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R&D for Dual-Readout Fibre-Sampling Calorimetry

@ECFA Detector R&D Roadmap Symposium
Task Force 6: Calorimetry

Dual-readout in a nutshell

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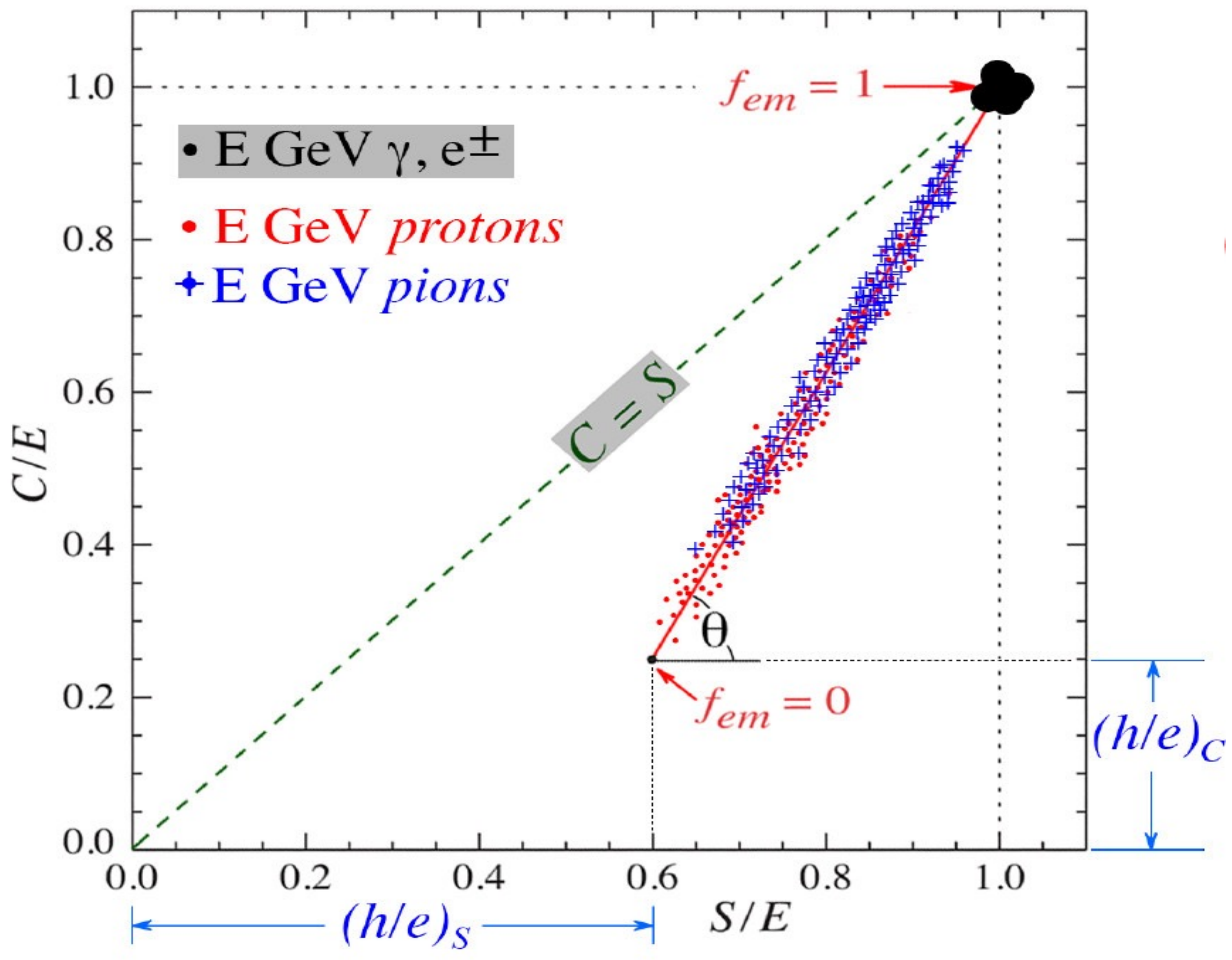
Simultaneous measurement on event-by-event basis of em fraction of hadron showers

$$\begin{cases} S = \left[f_{em} + \left(\frac{h}{e}\right)_S (1 - f_{em}) \right] E \\ C = \left[f_{em} + \left(\frac{h}{e}\right)_C (1 - f_{em}) \right] E \end{cases}$$

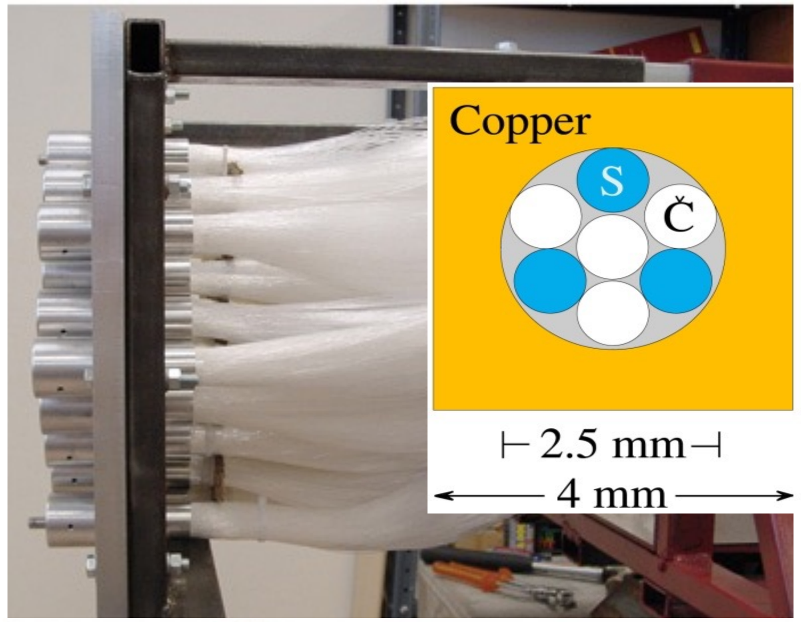
$$s = \left(\frac{h}{e}\right)_S ; \quad c = \left(\frac{h}{e}\right)_C$$

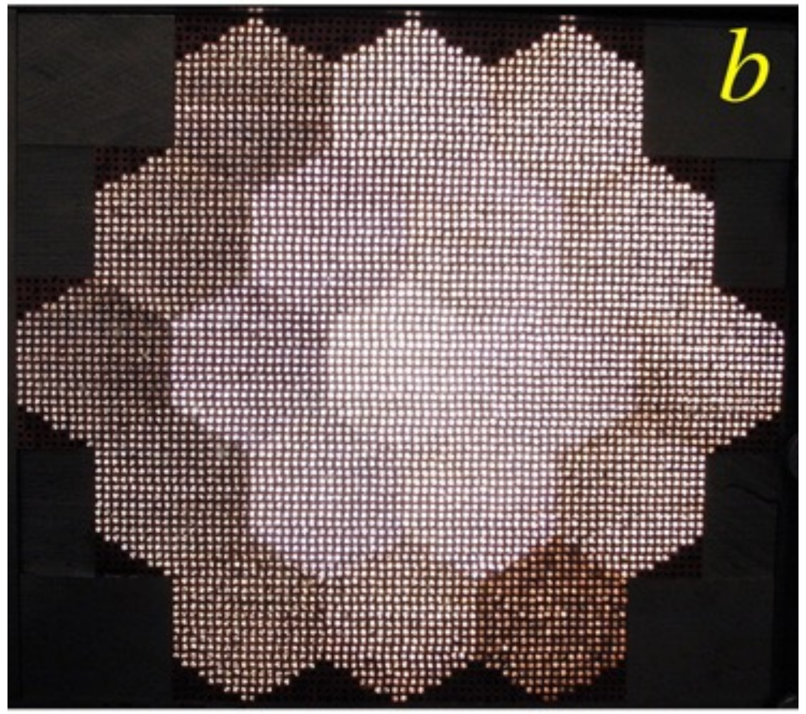
$$\begin{cases} f_{em} = \dfrac{c - s(C/S)}{(C/S)(1-s) - (1-c)} \\ E = \dfrac{S - \chi C}{1 - \chi} \end{cases}$$

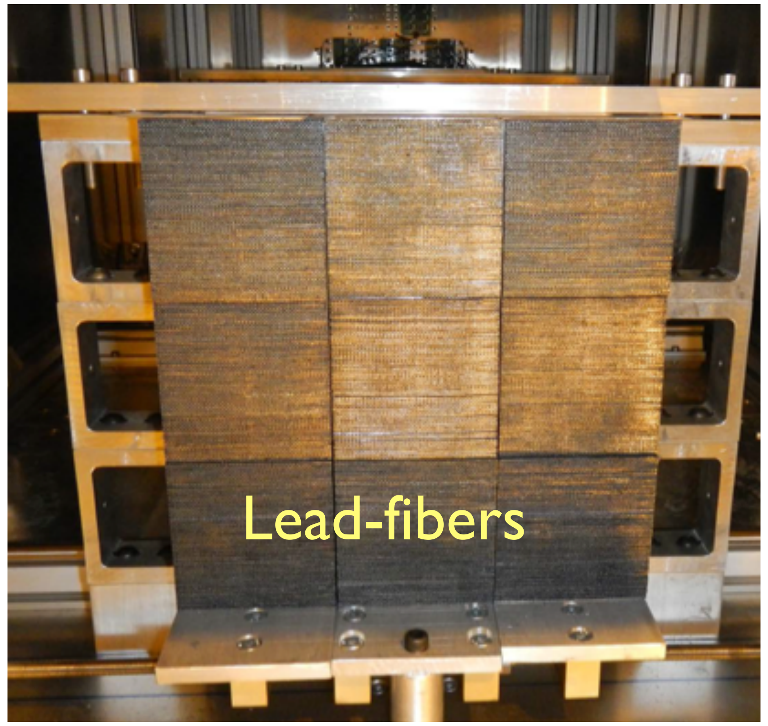


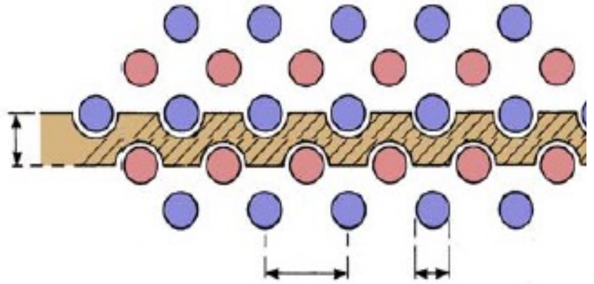
S. Lee, M. Livan, R. Wigmans, , Rev. Mod. Phys. 90 (2018) 025002

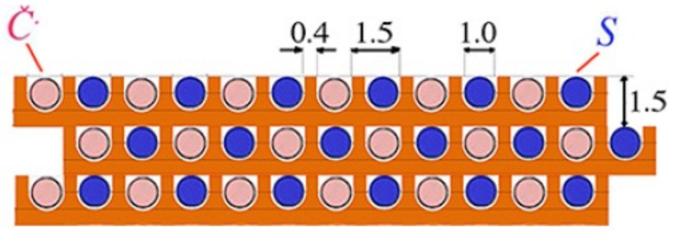
State of the Art – DREAM & RD52 collaboration



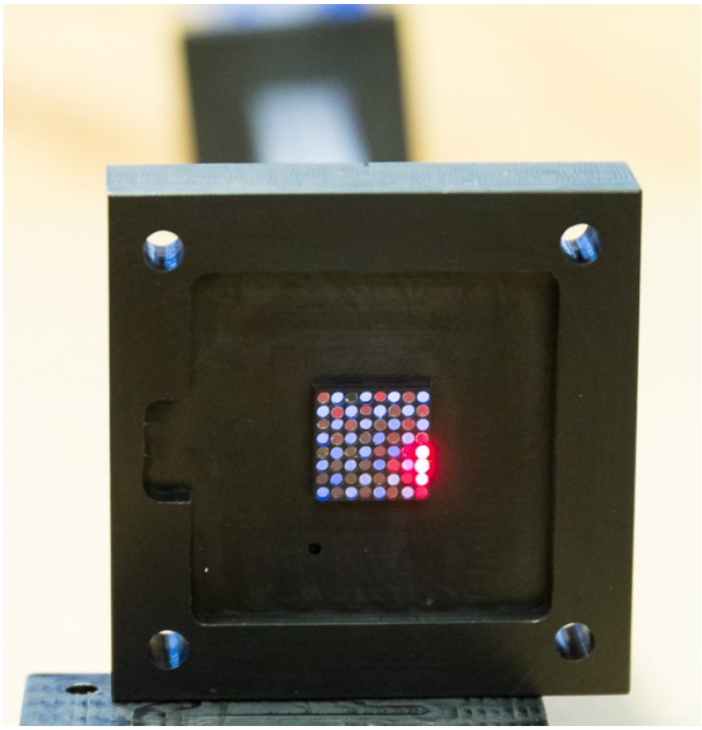


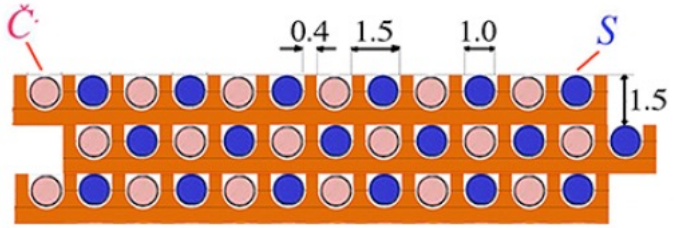






PMT readout

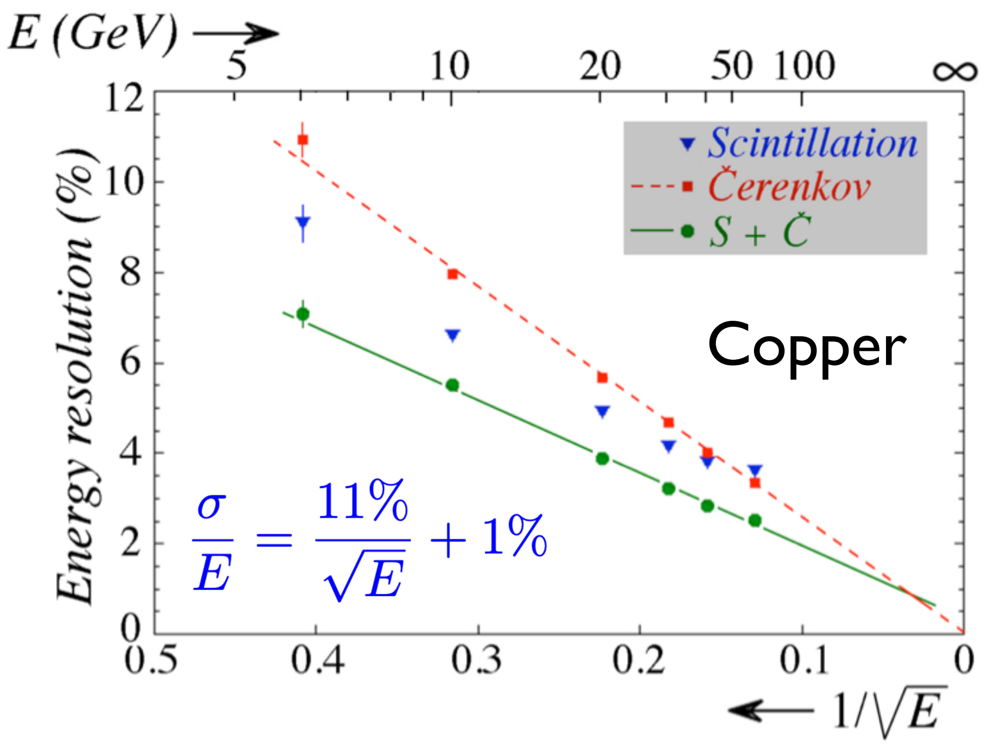




SiPM readout

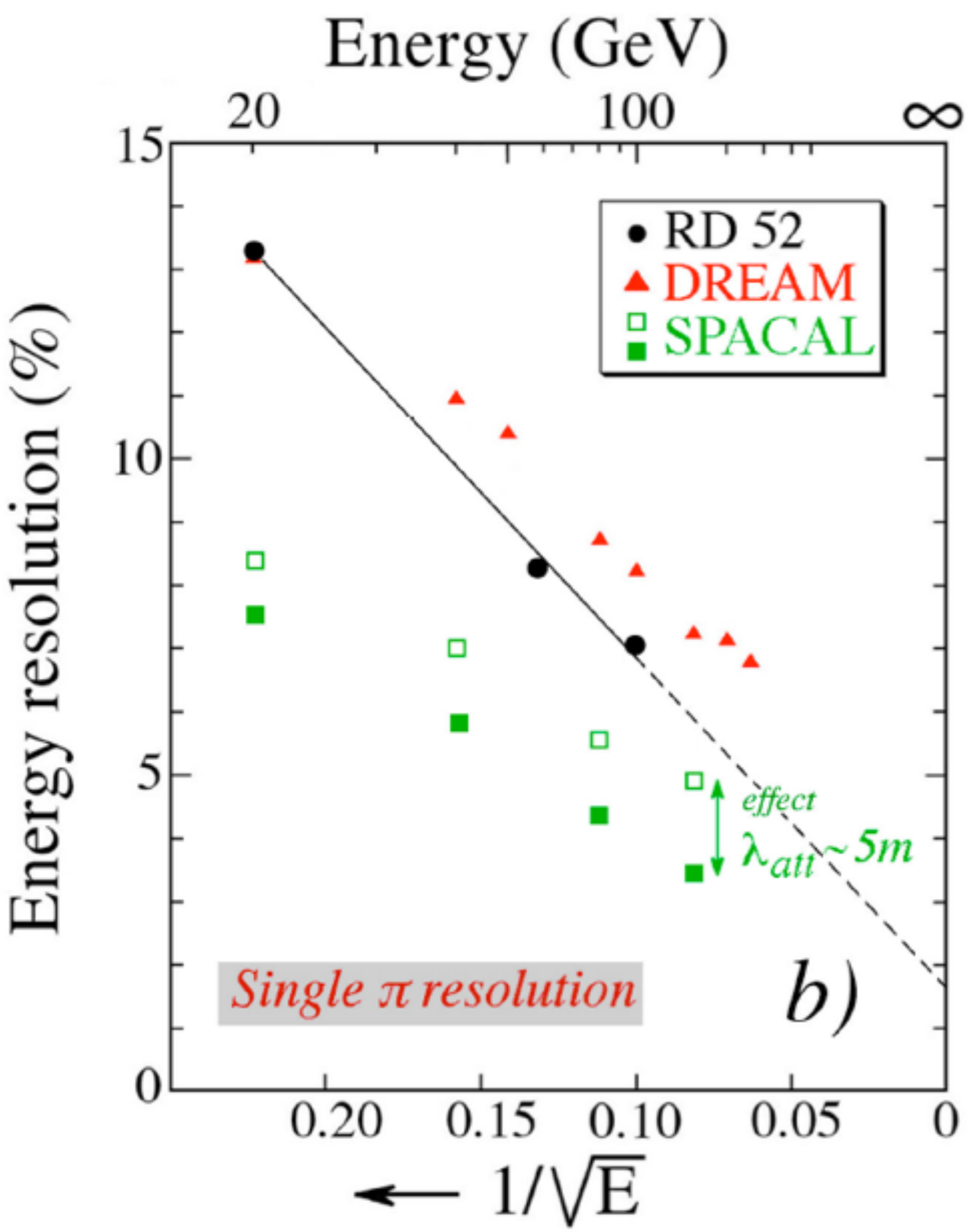
State of the Art – DREAM & RD52 collaboration

Electromagnetic Resolution



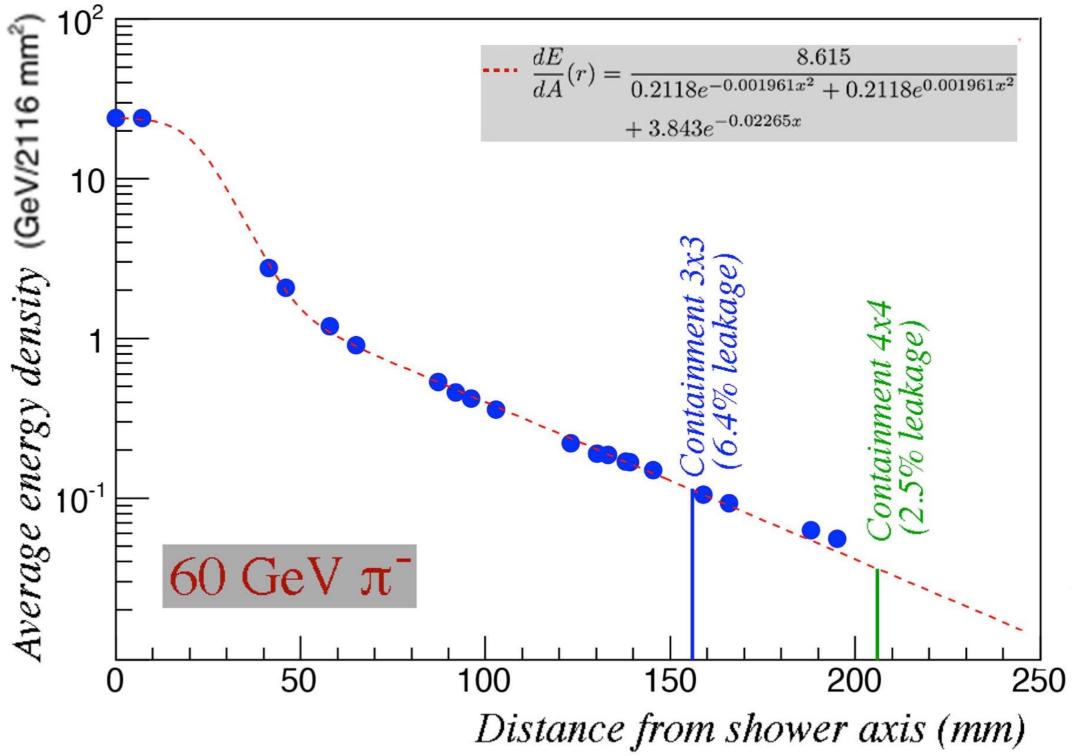
N. Akchurin, et al., NIM. A 735 (2014) 130.

Hadronic Resolution (Lead Module)



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

To include corrections on:
- light attenuation
- lateral leakage



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State of the Art – DREAM & RD52 collaboration

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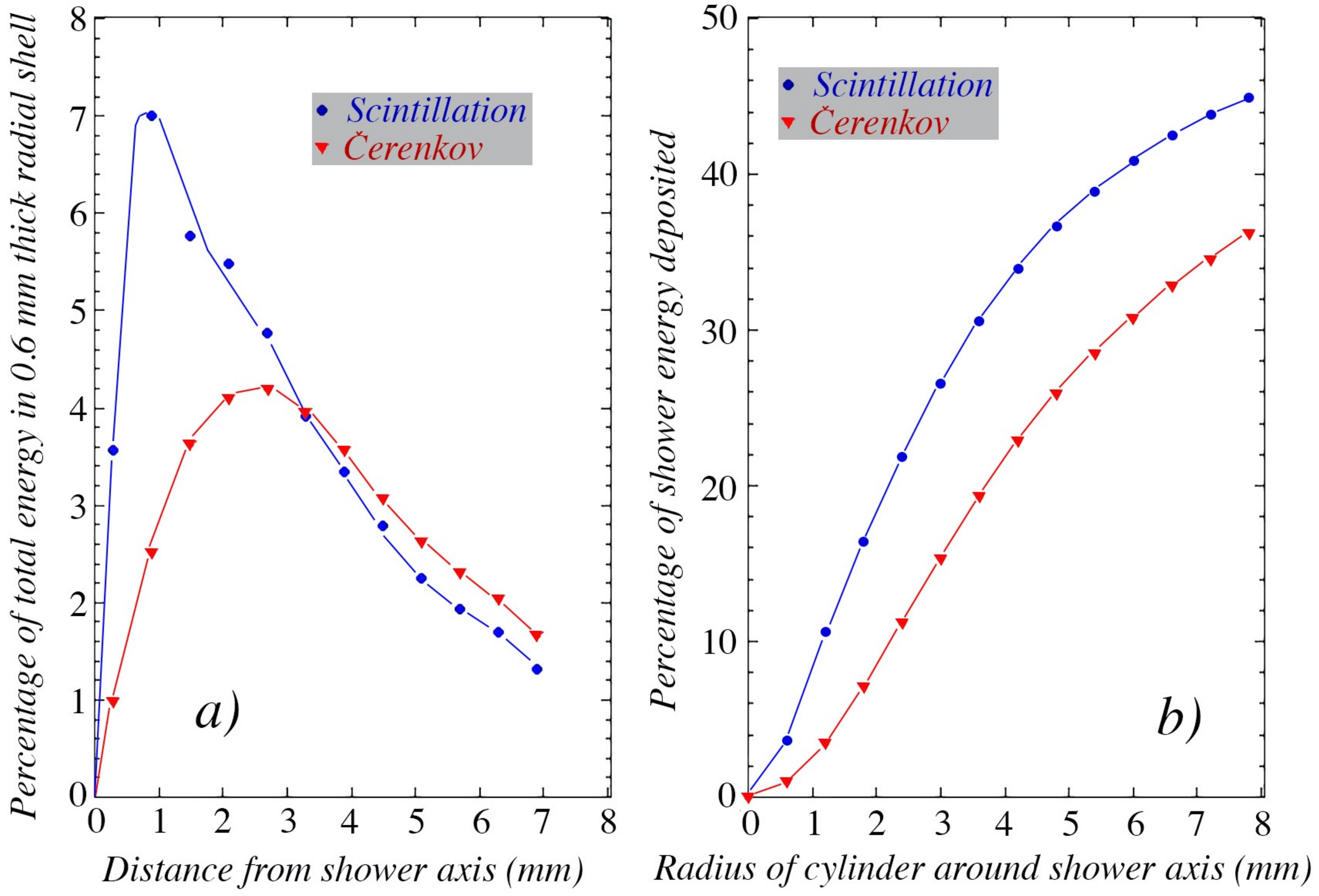
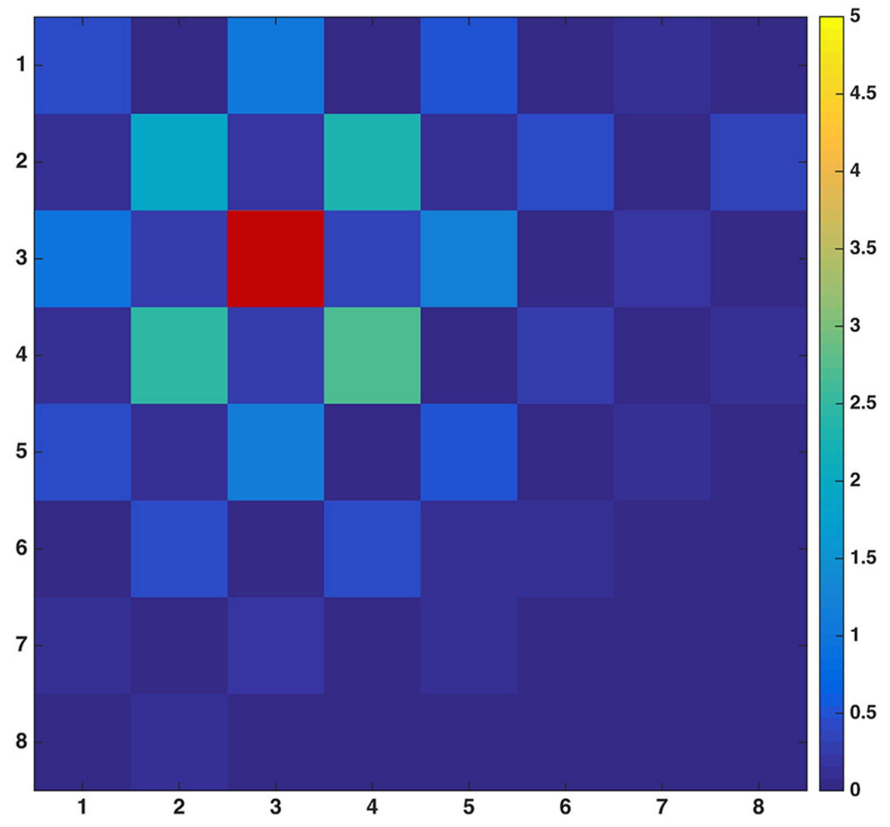


M. Antonello, et al, NIM. A 899 (2018) 52

High granularity mapping of an electromagnetic shower achieved by reading out single fibres with SiPM



State of the Art: Dual Readout in IDEA@FCC (CepC)

Physics Requirements:

HADRONIC CALORIMETER

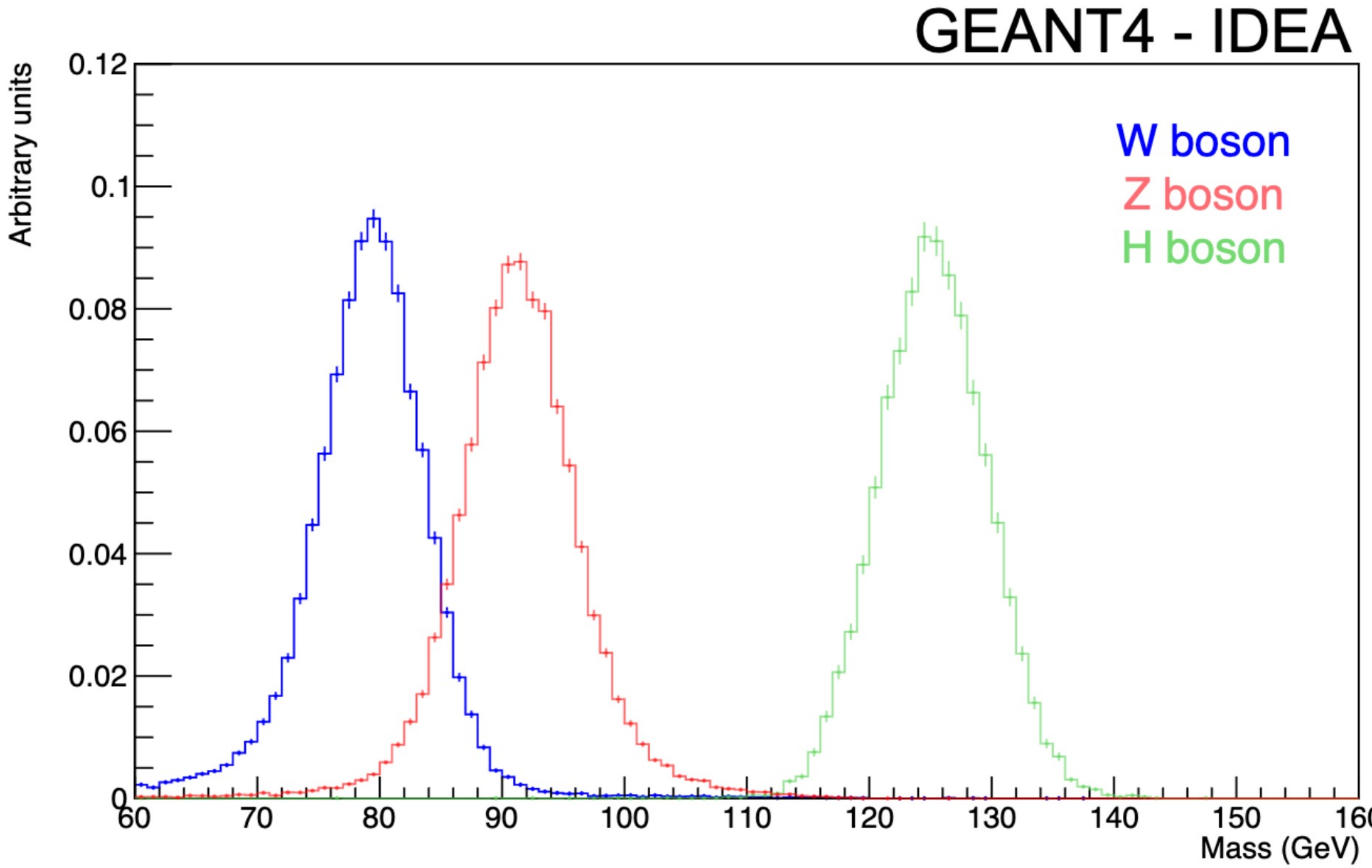
H→qq, WW*, ZZ* in hadronic final states

$$\frac{\sigma}{E} = \frac{30\%}{\sqrt{E}}$$

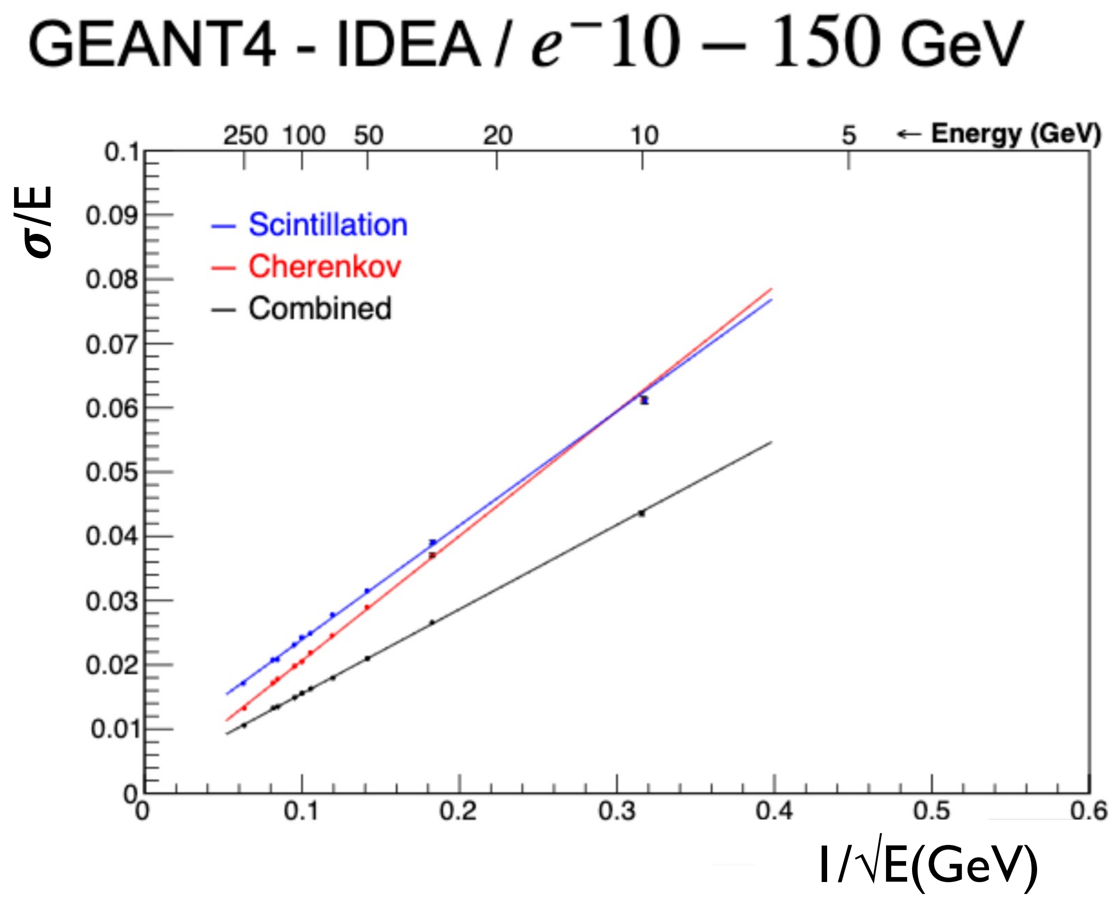
ECAL CALORIMETER

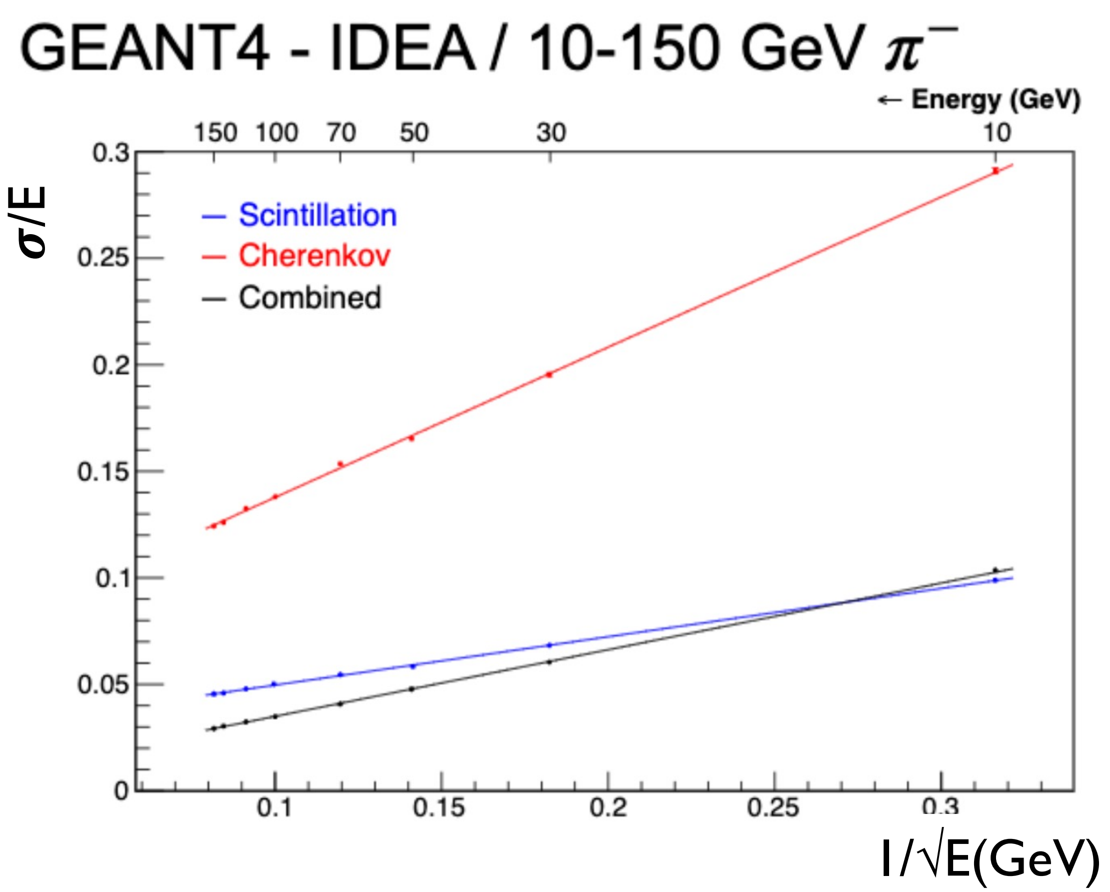
H→$\gamma\gamma$, ALP, ... better than

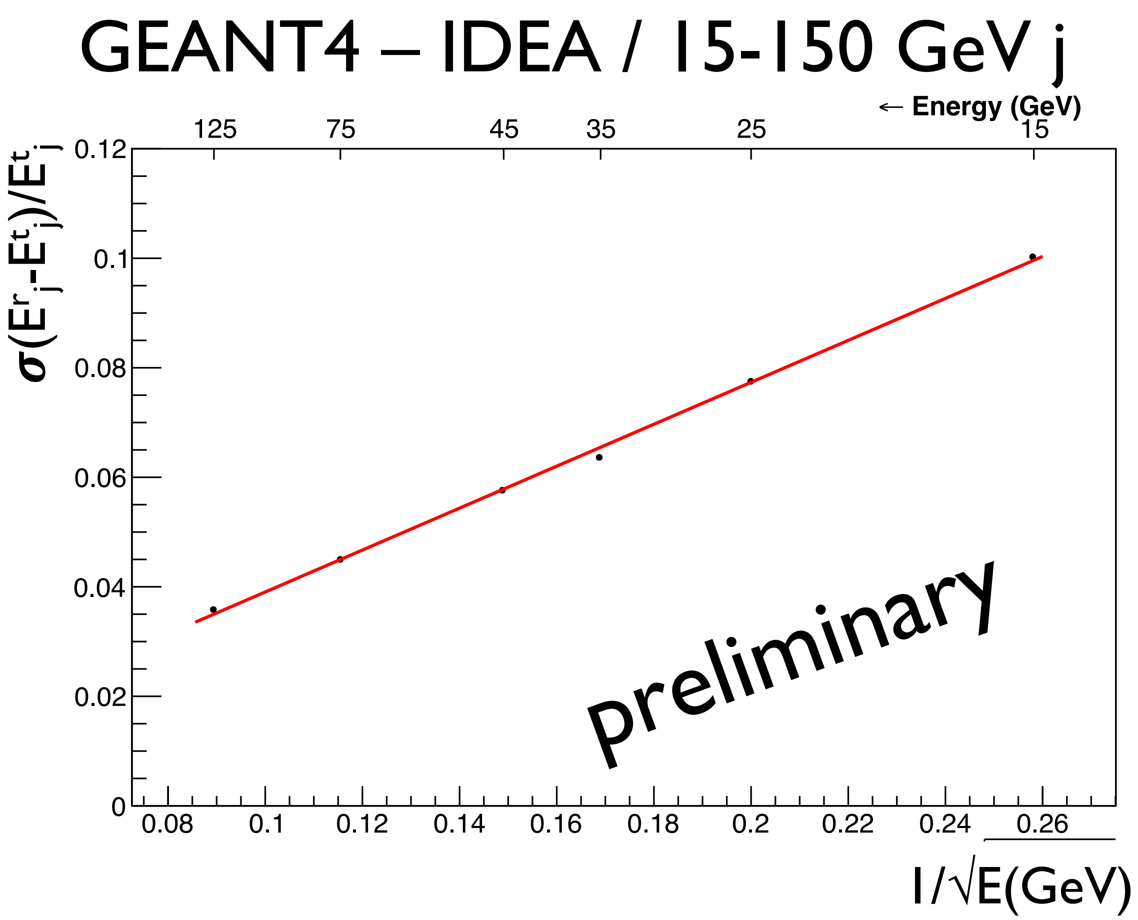
$$\frac{\sigma}{E} = \frac{20\%}{\sqrt{E}} \oplus 0.01$$



State of the Art: Dual Readout in IDEA@FCC (CepC)







electrons

$$\frac{\sigma}{E} = \frac{14\%}{\sqrt{E}} \oplus 0.6\%$$

pions

$$\frac{\sigma}{E} = \frac{32\%}{\sqrt{E}} \oplus 1.3\%$$

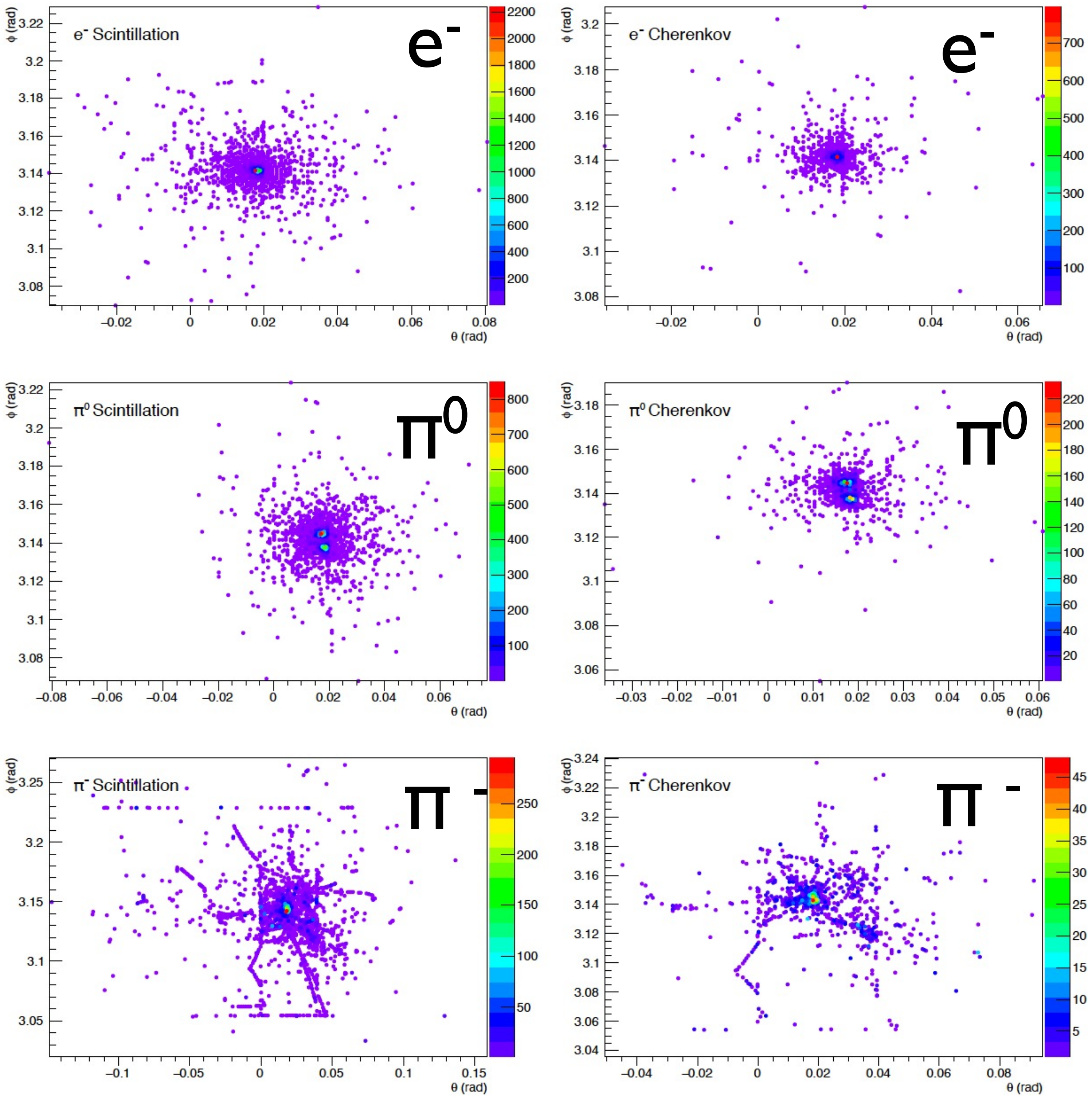
jet resolution in 2j final states

$$\frac{\sigma}{E} = \frac{38\%}{\sqrt{E}}$$

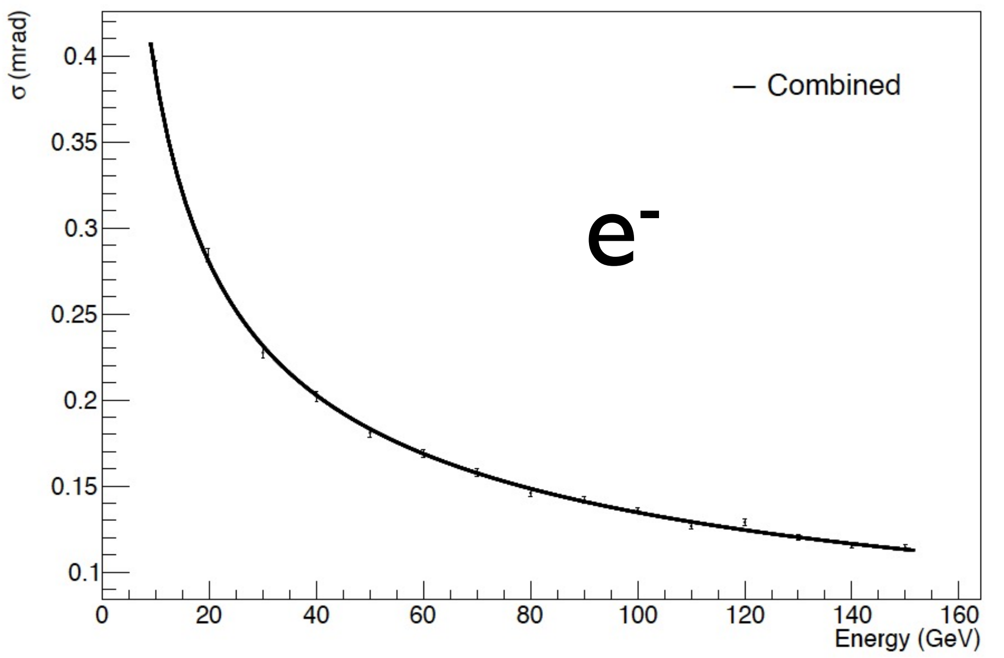
State of the Art: Dual Readout in IDEA@FCC (CepC)

Scintillation Cherenkov

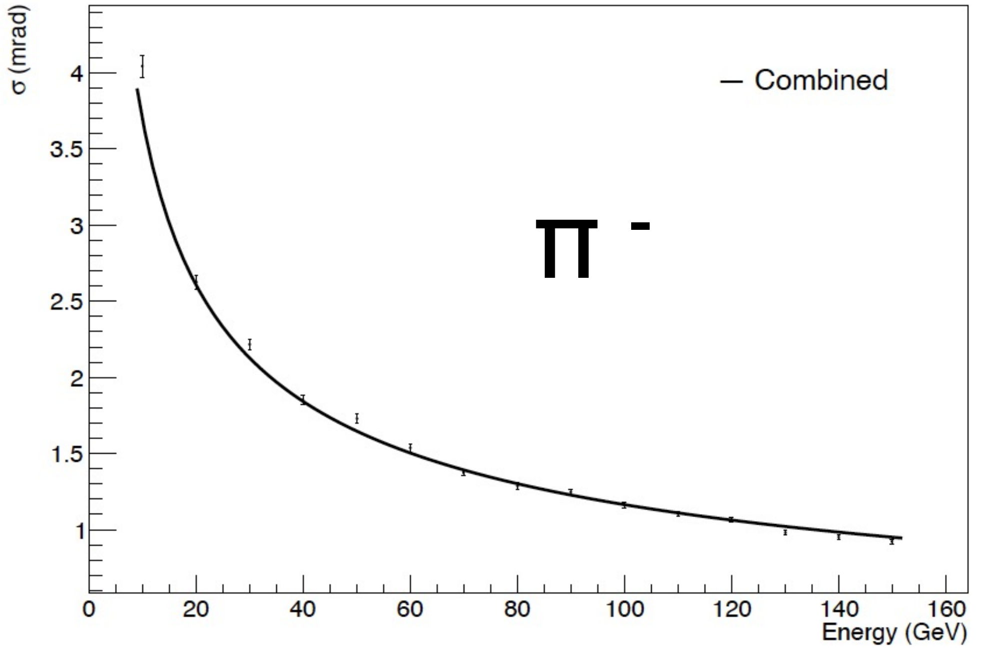
GEANT4 – IDEA



GEANT4 – IDEA / e⁻ 15-150 GeV



GEANT4 – IDEA / π⁻ 15-150 GeV



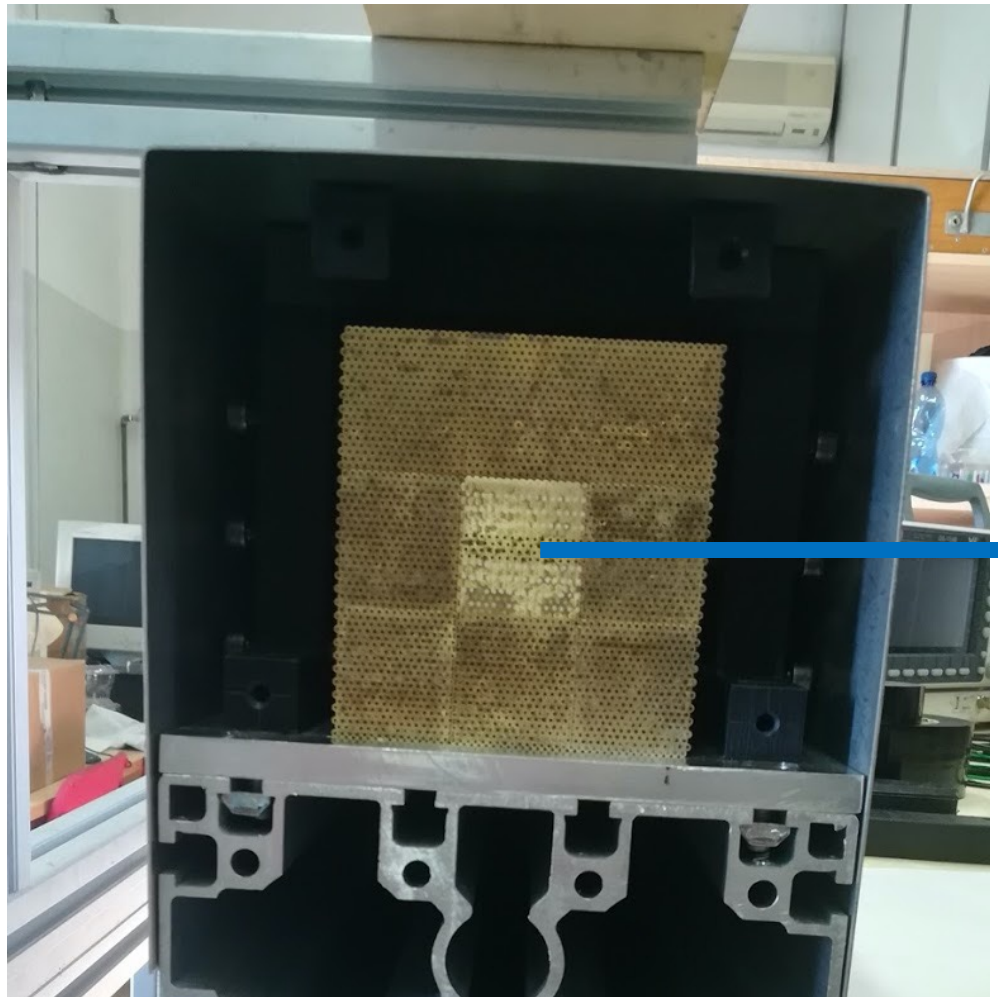
High granularity

good angular resolution

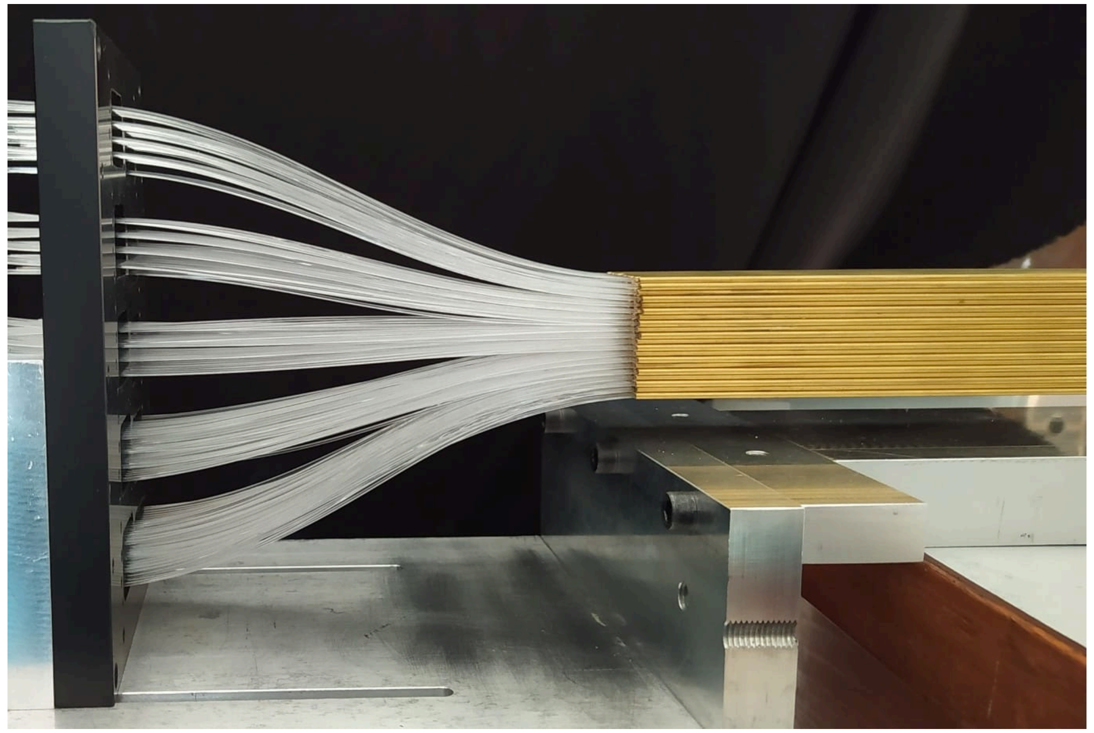
$$\sigma(mrad) = \frac{1.23}{\sqrt{E}} \oplus 0.05$$

$$\sigma(mrad) = \frac{11.6}{\sqrt{E}}$$

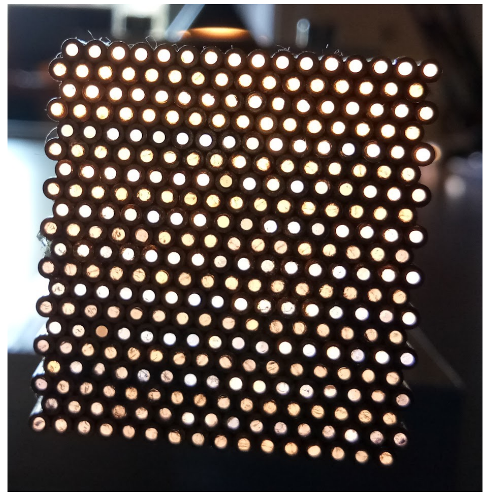
State of the Art: Dual Readout in IDEA@FCC (CepC)



SiPM readout for central tower



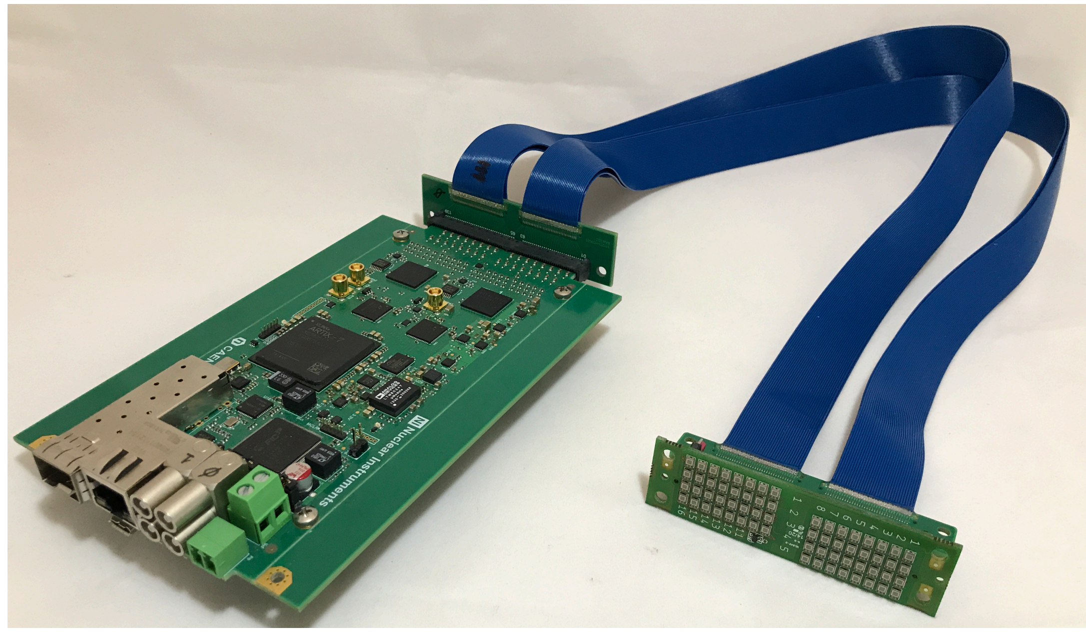
2020 "EM-size" prototype
10x10 cm^2 divided in 9 towers
16x20 capillary each
160 C + 160 S fibres
Capillary: brass CuZn37
2 mm OD, 1.1 mm ID, L = 1 m



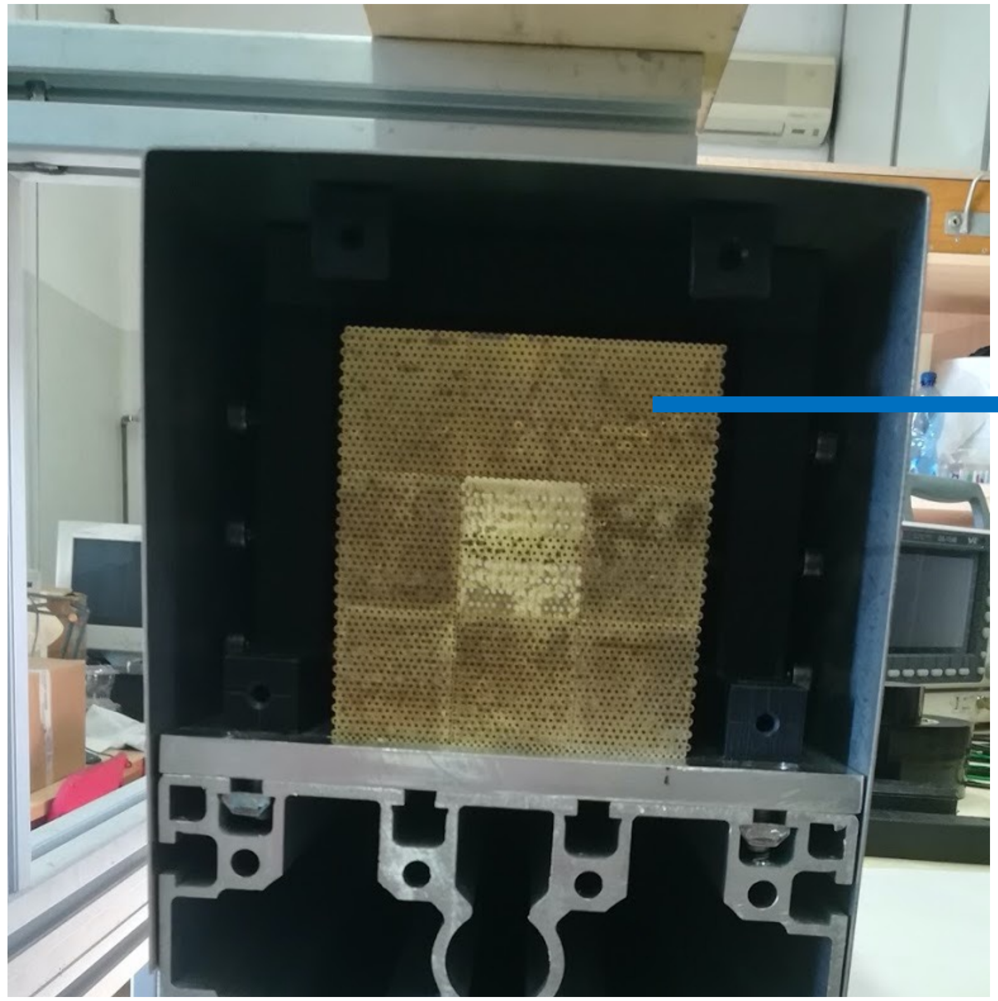
FEE – Boards
5 Boards

Each board:
64 SiPMs
(32 S +32 C)

Readout Boards:
5 FERS - A5202
CITIROC ASIC

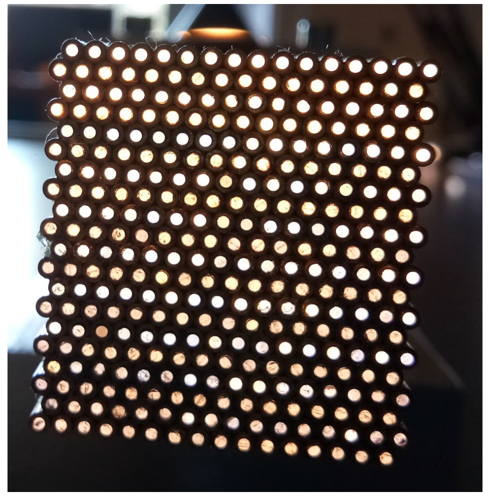


State of the Art: Dual Readout in IDEA@FCC (CepC)



PMT readout for external towers

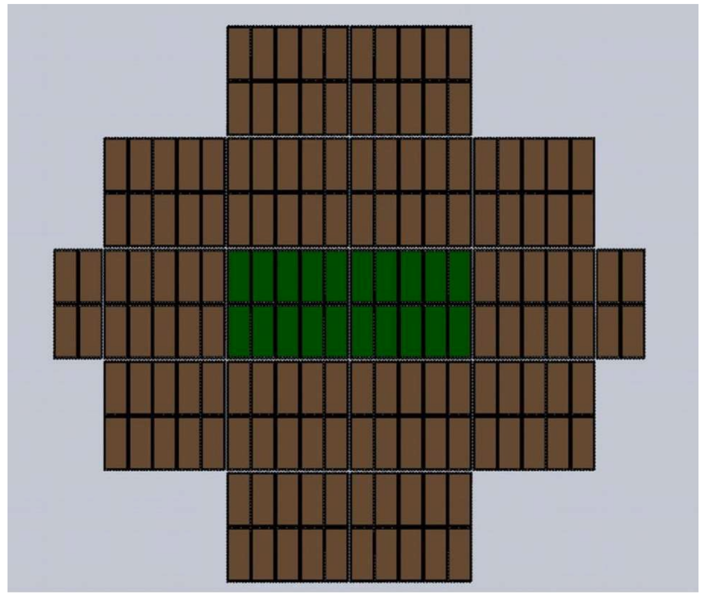
2020 "EM-size" prototype
10x10 cm^2 divided in 9 towers
16x20 capillary each
160 C + 160 S fibres
Capillary: brass CuZn37
2 mm OD, 1.1 mm ID, L = 1 m

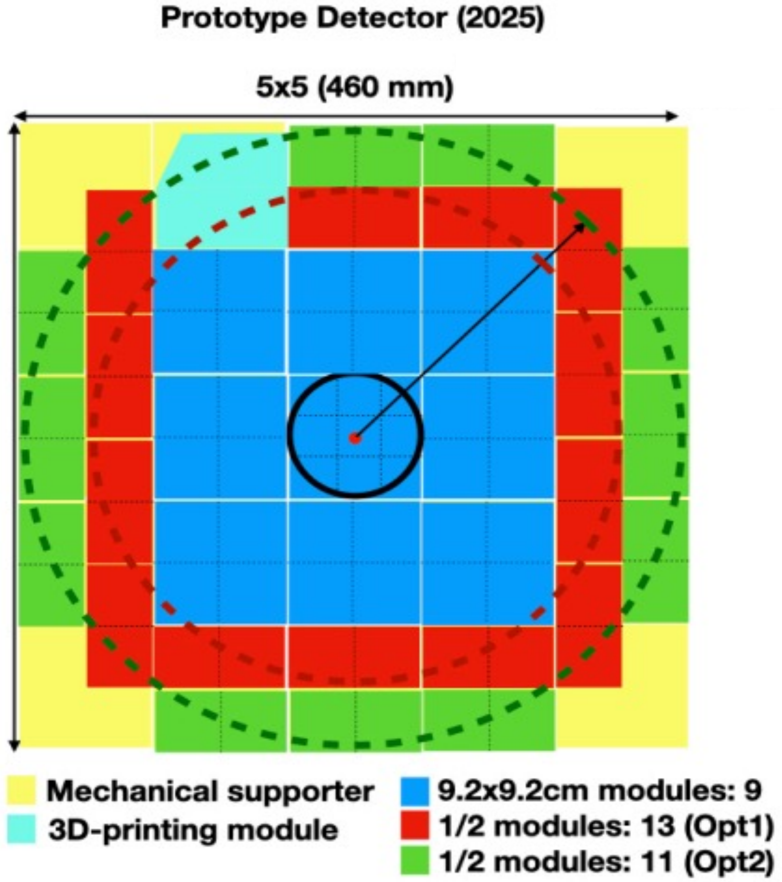


Short-term program: scaling up

“Hadronic-size” prototype is the goal for the next 3-4 year program

- validate GEANT4 simulations for hadronic showers
- assess (in particular) hadronic resolution performance
  - overcome limitation from shower containment
- assess feasibility in scalable mechanical structure
- handling of O(10k) SiPMs for dual-readout
  - target to a scalable sensor – readout – DAQ chain
  - timing and shower shape info for PID
- test “experiment-like” supports and services





(Some) key elements for future DR

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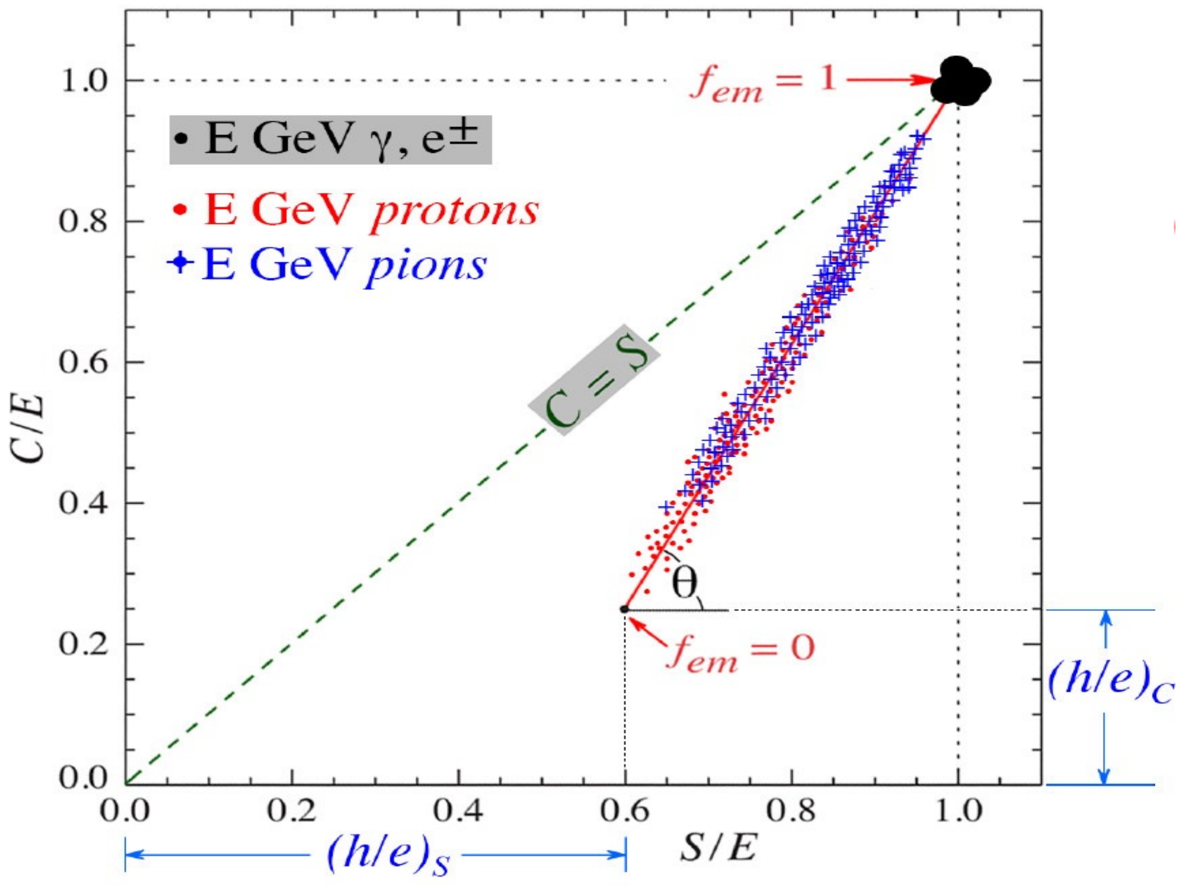
- Full understanding of dual readout (χ parameter)
- Invisible energy and triple readout
- MIP-like particles in the calorimeter

deepening the understanding of DR mechanism and of calorimetric response

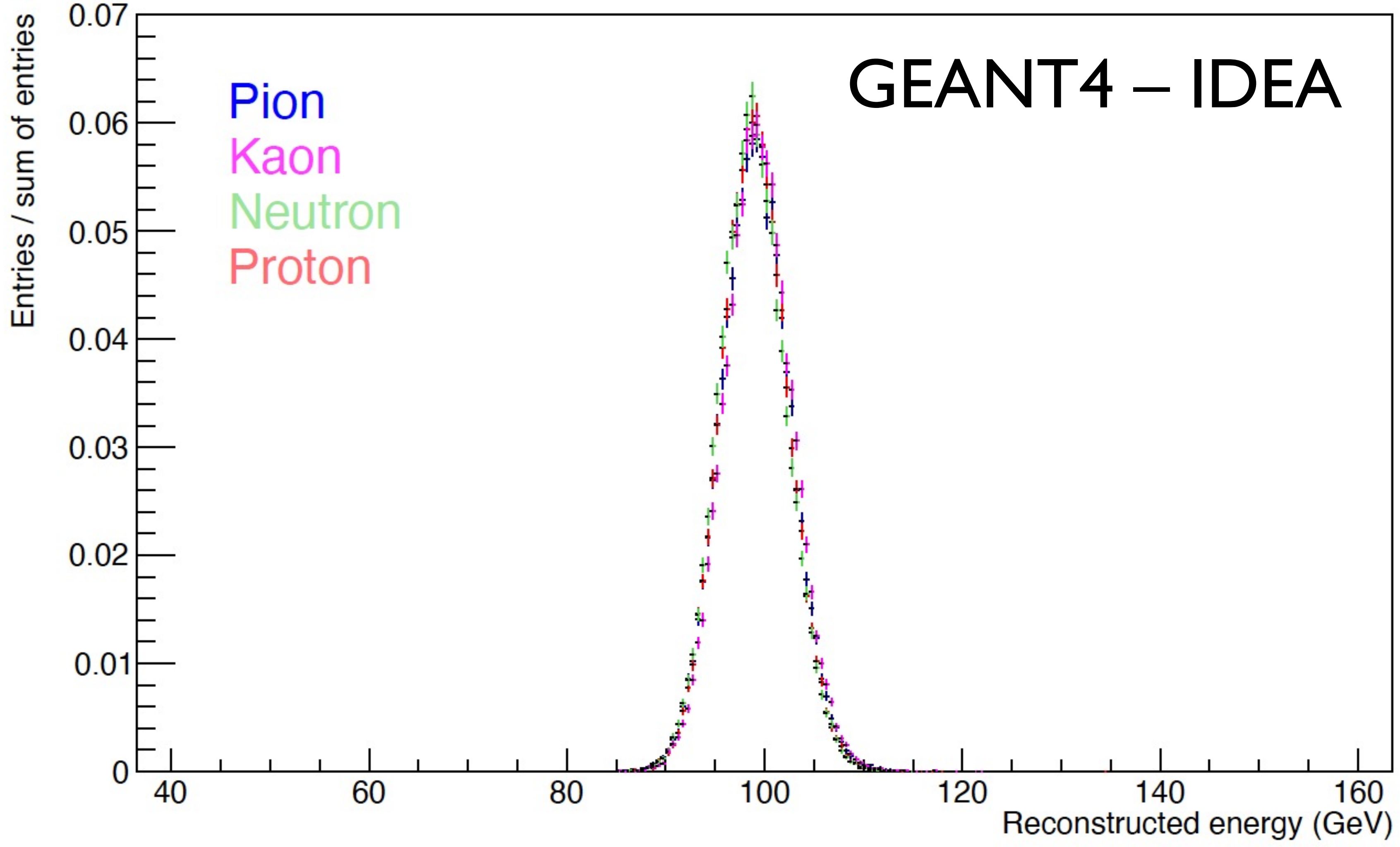
- The Cherenkov component
- How to shape the absorber
- Effect of non-uniformity on the calibration and performance
- Longitudinal segmentation... or not?
- Crystal fibers
- SiPM and dSiPM

detector related development

Full understanding of dual readout



$$E = \frac{S - \chi C}{1 - \chi} \quad \Rightarrow \quad \chi = \frac{1 - (h/e)_S}{1 - (h/e)_C} = \frac{E - S}{E - C}$$



- χ is fundamental parameter of the DR method
- assumed to be independent of the particle type
- measurable if E is known

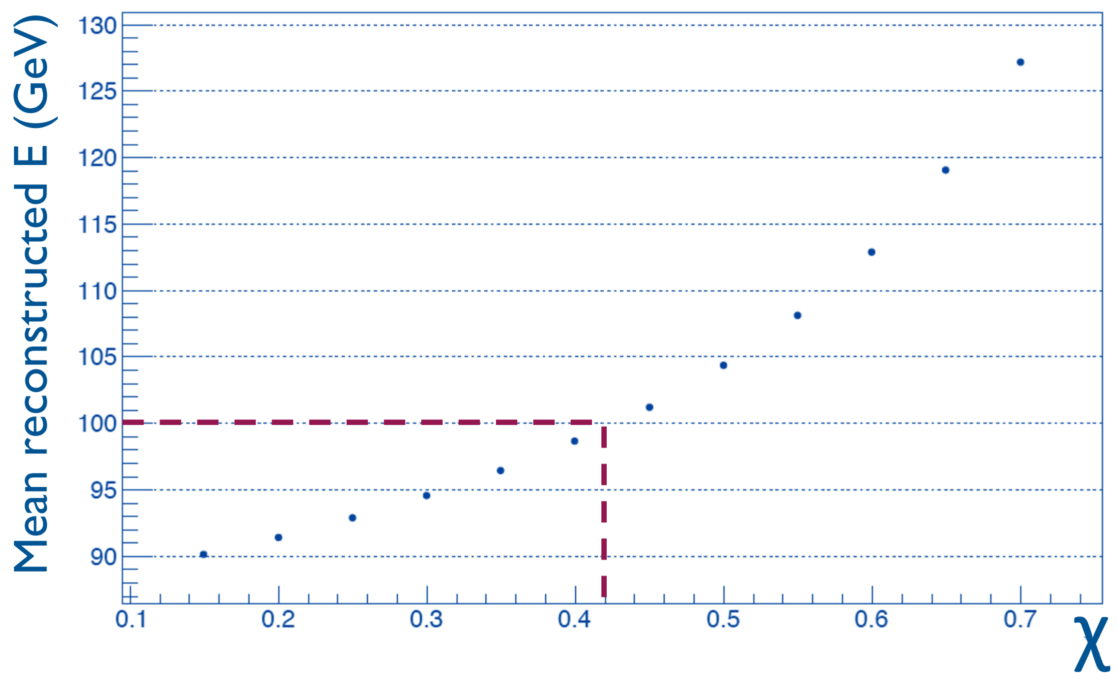
Full understanding of dual readout

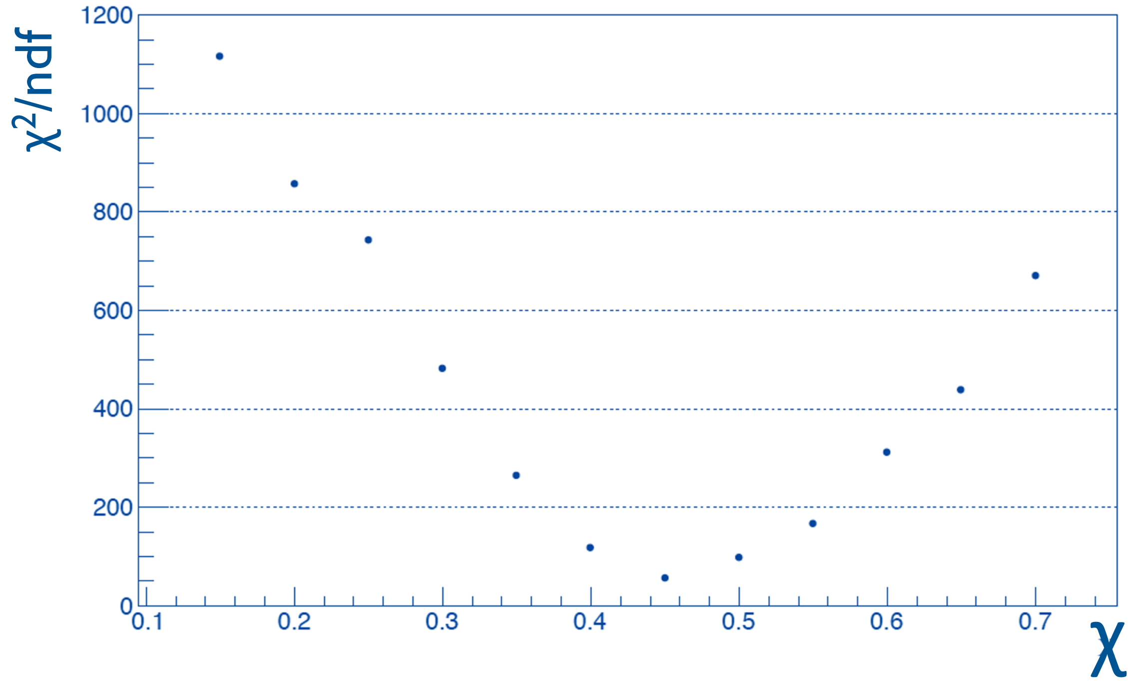
$$\chi = \frac{1-(h/e)_S}{1-(h/e)_C} = \frac{E-S}{E-C}$$

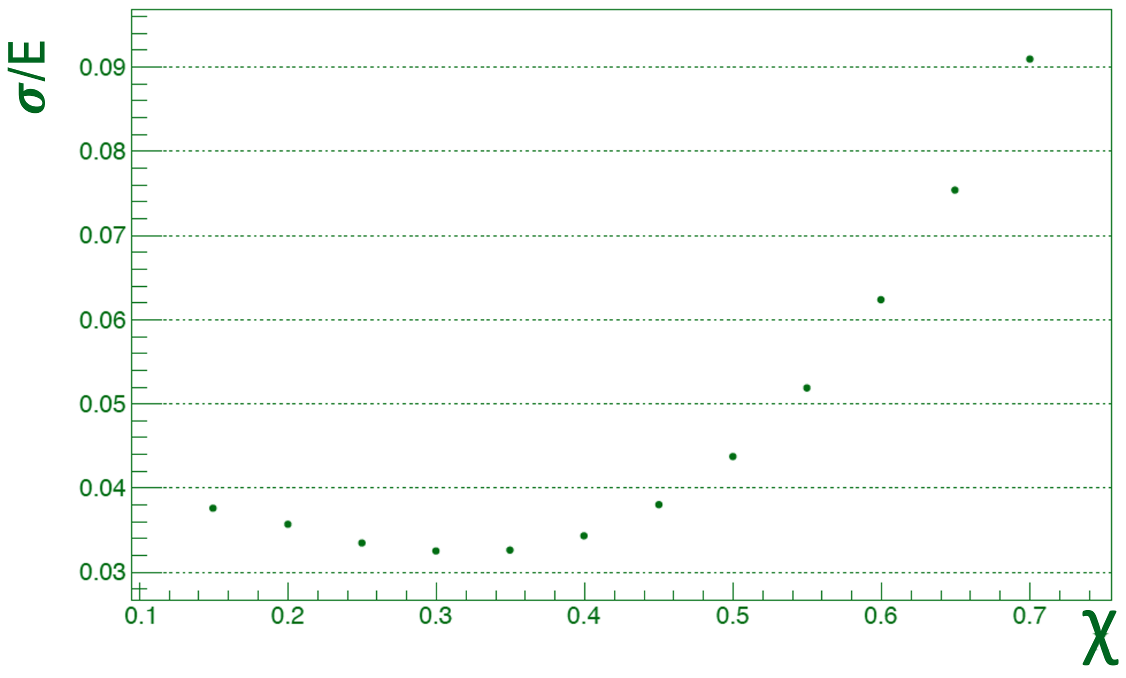
estimation

100 GeV π ⁻

GEANT4 – IDEA







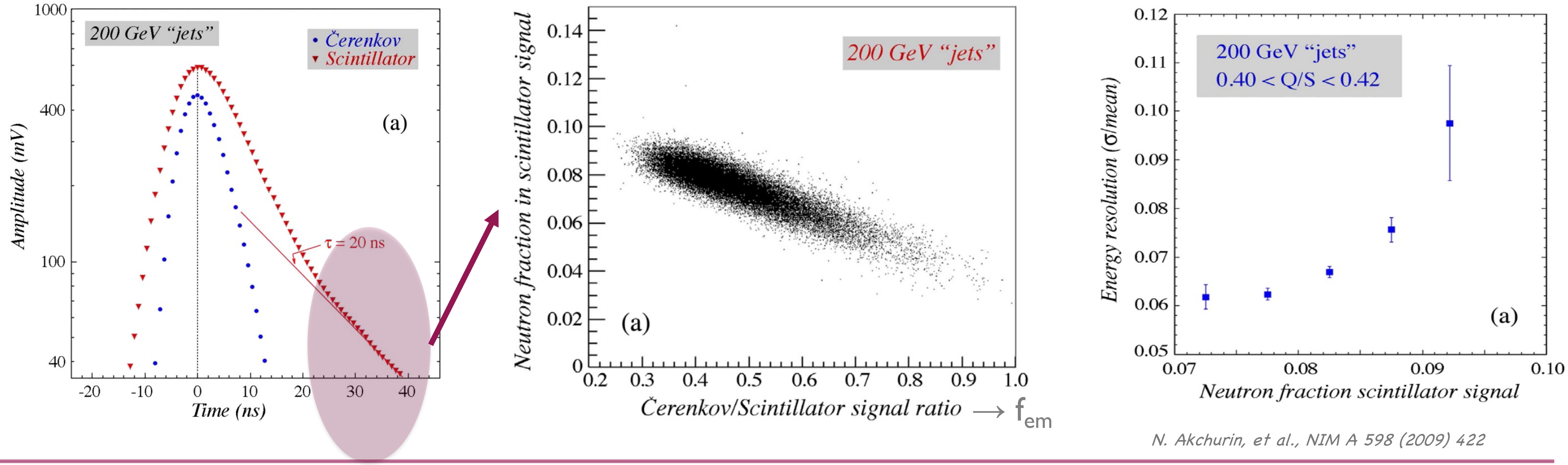
linearity optimisation:
best accuracy (how much the mean value is close to the true value)

resolution optimisation:
best sensitivity (how much the measurements are close to the mean value)

To be assessed with (hadronic) data

The invisible energy and triple readout

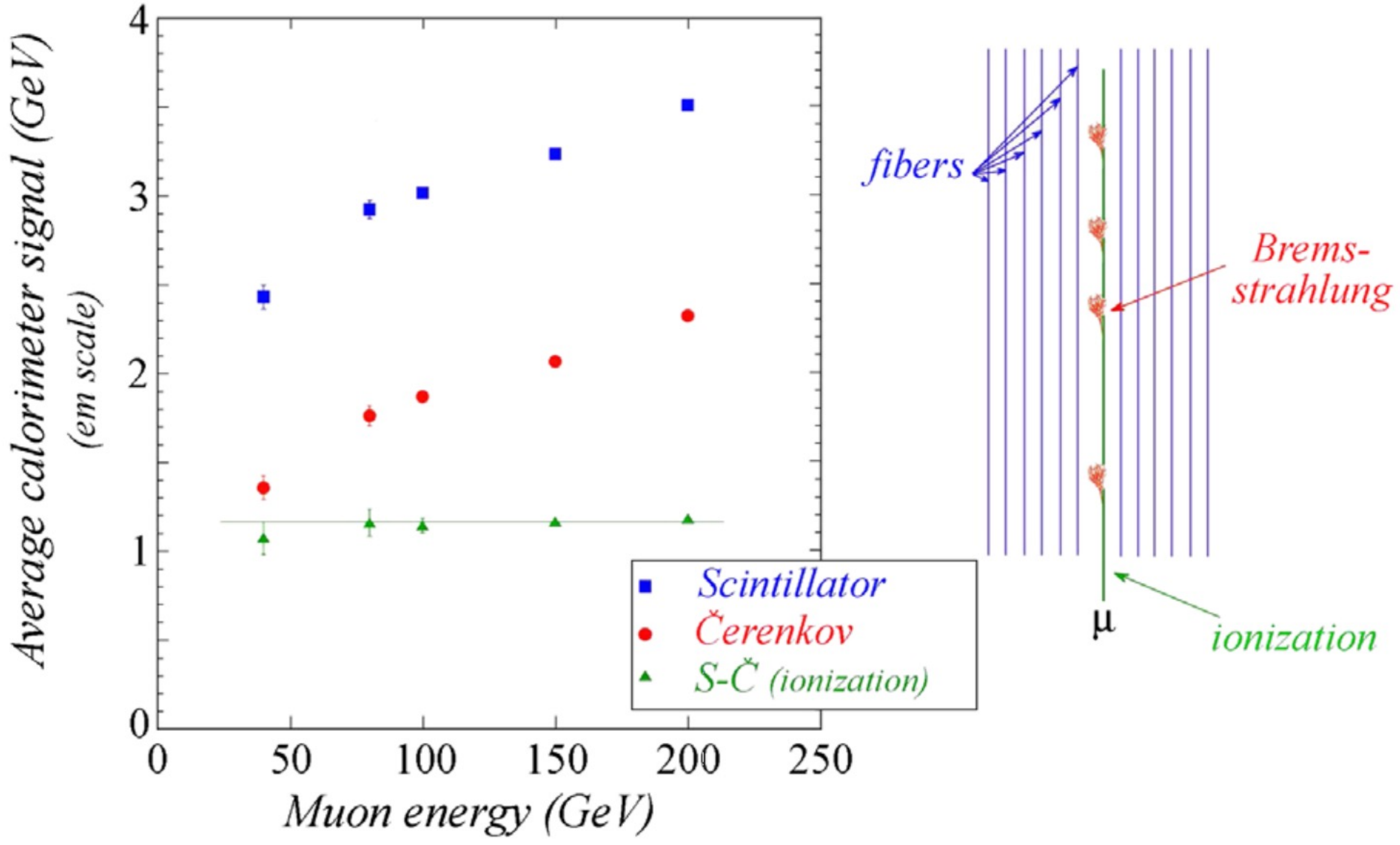
- limitation due to invisible energy fluctuation on the hadron resolution
- f_{em} and f_{inv} are anti-correlated, but still there are residual fluctuations
- to which extent having a triple readout may help?
- how to achieve it? signal shape? other media?

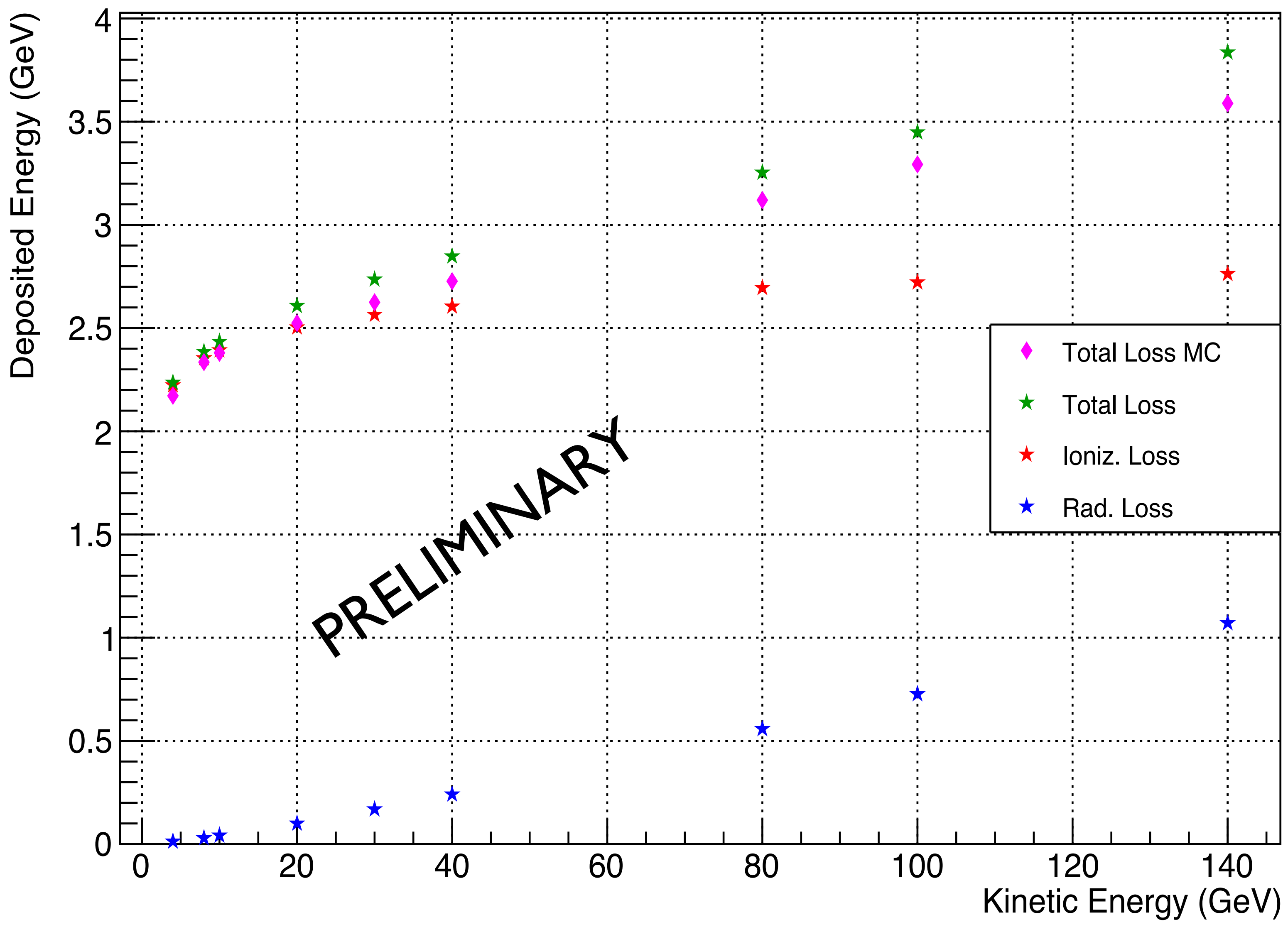


N. Akchurin, et al., NIM A 598 (2009) 422

MIP-like particles in the calorimeter

- Calorimeters deal with MIP particles all the time
  - muons
  - hadrons in some low energy range
- Does the DR approach correctly account for them?
  - energy lost by ionization only (mostly) detected in scintillation signals





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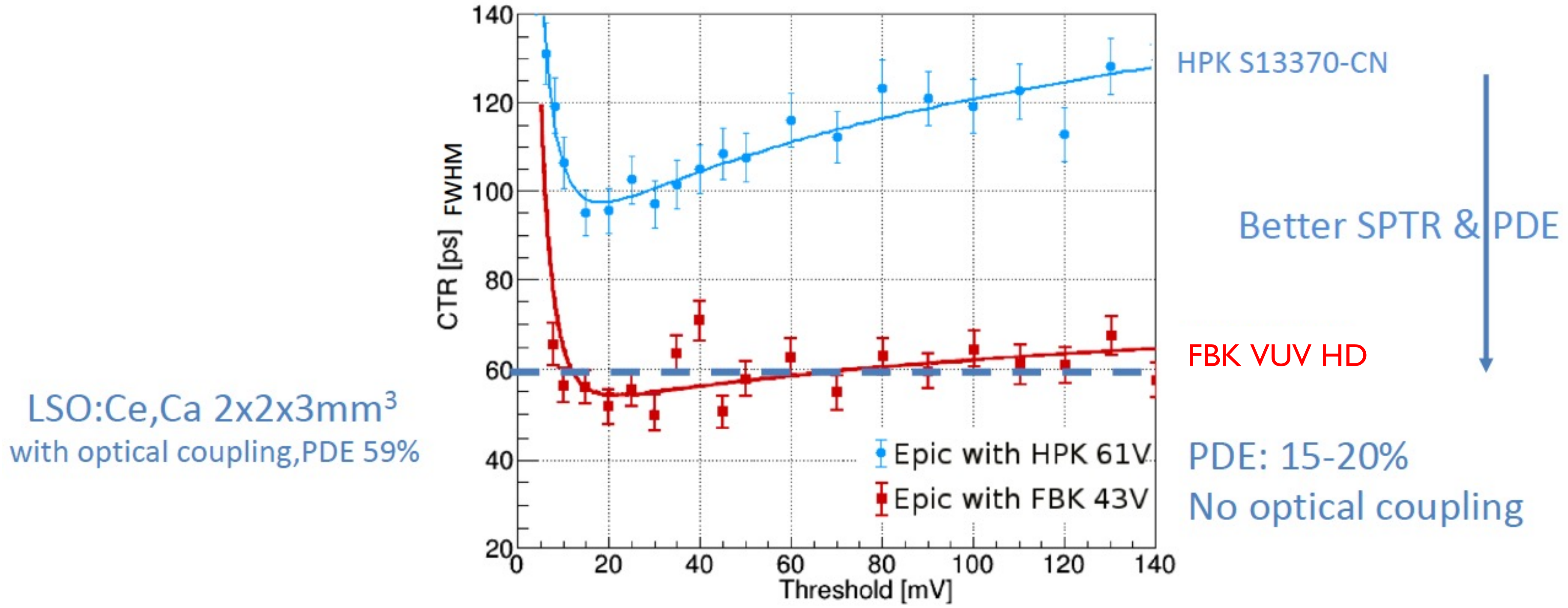
The Cherenkov component

- (So far) Cherenkov photostatistics is more limited than scintillation one
- Improving Cherenkov photostatistics
  - currently used PMMA, using other materials?
  - Improve numerical aperture?
  - larger diameter of the fibres?
  - improve SiPM readout in the UV region?
    - Development on going on VUV SiPM
      - Hamamatsu HPK S13370-CN
      - FBK VUV HD

C fibres: SK-40 Mitsubishi
core: PMMA,
cladding: Fluorinated Polymer
n_{core}= 1.49
N_A = 0.5

Time resolution measured @CERN with BaF_2 (2x2x3mm^3) pixels @511keV



Dedicated optimisation needed

R. Pots et all, Front. Phys. | doi: 10.3389/fphy.2020.592875
S. Gundacker et al., 2021 Phys. Med. Biol. in press https://doi.org/10.1088/1361-6560/abf476

How to shape the absorber

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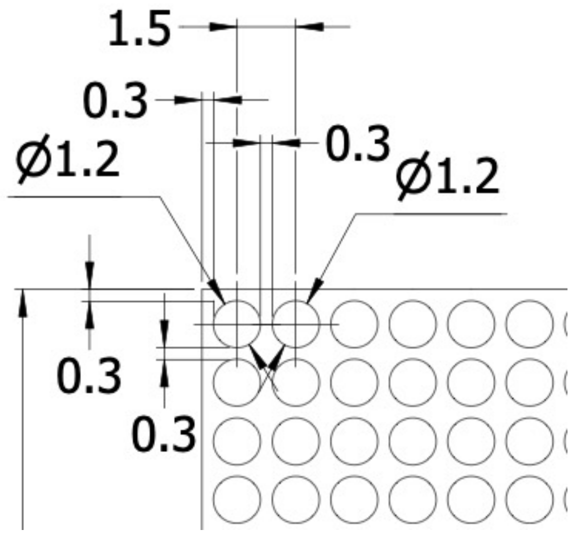
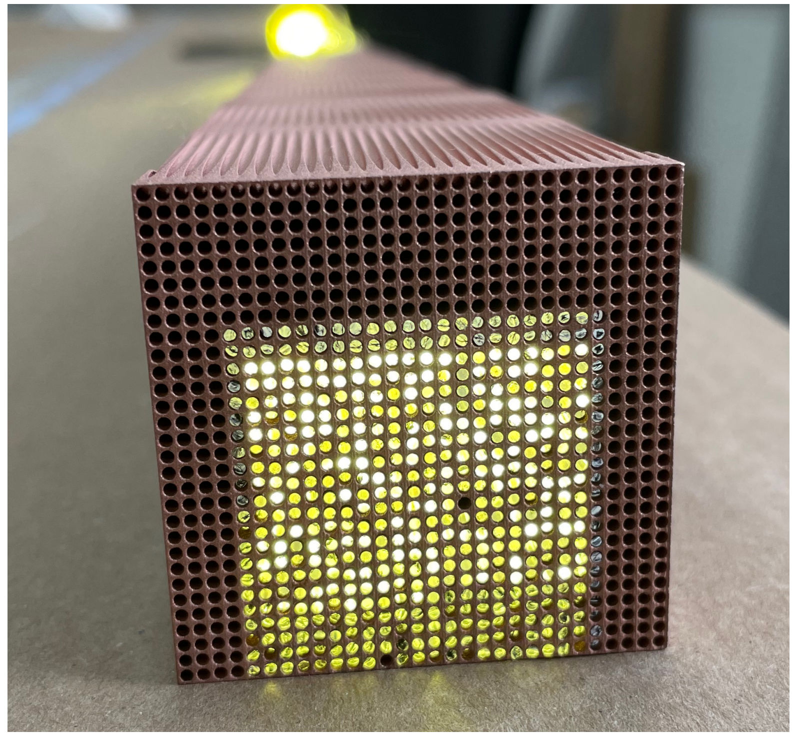
- so far, mostly grooved plates: very high initial cost, assembly technique not easily scalable
- capillary option: good quality at affordable price, many channel to assembly
- 3D-printing option: innovative but high cost, good quality reachable

preliminary study on calorimetric performance ongoing to choose optimal and usable material



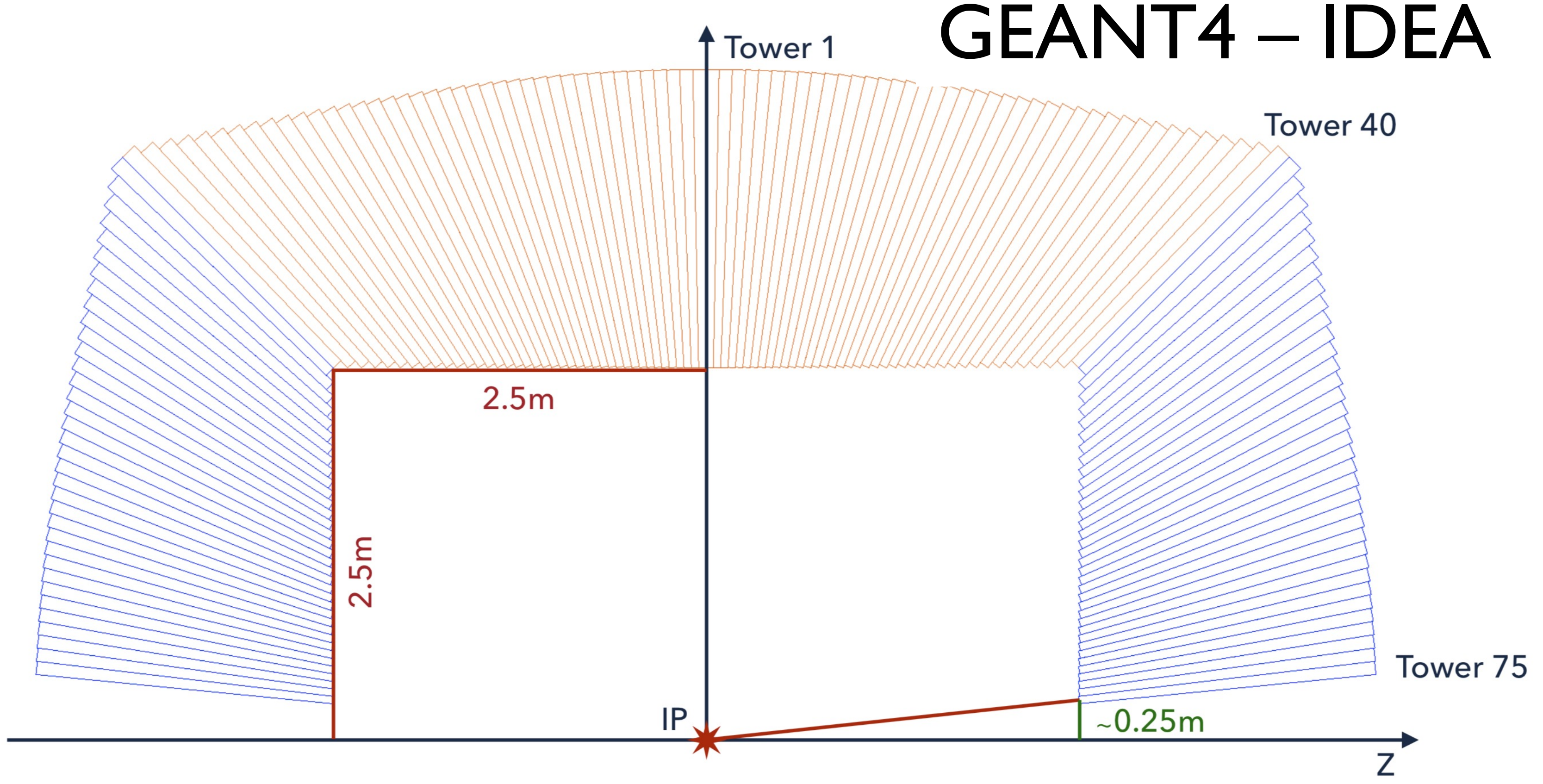
Copper 3D-printed projective geometry
20x20 holes front
30x30 holes rear
5 pieces 100 mm long

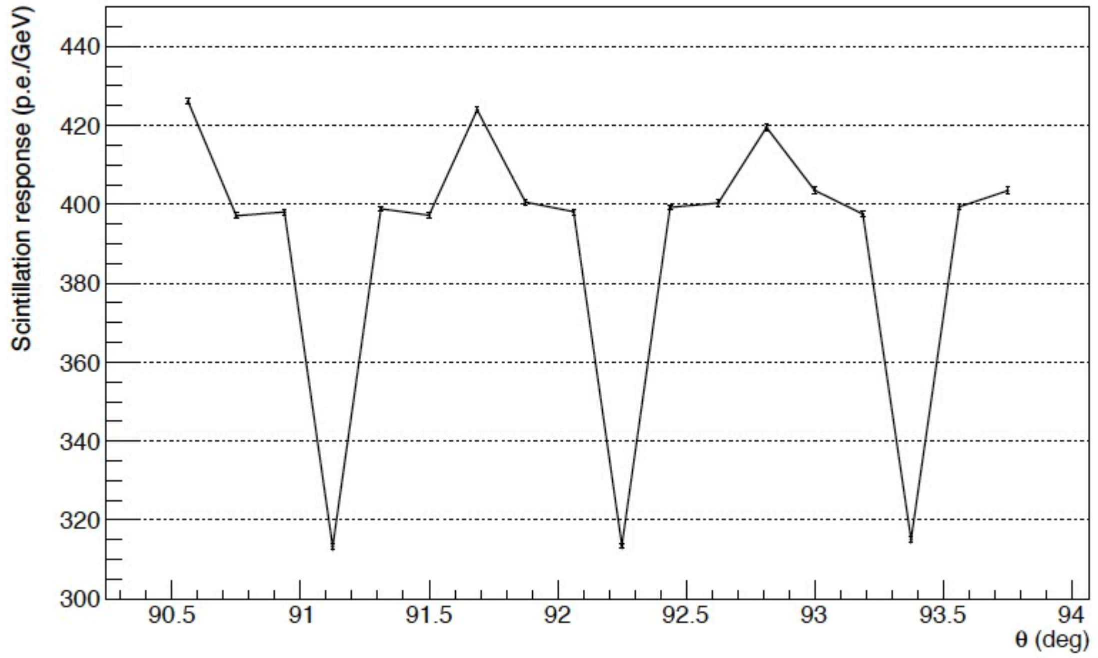


Non-uniformity effect on calibration and performance

- G4 Simulation uses perfect geometry (so far)
- Study effects of non-uniformity on calibration and performance
  - mechanical support
  - ID services crack
  - projectivity: border effect
  - tower-to-tower non-uniformity
- Calibration at EM scale
  - known e⁻ energy at testbeam
  - Z → ee, J/ψ→ee on the experiment
  - electron showers only "scan" the first ~ 20 cm of the detectors
    - non-uniformities can add contributions to the constant term. How to measure?

GEANT4 – IDEA





Border effects: 40 GeV e⁻ change in sampling fraction at tower junction

Longitudinal segmentation… or not?

DR fibre calorimeter is meant to be a high resolution ECAL + HCAL in one detector

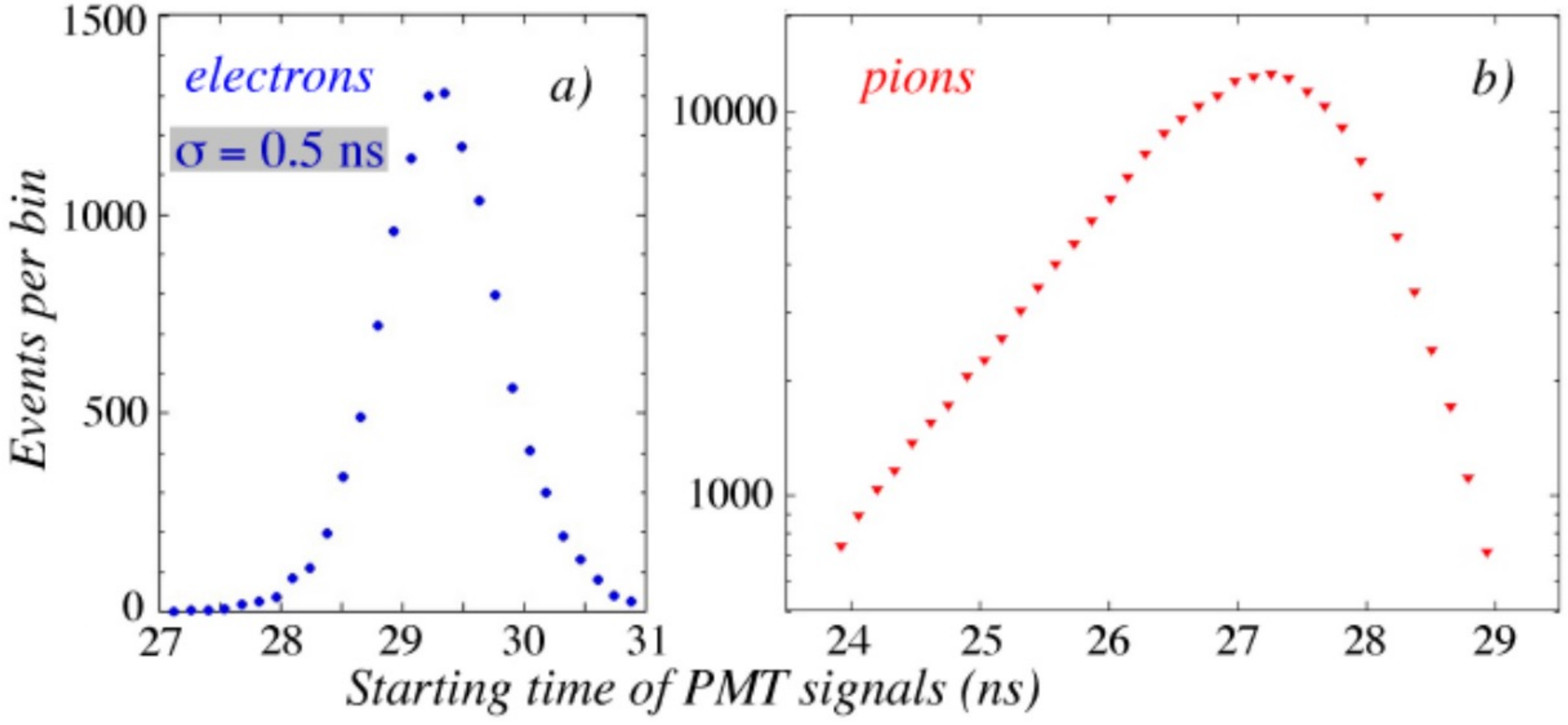
- Common features
  - calibrated at EM scale with electrons (*"one calibration constant to rule them all"*)
    - DR method does the rest
  - no fluctuation due to hadronic shower starting point
- ECAL performance
  - sampling calorimeter with high sampling fraction and frequency
    - high granularity and angular/position resolution
- HCAL performance
  - DR method to eliminate fluctuations in f_{em}
  - high granularity for jet reconstruction (PFA-friendly)

Longitudinal segmentation... or not?

There are several methods to achieve an efficient PID in a longitudinally unsegmented calorimeter, among which

- ✦ shower shape (high granularity)
- ✦ timing information (starting point of the signal)

They can be combined in cut-based algorithm or in machine learning approach



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DRS (Domino Ring Sampler) chip
based in SCA (Switched Capacitor Array)
1-5 GSPS sampling frequency
1– 0.2 ns sampling period
1024 storage cells

AARDVVARC V3@Naluscientific waveform digitiser
2 GHz analog bandwidth
4-6 ps timing resolution
10-14 GSPS sampling rate

see Nural's talk

see Marco’s talk

Longitudinal segmentation… or not?

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The DR crystal calorimeter option

Homogeneous calorimeter allows to eliminate contribution due to sampling fraction $\frac{\sigma}{E} = 2.7\% \frac{\sqrt{d/f_{samp}}}{\sqrt{E}}$

but

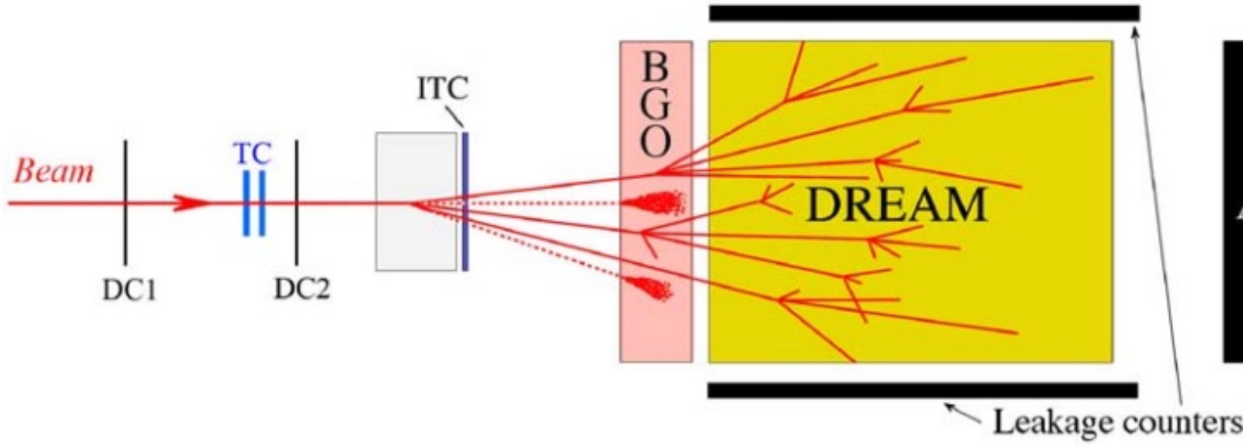
Large e/h difference spoils the hadronic resolution of the rear compartment

unless using DR approach in the crystals as well

Working principle demonstrated by RD52 collaboration

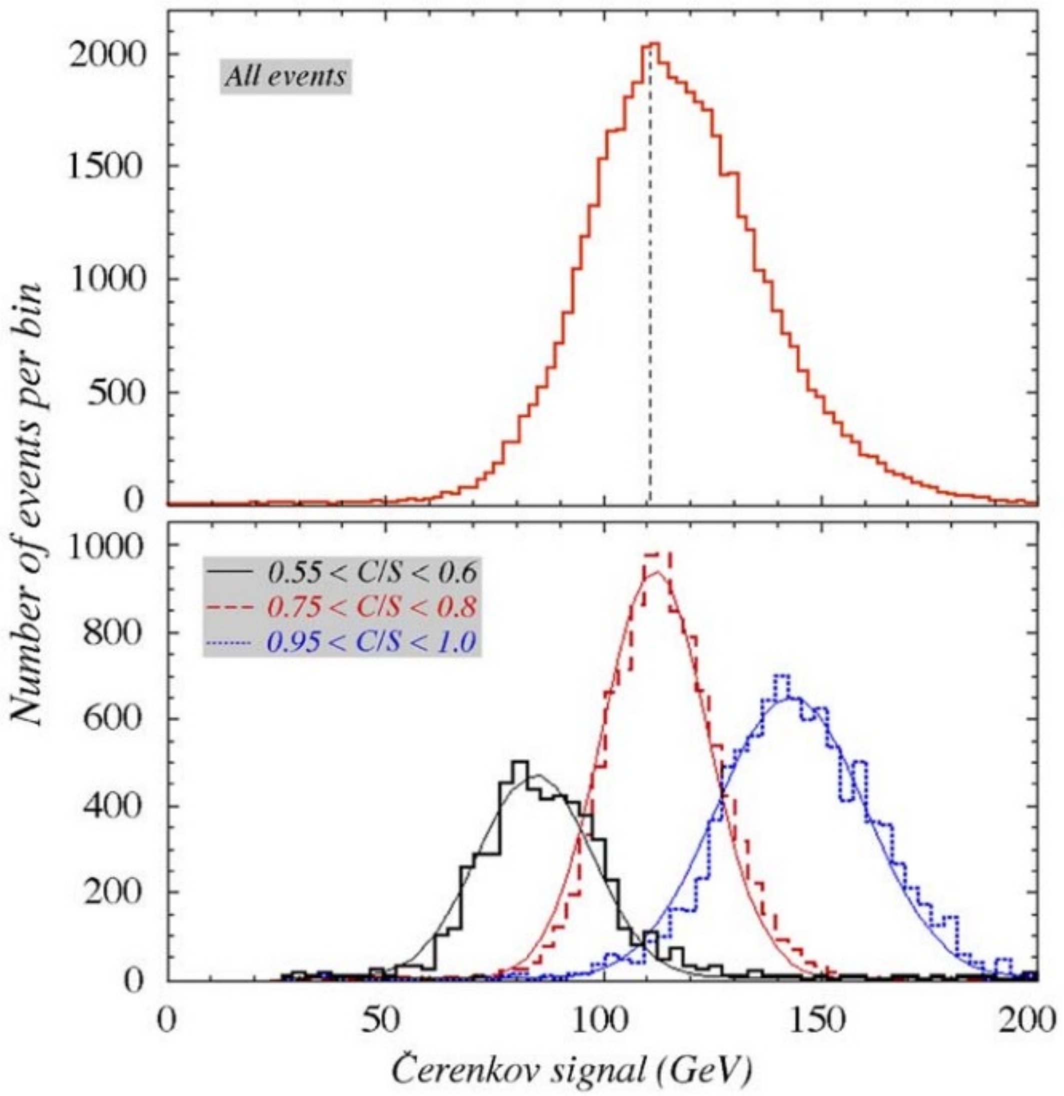
Drawback:
poor EM resolution in BGO (PWO_4) matrix due to technique to extract C and S from the same media

- time structure
- filtering



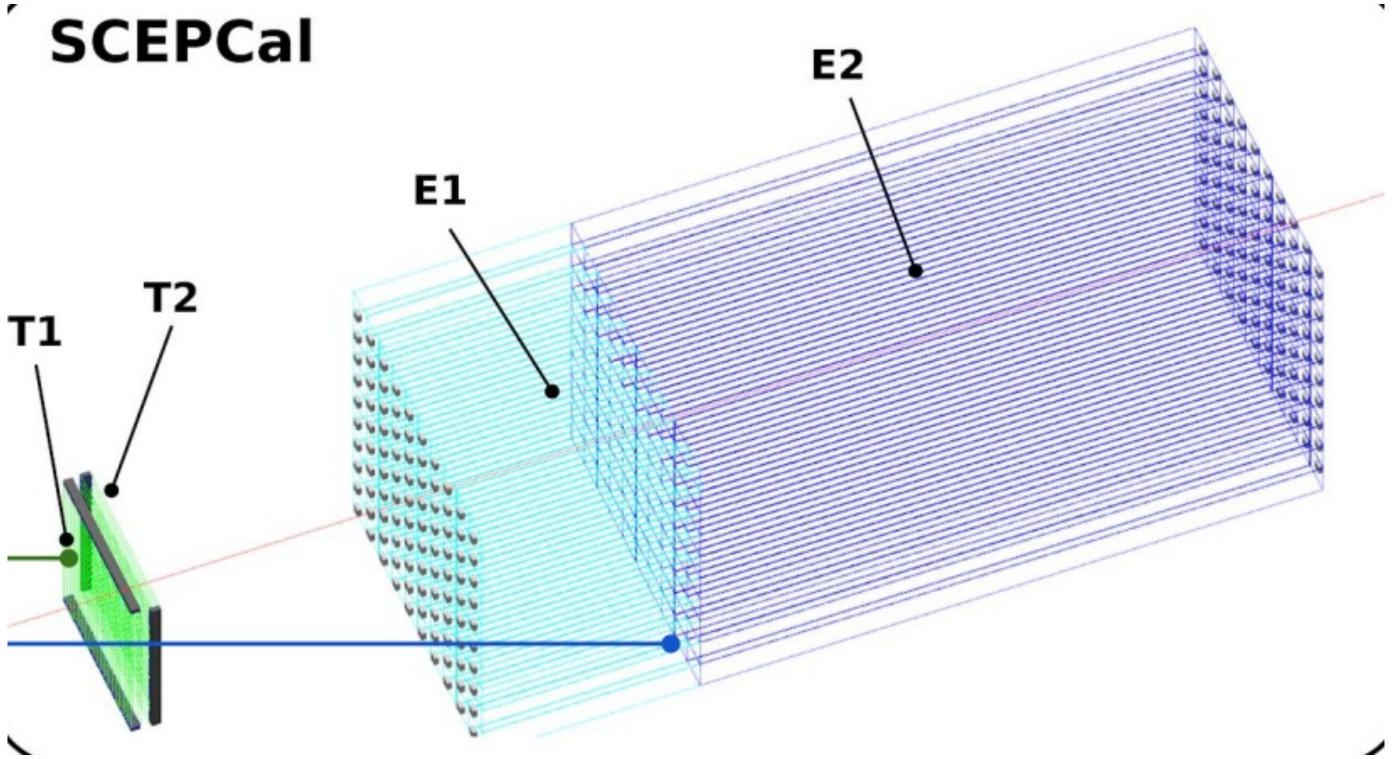
N. Akchurin, et al., NIM A 610 (2009) 488

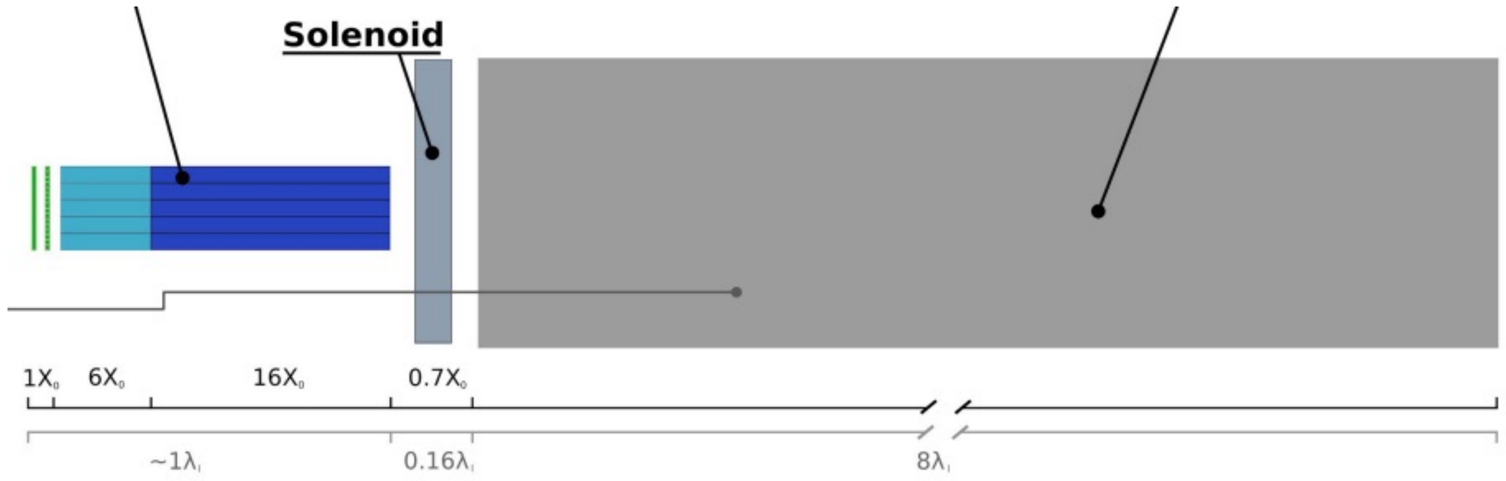
BGO+fiber C signal



see Marco's talk

Crystal option revisited





ECAL layers — $\sigma^{EM}_E/E \sim 3\%/\sqrt{E}$

- PWO crystals
- Front segment (~$6X_0$)
- Rear segment (~$16X_0$)
- 10x10x200 mm³ crystal
- 5x5 mm² SiPMs (10-15 um)

other options are BGO/BSO

Majority of the energy deposit from hadron is in the rear ECAL section (E2) → apply DR here

Use two SiPMs to optimise independently C and S readout from each crystal

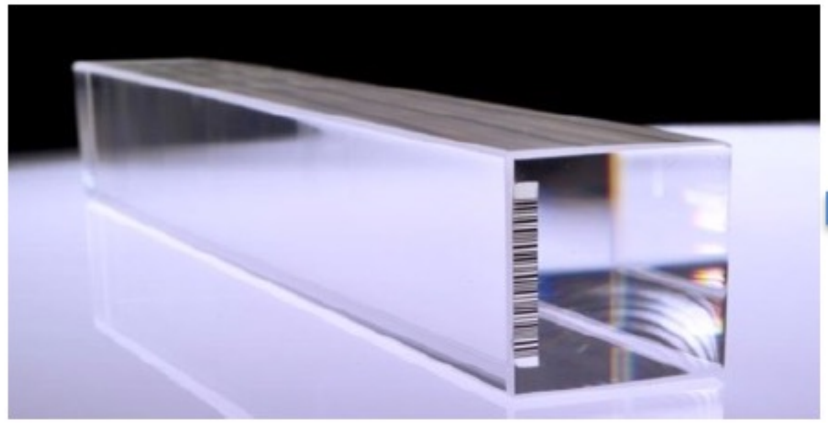
Sensitivity in both the UV and infrared regions with SiPM

Crystal fibres

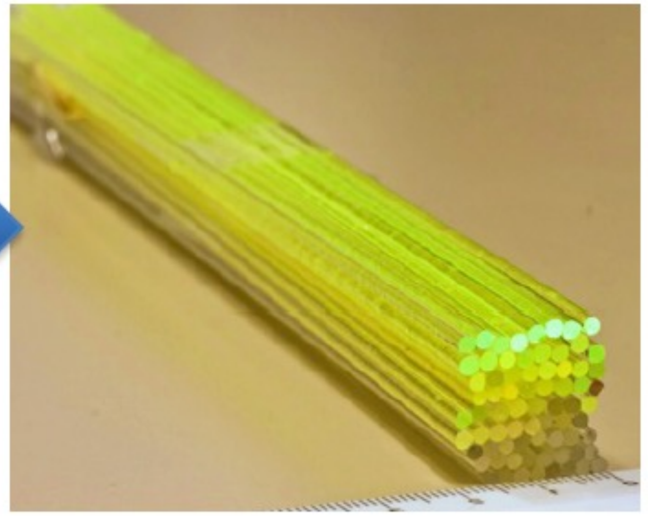
HOMOGENEOUS CALO
high density
increased granularity

SAMPLING CALO
adapt granularity at need
choose proper crystal
(e.g C and S optimised)

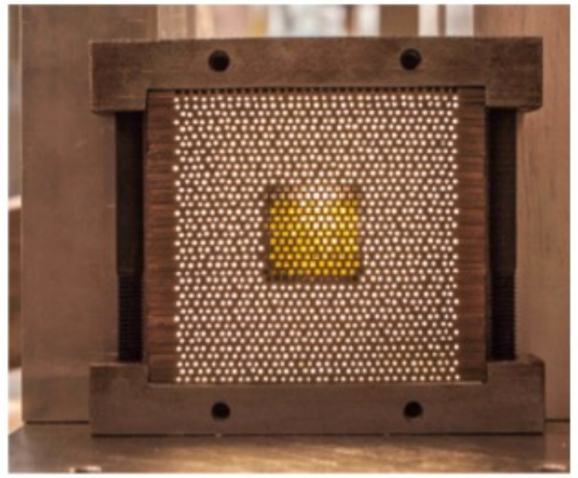
From bulk crystal



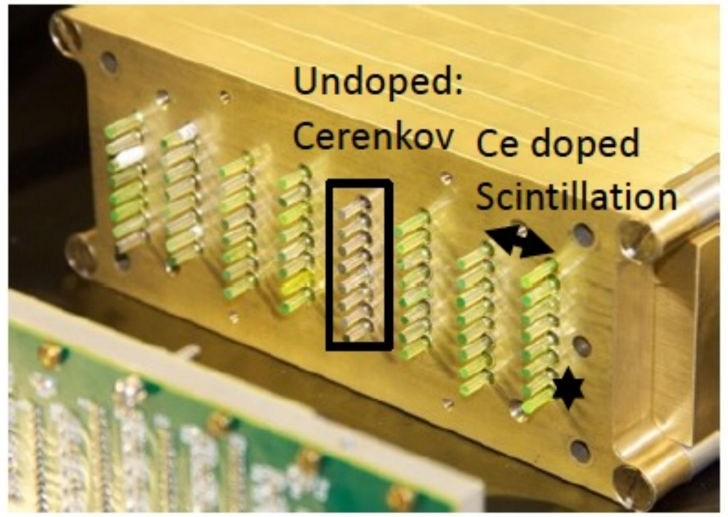
To bloc of fibers



Pointing Fibers : SPACAL

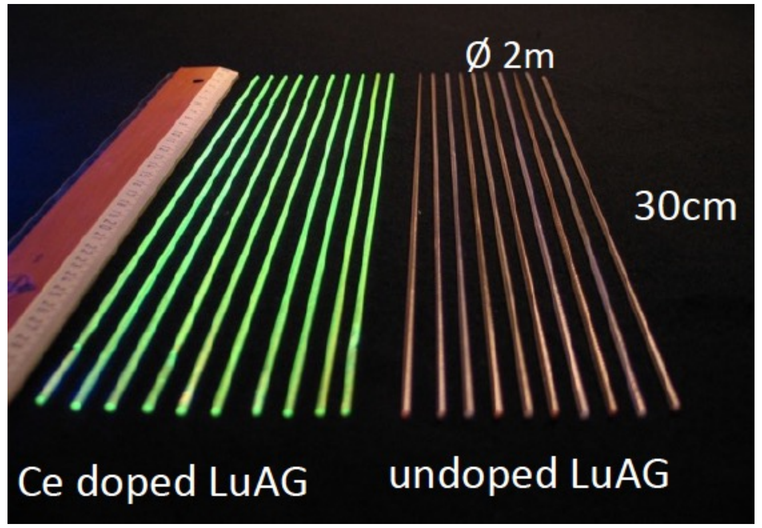


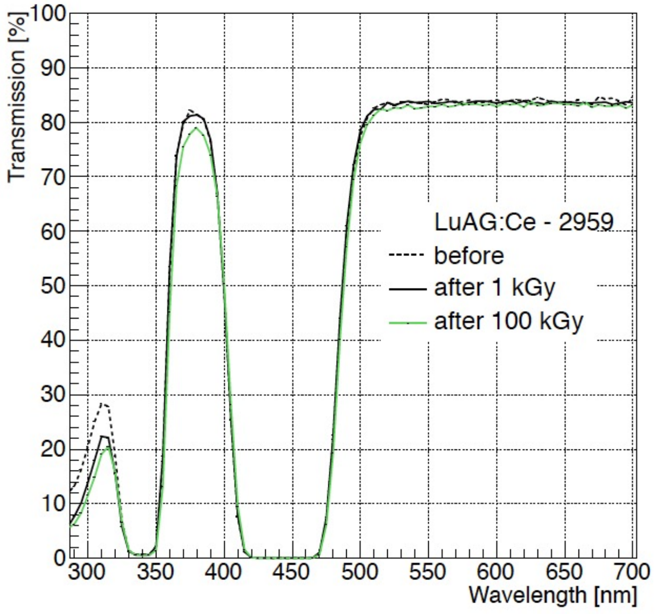
Layers of crystal fibers



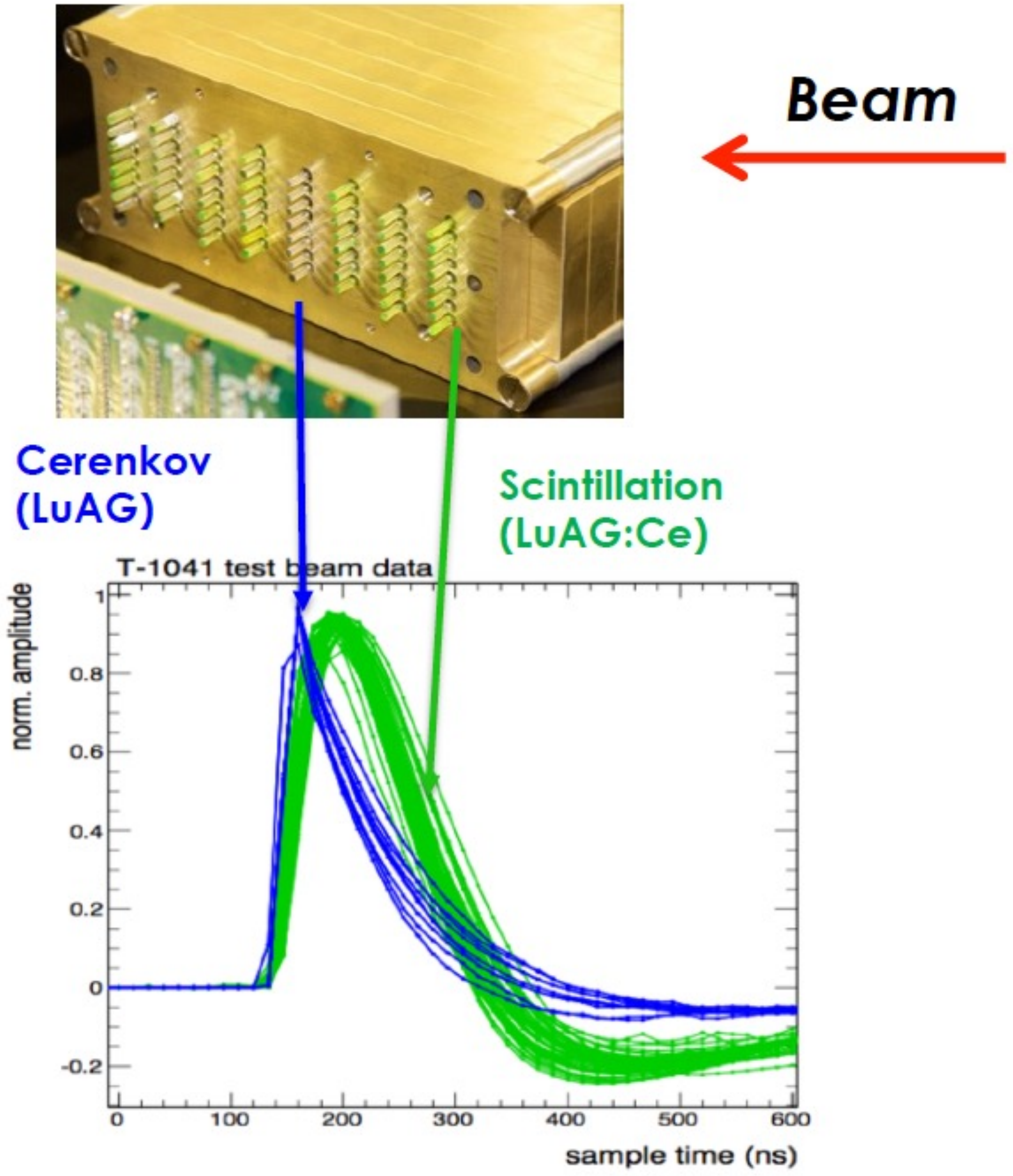
see Marco's talk

Dual readout with crystal fibers



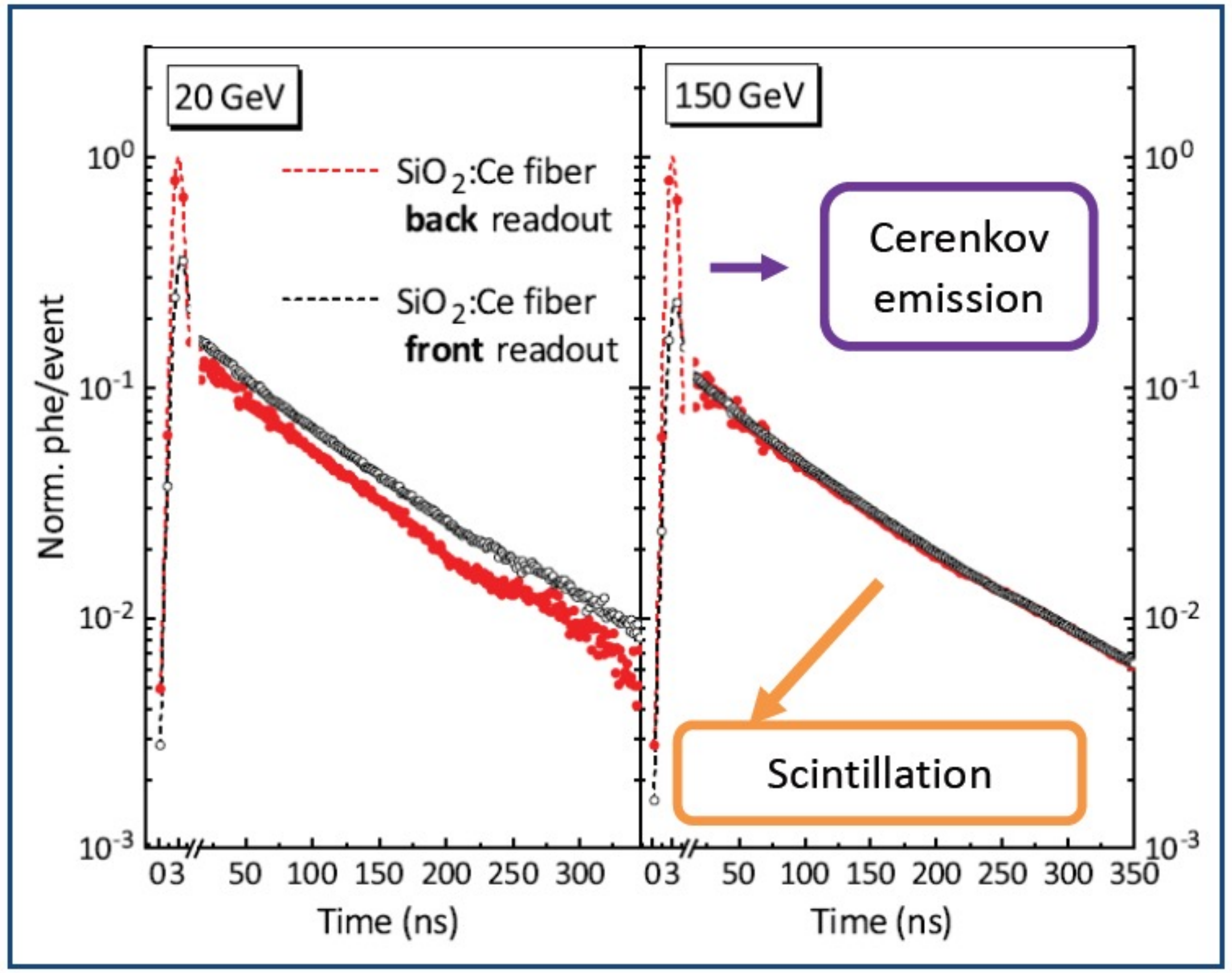


radiation tolerant



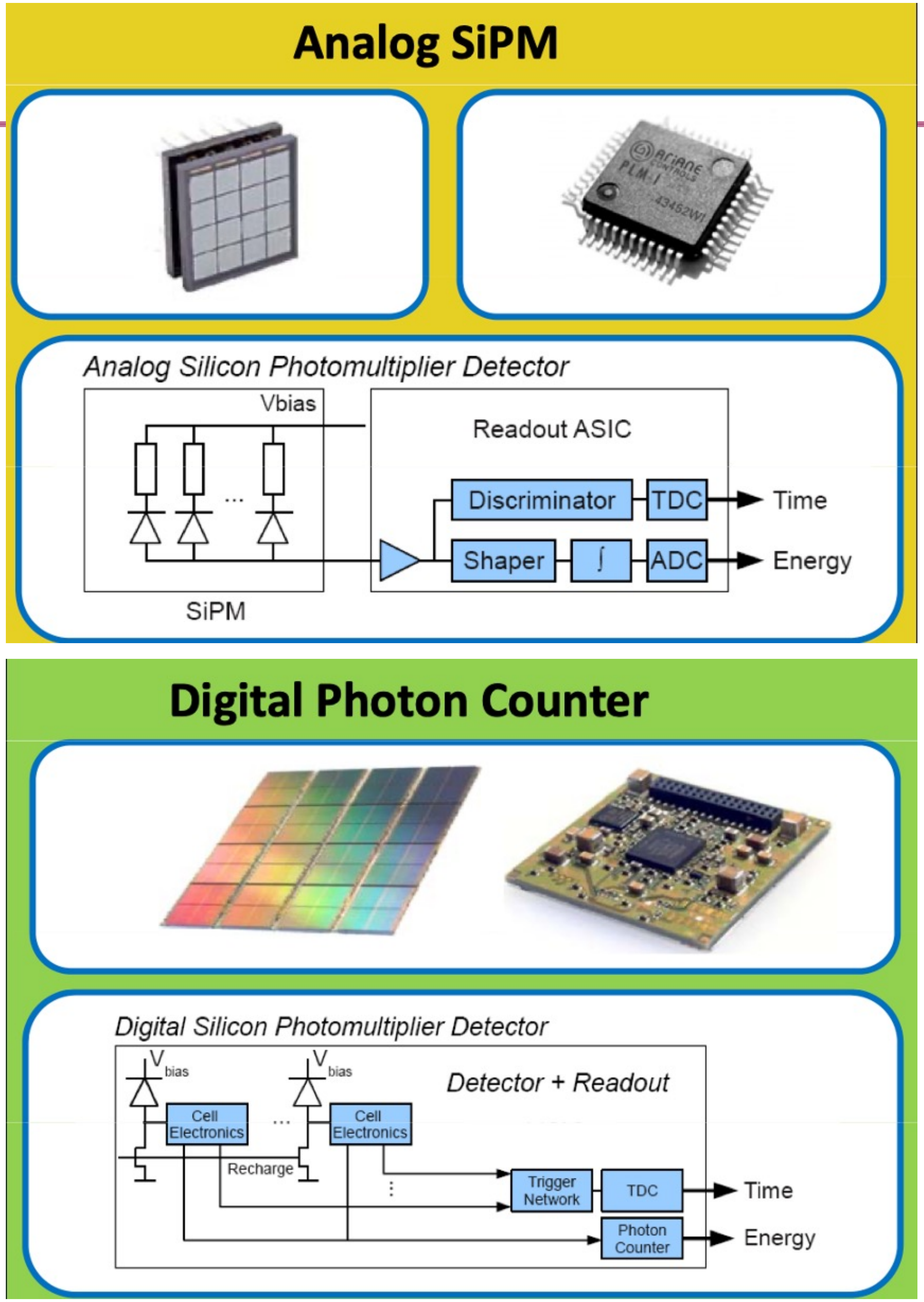
Good separation of Scintillation & Cerenkov

Dual readout of Cherenkov and scintillation light with the same silica doped (SiO_2:Ce) fibres



M. T. Lucchini, et al.,, IEEE Transactions on Nuclear Science (2016), 63, 2
E. Auffray, et al, Rad. Phys.Chem. (2019), 164, 108365
V. Alenkov, et a., NIM A (2019), 916, 418 226{229
P. Lecoq CALOR 2008 [J PHYS 160 (2009) p12016]
K. Pauwels et al., JINST428 (2013), 8, P09019
A. Benaglia et al, JINST 11(5) 05004 (2016)
B. F. Cova et al., Phys. Rev. Appl. 11 (2), 024036 (2019)

SiPM and dSiPM



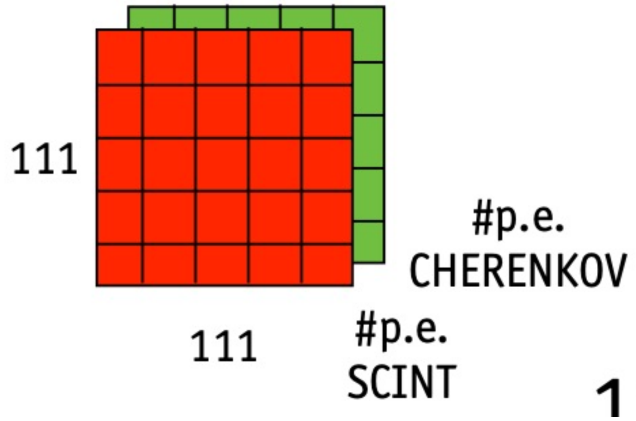
- dSiPM technology not yet consolidated, and performance is not yet at the level of the SiPMs.
- Nevertheless, they are rapidly improving
- This R&D could bring to a series of advantages:
  - Custom sensor design with reduced cost for mass production
  - Simplified readout system
  - Improved timing performance
  - The non-linearity could be corrected before merging the information from different sensors
- Interesting for other fields as well
  - Medical application
  - Biological studies

see Nural’s talk

Sensor readout

- Two main options for the sensor readout under evaluation
  - charge integrator + timing information → ADC + TDC
  - waveform sampler + feature extraction → Digital Signal Processing + FPGA
- Signal characteristics we use for PID
  - C/S, Time of Arrival, Time over Thresholds, R95 (radius of cylinder with 95% of total signal), peak, …
- Machine-learning approach for reconstruction and particle identification

3-class label	8-class label	
0	0	τ → μνν
0	1	τ →eνν
1	2	τ →πν
1	3	$\tau \to \pi\pi^0\nu$
1	4	$\tau \to \pi\pi^0\pi^0\nu$
1	5	τ →πππν
1	6	$\tau \to \pi\pi\pi\pi^0\nu$
2	7	Z →qq jets



Truth BR \ Predicted BR	τ → μνν	τ →eνν	τ →πν	$\tau \to \pi\pi^0\nu$	$\tau \to \pi\pi^0\pi^0\nu$	τ →πππν	$\tau \to \pi\pi\pi\pi^0\nu$	Z →qq jets
τ → μνν	97%	2%	1%					
τ →eνν	1%	97%	1%	1%				
τ →πν	1%	3%	87%	4%	1%	2%		1%
$\tau \to \pi\pi^0\nu$		1%	5%	76%	13%	1%	3%	1%
$\tau \to \pi\pi^0\pi^0\nu$				7%	88%		4%	1%
τ →πππν			5%	2%		75%	15%	2%
$\tau \to \pi\pi\pi\pi^0\nu$			1%	1%	4%	8%	81%	5%
Z →qq jets					1%	1%	2%	96%

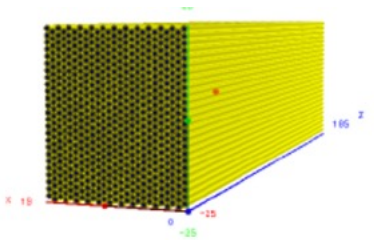
Predicted BR

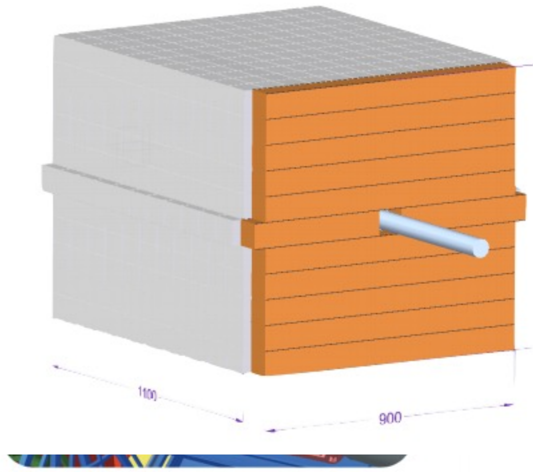
(B field and material)

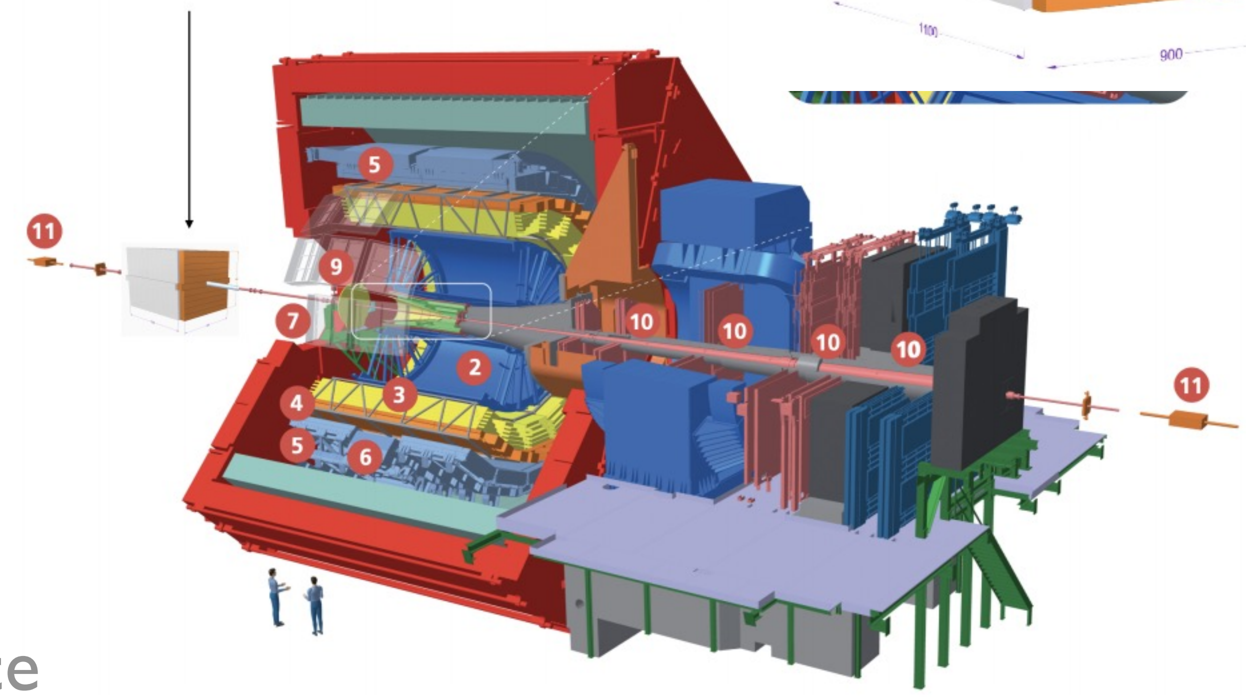
average accuracy: 87%

Synergies among HEP/non-HEP projects and industries

- High-granularity and timing feature
  - common with PF calorimeter
  - similar problematics for Inner Detectors for present/future experiment (feature extraction, number of channels)
- A DR option has been mentioned for interest in project other then FCC_ee / CepC
  - EIC (forward) calorimeter
  - ALICE FoCal-H upgrade
  - muon collider (it was mentioned, to be confirmed)
- Fibres, crystal and crystal fibres
  - important role of industries and expert in matter physics
- SiPMs
  - synergy with Task Force 4: Photon Detectors and PID
  - working together with producers to obtain required performance
- ASIC and RO boards
  - looking at the market and co-developing of needed electronics





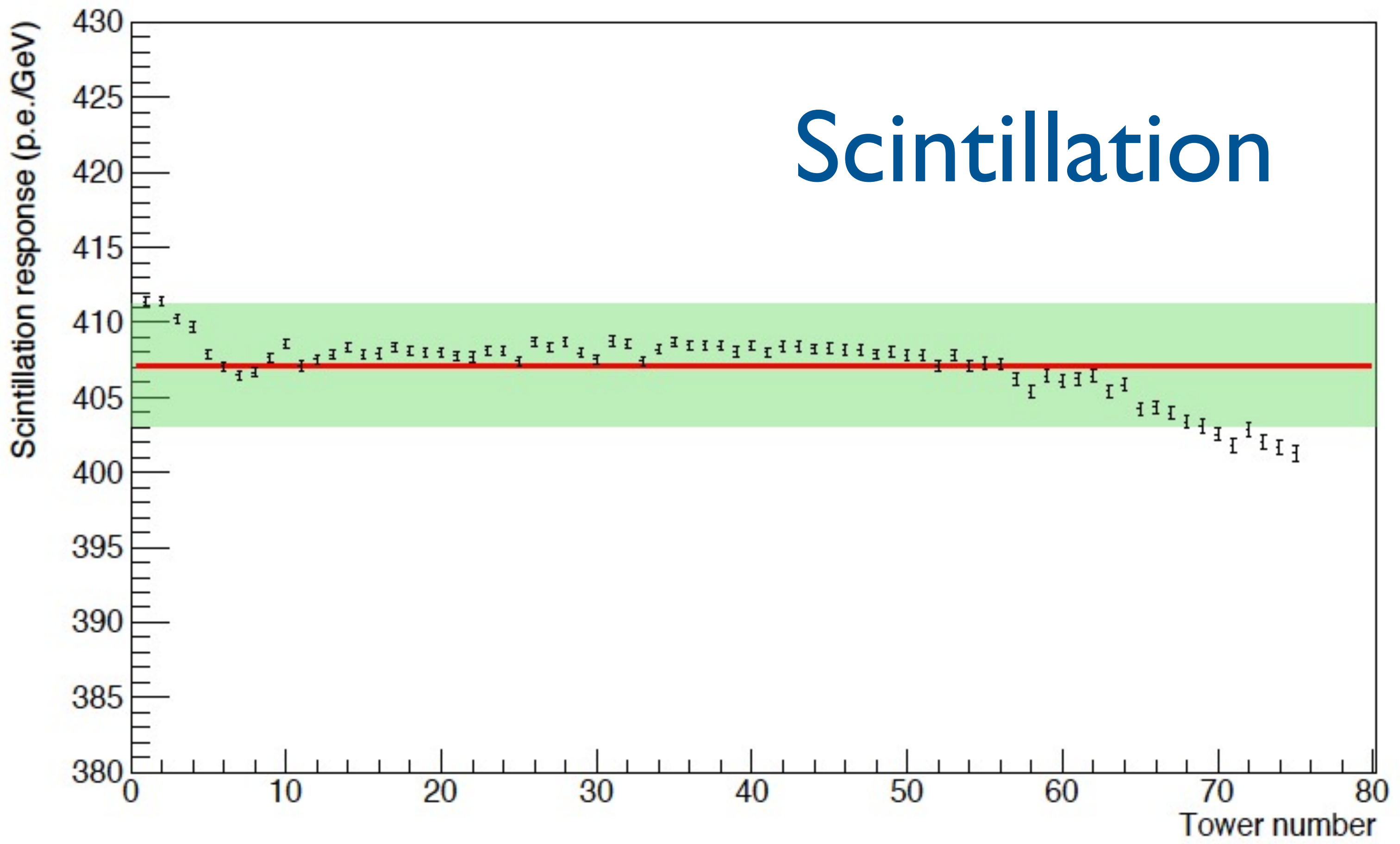


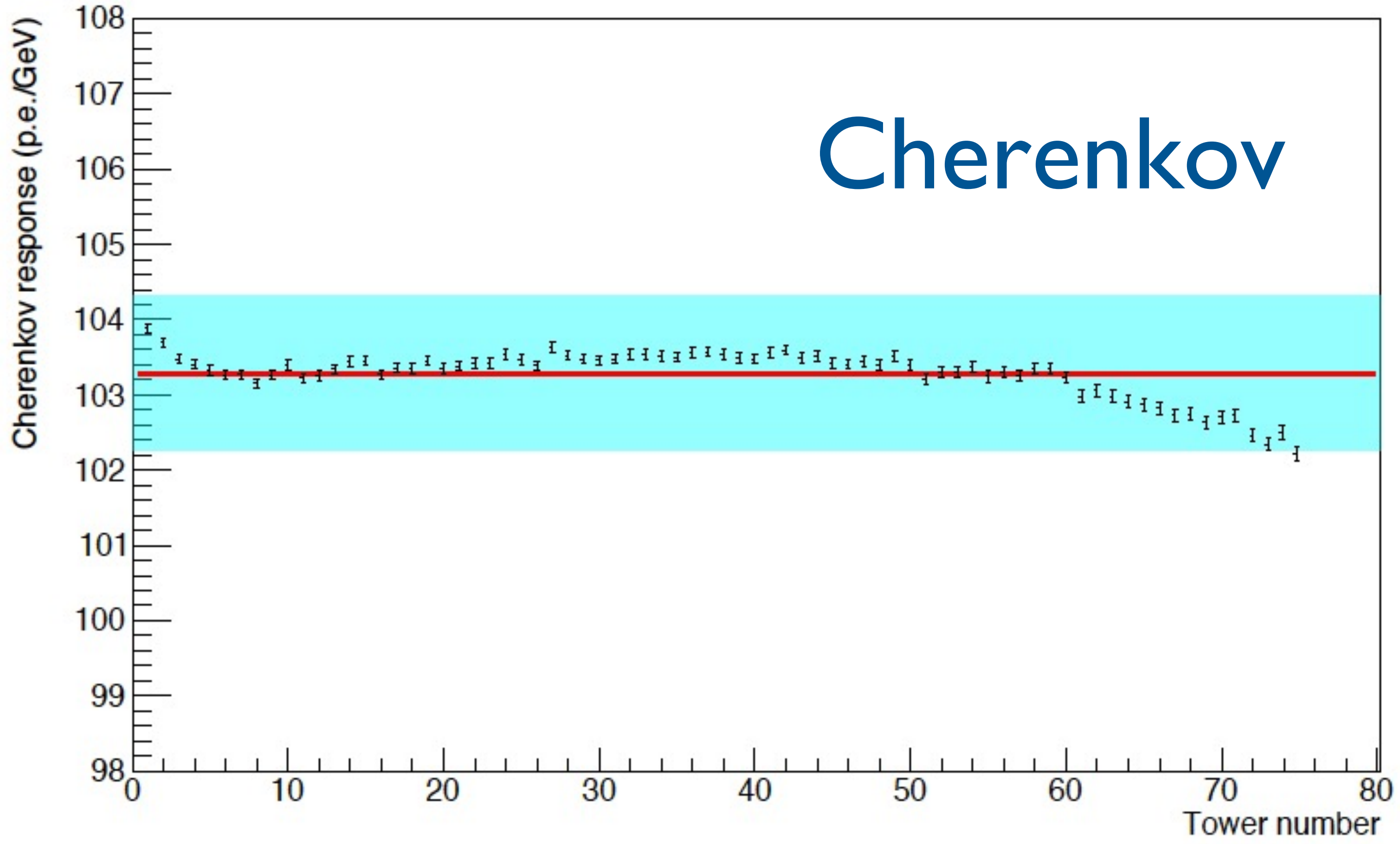
dual-readout keynote

- Dual readout development based on
  - deep understanding of calorimeter physics
  - simulation and experimental data from prototypes
- Full-containment prototype is required next step toward full-scale experiment
- Many problems common to other detector/systems: exploit synergies

Additional material

Response Uniformity

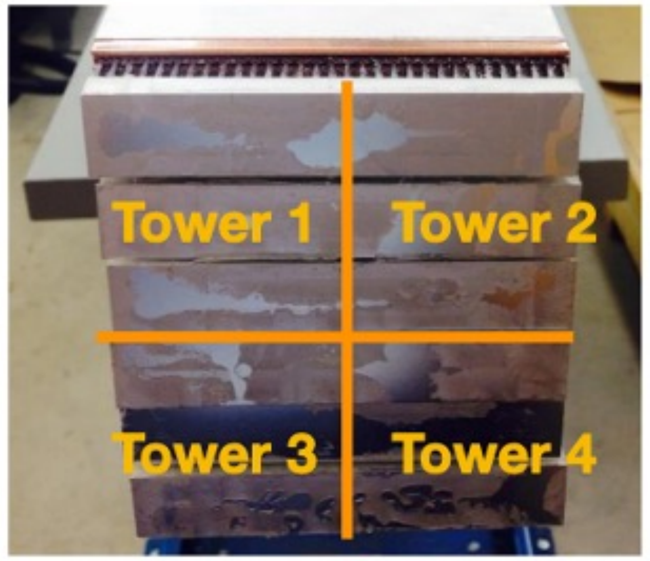




Response of the IDEA Calorimeter when 40 GeV electrons enter the calorimeter at the geometrical centre of the tower inner face, from tower 1 to tower 75.
Colour bans represents deviation of 1% to the mean response.

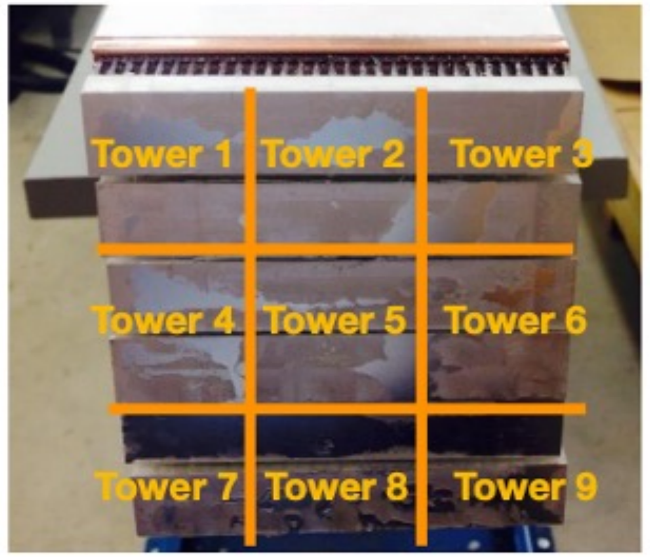
DR-scaling up: Copper Plates

Module #1 (2x2)



Tower#1	Tower#2
Tower#3	Tower#4

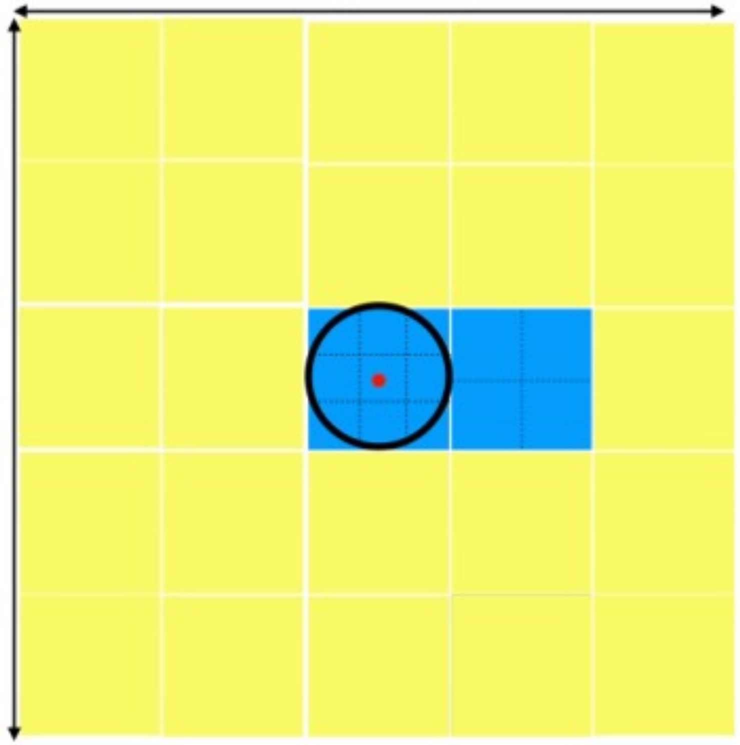
Module #2 (3x3)



Tower#1	Tower#2	Tower#3
Tower#4	Tower#5	Tower#6
Tower#7	Tower#8	Tower#9

Prototype Detector (2021)

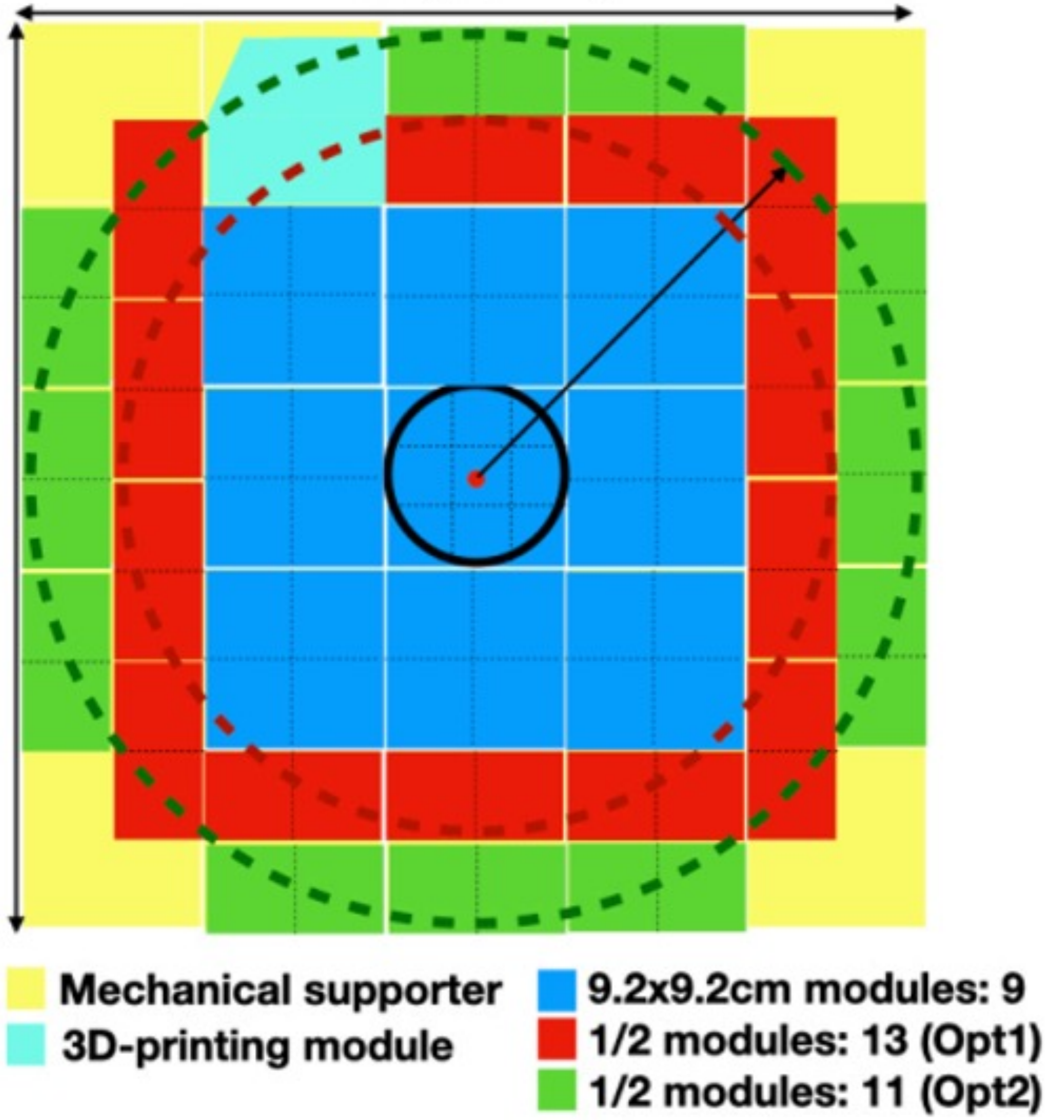
5x5 (460 mm)



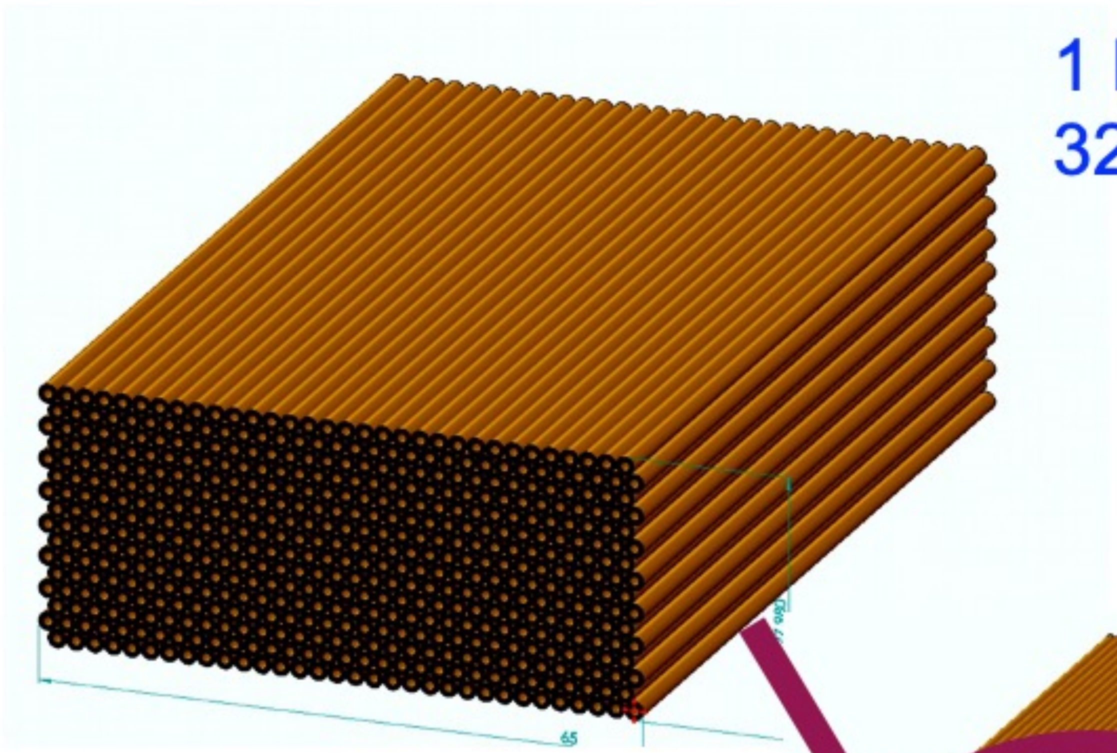
Building more and more module 2022-2025

Prototype Detector (2025)

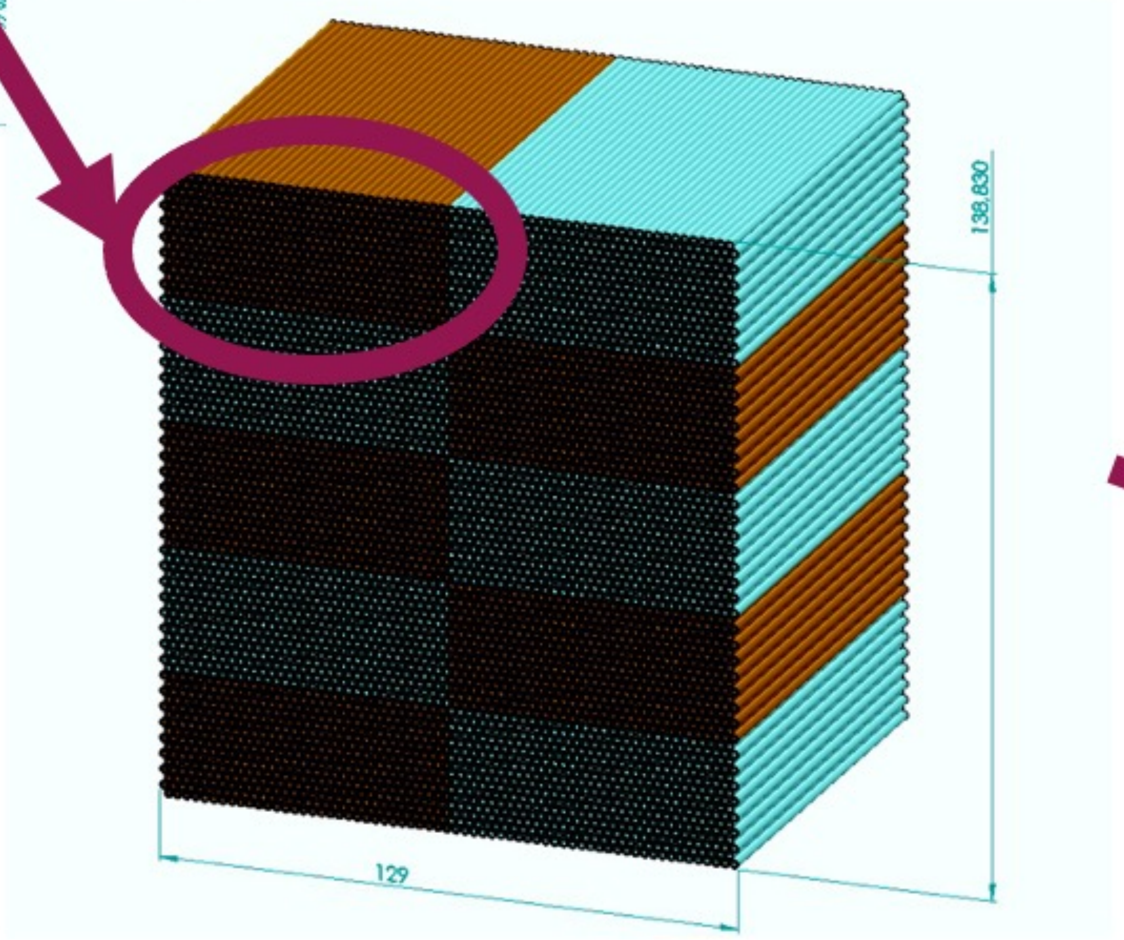
5x5 (460 mm)



DR-scaling up: capillary tubes



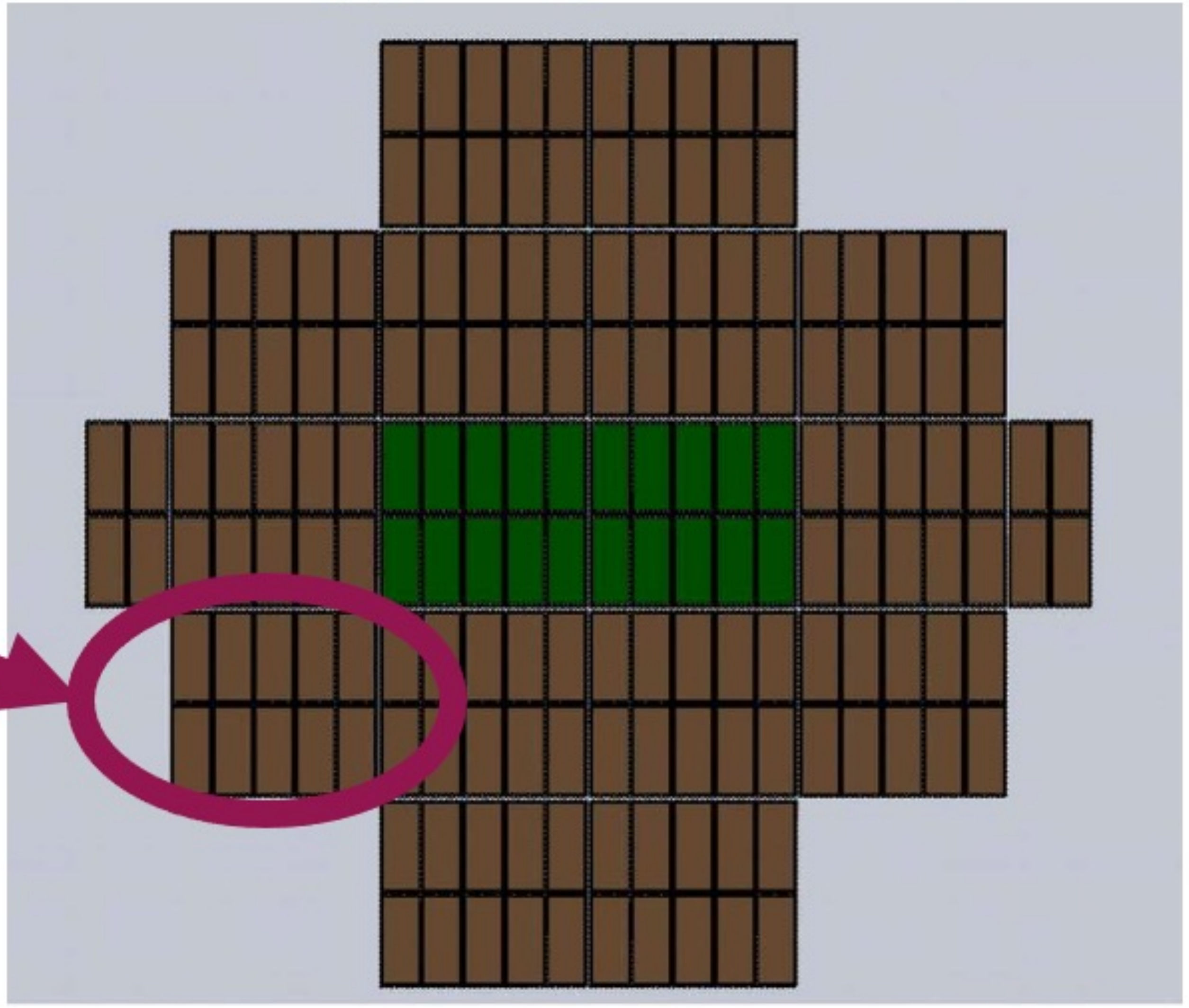
1 Mini-Module (MM):
32 x 16 channel (512 ch)



1 Module:
2 x 5 MMs
→ 10 FEE boards
(8-channel grouping)
~ 13 x13 x 200 cm^3

17 modules, ~ 65 x 65 x 200 cm^3

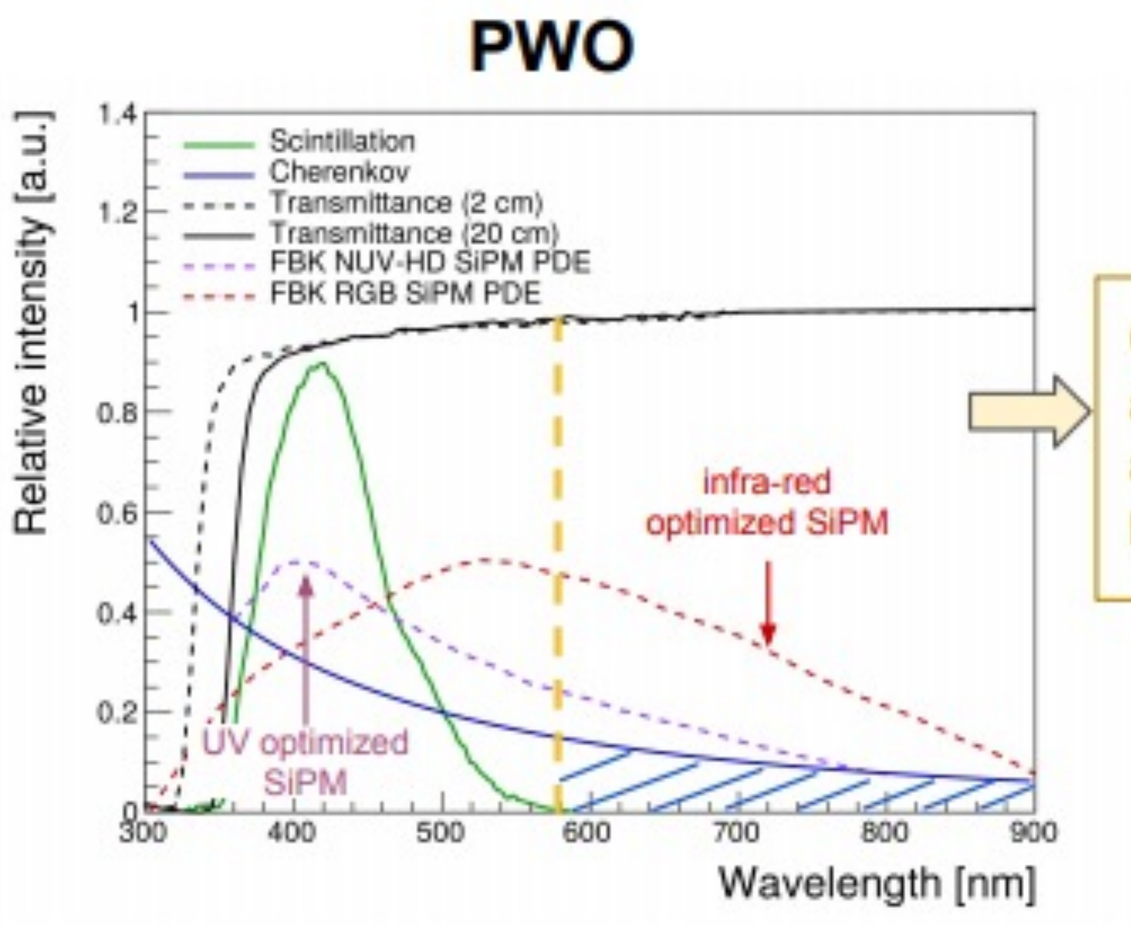
- 2 central modules with SiPMs
  → ~ 10 k SiPMs, ~ 20 FEE boards
- all others with PMTs
  → ~ 150 PMTs



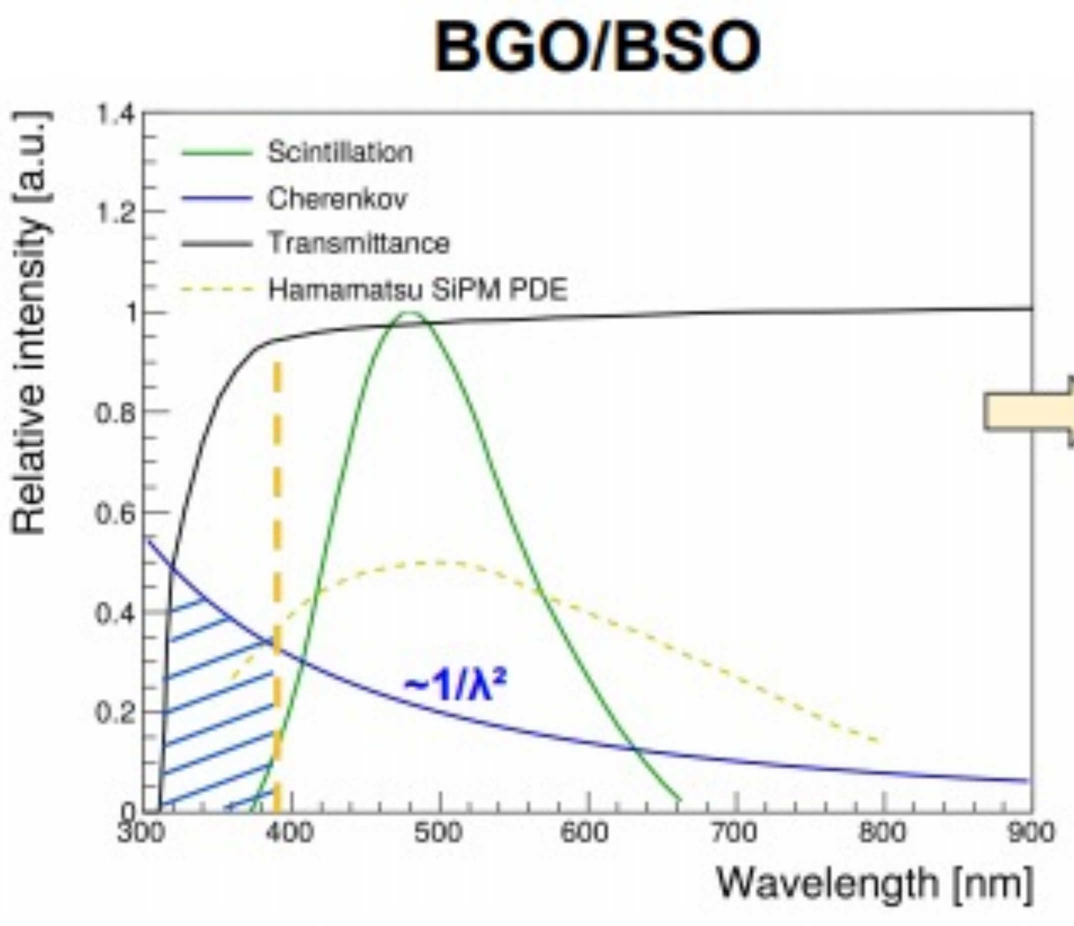
Crystal option revisited

Two SiPMs per crystal, each optimised to read out either S or C

Sensitivity in both the UV and infrared regions with SiPM



Cherenkov photons above scintillation peak are much less affected by self-absorption



BGO/BSO have larger stokes shift, i.e. a wider range of transparency for 'UV Cherenkov'