Dual-Readout Calorimetry @ CepC

International Workshop on
High-Energy Circular Electron-Positron Collider
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Dual-Readout Calorimetry

What:

correct hadronic energy measurements for f_{em} *fluctuations*

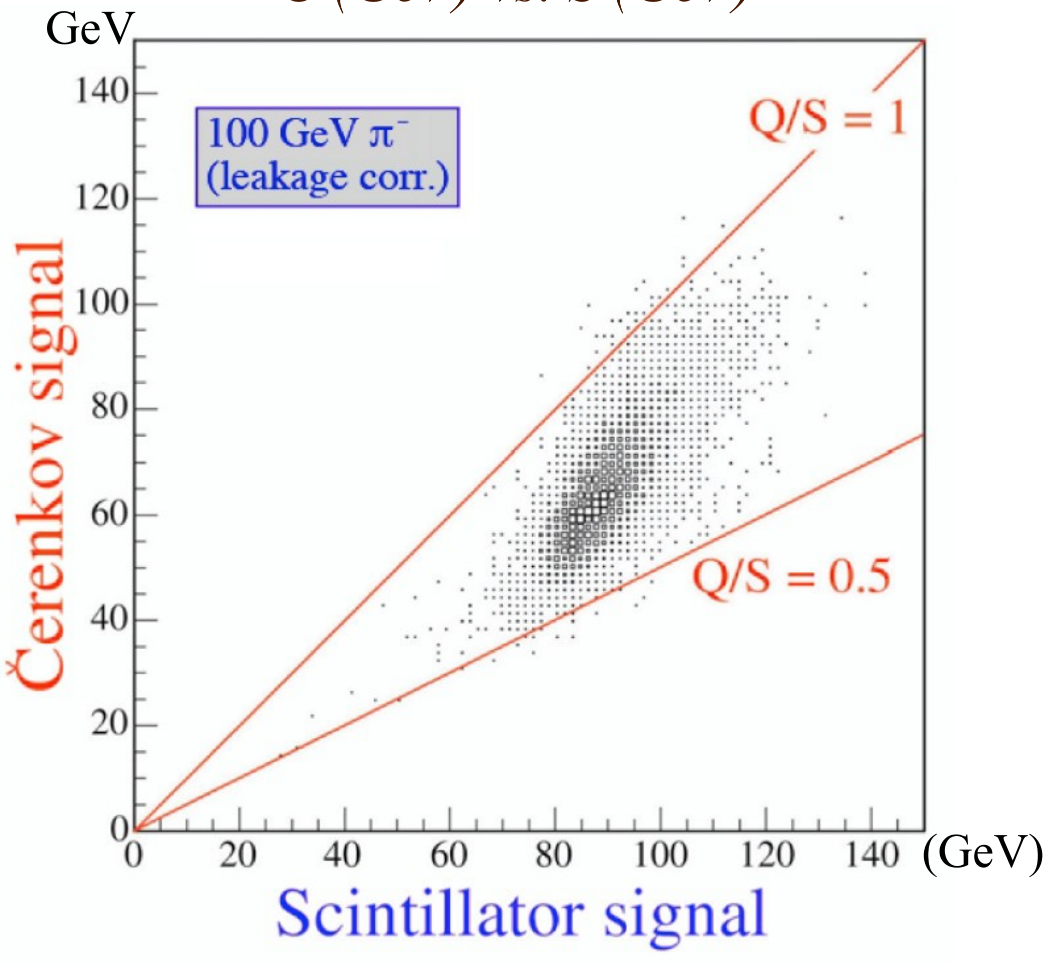
How:

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

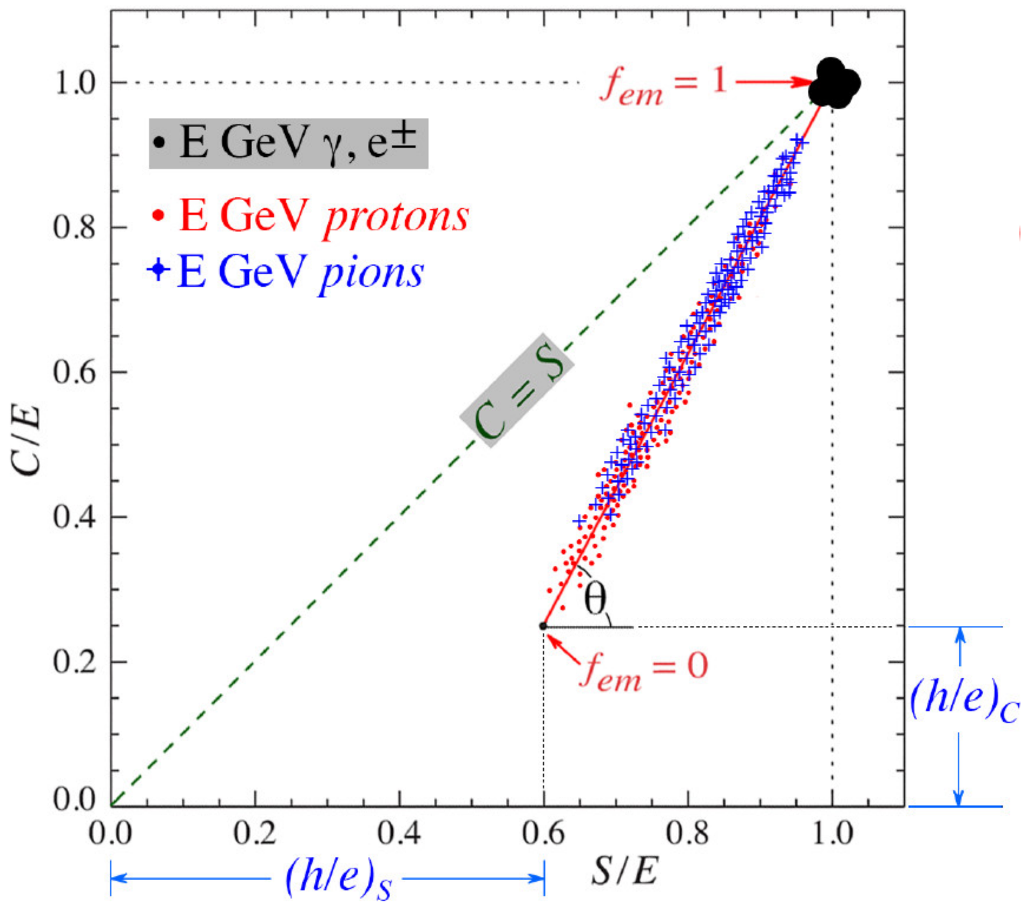
(see backup slides)

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:

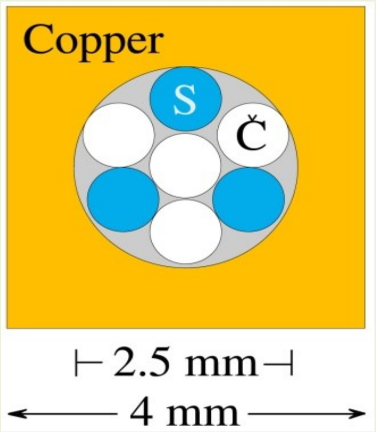
i) energy (!)

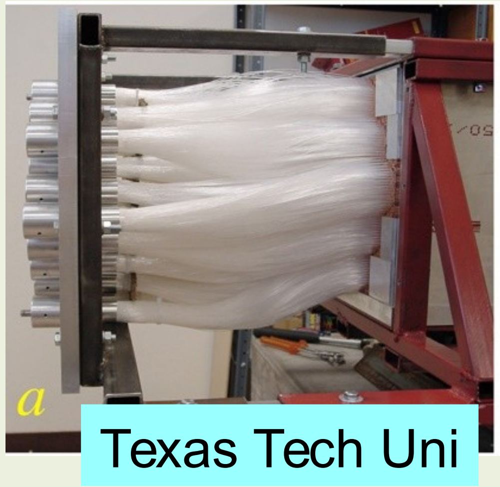
ii) type of hadron (!!)

Dual Readout w/ Fibre Sampling Calorimeters

2003
DREAM

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

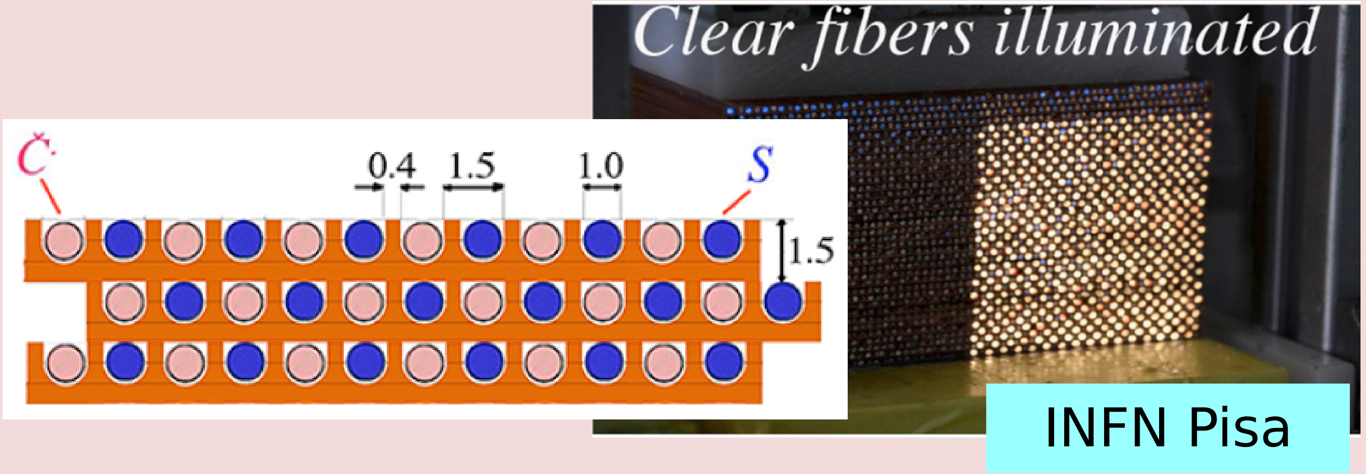




Texas Tech Uni

2012
RD52

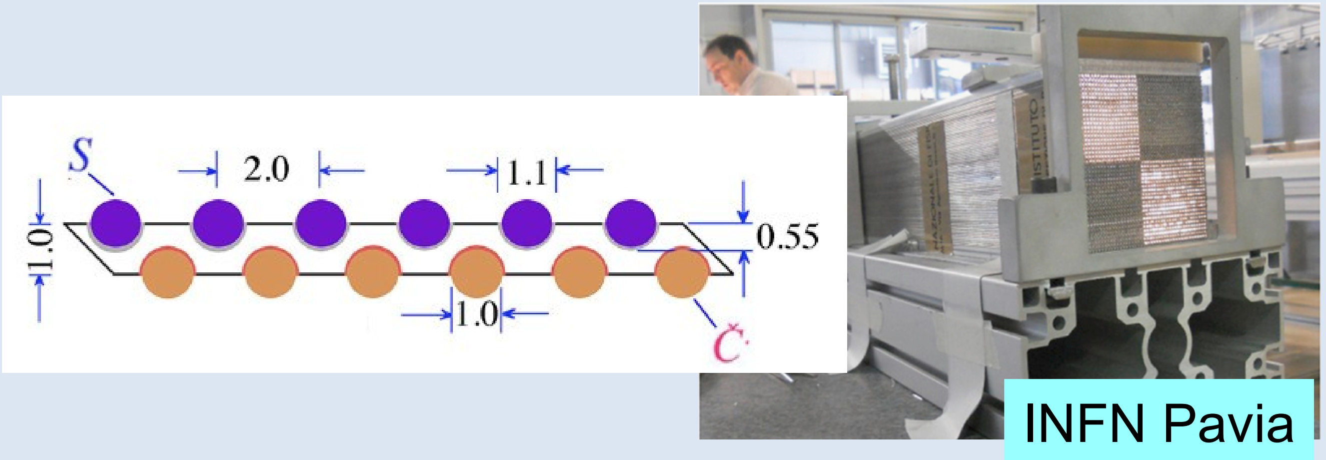
Cu, 2 modules
Each module: 9.2 × 9.2 × 250 cm^3
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: ~4.6%
Depth: ~10 λ_{int}



INFN Pisa

2012
RD52

Pb, 9 modules
Each module: 9.2 × 9.2 × 250 cm^3
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: ~5.3%
Depth: ~10 λ_{int}



INFN Pavia

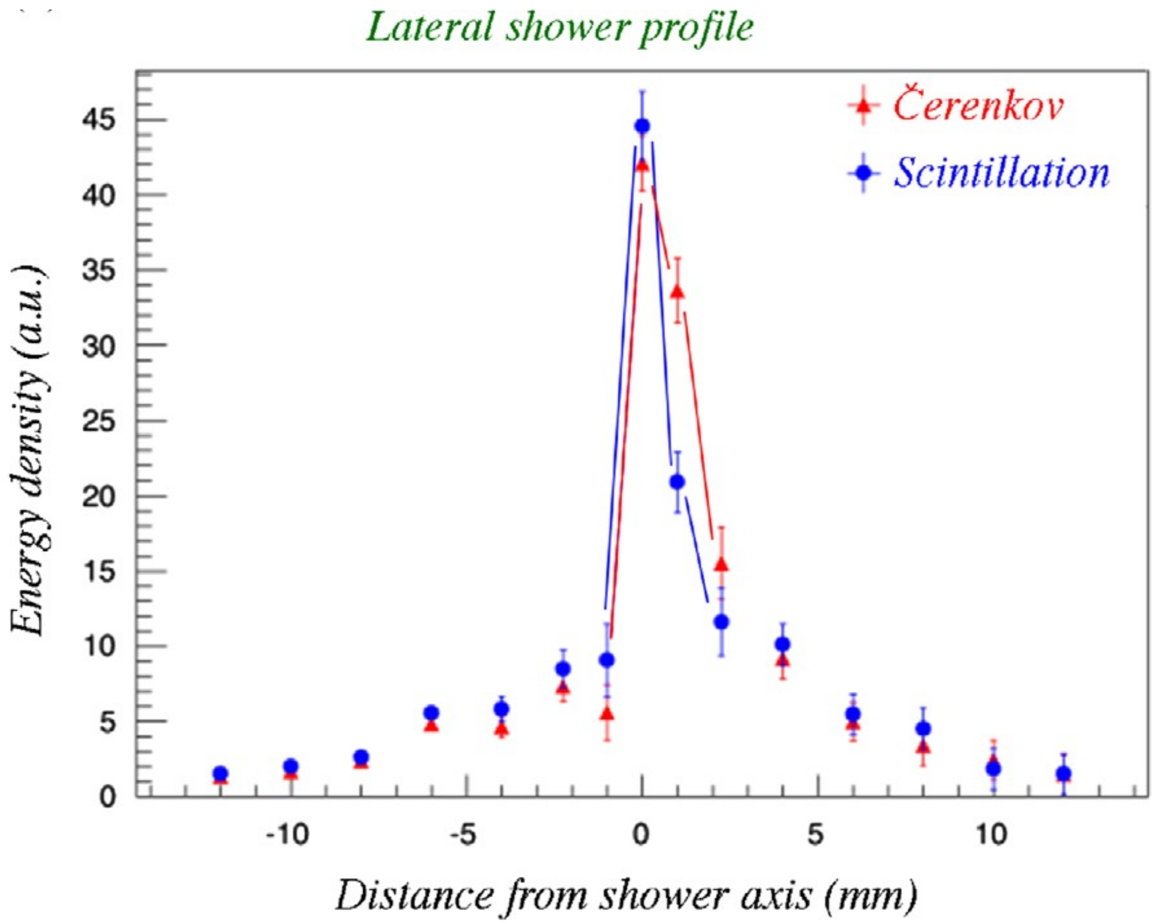
Lateral shower profile

RD52 lead calorimeter

100 GeV e^-

$\theta, \Phi = 0°$

NIM A 735 (2014) 130



em shower are very narrow

→ fibre readout can easily provide (powerful) input to PFA

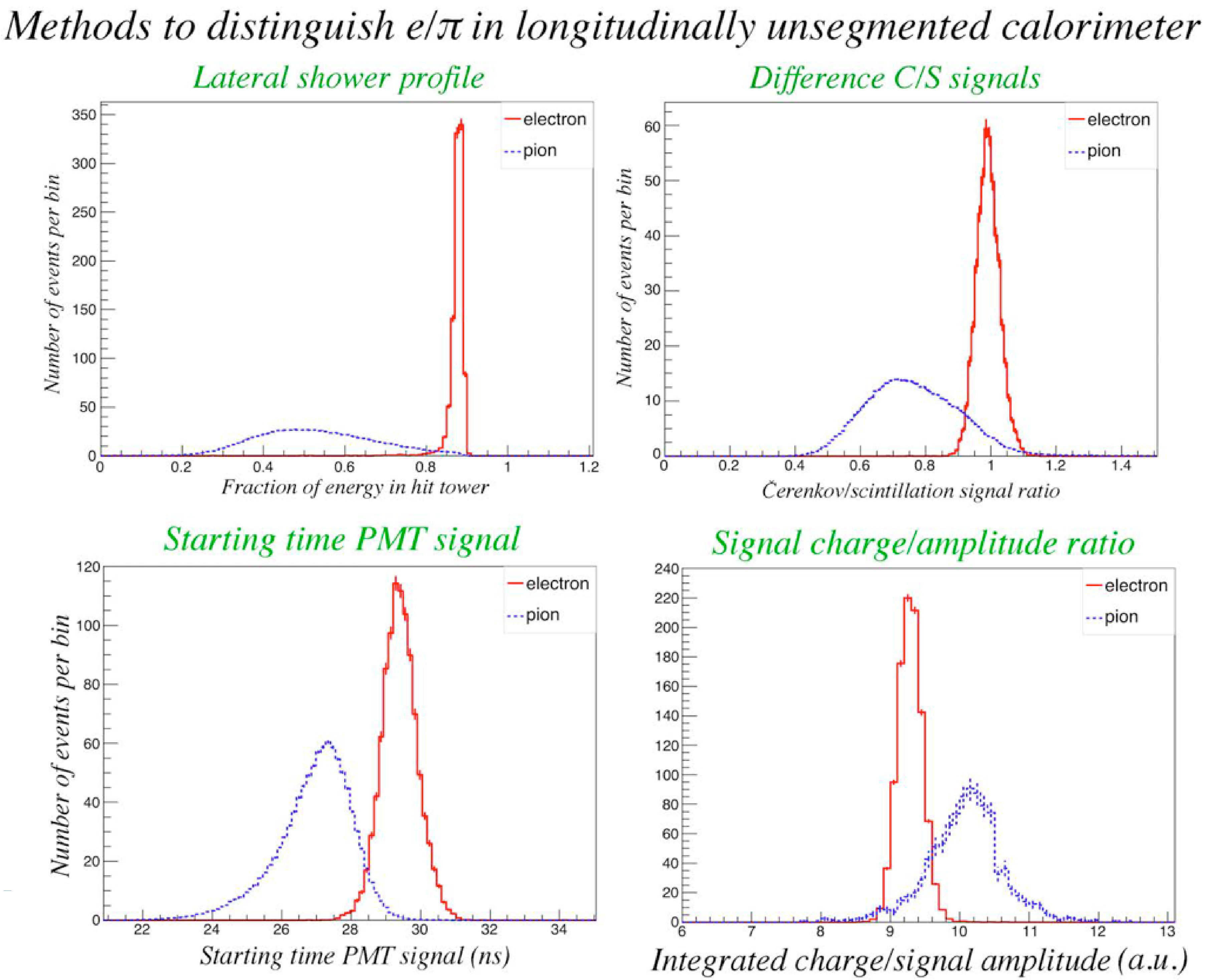
Particle ID (electron/hadron separation)

RD52 lead calorimeter

(60 GeV) e^- vs. π^-

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

NIM A 735 (2014) 120



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)

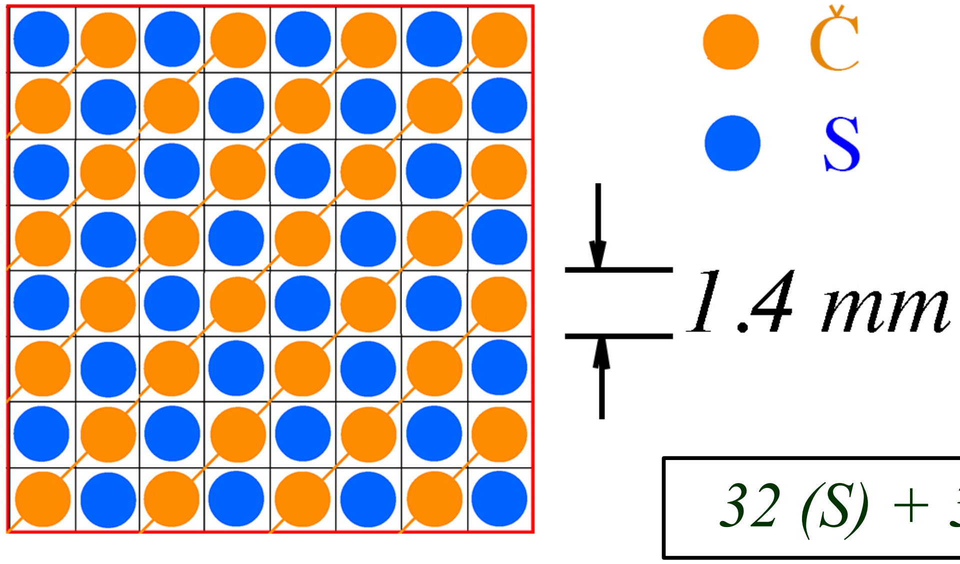
S ≥ 30×Č ! → crosstalk (light leakage) critical

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

2017 RD52 Testbeam Layout

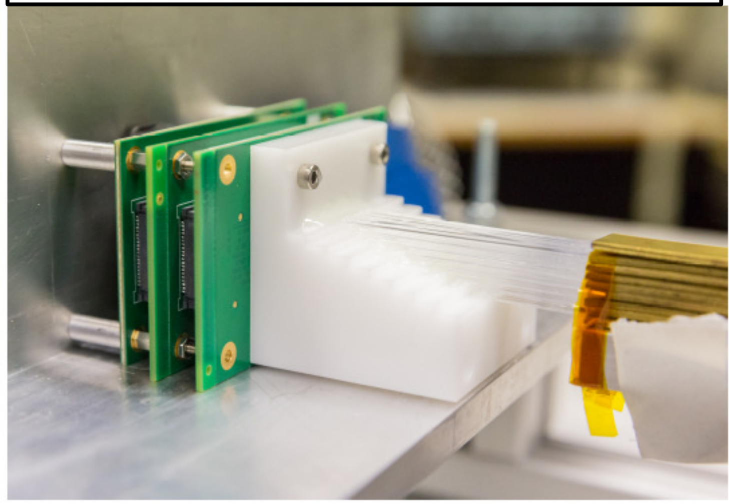
Brass module, dimensions: ~ 112 cm long, 12 x 12 mm^2

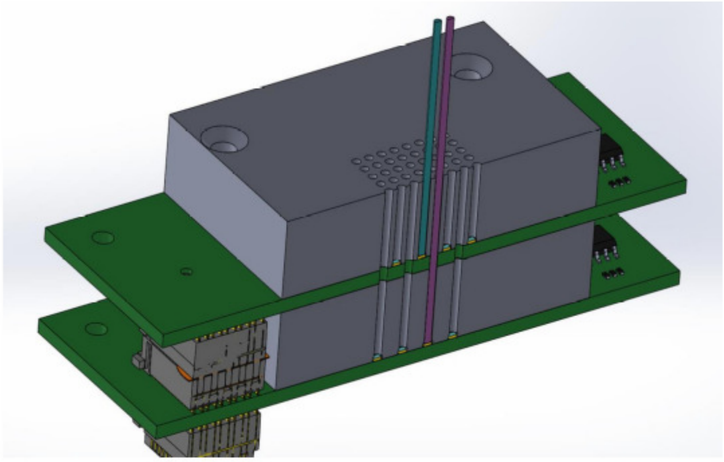
section



32 (S) + 32 (Č) fibres

Back

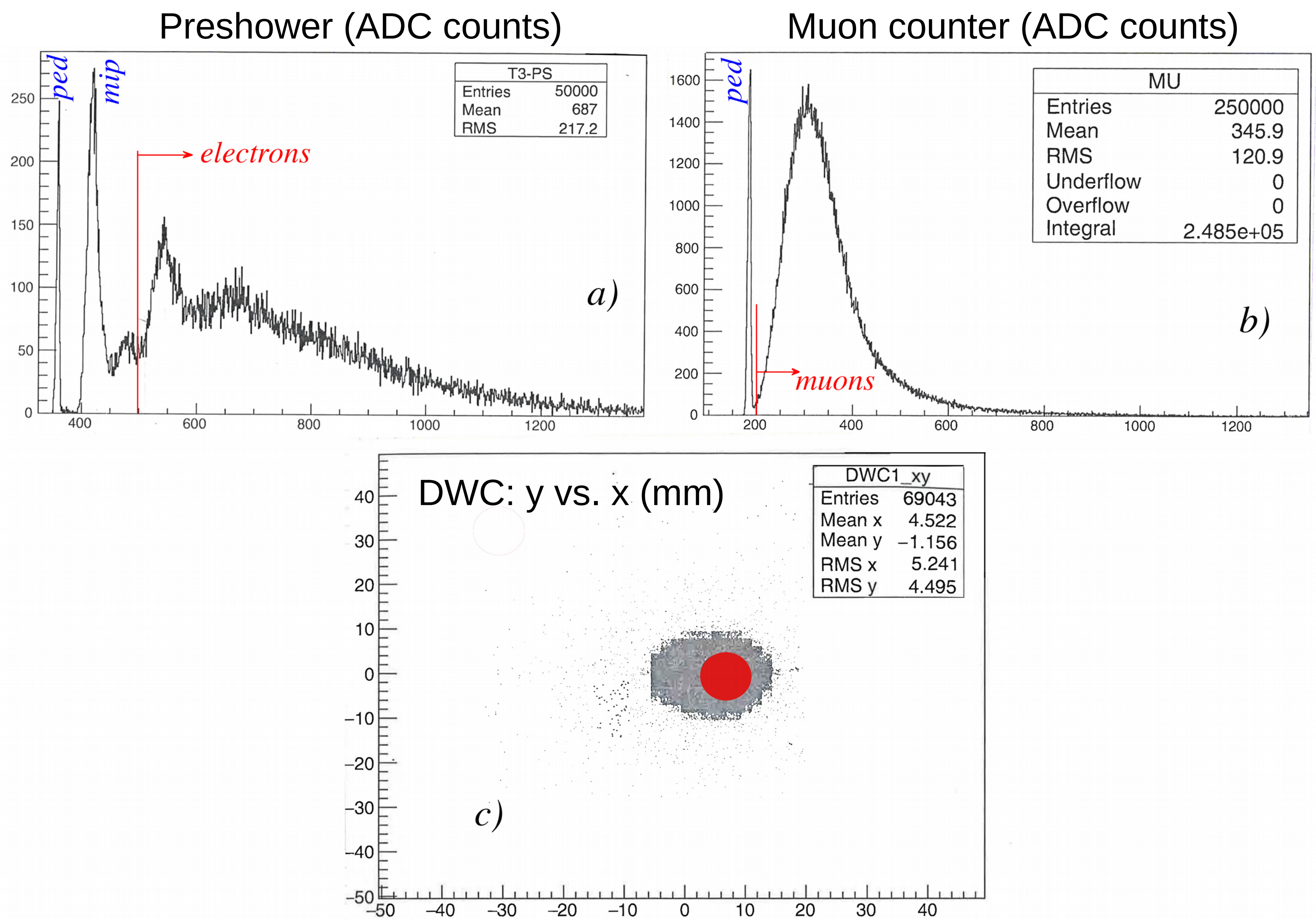




Experimental setup

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

Testbeam - Data Selection and Tagging

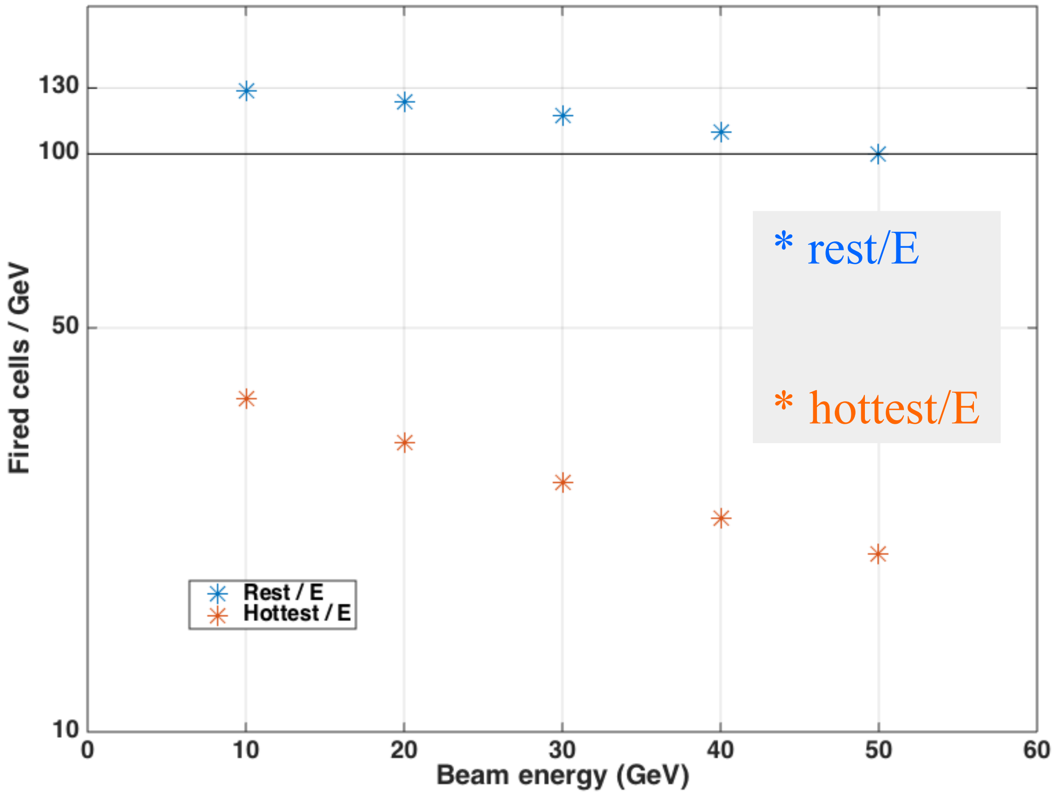


Preshower detector and muon counter: select electrons or muons

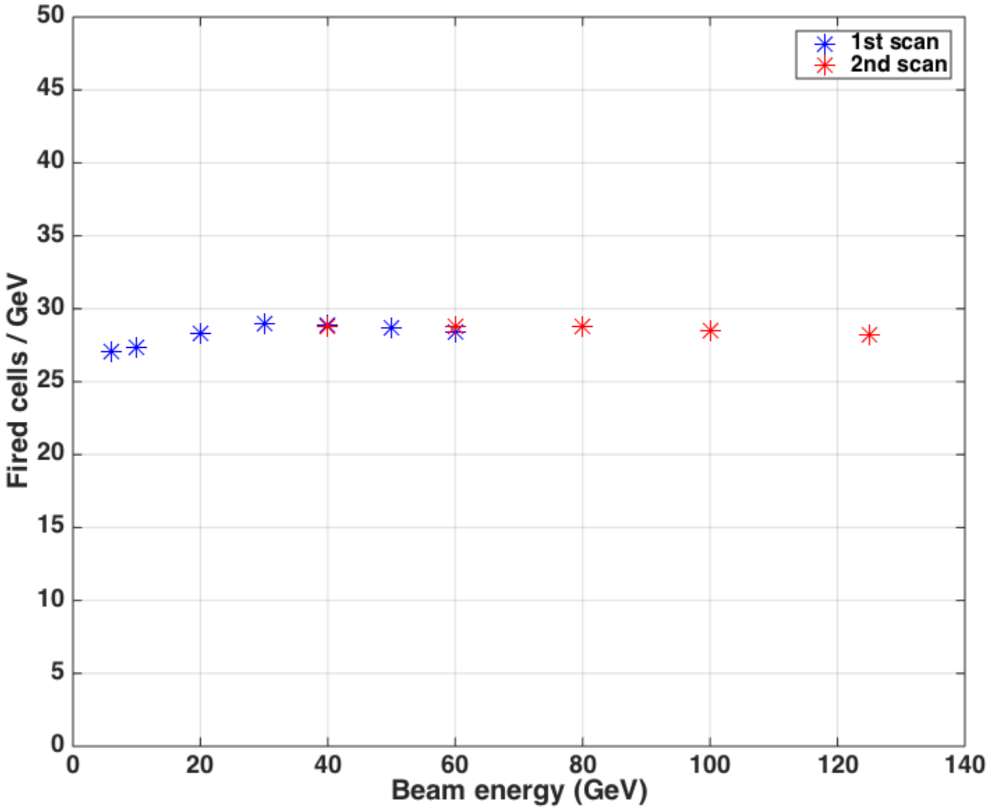
Delay Wire Chamber: select events in central region

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)

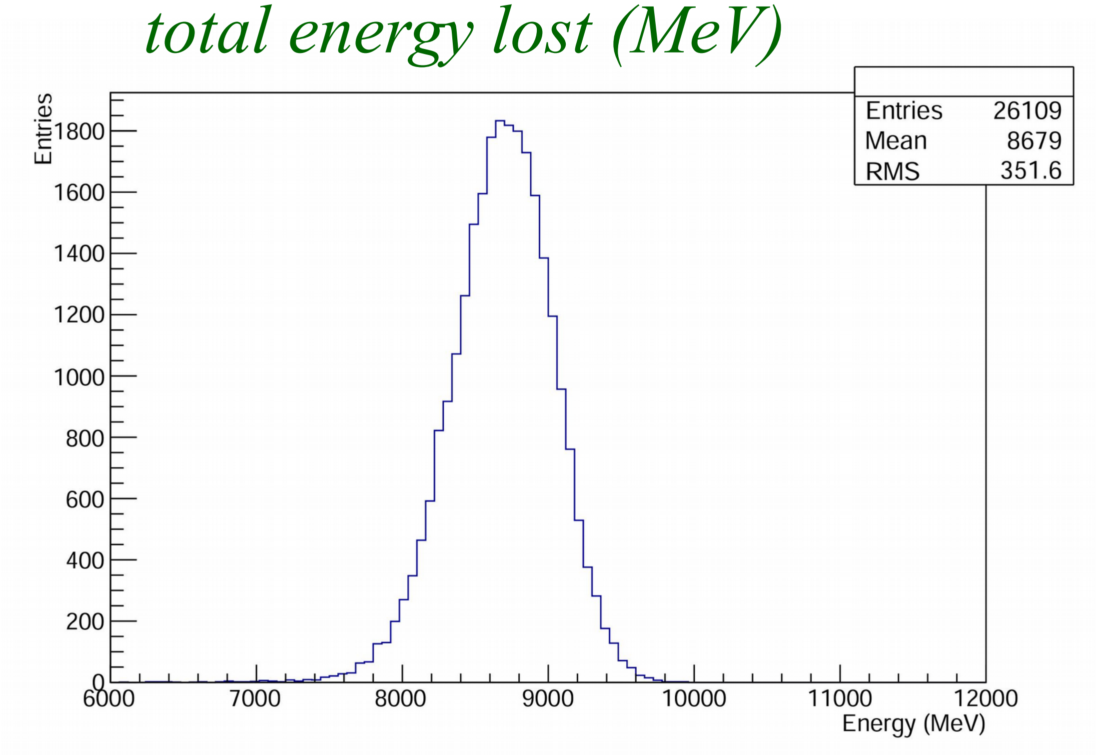
b) S : non linearity even at ultra low PDE

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

Geant4: 20 GeV electron shower containment

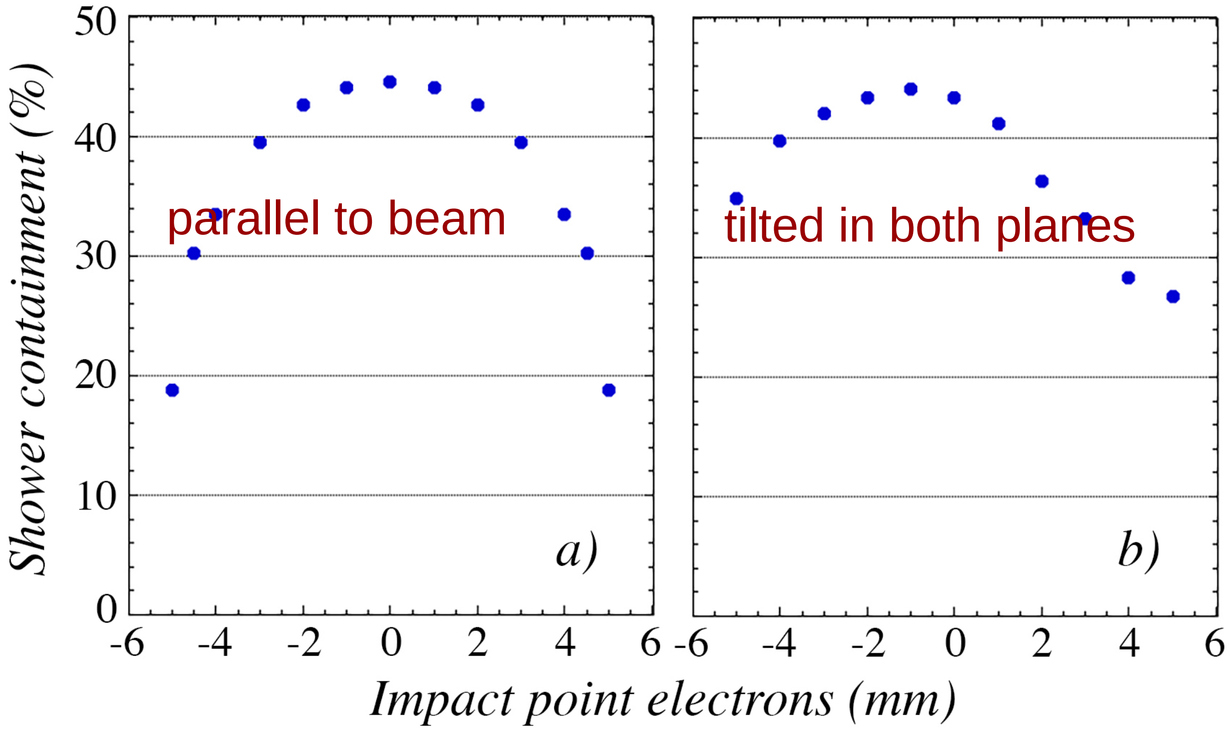
RD52 testbeam module: 1.014 x 1.014 x 112.30 cm^3

total energy lost (MeV)



centered events: ~43% containment

containment .vs. impact point



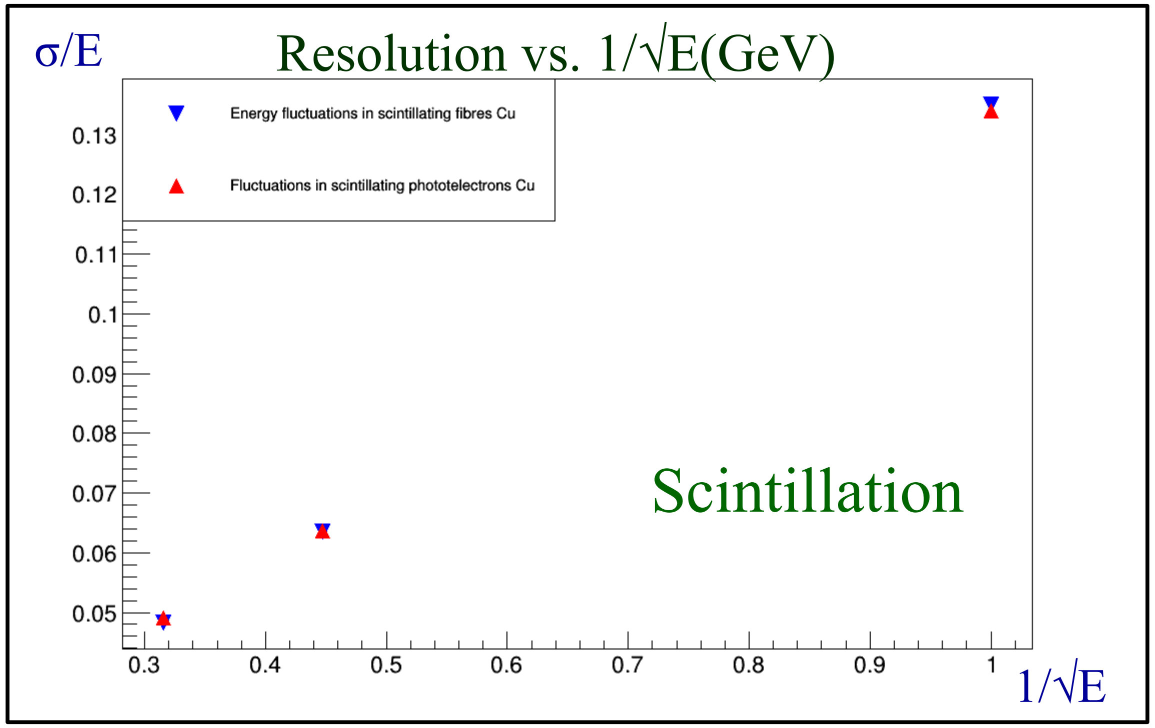
e.m. calorimeter: 31.4 x 31.4 x 112.30 cm^3

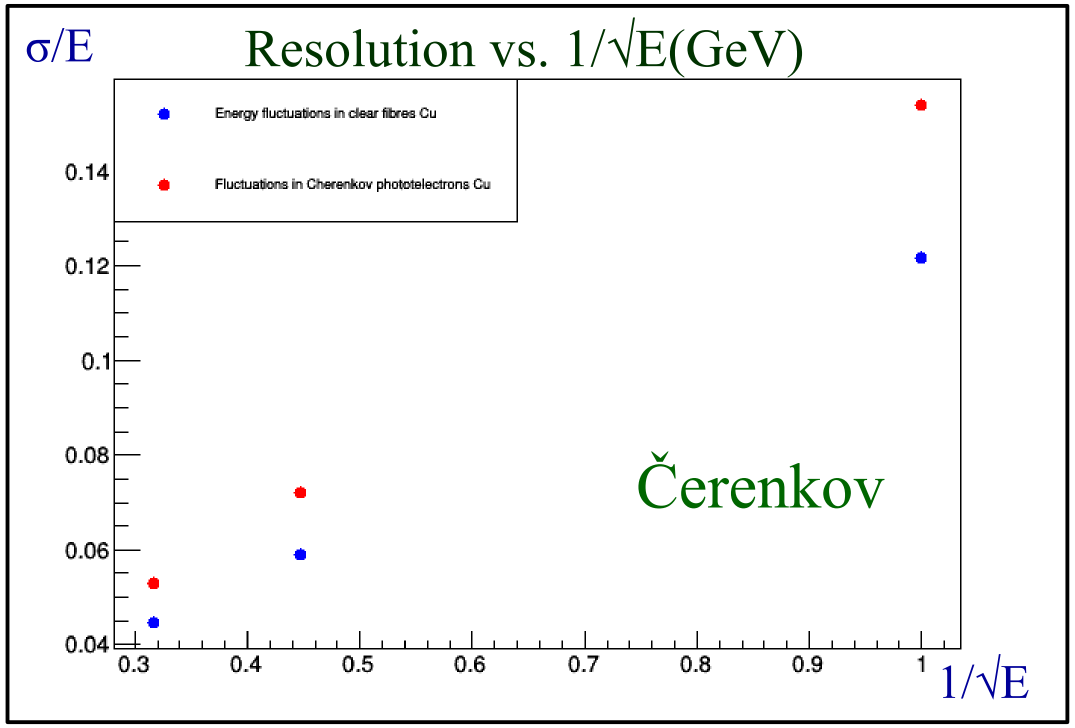
containment > 99%

(all plots for copper unless specified differently)

Geant4 – signal fluctuations

Energy deposition and p.e. number fluctuations





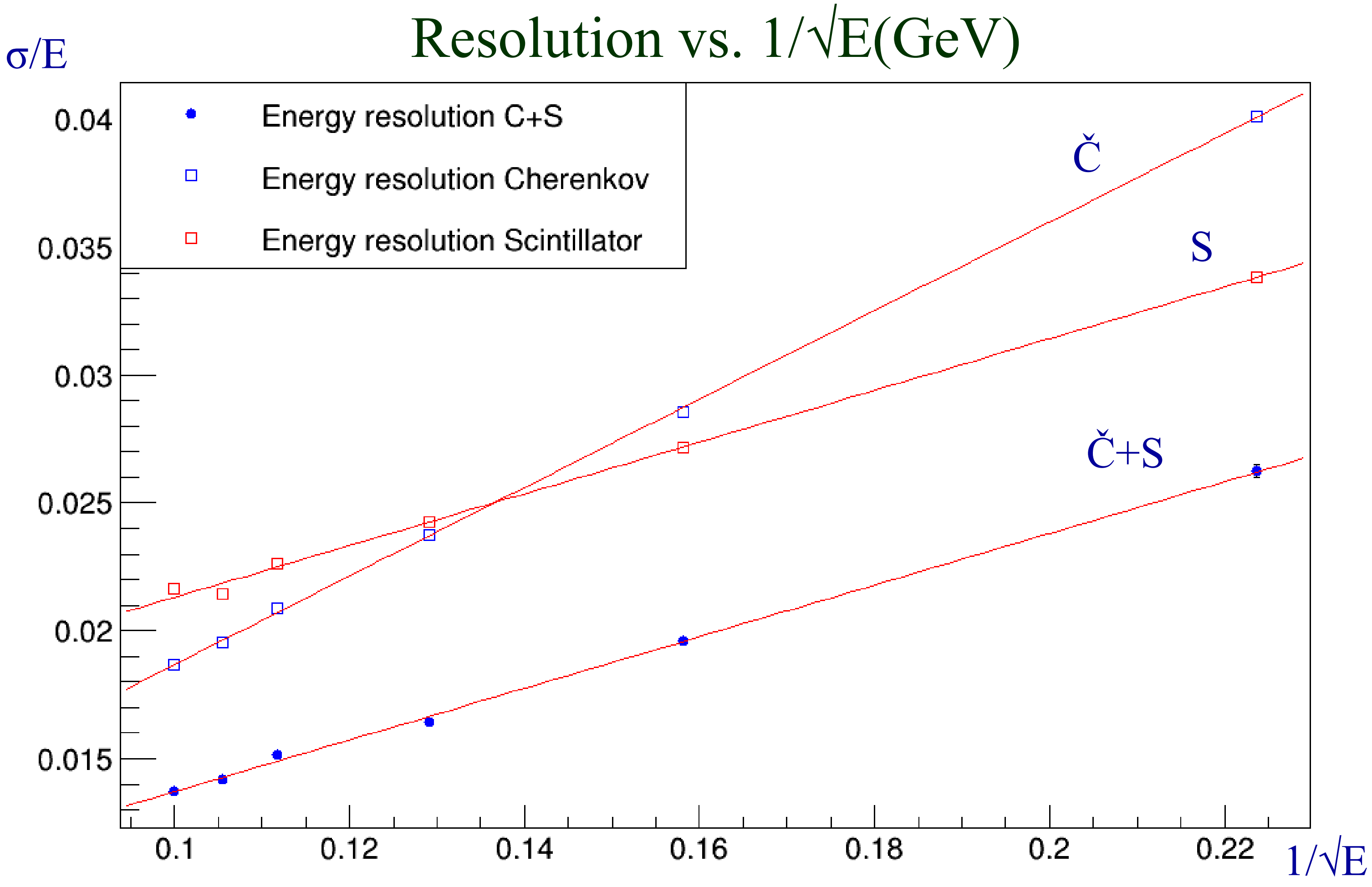
S: ~5500 p.e. / GeV
→σ/E driven by fluctuations in en. depositions

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 – 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 → (h/e)

or:

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

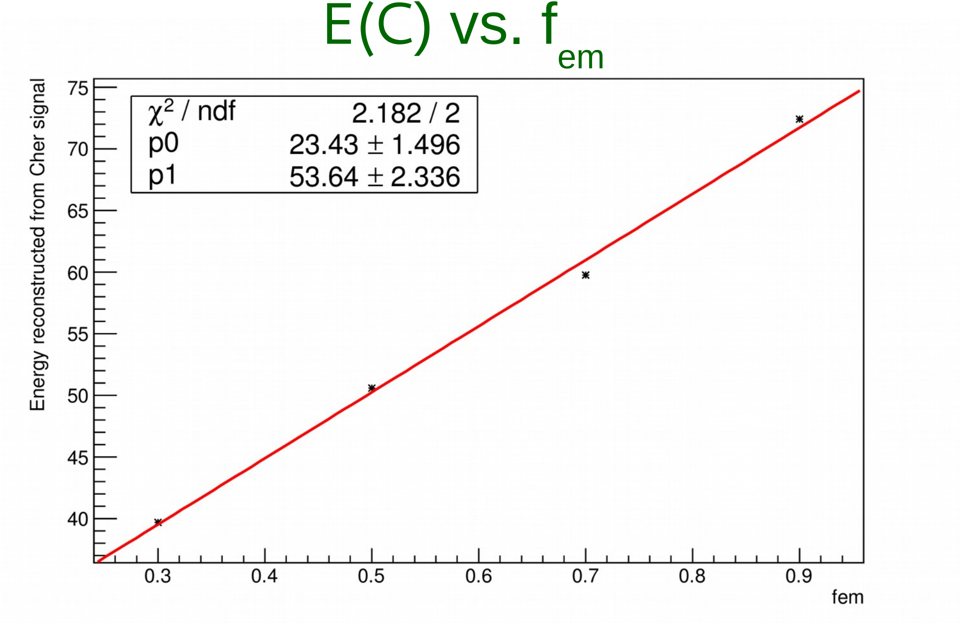
$(h/e)_{S} = (S/E - f_{em}) / (1 - f_{em})$

while:

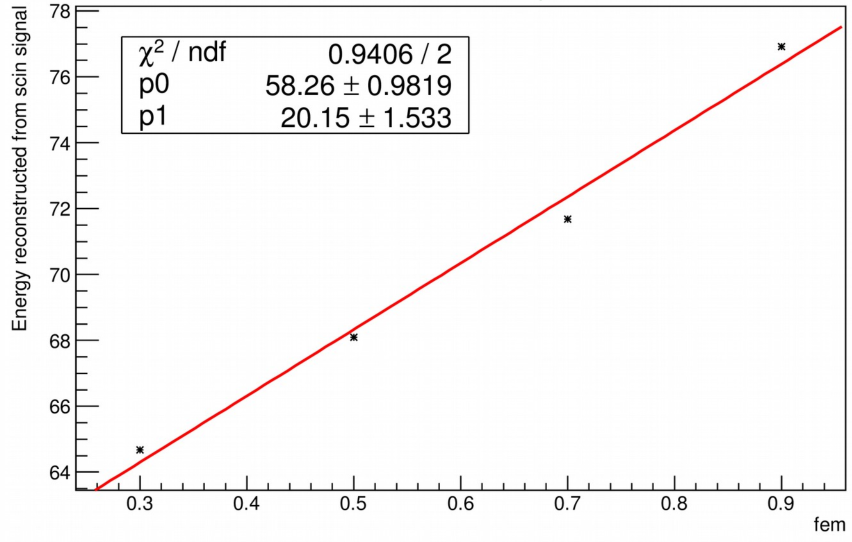
$\chi = (1 - (h/e)_{S}) / (1 - (h/e)_{Č}) = (E - S) / (E - C)$

Geant4 - hadronic performance (preliminary)

E(Č) vs. f_{em}

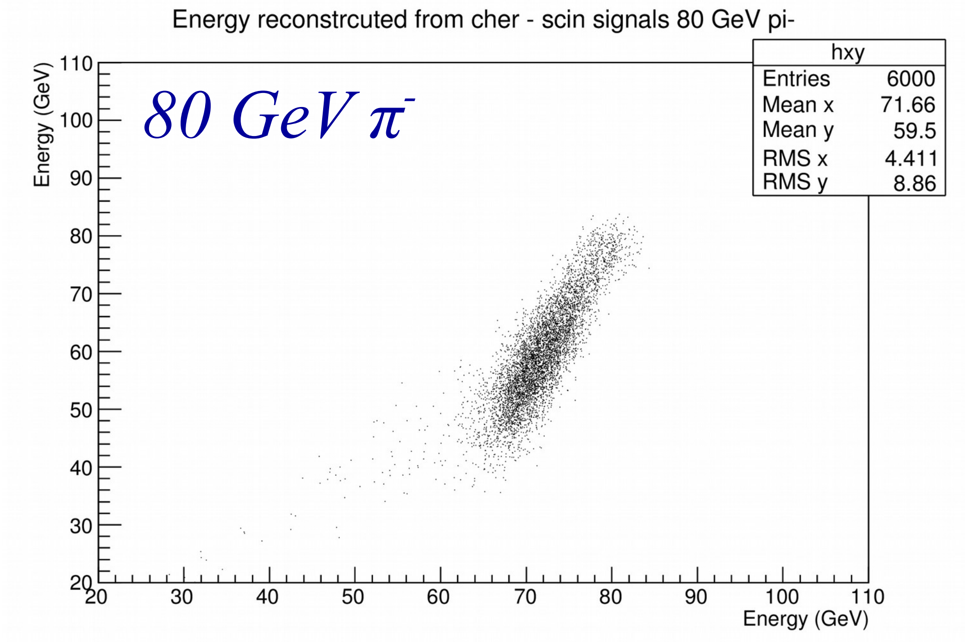


E(S) vs. f_{em}

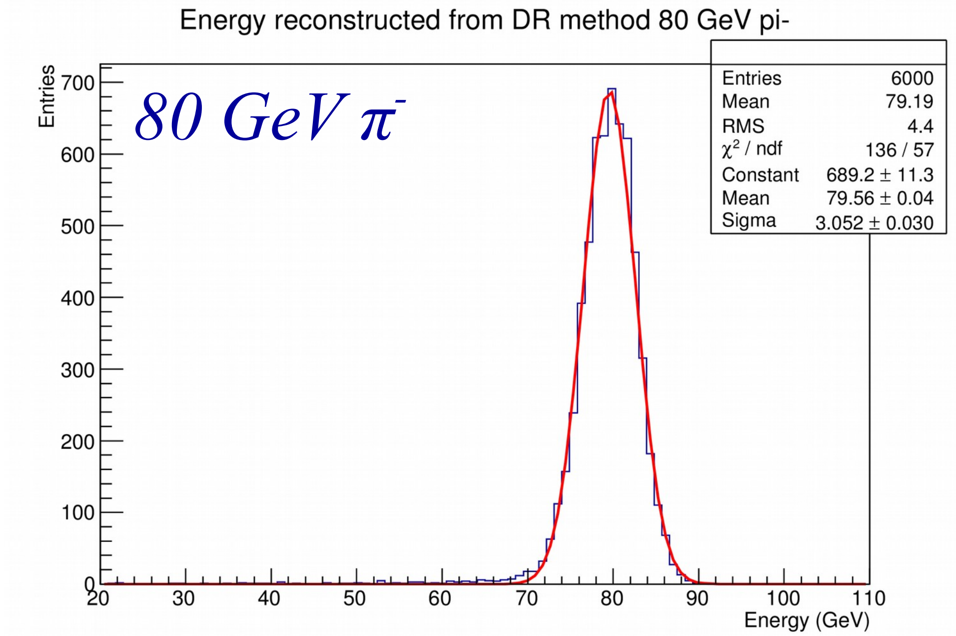


Copper

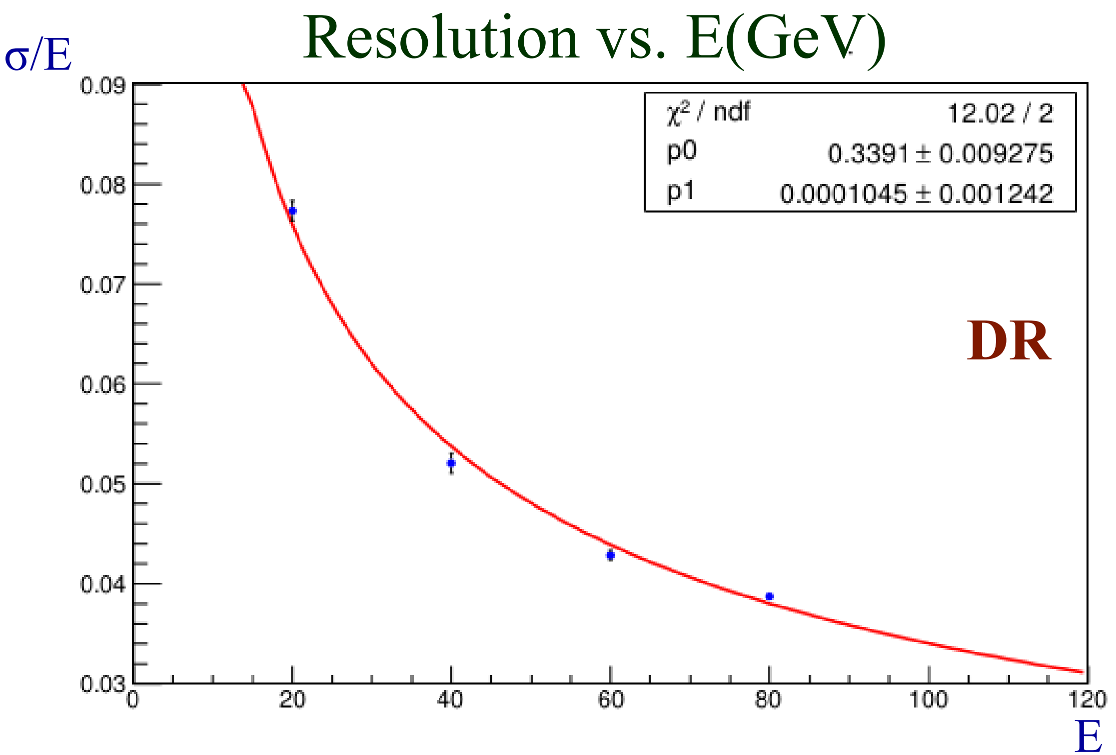
E(Č) vs. E(S)

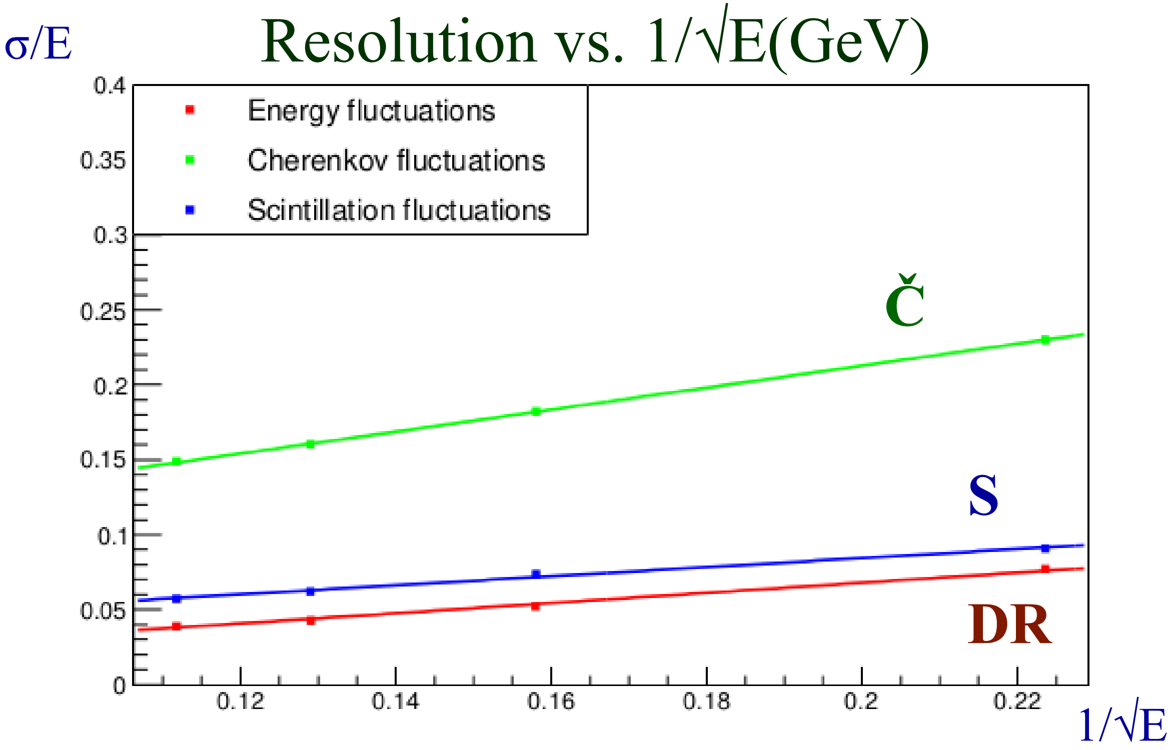


E (DR)



Geant4 – Cu hadronic performance (preliminary)





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

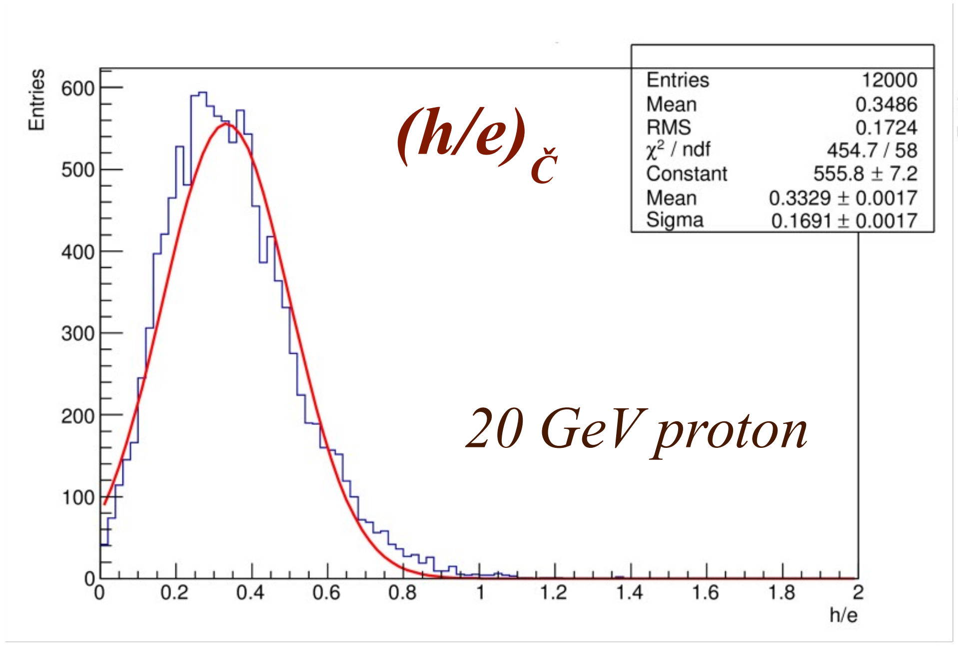
DR: ~34/√E (%)

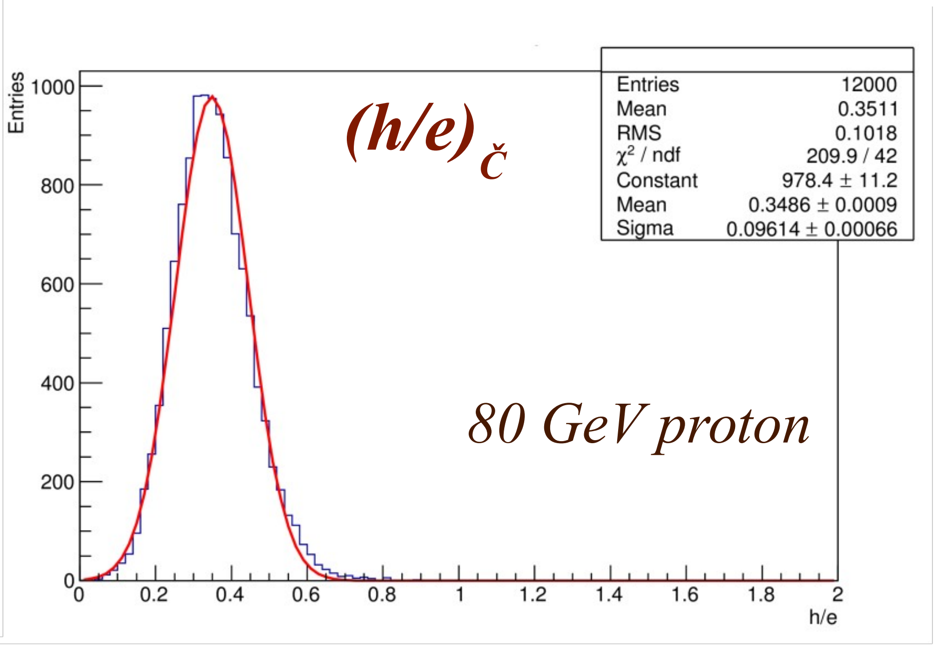
High-energy single-π resolutions:

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

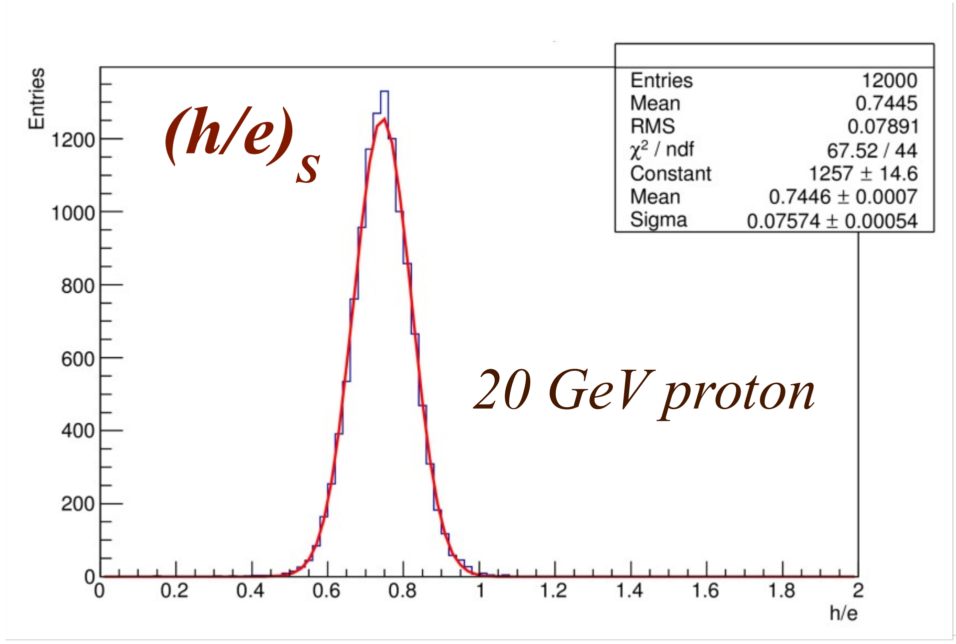
Geant4 – h/e factors for Copper

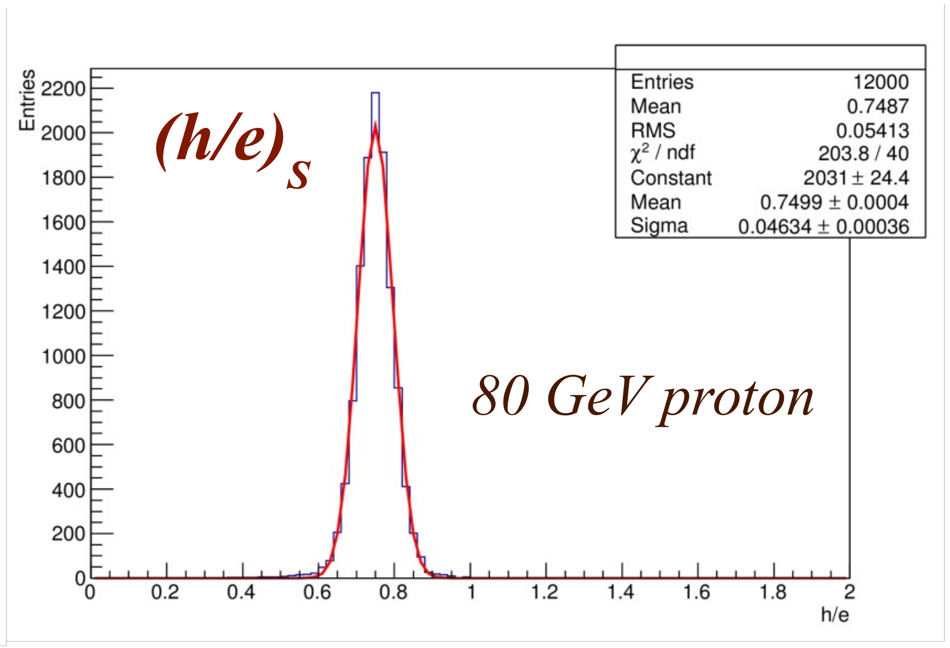
Copper





$(h/e)_{Č} \approx 0.35$

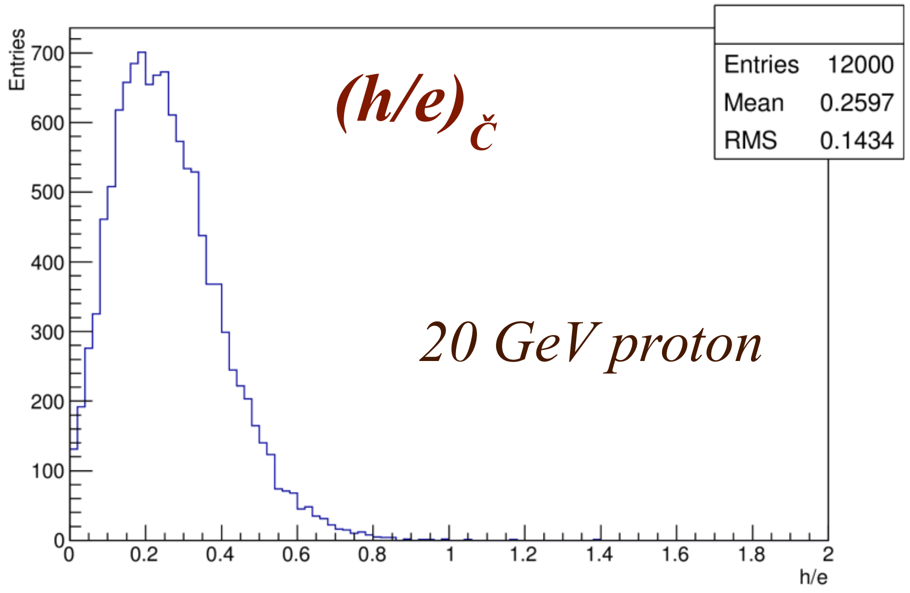


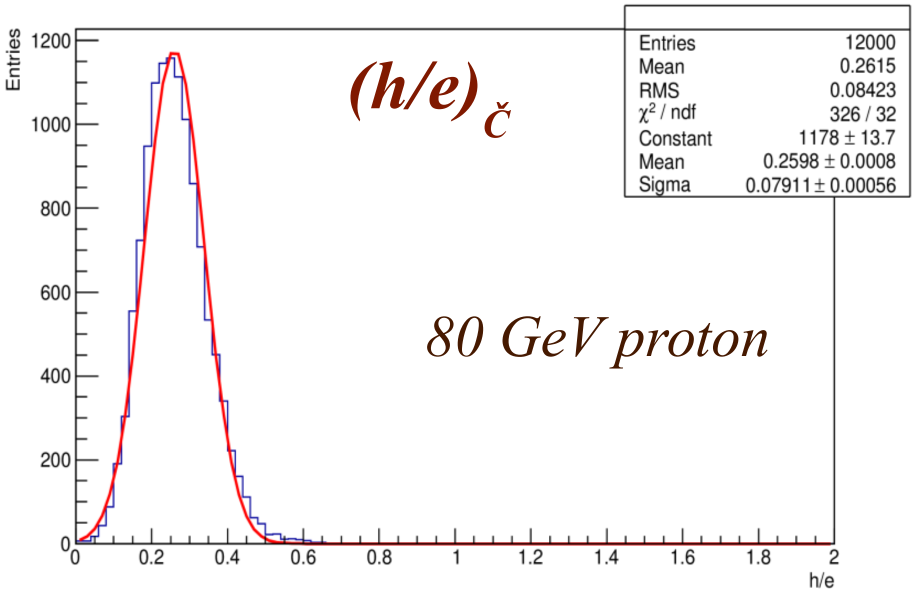


$(h/e)_{S} \approx 0.75$

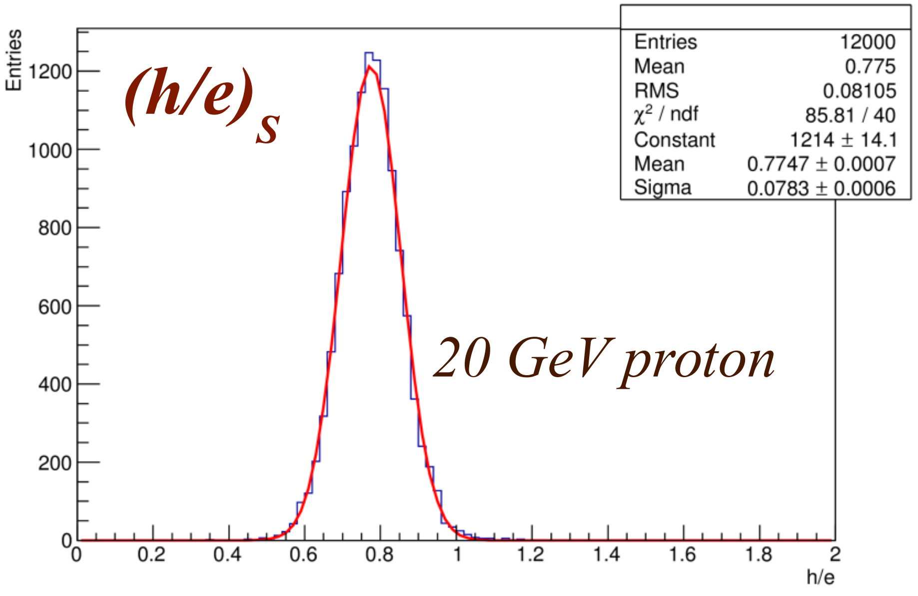
Geant4 – h/e factors for Lead

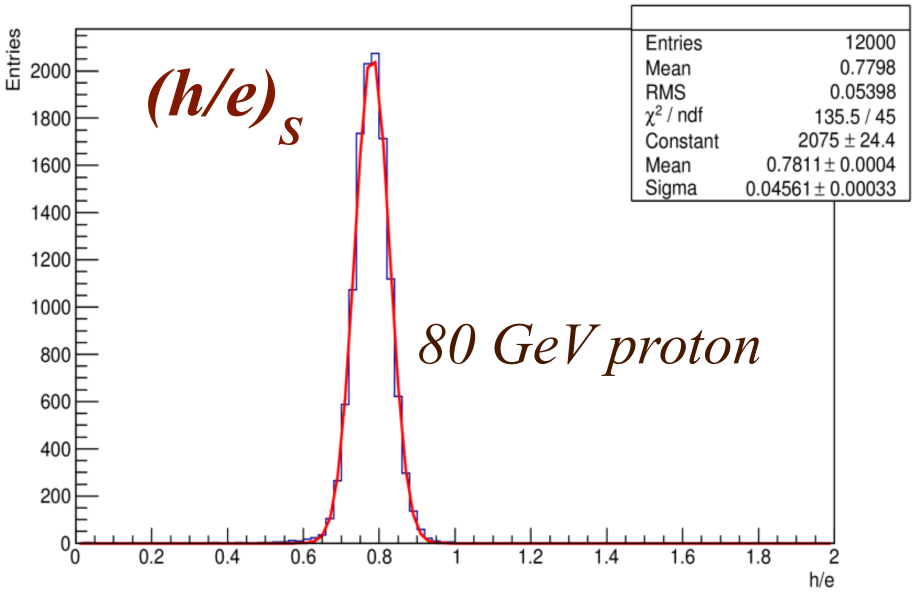
Lead





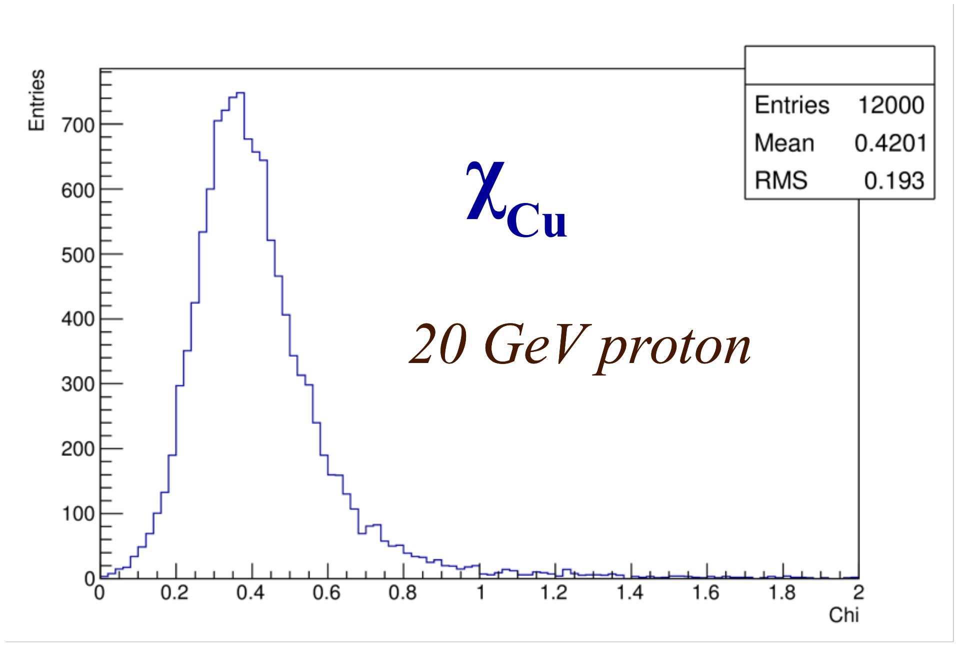
$(h/e)_{Č} \approx 0.26$





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

Geant4 – χ factors for Copper and Lead

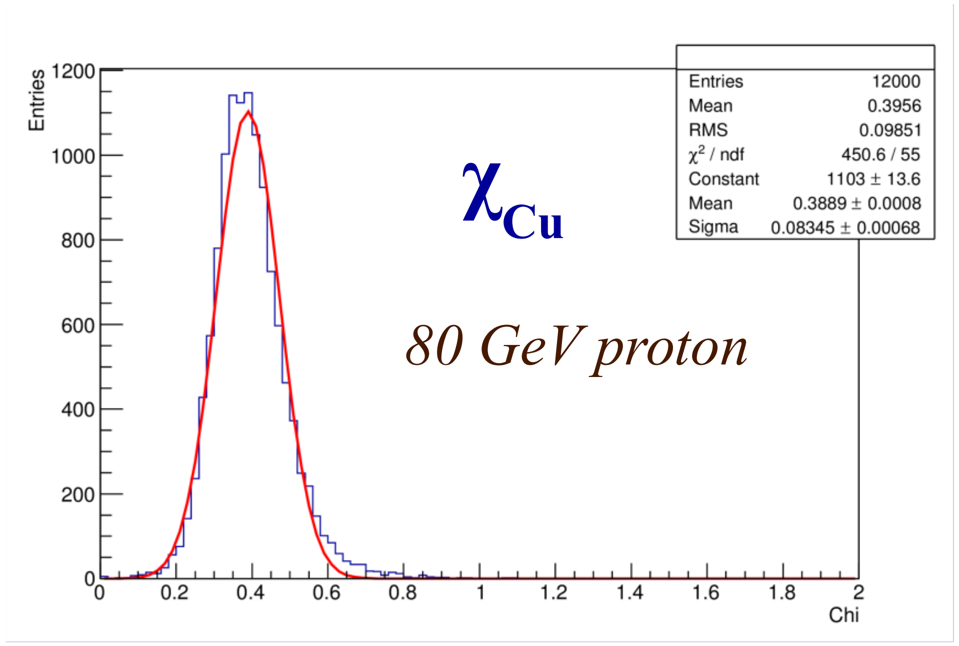


χ_{Cu}

20 GeV proton

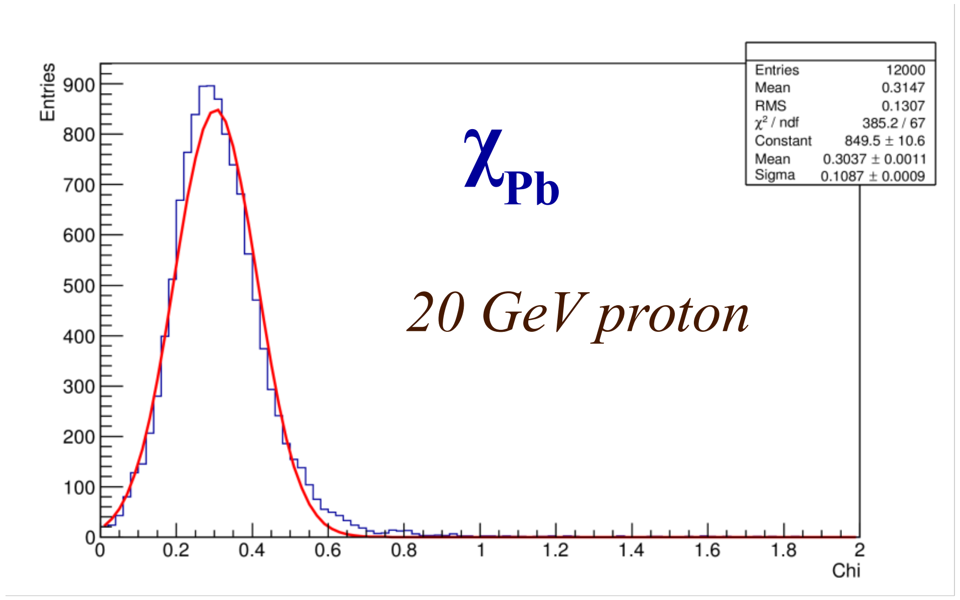
Copper

$$\chi_{Cu} \approx 0.39$$



χ_{Cu}

80 GeV proton

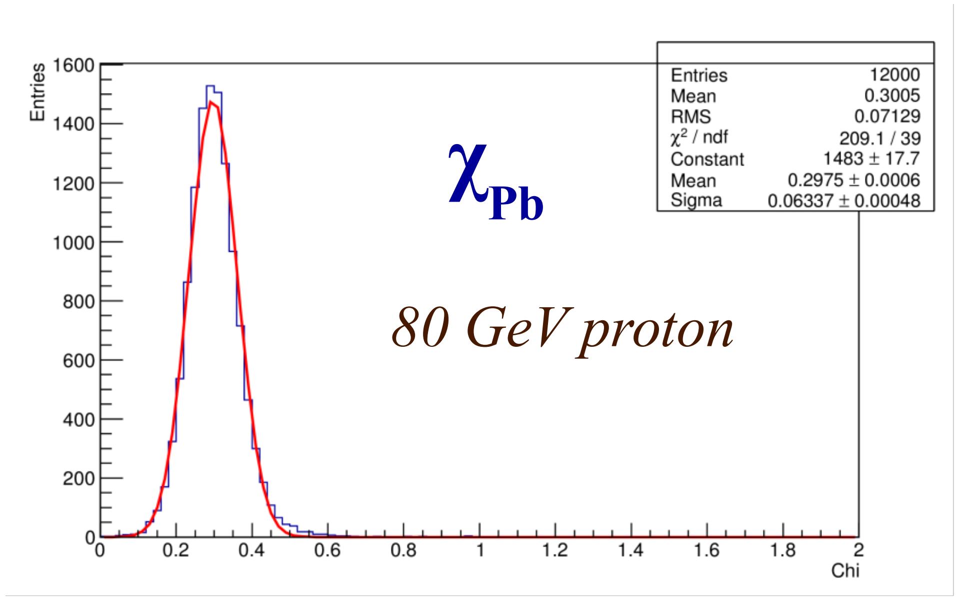


χ_{Pb}

20 GeV proton

Lead

$$\chi_{Pb} \approx 0.30$$

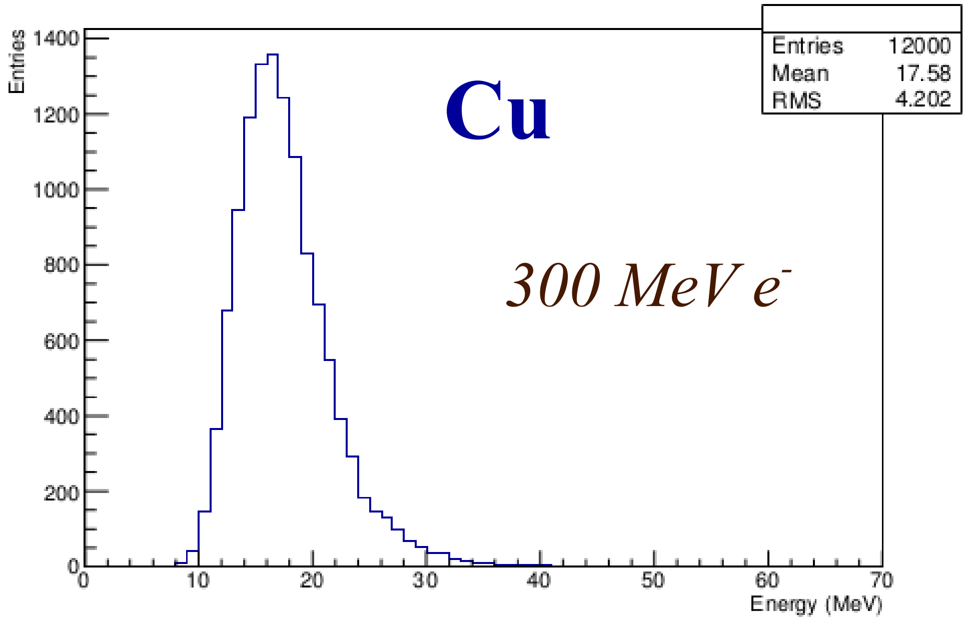


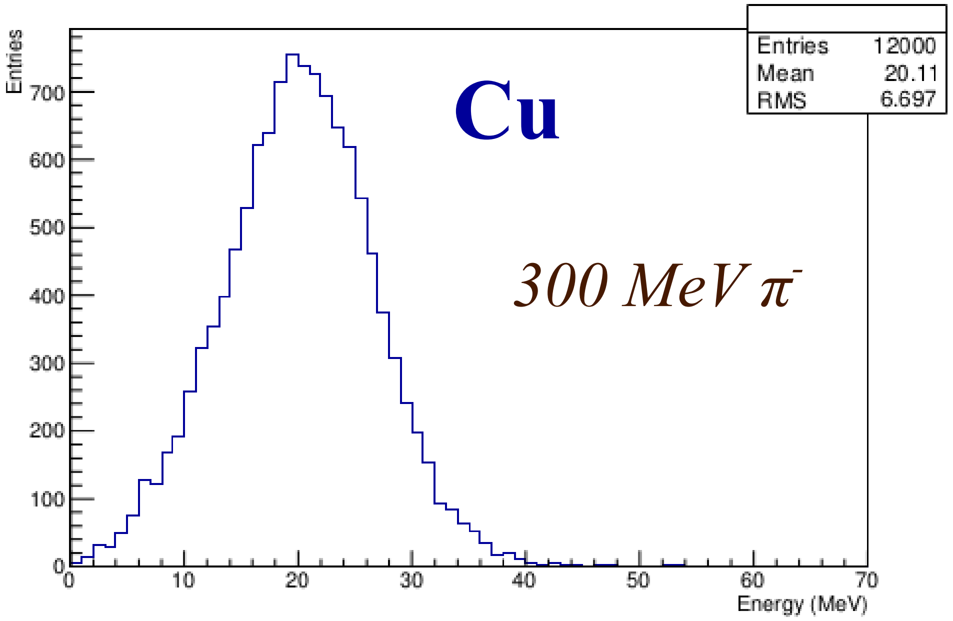
χ_{Pb}

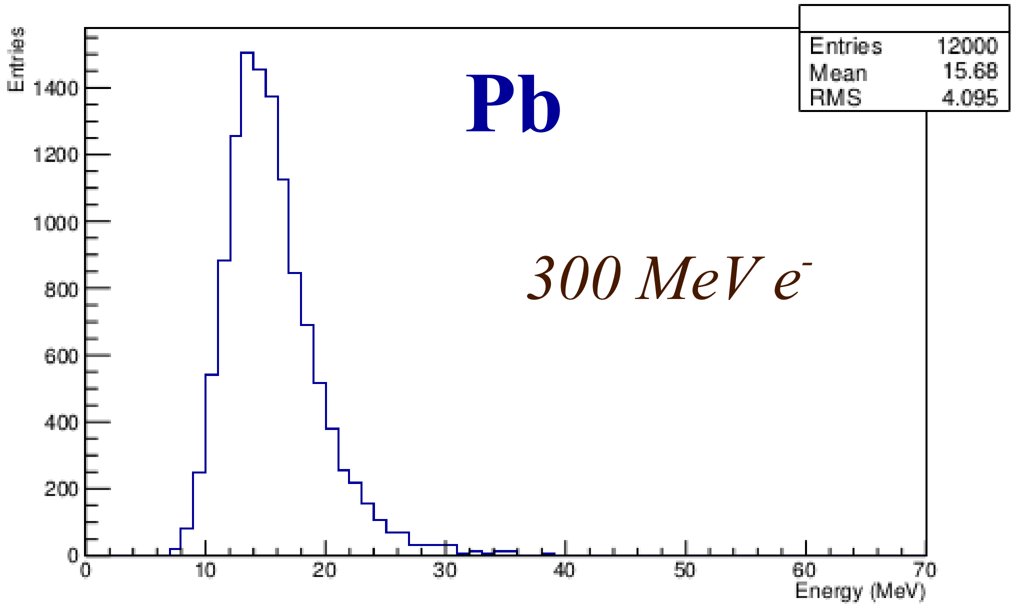
80 GeV proton

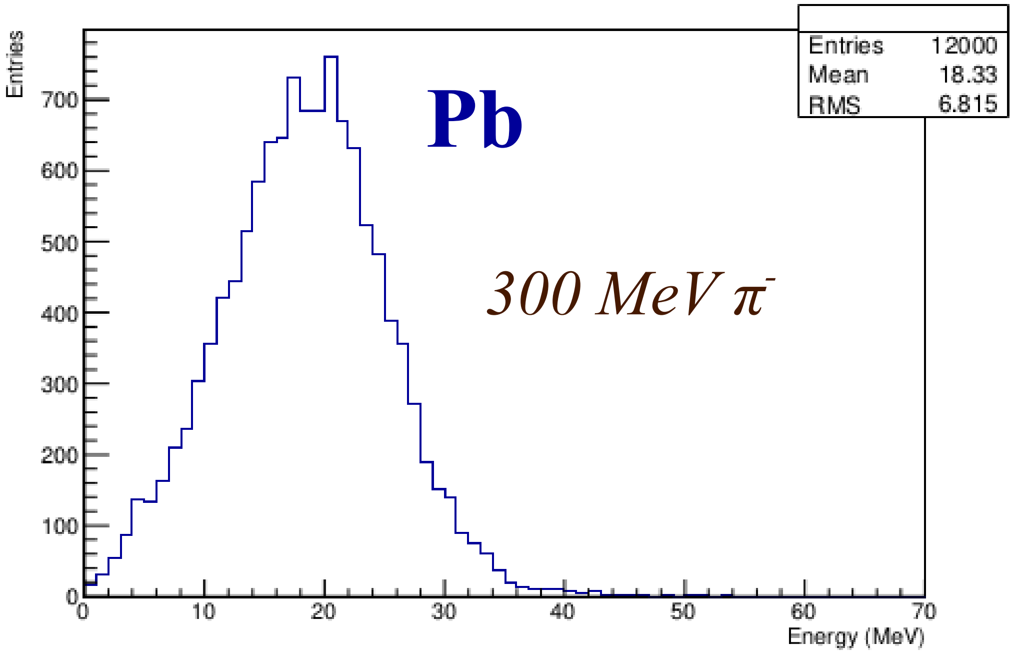
Low-energy performance - Copper vs. Lead

Energy deposited in scintillating fibres



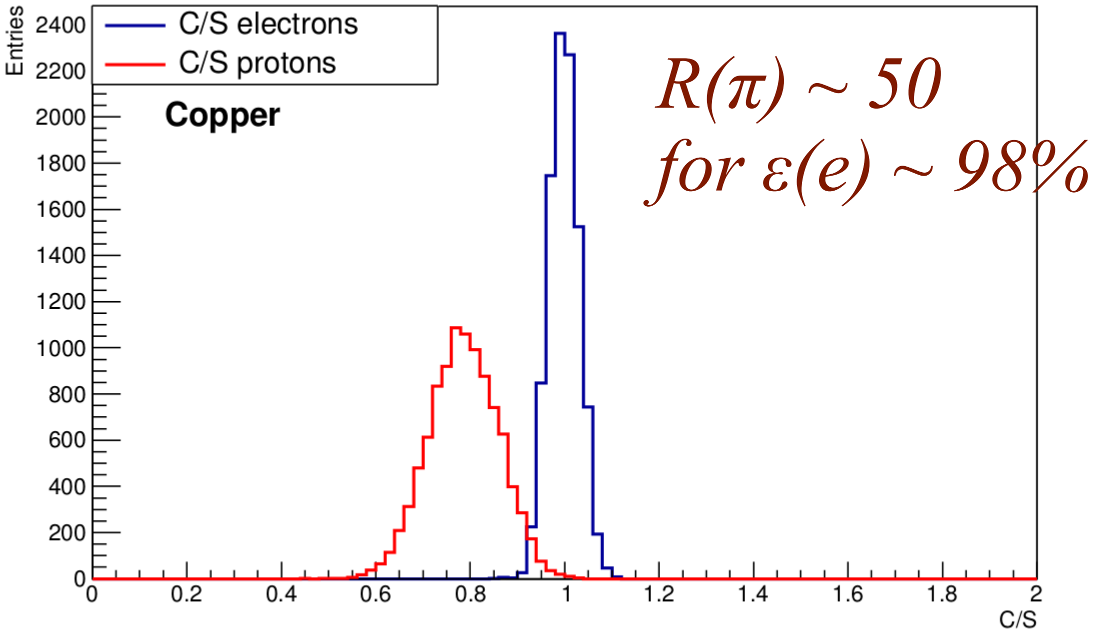




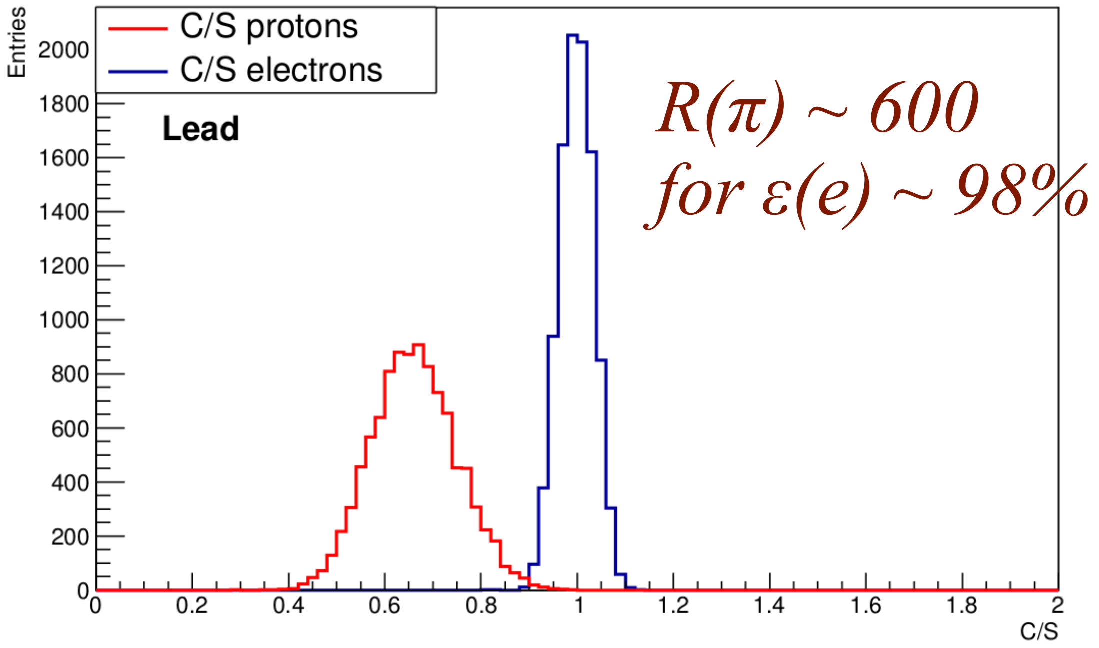


Particle Id & W/Z - Copper vs. Lead

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

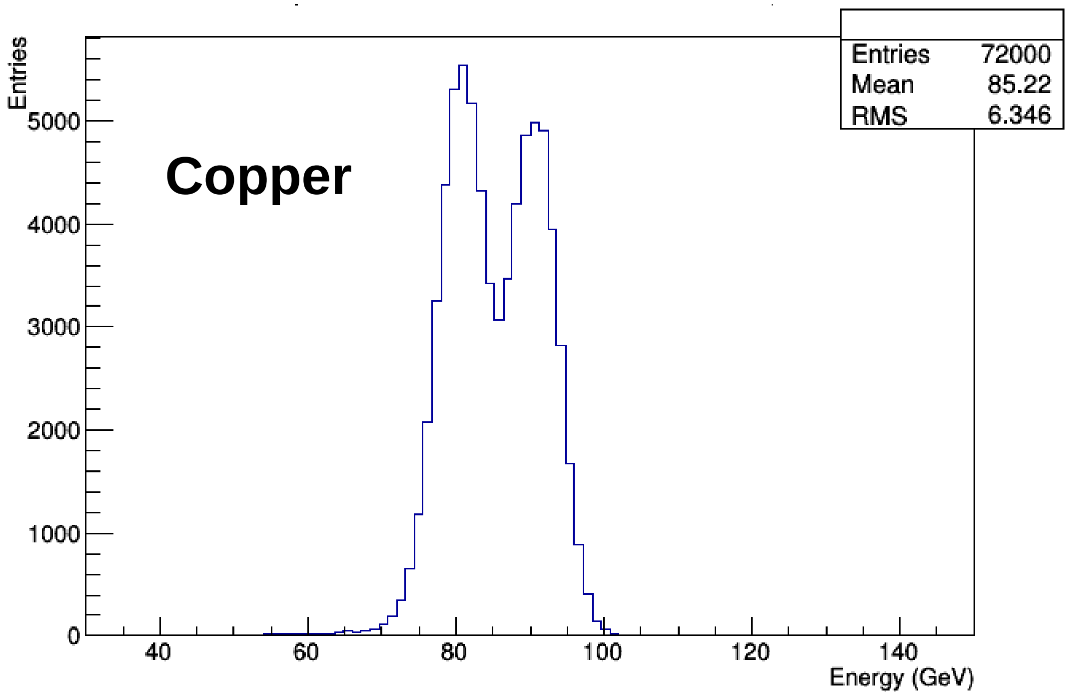


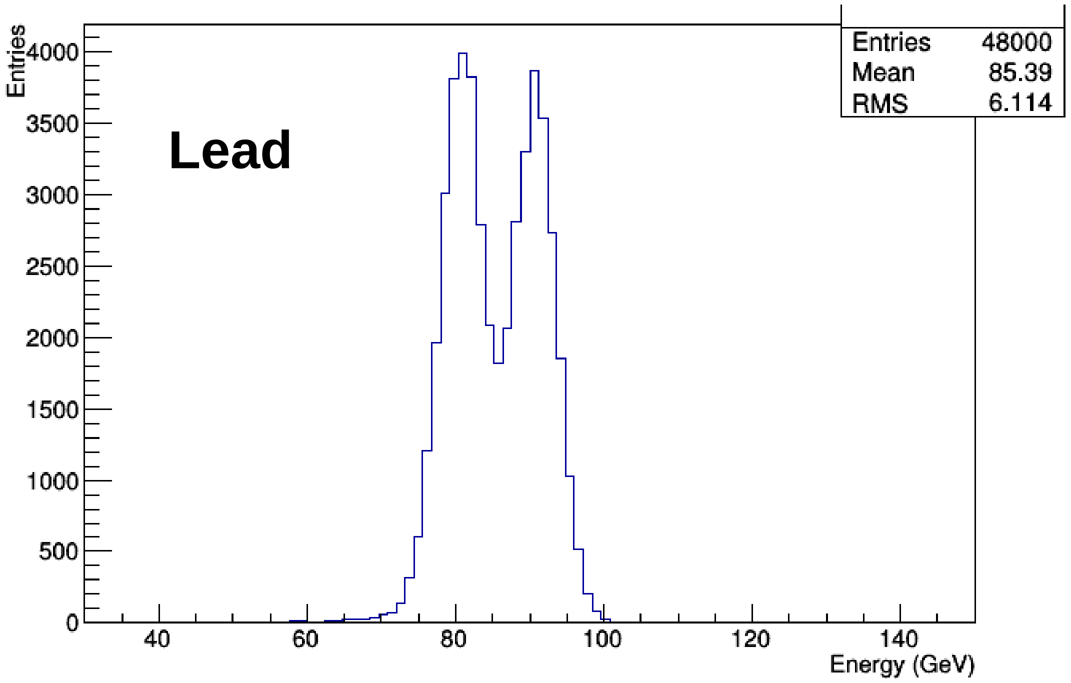
R(π) ~ 50
for ε(e) ~ 98%



R(π) ~ 600
for ε(e) ~ 98%

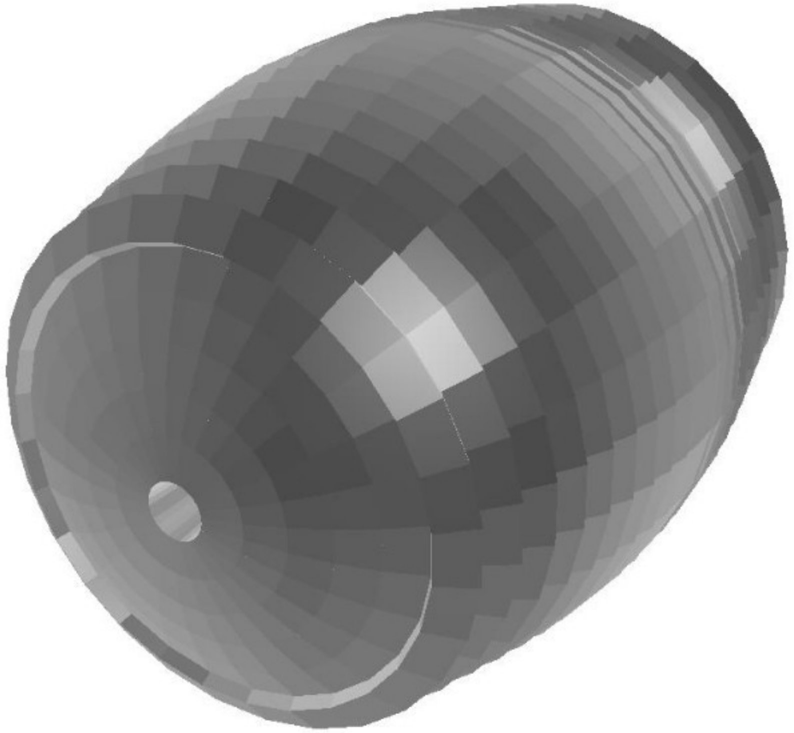
Multiple hadrons, 81 & 91 GeV

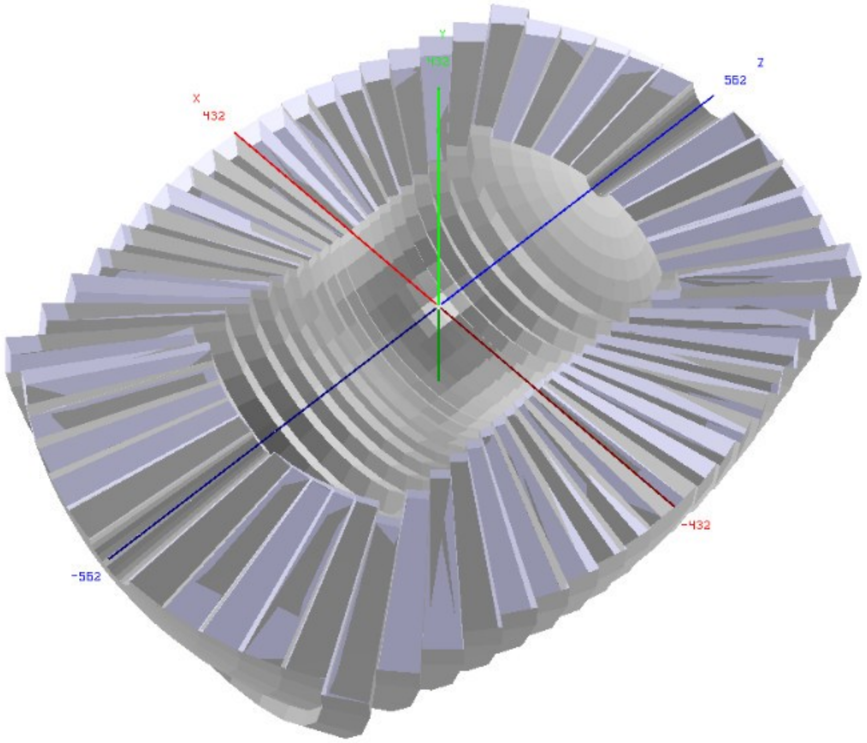


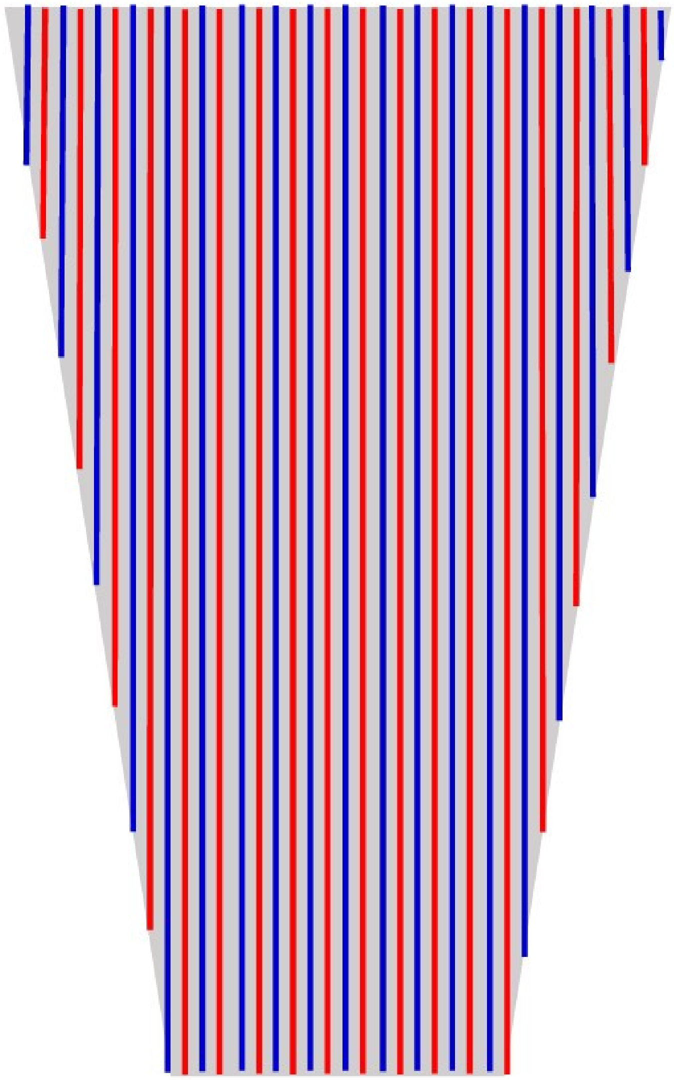


4π Simulations

Dual-readout calorimeter description for CepC/FCCee simulation sw:







a) full coverage

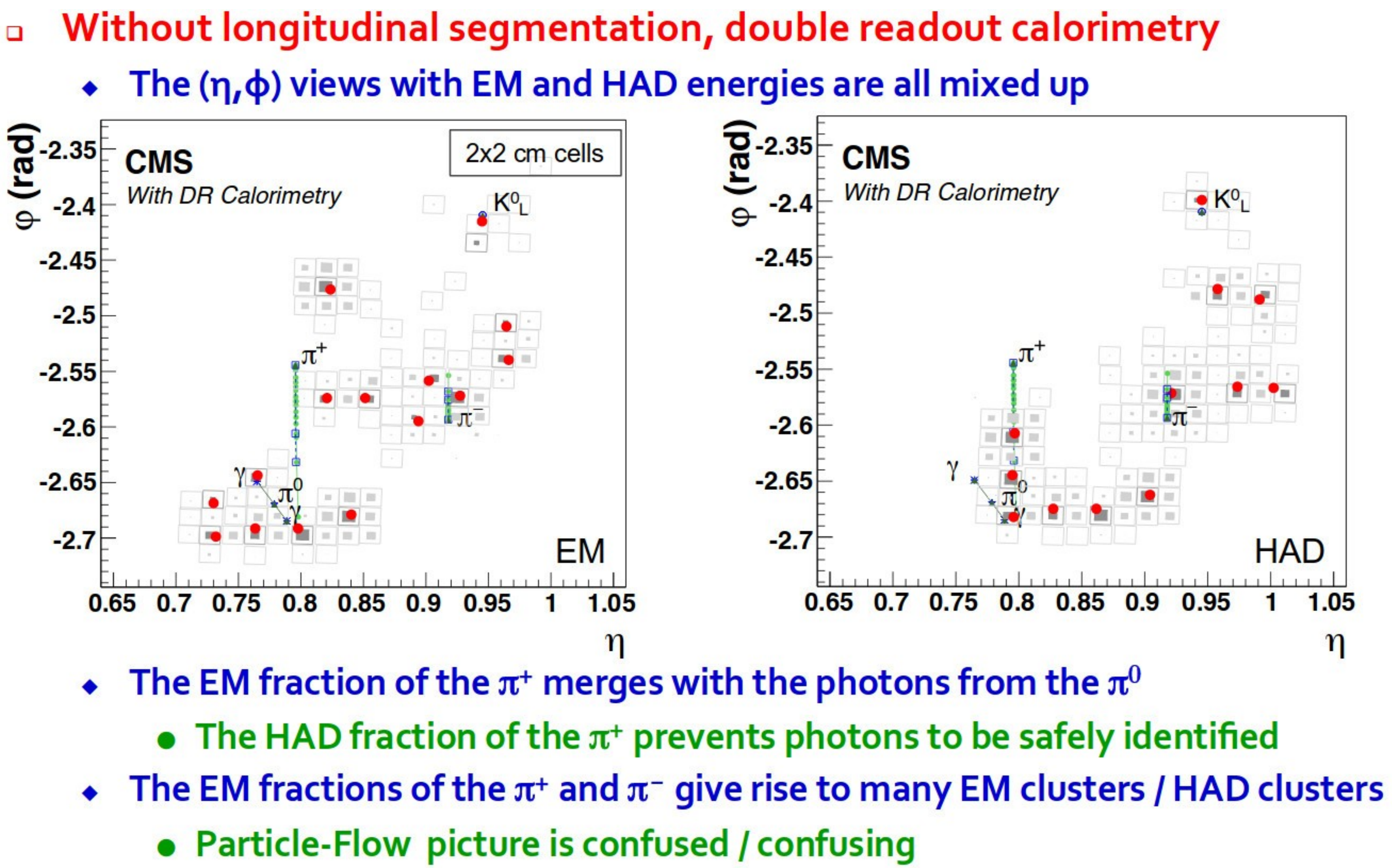
b) projective geometry

Longitudinal Segmentation & PFA

Last but not least:

addressing the issue of overlapping hadronic and em showers

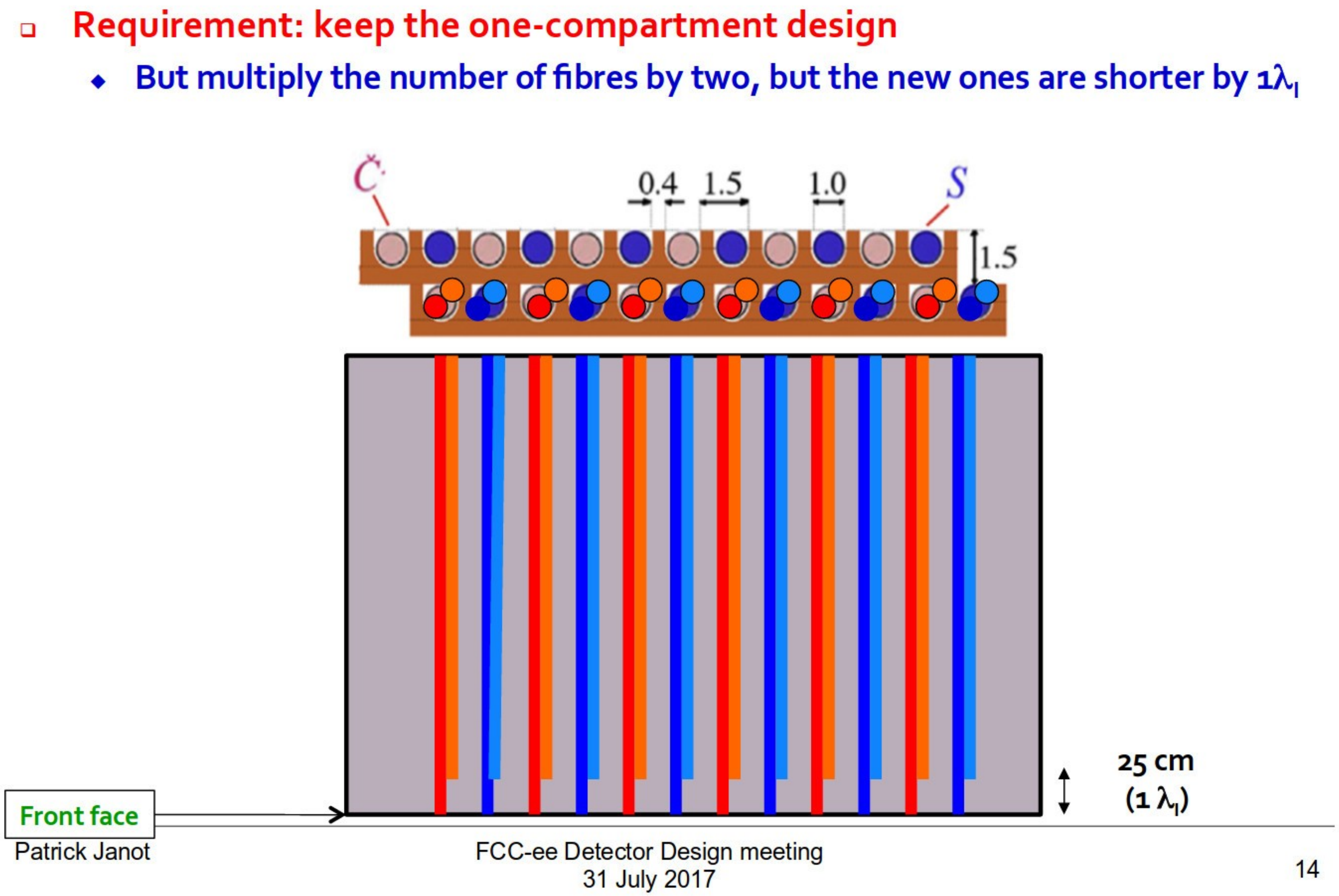
→ Patrick Janot proposes longitudinal segmentation (and PF w/ DR)



- **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 $1\lambda_I$

Patrick Janot

FCC-ee Detector Design meeting
31 July 2017

14

Alternative approaches ? Measure time properties (ToT, PkT, Ti, Tf) ?

→ A real-time (feature-extraction) processor ?

Mechanics/Sensors/Electronics

Mechanics:

from ~O(~1 cm^2) → 5x5 / 10x10 cm^2 few modules

Sensors:

→ *SiPM performance: go to 10x10 μm^2, 10000 pixels, sensors*

→ *follow developments on SiC devices (meant to be solar light blind and provide exclusive UV sensitivity) ?*

Electronics:

search for SiPM tailored multi-channel ASIC.s

→ *test channel grouping / adding (1, 3, 5, 6 channels summed up)*

target: demonstrate the feasibility of a scalable solution made of ~10x10 cm^2 modules w/ 5000-10000 fibres, individually coupled to electronics

Readout

We have this:

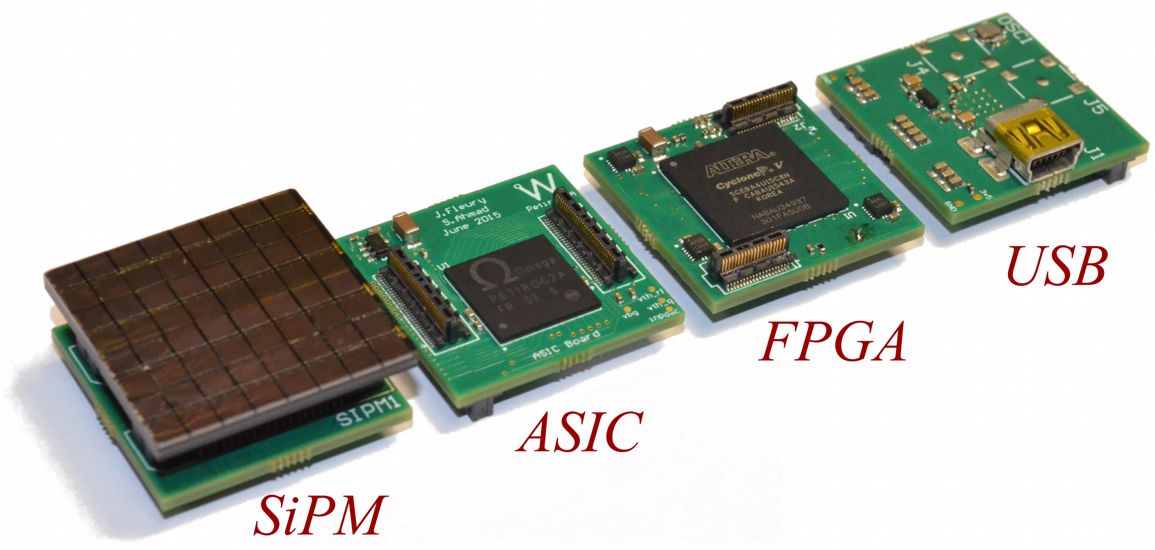
:-)

- *32-channel read out system*
- *FPGA based charge integration algorithm*
- *data: event timecode and integrated charge for all pixels*

→ need something more tailored (shorter integration time, time information, peak/charge ratio, ...)

but we would like this:

:-(



first step: ASIC (to be identified)

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

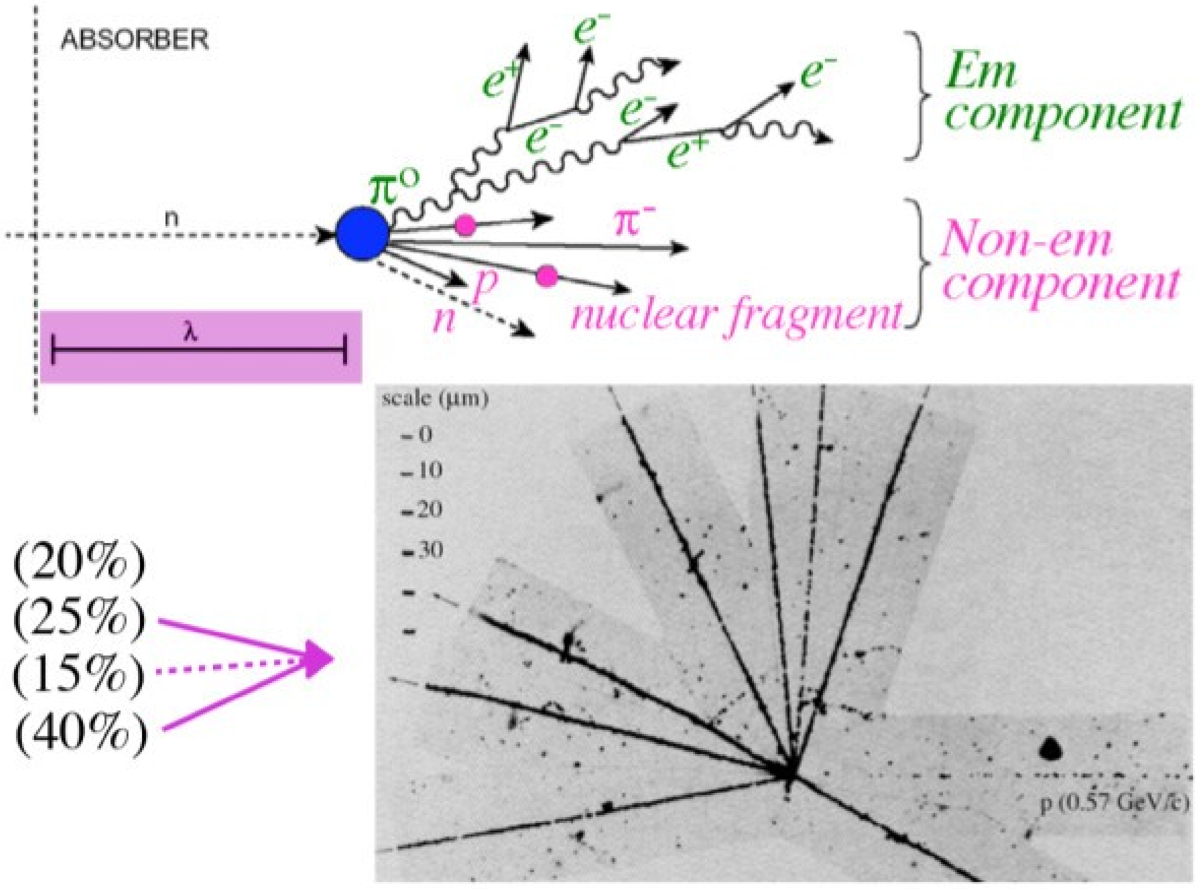
b) 3-year R&D plan on mechanics, frontend electronics, readout:

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:



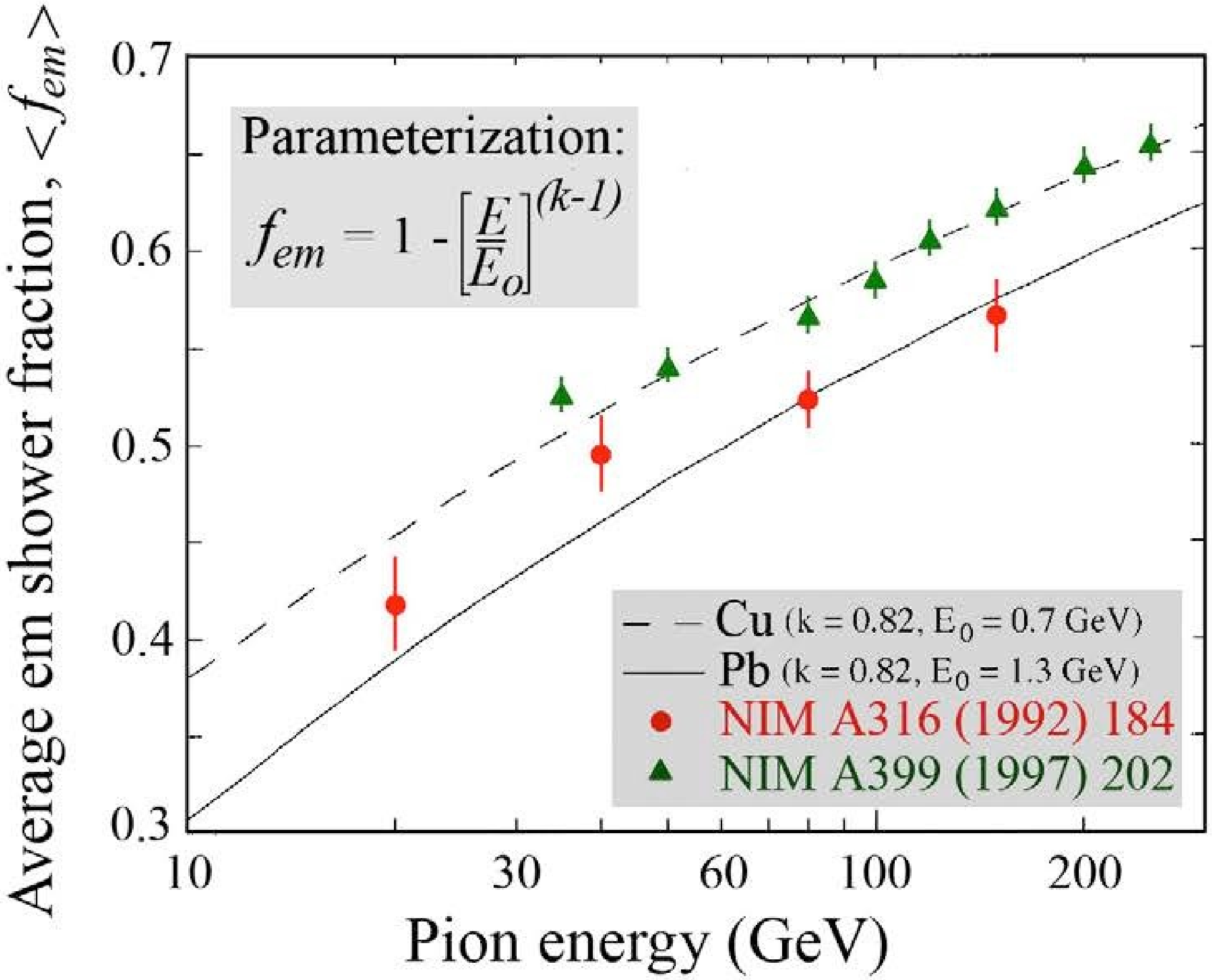
- *Electromagnetic component*
  - electrons, photons
  - neutral pions → 2 γ
- *Hadronic (non-em) component*
  - charged hadrons $\pi^\pm$,$K^\pm$ (20%)
  - nuclear fragments, p (25%)
  - neutrons, soft γ's (15%)
  - break-up of nuclei (*"invisible"*) (40%)

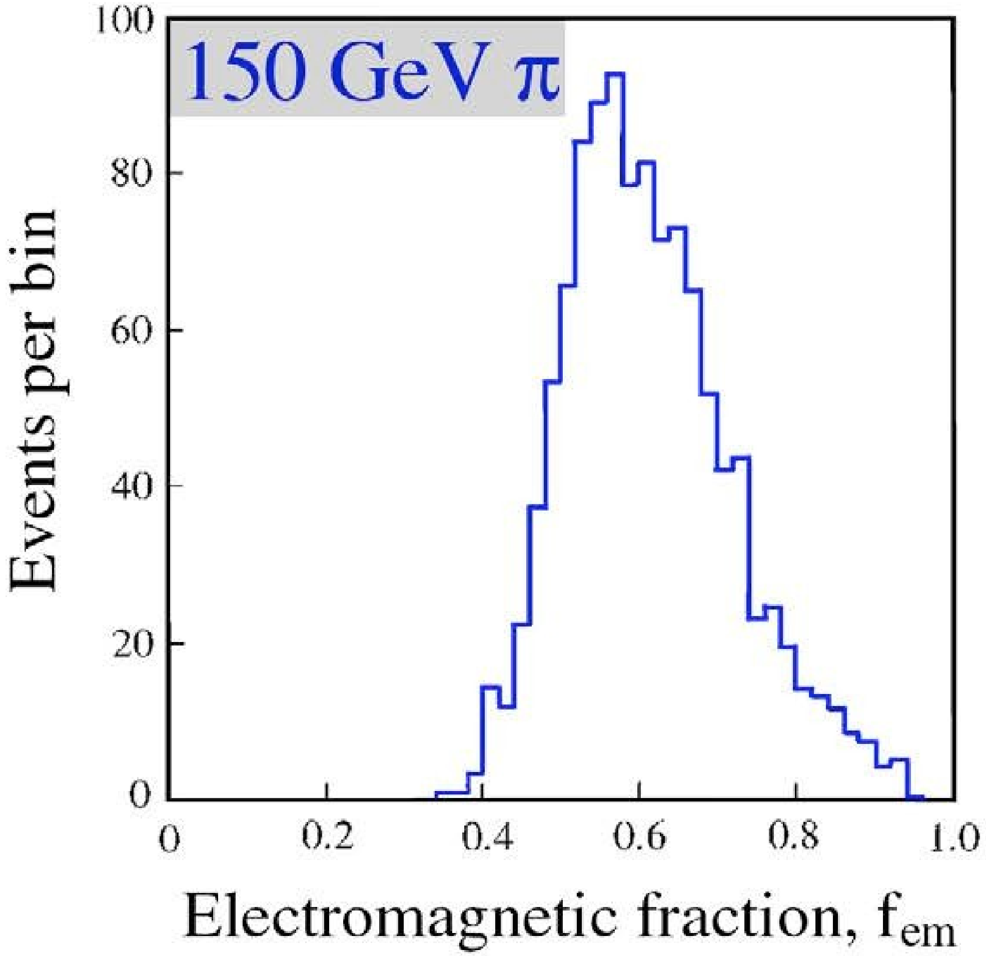
To be faced in hadronic energy measurements:

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

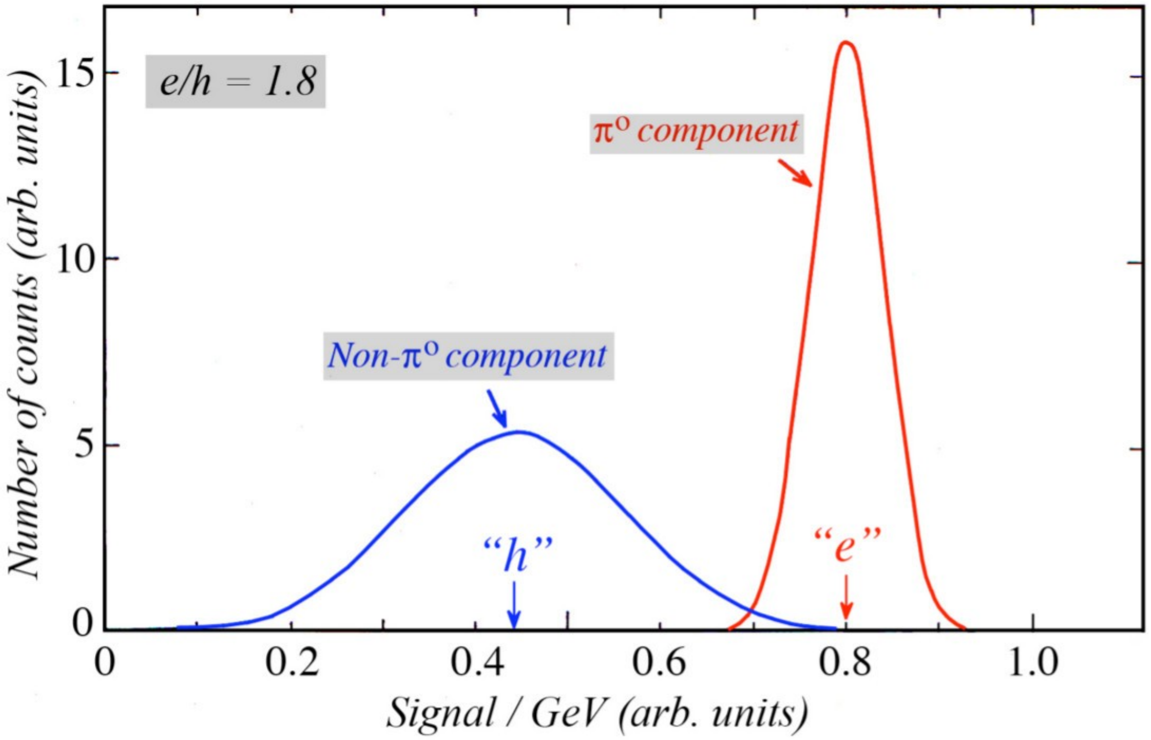
Fluctuations in f_{em} are
large and non-Poissonian

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

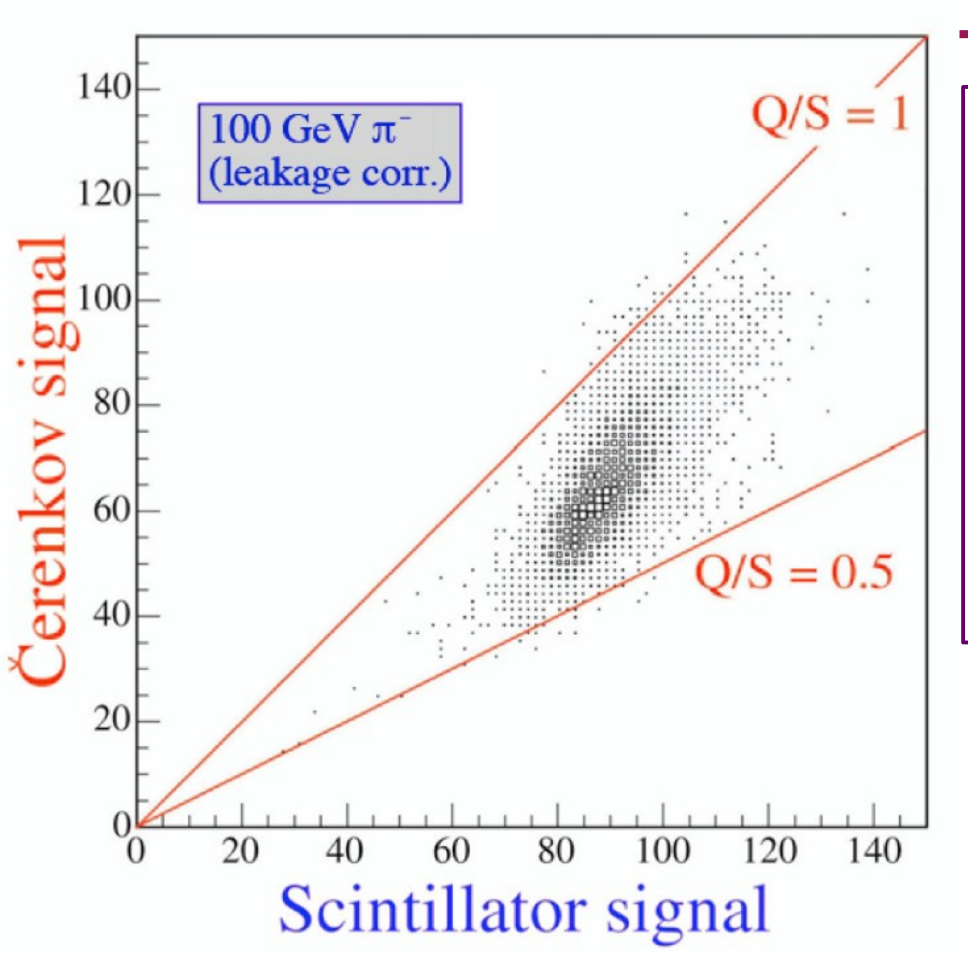
Don’t spoil em resolution to get e/h = 1 (i.e. keep e/h > 1) *BUT* measure f_{em} event-by-event

⟹ *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)

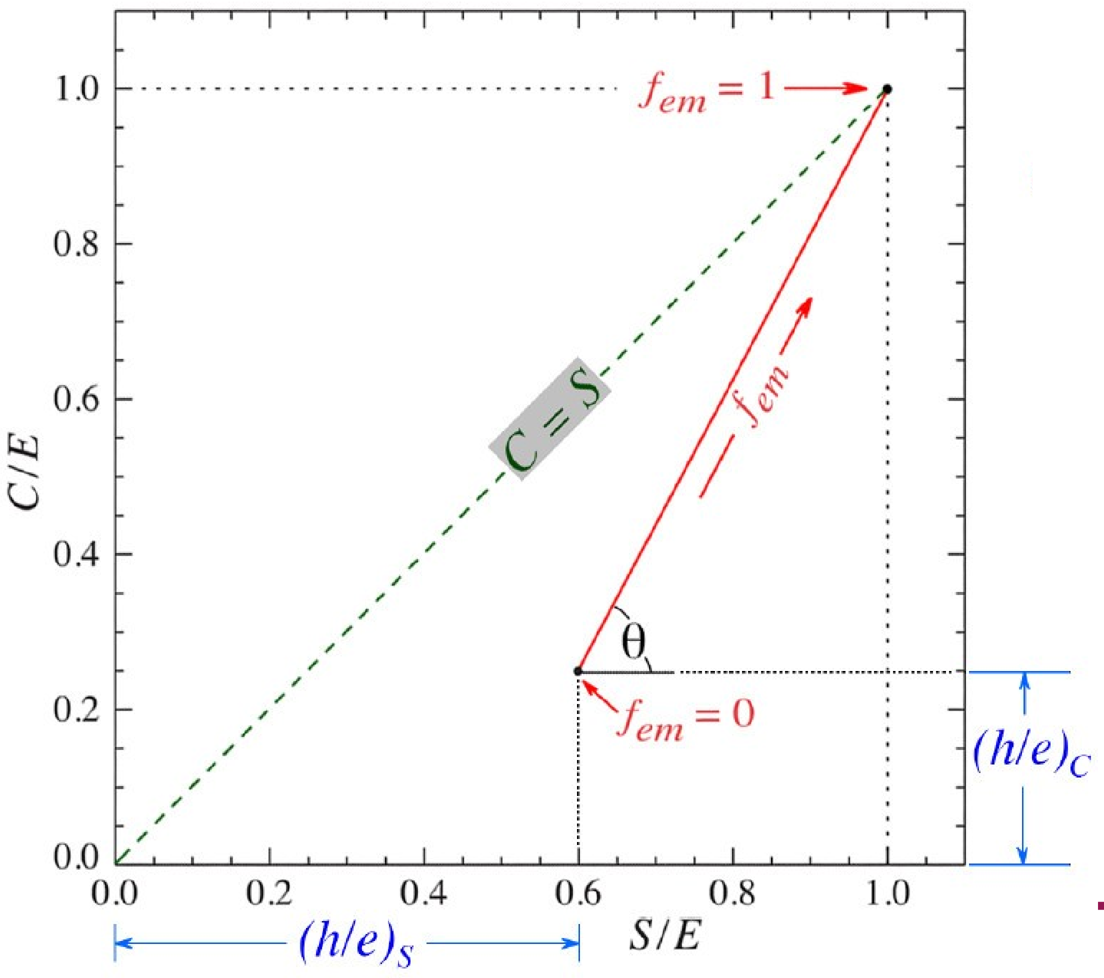
DREAM: How to Determine f_{em} ?



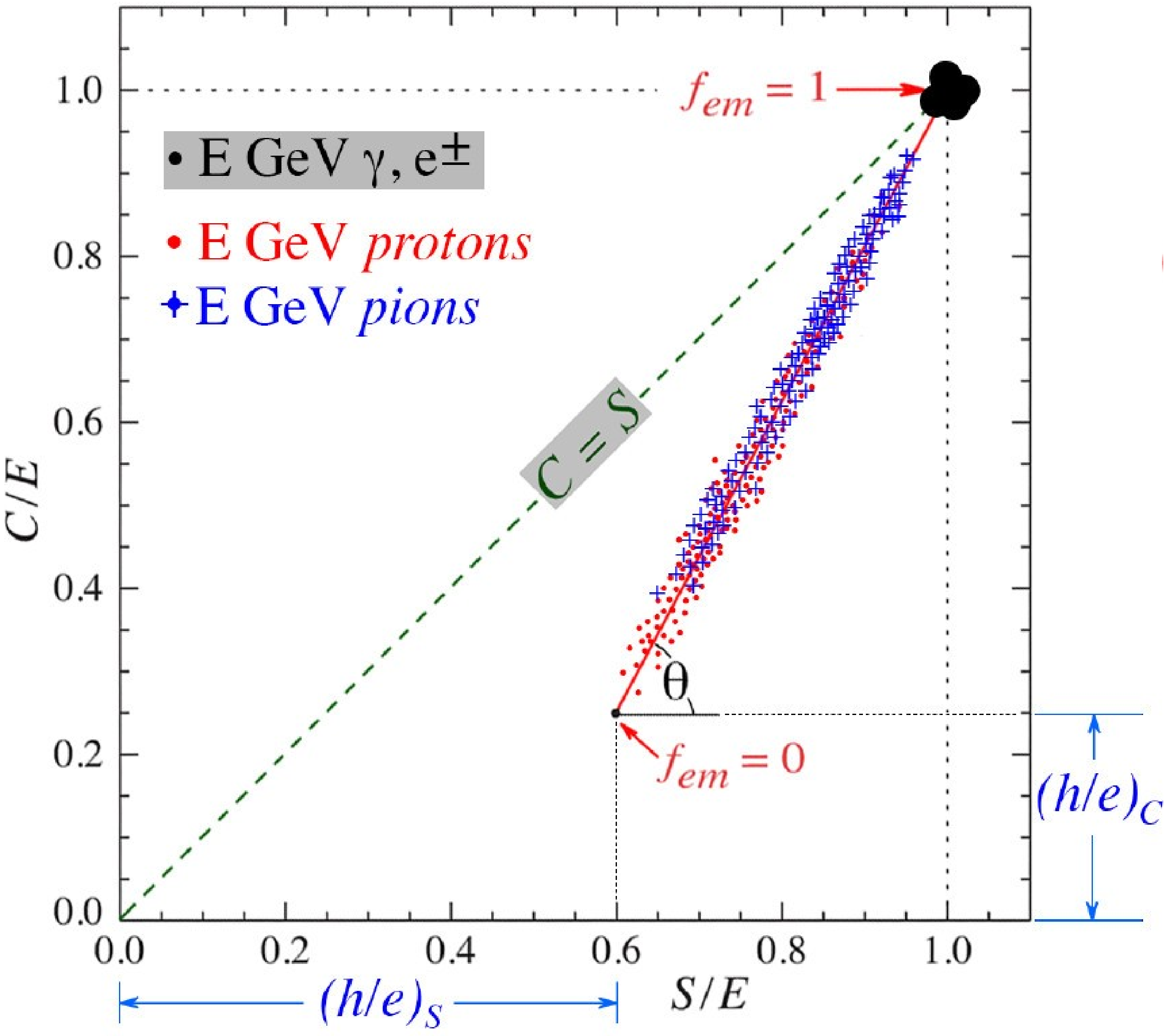
- $S = E \times [\ f_{em} + (h/e)_s \times (1 - f_{em})\ ]$
- $C = E \times [\ f_{em} + (h/e)_c \times (1 - f_{em})\ ]$
- e.g. if: (e/h) = 1.3(S) .vs. 4.7(C)
- $\longrightarrow S/C = (0.21 + 0.79 \times f_{em}) / (0.77 + 0.23 \times f_{em})$

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

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



Dual Readout at Work (1)



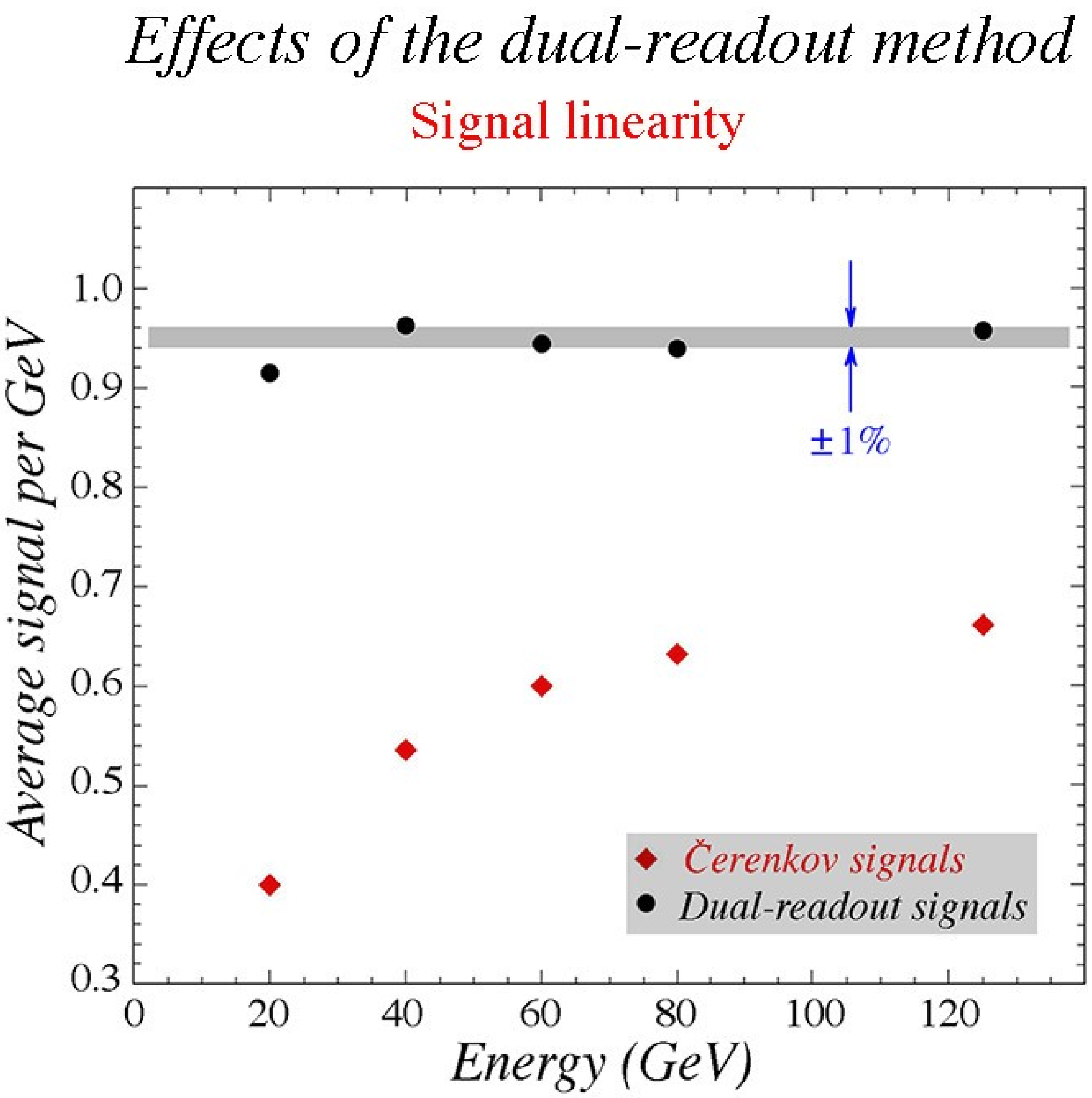
$$\cot g\,\theta = \frac{1-(h/e)_S}{1-(h/e)_C} = \chi$$

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

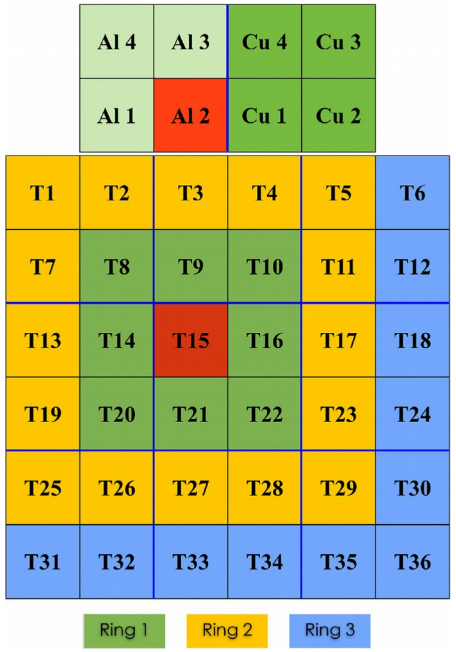
$$E = \frac{S-\chi C}{1-\chi}$$

is universally valid

Dual Readout at Work (2)



Dual Readout at Work (3)



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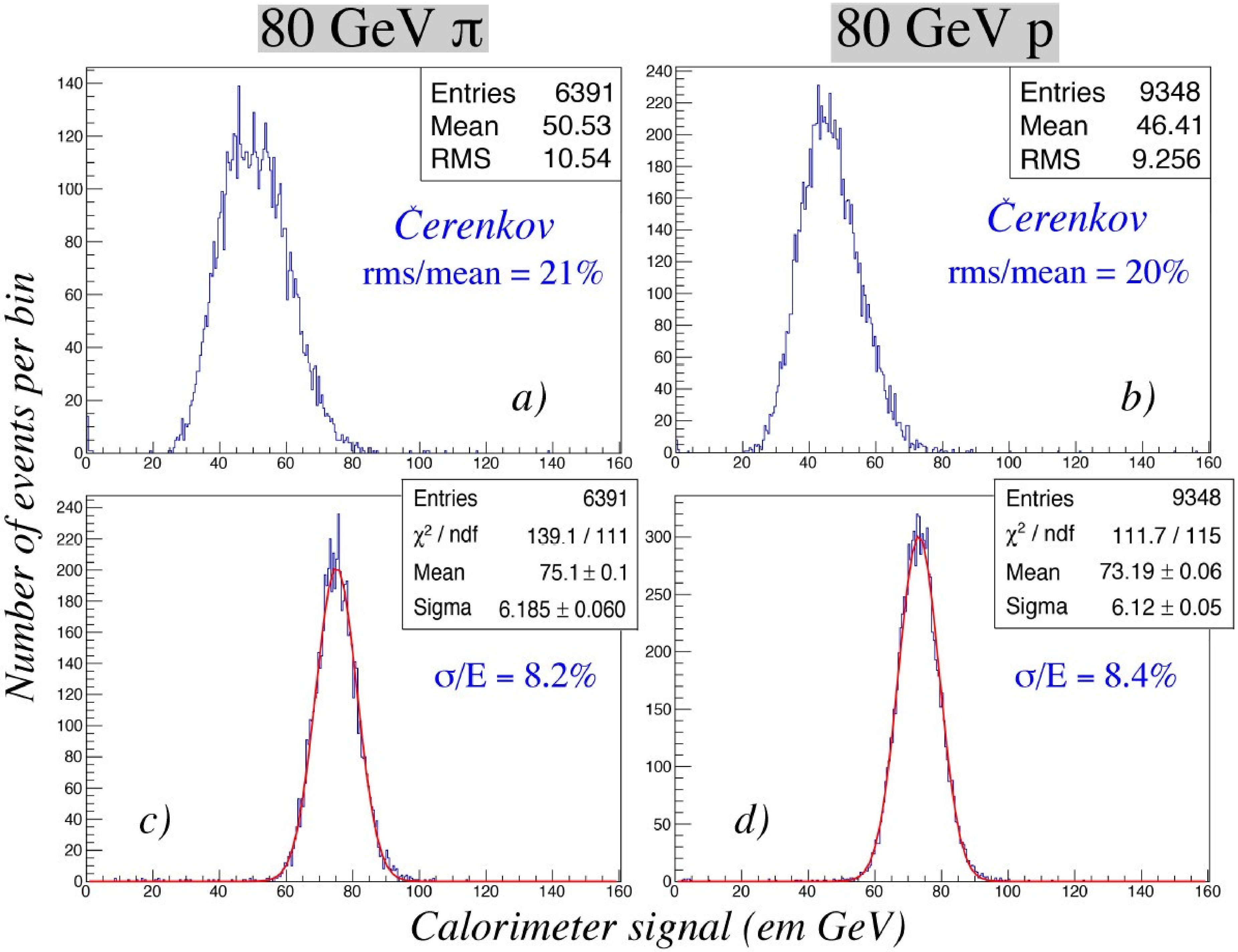
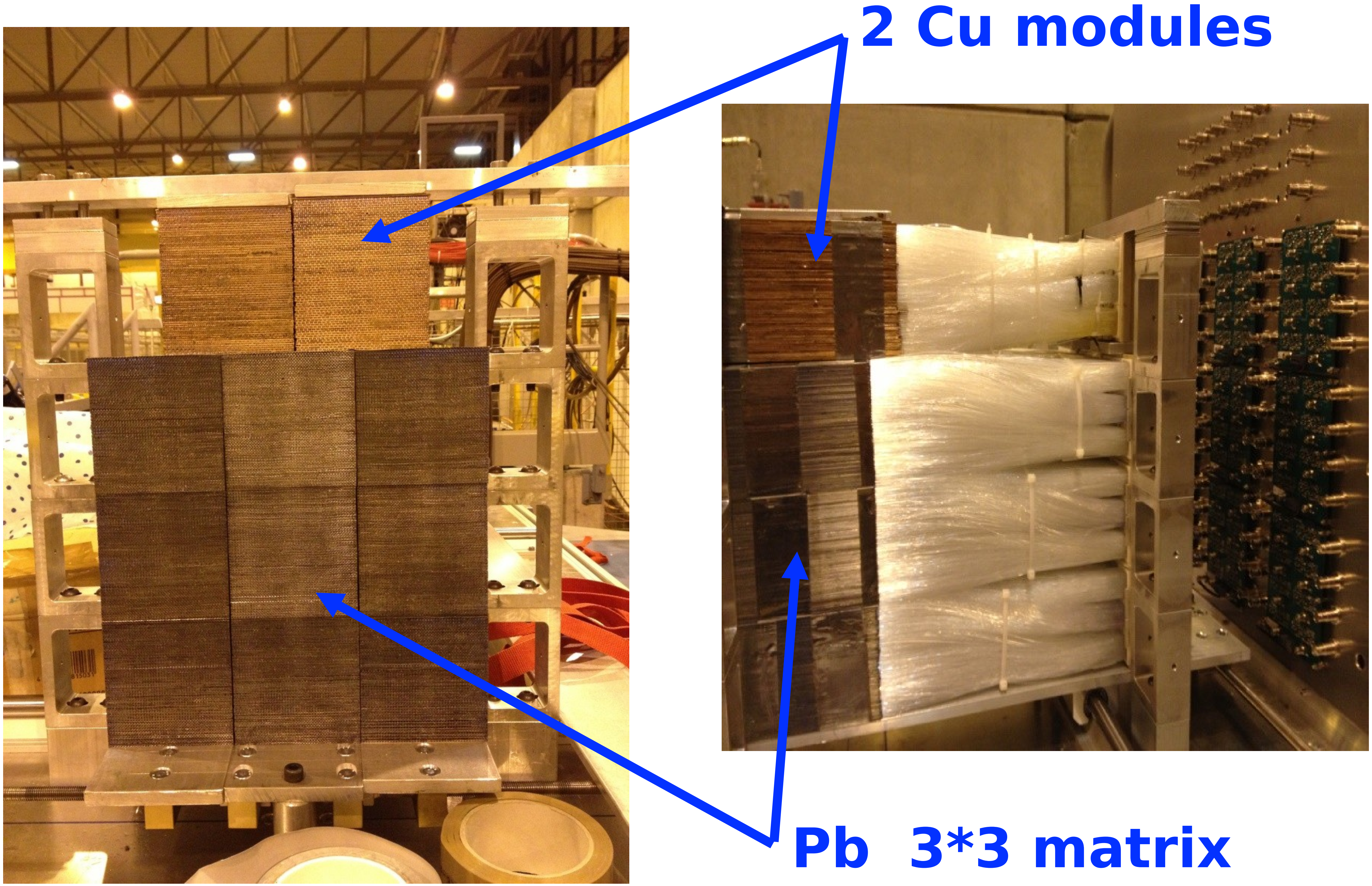


RD52 DR Fibre Calorimeters



2 Cu modules

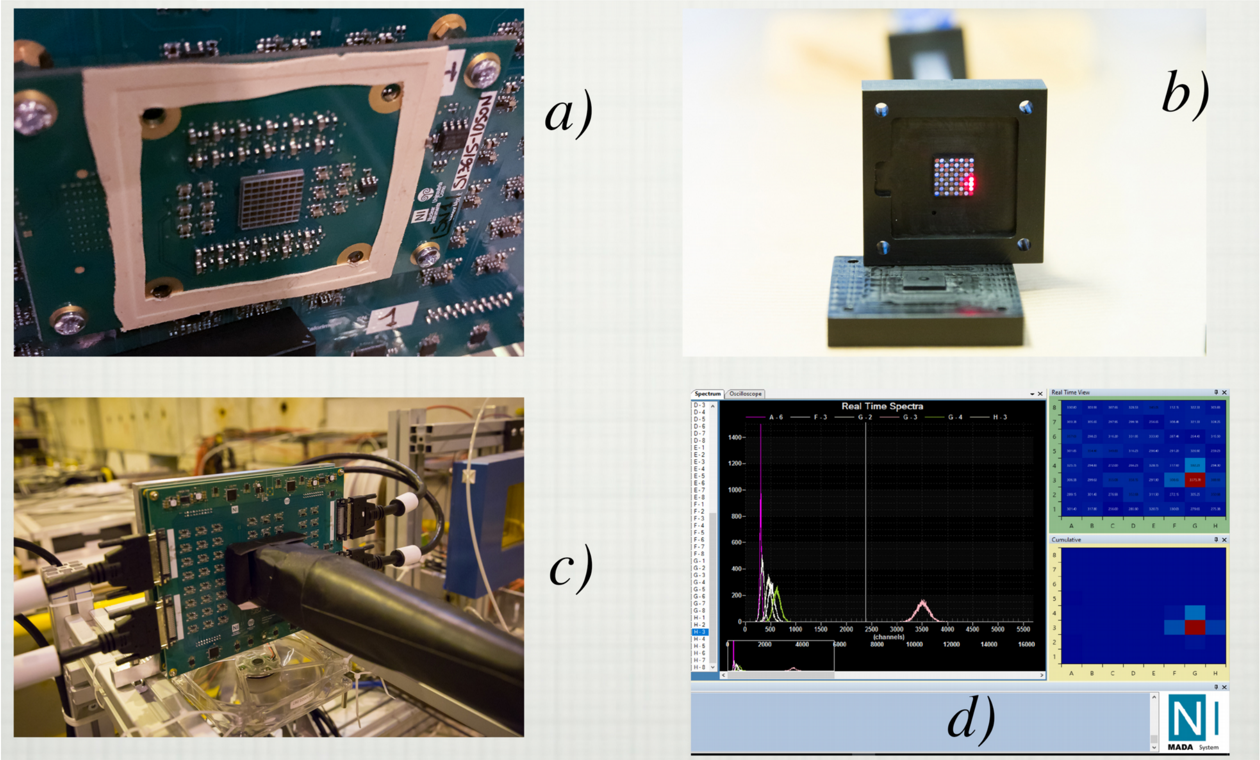
Pb 3*3 matrix

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



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

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

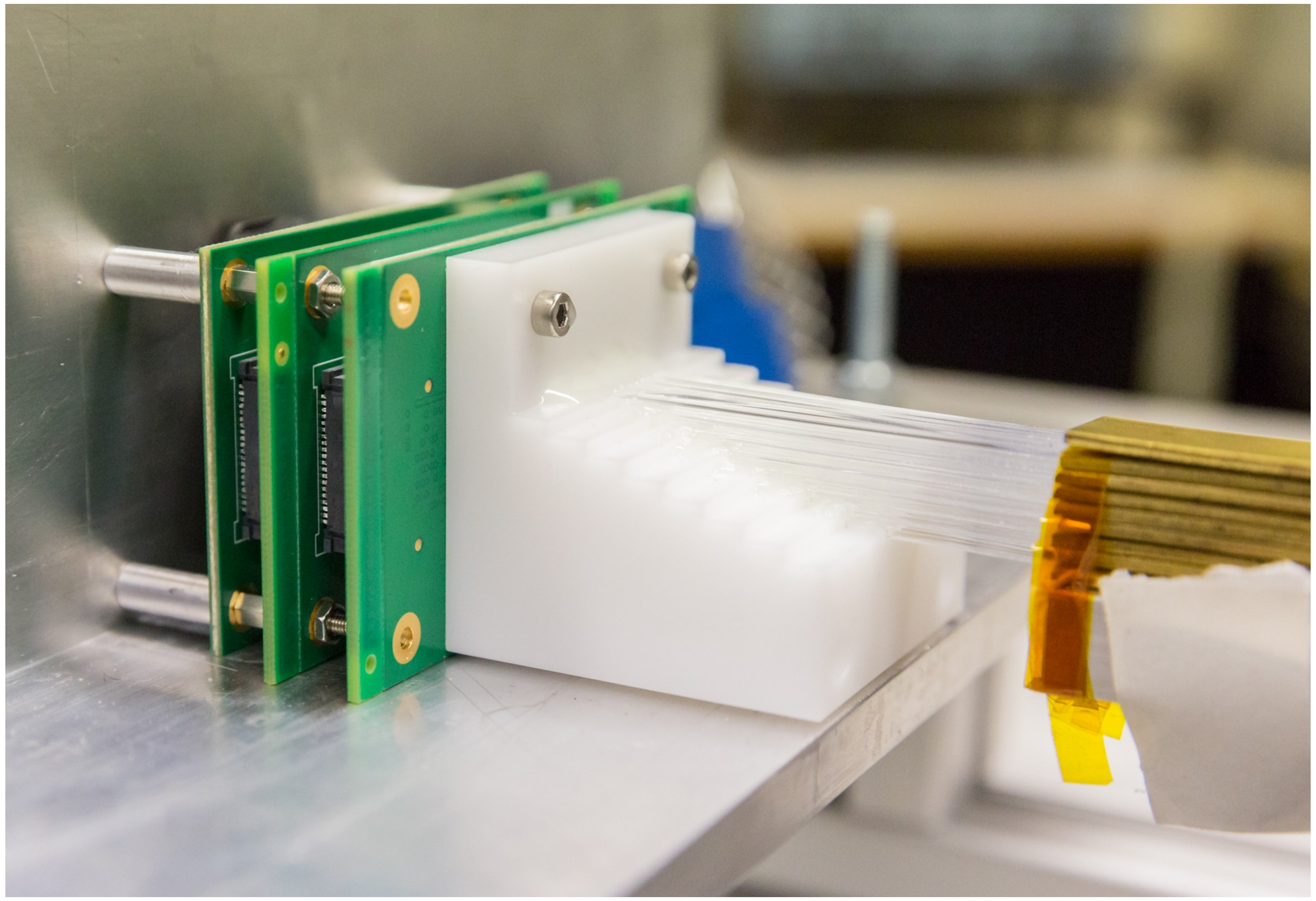
2016

a) 400 cells

b) 40% PDE

limitations:

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



2017

a) 4 x dynamic range (1600 cells)

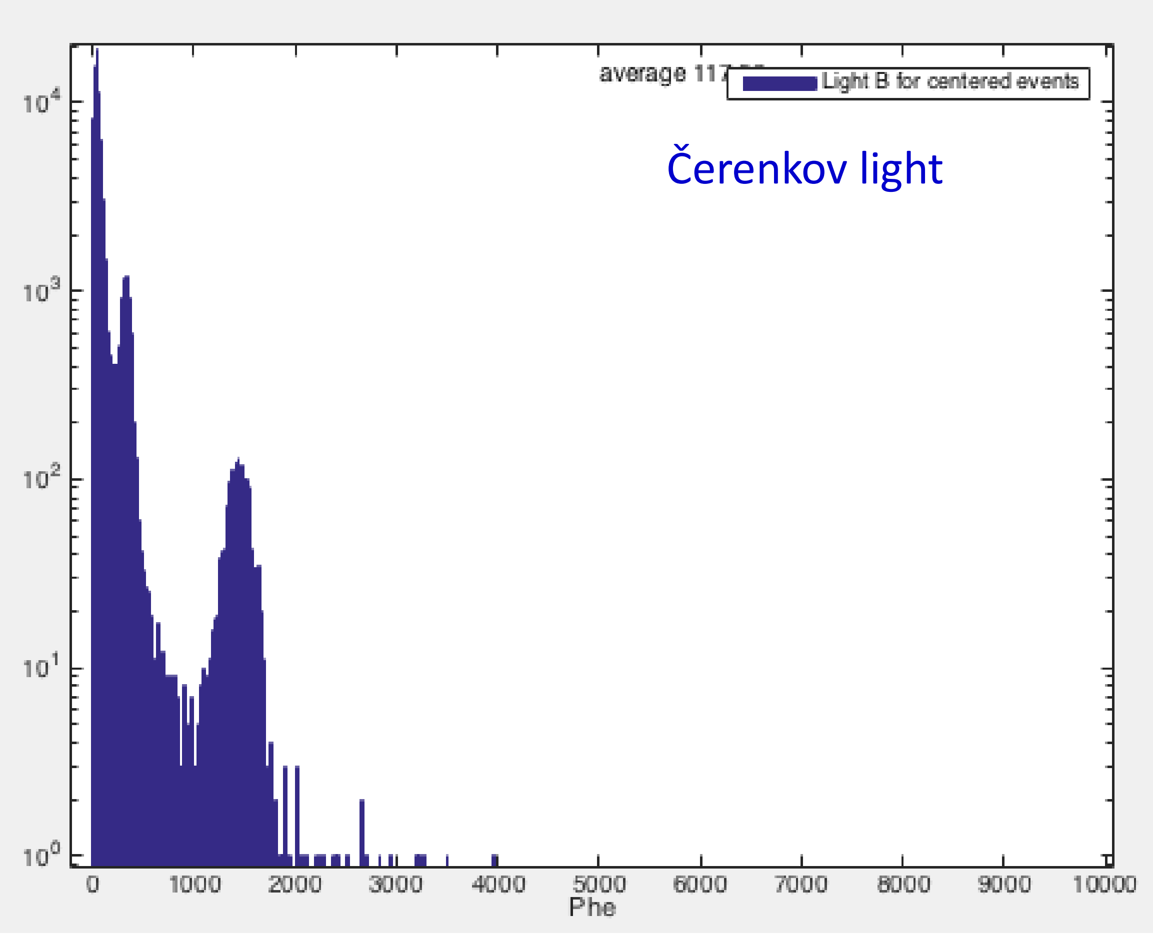
b) 25% PDE

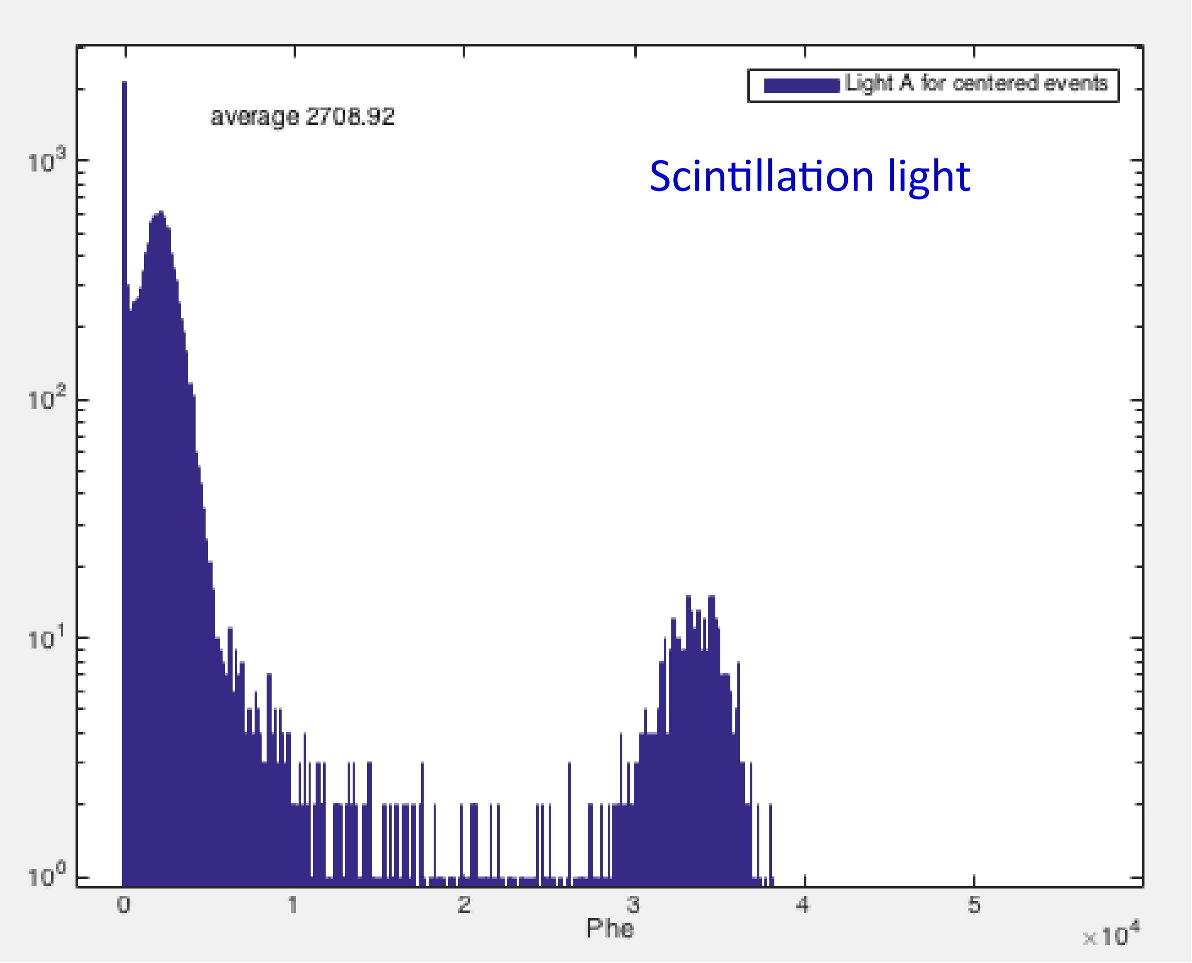
c) photo-detection at 2 different levels

RD52 Preliminary Results (2017)

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

50 GeV electron beam



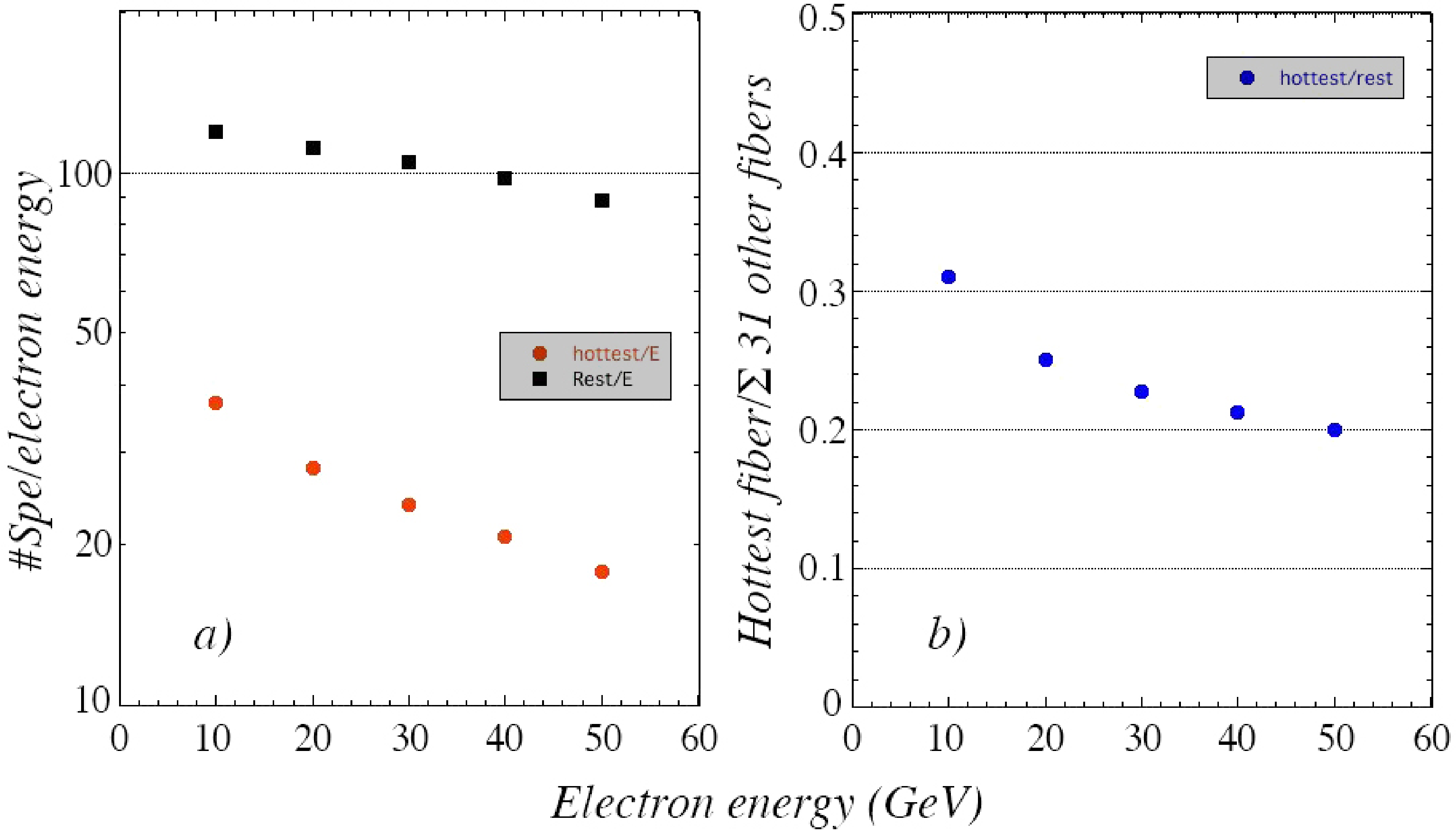


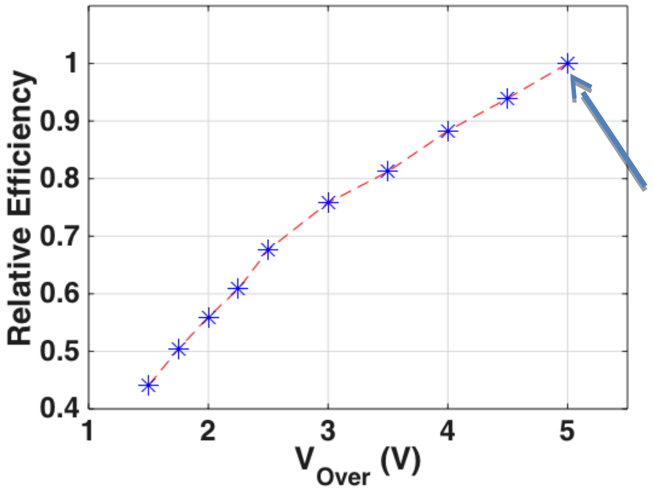
Preliminary Results (2017) – Scintillation Signals

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

Number of p.e. / GeV in hottest

Ratio hottest/rest



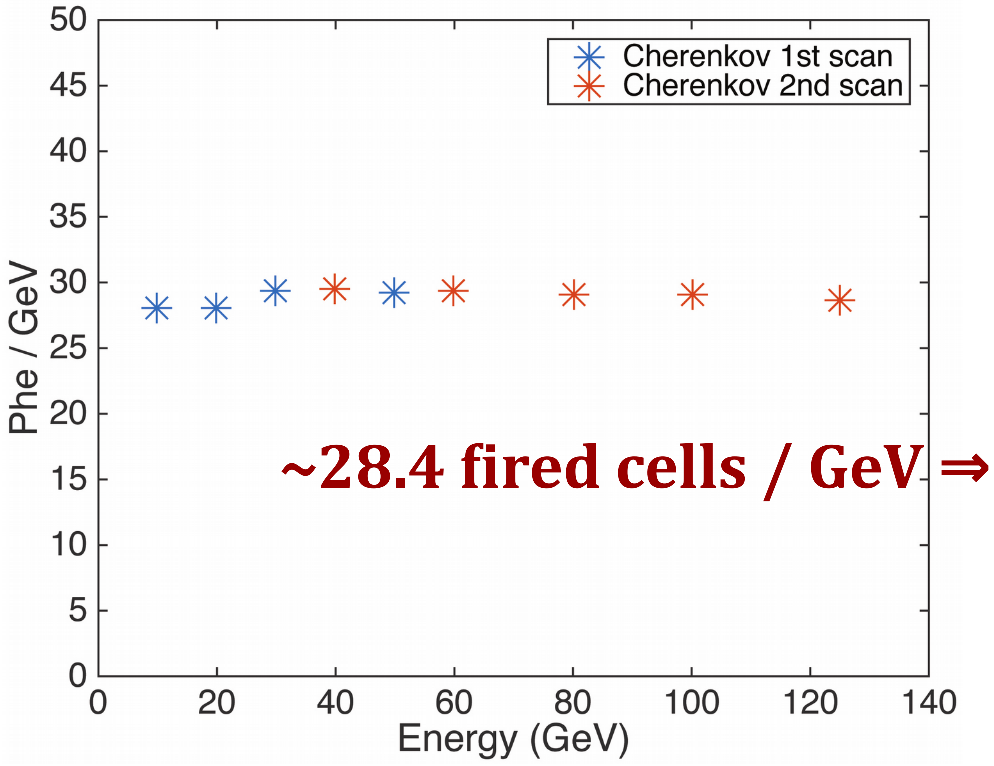


Operating Voltage

**** 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*

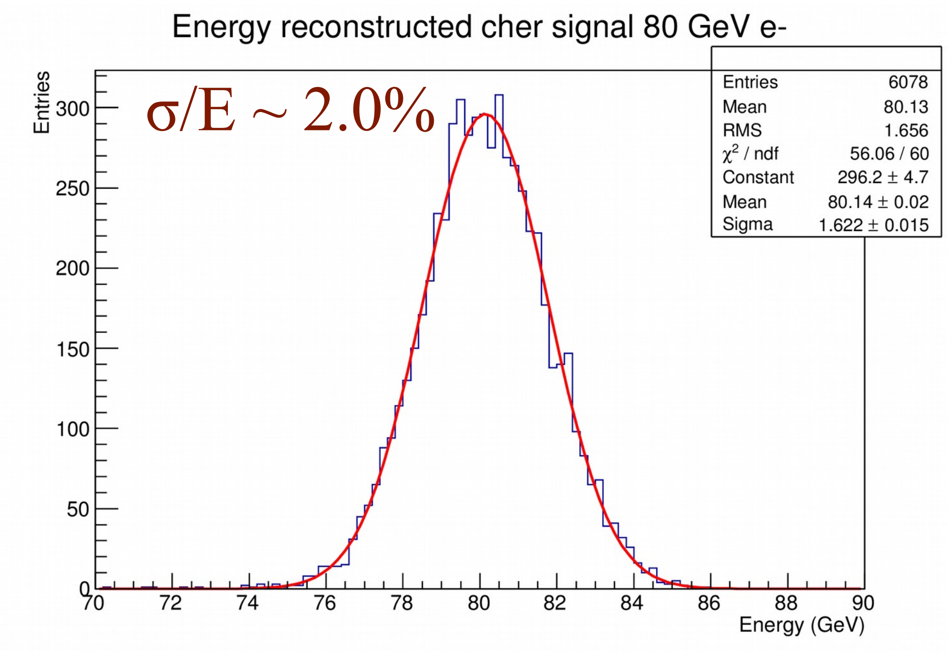
→ *average shower containment independent of energy*

Geant4 – e.m. energy reconstruction (Cu)

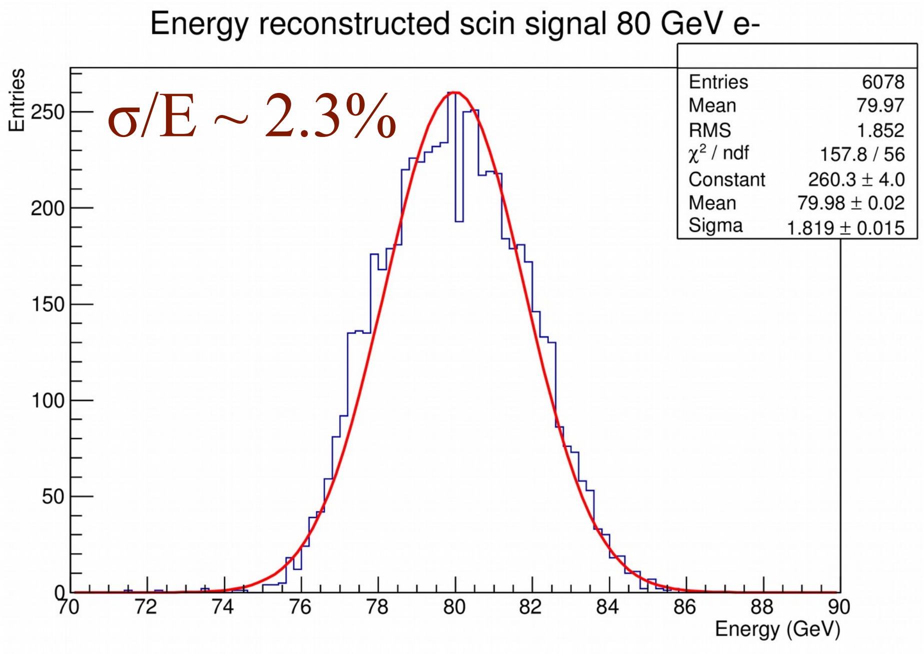
e.m. calorimeter: 31.4 x 31.4 x 112.30 cm^3

containment >~99%

Č only

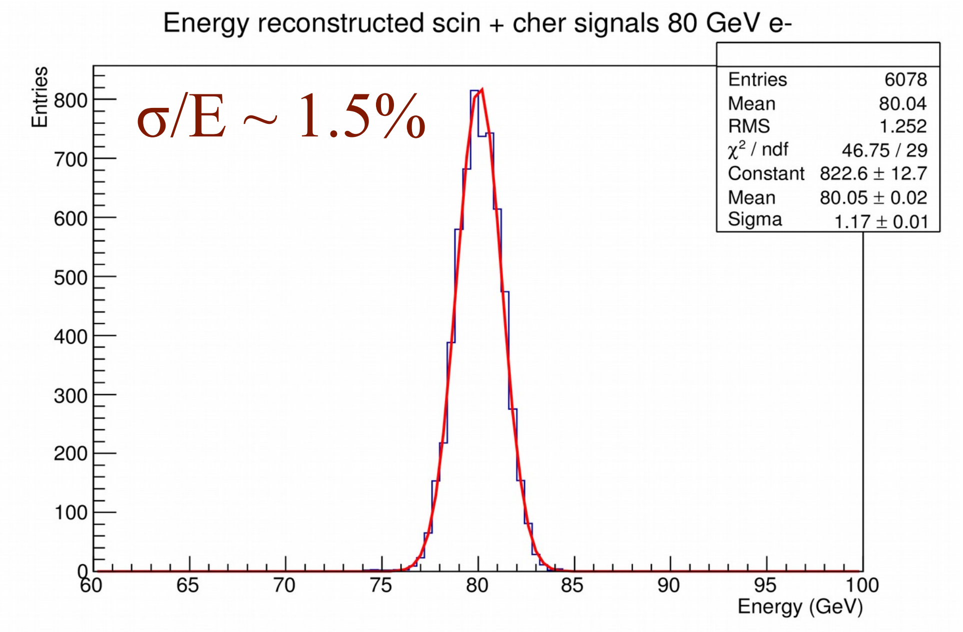

σ/E ~ 2.0%

S only


σ/E ~ 2.3%

energy reconstructed
80 GeV electrons

S+Č

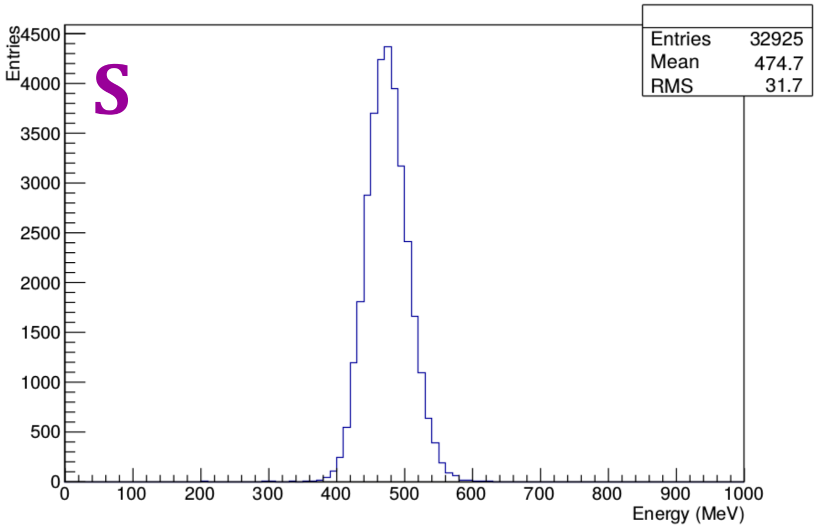

σ/E ~ 1.5%

Geant4: sampling fraction (Cu)

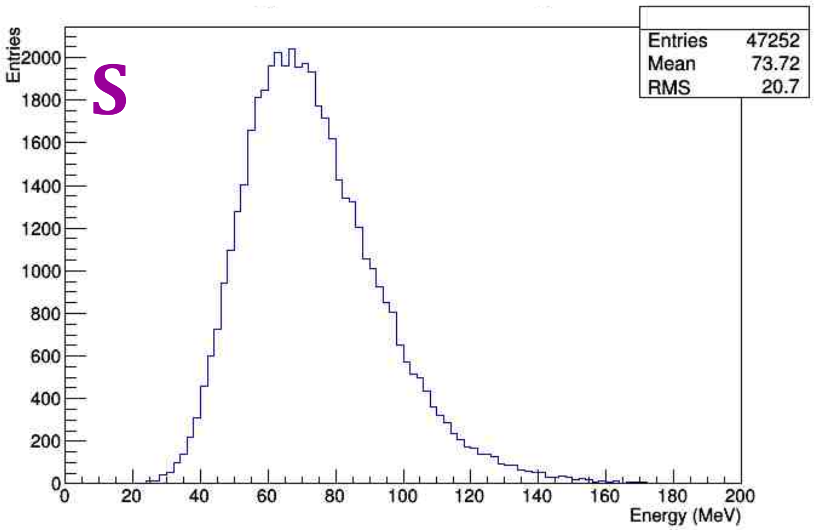
e.m. calorimeter: 31.4 x 31.4 x 112.30 cm^3

containment >~99%

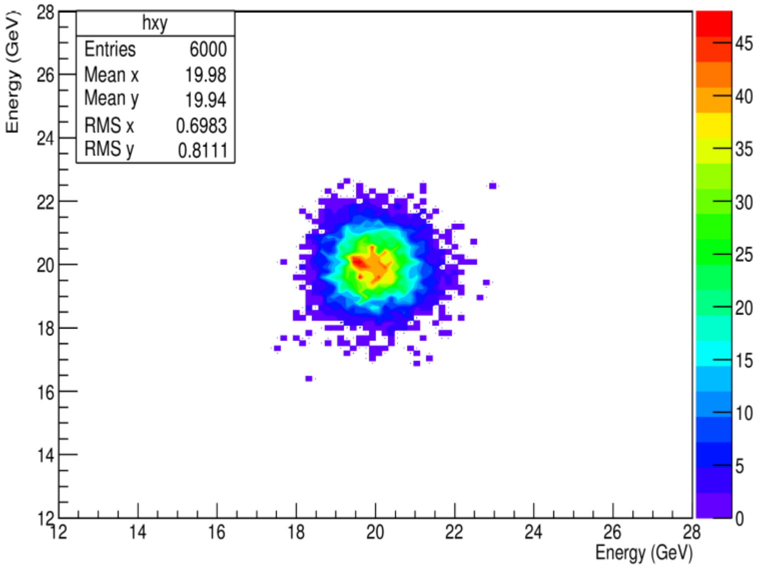
E(MeV) S fibres: ~5.5%



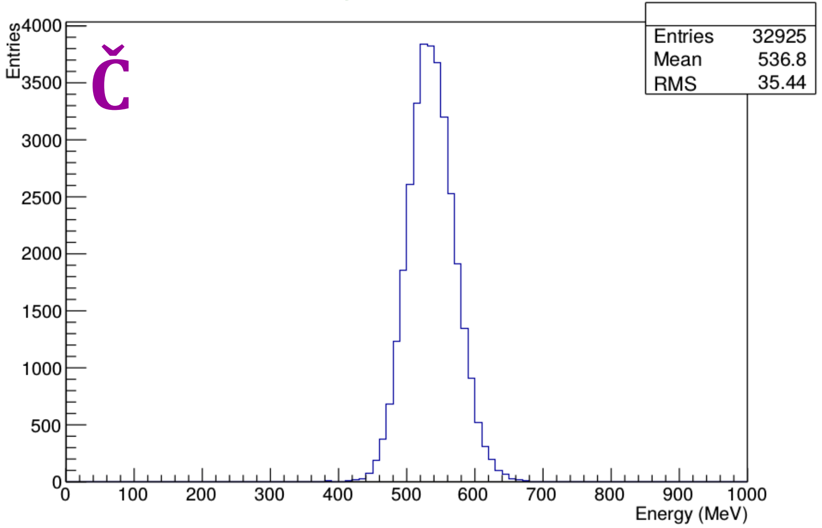
E (MeV) in hottest fibre



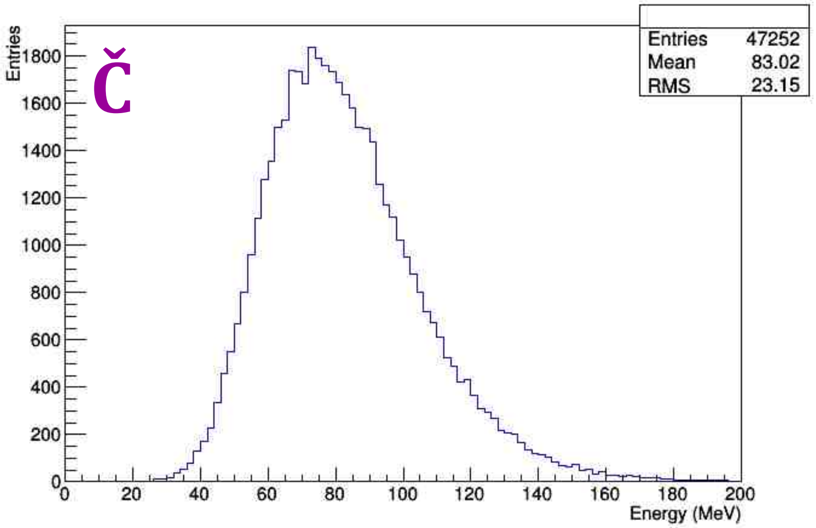
C vs. S



E(MeV) in fibres: ~6.2%



E (MeV) in hottest fibre

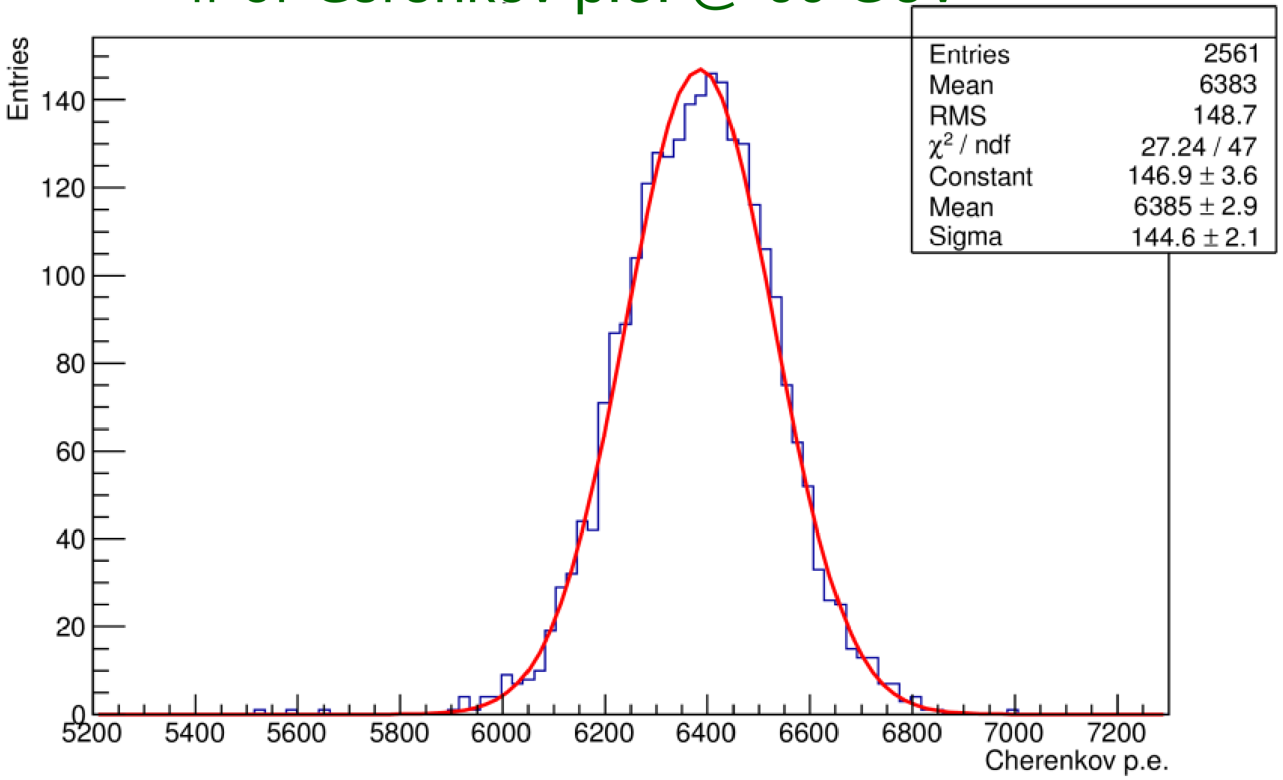


Geant4 – e.m. performance (Cu)

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