Status of MEC simulation

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Scuola Superiore Meridionale

INFN NAPOLI

NA62 P326

Geant4 simulation

Geometry

Tiles

➡ Scintillator 1.5 mm

➡ Absorber 0.275 mm

➡ Tyvek 0.1 mm

Module Characteristics

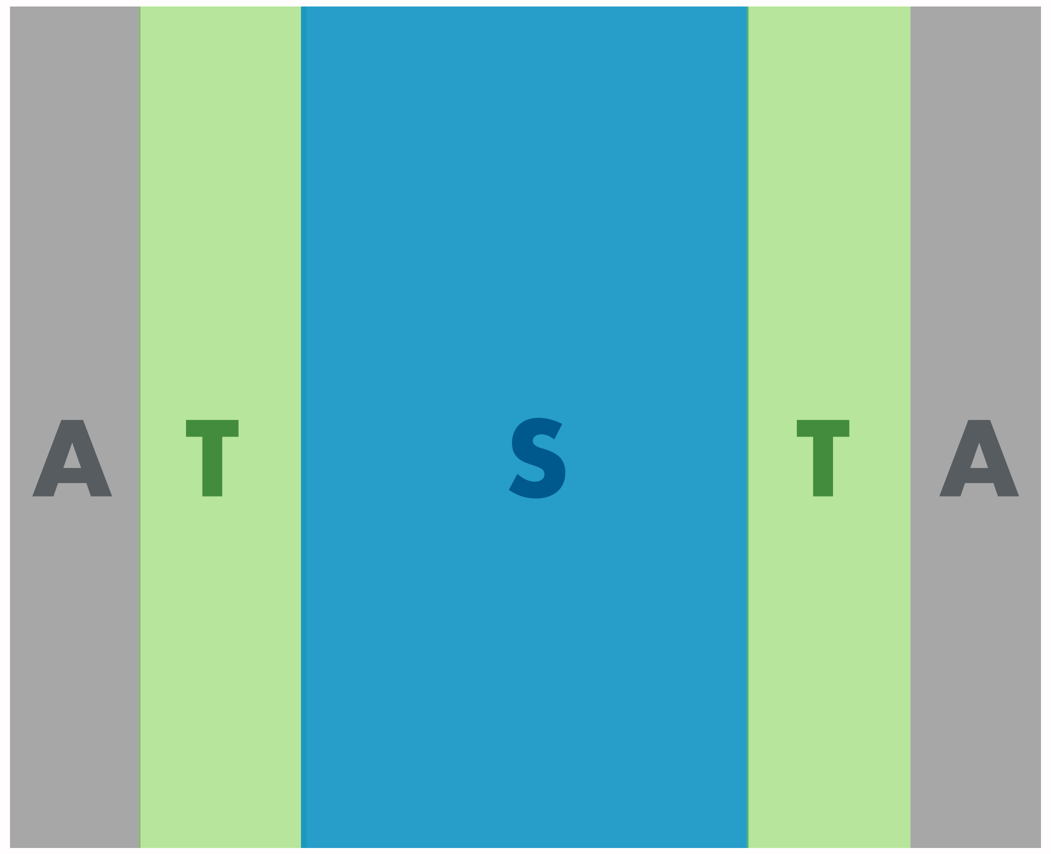
✦ 500 layers (A-T-S-T, ~ 26 X_0)

✦ No spy tiles

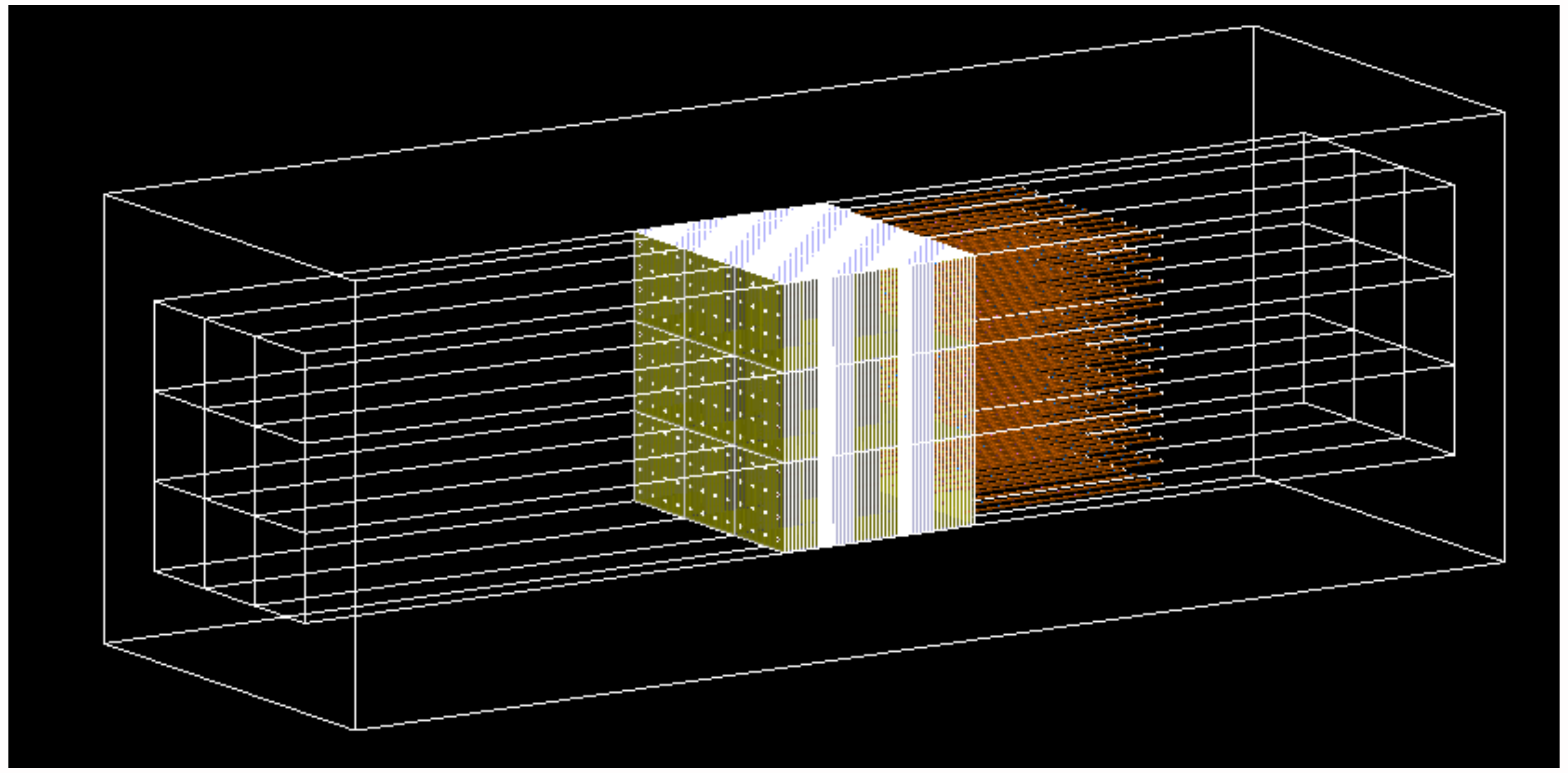
✦ Possibility to create a matrix of modules

Material

- Scintillator (Protvino, $C_{19}H_{21}$, BC408)
- Absorber Pb-Sb 96-4% (density 11.35 g/cm^3)
- Tyvek CH_2 (density 0.96 g/cm^3)



The idea



The realisation

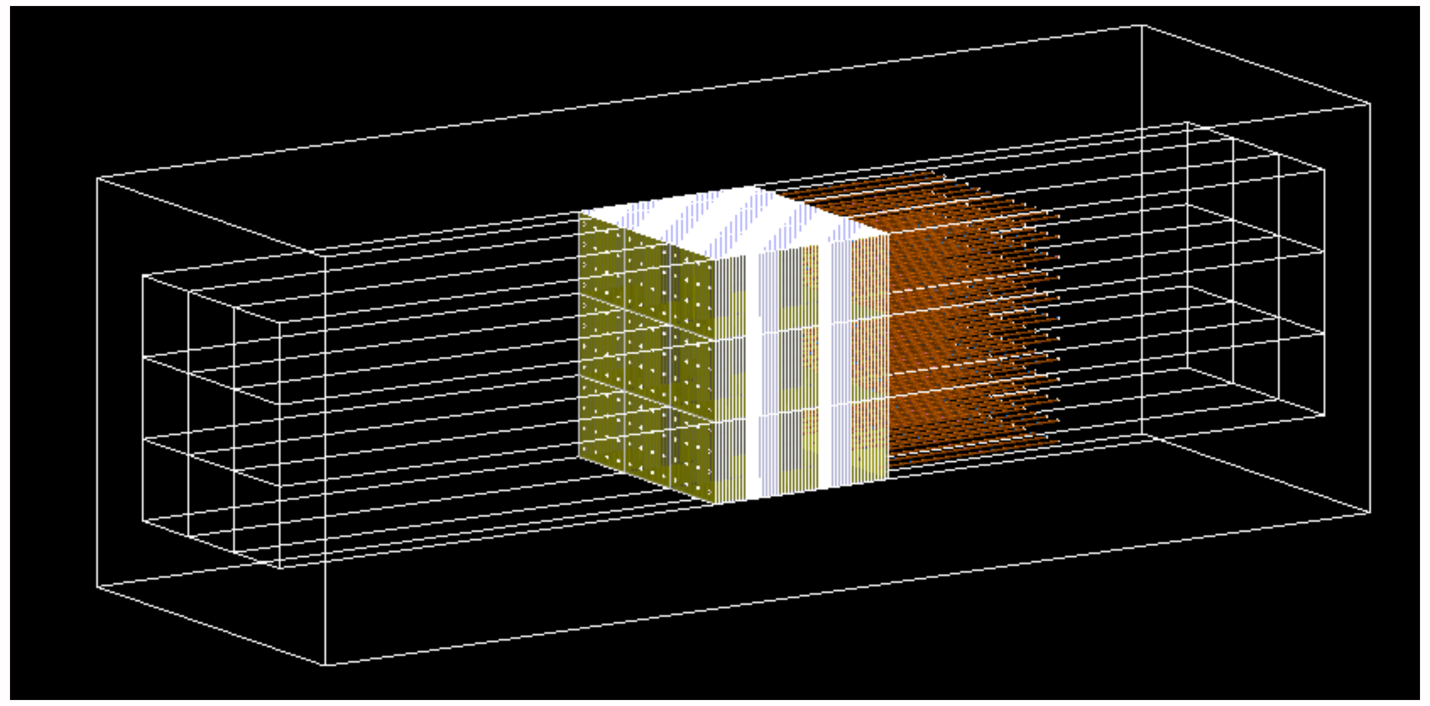
Simulation strategy

Step 1

Molière radius study, first validation of the simulation

Step 2

energy resolution measurement

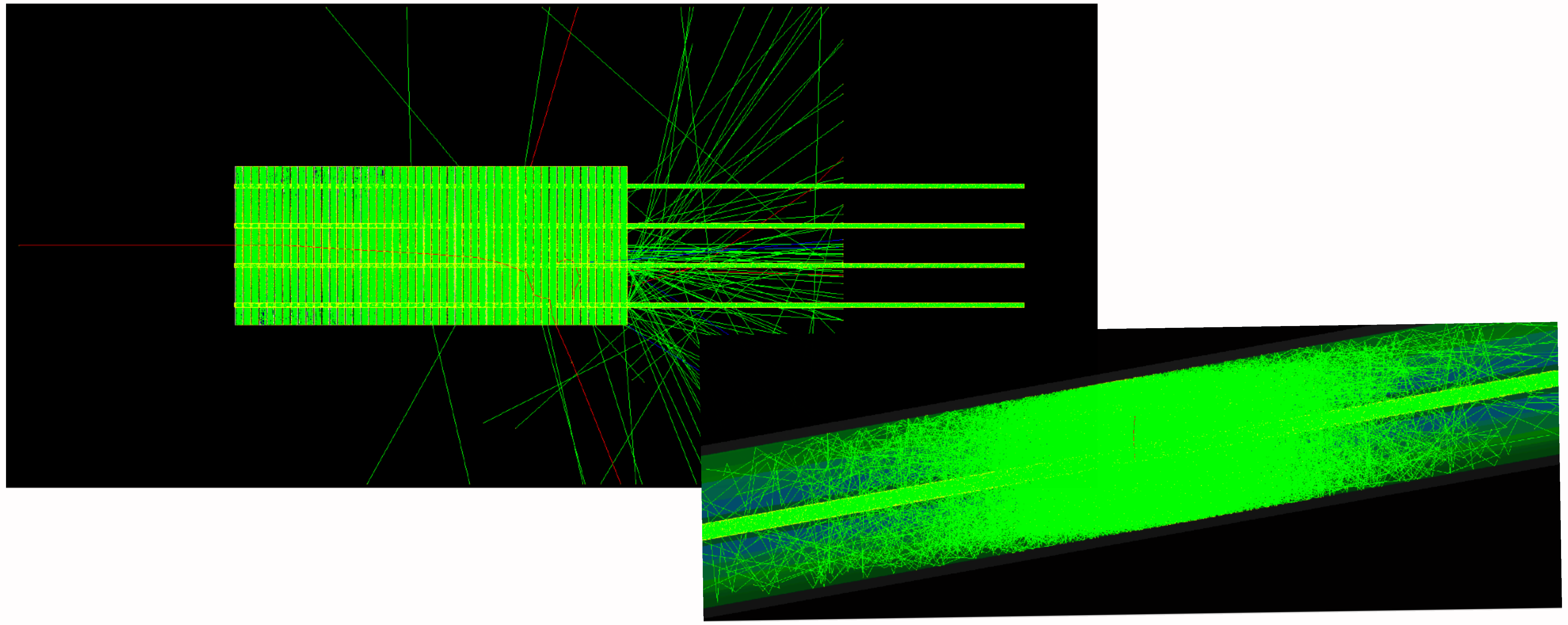


Step 3

optical photons simulation (study of the material properties and surfaces properties)

Step 4

energy resolution with optical photons



Step 2

HowTo

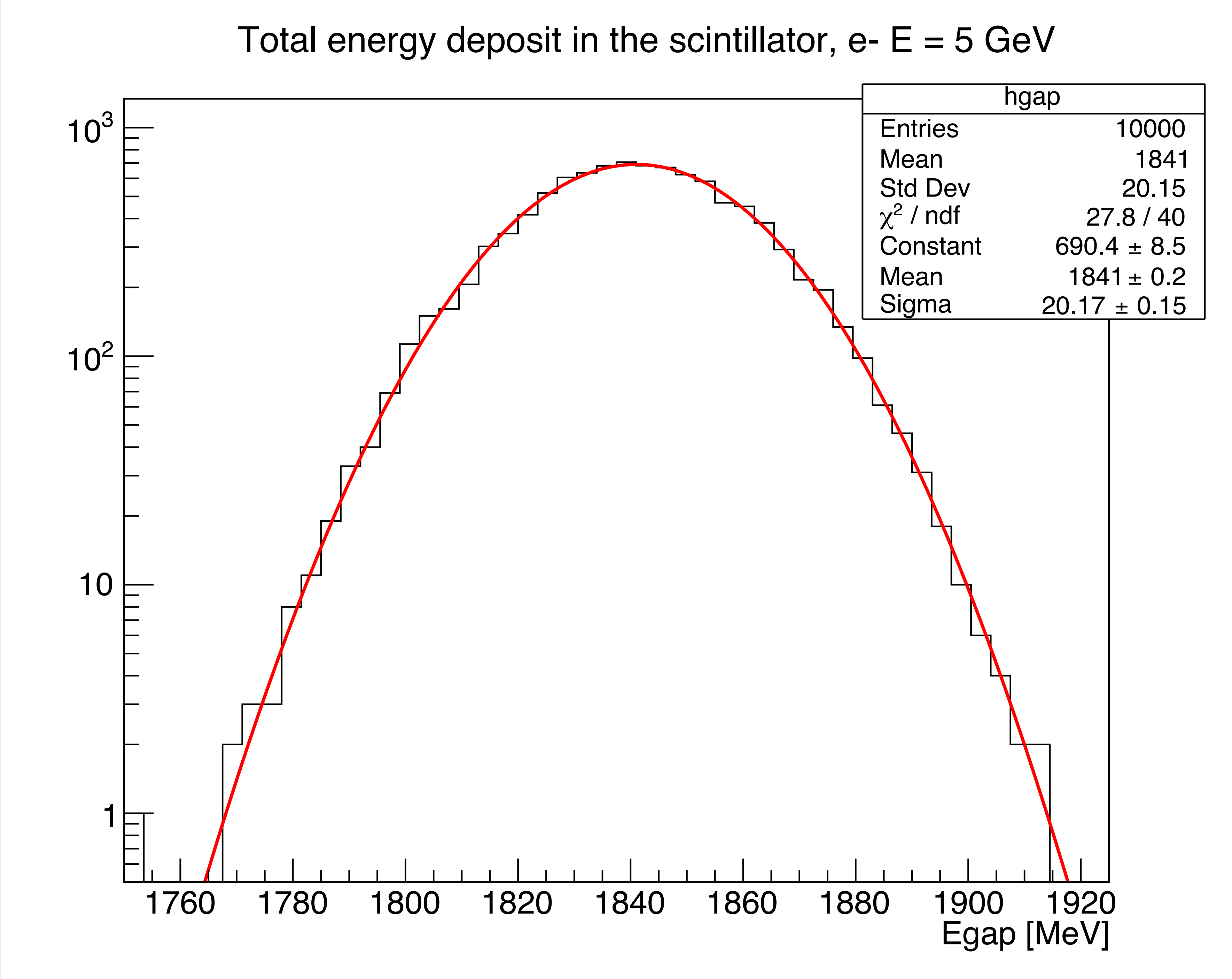
Energy resolution

$$\frac{\sigma(E)}{E} = P_0 \oplus \frac{P_1}{\sqrt{E}}$$

σE /E defined as RMS/E_{mean}

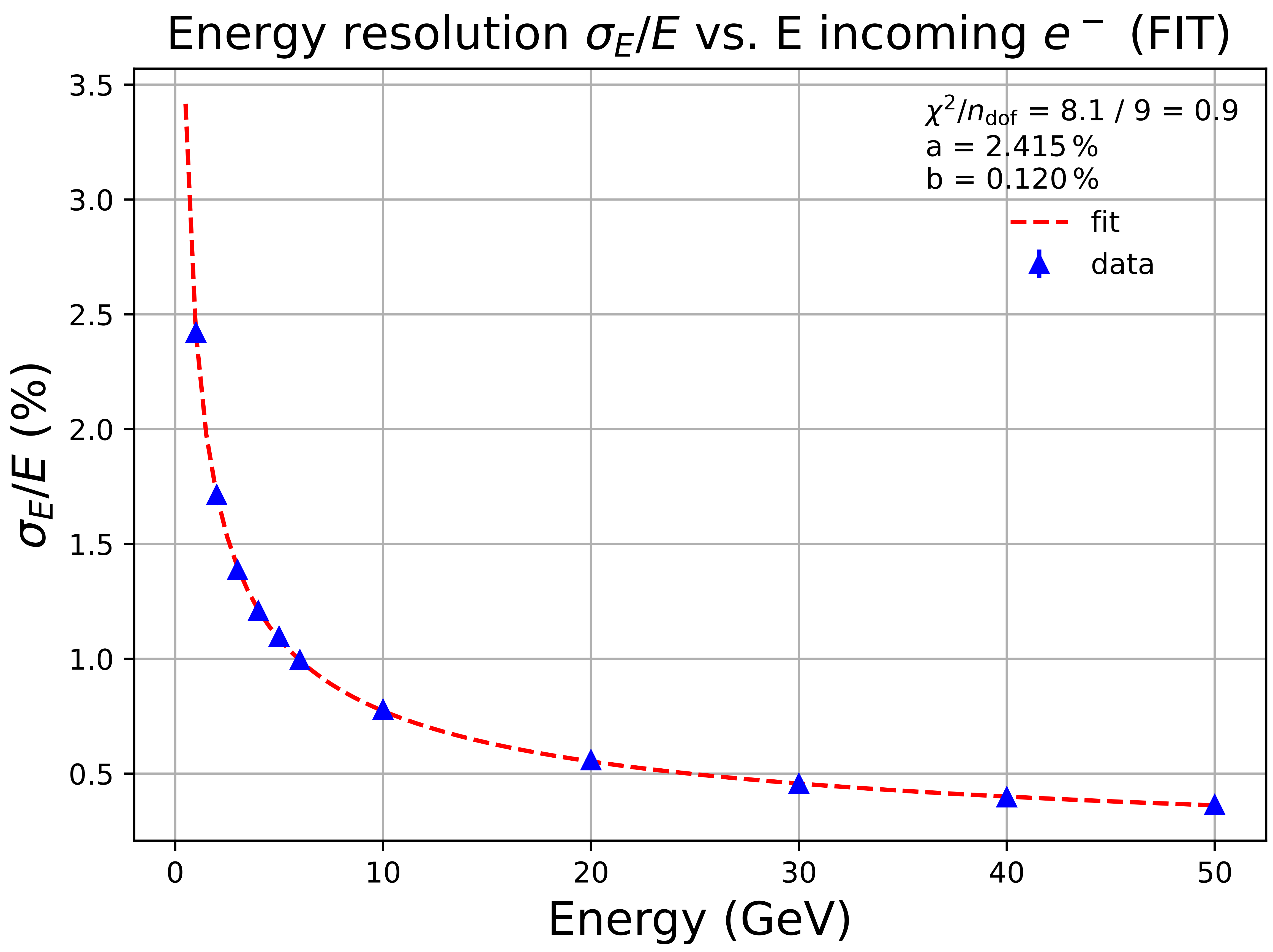
G4 implementation

- XY dimensions of tiles **500 mm** (minimised lateral leakage)
- **10^4** events
- Sum of **energy deposition in scintillator** tiles for each event
- **Energy scan** (1 – 50) GeV
- **χ2** fit with the MIGRAD algorithm



Step 2 Results

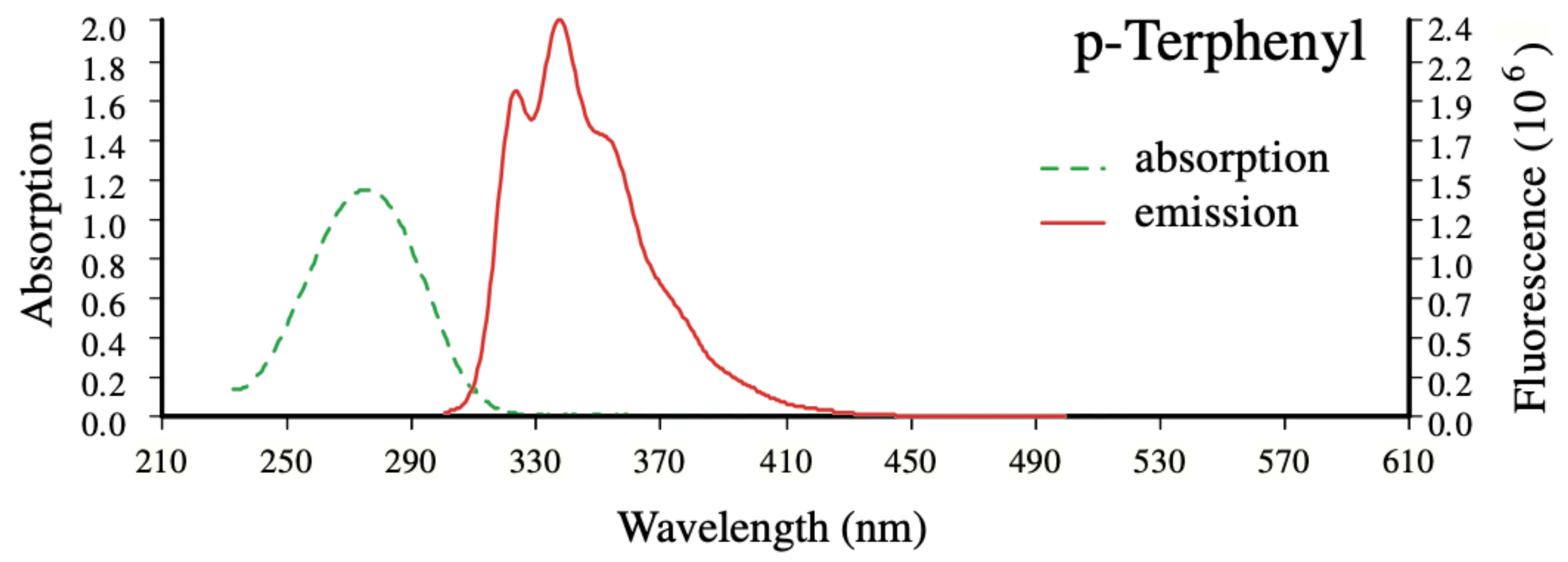
Energy	Mean [MeV]	RMS [MeV]
1 GeV	367.3 $\pm$ 0.1	8.887 $\pm$ 0.066
2 GeV	735.7 $\pm$ 0.1	12.6 $\pm$ 0.1
3 GeV	1104 $\pm$ 0.2	15.3 $\pm$ 0.1
4 GeV	1473 $\pm$ 0.2	17.79 $\pm$ 0.12
5 GeV	1841 $\pm$ 0.2	20.17 $\pm$ 0.15
6 GeV	2209 $\pm$ 0.2	21.95 $\pm$ 0.16
10 GeV	3682 $\pm$ 0.3	28.65 $\pm$ 0.21
20 GeV	7364 $\pm$ 0.4	41.09 $\pm$ 0.31
30 GeV	1.10×10^4 $\pm$ 0.5	50.07 $\pm$ 0.39
40 GeV	1.47×10^4 $\pm$ 0.6	58.26 $\pm$ 0.47
50 GeV	1.84×10^4 $\pm$ 0.7	66.91 $\pm$ 0.53

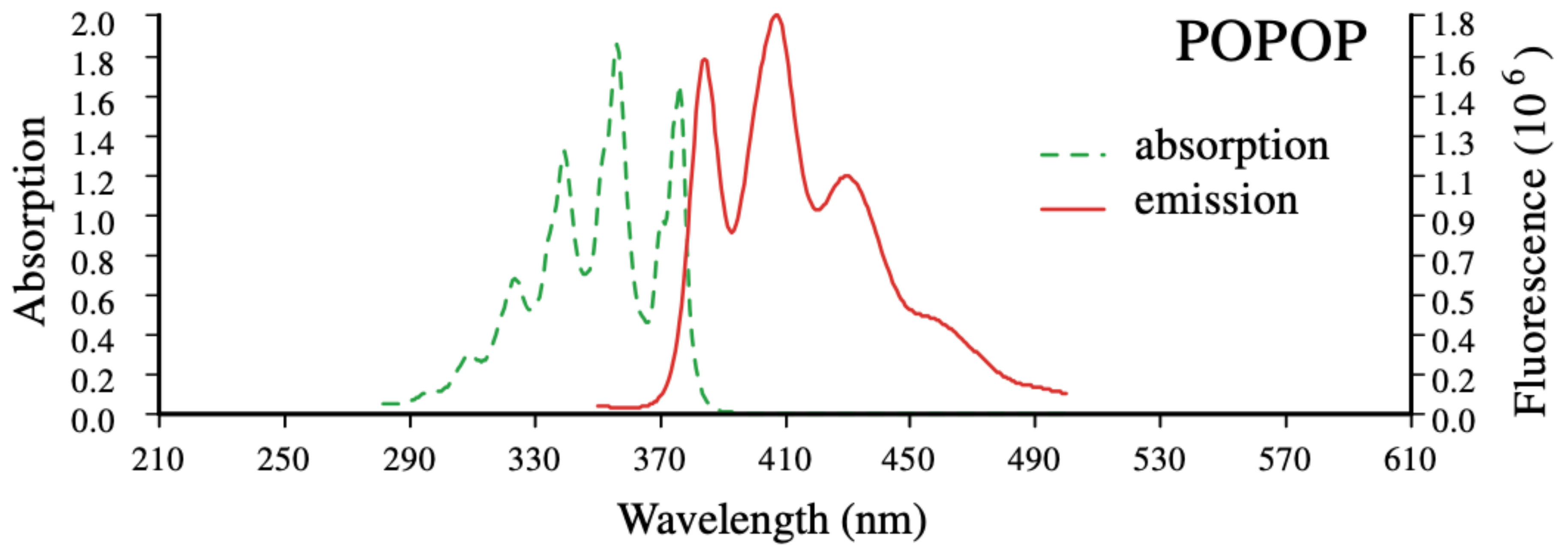


$$\frac{\sigma_E}{E} = \frac{2.415\,\%}{\sqrt{E}} + 0.120\,\%$$

Step 3 Material properties

Scintillator

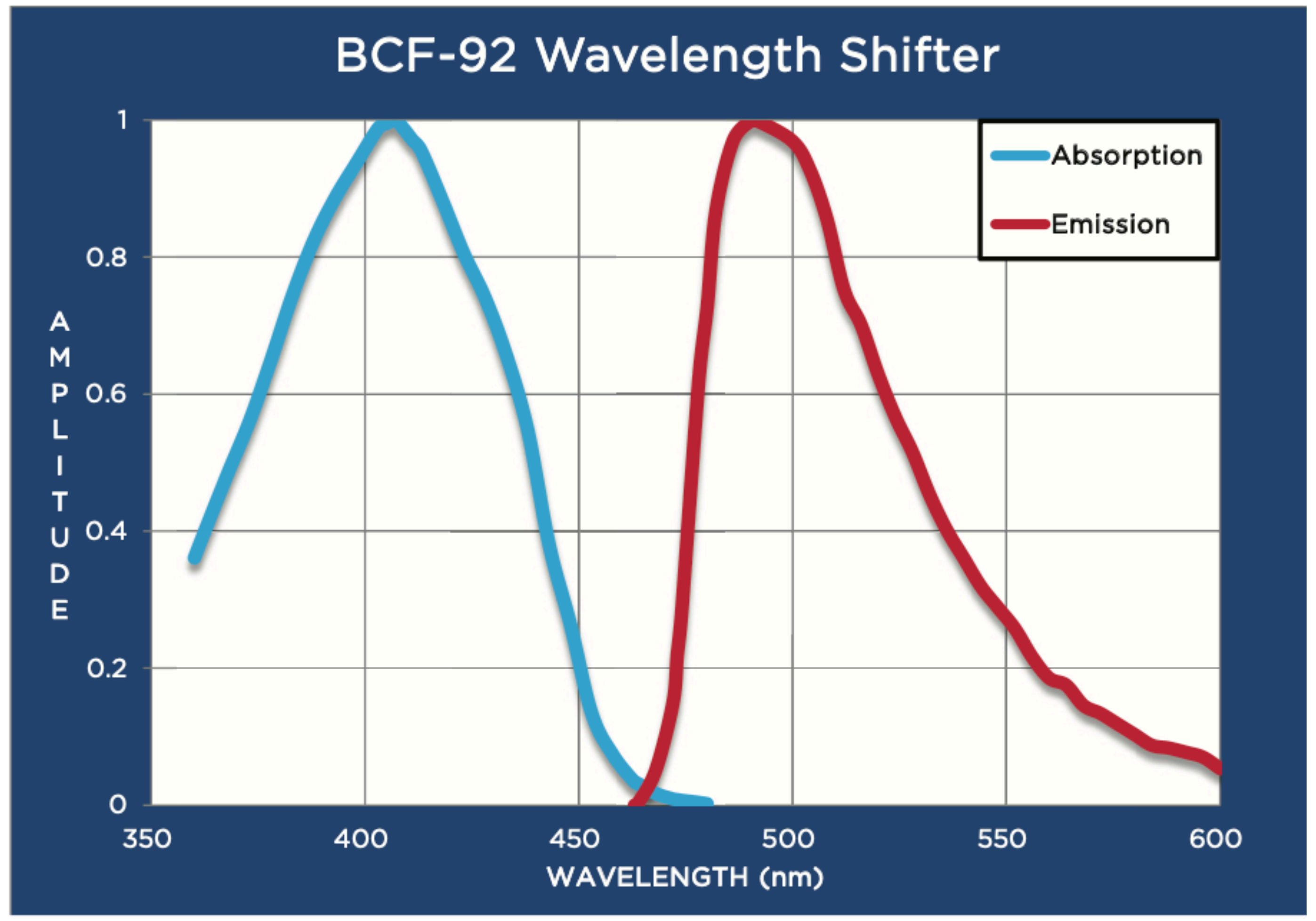


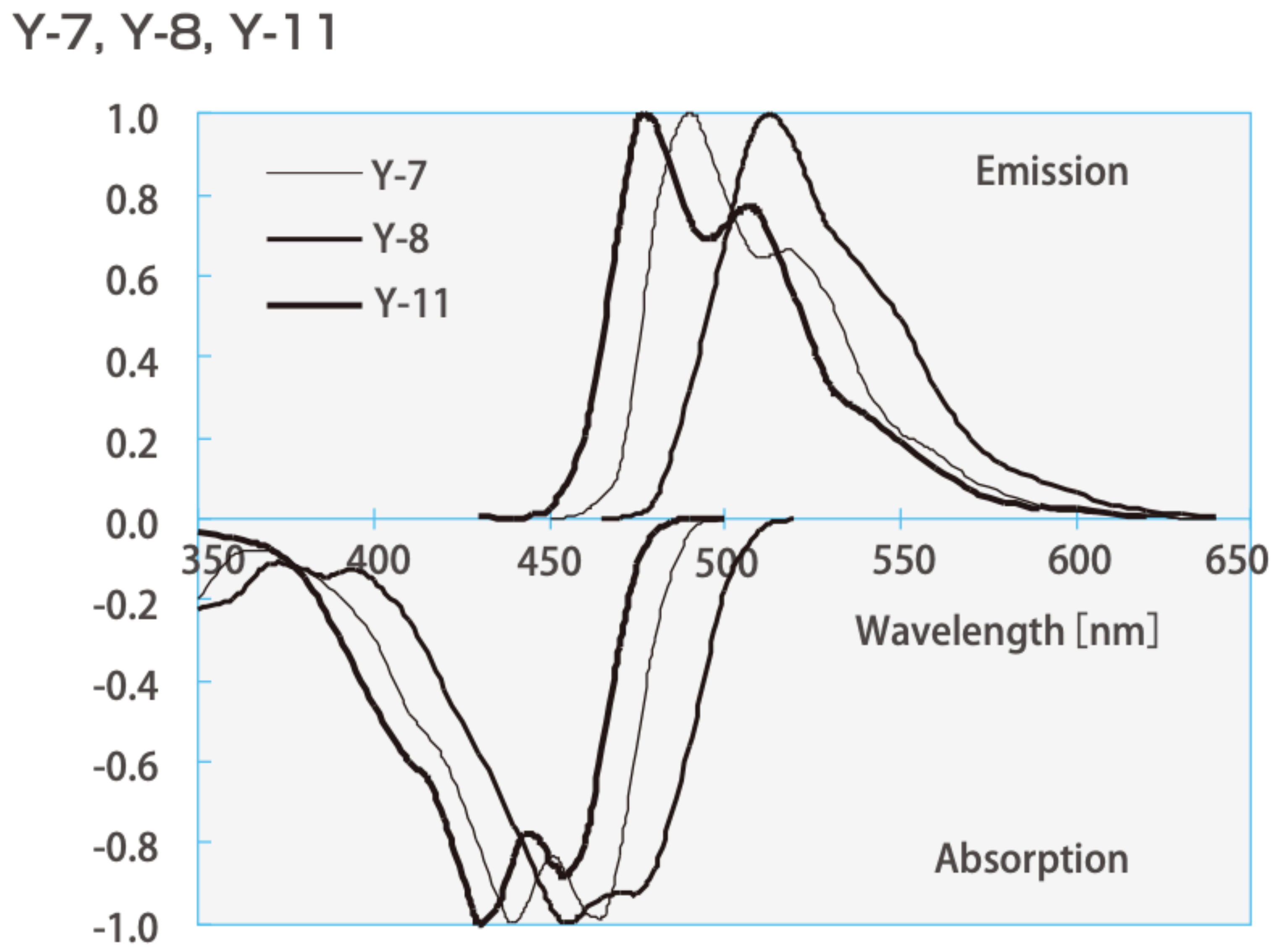


PTP emits light in the range 320-400 nm which is absorbed by POPOP which then re-emits in blue wavelength.

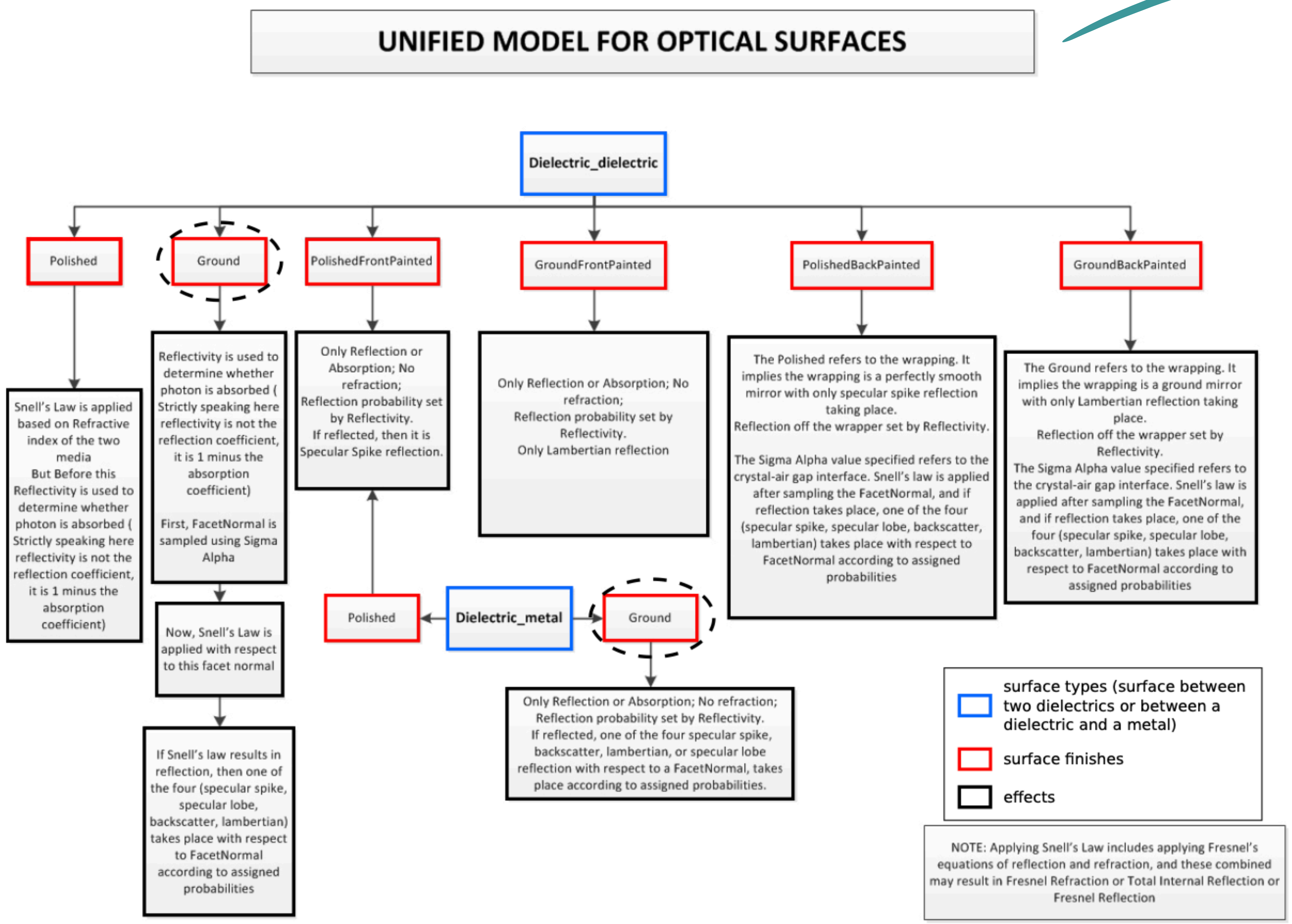
Fibers

Common Properties of Single-clad Fibers –	
Core material	Polystyrene
Core refractive index	1.60
Density	1.05
Cladding material	Acrylic
Cladding refractive index	1.49
Trapping efficiency, round fibers	3.44% minimum

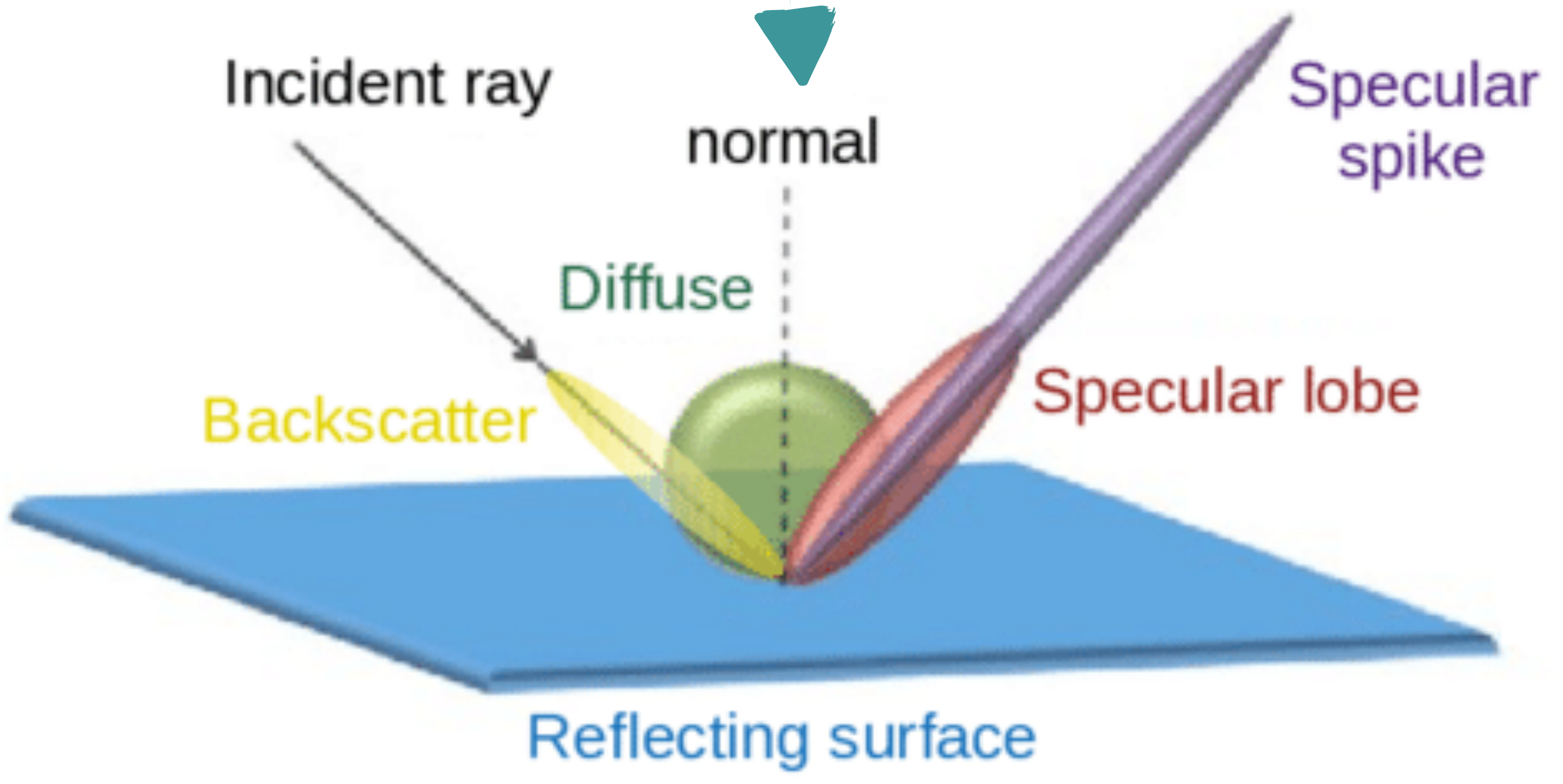




Step 3 Surfaces definition



Dumb down



Step 4 Energy resolution with optical photons

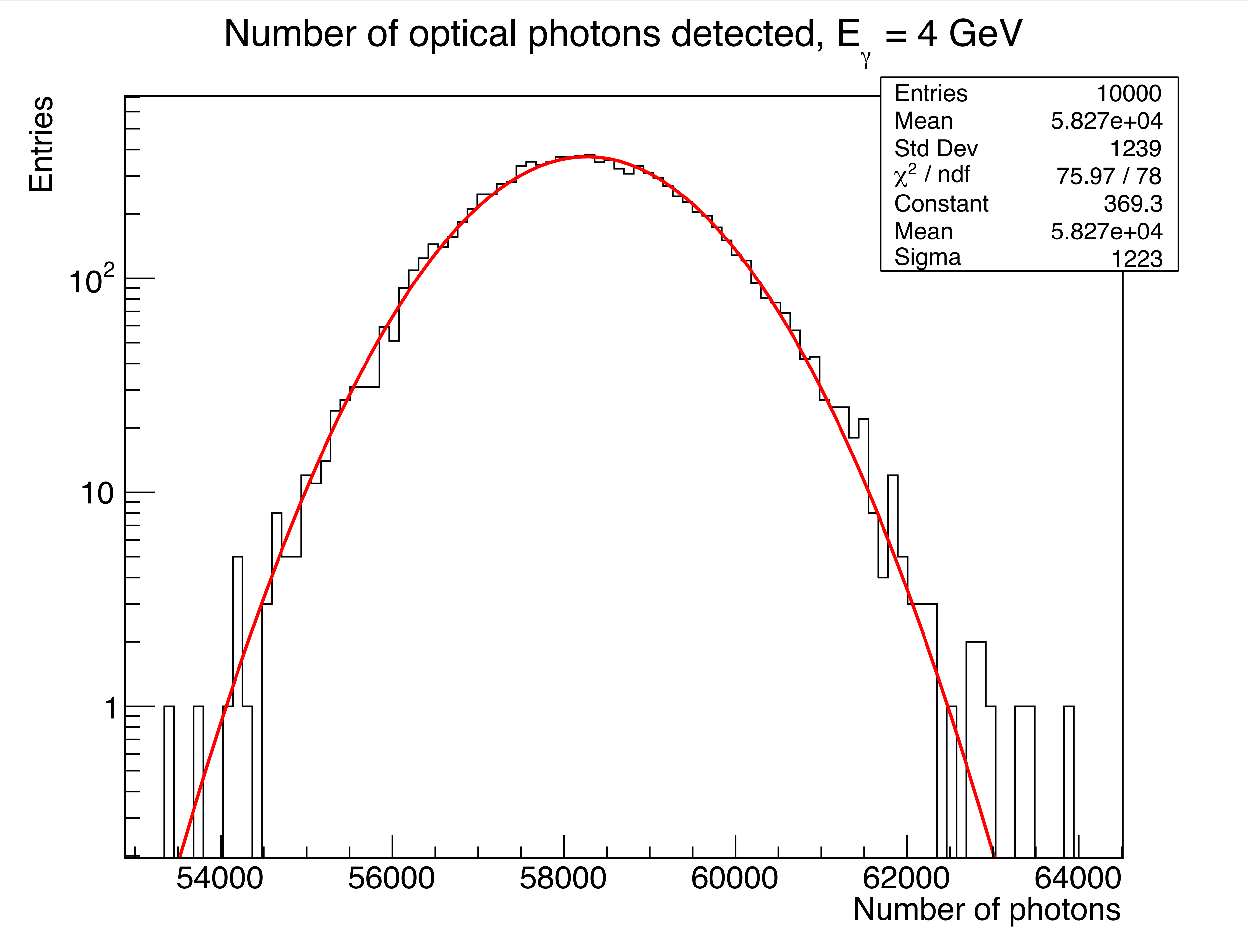
Energy resolution

$$\frac{\sigma(N)}{N} = P_0 \oplus \frac{P_1}{\sqrt{E}}$$

σ_N /N **defined as** **RMS/N_{mean}**

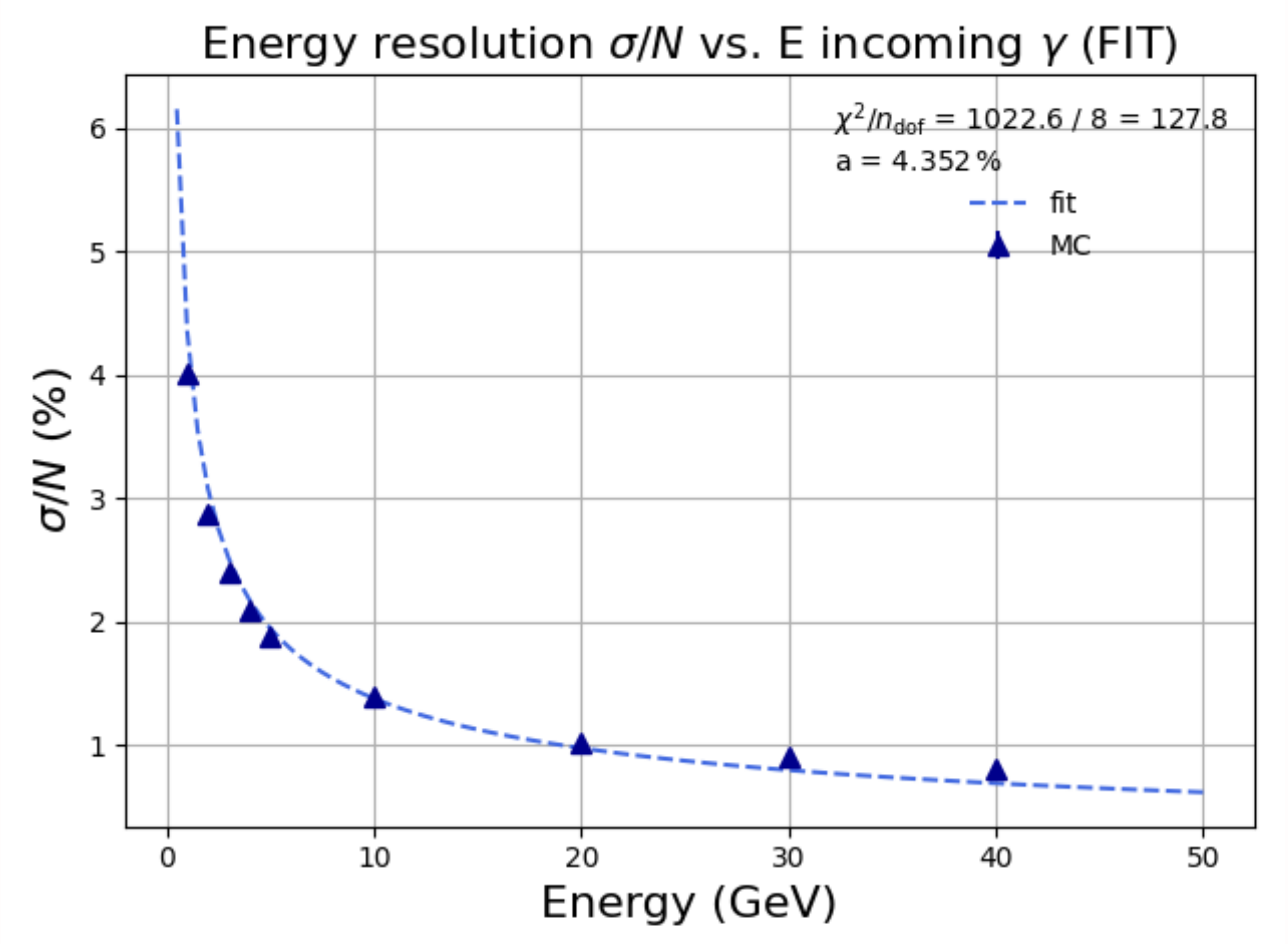
G4 implementation

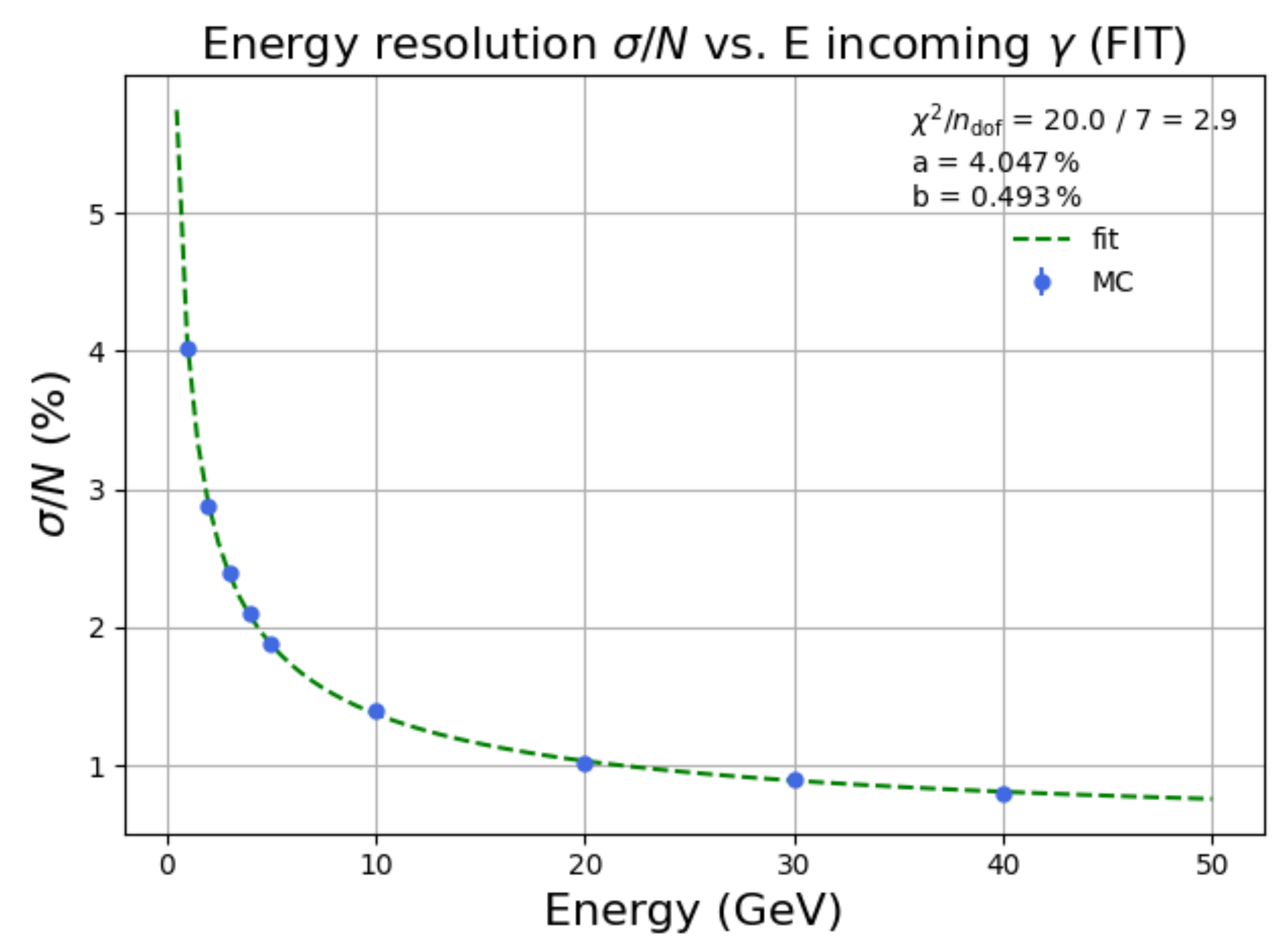
- **Matrix of 5x5** modules
- Sum of **optical photons** collected by PD for each event
- **Energy scan** (1 – 40) GeV
- **χ2** fit with the MIGRAD algorithm



Step 4 Results

5x5 matrix (40 mm tile XY dimension) black painted fibre





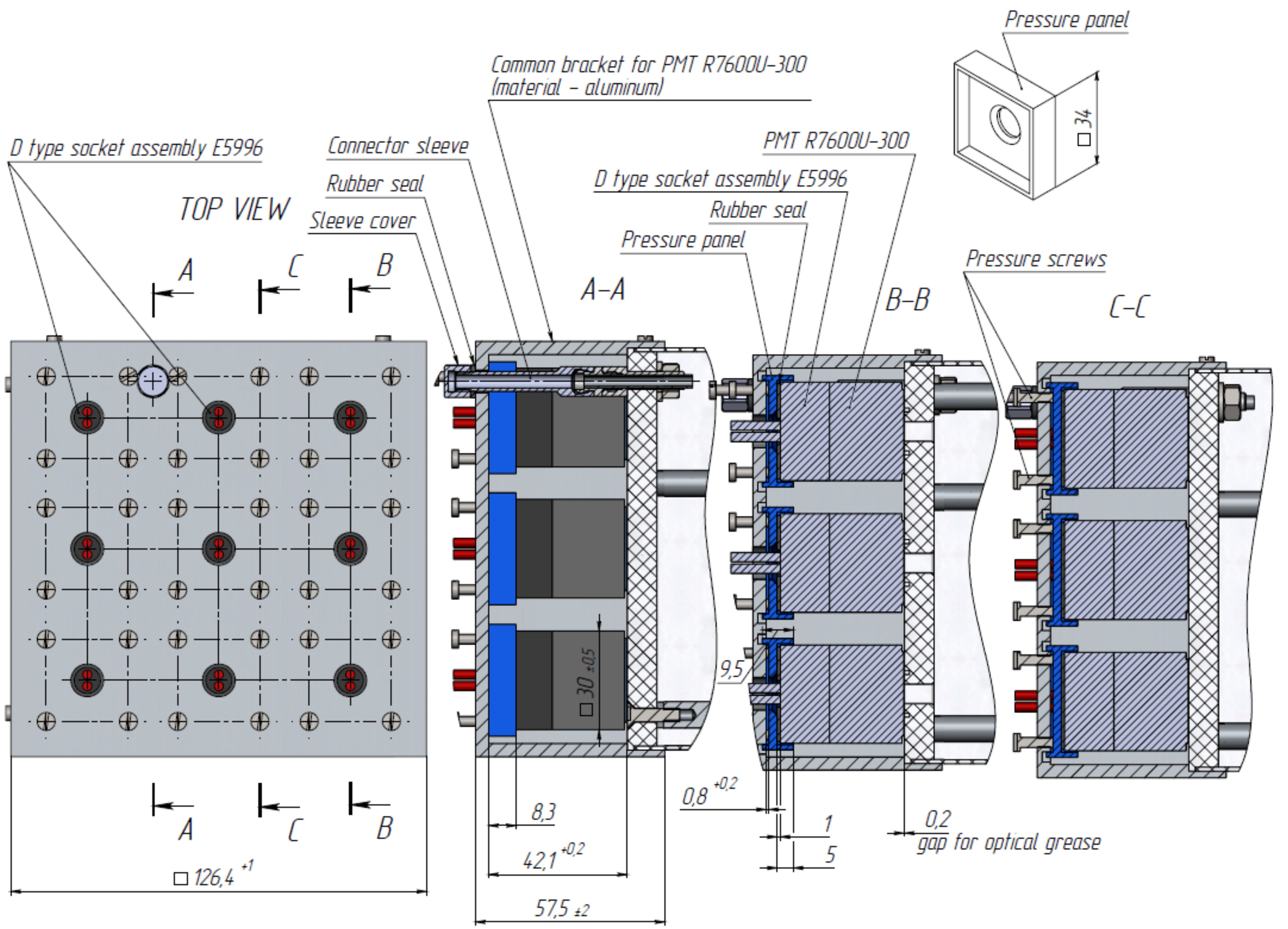
$$\frac{\sigma_N}{N} = \frac{4.352\,\%}{\sqrt{E}}$$

$$\frac{\sigma_N}{N} = \frac{4.047\,\%}{\sqrt{E}} + 0.493\,\%$$

Step 5 TB module implementation

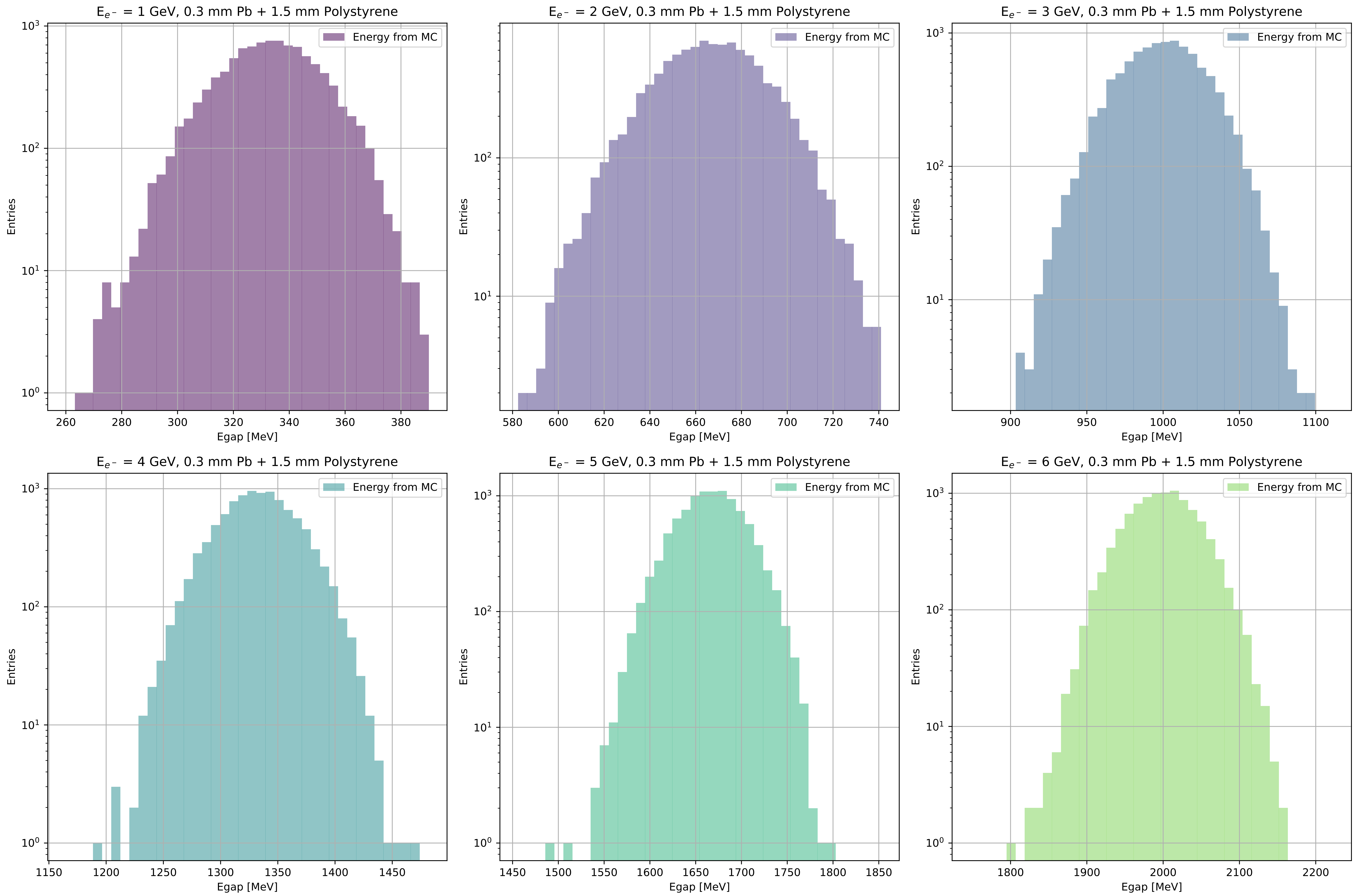
Main characteristics

- $120 \times 120 \times 1000\ mm^3 = 2R_M \times 27X_0$
- Cell size $40\ mm \times 40\ mm$
- Alternation of $0.3\ mm$ of lead and $1.6\ mm$ of Protvino scintillator
- TiO_2 coating (reduced thickness)
- Gaussian beam



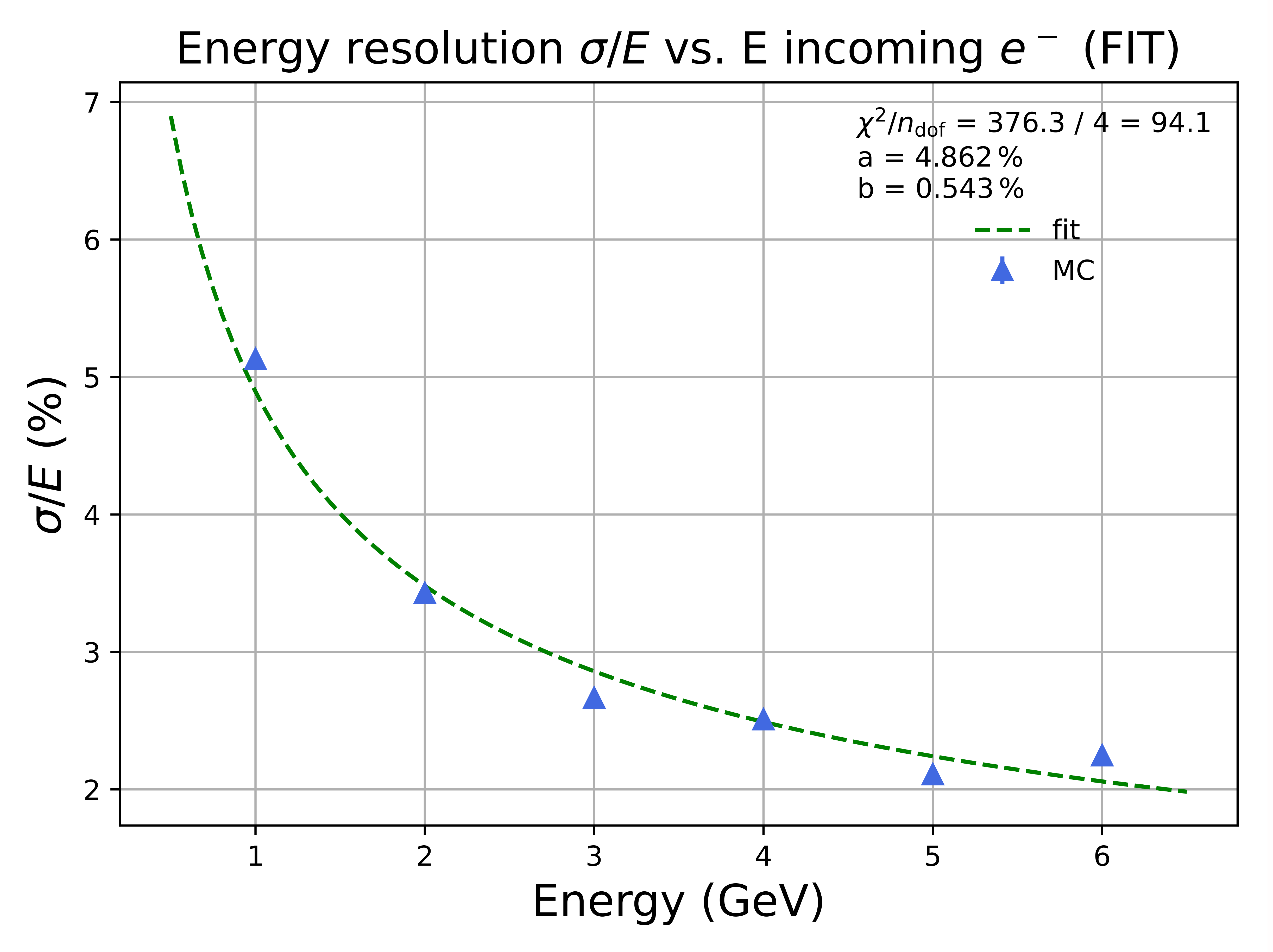
Step 5 Energy deposition in the scintillator

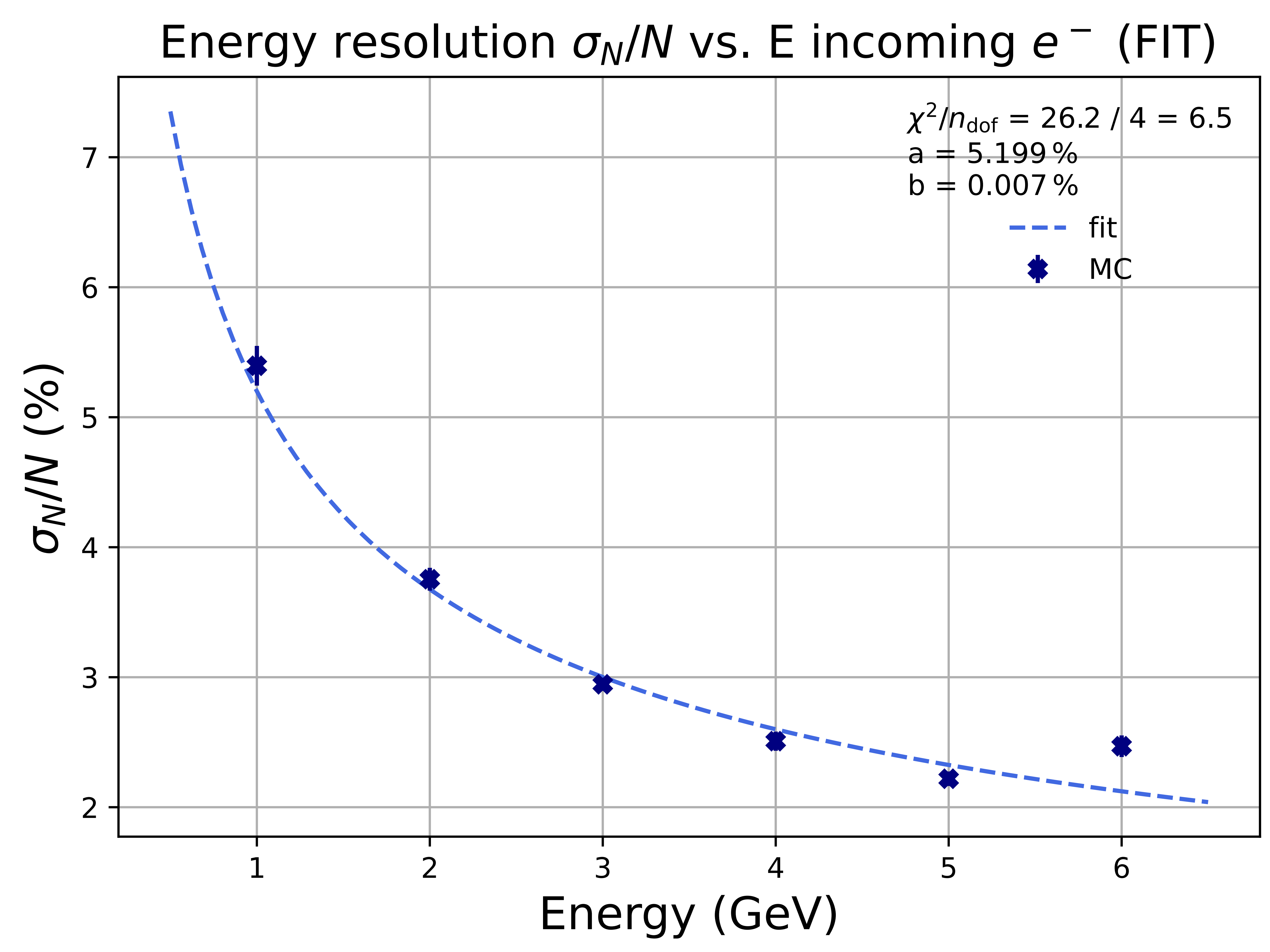
DETEC Prototype + PS Beam 3x3 matrix (40 mm tile XY dimension) mirrored fibers



Step 5 TB module implementation

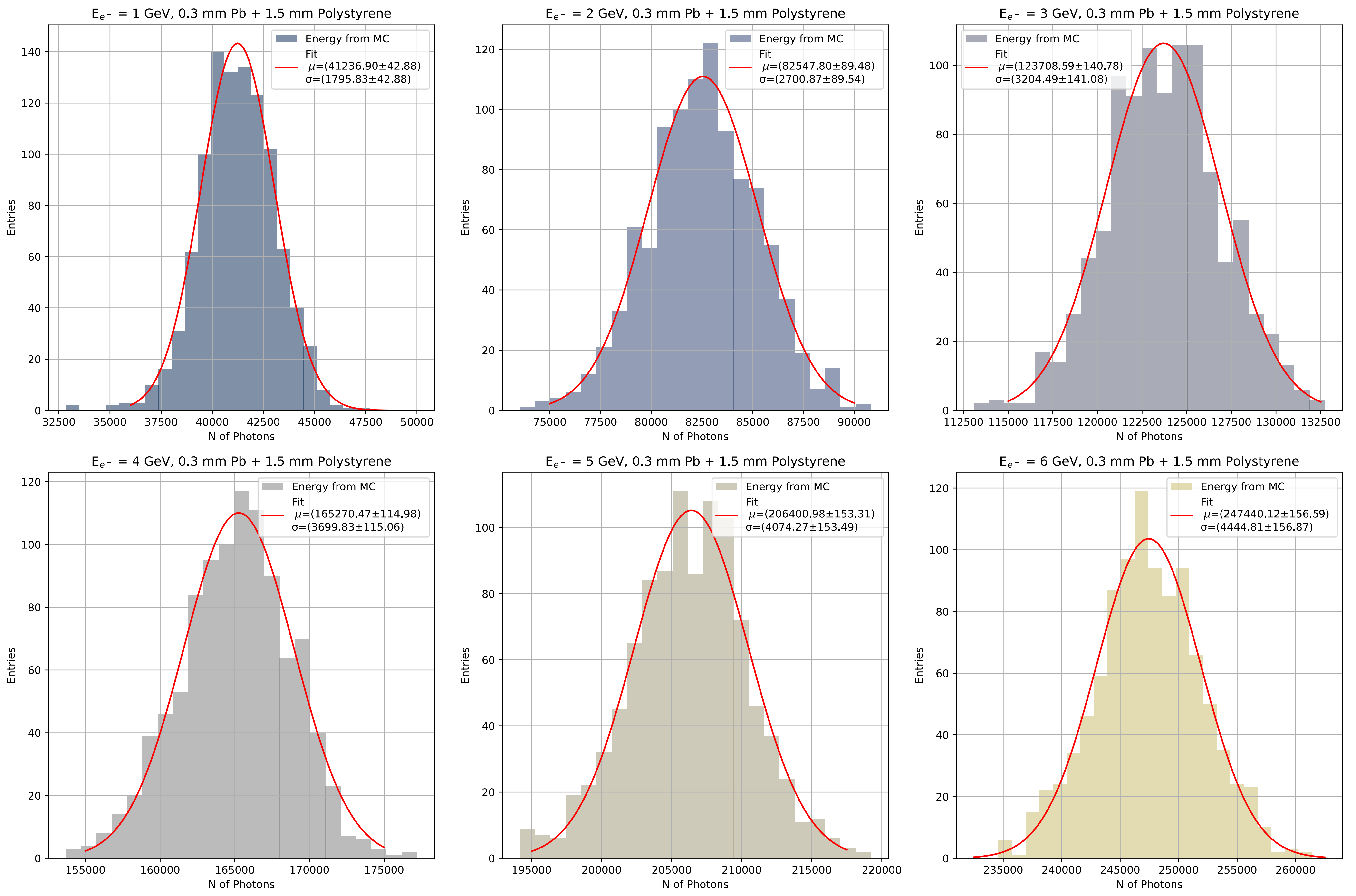
DETEC Prototype + PS Beam (only energy) 3x3 matrix (40 mm tile XY dimension) mirrored fibers

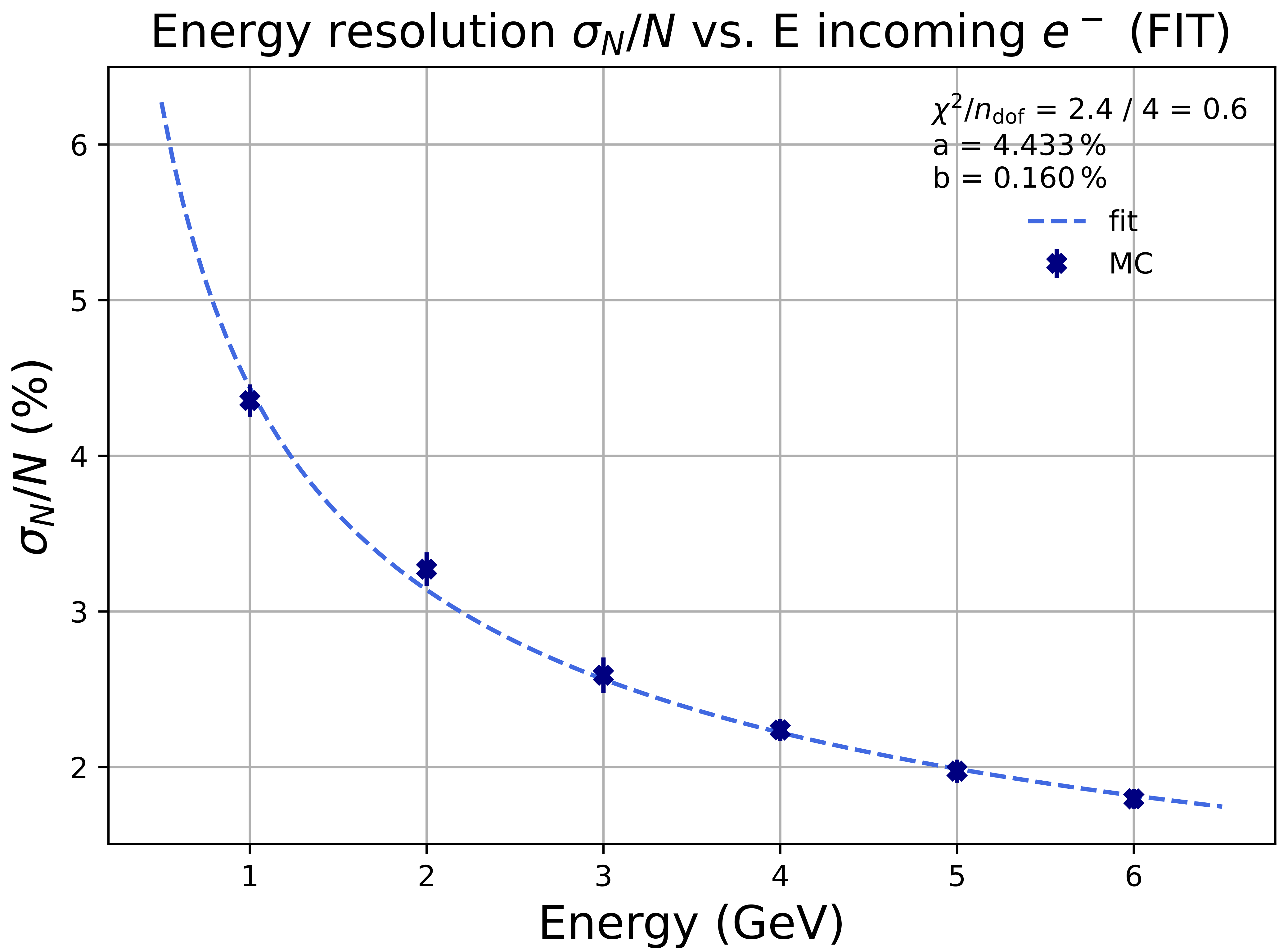




Step 5 TB module implementation

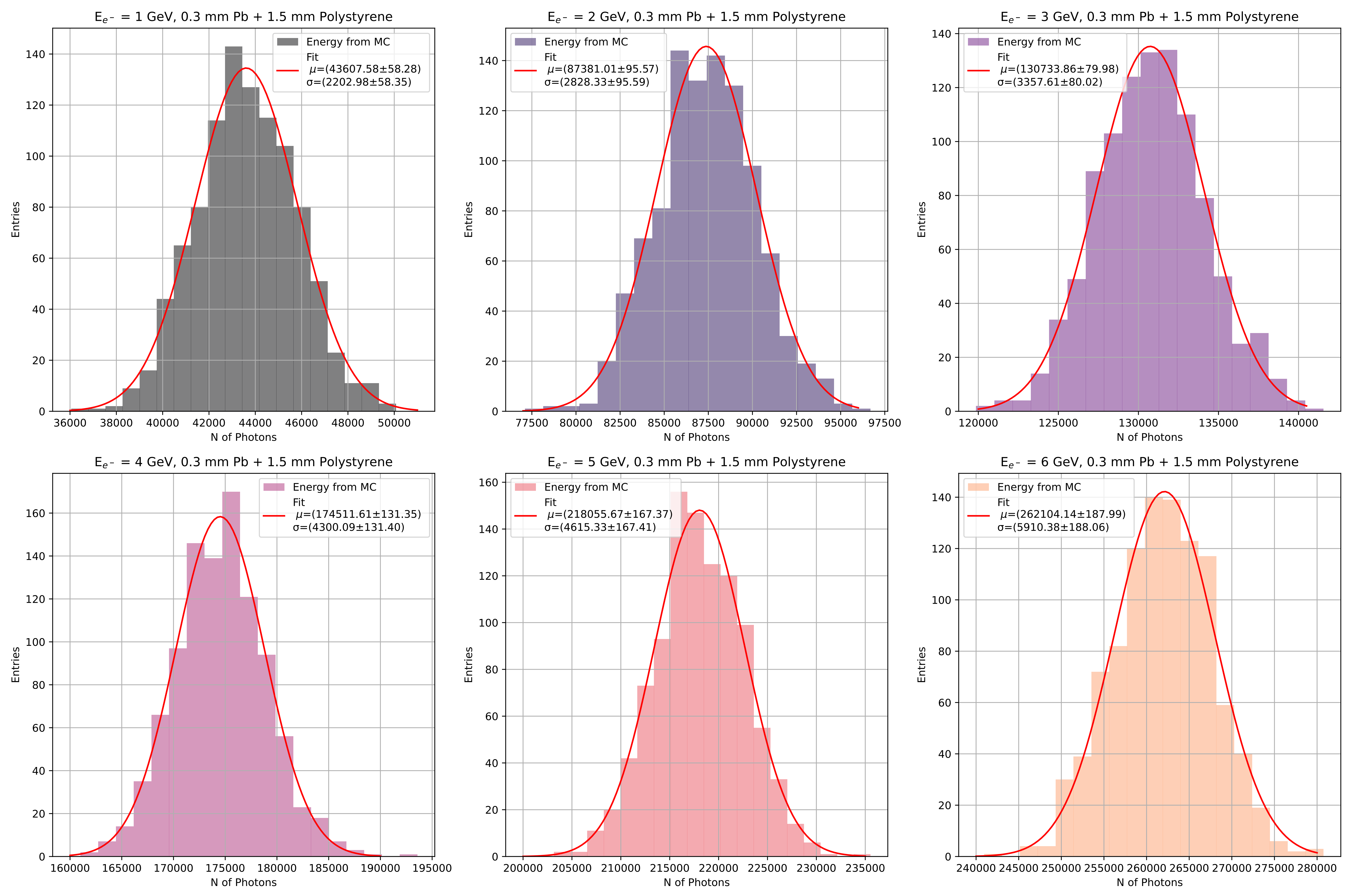
DETEC Prototype + Monoenergetic Beam 3x3 matrix (40 mm tile XY dimension) mirrored fibers

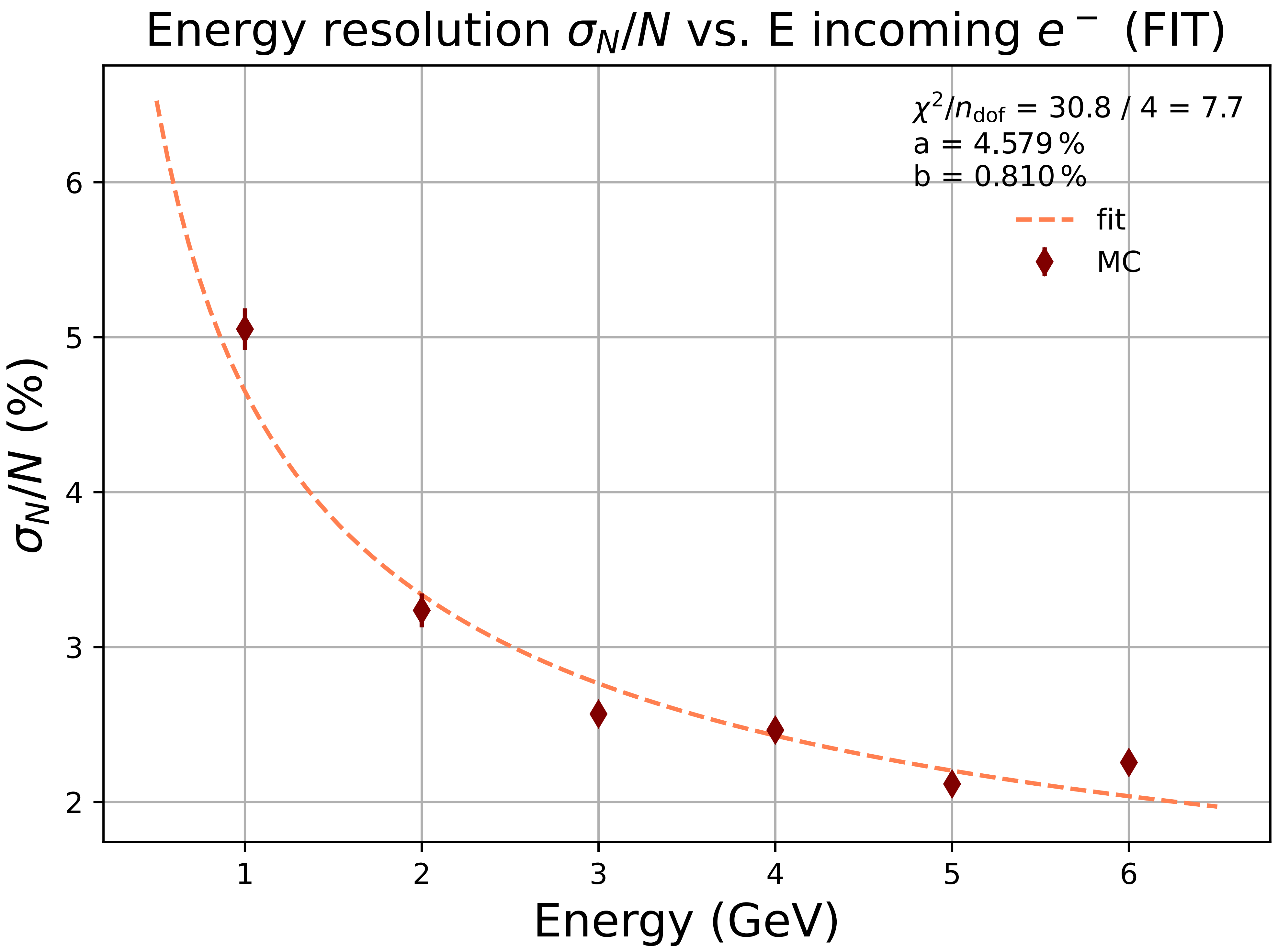




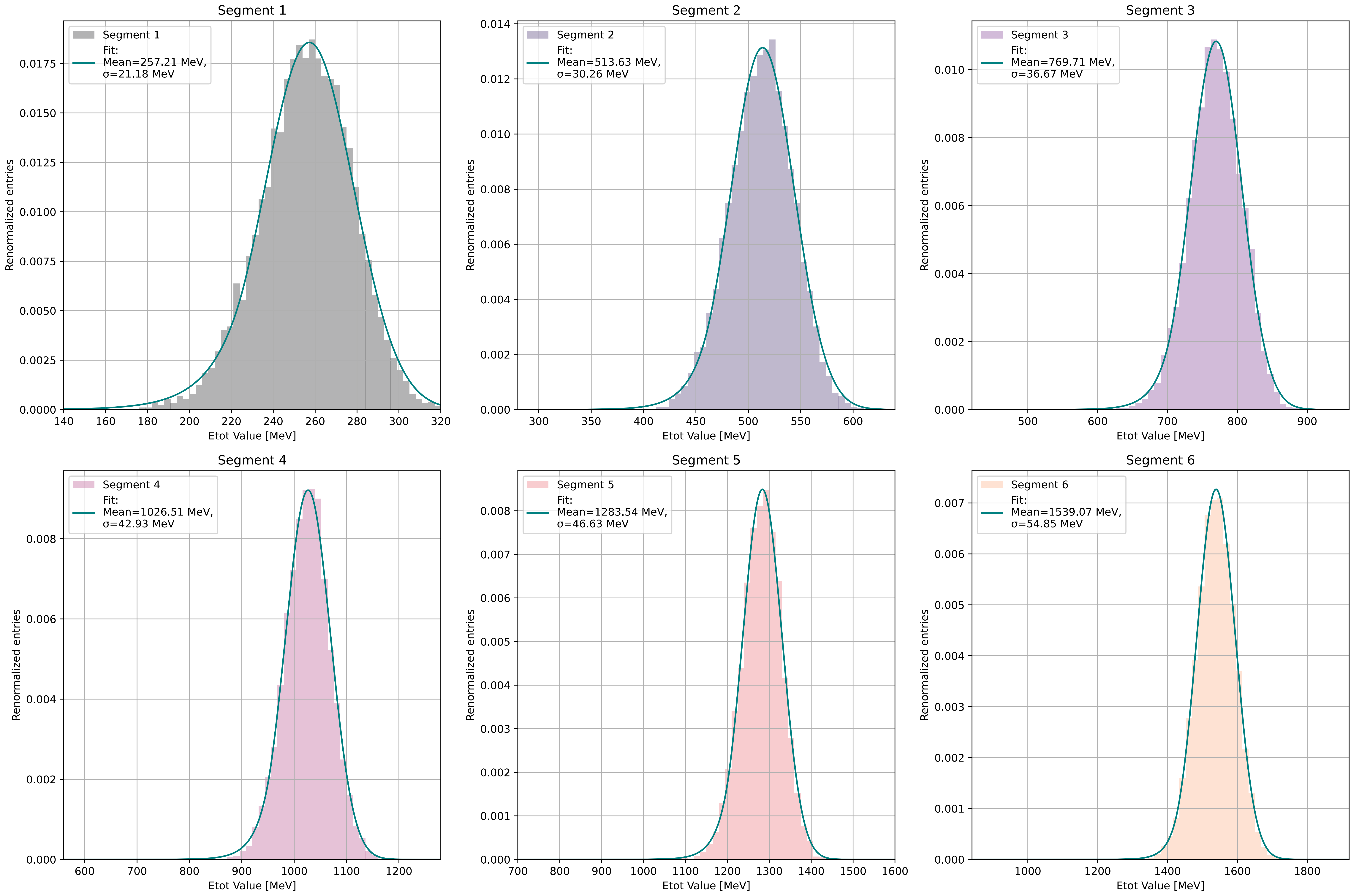
TB module implementation

DETEC Prototype + PS Beam (only energy) 5x5 matrix (40 mm tile XY dimension) mirrored fibers





Step 5 TB module implementation



Future plans

➡ Technological solution

- Fine-sampling shashlyk design with alternating layers of conventional scintillator (polystyrene matrix + fluors) and lead

➡ Current status

- **2024:** construct one full-size shashlyk cell and validate performance with beam test:
  - cell size 120x120x1000 mm^3 = 2 R_M x 27 X_0 , module ready delivered in sep 2024
  - 9 readout channels with full digitization at 1/5 GHz
  - PS TB performed in sept-oct 2024

PRIN HetCal

➡ Future plans

- **2025:** minor improvements on the calorimeter (fibers, readout) and new test at the end of 2025
  - Adding the PD response in the simulation
  - Tune the geometry and the optical properties

Thank you for the attention!

Backup

HIKE brief introduction

➡ **HIKE project: high-intensity beam and kaon decay measurements at a new level of precision**

➡ **An integrated programme with multiple phases: K^+ and K_L beams + beam dump mode exploiting high intensity Kaon beam in CERN NA after LS3**

Phase 1

BR($K^+ \to \pi^+\nu\bar{\nu}$) **at 5% of precision**

Phase 2

BR($K_L \to \pi^0\nu\bar{\nu}$) **at 20% of precision**

$K^+ \to \pi^+\nu\bar{\nu}$	$\sigma_{\mathcal{B}}/\mathcal{B} \sim 5\%$	BSM physics, LFUV
$K^+ \to \pi^+\ell^+\ell^-$	Sub-% precision on form-factors	LFUV
$K^+ \to \pi^-\ell^+\ell^+$, $K^+ \to \pi\mu e$	Sensitivity $\mathcal{O}(10^{-13})$	LFV / LNV
Semileptonic K^+ decays	$\sigma_{\mathcal{B}}/\mathcal{B} \sim 0.1\%$	V_{us}, CKM unitarity
$R_K = \mathcal{B}(K^+ \to e^+\nu)/\mathcal{B}(K^+ \to \mu^+\nu)$	$\sigma(R_K)/R_K \sim \mathcal{O}(0.1\%)$	LFUV
Ancillary K^+ decays (e.g. $K^+ \to \pi^+\gamma\gamma$, $K^+ \to \pi^+\pi^0 e^+e^-$)	% – ‰	Chiral parameters (LECs)
$K_L \to \pi^0\ell^+\ell^-$	$\sigma_{\mathcal{B}}/\mathcal{B} < 20\%$	Imλ_t to 20% precision, BSM physics, LFUV
$K_L \to \mu^+\mu^-$	$\sigma_{\mathcal{B}}/\mathcal{B} \sim 1\%$	Ancillary for $K \to \mu\mu$ physics
$K_L \to \pi^0(\pi^0)\mu^\pm e^\mp$	Sensitivity $\mathcal{O}(10^{-12})$	LFV
Semileptonic K_L decays	$\sigma_{\mathcal{B}}/\mathcal{B} \sim 0.1\%$	V_{us}, CKM unitarity
Ancillary K_L decays (e.g. $K_L \to \gamma\gamma$, $K_L \to \pi^0\gamma\gamma$)	% – ‰	Chiral parameters (LECs), SM $K_L \to \mu\mu$, $K_L \to \pi^0\ell^+\ell^-$ rates

Challenges: 20-40 ps time resolution for key detectors to keep random veto under control, while maintaining all other NA62 specifications.

Why not keeping the LKr?

The LKr energy resolution meets the HIKE requirements, while the time resolution must be substantially improved

How can HIKE requirements be met?

The energy, position, and time resolution of the LKr calorimeter

$$\frac{\sigma_E}{E} = 0.0042 \oplus \frac{0.032}{\sqrt{E(GeV)}} \oplus \frac{0.09}{E(GeV)},$$

$$\sigma_{x,y} = 0.06\,cm \oplus \frac{0.42\,cm}{\sqrt{E(GeV)}},$$

$$\sigma_t = \frac{2.5\,ns}{\sqrt{E(GeV)}}$$

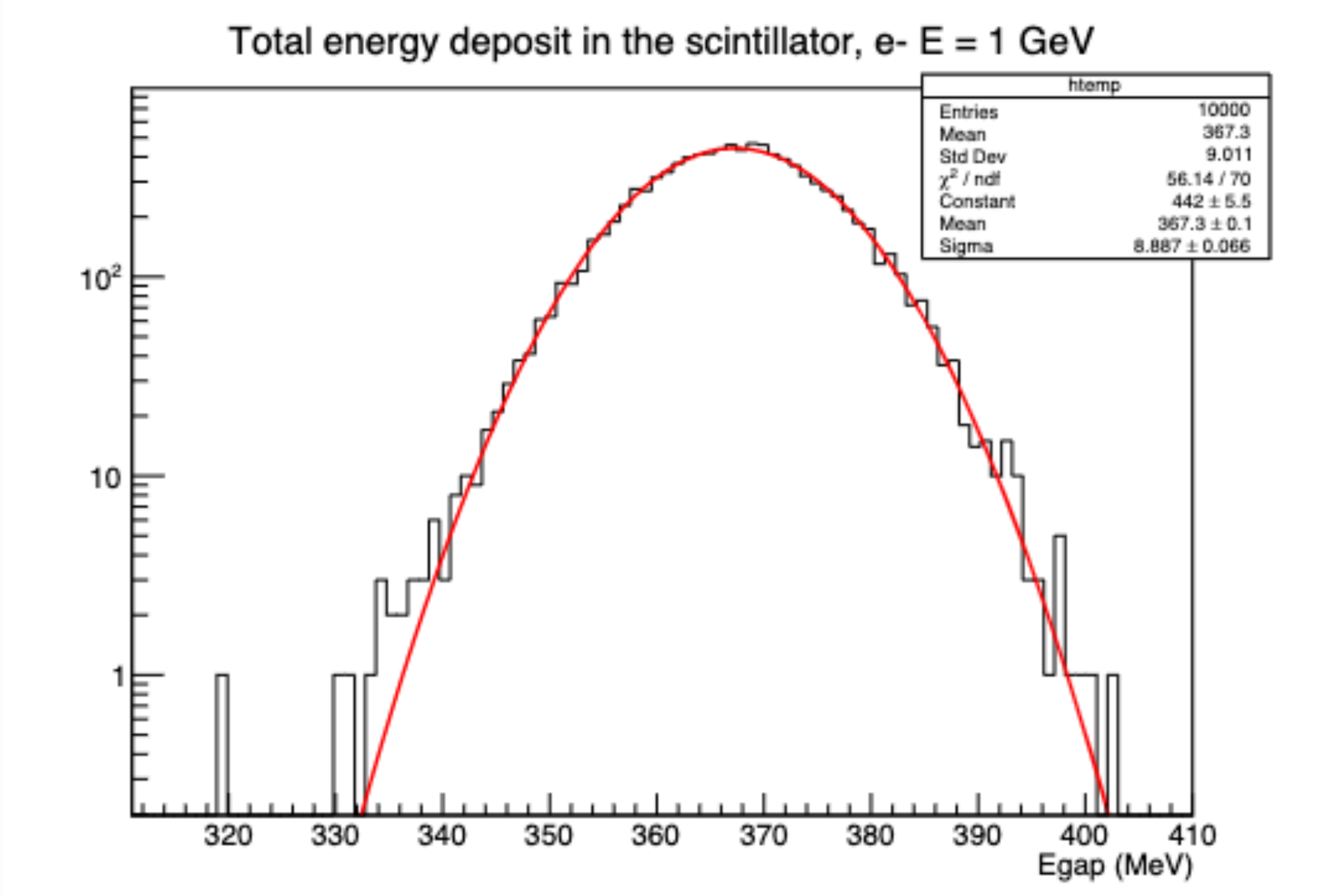
Upgrades of LKr electronics

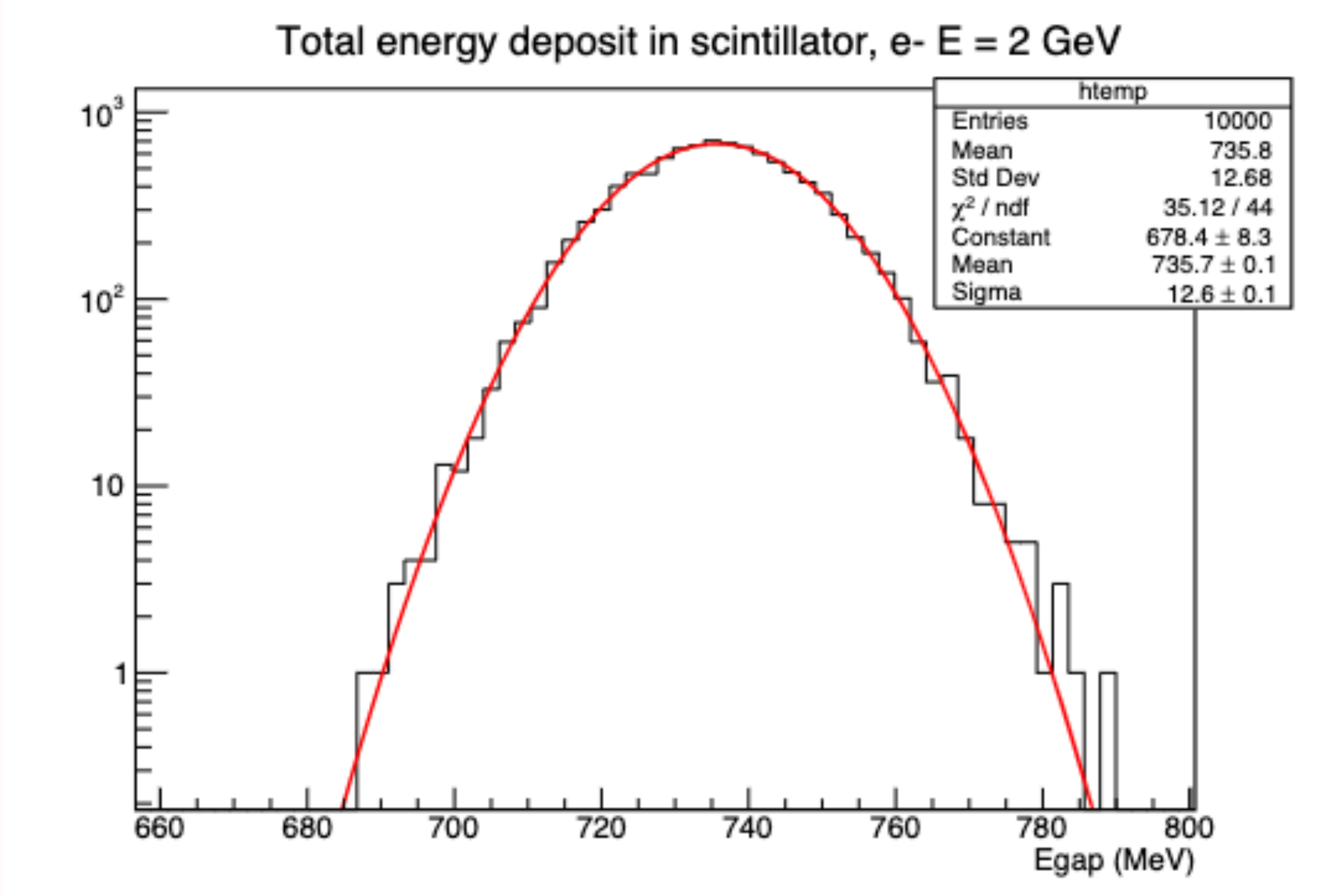
- reduction of the shaping time to the minimum possible of about 28 ns
- reduction of the amplitude of about 40%, and subsequent digitization at 160 MHz

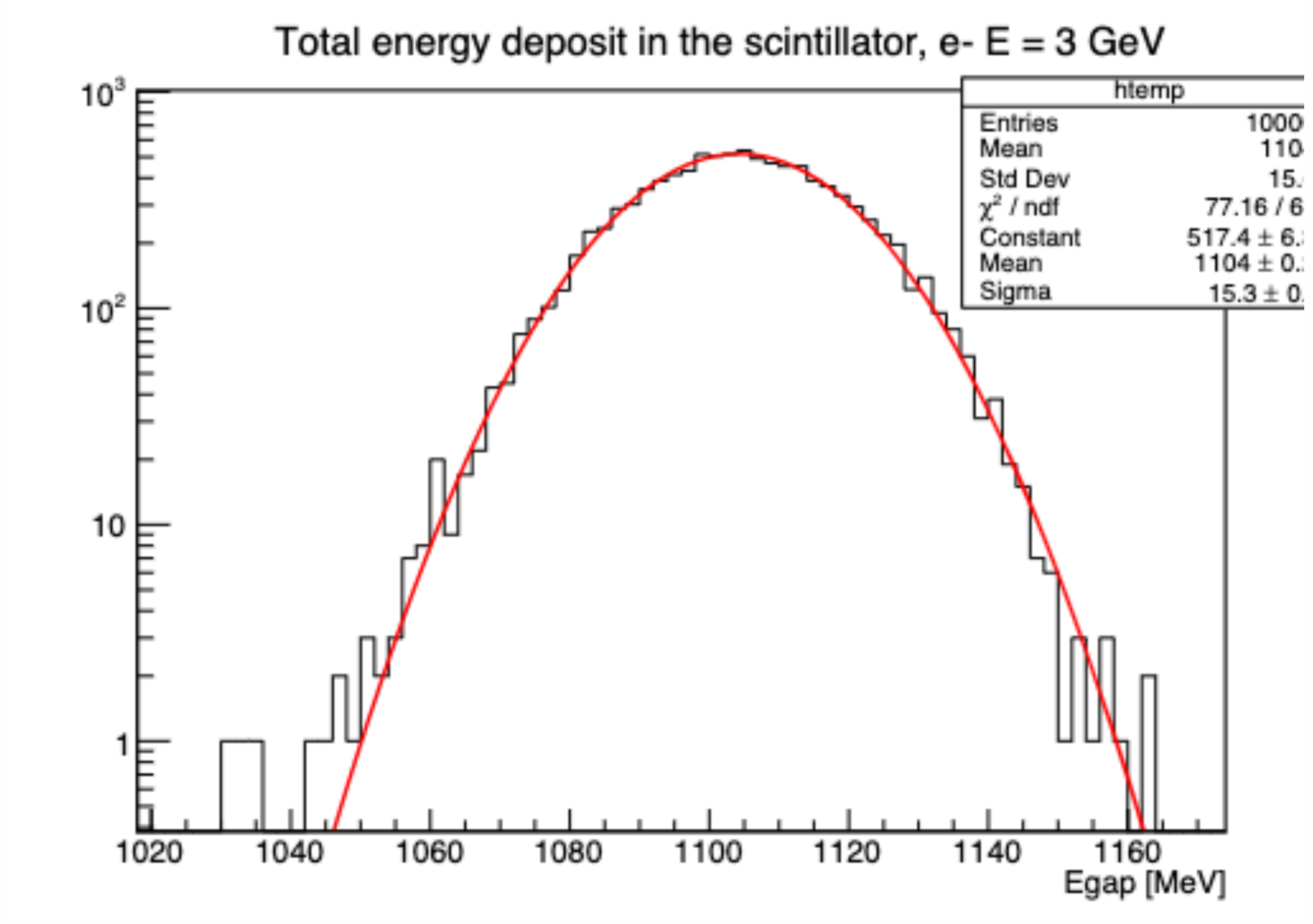
Space charge

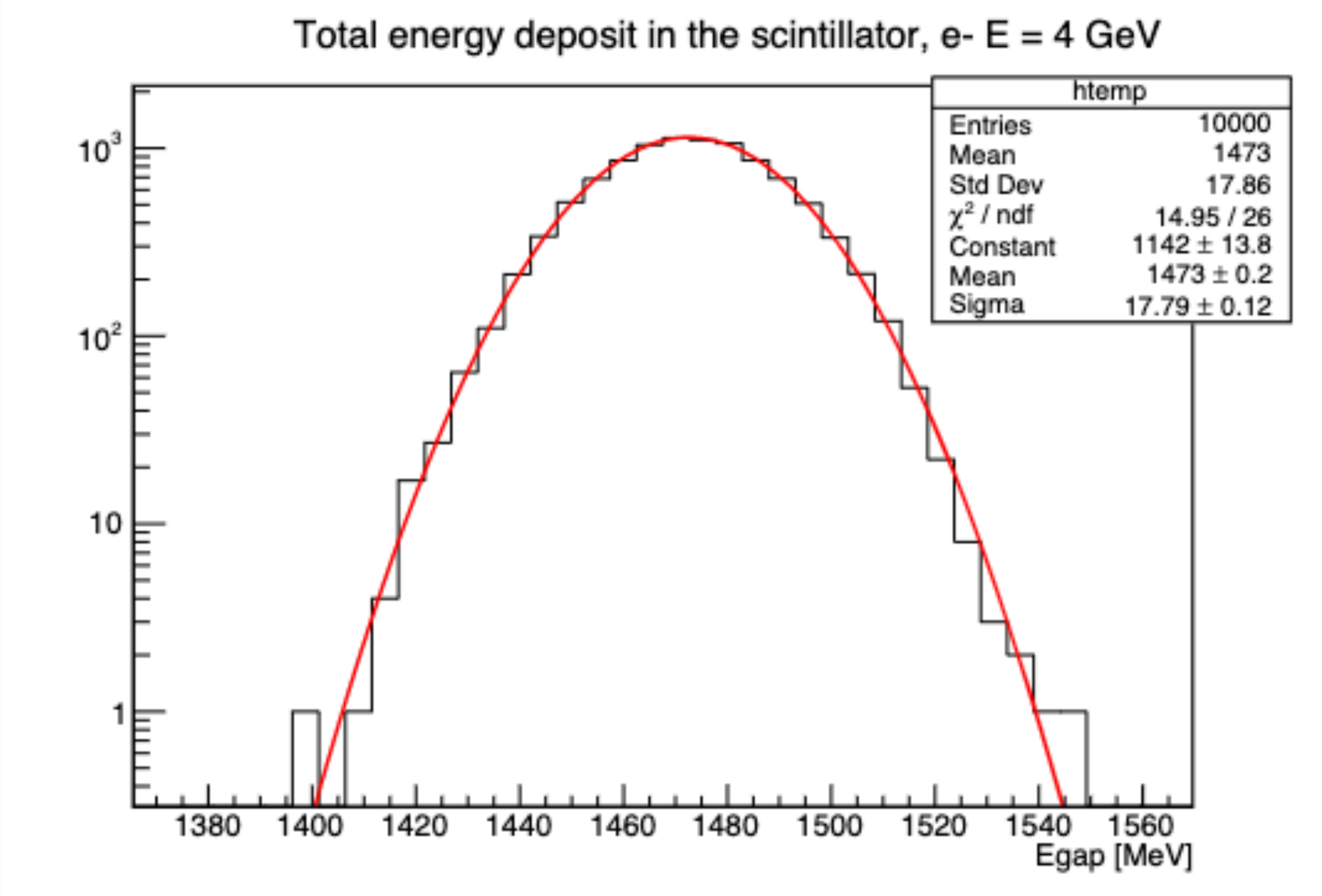
- going from the actual 3.5 kV to 5 kV will reduce by two the value of the critical parameter

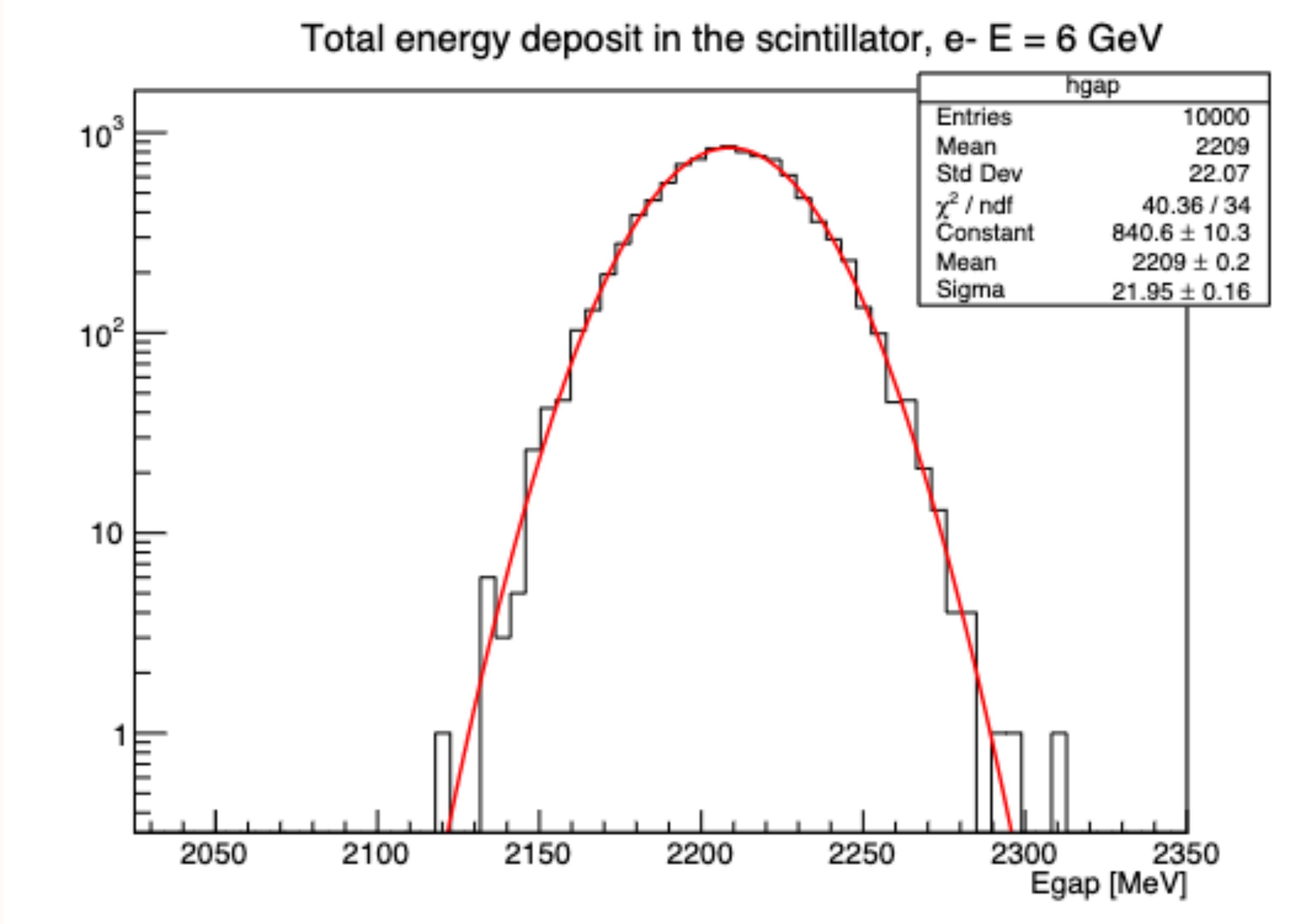
Energy resolution

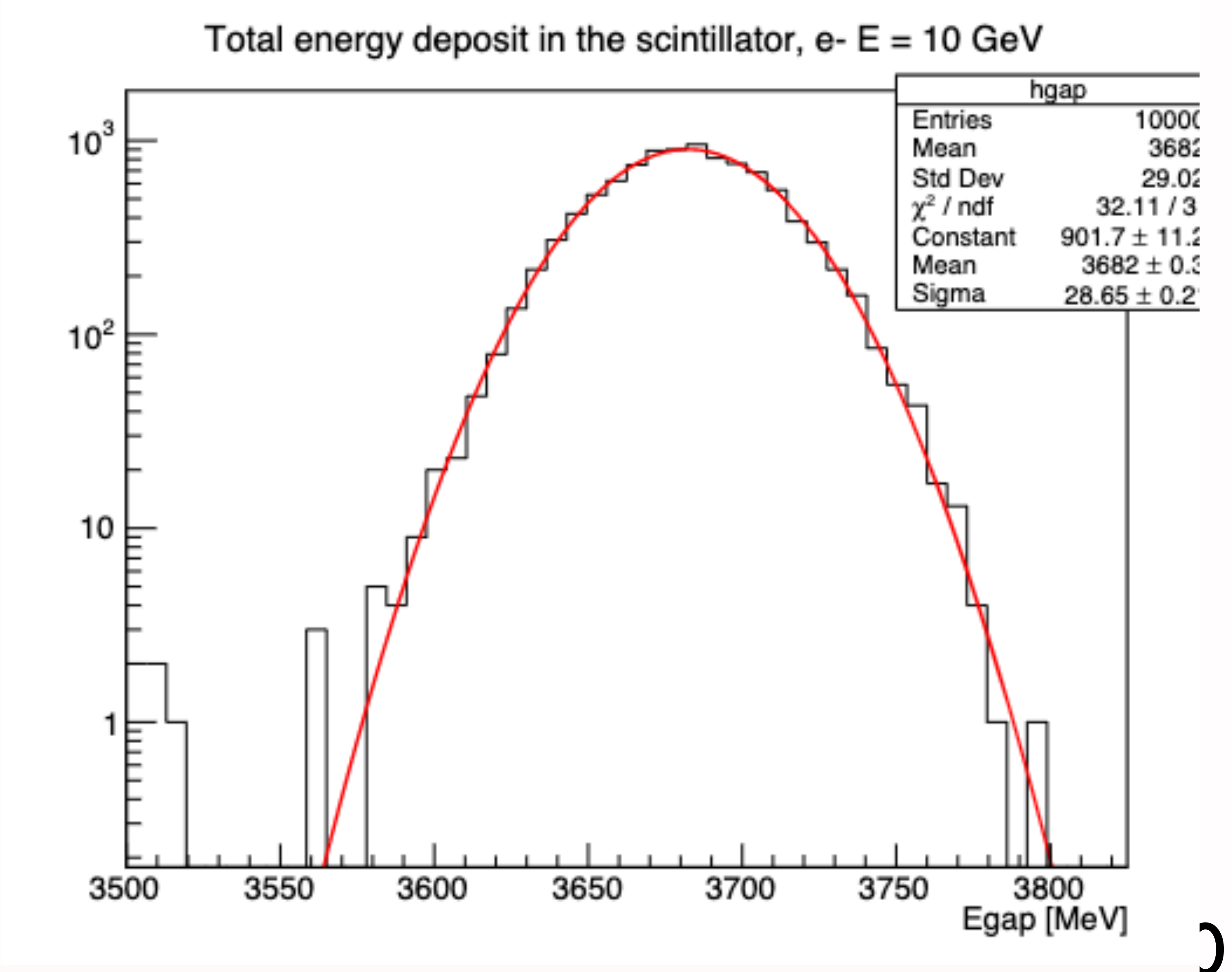




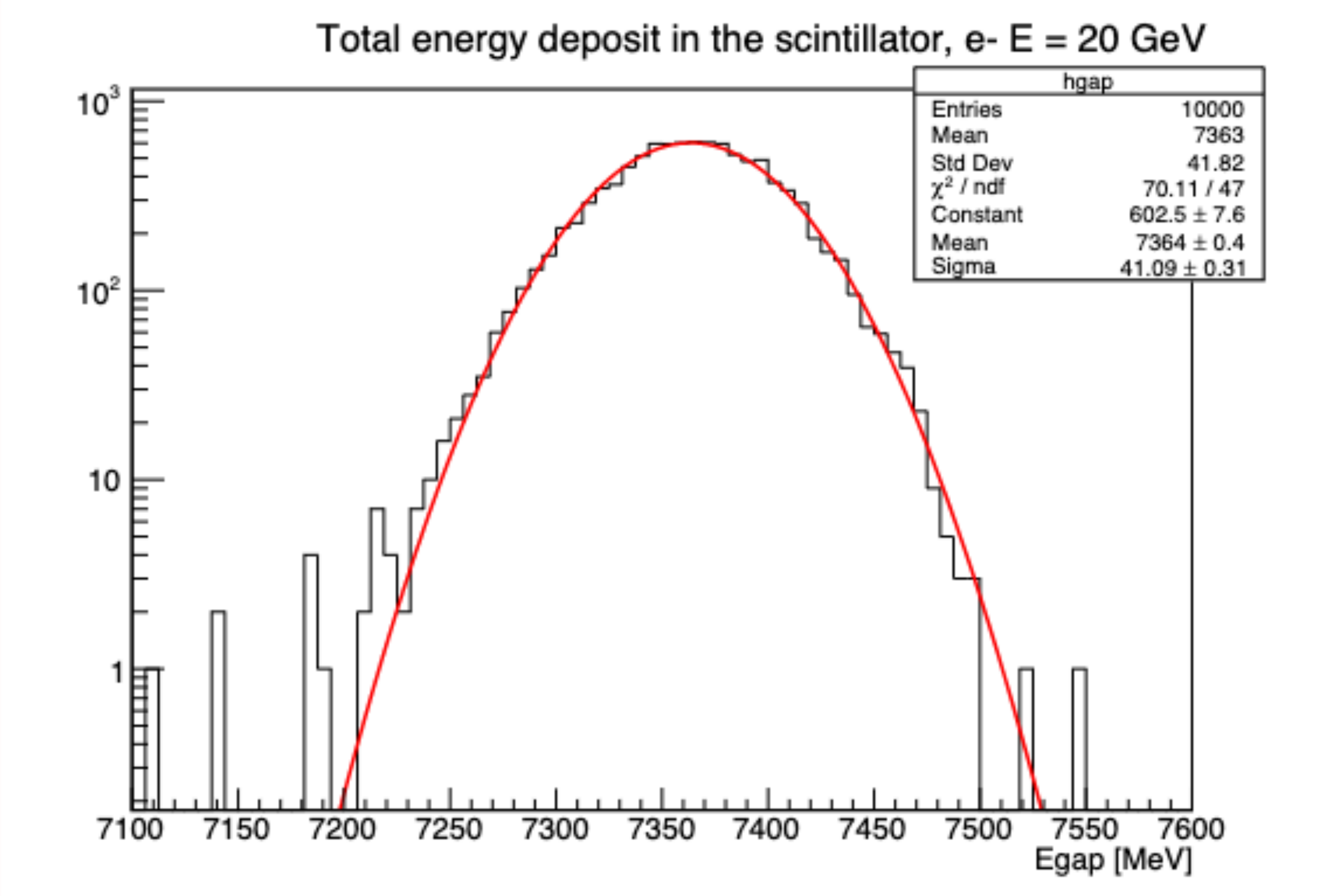


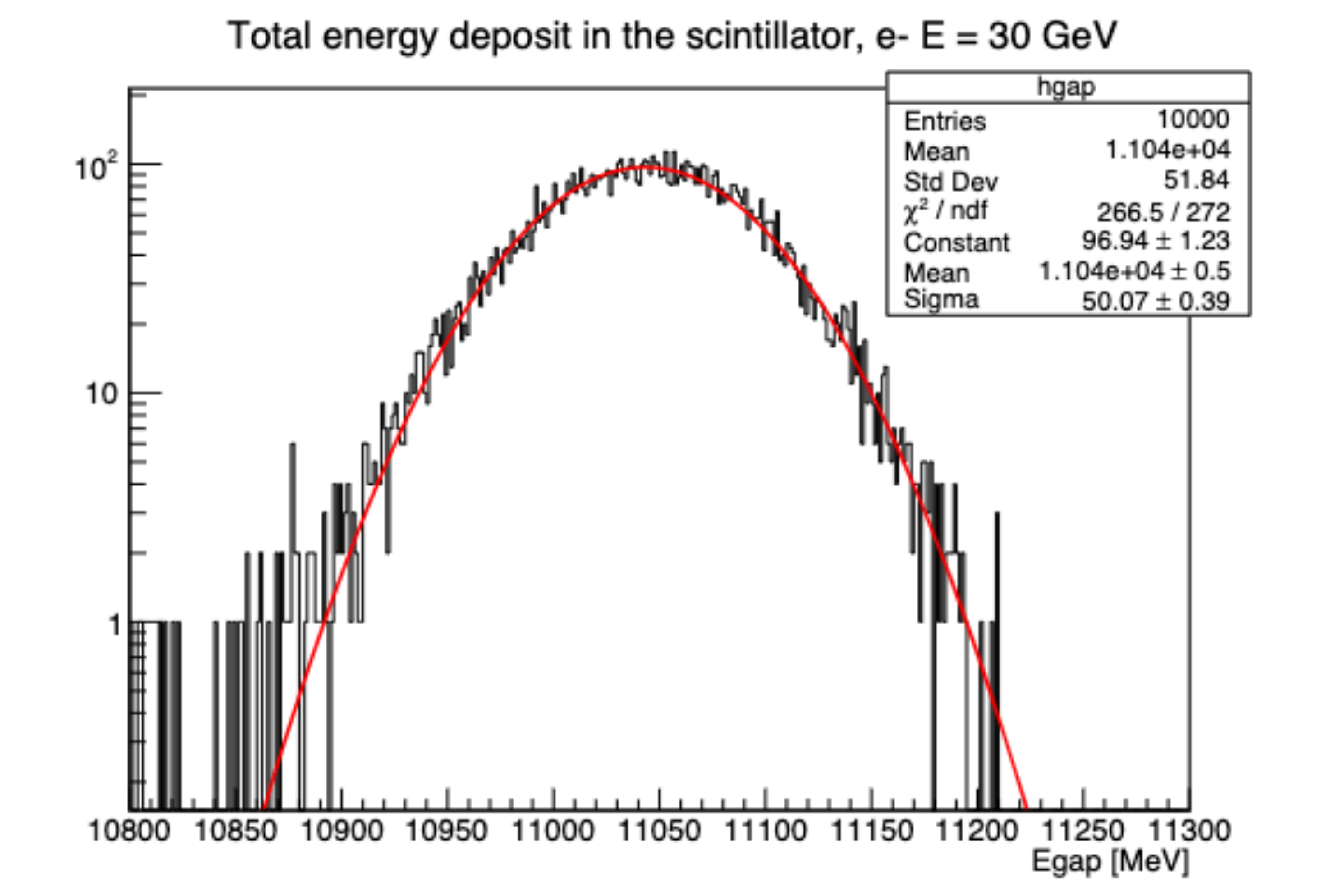


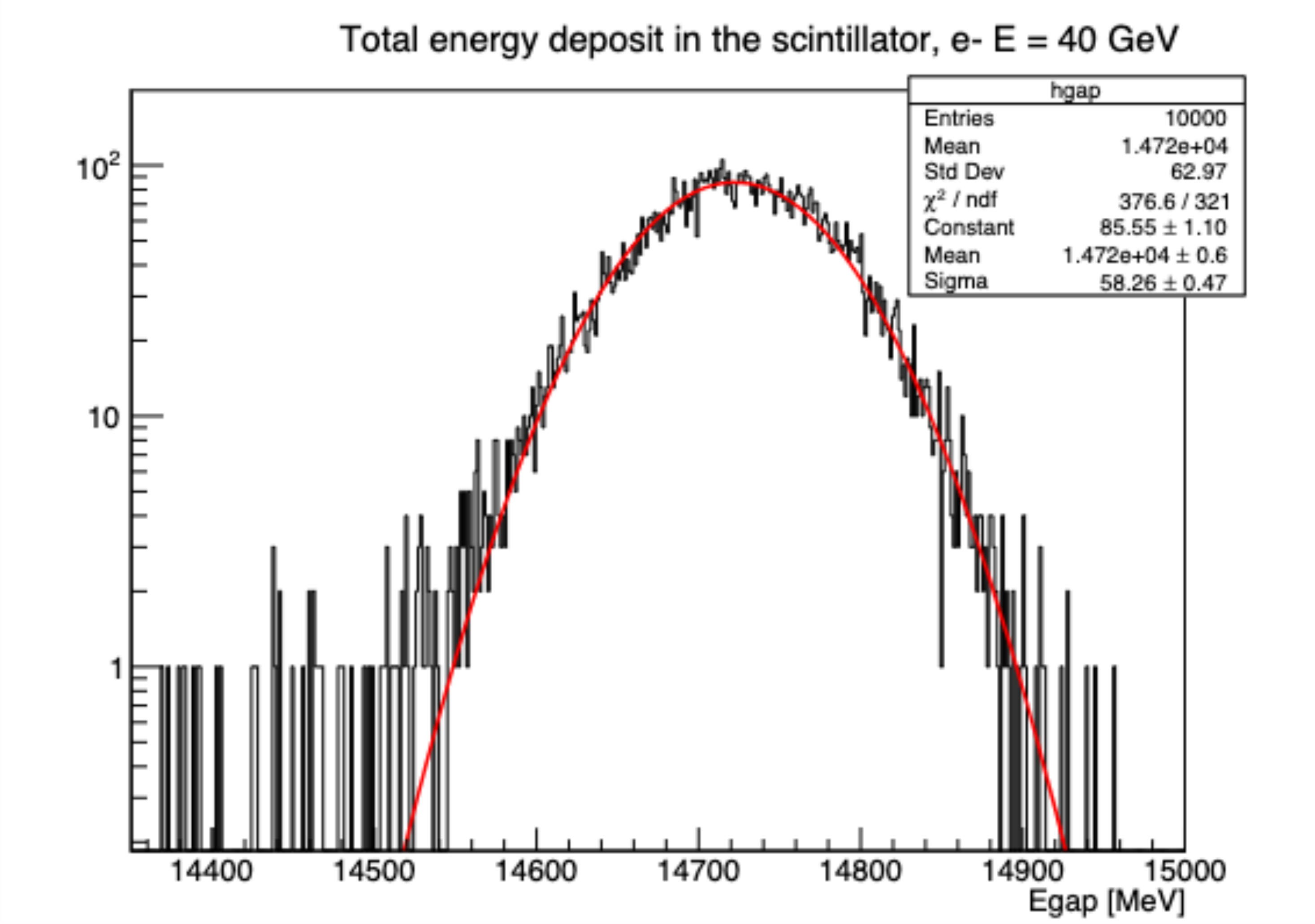


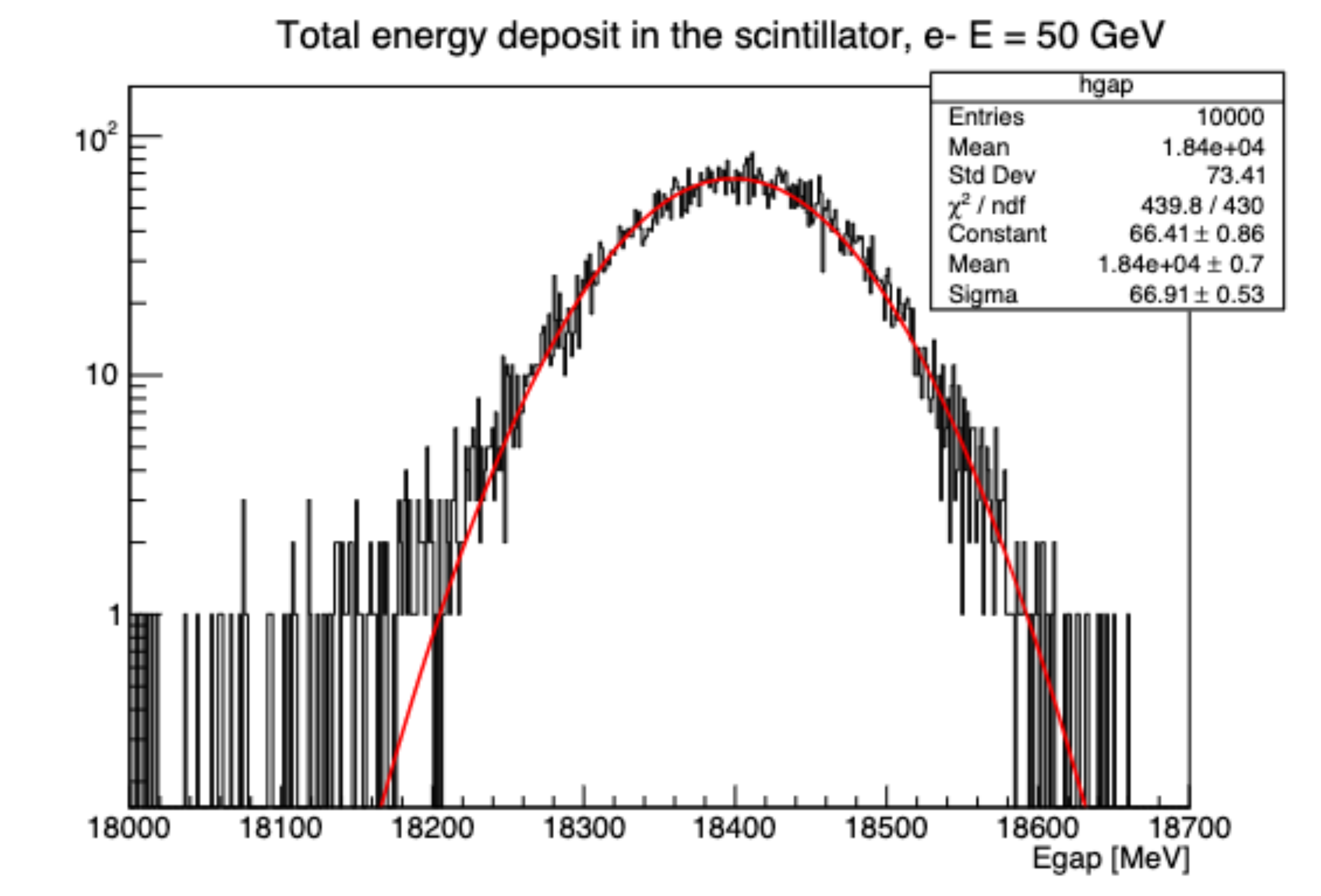


Energy resolution





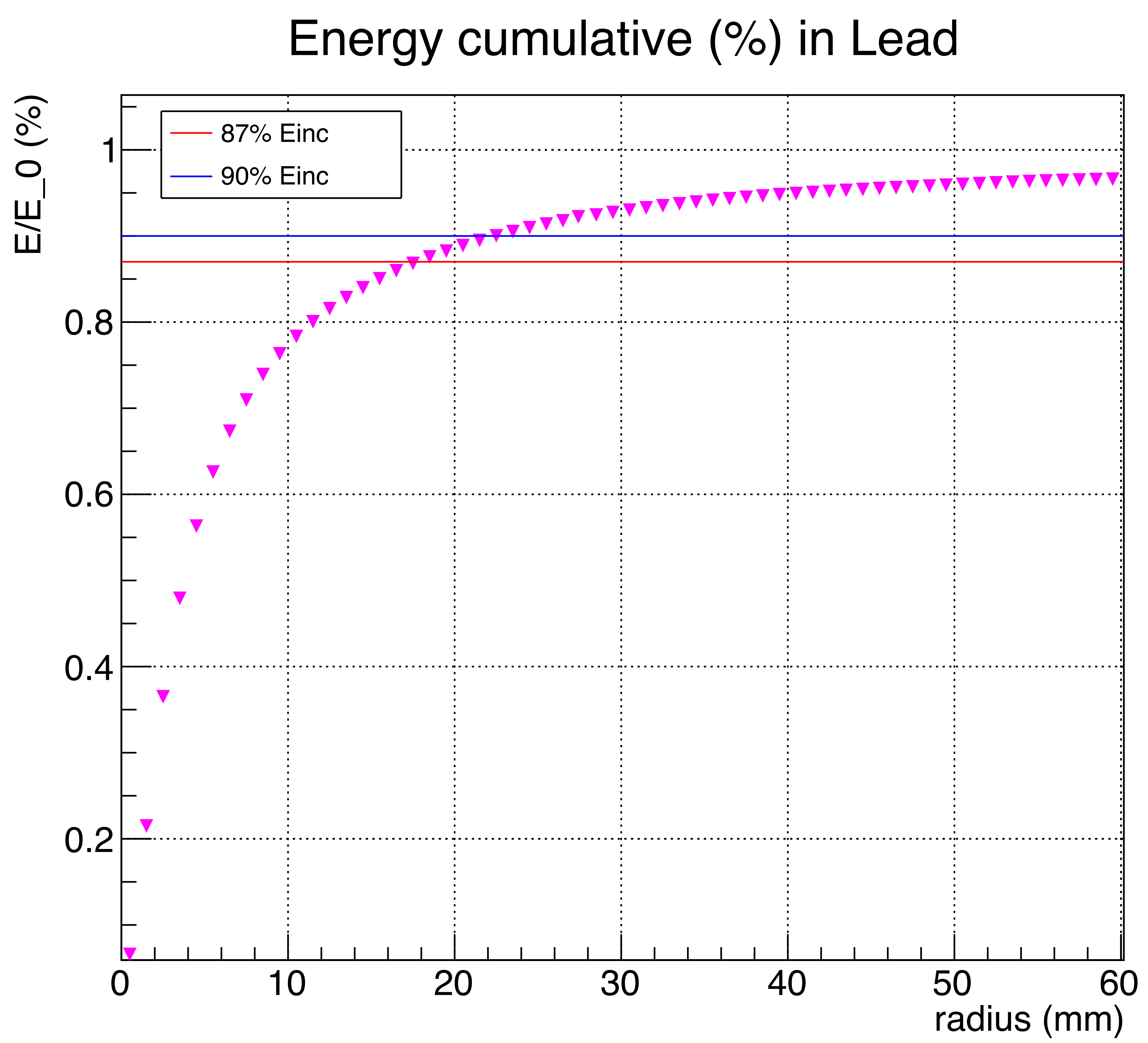




Step 1 Validation test with lead only

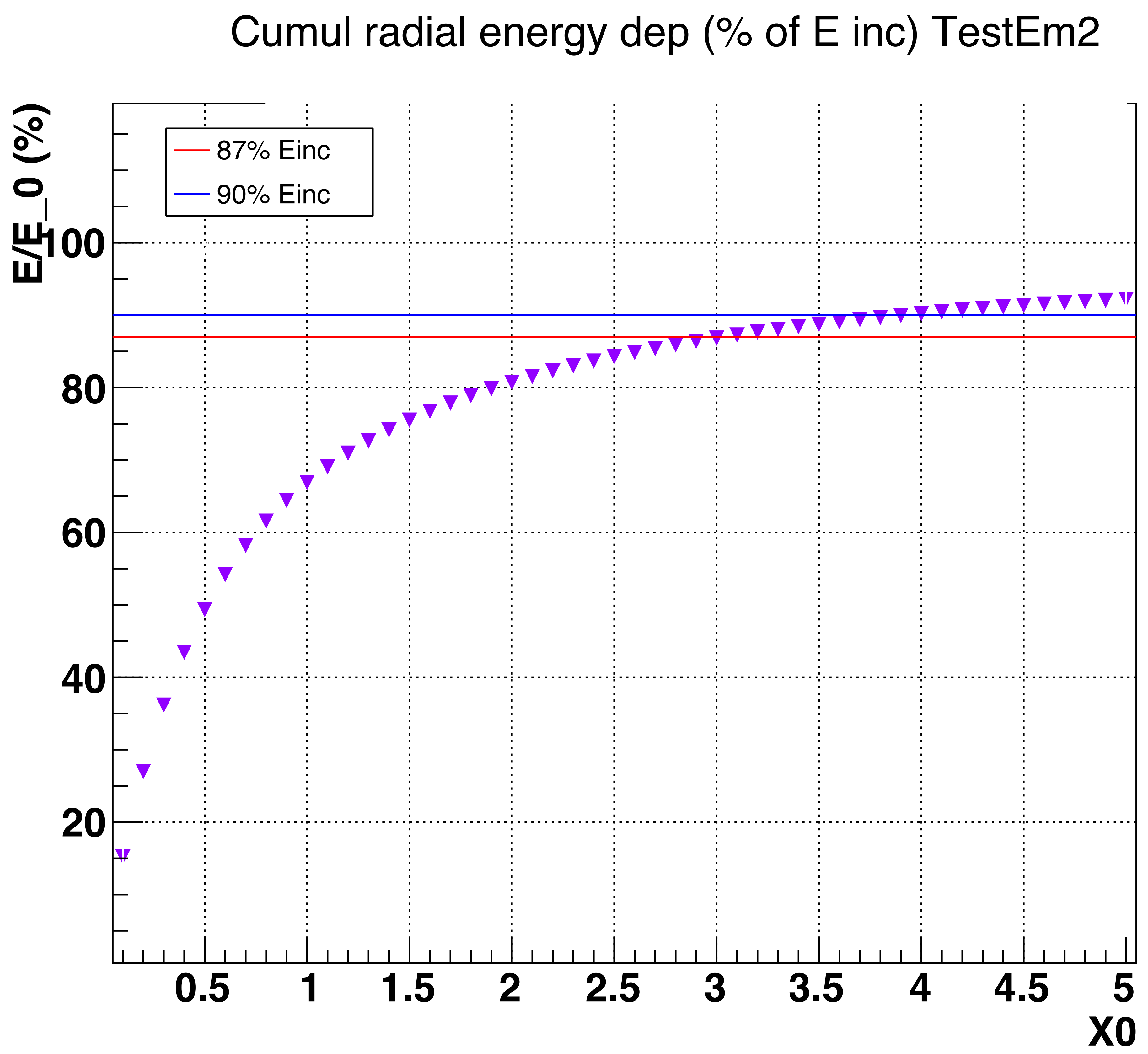
MEC like simulation (lead only)

- 200 × 200 mm² module
- 1 GeV e−
- cylindrical mesh r = 100 mm dr = 1 mm
- R_M(Lead) = 1.602 cm

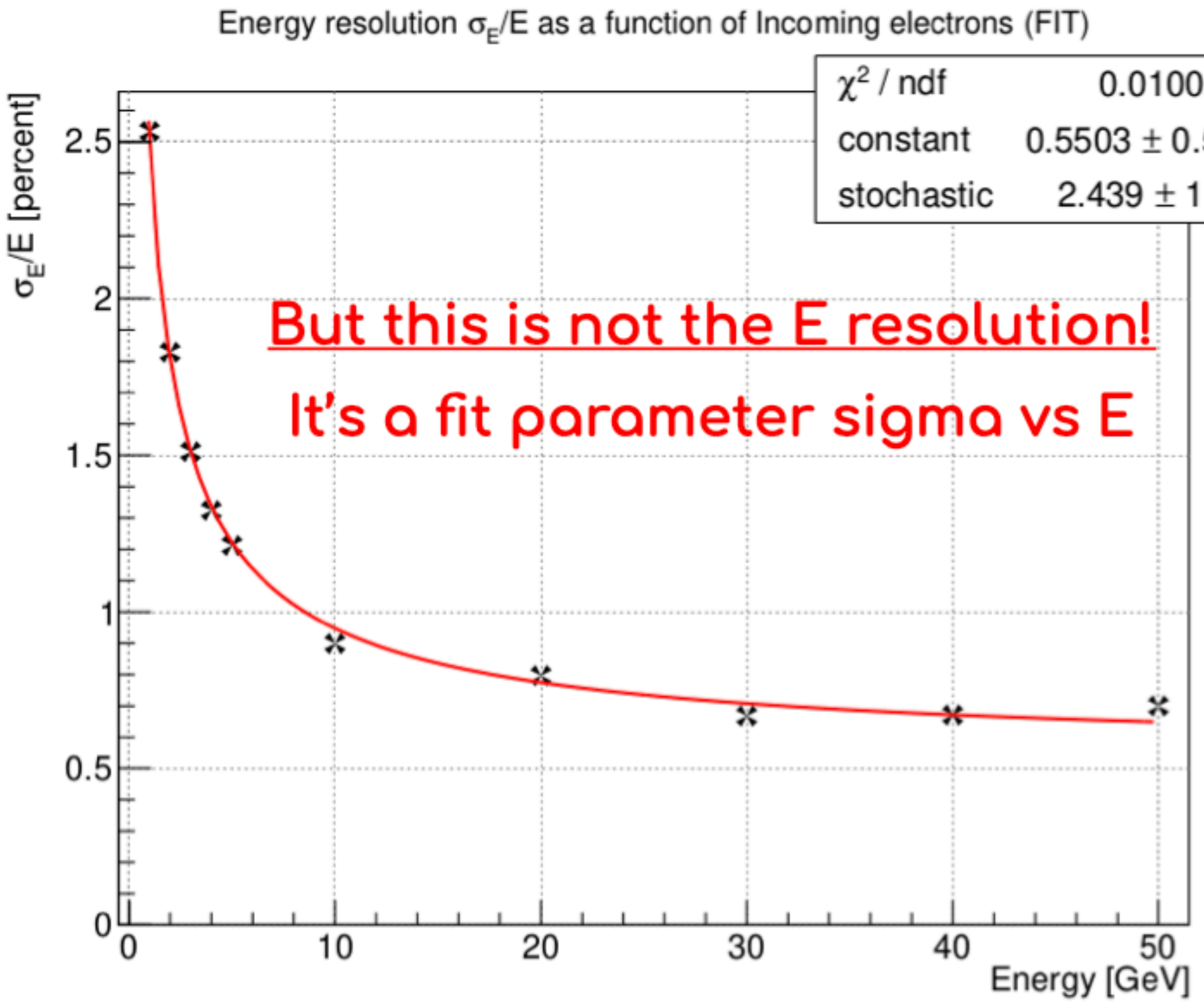


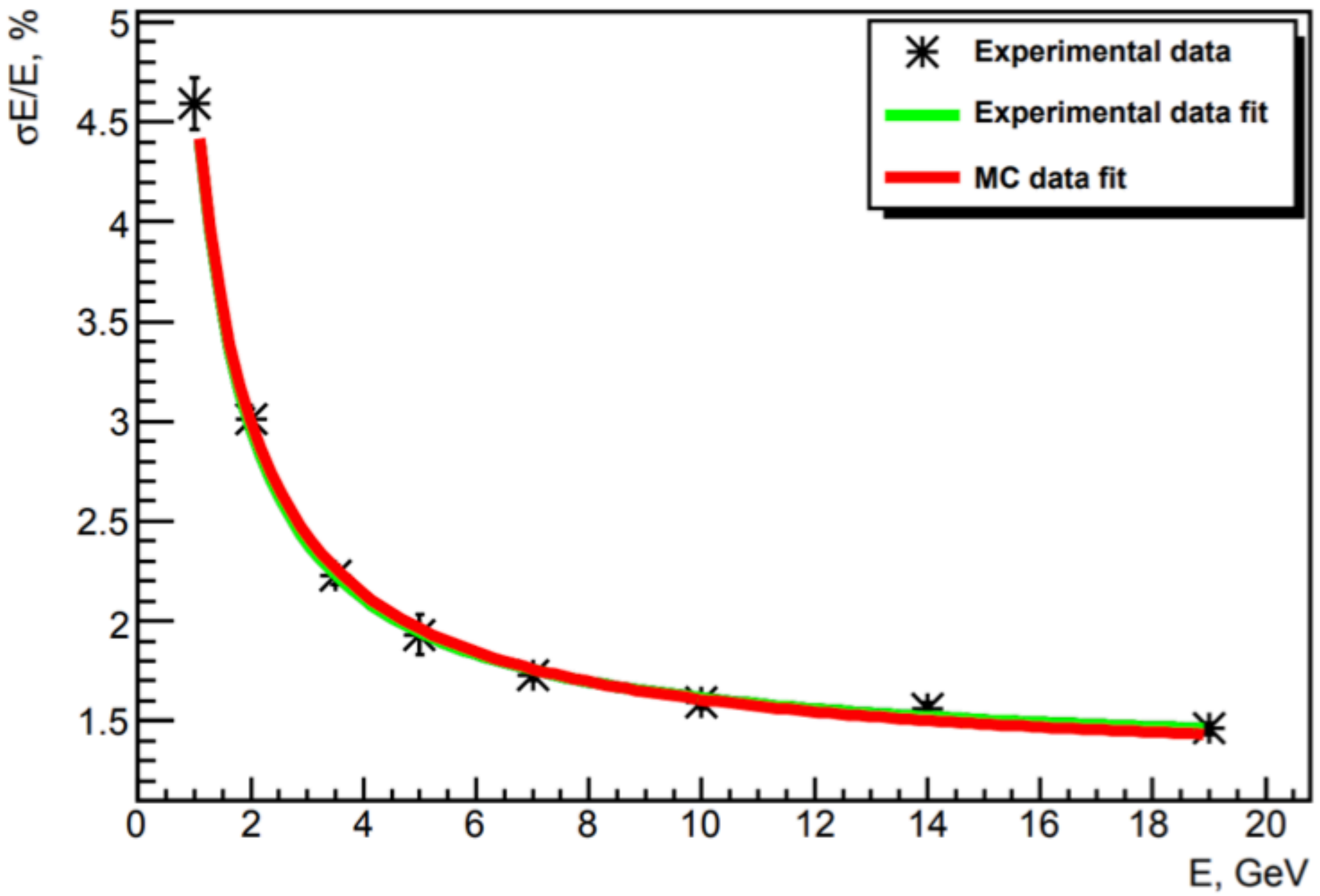
Geant4 EMcalo example

- Cylindrical geometry
- Radial segmentation set by the user
- Cumulative radial energy vs. radius (in X_0 unit)
- X_0(Lead) = 0.5612 cm



Step 2 Comparison with previous estimations





$$\sigma_E/E = 2.8/\sqrt{E} \oplus 1.3[\%]$$

Sergey Kholodenko report 27-04-2024

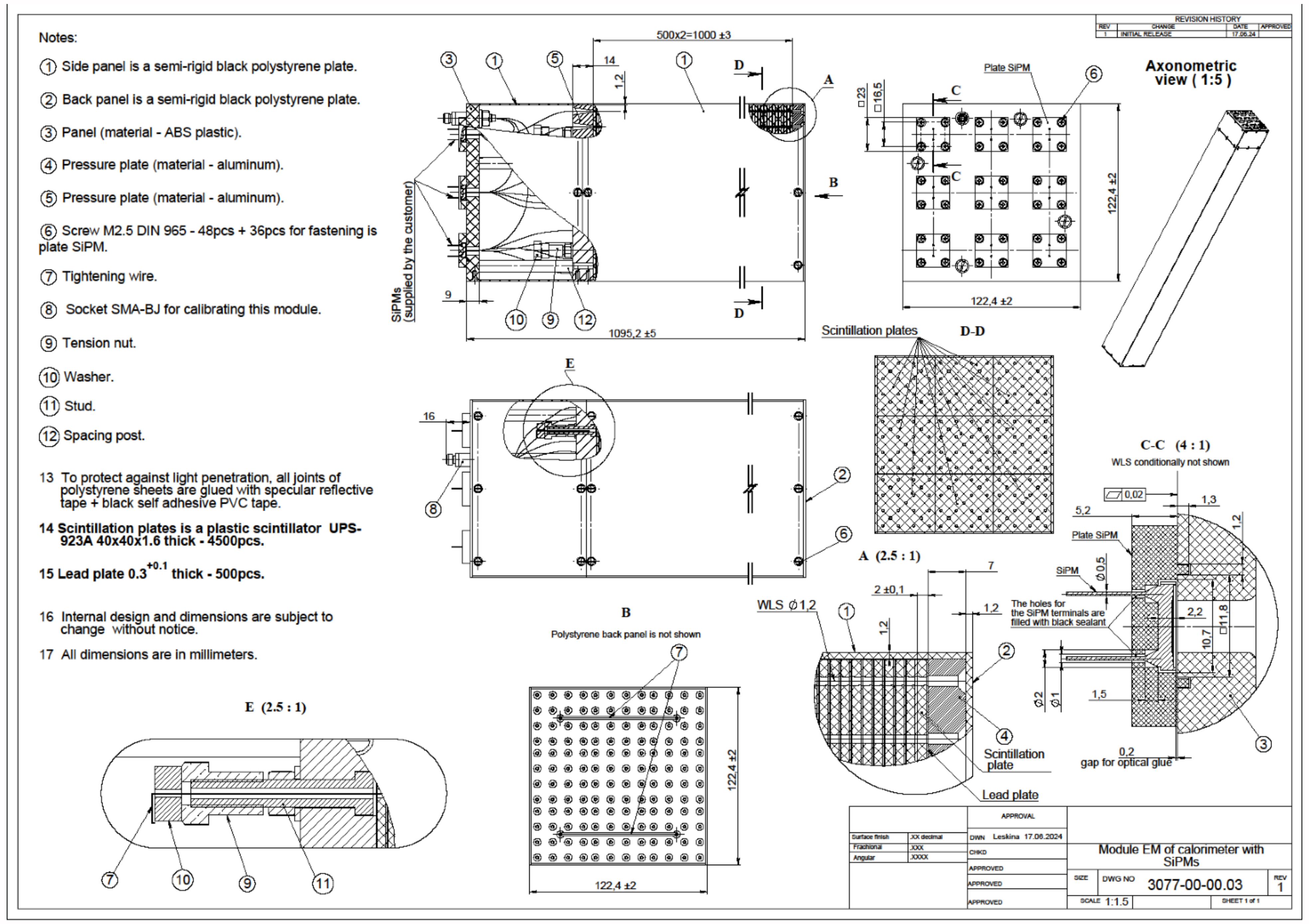
[Test beam study of the PANDA shashlyk calorimeter prototype]

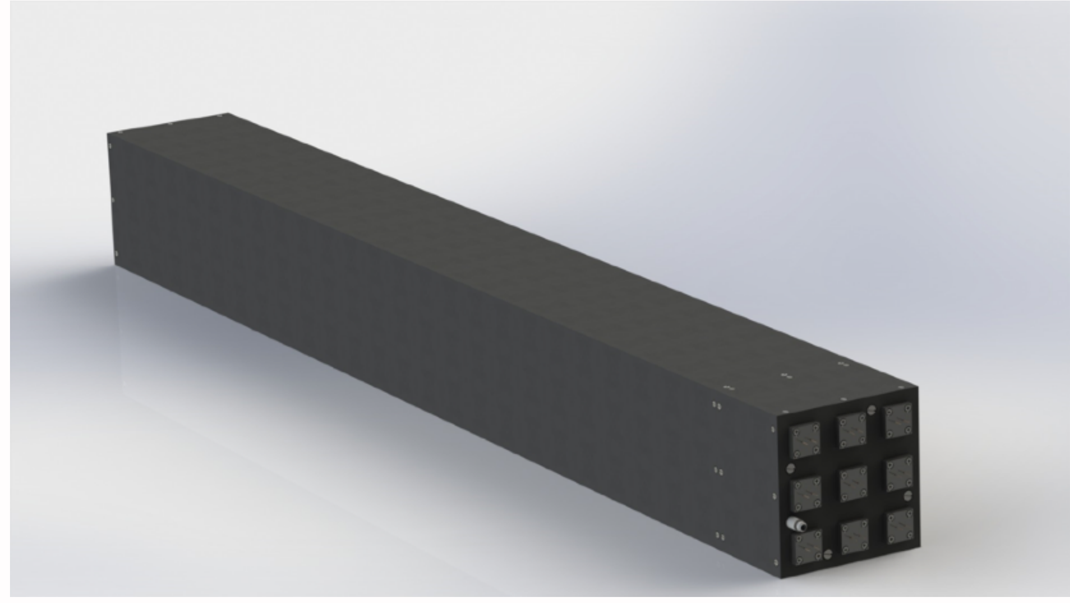
Shashlyk prototype construction

Shashlyk prototype design:

- 3x3 channel matrix with cell size 4x4 cm
- 500 layers of scintillator + lead. All edges tiles and both lead tiles sides coated with reflective paint.
- Lead layer: 120x120x0.3 mm, scintillator layer: 40x40x1.5 mm
- WLS fibers BCF-92XL with 1.2mm diameter, mirrored at one side

Prototype developed in collaboration with the DETEC company

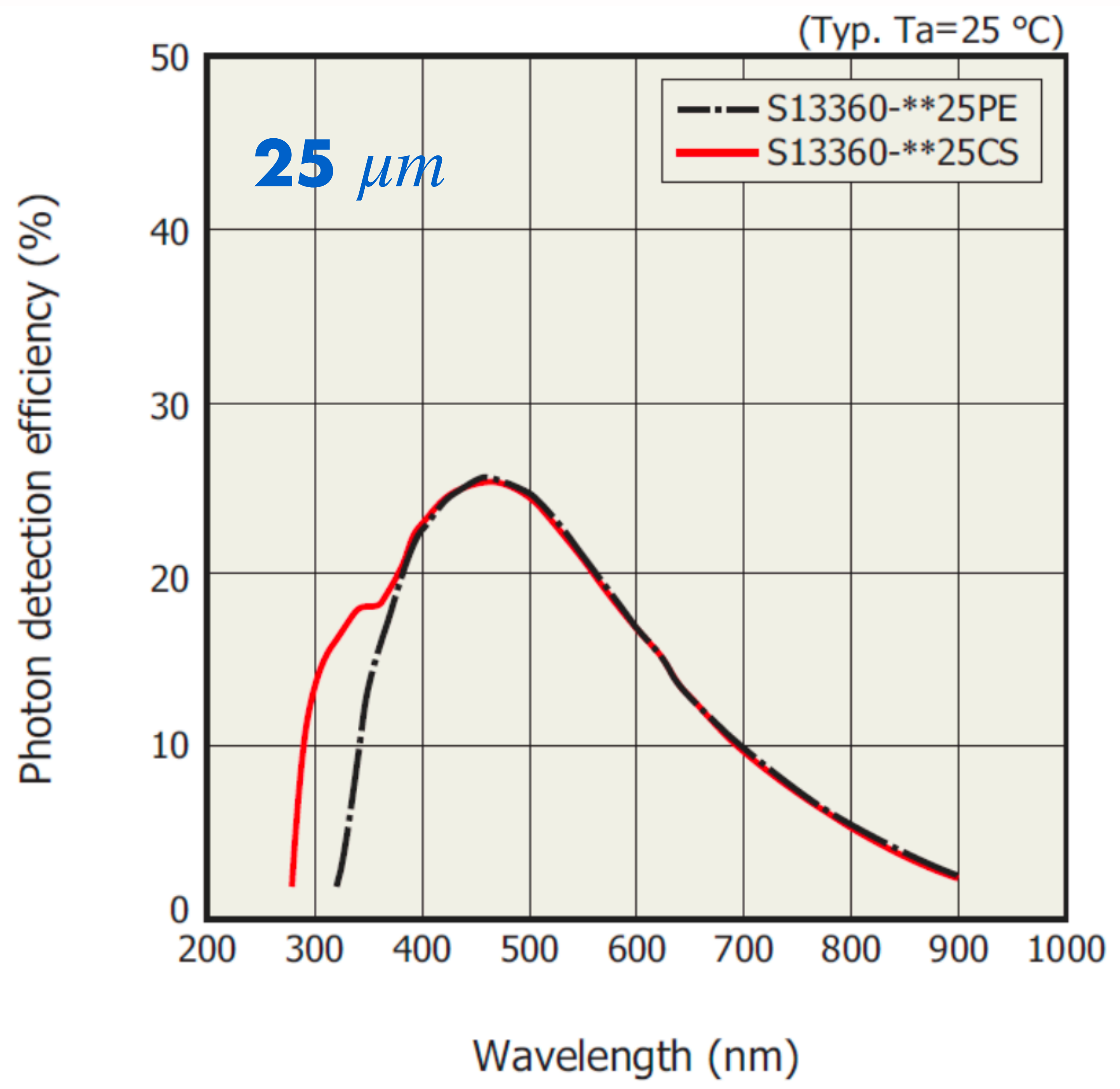


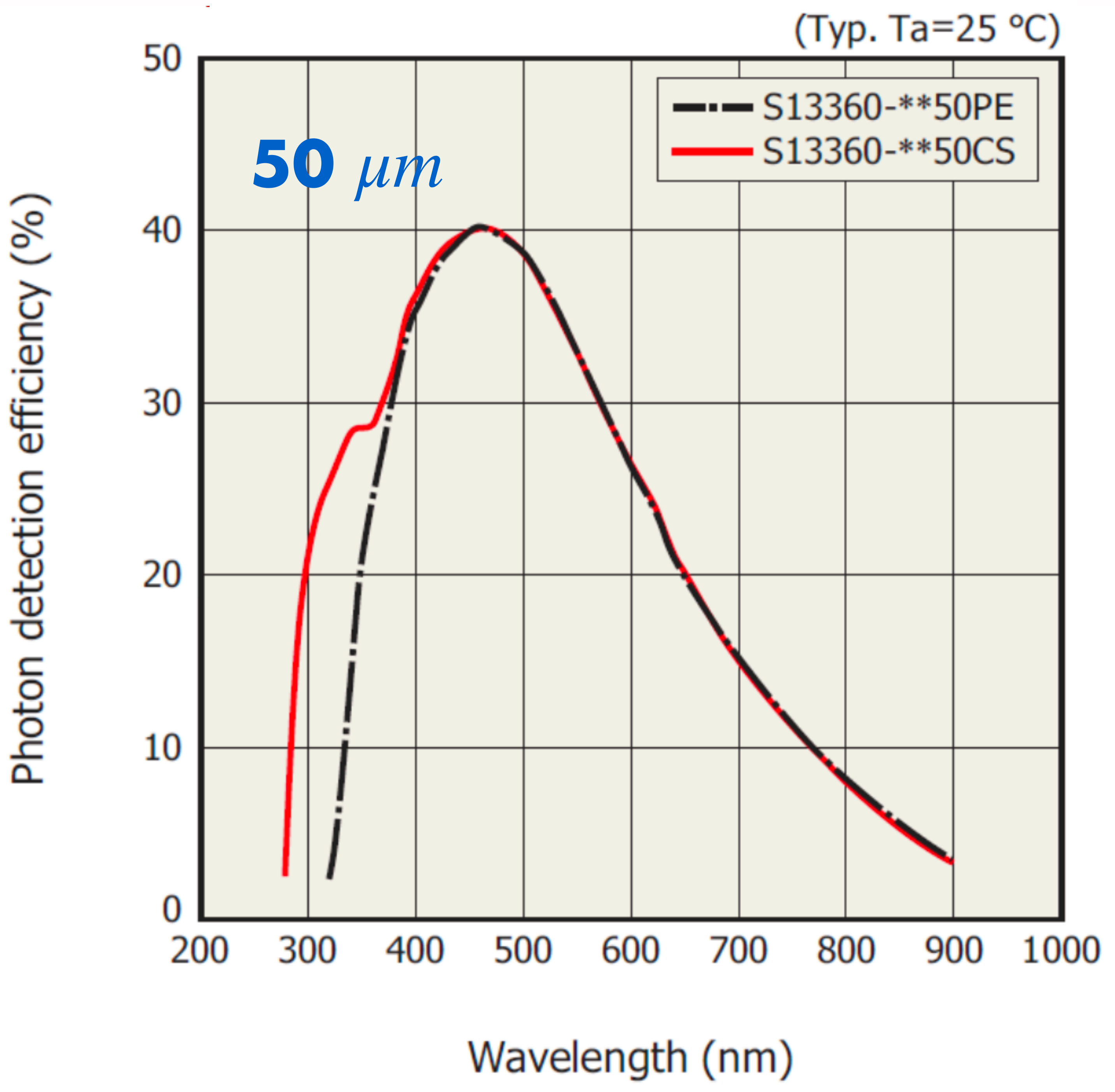


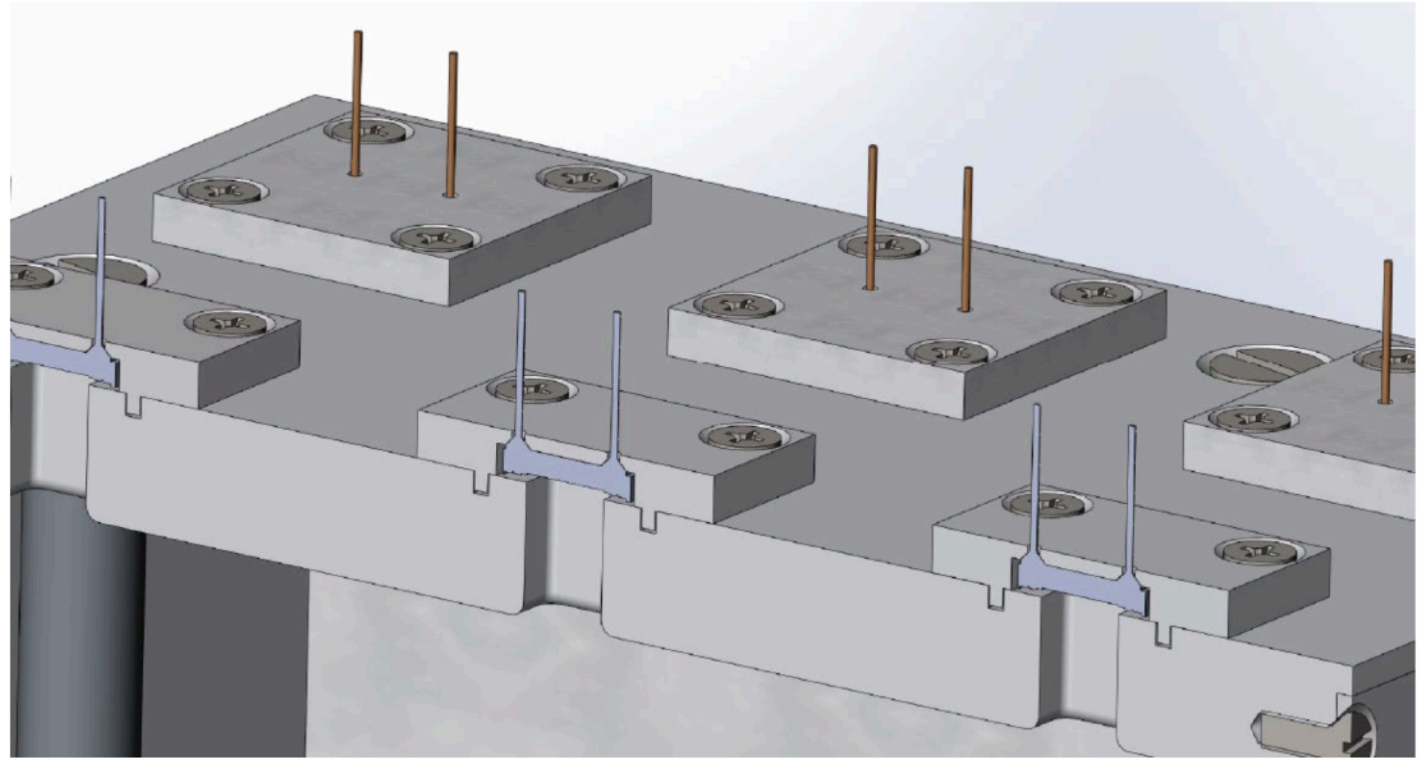
Shashlyk prototype construction

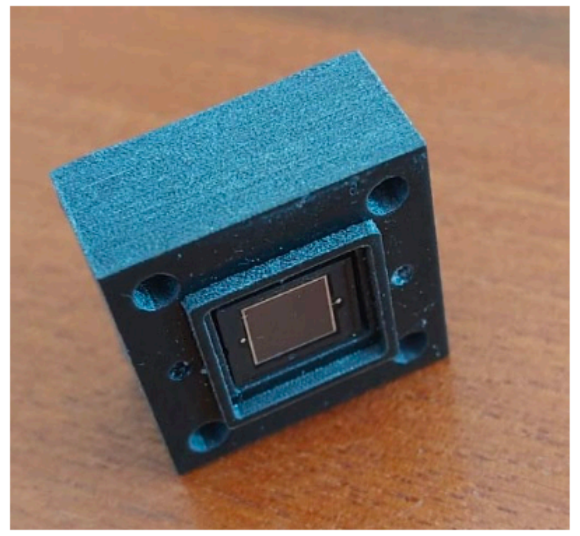
Switch between two possible PD

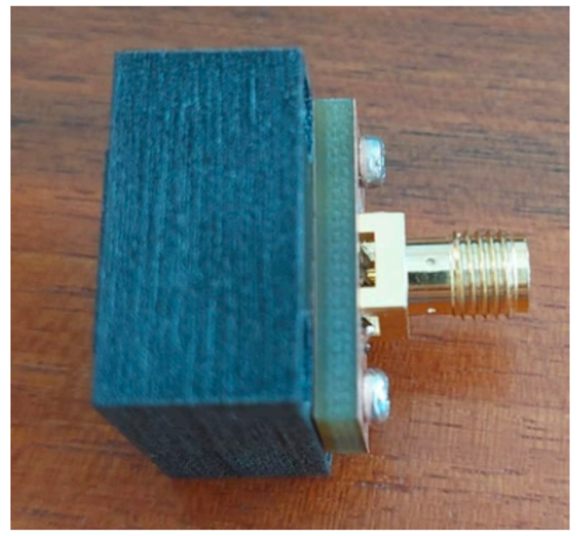
1. **SiPM solution**: Hamamtsu S13360-6050/25CS
2. **PMT solution:** Hamamtsu R7600U-300 extended green

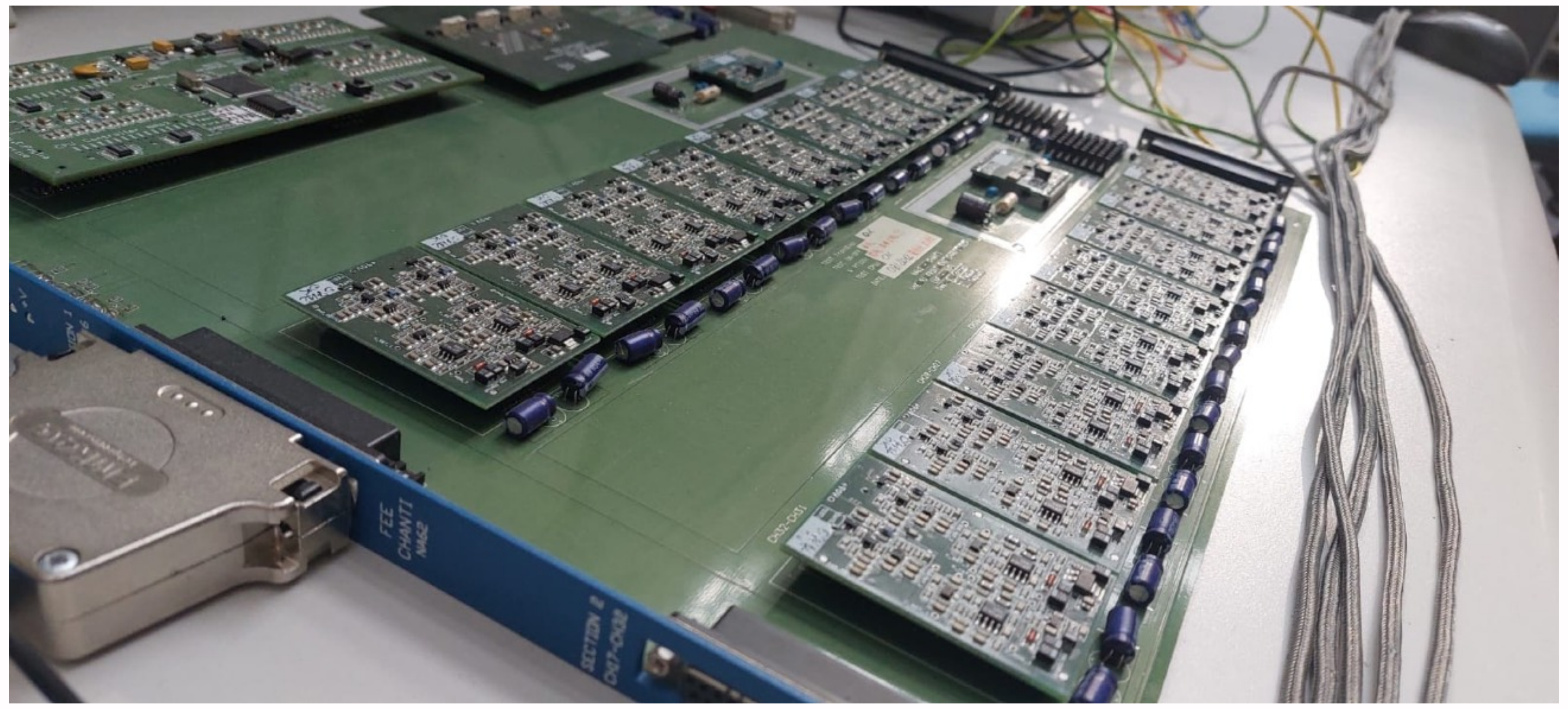










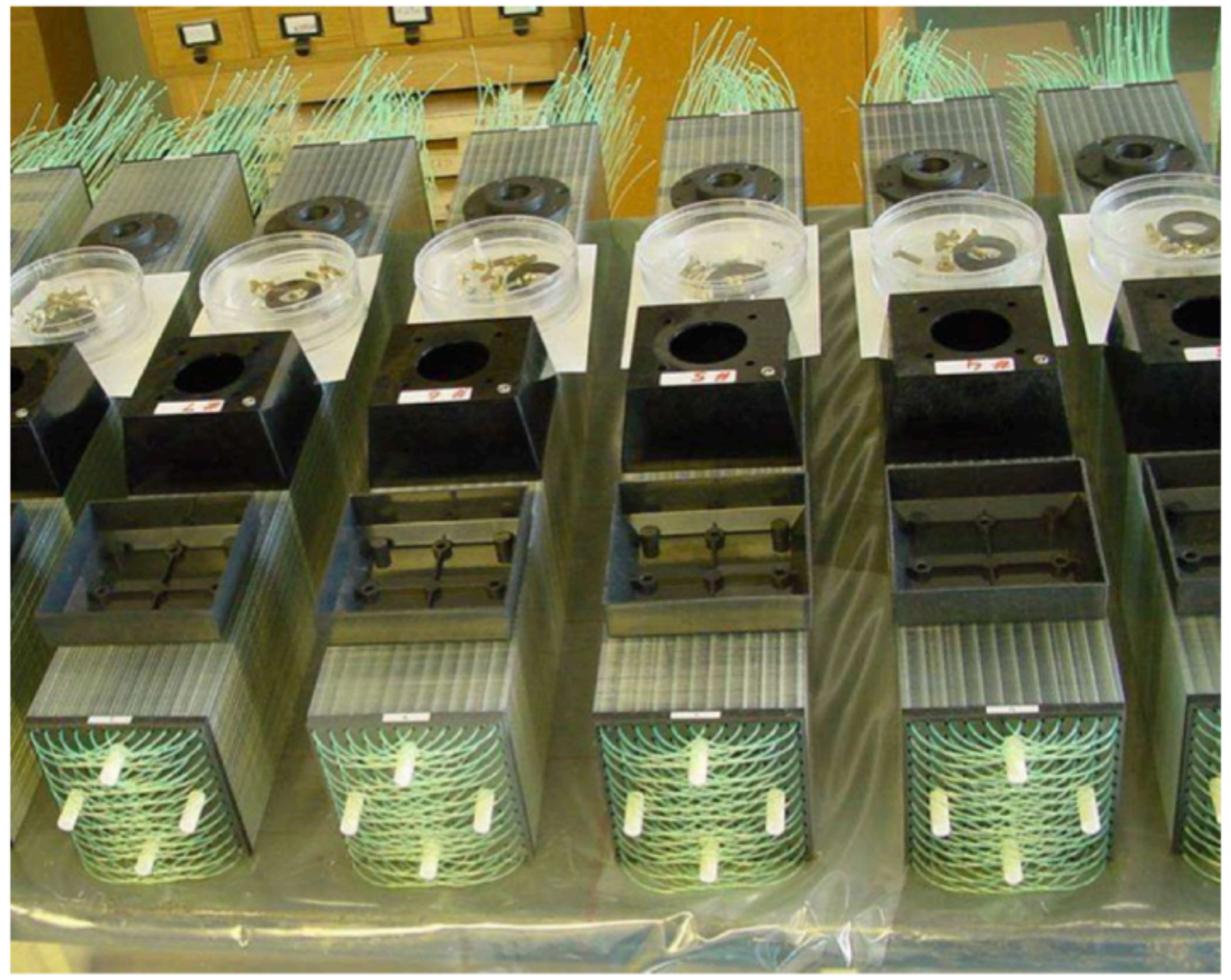


Shashlik calorimeter

PANDA/KOPIO prototype performance

- $\sigma_t \sim 72\,ps$ (at 1 GeV)
- $\sigma_E/\sqrt{E} \sim 3.3\,\%$ (at 1 GeV)
- $\sigma_x \sim 13\,mm$ (at 1 GeV)

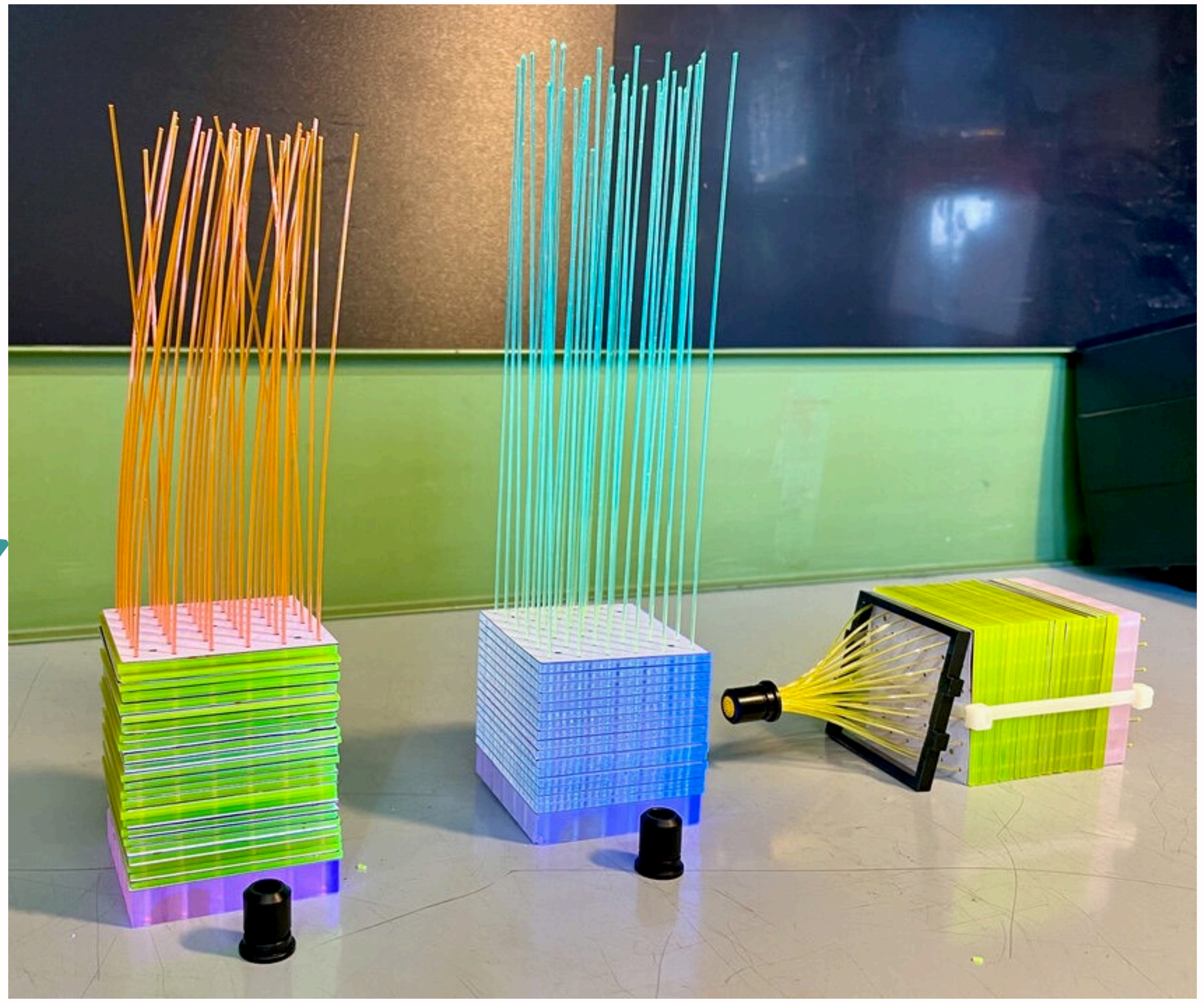
providing the same energy resolution as the LKr while meeting the time resolution requirements for HIKE



Calorimeter	Pb/Scint [mm]	Energy resolution	Sampling fraction
ALICE EMCal	1.44/1.76	$10\,\%/\sqrt{E} \oplus 5\,\%$	16%
LHCb ECAL	2.0/4.0	$8\,\%/\sqrt{E} \oplus 1\,\%$	24%
PANDA/KOPIO	0.275/1.5	$2.8\,\%/\sqrt{E} \oplus 1.3\,\%$	47%

HIKE MEC design

- **Fine-sampling Shashlyk** based on PANDA forward calorimeter produced at Protvino (0.275 mm Pb +1.5 mm scintillator)
- **time resolution** of 100 ps or better for the reconstruction of π^0's with energies of a few GeV
- **Longitudinal shower information from spy tiles:** PID
- **Neutron rejection** ~10^3

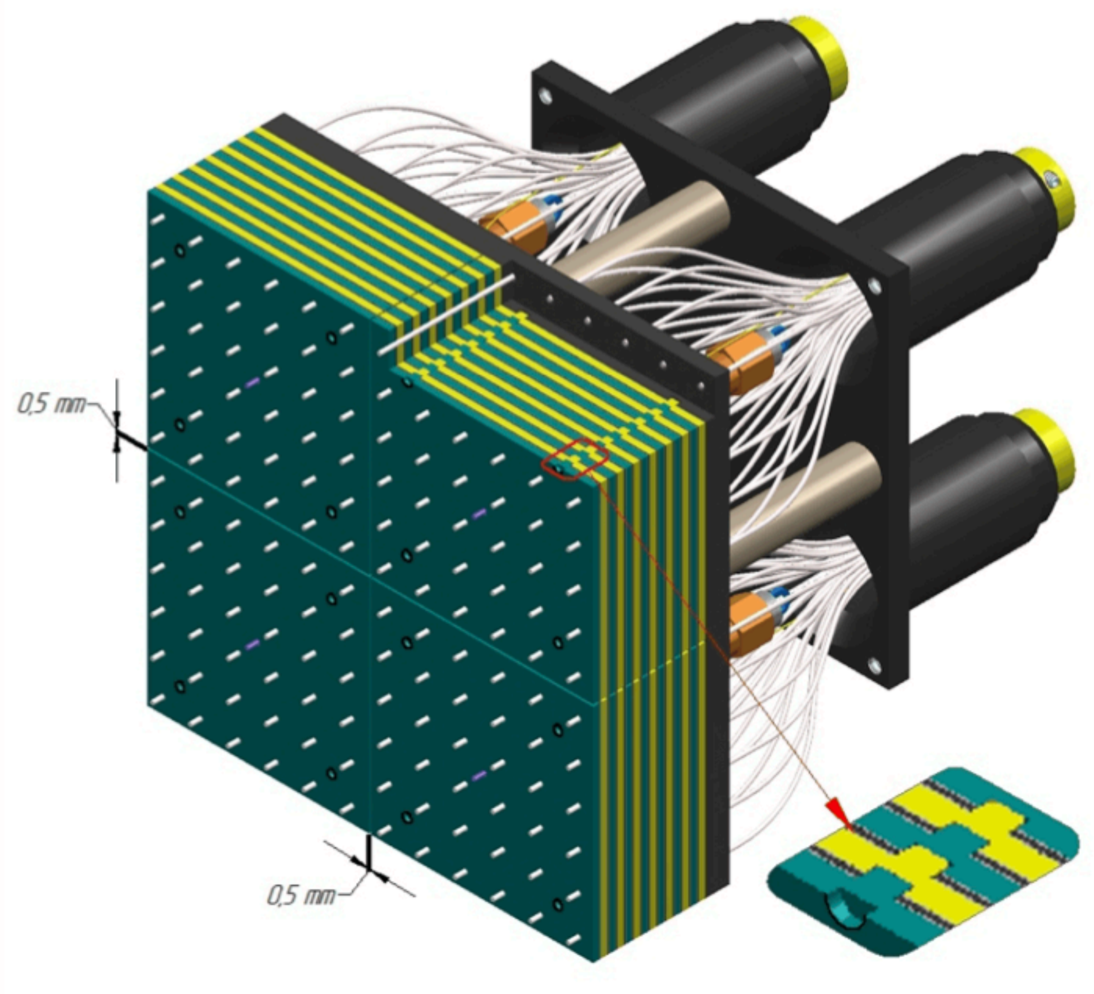


Use of nanocomposite scintillators under investigation in collaboration with AIDAinnova project NanoCal: Perovskite ($CsPbX_3$, X=Br, Cl...) nanocrystals cast into polymer matrix

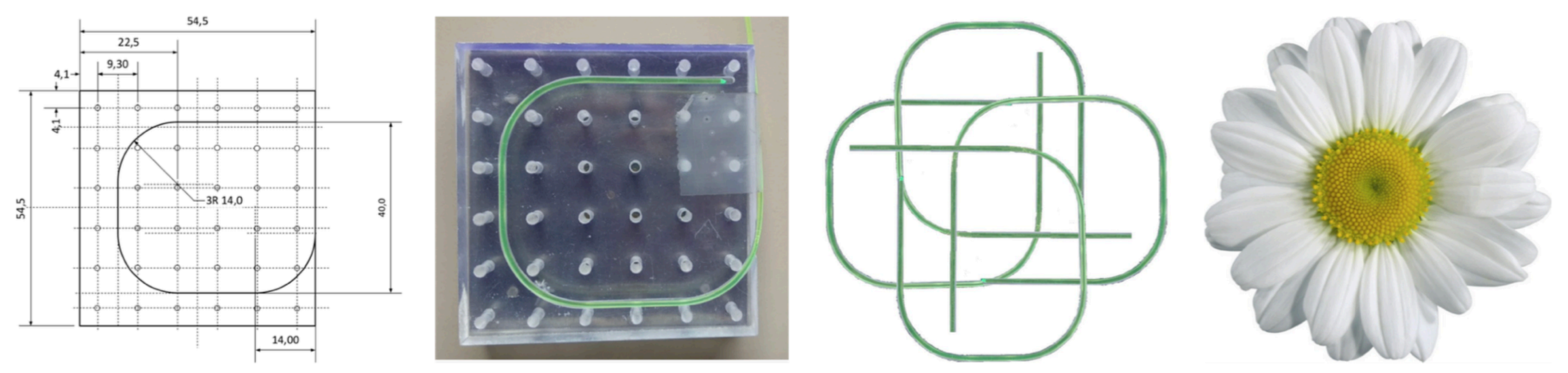
See Matt's talk tomorrow

A closer look at the design

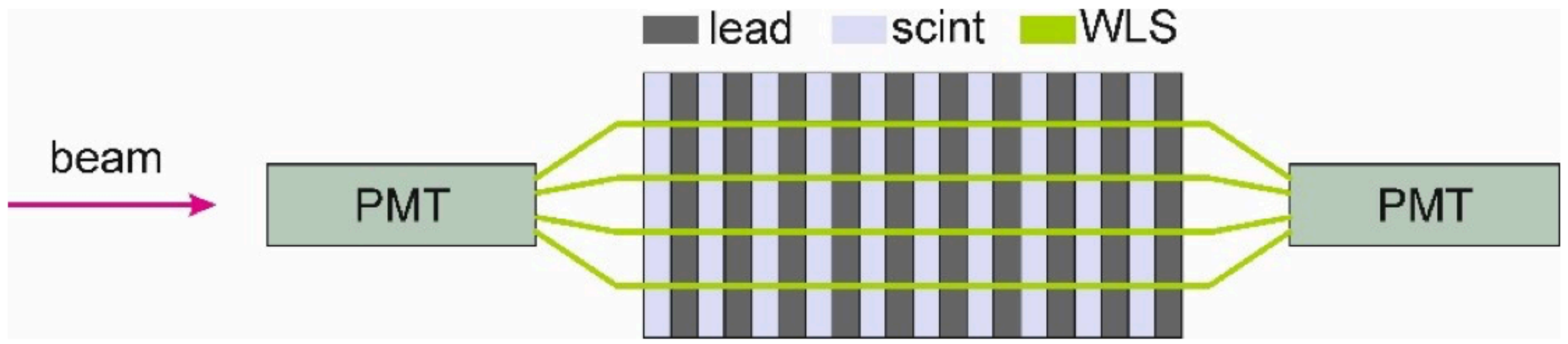
Abso/Scint Tiles
- traditional design
- matrix of fibers
- 1SiPM for channel



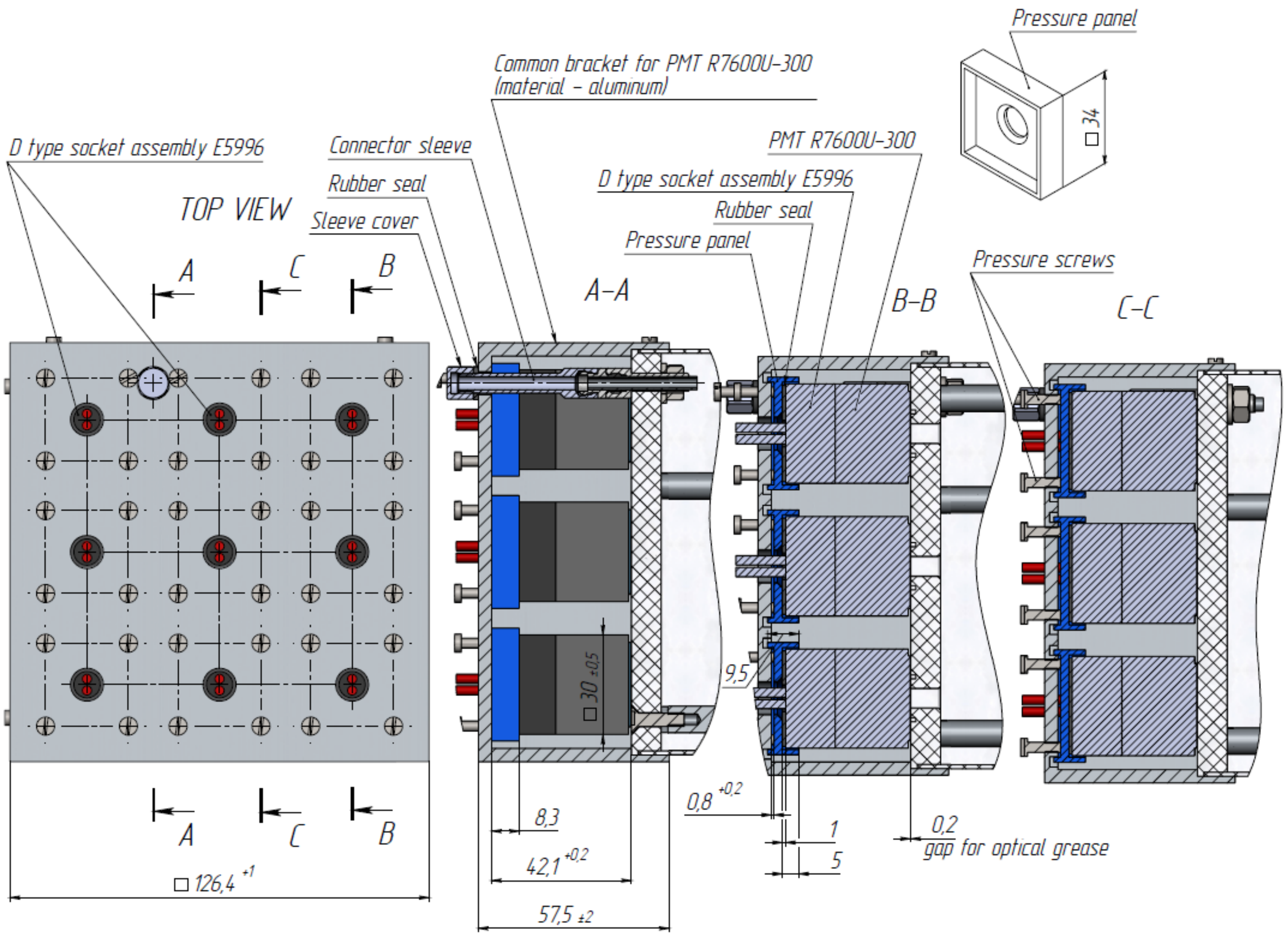
Spy Tiles
- necessity to be optically isolated
- romanshka design



Alternatives
- On-board SiPMs to read the Spy tiles
- Two-sides front/back readout
- Explicit segmentation



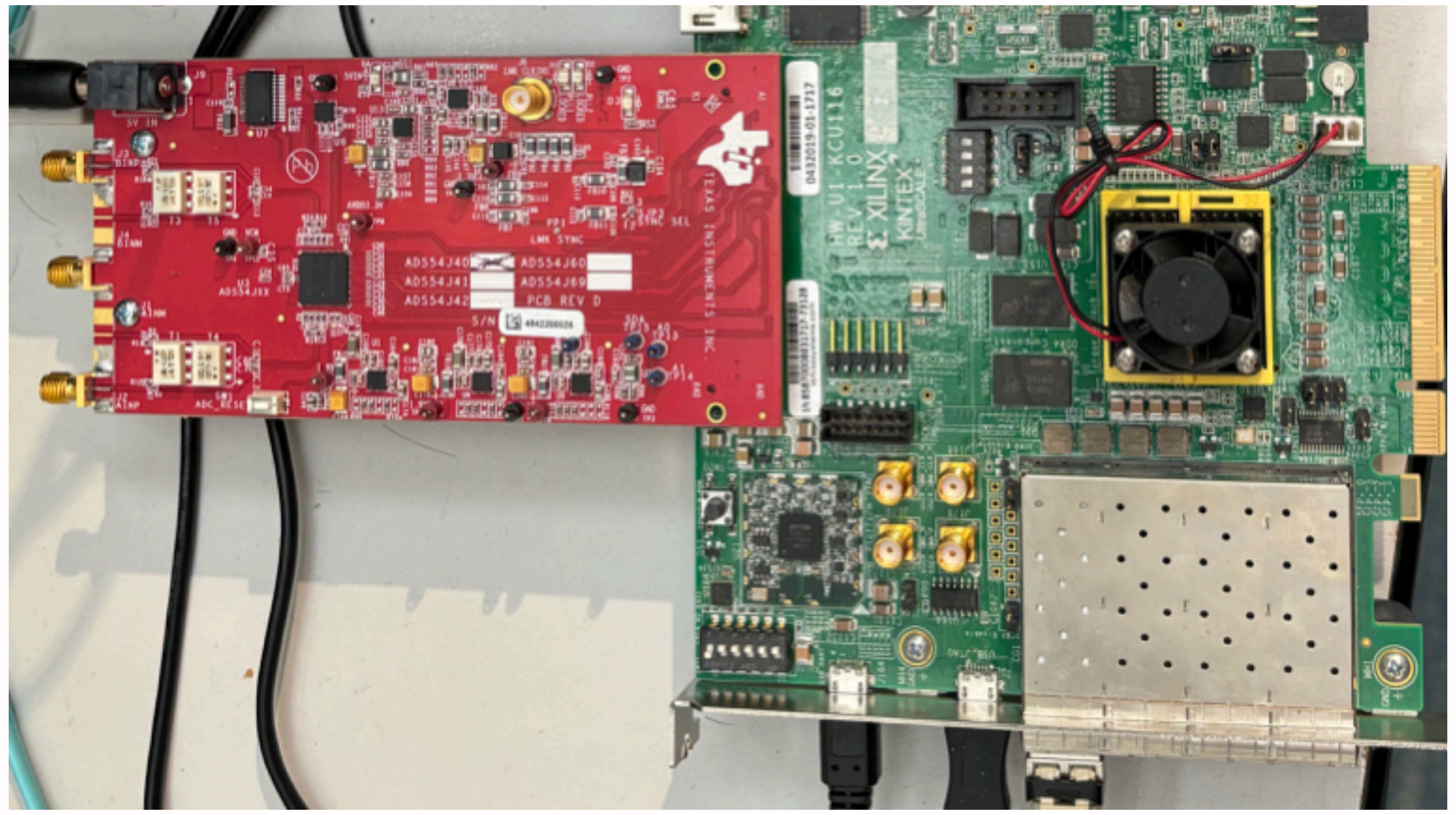
Shashlyk prototype design



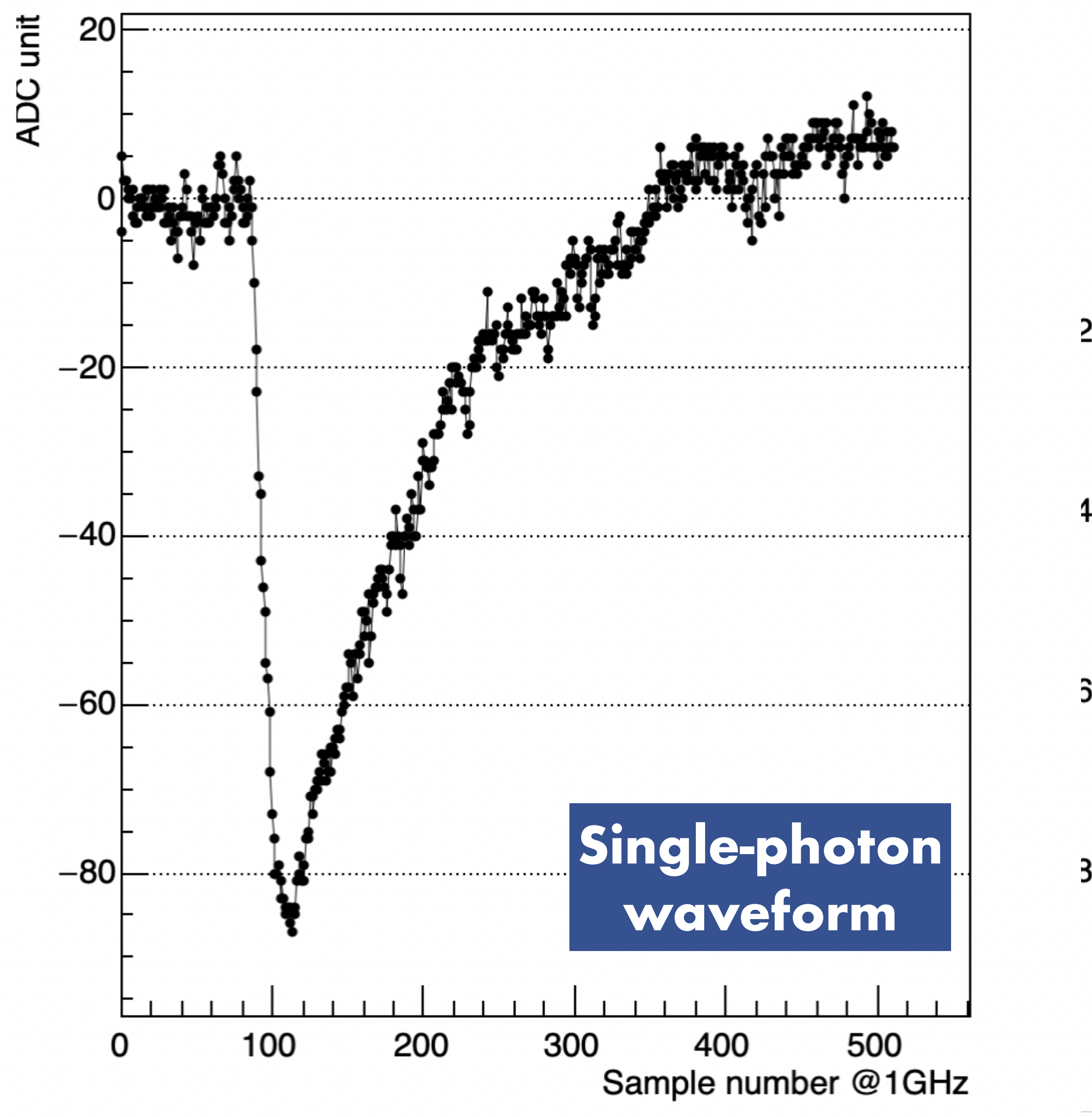
Shashlyk prototype readout

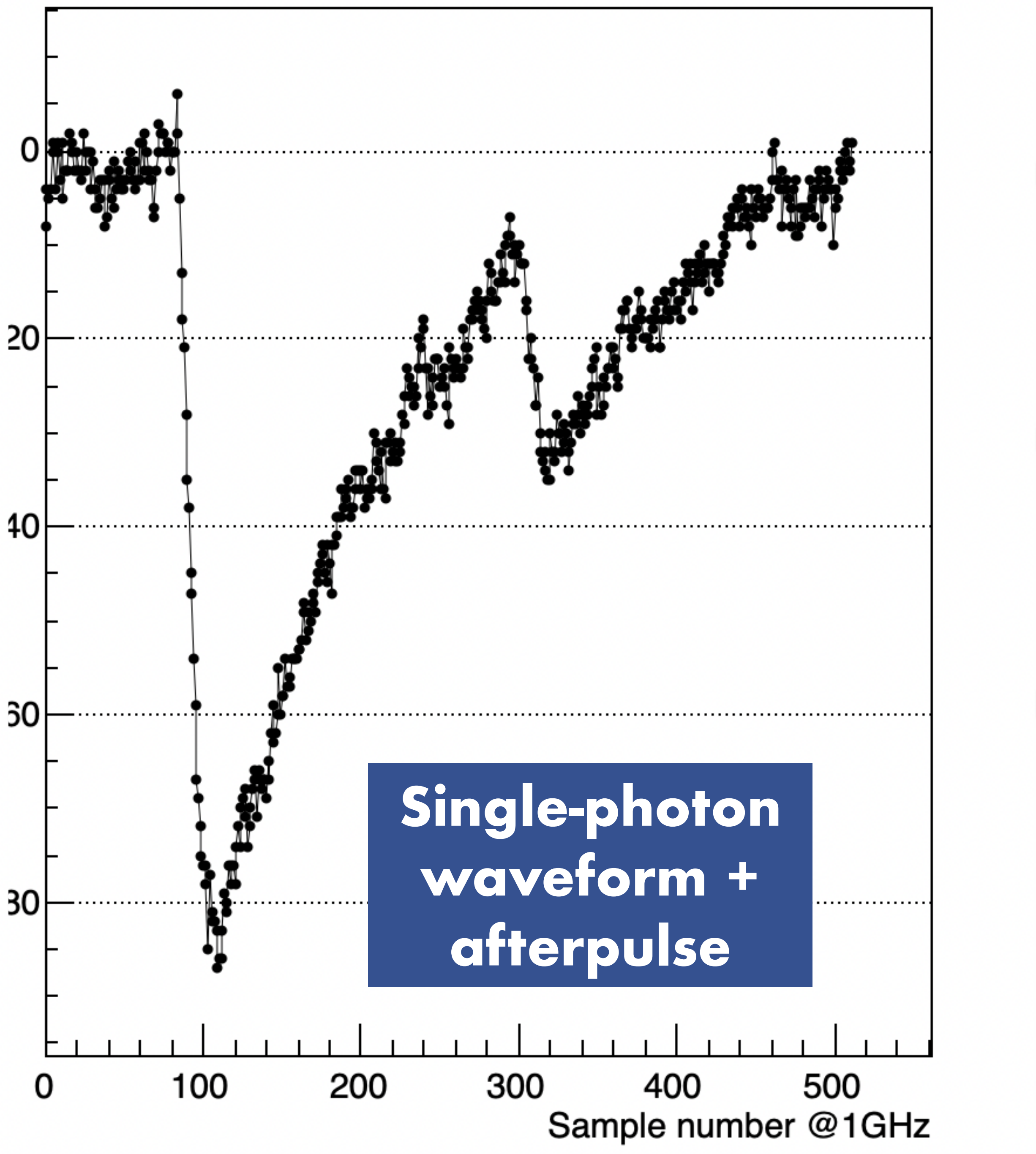
Two available ADCs identified (1 GHz and 14 bit)

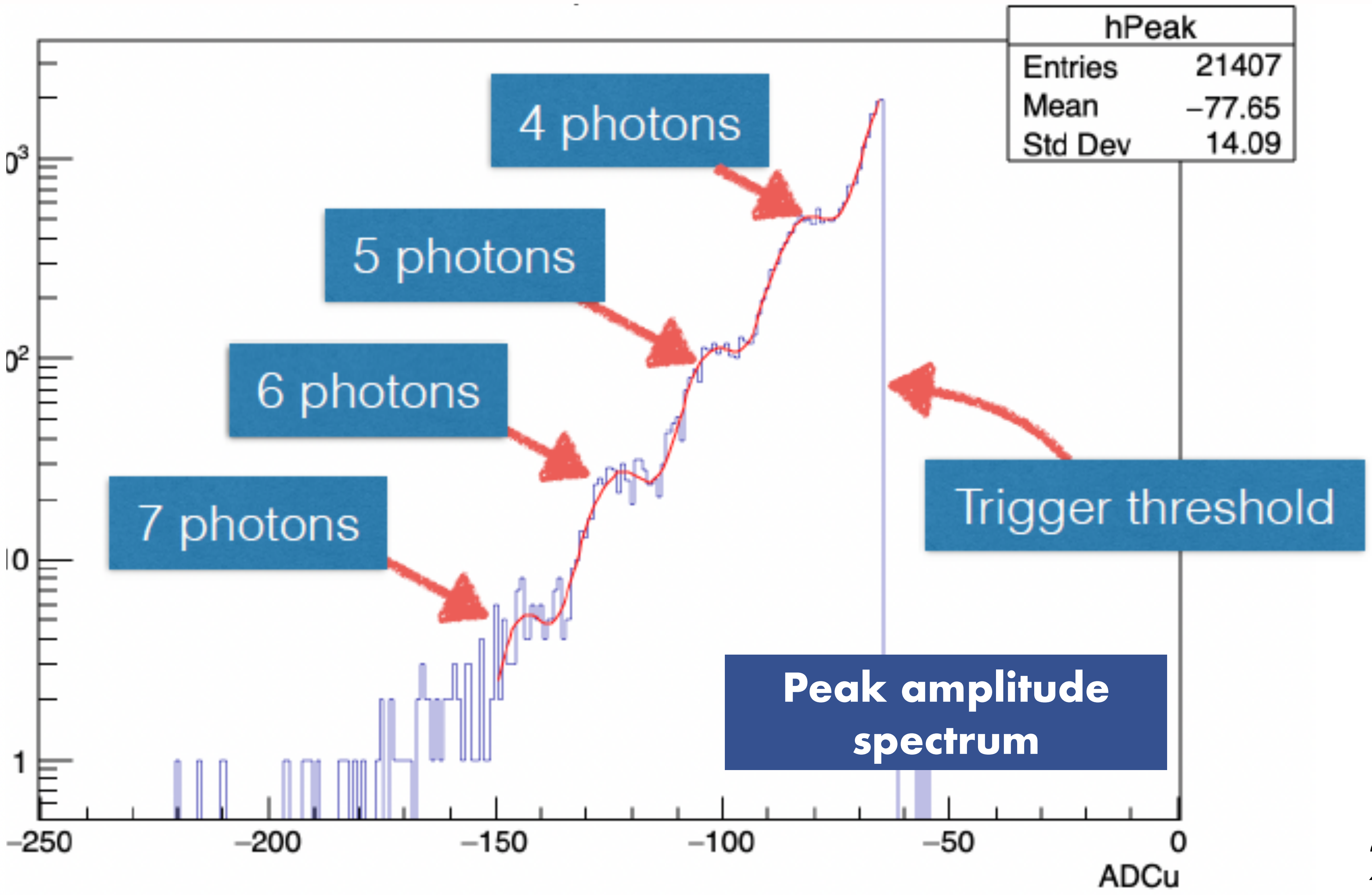
TEXAS INSTRUMENTS **ADS54J40, 2ch** ANALOG DEVICES **AD9680, 2ch**



Full chain implemented with the Texas one and Xilinx Kintex Ultrascale+ : successful read out of SiPM dark noise signals 6mm x 6mm Hamamatsu SiPM with 75 μm spad (using a Transimpedence preamplifier)







Shashlyk prototype readout

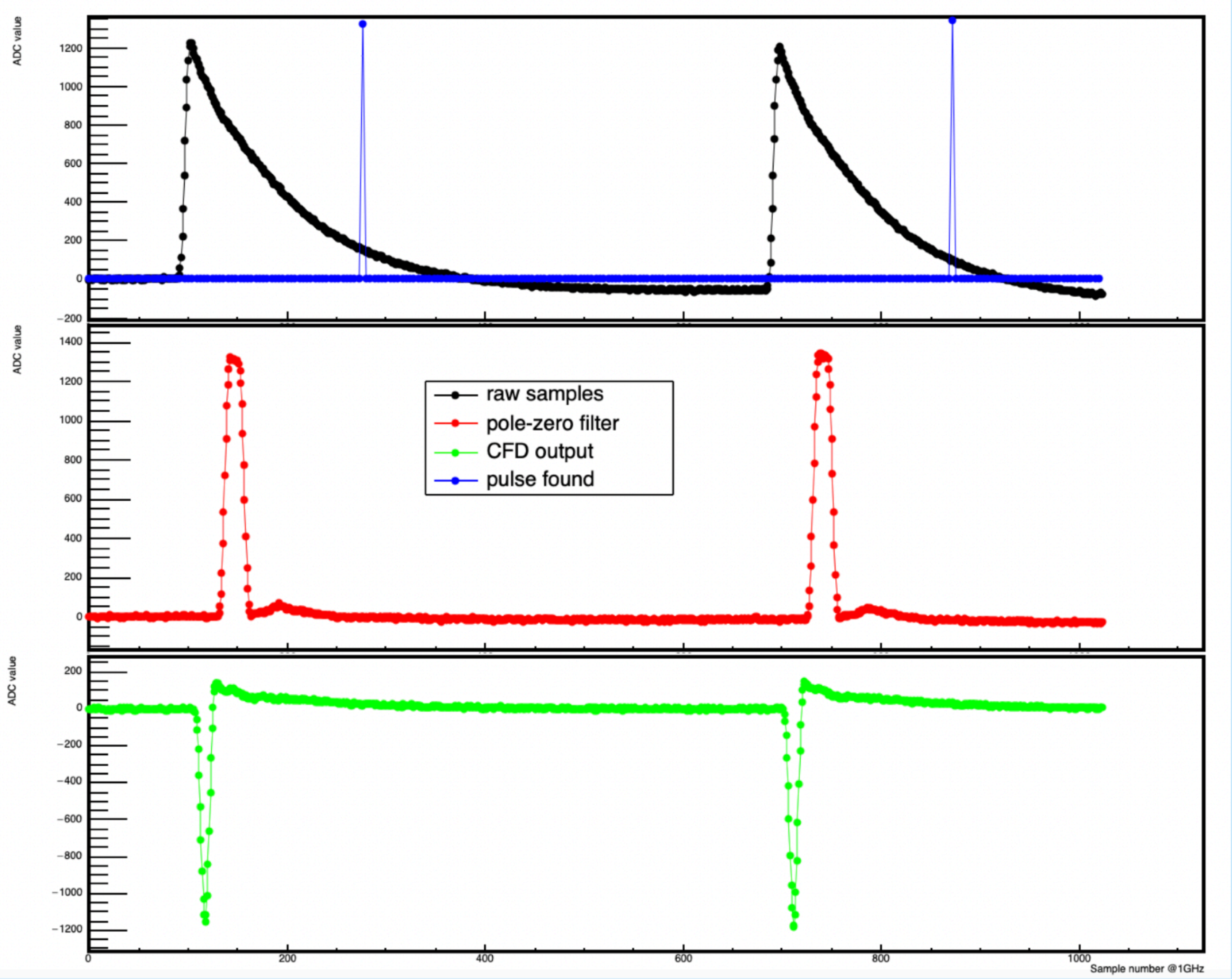
➡ The HIKE proposal included ~3000 channels all equipped with ADCs, so feature extraction and data reduction is key.

➡ With SiPM readout, falling time will be defined by detector capacitance: pole-zero filter used to remove the tail and improve pileup identification. Algorithms tested on a in **Xilinx Kintex Ultrascale+** using CAEN DT5810 and Agilent 33250 waveform generators.

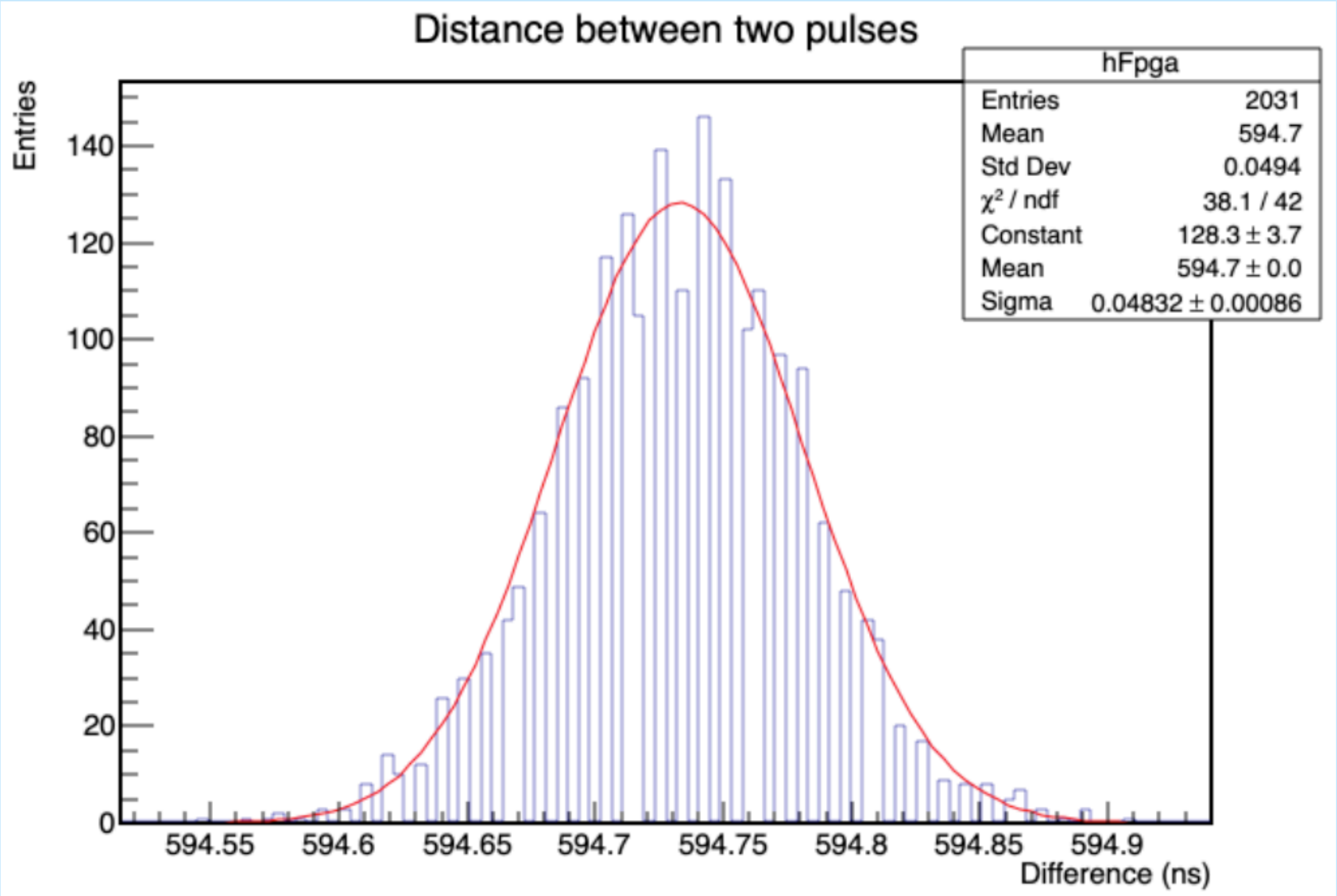
16th Pisa Meeting on Advanced Detectors, Proceedings under review on NIM A

NEW!

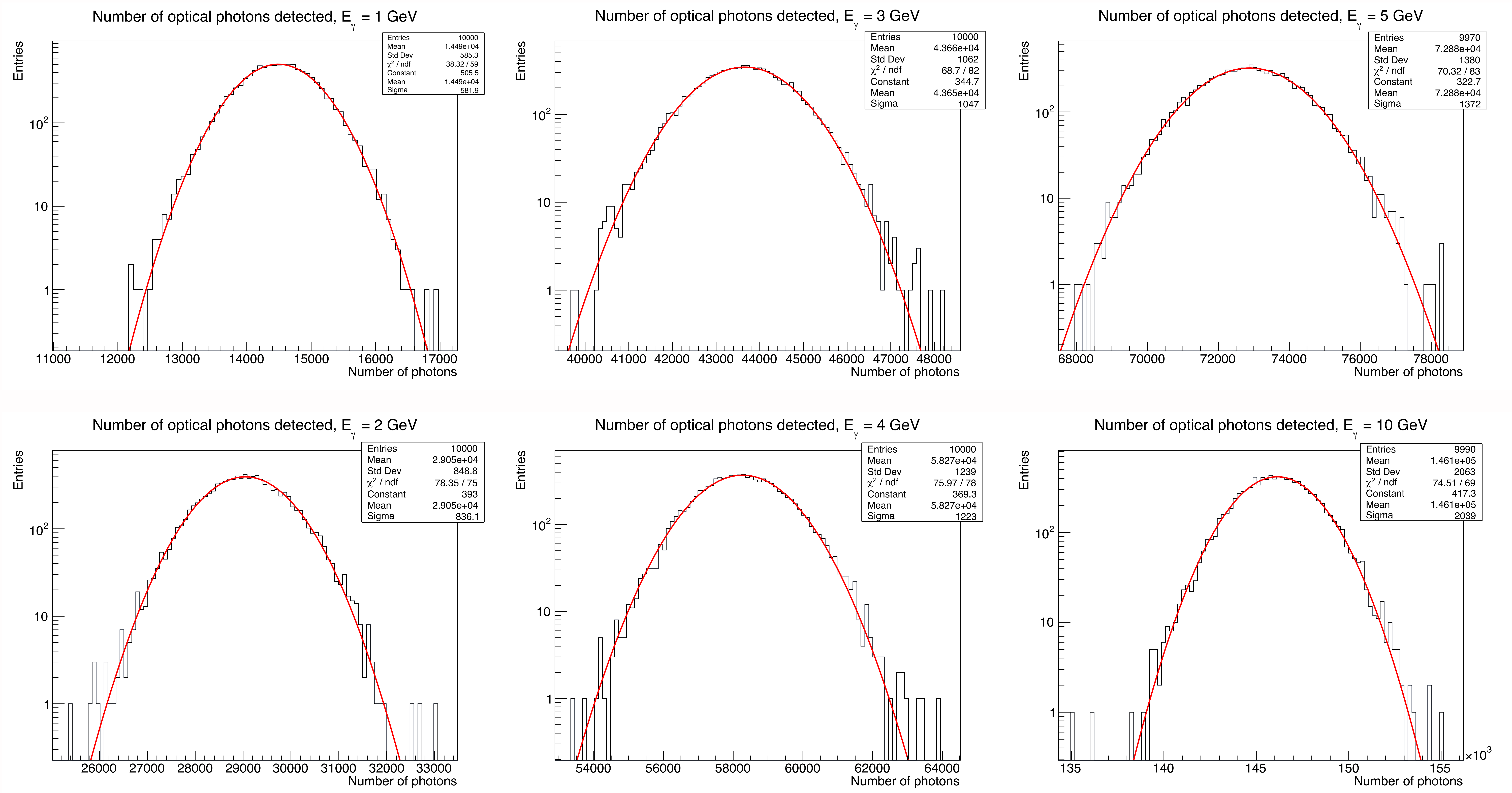
Double-pulse signal from generator



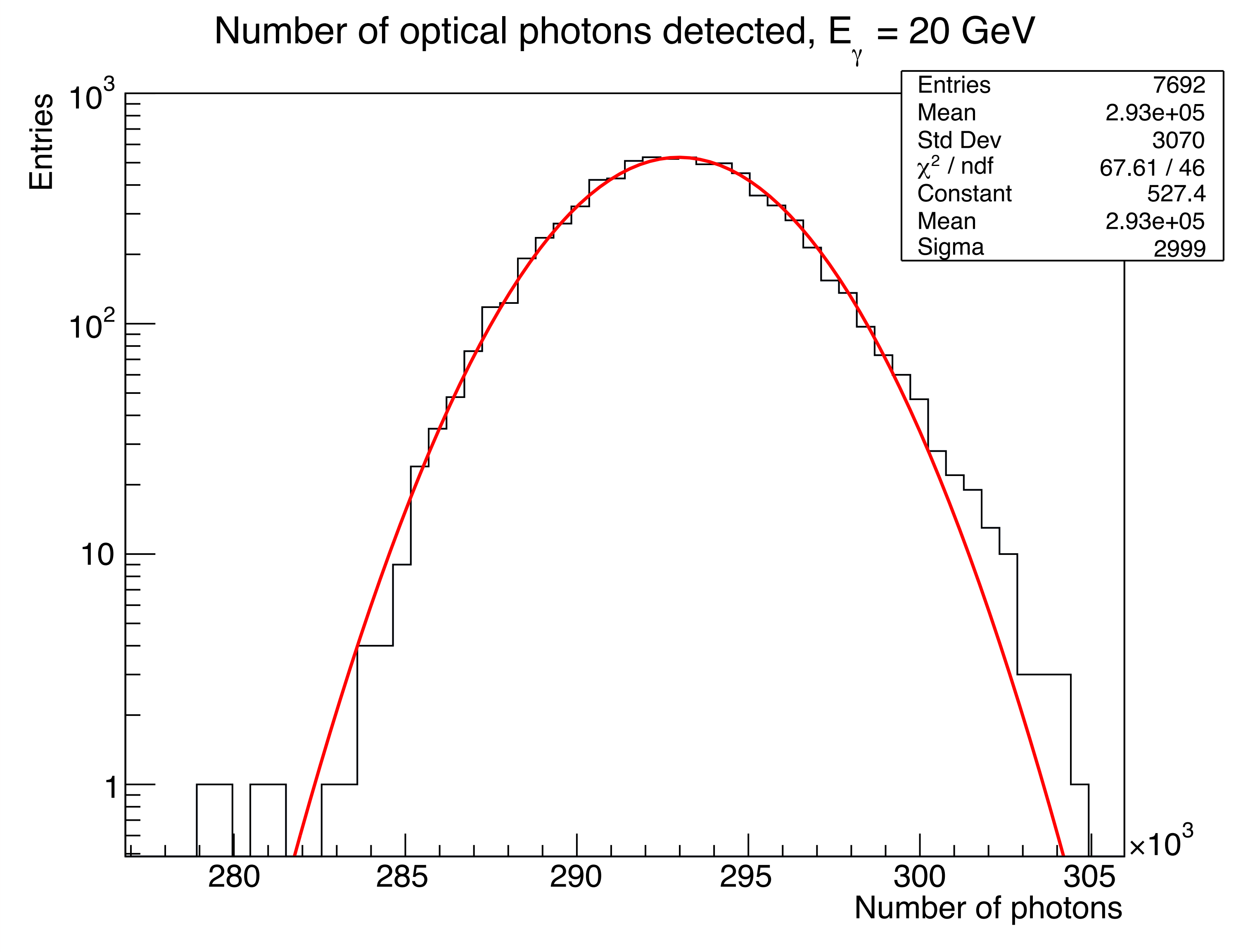
CFD resolution of 49 ps with double pulse

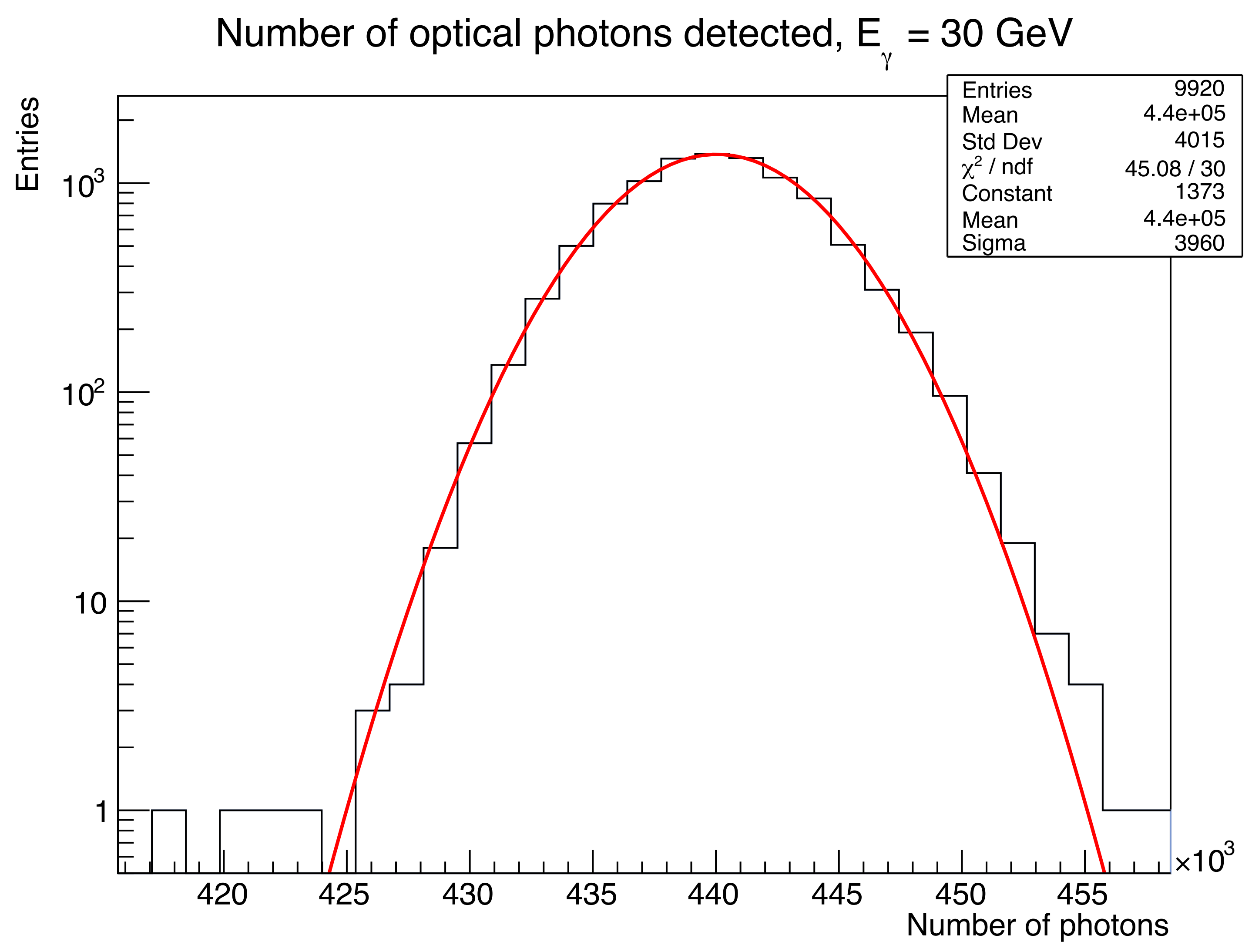


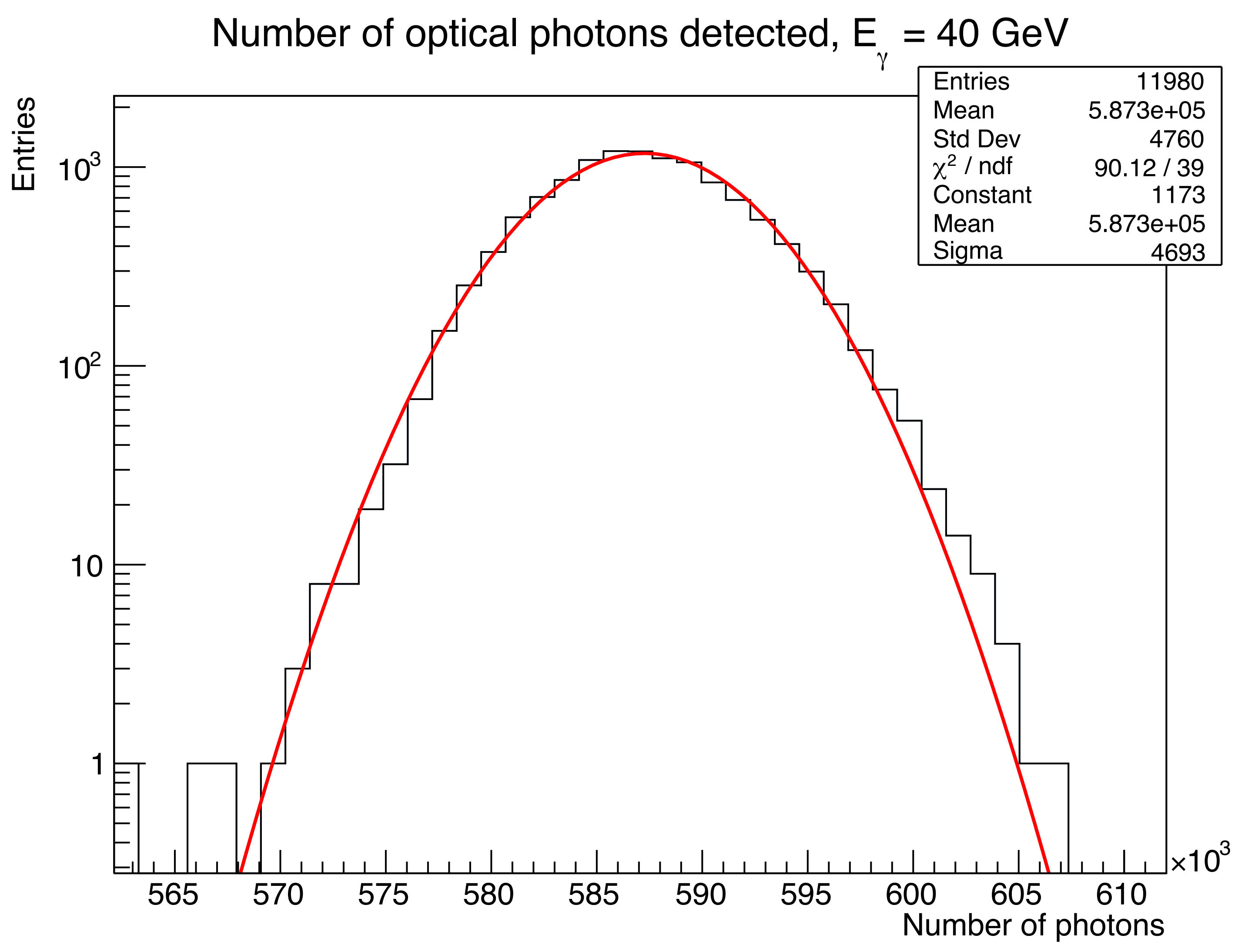
Step 4 Energy resolution



Step 4 Energy resolution





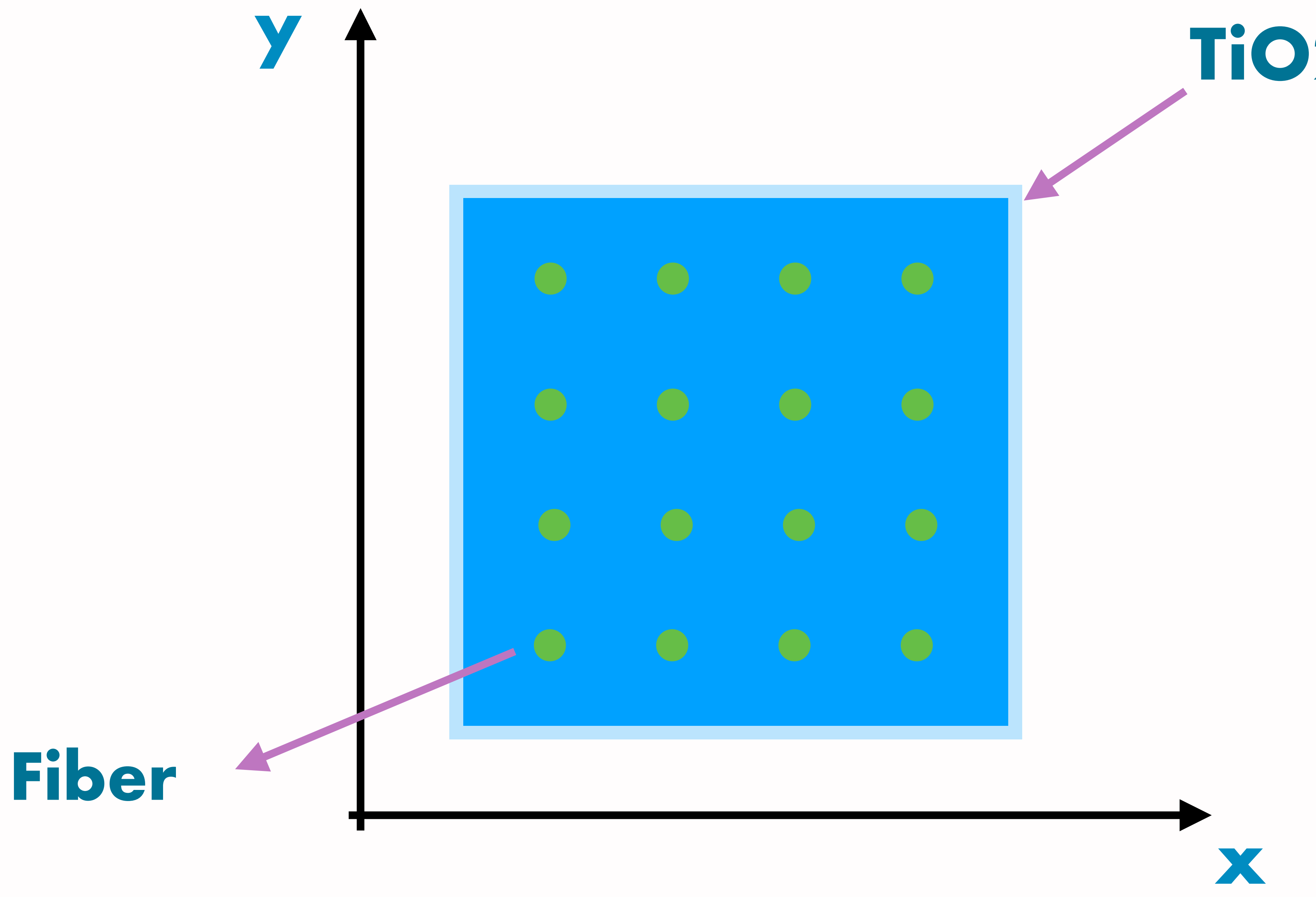


Geometry implementation

Scintillator	1.5 mm
Absorber	0.275 mm
Tyvek	0.1 mm
Paint	0.1 mm
Fiber	1.2 mm (diameter)

Sci Tile

$40 \times 40\ mm^2$

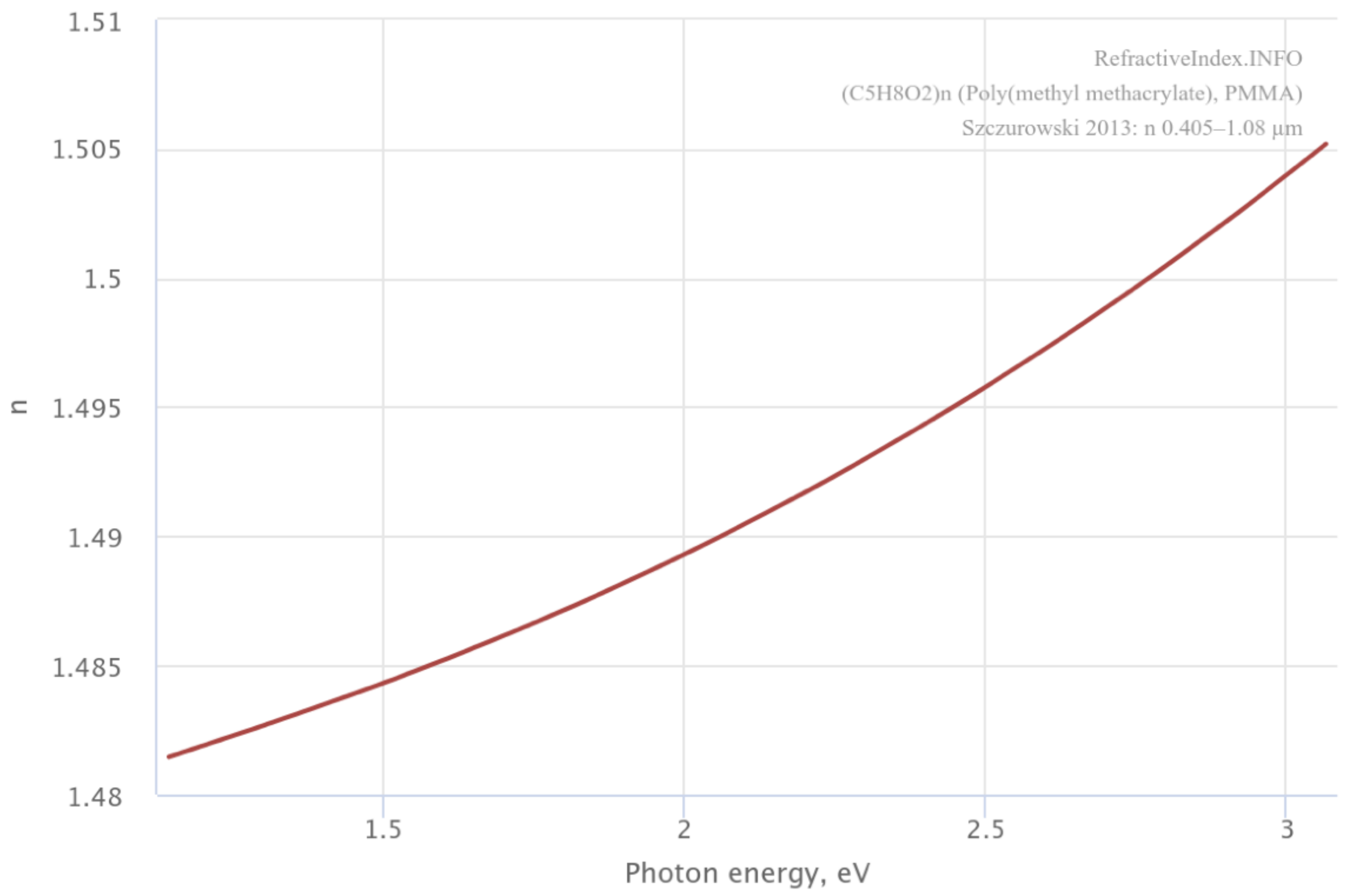


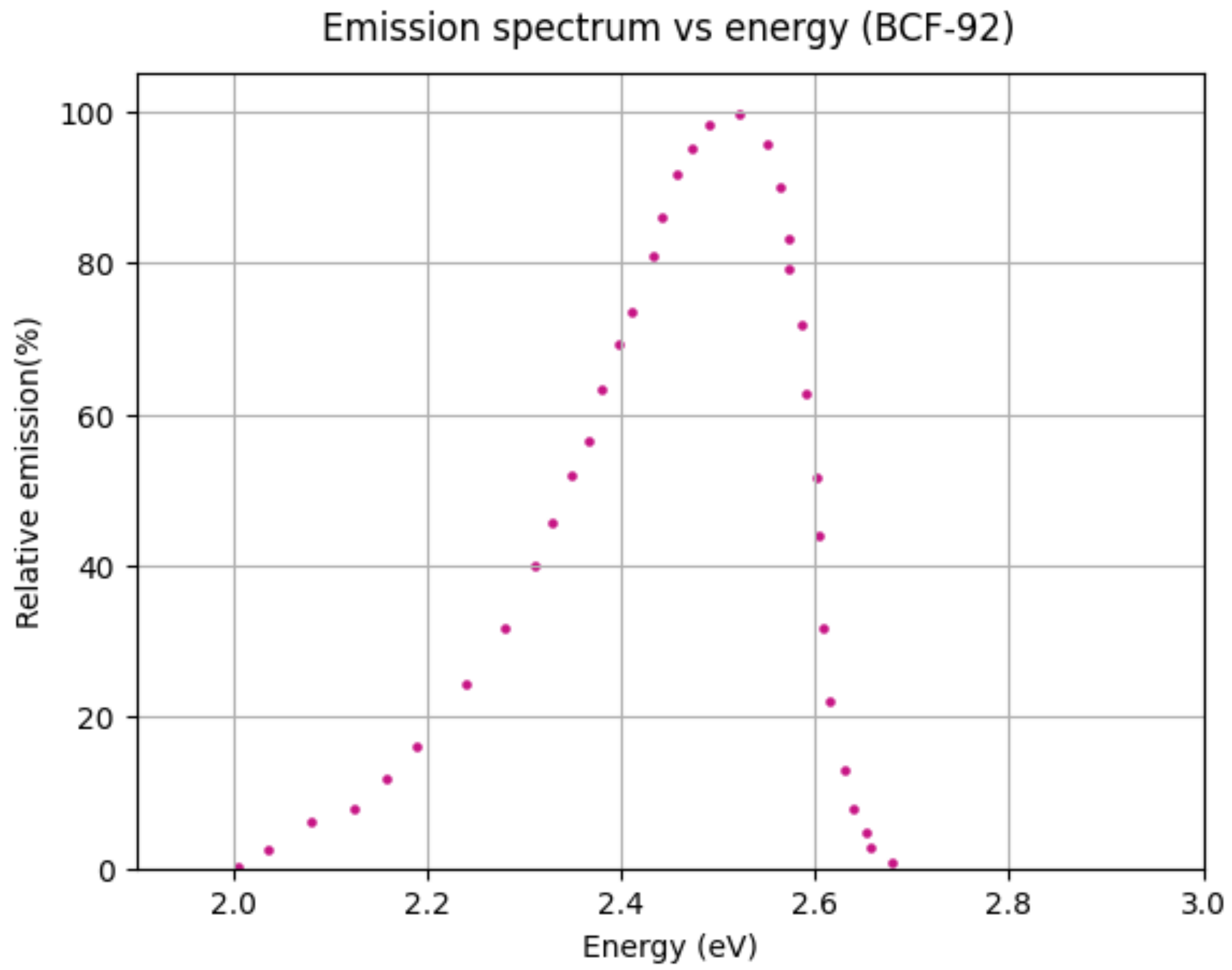
* **Sensitive detector** to count optical photons
* Possibility to choose a **mirrored** or a **black painted fiber**

Abs and a Sci **Tile** with the fiber segment as daughter (Sci Tiles are **painted with TiO2**)

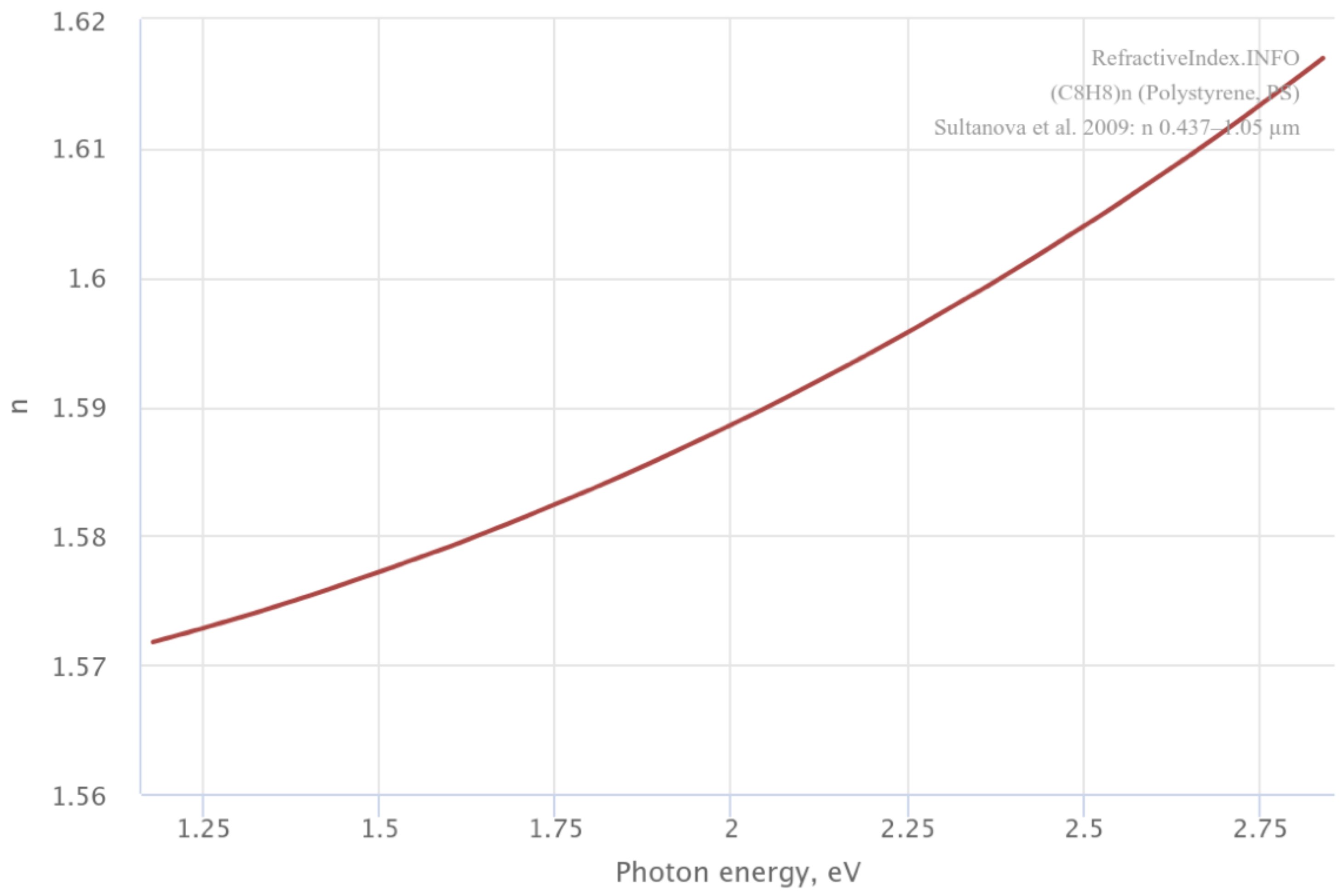
WLS optical properties

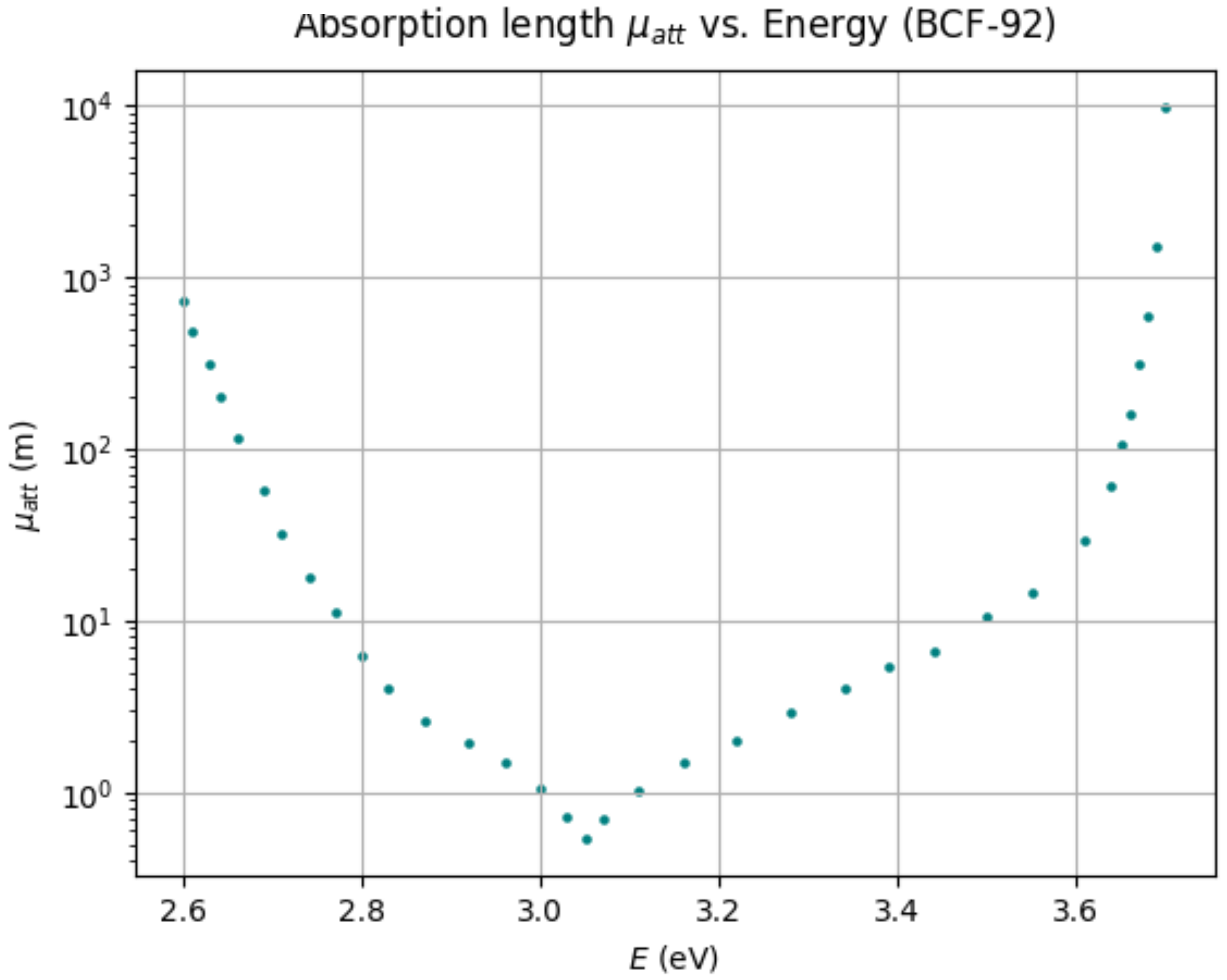
Cladding1



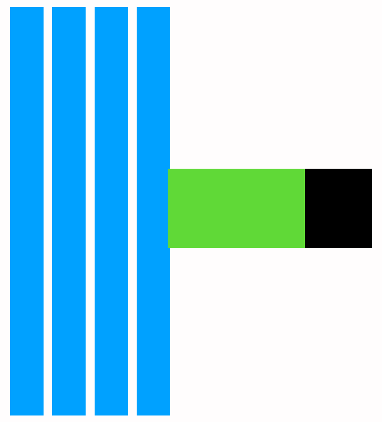


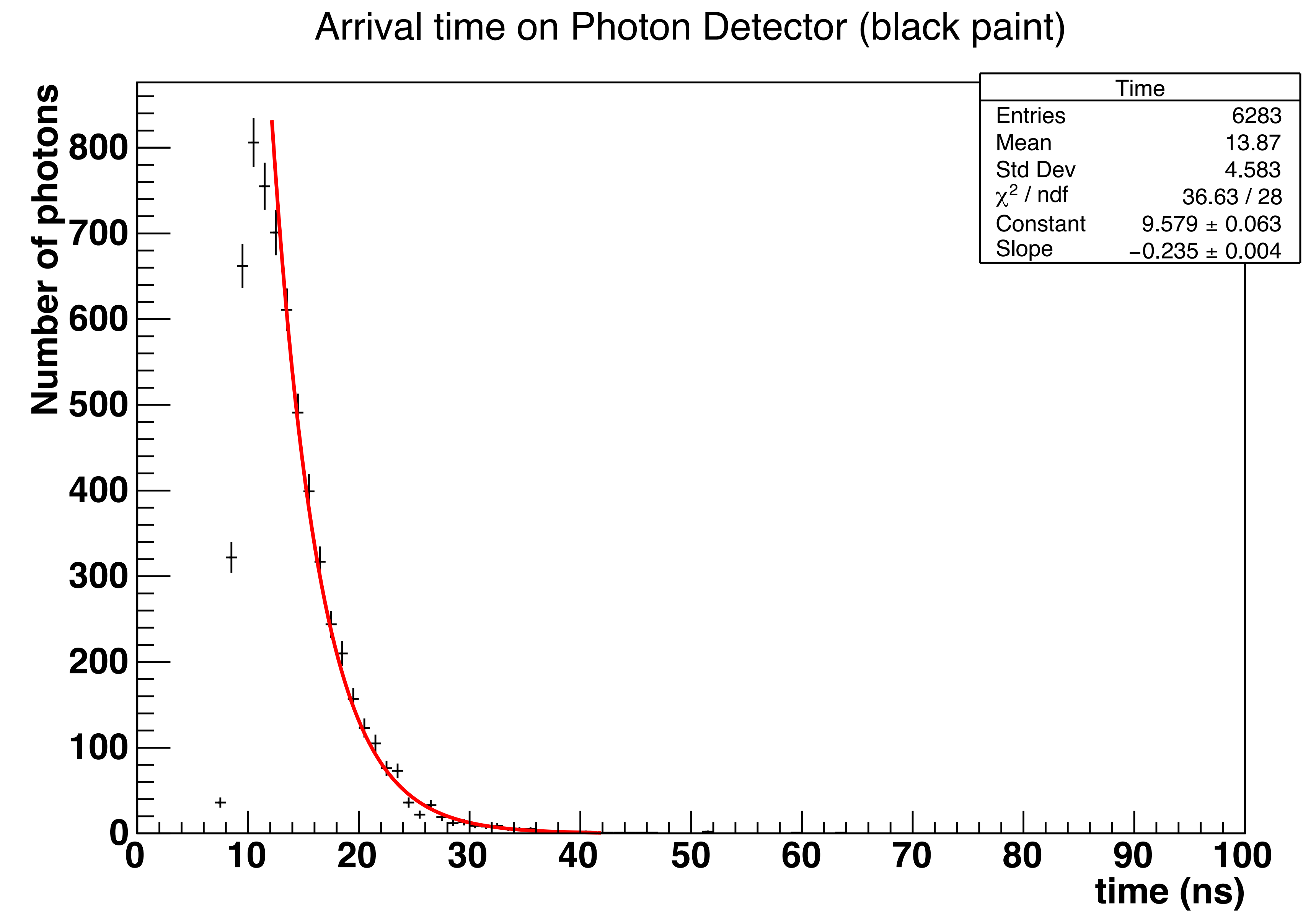
Core

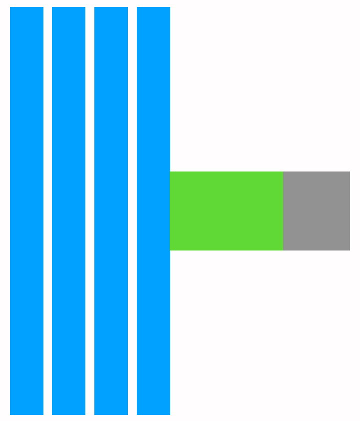


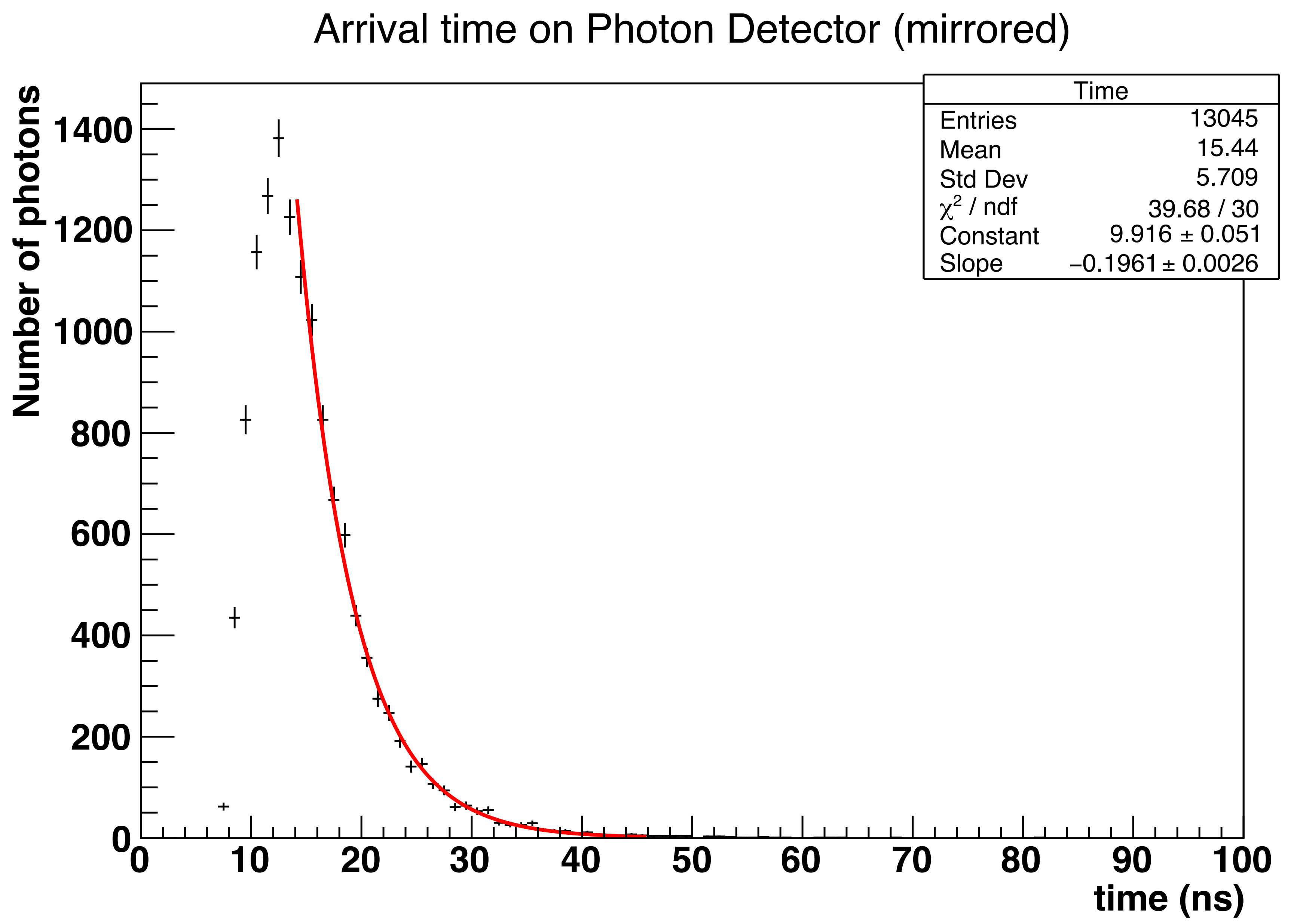


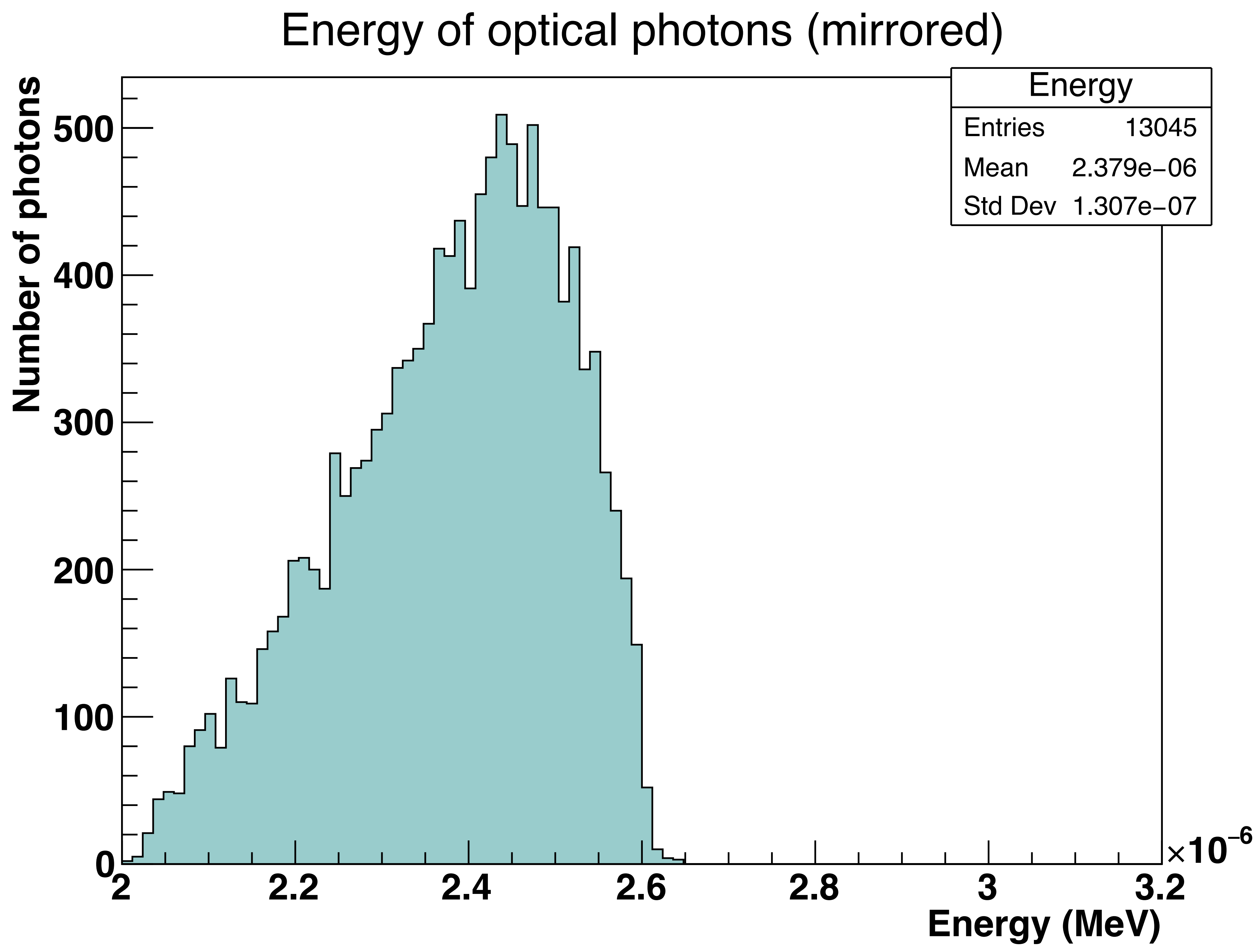
Time and energy distribution (1 GeV photon)











- Compatibility with the WLS emission spectrum
- ~50% reduction of the photons in the PD

Step 1 Procedure

Molière radius R_M

- Average lateral deflection of electrons at the critical energy after traversing $1X_0$

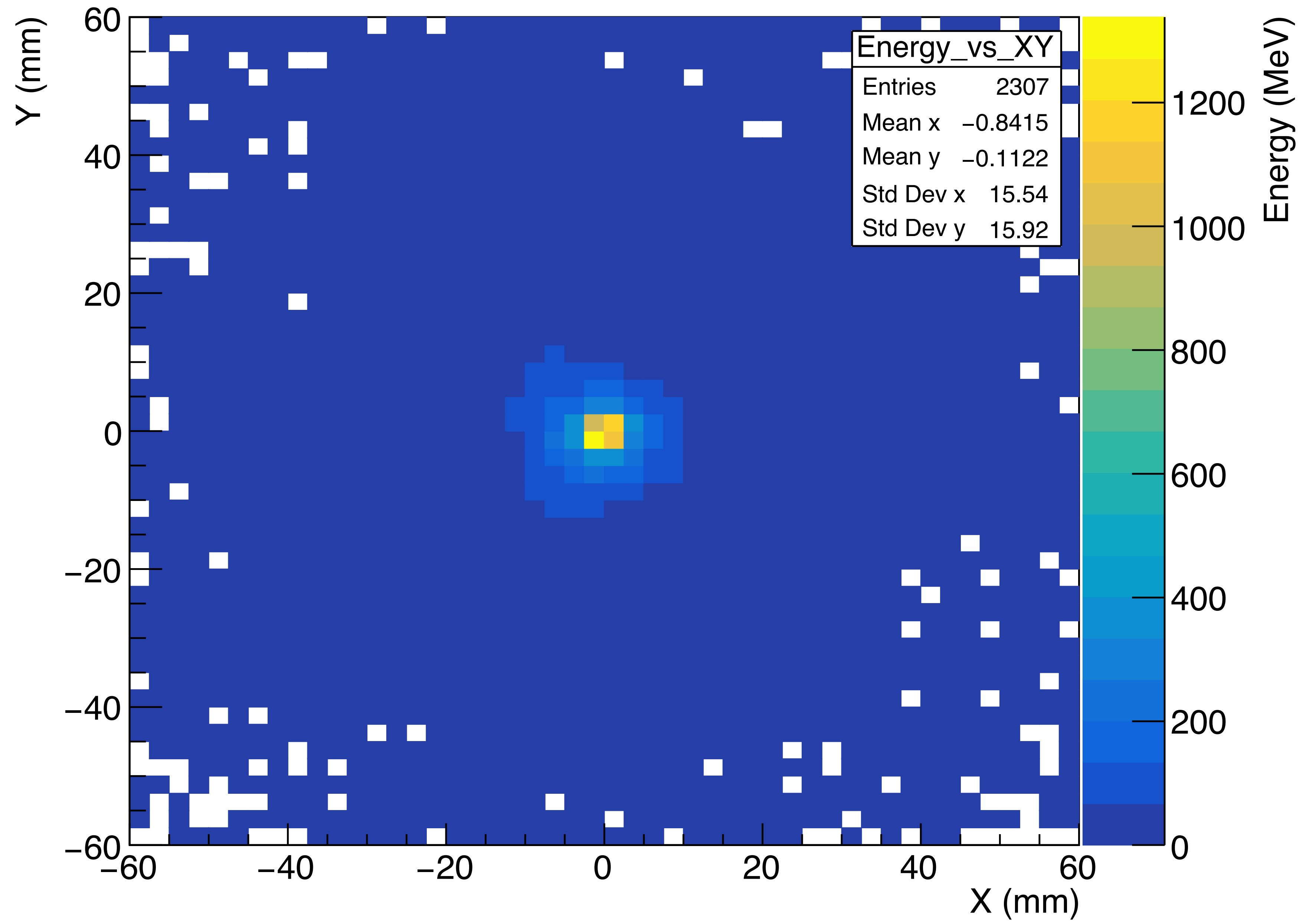
$$R_M\ (g/cm^2) \simeq 21\ MeV \frac{X_0}{\epsilon_C\ (MeV)}$$

- On average, about 90% of the shower energy is contained in a cylinder of radius ~$1R_M$

$$\frac{1}{R_M} \approx \frac{1}{21\ MeV} \sum_j \frac{w_j \epsilon_{Cj}}{X_{0j}}$$

Geant4 implementation

- XY module segmentation
- Numerical integration (cumulative curves)
- Shower profile in homogeneous media and MEC
- Optimisation of the transverse module dimensions

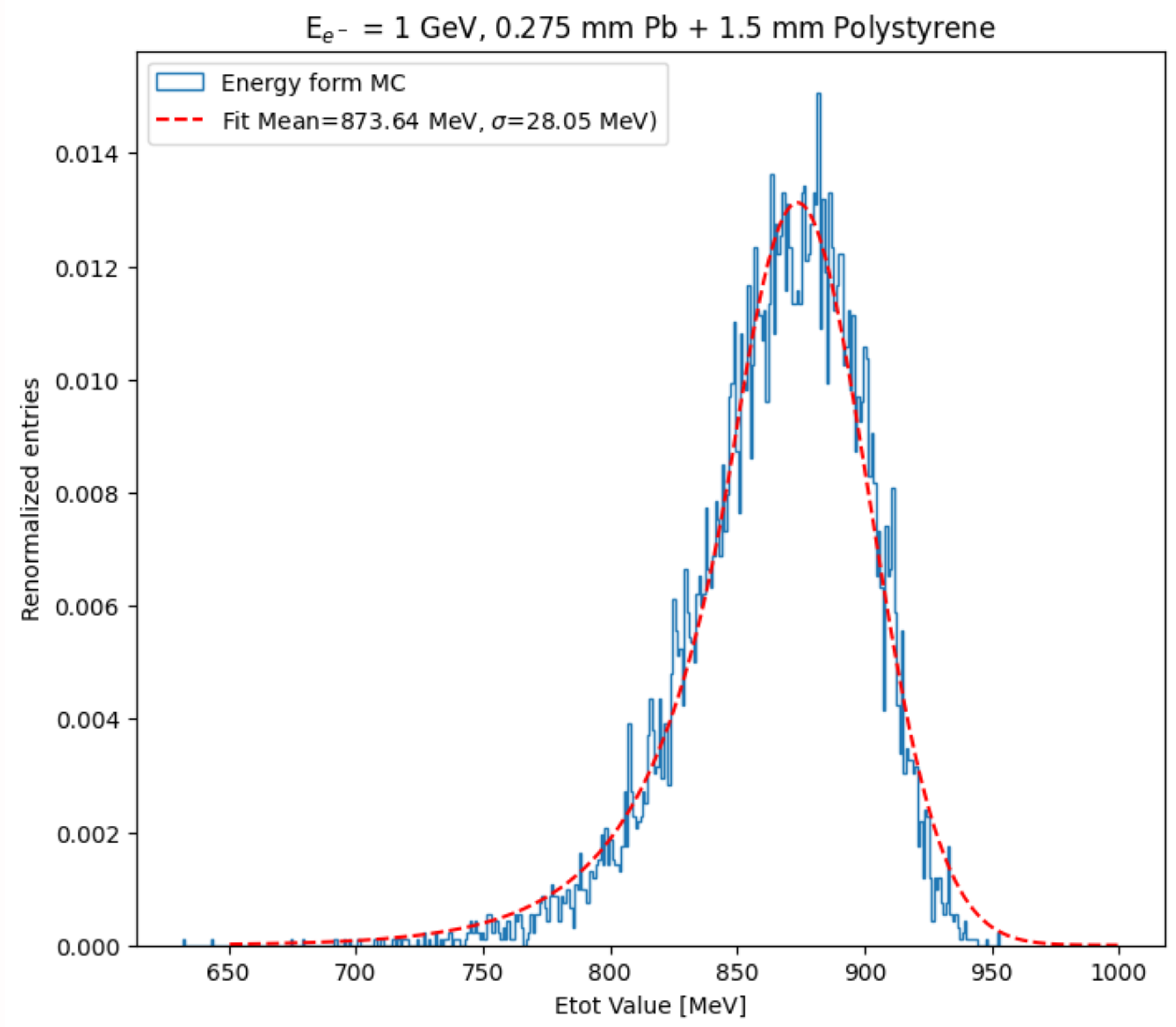


E_{e^-} = 30 GeV, 12x12 cm^2 module (~27 X_0)

Step 1

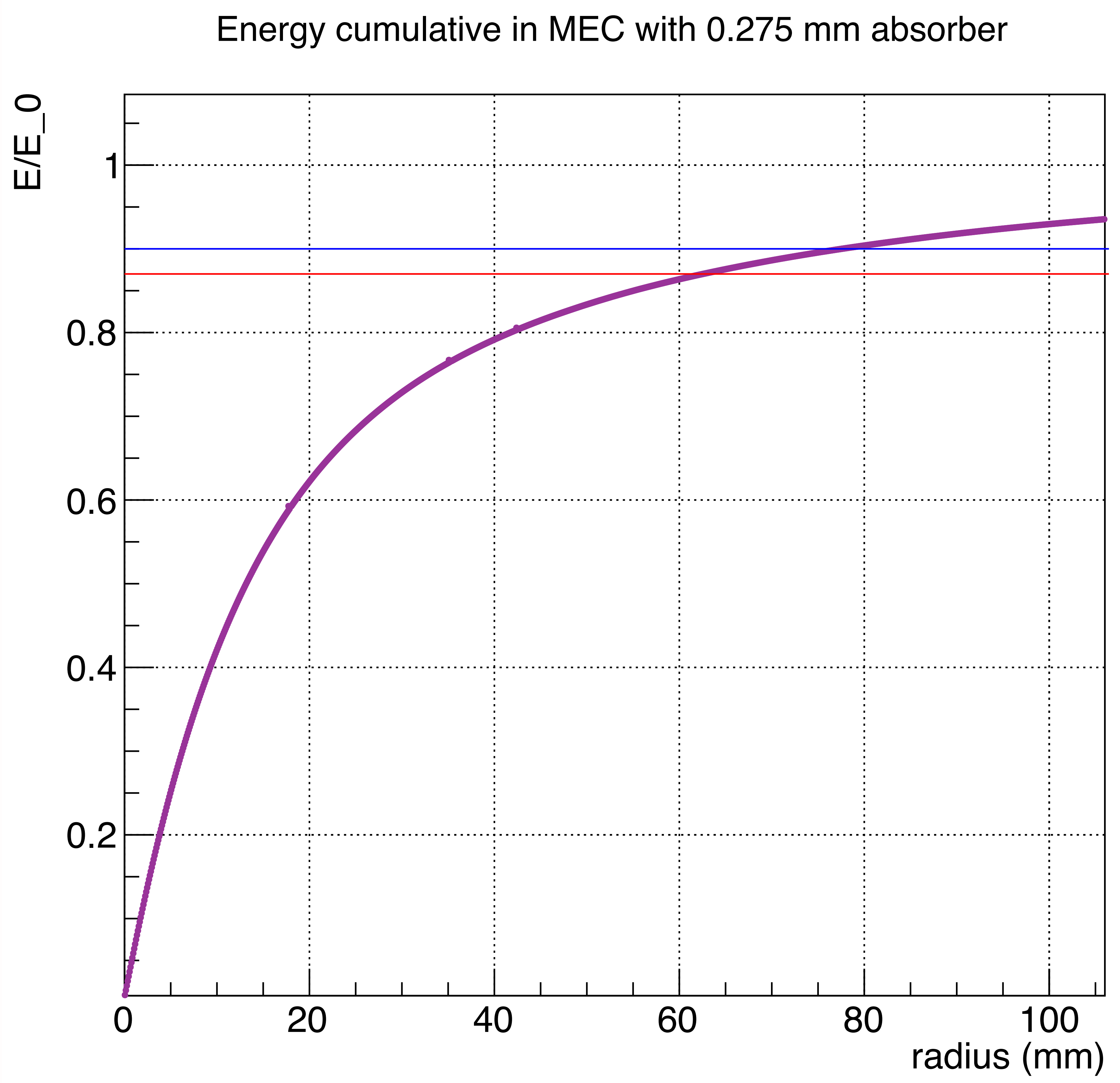
Results

Method 1



Deposited energy spectrum for a cylinder with a radius of 1R_M (~**6 cm**) of the KOPIO calorimeter sampling structure fitted with a Crystal ball function [ISSN 1562-6016. **BAHT**. 2021. No 3(133)]

Method 2



~87% of the incident particles energy is deposited in a cylinder of radius R_M (nominal value)

BCF-92XL

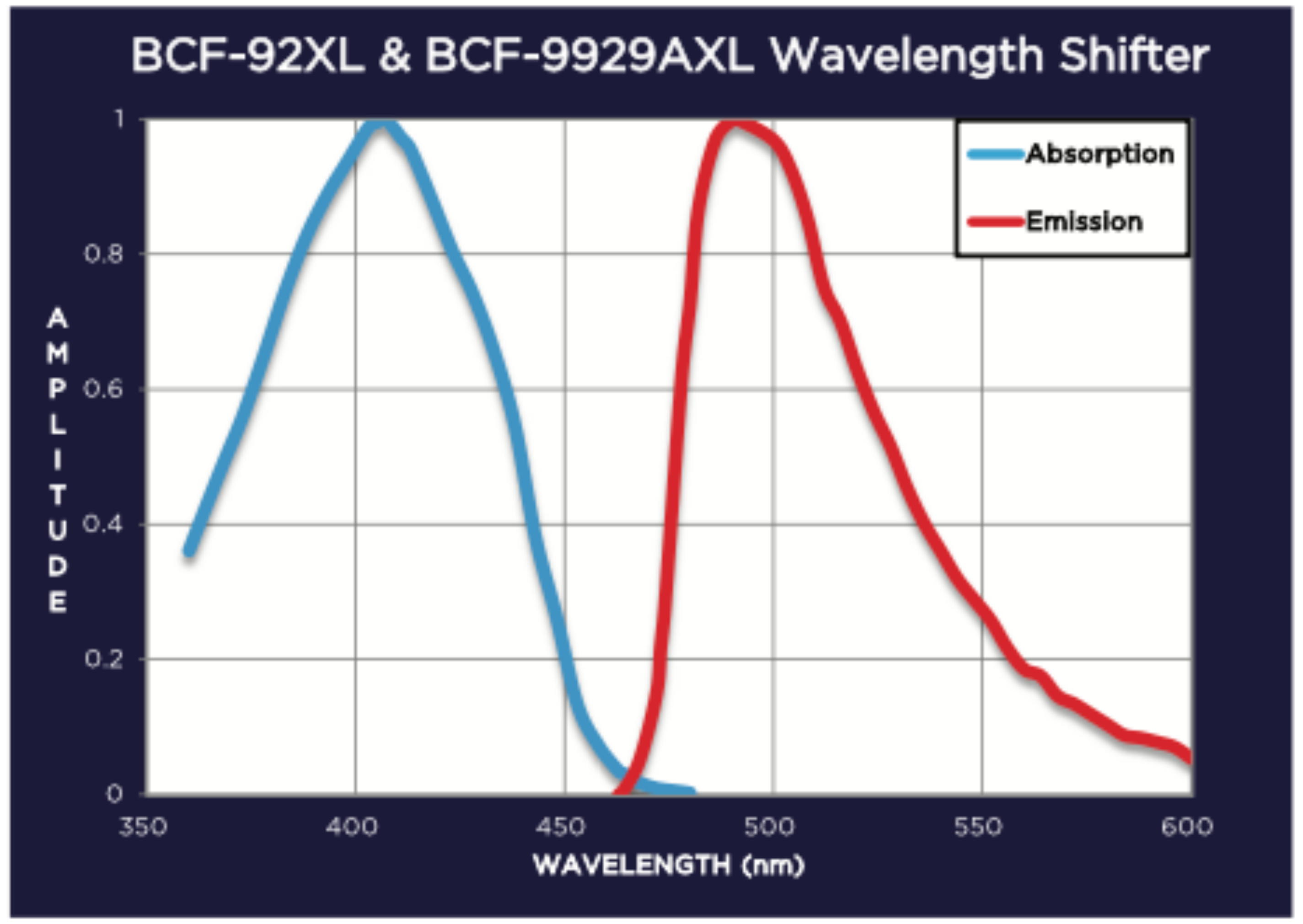
Luxium Solutions manufactures a variety of plastic scintillating, wavelength-shifting and light-transmitting fibers used for research and industry.

Starting in 2023, Luxium Solutions introduced the BCF-XL series of scintillating and wavelength shifting fibers with improved, market-leading attenuation length for optimal, reliable performance for a variety of different applications.

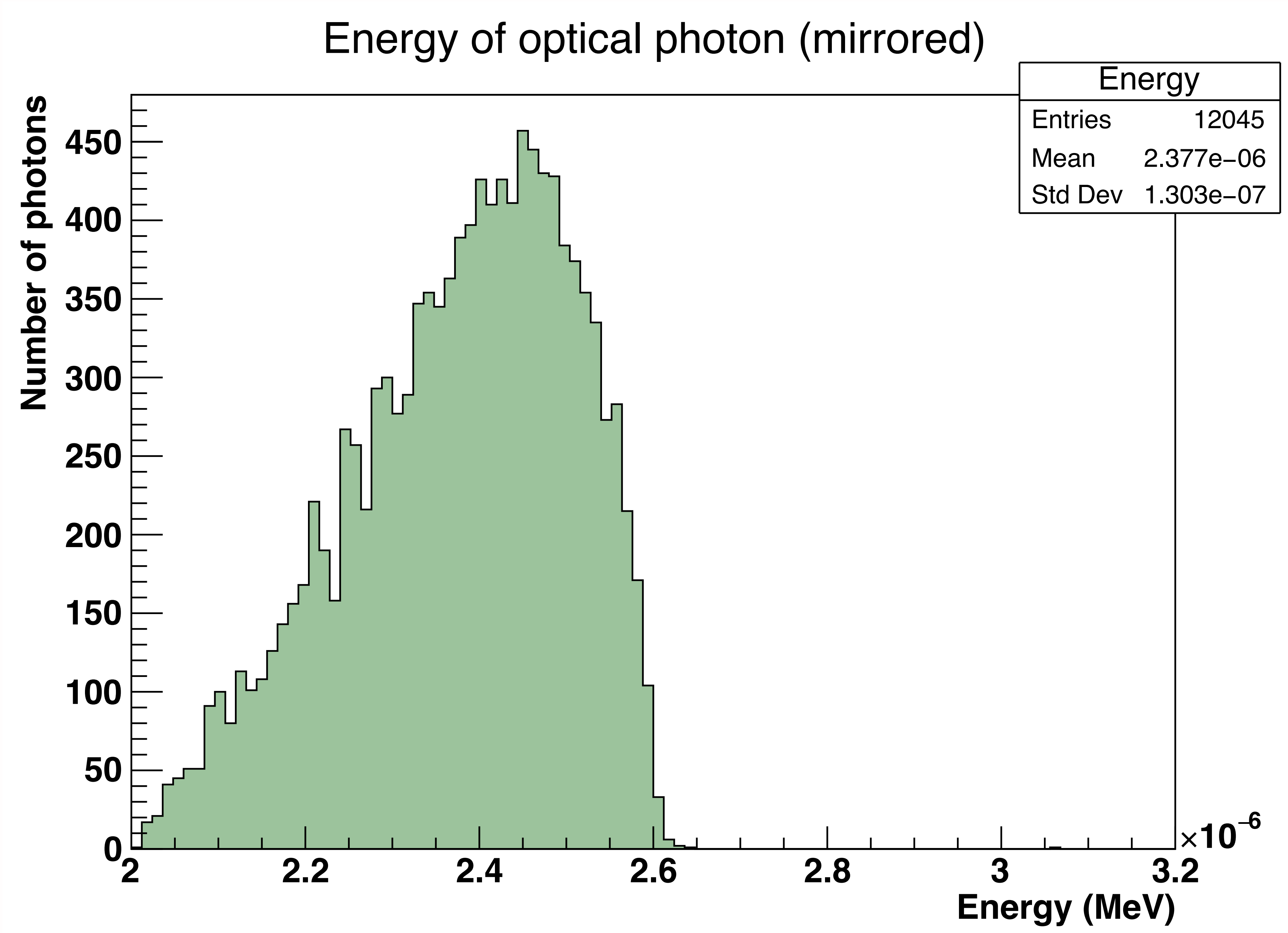
Specific Properties of BCF-XL Series Formulations

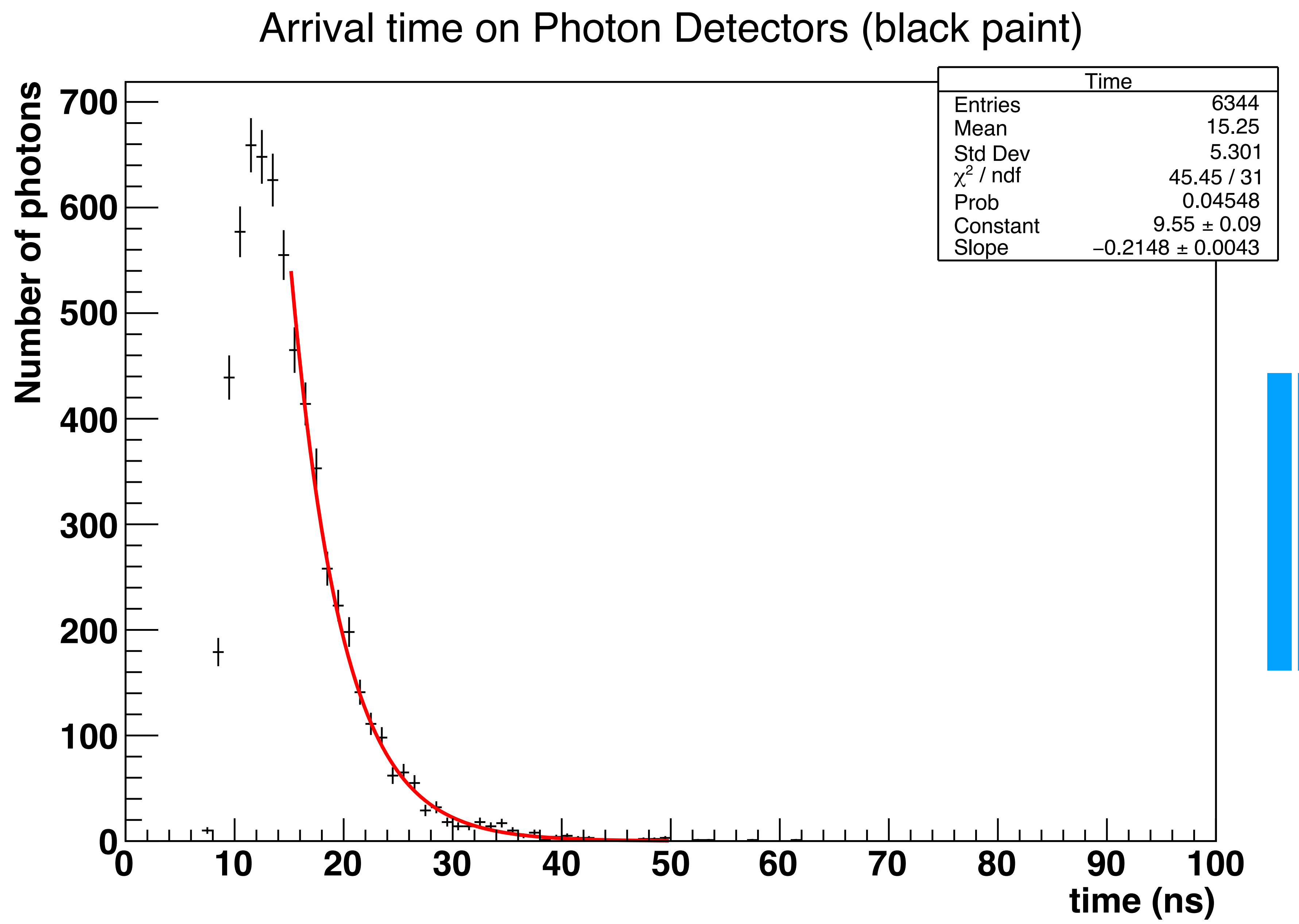
Fiber	Emission Color	Emission Peak, nm	Decay Time, ns	# of Photons per MeV*	Attenuation Length (m)**	Characteristics / Applications
BCF-10XL	blue	432	2.7	~8000	>4	General purpose; optimized for diameters >250µm
BCF-12XL	blue	435	3.2	~8000	>4	Improved transmission for use in long lengths
BCF-20XL	green	492	2.7	~8000	>4	Fast green scintillator
BCF-60XL	green	530	7	~7100	>4	3HF formulation for increased hardness
BCF-91AXL	green	494	12	n/a	>4	Shifts blue to green
BCF-92XL	green	492	2.7	n/a	>4	Fast blue to green shifter
BCF-9929AXL	green	492	2.7	n/a	>4	Blue to green shifter. Pairs well when exciting wavelengths are >425nm (e.g. injection-molded and extruded scintillators)
BCF-9995XL	blue	450	2.7	n/a	>4	UV to blue shifter
BCF-98XL	n/a	n/a	n/a	n/a	Not available	Clear Waveguide

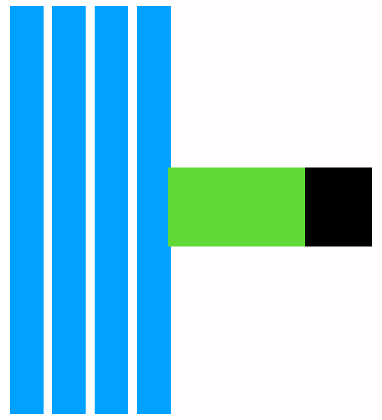
*For Minimum Ionizing Particle (MIP), corrected for PMT sensitivity
** For 1mm diameter fiber, measured using silicon photodiode



Step 3 Time and energy distribution (1 GeV photon with Protvino)







Scintillator

Protvino 8000 photons/MeV
3.3 ns (time constant)

BC408 10^4 photons/MeV
2.1 ns (time constant)

Fibers

BCF92 2.7 ns (time constant)

Y11 7.9 ns (time constant)