Study of the sensitivity of TERZINA to the detection of the Ultra-High Energy Cosmic Rays

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11 aprile 2022

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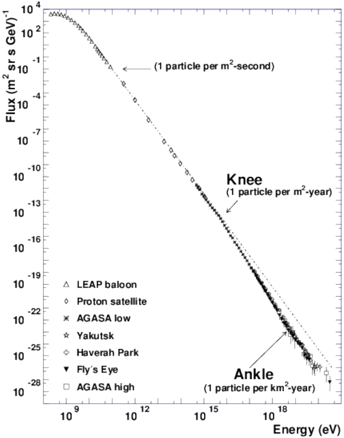
Cosmic Rays Flux

- Cosmic rays are particles coming from extraterrestrial sources
- Flux scales roughly as E^{-3}
- $E > 5 \times 10^{18}$ eV $\rightarrow$ Ultra-High Energy Cosmic Rays
- Very poor flux:
  - 1 particle/km^2/years at 5×10^{18} eV
  - 1 particle/km^2/10^3 years at 10^{20} eV



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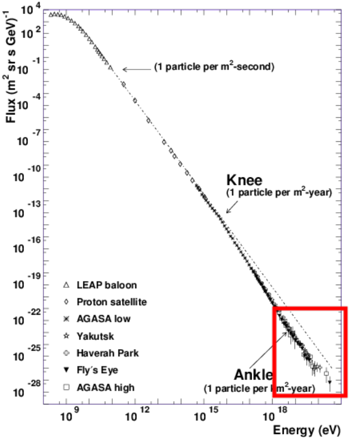
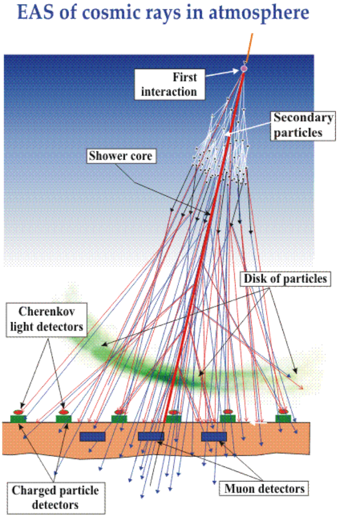


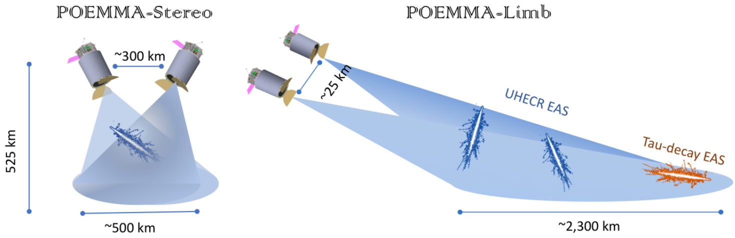
EAS and Cherenkov light



- UHECR can produce several secondary particles interacting with atoms and molecules, which can interact in turn $\rightarrow$ "shower"
- In the atmosphere $\rightarrow$ Extensive Air Shower (EAS)
- Showers can produce light by Cherenkov emission:
  - photons emitted between ~ 300 nm and ~ 1000 nm
  - fast signals ($\sim 95\%$ photons in ~ 20) ns

POEMMA

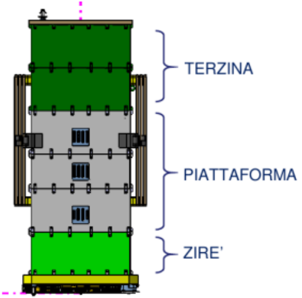
- EUSO program's goal: study UHECRs from space
- Main project: Probe Of Extreme Multi-Messenger Astrophysics (POEMMA)
- Two identical telescopes flying in a loose formation on a low Earth orbit (LEO) at an altitude of 525 km for 5 years of mission duration goal
- Two spacecrafts fly in tandem separated by less than ~ 300 km
- Two operational modes: POEMMA-Stereo and POEMMA-Limb



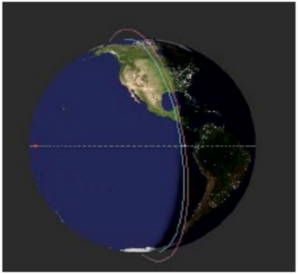
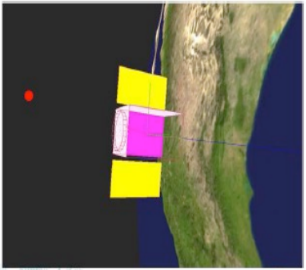
- Optimized respectively for UHECR fluorescence observations and Cherenkov emissions from EAS induced by τ-leptons produced by cosmic ν_τ interactions in the Earth
- Nearly 2×10^5 km^2 (POEMMA-Stereo) to 2×10^6 km^2 (POEMMA-Limb) observed area

NUSES mission

- TERZINA is a payload of NUSES mission (GSSI/TAS-I)
- NUSES project consists of two experiments: ZIRÉ and TERZINA
- ZIRÉ will monitor variations of particles' flux in the ionosphere and magnetosphere induced by seismic activities
- TERZINA is a pathfinder of POEMMA missions, devoted to testing the technologies (SiPMs) and detection technique (limb observation)



- NUSES will fly at a Low Earth Orbit (LEO) at an altitude of ~ 525 km with high inclination (97.8°), travelling in a Sun-Synchronous and dusk-dawn orbit along the day/night boundary line
- Mission life-time ~ 3 years (duty cycle $\sim 40\%$)

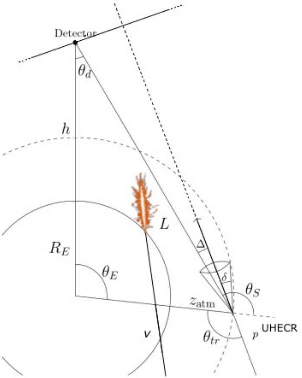



TERZINA

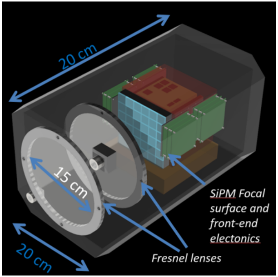
TERZINA goals:

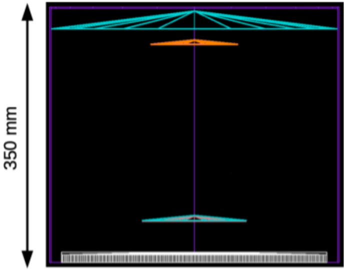
- testing the detection technique of the observation around the Earth limb to collect Cherenkov photons from EAS induced by UHECRs
- measuring for the first time the sky background at the limb with a timing resolution of tens of nanoseconds (required for Cherenkov measurement)
- using SiPMs as photo-sensors

SiPM advantages (over a normal PMT): compactness, high spectral sensitivity and not High-Voltage necessities



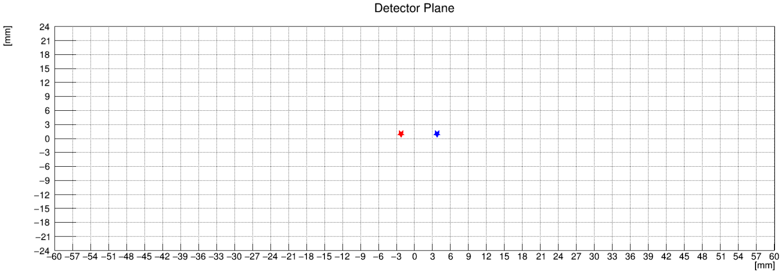
- TERZINA layout is still in the design phase
- The choice of the optics system is between a Fresnel lens system (Mini-EUSO like) and a Schmidt camera (POEMMA like)
- under study by dr. Burmistov (Geneva,UniGE)
- Effective collection area $\sim 0.1\ m^2$





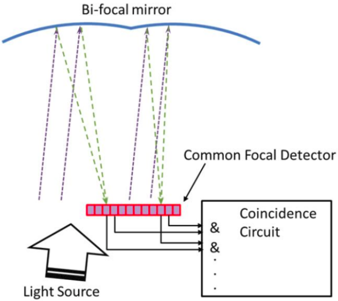
TERZINA focal surface last design:

- 640 SiPM pixels, divided in arrays of 8×8 for a total of 5×2 arrays (40×16 pixels disposition)
- SiPM pixels dimension: $3 \times 3\ mm^2$, FoV $= 0.184°$
- Total TERZINA FoV: $7.360° \times 2.944°$



Bifocal optical technique:

- Photons are split equally between two focuses
- Distance between two focuses set at 2 pixel size to have one pixel "empty" between
- Trigger requires time coincidence between pairs of pixels



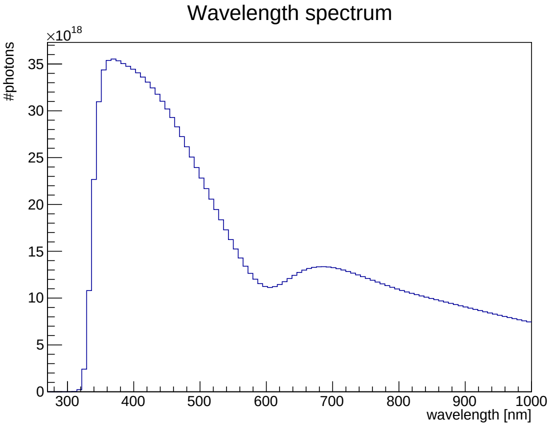
Bifocal optical technique:

- Photons are split equally between two focuses
- Distance between two focuses set at 2 pixel size to have one pixel "empty" between
- Trigger requires time coincidence between pairs of pixels
- Two advantages:
  - capability to reject events triggered from a direct hit of a charged particle or from an internal signal from electronic disturbances (single bright pixel)
  - additional discrimination on SiPM noise events based on offline analysis
- Disadvantages:
  - Halved signal in a pixel (50% SNR)
  - Construction difficulties (optical system, electronic connections)

- Modelling and simulation of the EAS Cherenkov emission
- Due to geometrical limitations of CORSIKA, dr. Austin Lee Cummings (GSSI) modelled the upward-going EAS development induced by CRs
- Its code provides Cherenkov photons characteristics at the detector altitude:
    - wavelength distribution
    - distance distribution (photon density)
    - time distribution at a selected distance

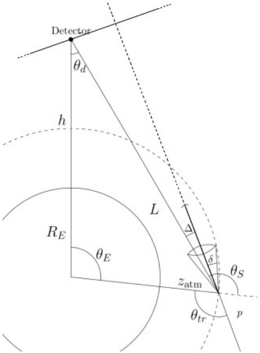
EAS with 10^{18} eV at $\theta = 68.1^\circ$

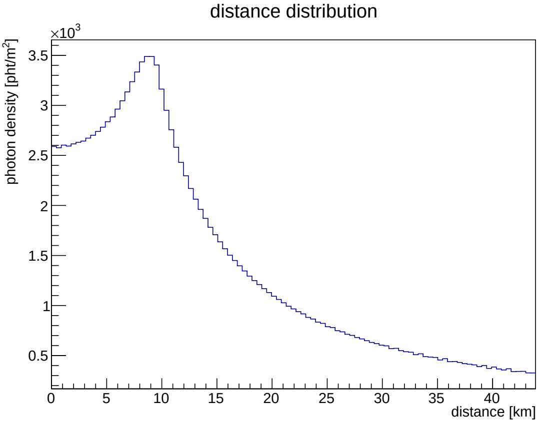
- Wavelength spectrum



EAS with 10^{18} eV at $\theta = 68.1°$

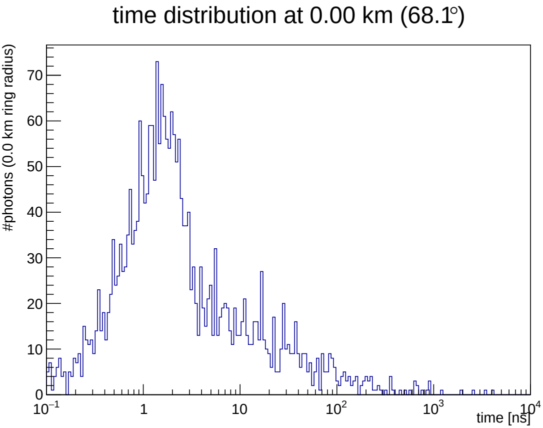
- Distance distribution





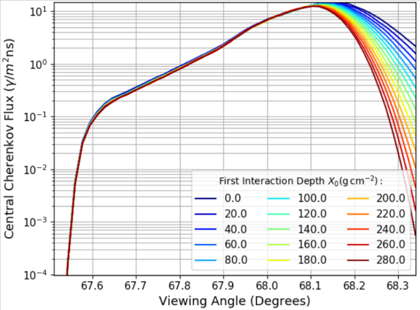
EAS with 10^{18} eV at $\theta = 68.1°$

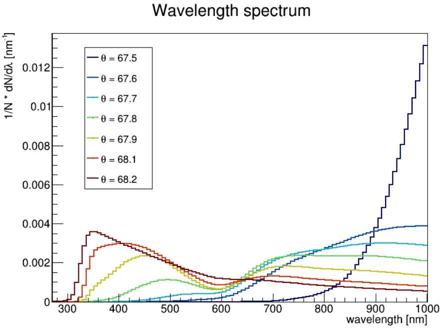
- Timing distribution (for 0 km distance)



θ dependence

- Cherenkov characteristics can change significantly depending on the θ angle:





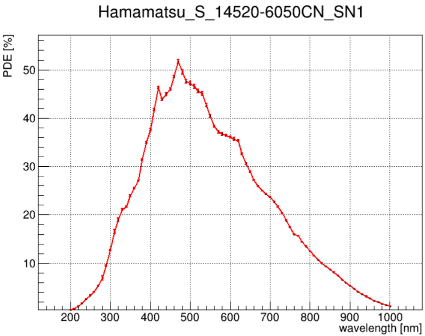
PDE

- SiPM model: Hamamatsu S14520-6050CN_SN1
- Additional factor of 50% including the optics response

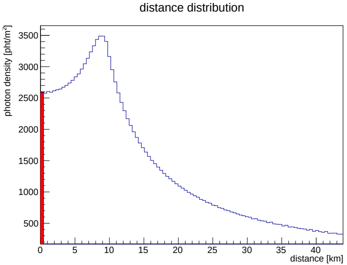
$$\langle PDE(\lambda)\rangle_{orig} \simeq 20\%$$

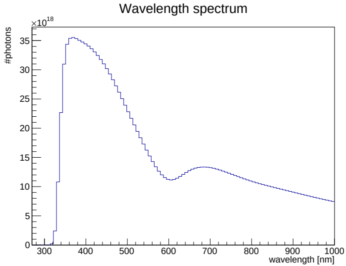
$$+$$

$$\epsilon_{optics} \simeq 50\%$$



SiPM Photon Detection Efficiency





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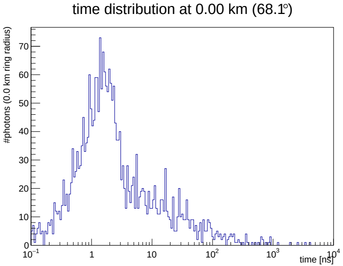

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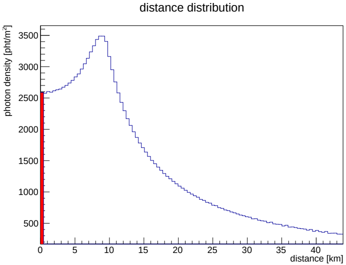

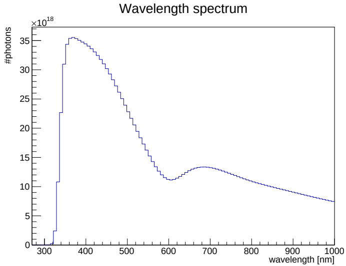

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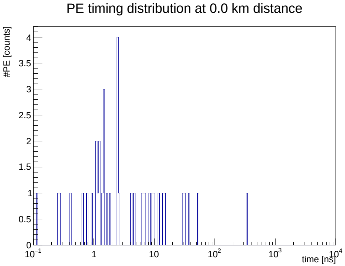
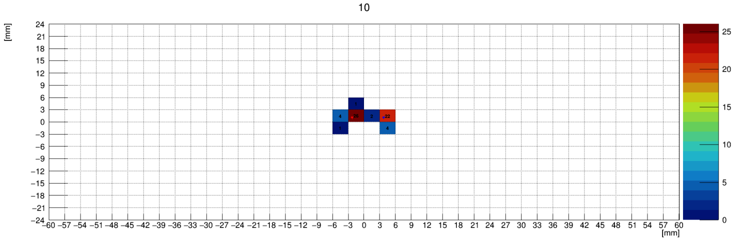


PSF and bifocal

- Random incidence point
- Assumed Gaussian PSF $\rightarrow \sigma = 1$ mm
- 10 ns of integration time (frame length)



Background and Optical Crosstalk

- Background from the Earth's **airglow** phenomenon (de-excitation of atoms and molecules in the upper atmosphere (mainly nitrogen), excited by sunlight)
- **Optical crosstalk** occurs when a primary discharge (avalanche) in a SiPM triggers secondary discharges in one or more adjacent SiPM (OC 5%)

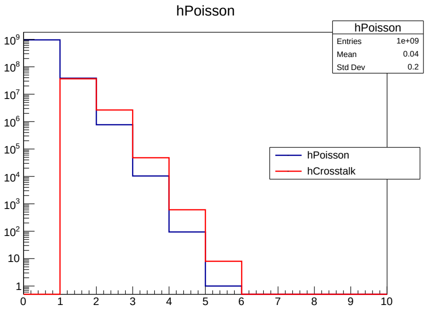
Photons/(m^2 *ns sr*)	15041
Altitude [km]	525
van Rhijn multiplier	6
Time width [ns]	10
Pixel FoV [deg/sr]	$0.184/1.03\times10^{-5}$
Photons/m^2	9.31
Aperture [m^2]	0.1
$\langle PDE \rangle[\%]$	10
Photon counts	0.093

$$\rho_{pht} = \rho_{\Omega} \cdot \alpha \cdot t_{width} \cdot \Omega_{pxl}$$

$$\text{pht counts} = \rho_{pht} \cdot A[m^2] \cdot \langle PDE \rangle [\%]$$

Airglow data and evaluations provided by dr. Krizmanic (NASA/GSFC)

- Evaluated photon counts used as mean value for a Poissonian extraction (every 10 ns) plus the crosstalk effect (5%)
- Reasonable background even rate: 1 event/minute (entire focal surface) $\rightarrow$ Threshold = 5 photon counts



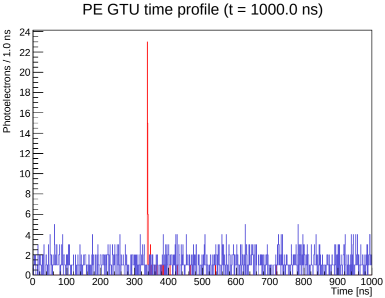
$$f_{coinc} = f(n)^2_{bkg} \cdot t_{width}$$

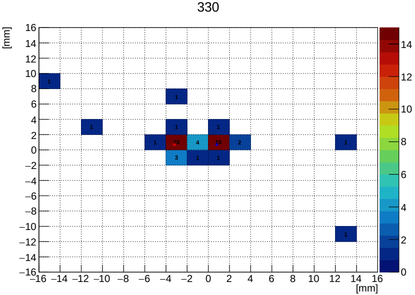
Threshold= 5 pht counts

bkg coinc rate [Hz]	17.7
coinc gate [sec]	10^{-8}
pxls coinc/sec	1.90×10^{-3}
pxls coinc/hour	6.86
pxls coinc/day	1.65×10^{2}

Bkg and Cherenkov signal together

- Background randomly in time and space
- Cherenkov signal with its timing distribution



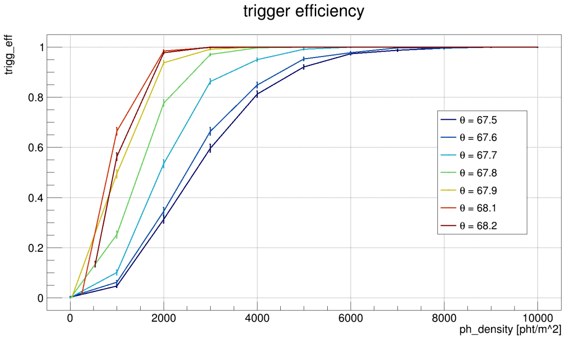


Trigger efficiency

- Trigger works on pairs of correspondent pixels (2 pixels size distance = 6 mm)
- Checking each frame (10 ns) for the simulated interval (1 μs)
- Starting with 7 events with 10^{17} eV and seven different trajectory angles (from 67.5°to 68.2°) $\rightarrow$ artificial increasing of the photon density assuming linear relationship between energy and photon density

Angles [°]	Photon density [pht/m^2]
$67.5°$	0.004
$67.6°$	1.093
$67.7°$	4.365
$67.8°$	11.47
$67.9°$	32.77
$68.1°$	257.6
$68.2°$	535.1

- Trigger efficiency evaluated repeating the process 1000 times for each "energy"



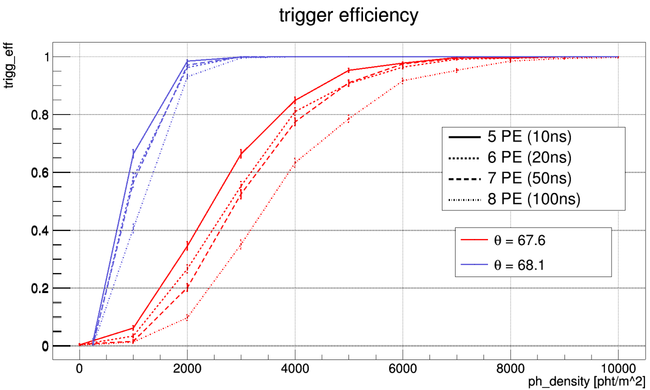
$$\epsilon_{trigg} = \frac{N_{trigg}}{N_{event}}$$

$$\delta\epsilon_{trigg} = \sqrt{\epsilon_{trigg} \cdot \frac{1-\epsilon_{trigg}}{N_{events}}}$$

- Threshold is evaluated according to frame length: the longer the frame, the higher is the background rate
- Increasing the frame length means increasing the threshold:

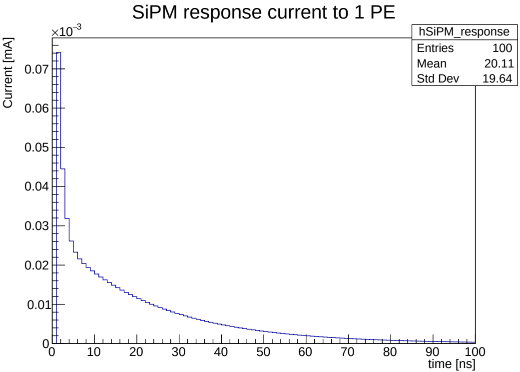
Thresholds, Frame length	**6 PE, 20 ns**	**7 PE, 50 ns**	**9 PE, 100 ns**
bkg coinc rate [Hz]	4.9	15.3	9.3
coinc gate [sec]	2×10^{-8}	5×10^{-8}	10^{-7}
pxls coinc/sec	2.92×10^{-4}	7.12×10^{-3}	5.26×10^{-3}
pxls coinc/hour	1.05	2.56×10^{1}	1.89×10^{1}
pxls coinc/day	2.52×10^{1}	6.15×10^{2}	4.54×10^{2}

Trigger efficiency

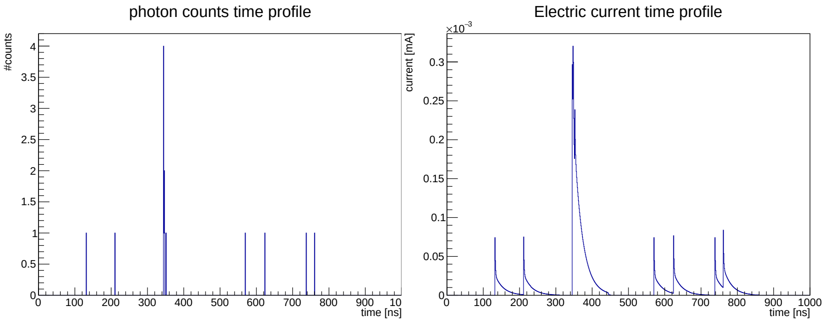


SiPM waveform

- Until now, just the number of photons detected or rejected are taken into account
- SiPM produces an electric current with the following waveform:

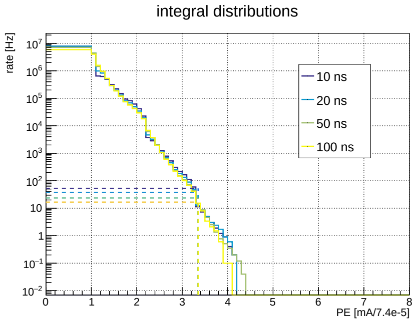


- Applying it to the photon counts timing profile previously described, the obtained electric current profile for a single SiPM:



- 1 μs simulated time interval, 1 ns of resolution

- Now the trigger must check the maximum value reached by the electric current in the frame interval, not the photon counts
- Thresholds evaluated applying the waveform to the background coincidence rate and checking the maximum reached value



- Electric current will be collect by the ASIC chip developed by the INFN team of Turin

- Keeping the same acceptable bkg rate of 1 event/minute, the rate on a single pixel is evaluated

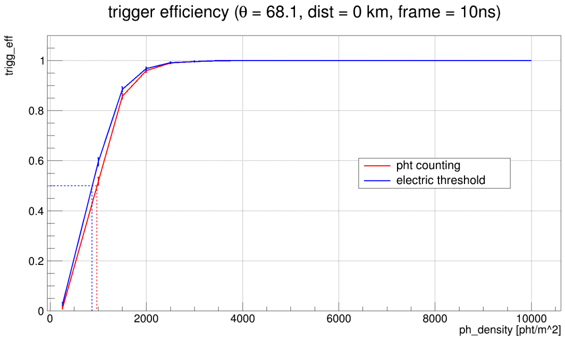
$$f(n)_{bkg}[\text{Hz}] = \sqrt{\frac{0.017[\text{Hz}]}{\text{frame length [sec]} \cdot 608}}$$

- Different frame lengths but same thresholds

frame length [ns]	bkg rate single pixel [Hz]	equivalent PE [mA/0.07×10^{-3}]
10	52.9	3.3
20	37.4	3.3
50	23.7	3.3
100	16.7	3.3

Techniques comparison

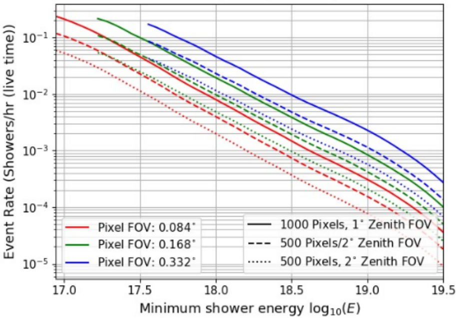
- Comparison between two techniques: photon-counting and electric current checking



	ρ_{pht} [pht/m^2]	energy [eV]
photon counting	980	3.8×10^{17}
electric current	880	3.4×10^{17}

Event rate estimation

- Preliminary estimate of the expected event rate and the bifocal optics significance
- Rough scaling from dr. Cummings geometric aperture evaluation



- $F \propto E^{-\gamma}$
- γ index slope $\simeq 1.5$
- 10^{-1} event/hr with 40% of DC

$\downarrow$

$\simeq 1$ event/day

- FoV factor ~ 4 (horizontally)
- energy threshold factor ~ 2 (between ~ 1.3 and ~ 3)

$$\frac{F_2}{F_1} = \left(\frac{E_1}{E_2}\right)^{\gamma}$$

	event rate estimation
50% optics throughput, bifocal optics	~ 2.6 event/month
100% optics throughput, bifocal optics	~ 4.4 event/month
50% optics throughput, not bifocal optics	~ 3.6 event/month
100% optics throughput, not bifocal optics	~ 5.9 event/month

trigger efficiency $\simeq 90\% \rightarrow$ factor $\sim \times 0.55$

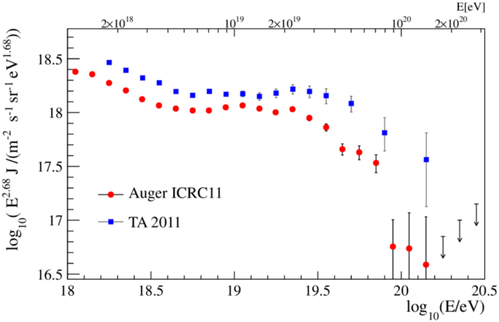
Summary

- Preliminary simulation of the TERZINA response, taking into account:
  - SiPM PDE
  - Gaussian PSF
  - Bifocal optical system
  - Airglow background, considering also the SiPM optical crosstalk
  - SiPM waveform response
- Implementation of a first level of trigger and evaluation of trigger efficiency for different showers
- Preliminary estimation of the energy threshold ($\sim 3.5 \times 10^{17}$ eV) and correspondent event rate, together with the significance of the effects taken into account

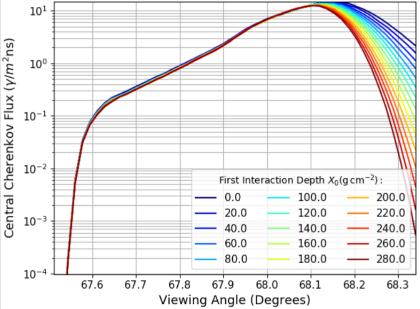
Thanks!

Back-up slides

- Pierre Auger Observatory ($\sim 3000 km^2$, Argentina) and Telescope Array ($\sim 700 km^2$, Utah, USA) experiments combined an EAS array spread on a large surface with fluorescence telescopes
- Discrepancies between Auger's and TA's results
- Despite having these extensions, the poor number of detected events limits the statistics and affects the validity of the results

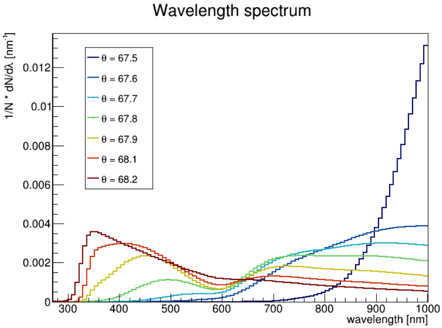


Different θ angles study



- Flux of Cherenkov photons of EAS at 10^{17} eV for different θ angles as observed at 525 km altitude

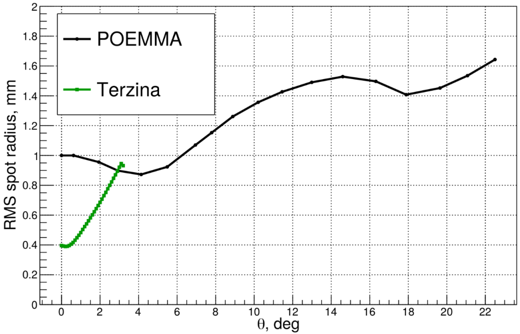
- From $\sim 67.5^\circ$ (limb) to $\sim 68.1^\circ$ the atmosphere produces and absorbs the Cherenkov photons $\rightarrow$ two phenomena in competition
- Near the limb, the absorption is dominant
- Increasing the viewing angle the atmosphere becomes less dense, improving the photons production over the absorption
- Above $\sim 68.2^\circ$ the atmosphere becomes too little dense for complete development of an EAS, so even the photon intensity decreases



- Wavelength spectra for EAS at 10^{17} eV for different θ angles (area normalized to 1)

- The closest showers to the limb show a higher suppression of the shorter wavelengths
- Ozone absorbs the UV light below 300 nm
- Dip around 600 nm caused by Ozone scattering cross-section
- Two types of scattering: Rayleigh ($\propto \lambda^4$) and Mie ($\propto \lambda$)

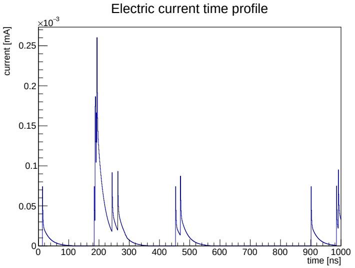
PSF's σ



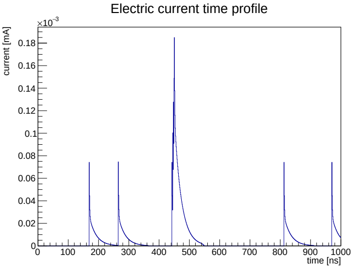
- $\sigma = 1$ mm is chosen according to Geant4 simulation provided by L. Burmistov
- At the edge of the FoV ($\sim \pm 3.5°$) RMS reaches the maximum value of ~ 1 mm
- Near the center the situation improves to RMS ~ 0.4 mm

Discrimination between real and fake event near the threshold

- Discrimination between real event and fake coincidence:



(a) Cherenkov signal (E= 4×10^{17} eV)



(b) Background coincidence