Dual-Readout Calorimetry – Latest Results

FCC Detector Design Meeting
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Dual-Readout Calorimetry

What:

correct hadronic energy measurements for f_{em} fluctuations

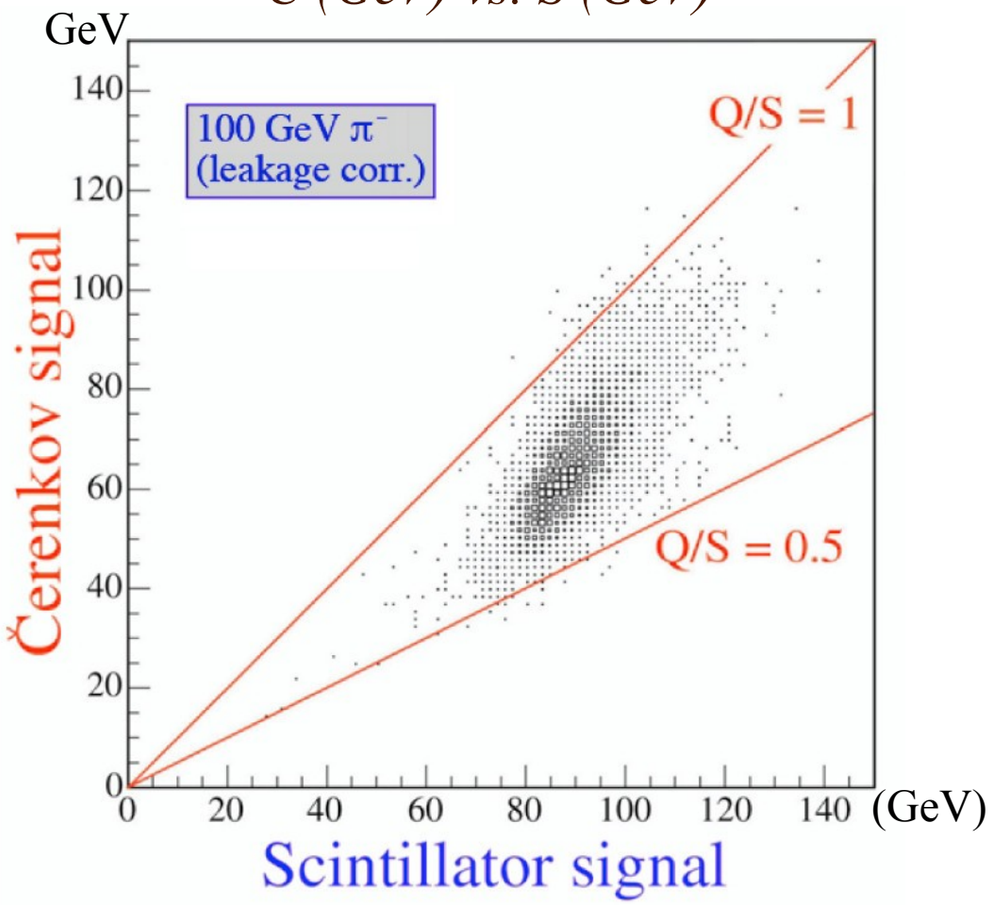
How:

use two independent sampling processes, with different sensitivity to em and non-em shower components, to reconstruct f_{em} event-by-event

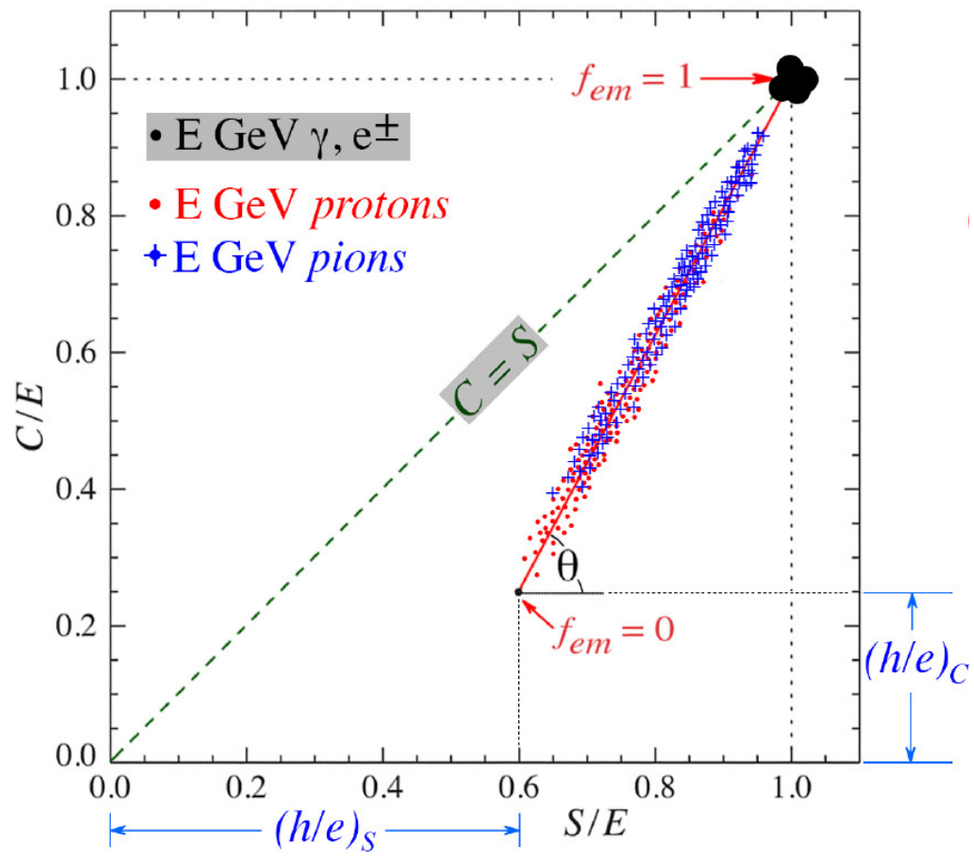
(see backup slides)

The Alchemy

Č (GeV) vs. S (GeV)



C/E vs. S/E



Hadronic data points (S, C) located around straight lines

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

is universally valid

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

θ, χ independent of both:

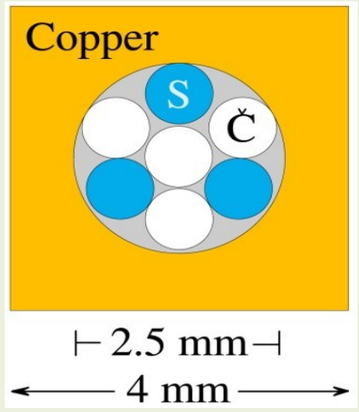
i) energy (!)

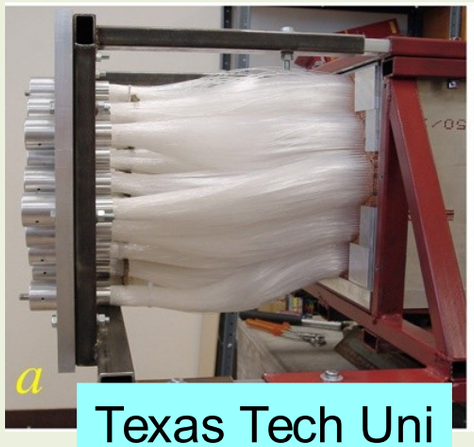
ii) type of hadron (!!)

Dual Readout w/ Fibre Sampling Calorimeters

2003
DREAM

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

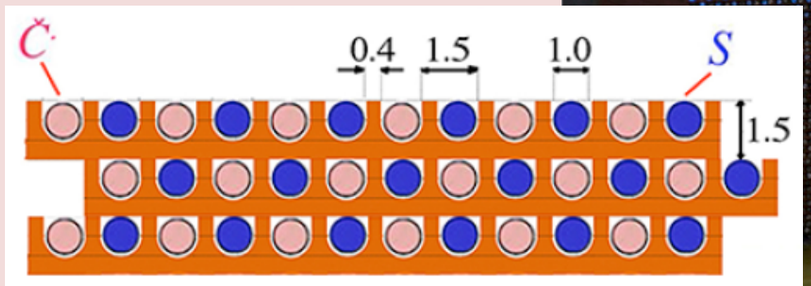


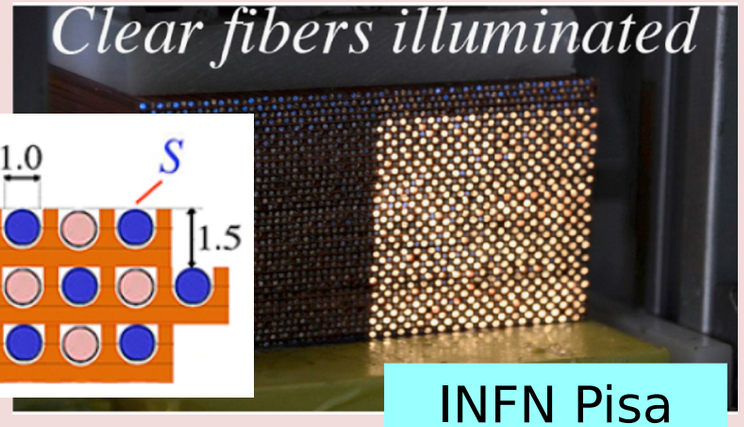


Texas Tech Uni

2012
RD52

Cu, 2 modules
Each module: 9.2 × 9.2 × 250 cm³
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: ~4.6%
Depth: ~10 λ_{int}

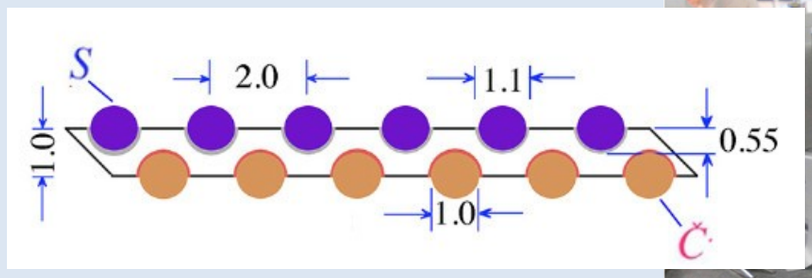




INFN Pisa

2012
RD52

Pb, 9 modules
Each module: 9.2 × 9.2 × 250 cm³
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: ~5.3%
Depth: ~10 λ_{int}



INFN Pavia

Particle ID (electron/hadron separation)

RD52 lead calorimeter

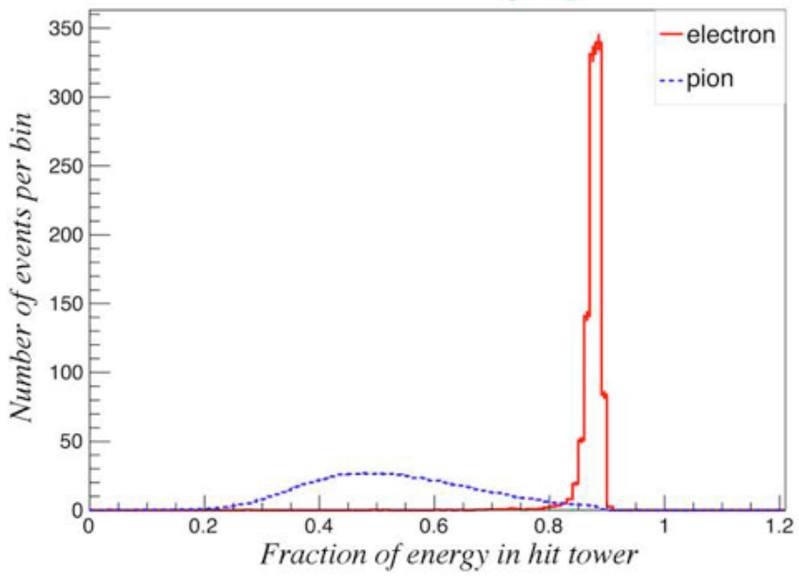
(60 GeV) e^- vs. π^-

$\varepsilon(e^-) > 99\%$
$R(\pi^-) \sim 500$

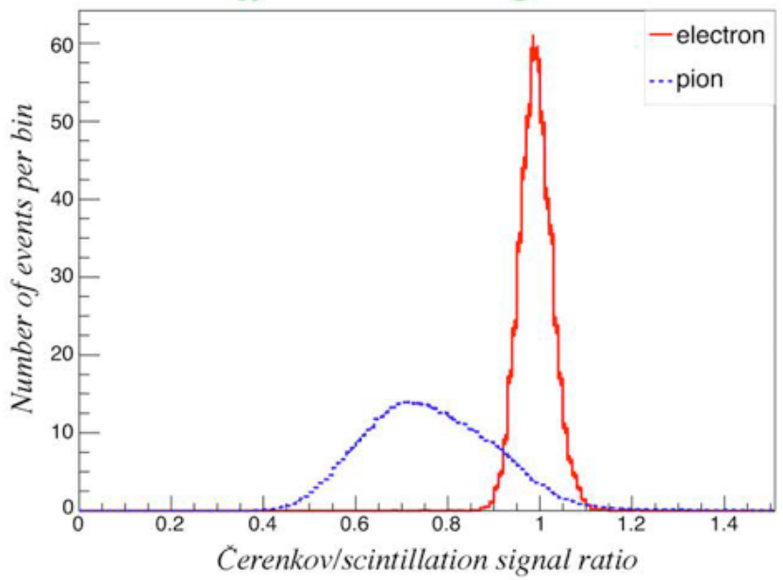
NIM A 735 (2014) 120

Methods to distinguish e/π in longitudinally unsegmented calorimeter

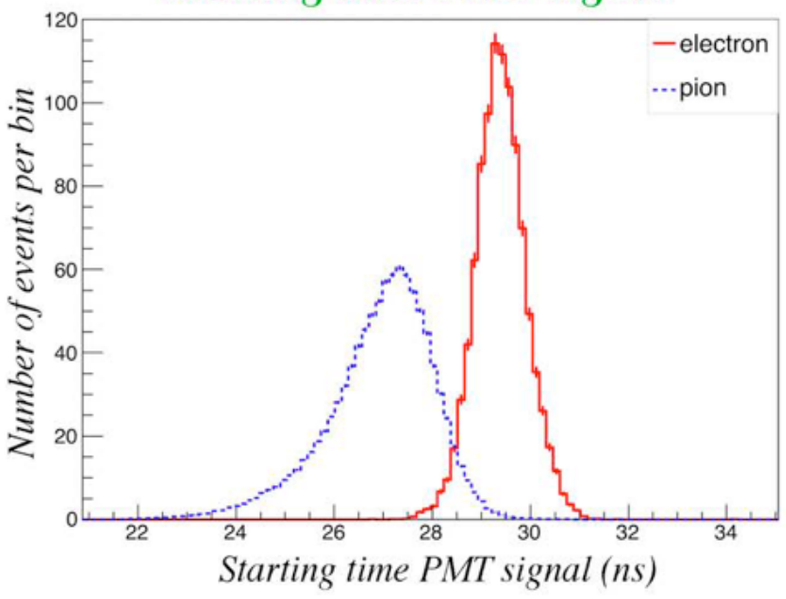
Lateral shower profile



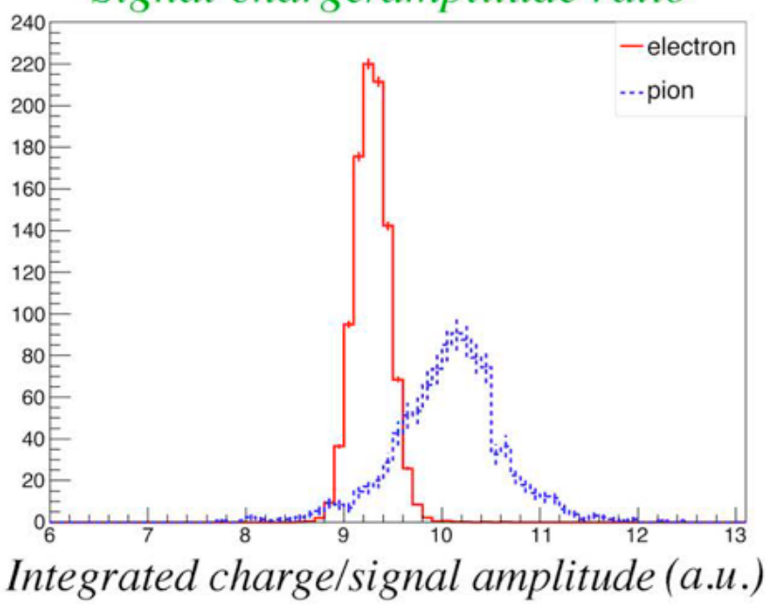
Difference C/S signals



Starting time PMT signal



Signal charge/amplitude ratio



PMT → SiPM Readout

SiPM + :

- *compact readout (no fibres sticking out)*
- *longitudinal segmentation possible*
- *operation in magnetic field*
- *larger light yield (main limitation to Čerenkov signal)*
- *high readout granularity → particle flow "friendly"*

SiPM - :

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

2017 Testbeam

New SiPM.s :

a) larger dynamic range:

from 50x50 μm^2, 400 cells (2016) → 25x25 μm^2, 1600 cells (2017)

b) lower PDE (lower fill factor)

→ avoid saturation ?

c) staggered fibre layout (readout at two different planes)

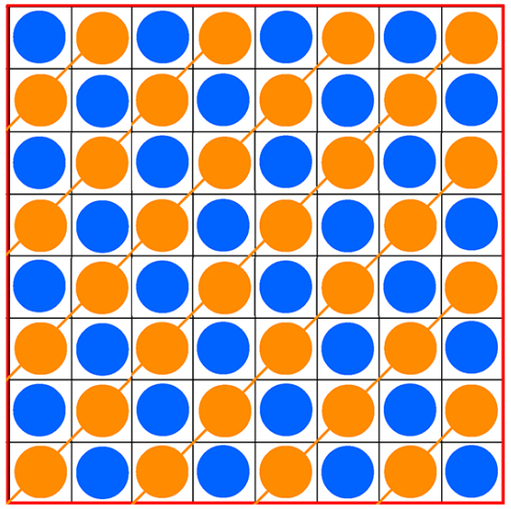
S ≥ 30×Č ! → crosstalk (light leakage) critical

Data taking w/ electrons and muons (energy scans and position scans)

2017 RD52 Testbeam Layout

Brass module, dimensions: ~ 112 cm long, 12 x 12 mm²

section



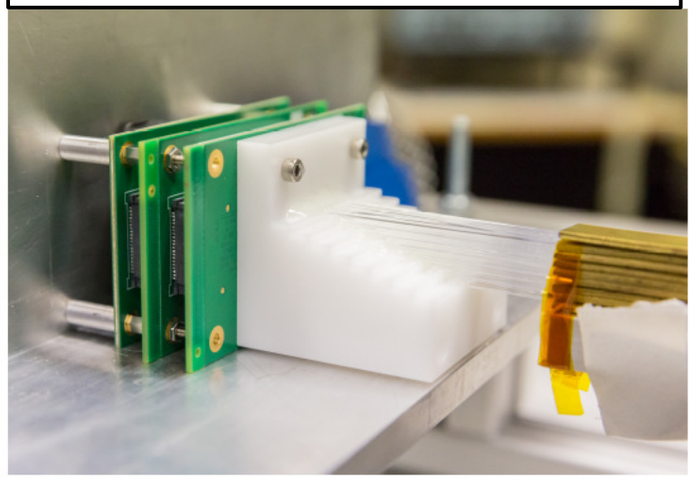
Č

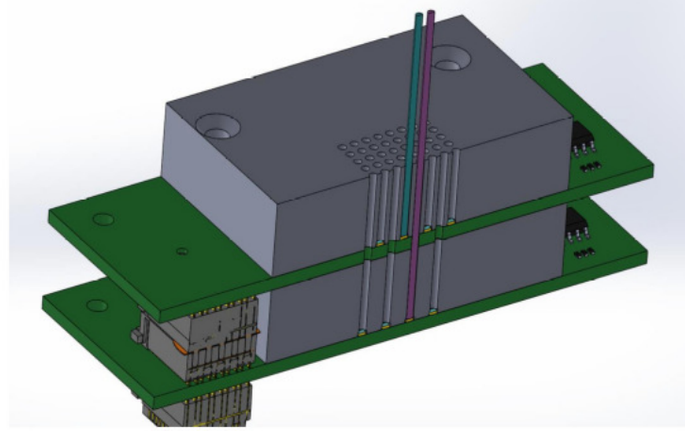
S

1.4 mm

32 (S) + 32 (Č) fibres

Back



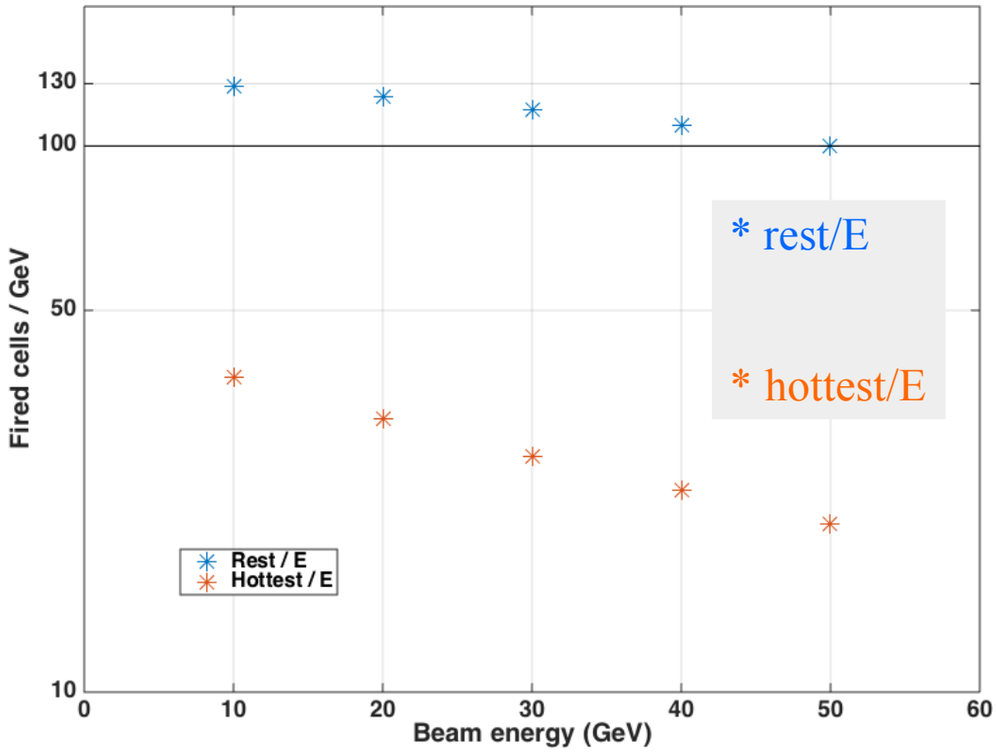


Experimental setup

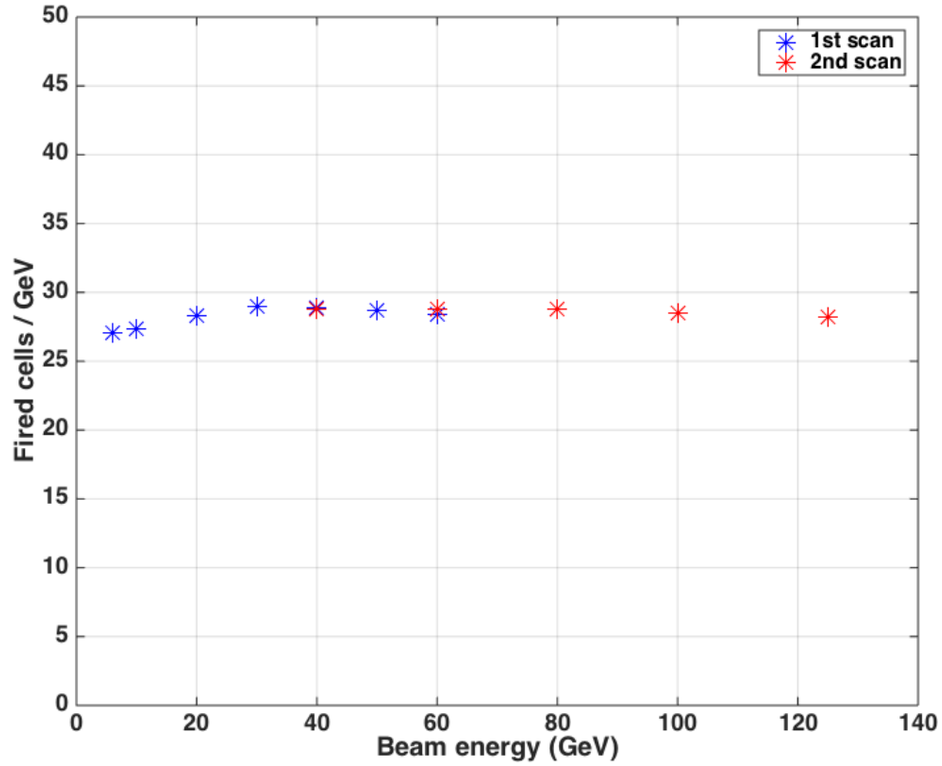
Trigger : $(T_1 \cdot T_2 \cdot \overline{T_H})$

RD52 preliminary results (2017)

S signal/GeV vs. E(GeV)
(ultra low PDE)



Č signal/GeV vs. E(GeV)
(intermediate PDE)



~28.4 fired cells / GeV
⇒
~70 p.e. / GeV @ full containment

a) Č : linear response (independent of energy)

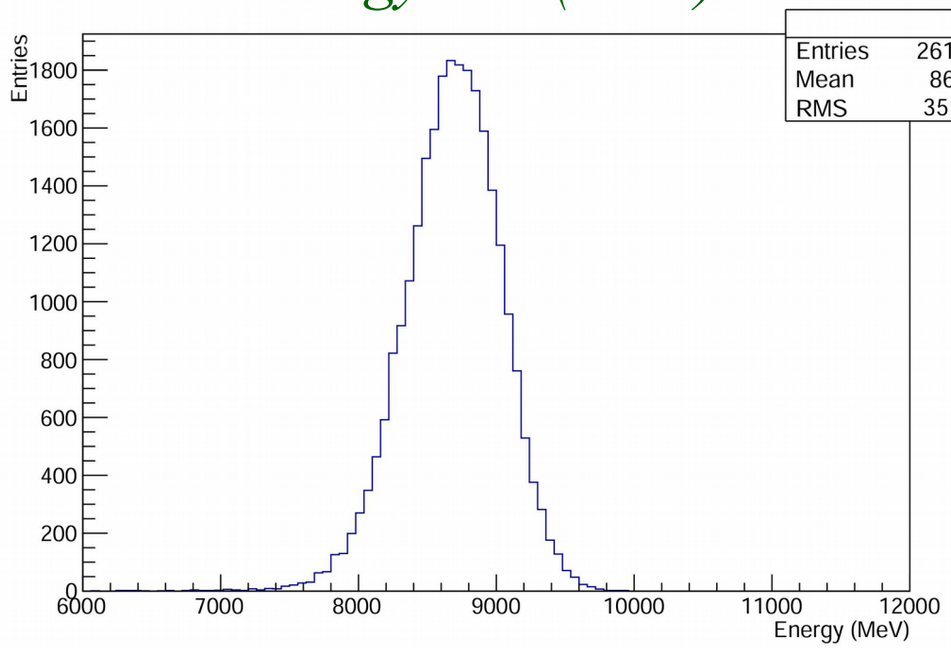
b) S : non linearity even at ultra low PDE

→ go to 10x10 μm^2, 10000 cells in scintillating fibres

Geant4: 20 GeV electron shower containment

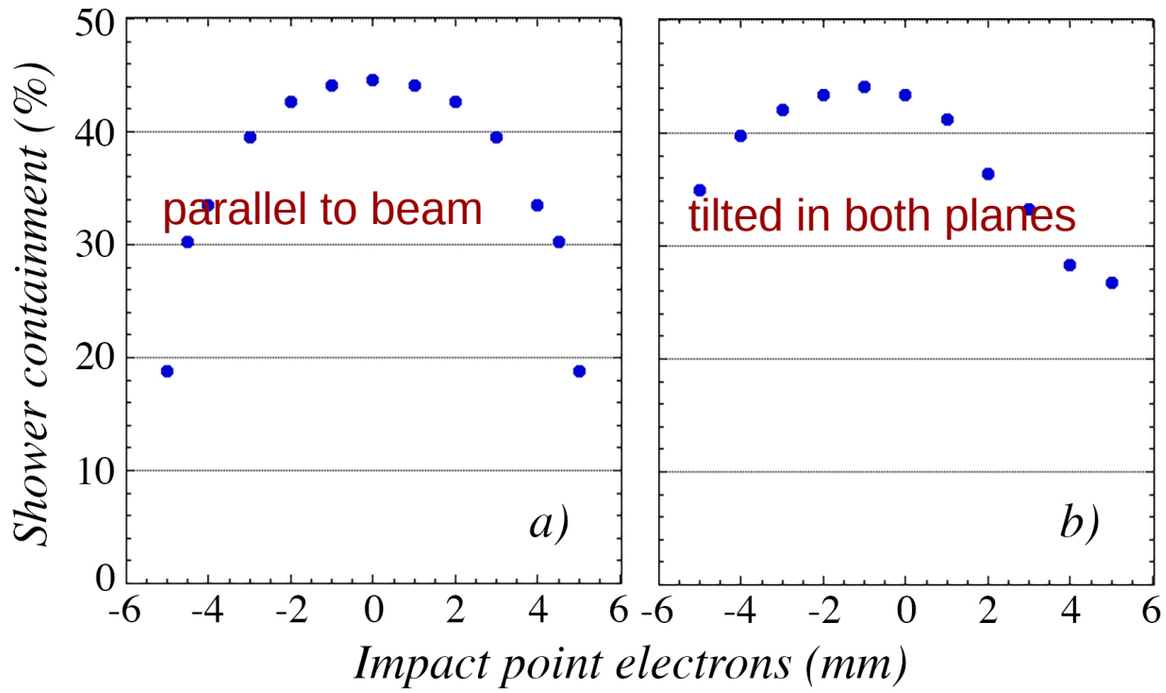
RD52 testbeam module: 1.014 x 1.014 x 112.30 cm^3

total energy lost (MeV)



centered events: ~43% containment

containment .vs. impact point



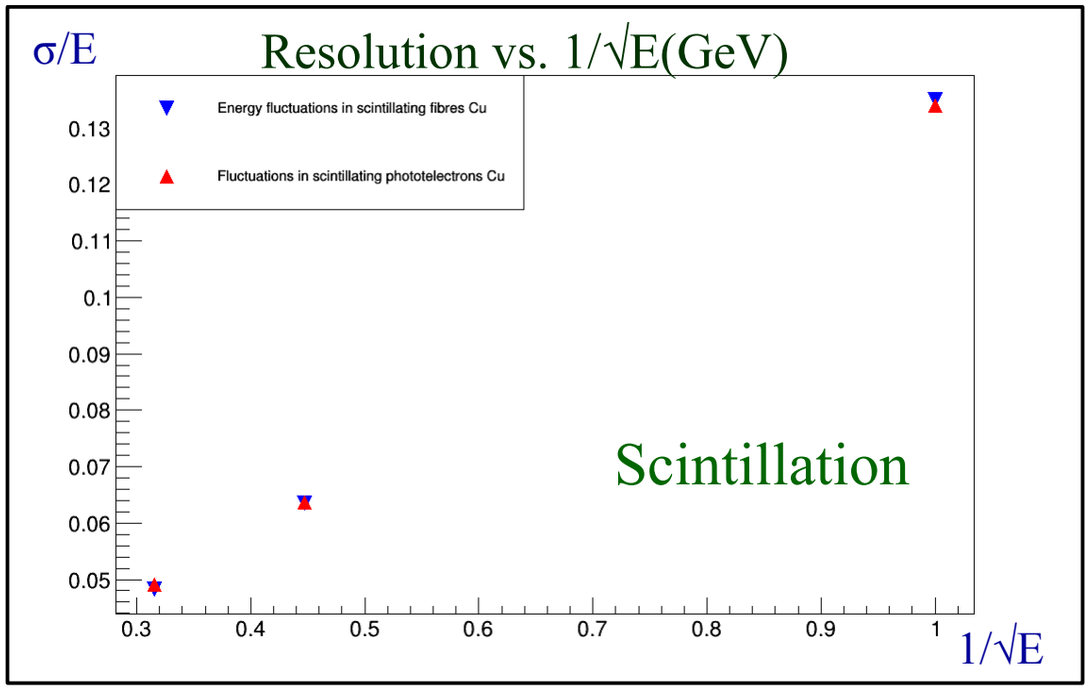
e.m. calorimeter: 31.4 x 31.4 x 112.30 cm^3

containment > 99%

(all plots for copper unless specified differently)

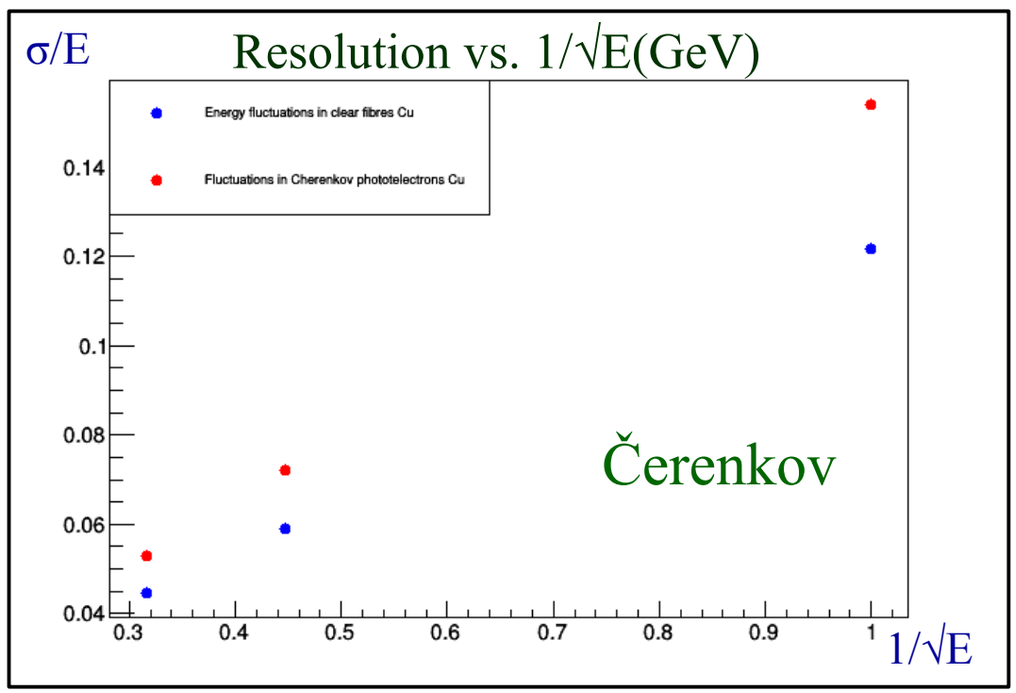
Geant4 – signal fluctuations

Energy deposition and p.e. number fluctuations



S: ~5500 p.e. / GeV

→ σ/E driven by fluctuations in en. depositions



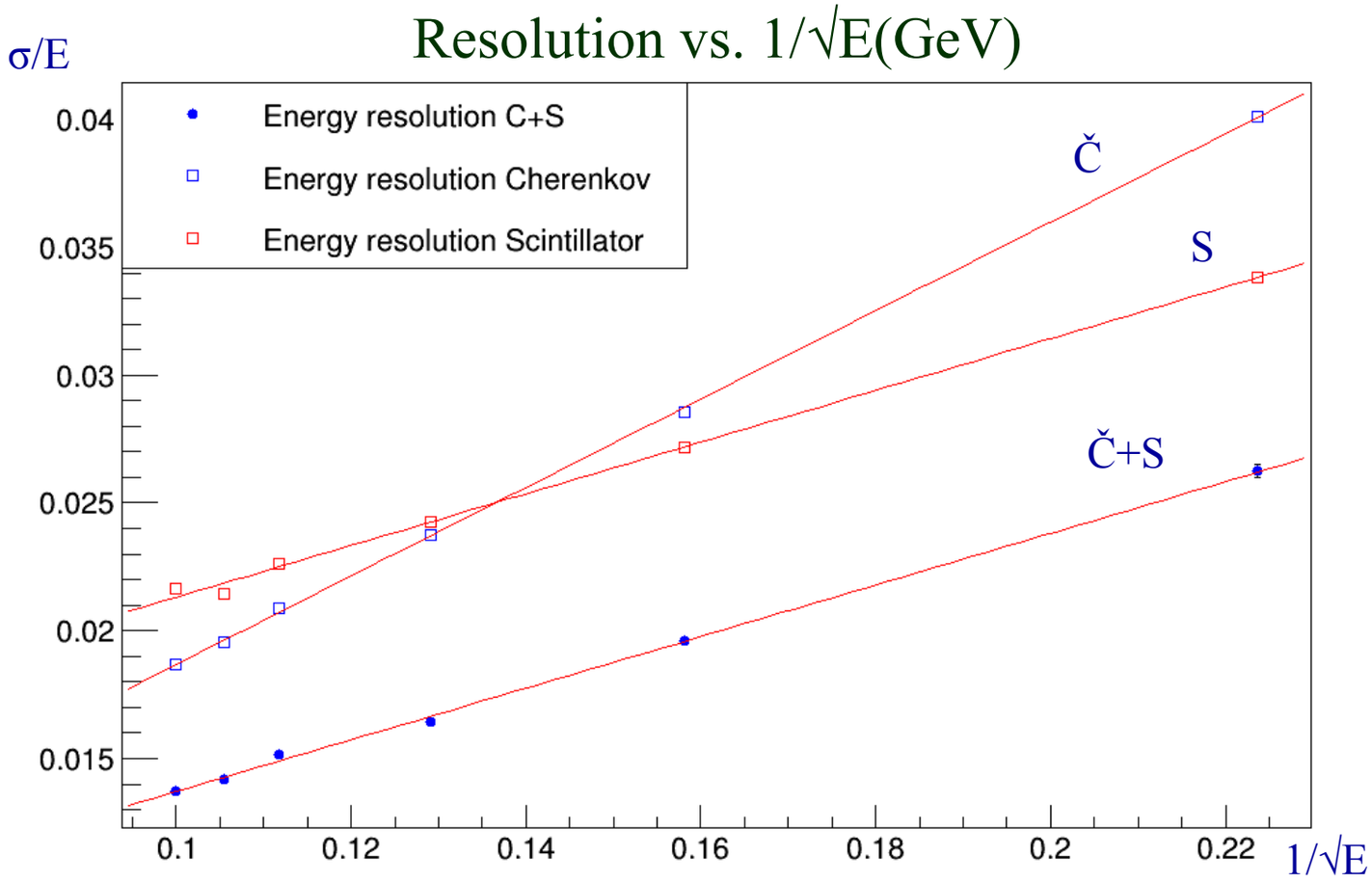
Č: ~110 p.e. / GeV

→ σ/E driven by fluctuations in p.e. number

Sampling fluctuations contribution to resolution:

$$\frac{\sigma}{E} = 2.7\% \times \frac{\sqrt{1/0.113}}{\sqrt{E}} = \frac{8.0\%}{\sqrt{E}}$$

Geant4 – e.m. resolution(s)



S-only: 10.5/√E+1.1 (%)

Č-only: 17.9/√E (%)

(unweighted) average: 10.3/√E+0.3 (%)

Geant4 - hadronic shower simulations

Dimensions:

71 x 71 units

1 unit:

1.014 x 1.014 x 250 cm^3 copper module

32 (S) + 32 (Č) fibres

SiPM readout

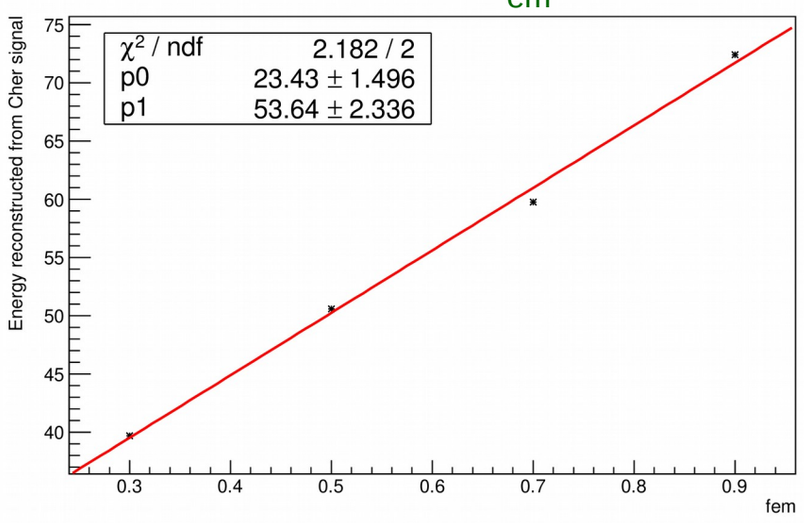
Containment: ~99%

Calibration of both S and Č w/ 40 GeV e^-

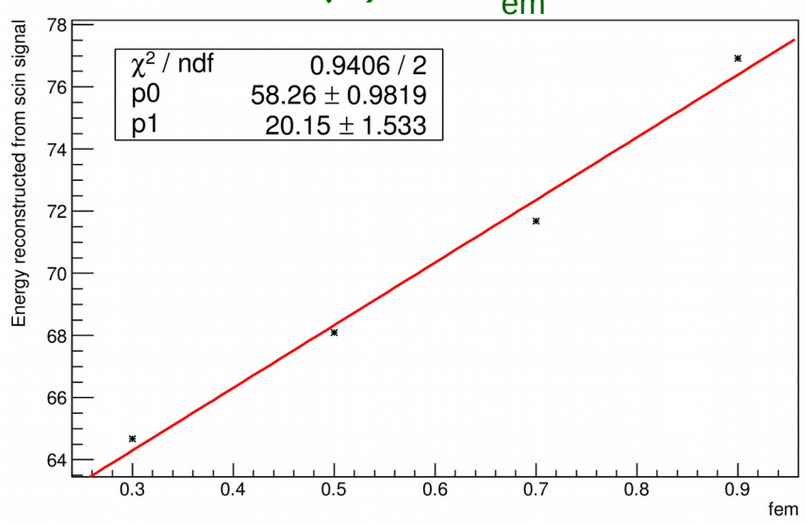
***** Preliminary results! *****

Geant4 - hadronic performance (preliminary)

E(Č) vs. f_{em}

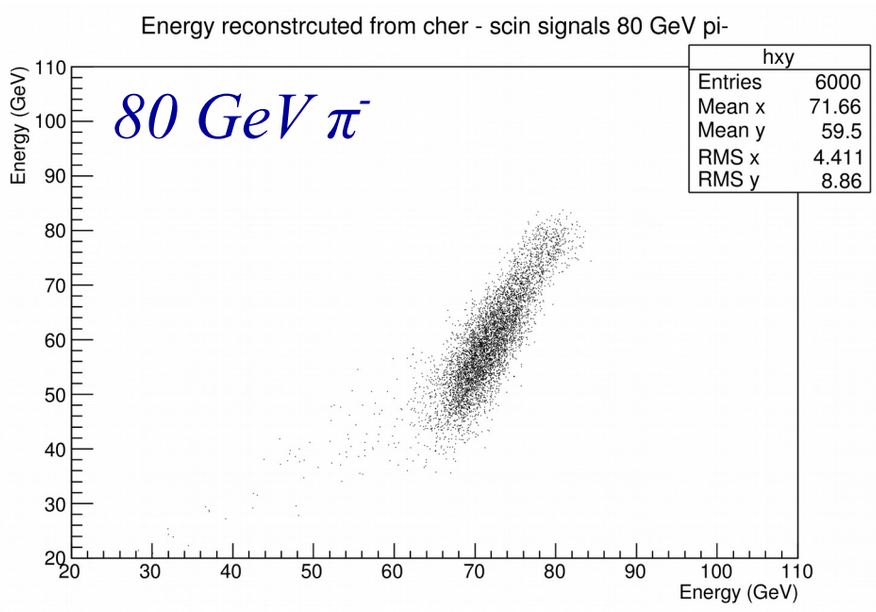


E(S) vs. f_{em}

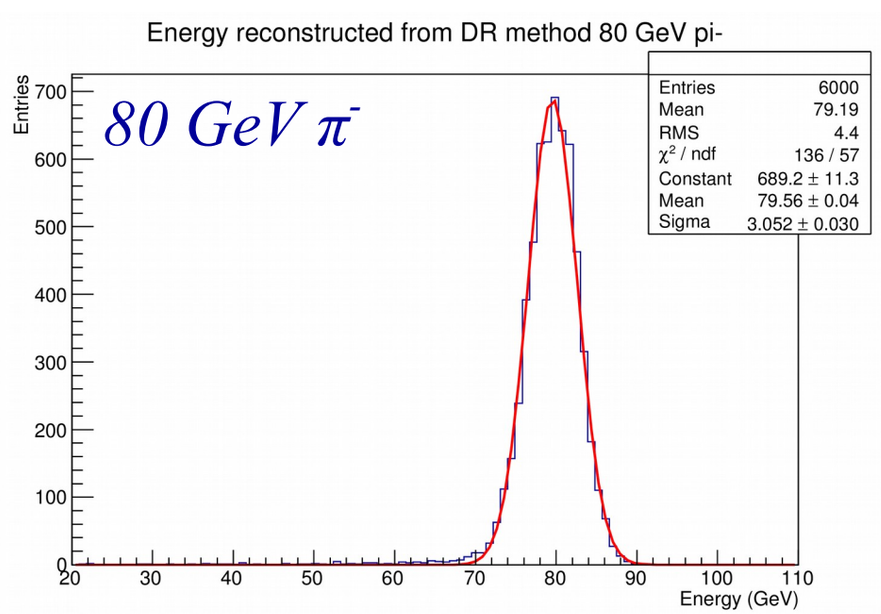


Copper

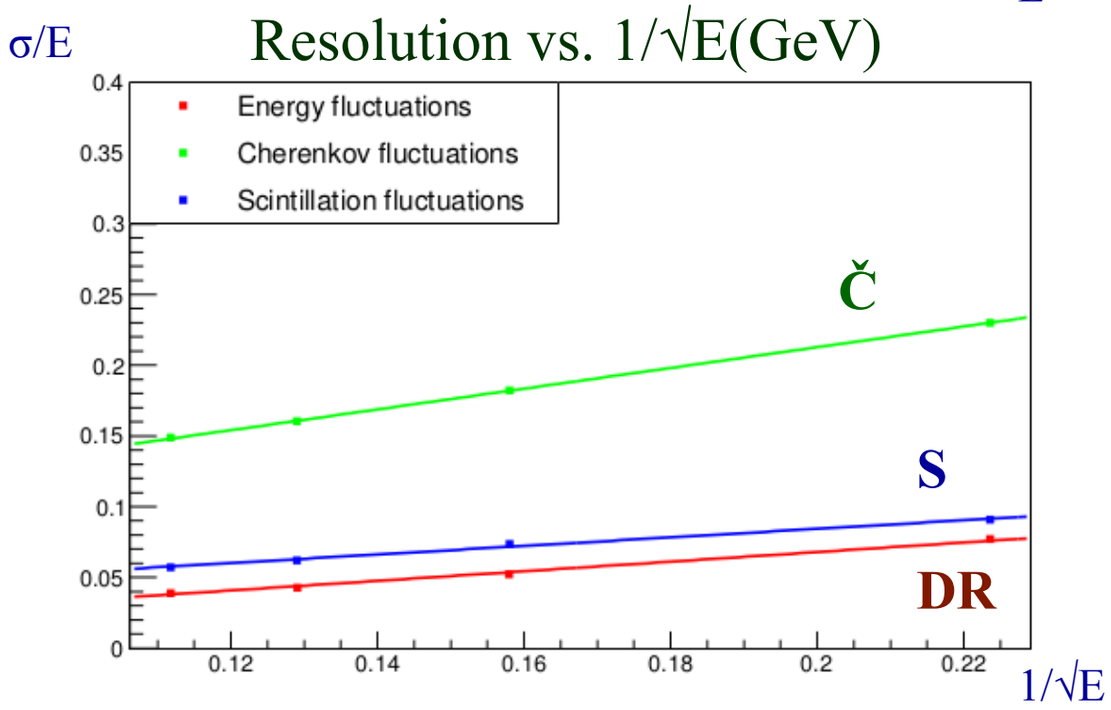
E(Č) vs. E(S)



E (DR)



Geant4 – Cu hadronic performance (preliminary)



Č: ~73/√E + 6.6 (%)
S: ~30/√E + 2.4 (%)

DR: ~34/√E (%)

High-energy single-π resolutions:

σ/E(100 GeV) ~ 3.5%
σ/E(300 GeV) ~ 2.3%
σ/E(1000 GeV) ~1.7 %

Geant4 – h/e and χ factors

f_{em} = MC truth

E = average contained energy

C, S = signals

either:

$$f_{em} \rightarrow 0 : C/E,\ S/E \rightarrow (h/e)$$

or:

$$(h/e)_{\check{C}} = (C/E - f_{em}) / (1 - f_{em})$$

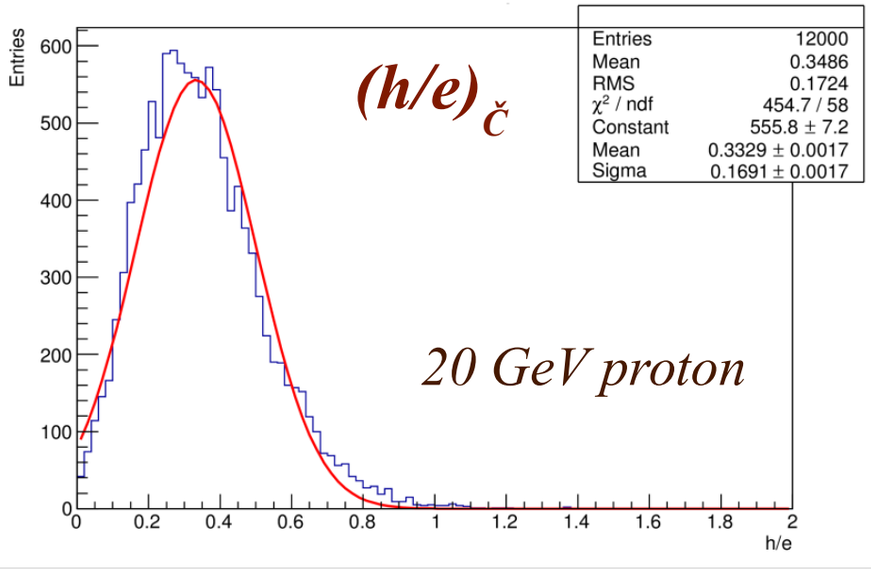
$$(h/e)_{S} = (S/E - f_{em}) / (1 - f_{em})$$

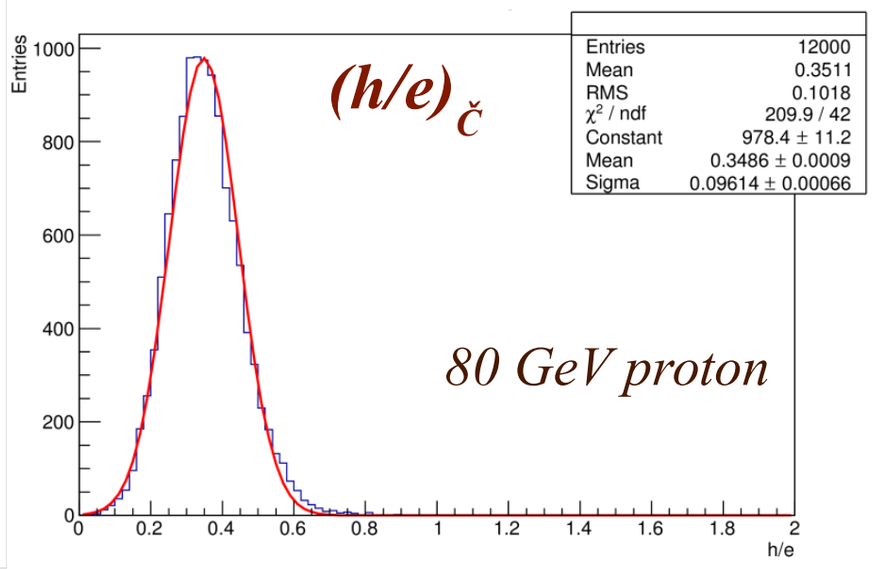
while:

$$\chi = (1 - (h/e)_{S}) / (1 - (h/e)_{\check{C}}) = (E - S) / (E - C)$$

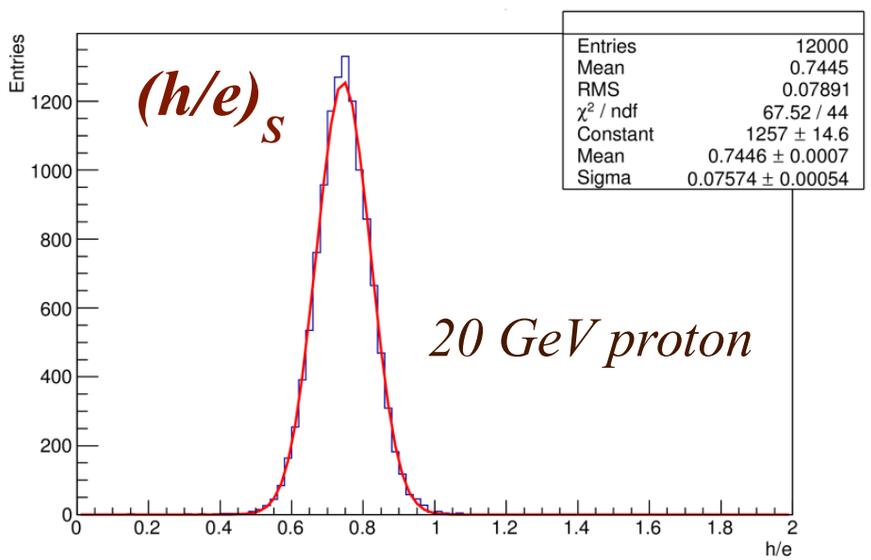
Geant4 – h/e factors for Copper

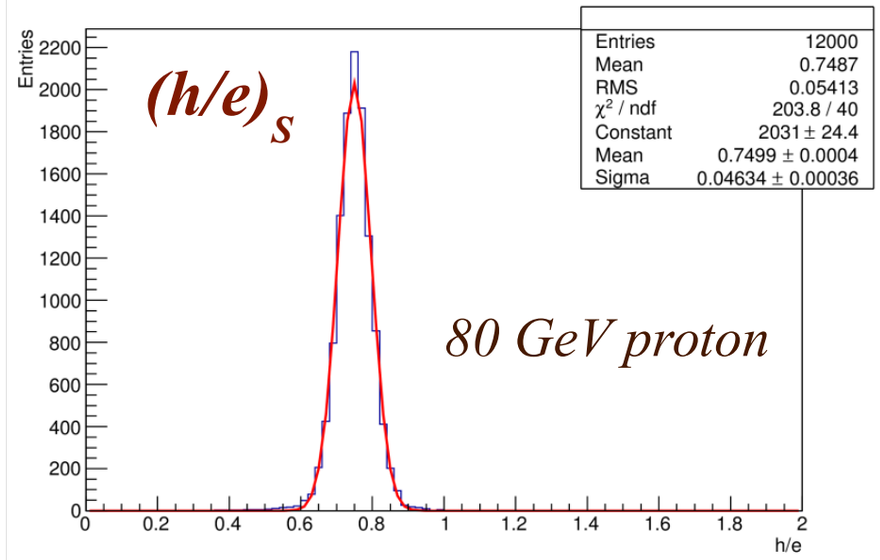
Copper





$(h/e)_{\check{C}} \approx 0.35$

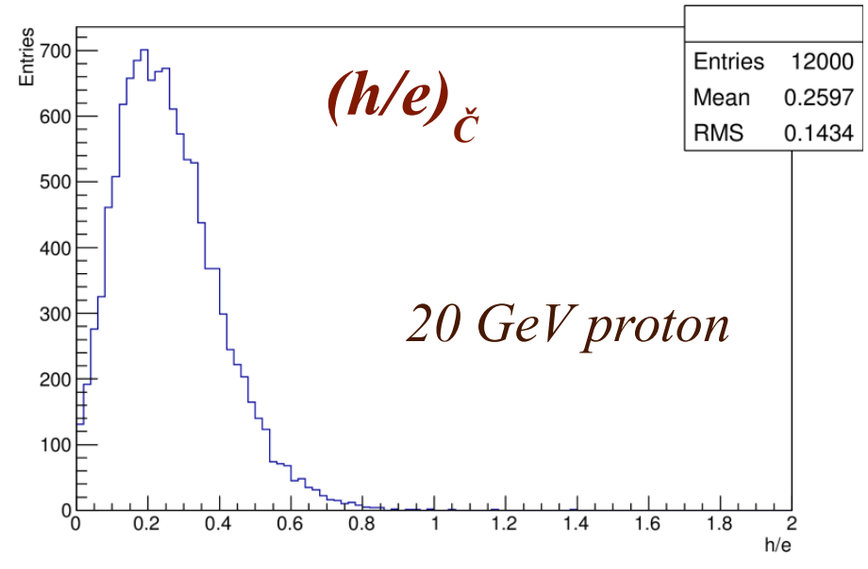


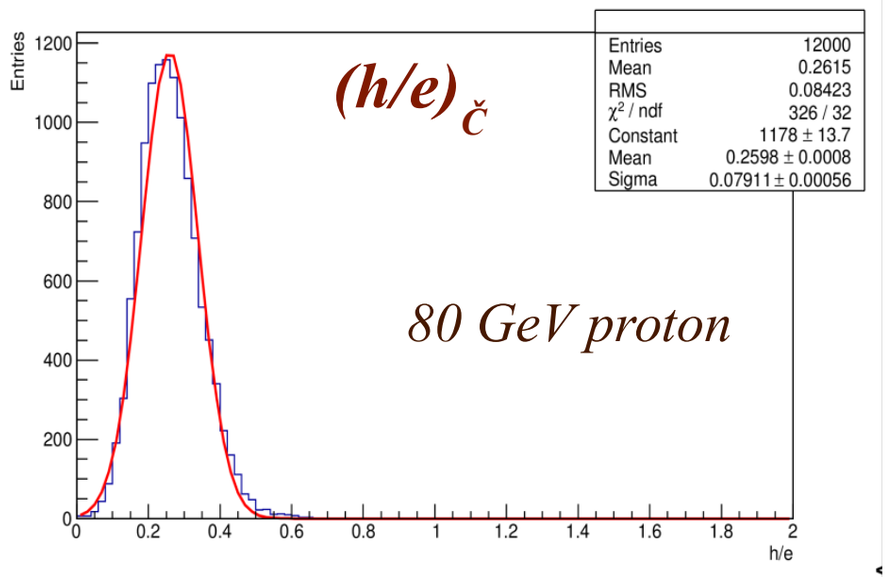


$(h/e)_{S} \approx 0.75$

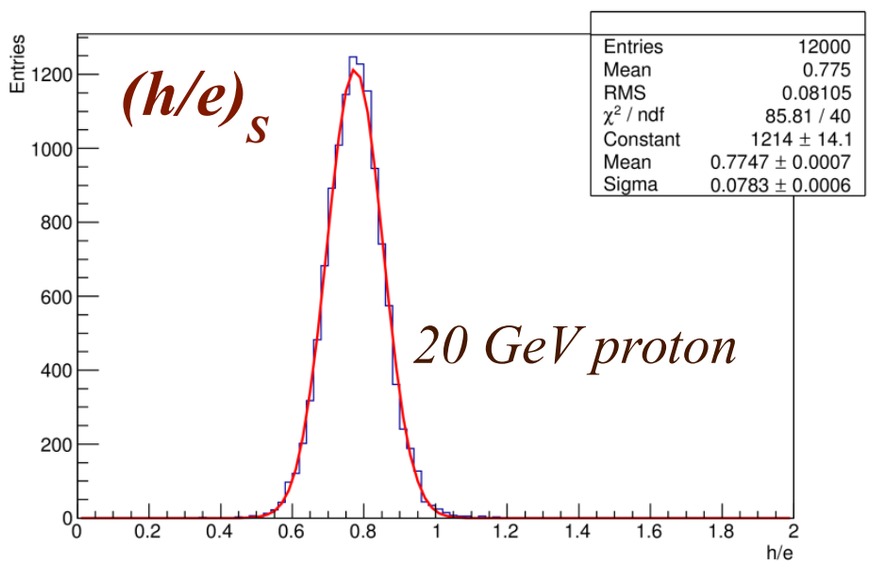
Geant4 – h/e factors for Lead

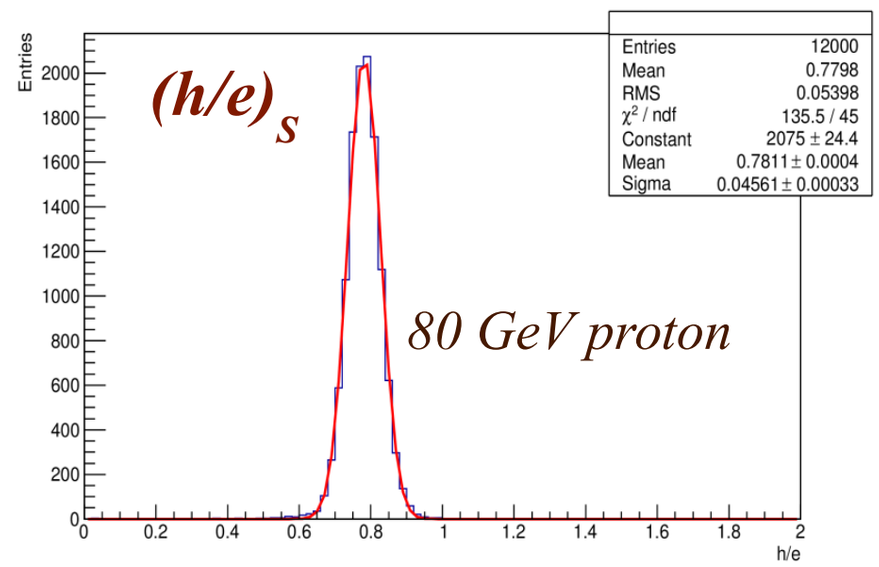
Lead





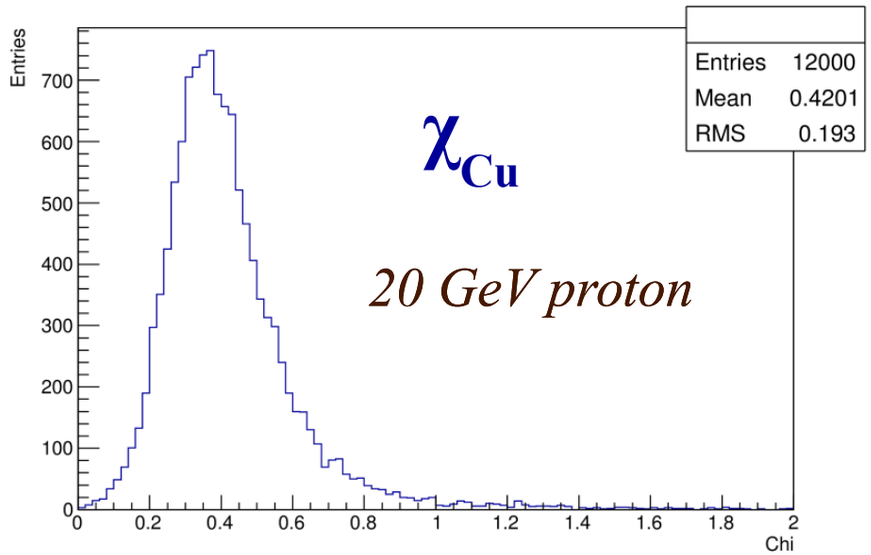
$(h/e)_{Č} \approx 0.26$





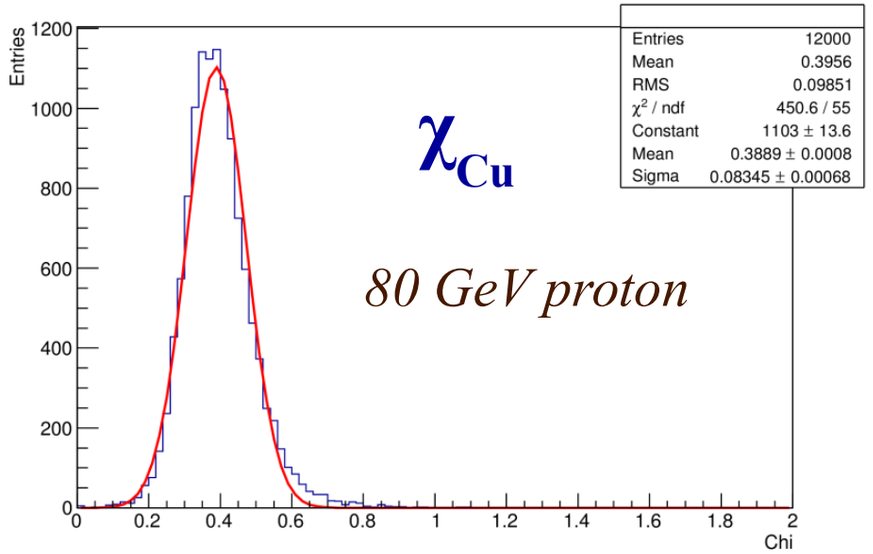
$(h/e)_{S} \approx 0.78$

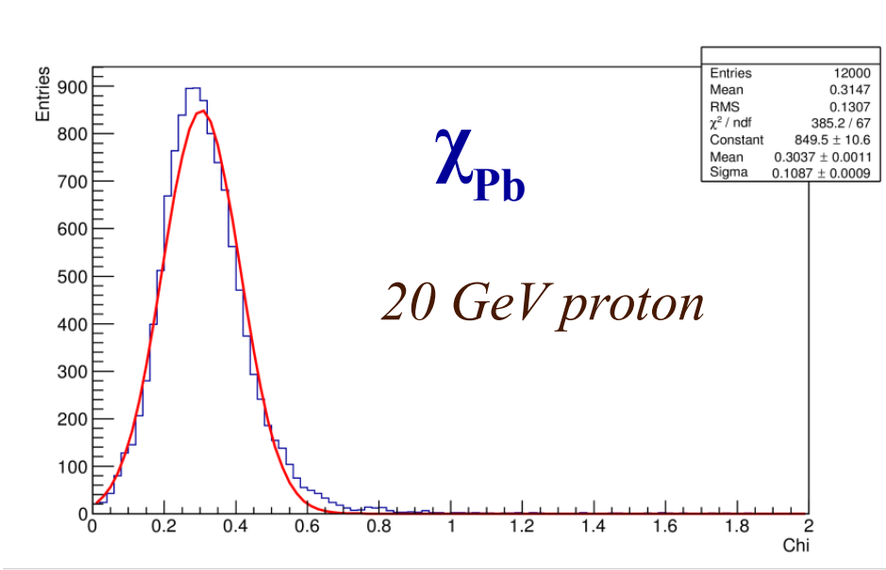
Geant4 – χ factors for Copper and Lead



Copper

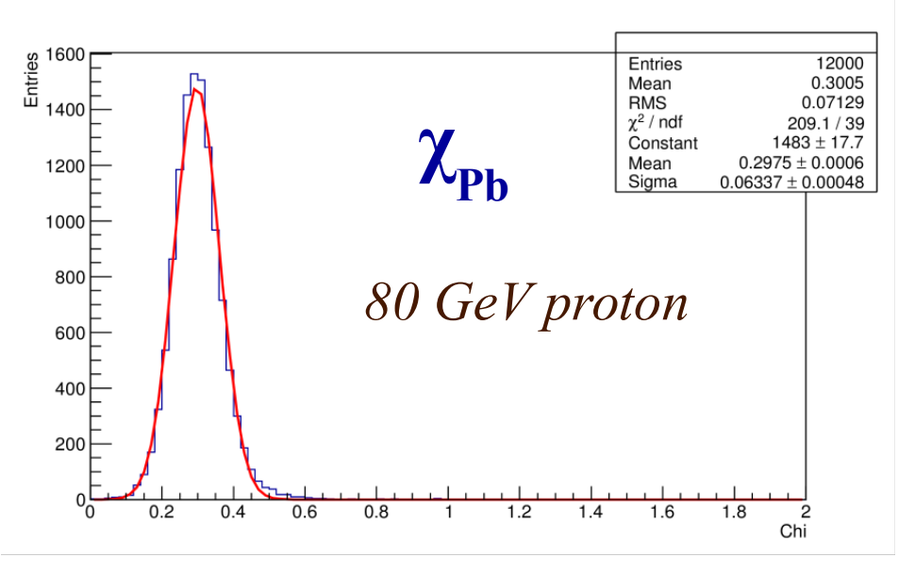
$\chi_{Cu} \approx 0.39$





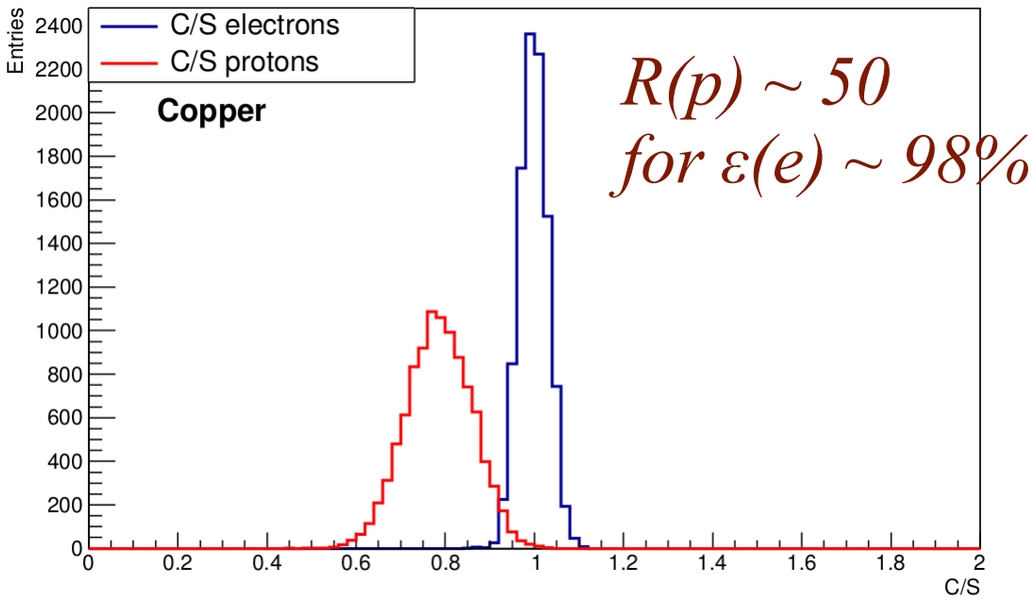
Lead

$\chi_{Pb} \approx 0.30$

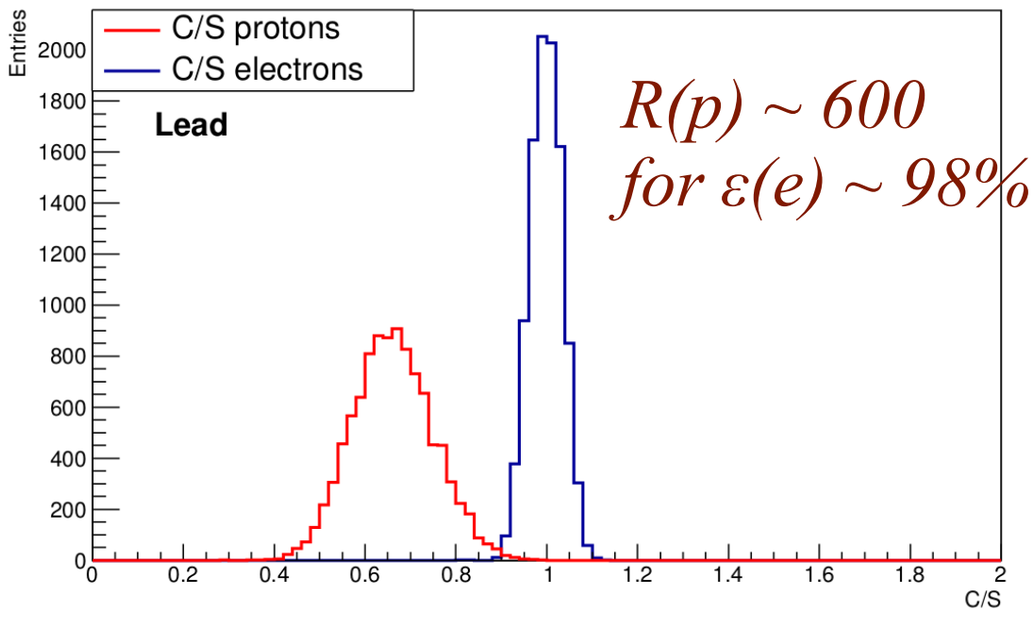


Particle Id & W/Z - Copper vs. Lead

C/S ratio for 80 GeV e^- and p

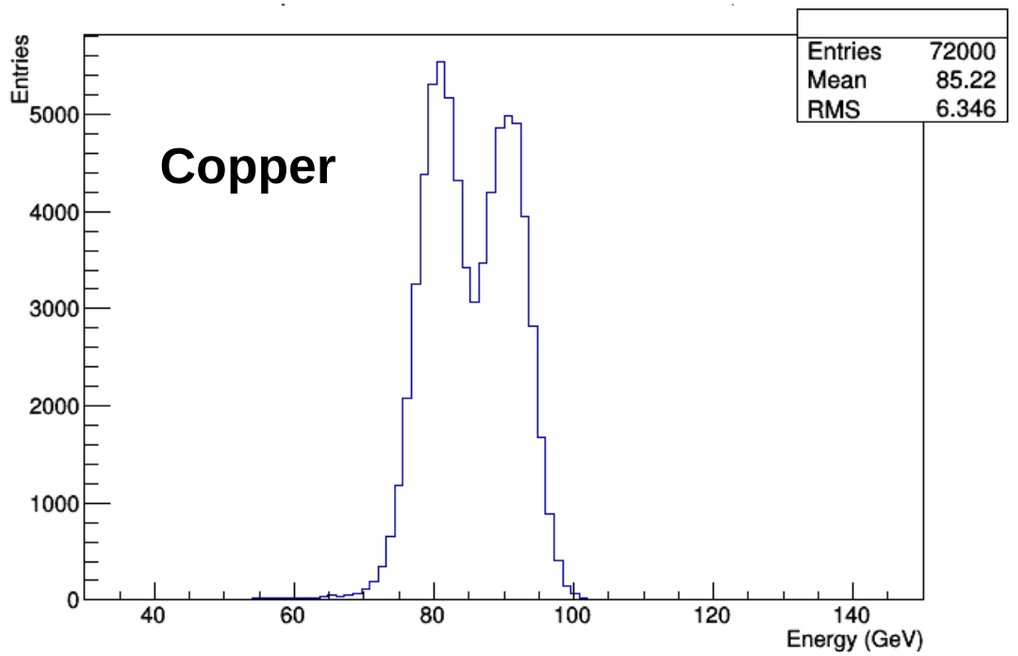


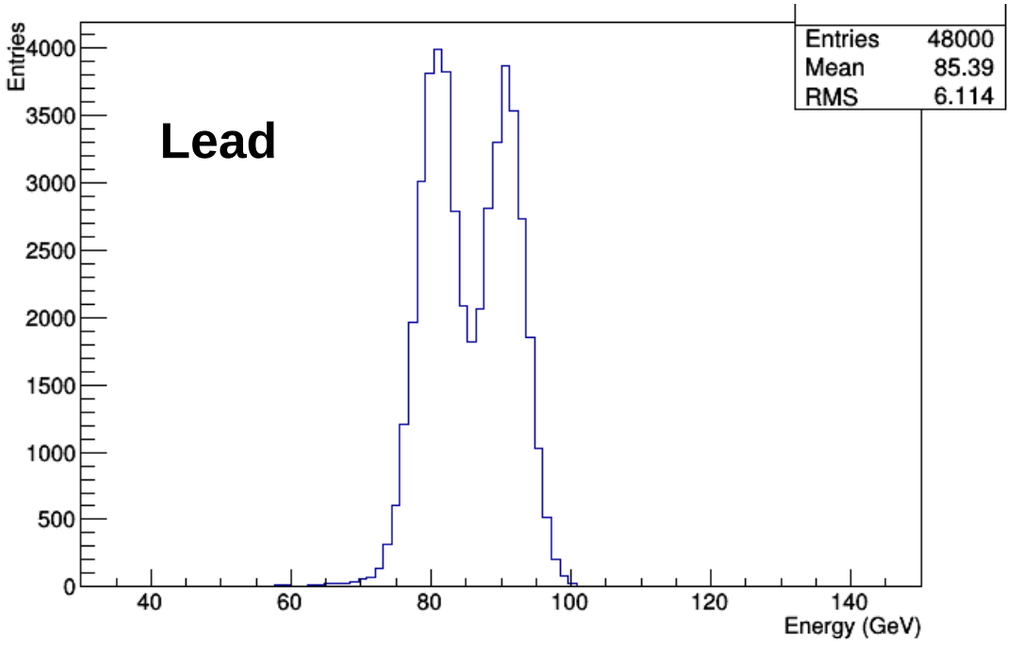
R(p) ~ 50
for ε(e) ~ 98%



R(p) ~ 600
for ε(e) ~ 98%

Multiple hadrons, 81 & 91 GeV





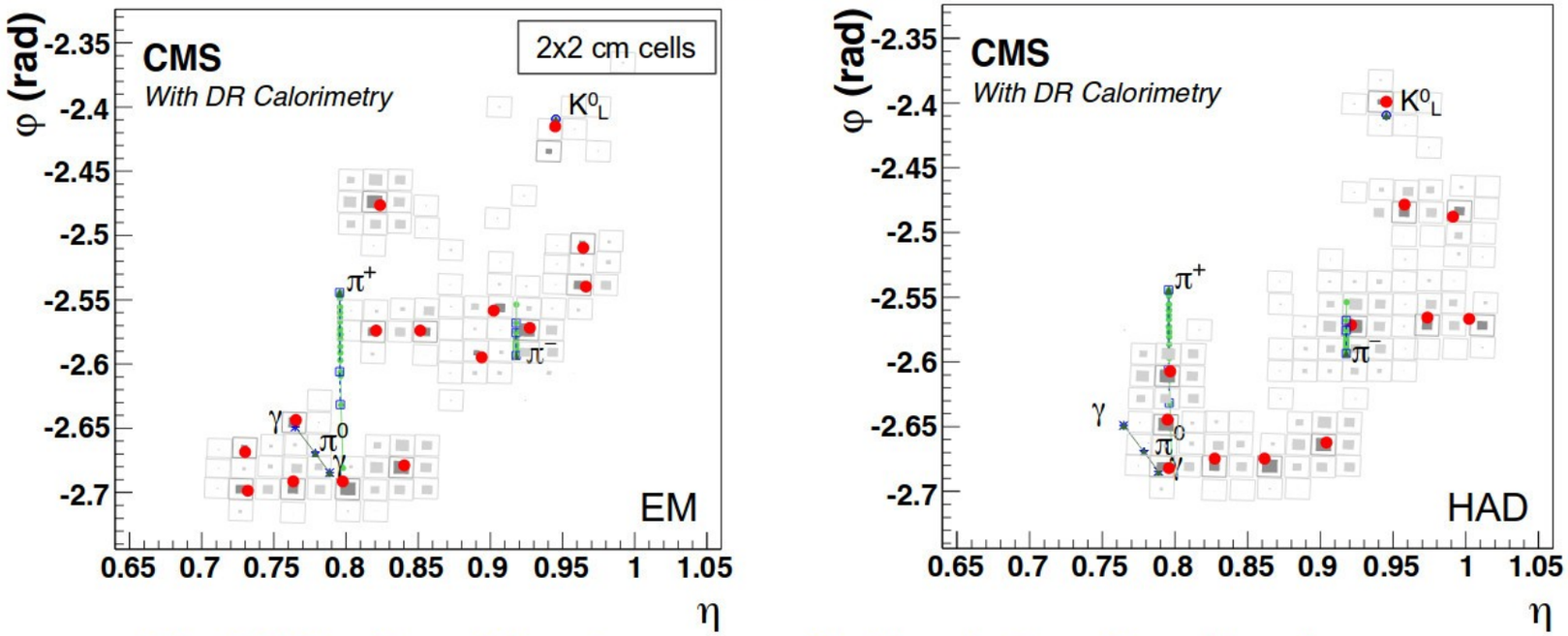
Longitudinal Segmentation & PFA

Last but not least:

addressing the issue of overlapping hadronic and em showers

→ Patrick Janot proposes longitudinal segmentation (and PF w/ DR)

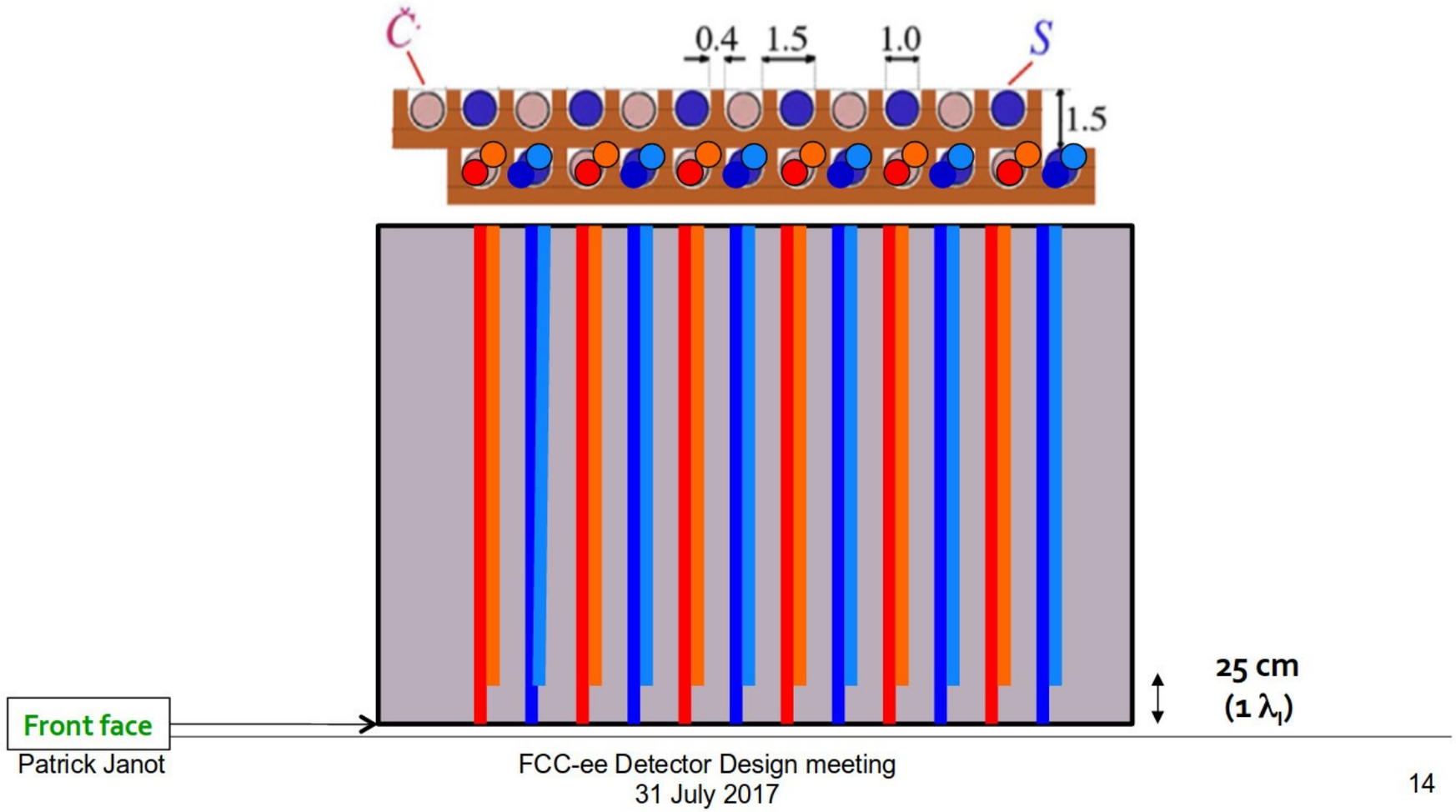
- **Without longitudinal segmentation, double readout calorimetry**
  - **The (η,ϕ) views with EM and HAD energies are all mixed up**



  - **The EM fraction of the π^+ merges with the photons from the π^0**
    - **The HAD fraction of the π^+ prevents photons to be safely identified**
  - **The EM fractions of the π^+ and π^- give rise to many EM clusters / HAD clusters**
    - **Particle-Flow picture is confused / confusing**

Put more (different length) fibres ?

- **Requirement: keep the one-compartment design**
  - **But multiply the number of fibres by two, but the new ones are shorter by $1\lambda_I$**



Alternative approaches ? Measure time properties (ToT, PkT, Ti, Tf) ?
→ A real-time (feature-extraction) processor ?

2018 Testbeam

All possible goals:

a) 1x1x250 cm^3 prototype

1) go to 10x10 μm^2, 10000-cell, SiPMs for scintillation light sensing

2) decouple voltage biasing for scintillating and Čerenkov SiPM sensors

3) test channel grouping

4) readout ASIC (?)

b) RD52 lead (single module) prototype (!?):

5) rebuild single (9x9x250 cm^3) module w/ 50% of displaced sci-fibres & separate (PM) light collection

Q: Who can do (and where) the hardware work ?

c) 'IDEA vertical slice' @ end of year (?), strongly supported by CSN1

How, who, where ?

Preparing testbeam request(s) under FCCee 'hat' (P. Janot)

**** Fine ? ****

**** Impossible to do everything ! ****

Conclusions

Preliminary results look interesting … nevertheless many issues still to be addressed.

a) G4 Simulations … long list:

terminate Cu & Pb characterisation
impact of finite attenuation length
need/impact of longitudinal segmentation
jet (τ→had) em/had component separation
more realistic integrated 4π detector
physics performance (W, Z, H, …)!
particle flow algorithms

+ (some) VALIDATION w/ RD52 lead prototype

b) 3-year R&D plan on mechanics, frontend electronics, readout:

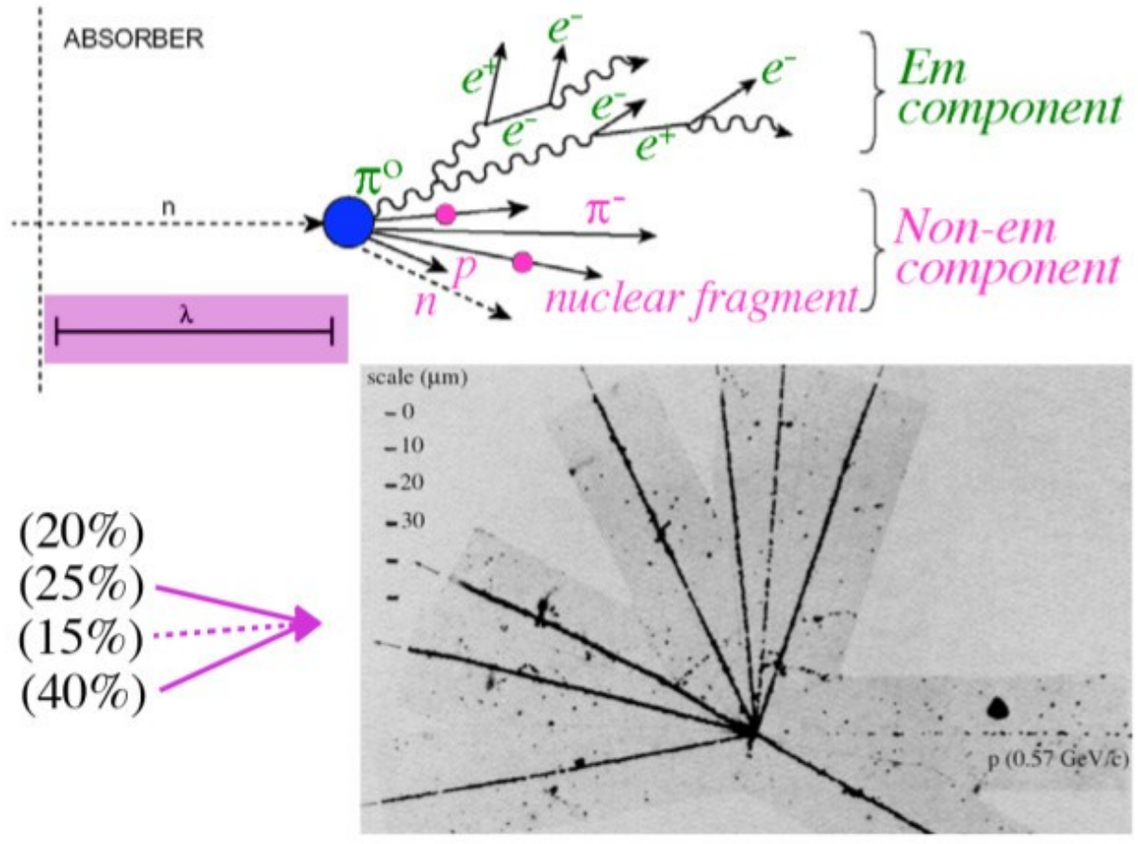
develop a scalable solution made of ~10x10 cm^2 modules w/ 5000-10000 fibres, individually coupled to photo-detectors w/ data compression/reduction, feature-extraction processor (?), …

Backup

Hadron Showers Development

Hadronic showers consist of two components:

- *Electromagnetic component*
  - electrons, photons
  - neutral pions → 2 γ
- *Hadronic (non-em) component*
  - charged hadrons $\pi^{\pm}$,$K^{\pm}$ (20%)
  - nuclear fragments, p (25%)
  - neutrons, soft γ's (15%)
  - break-up of nuclei (*"invisible"*) (40%)

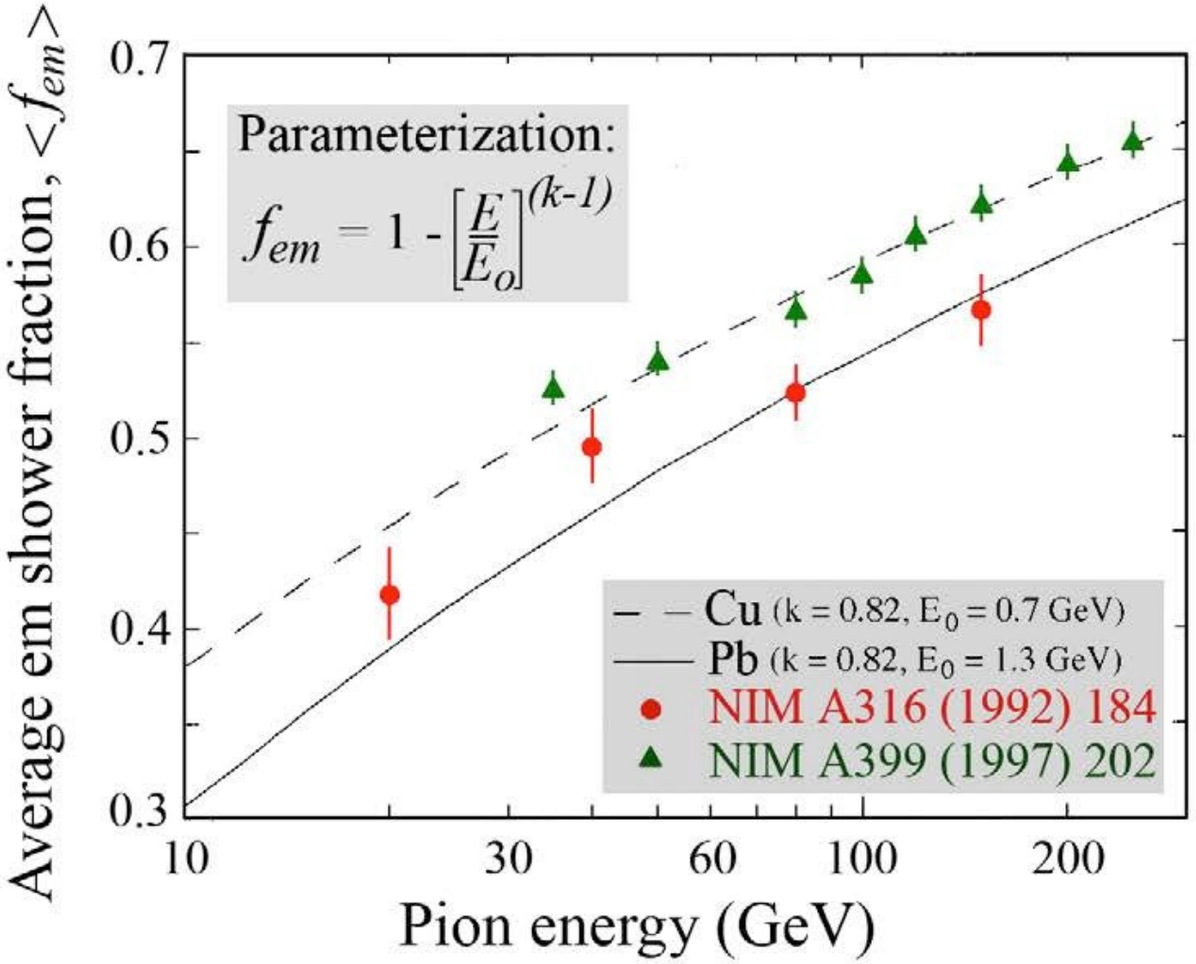


To be faced in hadronic energy measurements:

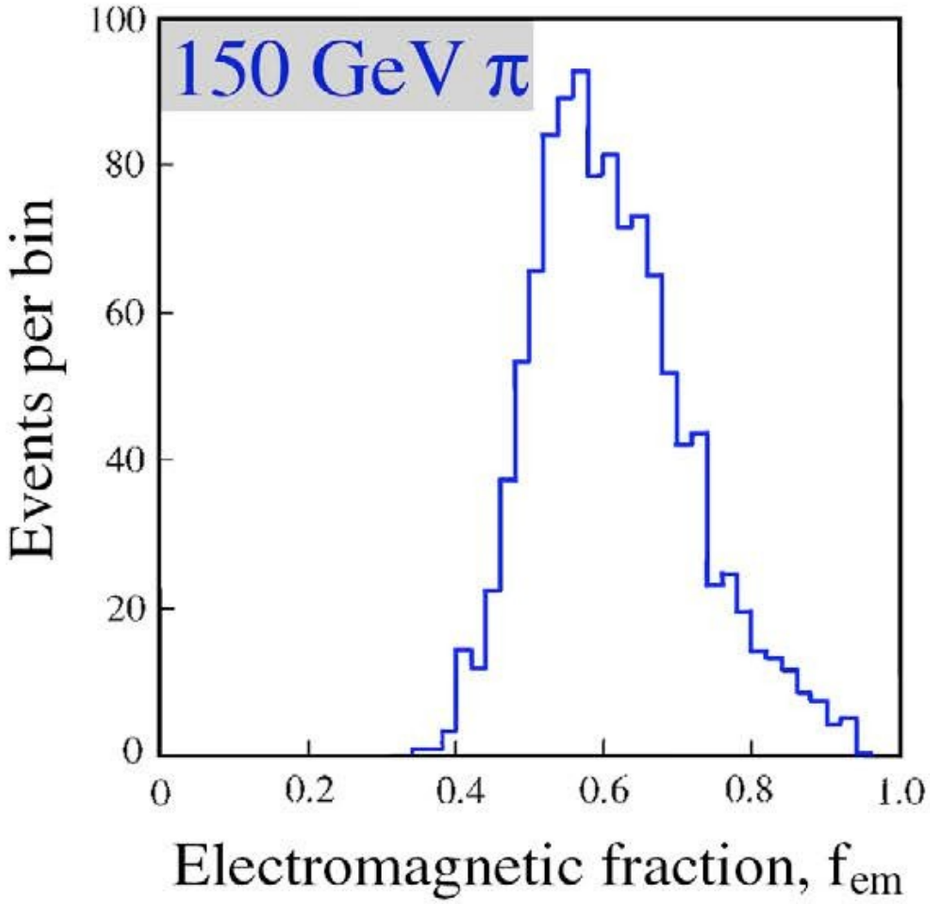
1. Large non-gaussian fluctuations in energy sharing em/non-em
2. Increase of em component with energy
3. Large, non-gaussian fluctuations in "invisible" energy losses

(Fluctuations in) the 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*



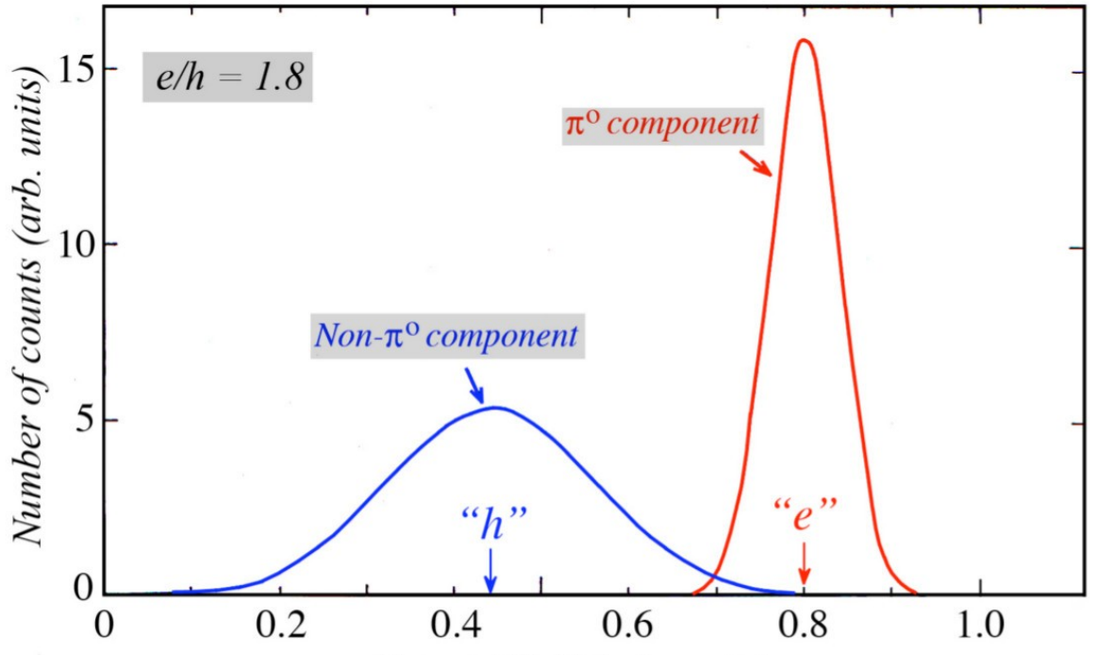
Fluctuations in f_{em} are *large and non-Poissonian*

Calorimeter Response to Hadron Showers

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 ≈ 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

Don't spoil em resolution to get e/h = 1 (i.e. keep e/h > 1) *BUT* measure f_{em}

event-by-event

$\Longrightarrow$ *eliminate effects of fluctuations in* f_{em} *on calorimeter performance*

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

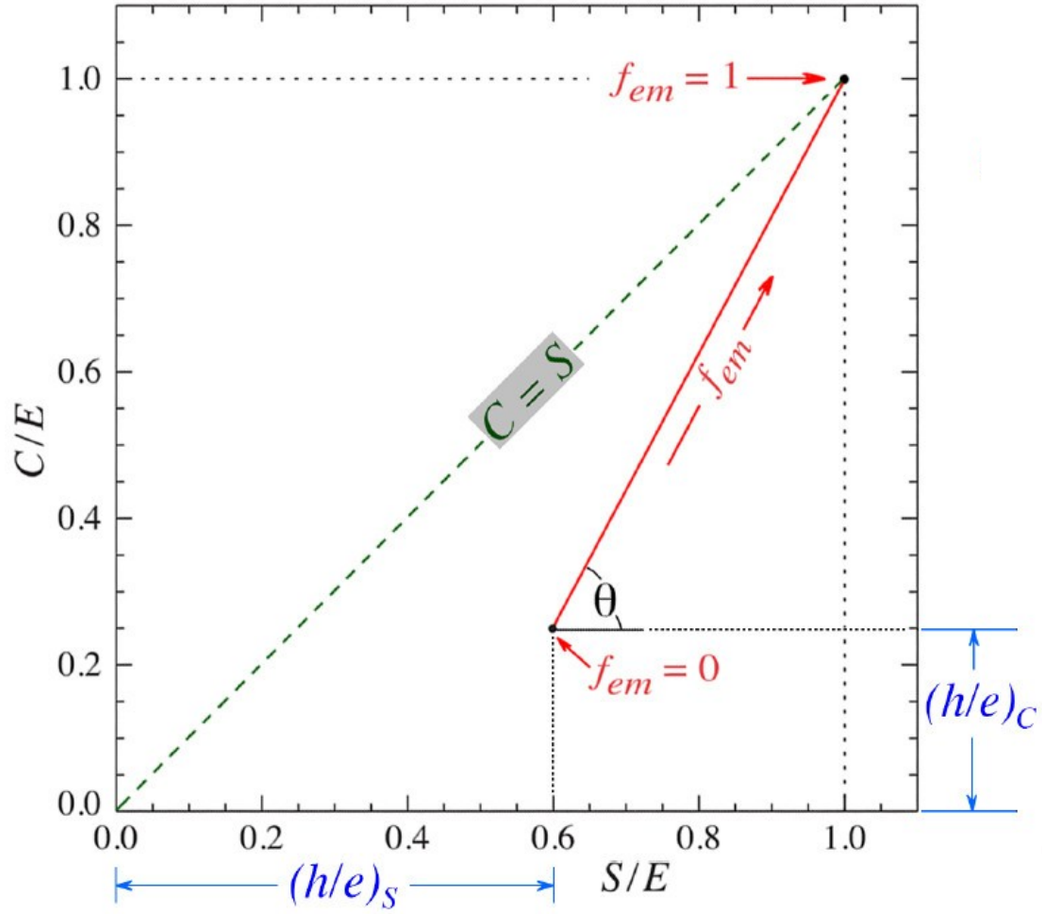
(e.g. protons contribute to S but not to Č signals)

DREAM: How to Determine f_{em} ?

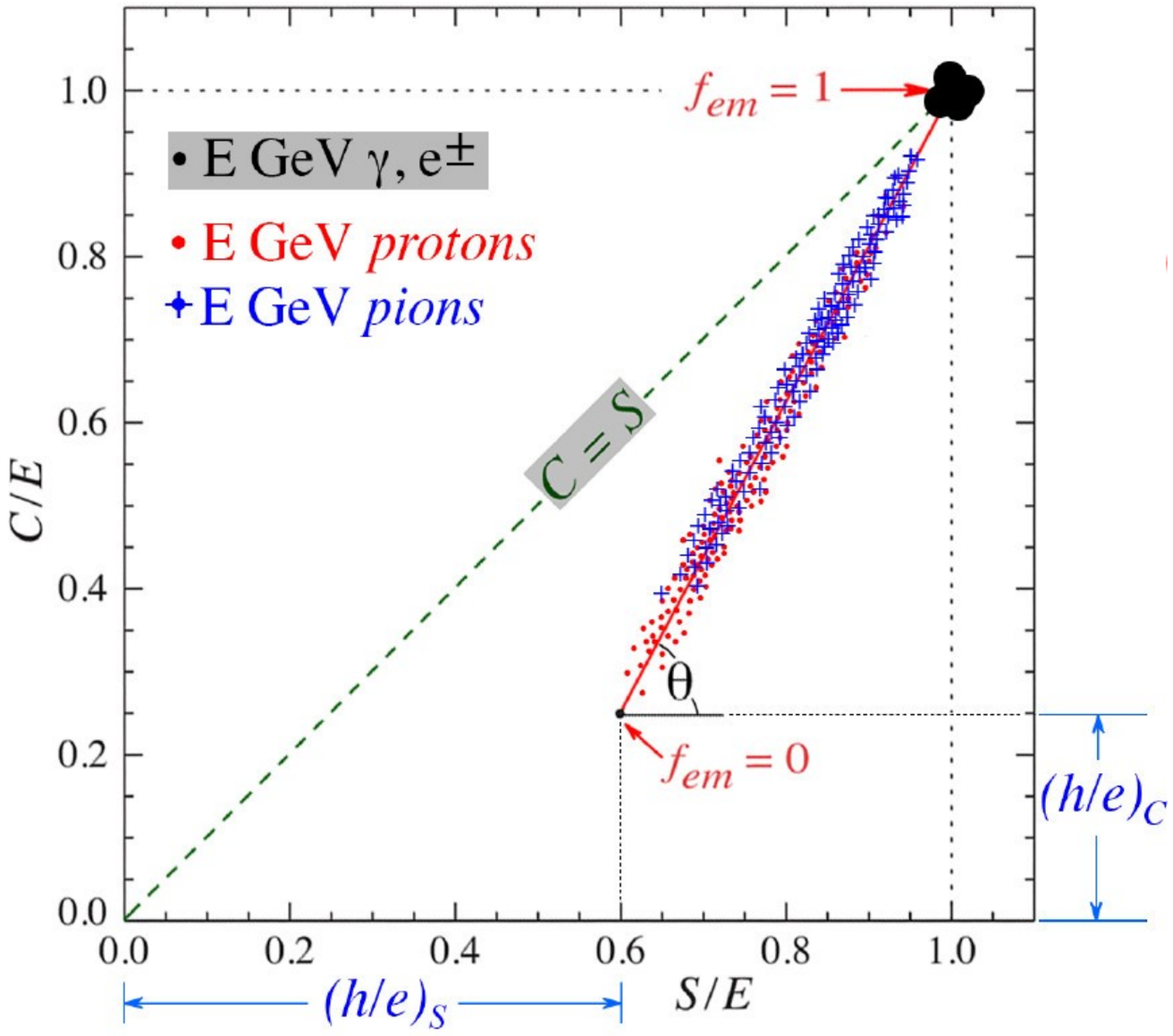
- $S = E \times [\ f_{em} + (h/e)_s \times (1 - f_{em})\ ]$
- $C = E \times [\ f_{em} + (h/e)_c \times (1 - f_{em})\ ]$
- e.g. if: (e/h) = 1.3(S) .vs. 4.7(C)
- $\rightarrow S/C = (0.21 + 0.79 \times f_{em}) / (0.77 + 0.23 \times f_{em})$

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

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

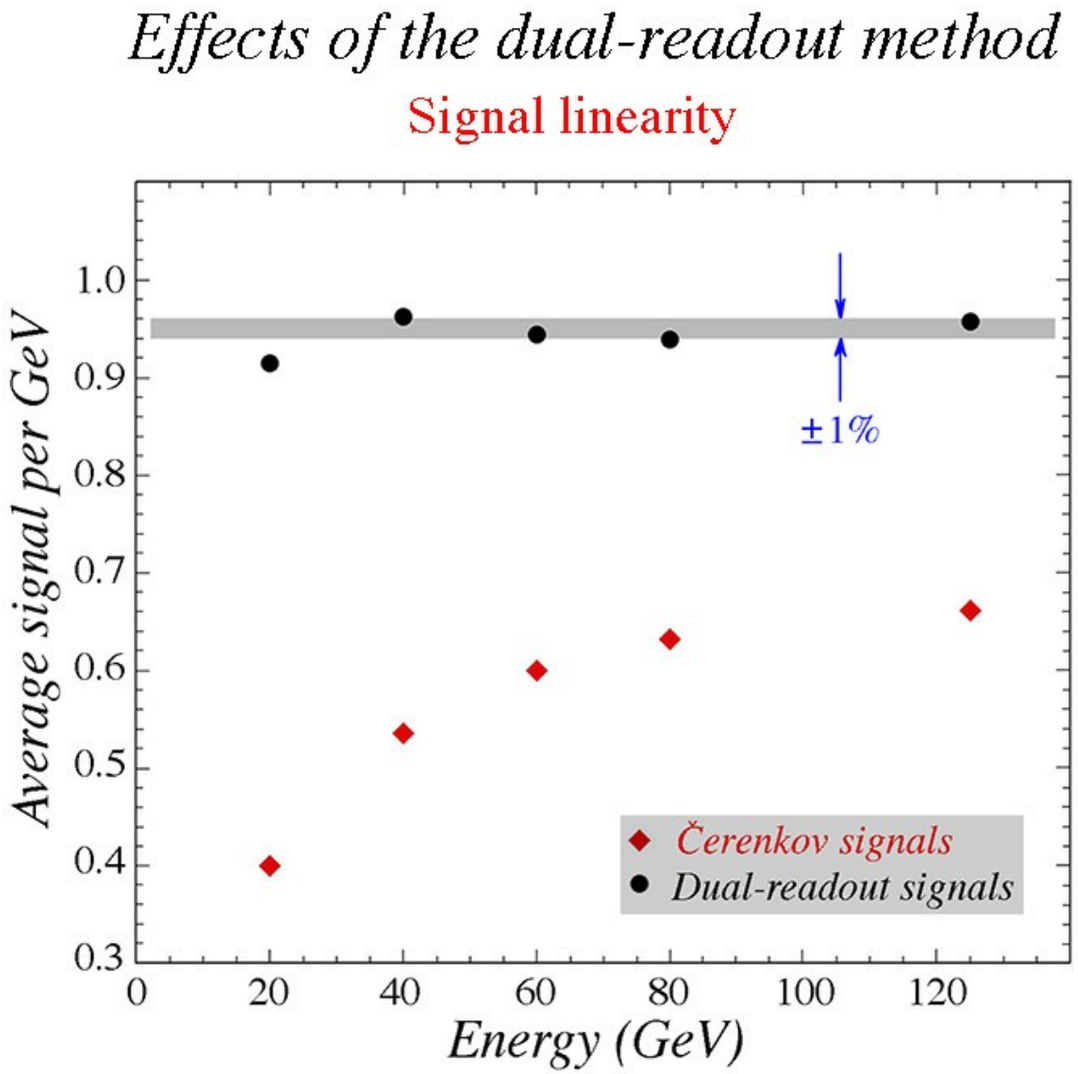


Dual Readout at Work (1)

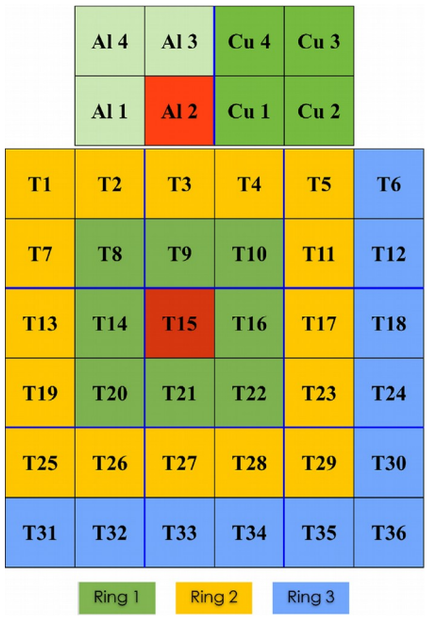


- *Θ, χ independent of both*:
  - *i) energy* (!)
  - *ii) type of hadron* (!!)

Dual Readout at Work (2)



Dual Readout at Work (3)



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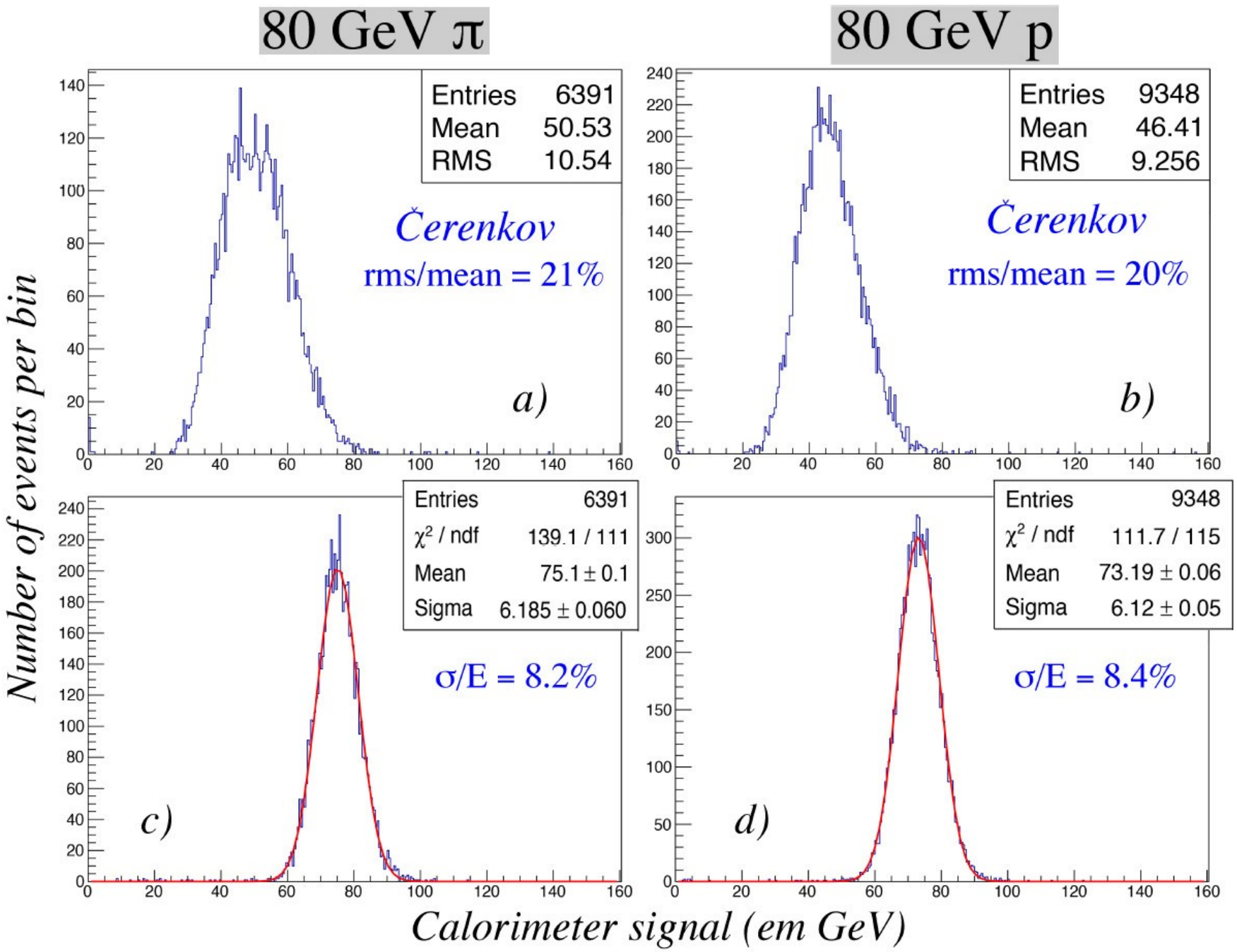
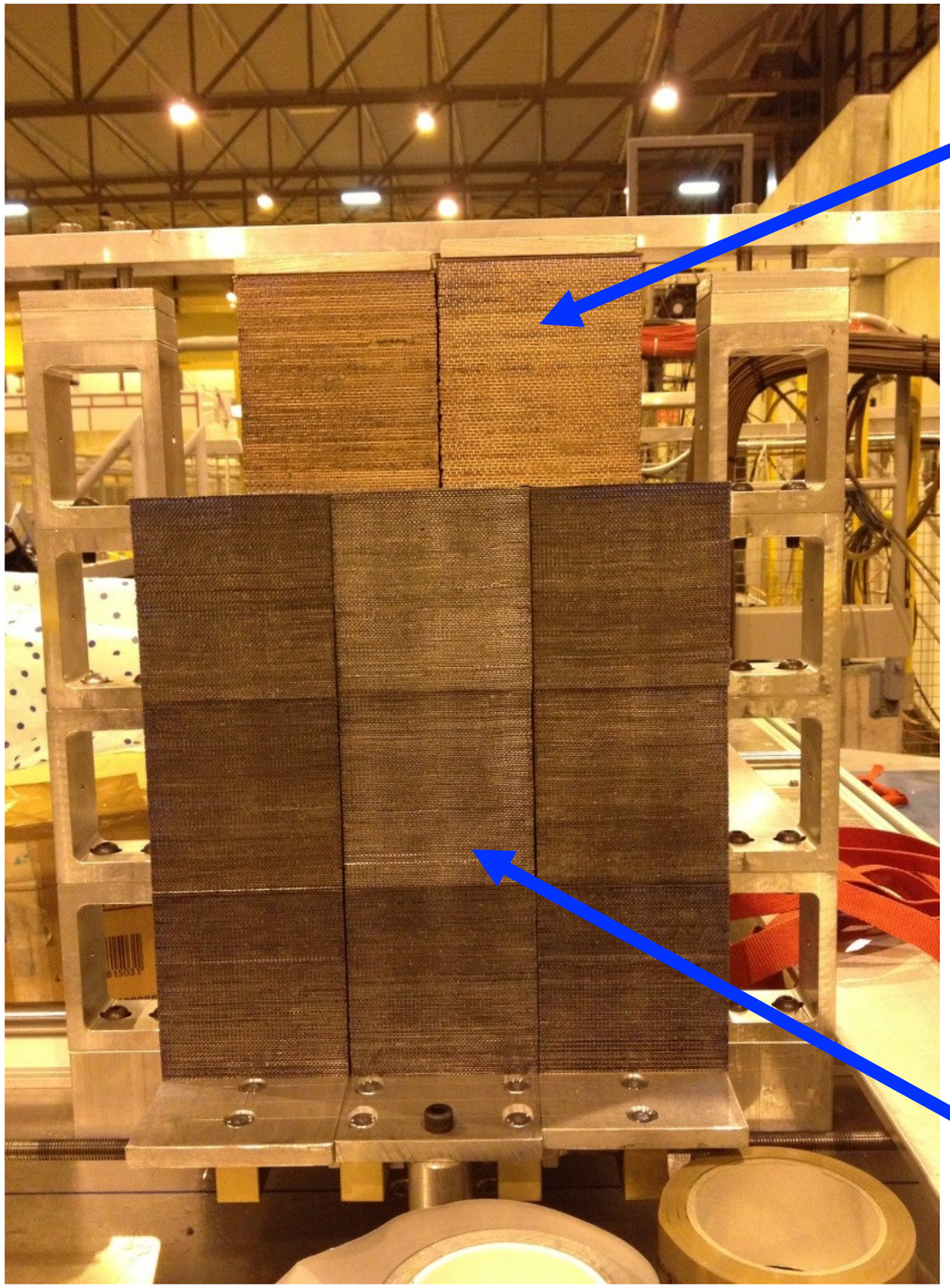
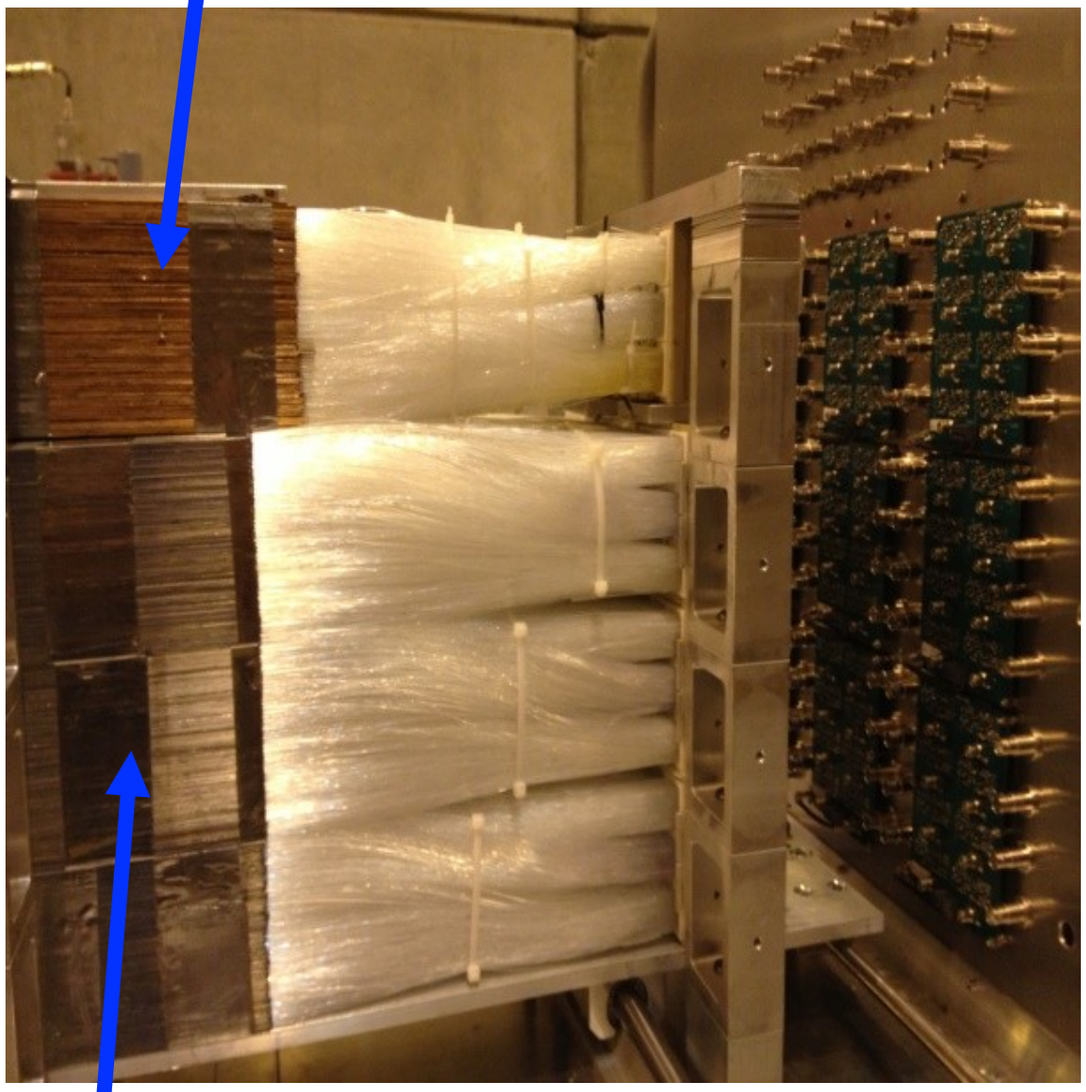


RD52 DR Fibre Calorimeters





2 Cu modules

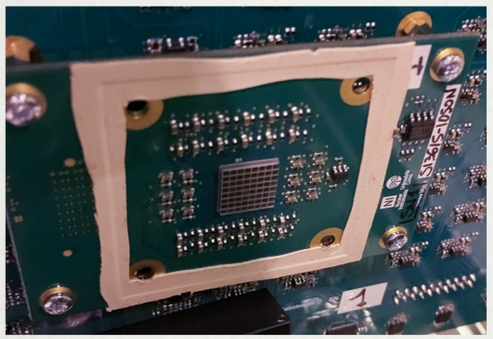
Pb 3*3 matrix

RD52 SiPM Readout

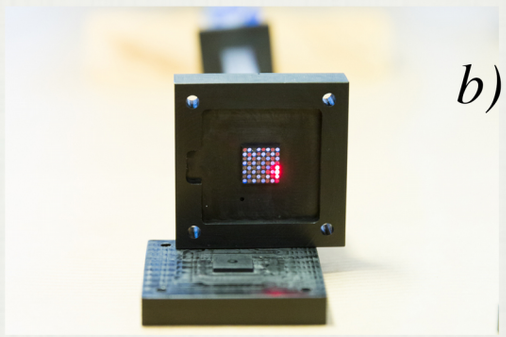
The very first SiPM test of a DR calorimeter (10/2016)

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

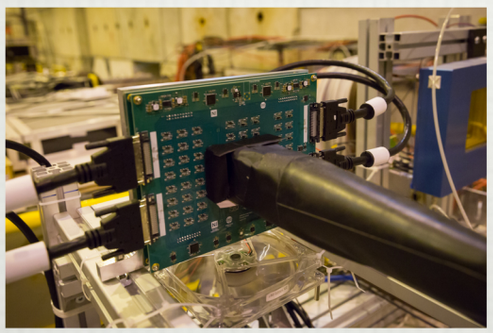
1 fiber per SiPM



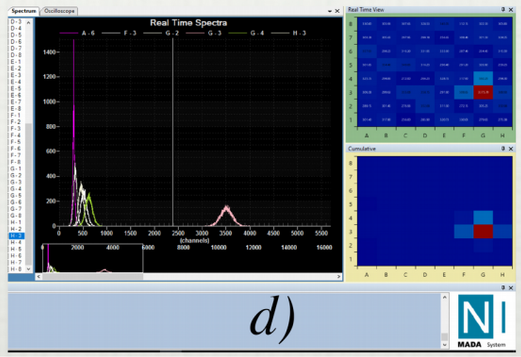
a)



b)



c)



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

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

2017

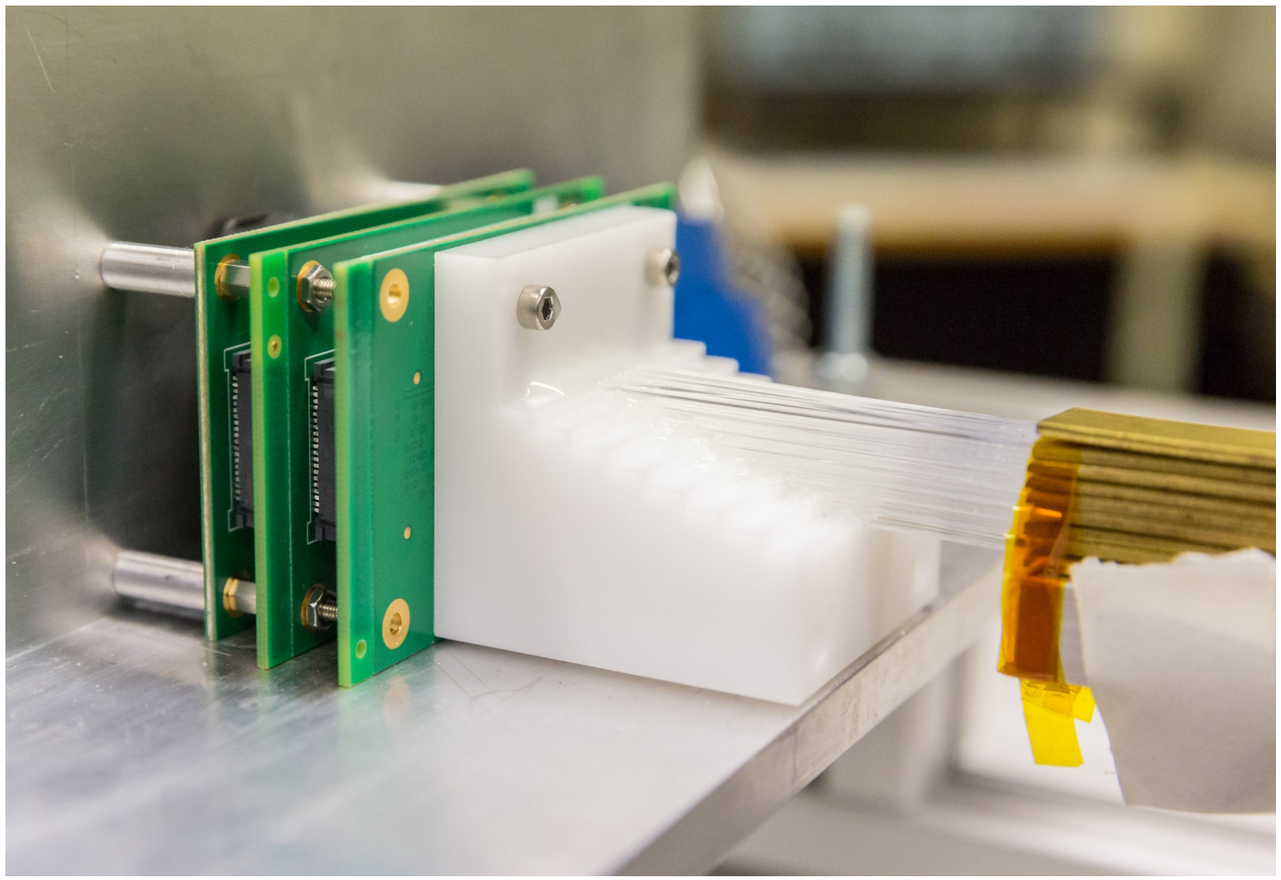
a) 4 x dynamic range (1600 cells)
b) 25% PDE
c) photo-detection at 2 different levels

2016

a) 400 cells
b) 40% PDE

limitations:

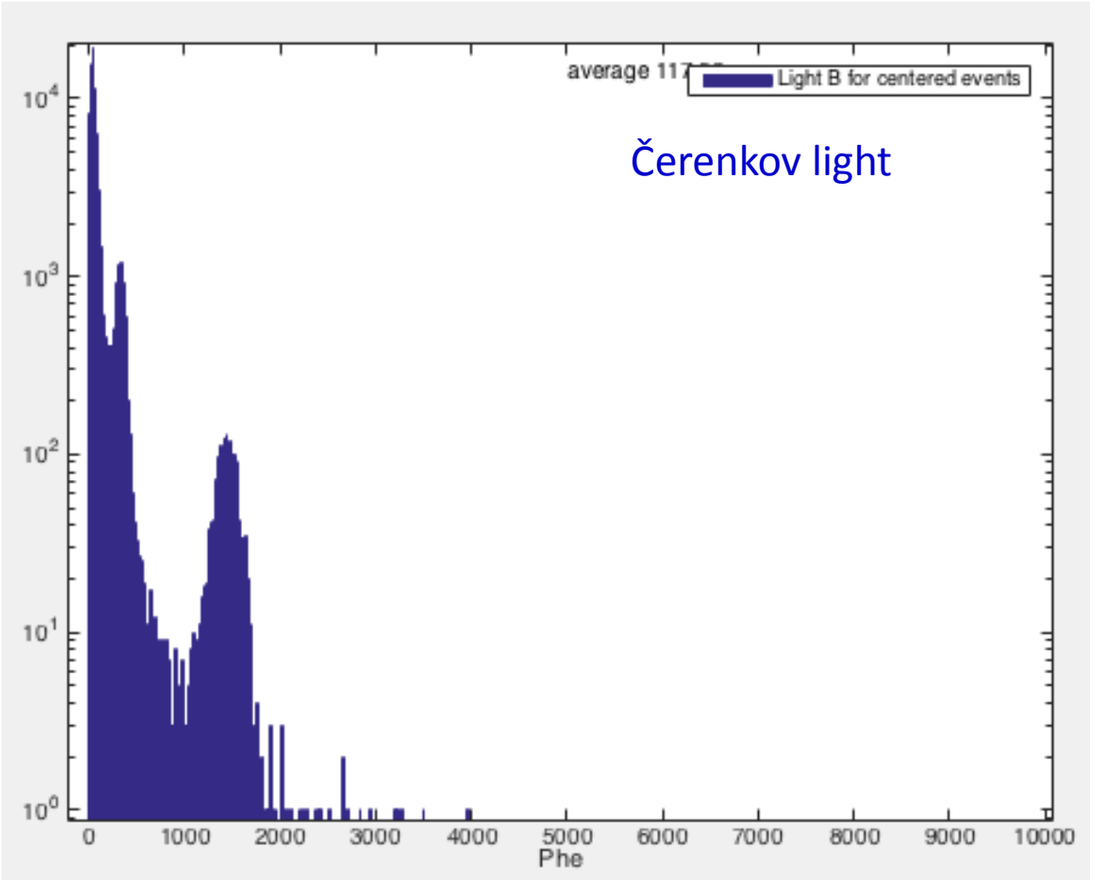
- dynamic range saturation
- cross-talk (light leakage)



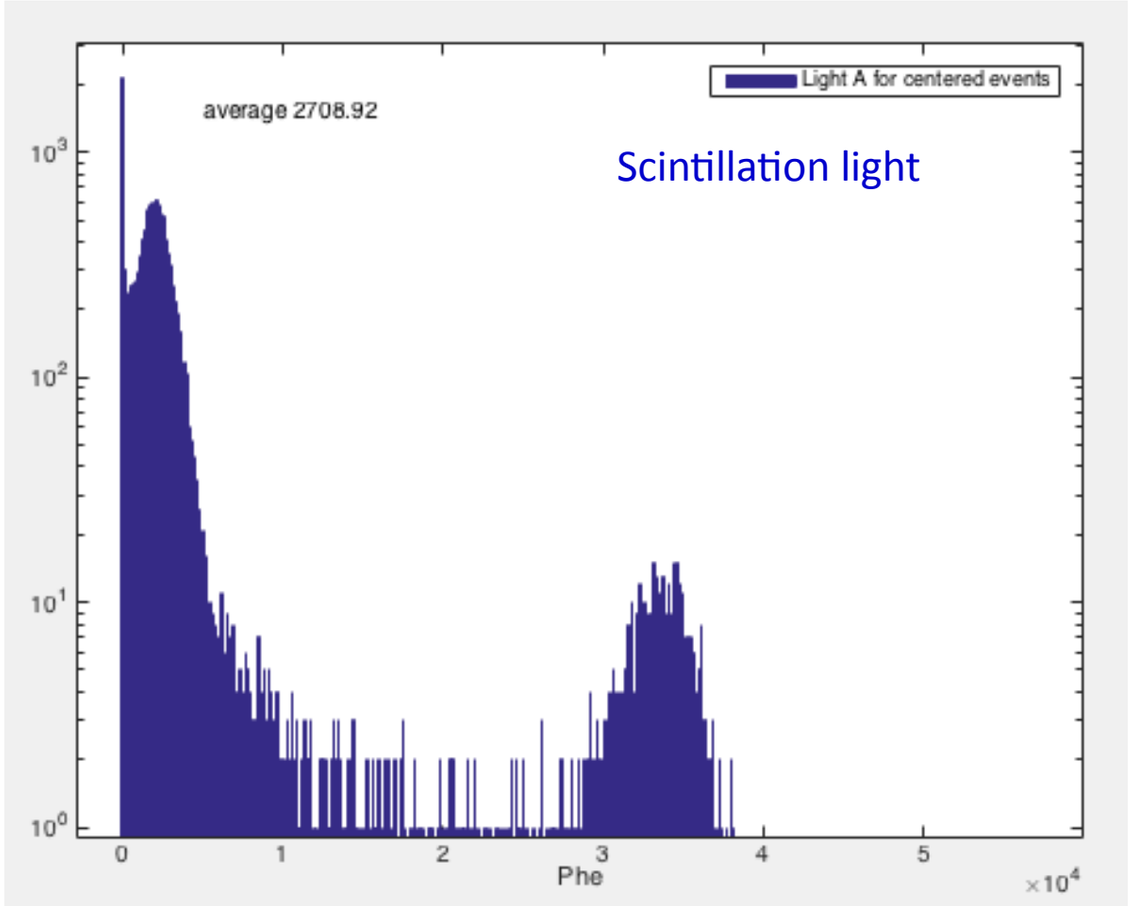
RD52 Preliminary Results (2017)

64 Hamamatsu SiPM
1x1 mm^2
25x25 μm^2 cell
1600 cells
nominal detection efficiency 25%

50 GeV electron beam



Čerenkov light



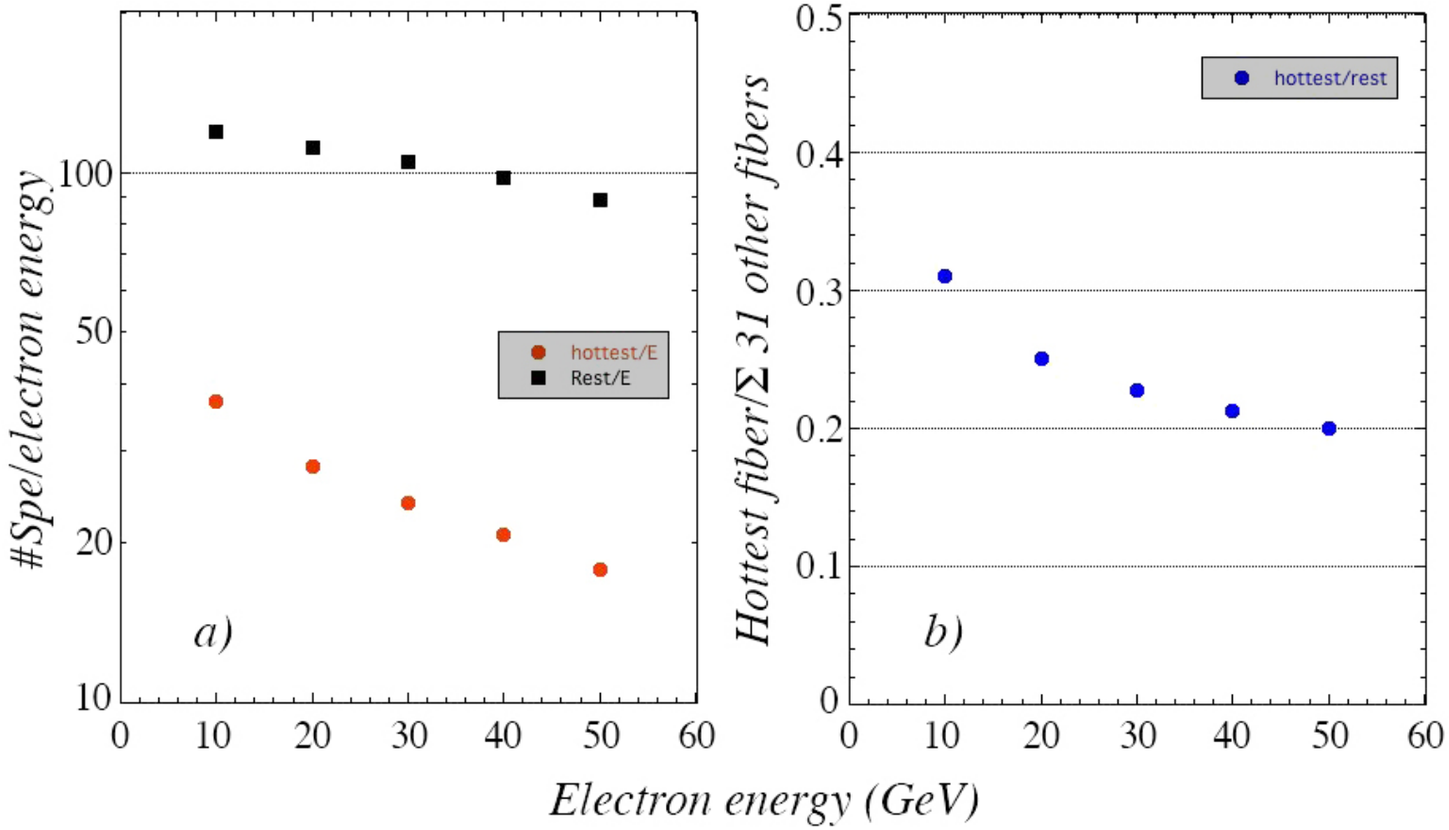
Scintillation light

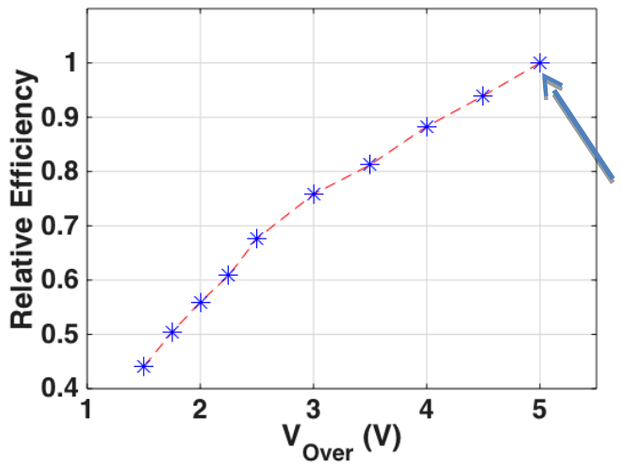
Preliminary Results (2017) – Scintillation Signals

Number of p.e. / GeV in all fibres but hottest

Number of p.e. / GeV in hottest

Ratio hottest/rest



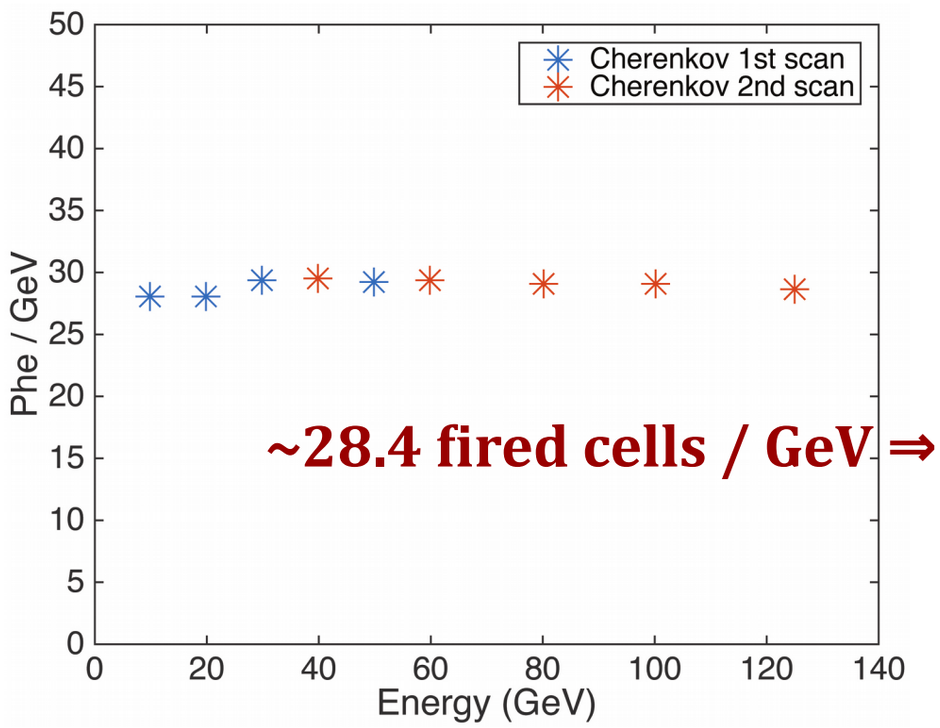


Operating Voltage

**** Take care: bias voltage lowered by 5 V → PDE very low! ****

Preliminary Results (2017) – Čerenkov Signals

p.e. per GeV .vs. Beam Energy



~28.4 fired cells / GeV ⇒ ~70 p.e. / GeV (full containment)

→ *no saturation in Čerenkov signals*

→ *average shower containment independent of energy*

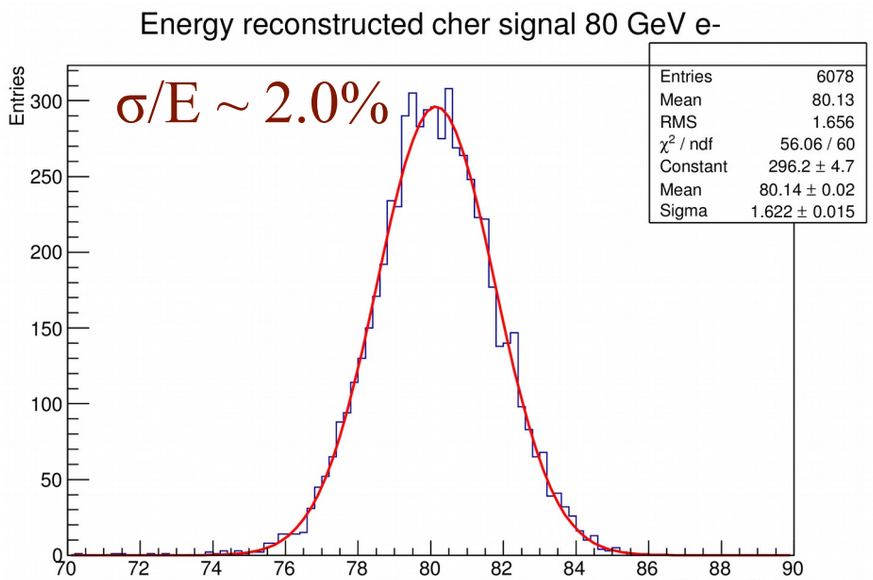
Geant4 – e.m. energy reconstruction (Cu)

e.m. calorimeter: 31.4 x 31.4 x 112.30 cm^3

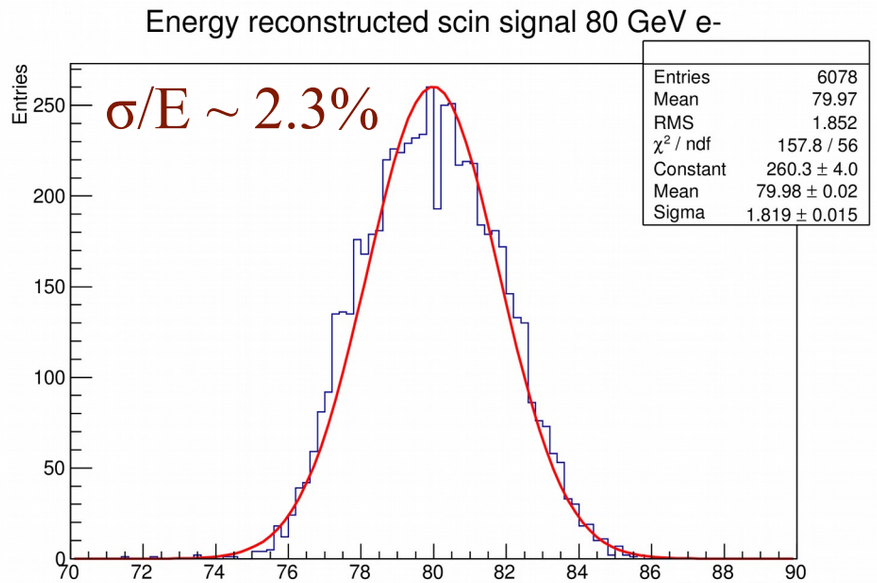
containment >~99%

energy reconstructed 80 GeV electrons

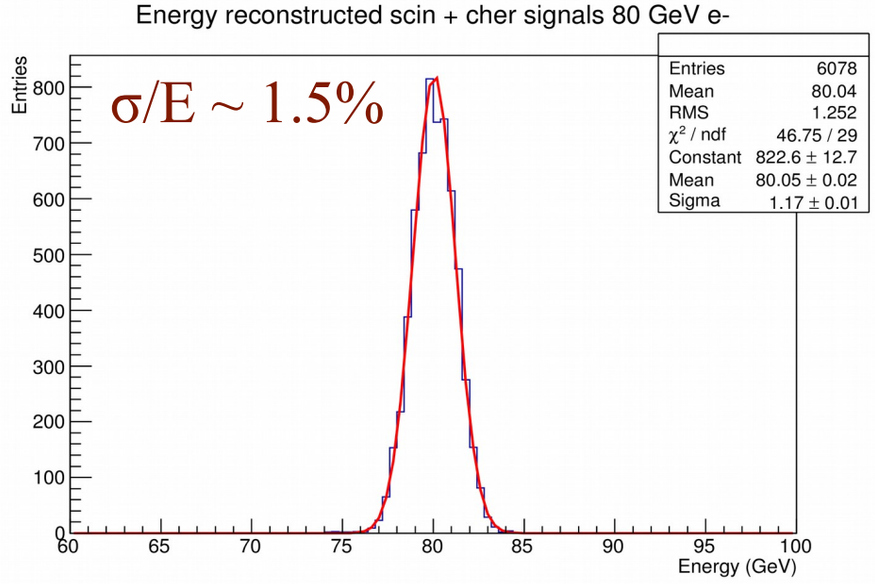
Č only



S only



S+Č

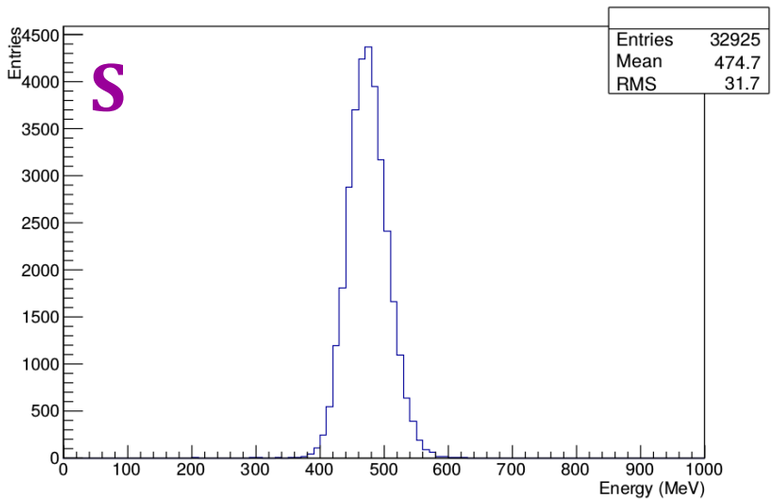


Geant4: sampling fraction (Cu)

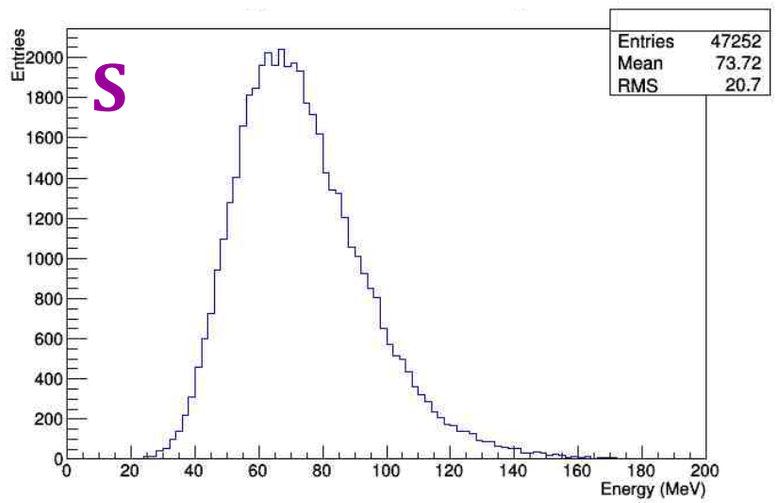
e.m. calorimeter: 31.4 x 31.4 x 112.30 cm^3

containment >~99%

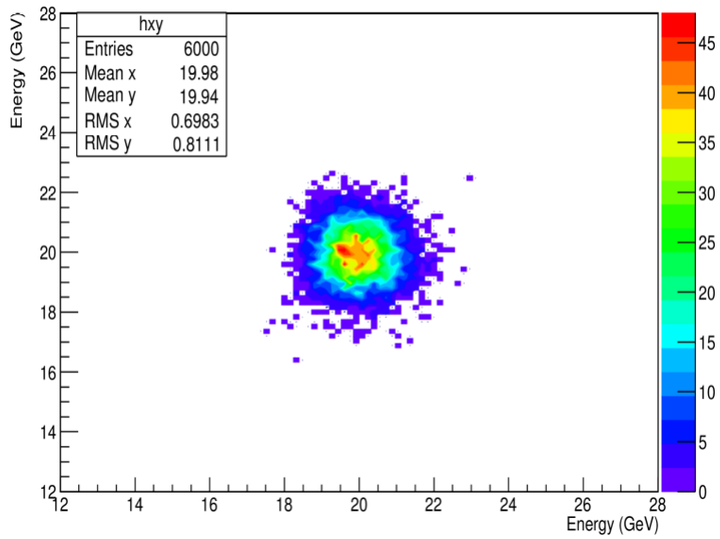
E(MeV) S fibres: ~5.5%



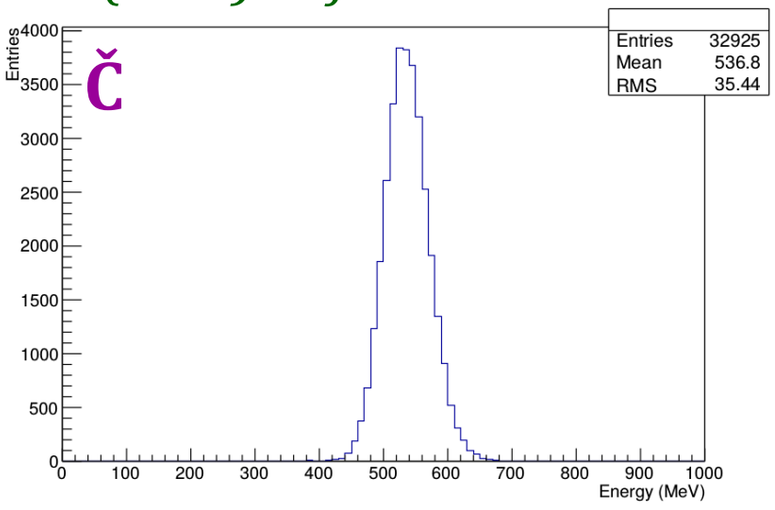
E (MeV) in hottest fibre



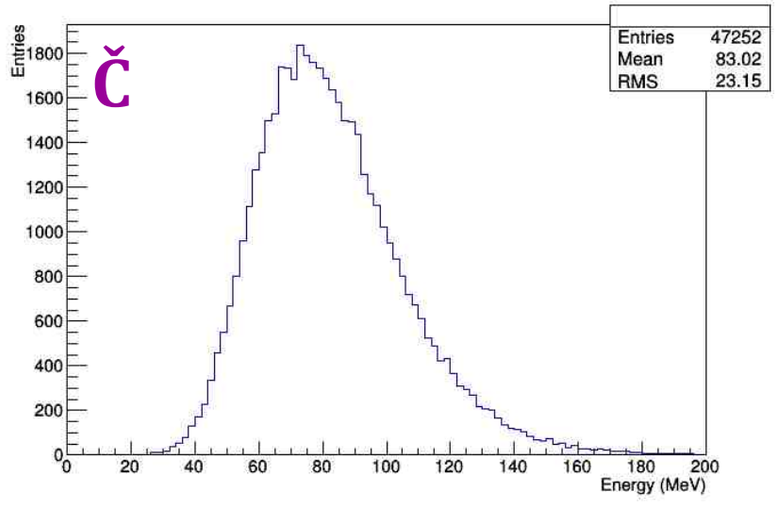
C vs. S



E(MeV) in fibres: ~6.2%



E (MeV) in hottest fibre

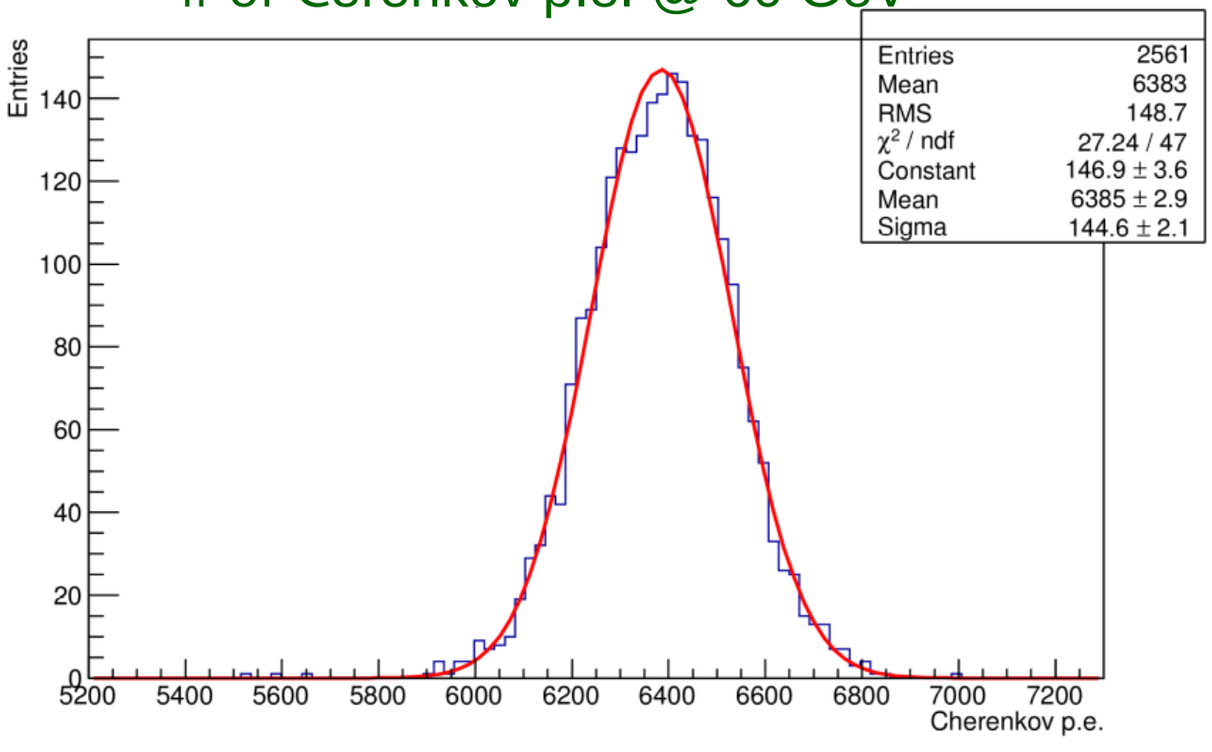
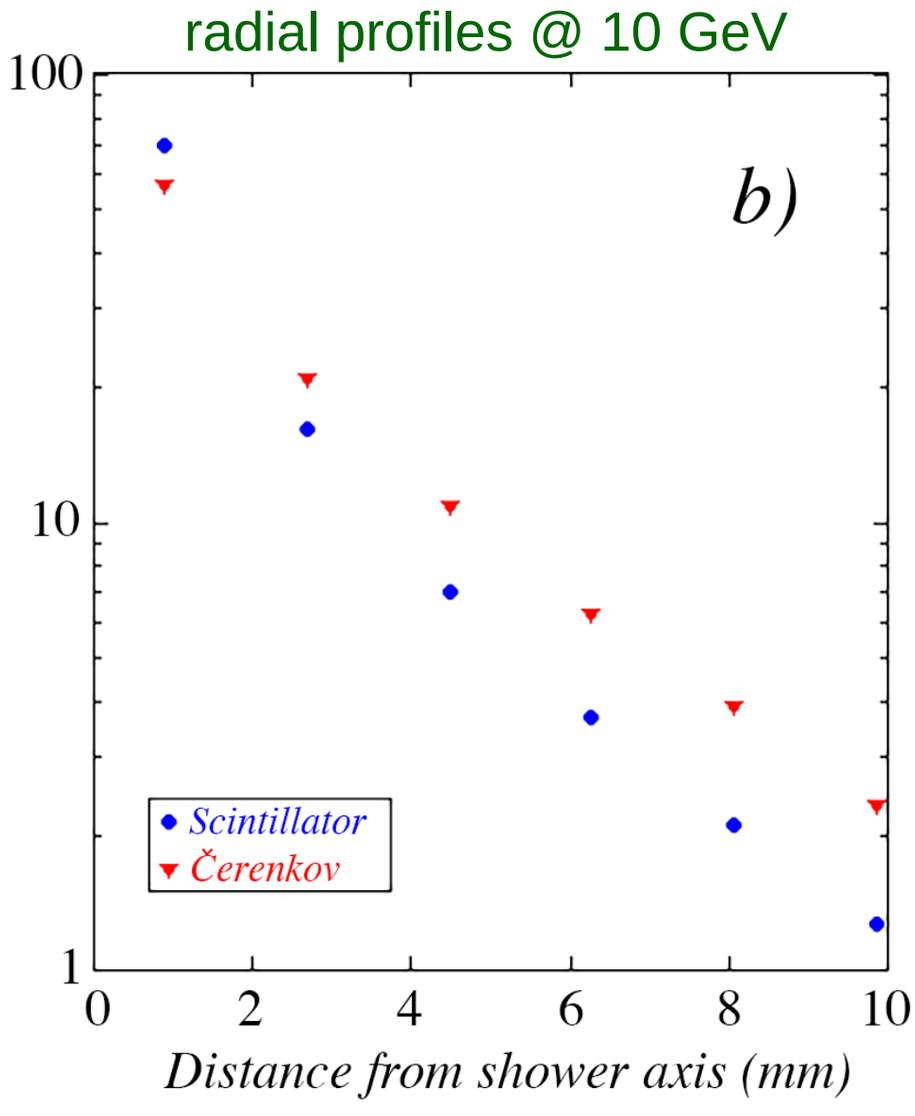


Geant4 – e.m. performance (Cu)

e.m. calorimeter: 31.4 x 31.4 x 112.30 cm^3

containment >~99%

# of Čerenkov p.e. @ 60 GeV



radial profiles @ 10 GeV