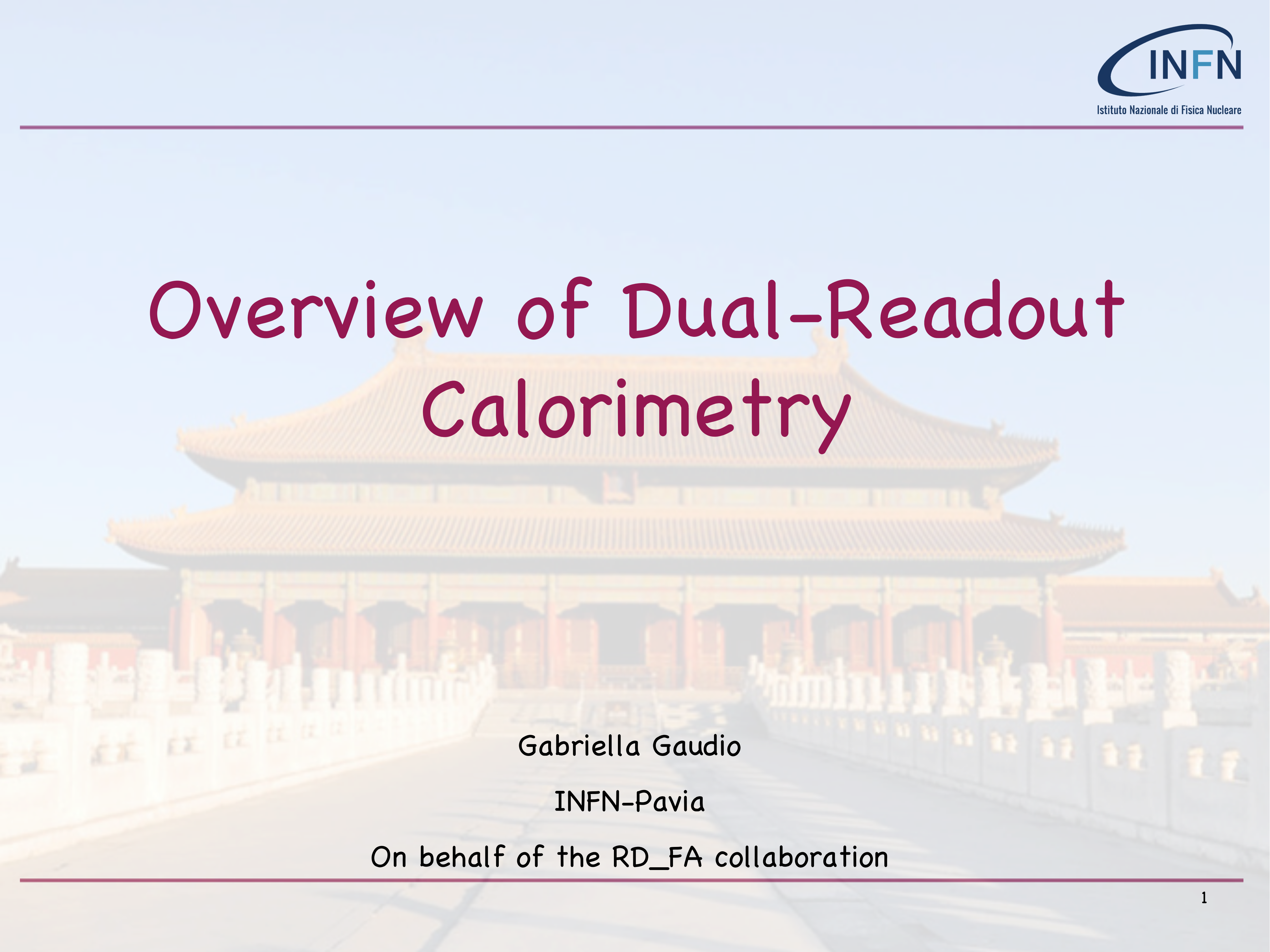


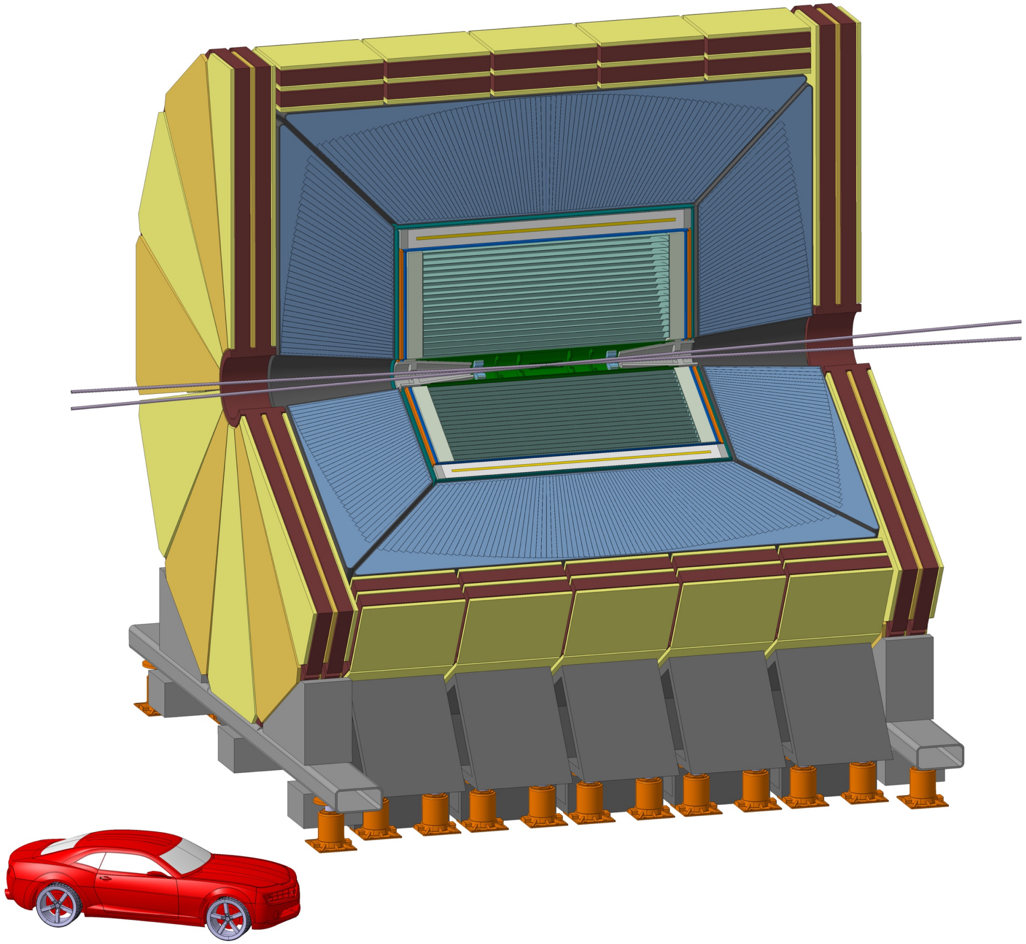
Overview of Dual-Readout Calorimetry

Gabriella Gaudio

INFN-Pavia

On behalf of the RD_FA collaboration

Outline



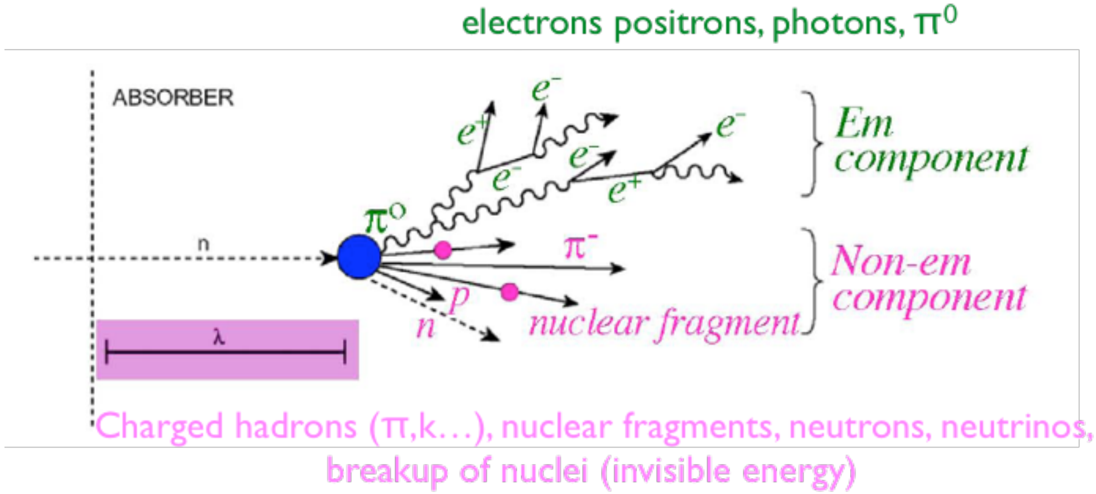
- **Dual Readout Calorimeter Performance**
  - Electromagnetic performance
  - Hadronic performance
  - Jet performance
- **Update on calorimeter development**
  - Mechanics
  - Readout
  - Prototype plans

IDEA: Innovative Detector for Electron-positron Accelerator

Dual-readout in a nutshell

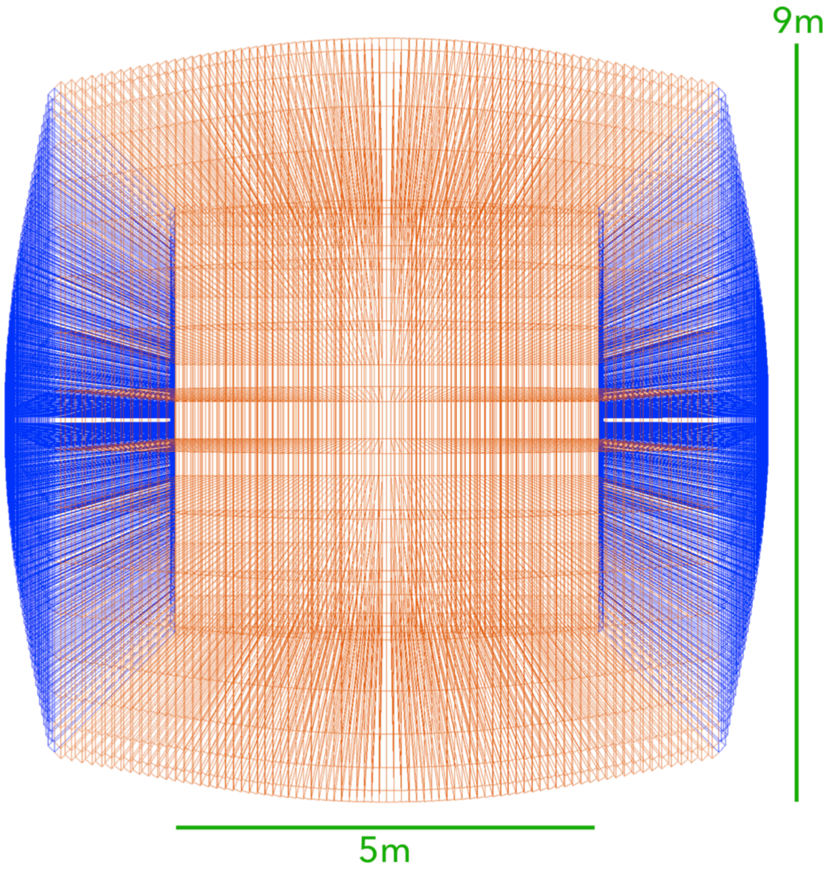
Measure the electromagnetic fraction event by event to equalize the response off-line

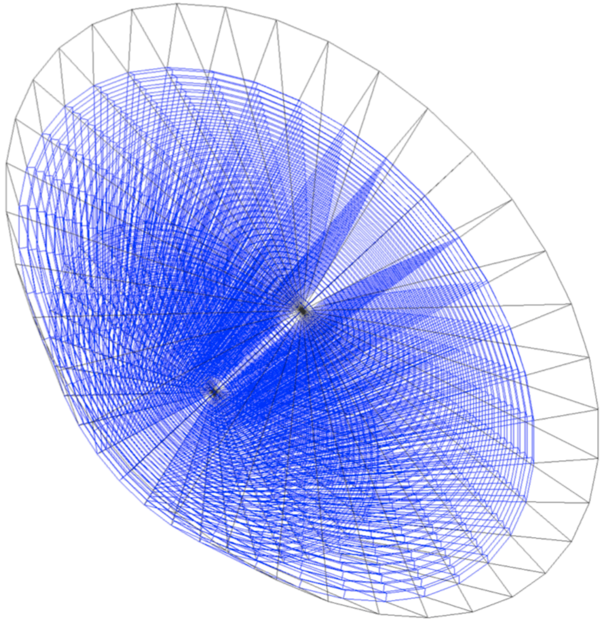
- Scintillation light to measure all charged particles
- Cherenkov light to measure only relativistic particles, namely mainly e+ and e- (em component of the hadronic shower).

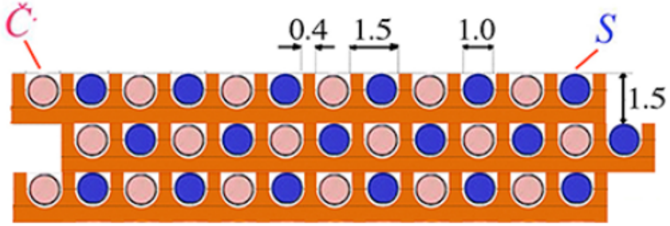


- ✦ **Compensation** achieved without construction constraints
- ✦ **Calibration** of a hadron calorimeter just with electrons
- ✦ **High resolution** EM and HAD calorimetry

G4 Simulation for performance studies

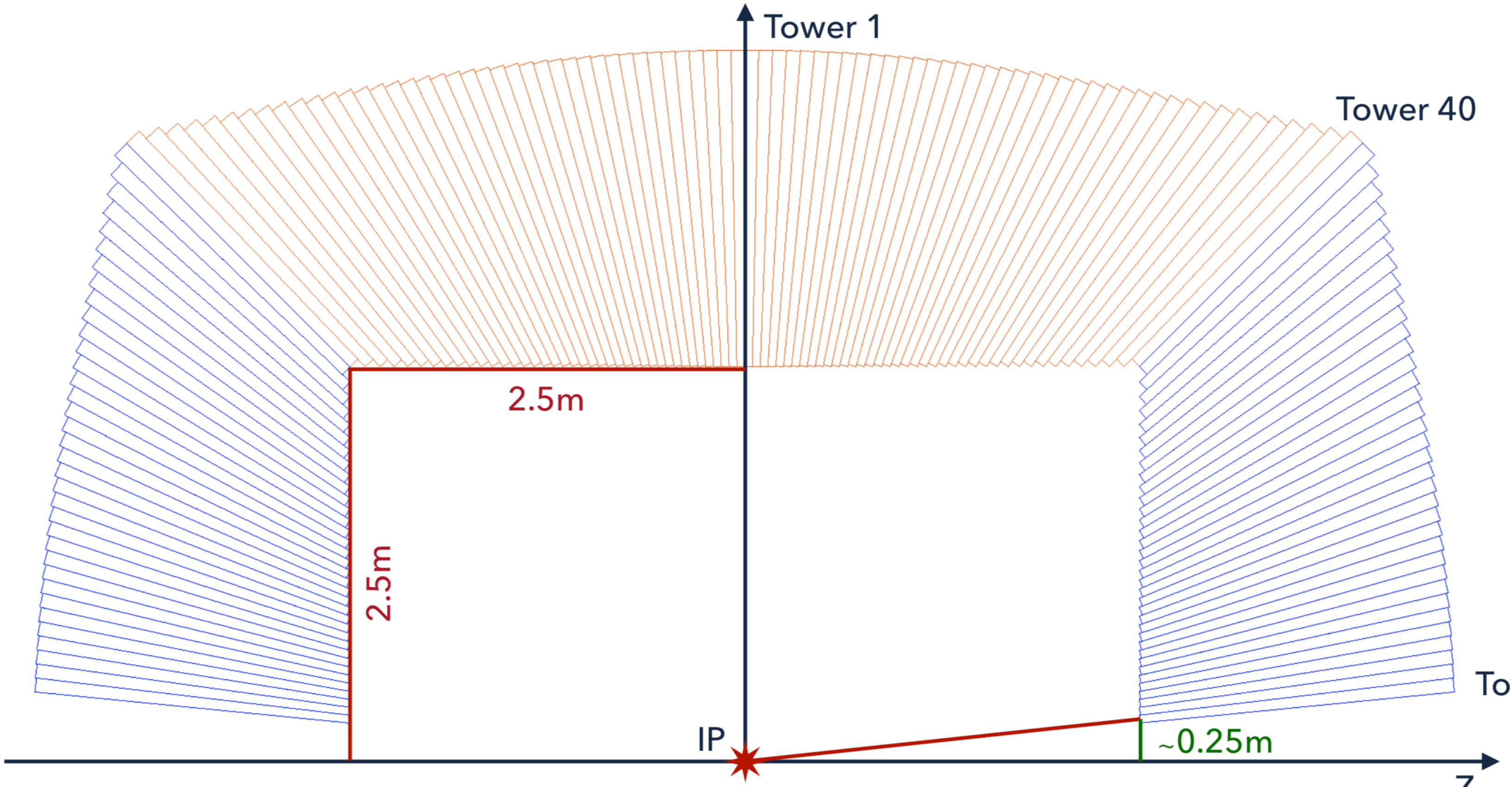






Copper + scintillating
and Cherenkov fibers

G4 Simulation for performance studies



75 projective elements x 36 slices

Read out the single fiber: 130 M channels

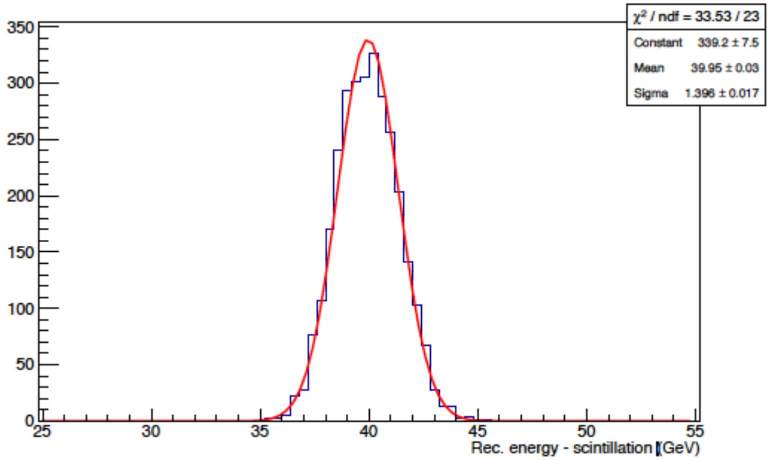
Tower size:

$$\Delta\theta = 1.125^\circ$$

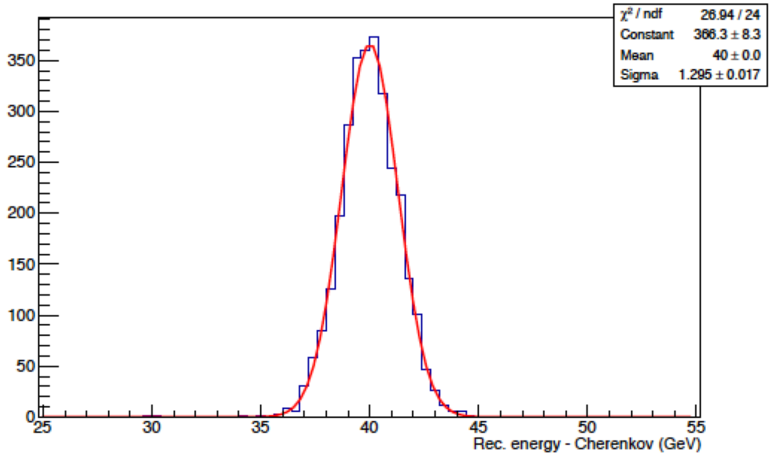
$$\Delta\phi = 10^\circ$$

Em. Performance: energy resolution

Scintillation

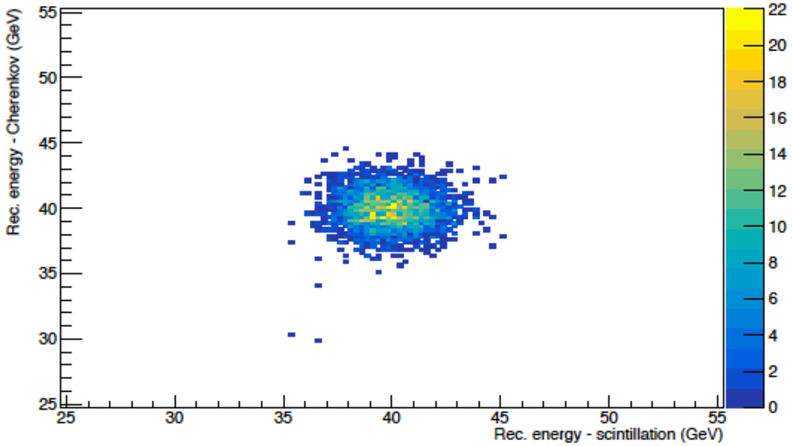


Cherenkov

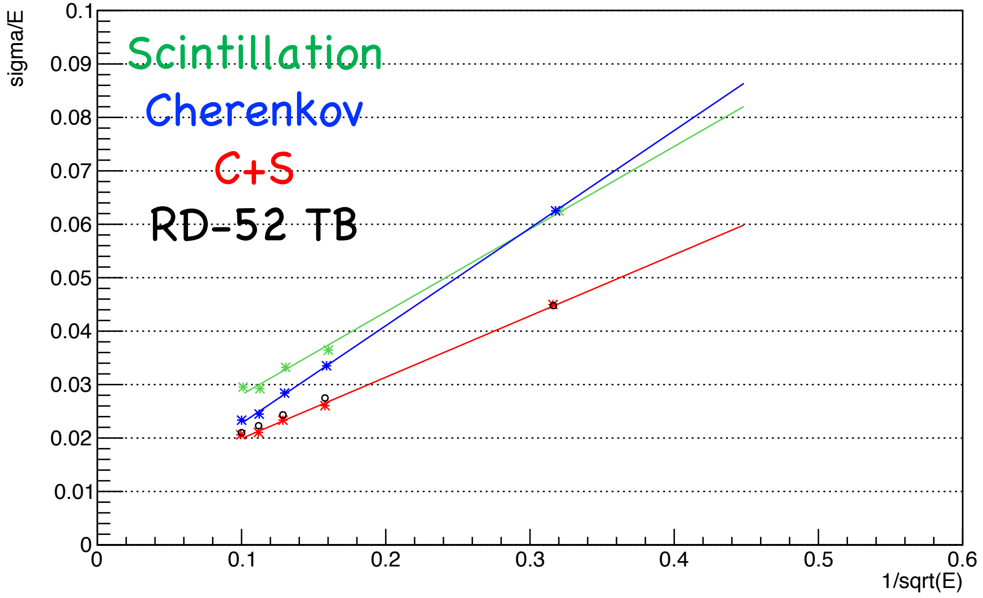


Simulated
40 GeV e-
in IDEA calo

θ=φ=1.5°



Em. Performance: energy resolution



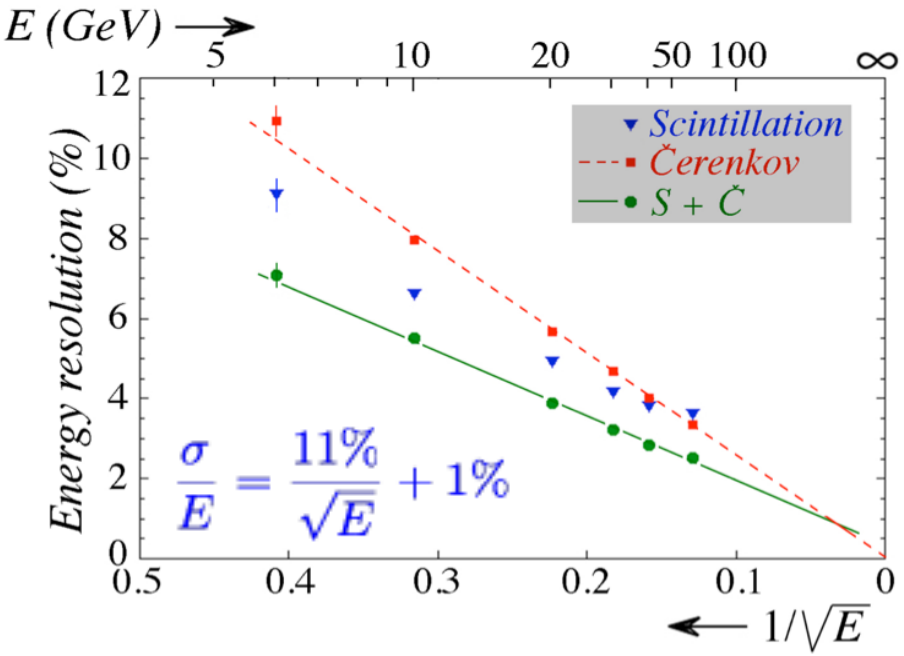
Cherenkov and scintillation sample the em. shower independently
➡ can be combined

RD52 TB data
Copper-fibers module
NIMA 735, 130(2014)

$$S: \quad \frac{\sigma}{E} = \frac{15.5\%}{\sqrt{E}} + 1.2\%$$

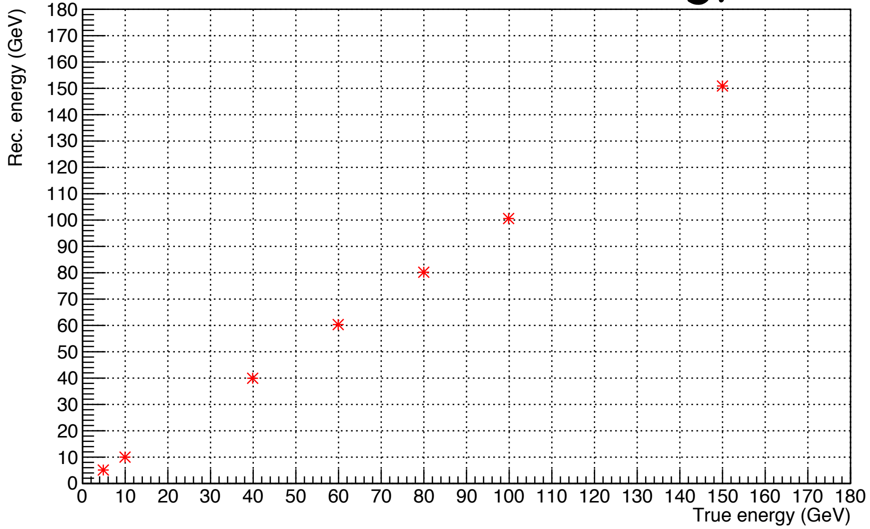
$$C: \quad \frac{\sigma}{E} = \frac{18.3\%}{\sqrt{E}} + 0.5\%$$

$$\frac{\sigma}{E} = \frac{11.0\%}{\sqrt{E}} + 0.8\%$$



Em. Performance: energy resolution

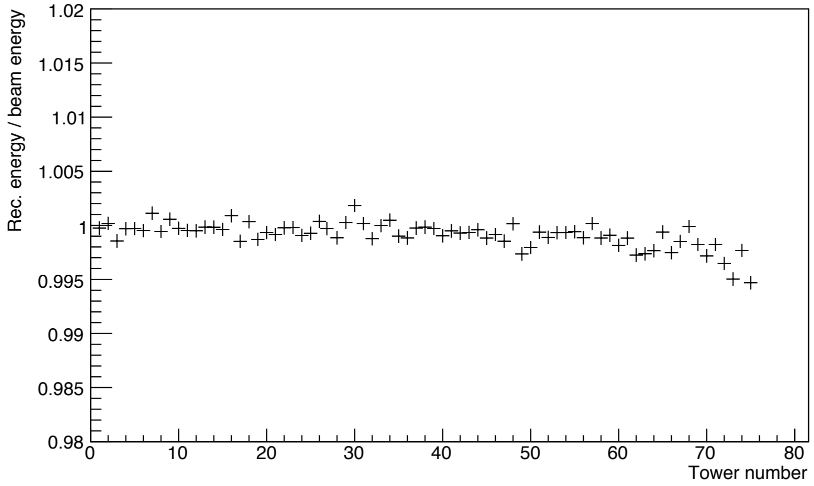
Reco vs True energy



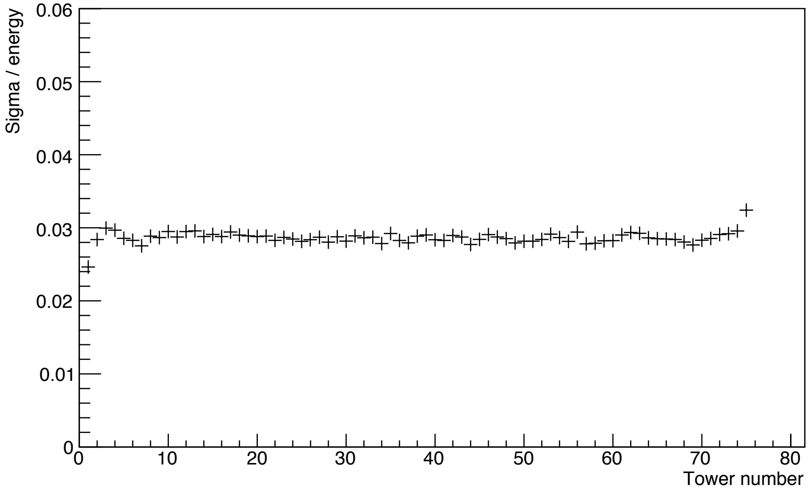
Response uniformity:

- Fibers pointing to interaction point
- Constant sampling fraction
- Constant sampling frequency

Reco/true energy vs tower num



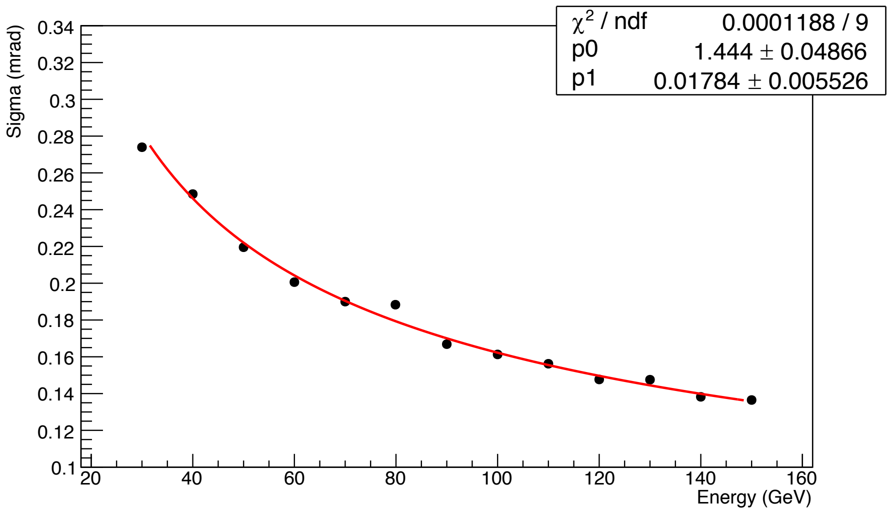
σ/E @40 GeV vs tower num

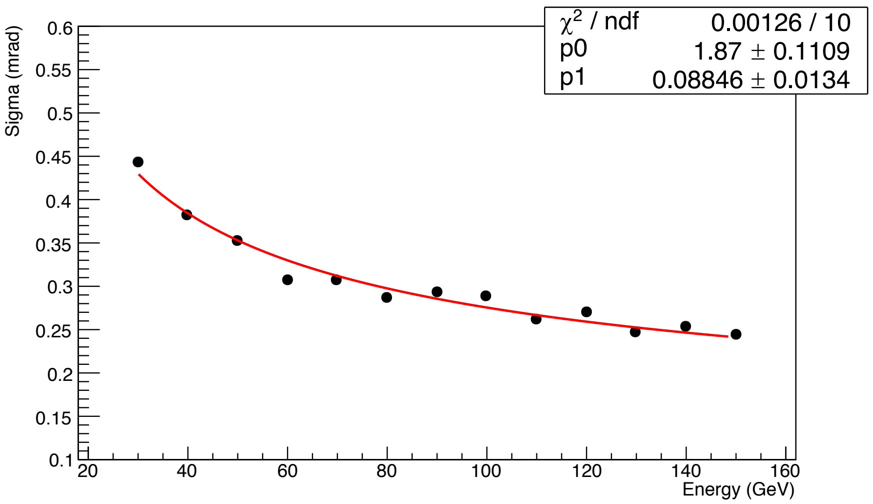


Em. Performance: angular resolution

Position of impinging particle reconstructed with barycentre method
with both scintillation and Cherenkov signals

- Independent sampling of the showers can be combined
- Assumed all the fibers are readout independently
  - If grouping is applied it will need to be revaluated





$$\sigma_\theta = \frac{1.4}{\sqrt{E}} + 0.018\ (mrad) \qquad \sigma_\phi = \frac{1.8}{\sqrt{E}} + 0.088\ (mrad)$$

Had. Performance: DR method

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

Cherenkov light C	only produced by relativistic particles, dominated by electromagnetic shower component
Scintillation light S	measure dE/dx

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

e/h ratios (c = $(\mathrm{h/e})_c$ and s = $(\mathrm{h/e})_s$ for either Cherenkov or scintillation structure) can be measured

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

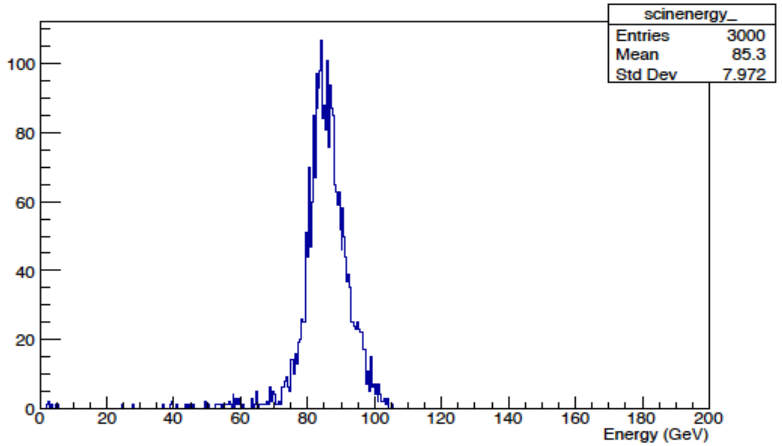
Θ and $\boldsymbol{\chi}$ are independent of both energy and particle type

It is possible to evaluate $$f = \frac{c - s(C/S)}{(C/S)(1-s) - (1-c)}$$ and $$E = \frac{S - \chi C}{1 - \chi}$$

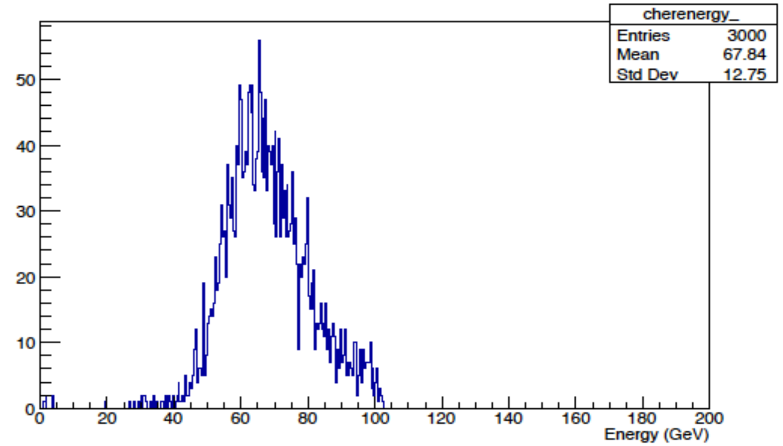
Had. Performance: pion energy resolution

Simulated 100 GeV π in IDEA calo (FTFP-BERT phys list)

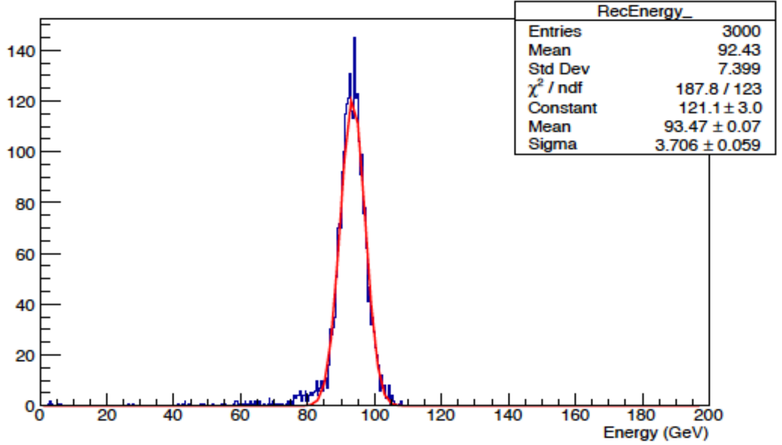
Scintillation

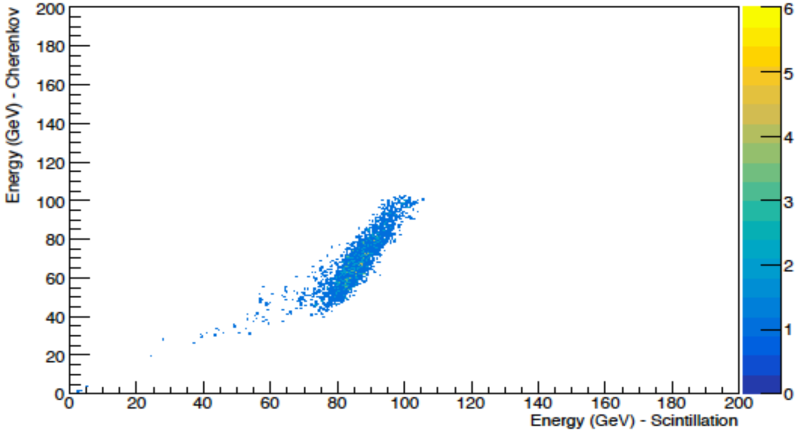


Cherenkov

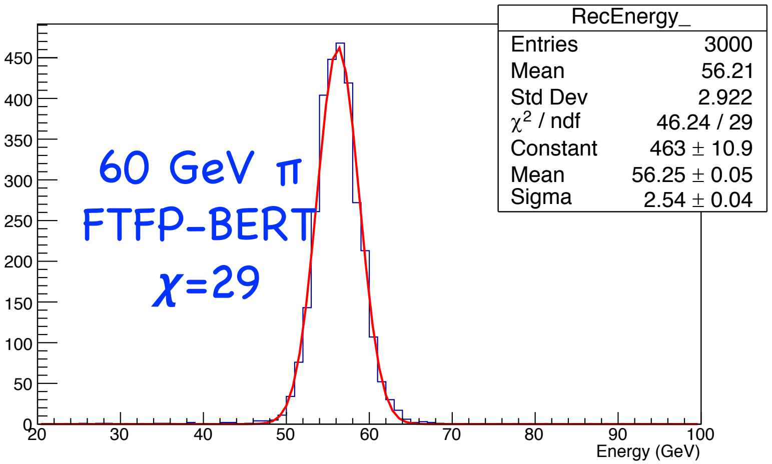


DR method

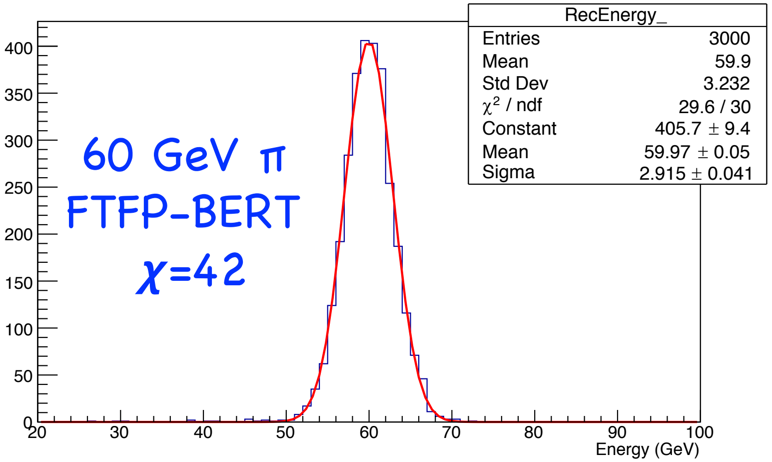




Had. Performance: pion energy resolution

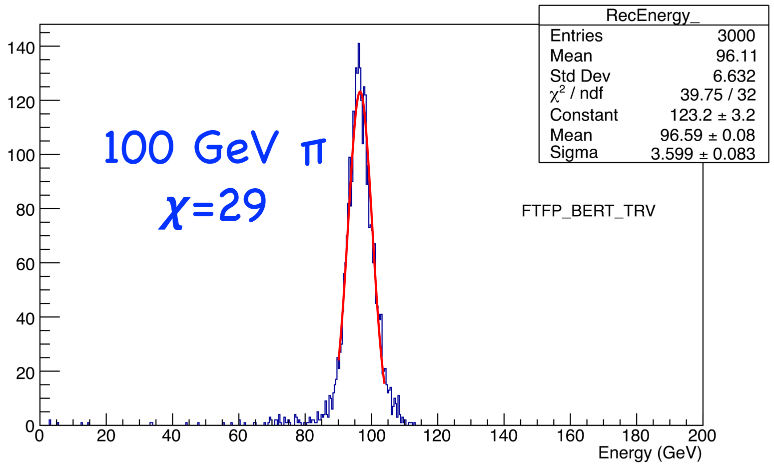


60 GeV π
FTFP-BERT
χ=29

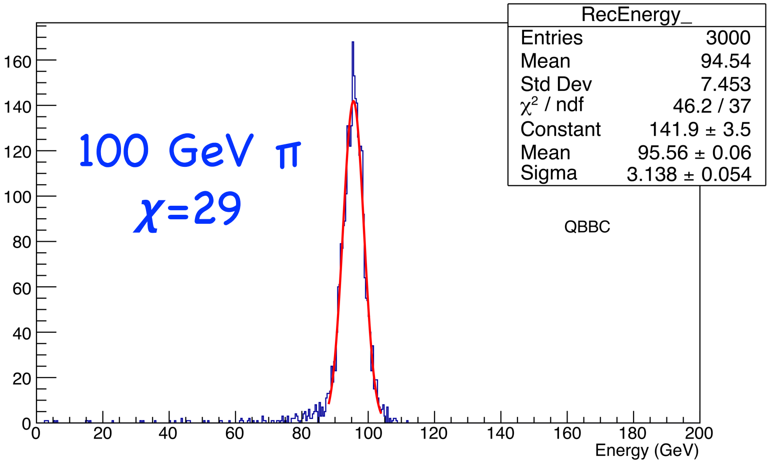


60 GeV π
FTFP-BERT
χ=42

Optimization of hadronic simulation, based on comparison to RD52 test beam data



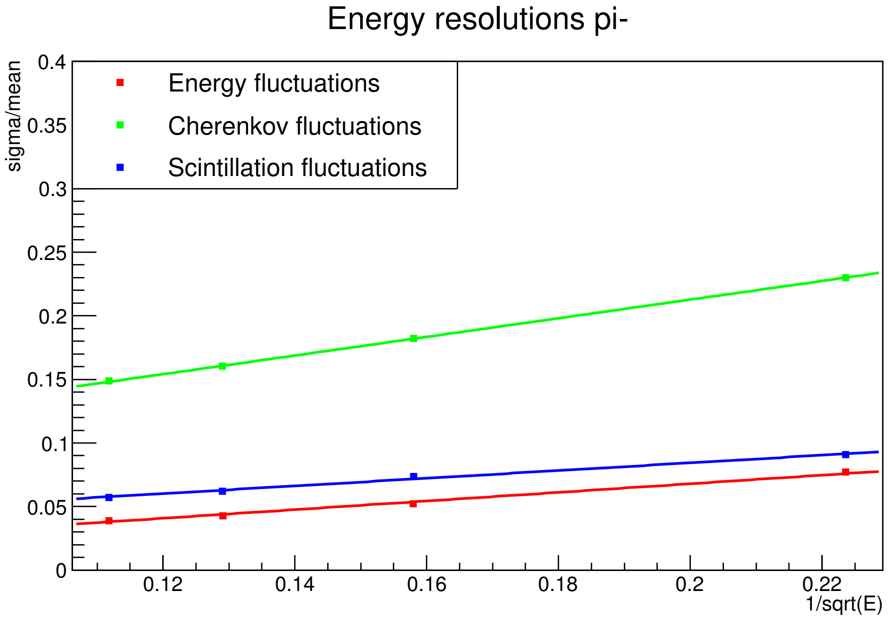
100 GeV π
χ=29



100 GeV π
χ=29

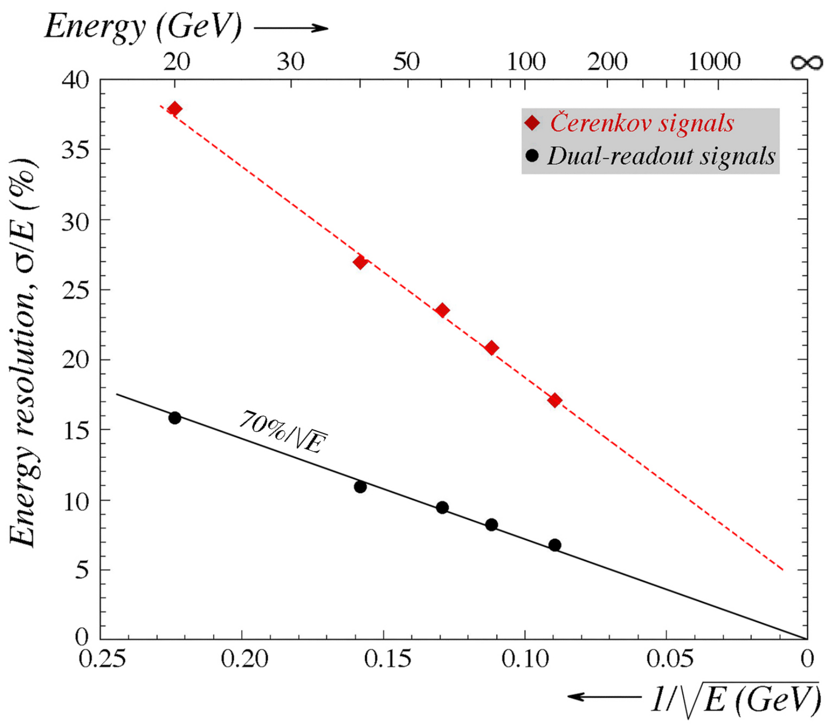
Promising preliminary results with FTFP_BERT_TRV and QBBC new phys list

Had. Performance: pion energy resolution



$$\frac{\sigma}{E} \sim \frac{33\%}{\sqrt{E}}$$

RD52 TB data - Lead-fibers module
NIMA 866, 76 (2016)



- 30x30 cm^2 lead/fibers module
- Containment ~ 90%
- not corrected for fiber attenuation length

Had. Performance: jet energy resolution

Jet composition:

- Electromagnetic component
- High-energy hadrons/mesons

DR-method

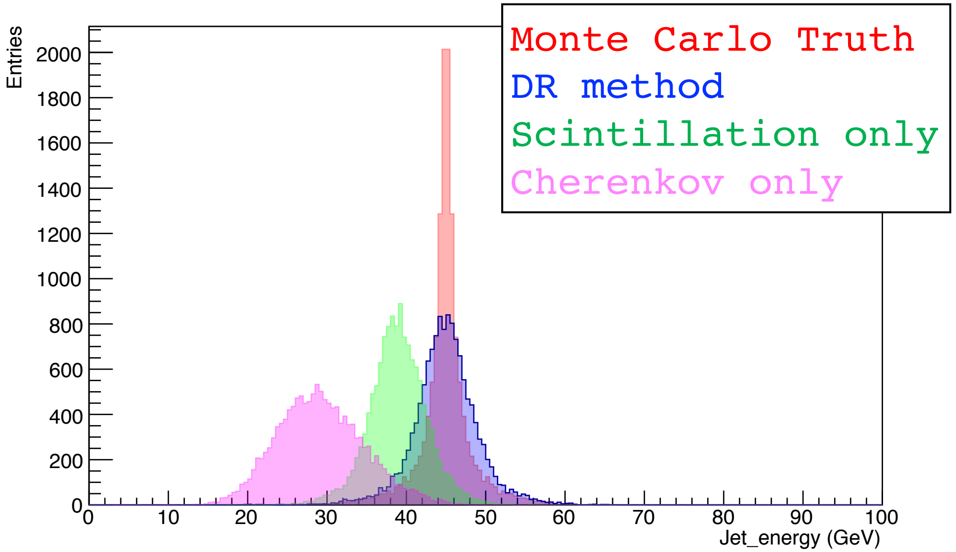
- Low-energy hadrons (mip-like particle)
  - thanks to low-Z material: e/mips ≃ 1

Jet reconstruction:

- Jet generated with PYTHIA8, tuned to LEP measurement
- Propagated in GEANT4 calorimeter
  - Obtain C and S response + (θ,φ) of the tower ➡ get jet 4-momenta
- Clustering with FASTJET (kt algorithm)

$$e^+e^- \rightarrow q\bar{q}$$

90 GeV center-of-mass

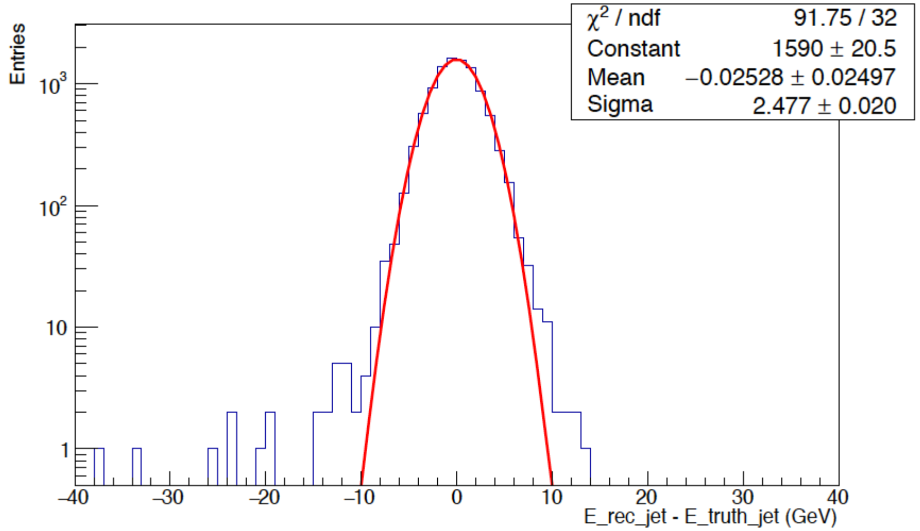


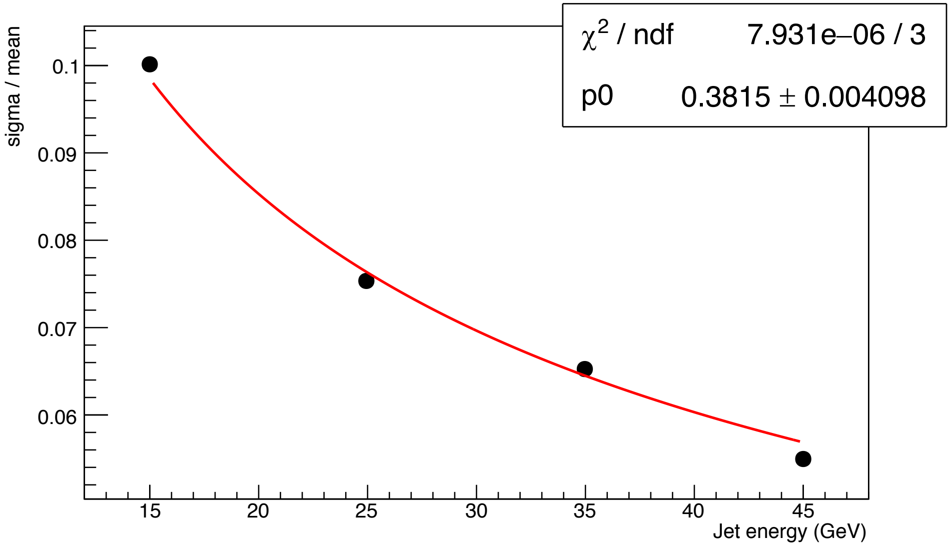
PYTHIA8 + GEANT4 + FASTJET

	Average (GeV)	std
MC Truth	45.01	1.11
DR method	44.94	2.40
Scintillation	38.98	2.80
Cherenkov	29.37	5.30

Had. Performance: jet energy resolution

PYTHIA8 + GEANT4 + FASTJET



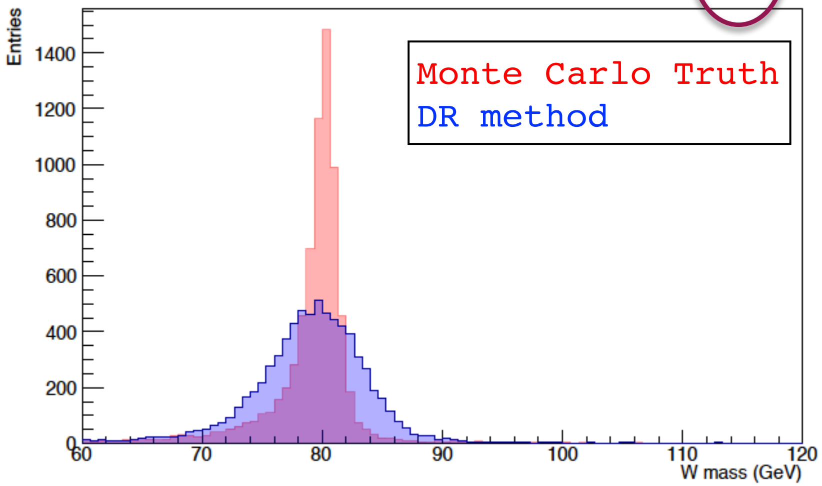


$$\frac{\sigma}{E} = \frac{38\%}{\sqrt{E}}$$

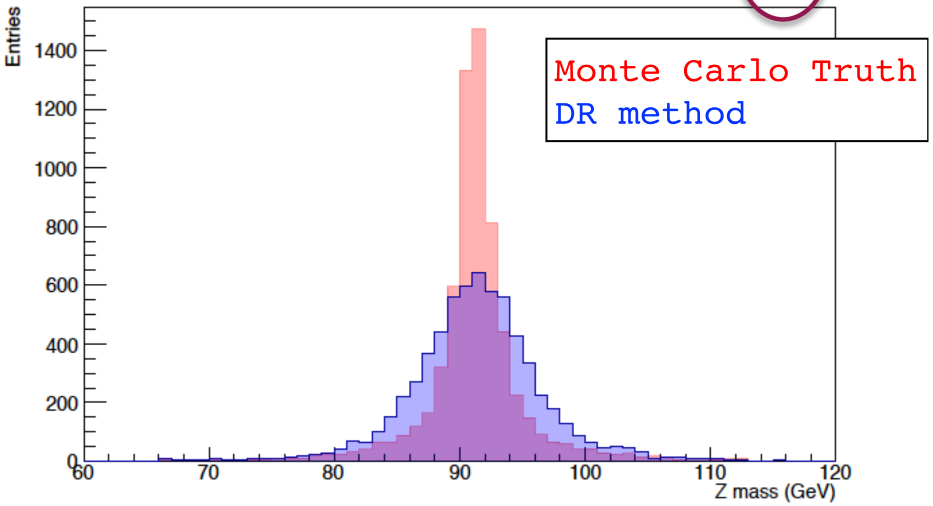
W and Z reconstruction

PYTHIA8 + GEANT4 + FASTJET

$$e^+e^- \to WW \to \mu\nu_\mu jj$$



$$e^+e^- \to HZ \to \tilde{\chi}^0\tilde{\chi}^0 jj$$



W	Average (GeV)	std
MC Truth	79.3	4.2
DR method	79.14	5.1

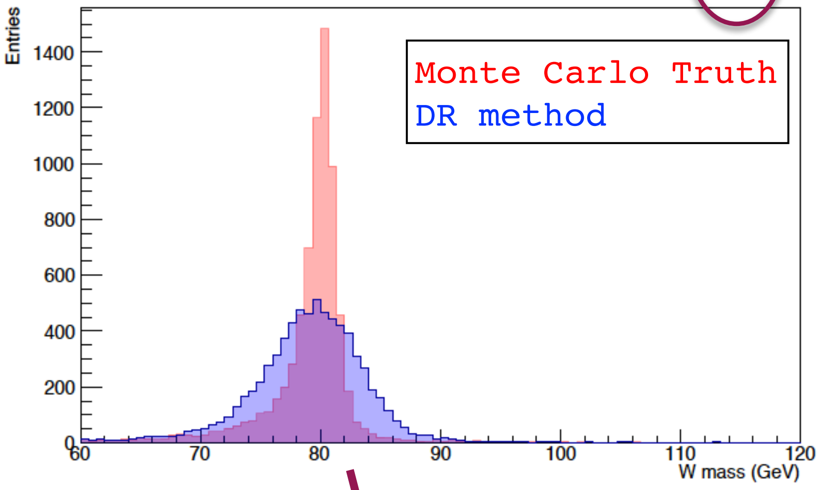
Z	Average (GeV)	std
MC Truth	91.24	4.32
DR method	91.32	5.43

W Peak 80.38 GeV

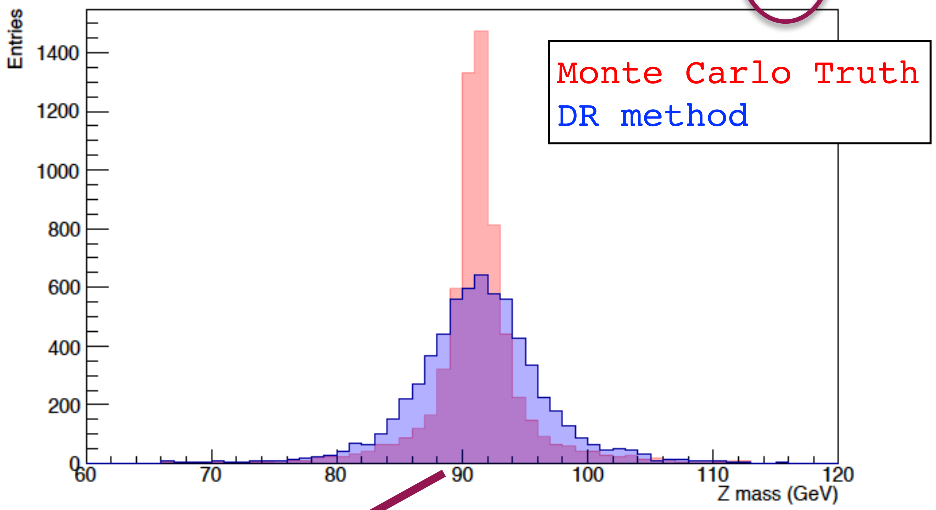
W and Z reconstruction

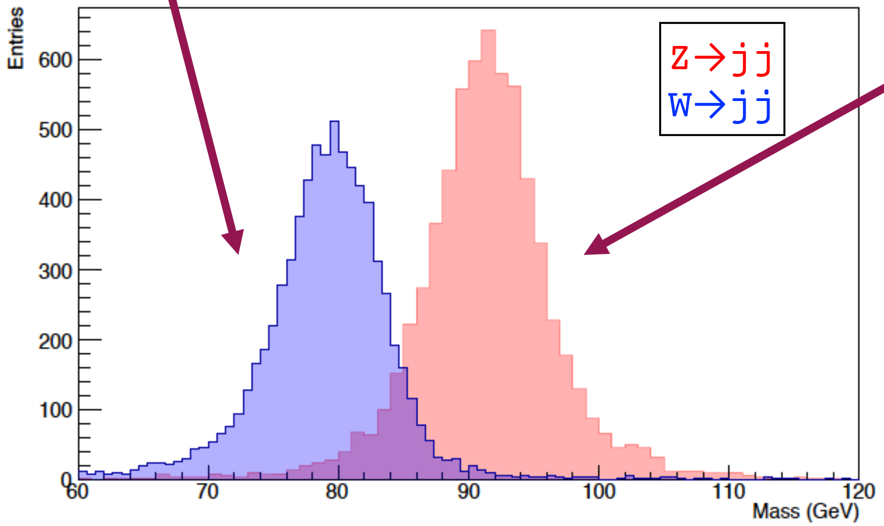
PYTHIA8 + GEANT4 + FASTJET

$$e^+e^- \to WW \to \mu\nu_\mu \boxed{jj}$$



$$e^+e^- \to HZ \to \tilde{\chi}^0\tilde{\chi}^0 \boxed{jj}$$



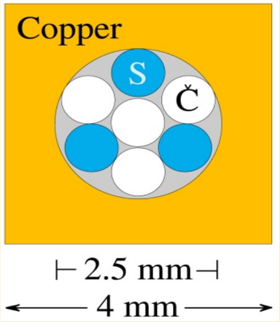


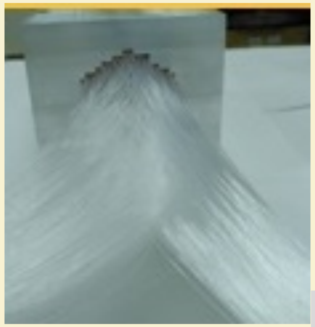
	Average (GeV)	std
W	79.14	5.13
Z	91.32	5.43

The dual-readout fiber calorimeters

2003
DREAM

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



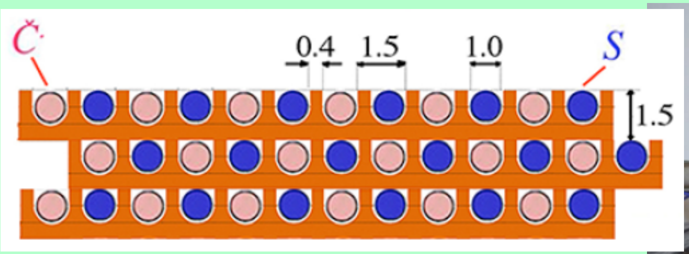


Texas Tech Uni

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}

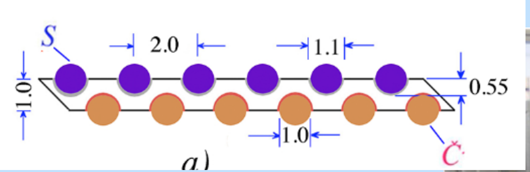


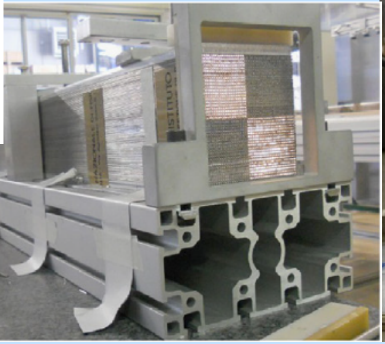
INFN Pisa

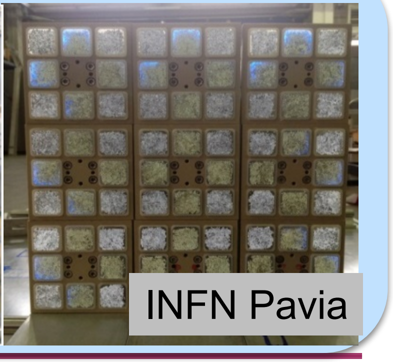
2012
RD52

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}







INFN Pavia

Next step: prototype in 2020

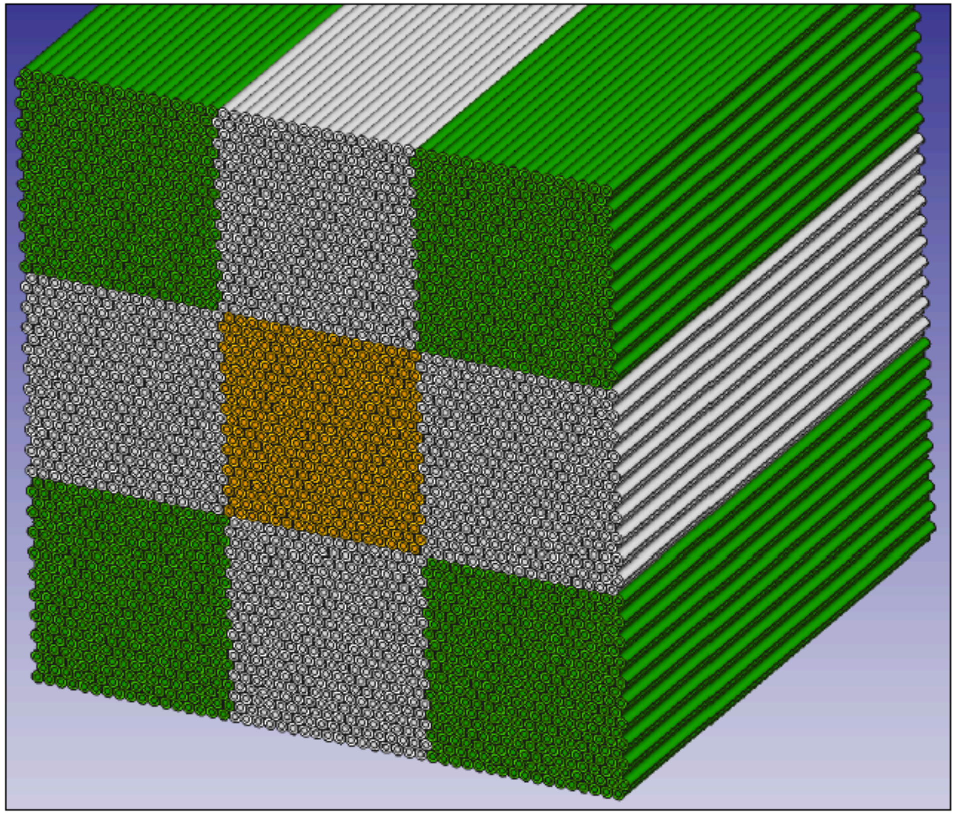
10x10 cm^2 divided in 9 towers, 1m long

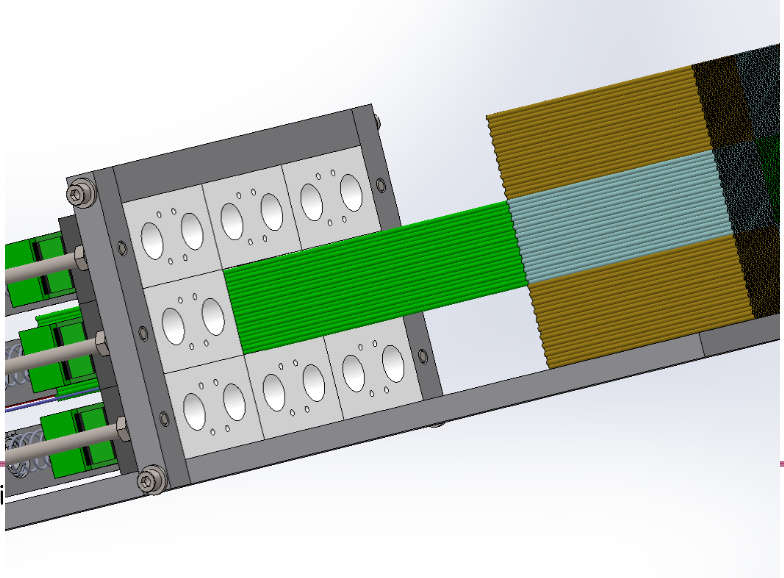
16x20 capillary each (160 C + 160 S)

- 2mm outer diameter, 1mm inner diameter
- Material: brass CuZn37

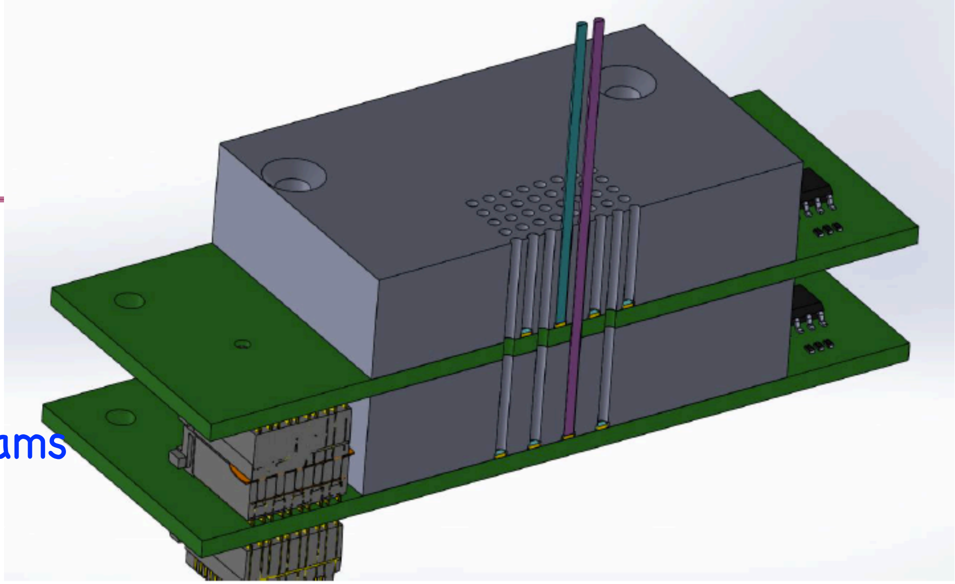
Readout:

- 1 central tower readout by SiPM
- 8 surrounding towers readout by PMT (à la RD_52)

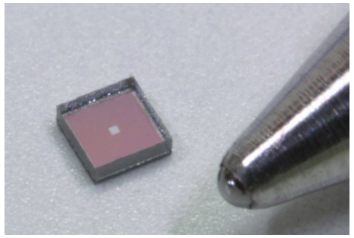




SiPM Readout: RD52 TB



- Dual-layer SiPM readout in previous TB
  - Avoids optical cross-talk
- Saturation studied with dedicated test beams
  - 25 μm pixels OK for Cherenkov
  - Yellow filter used to control saturation in Scintillation channel

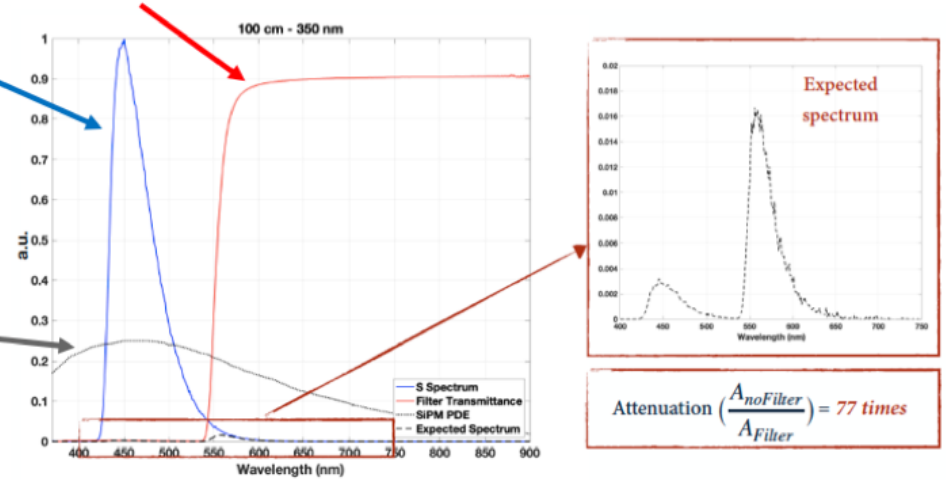


Yellow filter: transmittance spectrum (measured)

Expected spectrum and its attenuation

Scintillating fiber: emitted light spectrum (measured)

SiPM: Photodetector efficiency (from datasheet)



Attenuation $\left(\frac{A_{noFilter}}{A_{Filter}}\right)$ = *77 times*

The sensors used were 25 μm cell pitch (S13615-1025)

Signal linearity results

Measurement conditions (containment correction not applied):

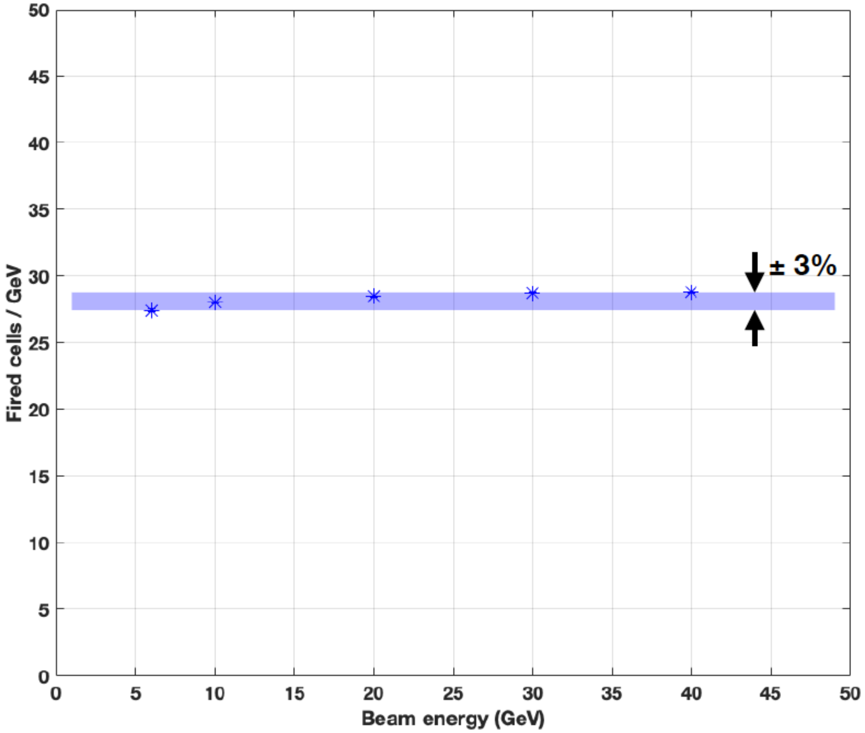
* Values already corrected for the sensor non linearity response

$V_{op} = 5.5\ V_{ov}$ (57.5 V) and **$PDE_C \sim 25\%$ (440nm) - $PDE_S \sim 20\%$ (556nm)**

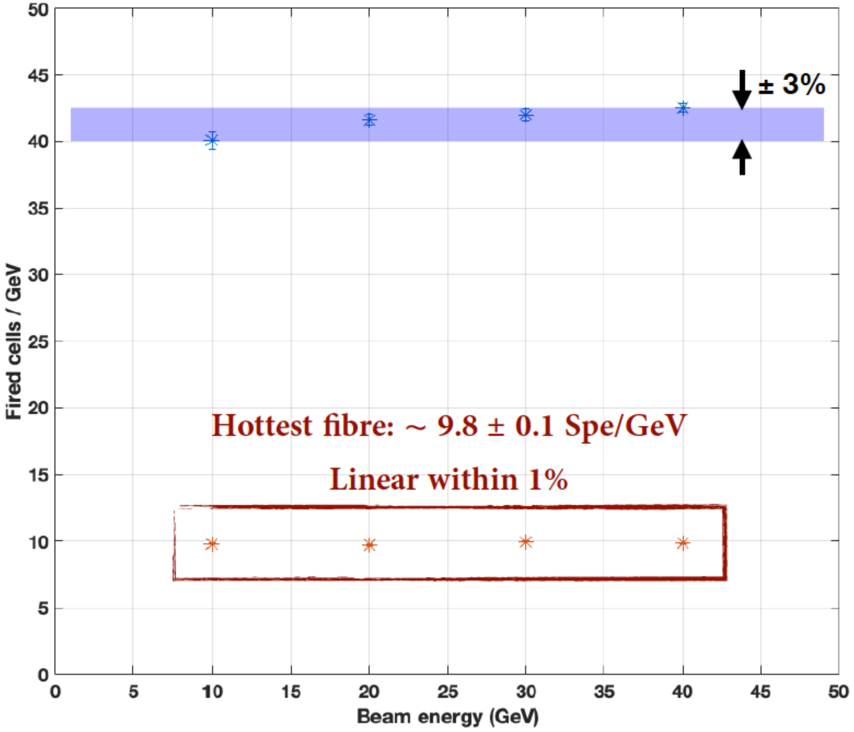
Temperature stability correction:

$\Delta T < 0.5°C$ during a single run (negligible) || $\Delta T \sim 1°C$ during the full scan (considered)

Cherenkov Light Yield (*2017*) ~ 28.6 ± 0.4 Cpe/GeV



Scintillation Light Yield (*2018*) ~ 41.9 ± 0.3 Spe/GeV



Hottest fibre: ~ 9.8 ± 0.1 Spe/GeV

Linear within 1%

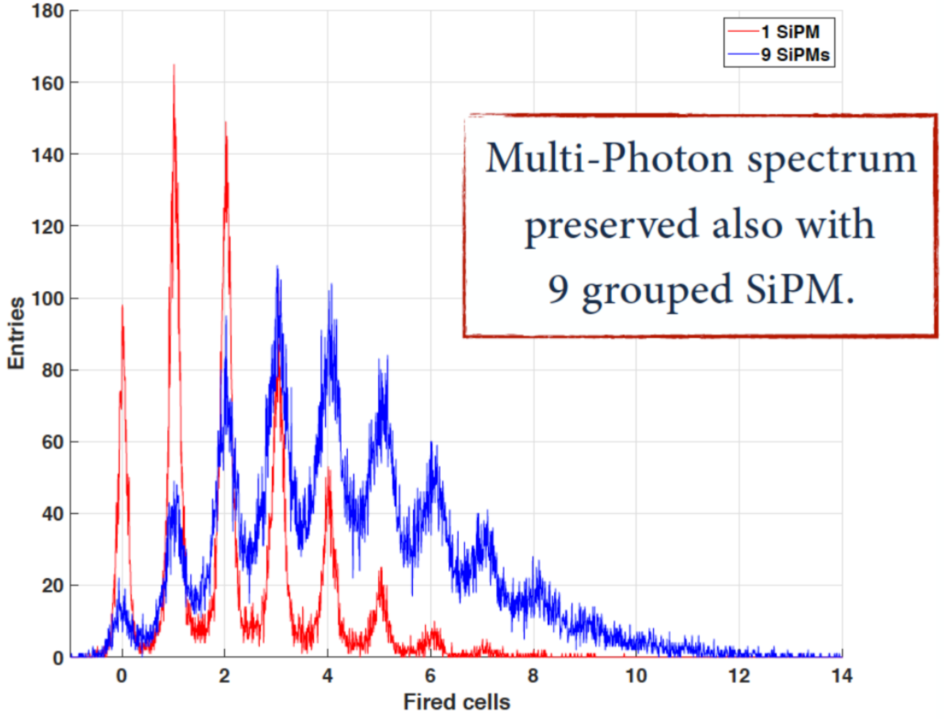
Signal grouping

Full scale module: O(10^8) readout channel

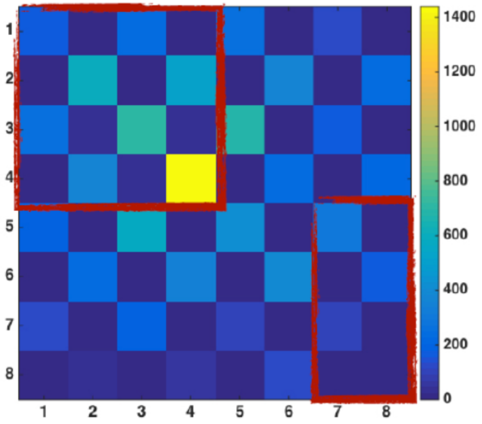
Analogic signal grouping to reduce channel number under study

Critically requiring linear working regime

- No way to apply correction on summed signals
- Need to guarantee multi-photon spectrum detection
- Push for higher dyn range (25 to 5 µm)



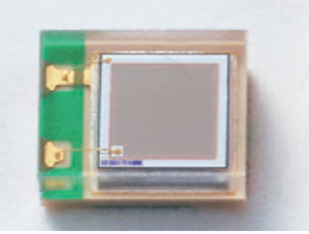
Multi-Photon spectrum preserved also with 9 grouped SiPM.



SiPM number	1	4	8
Space granularity (mm²)	4.5	18	36

NIMA 936, 127 (2019)

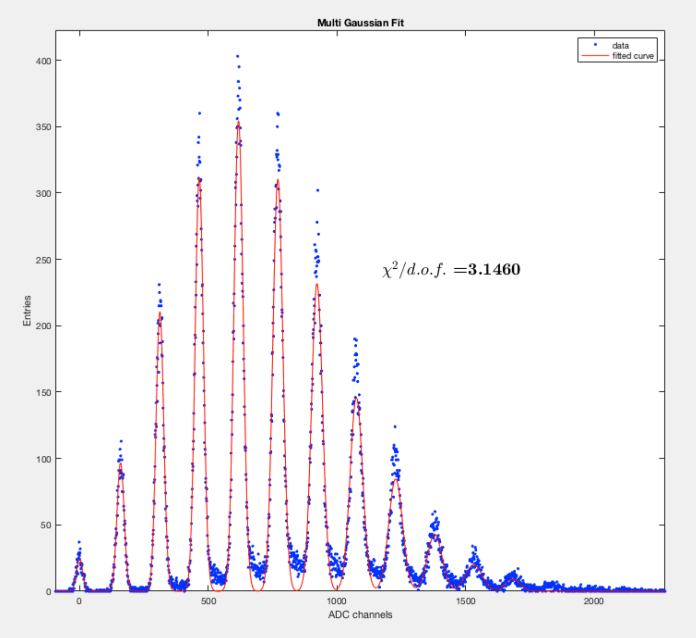
First test with new SiPM



We tested new SiPMs using our standard equipment (SP5600 and DT5720A from Caen) together with an automatic software tool developed to characterize SiPMs (JINST 10, C08008)

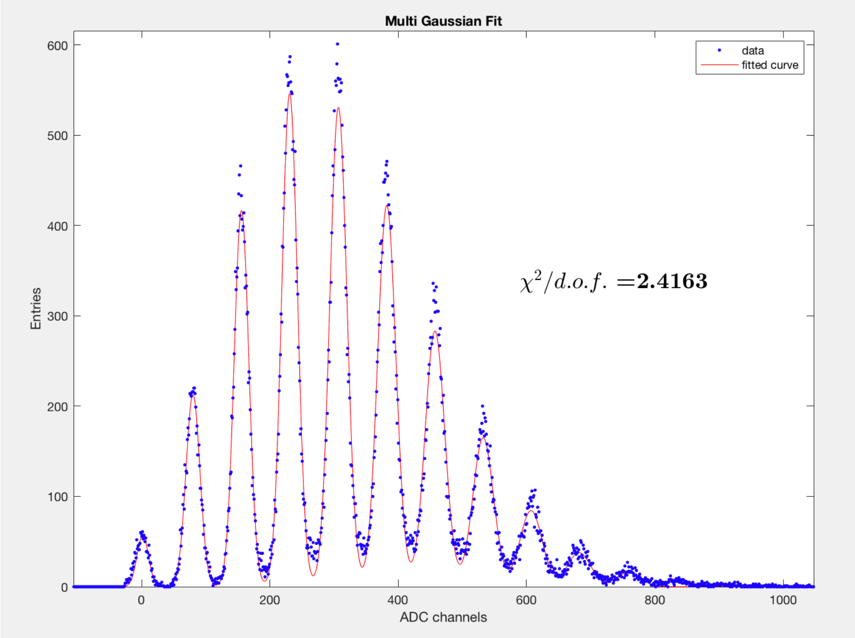
Sensor: S14160-1315PS
Cell size =15μm

Vbias = 42 ($\approx$ 4 V over breakdown)
Signal amplification: 40dB
Measured Xtalk = 2%



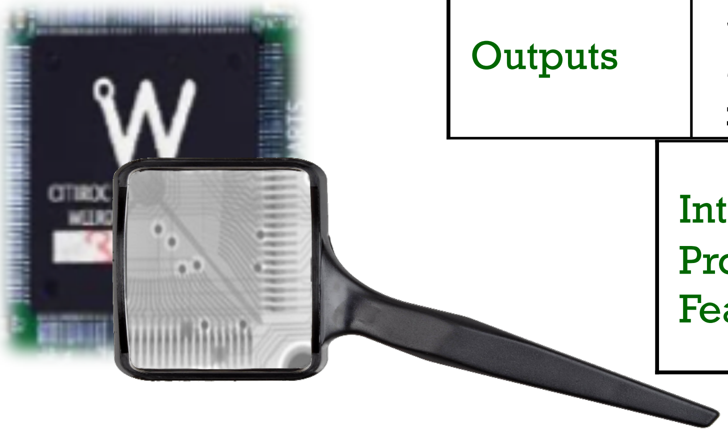
Sensor: S14160-1310PS
Cell size =10μm

Vbias = 42.5 ($\approx$ 4.5 V over breakdown)
Signal amplification: 40dB
Measured Xtalk = 1.8%



Readout: Citiroc1A

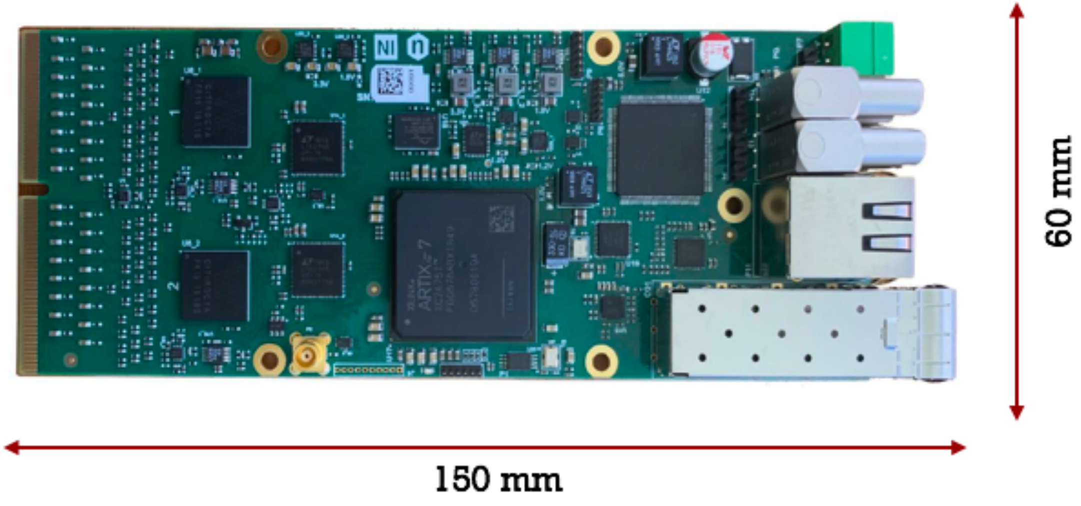
Detector Read-Out	SiPM, SiPM array
Number of Channels	**32**
Signal Polarity	Positive
Sensitivity	Trigger on **1/3 of photo-electron**
Timing Resolution	Better than **100 ps RMS** on single photo-electron
Dynamic Range	0-400 pC i.e. 2500 photo-electrons @ 10^6 SIPM gain
Packaging & Dimension	TQFP160-TFBGA353
Power Consumption	225mW - Supply voltage: 3.3V
Inputs	32 voltage **inputs with independent SiPM HV adjustments**
Outputs	**32 digital outputs (for timing)** **2** multiplexed **charge output, 1** multiplexed **hit register and 2 trigger outputs**
Internal Program. Features	32 HV adjustment for SiPM (32x8bits), Trigger Threshold Adjustment, channel by channel gain tuning, 32 Trigger Masks, Trigger Latch, internal temperature sensor



Proposed readout for 2020 Prototype

If the Citirorc1A qualification will fulfil our requirements we still need a compact and scalable solution for a test beam: the FERS-5200 system from CAEN could be a possible solution

FERS: A5202



The basic principle

- 2 Citiroc1A (64 ch)
- Timing with a TDC implemented into the FPGA (≈ 0.5 ns)
- 2 ADC to measure the charge
- 1 HV power supply (20 – 100V) with temperature compensation
- Interface for readout

Summary

Dual-readout calorimetry development in the IDEA framework

- A number of new performance studies with full simulation, tuned on TB data
    - EM E resol. 11%/$\sqrt{E}$ uniform in the whole detector;
    - Optimal angular resolution (1.4/$\sqrt{E}$ mrad in θ and 1.8/$\sqrt{E}$ mrad in φ) when all the fibers are readout
    - Good di-photon separation and Particle ID
    - Hadronic energy resolution as good as 33%/$\sqrt{E}$ to single particle, and 38%/$\sqrt{E}$ to jets

- Detector and Readout development
    - TB in 2020 on new 10x10x100 cm^2 prototype includes all new proposed solution
        - Detector unit based on 2mm capillary with fiber core
        - SiPM readout of 320 channel with dedicated electronics

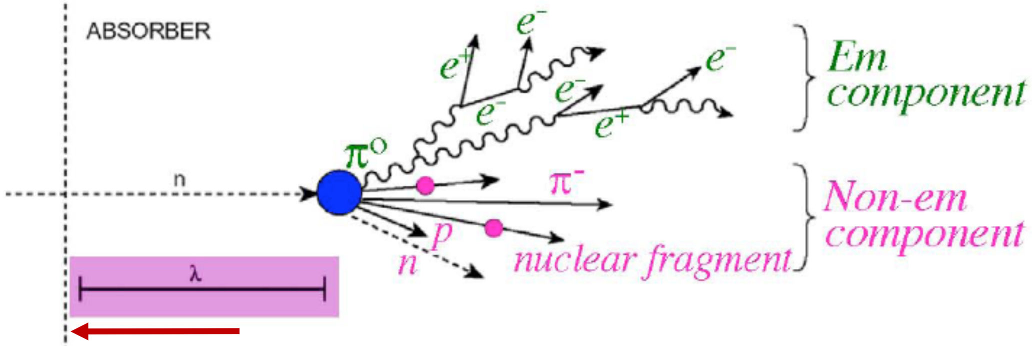
Backup

BACKUP

Limits to high-resolution Had Calorimetry

Hadronic showers consist of two components:

electrons positrons, photons, π^0



Charged hadrons (π,k…), nuclear fragments, neutrons, neutrinos, breakup of nuclei (invisible energy)

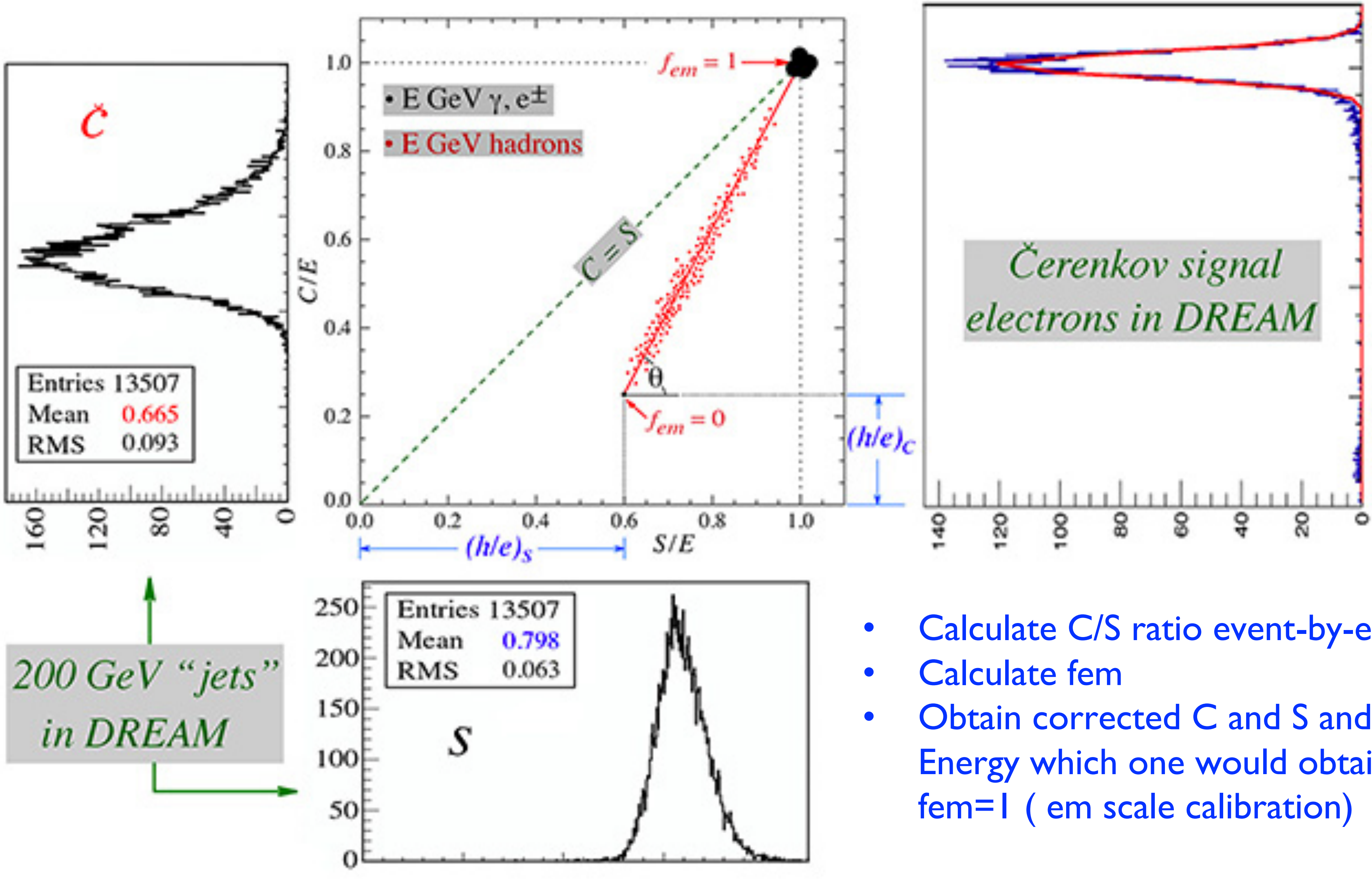
- The calorimeter response to these two components is typically very different (e/h ≠1)
- Hadronic showers are characterized by very large fluctuations due the energy sharing between these two components

1. f_{em} varies event-by-event (fluctuations in calorimetry response)
2. f_{em} grows with energy (non linearity)
3. fluctuations in the amount of invisible energy

$$\langle f_{em} \rangle = 1 - \left(E / E_0 \right)^{(k-1)}$$

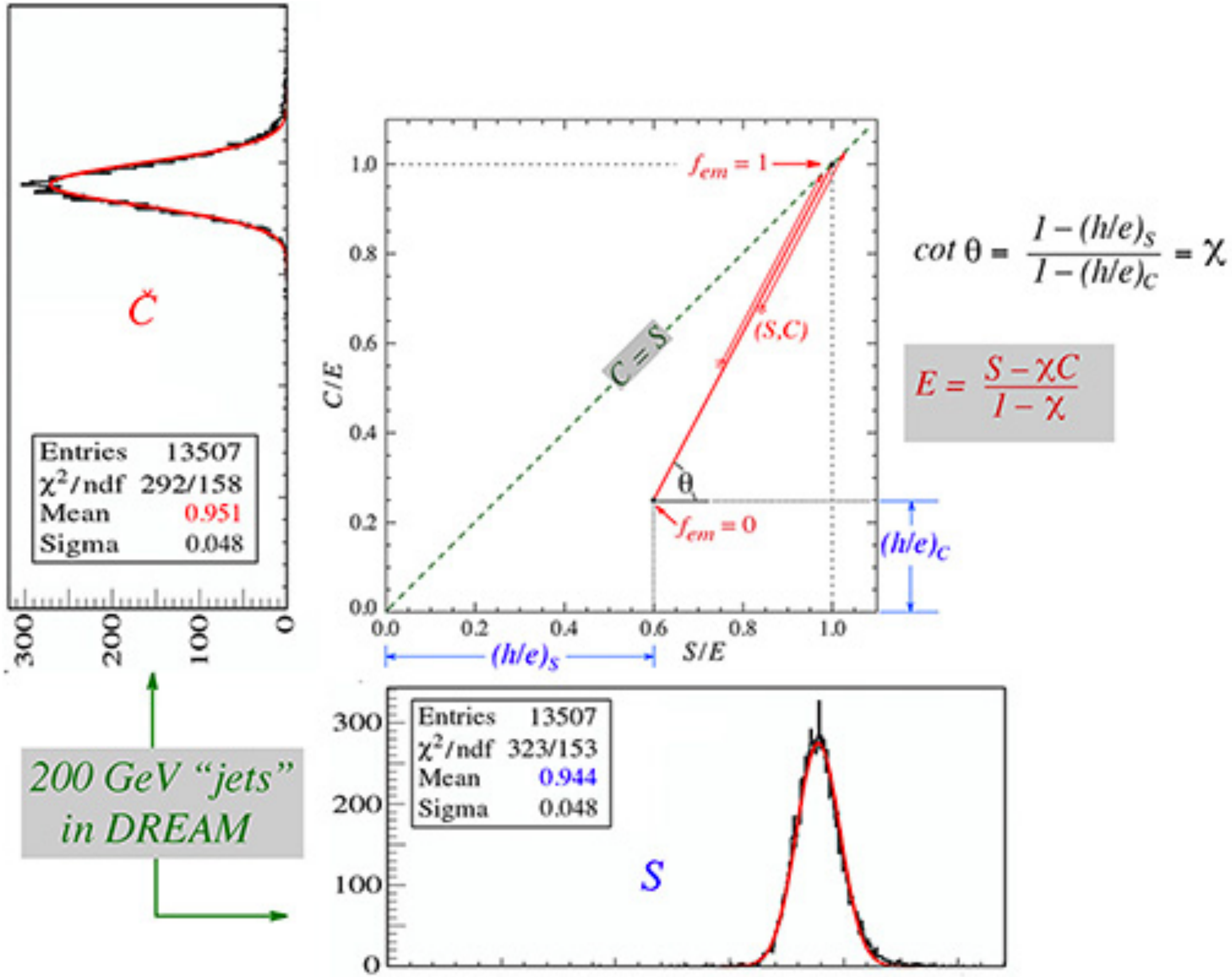
E_0 = average energy to produce a π^0
(k-1) related to average multiplicity

Before Correction



- Calculate C/S ratio event-by-event
- Calculate fem
- Obtain corrected C and S and Energy which one would obtain if fem=1 (em scale calibration)

Dual-Readout approach at work



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

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

200 GeV "jets" in DREAM

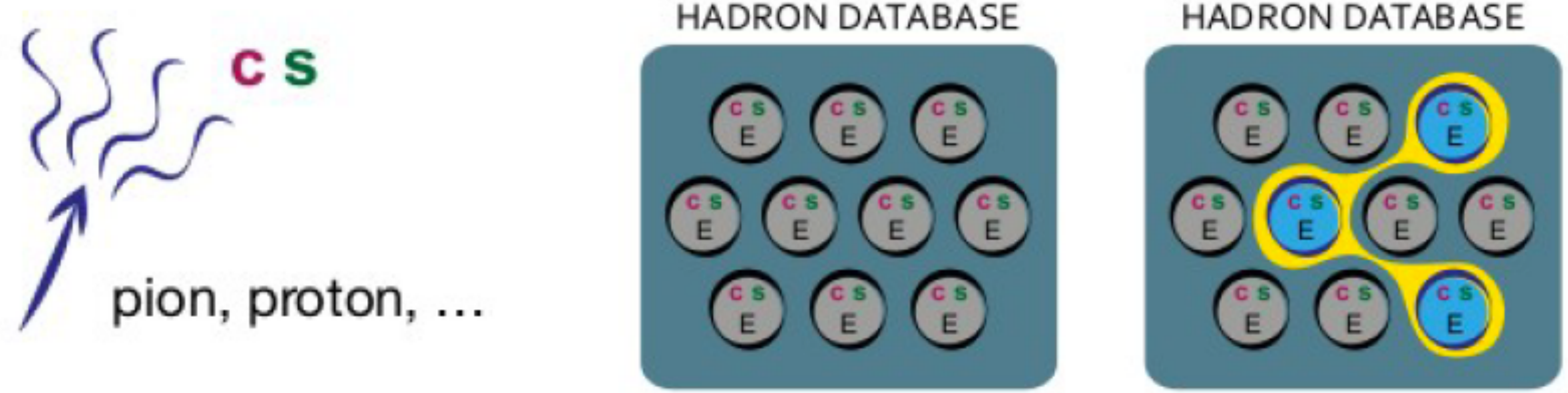
A different way for dual readout

Work in progress

Machine Learning:

- create a calibration DB of events with C, S, E values
- search the closest (C, S) (really C/S) events → get E

→ *allows calibration with hadrons*



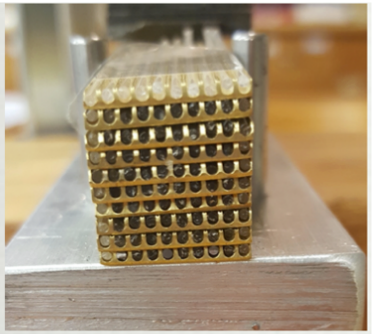
Reconstruct energy with:

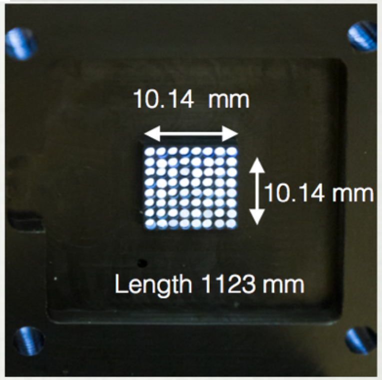
$$E = \frac{1}{2n}\sum_{i}^{n}\frac{E_i}{s_i}\times s + \frac{1}{2n}\sum_{i}^{n}\frac{E_i}{c_i}\times c$$

PMT vs SiPM readout

- *SiPM advantages:*
  - *compact readout (no fibers 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, ...)*



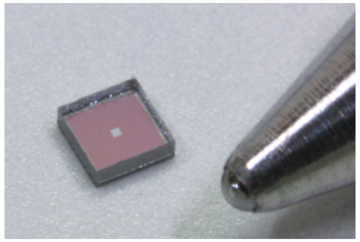


Brass absorber
10x10x1500 mm^3

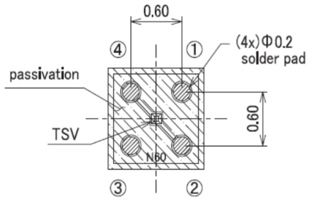
X$_0$: 29 mm
R$_M$: 31 mm
Shower containment: ~45%
(from simulations)

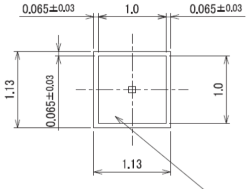
25 um cell size sensor

The sensors used were 25 μm cell pitch (S13615-1025)



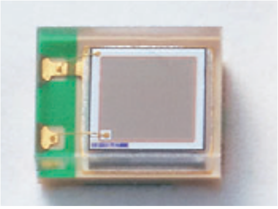
Parameters	S13615		Unit
	-1025	-1050	
Effective photosensitive area	1.0x1.0		mm^2
Pixel pitch	25	50	μm
Number of pixels / channel	1584	396	-
Geometrical fill factor	47	74	%

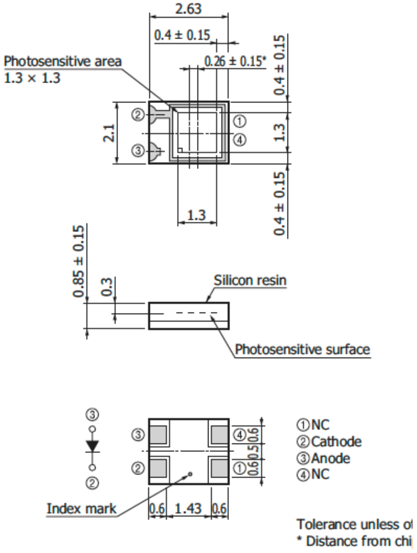


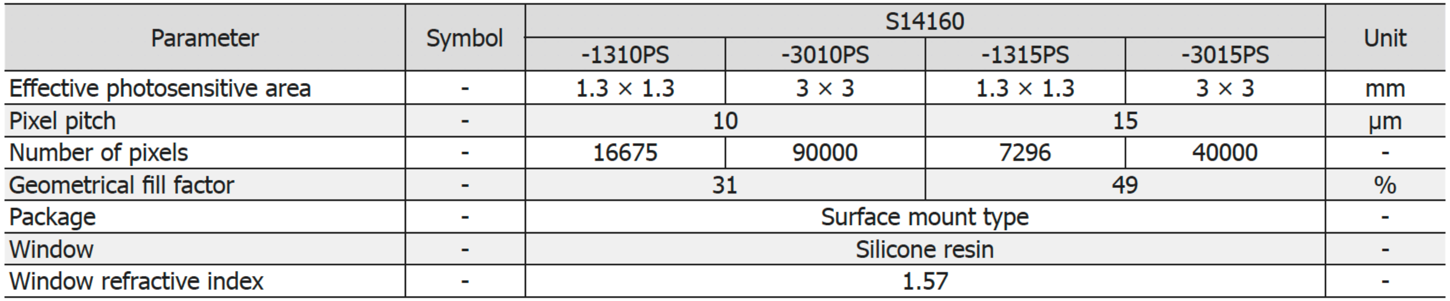


Parameters		Symbol	S13615		Unit
			-1025	-1050	
Spectral response range		λ	320 to 900		nm
Peak sensitivity wavelength		λp	450		nm
Photon detection efficiency at λp[*3]		PDE	25	40	%
Breakdown voltage		V_{BR}	53 ±5		V
Recommended operating voltage[*4]		V_{op}	V_{BR} + 5	V_{BR} + 3	V
Dark Count	Typ.	-	50		kcps
	Max.		150		
Crosstalk probability	Typ.	-	1	3	%
Terminal capacitance		Ct	40		pF
Gain[*5]		M	7.0×10^5	1.7×10^6	-

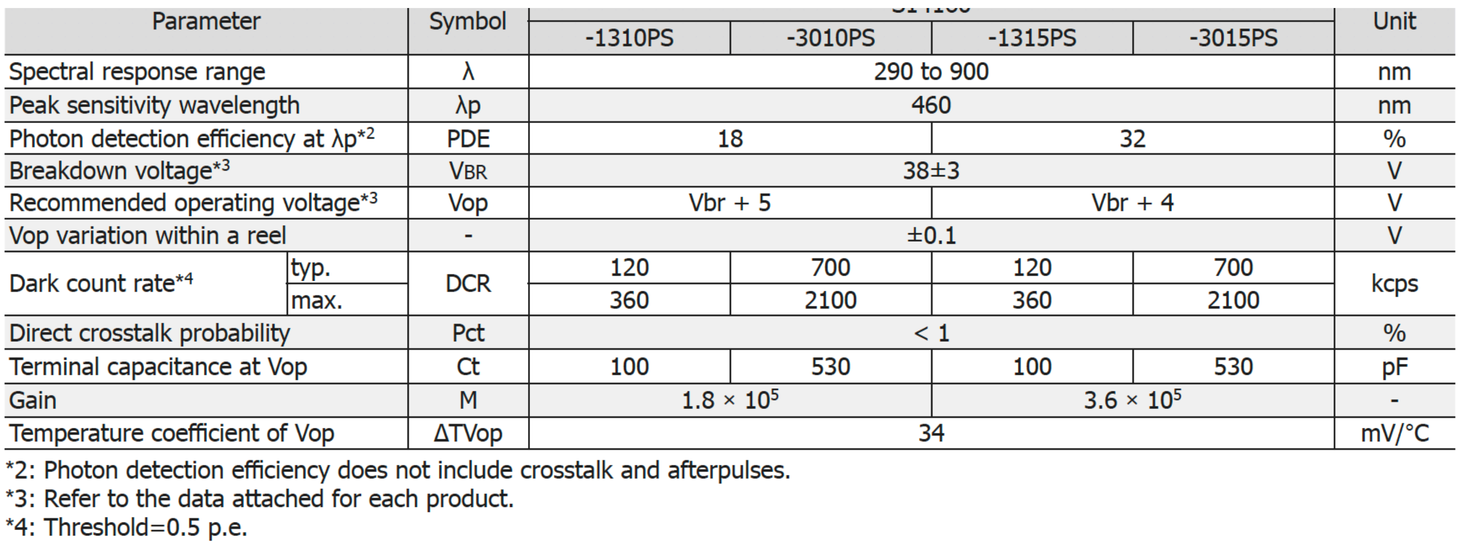
New sensors: S14160-1310PS / S14160-1315PS







Parameter	Symbol	S14160 -1310PS	S14160 -3010PS	S14160 -1315PS	S14160 -3015PS	Unit
Effective photosensitive area	-	1.3 × 1.3	3 × 3	1.3 × 1.3	3 × 3	mm
Pixel pitch	-	10		15		μm
Number of pixels	-	16675	90000	7296	40000	-
Geometrical fill factor	-	31		49		%
Package	-	Surface mount type				-
Window	-	Silicone resin				-
Window refractive index	-	1.57				-



Parameter		Symbol	-1310PS	-3010PS	-1315PS	-3015PS	Unit
Spectral response range		λ	290 to 900				nm
Peak sensitivity wavelength		λp	460				nm
Photon detection efficiency at λp*2		PDE	18		32		%
Breakdown voltage*3		VBR	38±3				V
Recommended operating voltage*3		Vop	Vbr + 5		Vbr + 4		V
Vop variation within a reel		-	±0.1				V
Dark count rate*4	typ.	DCR	120	700	120	700	kcps
	max.		360	2100	360	2100	
Direct crosstalk probability		Pct	< 1				%
Terminal capacitance at Vop		Ct	100	530	100	530	pF
Gain		M	1.8×10^5		3.6×10^5		-
Temperature coefficient of Vop		ΔTVop	34				mV/°C

*2: Photon detection efficiency does not include crosstalk and afterpulses.

*3: Refer to the data attached for each product.

*4: Threshold=0.5 p.e.

What compensation does and does not for you

- Compensation does not guarantee high resolution
  - Fluctuations in f_{em} are eliminated, but others may be very large
- Compensation has some drawbacks
  - High Z absorber required → small e/mip → non linearity
  - Small sampling fraction required → em resolution limited

$$\frac{\sigma}{E} = 2.7\% \frac{\sqrt{d/f_{sampl}}}{\sqrt{E}}$$

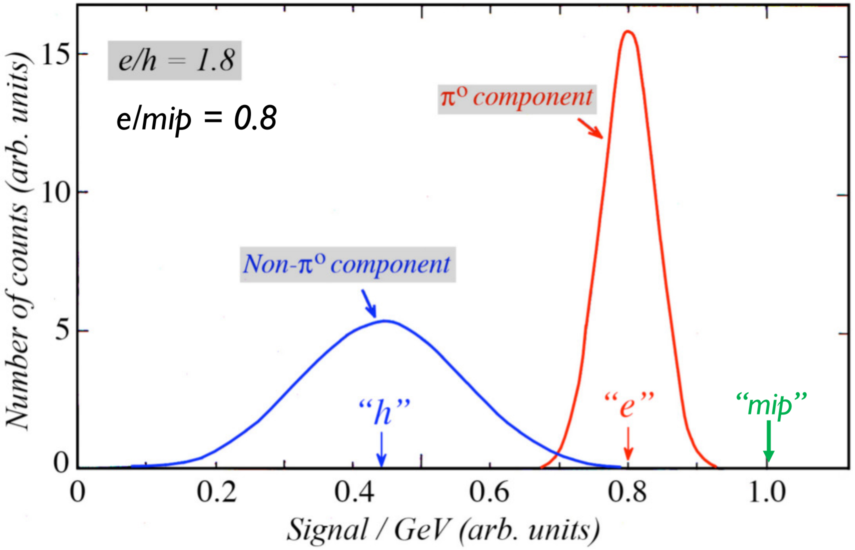
  - Relies on neutrons → calorimeter signals have to be integrated over large volume and time. SPACAL's 30%/√E needed 15 tonnes and 50 ns. Not always possible in practice
- High-resolution electromagnetic and high-resolution hadronic calorimetry are mutually exclusive:
  - Good jet energy resolution ⇒ Compensation ⇒ very small sampling fraction (~ 3%) ⇒ poor electron/photon resolution
  - Good electromagnetic resolution ⇒ high sampling fraction (100% Crystals, 20% LAr) ⇒ large non compensation ⇒ poor jet resolution

Calorimeter Response

The detector response to the em (e) and non-em (h) components is NOT the same

This effect is quantified by the e/h ratio

In this example, only 1/1.8 ≈ 56% of non-πo energy is accounted in the signal



<u>*Take care:*</u>

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 (*fem depends on E and shower "age"*)
2) fem different for π, K, p → response depends of particle type

Working principle

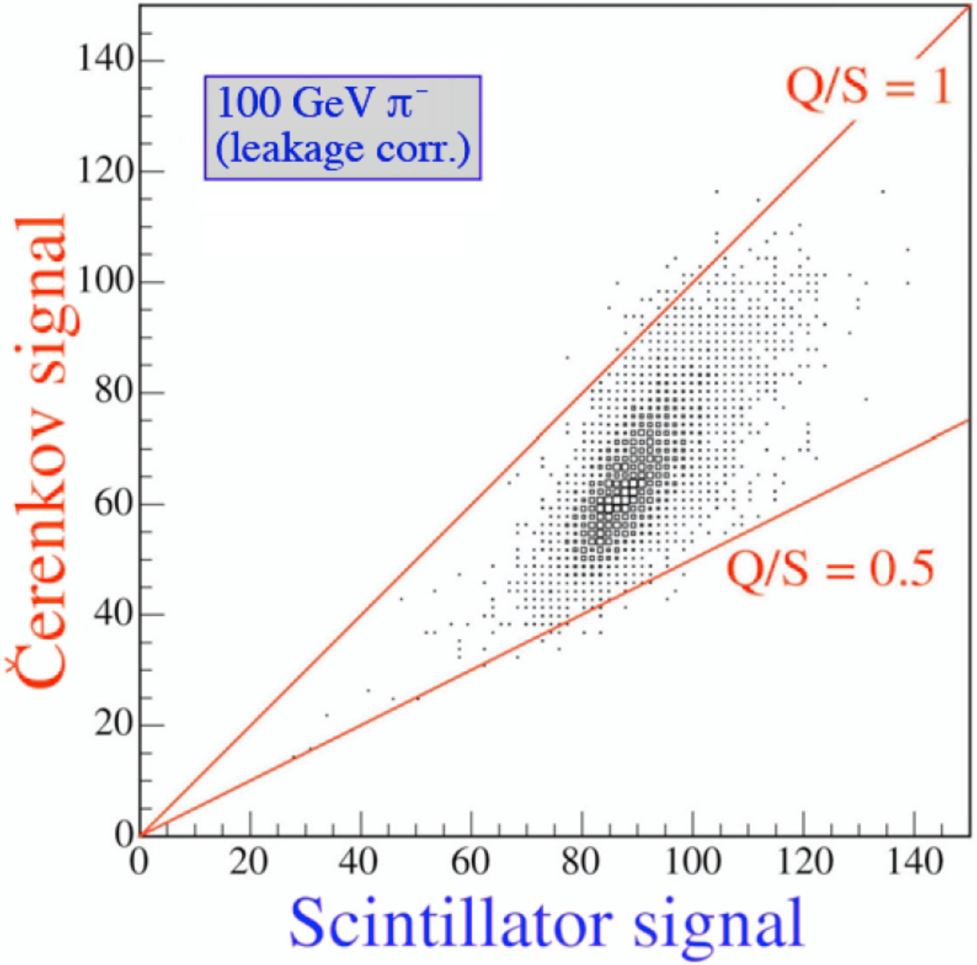
- Measure simultaneously:
  - Scintillation signal (S)
  - Cherenkov signal (Q)
- Calibrate both signals with e-
- Unfold event by event f_{em} to obtain corrected energy

$$S = E\left[f_{em} + \frac{1}{(e/h)_S}(1 - f_{em})\right]$$

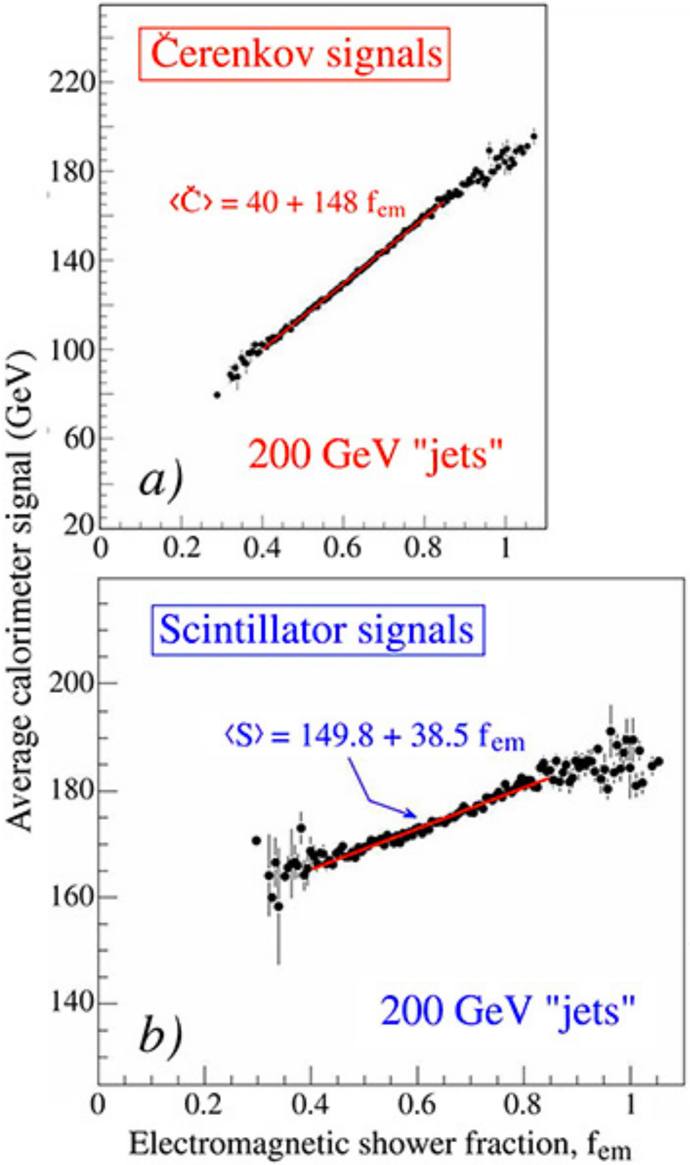
$$Q = E\left[f_{em} + \frac{1}{(e/h)_Q}(1 - f_{em})\right]$$

$$\boxed{E = \frac{S - \chi Q}{1 - \chi}}$$

with $\chi = \frac{1 - (h/e)_S}{1 - (h/e)_Q} \sim 0.3$



Measuring h/e



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

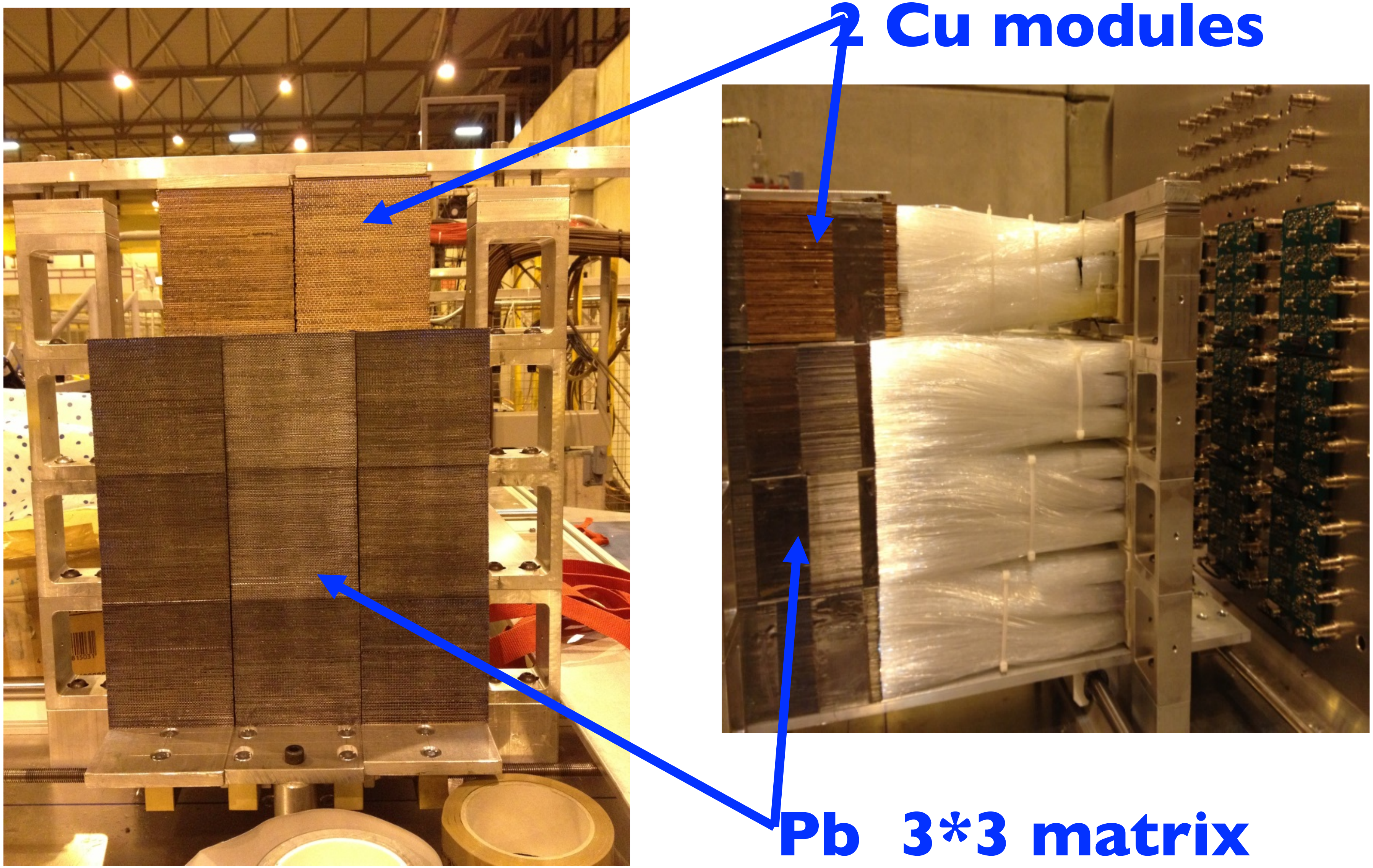
$$S/E = f_{em} + (h/e)_s \times (1 - f_{em})$$

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

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

From the linear fit it is possible to determine the (e/h) values for both calorimeter structure (scintillation and Cherenkov)

The dual readout fiber calorimeters



2 Cu modules

Pb 3*3 matrix

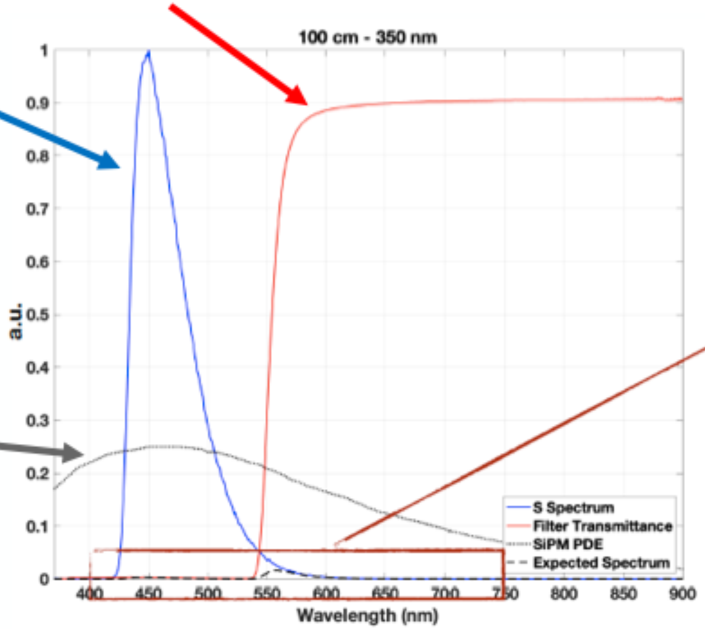
Scintillation Light attenuation: 2018

- To operate the SiPMs at nominal over-voltage, we interposed a yellow filter between the sensors and the fiber tips
- A series of preliminary measurements has been performed in the lab in order to select the proper attenuation ratio

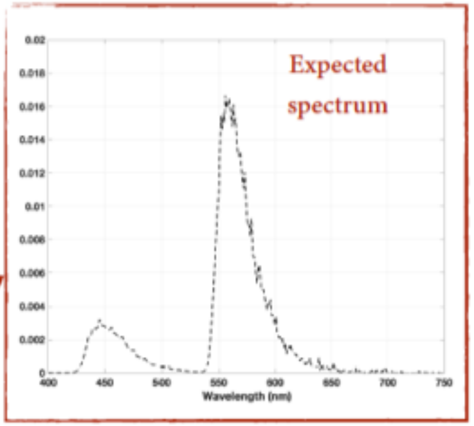
Yellow filter: transmittance spectrum (measured)

Scintillating fiber: emitted light spectrum (measured)

SiPM: Photodetector efficiency (from datasheet)



Expected spectrum and its attenuation

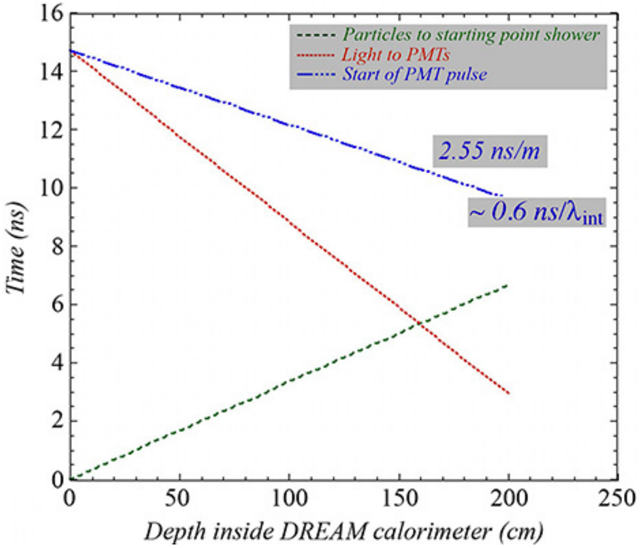


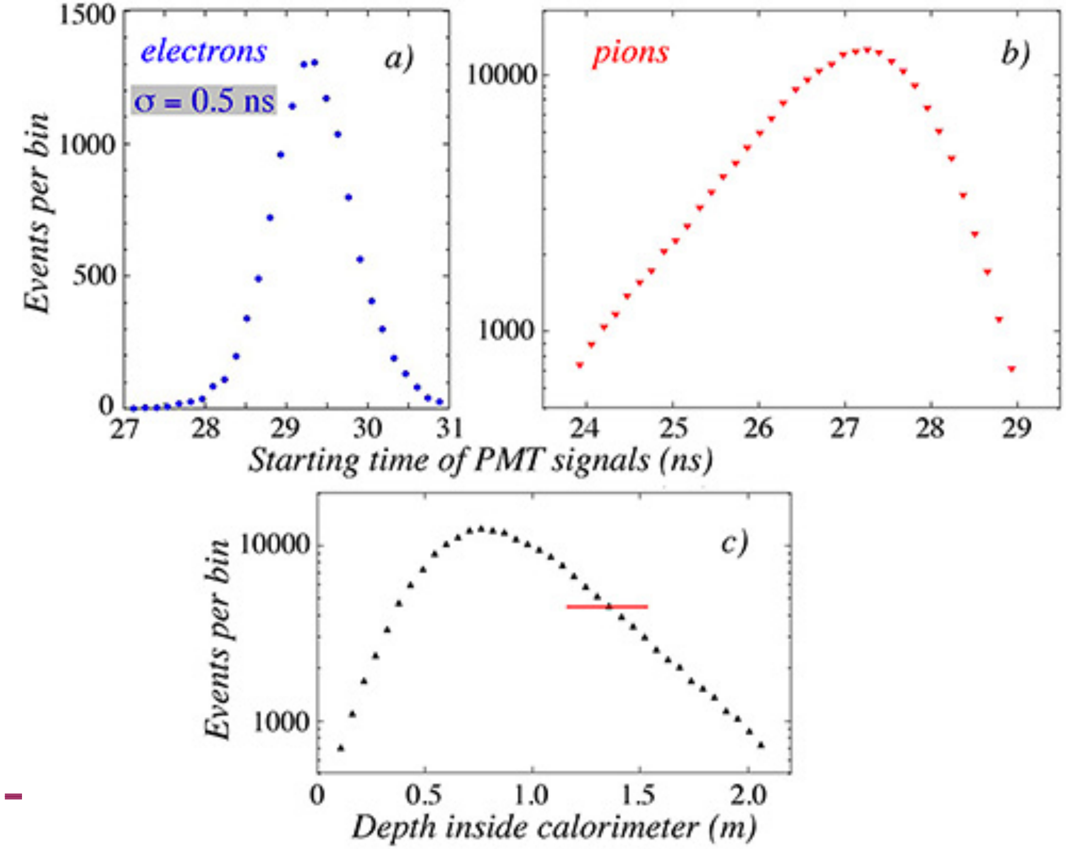
$$\text{Attenuation}\left(\frac{A_{noFilter}}{A_{Filter}}\right) = \mathit{77\ times}$$

Light attenuation and longitudinal profile

Depth at which light is produced in had shower fluctuate at the level of a $\boldsymbol{\lambda}_{int}$ (~25 cm in RD52 calo)

Costant term (~ 1%) due to light attenuation (8m per Scintillation and 20m for Cherenkov)





Particles travel ~ c

Light in media travel at c/n

Using PMT signal starting time it is possible to correct for light attenuation effect