Study of SiPMs for calorimetry applications in the DUNE Near Detector complex

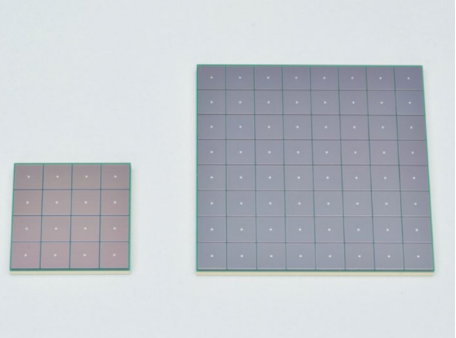
F. Alemanno [b], P. Bernardini [a,b], A. Corvaglia [b], G. De Matteis [a,b], L. Martina [a,b], A. Miccoli [b], M. Panareo [a,b],
M.P. Panetta [b], C. Pinto [a,b], A. Surdo [b]
(a) Dipartimento di Matematica e Fisica, Università del Salento, Italy
(b) Istituto Nazionale di Fisica Nucleare, Lecce, Italy

ABSTRACT

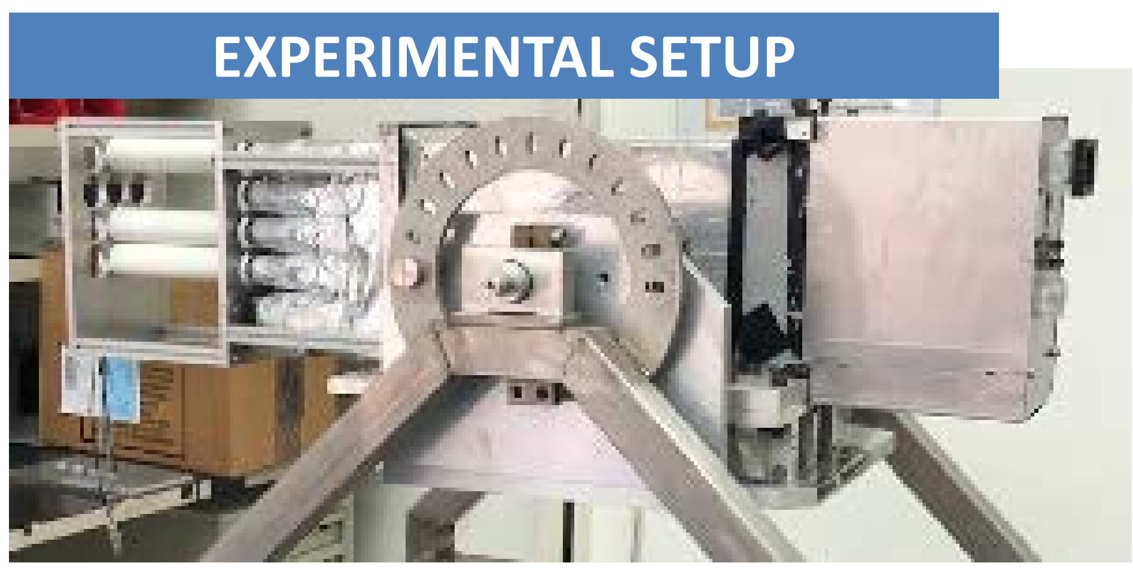
DUNE experiment at Fermi National Accelerator Laboratory is mainly devoted in study of neutrino mass ordering and CP symmetry violation in the leptonic sector. The experiment comprises three main components: a high-intensity neutrino source, a massive Far Detector situated 1.5km underground at the Sanford Underground Research Facility in South Dakota, about 1300km far from neutrino source, and a composite Near Detector installed just downstream of neutrino source. The KLOE experiment lead-scintillating fiber electromagnetic calorimeter is expected to be reused in the Near Detector (SAND). The study here presented aims to evaluate the possibility of replacing the Photomultiplier Tubes (PMT) used for reading the KLOE calorimeter with Silicon Photomultipliers (SiPM). To compare both readout approaches, signals induced by cosmic rays have been collected on one side of a block of the KLOE calorimeter by SiPM arrays, and on the opposite one by conventional PMTs. Efficiency, stability, and timing resolution of SiPMs have been studied and compared with similar PMTs performances

THE SILICON PHOTOMULTIPLIERS (SiPMs)

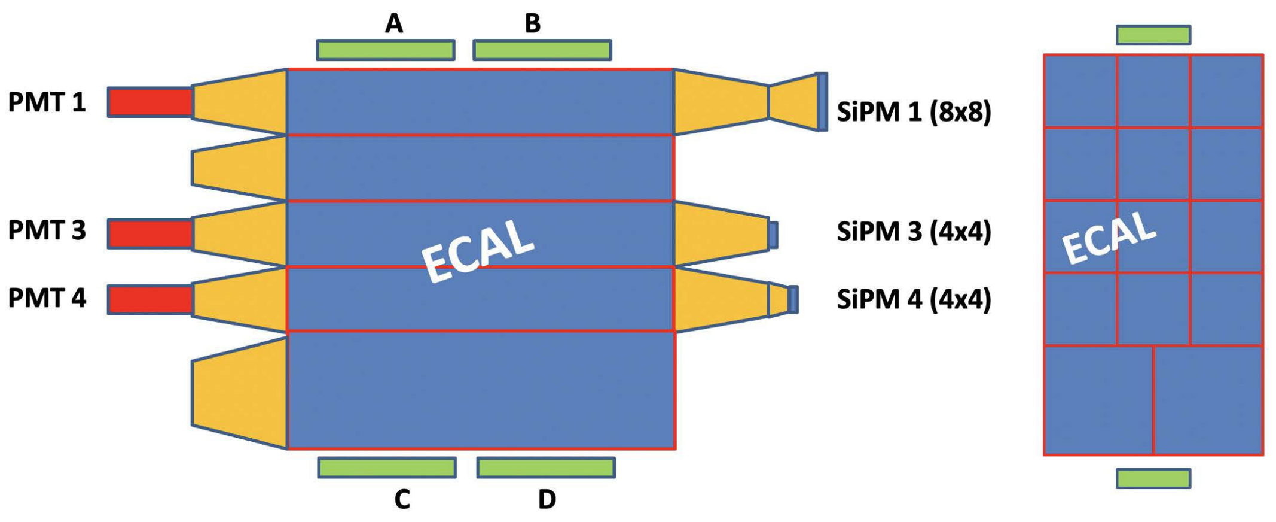
The SiPMs used in this test are the MPPC (Multi-Pixel Photon Counters) arrays of the Hamamatsu S13361-3050 series [1]. Both the available configurations (4 × 4 and 8 × 8 channels) were mounted, but only the performances of 16-channels arrays (SiPM 3 and 4 in the next schematic) are reported in this poster. The MPPC series is chosen since it achieves the maximum Photo-Detection Efficiency (PDE_{MAX}) close to the peak wavelength of the scintillating fibers (typically PDE_{MAX} = 40% at λ = 450 nm, ranging from ~30% to ~60% as a function of the overvoltage). Furthermore, the SiPM arrays are characterized by a large effective photosensitive area of 3 × 3 mm² for each channel, a 50 μm pixel size which ensures a wide dynamic range of photon counting, and a gain ≈ 10^6.

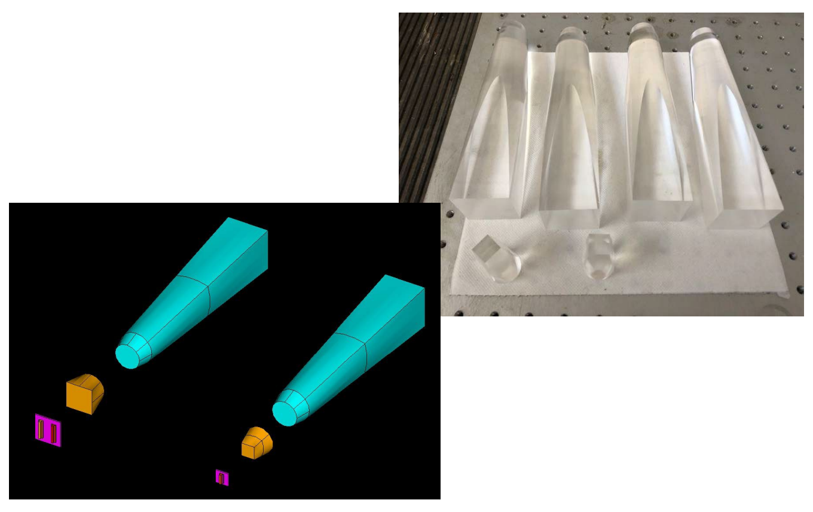


EXPERIMENTAL SETUP



The principal element (ECAL) of the experimental setup is a cut-out of the KLOE calorimeter. It is composed of a stack of thick grooved lead foils, alternating with layers of scintillating fibers (blue-green, type Po.Hi.Tech-0046) with the peak emission wavelength λ_{peak} ≈ 460 nm. The composite density results in 5 g/cm³.





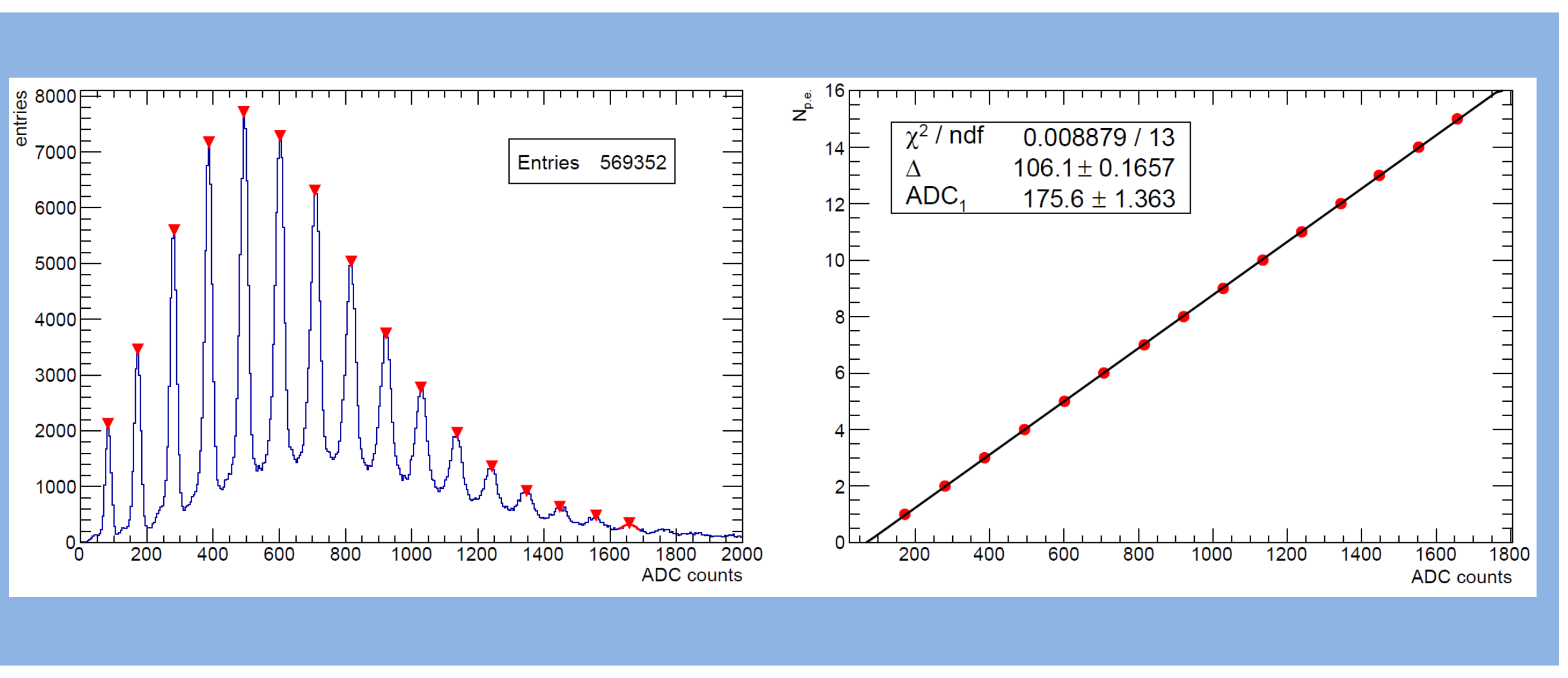
The upper part of the ECAL volume is segmented into 12 cells (section 4.4 × 4.4 cm², horizontal length 40.0 cm), while two larger cells (section 6.6 × 6.6 cm²) occupy the lower part. This results in a total ECAL thickness of ≈ 15 X_0 (≈ 2.7 X_0 for each smaller cell), considering a particle vertically crossing the calorimeter from top to bottom. Lucite light guides, similar to the KLOE ones, are glued at both the edges of the cells in the central column. SiPM 3 is directly coupled to the light guide (covered fraction ~ 34%). SiPM 3 is glued to the guide through a lucite adapter to fit the 4 × 4 array (area 170 mm²) in order to test the increase in the light collection. The SiPMs readout is performed with a desktop front-end unit, CAEN FERS-DT5202 [2], housing a Weeroc Citiroc-1A chips [3], which also hosts a SiPM power supply. SiPMs performances are compared with those of the Hamamatsu R5946 1.5' mesh photomultiplier, already used in the KLOE calorimeter. The quantum efficiency of this PMT is 23% at λ = 390 nm.

SiPM CHARACTERIZATION AND LIGHT YIELD

SiPMs channels are individually calibrated by regulating voltage bias, to get the same fixed rate (≈ 3.5 kHz) for each element of the array. Calibration works properly for all channels of tested SiPMs, indeed the peaks of the photoelectron spectrum from single channels of SiPM 3 are placed in the same position (same ADC value) for all of them and we do not observe any broadening of the peaks when multiple channels are plotted together. From the ADC values of the peaks, it is possible to infer the relationship to convert the ADC signal in number of photoelectrons (p.e.), expressed as follows

$$N_{p.e.} = 1 + \frac{ADC - ADC_1}{\Delta}$$

where ADC_1 is the ADC value for one photon (first peak after the pedestal) and Δ is the ADC-distance between adjacent peaks. The same measurement was performed for SiPM 4, showing that the light collection is ~ 40% higher for the coupling with the light guide through the adapter.



SiPM EFFICIENCY

Two scintillators placed above (A and B green elements in the experimental setup box) and two placed below (C and D green elements) the calorimeter, overlapping with the surface of its central modules, each with a surface of ~ 2 × 7.5 cm², provides an external trigger. When a cosmic muon activates this trigger, it is expected to pass through the stack of ECAL modules, generating photons in the fibers that can be detected by SiPMs and PMTs both. The trigger logic consists of a fired scintillator on the top (A or B) and a fired scintillator on the bottom (C or D) in a time window of 30 ns. The measured rate results in 2.6 mHz, as expected from cosmic muon flux, taking into account the narrow solid angle due to the trigger geometry. PMT signals are counted by a NIM Scaler module after they are shaped with a threshold of 40 mV, SiPM signals are processed by a FPGA internal to the FERS-DT5202 board. In order to exploit the full SiPM sensitivity a quite low threshold is set (210 a.u.) in such a way to collect also events with only 1 photon overall the SiPM array. When the validation from the external trigger is satisfied, the counts are acquired with the Scaler module and the digital full information on the SiPM signals is collected by the data acquisition program running on a desktop personal computer. As an effect of the DAQ board dead time due to the analog-to-digital conversion, events collected by the acquisition program (N_{DAQ}) are typically fewer than the shaped signals (k_{SiPM}) sent directly to the Scaler module. The sample collected by the DAQ is analyzed to identify and remove events due to random coincidence of noise in the external trigger and noise in the SiPM and real particles that do not deposit enough energy in the scintillating fibers. To remove these events a cut to the sum of the ADC of all channels has been applied. Therefore, the SiPM efficiency calculated from the scaler counts (ε) must be reduced accepting only the fraction of SiPM events surviving the latter cut (ε'). The corrected SiPM efficiency is expressed as:

$$E_{SiPM} = \varepsilon\,\varepsilon' = \frac{k_{SiPM}}{N_{SiPM}}\,\frac{k_{DAQ}}{N_{DAQ}}$$

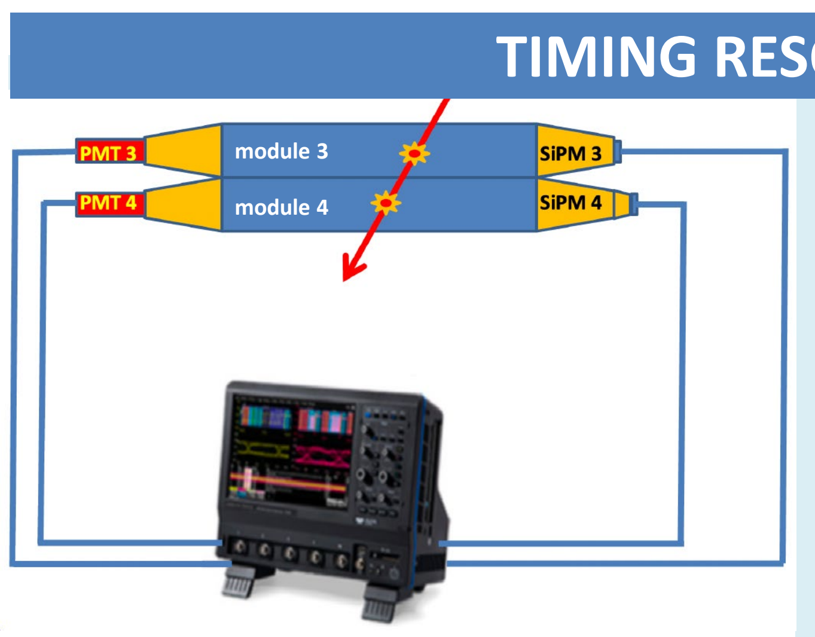
where k_{SiPM} is the number of SiPM events on the scaler, N_{SiPM} is the number of external triggers, k_{DAQ} and N_{DAQ} are respectively the number of selected events and the total number of events in the sample collected by the DAQ. On the other side, the PMT efficiency is calculated simply from the scaler counts:

$$E_{PMT} = \frac{k_{PMT}}{N_{PMT}}$$

where the meaning of k_{PMT} and N_{PMT} is obvious. As shown in the Table the efficiencies of PMTs and SiPMs are very close, with the PMT efficiencies being slightly higher than the SiPM ones.

PMT	k_{PMT}	N_{PMT}			E_{PMT} (%)
3	7010	7615			$92.06^{+0.14}_{-0.15}$
4	6739	7392			$91.17^{+0.15}_{-0.16}$
SiPM	k_{SiPM}	N_{SiPM}	k_{DAQ}	N_{DAQ}	E_{SiPM} (%)
3	4324	4552	2999	3141	$90.70^{+0.22}_{-0.23}$
4	4820	4982	2680	2855	$90.82^{+0.23}_{-0.25}$

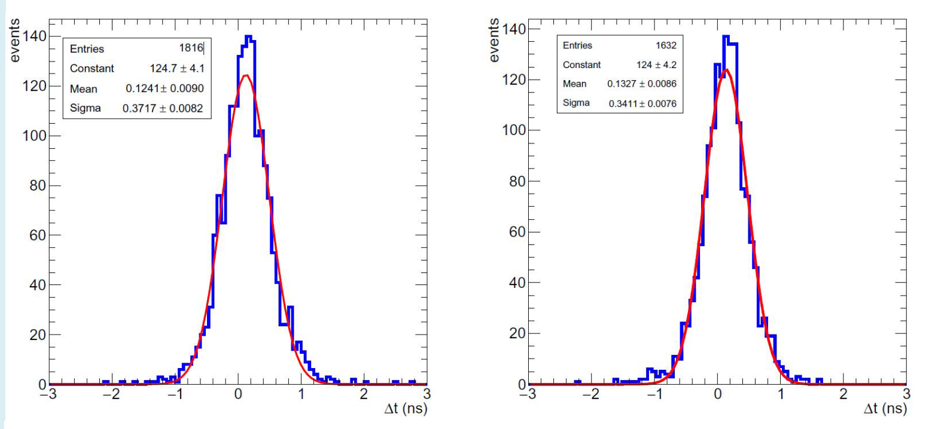
TIMING RESOLUTION



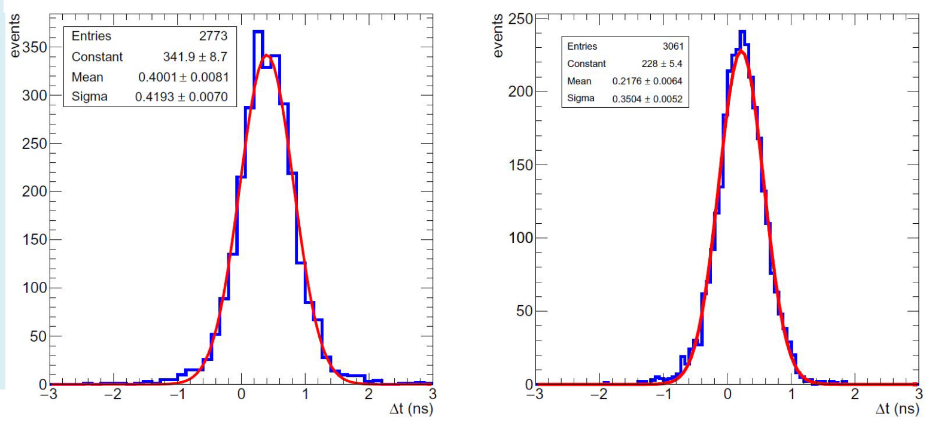
	$\sigma_{\Delta t}$ (ps)	σ_t (ps)
SiPM 3 α - β	372±8	263±6
SiPM 4 α - β	341±8	241±6
SiPM 3α - SiPM 4α	419±7	269±5
PMT 3 - PMT 4	350±5	217±4

Timing resolution of the photodetectors has been measured using the rising time at 50% of the signal amplitude. The experimental setup is shown on left, where the ECAL modules (modules 3 and 4) are coupled to PMTs on one side and SiPMs on the opposite side, both connected to an oscilloscope (Teledyne LeCroy HDO8108A Oscilloscope, 40 GHz sampling rate) without amplification. In the case of PMTs, the signals generated in coincidence by cosmic rays acquired from modules 3 and 4 are compared in order to measure Δt. For SiPMs, the measurement is carried out considering either two channels from the same array (SiPM 3 α and SiPM 3 β or SiPM 4 α and SiPM 4 β, with α and β indicating a specific channel) or one channel per array connected to modules 3 and 4; a custom passive electronic board is used to power the SiPMs and to pick up the signals. A typical signal amplitude is of several hundreds of mV for PMT and several tens of mV for SiPM. For two channels of the same SiPM array, since each SiPM in the array gives an independent signal readout, the intrinsic timing resolution (σ_t) of the single SiPM channel is $\sigma_{\Delta t}/\sqrt{2}$. In the case of detectors coupled with different ECAL modules the $\sigma_{\Delta t}$ of these distributions is affected by the additional jitter due to the various particle paths (geometrical jitter). The intrinsic timing resolution is estimated by simulating the experimental setup and a muon flux proportional to $\cos 2\theta$, with θ being the zenith angle [4]. The estimation consists of looking for the intrinsic timing resolution which reproduces the measured $\sigma_{\Delta t}$ when combined with the geometrical jitter. All the measurements of the timing resolution are summarized in the Table.

Time difference for two channels of SiPM 3 (left) and SiPM 4 (right).



Left: time difference for SiPM 3 and SiPM 4. Right: time difference for PMT 3 and PMT 4.



CONCLUSIONS

A piece of the KLOE calorimeter has been equipped with SiPMs and PMTs to compare their performances for a potential application in the Near Detector of the future DUNE experiment. The PMT coupling was optimized in the KLOE calorimeter, and it was kept unchanged for this study. Nevertheless, various optical couplings have been tested for adapting the SiPMs to the KLOE light guides and it was verified that the partial coverage of the light guide does not prevent reaching a proper readout of the signal. Efficiency and timing resolution have been measured and compared for both detectors. It was found that the SiPM noise cannot be neglected in the efficiency estimate. Specifically, the noise rejection involves a significant reduction of the possible SiPM efficiency making it lower by a few percent with respect to the PMT ones. For the timing resolution, it was observed that PMTs reach a value slightly higher than 200 ps for the scintillation signal, while SiPMs exhibit a resolution around 240 ps. Even if the difference is small, PMTs seem to perform better. Therefore, the difficulties in coupling SiPMs with ECAL without deep mechanical changes, the lack of improvement, the cost, and the necessary commissioning time advise against the substitution of 4880 available and tested PMTs with new SiPMs in the KLOE calorimeter to be reused in DUNE. Nonetheless, the results from this study do not exclude the possible use of SiPMs for other calorimetric applications.

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email: marco.panareo@le.infn.it