Dual-Readout Calorimetry: recent results from RD52 and plans for experiments at future e^+e^- colliders

Roberto Ferrari
INFN – Pavia
on behalf of the RD52 Collaboration

CHEF 2017, Lyon, October 3rd, 2017

Dual-Readout Calorimetry

What:

correct hadronic energy measurements for f_{em} fluctuations

How:

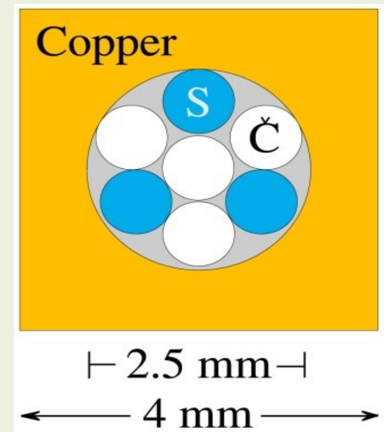
use two independent sampling processes, with different sensitivity to em and non-em shower components, to reconstruct f_{em} event-by-event

(see Richard Wigmans' talk)

Dual-Readout w/ Sampling Fibre Calorimeters

2003
DREAM

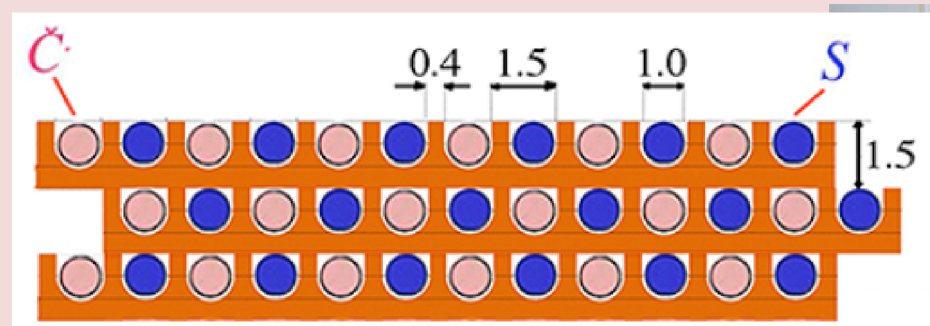
Copper
2m long, 16.2 cm wide
19 towers, 2 PMT each
Sampling fraction: 2%



2012
RD52

Copper, 2 modules

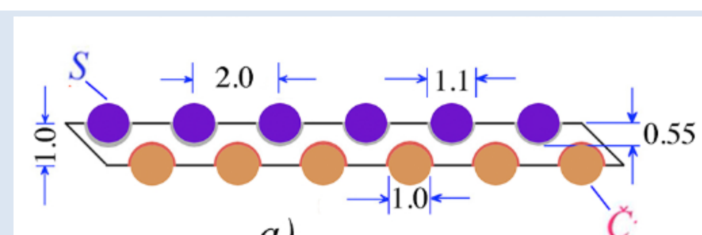
Each module: 9.3 * 9.3 * 250 cm^3
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: 4.5%, 10 λ_{int}

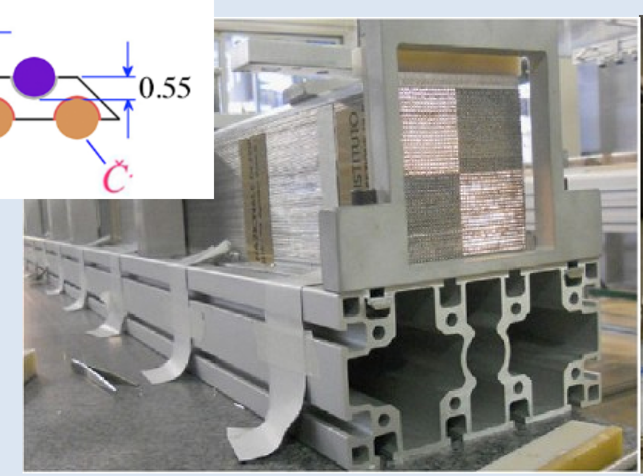


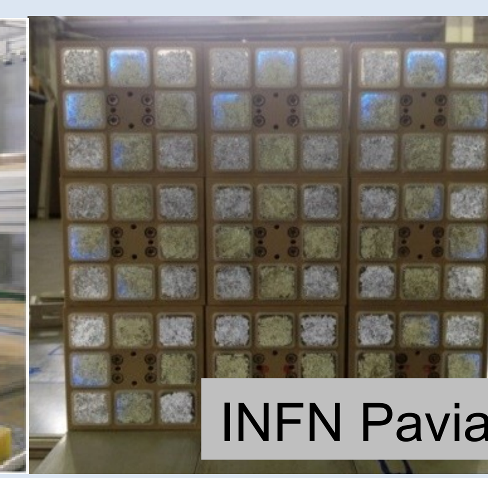
2012
RD52

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}

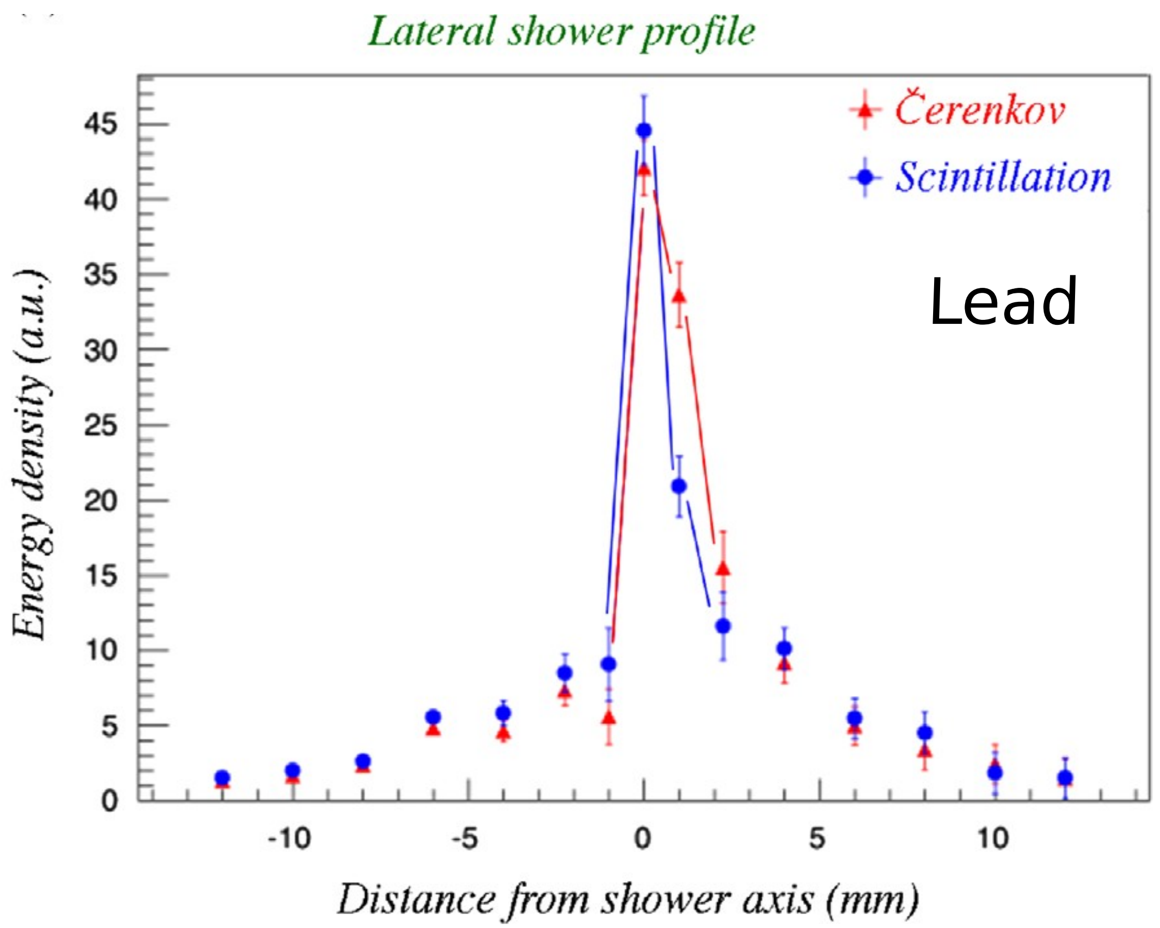






Lateral shower profile

NIM A 735 (2014) 130



em shower are very narrow

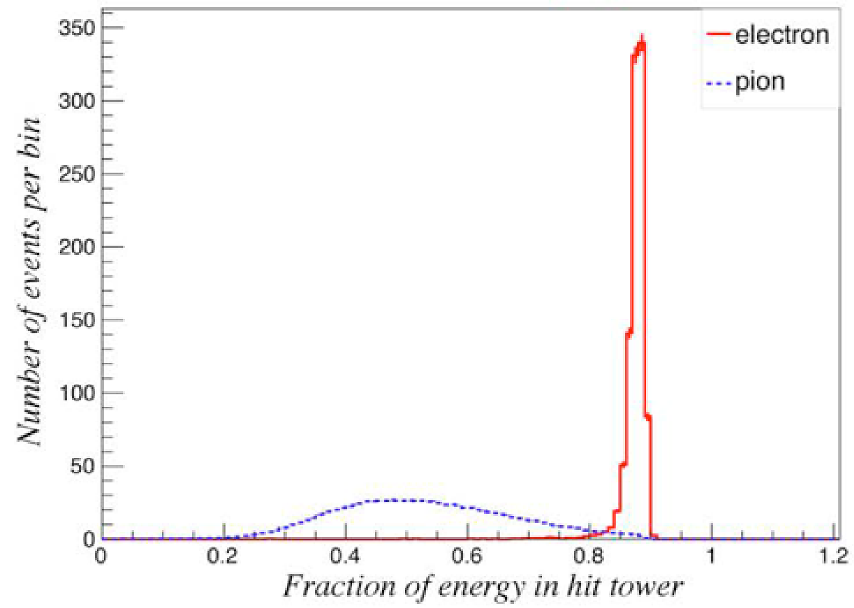
→ fibre readout can easily provide (powerful) input to PFA

Particle ID (electron/hadron separation)

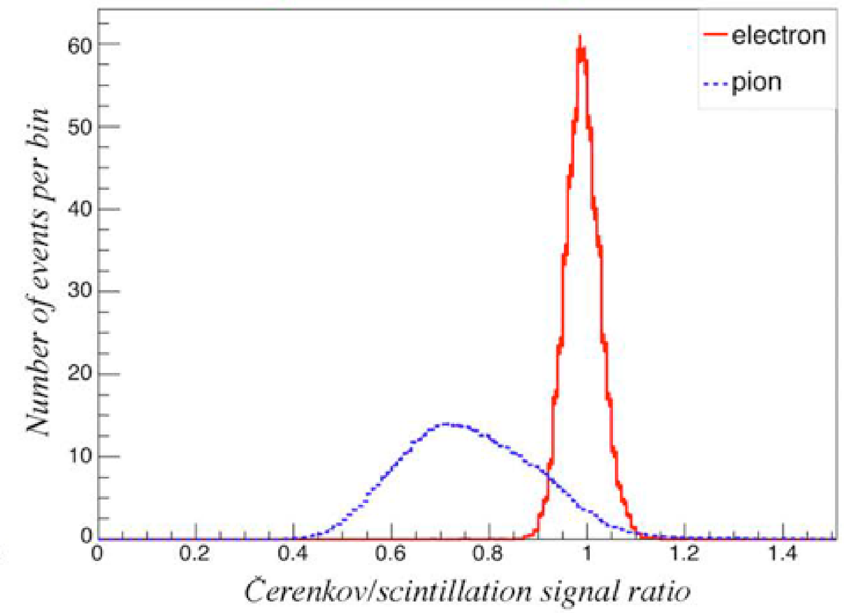
Methods to distinguish e/π in longitudinally unsegmented calorimeter

NIM A 735 (2014) 120

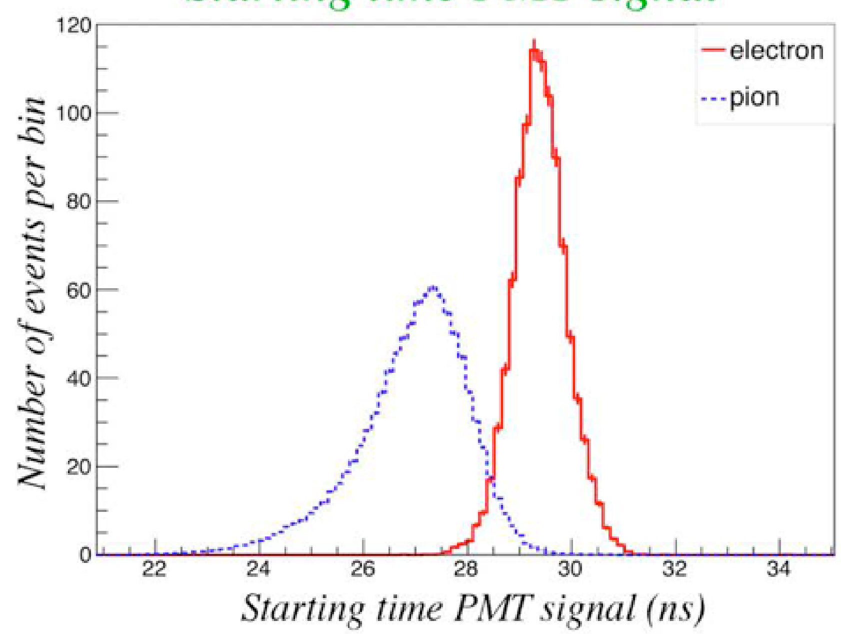
Lateral shower profile



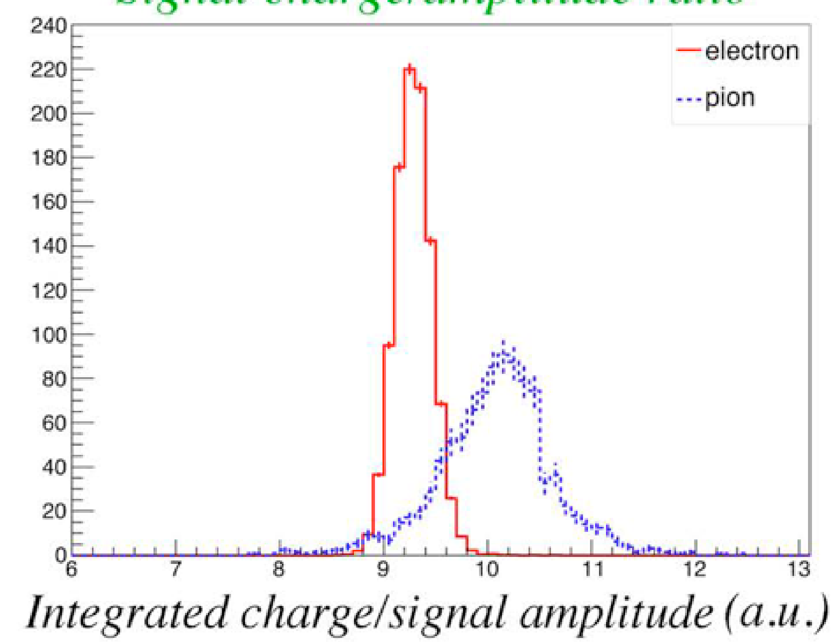
Difference C/S signals



Starting time PMT signal



Signal charge/amplitude ratio



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

PMT → 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:

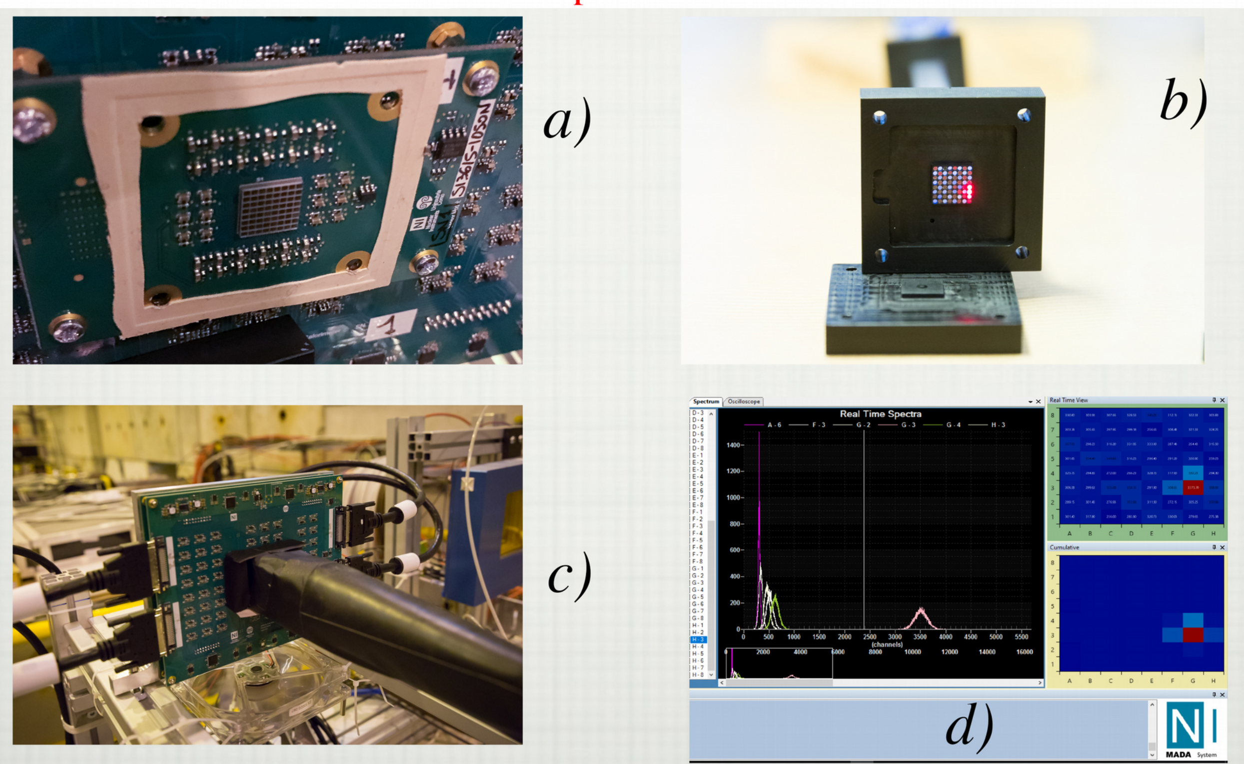
- *signal saturation (digital light detector)*
- *cross talk between Čerenkov and scintillation signals*
- *dynamic range*
- *instrumental effects (stability, afterpulsing, ...)*

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)*

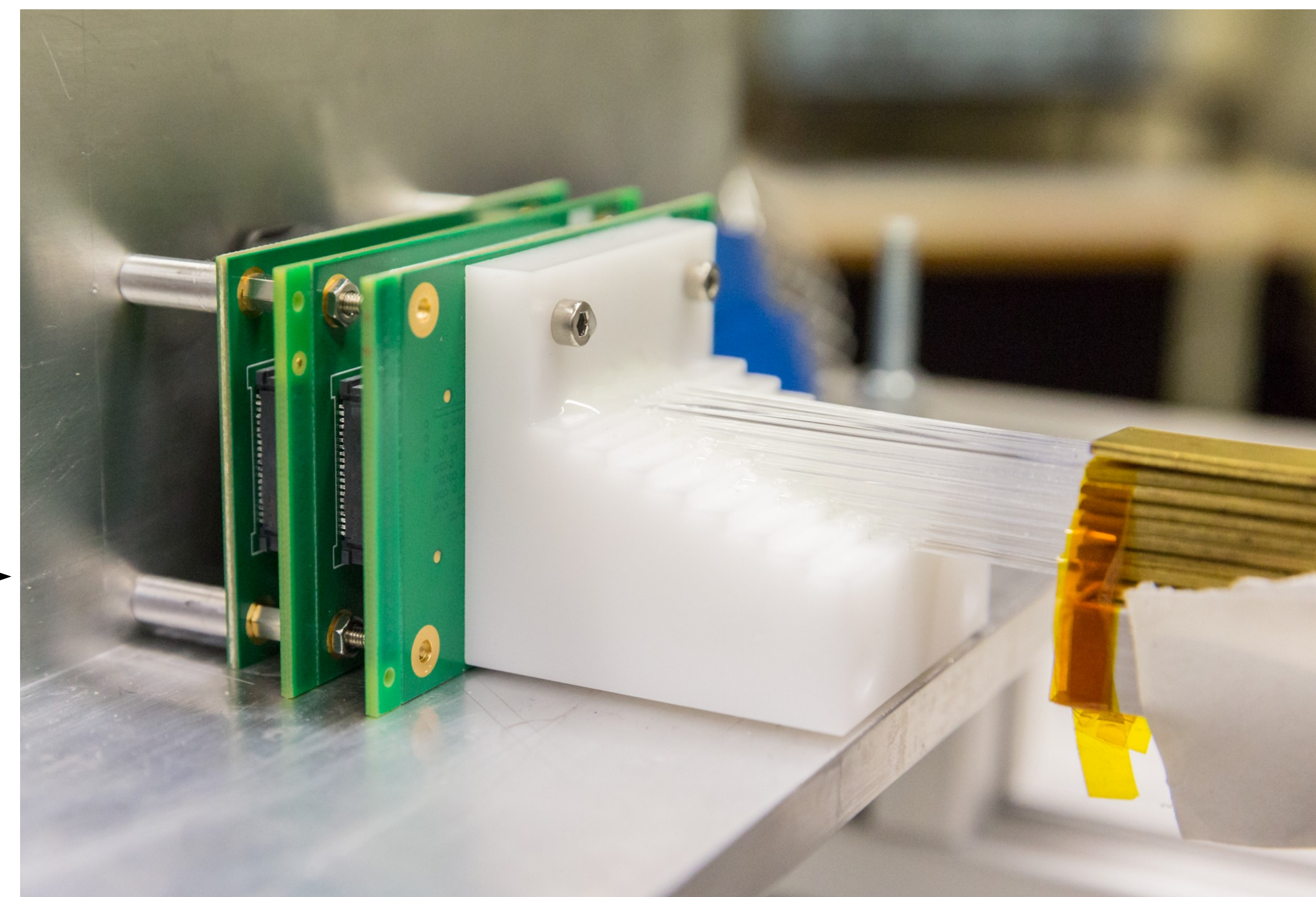
2016

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

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)

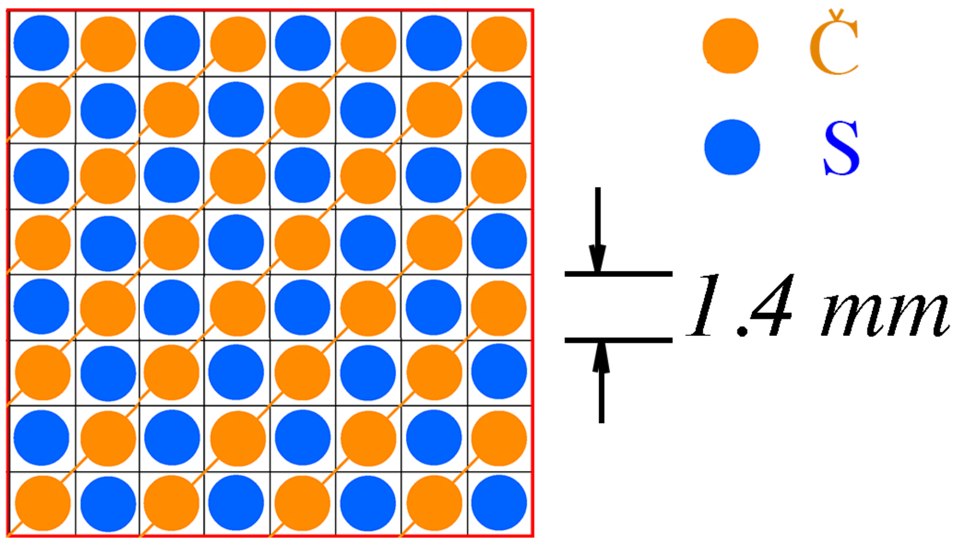
→ avoid light leakage ?

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

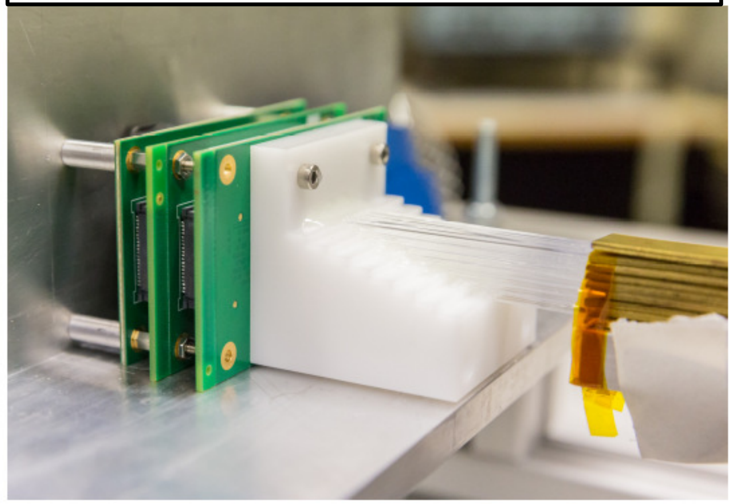
2017 Testbeam Layout

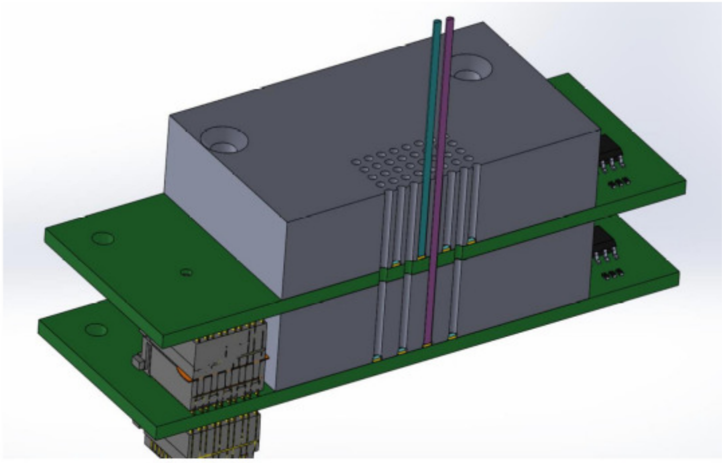
Brass module, dimensions: ~ 112 cm long, 12 x 12 mm^2

section



Back



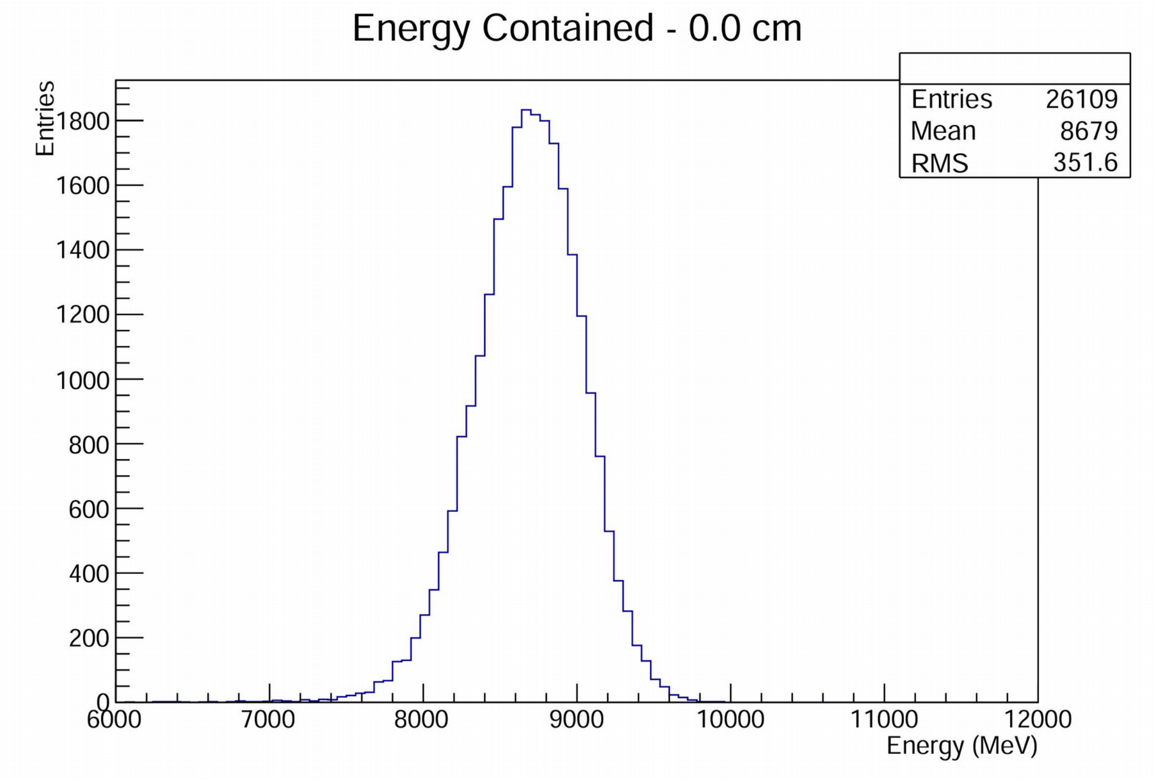


Experimental setup

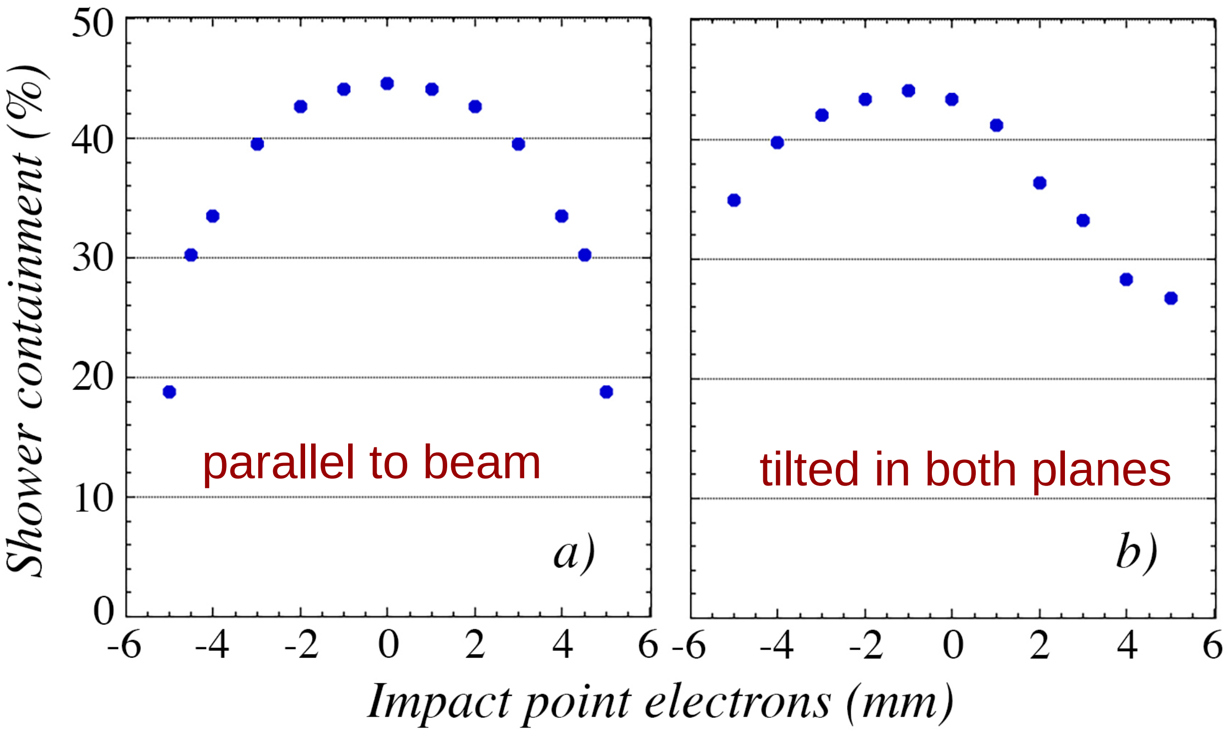
Trigger : $(T_1 \cdot T_2 \cdot \overline{T_H})$

MC(G4): 20 GeV Electron Shower Containment

Centered events: ~43% containment



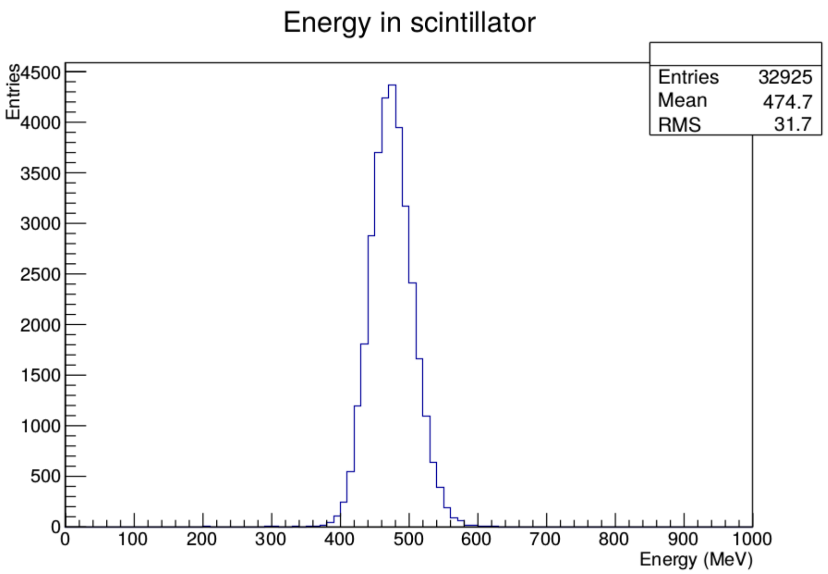
containment .vs. impact point



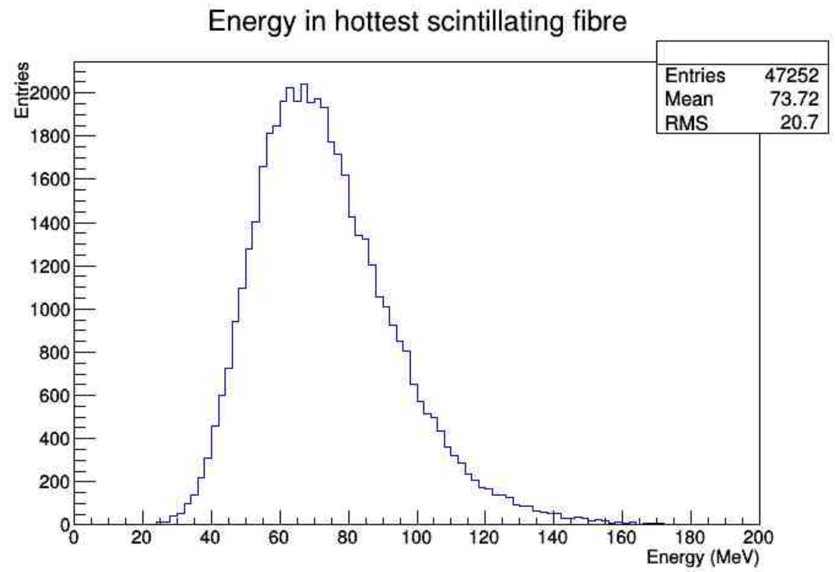
(all the G4 plots here and in the following slides are for copper)

Sampling Fraction (G4) – full containment @ 20 GeV

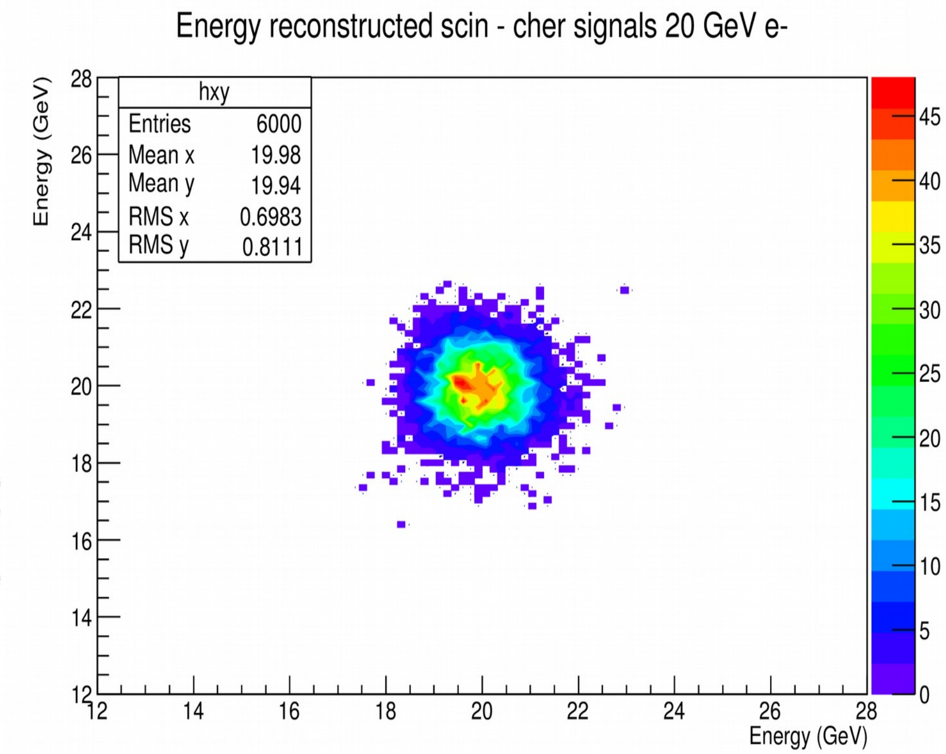
Scintillating fibres: ~5.5%



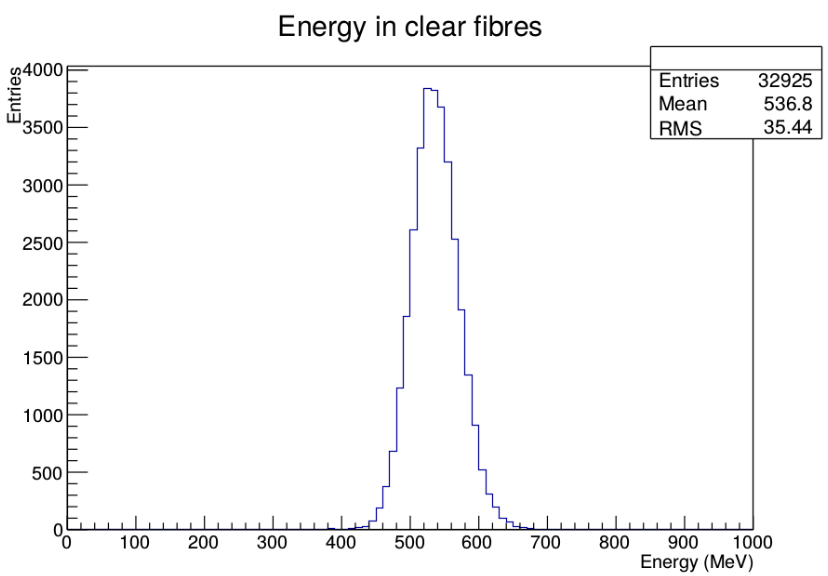
Energy in hottest S fibre



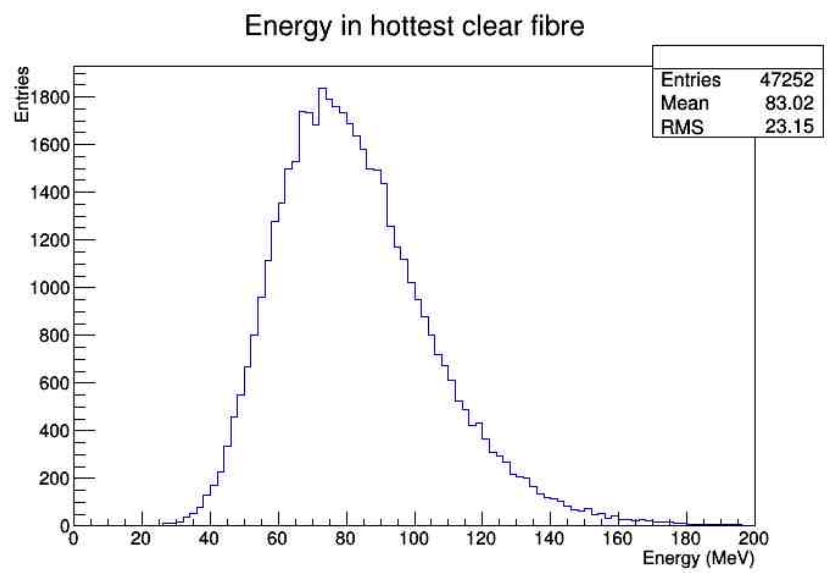
E(cher) .vs. E(sci)



Čerenkov fibres: ~6.2%

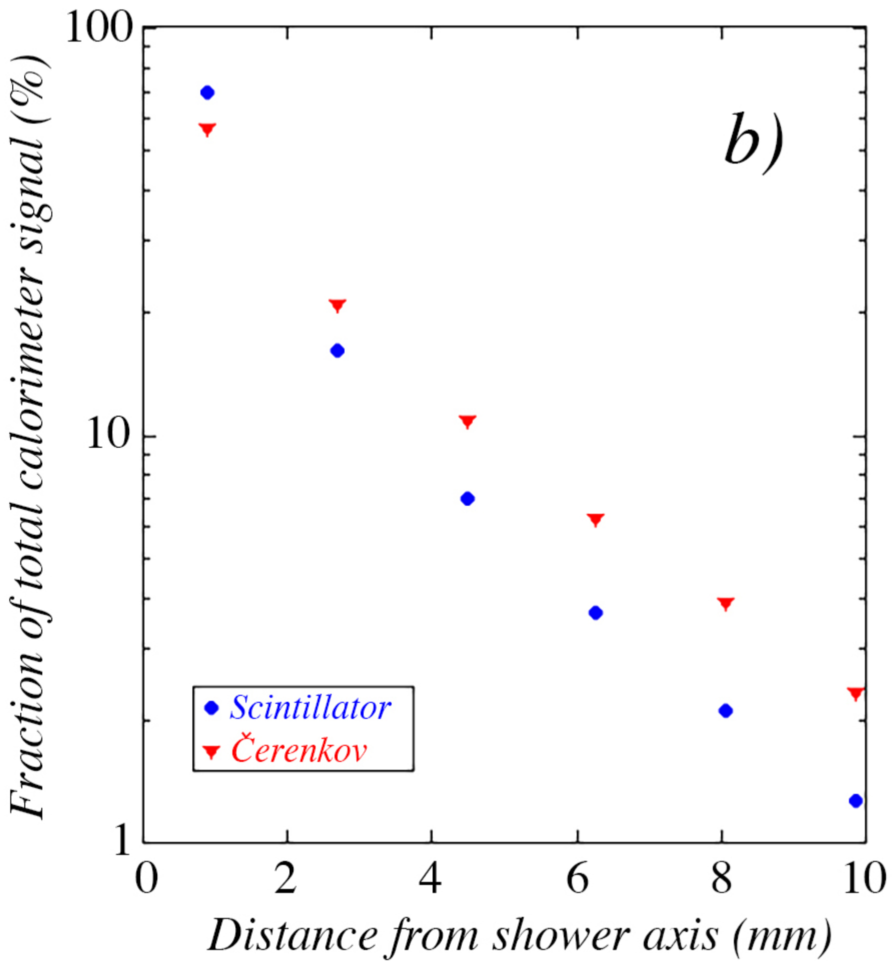


Energy in hottest C fibre

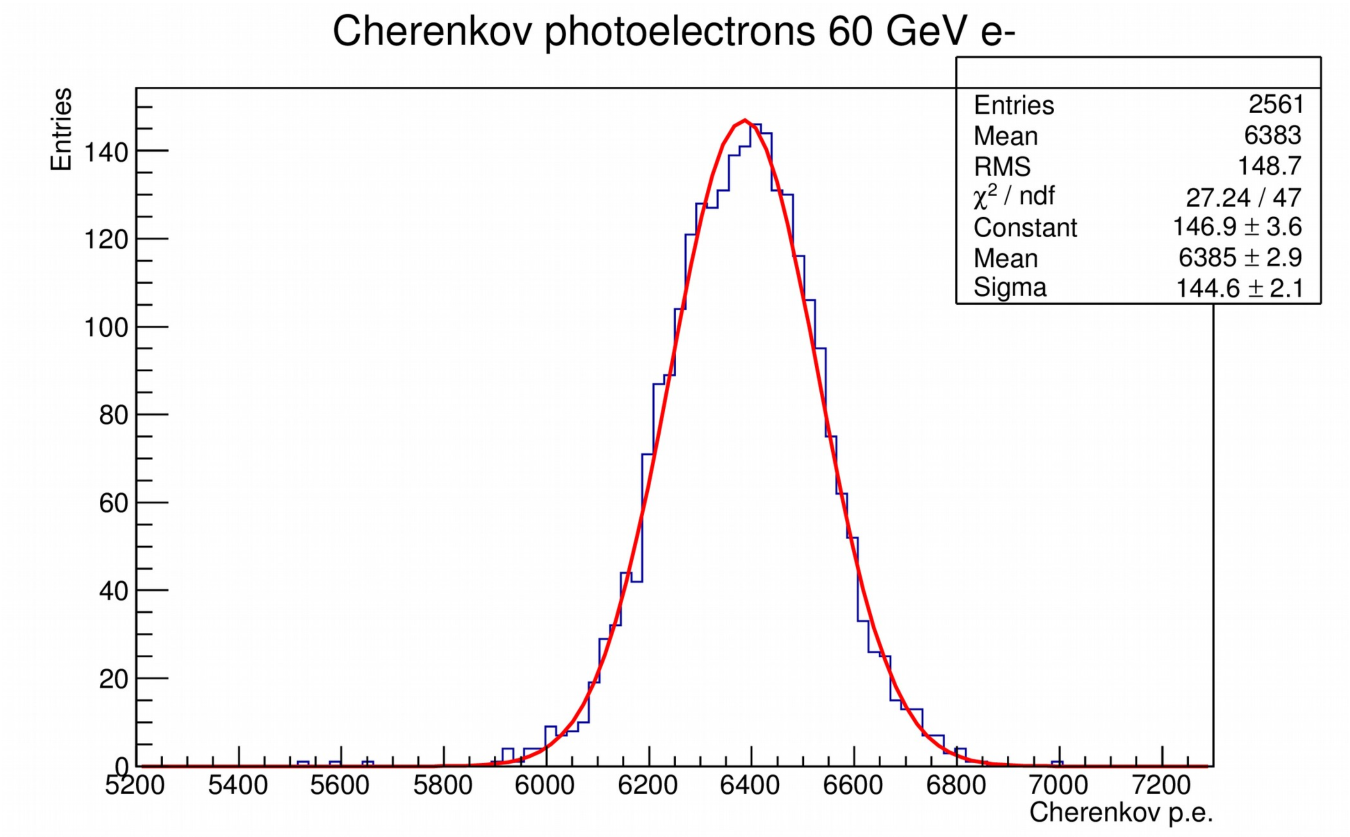


G4 – em signals

radial profiles @ 10 GeV



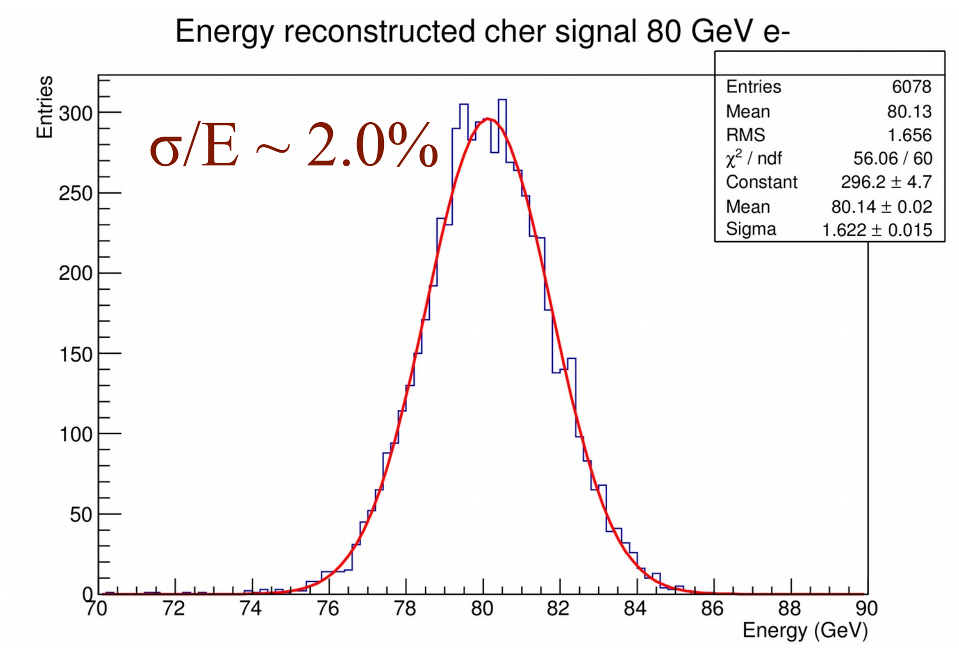
# of Čerenkov p.e. @ 60 GeV



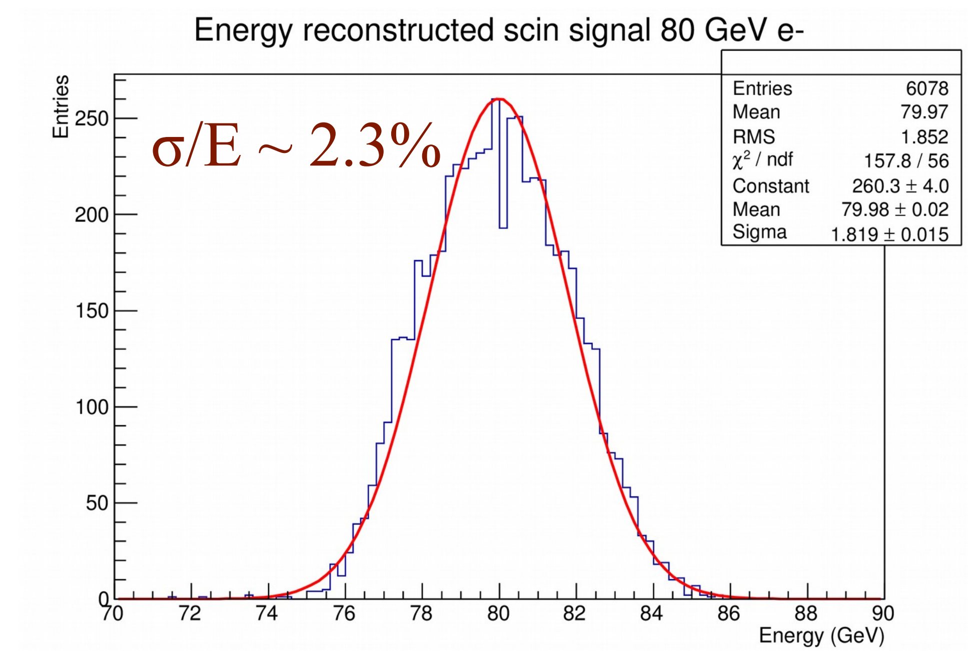
G4 - em performance: energy reconstruction

80 GeV electrons

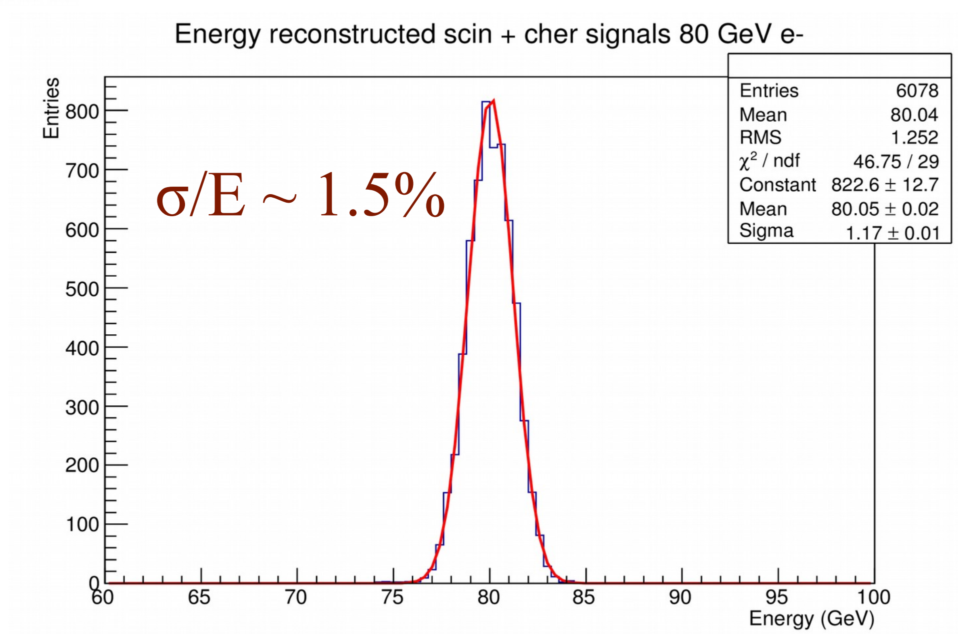
Čerenkov only



Scintillation only

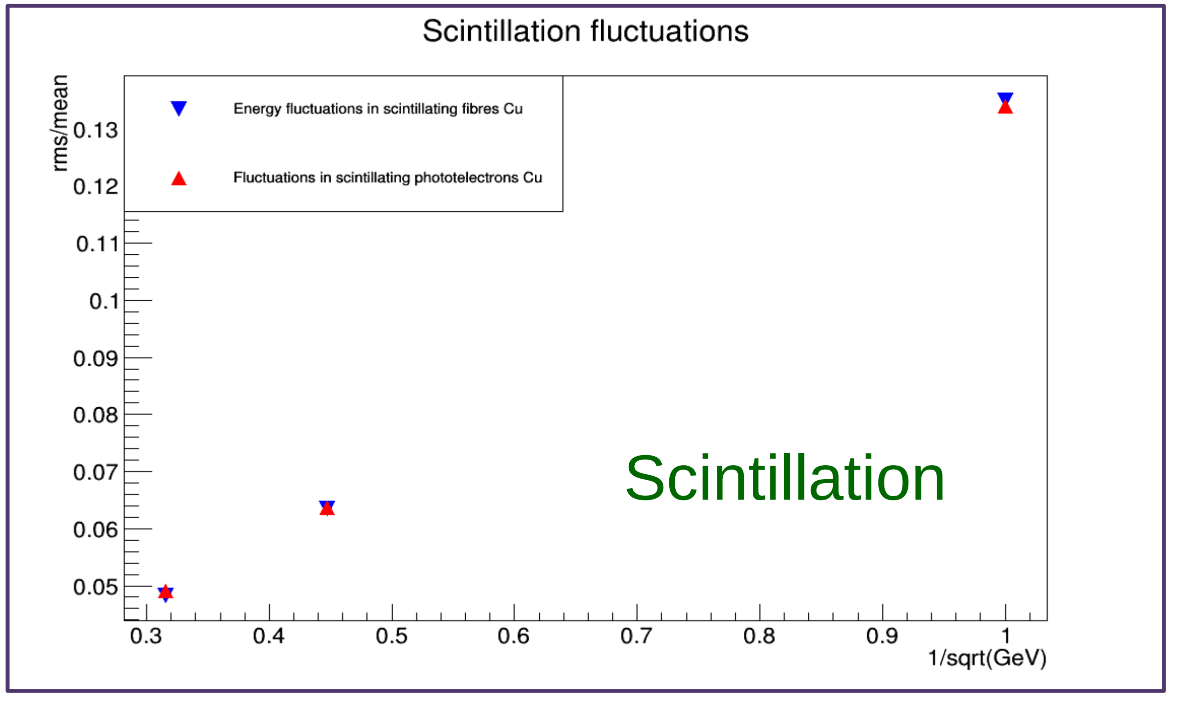


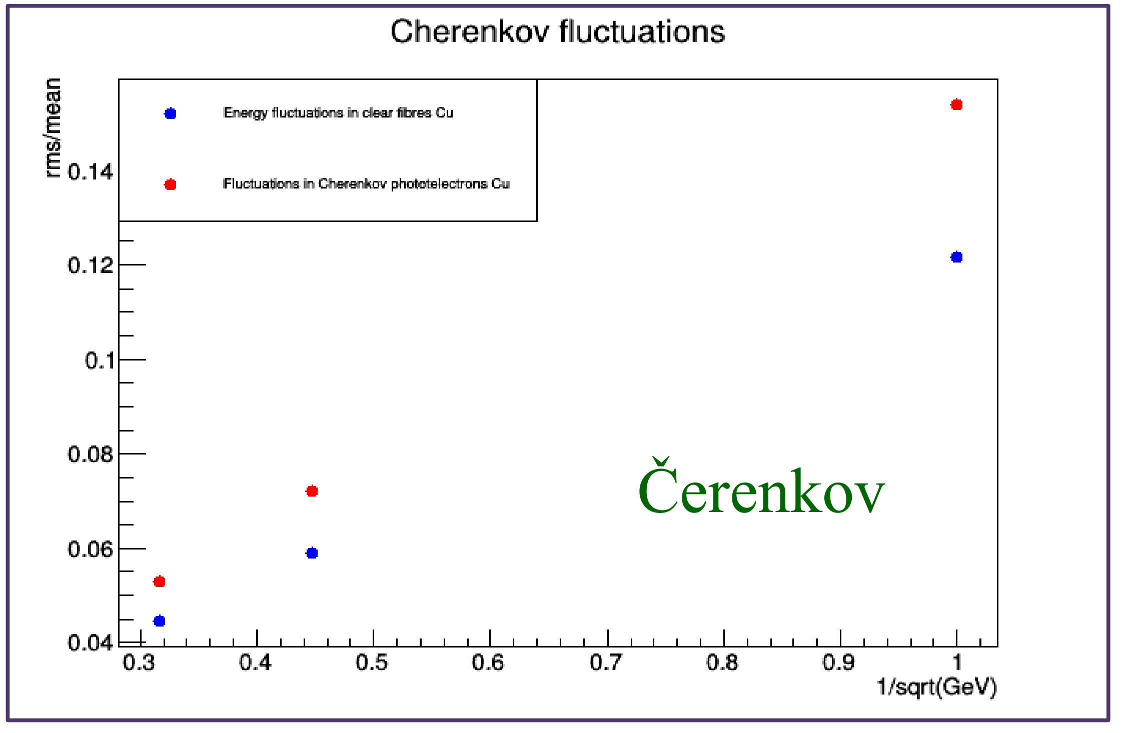
S+C



G4 - em performance: fluctuations

Energy deposition and p.e. number fluctuations





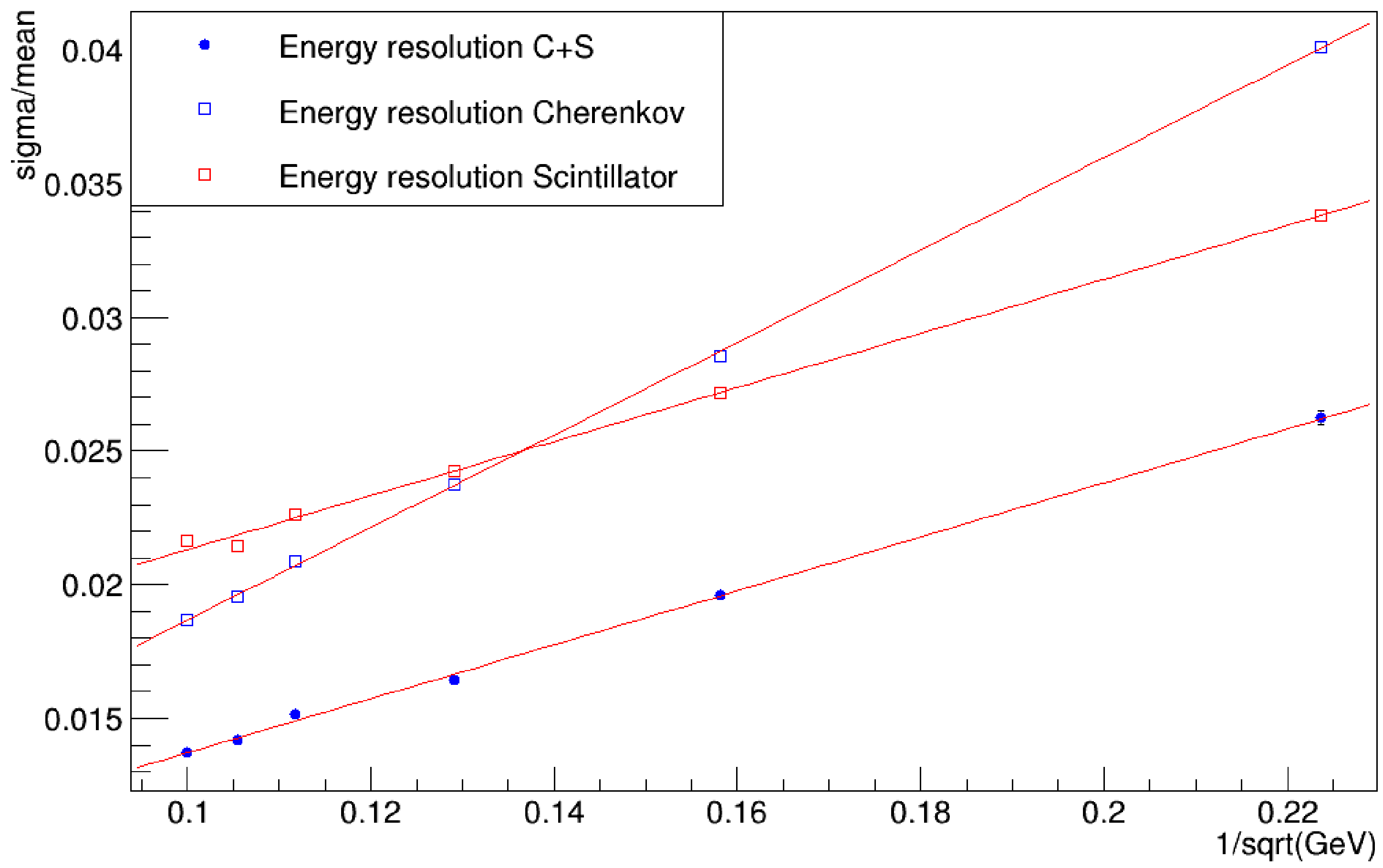
Scintillation: ~5500 p.e. / GeV
→resolution driven by fluctuations in energy depositions

Čerenkov: ~110 p.e. / GeV
→resolution driven by fluctuations in p.e. number

Sampling fluctuations contribution to resolution:

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

G4 - em resolution(s)



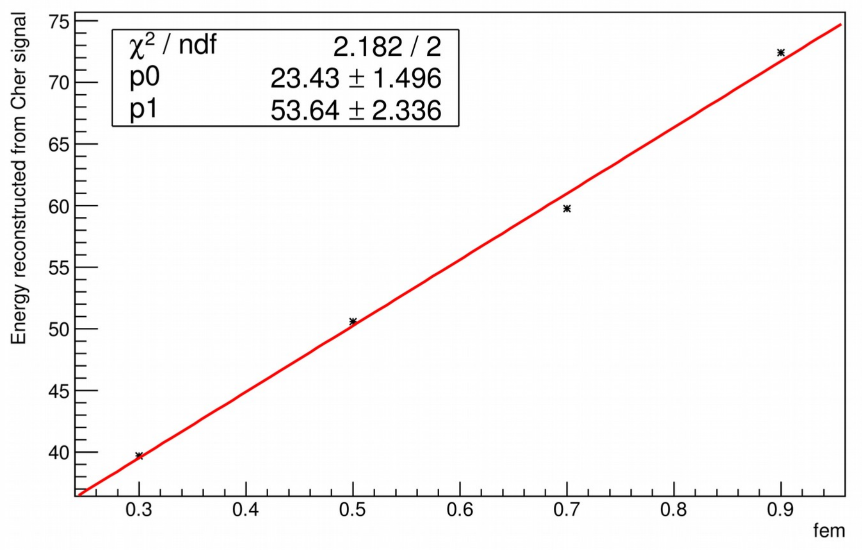
S-only: 10.1%/√E+1.1%

Č-only: 17.3%+0.1%

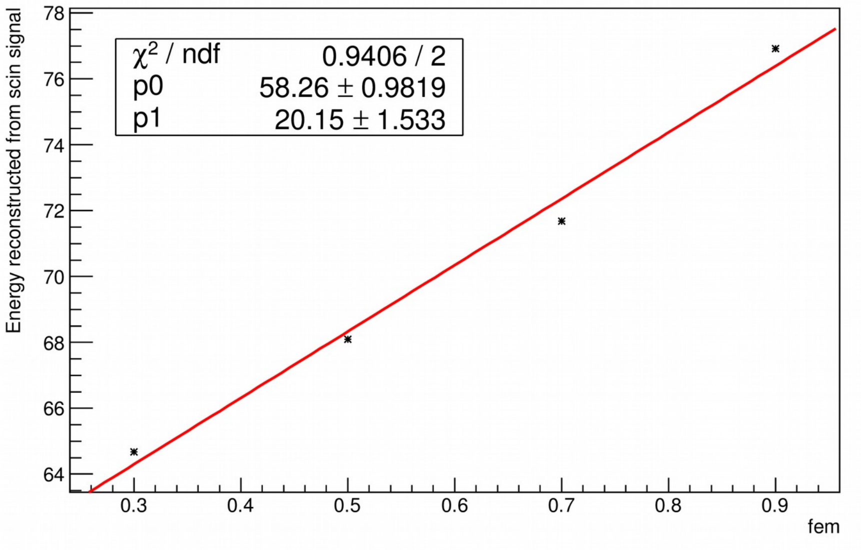
(unweighted) sum: 10.1%/√E+0.4%

G4 - Hadronic Performance (very preliminary)

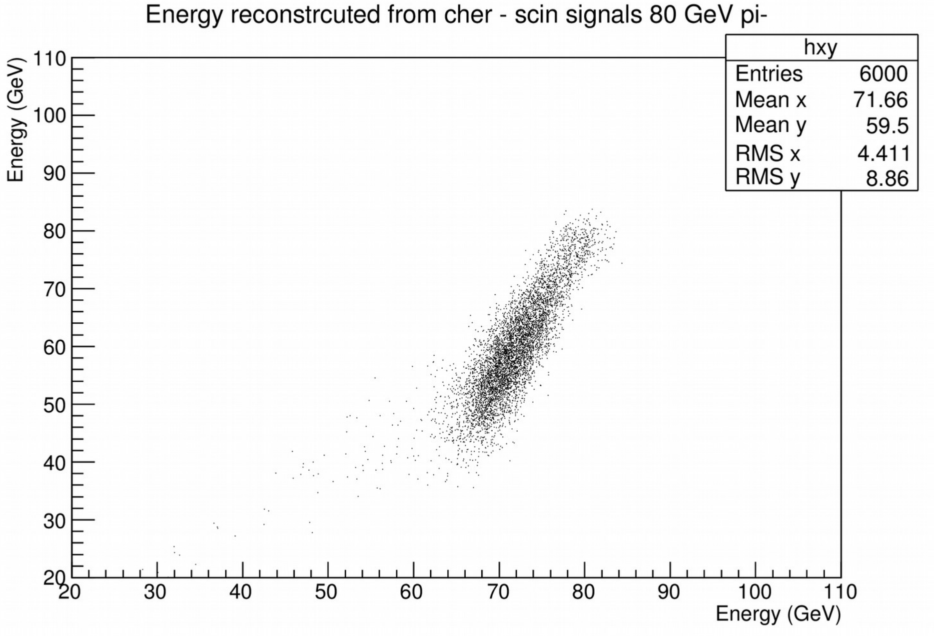
E(Čerenkov) .vs. fem @ 80 GeV



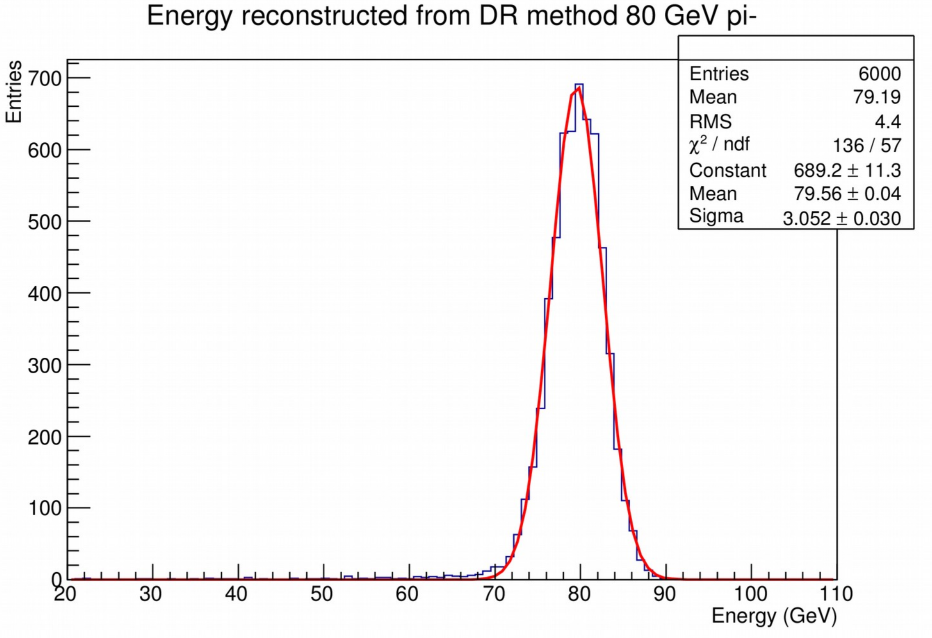
E(scintillation) .vs. fem @ 80 GeV



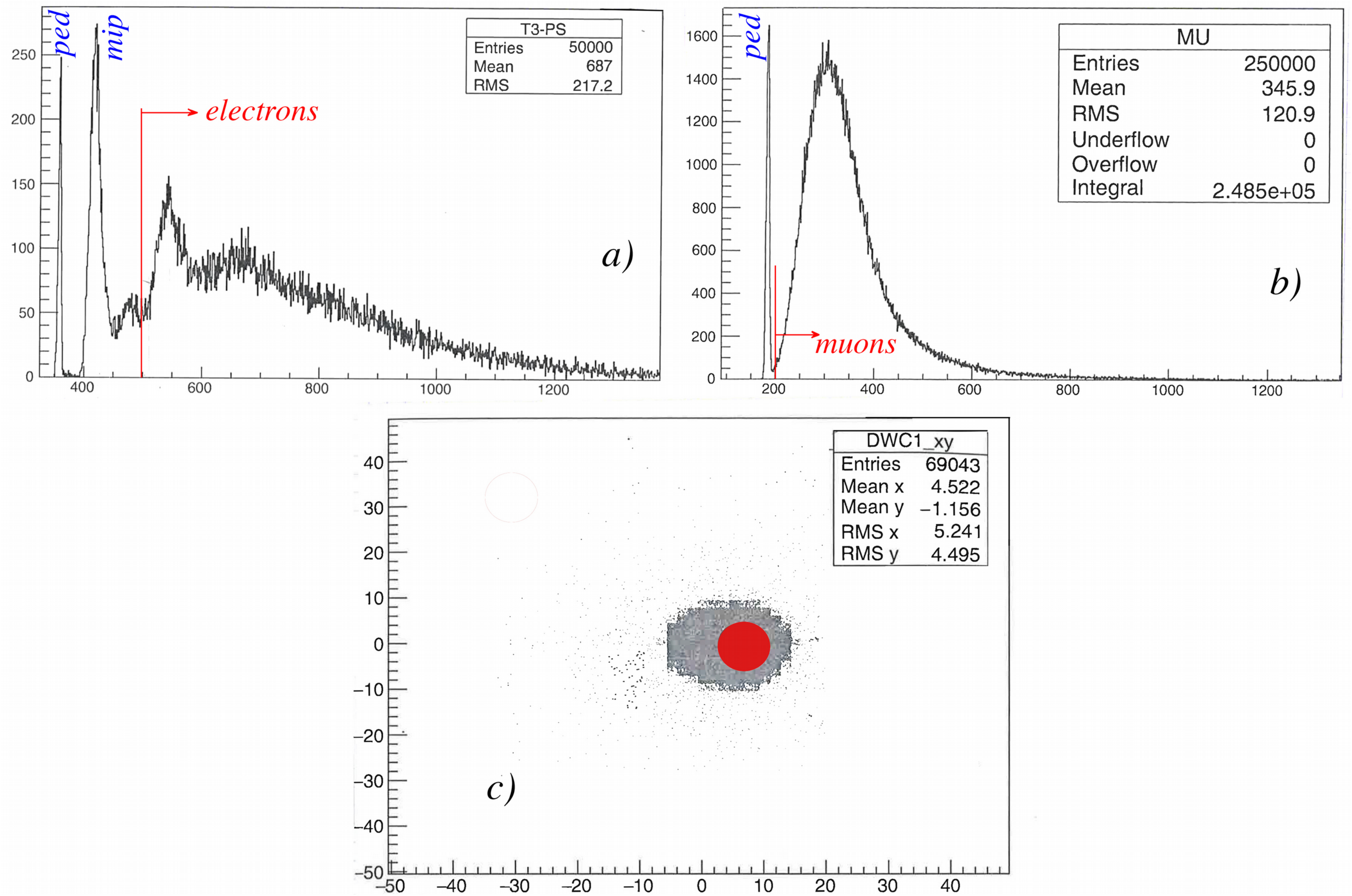
E(Čer.) .vs. E(scint.) @ 80 GeV



E (d.r.) @ 80 GeV



Testbeam - Data Selection and Tagging



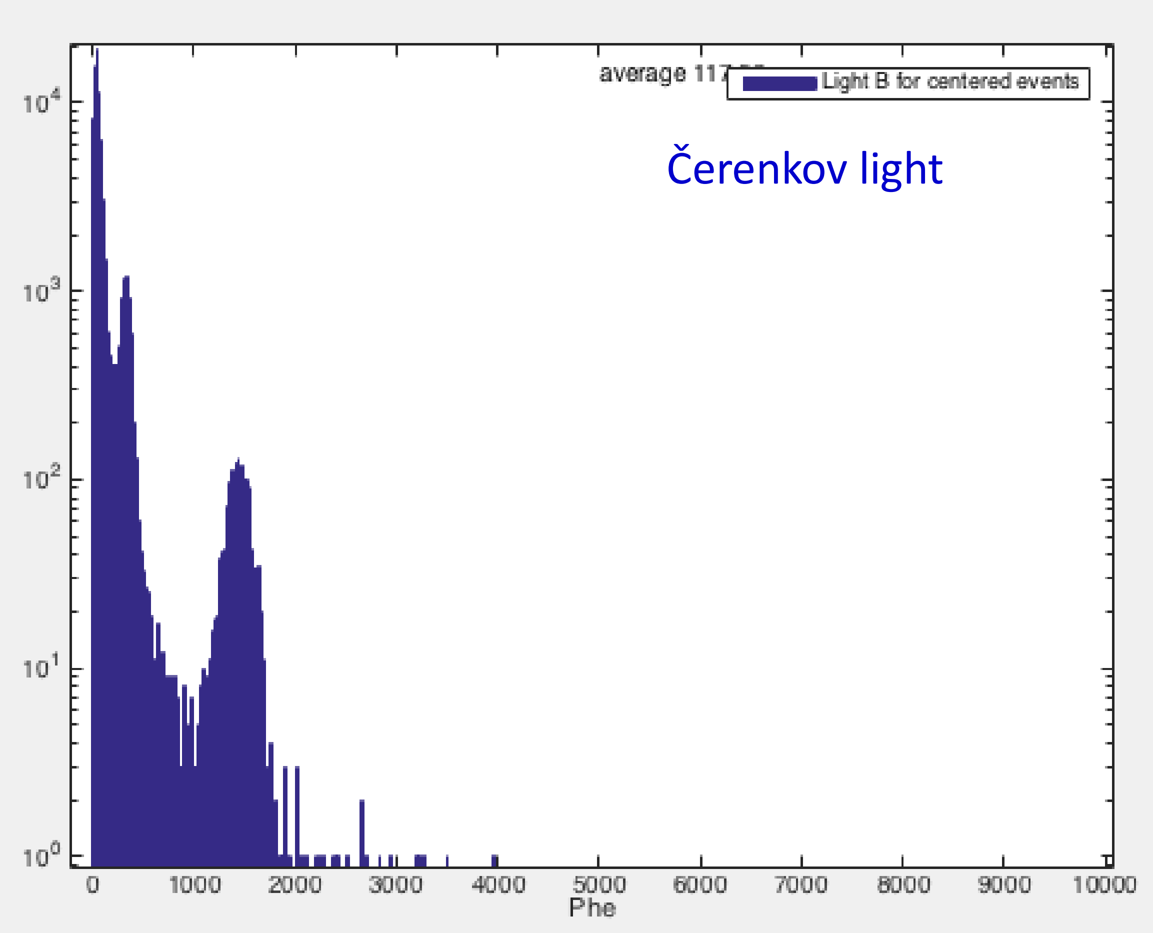
Preshower detector and Muon counter: select electrons or muons

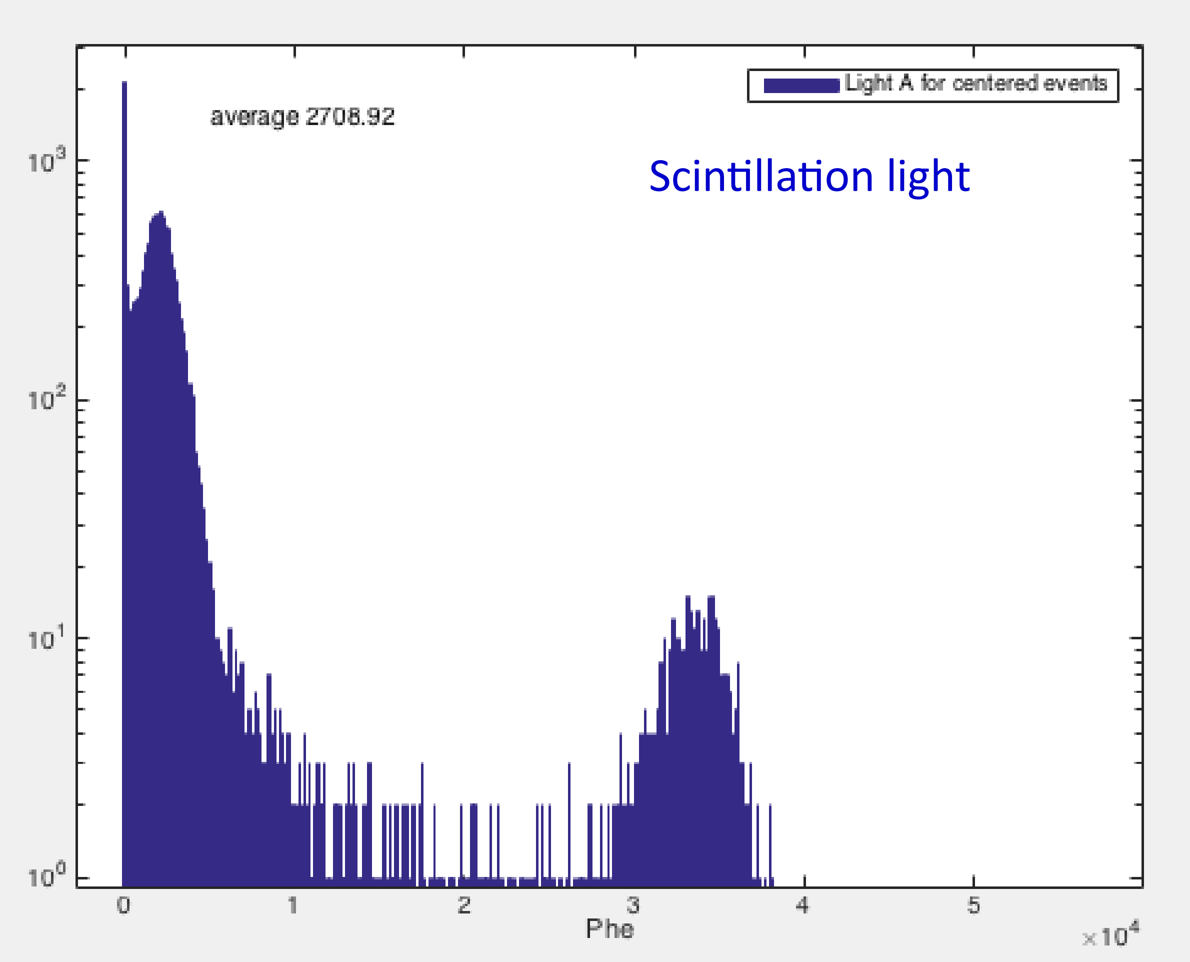
Delay Wire Chamber: select events in central region

RD52 Preliminary Results (2017)

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

50 GeV electron beam



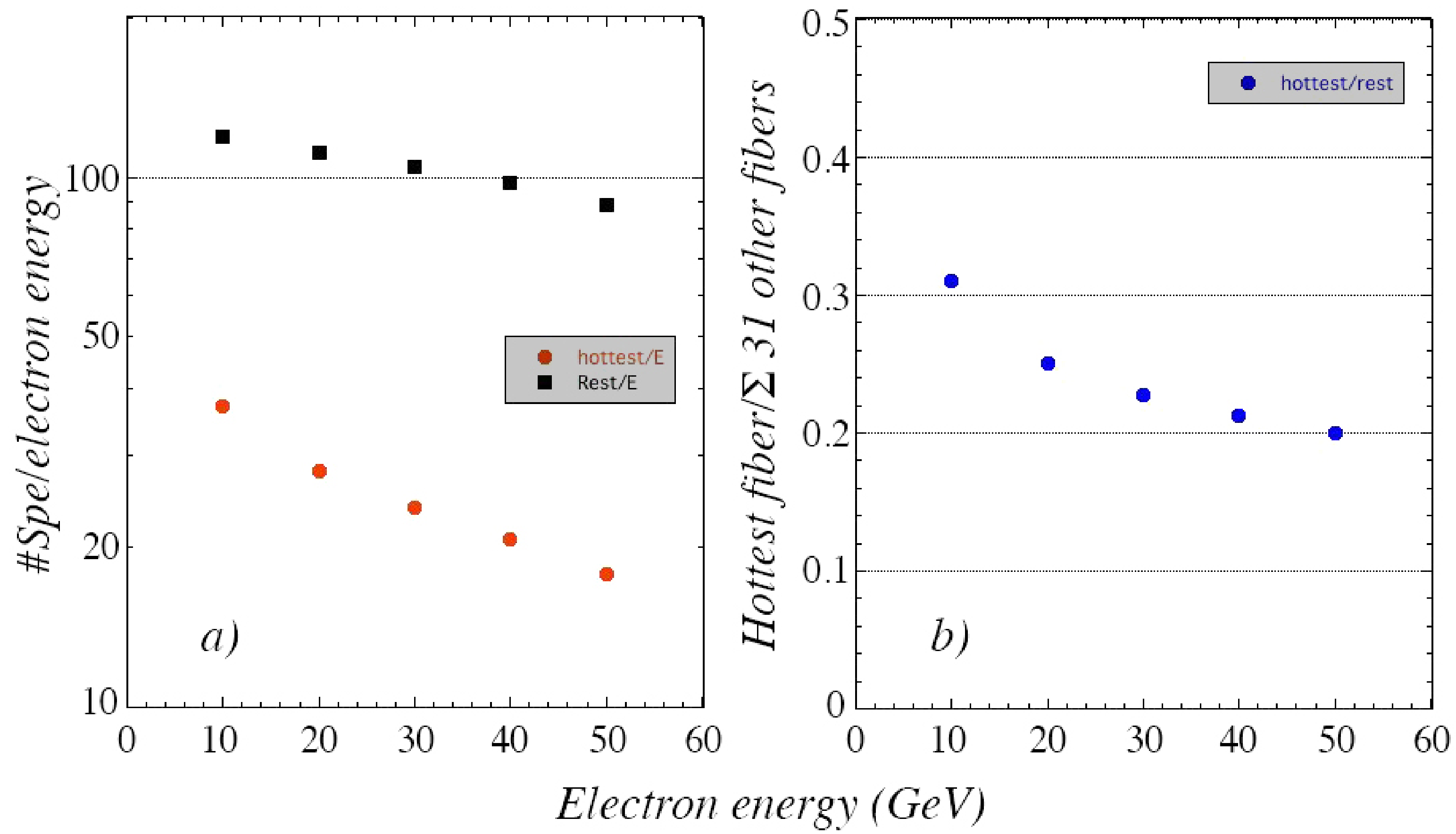


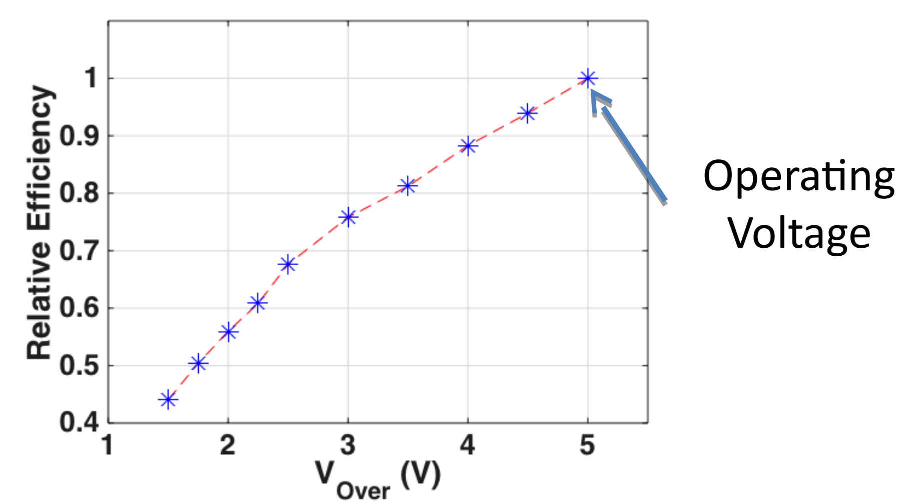
Preliminary Results (2017) – Scintillation Signals

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

Number of p.e. / GeV in hottest

Ratio hottest/rest

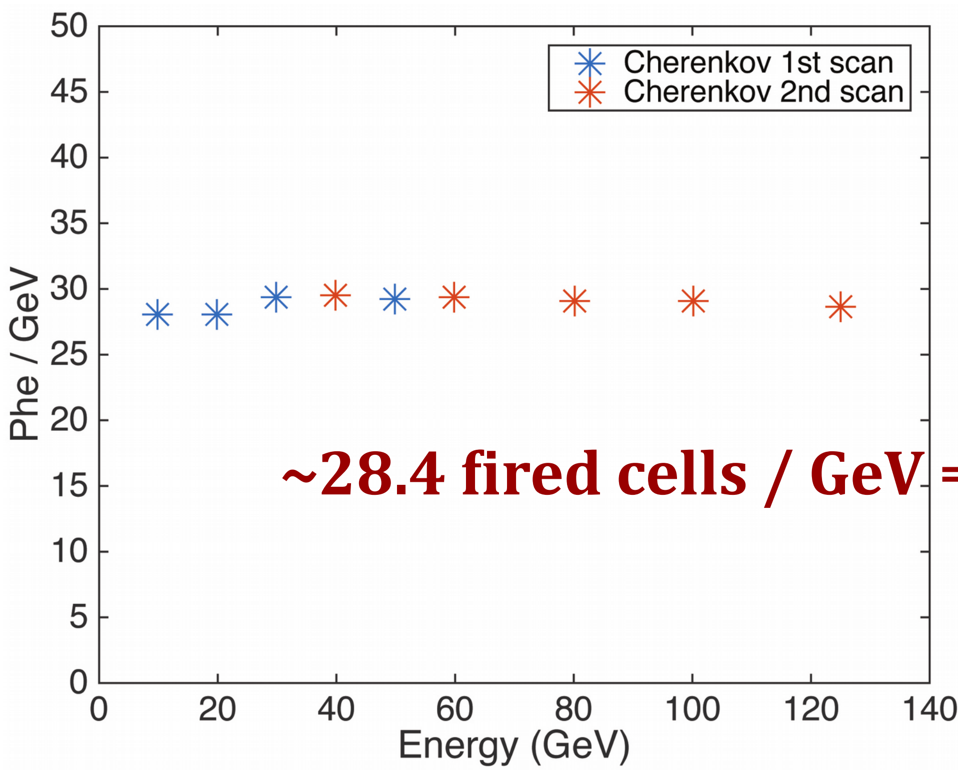




**** Take care: bias voltage lowered by 5 V → PDE very low! ****

Preliminary Results (2017) – Čerenkov Signals

Number of Photoelectrons 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*

Next Steps

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

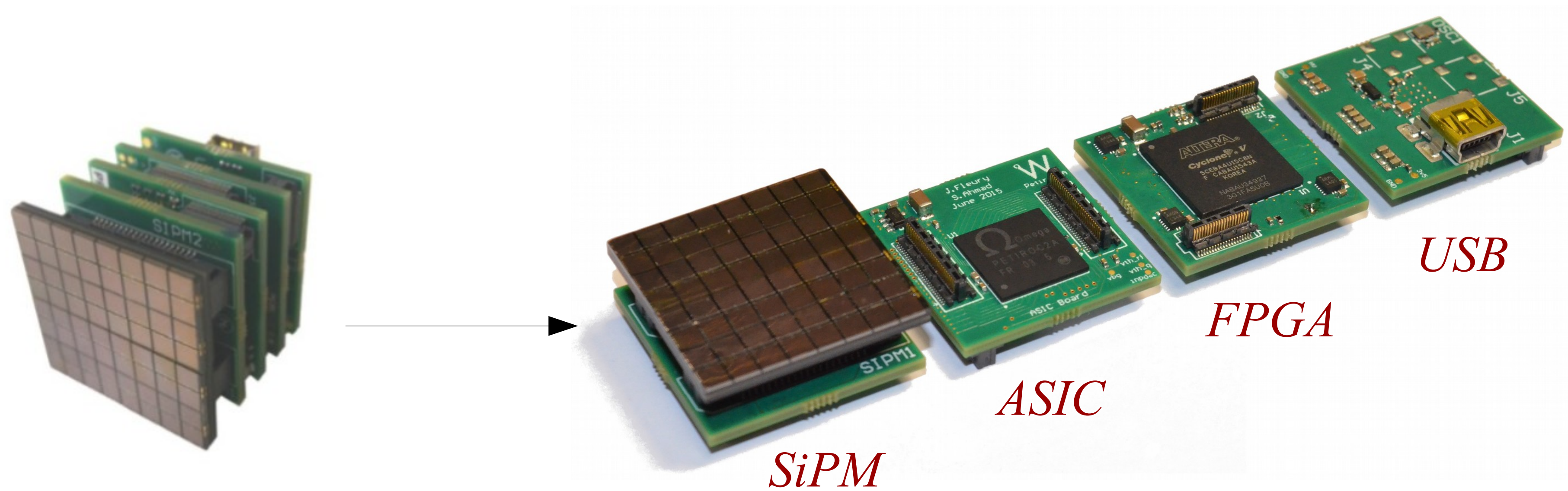
So far: Nuclear Instruments MADA system

- *multichannel read out system*
- *32 80Msps/14-bit ADC, to acquire up to 32 analog inputs*
- *FPGA based charge integration algorithm*
- *output: list of event timecode and integrated charge measured on all pixels*

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

Readout

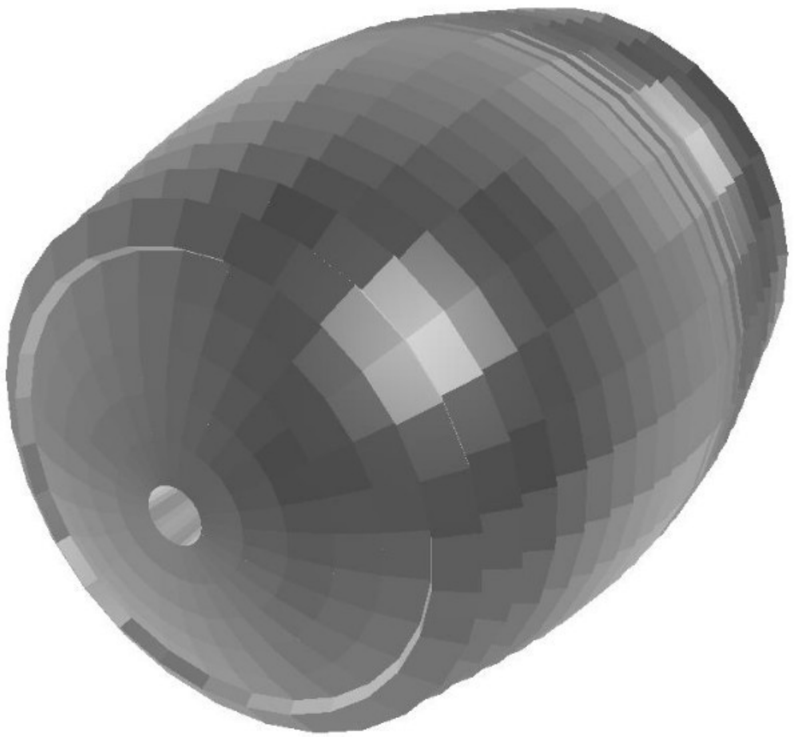
What we really would like to get:

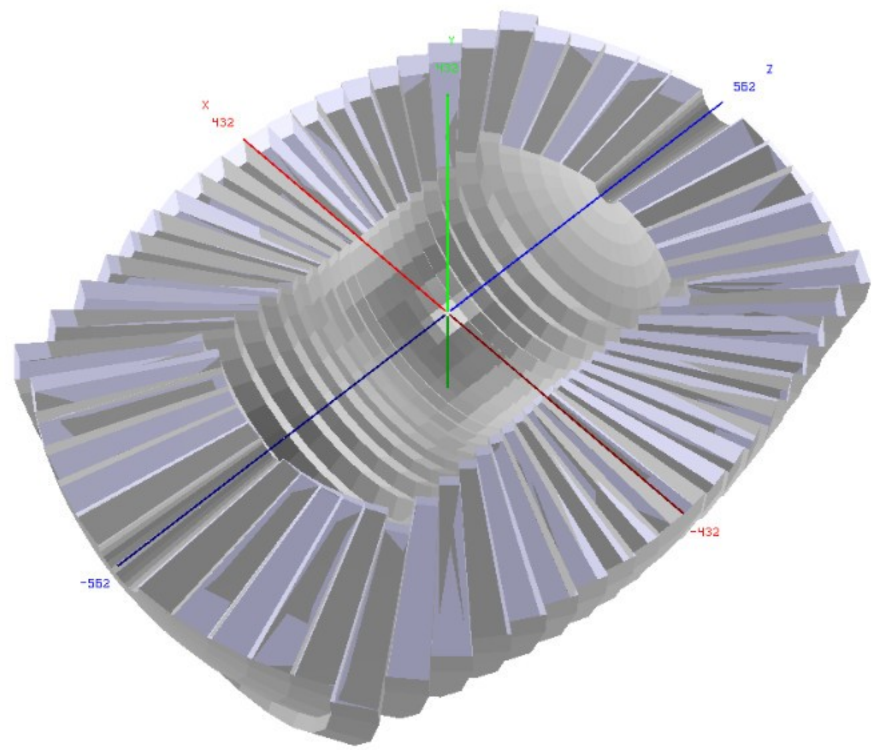


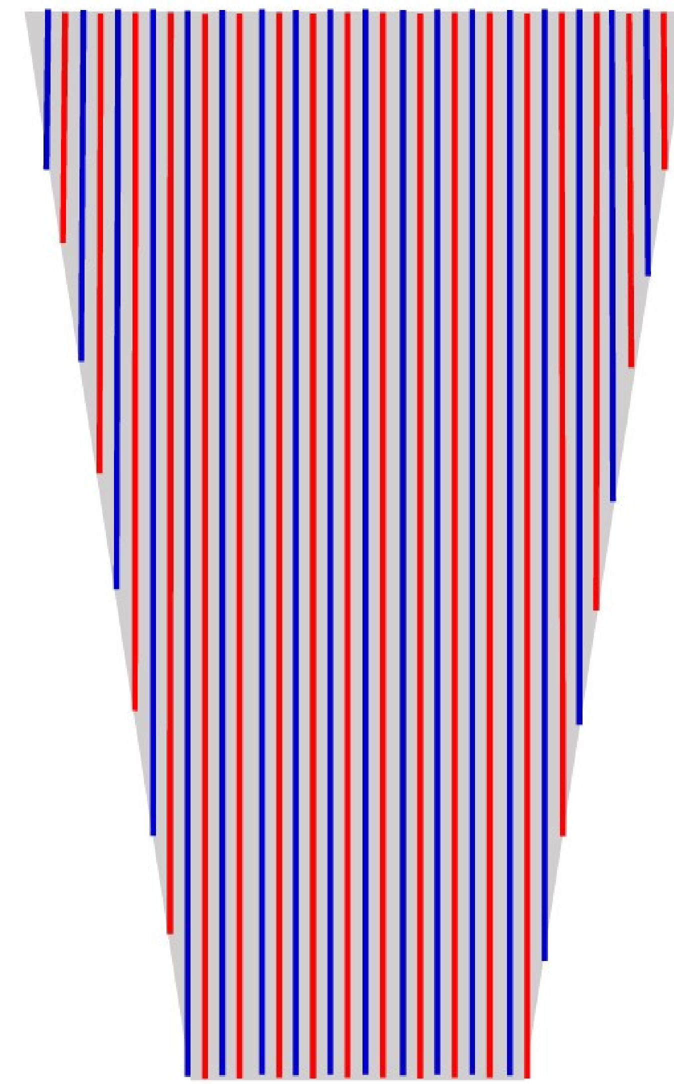
first step: ASIC (to be identified)

4π Simulations

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







a) full coverage
b) projective geometry

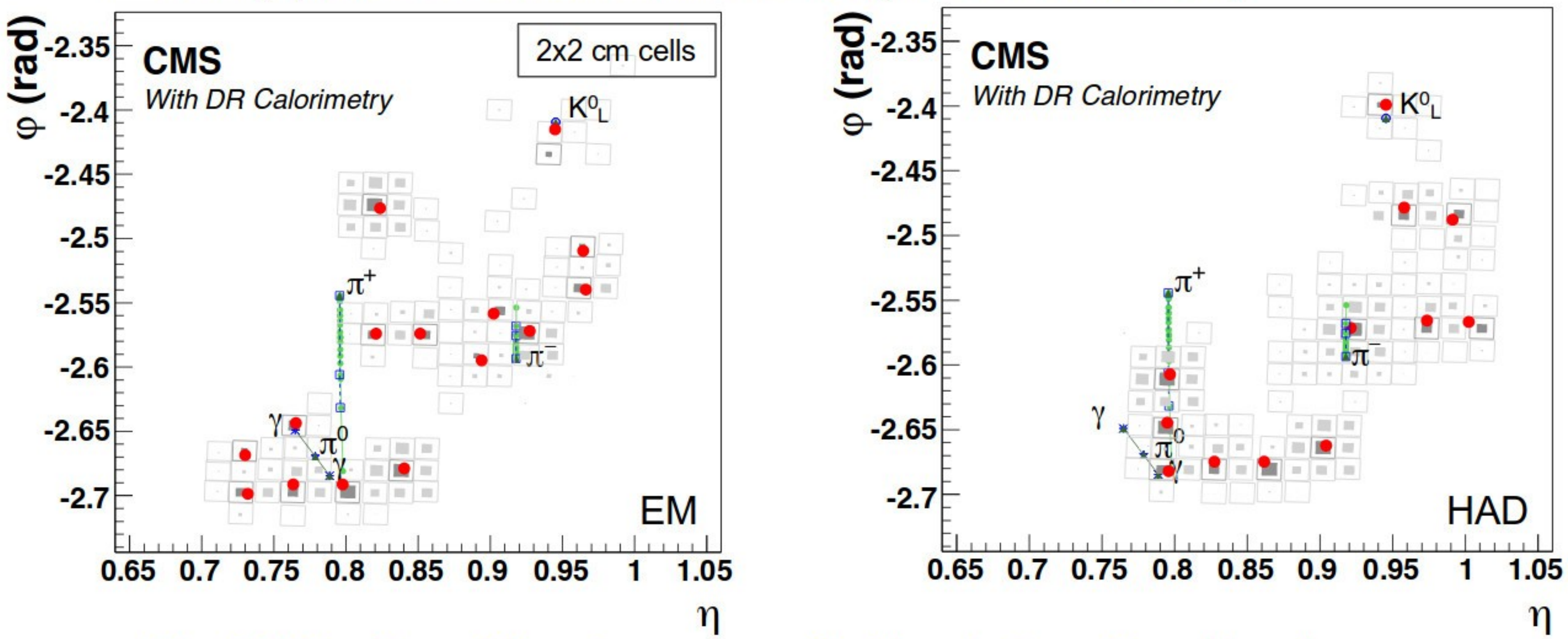
Longitudinal Segmentation & PFA

Last but not least:

addressing the issue of overlapping hadronic and em showers

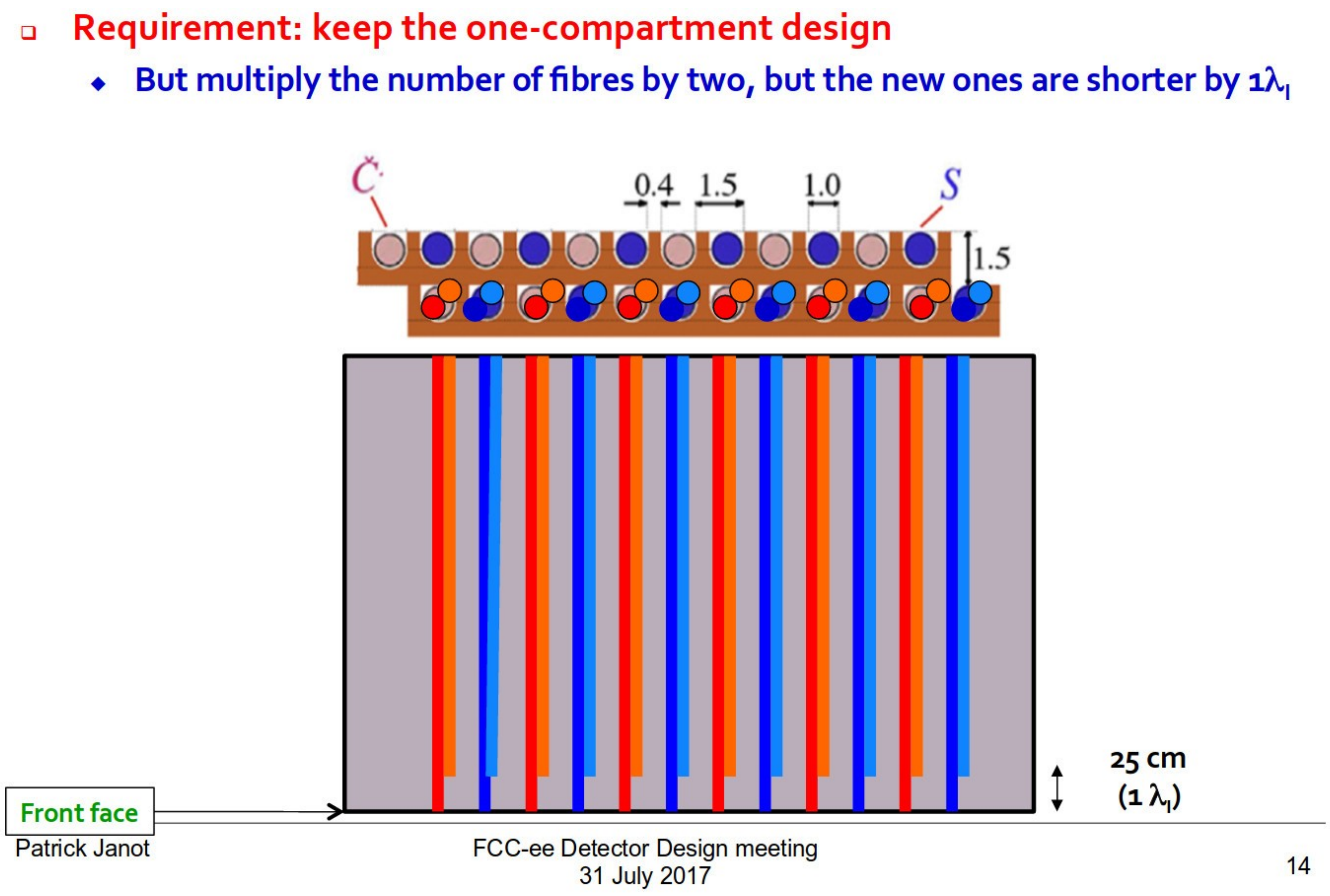
→ Patrick Janot proposes longitudinal segmentation (and PF w/ DR)

- **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 separation ?

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

Conclusions

- we are convinced that dual-readout may boost the performance of hadronic calorimetry at future e^+e^- colliders in a cost-effective way

- its possible implementation looks realistic but some issues still need to be answered/understood: in mechanical production, data readout, physics performance, ...

- work is ongoing (in collaboration with CepC and FCCee people) for both:

developing a scalable solution made of ~10x10 cm^2 modules w/ 5000-10000 fibres, individually coupled to photo-detectors

and:

assessing the expected performance through G4 simulations (also with PF approach), in an integrated detector (w/ tracker, preshower, magnetic field, coils)

Backup

The Alchemy

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

is universally valid

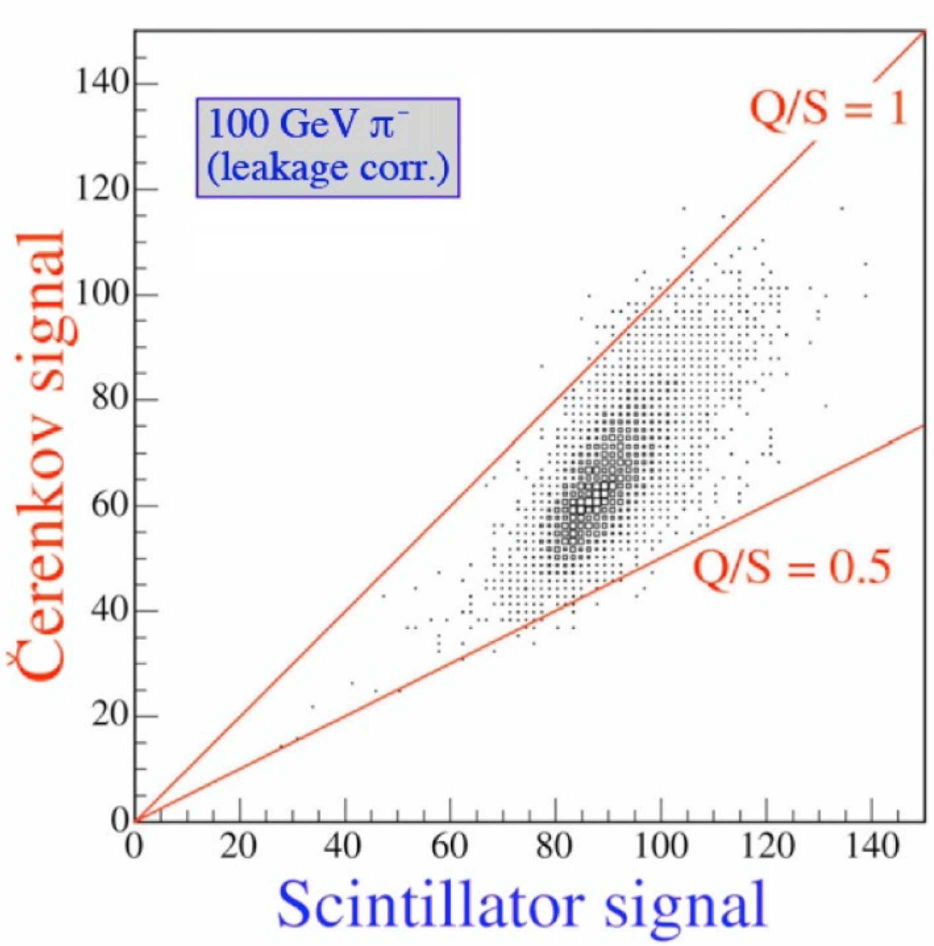
$$cotg\,\theta = \frac{1-(h/e)_S}{1-(h/e)_C} = \chi$$

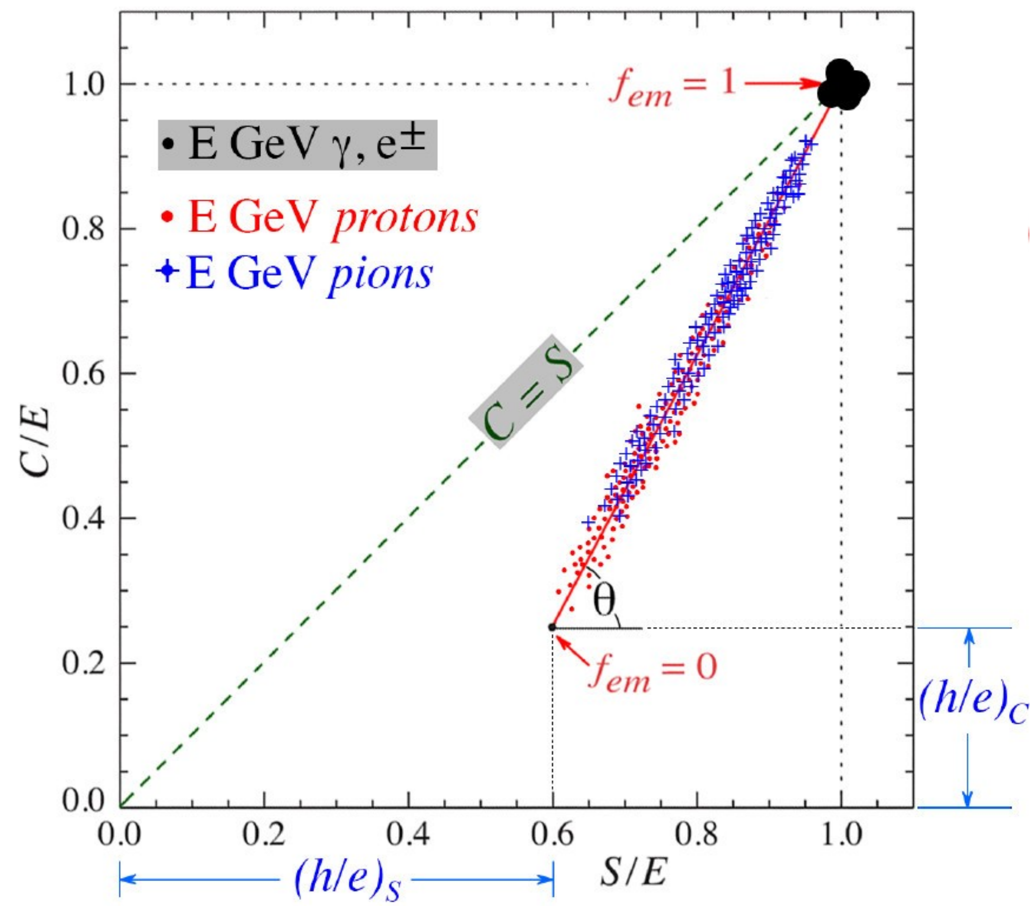
Θ, χ independent of both:

i) energy (!)

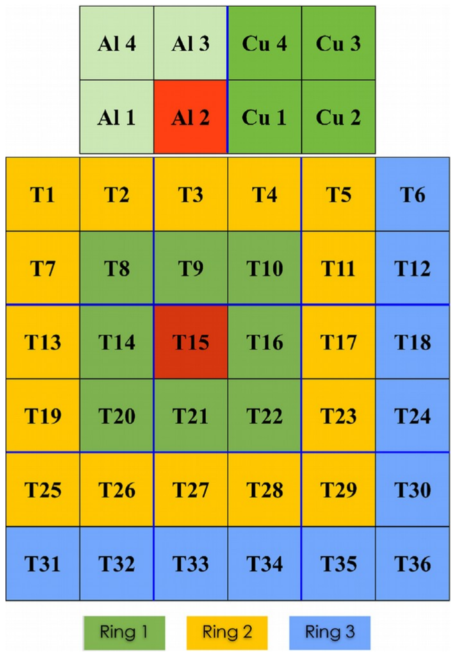
ii) type of hadron (!!)

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

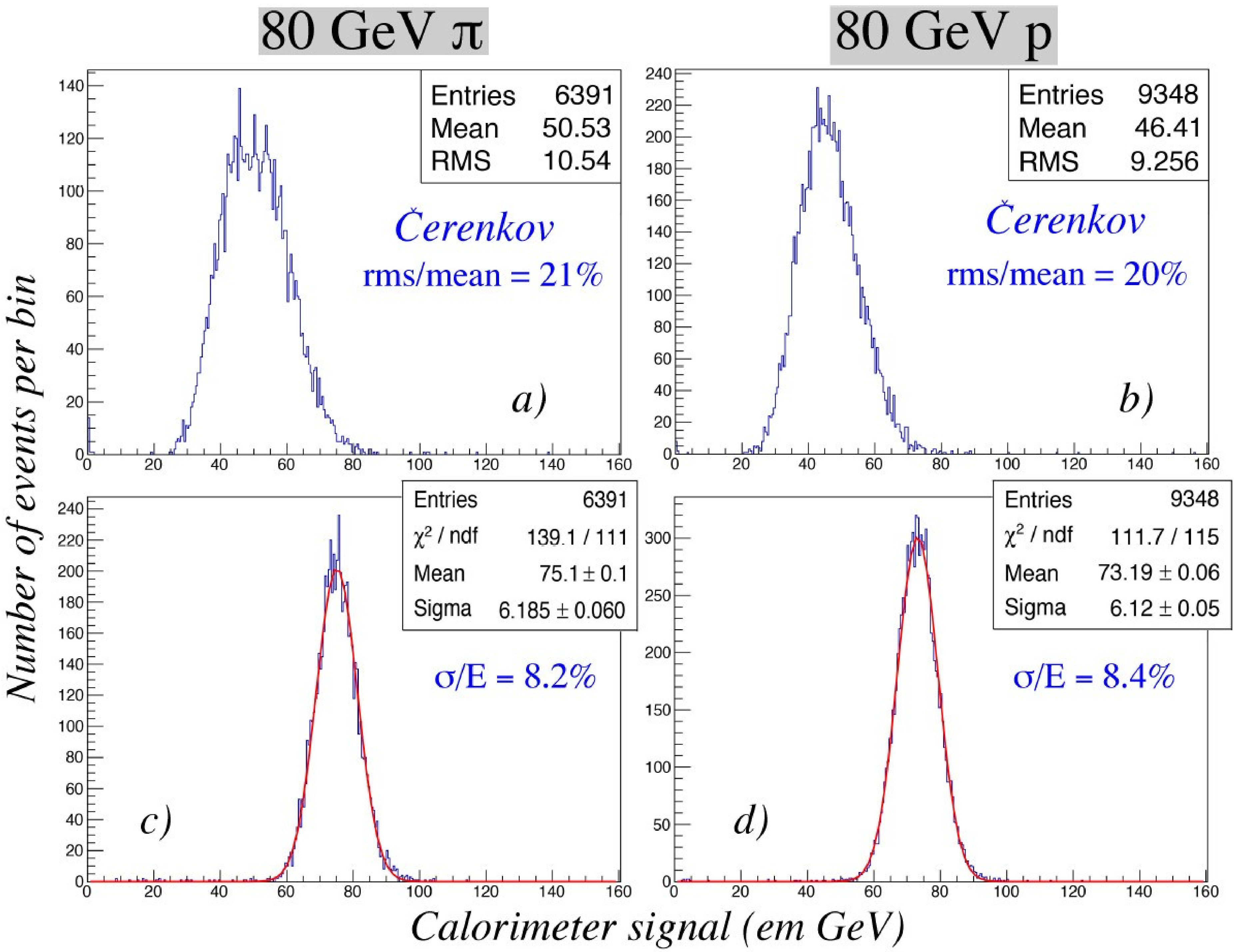




Dual Readout at Work

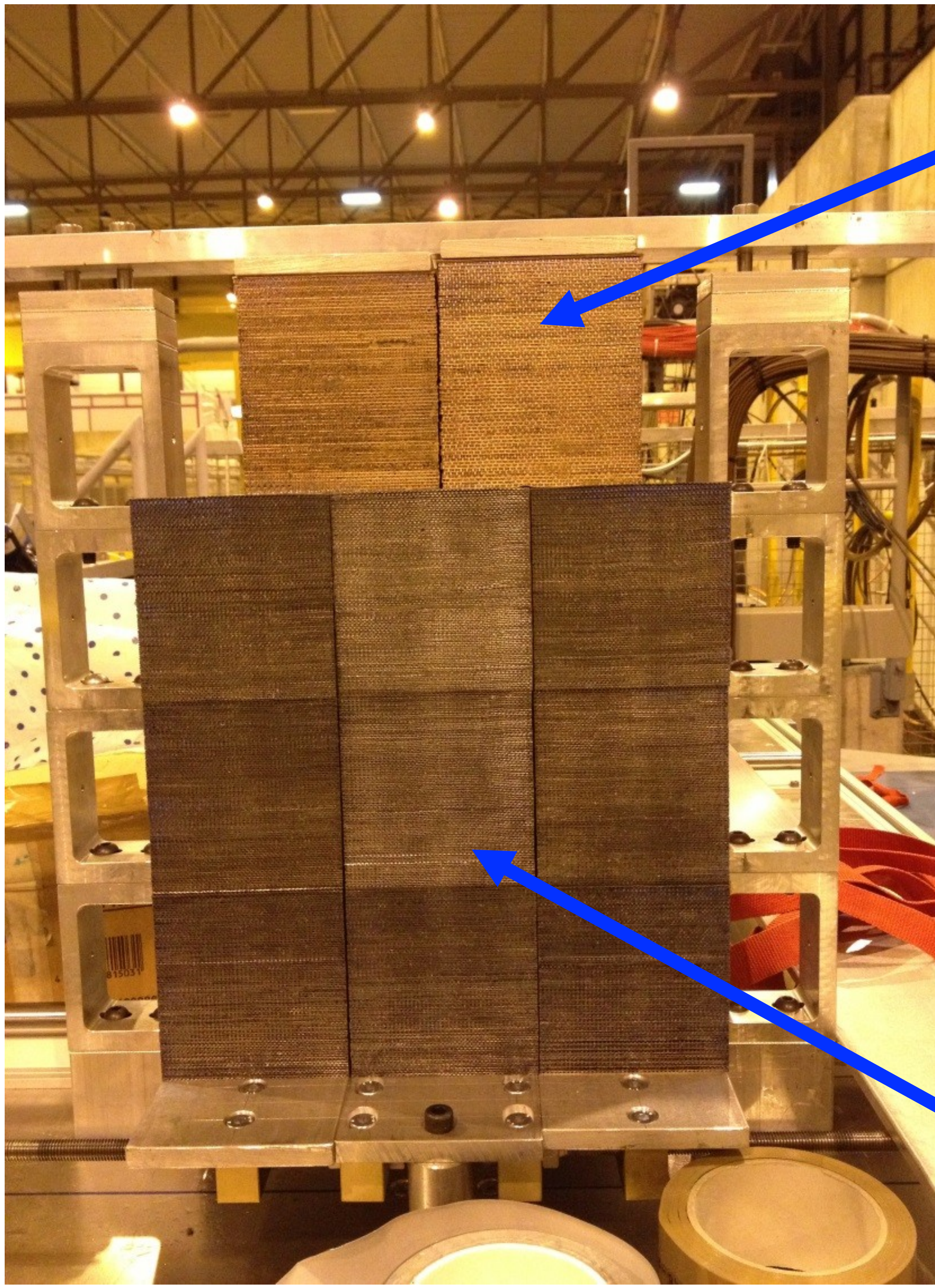


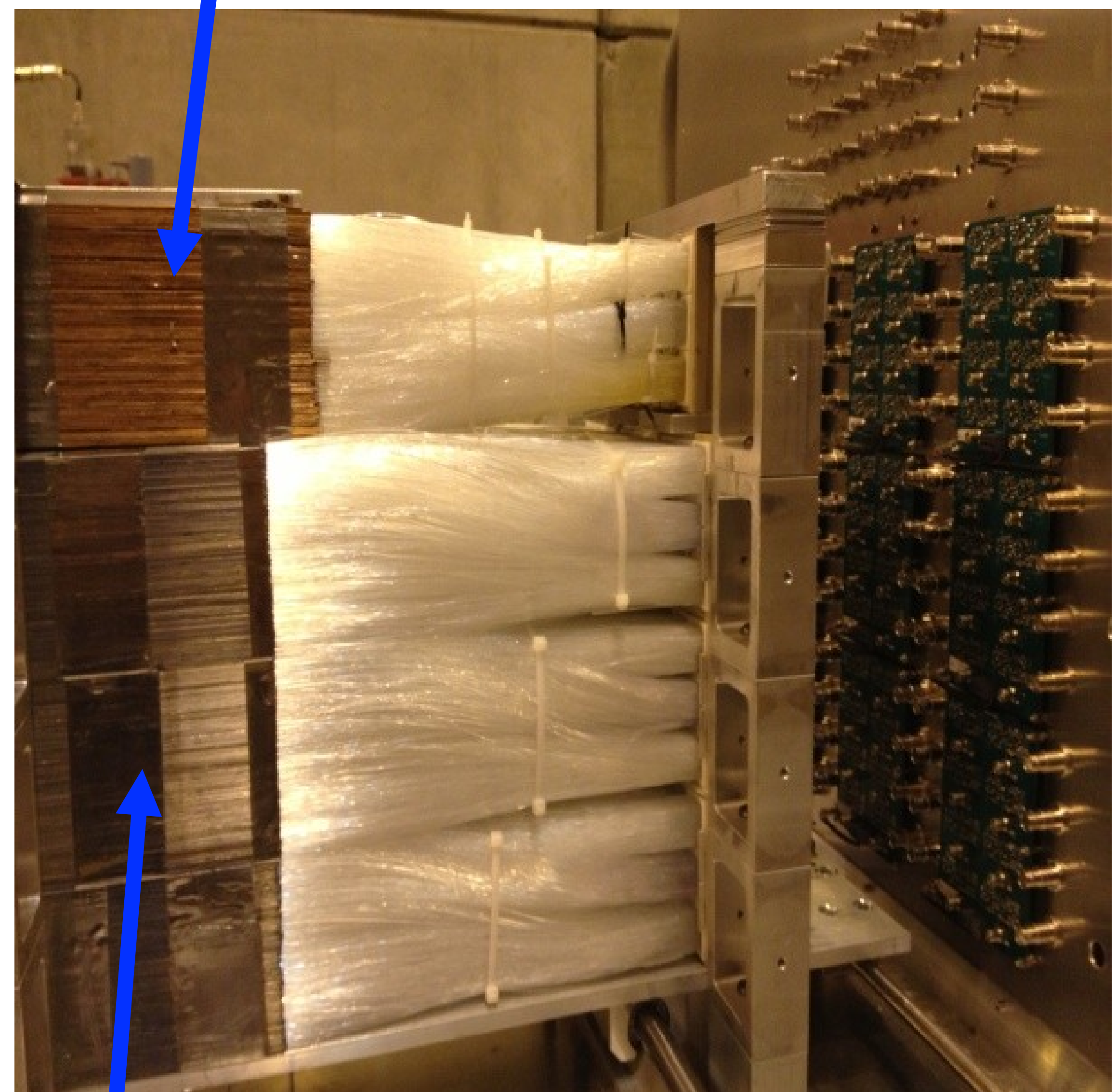
NIM A 866 (2017) 76



RD52 DR Fibre Calorimeters

2 Cu modules





Pb 3*3 matrix

Target

Build a scalable fibre-sampling module and demonstrate:

- *mechanical production process: precision and reproducibility*
- *sensors: sensitivity (Čerenkov light), linearity, dynamic range (scintillation light)*
- *signal readout: high granularity, information extraction and reduction*
- *physics performance: testbeams & simulation*
- *geometry for 4π detector, integration w/ a preshower det., ...*

Short term target: CepC & FCCee CDR.s