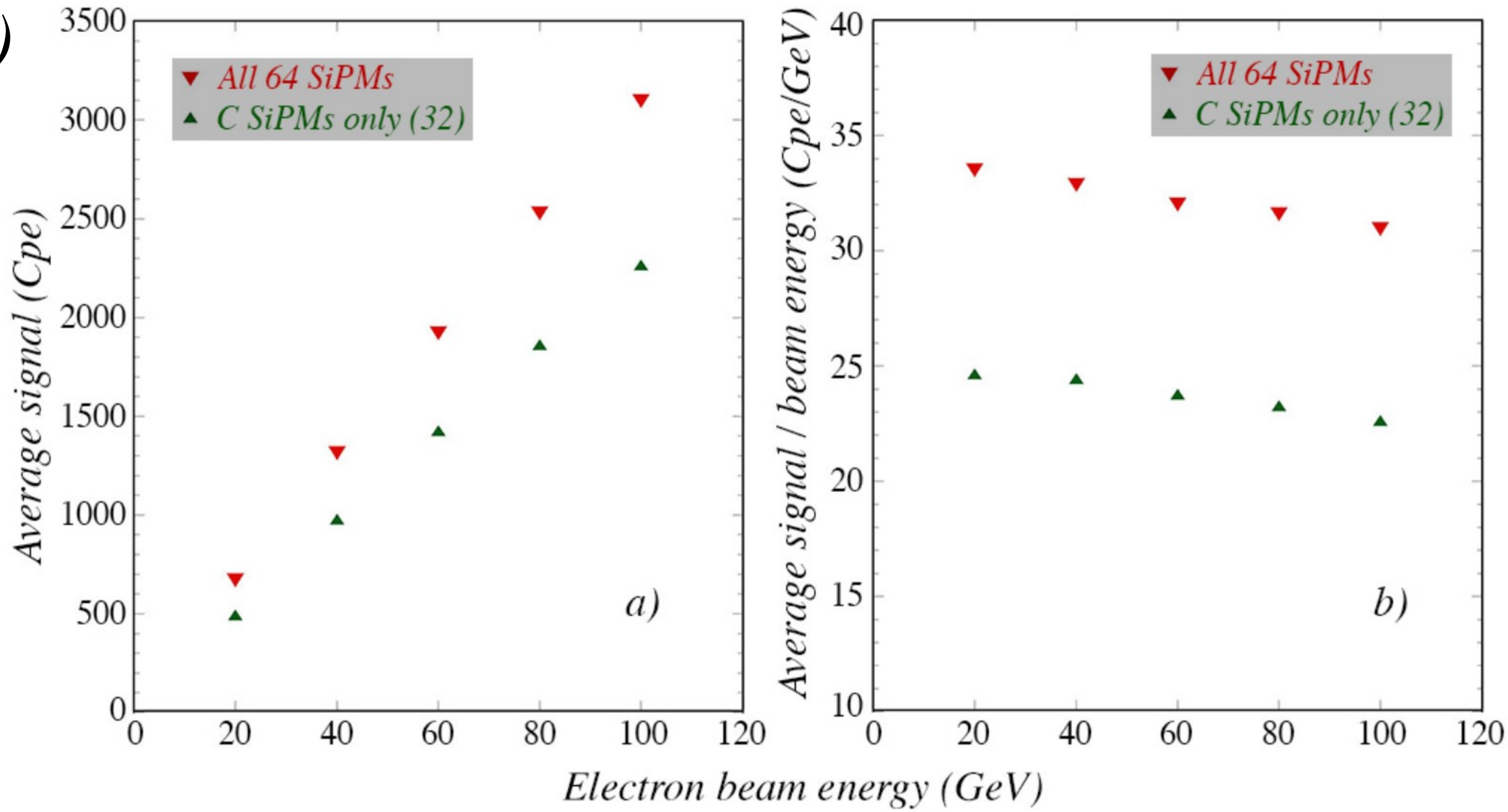
- **e^+:**
  - 20 GeV (> 54.000 events)
  - 40 GeV (> 146.000 events)
  - 60 GeV (> 173.000 events)
- μ^+: 180 GeV (> 100.000 events)

Module 2

- **e^+:**
  - 20 GeV (> 178.000 events)
  - 40 GeV (> 300.000 events)
  - 60 GeV (420.000 events)
  - 80 GeV (340.000 events)
  - 100 GeV (300.000 events)
- μ^+: 180 GeV (400.000 events)

Optical Cross Talk and Signal Saturation

(module 2)



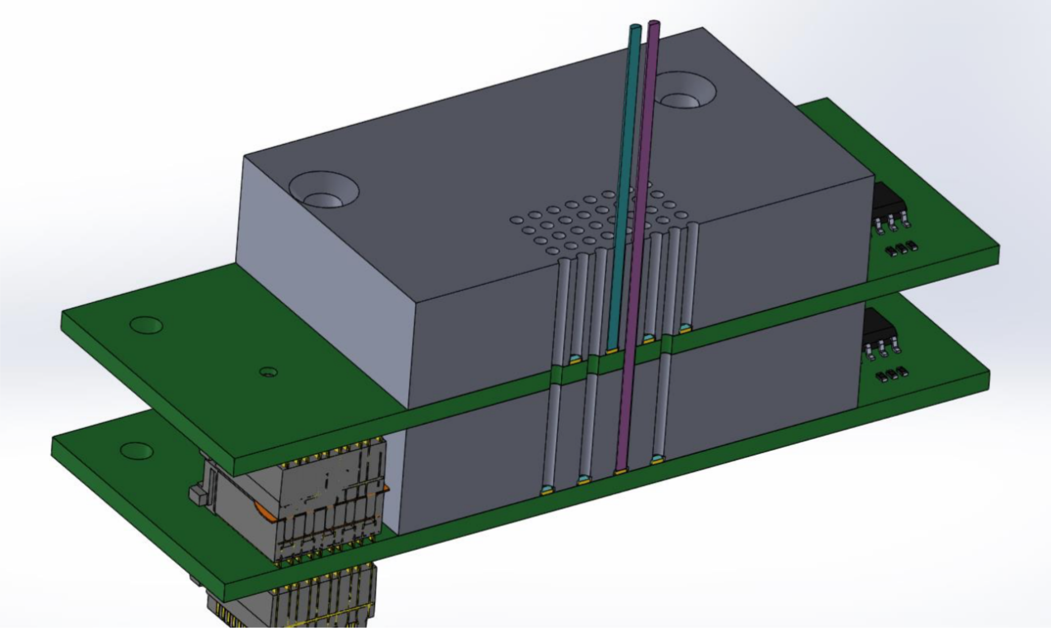
Čerenkov light yield ~ 60-70 p.e./GeV (2 x PMT)

~ 25% optical x-talk to neighboring SiPM.s

~ 8% non-linearity due to saturation

2017 RD52 Plans

a) Eliminate x-talk by using separate SiPM arrays
crucial issue: fibre feed-thru



b) Eliminate / strongly reduce saturation effects by using SiPM with 4 x larger dynamic range (4 x smaller pixel area)

c) Develop an electronic board to integrate up to 9 sensors in a single readout channel

→ details about on-going lab tests in Romualdo's talk

Growing up

Collaboration ongoing with CepC people → include the DR option in CepC CDR

a) Work in progress for a projective 4π DR option in Mokka
b) Submitted a joint Italian-Chinese proposal to MAE

Started discussing/collaborating with FCC-ee people (Gigi, Mogens, Patrick, ...)

→ Simulate a conceptual detector (IDEA) w/ DR calorimetry for CepC/FCCee

→ Computing resources available for us at TTU High Performance Computing Center (contact Alan Sill for that)

→ Collaborate in hw development / test (testbeam)

2017 Simulation Plans

Fully simulate a testbeam copper module (w/ parameterised description of Čerenkov light propagation)

Implement a 4π geometry description for the IDEA detector
→ *estimate W/Z/H resolution capability in benchmark channels*
→ *evaluate performance w/ PF algorithms*

Evaluate combined performance w/ a 2X_0 preshower (Si or MPGD) detector in front (need manpower!)

→ *details of ongoing work in Lorenzo's talk*

Middle term planning

a) Detector: build one (some) ~10x10x150 cm^3 module(s)

Copper grooving!

haven't yet a viable solution for massive production …

→ *Bronze ? Brass ? Other materials ?*

b) SiPM/SiC readout: signal aggregation/sum

→ *evaluate 64-channel ASIC-based modules*

c) UV sensitive devices (e.g. SiC) → see Sebastiano's talk

Open issues:

When/How build a full-containment detector ?

When/How develop projective geometry ?

Collaboration/Declarations of Interest

Long list ... seems promising ...

Cagliari, Como, Cosenza, Pavia, Pisa, TTU, Iowa State, Kyungpook KNU, Seoul SNU, CERN, IHEP, CAS, Nankai, UCL, University of Sussex

(but in some cases just single individuals)

Nevertheless some breakdown seems to be already effective ...

Backup slides

Conclusions

We believe that a Dual-Readout Sampling Calorimeter may provide, at the same time:

- e.m. resolution of about $10\%/\sqrt{E}$
- jet energy resolution ~ few % at ~100 GeV
- high performance in standalone e/h separation
- a cost effective solution for CepC/FCCee calorimetry

Finally, the excellent granularity coupled w/ a preshower detector should provide valuable input for particle-flow algorithms

2017 Testbeam Goals

Requested beam time (electron beams, with energies of 10-100 GeV)

Plan to test also two new full-scale copper-fiber modules, built at Iowa State University (standard PMT readout)

Dual-Readout Papers

Homogeneous Calorimeter	Sampling Calorimeter
Possibility to solve light yield and sampling fluctuation problem Need to separate Č and S light	Two types of fibers, sensitive to either Čerenkov or Scintillation light Č and S 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

New RD52 Paper

Hadron detection with a dual-readout fiber calorimeter

S. Lee[m], A. Cardini[c], M. Cascella[d], S. Choi[e], G. Ciapetti†[g], R. Ferrari[h], S. Franchino[i], M. Fraternali[f], G. Gaudio[h], S. Ha[e], J. Hauptman[j], H. Kim[m], A. Lanza[h], F. Li[j], M. Livan[f], E. Meoni[l], J. Park[m], F. Scuri[b], A. Sill[a] and R. Wigmans[a, 1]

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[m] *Kyungpook National University, Daegu, Korea*
† *Deceased*

Abstract

In this paper, we describe measurements of the response functions of a fiber-based dual-readout calorimeter for pions, protons and multiparticle "jets" with energies in the range from 10 to 180 GeV. The calorimeter uses lead as absorber material and has a total mass of 1350 kg. It is complemented by leakage counters made of scintillating plastic, with a total mass of 500 kg. The effects of these leakage counters on the calorimeter performance are studied as well. In a separate section, we investigate and compare different methods to measure the energy resolution of a calorimeter. Using only the signals provided by the calorimeter, we demonstrate that our dual-readout calorimeter, calibrated with electrons, is able to reconstruct the energy of proton and pion beam particles to within a few percent at all energies. The fractional widths of the signal distributions for these particles (σ/E) scale with the beam energy as $30\%/\sqrt{E}$, without any additional contributing terms.

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Key words: Dual-readout calorimetry, Čerenkov light, optical fibers

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Dual-Readout Technique

- Investigate and - possibly - eliminate the factors which prevent from measuring hadrons and jets as well as electrons and photons:
- - Different (energy dependent) hadronic and em scales
- - Hadronic non linearity
- - Non-gaussian response function
- - Poor energy resolution
- - Need of cross calibration of longitudinally segmented detectors
- Aims:
- - Calorimeter calibration with electrons only
- - High-resolution EM and HAD calorimetry
- - Comply with requirements for future-collider physics

RD52 DREAM

Research carried on by the RD52 experiment @ CERN
(USA, South Corea, INFN Collaboration)
http://dream.knu.ac.kr/

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)

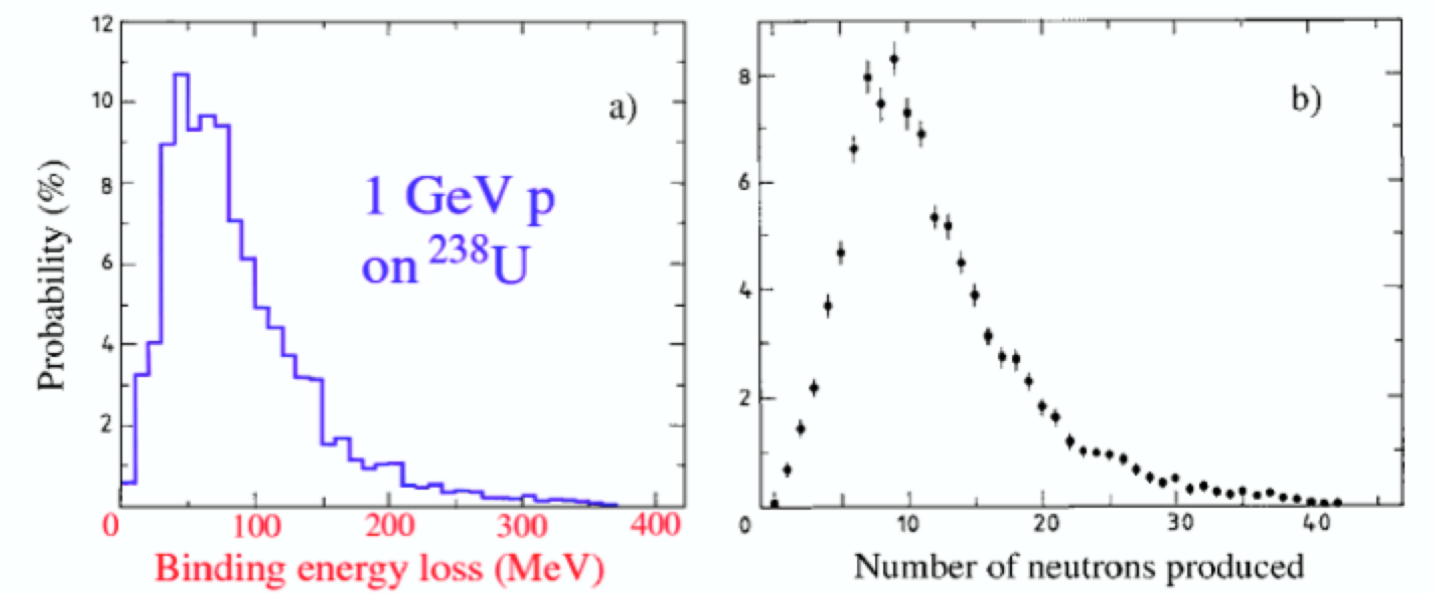
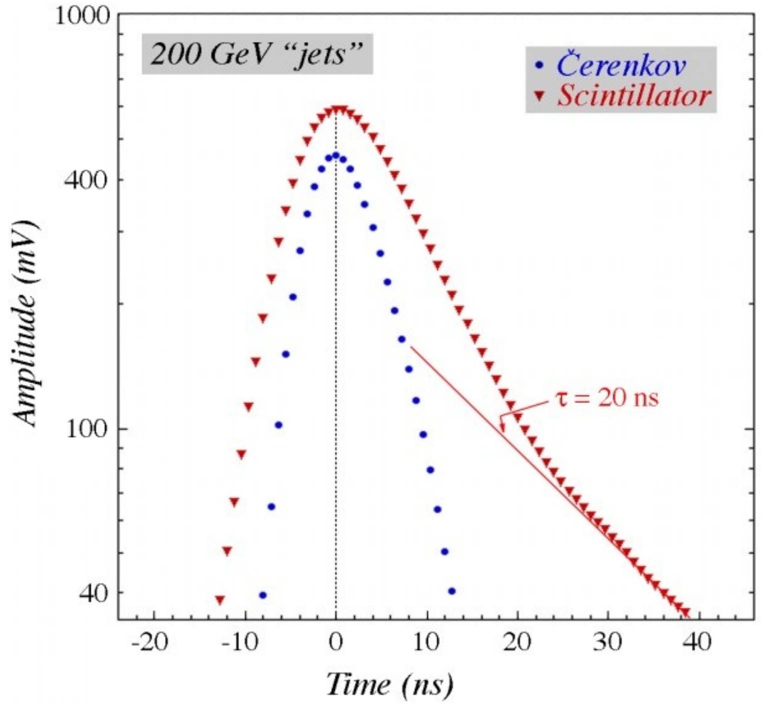


FIG. 4.43. The nuclear binding energy lost in spallation reactions induced by 1 GeV protons on ^{238}U nuclei (a), and the number of neutrons produced in such reactions (b). From [Wig 87].

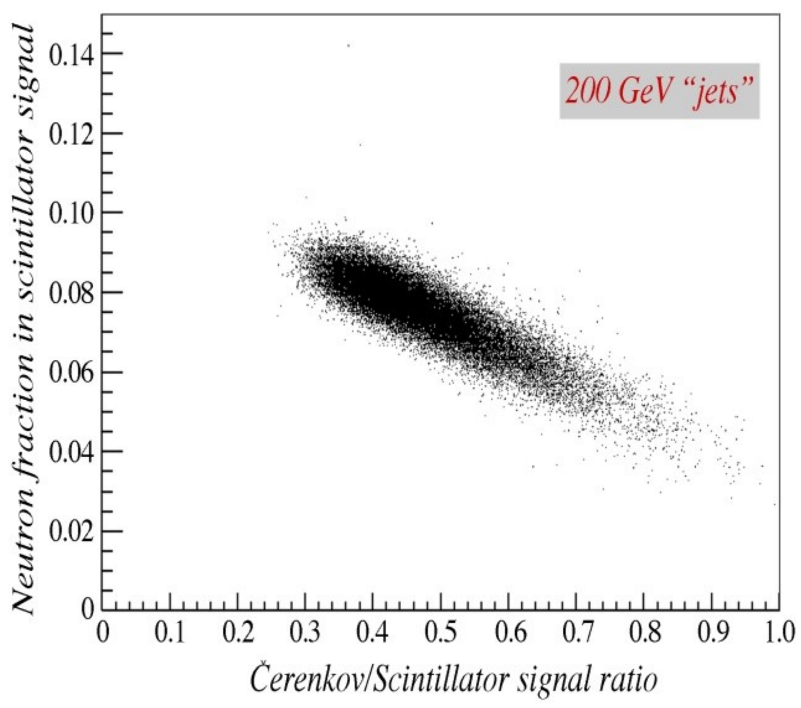
2 - Invisible Energy

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)

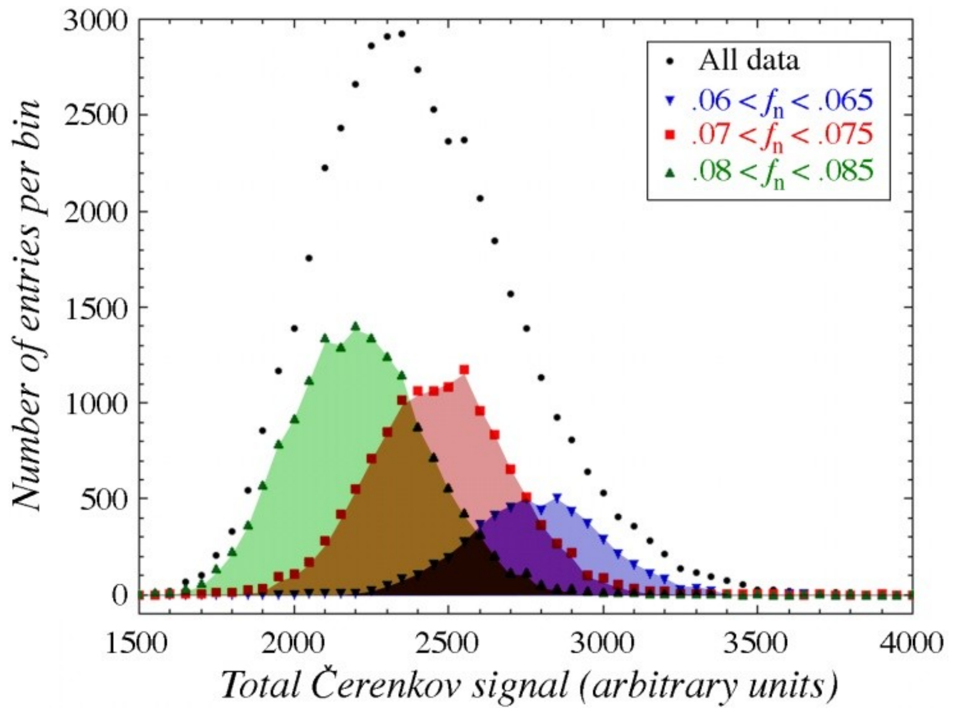
Time structure of DREAM signal.
Tail absent in em showers



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

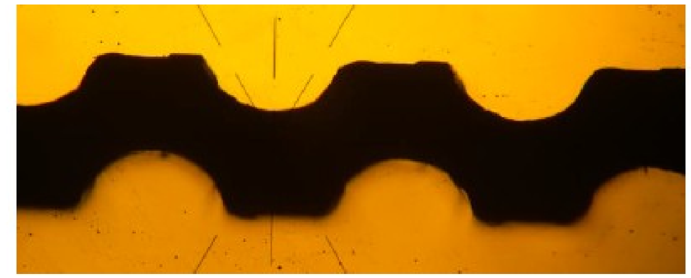


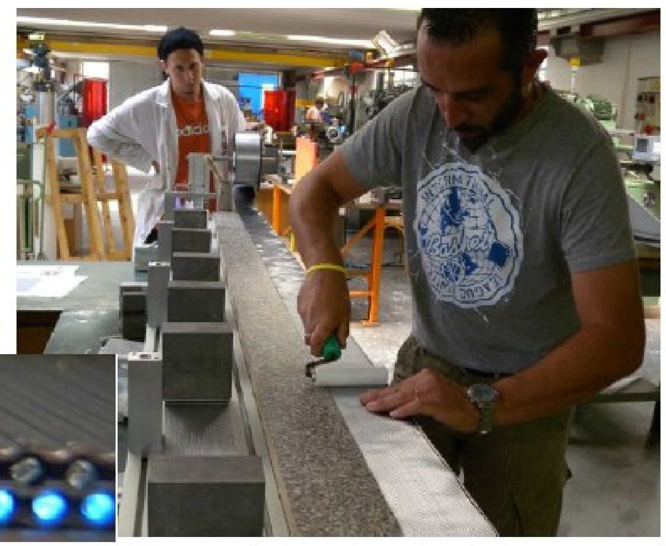
Probing the tot. signal distribution with N fraction

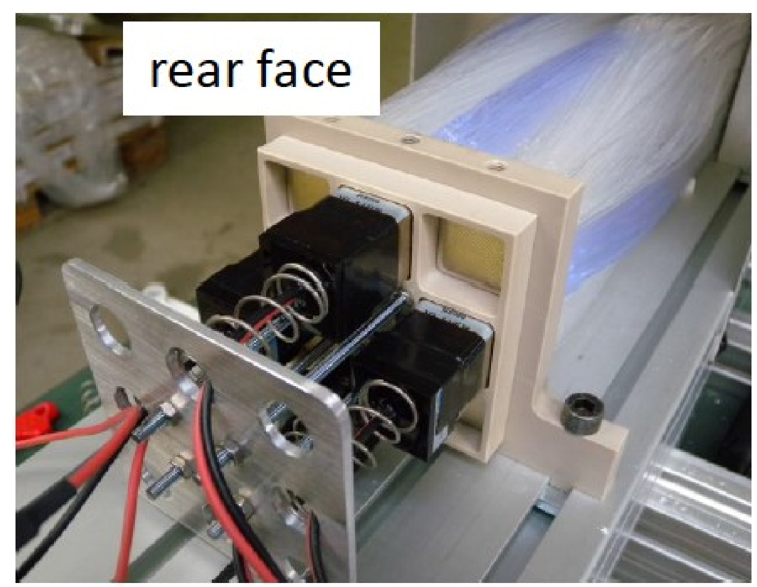


Pb-Fibre Module Construction

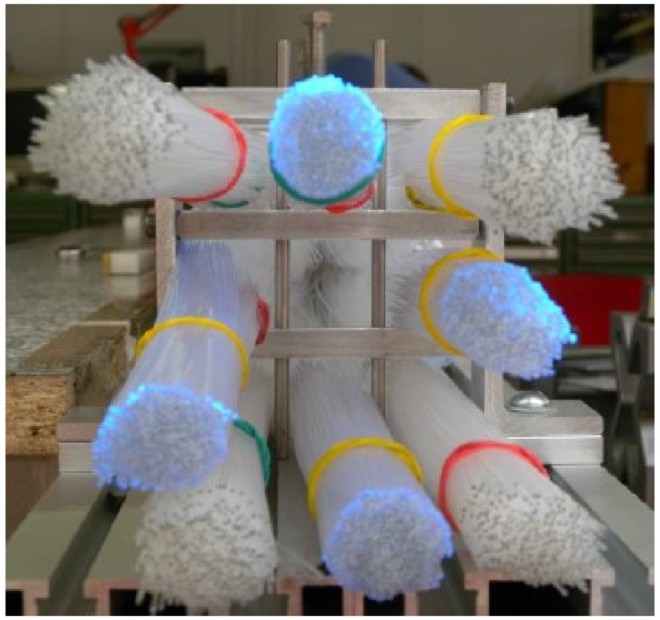
Pb fabrication:
Cold extrusion (industry, Italy), both sides.
Assembling in INFN Pavia, no glue used

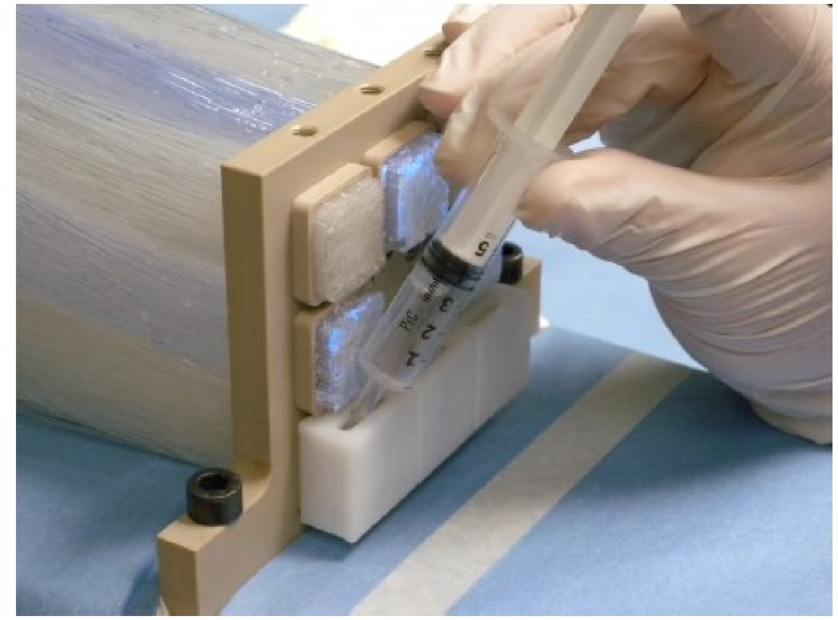
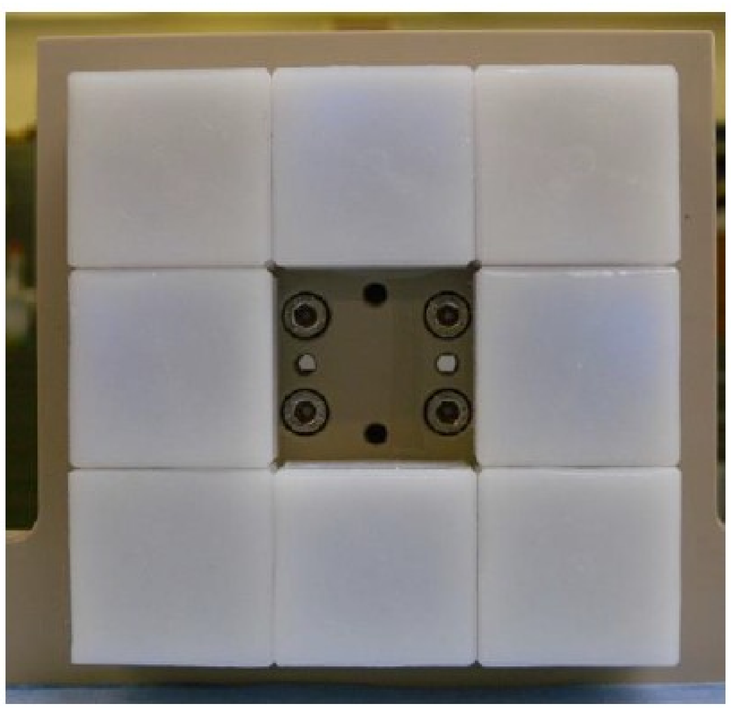
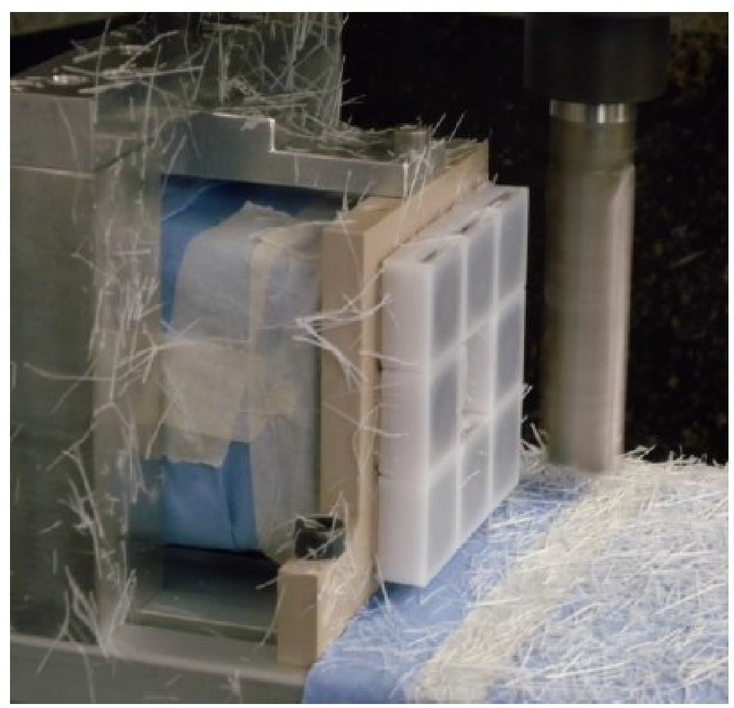
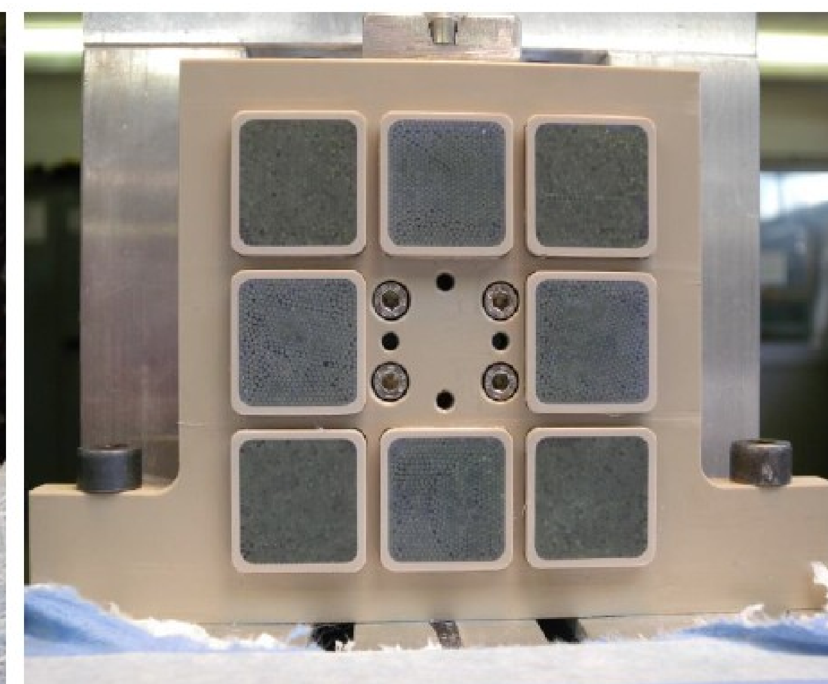






Pb-Fibre Module Construction



Cu-Fibre 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

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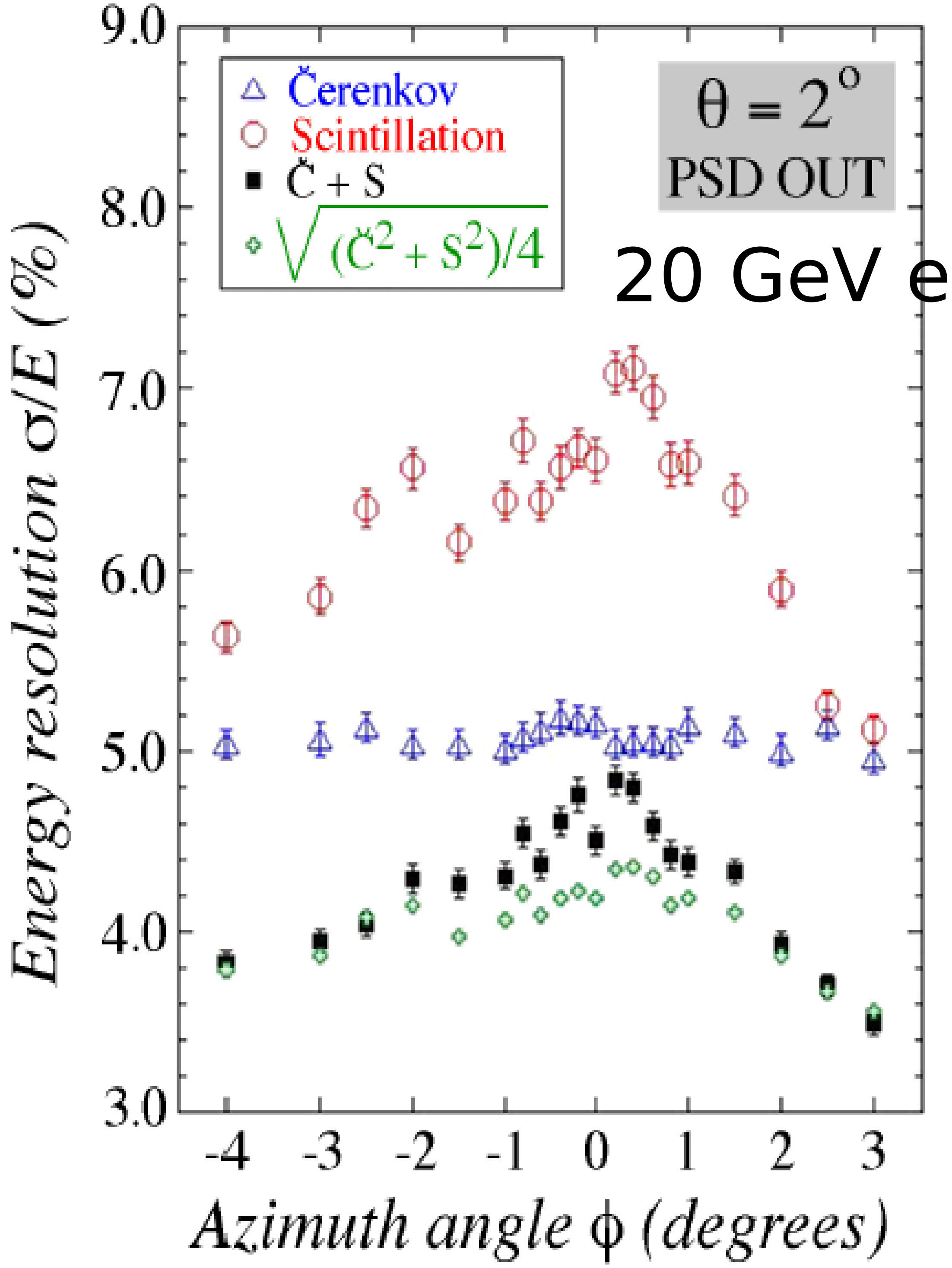
Small-Angle EM Performance of RD52 Cu Cal.



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

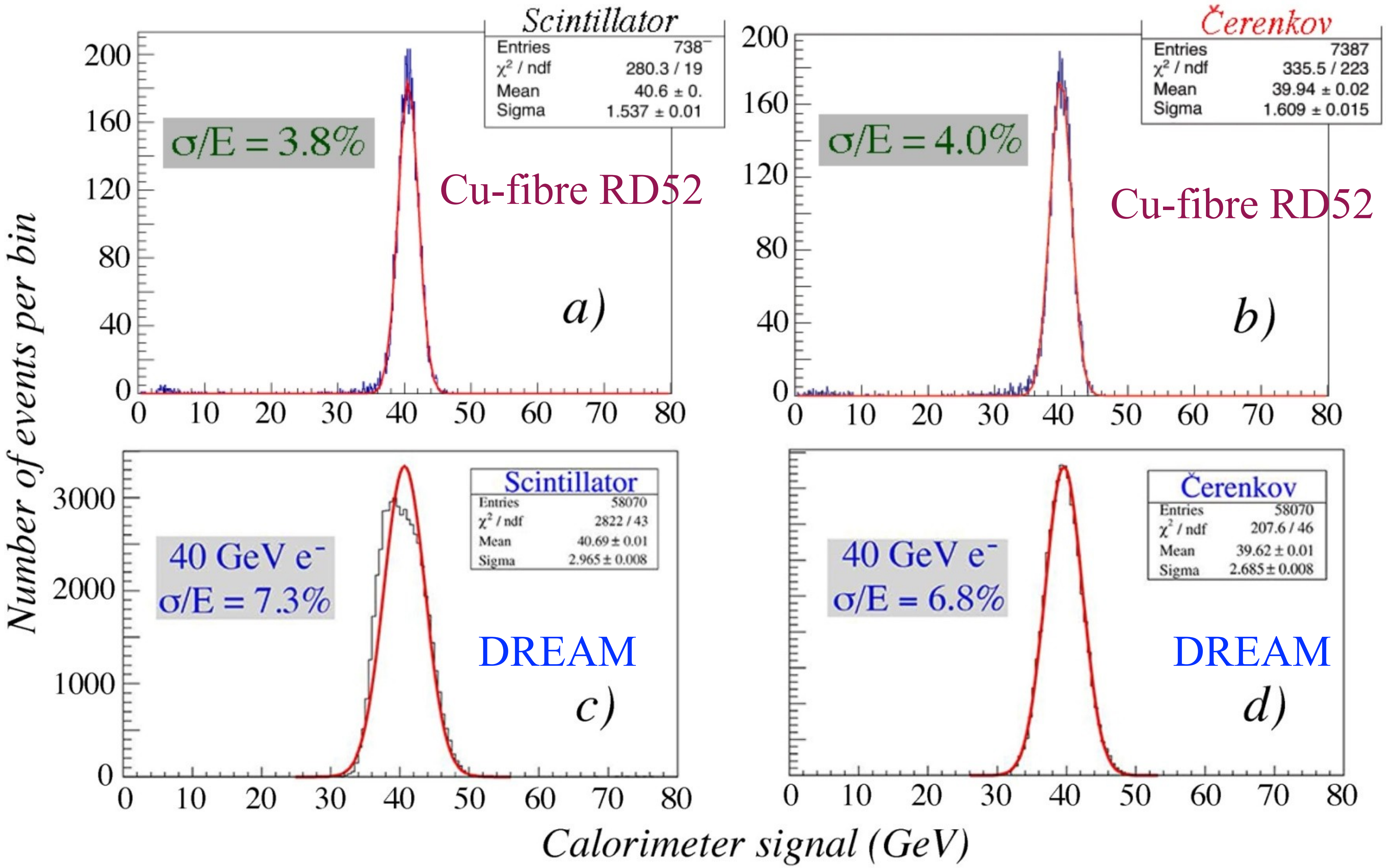
→ We can sum their contributions
→ em energy resolution improves
by a factor √2

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

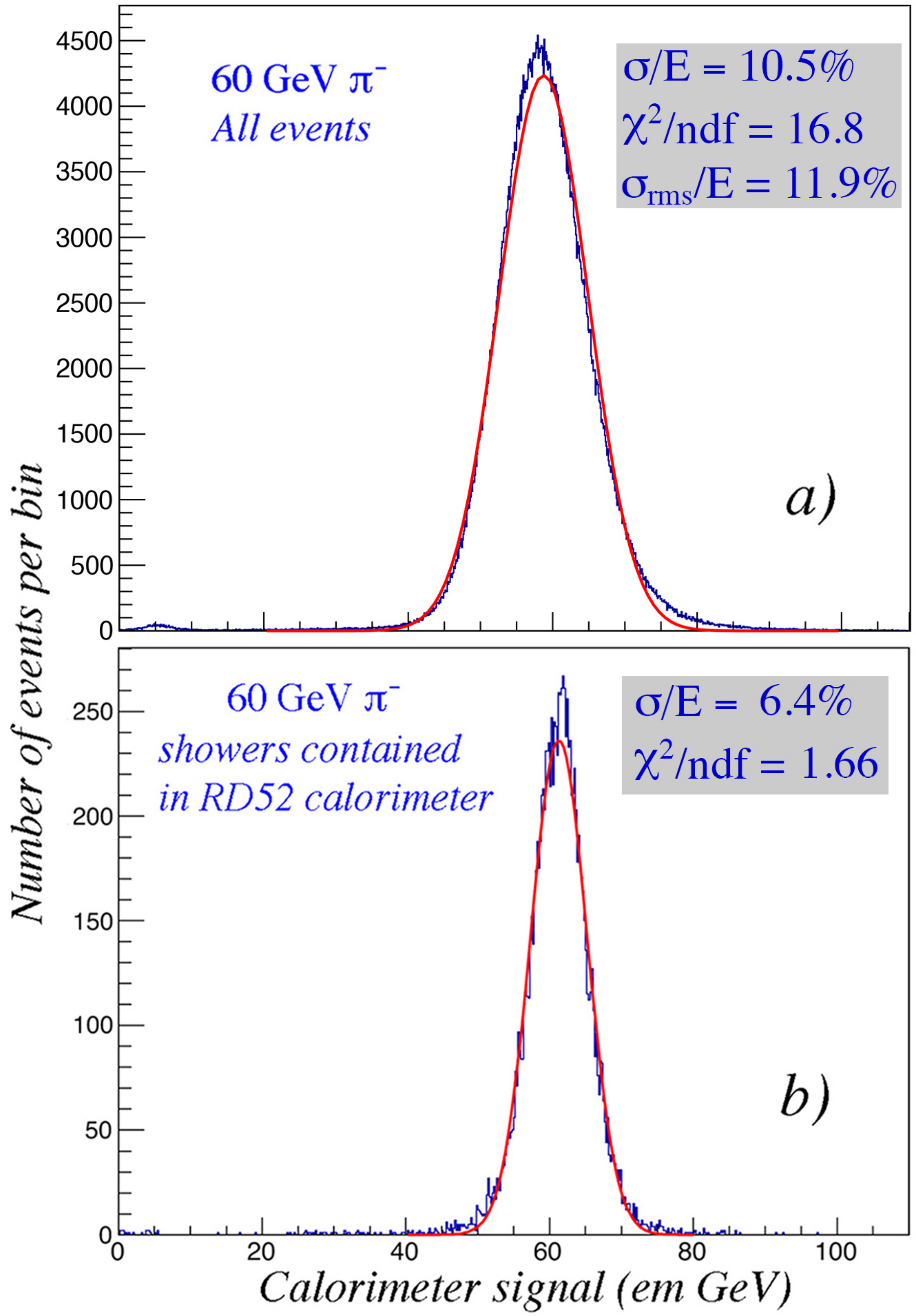
NIM A 735 (2014) 130

EM Performance RD52 Cu Calo

Em performance strongly improved with new RD52 Cu-fibre prototype
Better sampling fraction



Lateral-Leakage Effects

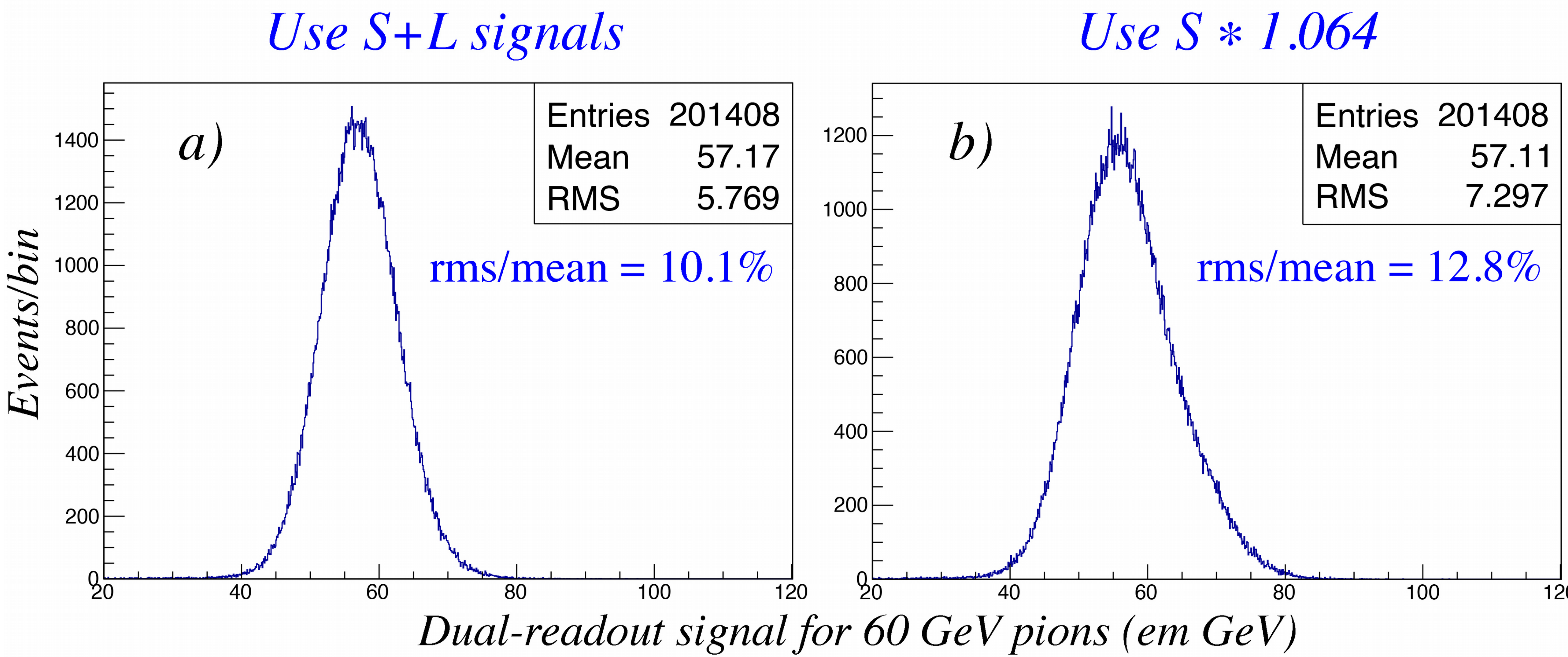


Effects of incomplete shower containment

Lateral leakage fluctuations

Leakage-Counter Corrections

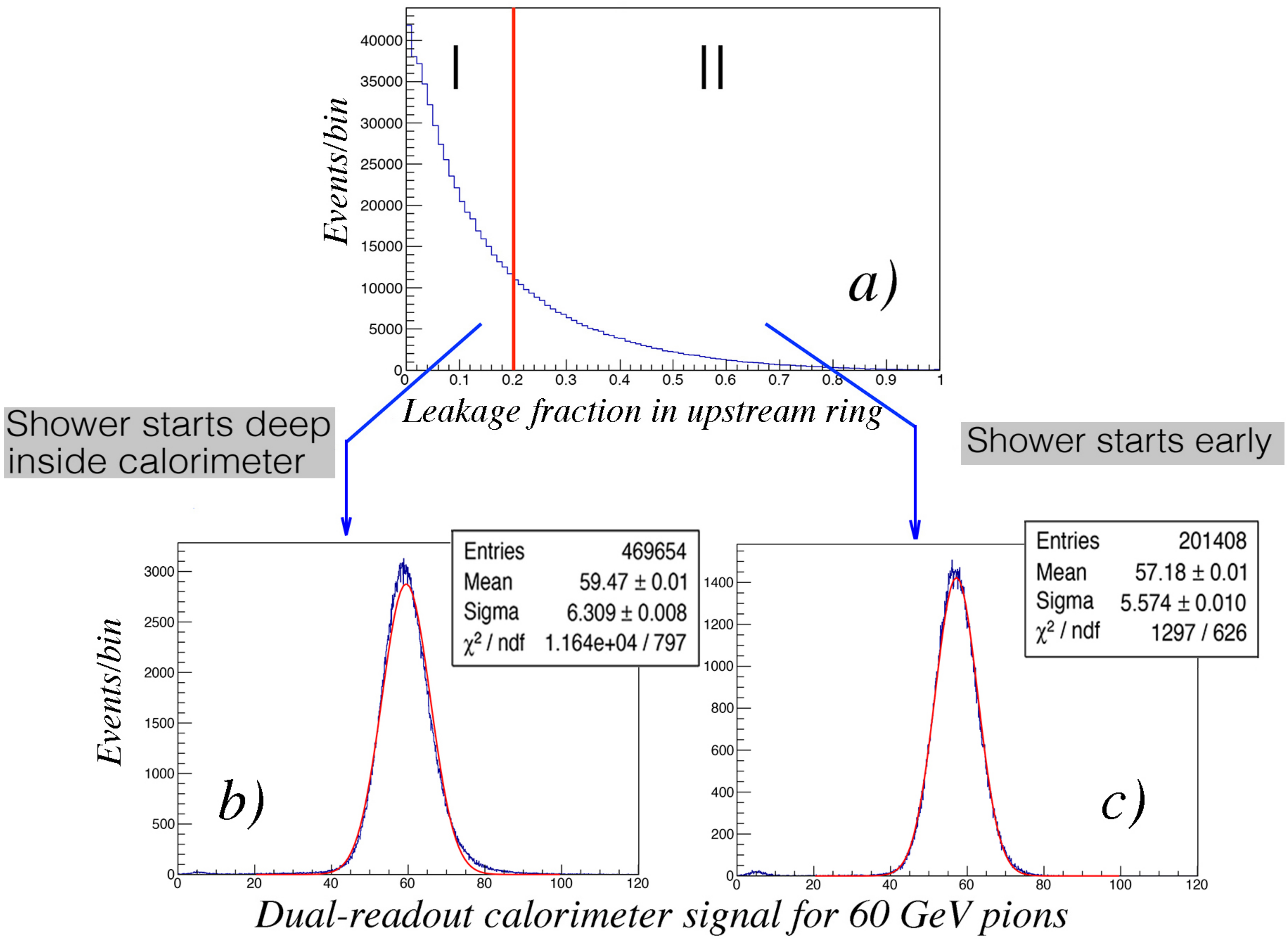
Effects of leakage counters on the hadronic energy resolution



Light Attenuation Effects

Early vs. late starting showers

(effects of light attenuation in S fibers)

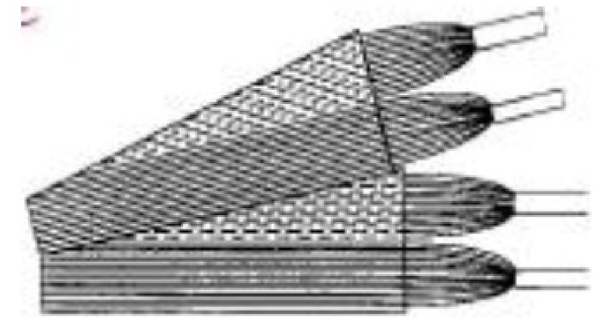


From RD52 to 4π Calorimeters

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*)



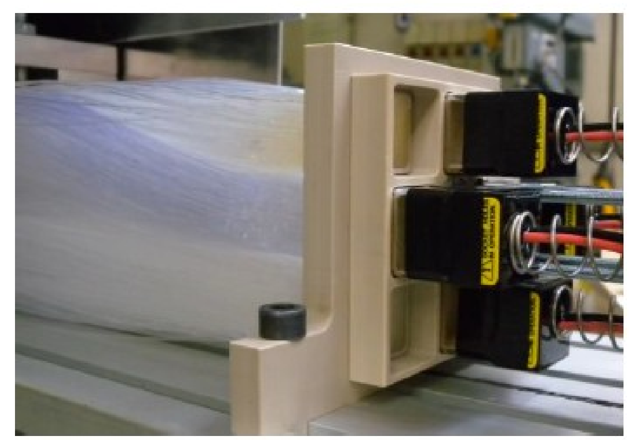
- Use of SiPm → two advantages:
  - Get rid of the “fiber forest”, readout closer to the end face
  - transversal segmentation as small as needed

- 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