Dual-Readout Calorimeter

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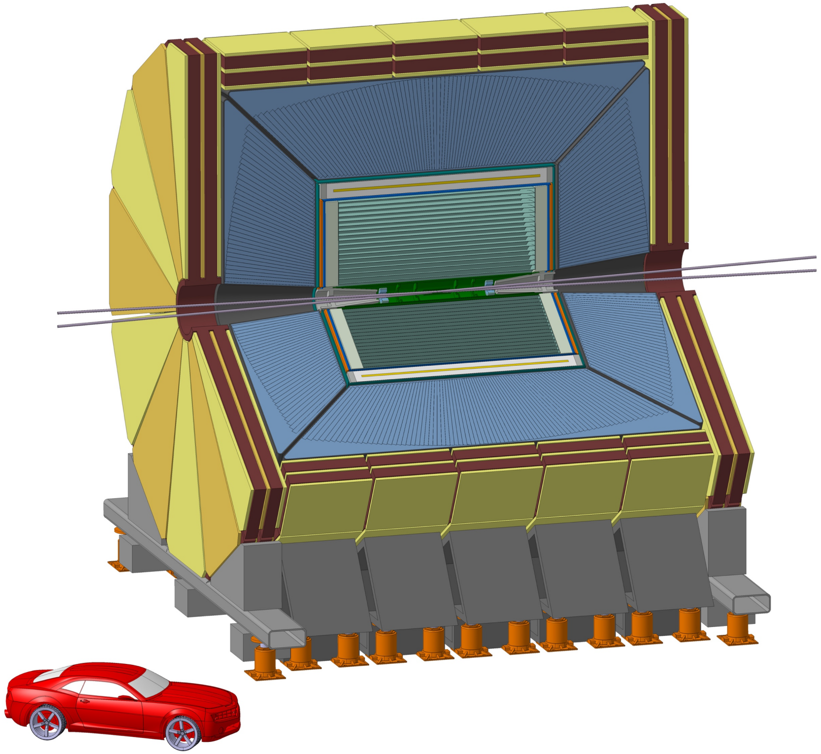
On behalf of the IDEA proto-collaboration

Outline



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

More in Elisa's talk

IDEA: Innovative Detector for Electron-positron Accelerators

Dual-readout in a nutshell

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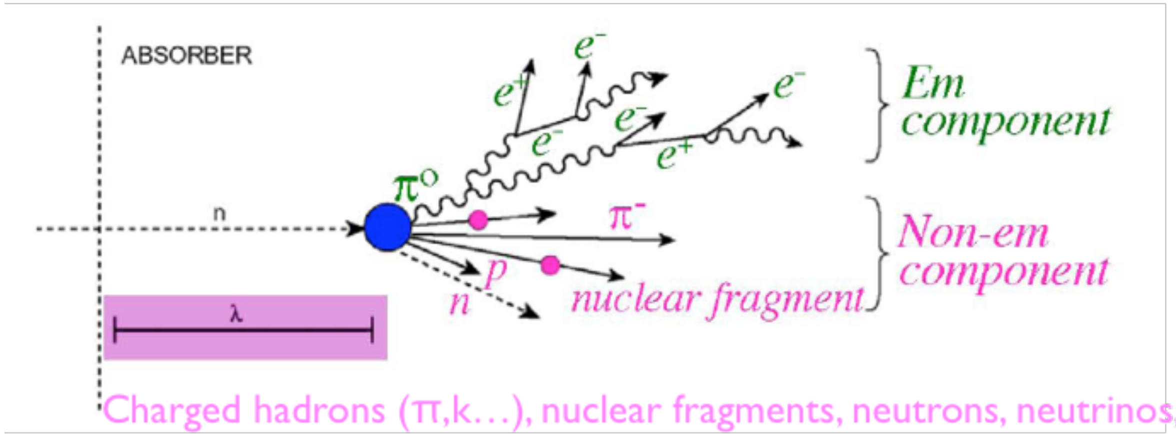
electrons positrons, photons, π^0



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

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

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

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

Dual-readout in a nutshell

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

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

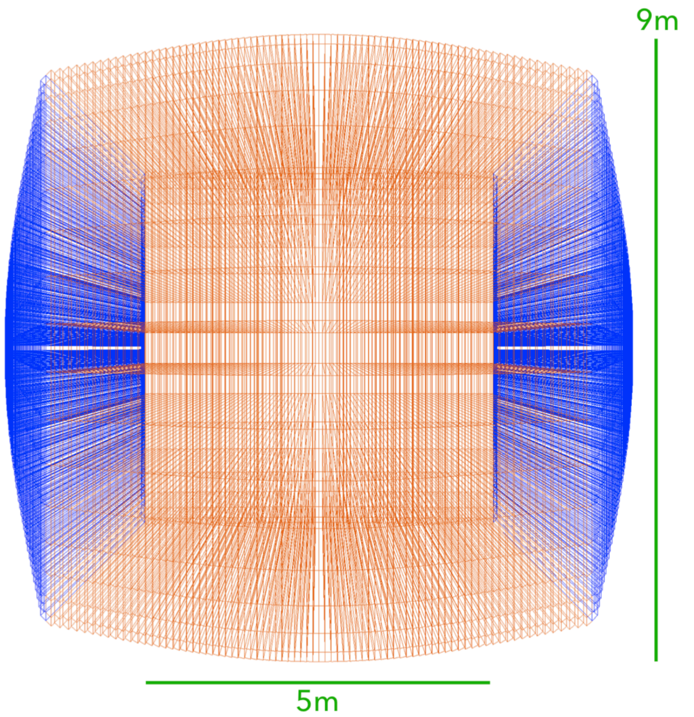
$$cotg\,\theta = \frac{1 - (h/e)_S}{1 - (h/e)_C} = \chi$$

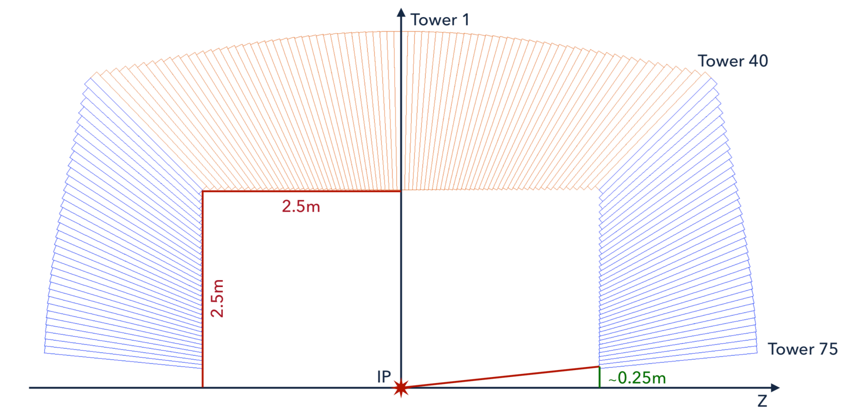
e/h ratios (c = $(h/e)_c$ and s = $(h/e)_s$ for either Cherenkov or scintillation structure) can be measured

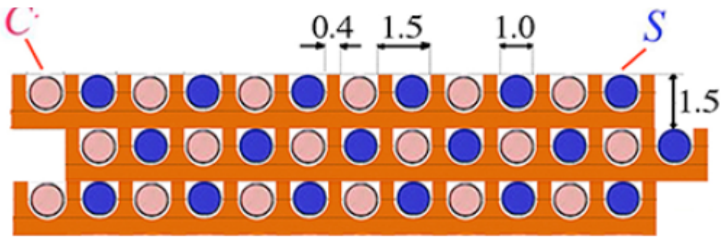
Θ and χ are independent of both energy and particle type

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

G4 Simulation for performance studies







Theta coverage up to ~0.1 rad

75 projective elements x 36 slices = 2700 tower

Tower size: $\Delta\theta = 1.125^\circ$

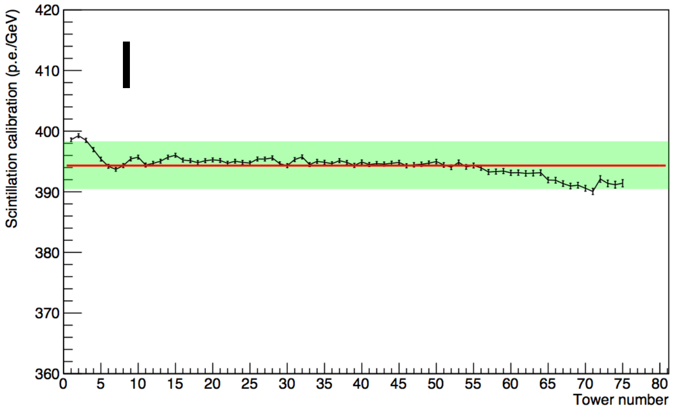
$\Delta\phi = 10^\circ$

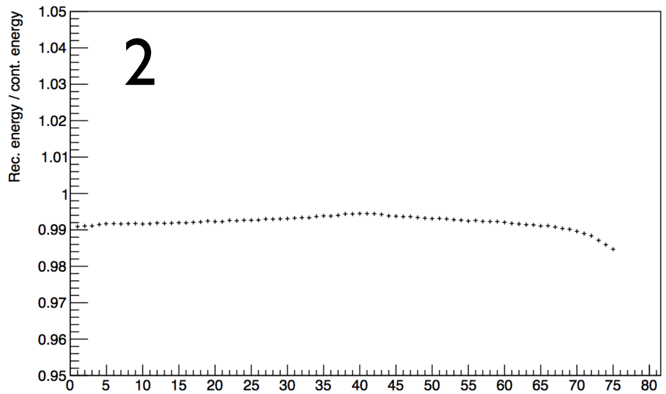
Copper + scintillating and Cherenkov fibers

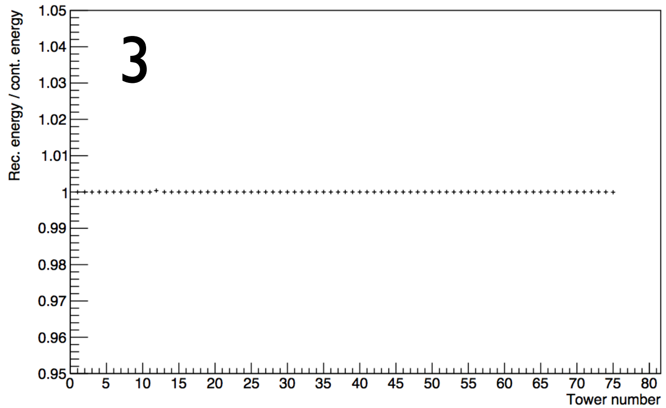
Read out the single fiber: 130 M channels

Calibration at the EM scale

1. Equalization constants are extracted per each tower by sending electrons of known energy and collecting signals (photo-electrons).
2. Electrons energy reconstructed by summing over all towers' signals multiplied by the tower equalization constant….
3. Calibration constants are applied to take into account the different response while sampling electromagnetic showers tails.







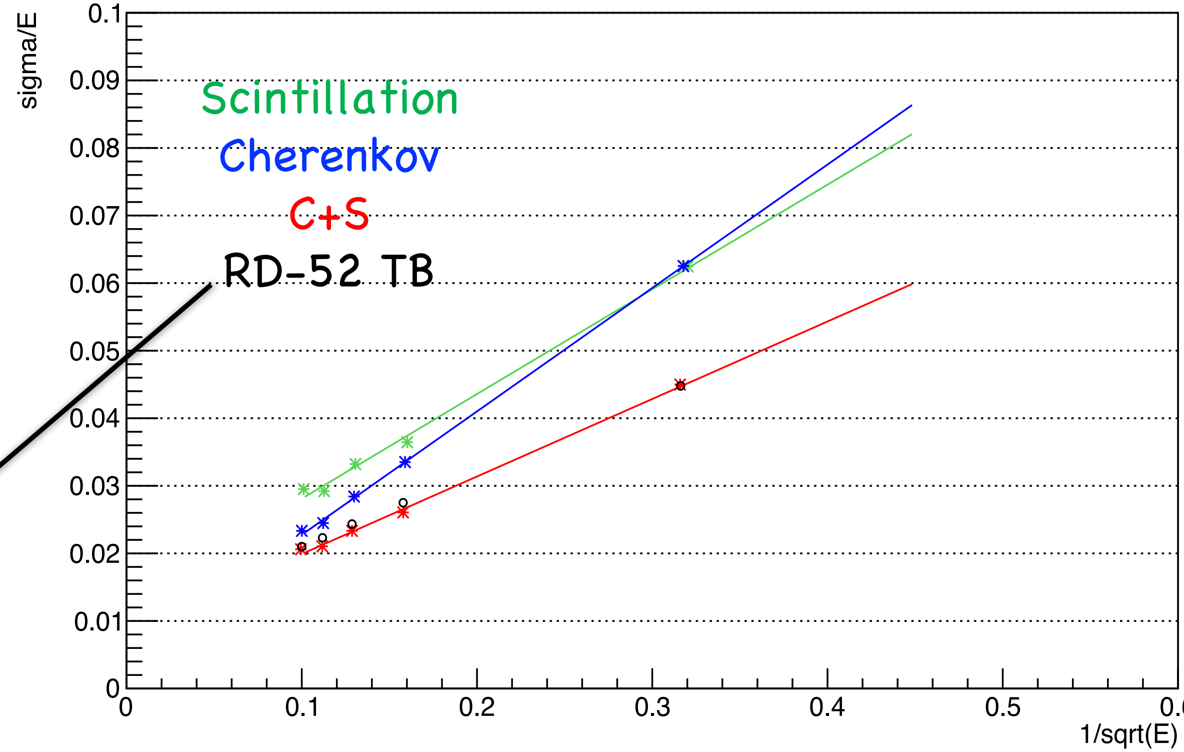
Em. Performance: energy resolution

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

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

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

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



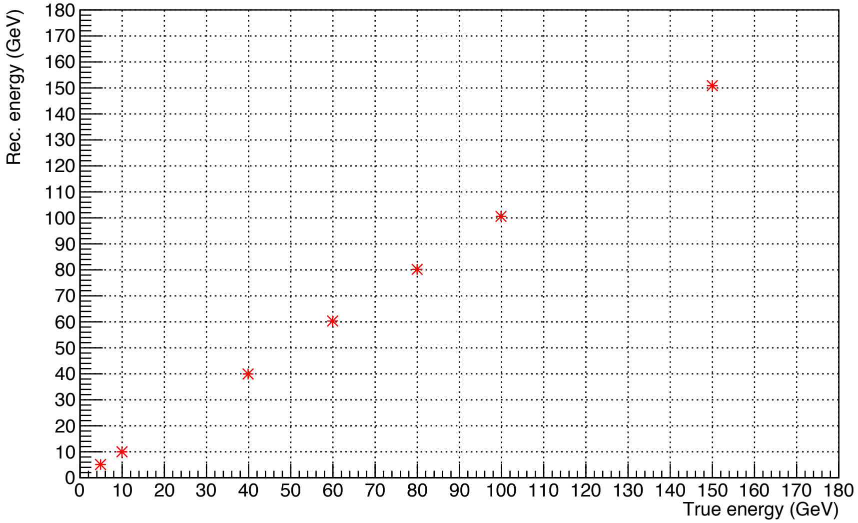
RD52 TB data
Copper-fibers module
NIMA 735, 130(2014)

Em. Performance: energy resolution

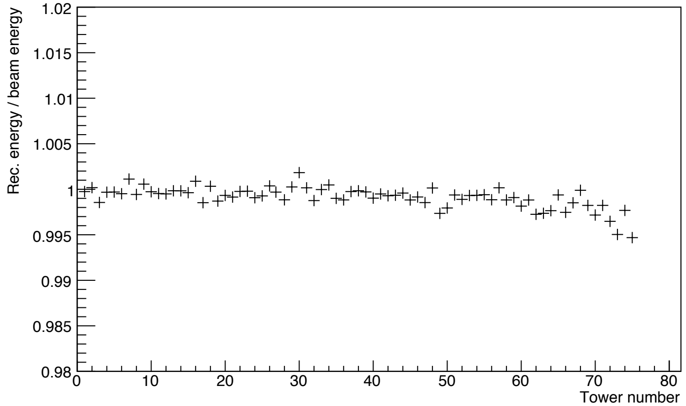
Response uniformity:

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

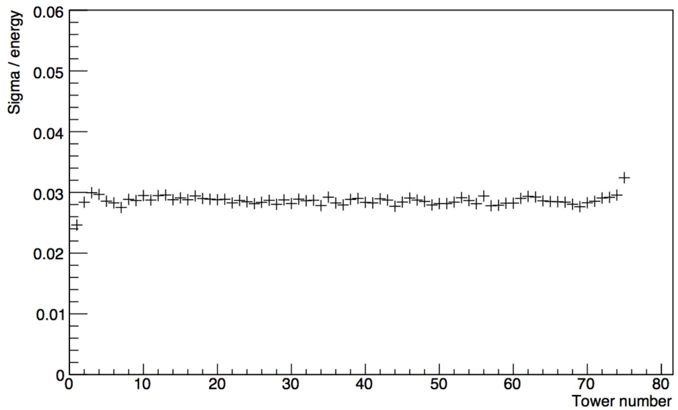
Reco vs True energy



Reco/true energy vs tower num



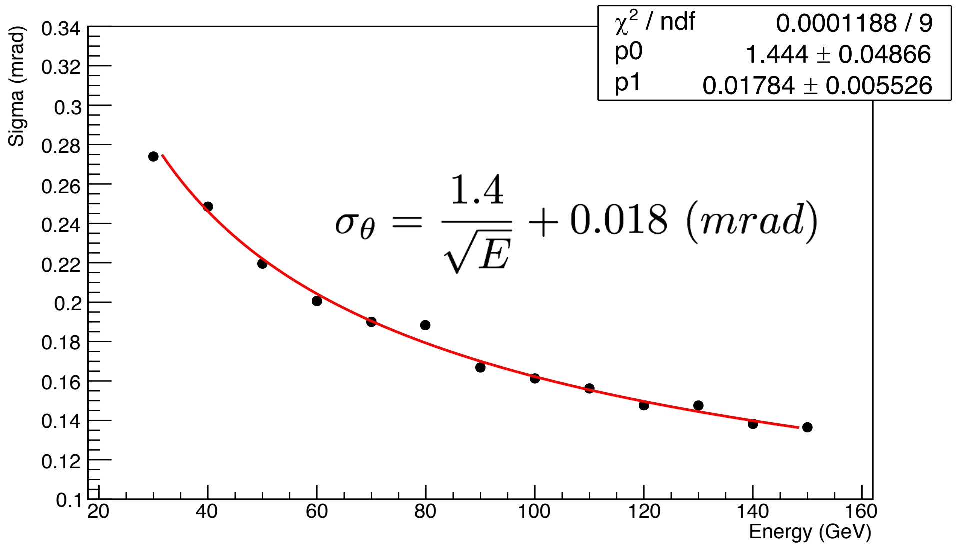
σ/E @40 GeV vs tower num

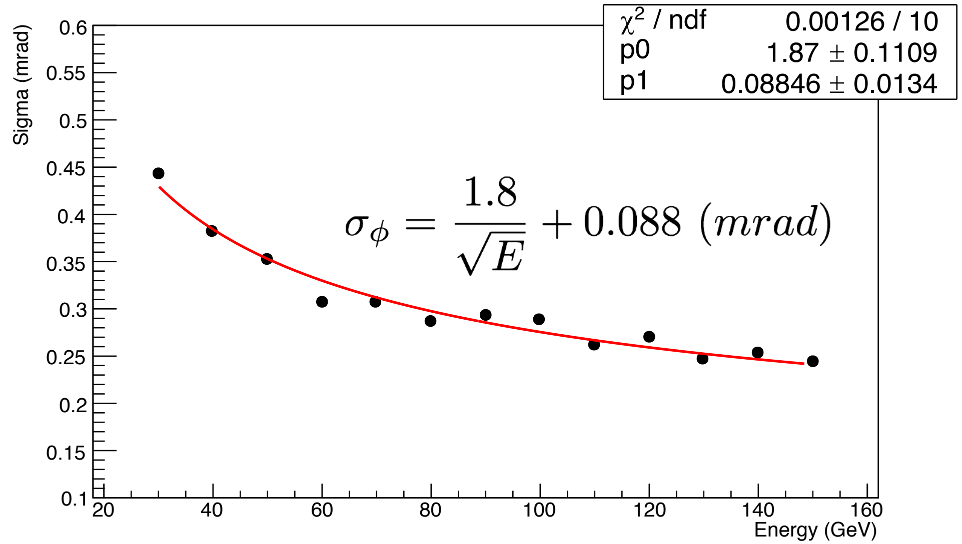


Em. Performance: angular resolution

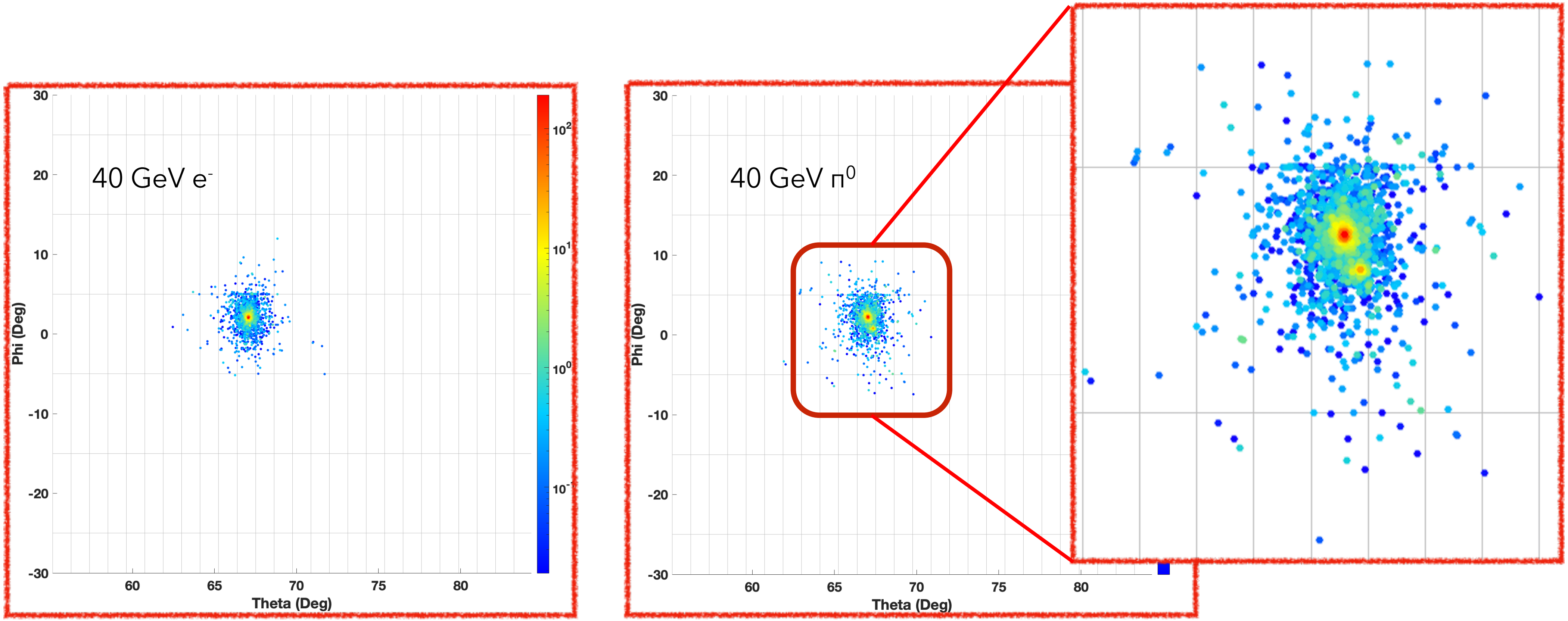
Position of impinging particle reconstructed with barycentre method with both scintillation and Cherenkov signals (combination of two signals)

All the fibers are readout independently (to be revaluated if grouping applied)





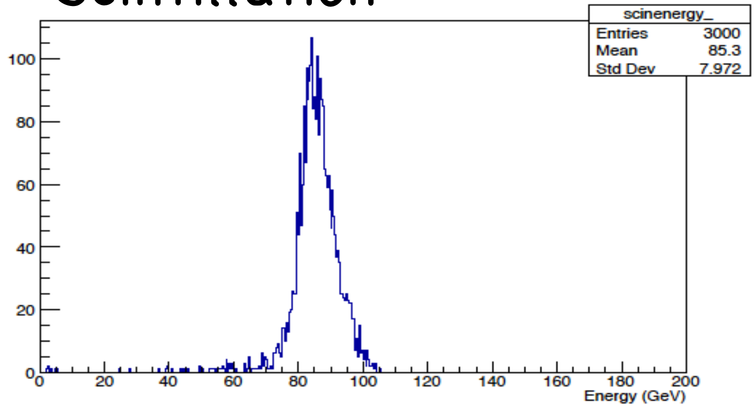
Di-photon performance



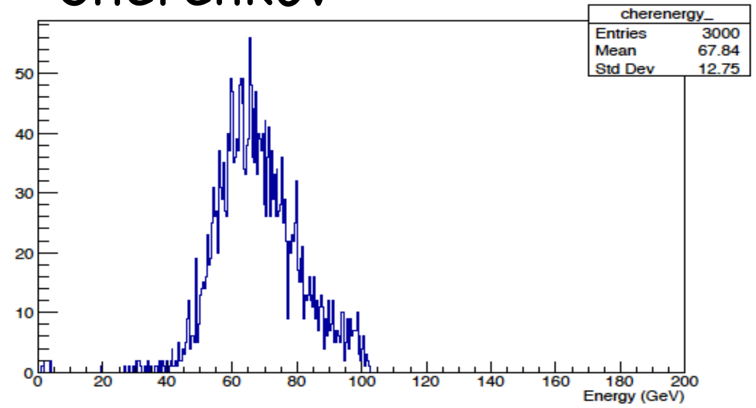
Had. Performance: pion energy resolution

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

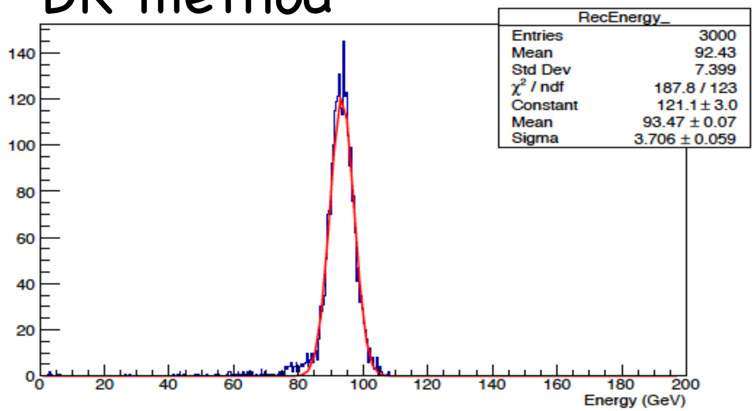
Scintillation

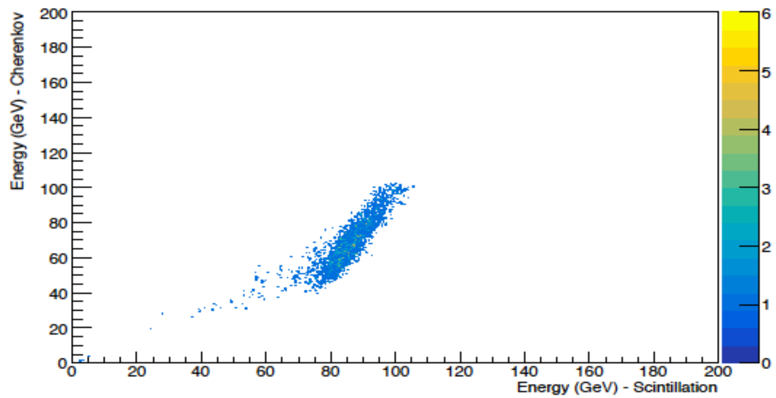


Cherenkov

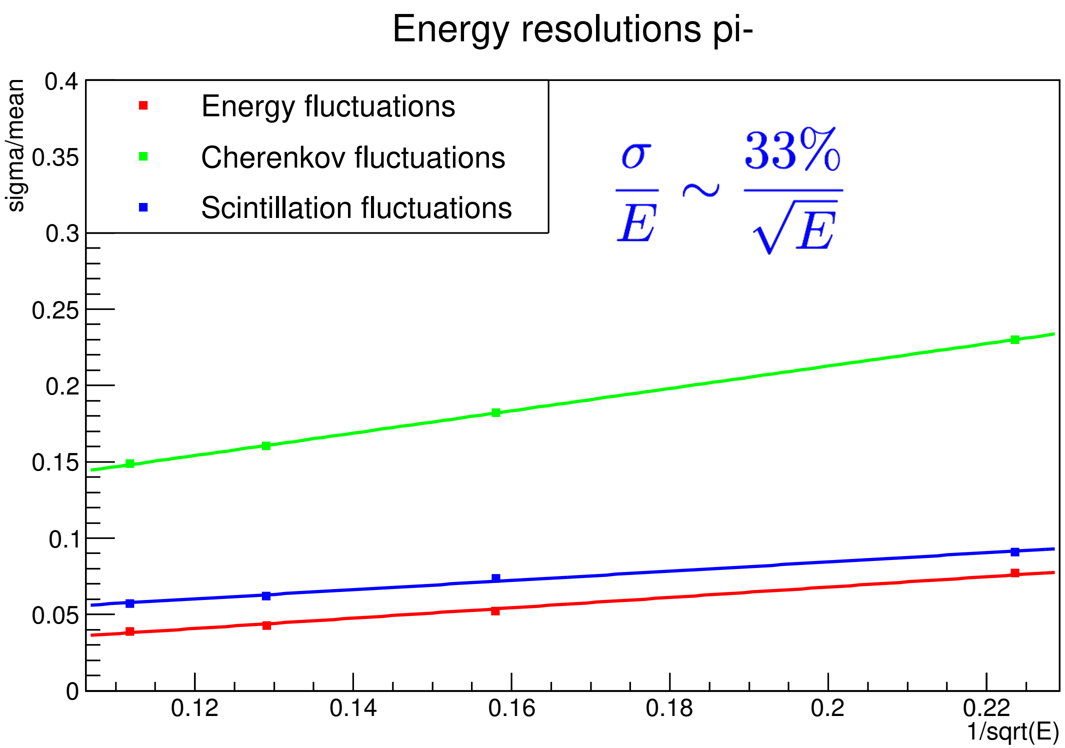


DR method

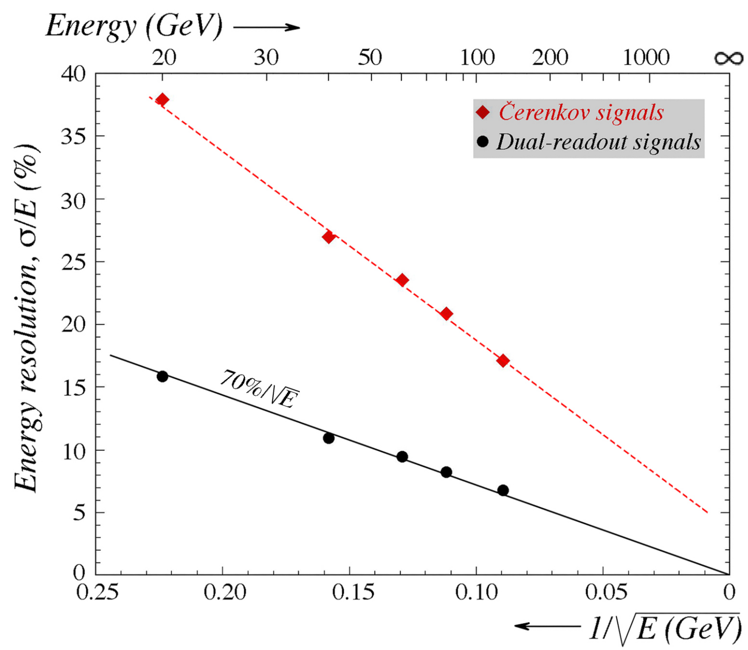




Had. Performance: pion energy resolution



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



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

Had. Performance: jet energy resolution

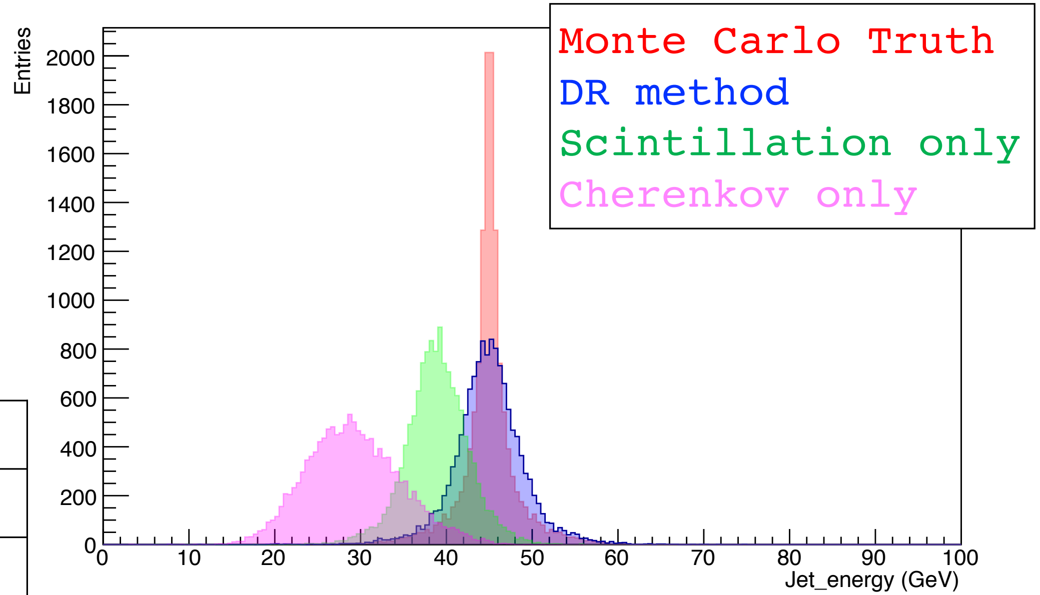
Jet reconstruction:

- 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 (Duhram kt algorithm)

	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

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

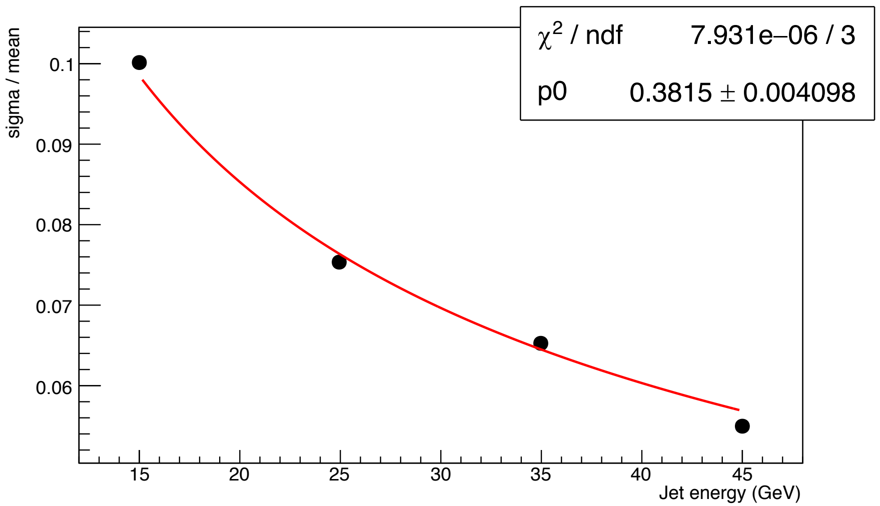
90 GeV center-of-mass



PYTHIA8 + GEANT4 + FASTJET

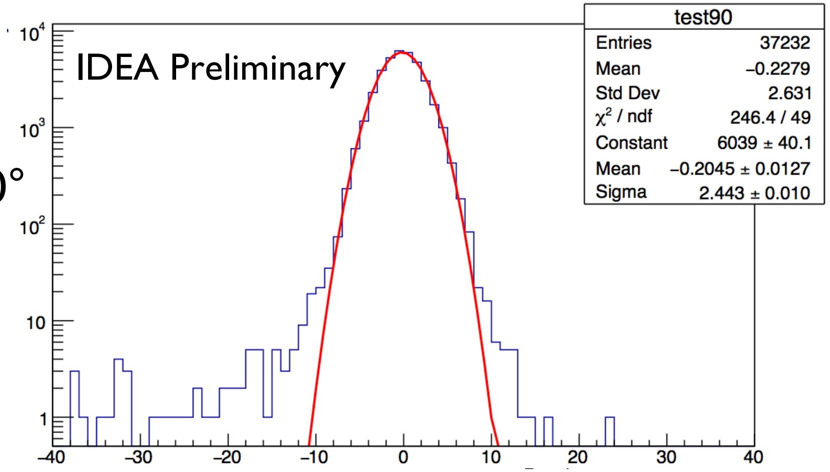
Had. Performance: jet energy resolution

PYTHIA8 + GEANT4 + FASTJET



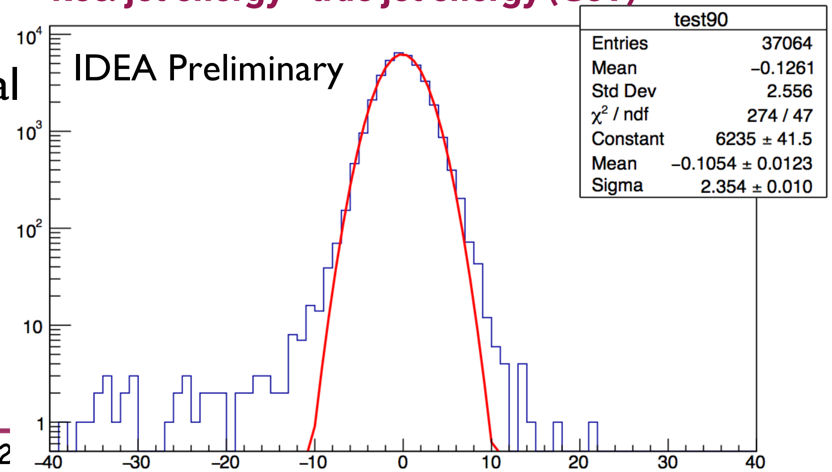
$$\frac{\sigma}{E} = \frac{38\%}{\sqrt{E}}$$

Material Budget: 1 X_0 at 90°



Rec. jet energy - true jet energy (GeV)

No Material Budget

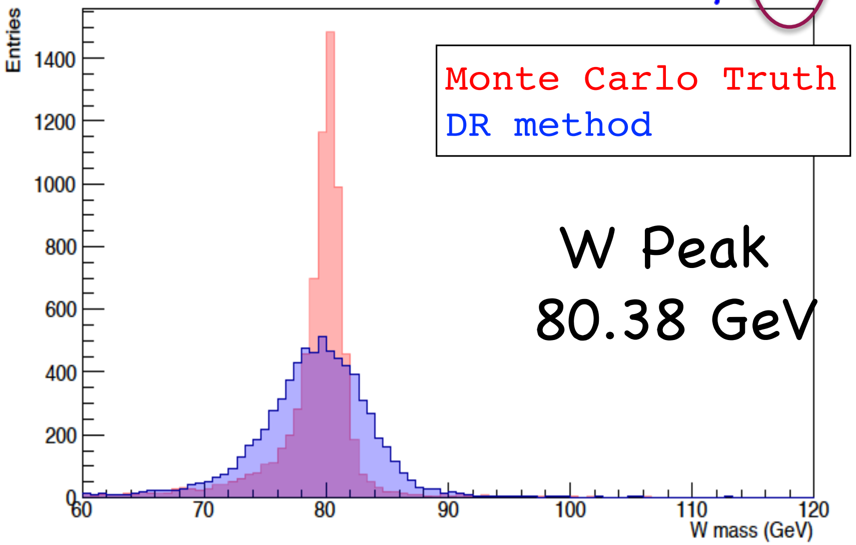


Rec. jet energy - true jet energy (GeV)

W and Z reconstruction

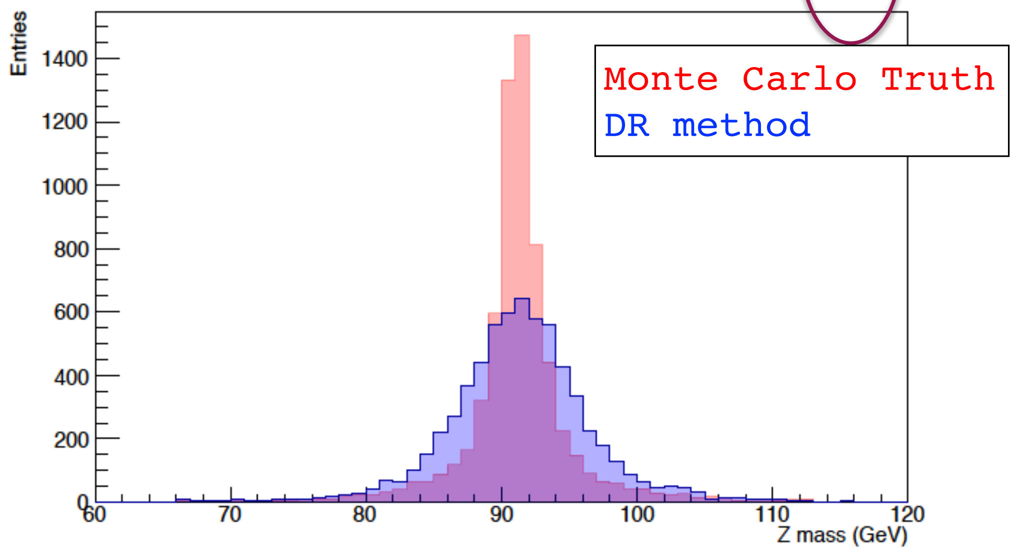
PYTHIA8 + GEANT4 + FASTJET

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



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

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



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

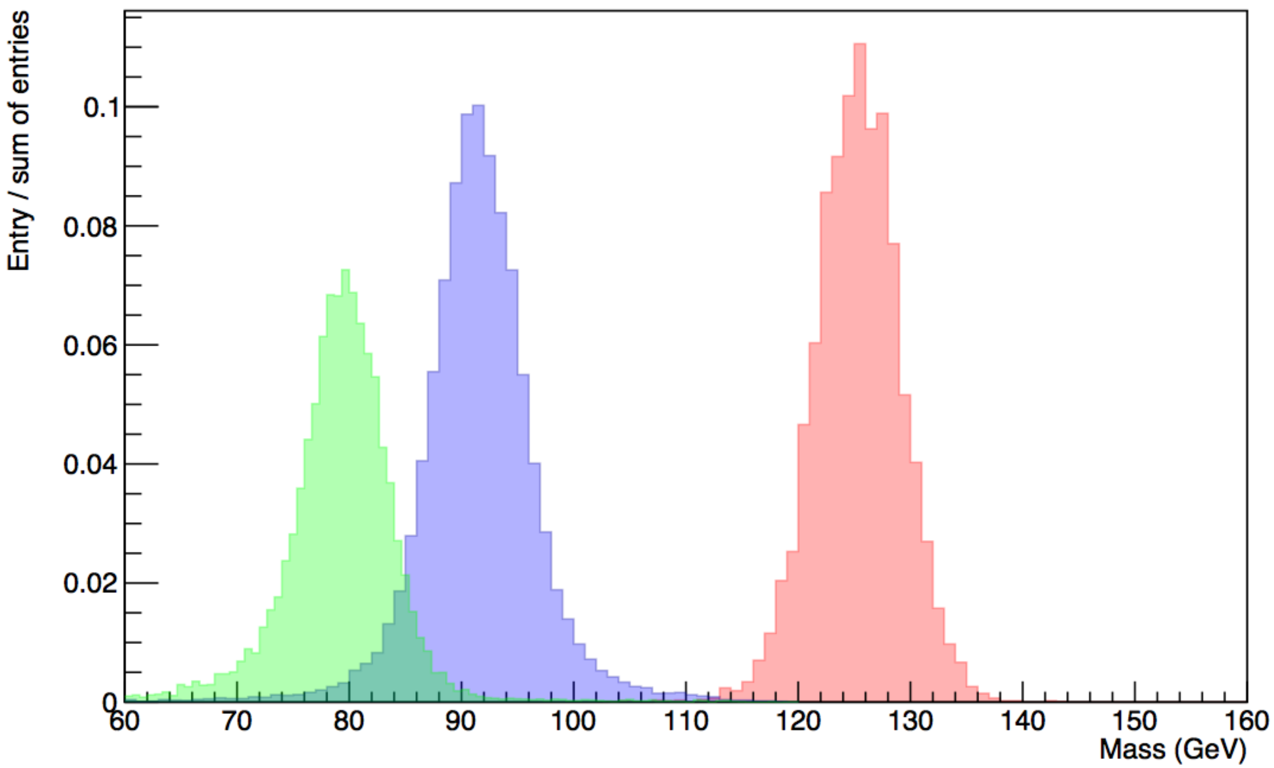
W/Z/H 2-jets final states

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

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

$$e^+e^- \rightarrow HZ \rightarrow bb\nu\nu$$

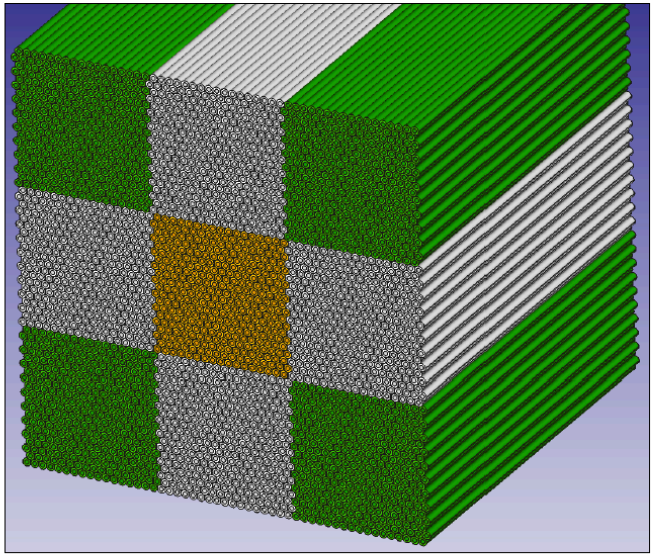
PYTHIA8 + GEANT4 + FASTJET



Contribution of tagged muon from Monte Carlo truth subtracted from the calorimeter signal

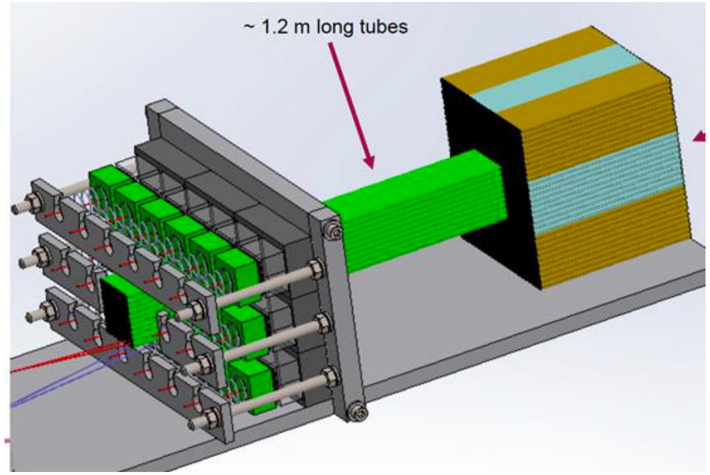
Only decays to u,d,s,c
c semileptonic decays excluded

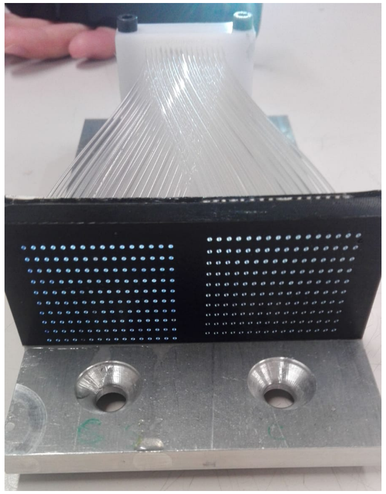
Next step: prototype in 2020

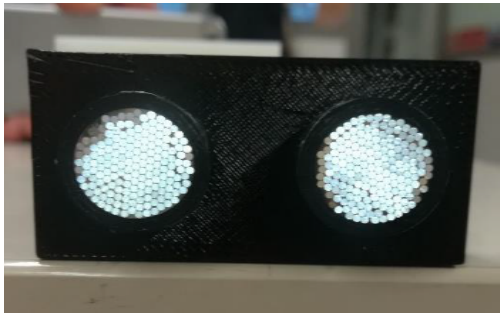


10x10 cm^2 divided in 9 towers, 1m long
16x20 capillary each (160 C + 160 S)
- 2mm outer diameter, 1mm inner diameter
- Material: brass CuZn37

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

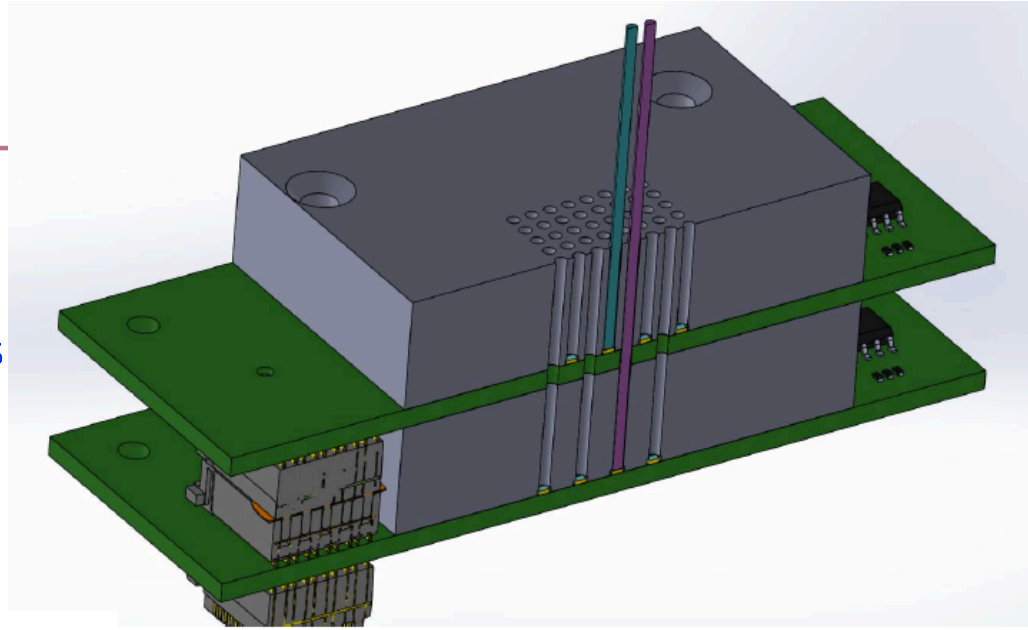


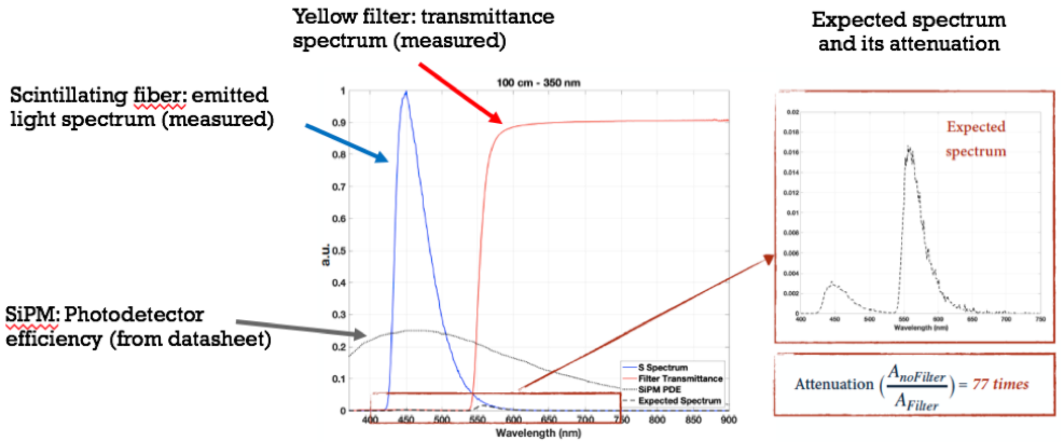


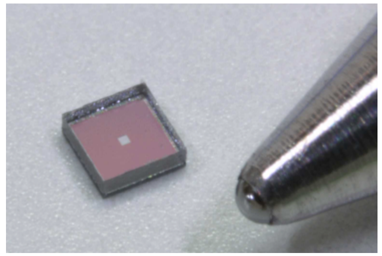


SiPM Readout: RD52 TB

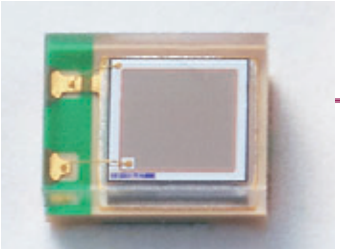
- Dual-layer SiPM readout in previous TB
  - Avoids optical cross-talk
- Saturation studied with dedicated test beams
  - 25 µm pixels OK for Cherenkov
  - Yellow filter used to control saturation in Scintillation channel







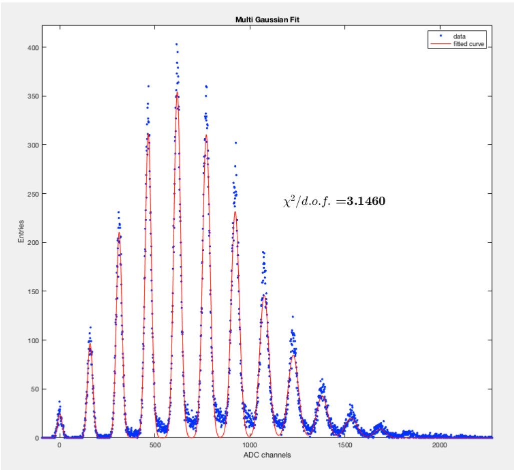
The sensors used were 25 µm cell pitch (S13615-1025)



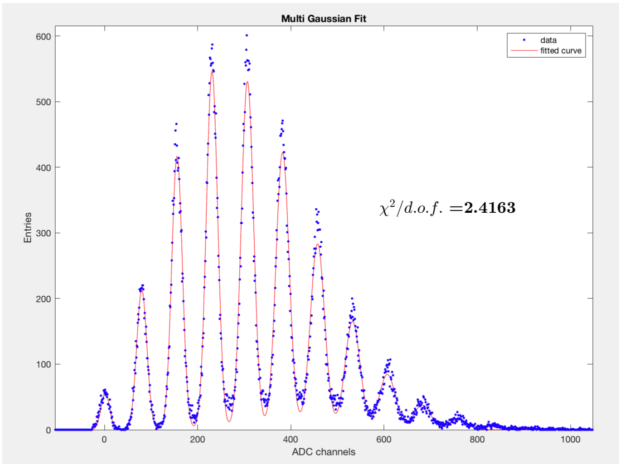
First test with new SiPM

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%



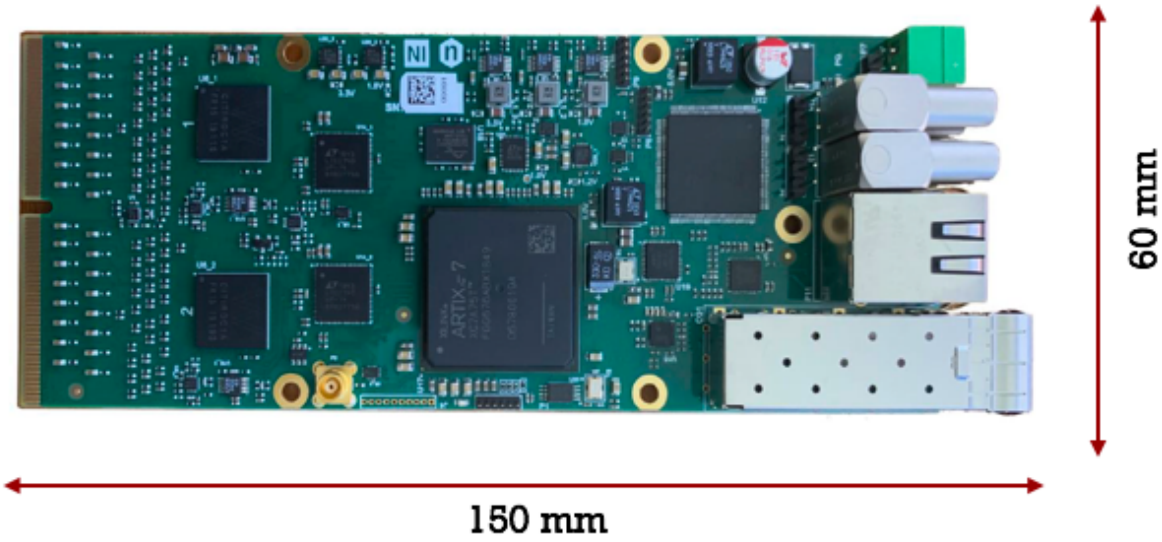
Sensor: S14160-1310PS
Cell size =10μm
Vbias = 42.5 ($\approx$ 4.5 V over breakdown)
Signal amplification: 40dB
Measured Xtalk = 1.8%



Proposed readout for 2020 Prototype

If the Citiroc1A 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

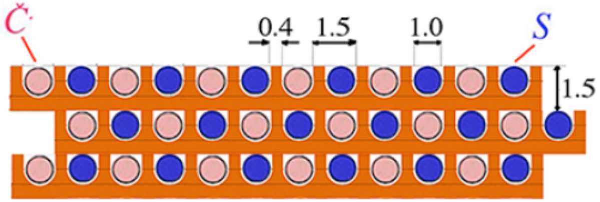


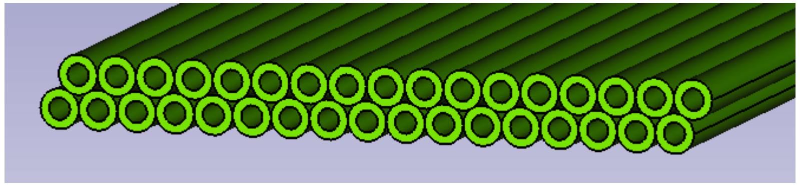
The basic principle

- 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

Challenges in 2020 prototype

Verify changes in mechanical construction procedure





Challenges in the Readout

- Improve the linearity response:
  - SiPMs with larger dynamic range (smaller cell size)
  - … in addition to yellow filters to attenuate the scintillating light
- Increased number of channels looking for a scalable and cost effective solution
  - The use of CITIROC 1A is under study
  - The SiREAD could allow for the longitudinal segmentation using the timing
- Signal grouping
  - possibility to be studied in order to reduce the number of channels to readout

Summary

Dual-readout calorimetry development in the IDEA framework

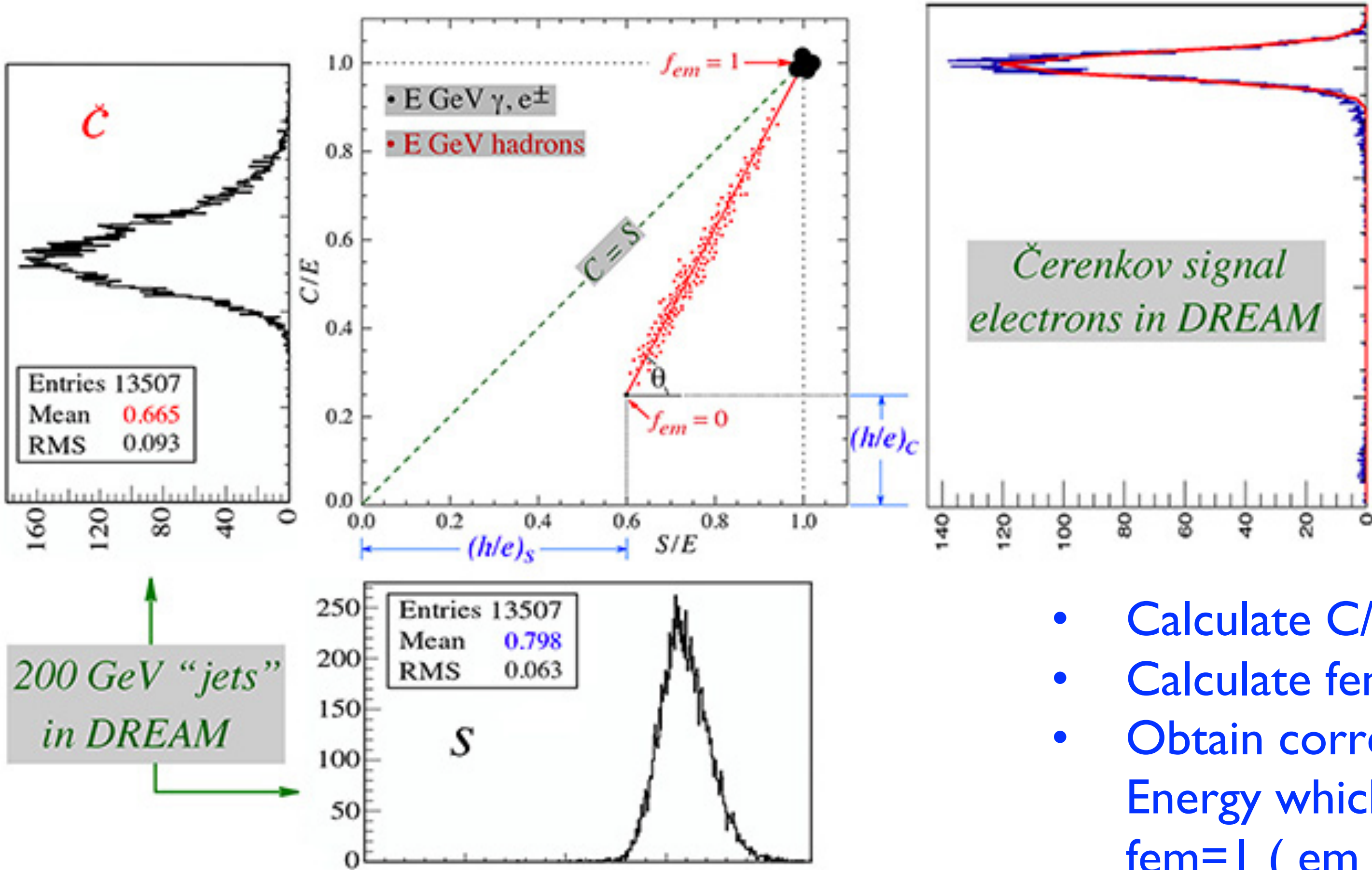
- A number of new performance studies with full simulation, tuned on TB data
  - EM E resol. $11\%/\sqrt{E}$ uniform in the whole detector;
  - Optimal angular resolution ($1.4/\sqrt{E}$ mrad in θ and $1.8/\sqrt{E}$ mrad in φ) when all the fibers are readout
  - Good di-photon separation and Particle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

- 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

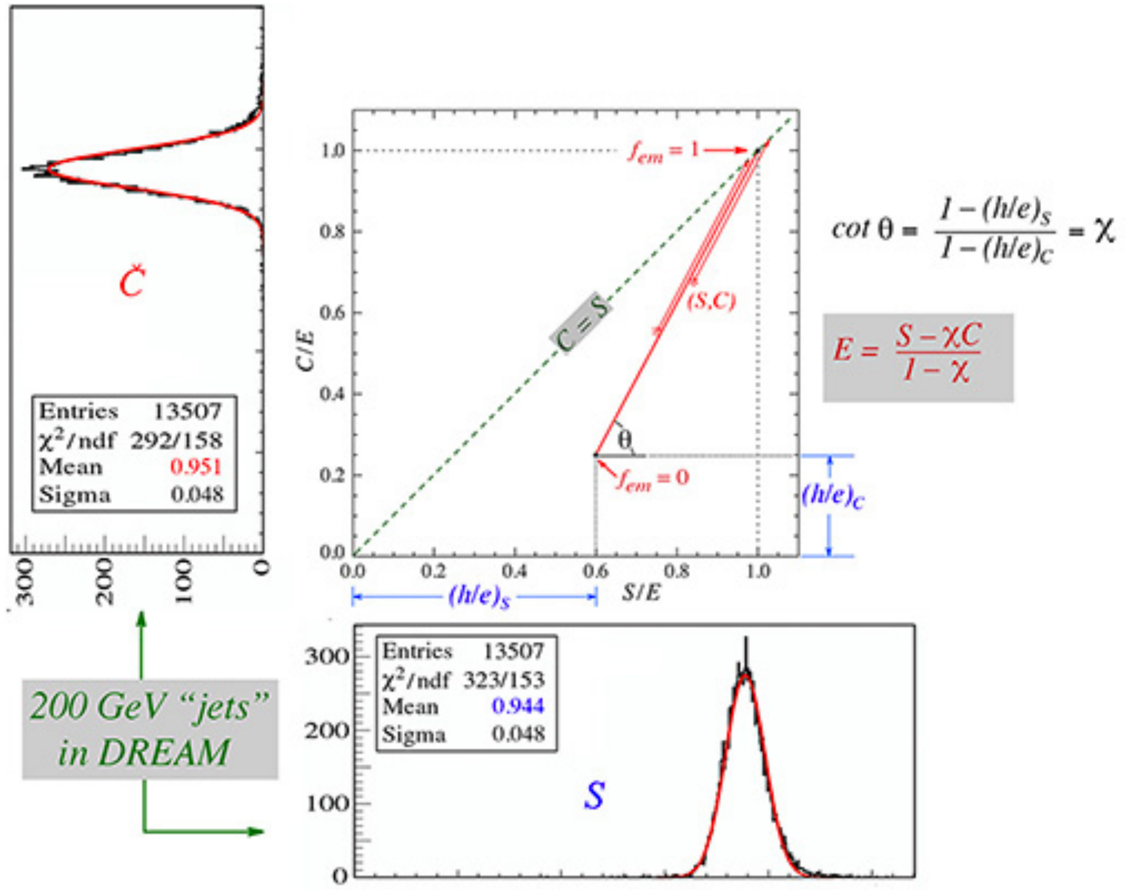
BACKUP

Before Correction



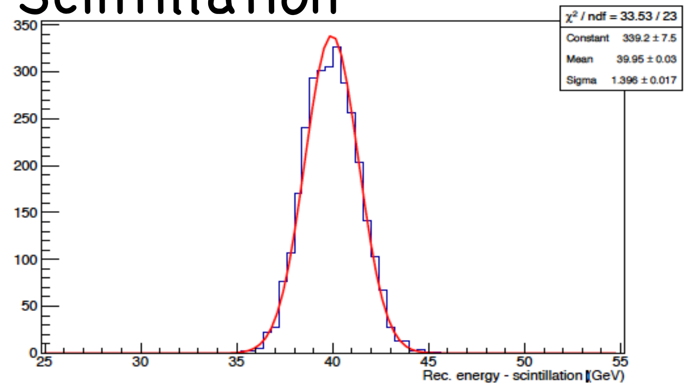
- Calculate C/S ratio event-by-event
- Calculate fem
- Obtain corrected C and S and Energy which one would obtain if fem=1 (em scale calibration)

Dual-Readout approach at work

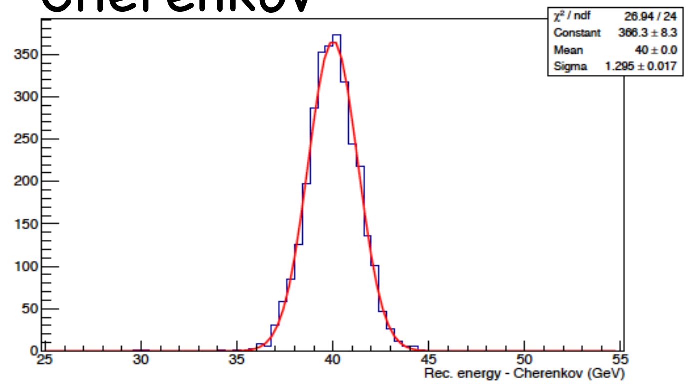


Em. Performance: energy resolution

Scintillation

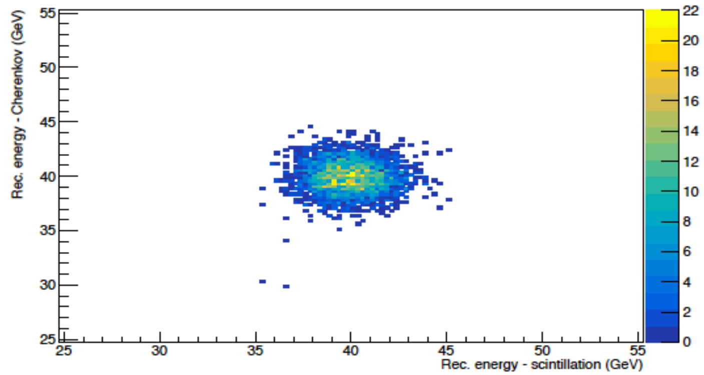


Cherenkov



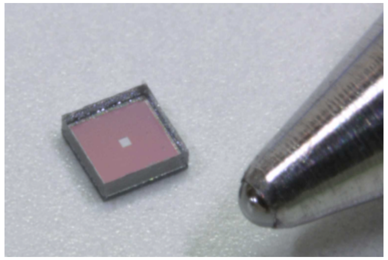
Simulated
40 GeV e-
in IDEA calo

θ=φ=1.5°

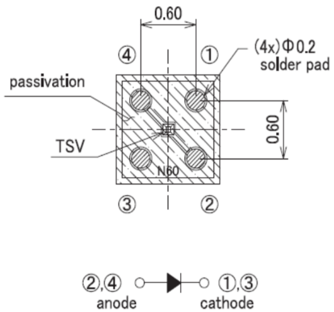


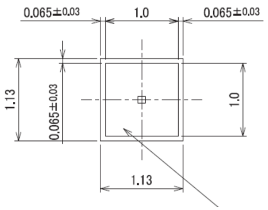
25 um cell size sensor

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



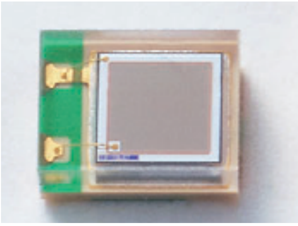
Parameters	S13615 -1025	S13615 -1050	Unit
Effective photosensitive area	1.0x1.0		mm^2
Pixel pitch	25	50	μm
Number of pixels / channel	1584	396	-
Geometrical fill factor	47	74	%





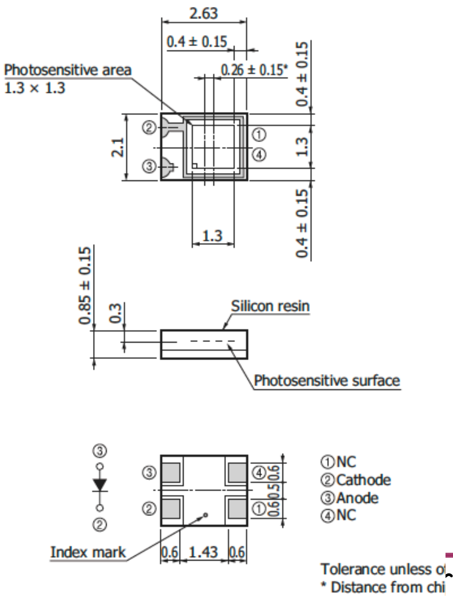
Parameters		Symbol	S13615 -1025	S13615 -1050	Unit
Spectral response range		λ	320 to 900		nm
Peak sensitivity wavelength		λp	450		nm
Photon detection efficiency at λp[*3]		PDE	25	40	%
Breakdown voltage		V_{BR}	53 ±5		V
Recommended operating voltage[*4]		V_{op}	V_{BR} + 5	V_{BR} + 3	V
Dark Count	Typ.	-	50		kcps
Dark Count	Max.	-	150		kcps
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

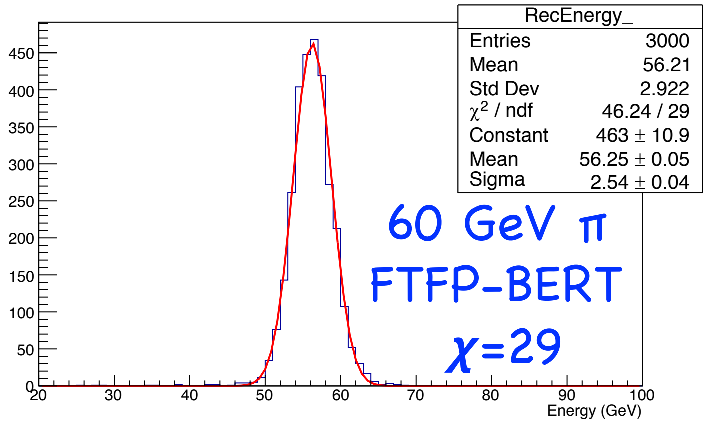


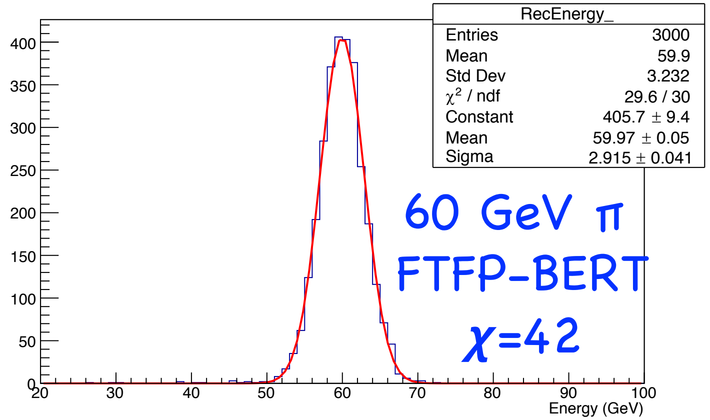
Parameter	Symbol	S14160 -1310PS	S14160 -3010PS	S14160 -1315PS	S14160 -3015PS	Unit
Effective photosensitive area	-	1.3 × 1.3	3 × 3	1.3 × 1.3	3 × 3	mm
Pixel pitch	-	10		15		μm
Number of pixels	-	16675	90000	7296	40000	-
Geometrical fill factor	-	31		49		%
Package	-	Surface mount type				-
Window	-	Silicone resin				-
Window refractive index	-	1.57				-
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	V_{BR}	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
Dark count rate*4 max.	DCR	360	2100	360	2100	kcps
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.

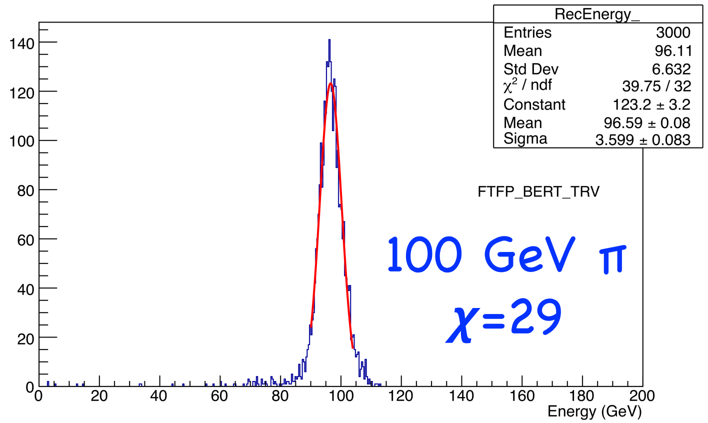


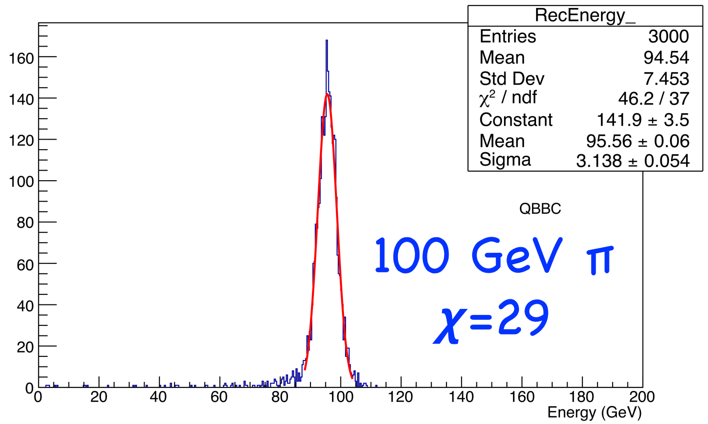
ram





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



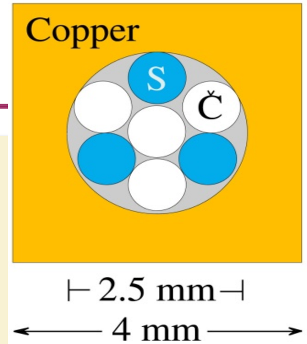


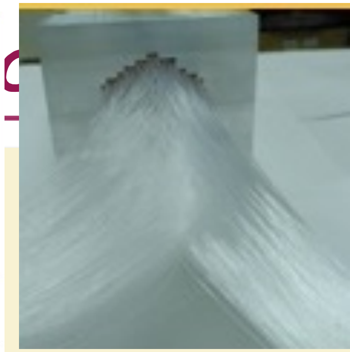
Promising preliminary results with FTFP_BERT_TRV and QBBC new phys list

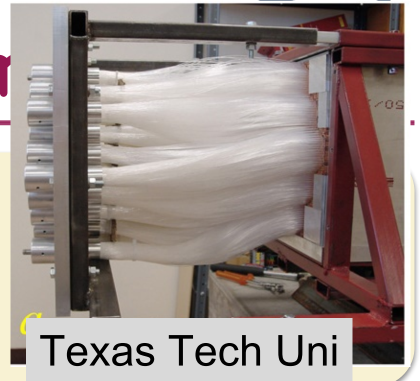
2003
DREAM

The dual-readout

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



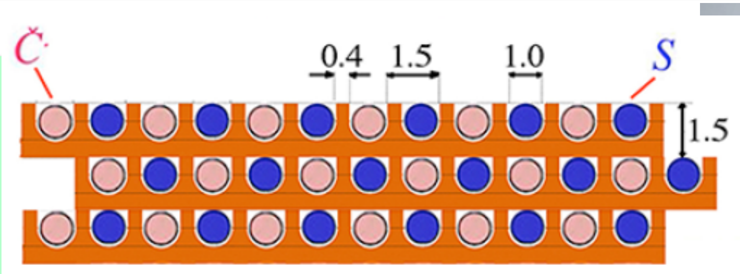


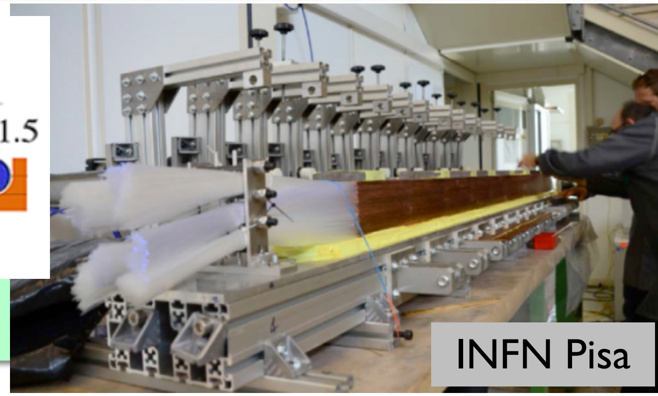


2012
RD52

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}

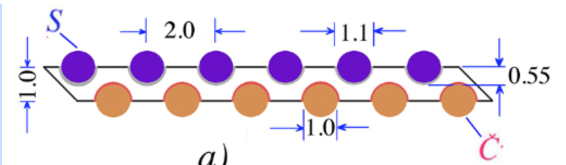


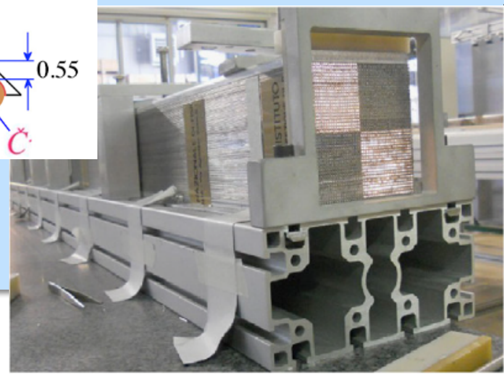


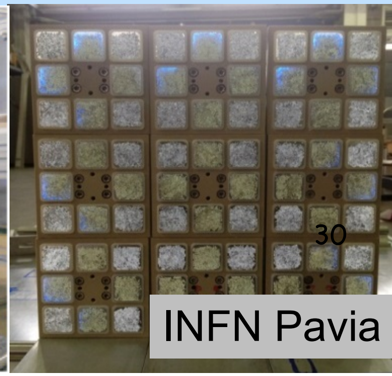
2012
RD52

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}



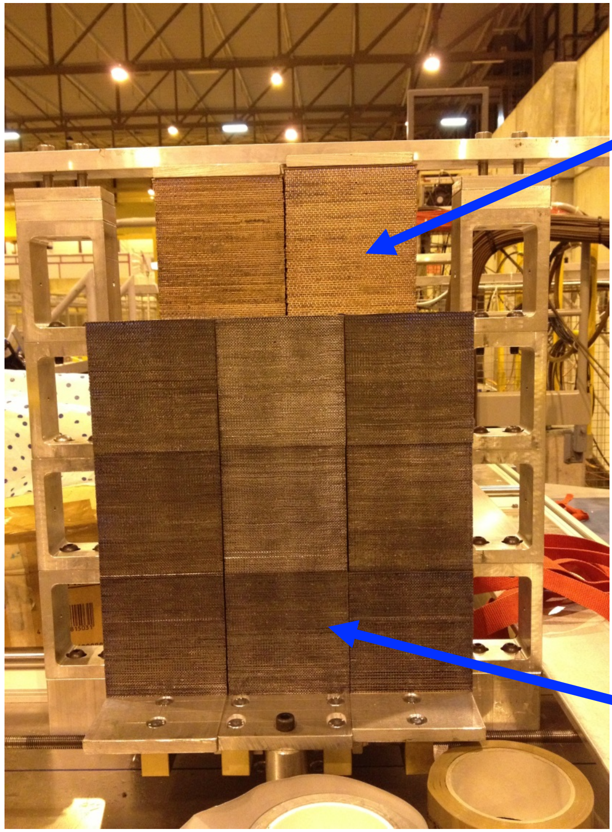


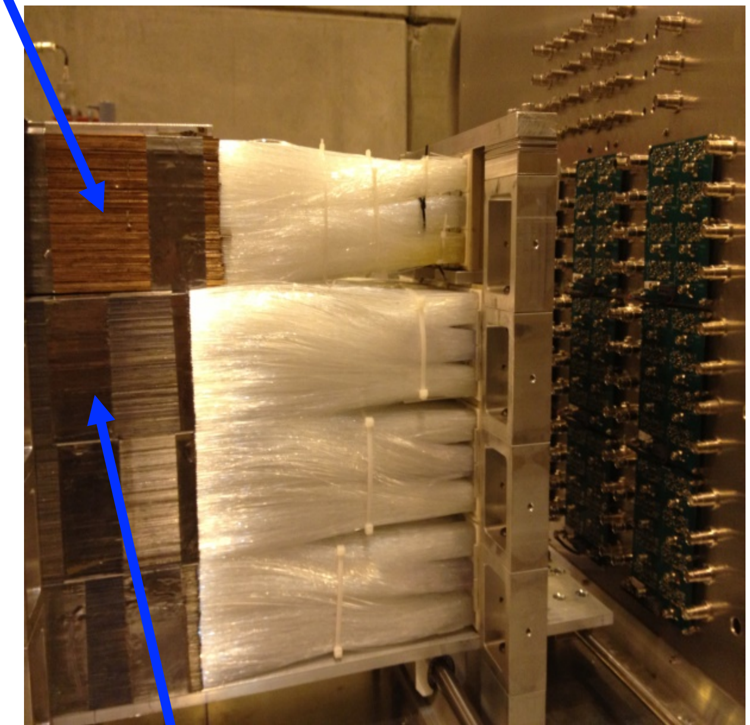


The dual readout fiber calorimeters

INFN
Istituto Nazionale di Fisica Nucleare

2 Cu modules



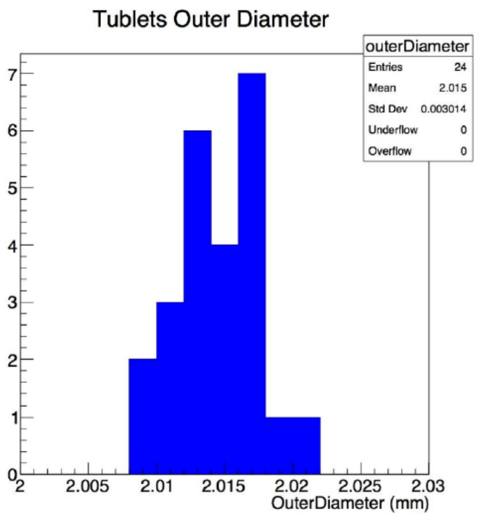


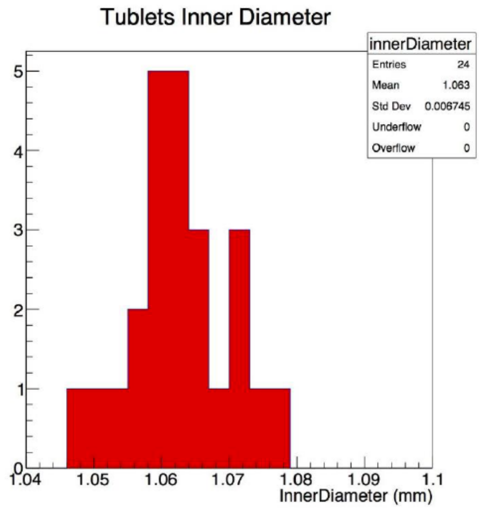
Pb 3*3 matrix

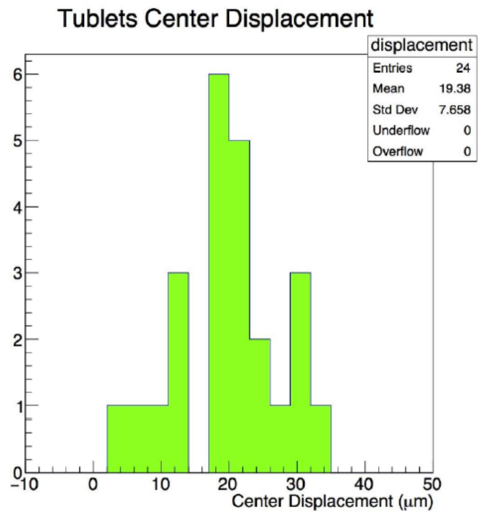
Test on tublets

Istituto Nazionale di Fisica Nucleare

Under the test 2 tubes were cut with electro erosion in pieces 1cm long
12 such pieces were measured twice with microscope + measuring system







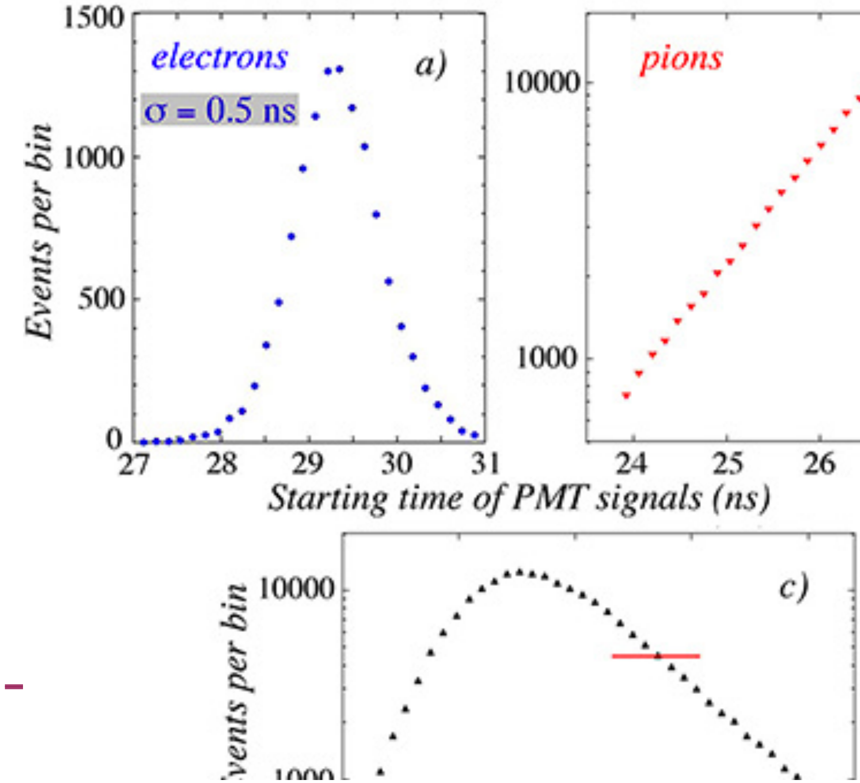
Outer Diameter:
Average: 2.015 mm
STD 3 μm

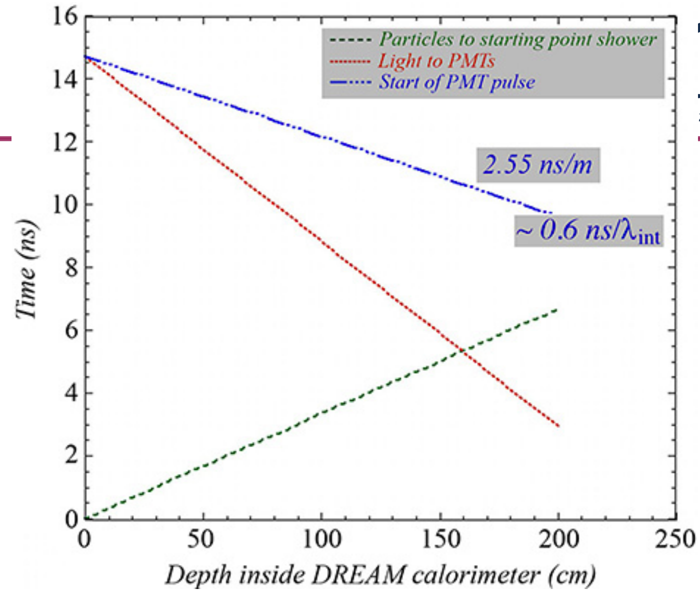
Inner Diameter:
Average: 1.063 mm
STD 7 μm

Concentricity Offset
Average 19 μm
STD 8 μm

Depth at which light is produced in had shower fluctuate at the level of a λ_{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

Signal linearity results

Istituto Nazionale di Fisica Nucleare

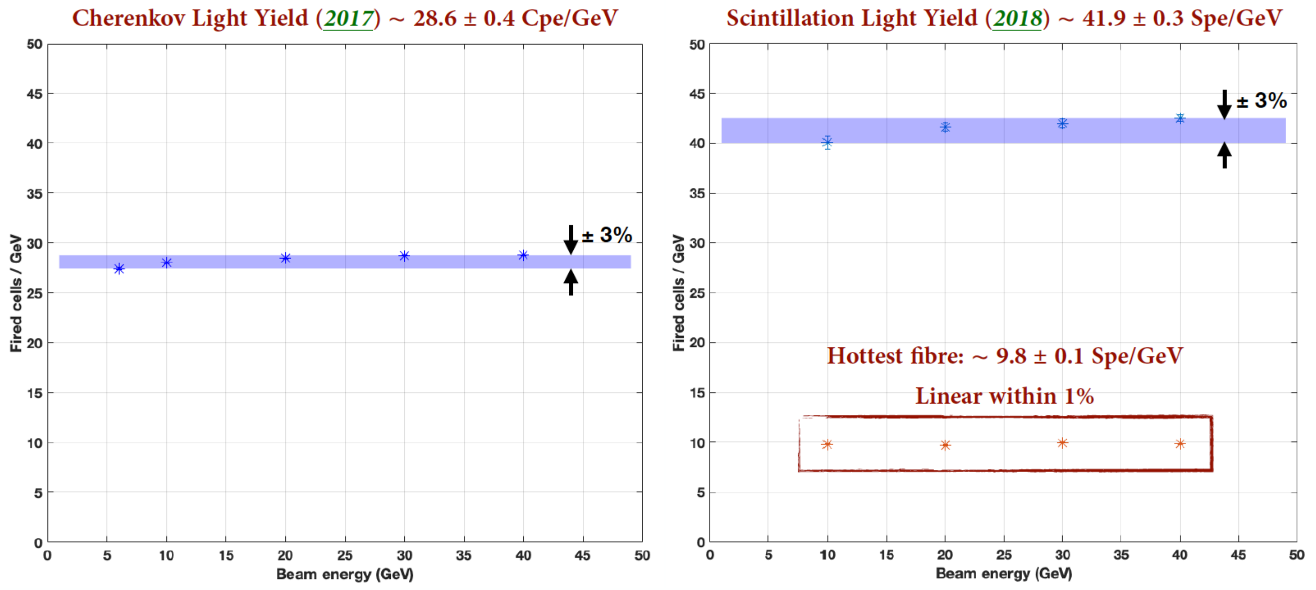
Measurement conditions (containment correction not applied):

* Values already corrected for the sensor non linearity response

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

Temperature stability correction:

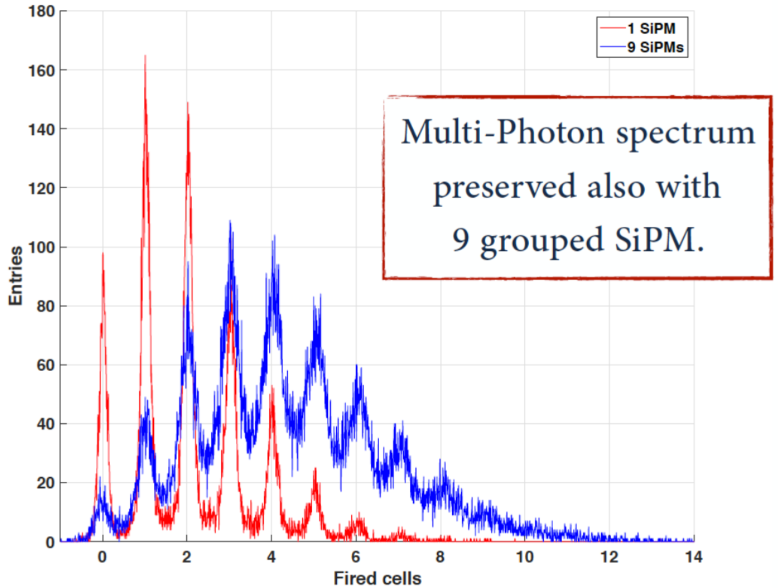
ΔT < 0.5°C during a single run (negligible) || ΔT ~ 1°C during the full scan (considered)

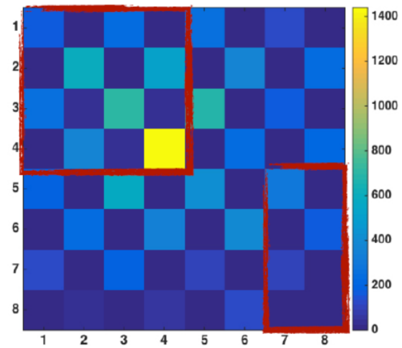


Signal grouping

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)





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

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