High segmentation shashlik calorimeter R&D for future intensity frontier experiments

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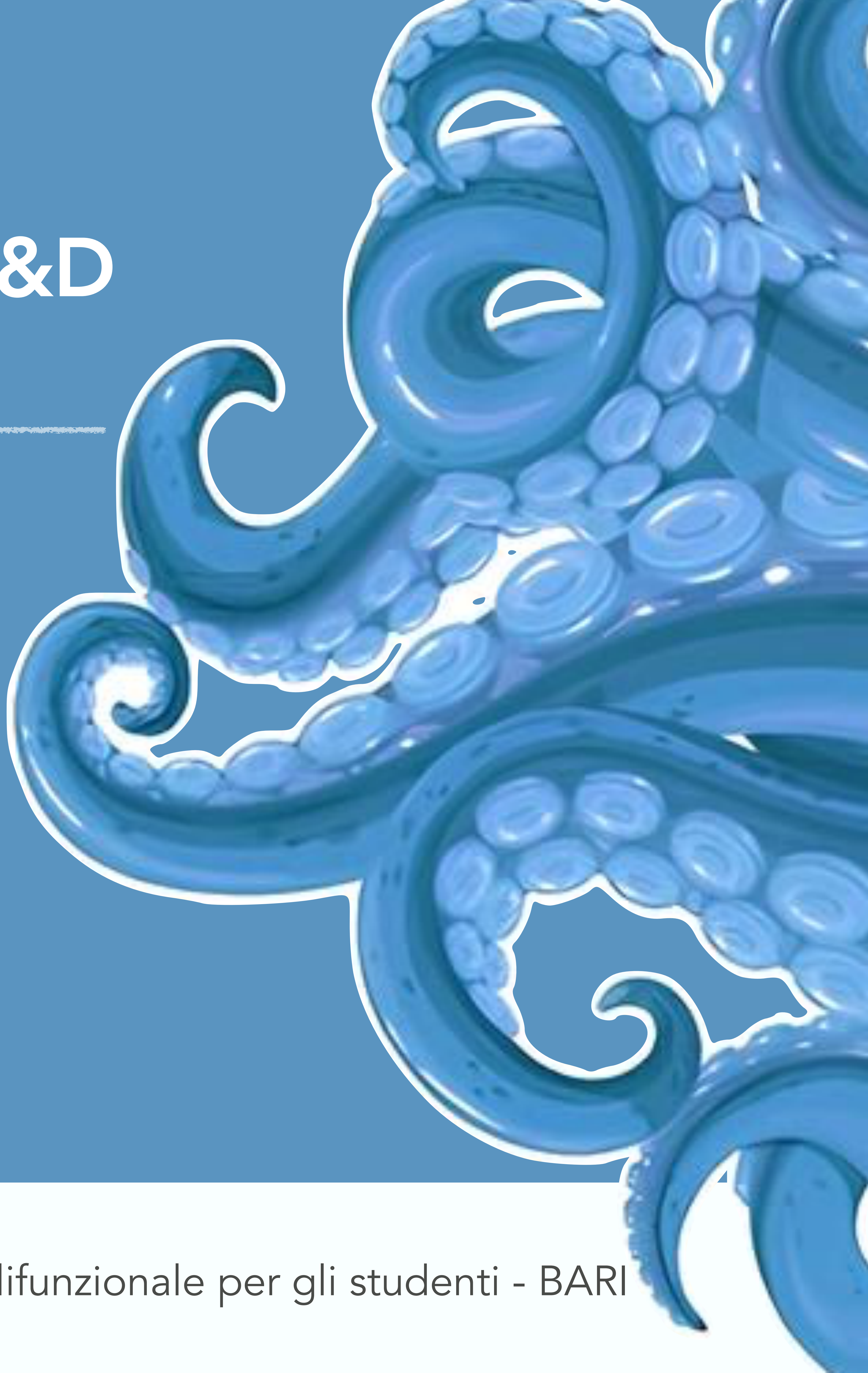

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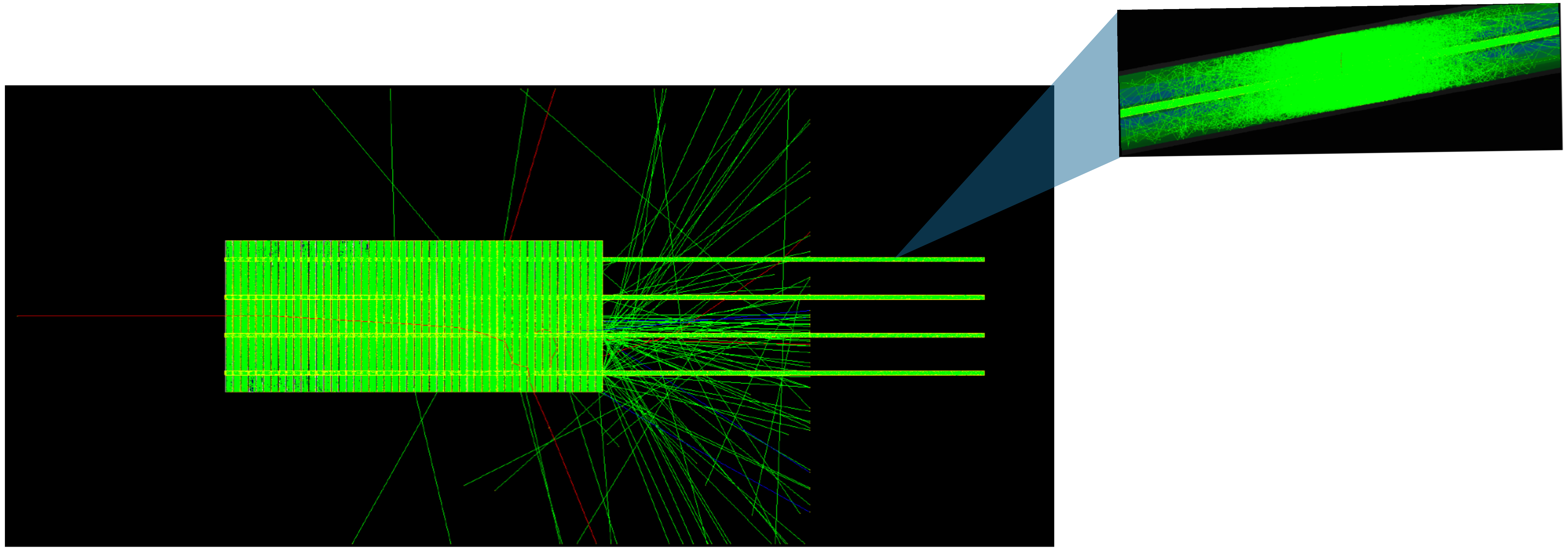
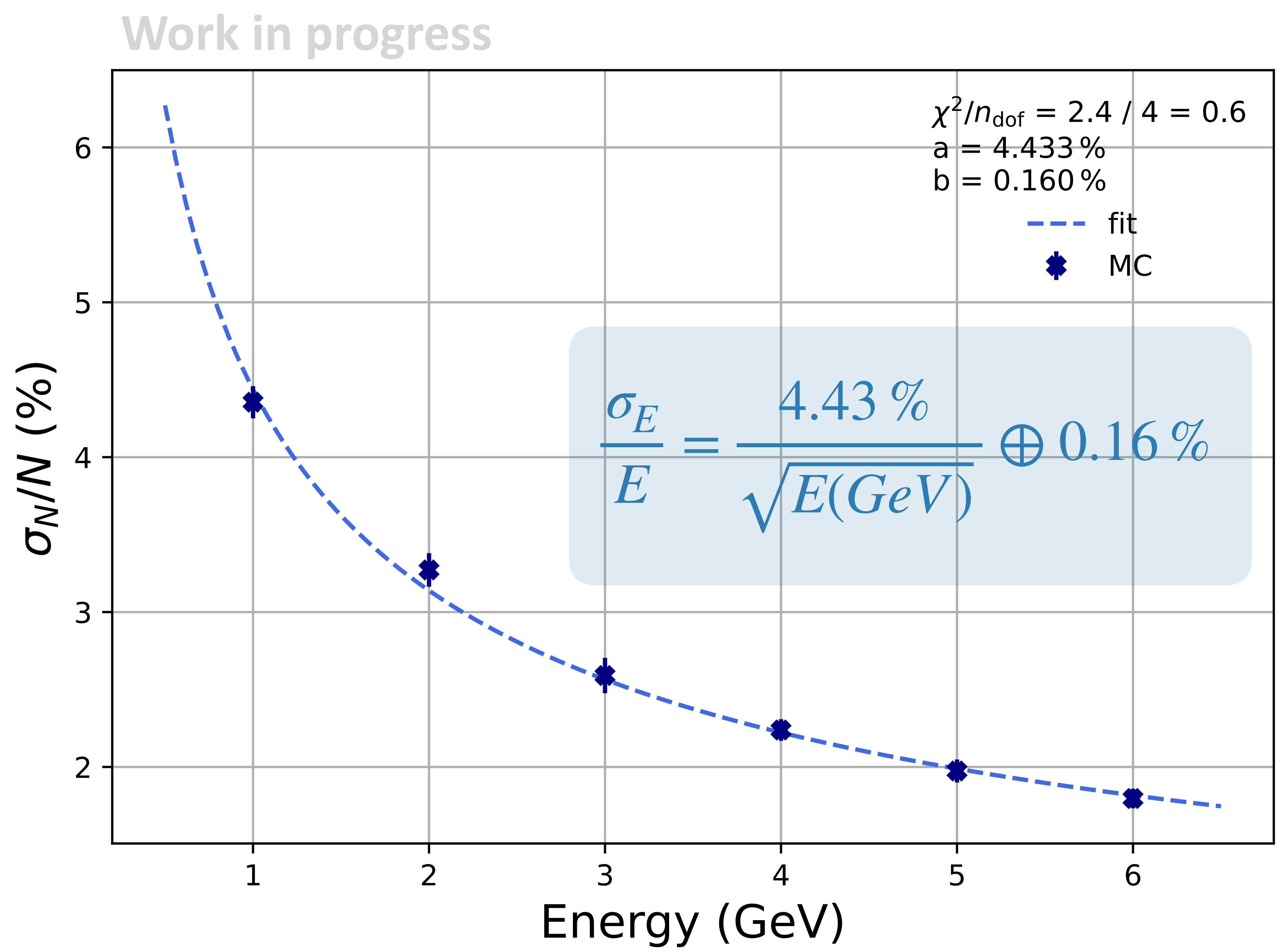
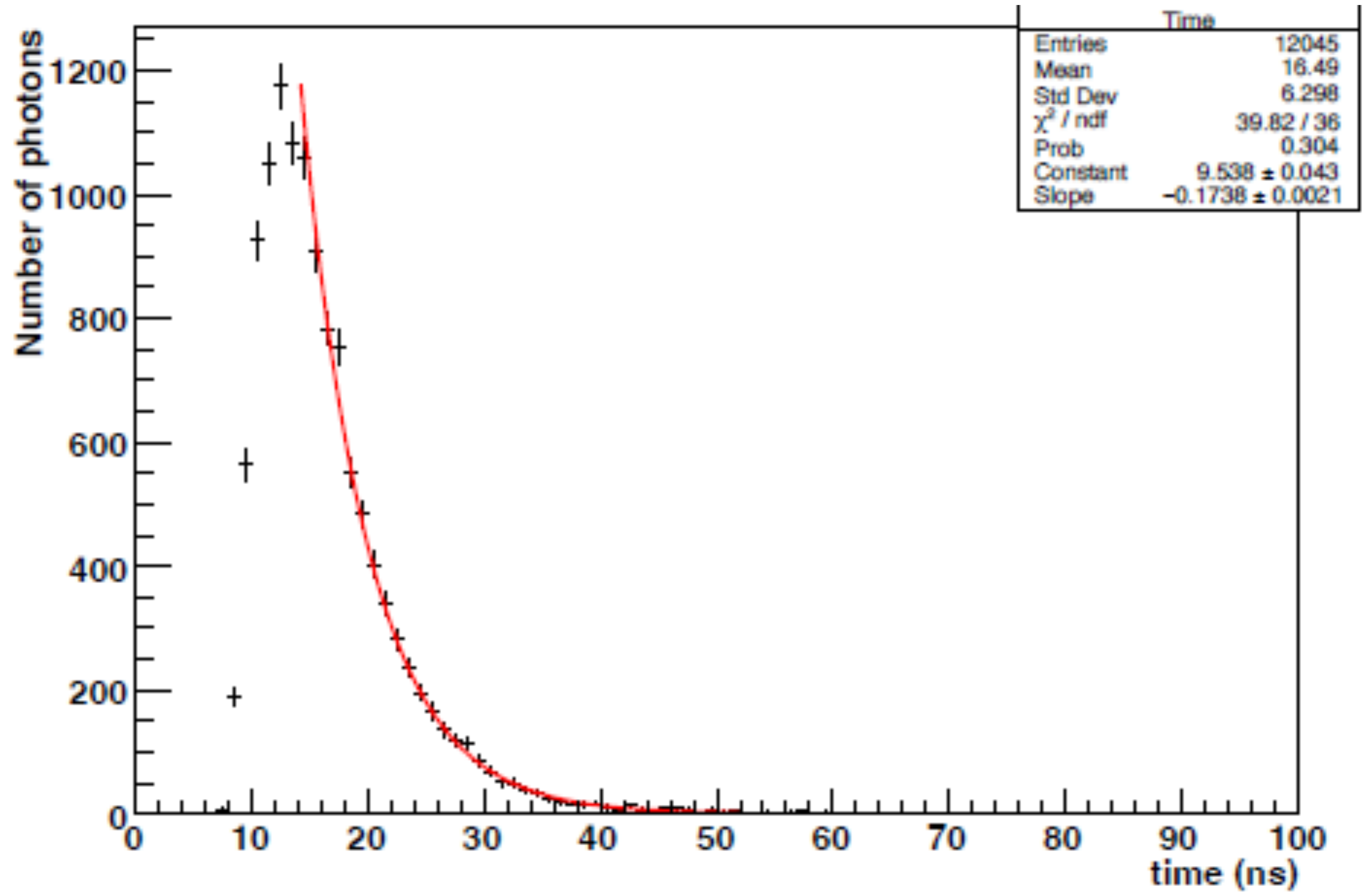
WIFAI-2025, Centro polifunzionale per gli studenti - BARI

Shashlyk simulation

- Geant4 simulation developed to drive the Shashlyk prototype design:
  - Alternating layers of PS+PTP+POPOP scintillator and lead
  - TiO_2 coating for the scintillator
  - WLS fibers with tunable absorption-emission spectrum (Y11-BCF92)
  - Optical photons tracking and sensitive detector for photon counting at the end of the WLS fibers



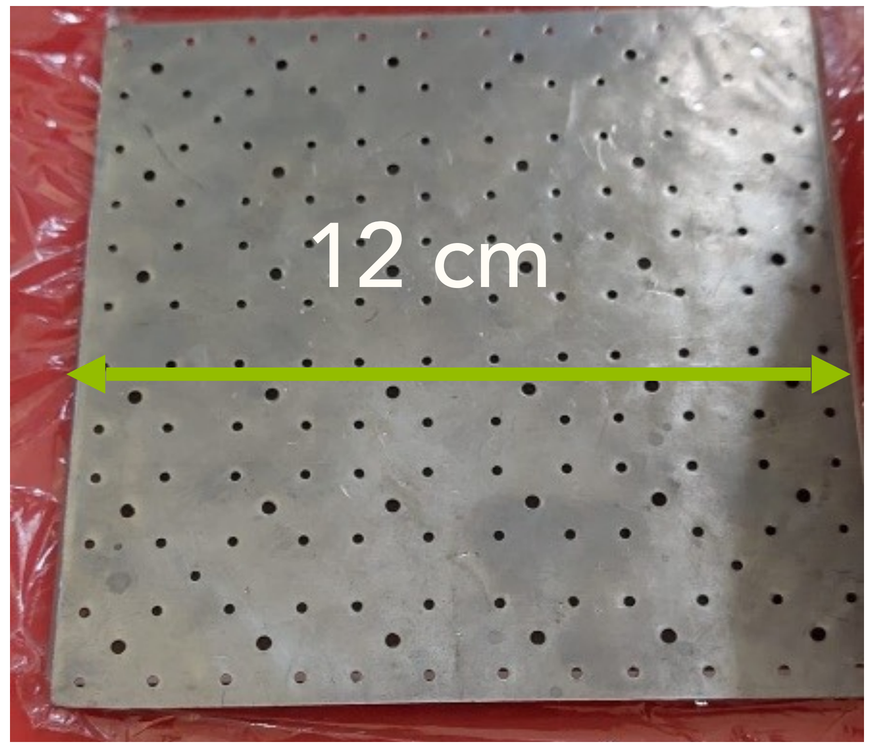


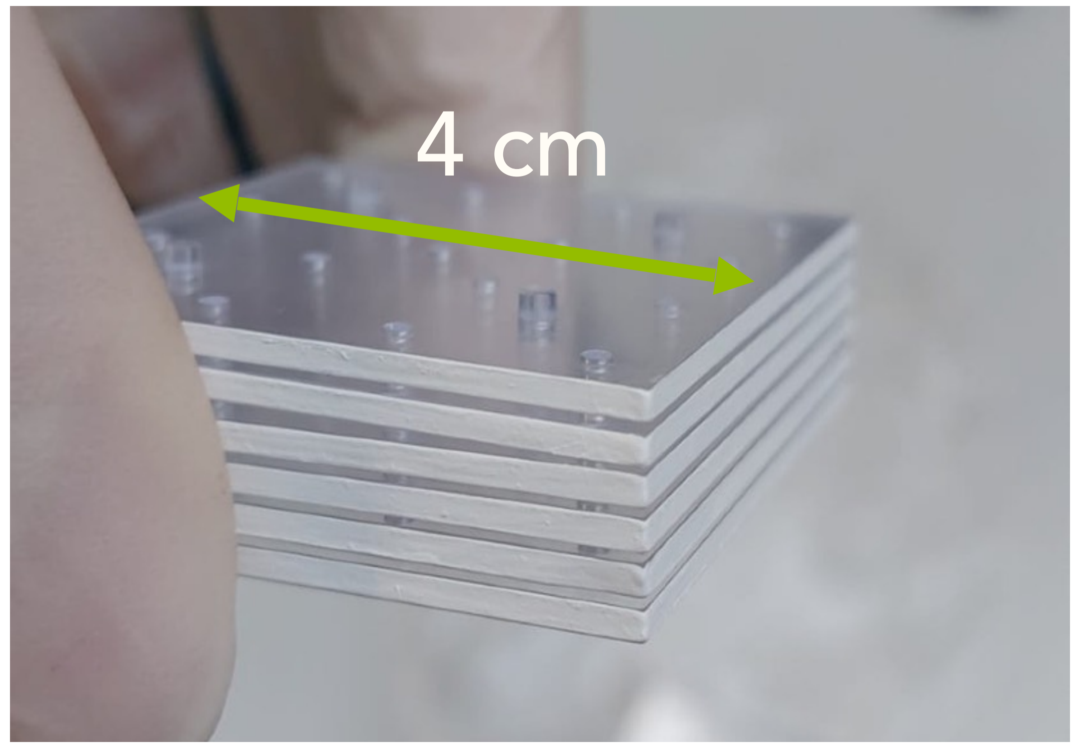


Shashlyk prototype design

Shashlyk prototype final design:

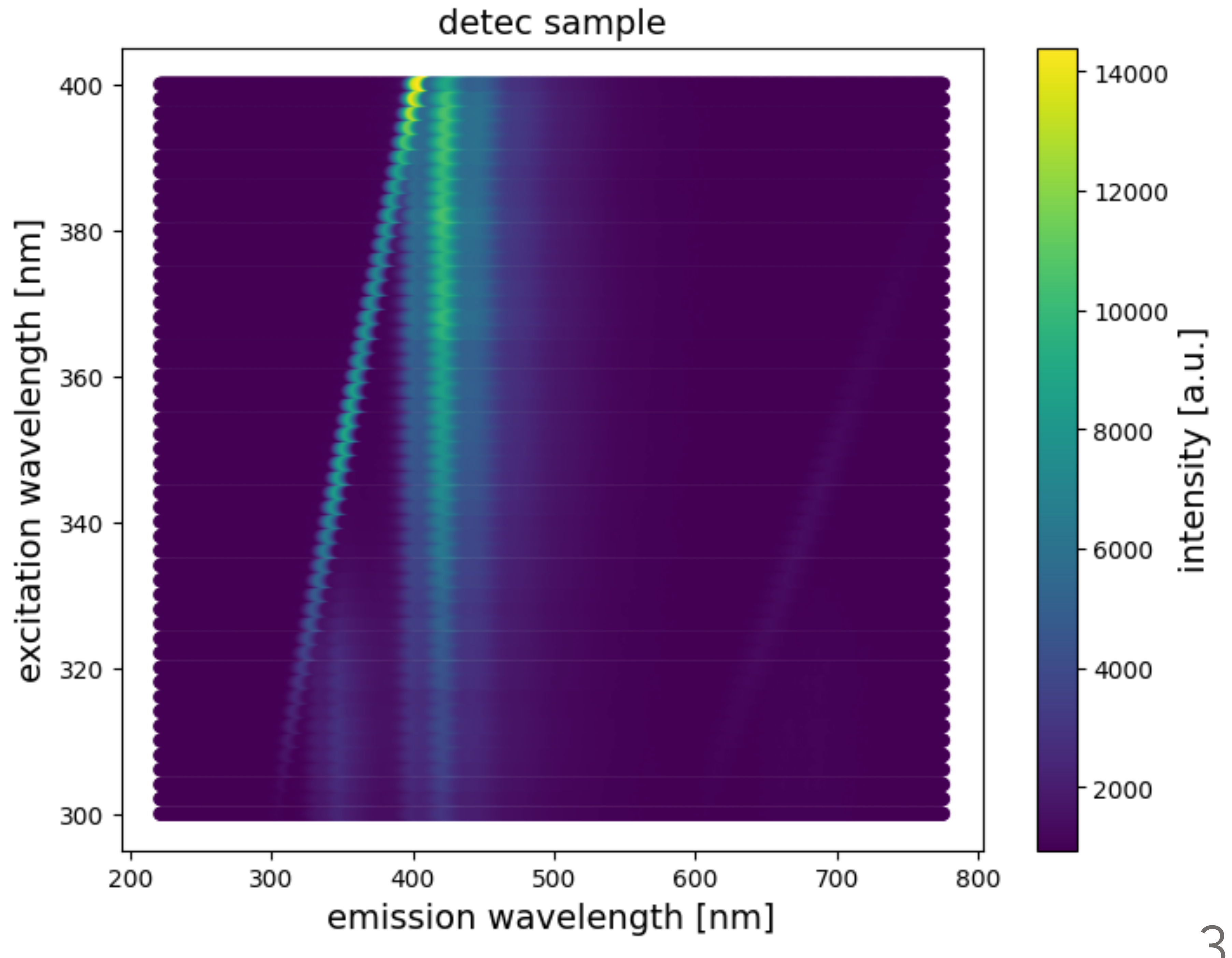
- 3x3 channel matrix with cell size 4x4 cm^2
- Layers of 1.6 mm PS+PTP+POPOP scintillator and 0.3 mm lead - sampling fraction 47%
- All scintillator and lead tile edges and both lead tiles sides coated with diffusive reflective paint.



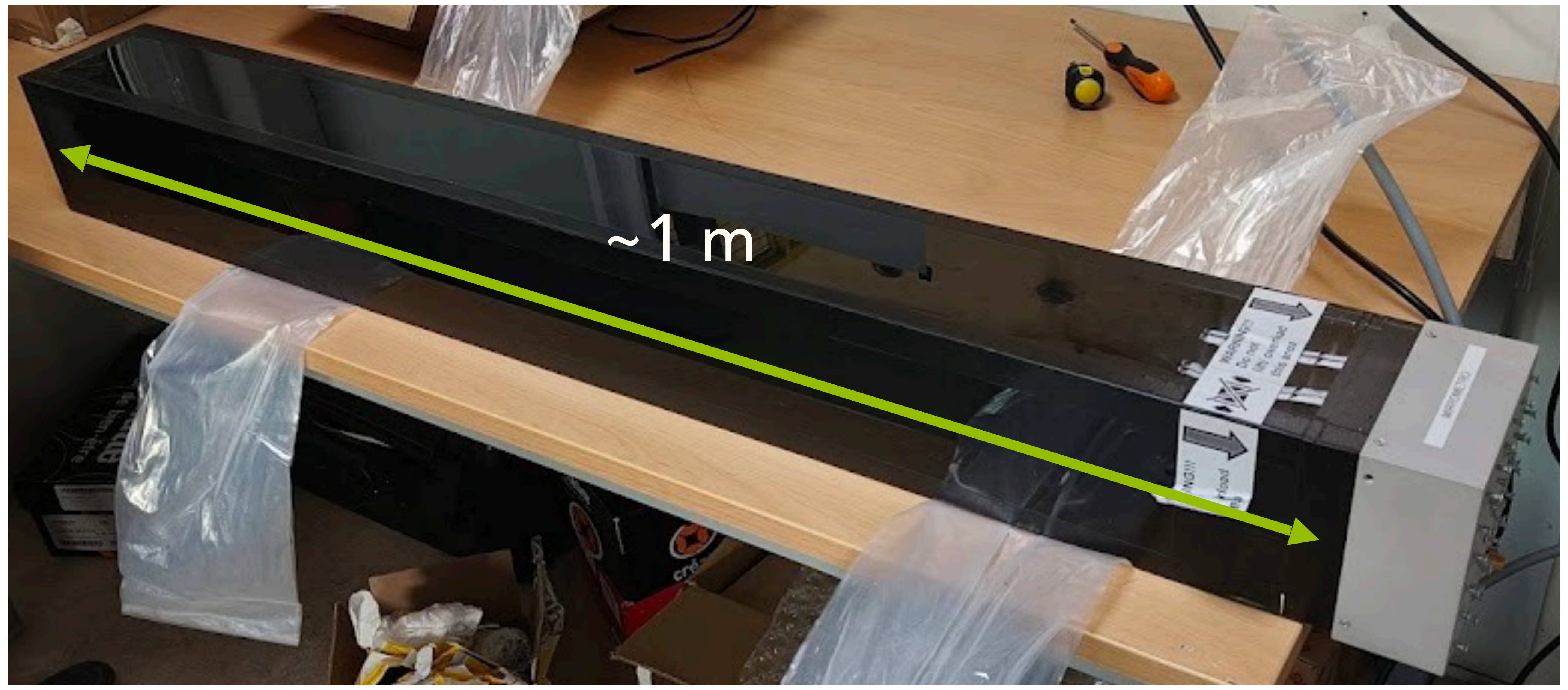


Polystyrene based plastic scintillators UPS-923A (POPOP: 0.05% ; PTP: 2%) and assembled at the Institute for Scintillation Materials, Kharkiv.

- Wavelength (max emission) 418 nm
- Decay time 2.3ns
- Refractive index (@430 nm) 1.55
- Light output 56% of anthracene



Shashlyk prototype design

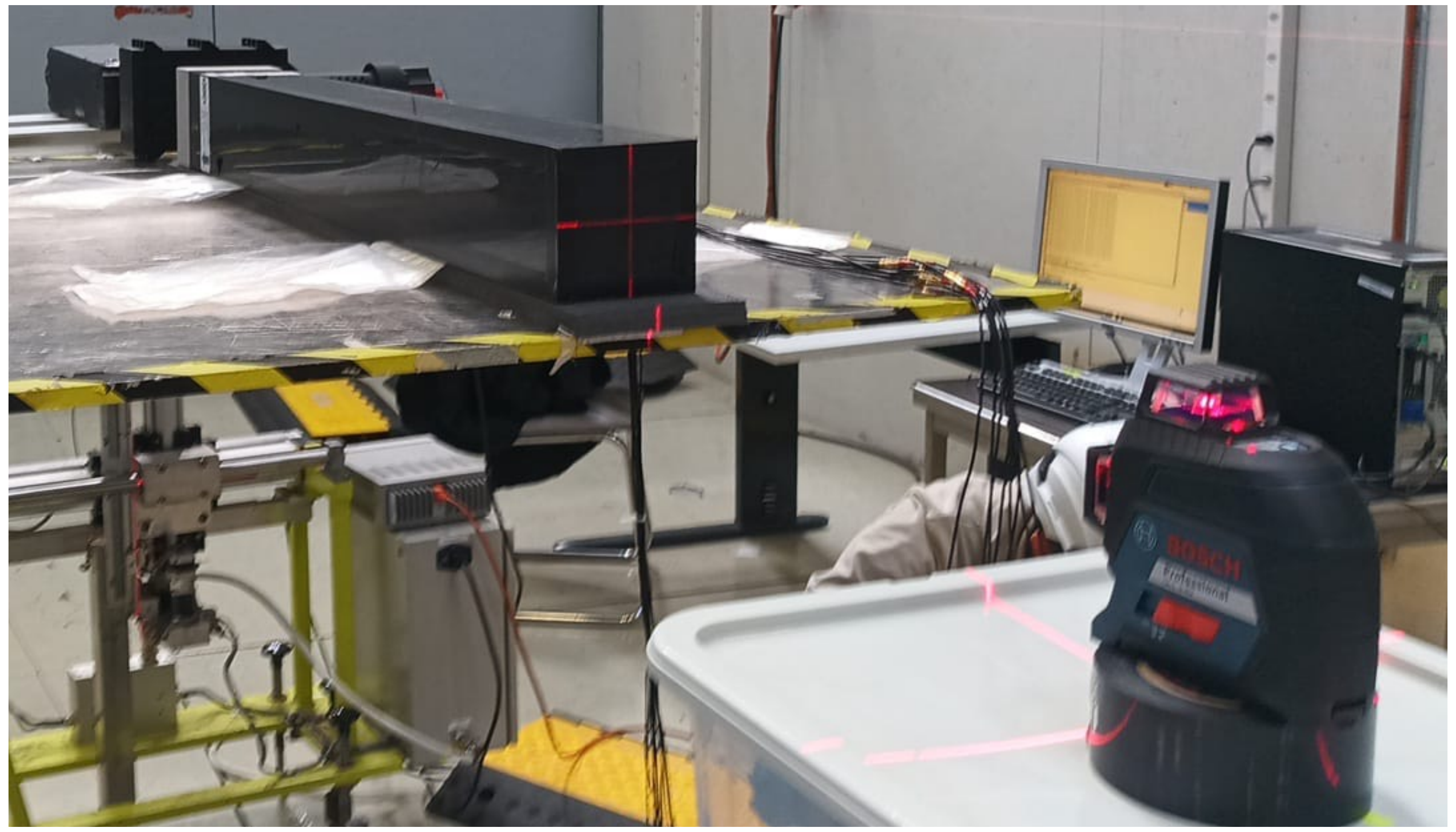


Two different prototypes developed* in collaboration with the DETEC company

1. 500 alternating scintillator+lead layers corresponding to 29 X_0 - WLS fibers BCF-92XL with 1.2mm diameter, mirrored at one side (**Single side** readout)
2. 350 alternating scintillator+lead layers corresponding to 20 X_0 - WLS fibers from Kuraray YS-4 with 1.2mm diameter. **Double side** readout implemented.

(*) funded by the Italian PRIN project PRIN_2022HNY9JC (HetCal)

2025 beam test of shashlyk prototypes



Test* at T9 CERN beamline, September 2025:

- Electron beam, 1-6 GeV
- MIP beam (μ^- or π^-), ~4 GeV
- Beamline with Cherenkov detectors to allow verification of beam ID $e/\mu/\pi/p$
- Signal waveforms collected with CAEN V1742 digitizer
  - 12 bit @ 5 GS/s
  - 1024 capacitor cells per channel (acquisition window of ~ 200 ns @ 5 GS/s)

S1, S2: Large upstream plastic scintillator for wide illumination

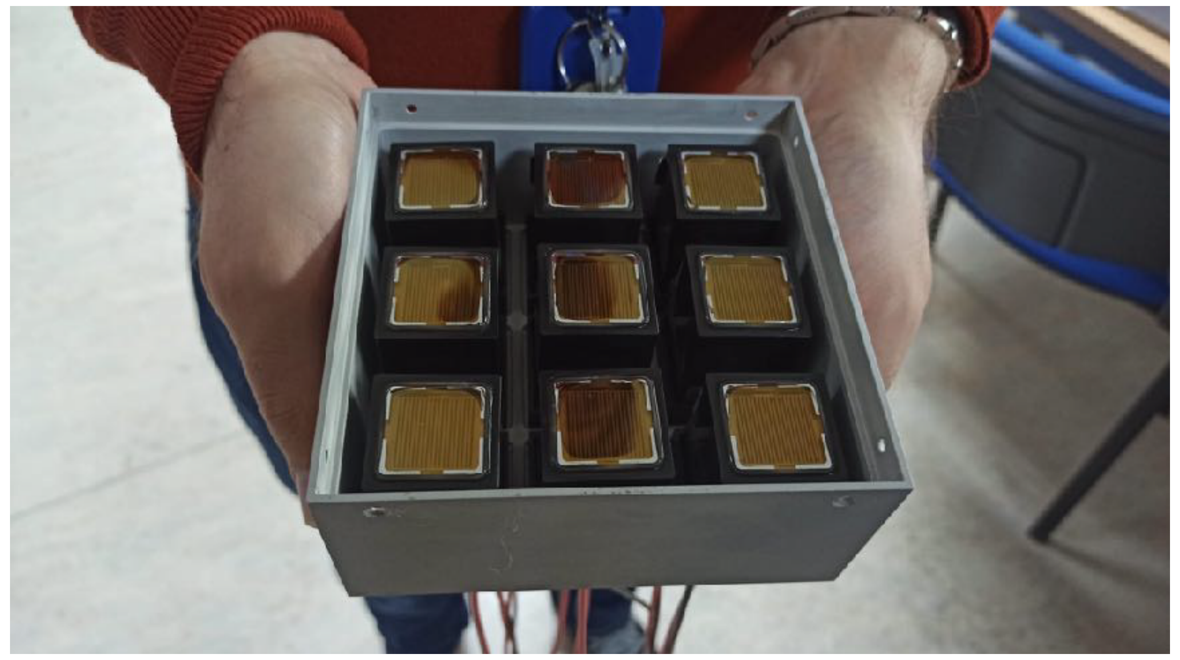
Timing Reference Detector : Ultra-fast plastic scintillator to trigger on particles hitting center of the Shashlyk, timing

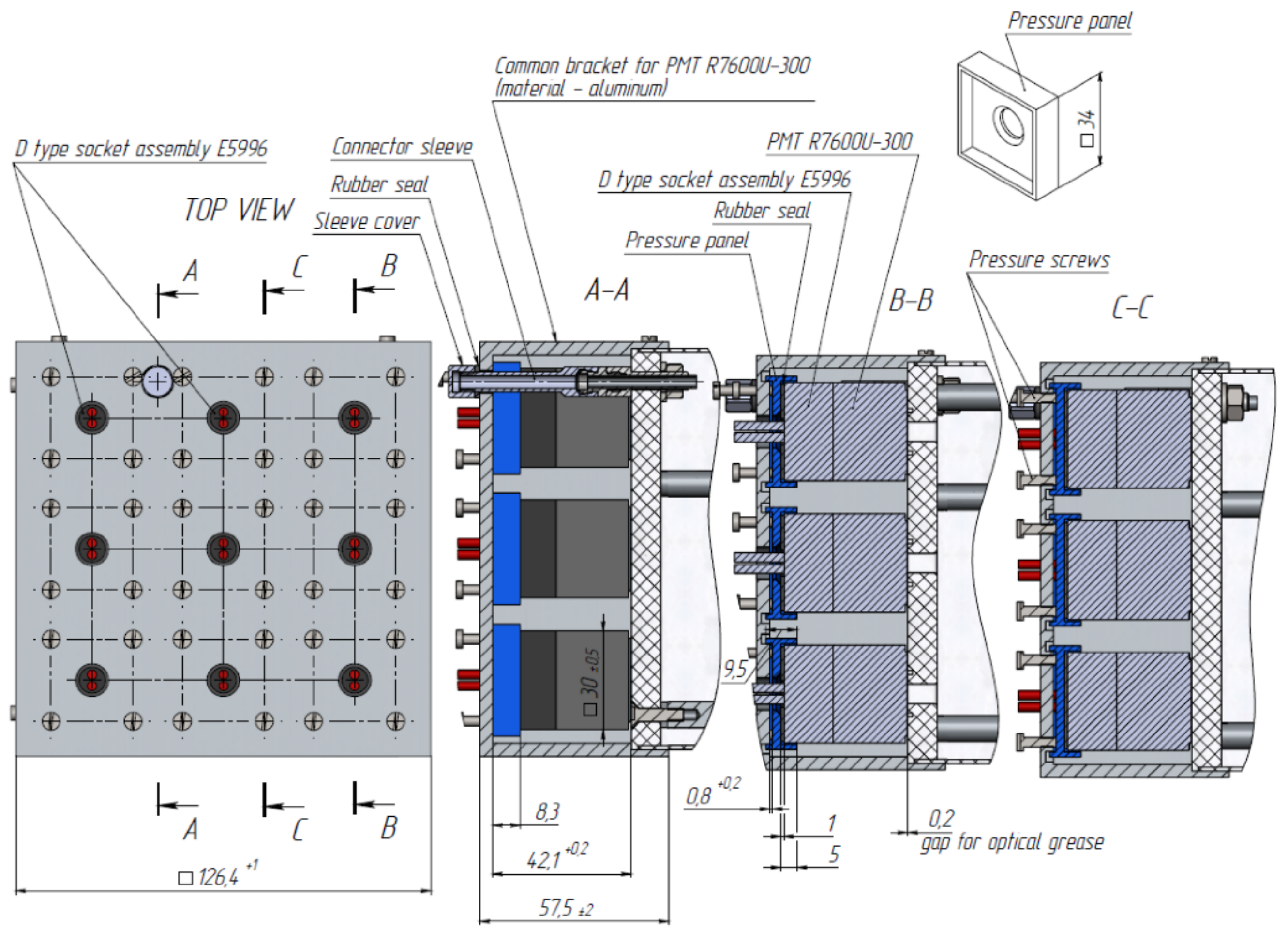
T1, T2: Si strip tracking chambers

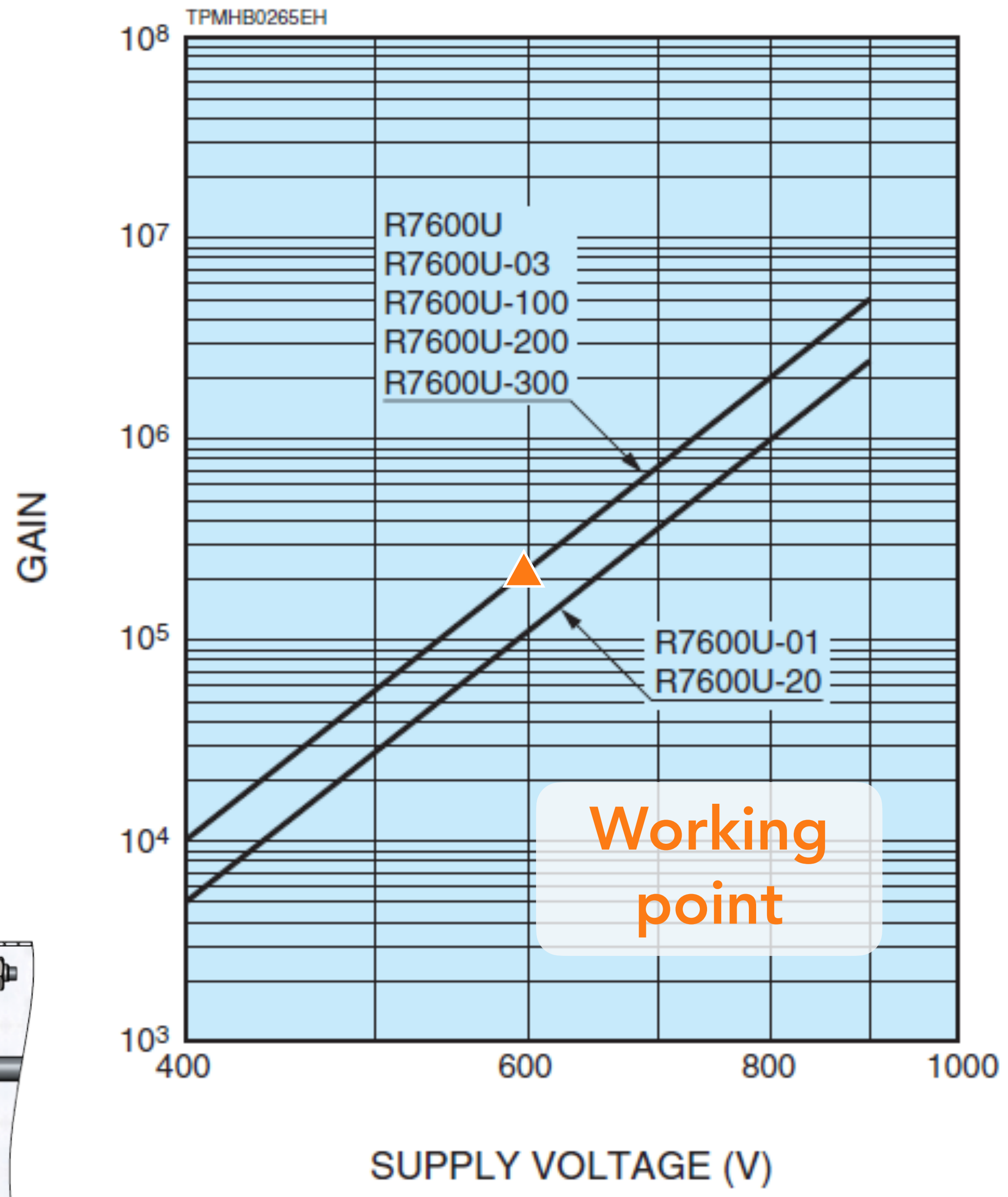
(*) funded by the Italian PRIN project PRIN_2022HNY9JC (HetCal)

Shashlyk prototype with single side readout

- PMT tested: *Hamamatsu R7600U-300*
- HV tuning required to uniform the shashlyk response

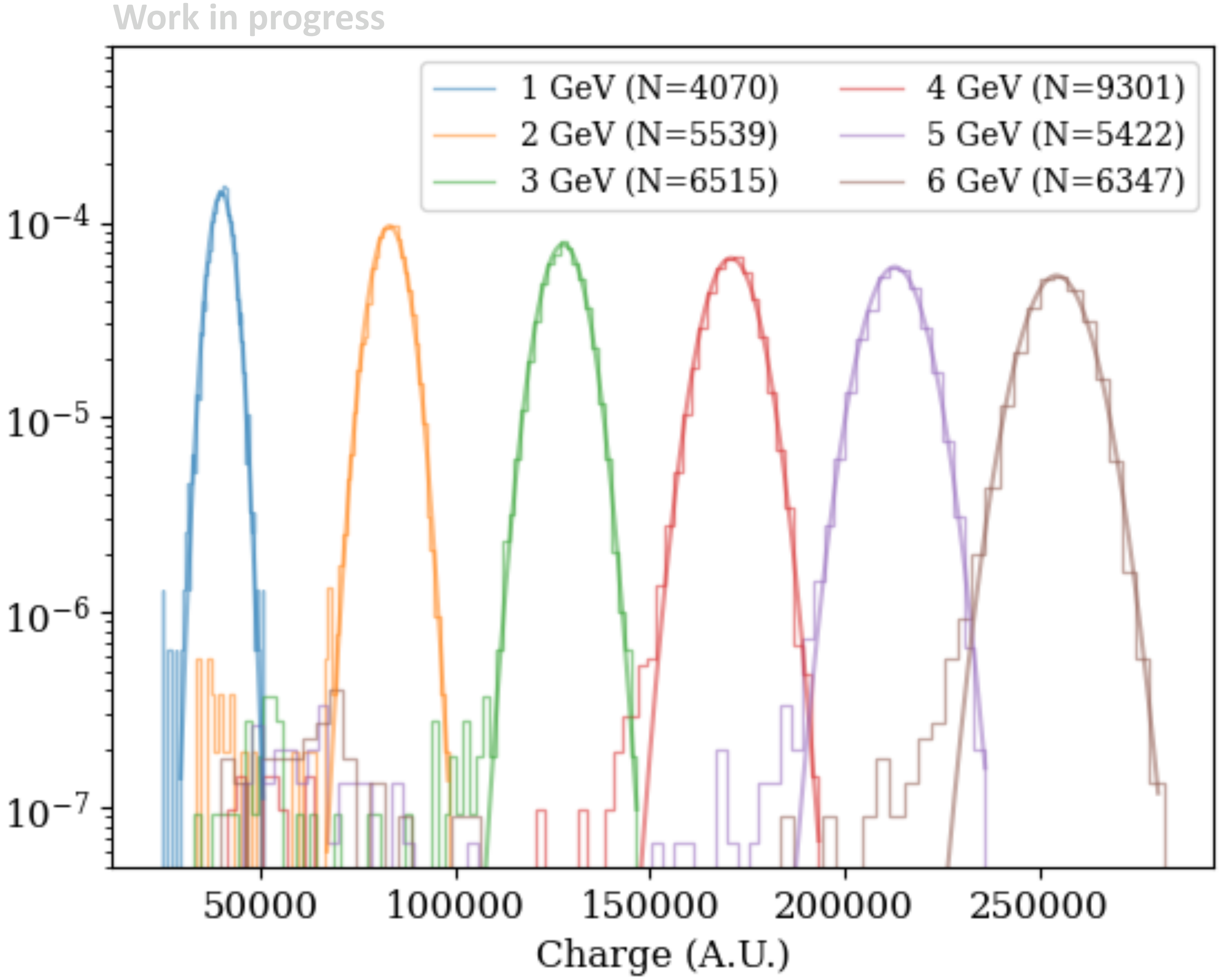






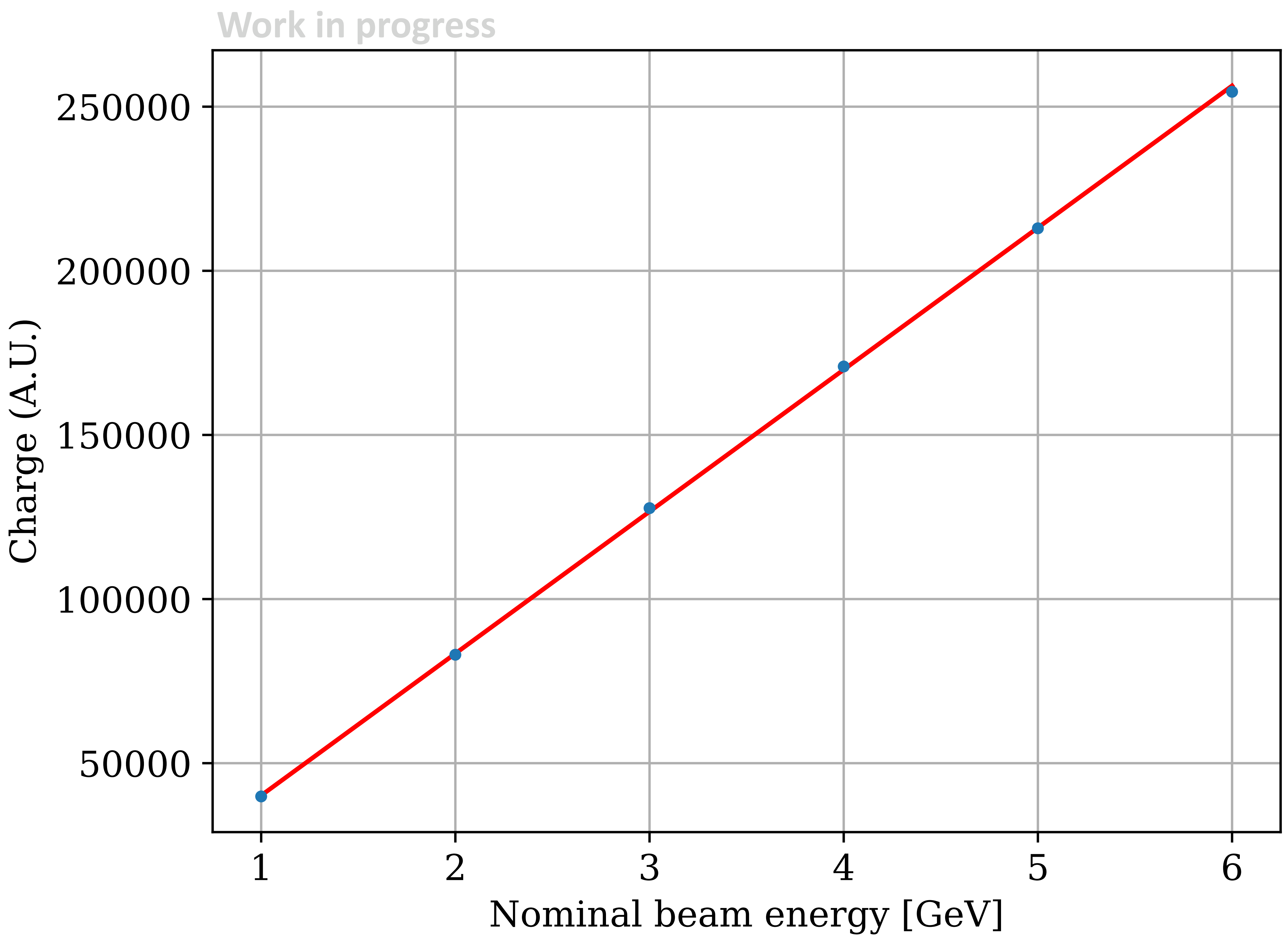
Analysis in a nutshell

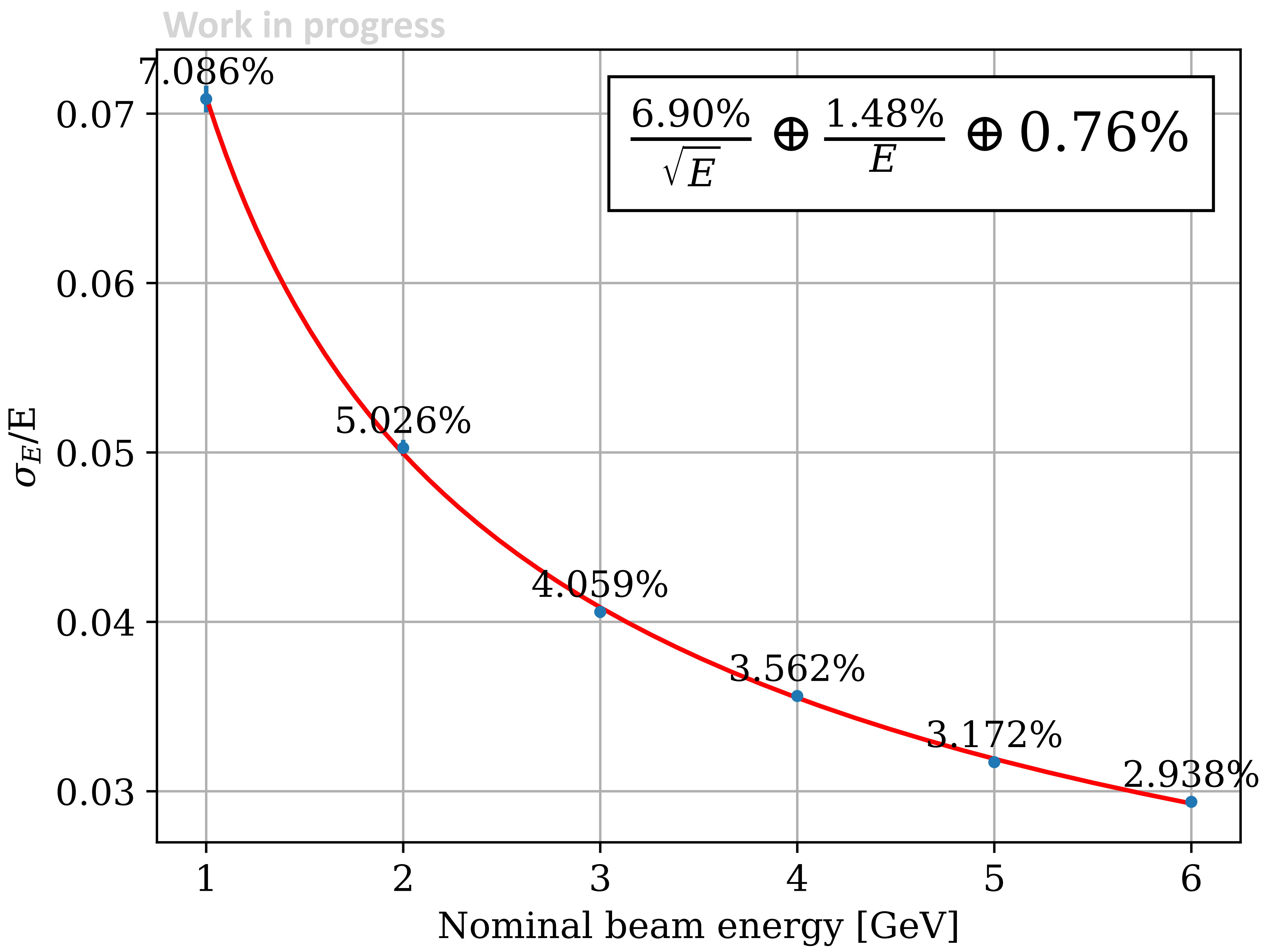
- Offline calibration applied (tune the PTMs response)
- electron PID using Cherenkov and lead-glass detectors
- geometrical fiducial hit requirement



Shashlyk prototype with single side readout

- Shashlyk performance: *linearity* and *energy resolution*
- Preliminary results using the integrated charge

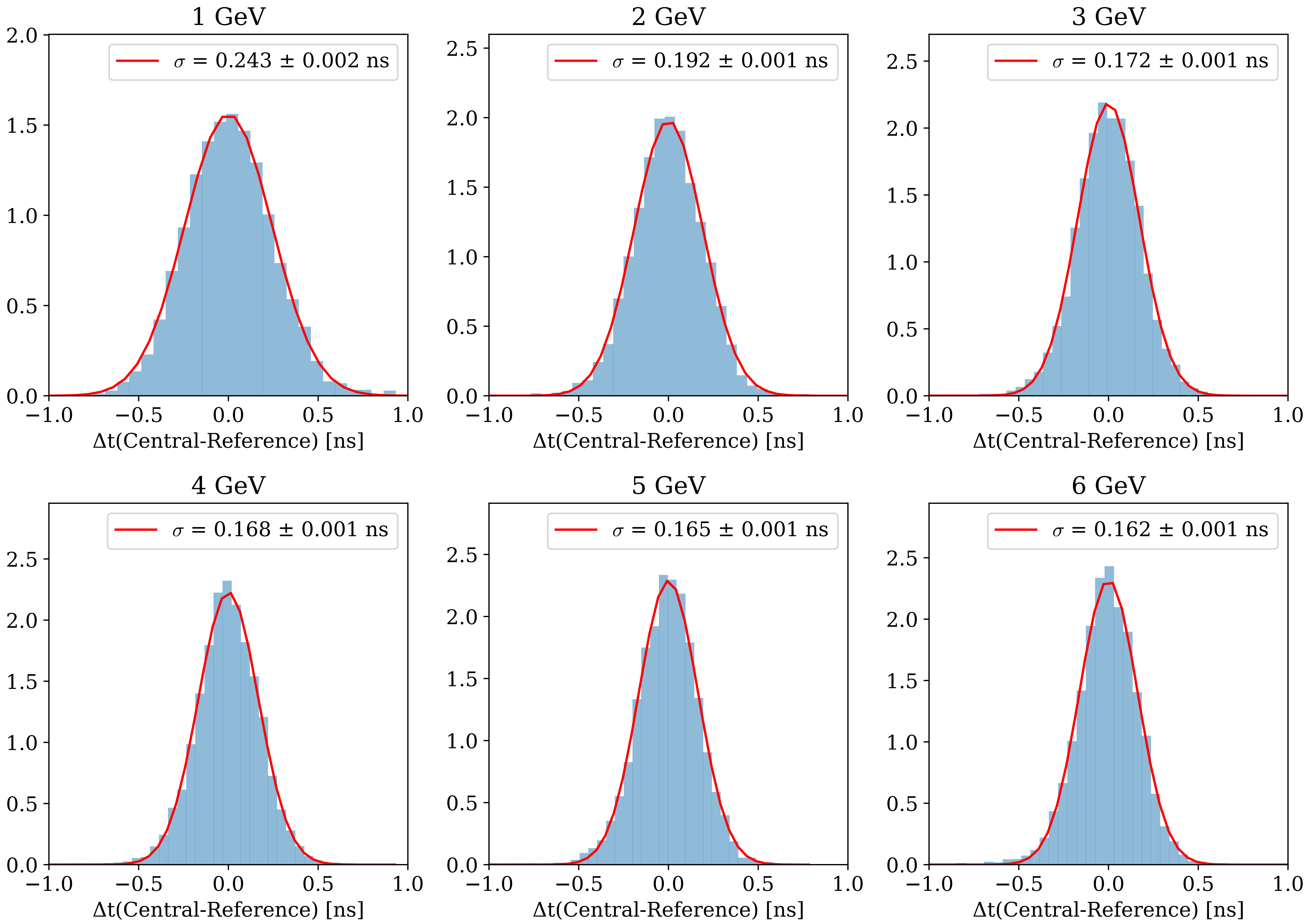


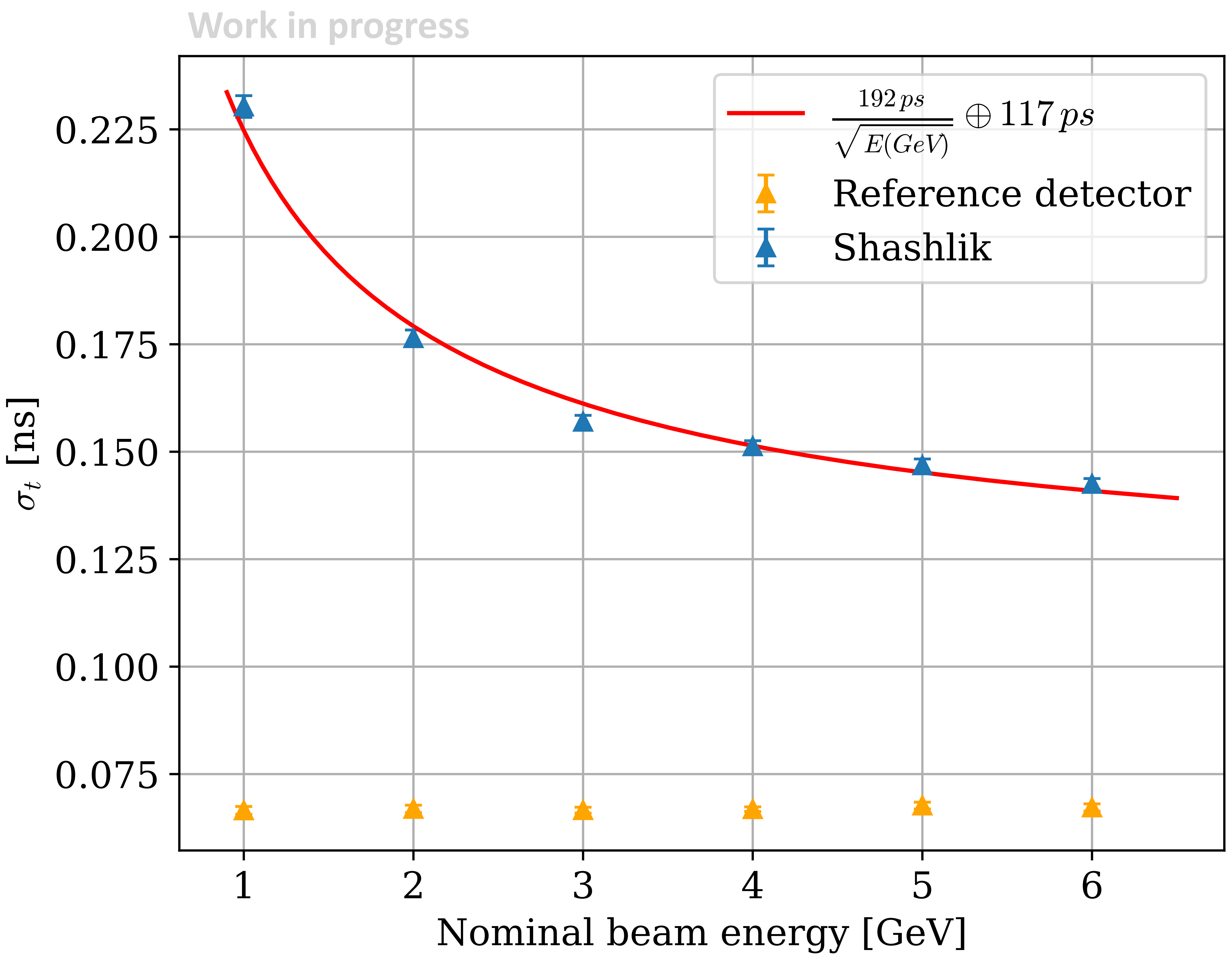


σ and E_{gauss} are the gaussian fit parameters of the integrated charge spectra

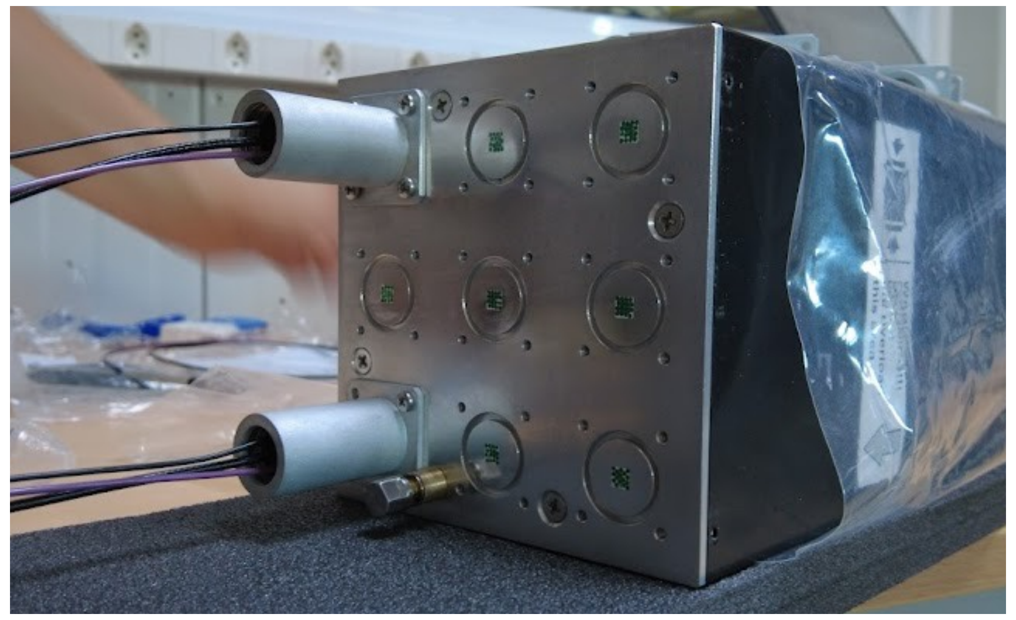
Shashlyk prototype with single side readout

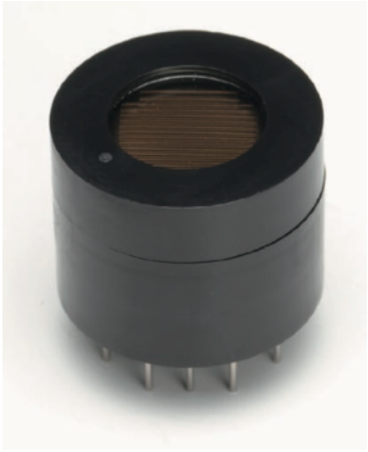
- Shashlyk performance: timing of the Shashlyk central channel only
- Time extracted with CFD at 30% on both Shashlyk and Reference counter channels (not yet optimized)
- Reference counter time resolution from difference of its two channels, used to subtract t_0 contribution to obtain central channel timing

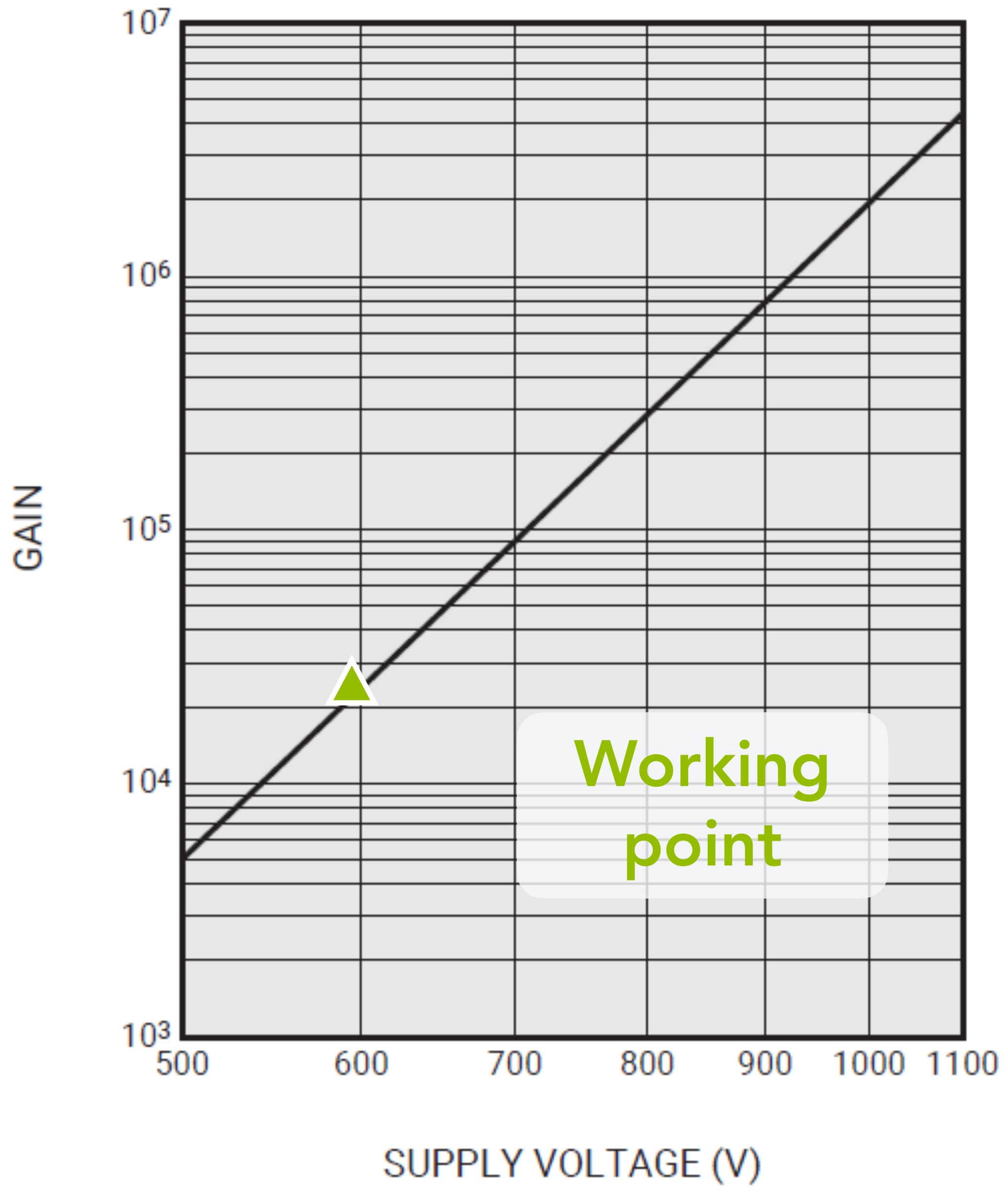


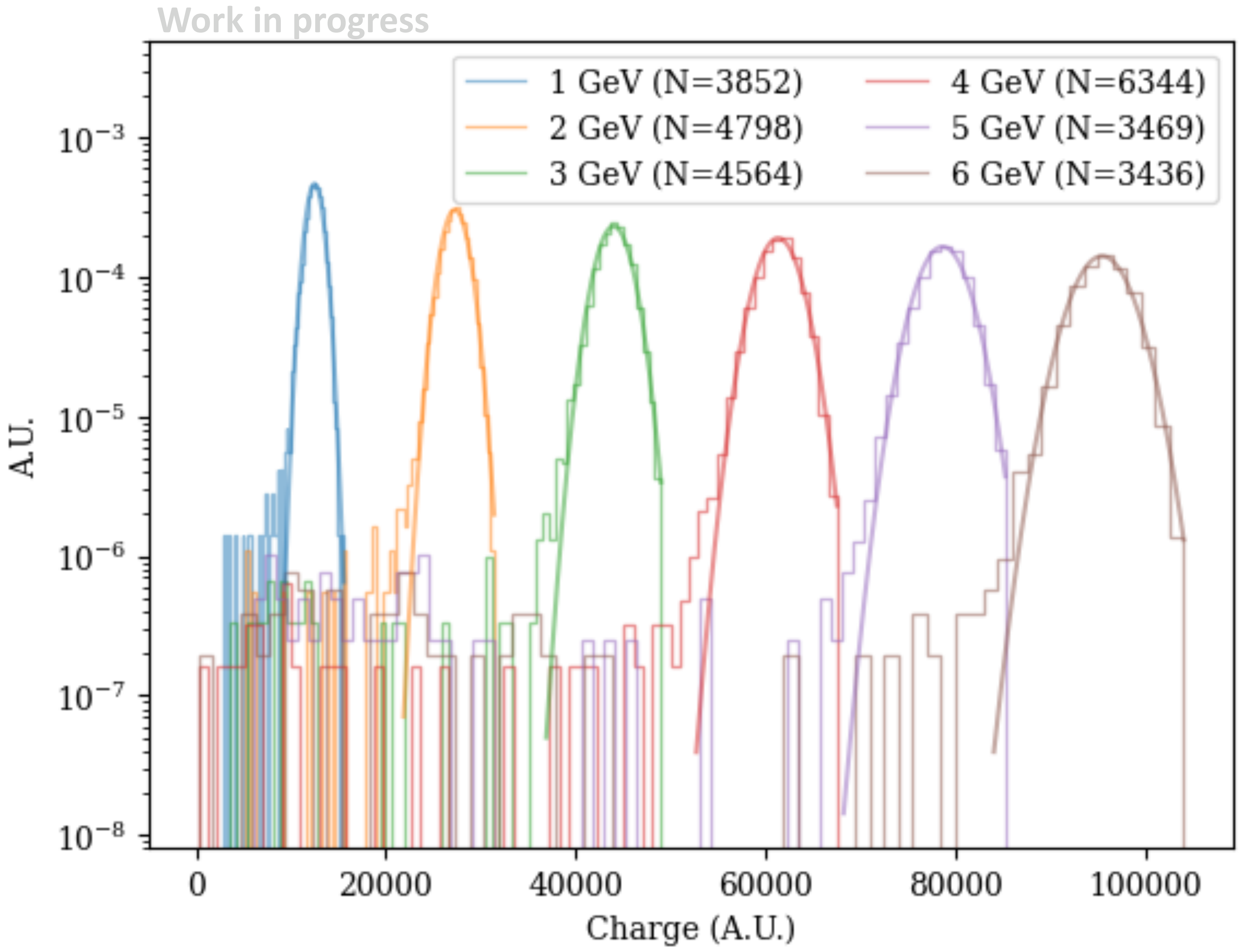


Shashlyk prototype with double side readout









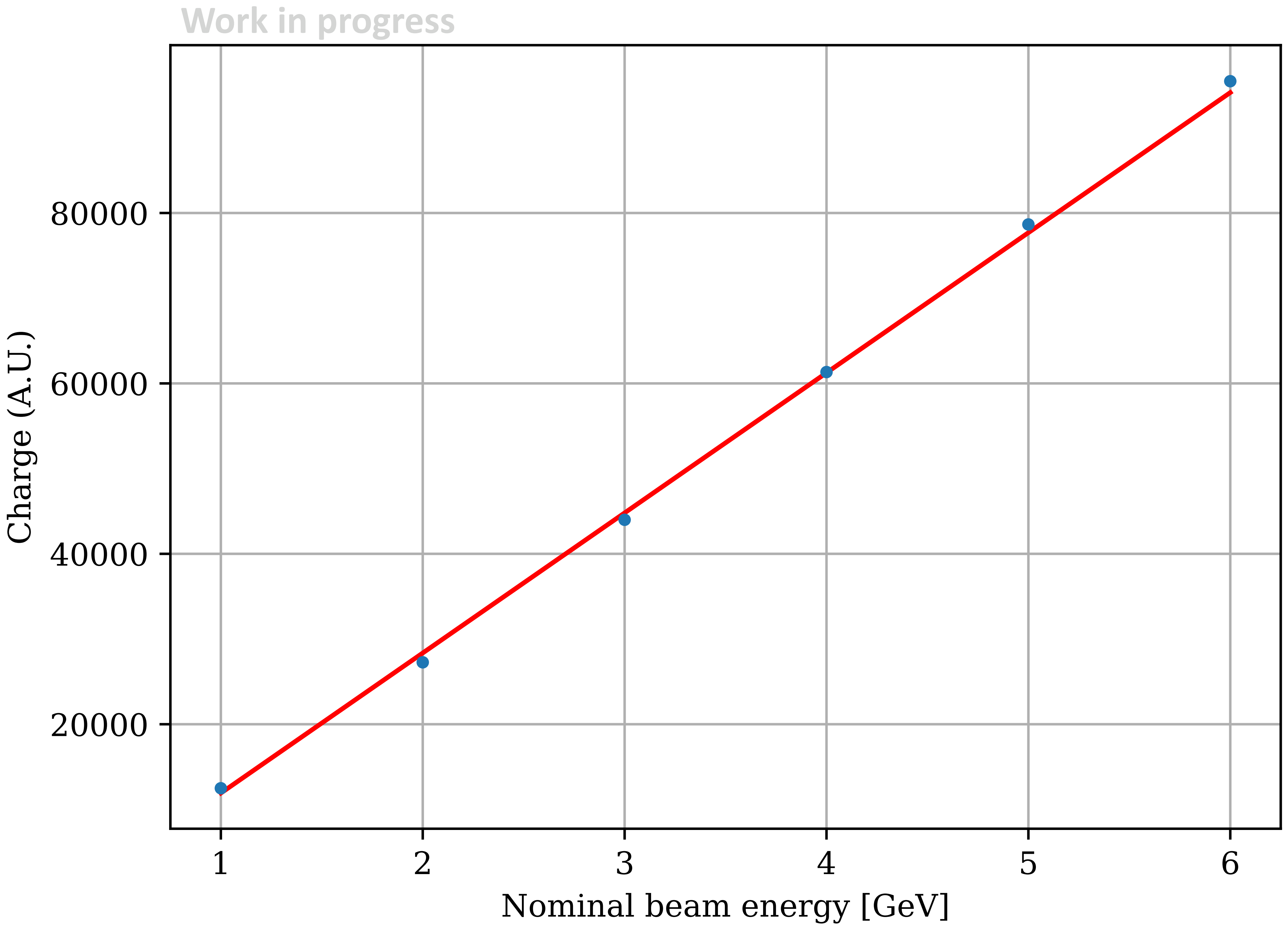
- PMT tested: *Hamamatsu R9880-20*
- More light observed in front channels compared to rear ones. HV tuning required to equalise the electron response between front and rear channels.
- MIP runs used to evaluate calibration parameters for offline application.
- Front-channel HV values are lower than those of the rear channels.

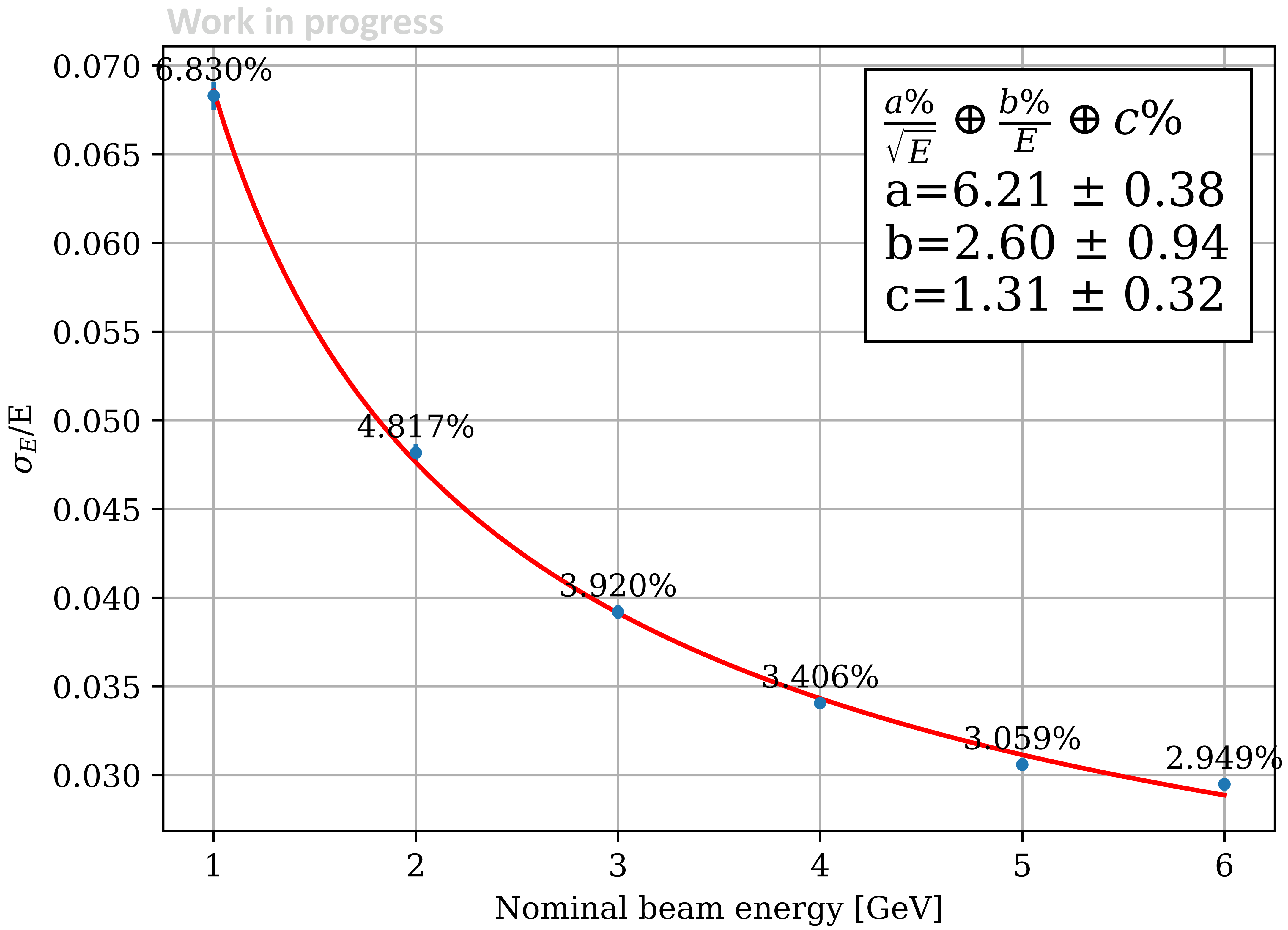
Analysis in a nutshell

- Offline calibration applied (tune the PTMs response)
- electron PID using Cherenkov and lead-glass detectors
- geometrical fiducial hit requirement

Shashlyk prototype with double side readout

- Shashlyk performance: *linearity* and ***energy resolution***
- Preliminary results using the integrated charge

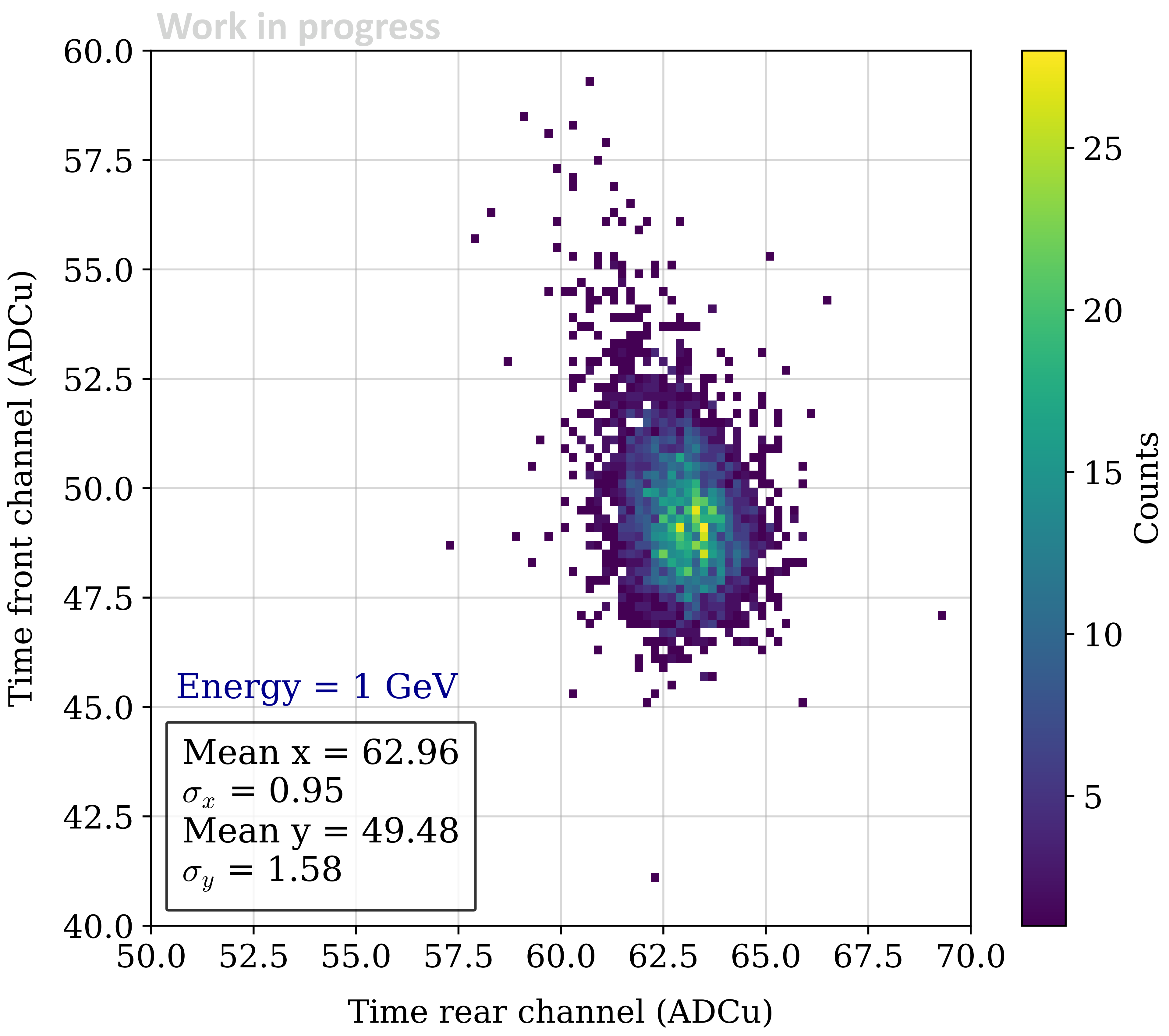


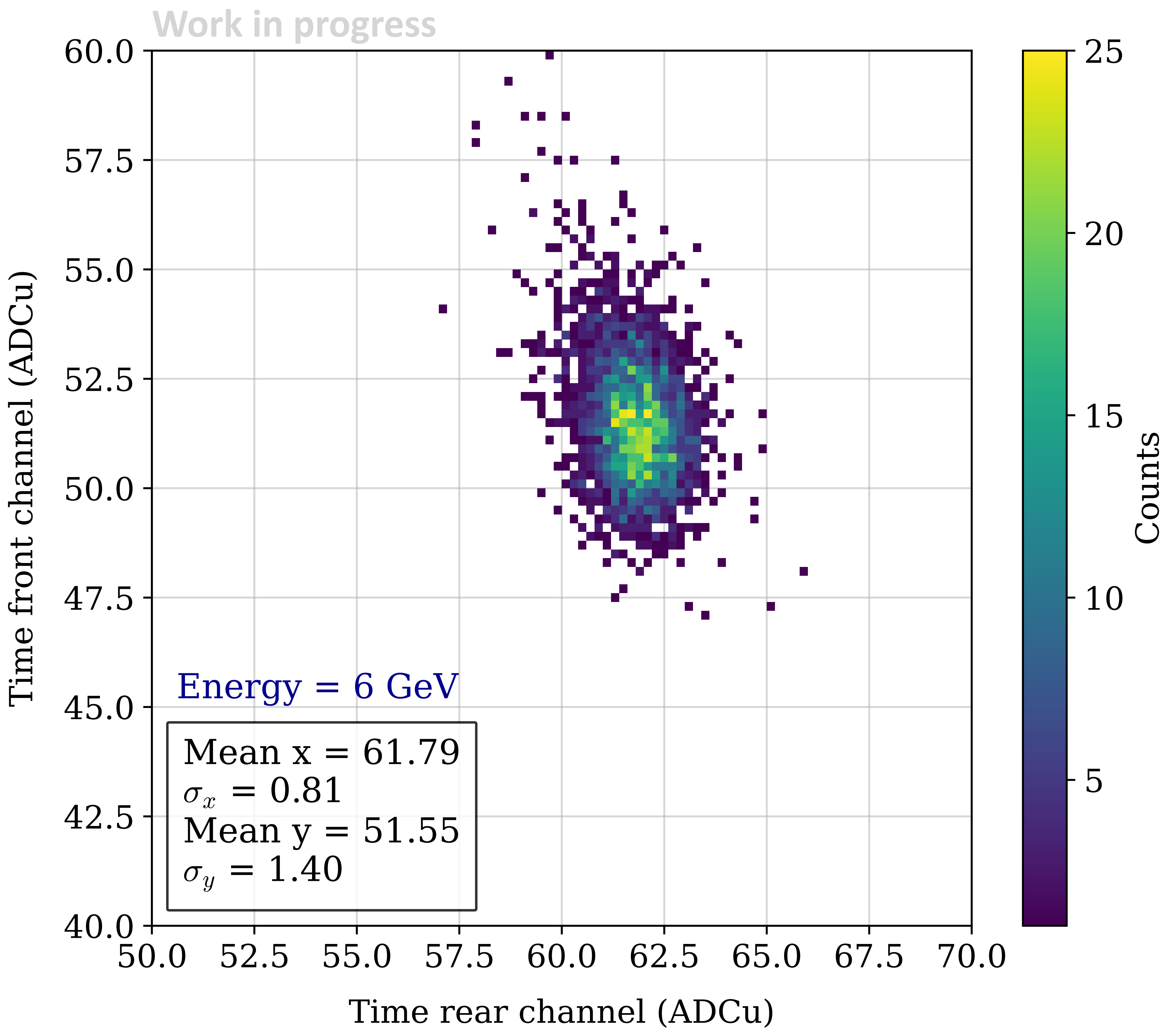


σ and E_{gauss} are the gaussian fit parameters of the charge spectra

Shashlyk prototype with double side readout

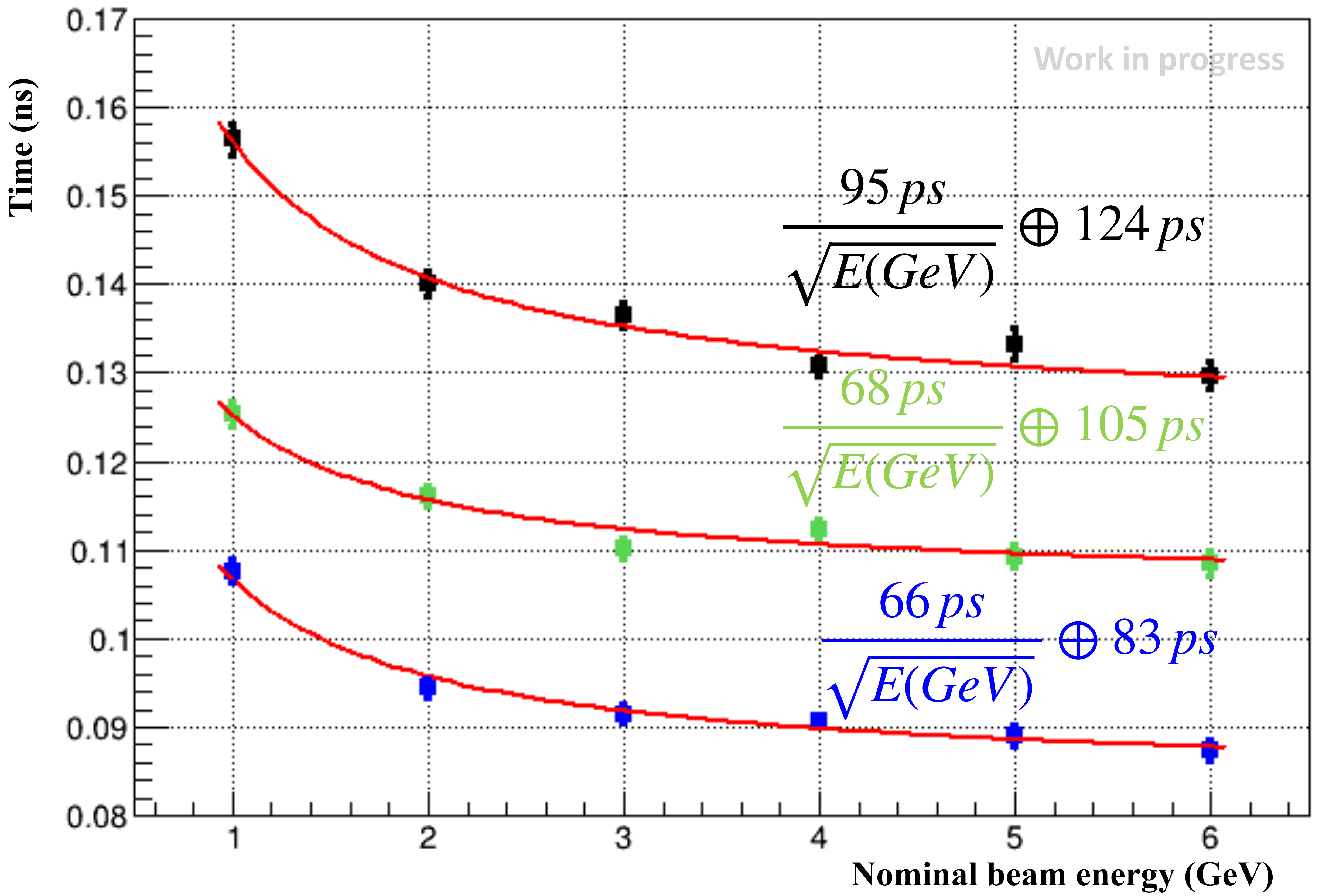
- Shashlyk performance: timing of the Shashlyk central channel only
- Time extracted with CFD at 30% on both MEC and Reference counter channels (not yet optimised)
- Anti-correlation between rear and front observed
- Narrower time distribution for the rear channels at all beam energies (investigation ongoing)





Shashlyk prototype with double side readout

- Shashlyk performance: timing of the Shashlyk central channel only
- Time extracted with CFD at 30% on both MEC and Reference counter channels (not yet optimised)
- Reference counter time resolution ~70 ps



Back channel only

Average of back/ front times

Weighted average of rear/front times, taking into account correlation

Conclusions and future prospects

- An extensive test beam campaign was conducted to gain familiarity with the setup and to assess the performance of the developed prototypes.
- Two different prototypes were tested, each with multiple combinations of photosensors
- The results in terms of time resolution and energy resolution are consistent with the design specifications of the constructed detector.
- The analysis of the collected data is still ongoing and will be further optimized in the coming months.
- The technologies and design solutions studied in this work could be considered for future applications within high-energy physics experiments requiring precise timing and energy measurements.

Thanks for your attention!

Backup

NA62 LKr calorimeter in HIKE

Quasi-homogeneous ionization calorimeter: 27 X_0 LKr

Photon efficiency likely adequate even for HIKE program

- NA48-era studies for NA62: $1 - \varepsilon < 10^{-5}$ for $E\gamma > 10$ GeV
- High-energy efficiency confirmed with NA62 data

Time resolution

- $\sigma_t \sim 500$ ps for with $E_{\gamma\gamma} > 20\,GeV$
- Would require 4x improvement in K^+ phase to hold accidental veto rate to current levels
- Critical for HIKE: Accidental rate ~140 MHz!

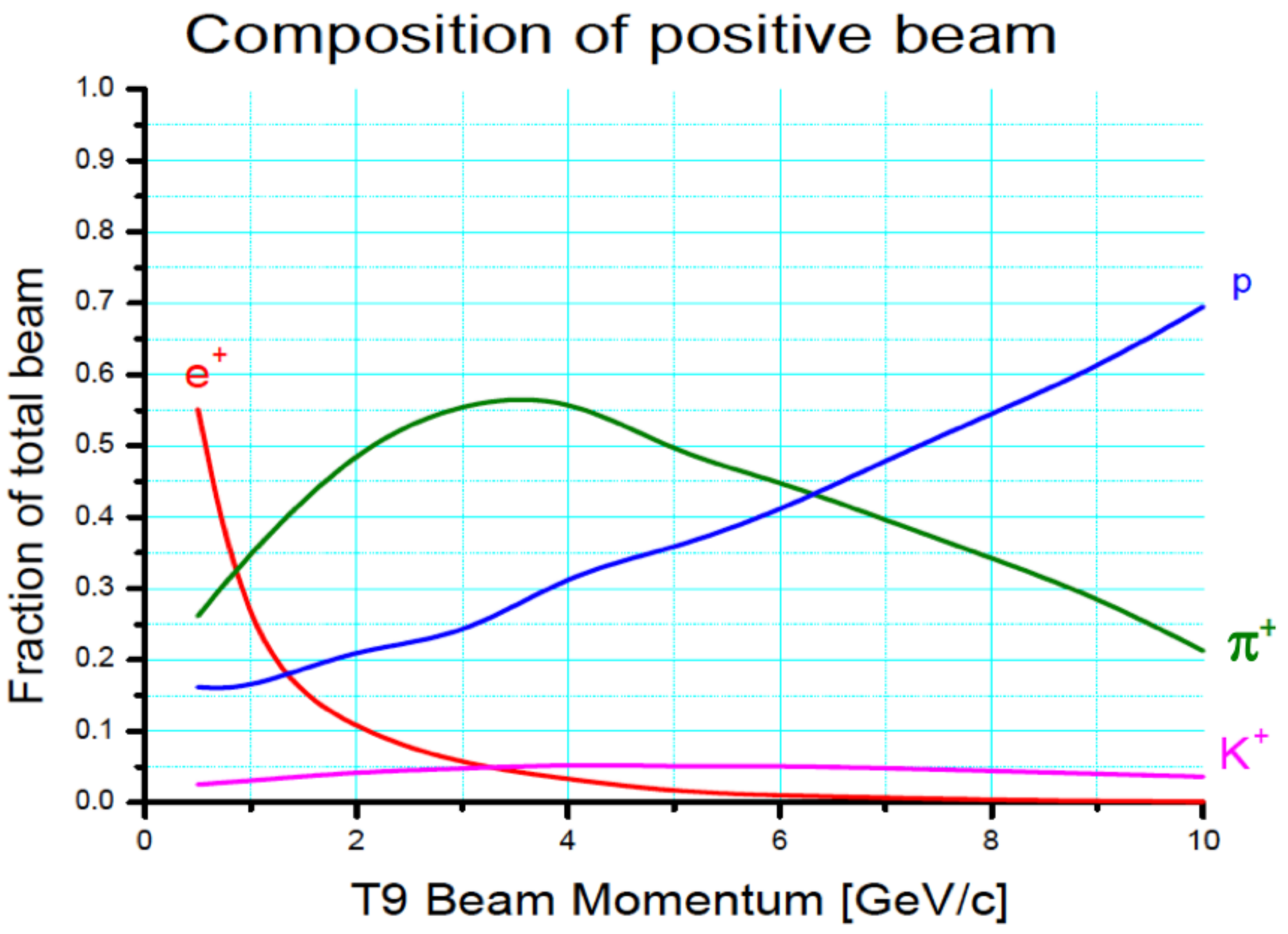
Consolidation work necessary

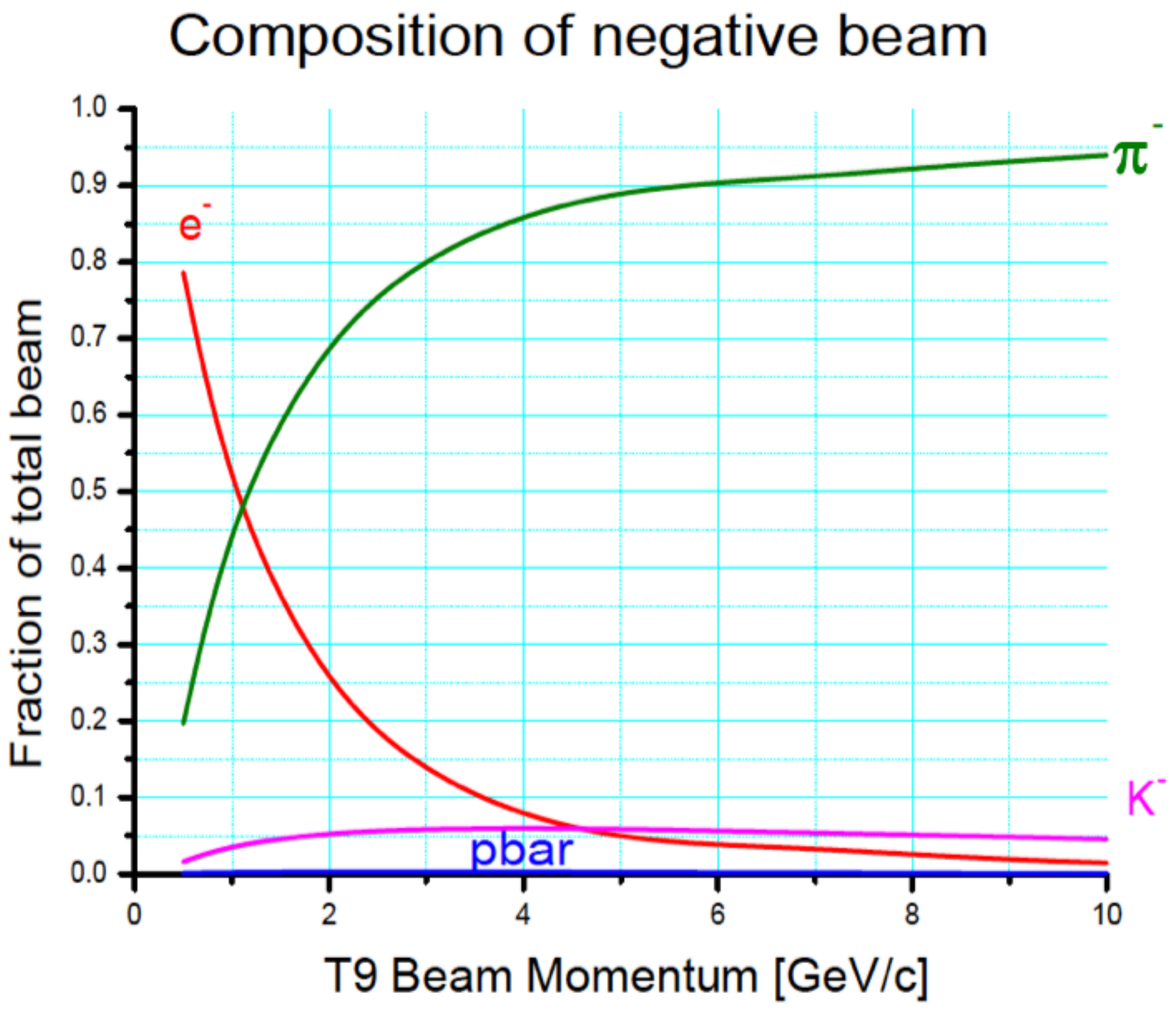
Investigating upgrade possibilities

- Increase operating voltage to increase drift velocity
- Faster digitizers and signal shaping

For K_L phase, LKr inner bore limits beam solid angle

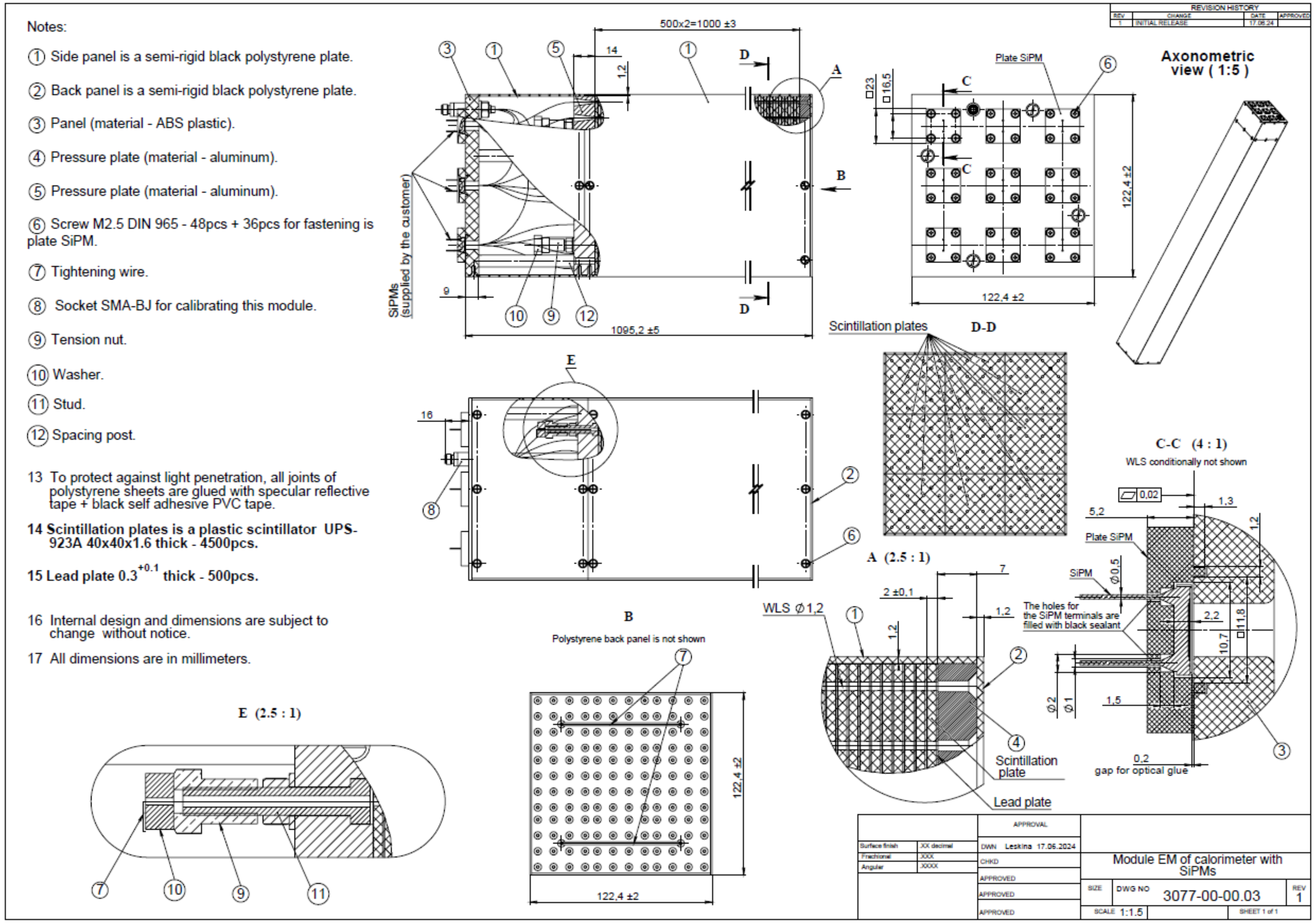
T9 beam line





Parameter	T9
Maximum momentum (GeV/c)	12
Production angle (mrad)	0
Beam length to ref. focus (m)	55.8
Beam height above floor (m)	2.50
Ang.acceptance Horizotal (mrad) Vertical (mrad)	±4.8 ±5.8
Acc. Solid angle (μsterad)	87
Theor. momentum resol. (%)	0.24
Max. momentum band (%)	±10
Magnification at reference focus	1.0, 1.2
Protons on North target	~2.5 10^{11}
Max. flux (depending on p, Q)	10^6

Shashlyk prototype construction



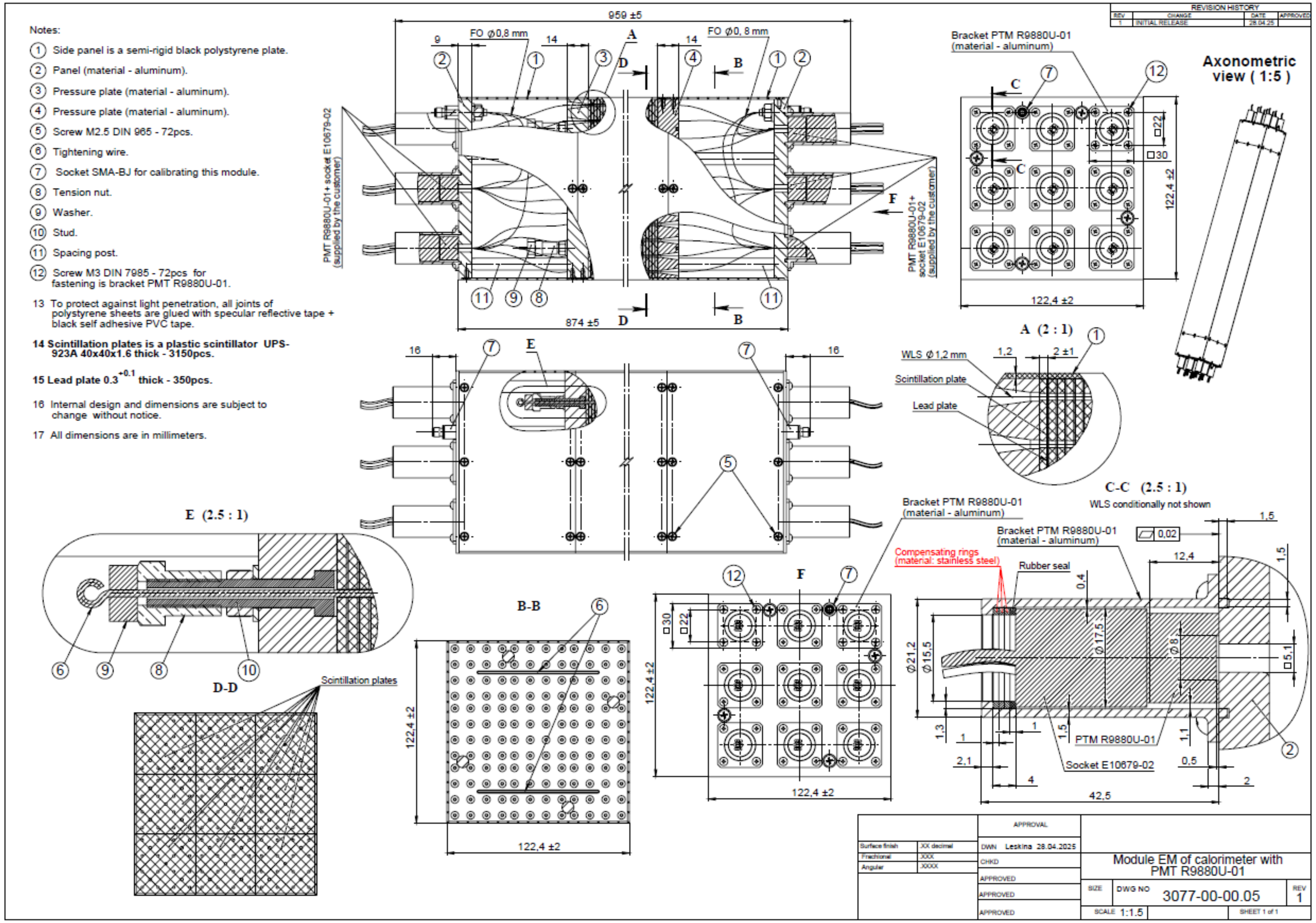
Single side readout

✓ 500 alternating scintillator+lead layers corresponding to 29 X_0 - WLS fibers BCF-92XL with 1.2mm diameter, mirrored at one side. Single side readout

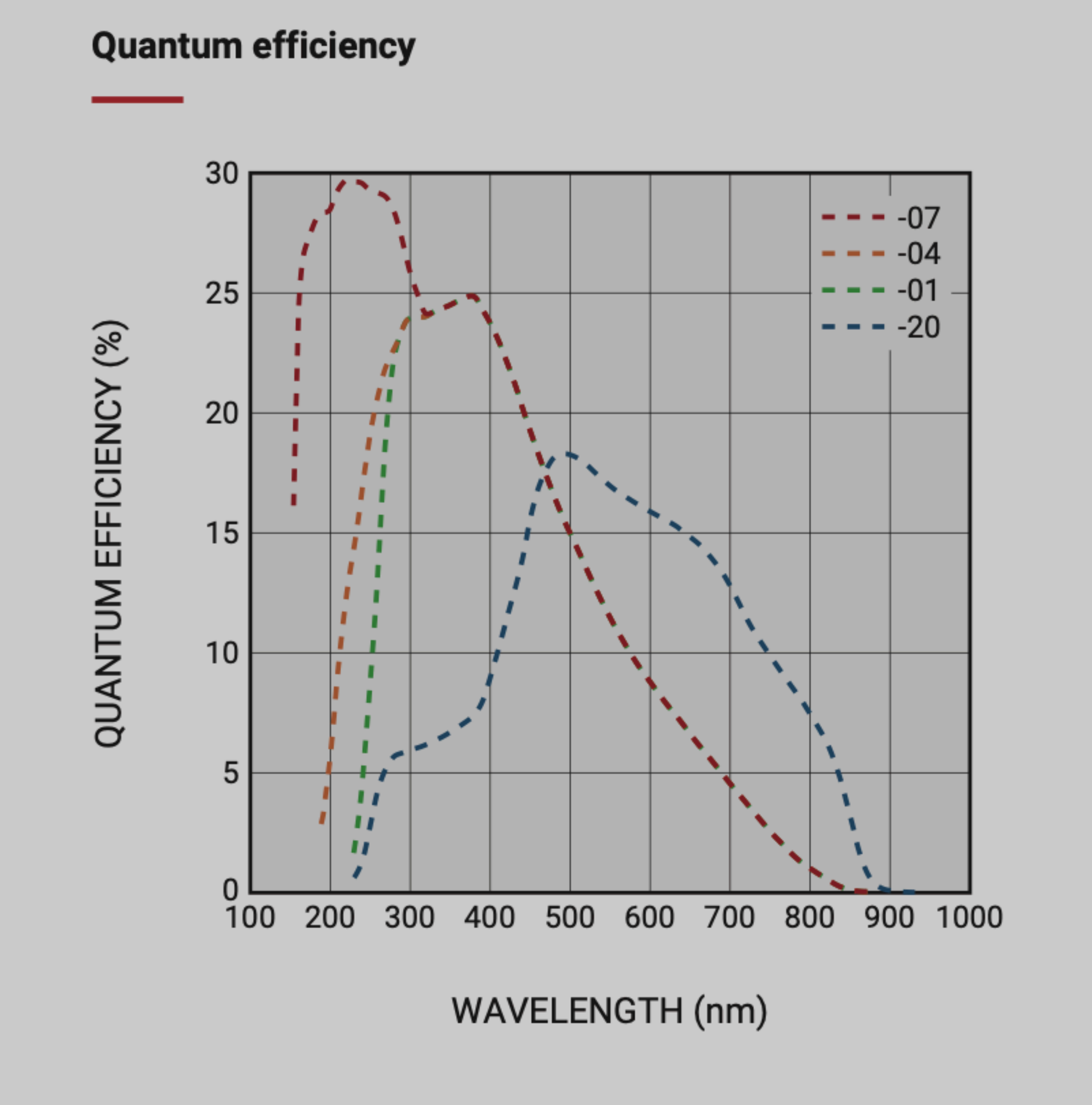
Shashlyk prototype construction

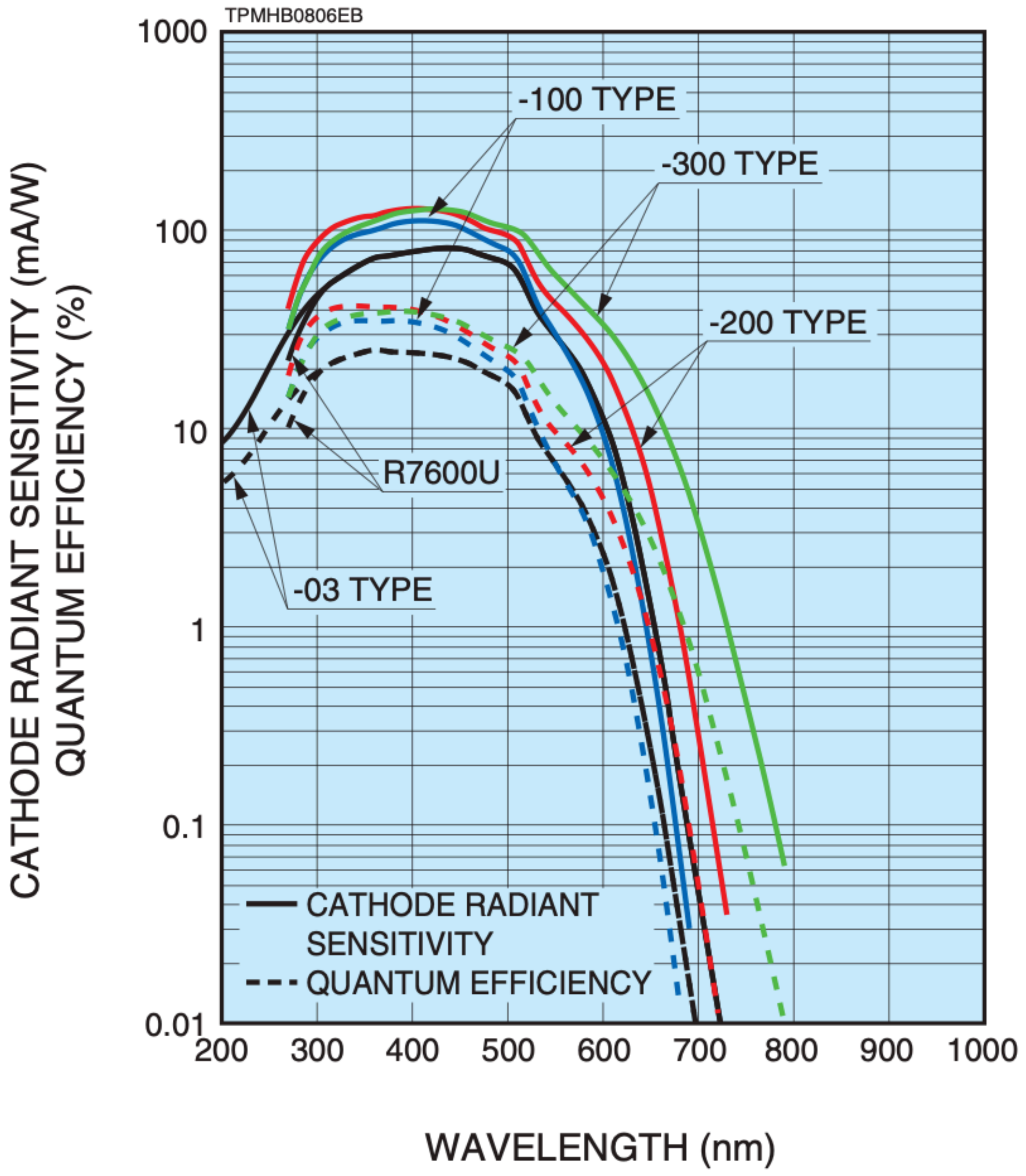
Double side readout

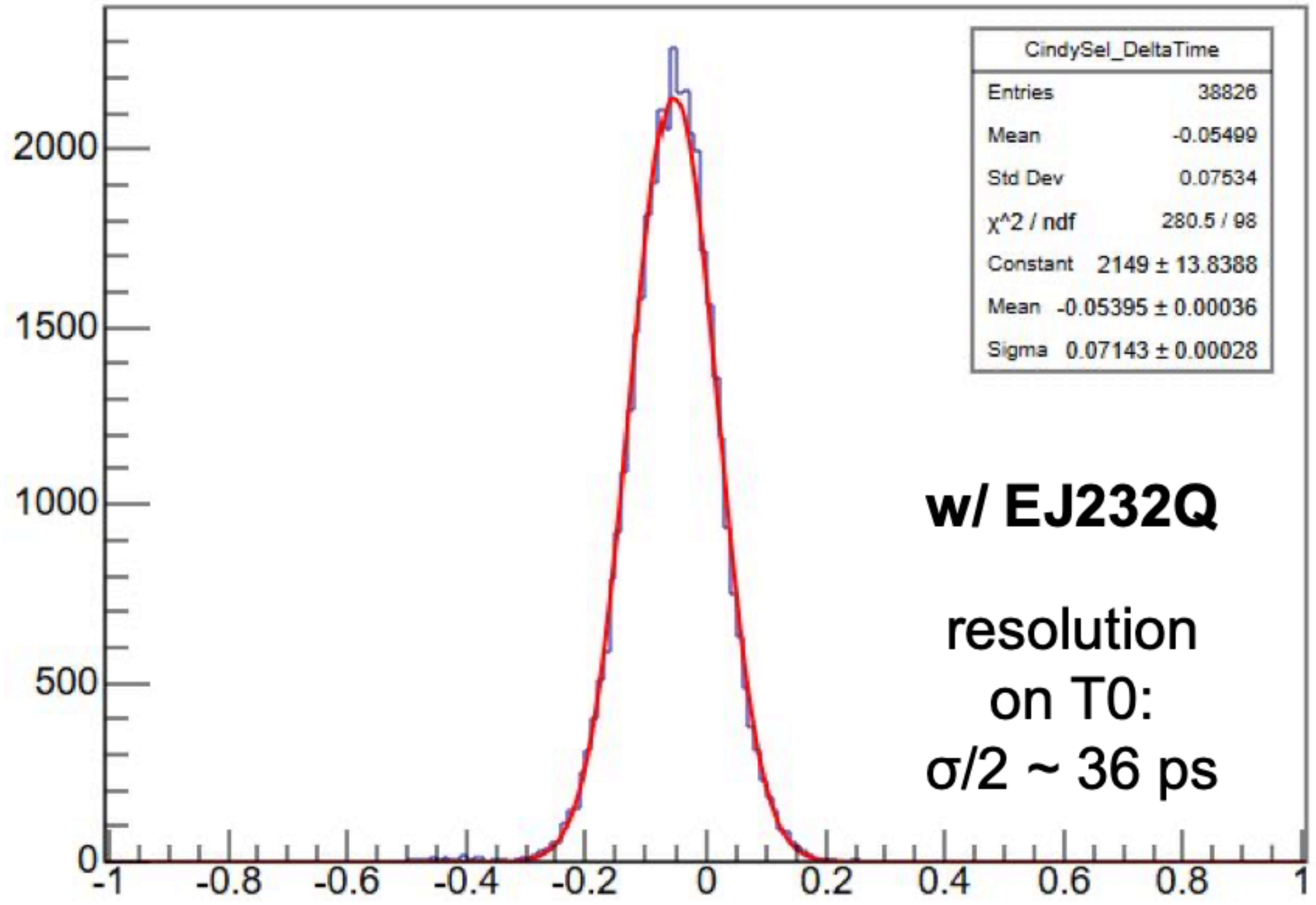
- ✓ 350 alternating scintillator+lead layers corresponding to 20 X_0 - WLS fibers from Kuraray YS-4 with 1.2mm diameter. Double side readout implemented



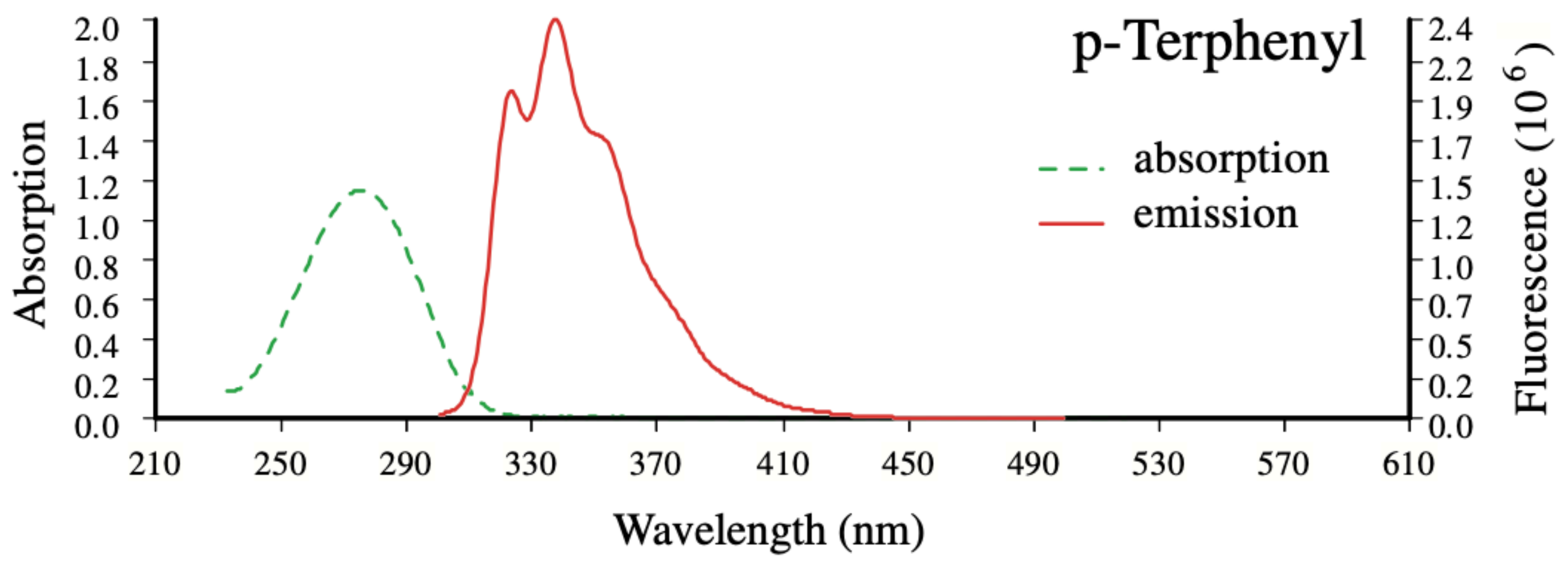
PMTs data sheet and Time reference detector

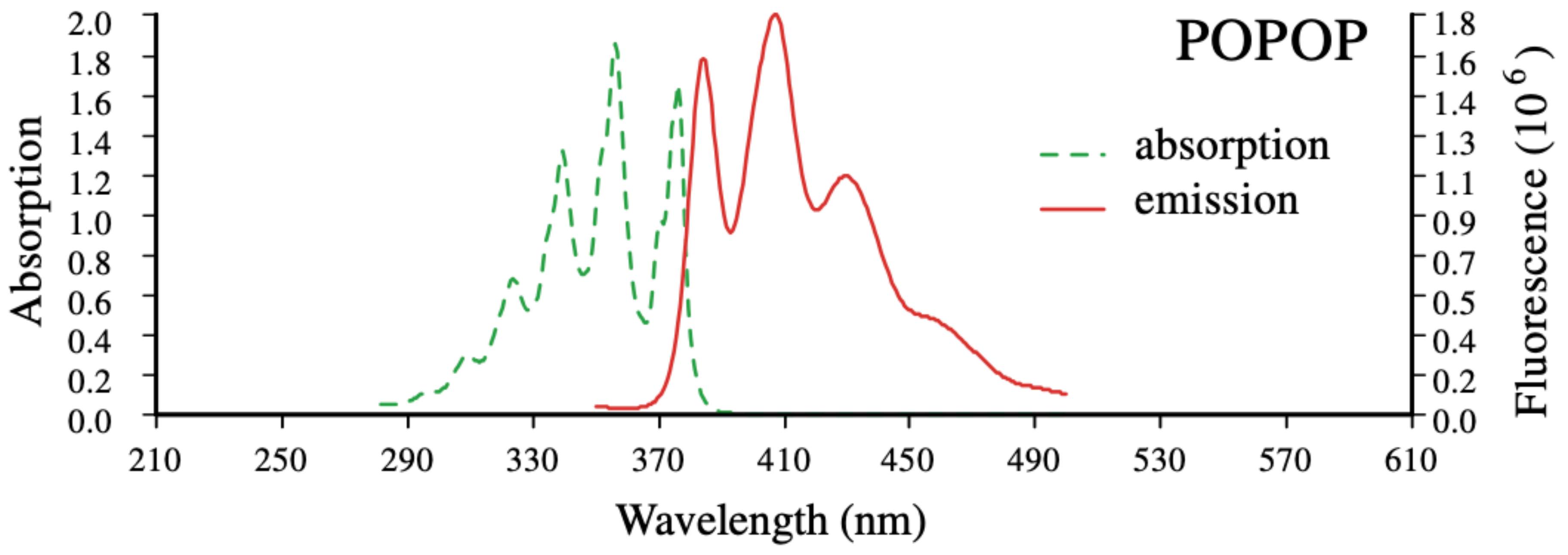




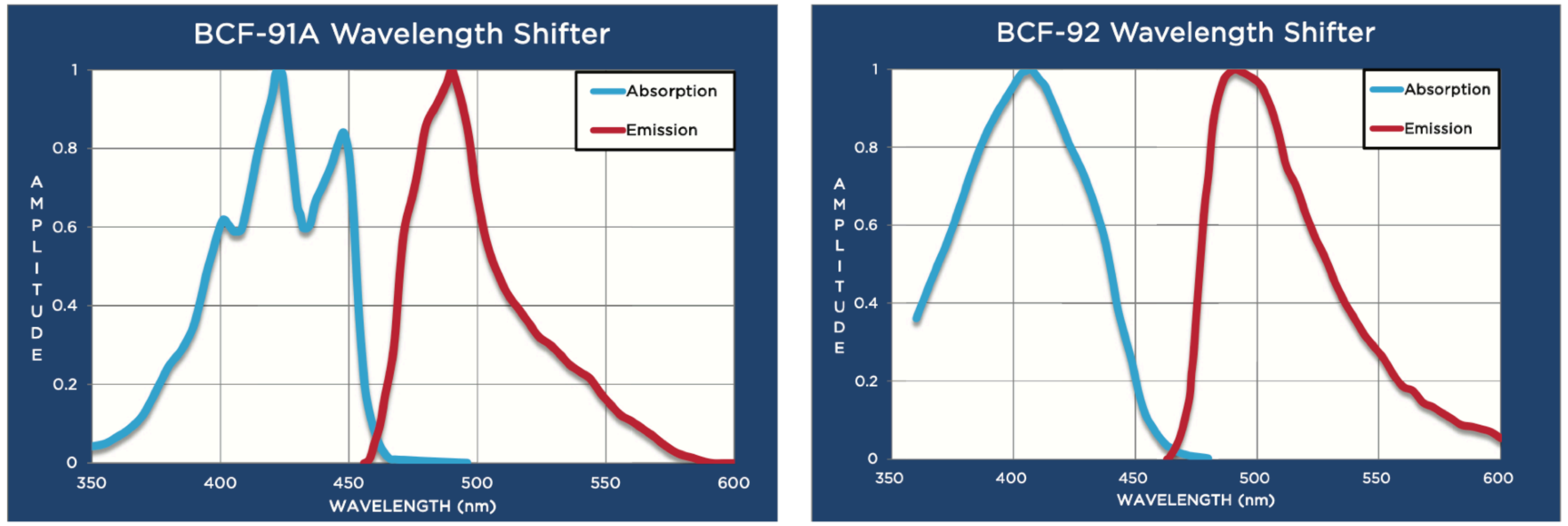


Scintillator and WLS optical properties

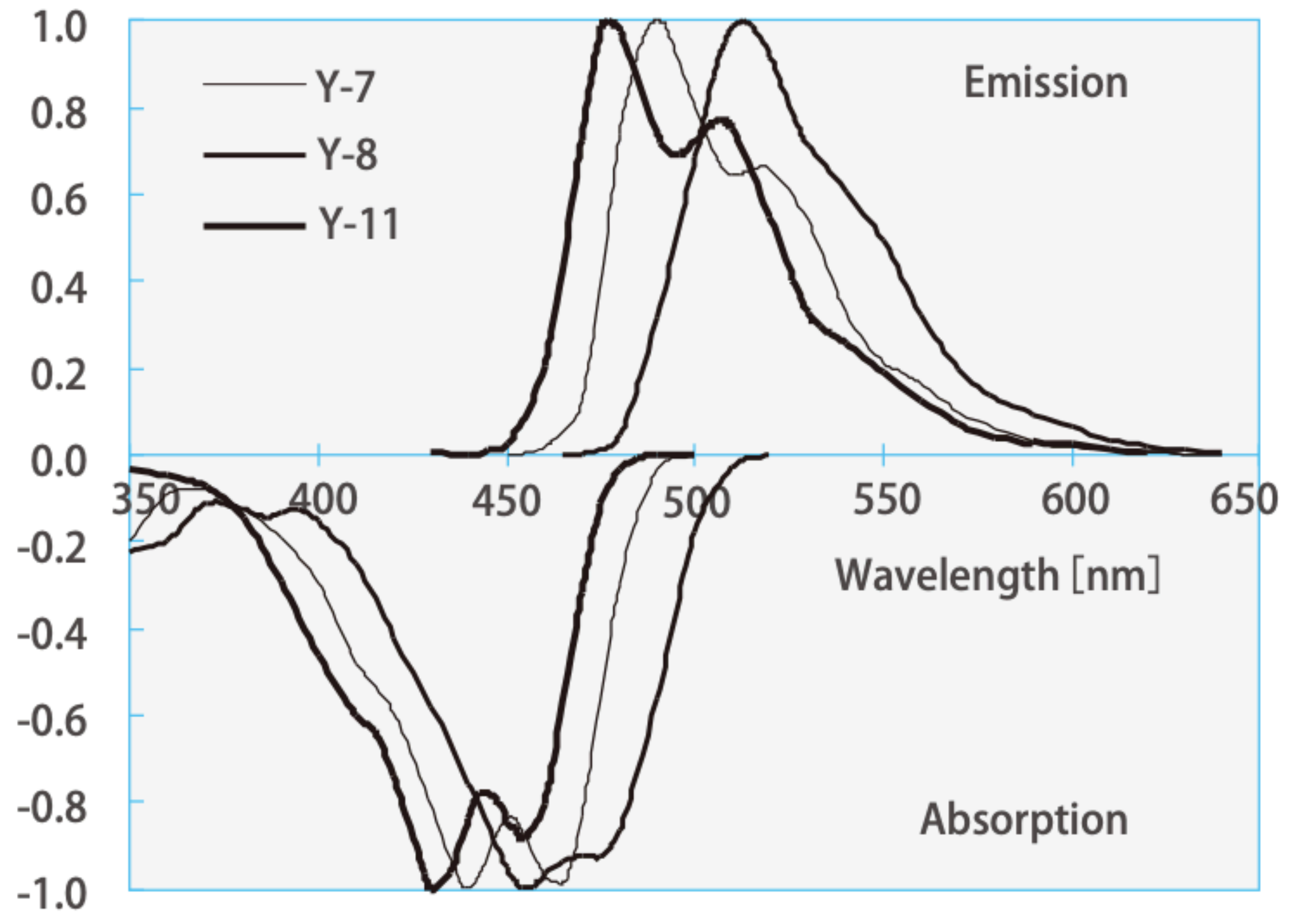




PTP emits light in the range 320-400 nm which is absorbed by POPOP which then re-emits in blue wavelength.



Y-7, Y-8, Y-11



Shashlyk prototype with single side readout

- Calibration run with muons to equalise the response of the 9 channels
- Cherenkov detector and LeadGlass used as PID detectors
- Only events in which the muon release energy in one module are selected
- A calibration factor is computed for every channel of the Shashlik as:

$$C_i = \frac{\sum_{i=1}^{9} Q_i/N}{Q_i}$$