Dual-Readout Calorimetry
@
RD_FA

Referee meeting

December 6th, 2017

Bob

Dual-Readout Calorimetry

What:

correct hadronic energy measurements for f_{em} fluctuations

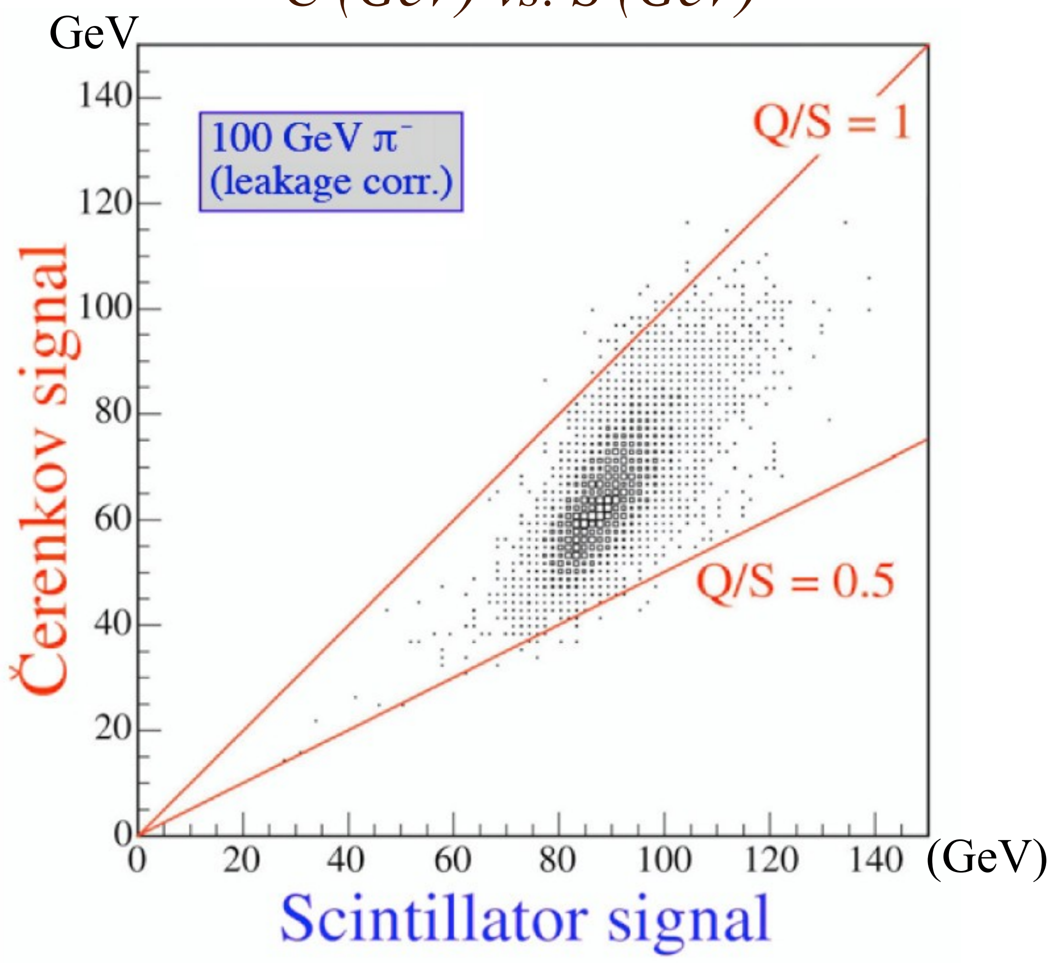
How:

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

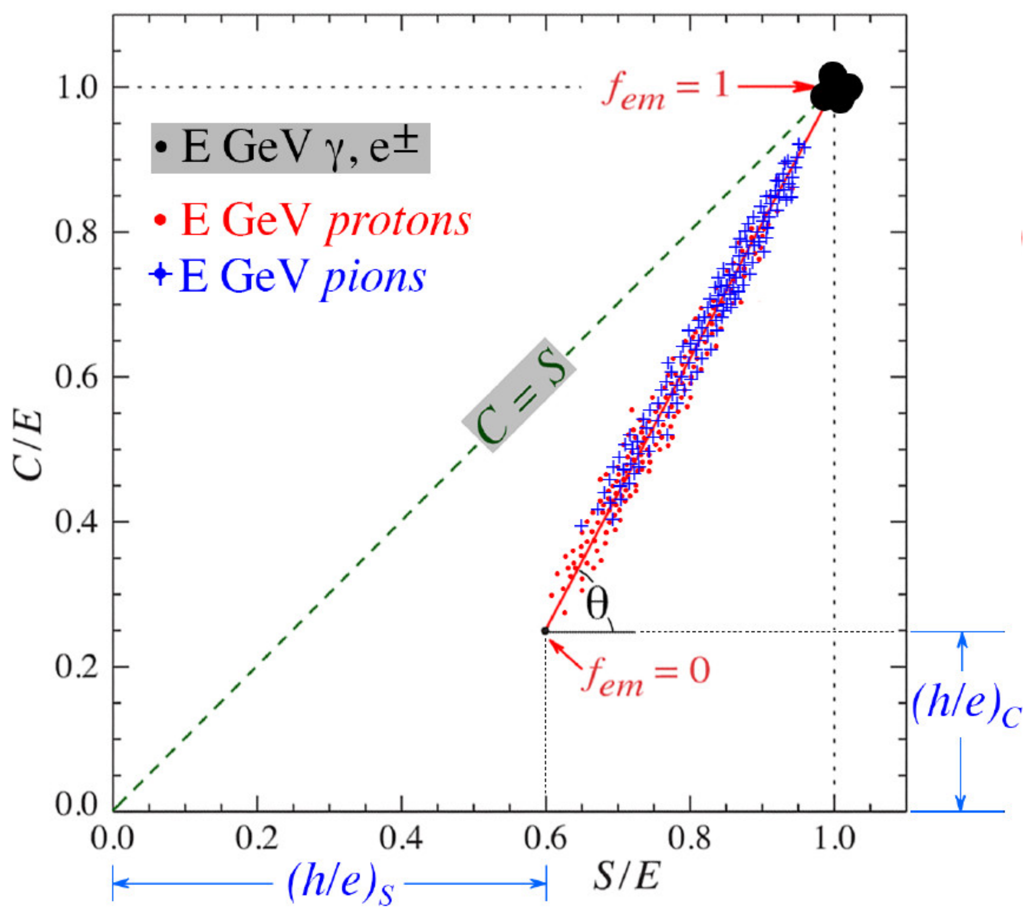
(see backup slides)

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 (!!)

DREAM/RD52 … an historical perspective

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
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*	*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* *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*

INFN CSN V (2008-2012)

1) DRC (2008-2009): crystals

2) New-DREAM (2010-2012): crystals → Pb/Cu + fibres

Experience with homogeneus (crystal) prototypes:

a) For C and S separation, crystals need *non conventional readout*

→ results not good as w/ standard EM calorimetry

b) Extraction of pure C and S signals implies

- *Large suppression of Č light yield* (optical filters)
- *Issue with Č light due to UV self absorption*

→ lower performance wrt fibre-sampling solutions

Pb/Cu fibre-sampling studies

2012 t.b.: issues with noise and ADC response for low signals

→ *actions/consequences:*

1) (Agostino) add low-noise preamp
2) (CAEN) fix charge integrator (V792AC and V862AC) QDC.s
3) no reliable results for hadronic showers

2013-2014: long shutdown (no testbeam)

2015: first results on hadronic performance

2016: 1 cm^2 *em* prototype w/ SiPM readout *(400, 50x50 μm^2, cells)*

→ *saturation, light leakage*

2017: 1 cm^2 *em* prototype w/ SiPM readout *(1600, 25x25 μm^2, cells)*

→ *non-linearity, (maybe marginal) light leakage*

Our assumptions

1) study of hadronic performance - so far - very crude

2) since 2012, no INFN support → efforts just for testbeam support

3) simulations - so far - very crude as well → need validation

4) design and study of a real detector limited to 4^{th} Detector Concept

5) growing interest for a circular e+e- machine at ZH “pole”

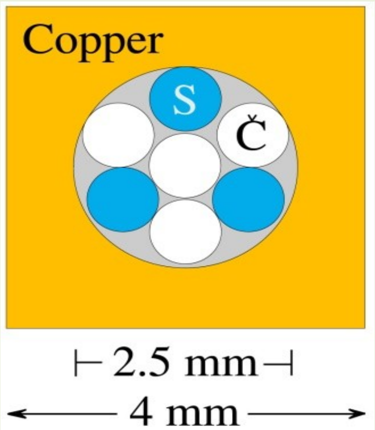
6) detector readout and longitudinal segmentation need to be addressed

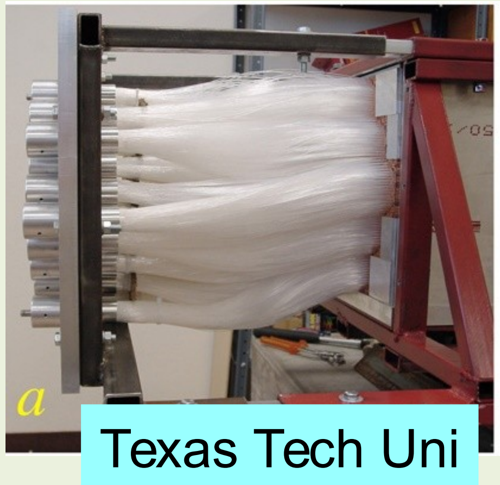
Prototype results and simulations

Dual Readout w/ Fibre Sampling Calorimeters

2003
DREAM

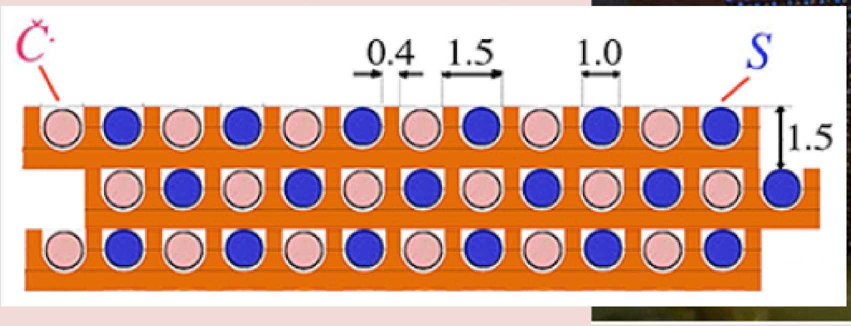
Cu: 19 towers, 2 PMT each
2m long, 16.2 cm wide
Sampling fraction: 2%

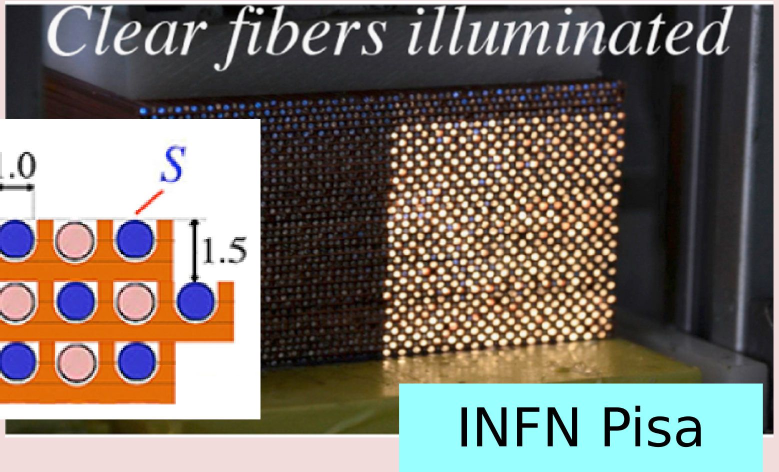




2012
RD52

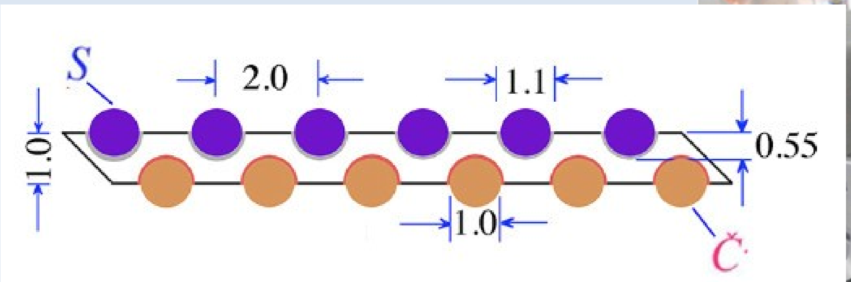
Cu, 2 modules
Each module: 9.2 × 9.2 × 250 cm^3
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: ~4.6%
Depth: ~10 λ_{int}





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}



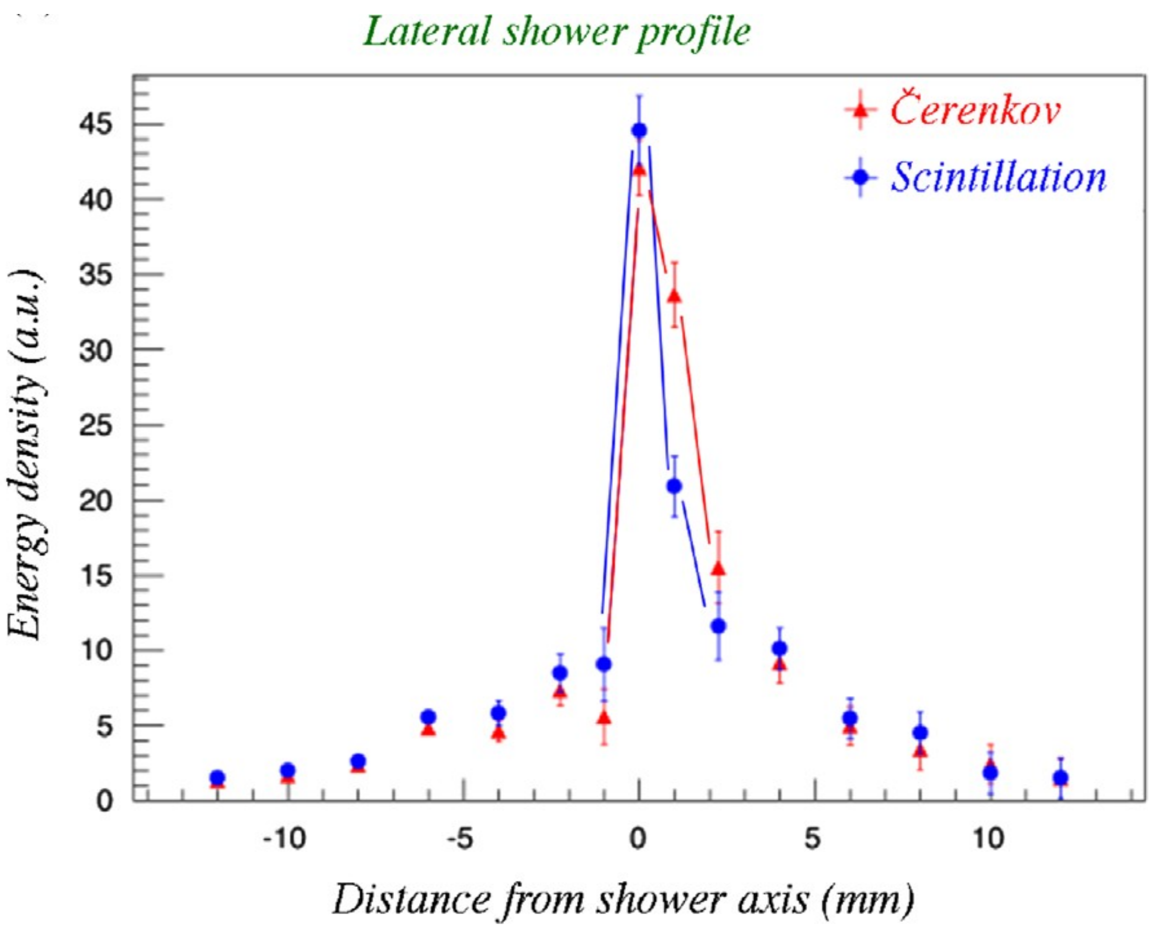
Lateral shower profile

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)

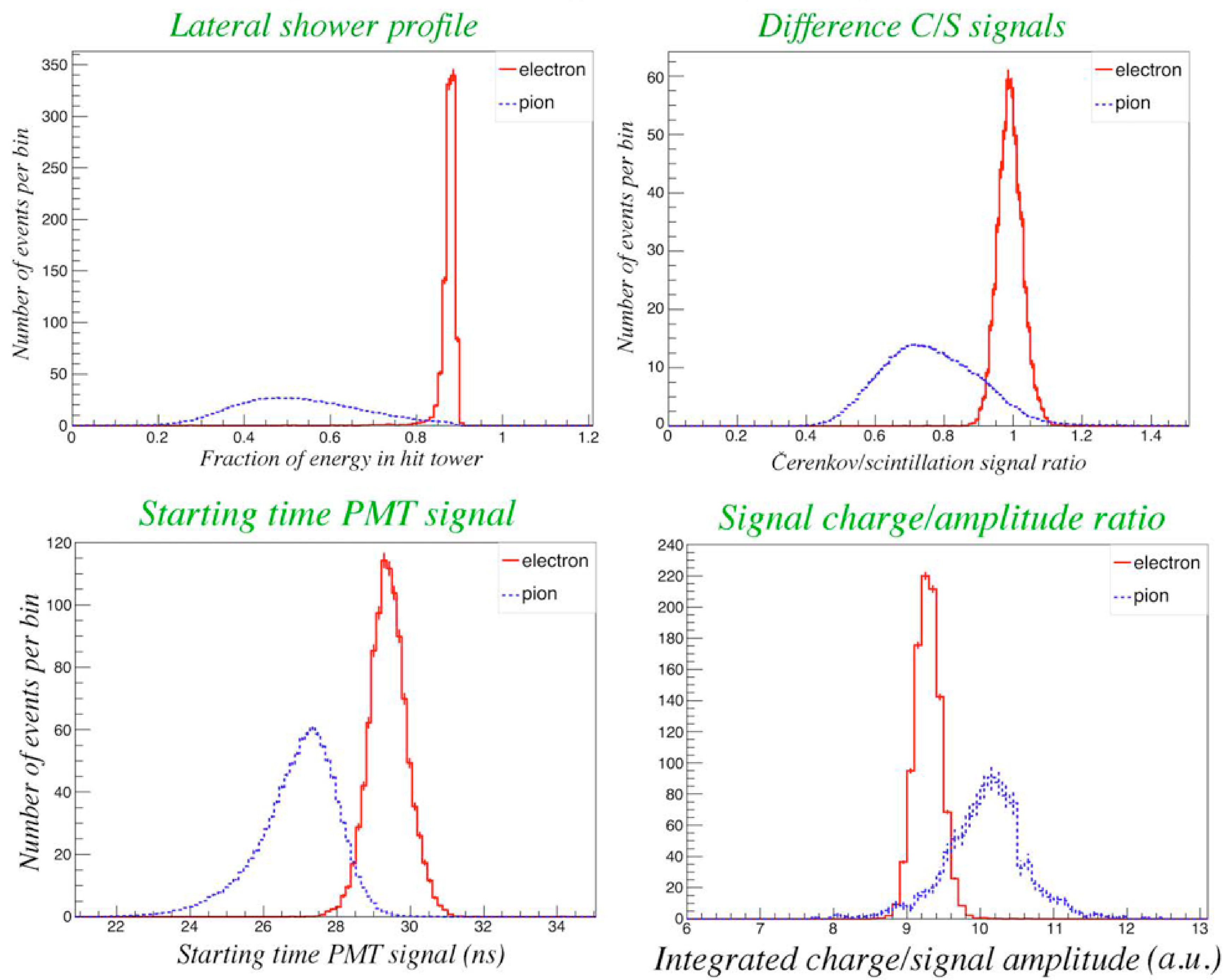
RD52 lead calorimeter

(60 GeV) e^- vs. π^-

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

NIM A 735 (2014) 120

Methods to distinguish e/π in longitudinally unsegmented calorimeter



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 μm², 400 cells (2016) → 25x25 μm², 1600 cells (2017)

b) lower PDE (lower fill factor)

→ avoid saturation ?

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

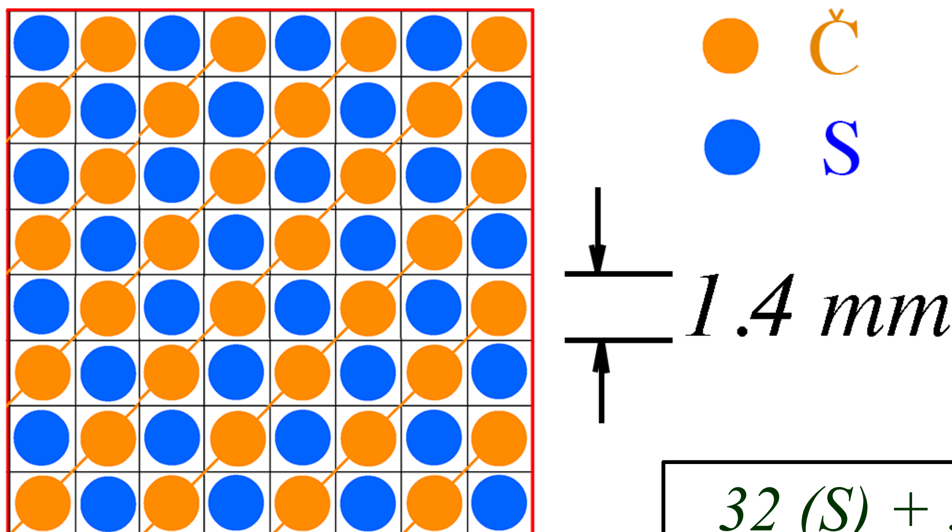
S ≥ 30×Č ! → crosstalk (light leakage) critical

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

2017 RD52 Testbeam Layout

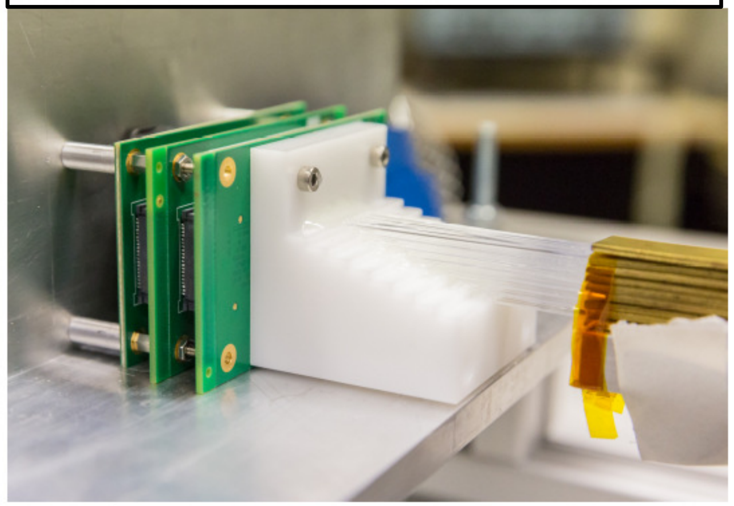
Brass module, dimensions: ~ 112 cm long, 12 x 12 mm²

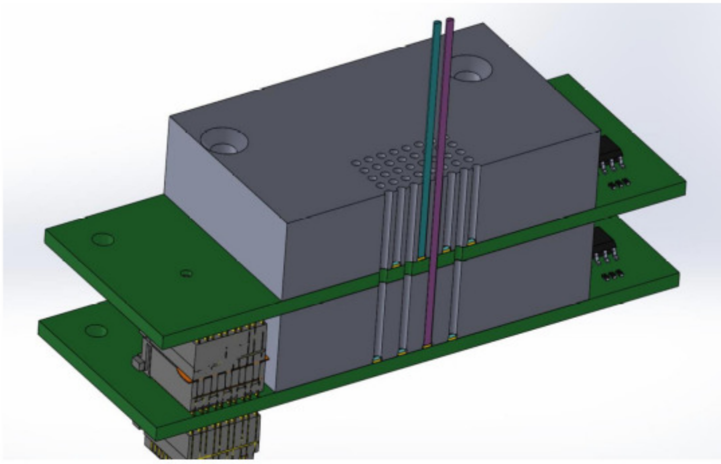
section



32 (S) + 32 (Č) fibres

Back

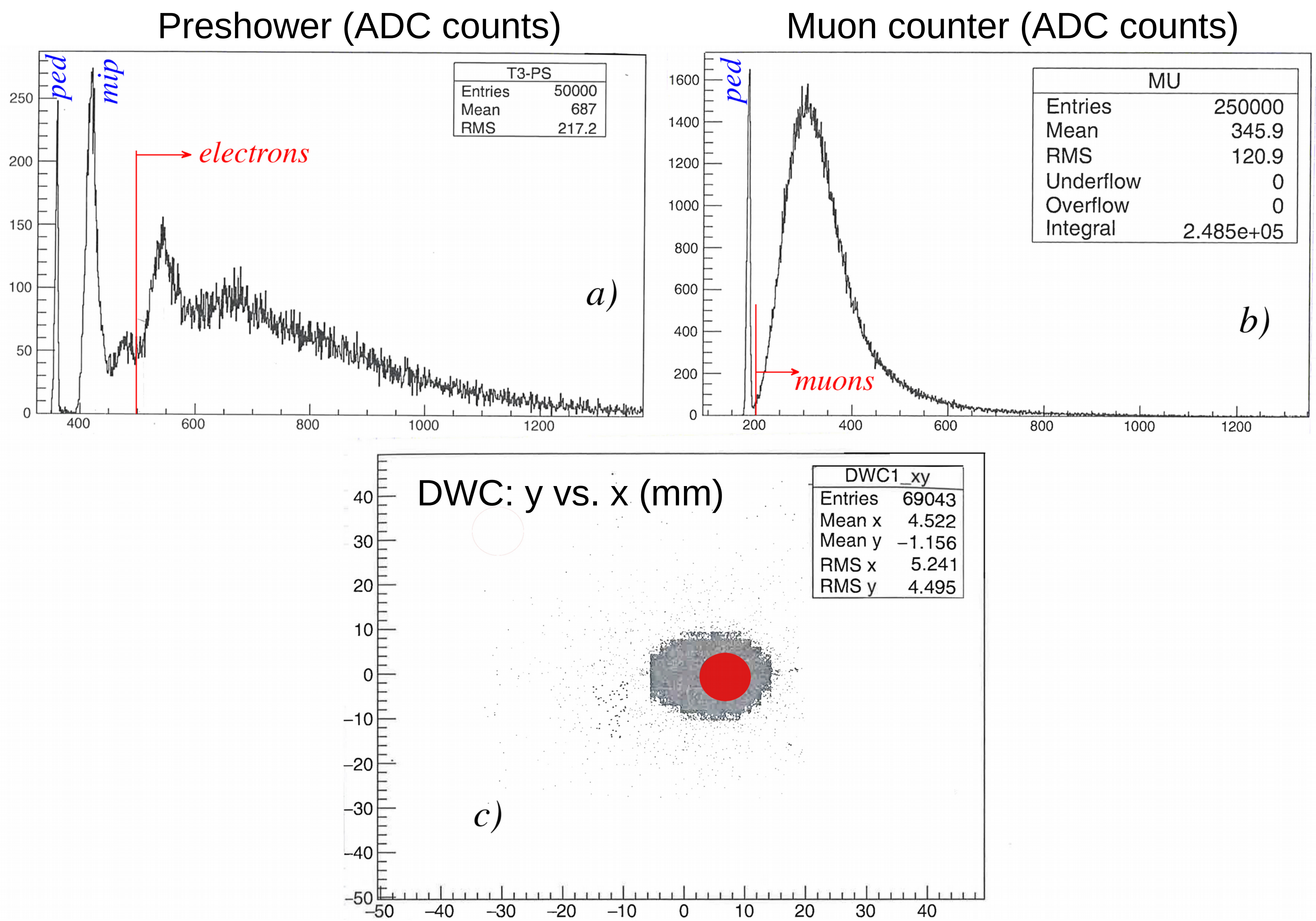




Experimental setup

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

Testbeam - Data Selection and Tagging

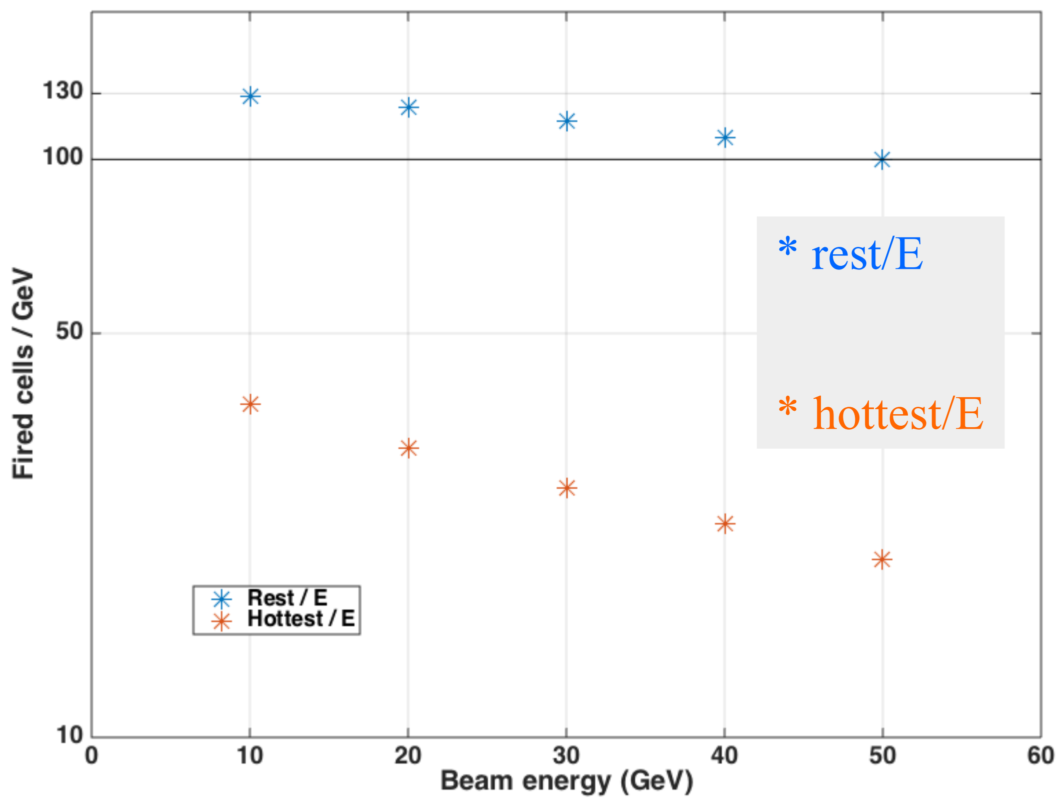


Preshower detector and muon counter: select electrons or muons

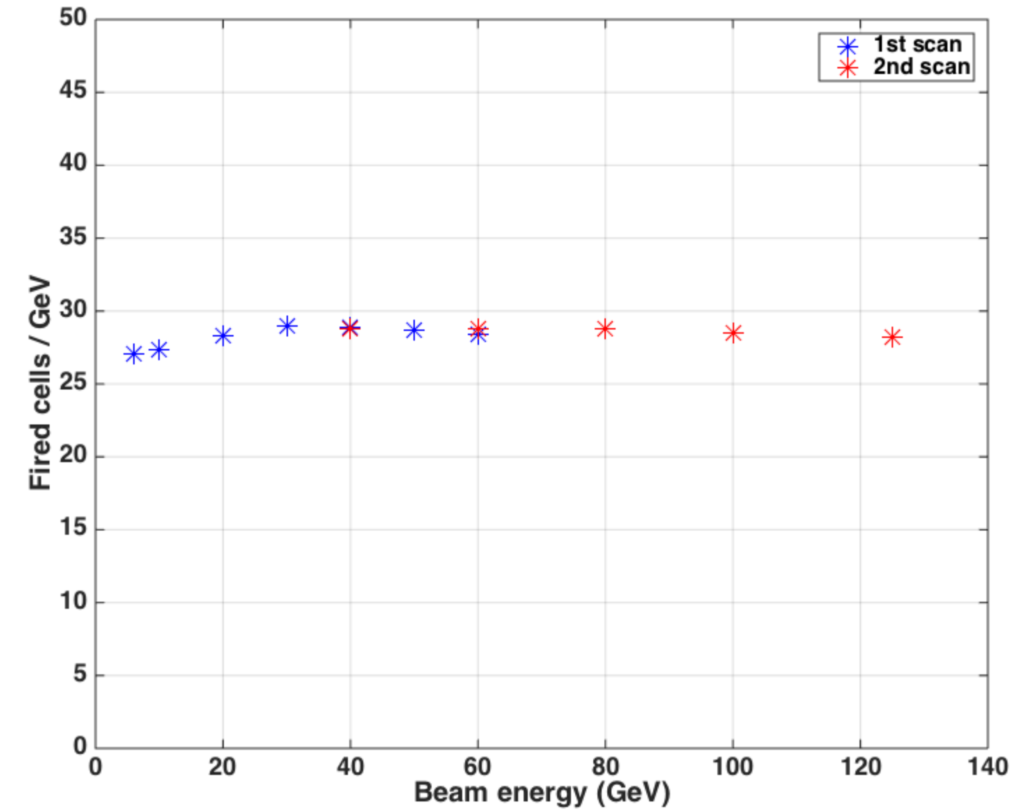
Delay Wire Chamber: select events in central region

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)

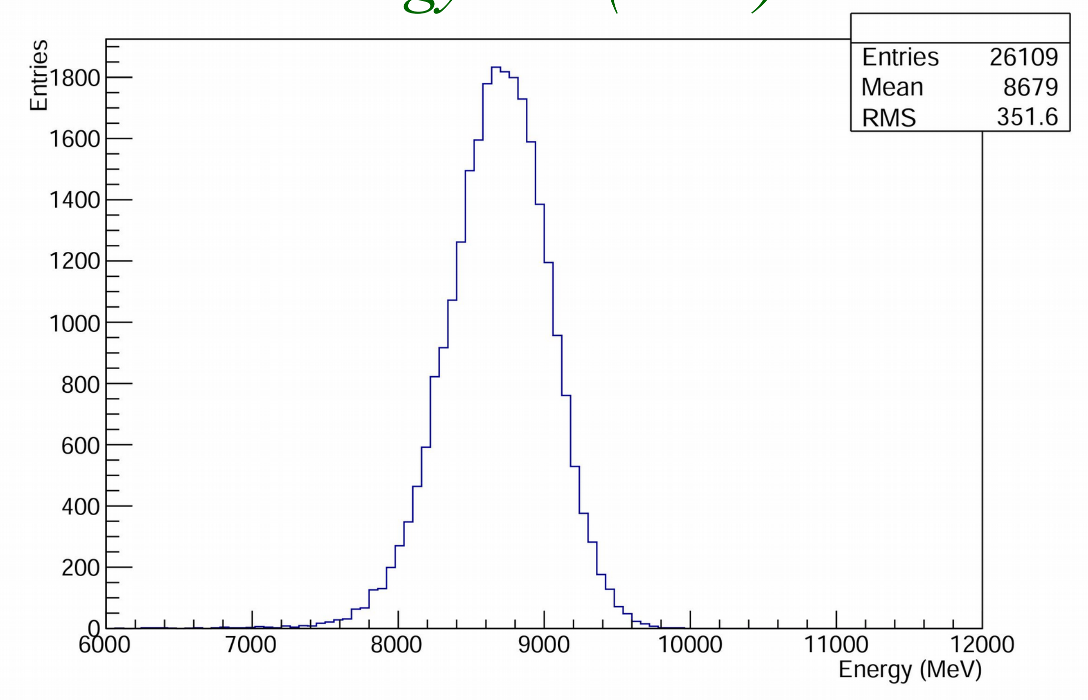
b) S : non linearity even at ultra low PDE

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

Geant4: 20 GeV electron shower containment

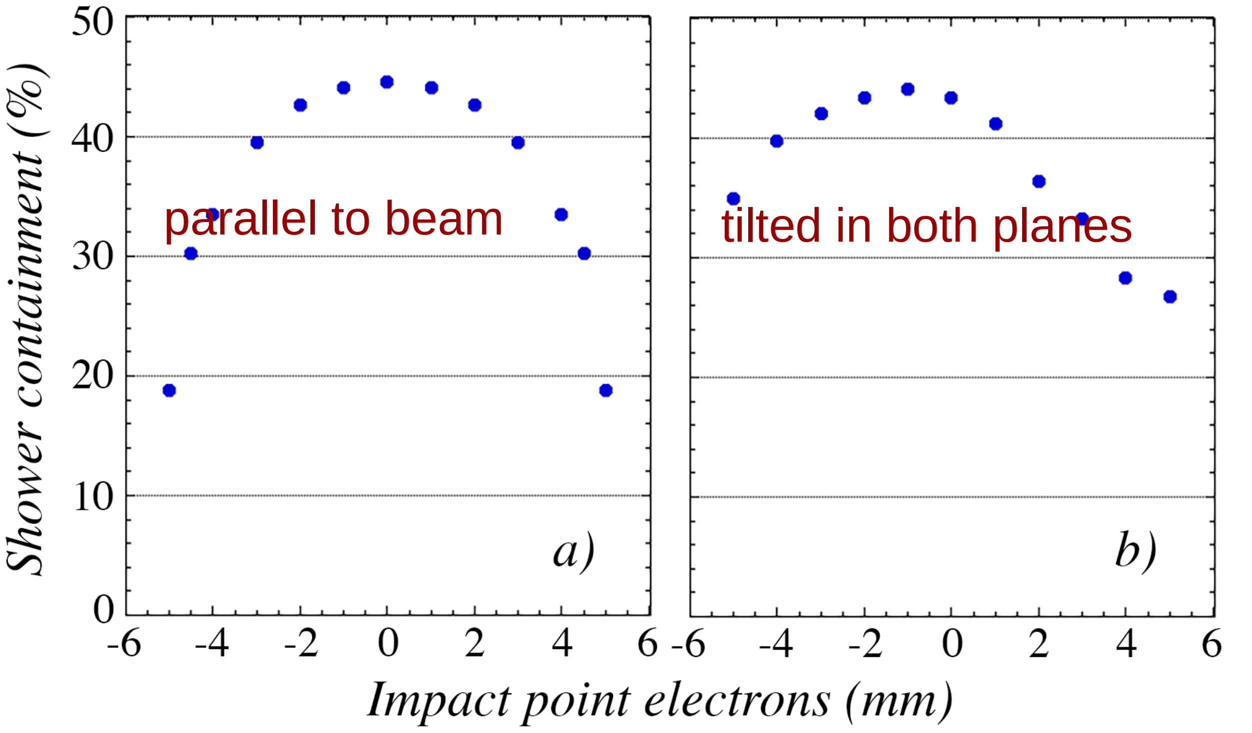
RD52 testbeam module: 1.014 x 1.014 x 112.30 cm^3

total energy lost (MeV)



centered events: ~43% containment

containment .vs. impact point



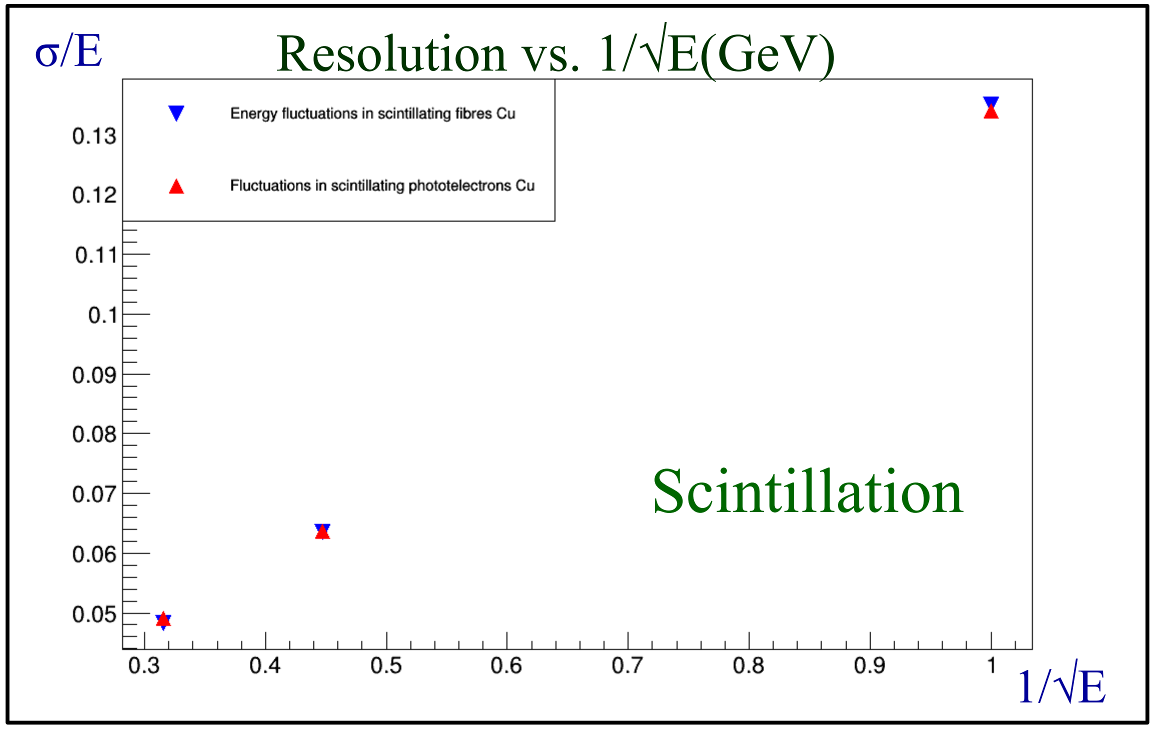
e.m. calorimeter: 31.4 x 31.4 x 112.30 cm^3

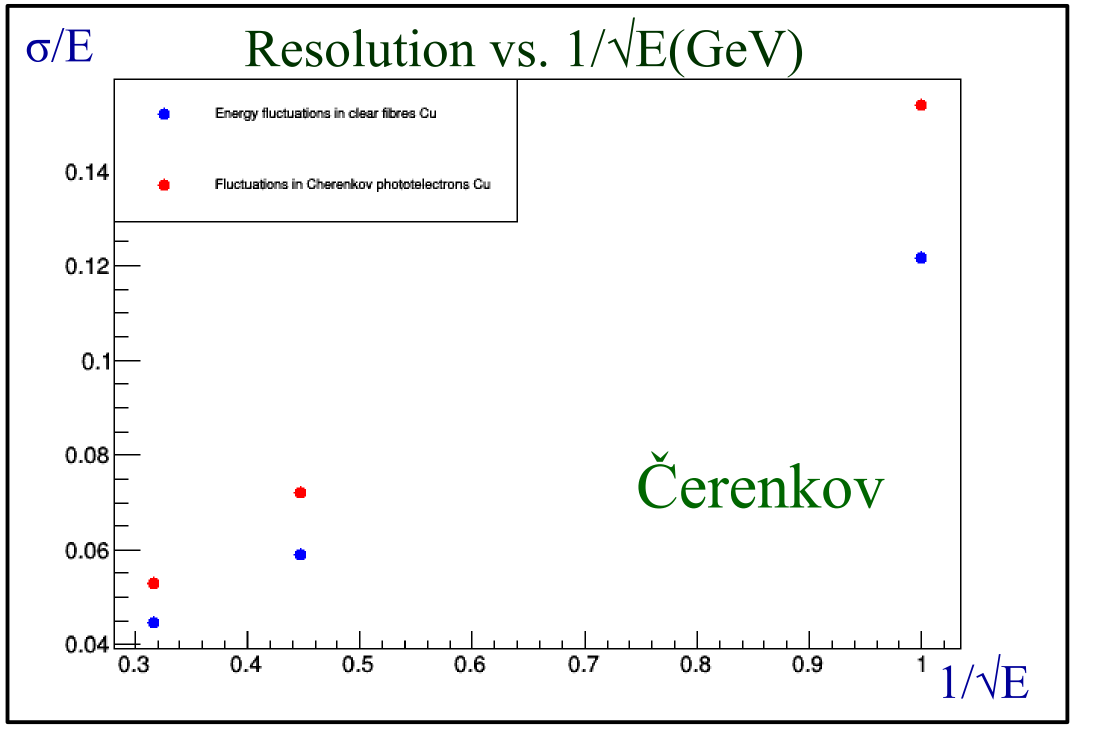
containment > 99%

(all plots for copper unless specified differently)

Geant4 – signal fluctuations

Energy deposition and p.e. number fluctuations





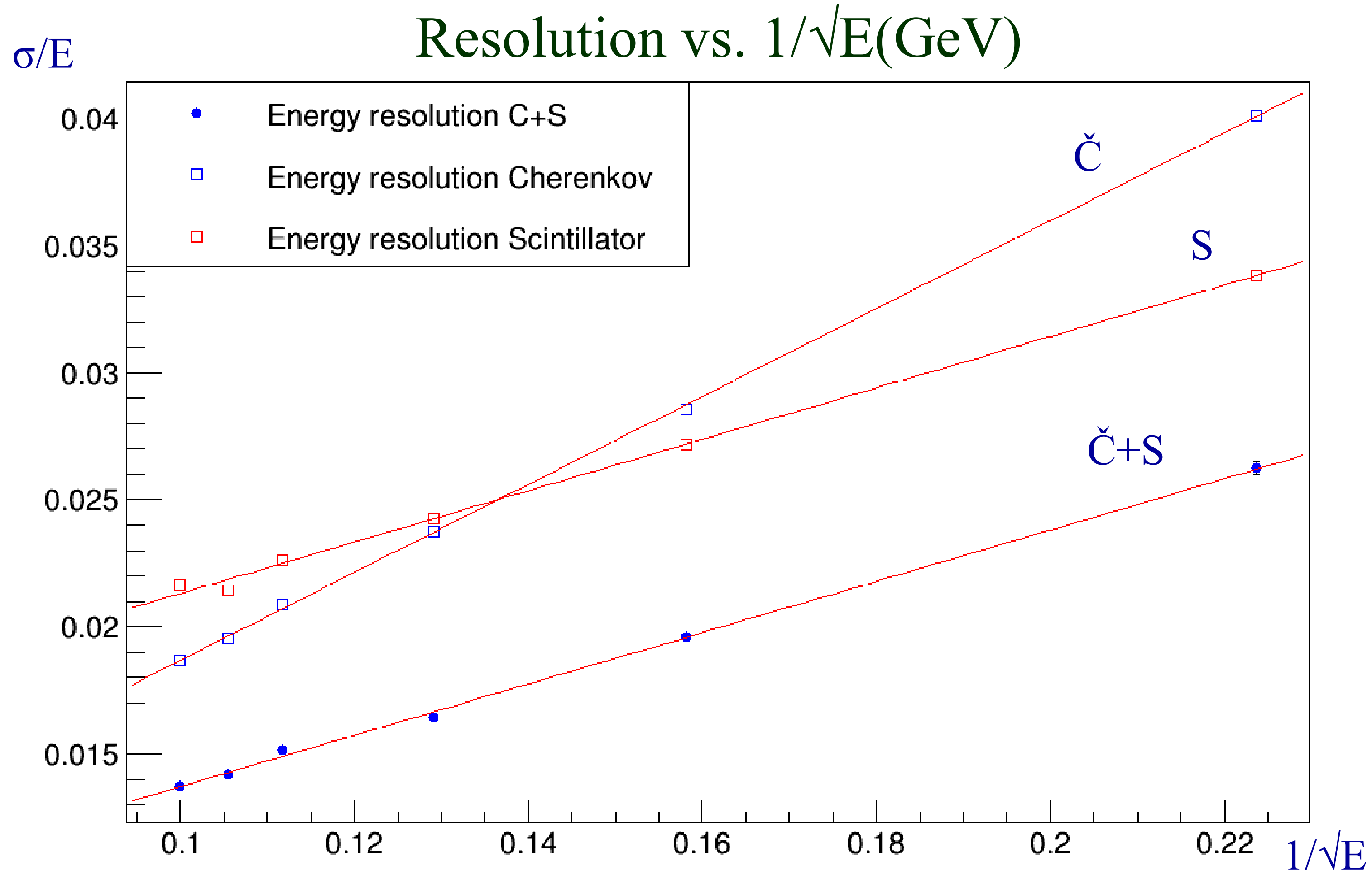
S: ~5500 p.e. / GeV
→σ/E driven by fluctuations in en. depositions

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:

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

or:

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

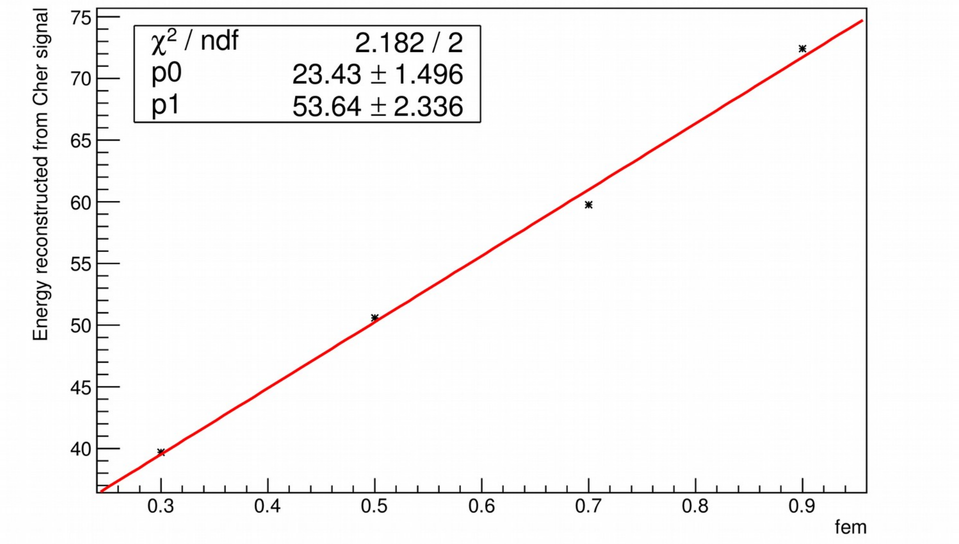
$$(h/e)_S = (S/E - f_{em}) / (1 - f_{em})$$

while:

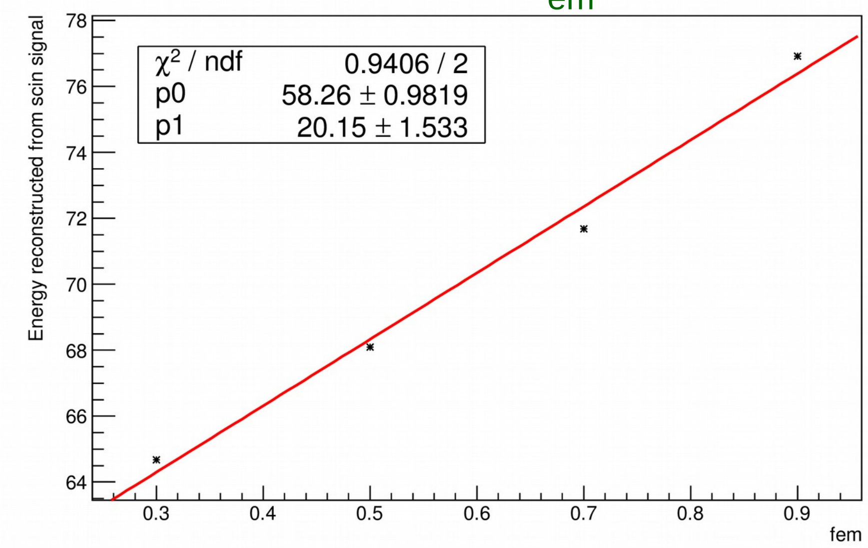
$$\chi = (1 - (h/e)_S) / (1 - (h/e)_{\check{C}}) = (E - S) / (E - C)$$

Geant4 - hadronic performance (preliminary)

E(Č) vs. f_{em}

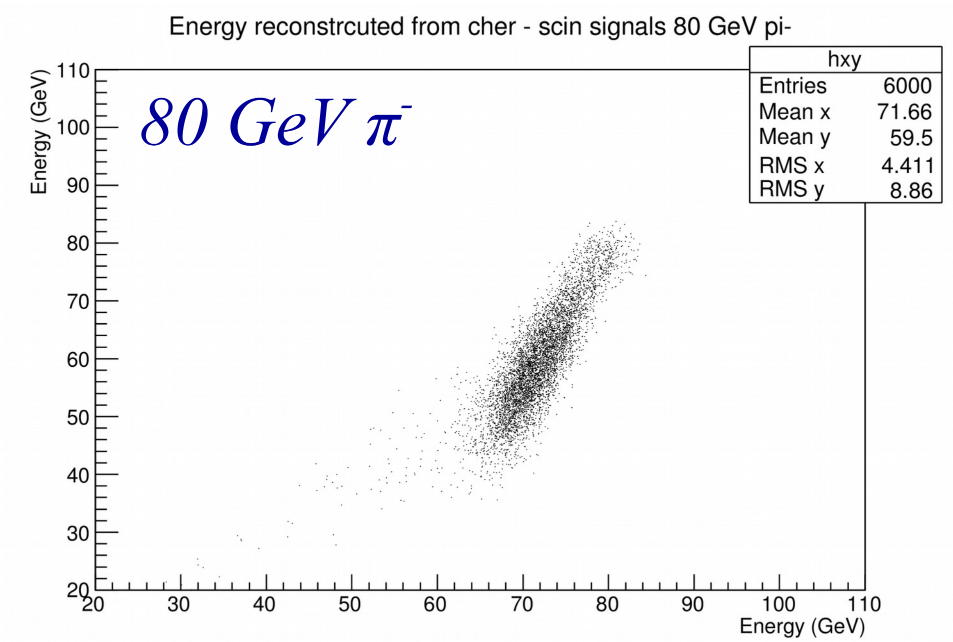


E(S) vs. f_{em}

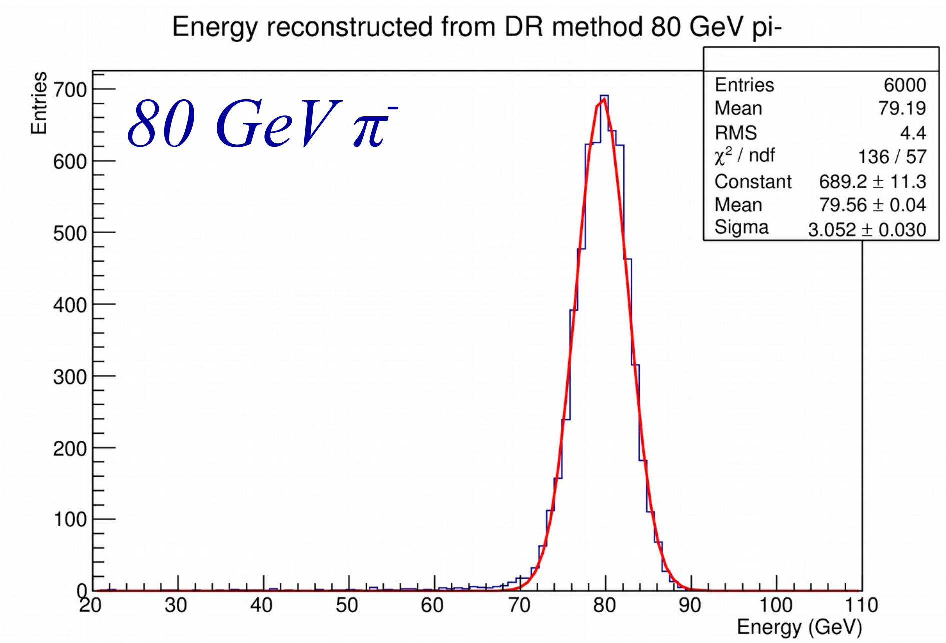


Copper

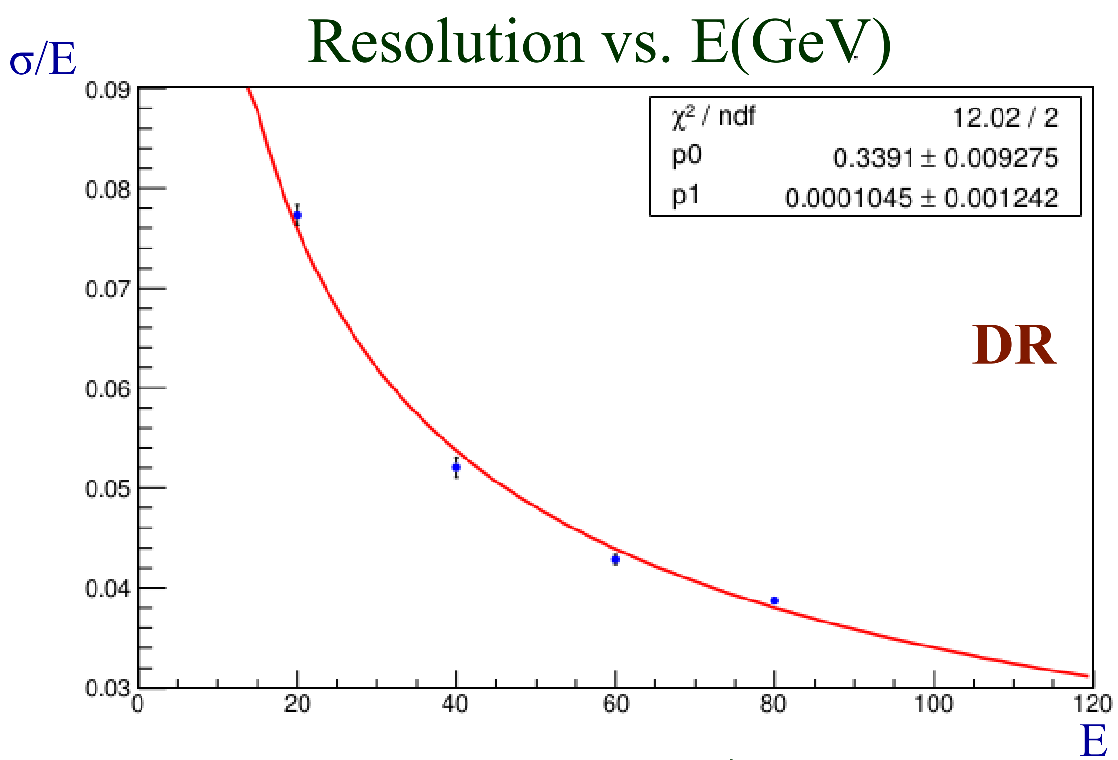
E(Č) vs. E(S)

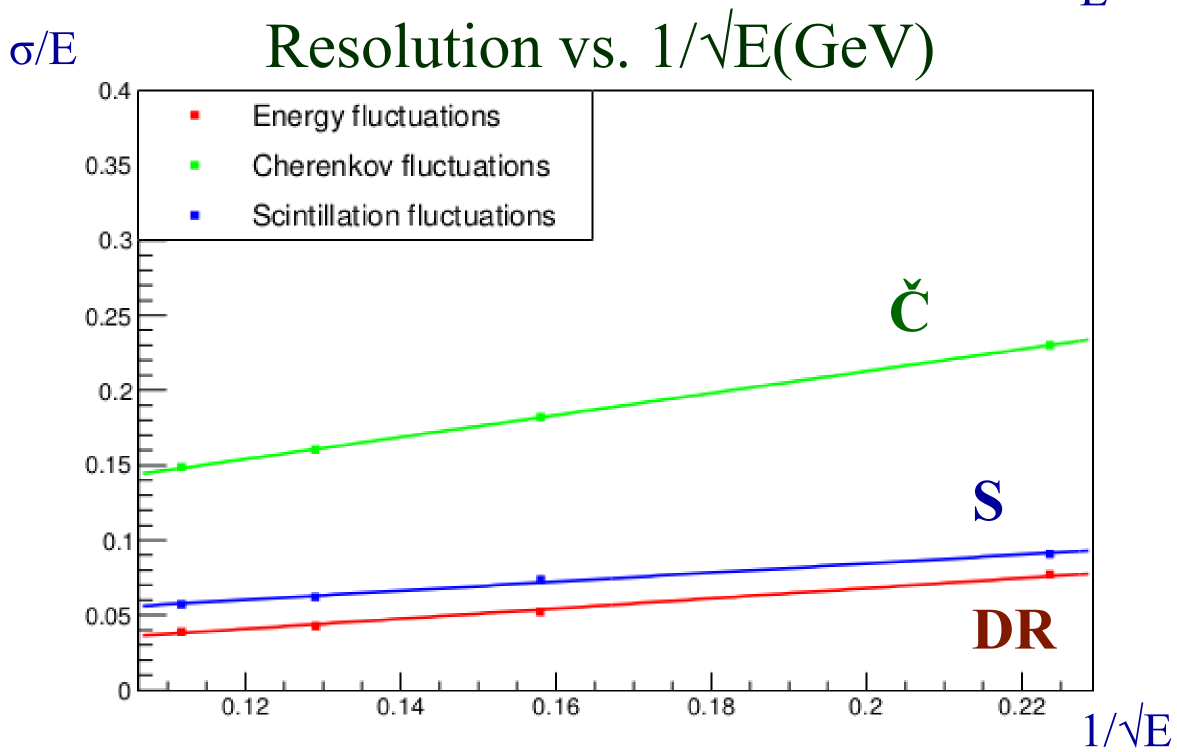


E (DR)



Geant4 – Cu hadronic performance (preliminary)





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

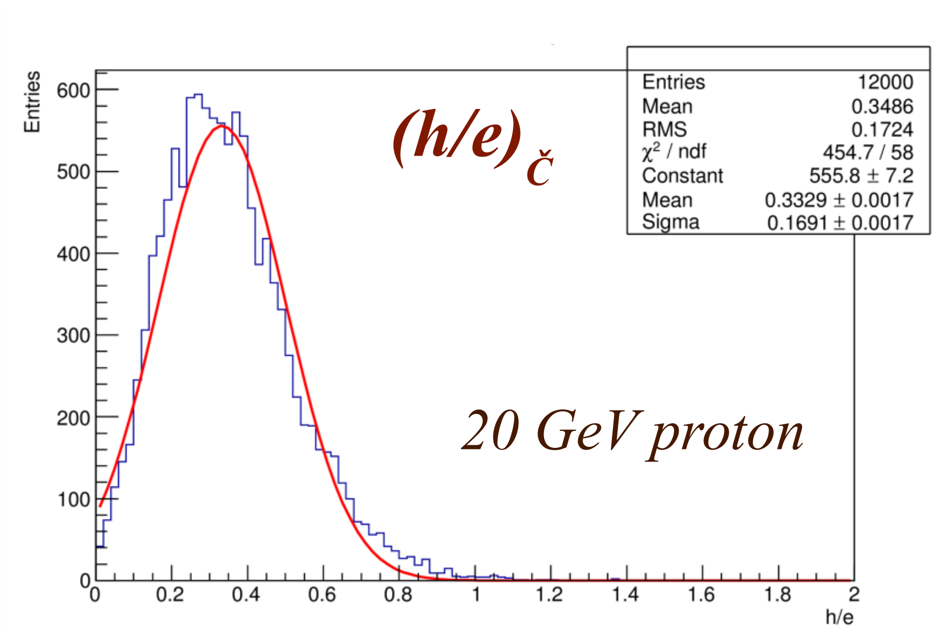
DR: ~34/√E (%)

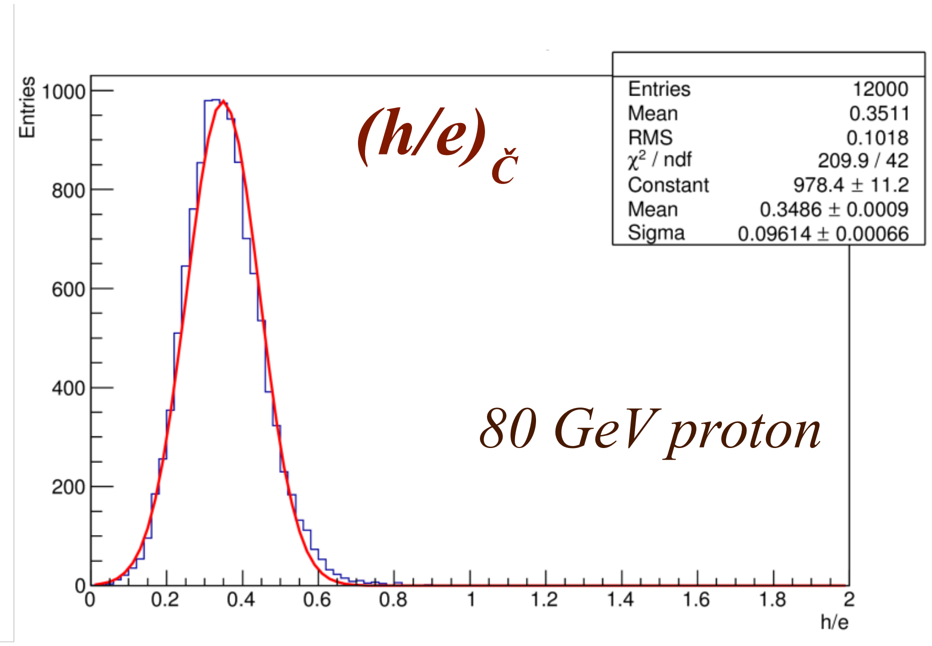
High-energy single-π resolutions:

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

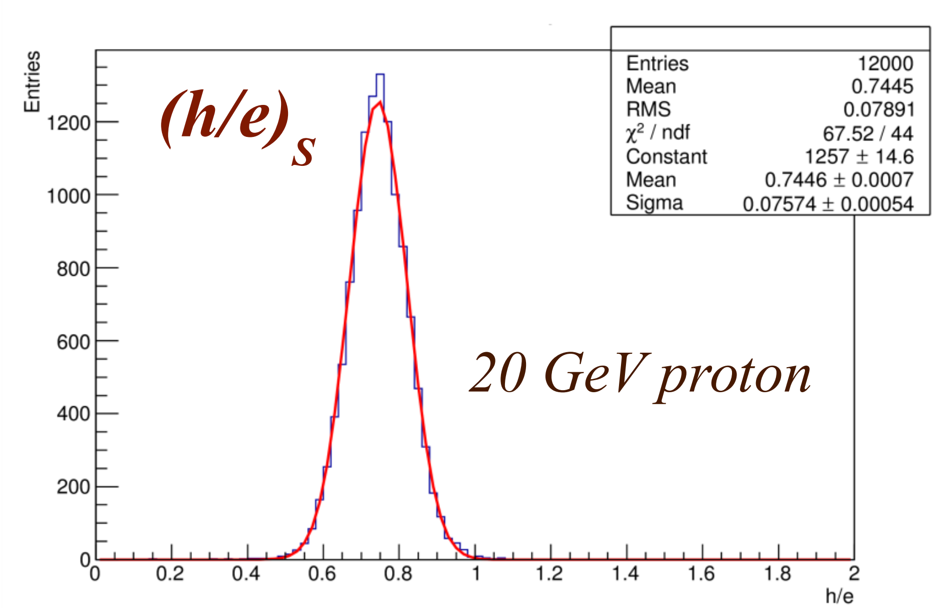
Geant4 – h/e factors for Copper

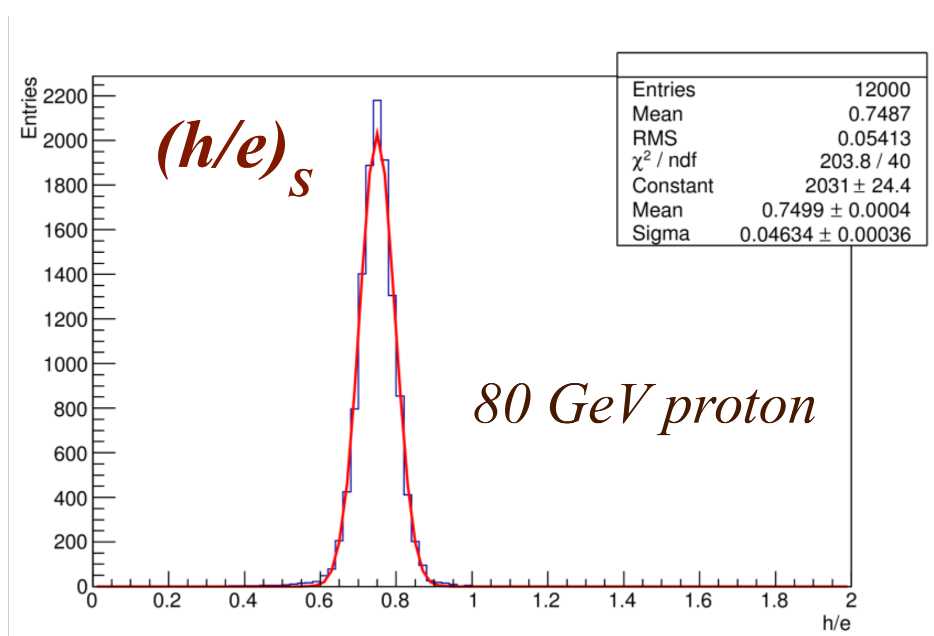
Copper





$(h/e)_{Č} \approx 0.35$

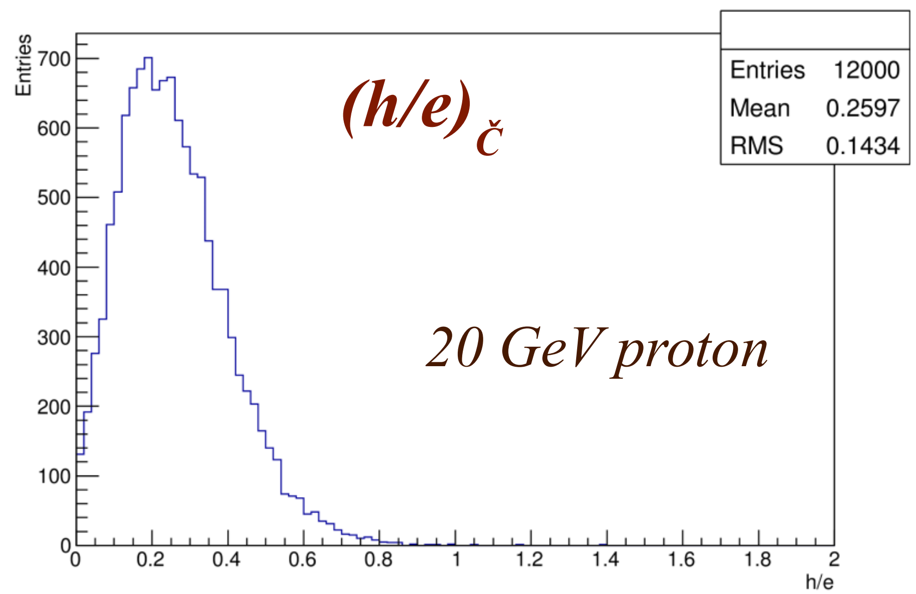


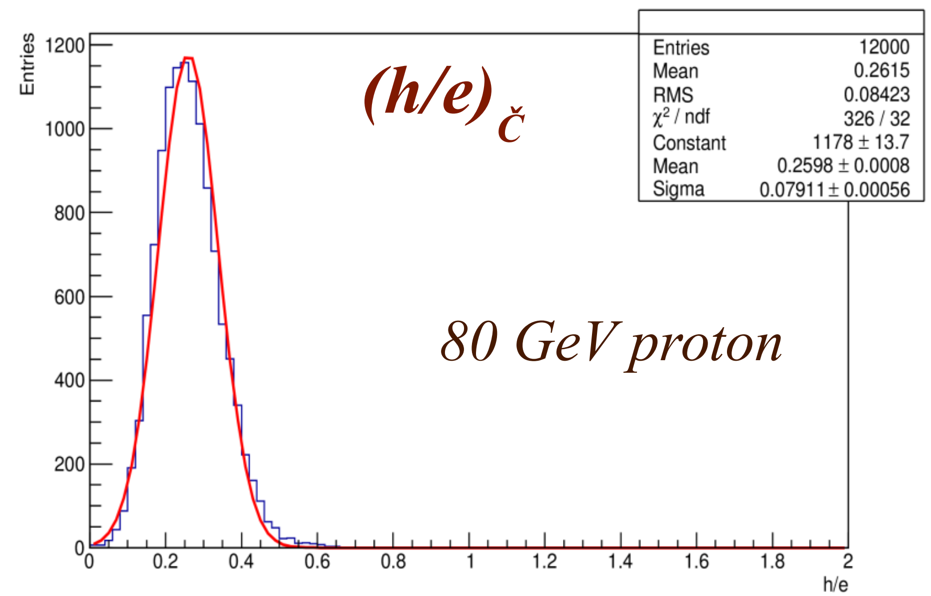


$(h/e)_{S} \approx 0.75$

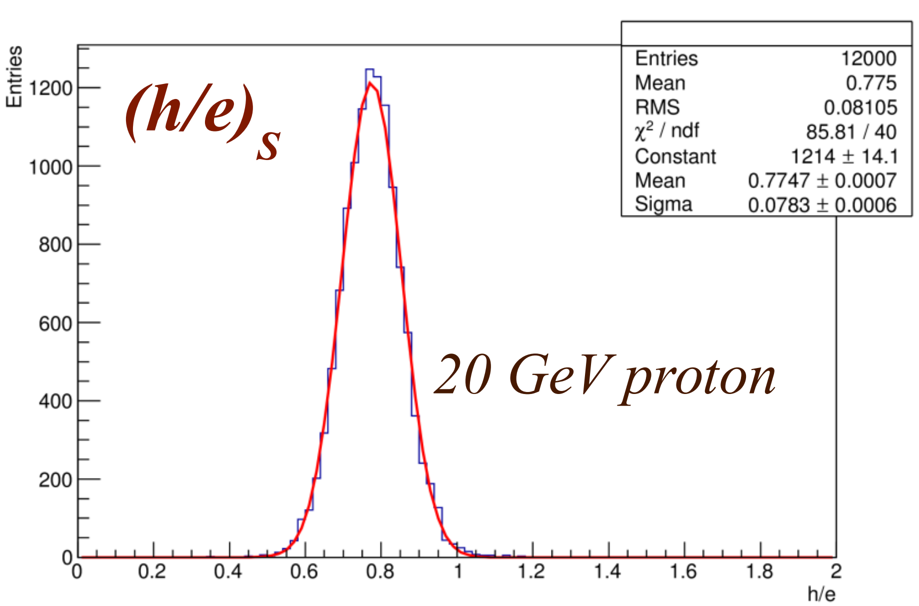
Geant4 – h/e factors for Lead

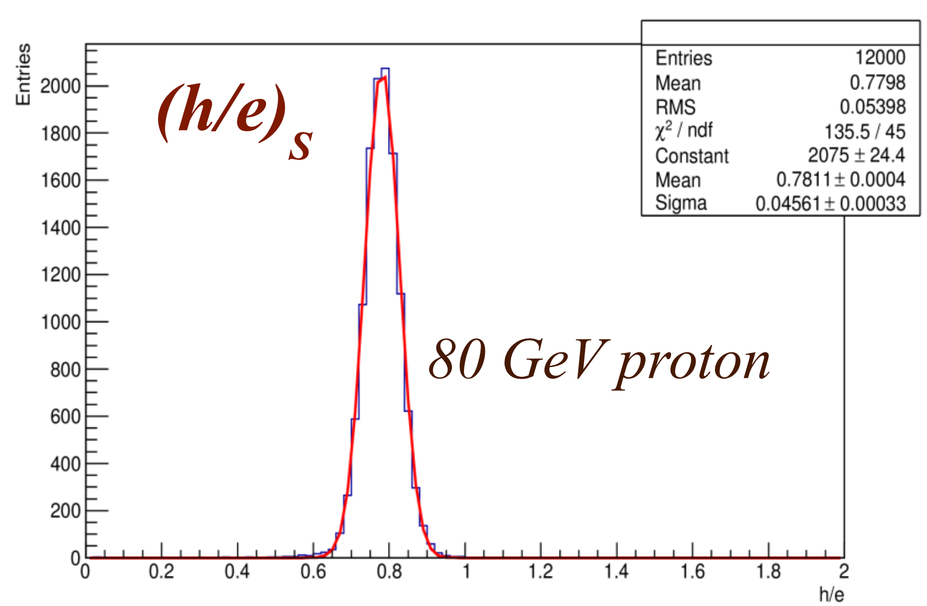
Lead





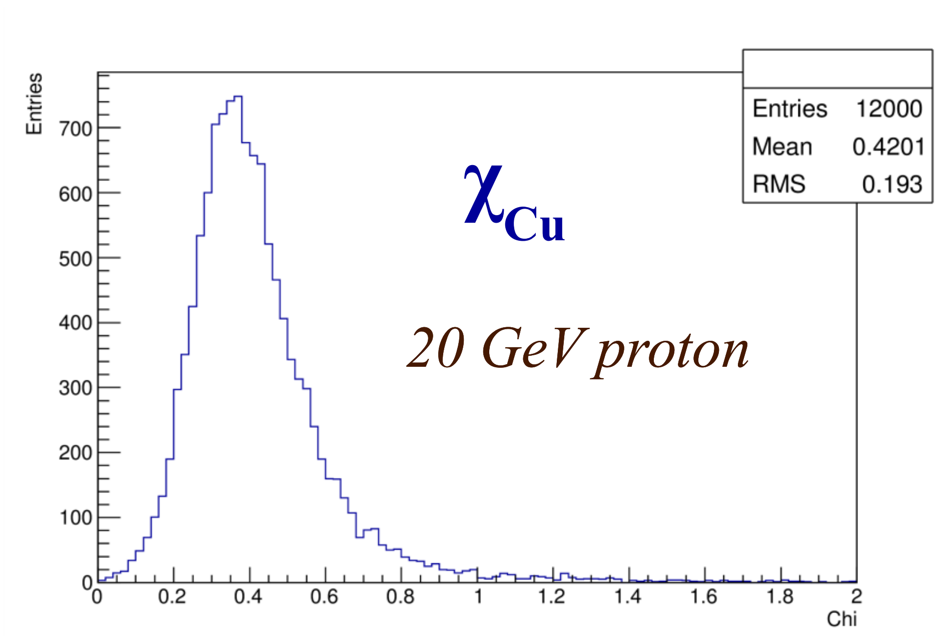
$(h/e)_{Č} \approx 0.26$





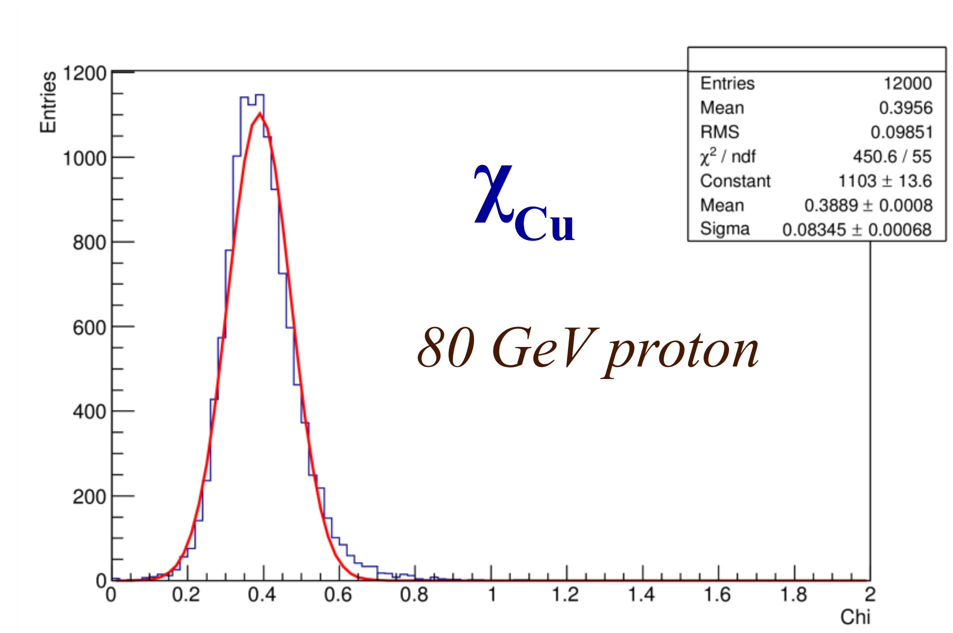
$(h/e)_{S} \approx 0.78$

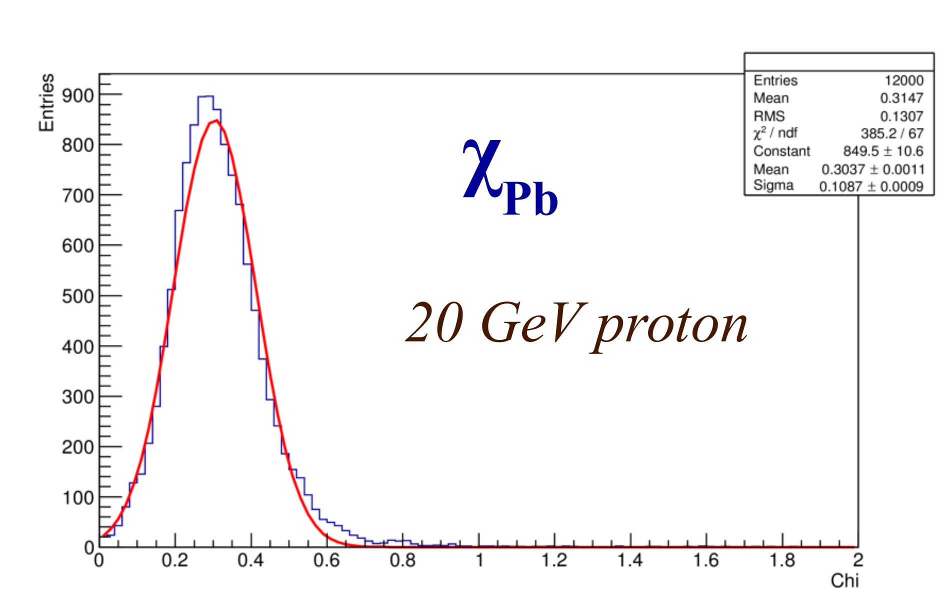
Geant4 – χ factors for Copper and Lead



Copper

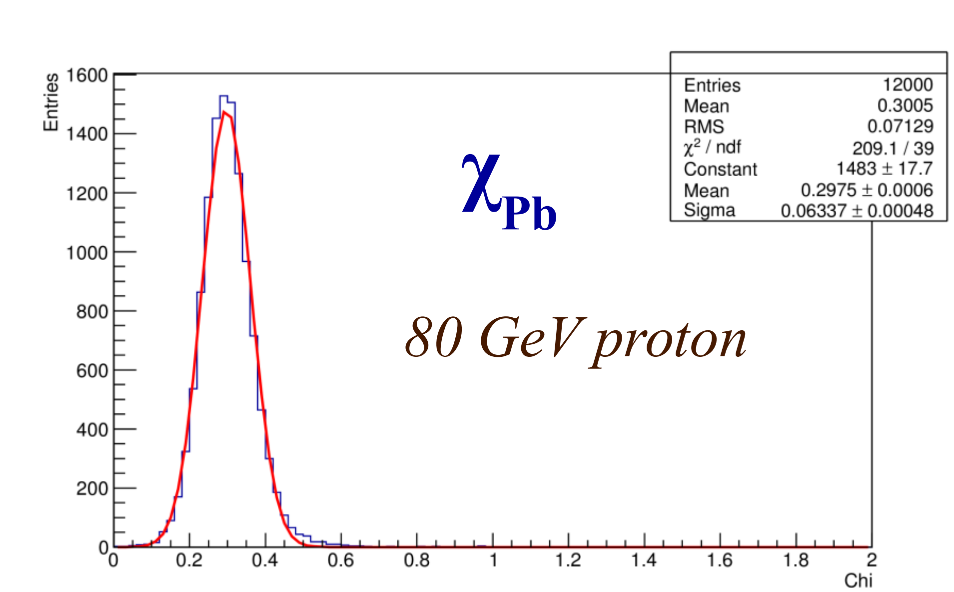
$\chi_{Cu} \approx 0.39$





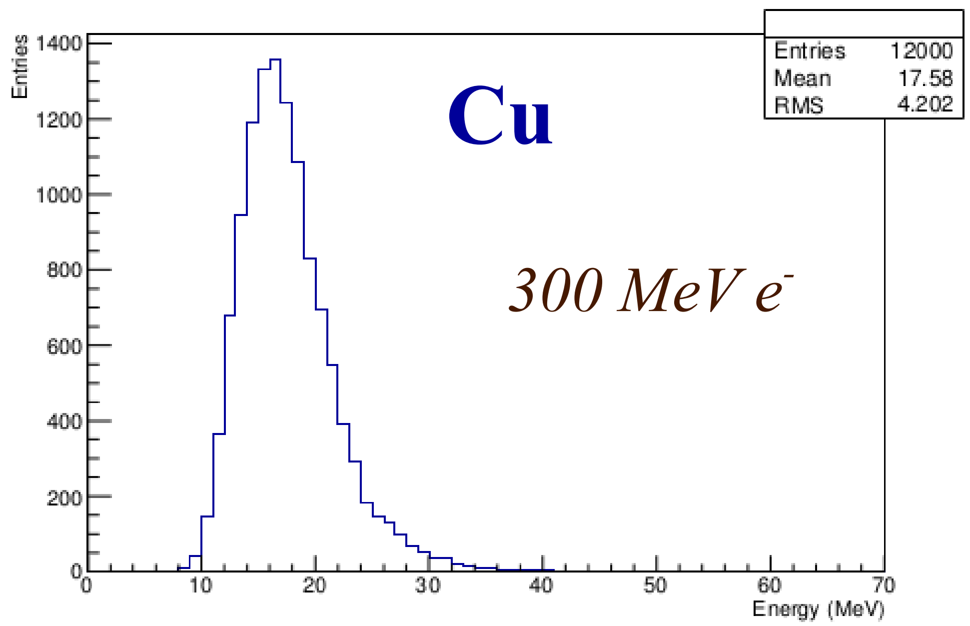
Lead

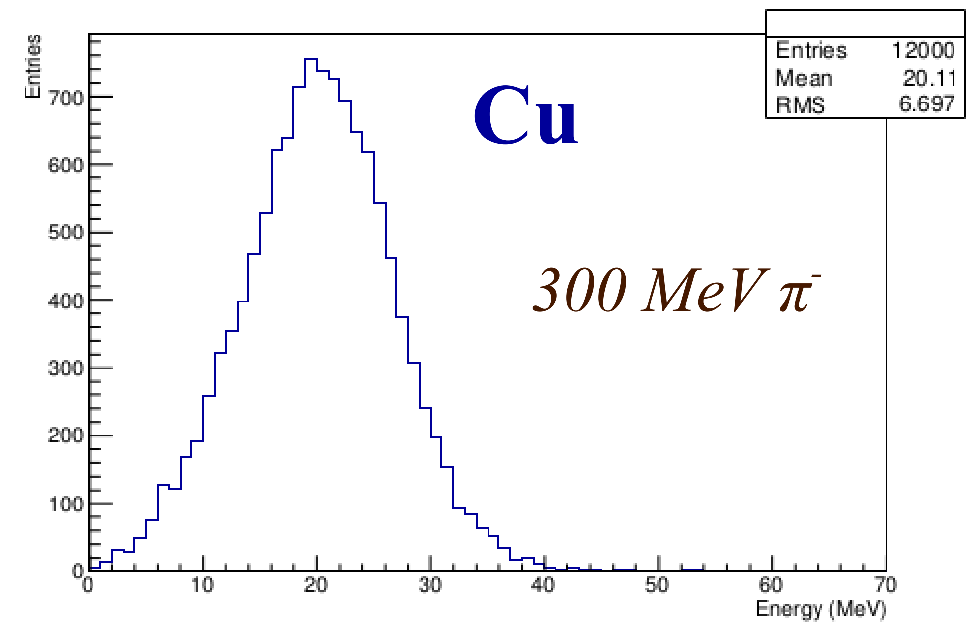
$\chi_{Pb} \approx 0.30$

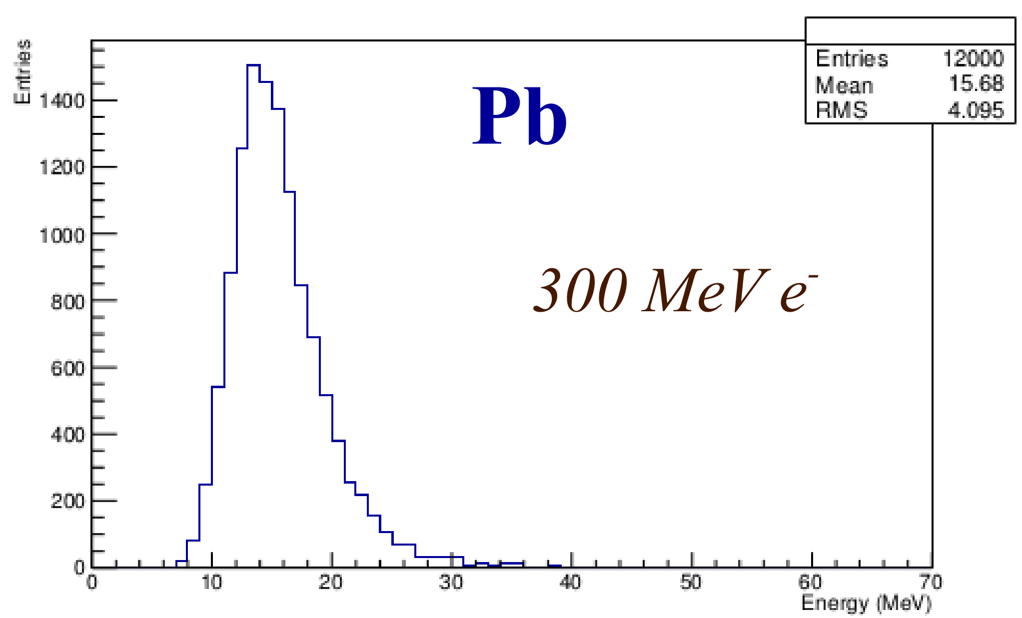


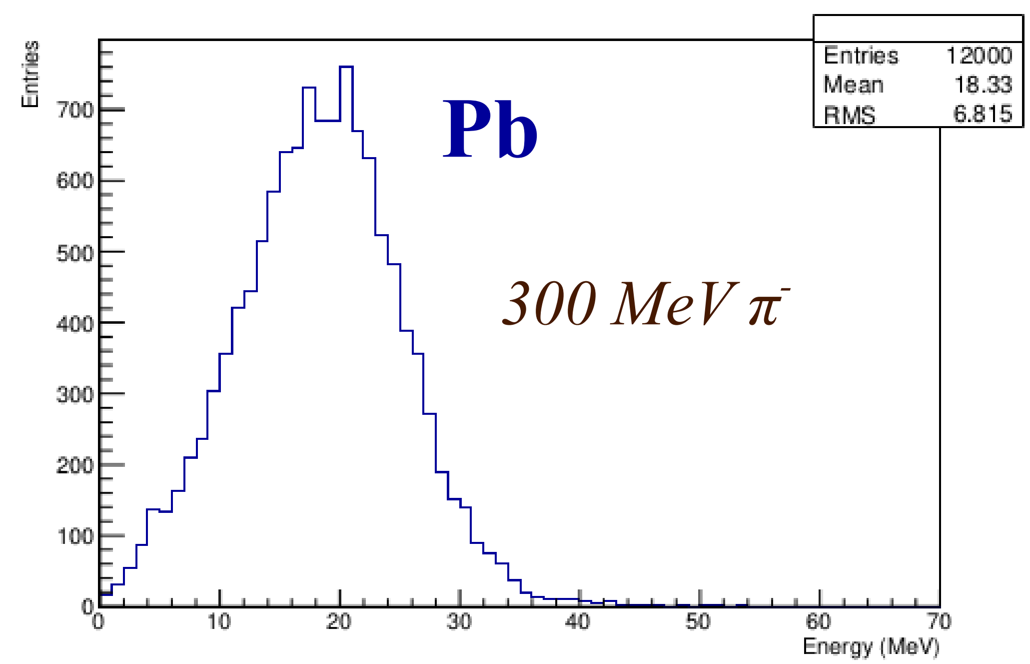
Low-energy performance - Copper vs. Lead

Energy deposited in scintillating fibres



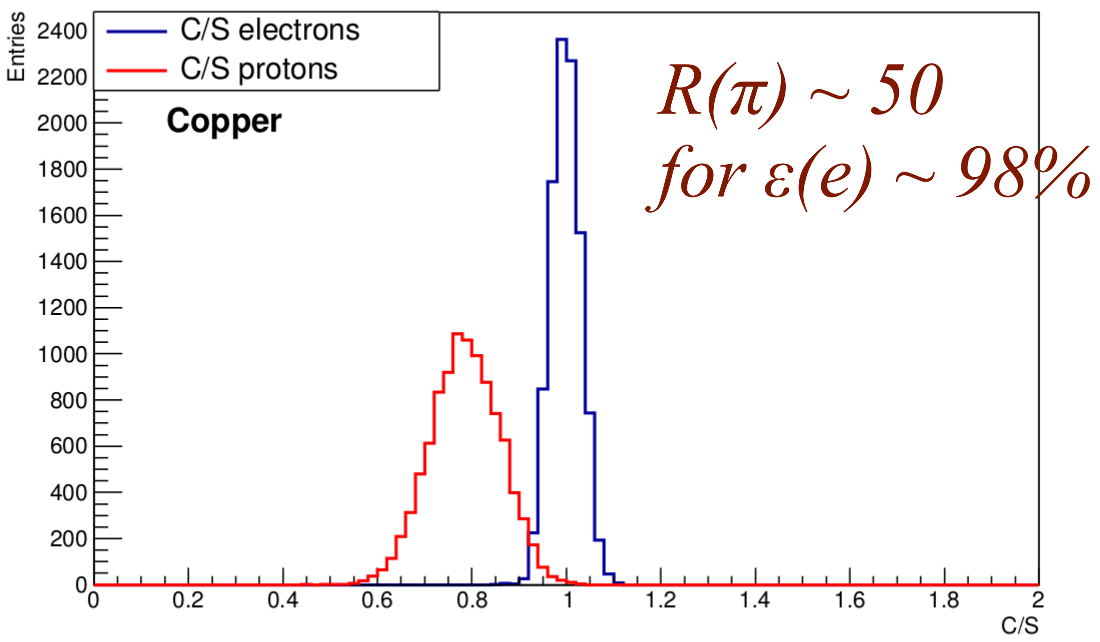


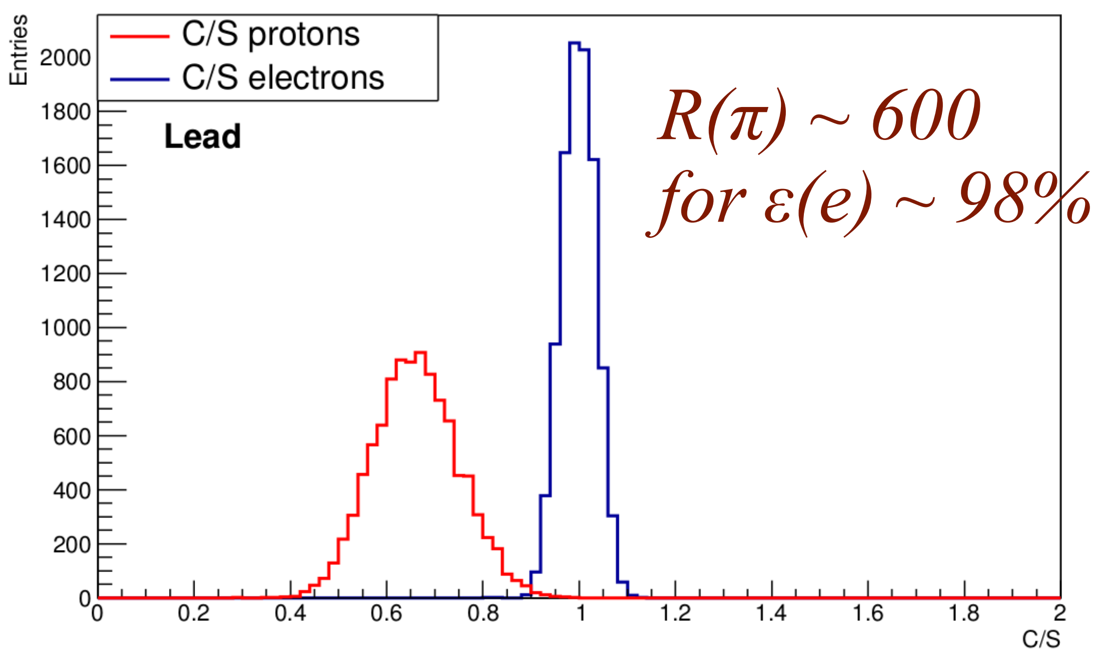




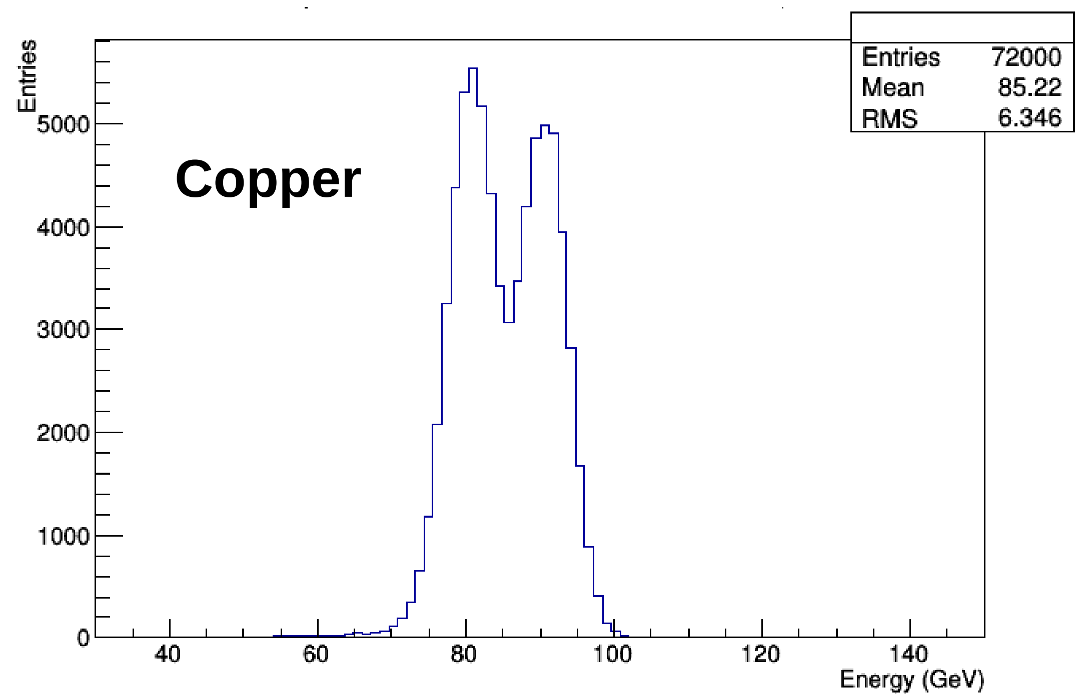
Particle Id & W/Z - Copper vs. Lead

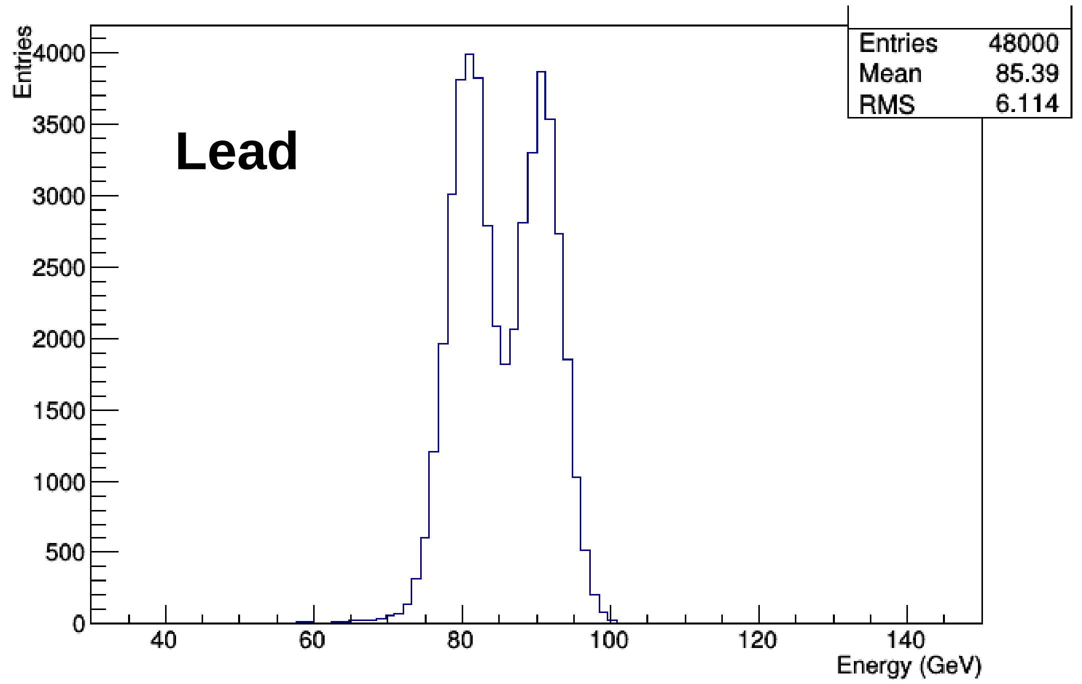
C/S ratio for 80 GeV e^- and p





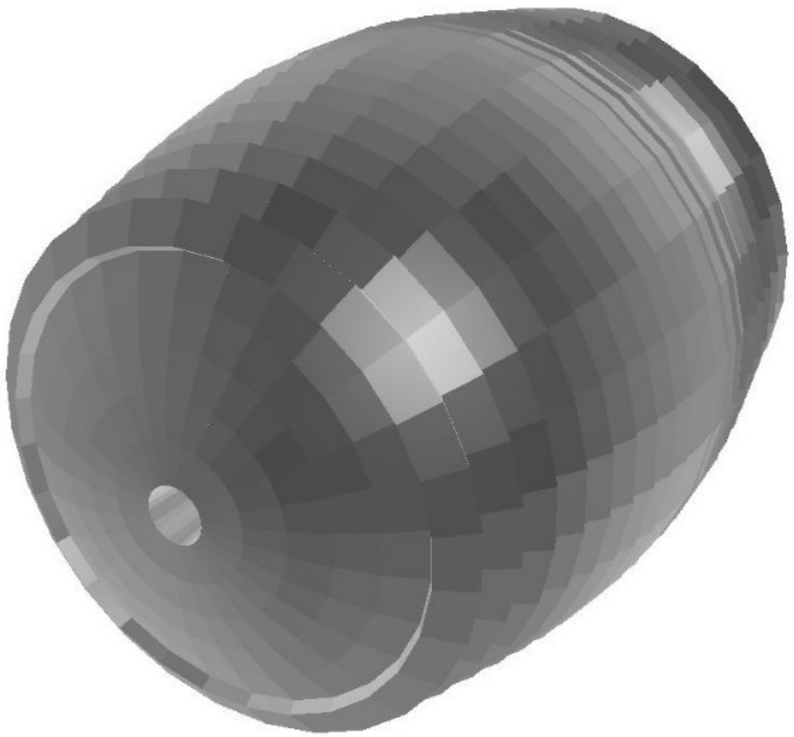
Multiple hadrons, 81 & 91 GeV

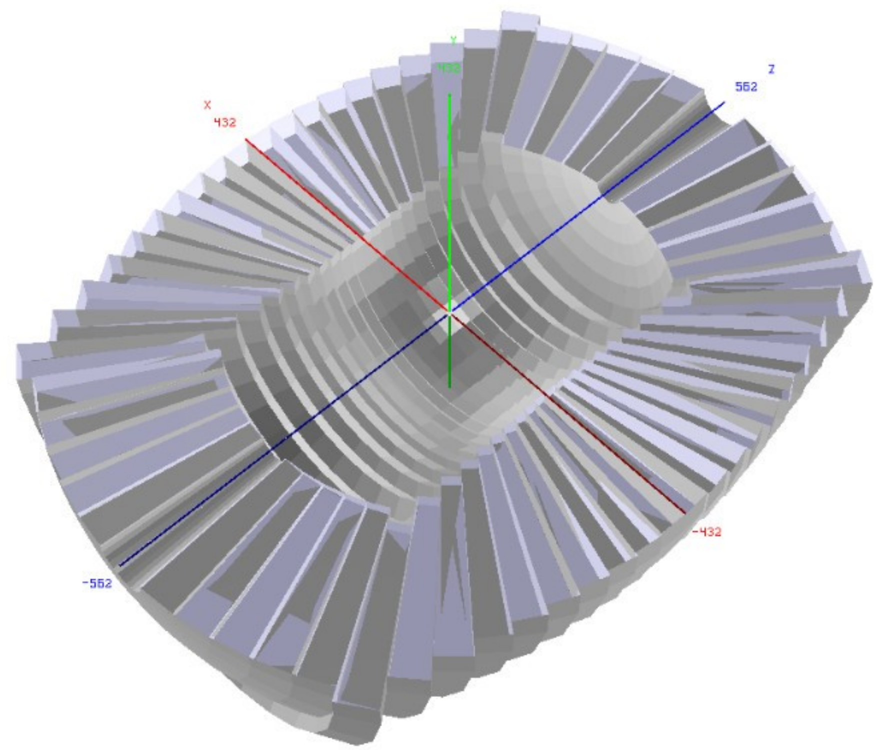


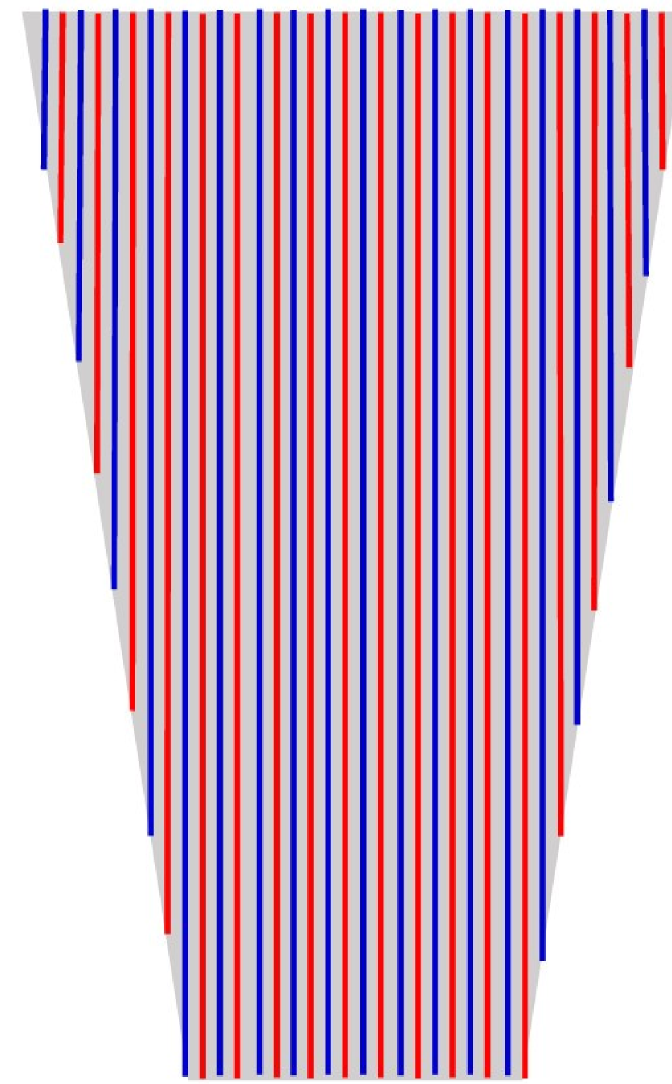


4π Simulations

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







a) full coverage
b) projective geometry

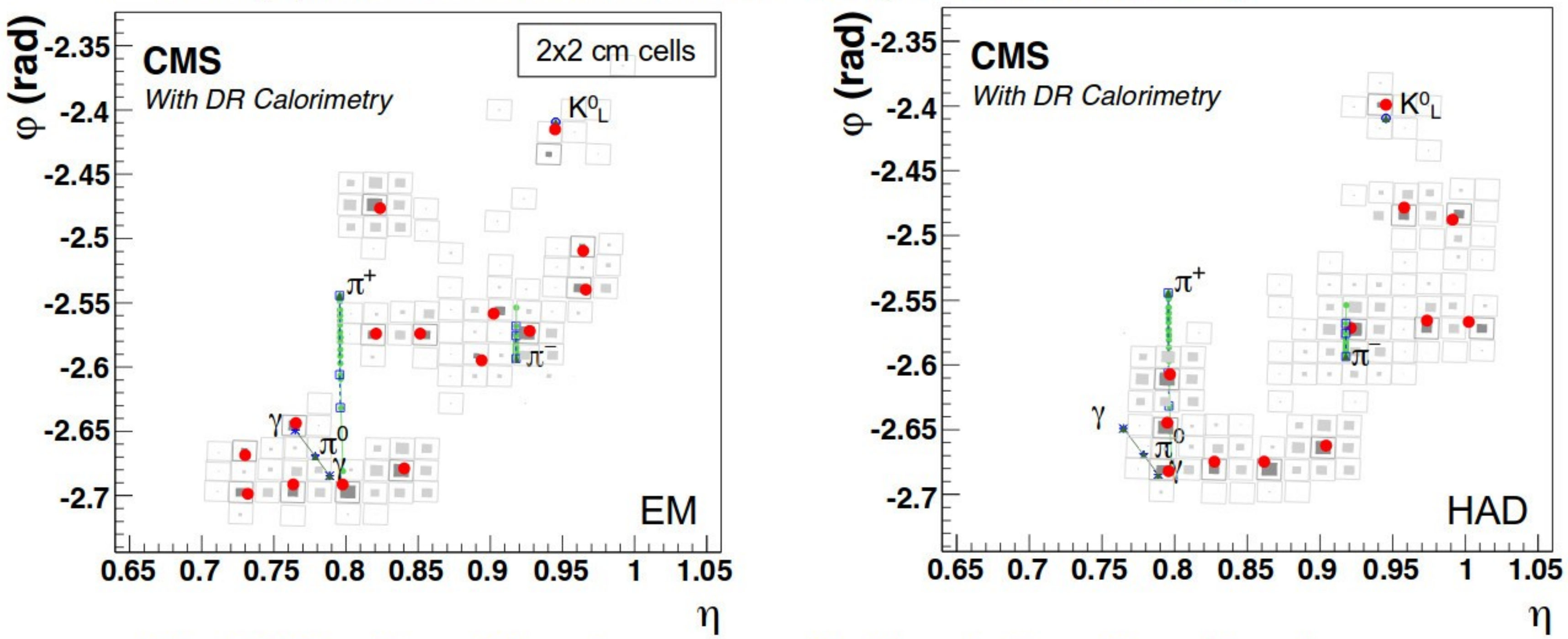
Longitudinal Segmentation & PFA

Last but not least:

addressing the issue of overlapping hadronic and em showers

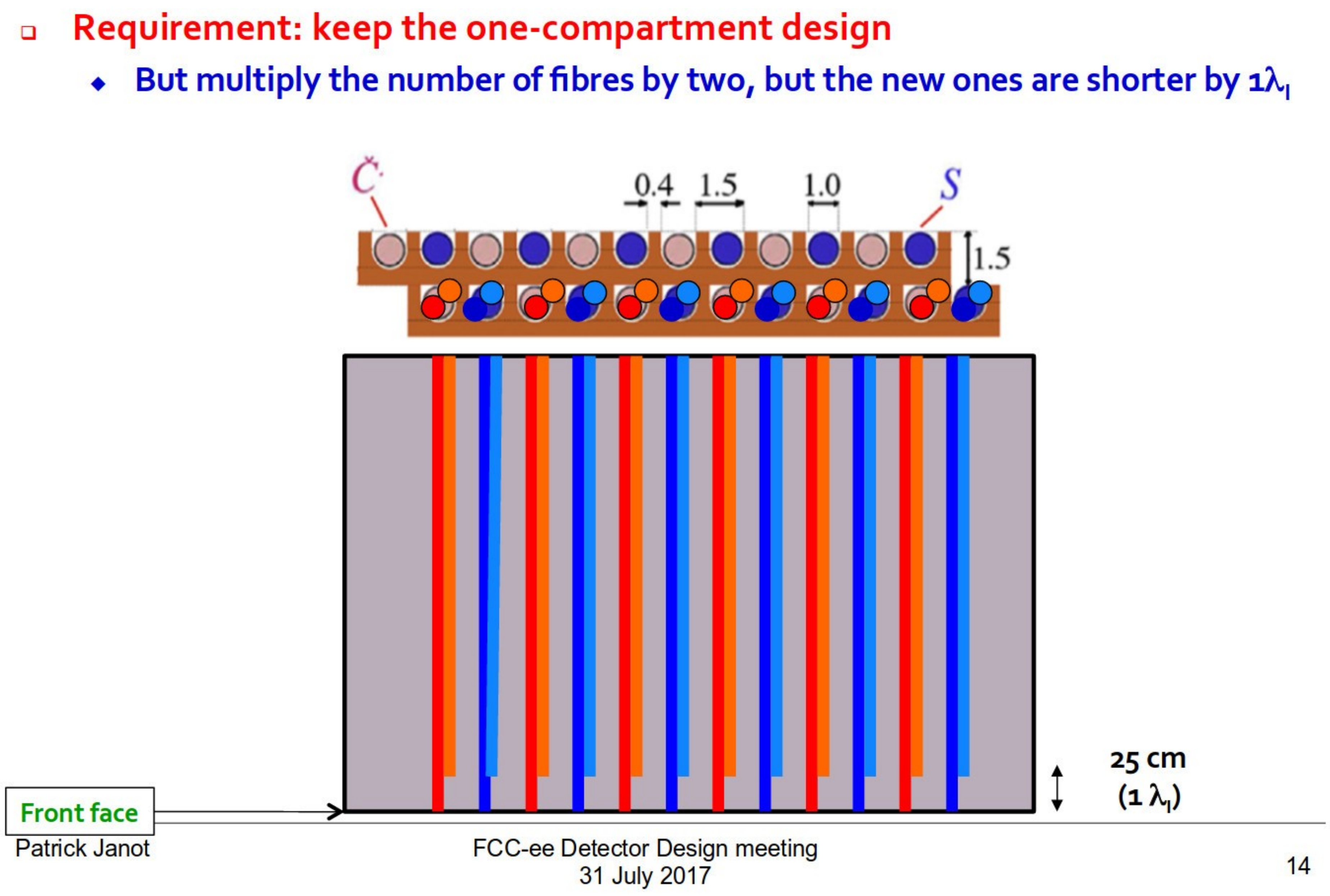
→ Patrick Janot proposes longitudinal segmentation (and PF w/ DR)

- **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 ?



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:

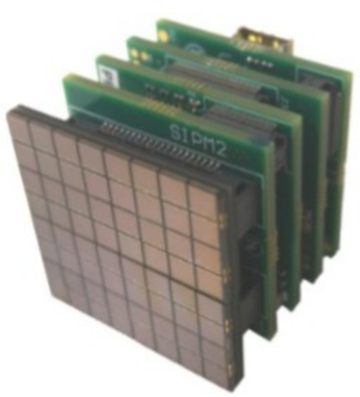
:-)

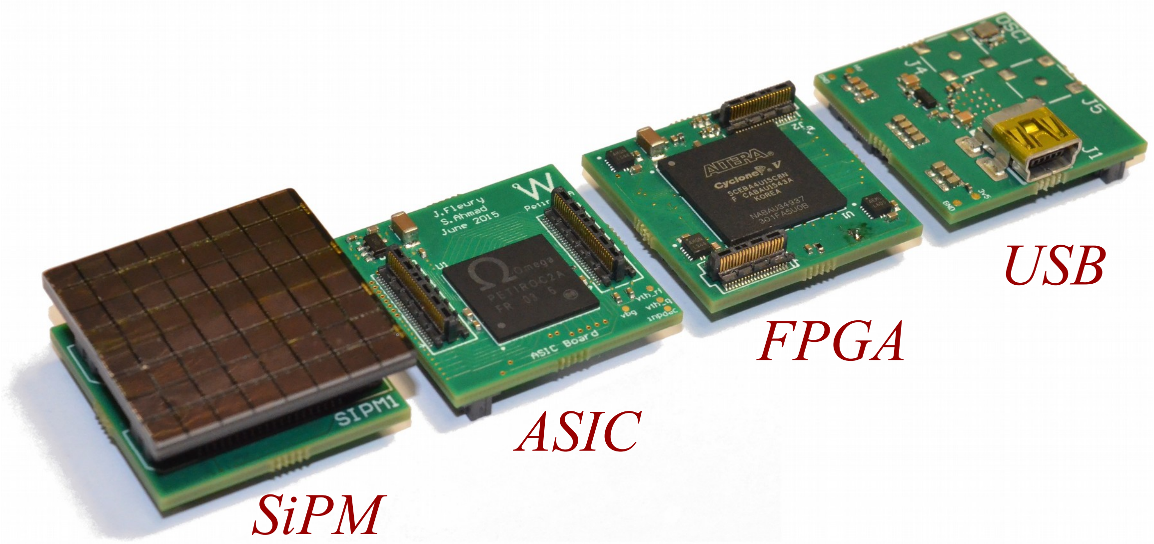
- *32-channel read out system*
- *FPGA based charge integration algorithm*
- *data: event timecode and integrated charge for all pixels*

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

but we would like this:

:-(





SiPM

ASIC

FPGA

USB

first step: ASIC (to be identified)

Conclusions

Preliminary results look very interesting, nevertheless what can be obtained in a real experiment has to be demonstrated/quantified

1) We believe we need (at least) a 3-year R&D plan on mechanics, frontend electronics, readout in order to develop a scalable solution made of:

- *a) ~10x10 cm^2 modules w/ 5000-10000 fibres,*
- *b) individually coupled to photo-detectors*
- *c) w/ data compression/reduction readout*
- *d) feature-extraction processor (?), ...*

2) G4 Simulations and test with beam ... long list:

- *a) terminate Cu & Pb characterisation*
- *b) evaluate impact of finite attenuation length*
- *c) evaluate need/impact of longitudinal segmentation*
- *d) jet ($\tau \rightarrow$had) em/had component separation*
- *e) performance in a realistic integrated 4π detector*
- *f) physics performance (W, Z, H, ...)!*
- *g) particle flow algorithms*

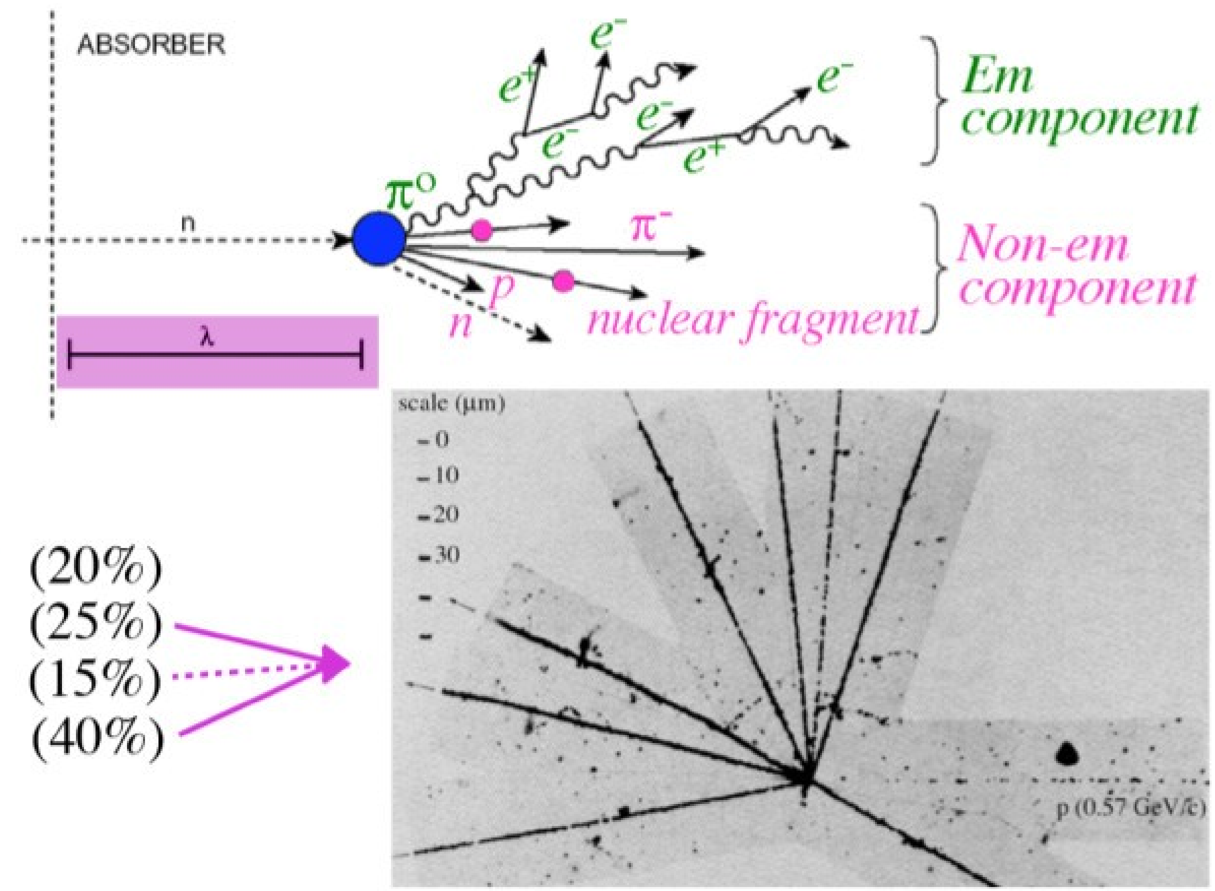
+ G4 VALIDATION w/ RD52 lead prototype

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%)

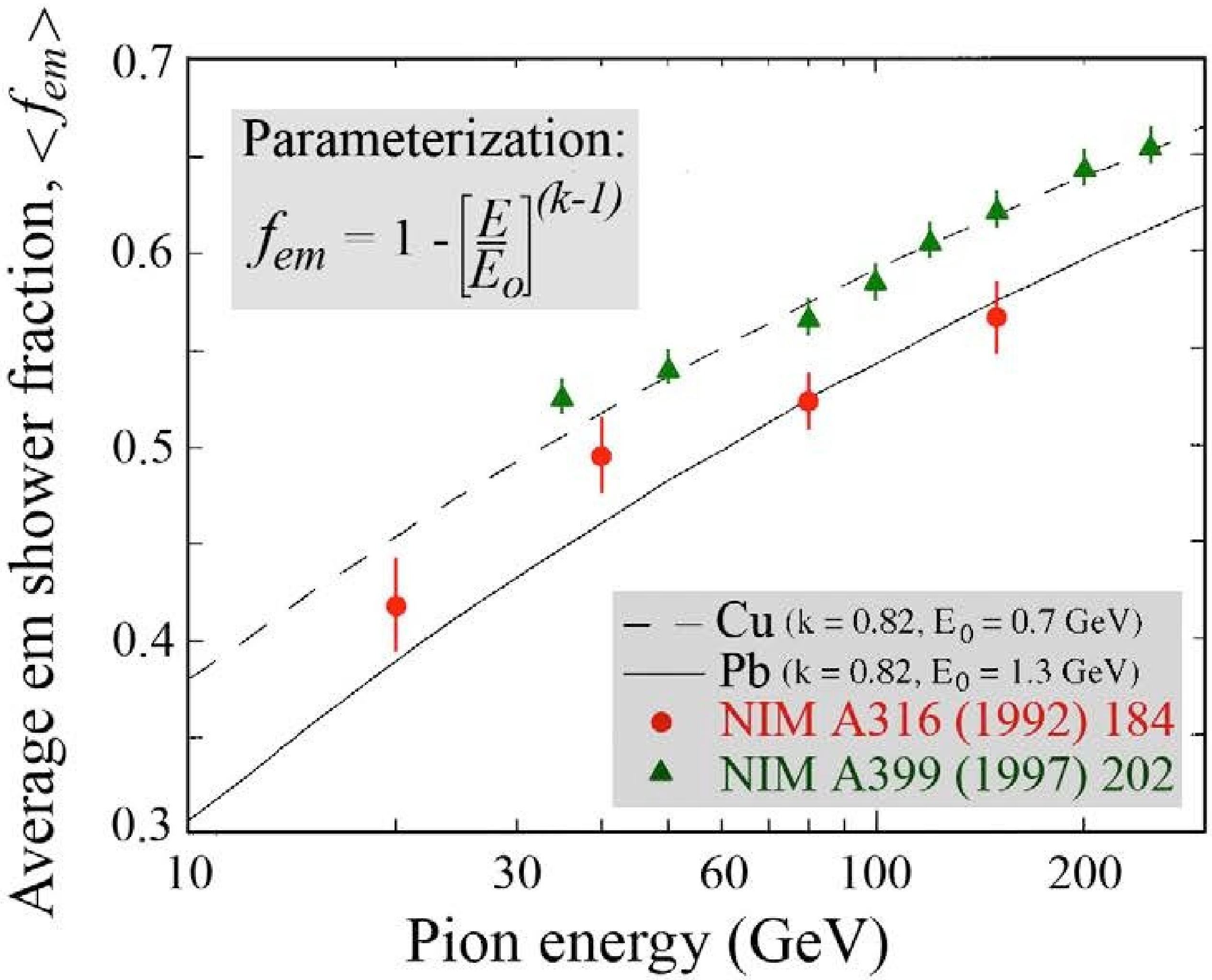


To be faced in hadronic energy measurements:

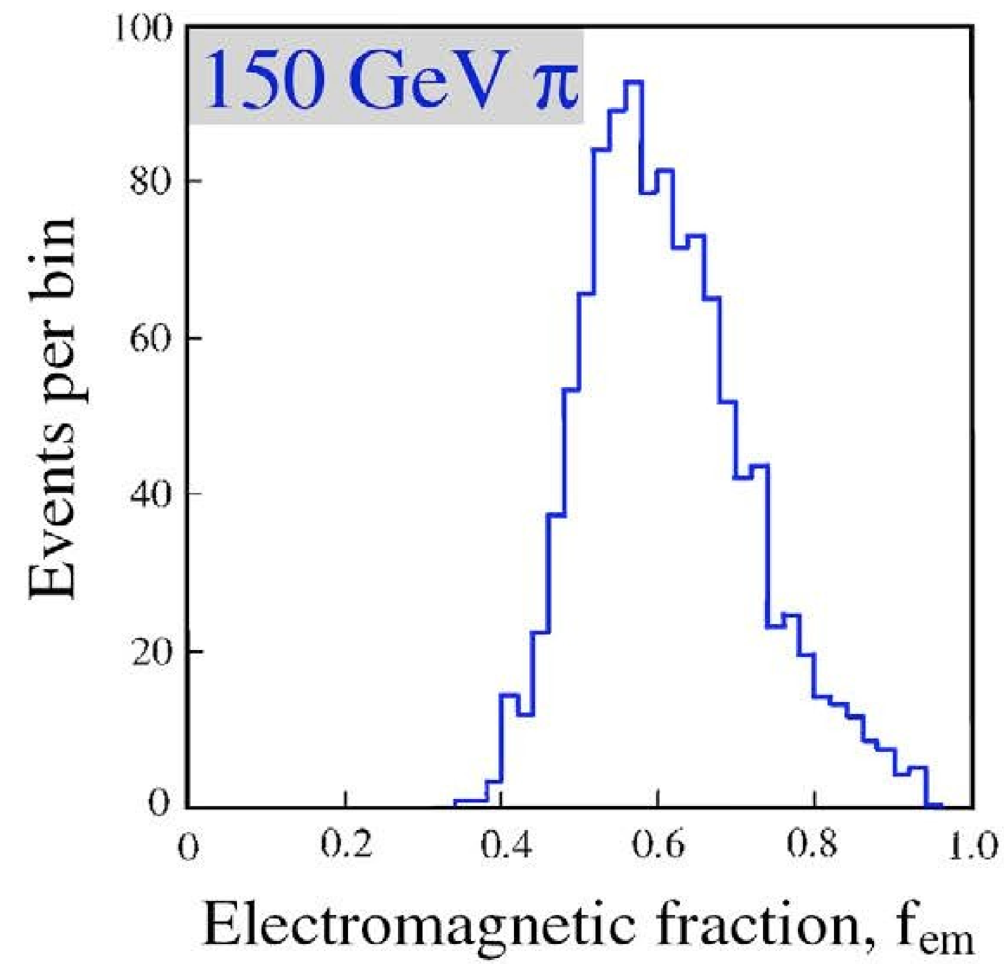
1. Large non-gaussian fluctuations in energy sharing em/non-em
2. Increase of em component with energy
3. Large, non-gaussian fluctuations in "invisible" energy losses

(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



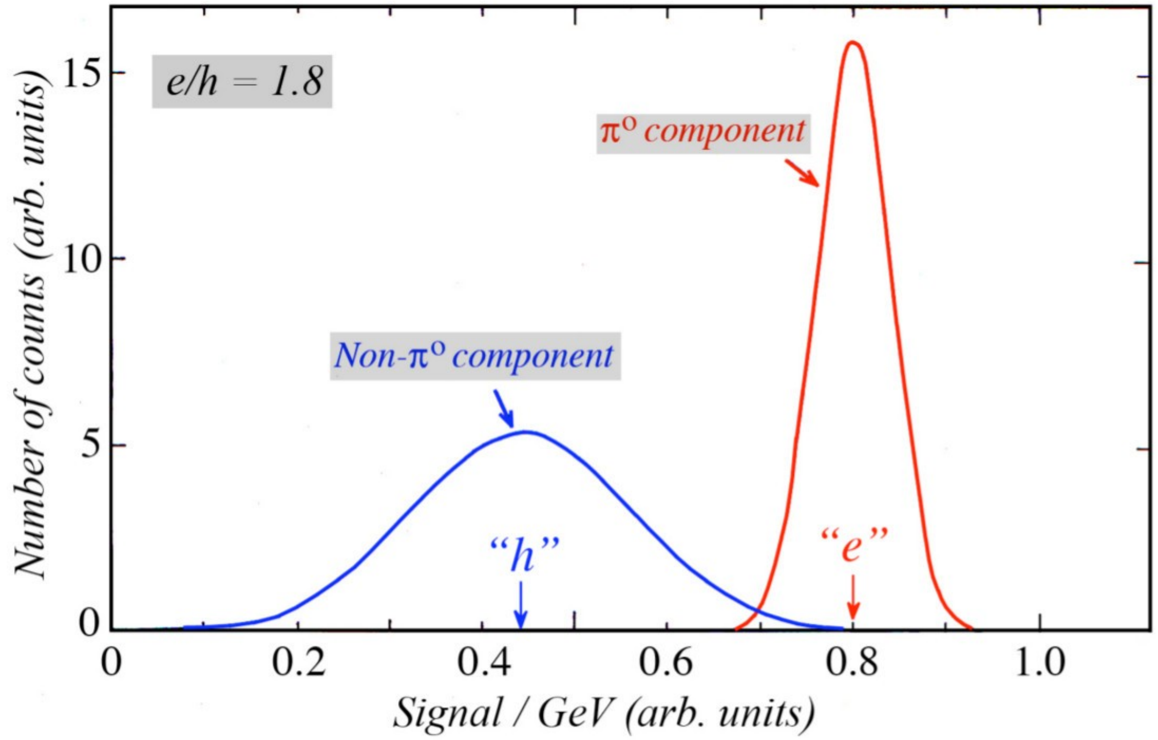
Fluctuations in f_{em} are
large and non-Poissonian

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

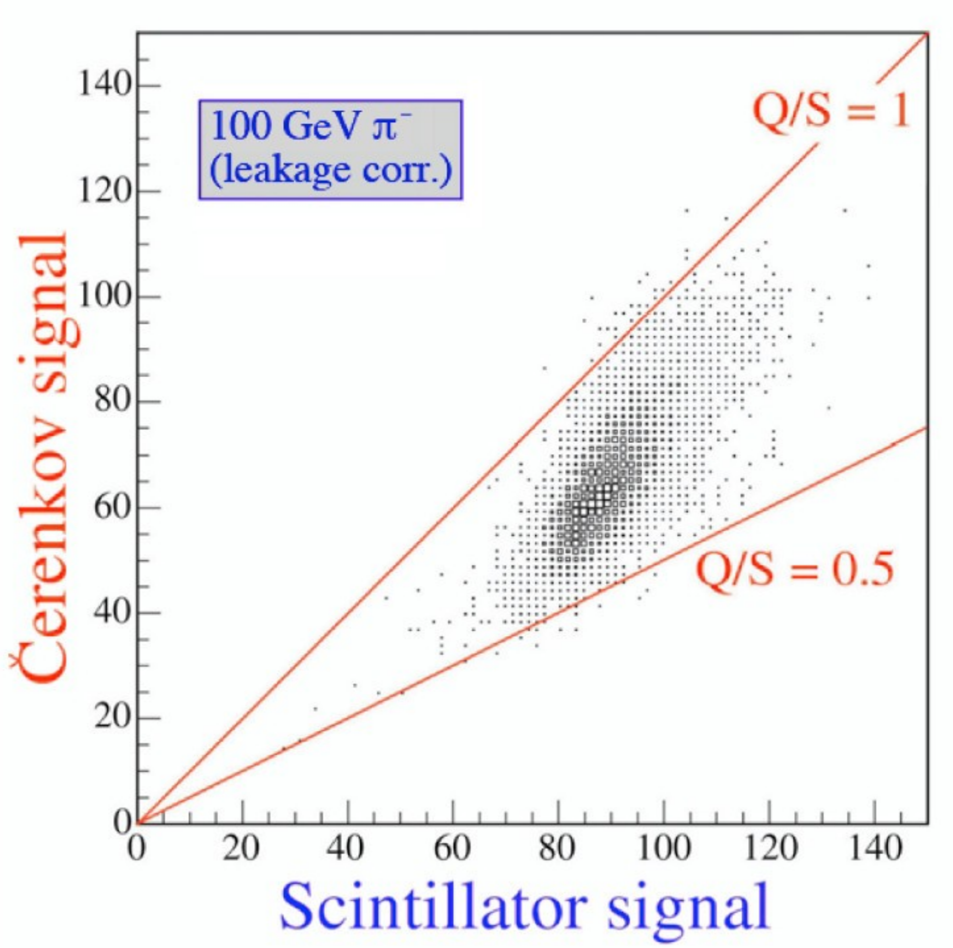
Don't spoil em resolution to get e/h = 1 (i.e. keep e/h > 1) *BUT* measure f_{em} event-by-event

⟹ *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)

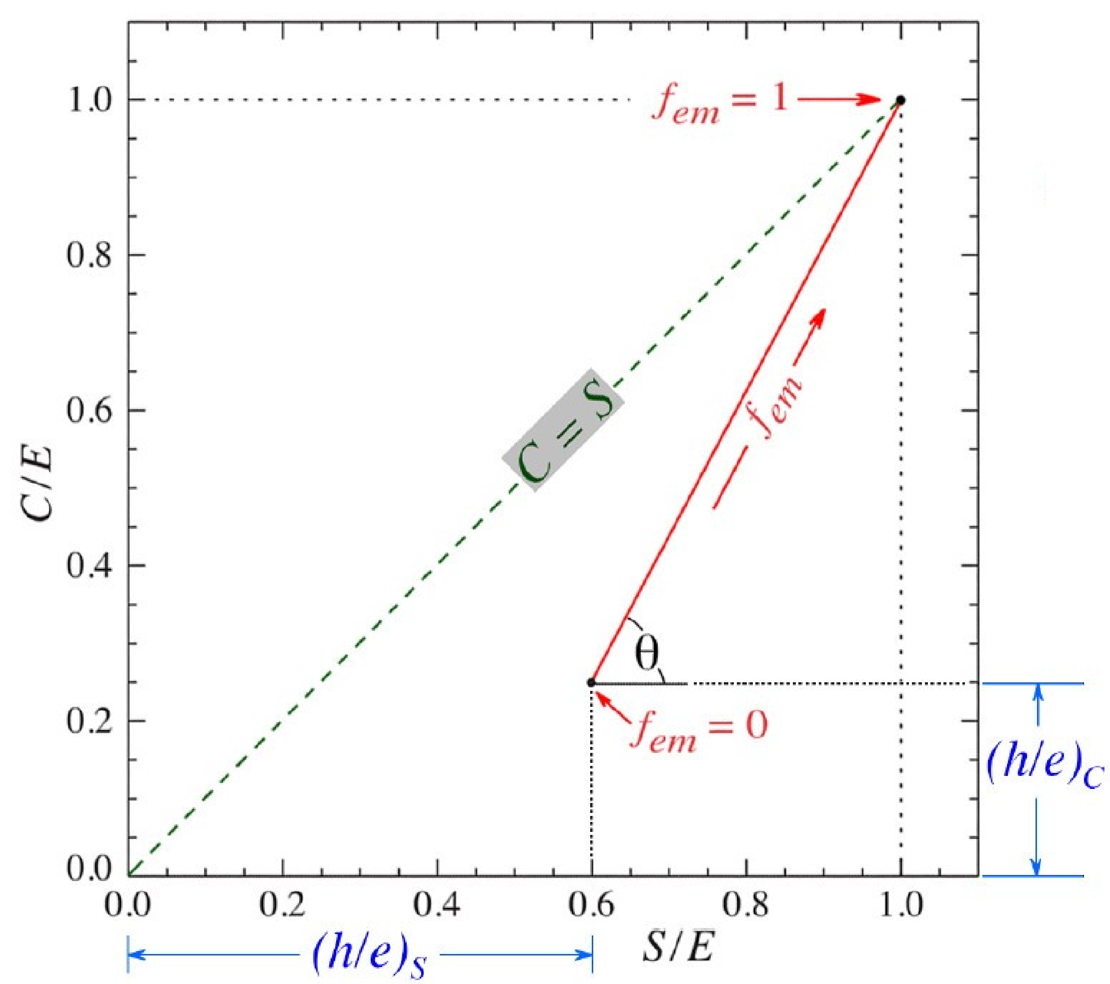
DREAM: How to Determine f_{em} ?



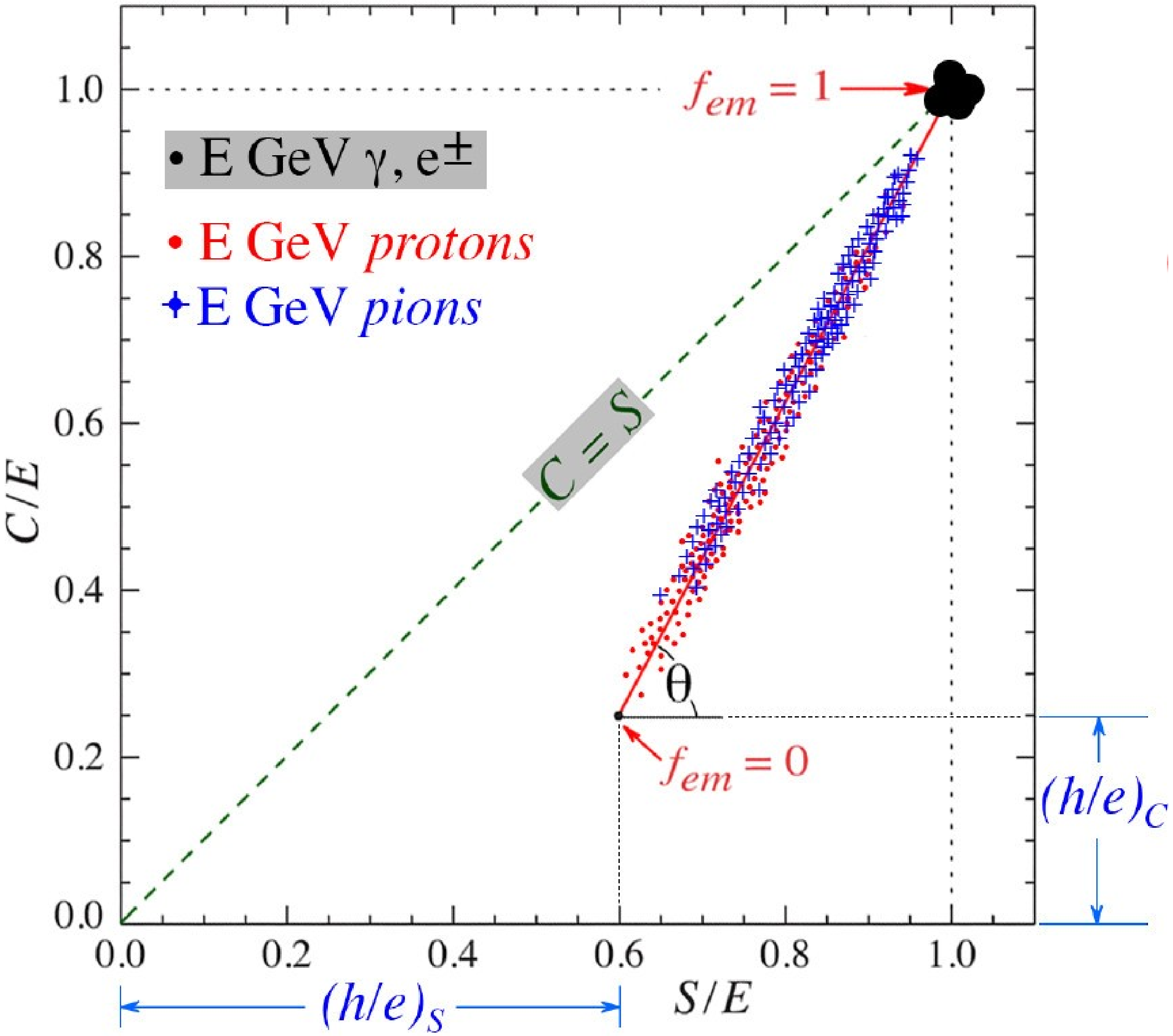
- $S = E \times [\ f_{em} + (h/e)_s \times (1 - f_{em})\ ]$
- $C = E \times [\ f_{em} + (h/e)_c \times (1 - f_{em})\ ]$
- e.g. if: (e/h) = 1.3(S) .vs. 4.7(C)
- $\rightarrow S/C = (0.21 + 0.79 \times f_{em}) / (0.77 + 0.23 \times f_{em})$

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

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



Dual Readout at Work (1)



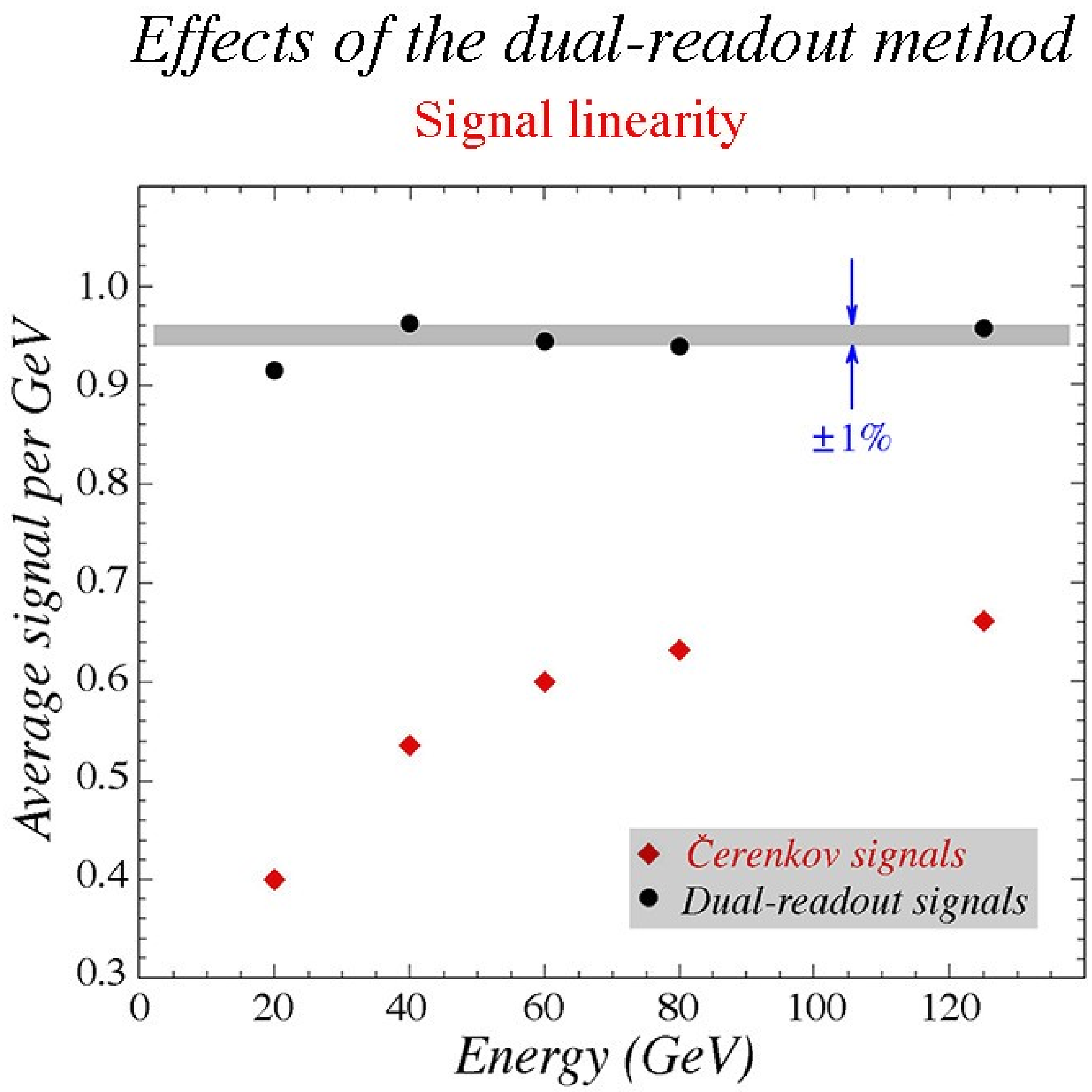
$$cotg\,\theta = \frac{1-(h/e)_S}{1-(h/e)_C} = \chi$$

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

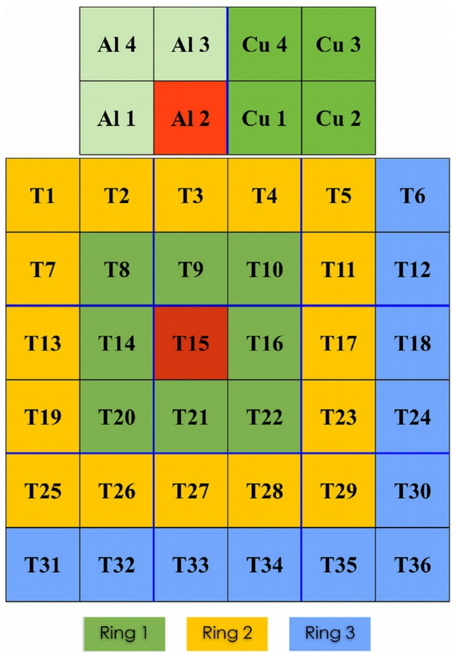
$$E = \frac{S-\chi C}{1-\chi}$$

is universally valid

Dual Readout at Work (2)



Dual Readout at Work (3)



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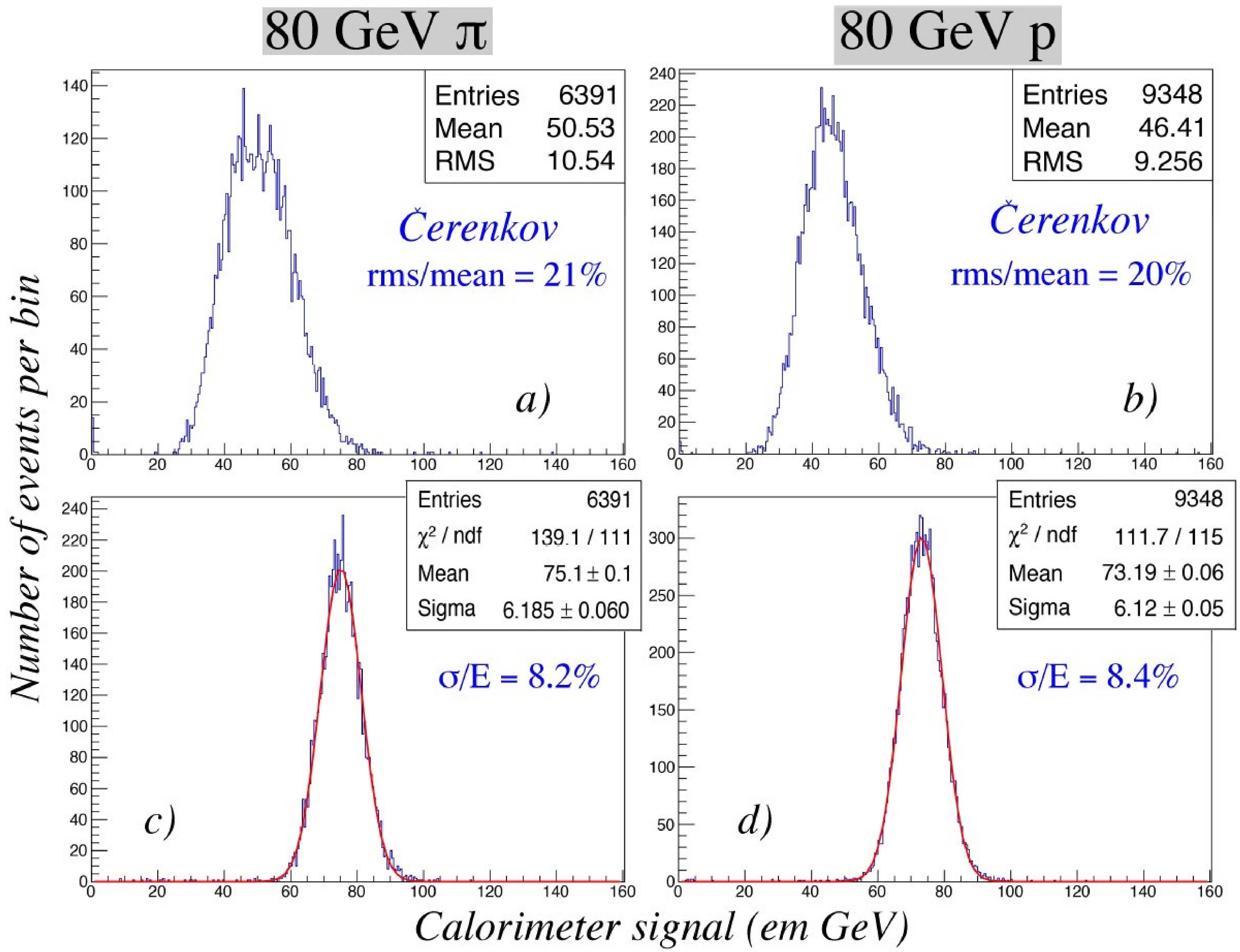
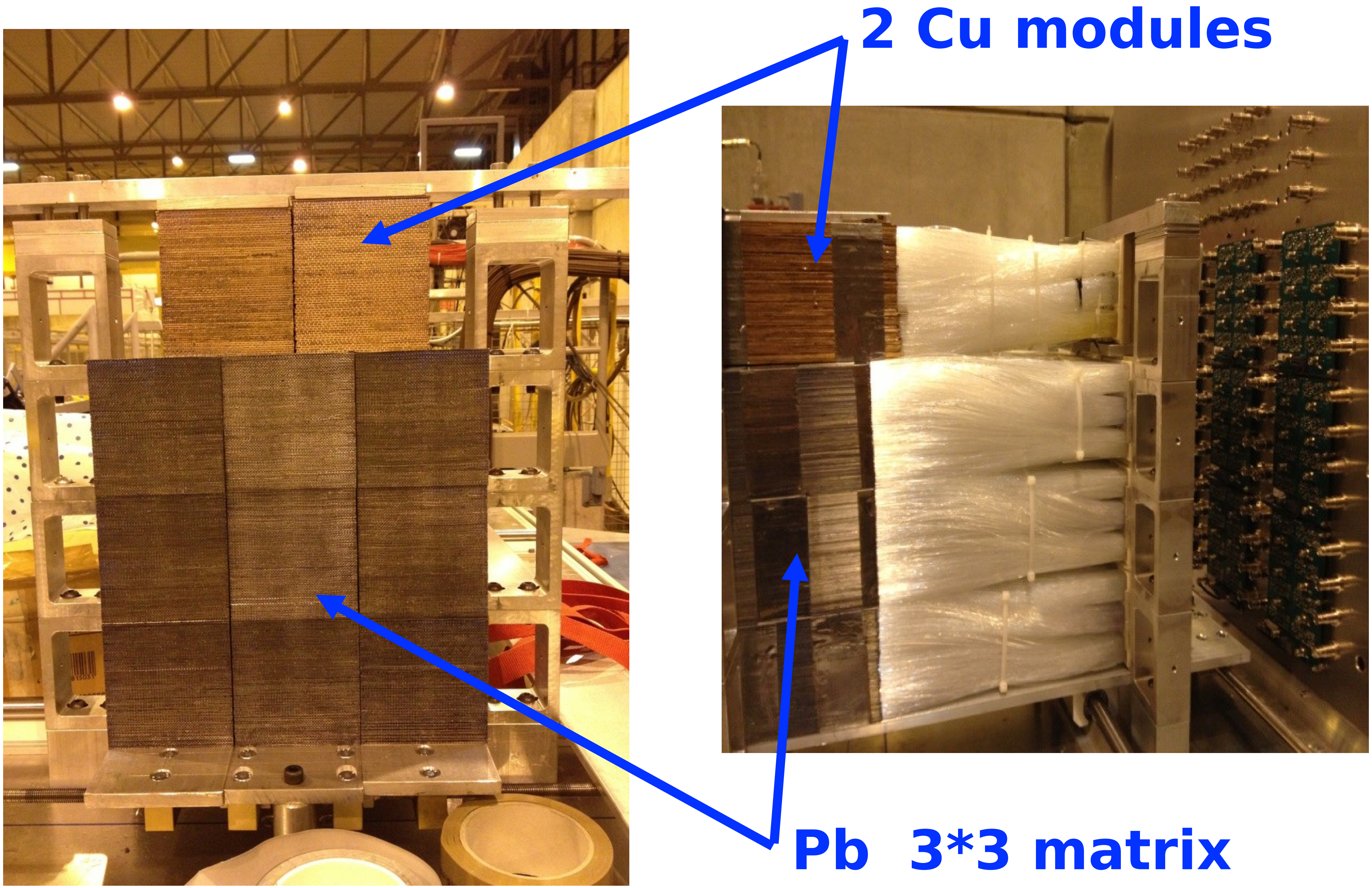


RD52 DR Fibre Calorimeters

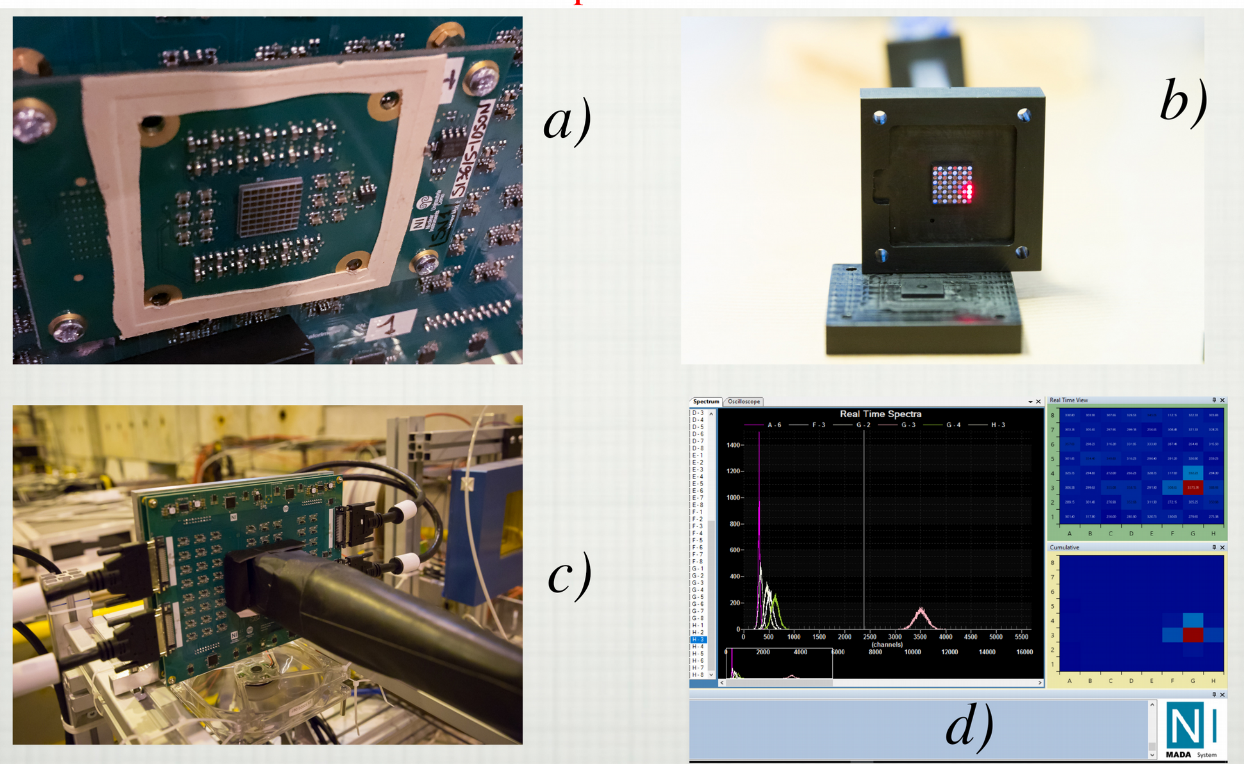


RD52 SiPM Readout

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)

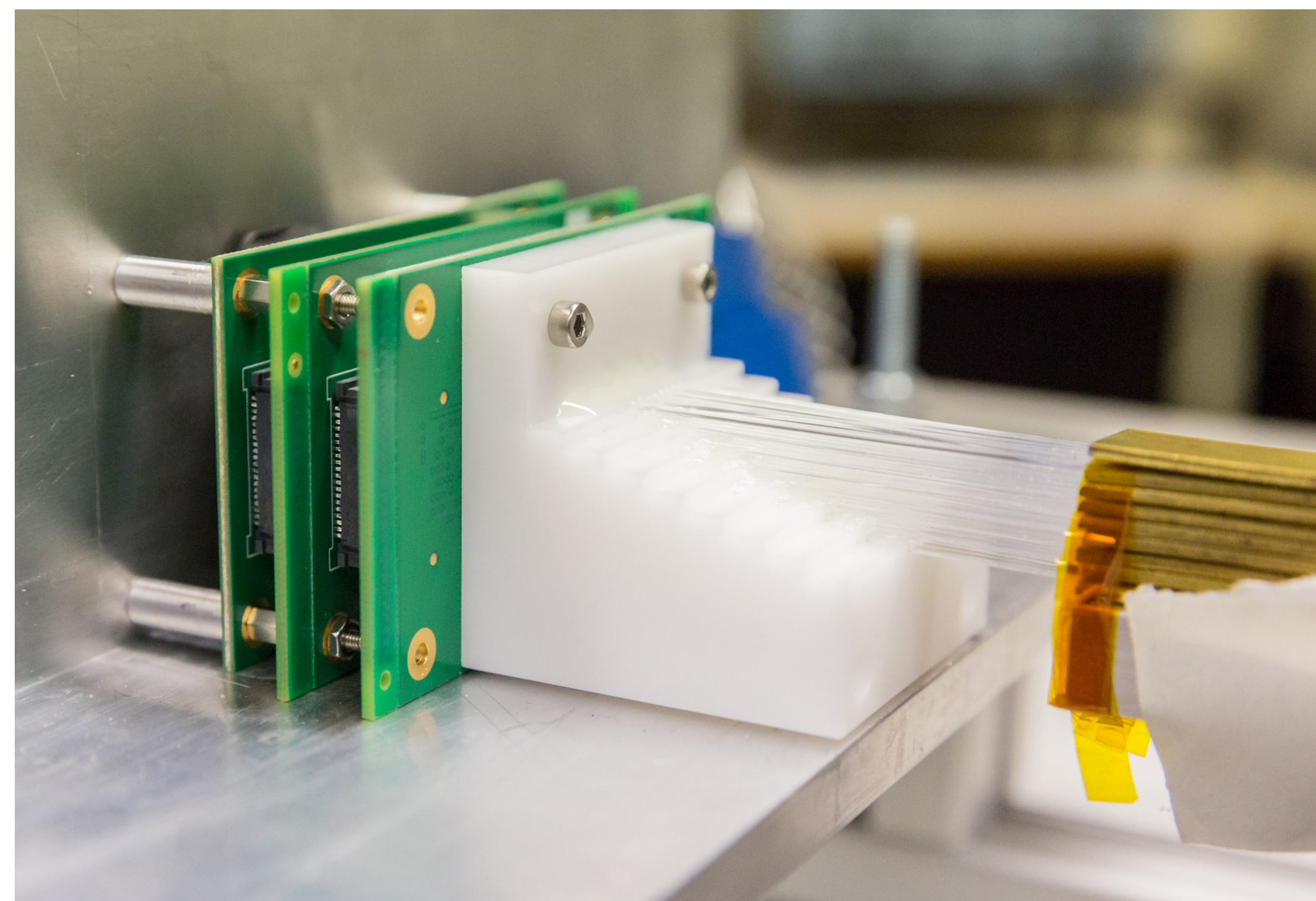
MODULE 2: *Only Čerenkov fibers connected (32)*

2016

a) 400 cells
b) 40% PDE

limitations:

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



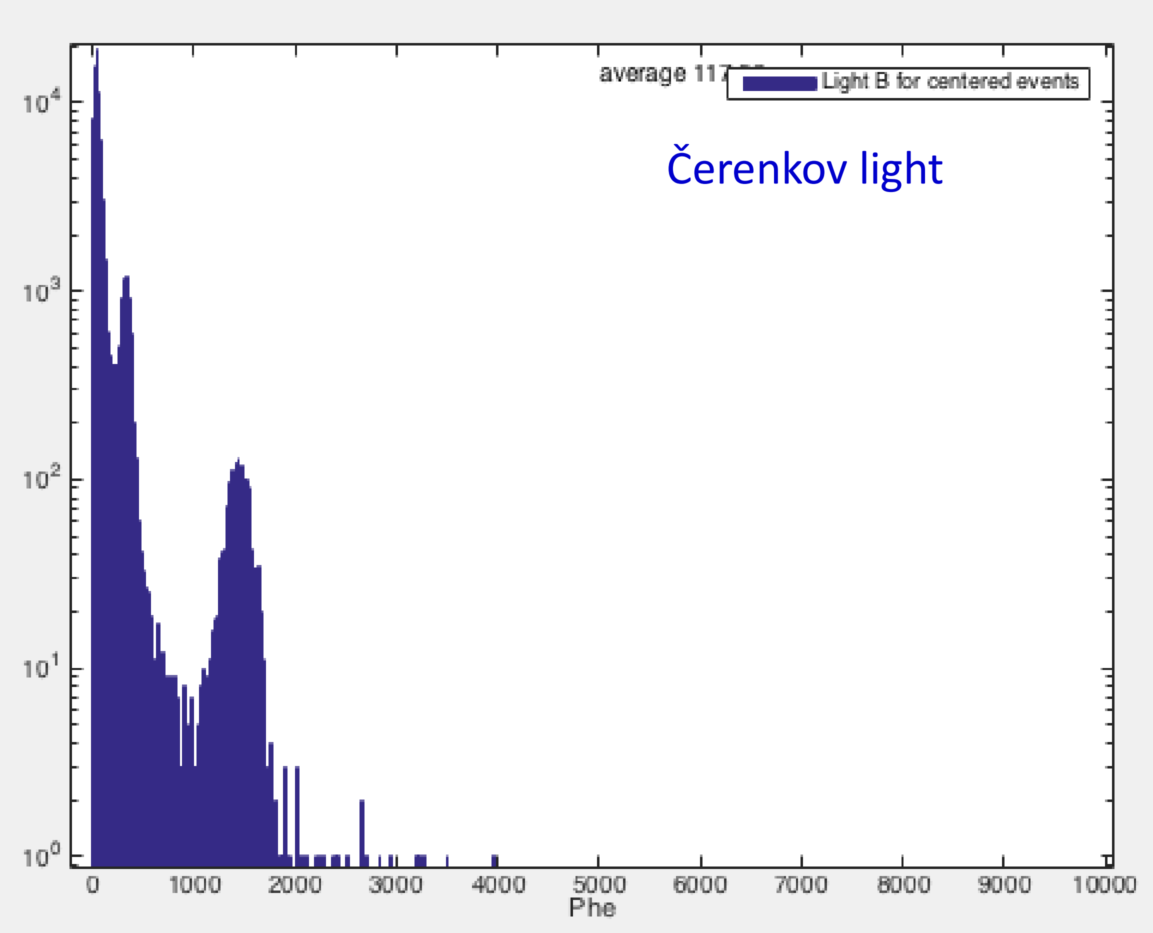
2017

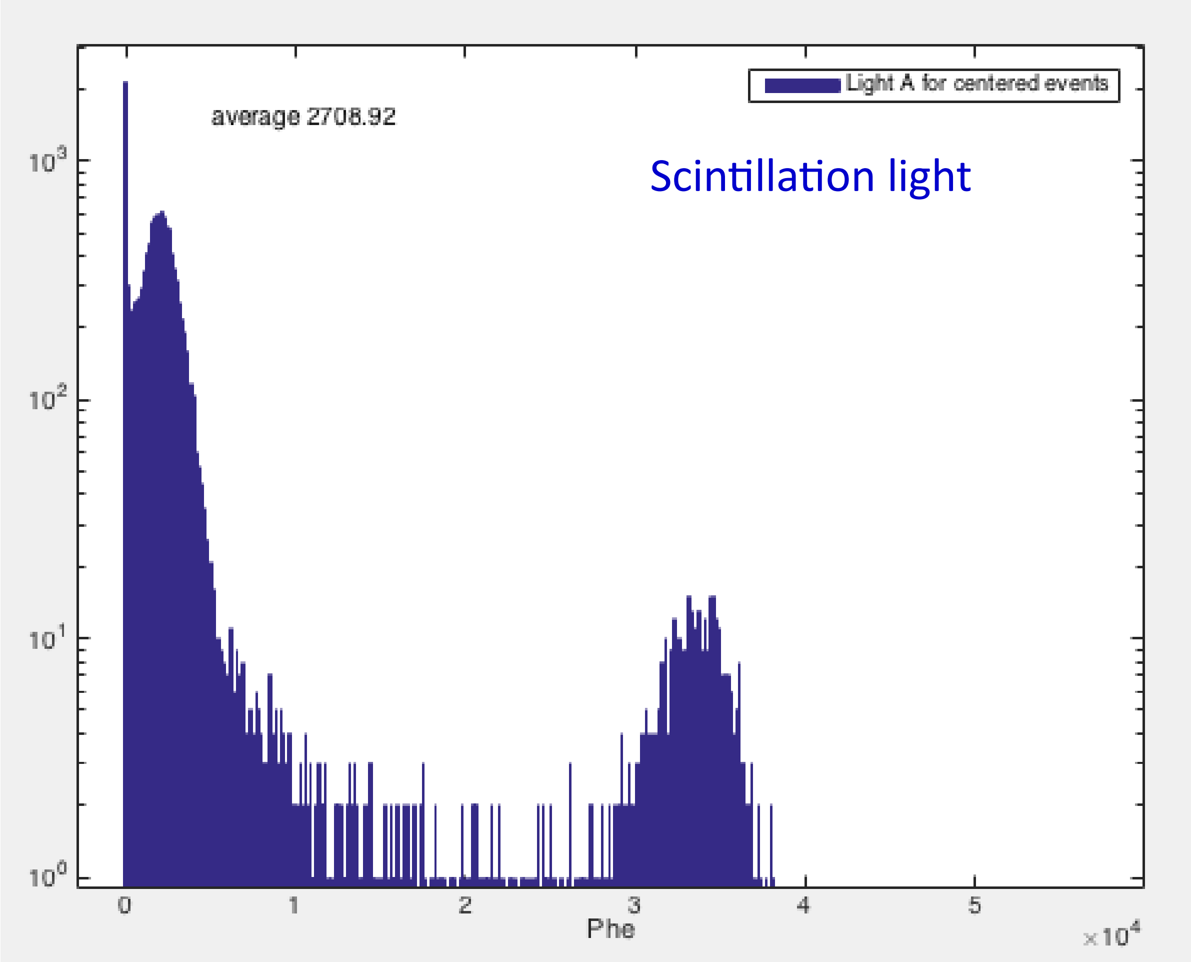
a) 4 x dynamic range (1600 cells)
b) 25% PDE
c) photo-detection at 2 different levels

RD52 Preliminary Results (2017)

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

50 GeV electron beam



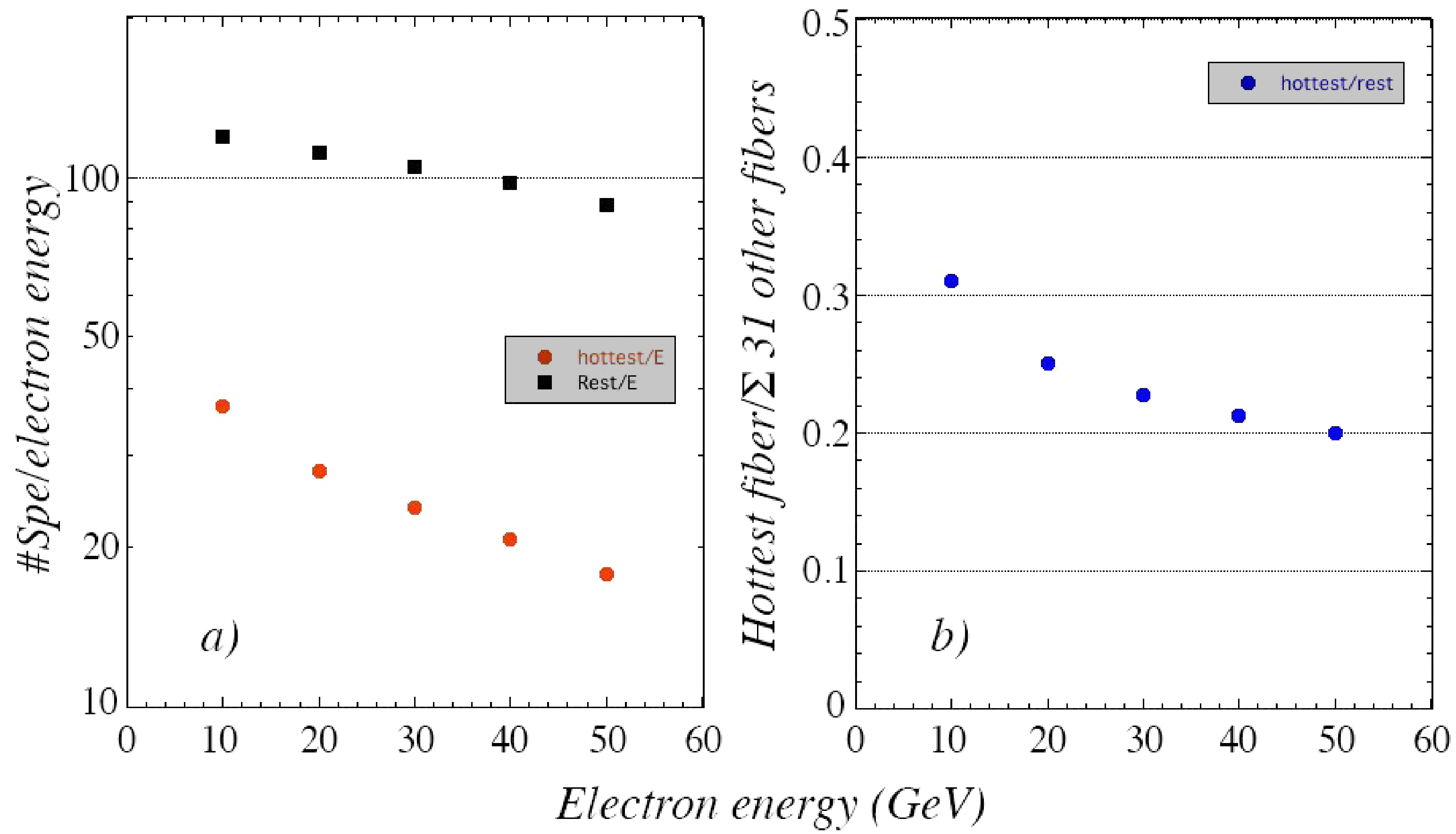


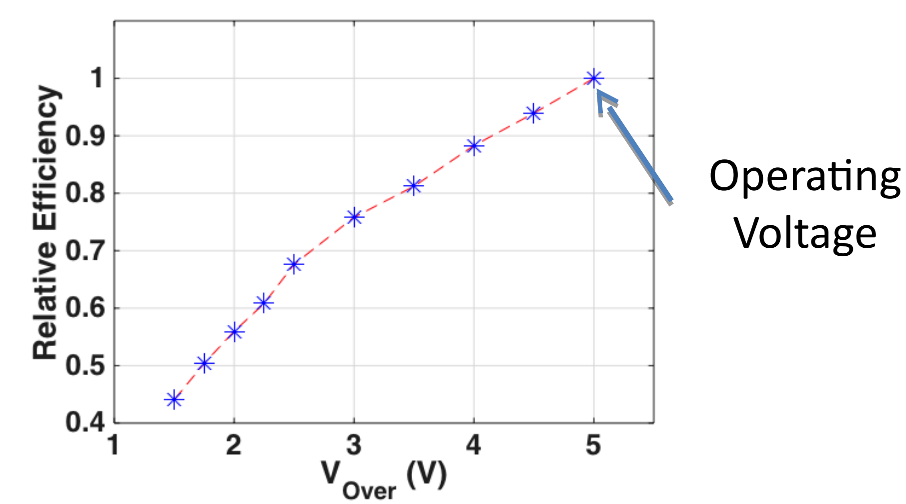
Preliminary Results (2017) – Scintillation Signals

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

Number of p.e. / GeV in hottest

Ratio hottest/rest

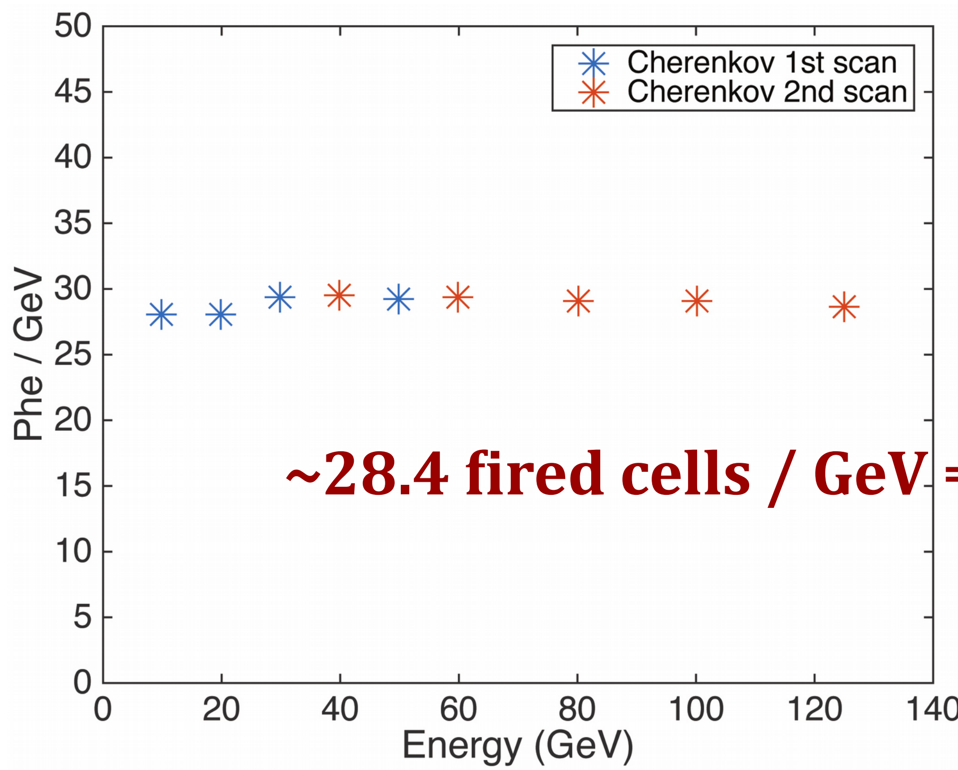




**** Take care: bias voltage lowered by 5 V → PDE very low! ****

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*

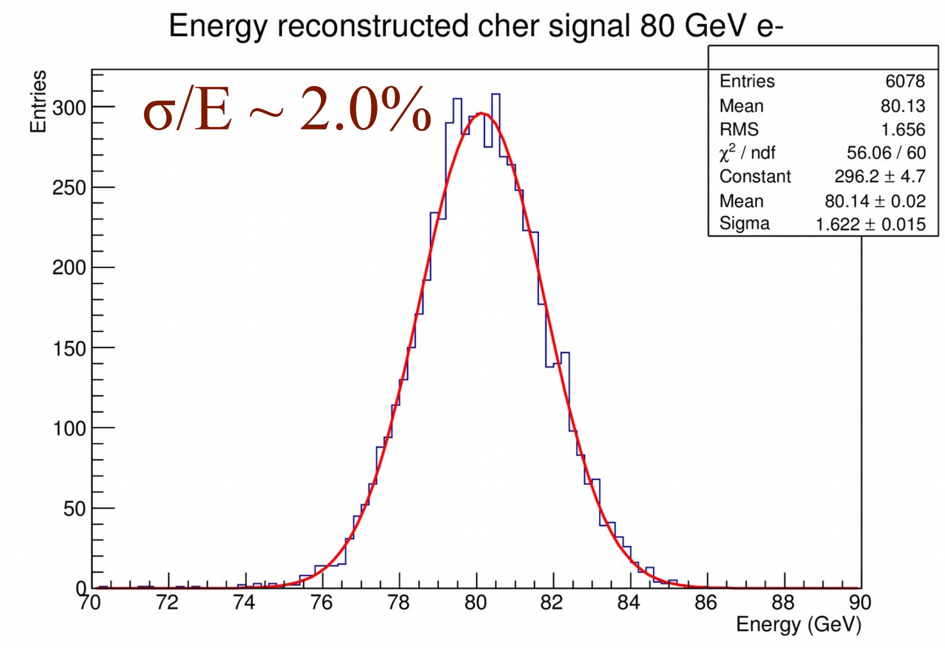
→ *average shower containment independent of energy*

Geant4 – e.m. energy reconstruction (Cu)

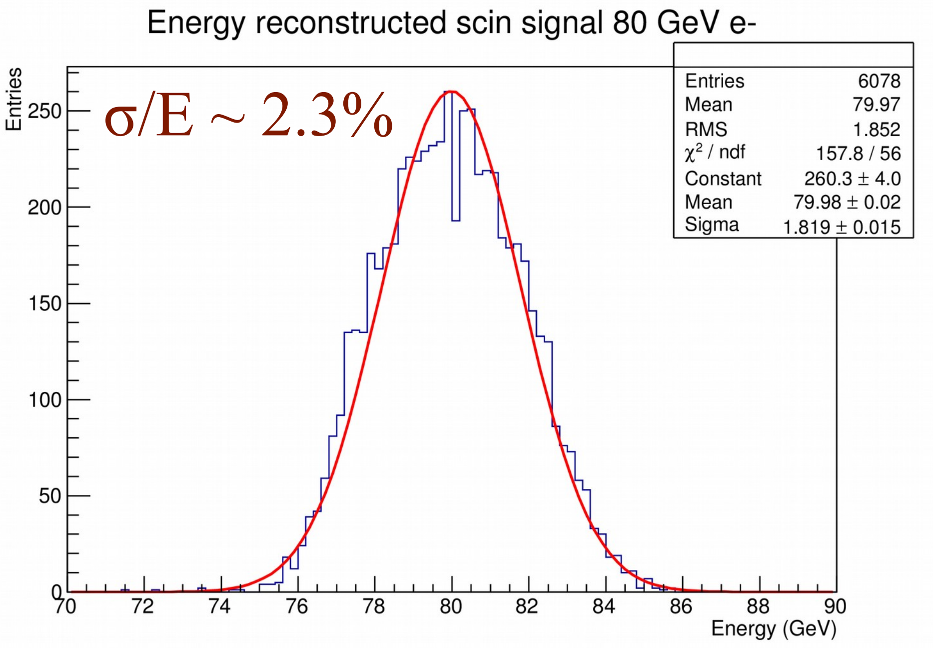
e.m. calorimeter: 31.4 x 31.4 x 112.30 cm^3

containment >~99%

Č only

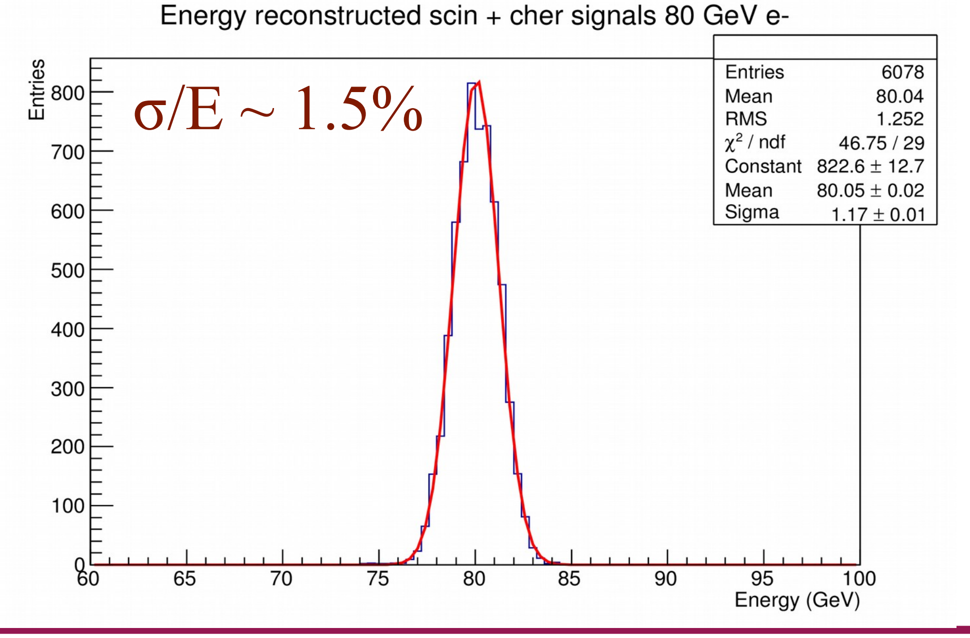


S only



energy reconstructed
80 GeV electrons

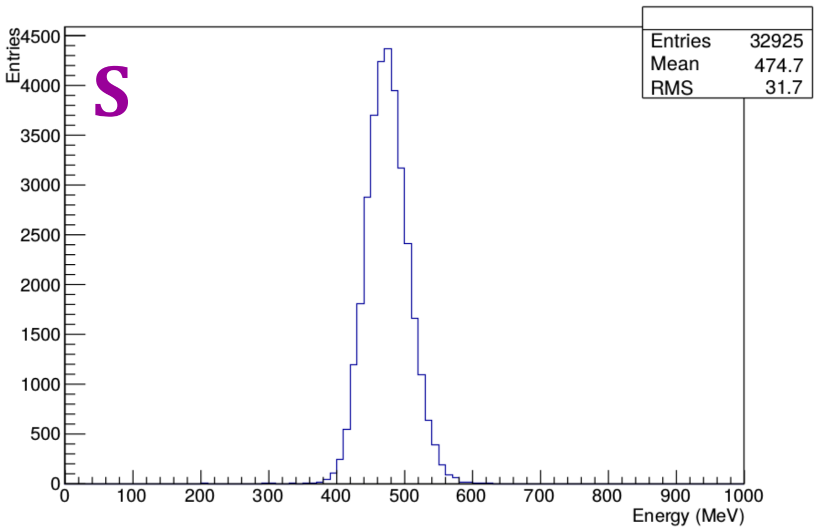
S+Č



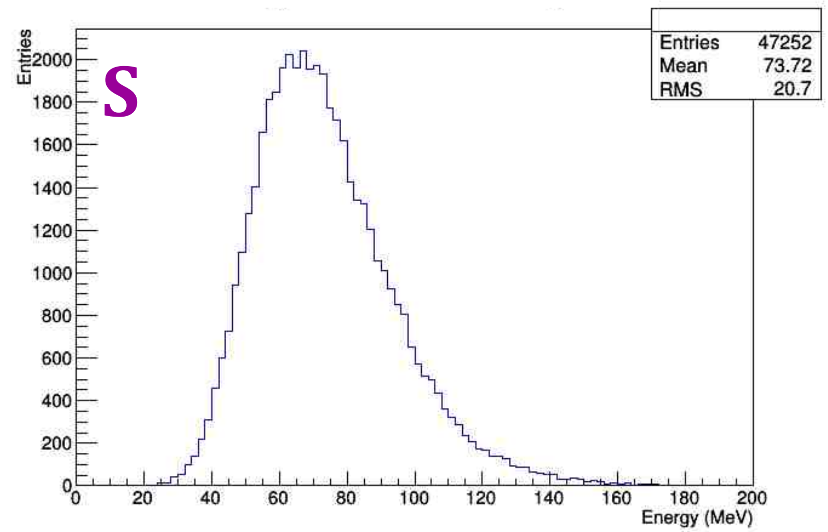
Geant4: sampling fraction (Cu)

e.m. calorimeter: 31.4 x 31.4 x 112.30 cm^3
containment >~99%

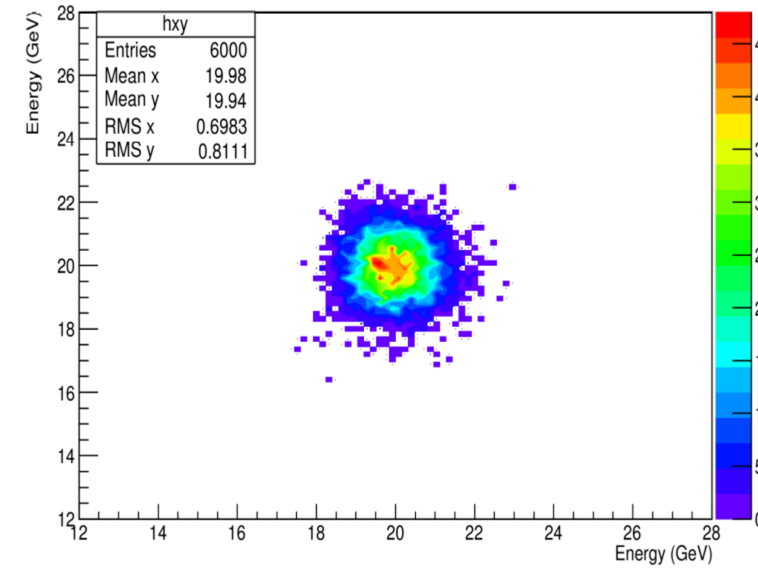
E(MeV) S fibres: ~5.5%



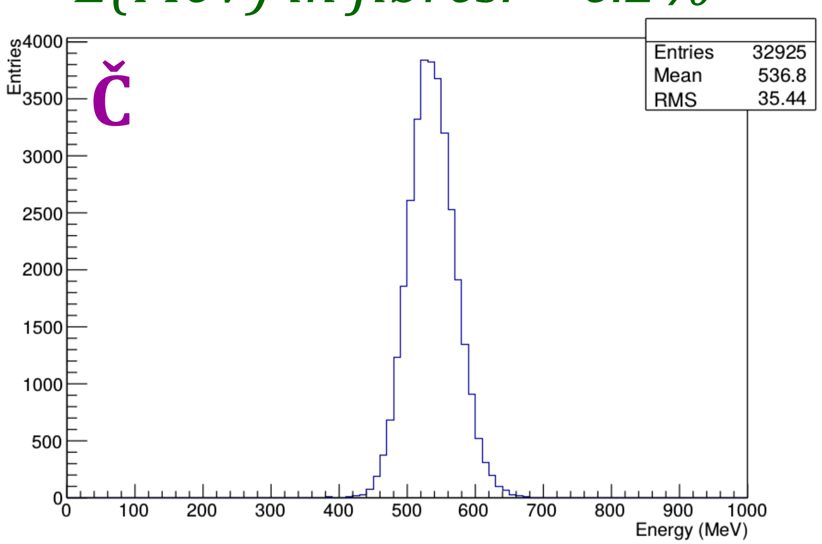
E (MeV) in hottest fibre



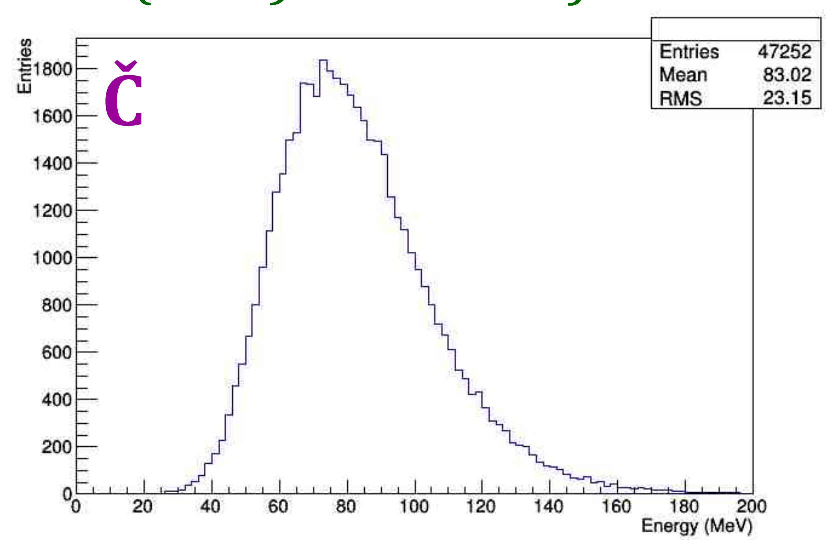
C vs. S



E(MeV) in fibres: ~6.2%



E (MeV) in hottest fibre

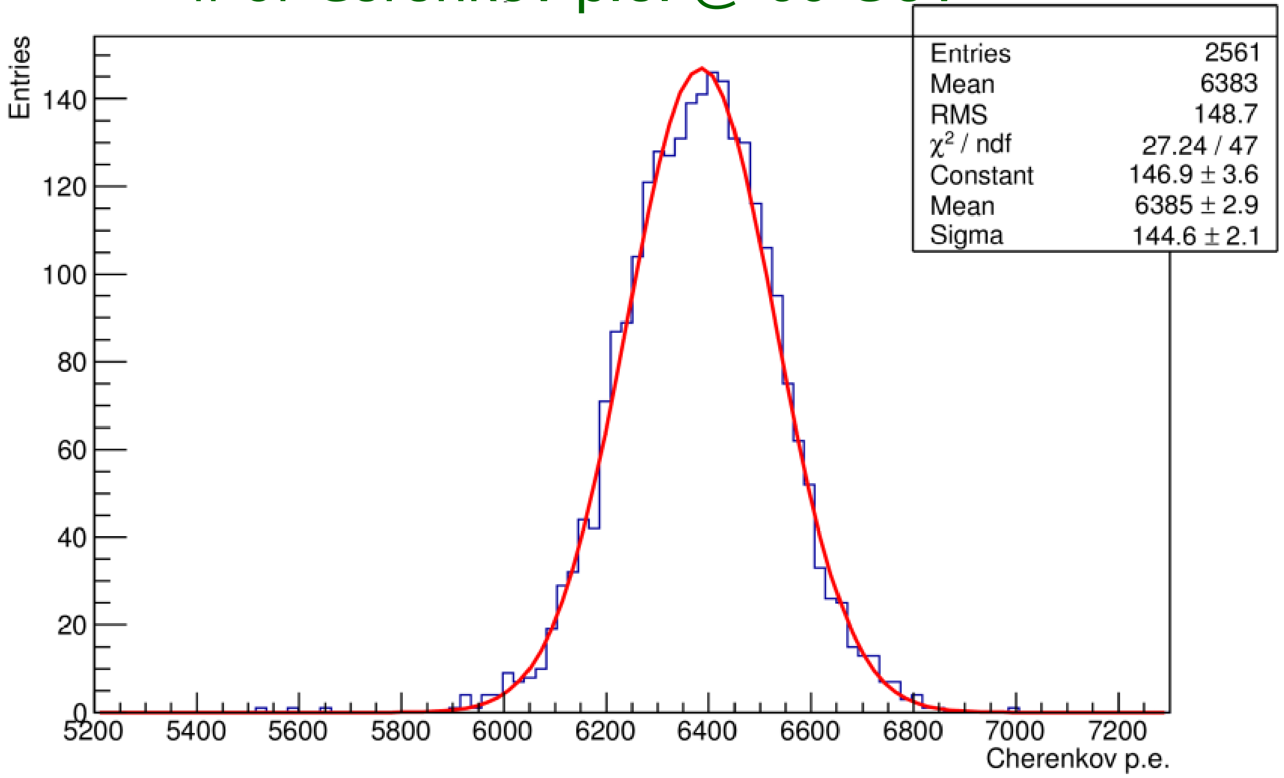


Geant4 – e.m. performance (Cu)

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