Implementation of a small PMT in the simulation of the Surface Detector of the Pierre Auger Observatory

C. Bleve [1,2], G. Cataldi[2], M. R. Coluccia[1,2], P. Creti[2], S. D'Amico[2,3] I. De Mitri[1,2], G. Marsella[1,2], D. Martello[1,2], L.Perrone[1,2], V. Scherini[1,2]

[1] Dipartimento di Matematica e Fisica "Ennio De Giorgi", Università del Salento, Italy
[2] Istituto Nazionale di Fisica Nucleare sez. di Lecce, Italy
[3] Dipartimento di Ingegneria dell'Innovazione Università del Salento, Italy

1. Abstract

We discuss the implementation of a small area PMT (SPMT) in the simulation of the surface detector of the Pierre Auger Observatory. The motivation for this study is to extend the dynamic range of the surface detector, reducing the impact of saturation for high-energy events with shower axis close to a station. This work complements the laboratory test and on-field measurements carried by the site of the Pierre Auger Observatory. Several software modules have been modified and/or newly developed, including a dedicated Example Application. The benefit of this design is studied in detail and its performance is quantified using a full simulation and reconstruction chain.

2. Introduction

Approximately 40% of cosmic ray showers with energy above 30 EeV induce saturation in the low-gain channel of PMTs in the SD detector closest to the shower axis. This may limit the reconstruction and the potential of physics analyses at the highest energies.

The idea of adding a small PMT for measuring large signals thus significantly extending the current dynamic range of the SD came from the Torino group at the beginning of the last year [1] and it is now part of the SDE upgrade proposal. The goal of this note is to describe in details how the implementation of the small area PMT in the Simulation-Reconstruction framework has been performed and to show the benefits thus obtained from the point of view of reconstruction.

3. Simulation design

The implementation of the small area PMT has been developed in the software framework of the Pierre Auger Collaboration. All the new and the modified modules have been designed to be fully compatible with the software relative to the other upgrade proposals. Adding a new PMT with different properties compared to the standard ones required several changes. The small area PMT used for our simulations is the Hamamatsu "R6095-100" [2].

Logical and physical volumes for SPMT are implemented following the Geant4 scheme. A sketch of the SPMT layout with relative settings is shown in Fig. 1. We used a similar layer structure as for the standard PMT, replacing the ellipsoid with a cylinder and sizing the volumes according to data sheet [2]. The current set-up has the SPMT face just inside the tank volume.

In the standard procedure, to speed up the simulation, only a fraction of Cherenkov photons are fully propagated through the SD station by Geant4, based on the product of the quantum and collection efficiency of PMTs. As this product is always larger for the SPMT, we used that as conservative reference for all PMTs. A correction is applied afterwards to reproduce the response of standard PMTs.

Aimed at increasing the overlapping signal dynamic range, the SPMT gain was set to 1.5 times the gain of the standard PMT at the anode. We used the new electronics at 120 MHz and 12 bits resolution.

In Fig. 2 the event display of a simulated proton at 10 EeV is shown. The photoelectron signal is plotted for the standard PMTs (upper panels 1-3) and SPMT (upper panel 4).

4. Mass Production

CORSIKA proton showers with energy in 3 bins of Log(energy) 18.5-19, 19.-19.5, 19.5-20 eV and zenith angle in the range $0° - 65°$ processed with the modified Simulation-Reconstruction chain (1000 showers for each energy bin and resampled twice for a total of about 5500 showers). Shower cores have been gener-

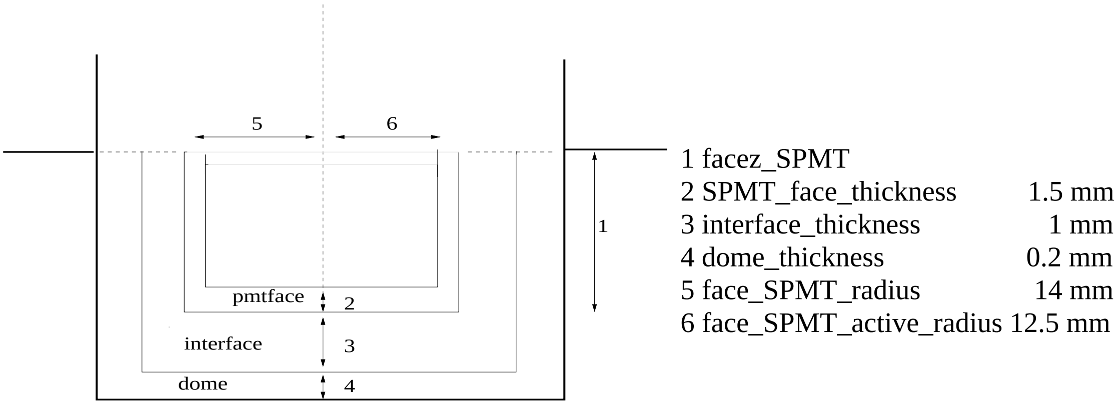
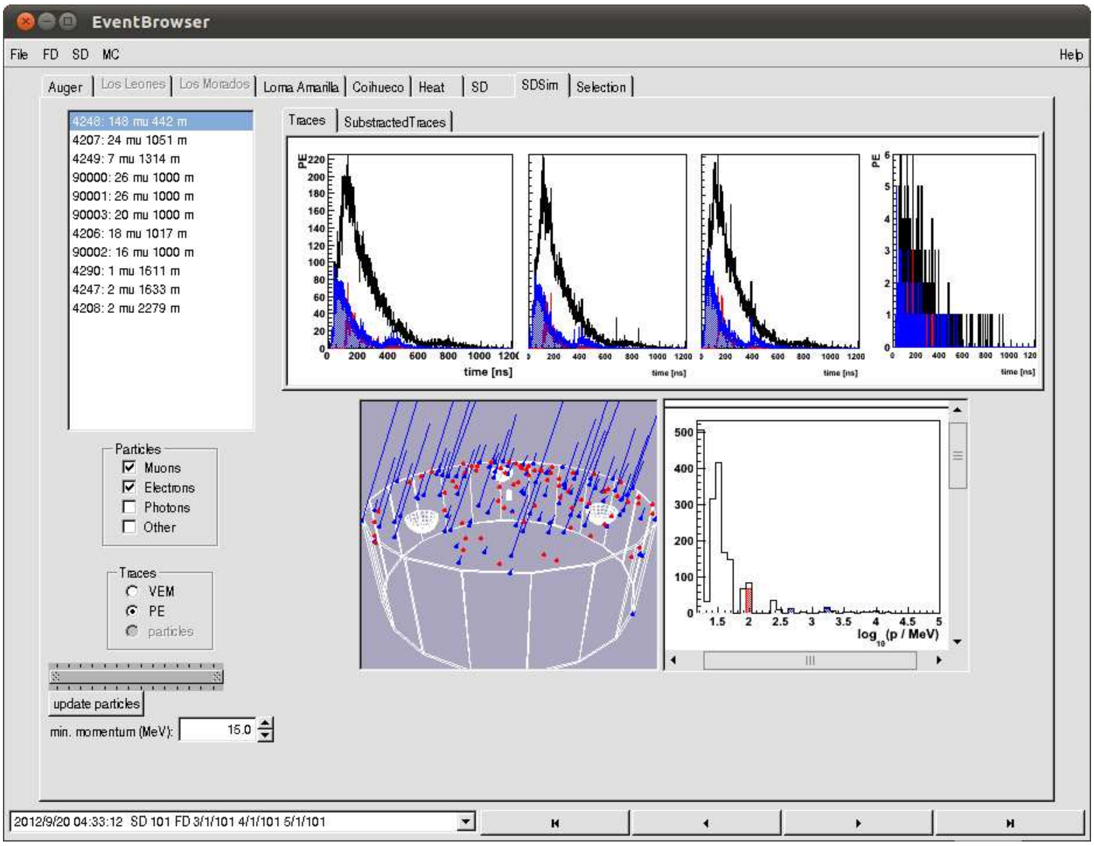


Figure 1. Sketch of the SPMT layout with the corresponding geometry settings.



4248: 148 mu 442 m
4207: 24 mu 1051 m
4249: 7 mu 1314 m
90000: 26 mu 1000 m
90001: 26 mu 1000 m
90003: 20 mu 1000 m
4206: 18 mu 1017 m
90002: 16 mu 1000 m
4290: 1 mu 1611 m
4247: 2 mu 1633 m
4208: 2 mu 2279 m

Particles
☑ Muons
☑ Electrons
☐ Photons
☐ Other

Traces
○ VEM
● PE
○ particles

min. momentum (MeV): 15.0

2012/9/20 04:33:12 SD 101 FD 3/1/101 4/1/101 5/1/101

Figure 2. Event Display of photoelectrons. Proton, 10 EeV, zenith = 32°, not saturated station at 442 m from axis. The fourth panel on the right shows the photoelectron signal in the SPMT.

ated on an ideal array composed by modified stations equipped with a small PMT placed at the side LED window. For comparison purposes, a run with the standard LDF reconstruction using the same detector and physics seeds was also performed.

5. Calibration: extension of the signal dynamic range

We selected simulated showers with stations having an average raw signal larger than 200 ADC counts at the low-gain channel.

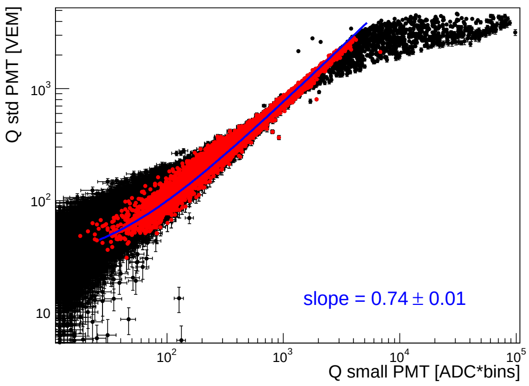


Figure 3. VEM Calibration by using simulated events: the average signal in the standard PMTs (VEM) is plotted versus the charge in the small PMT (ADC*bins). The slope gives the value for VEM-ization of the small PMT signal for 120 MHz 12 bits electronics.

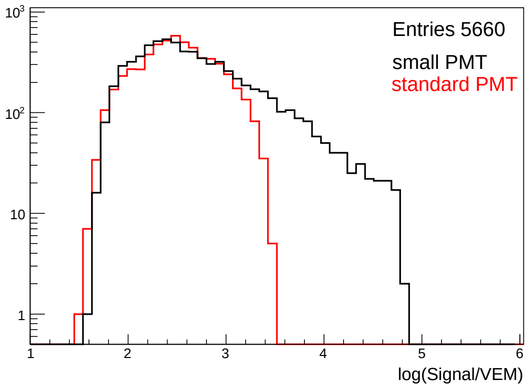


Figure 4. Distribution of the logarithm of the stations signal for small PMT (black histogram) and standard PMTs (red histogram).

In Fig. 3 the average signal in the standard PMTs, after the standard VEM conversion, is plotted as a function of the integrated charge in the SPMT for all the events (black dots) and for selected events (red dots), with signal larger than 200 ADC counts and no saturation in the low-gain channel. The obtained slope gives the value for VEM-ization of the small PMT response, for 120 MHz 12 bits electronics.

In Fig. 4 the distribution of the logarithm of the signal is plotted for small PMT (black histogram) and standard PMTs (red histogram). The addition of the SPMT will allow us to measure signals of more than one order or magnitude higher than the standard PMTs.

In Fig. 5 the profile of saturation probability (fraction of saturated events over total events) for the standard PMT (red dots) and small PMT (black dots) is shown. The fraction of saturated events for the standard PMTs is around 40% above 50 EeV. SPMT saturation is negligible all over the energy range and it only occurs in stations very close to the shower axis.

6. Impact on SD Reconstruction

The reconstruction of the lateral distribution function (LDF) has been modified in order to handle the fit using the SPMT signal. The impact of extending the SD station dynamic range has been quantified by comparing the outcome of the modified SdReconstruction chain with the standard one. By setting the same physics and detector seeds, a one-to-one comparison between reconstructed events is possible.

We checked for benefits of having the SPMT in the reconstruction of shower geometry such as for the axis space angle (MC versus reconstructed), and no sizable improvement was found at this level, as the reconstruction of the direction is not expected to be significantly affected by saturation.

Instead a better reconstruction of the distance of closest station has been found for the SPMT reconstruction. In Fig. 6 the LDF residual of the closest station in units of sigma is plotted as a function of distance of closest station for the standard PMT (red dots) and small PMT (black dots). As saturated stations enter the LDF fit, the performance of the reconstruction rapidly degrades (5 σ at $\sim$ 350 m from the axis) with the standard PMTs. On the other hand the SPMT reconstruction works fine up to very close to the shower axis.

In Fig. 7 the relative difference in derived signal at 1000 m for the small PMT reconstruction and standard PMT reconstruction, (S_{1000}^{small} - $S_{1000}^{standard}$)/ S_{1000}^{small}, gray dots) is plotted for saturated events along with its the profile with RMS of the distribution. The average difference in S1000 between the reconstructions is about 5% for the highest signals, (underestimation of S1000 if no smallPMT is implemented). For individual events larger differences, up to 20%, may occur.

In Fig. 8 we show the display of a saturated event induced by a proton at 2.5 × 10^{19}eV. In the top panel the event reconstruction now performed with the SPMT is shown. In the bot-

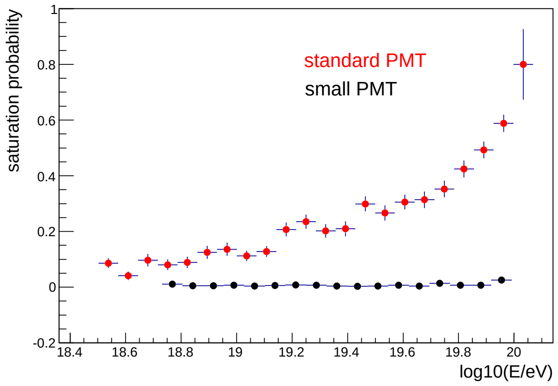


Figure 5. Profile of saturation probability (fraction of saturated events over total events) for the standard PMT (red dots) and small PMT (black dots).

tom panel the truncated VEM traces in the 3 standard channels and the full trace measured by the smallPMT (right) are plotted. The signal recorded in the closest station is recovered by the smallPMT measurement (one order of magnitude from about 3500 to about 43500).

7. Conclusions

We implemented the simulation of a small area PMT in the software framework of the Pierre Auger Observatory. This would allow us to extend the dynamic range of the measured signals by more than one order of magnitude.

By using a Monte Carlo production we evaluated the impact of the SPMT on the SD reconstruction. We showed that, adopting this design, the fraction of saturated events (so far 40% at 50 EeV) would be negligible up to the highest energies. This is a benefit for all analyses, and in particular for those requiring non-saturated stations within 600-700 m from the axis, such as those relying on the application of shower universality.

Moreover, as expected, we found that having the SPMT would result in a better description of the LDF close to the axis. On average we observed a 5% effect on S1000 for the highest signals when using the SPMT reconstruction with respect to the standard one.

This is the status with the current SD reconstruction strategy. With a reliable measurement of the signal close to the axis, as provided by the SPMT, one could think of refining the reconstruction procedure, for instance by having β as a free parameter in the LDF fit. This is relevant in particular for composition studies and photon search at the highest energies. We believe this is worth being investigated in further detail.

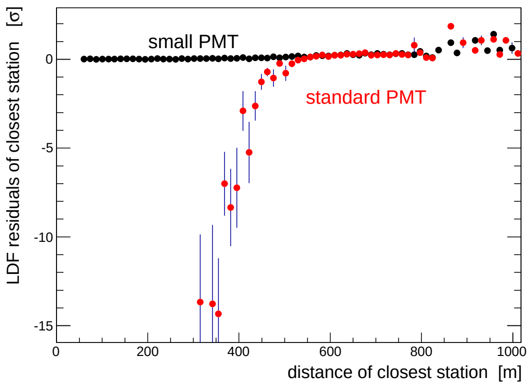


Figure 6. Profile of LDF residuals of closest station as a function of distance of closest station for the standard PMT (red dots) and small PMT (black dots).

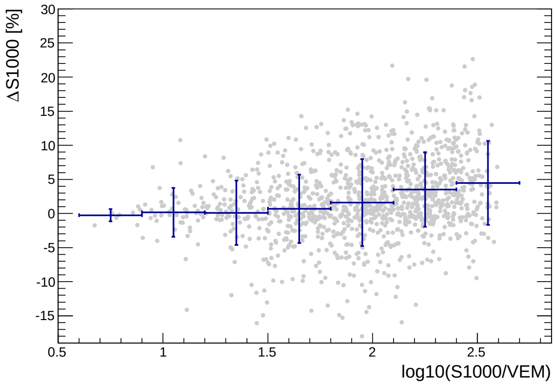
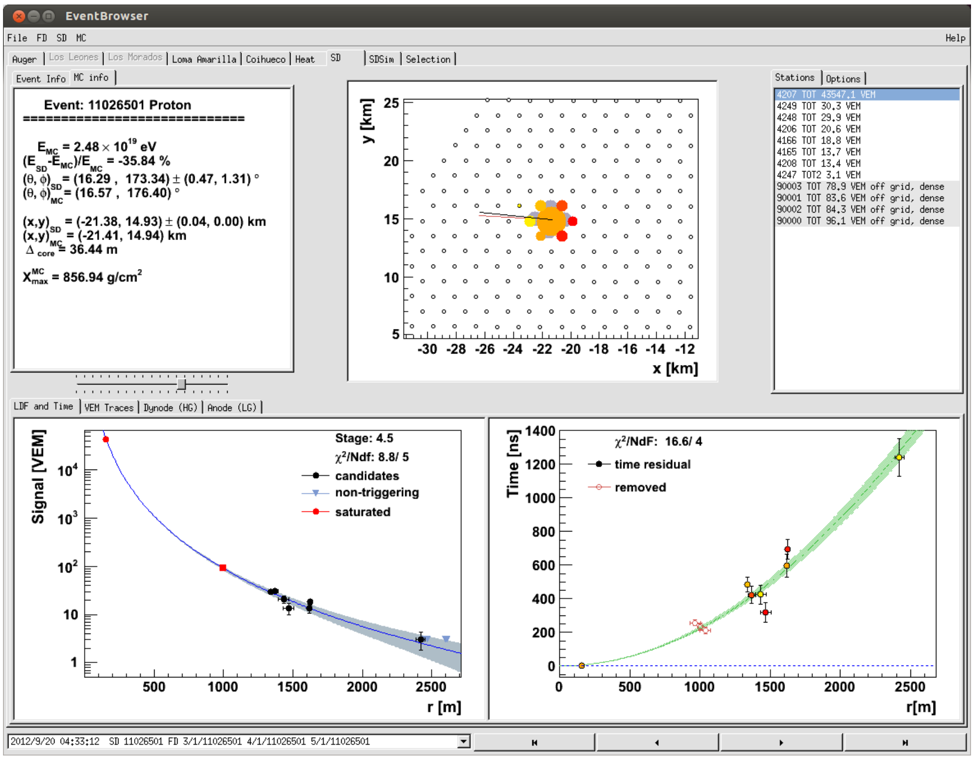


Figure 7. Relative difference in the derived signal at 1000 m for the small PMT reconstruction and standard PMT reconstruction ((S_{1000}smallrec - S_{1000}stdrec)/ S_{1000}smallrec, gray dots) along with the profile.

REFERENCES

1. M. Aglietta et al., GAP2013-021, “Small PMT – A proposal to extend the dynamic range of the Auger Surface Detector for operations beyond 2015”
2. Hamamatsu PMT Specifications for R6095 and R6095-100, `www.hamamatsu.com`



Event: 11026501 Proton

$E_{MC} = 2.48 \times 10^{19}$ eV

$(E_{SD}-E_{MC})/E_{MC}$ = -35.84 %

$(\theta, \phi)_{SD}$ = (16.29 , 173.34) ± (0.47, 1.31) °

$(\theta, \phi)_{MC}$ = (16.57 , 176.40) °

$(x,y)_{SD}$ = (-21.38, 14.93) ± (0.04, 0.00) km

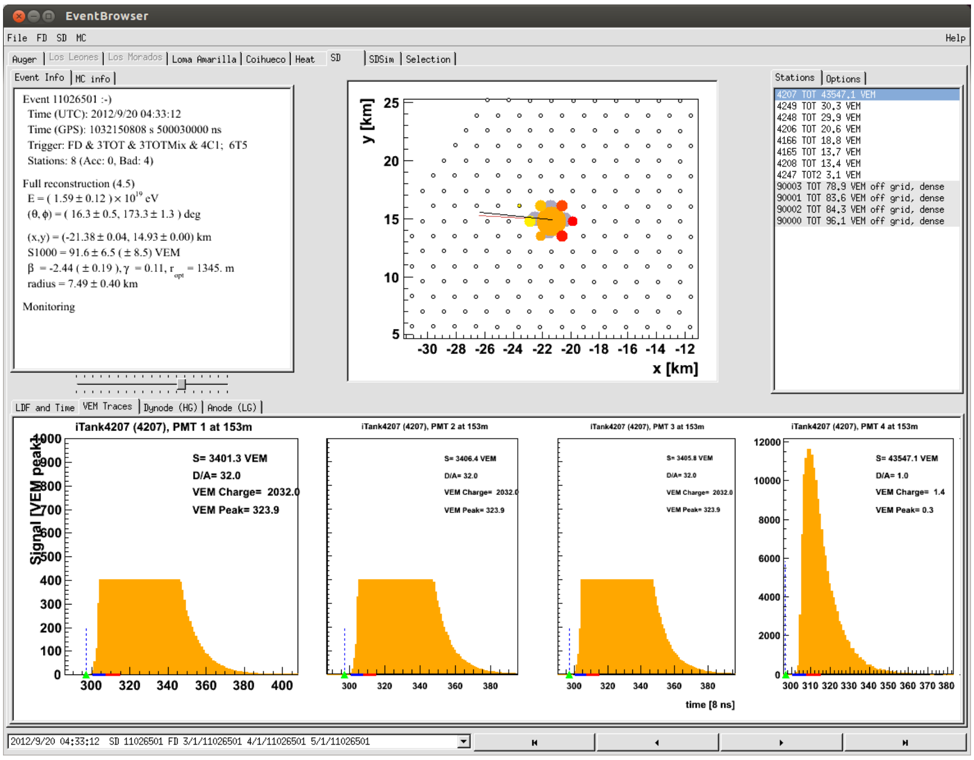
$(x,y)_{MC}$ = (-21.41, 14.94) km

Δ_{core} = 36.44 m

X^{MC}_{max} = 856.94 g/cm^2

```
4207 TOT 43547.1 VEM
4249 TOT 30.3 VEM
4248 TOT 29.9 VEM
4206 TOT 20.6 VEM
4166 TOT 18.8 VEM
4165 TOT 13.7 VEM
4208 TOT 13.4 VEM
4247 TOT2 3.1 VEM
90003 TOT 78.9 VEM off grid, dense
90001 TOT 83.6 VEM off grid, dense
90002 TOT 84.3 VEM off grid, dense
90000 TOT 96.1 VEM off grid, dense
```

```
2012/9/20 04:33:12  SD 11026501 FD 3/1/11026501 4/1/11026501 5/1/11026501
```



Event 11026501 :-)
Time (UTC): 2012/9/20 04:33:12
Time (GPS): 1032150808 s 500030000 ns
Trigger: FD & 3TOT & 3TOTMix & 4C1; 6T5
Stations: 8 (Acc: 0, Bad: 4)

Full reconstruction (4.5)
E = (1.59 ± 0.12) × 10^{19} eV
(θ, ϕ) = (16.3 ± 0.5, 173.3 ± 1.3) deg

(x,y) = (-21.38 ± 0.04, 14.93 ± 0.00) km
S1000 = 91.6 ± 6.5 (± 8.5) VEM
β = -2.44 (± 0.19), γ = 0.11, r_{opt} = 1345. m
radius = 7.49 ± 0.40 km

Monitoring

```
4207 TOT 43547.1 VEM
4249 TOT 30.3 VEM
4248 TOT 29.9 VEM
4206 TOT 20.6 VEM
4166 TOT 18.8 VEM
4165 TOT 13.7 VEM
4208 TOT 13.4 VEM
4247 TOT2 3.1 VEM
90003 TOT 78.9 VEM off grid, dense
90001 TOT 83.6 VEM off grid, dense
90002 TOT 84.3 VEM off grid, dense
90000 TOT 96.1 VEM off grid, dense
```

PMT 1: S= 3401.3 VEM, D/A= 32.0, VEM Charge= 2032.0, VEM Peak= 323.9

PMT 2: S= 3406.4 VEM, D/A= 32.0, VEM Charge= 2032.0, VEM Peak= 323.9

PMT 3: S= 3405.8 VEM, D/A= 32.0, VEM Charge= 2032.0, VEM Peak= 323.9

PMT 4: S= 43547.1 VEM, D/A= 1.0, VEM Charge= 1.4, VEM Peak= 0.3

```
2012/9/20 04:33:12  SD 11026501 FD 3/1/11026501 4/1/11026501 5/1/11026501
```

Figure 8. Display of a saturated event induced by a proton at 2.5×10^{19}eV. Top panel: event reconstruction; bottom panel: signal recorded in the 3 standard PMTs and in the small PMT. The signal recorded in the closest tank is recovered by the smallPMT measurement (one order of magnitude from about 3500 to about 43500).