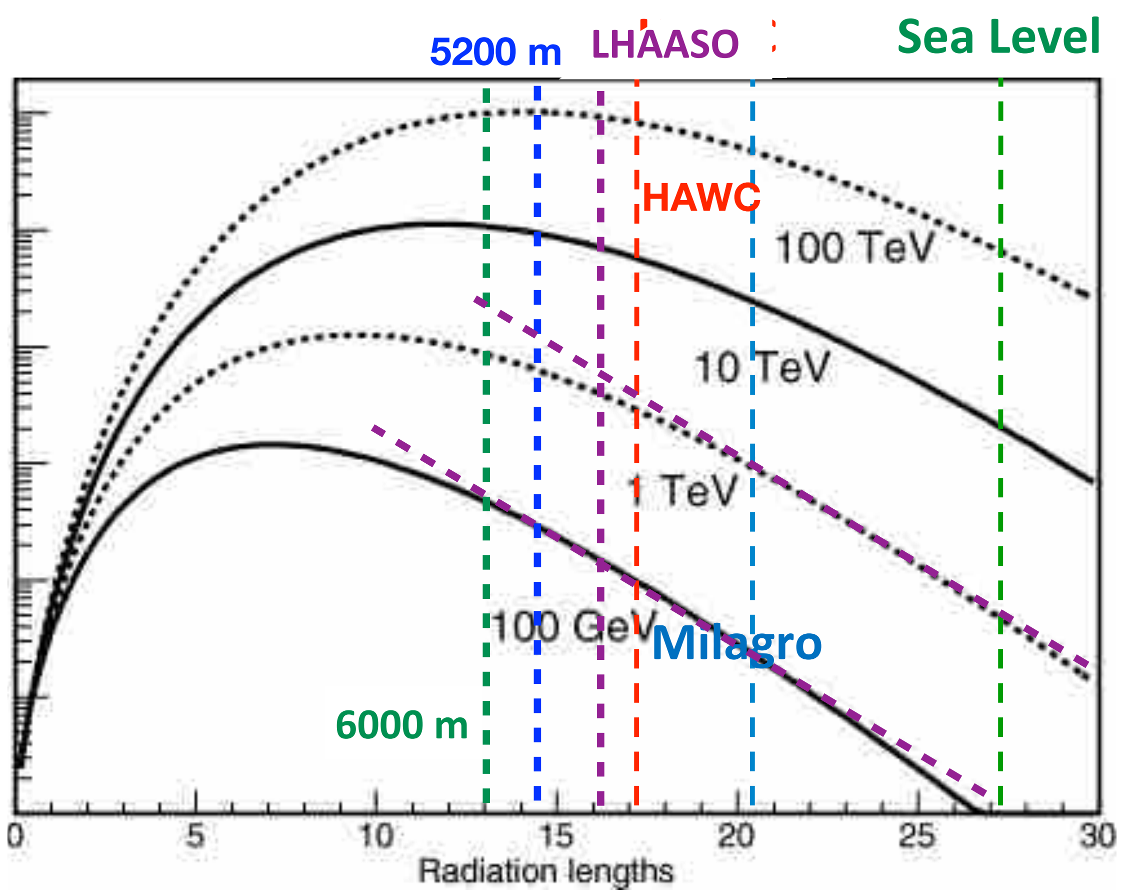
Compact WCD with a matrix of SiPM

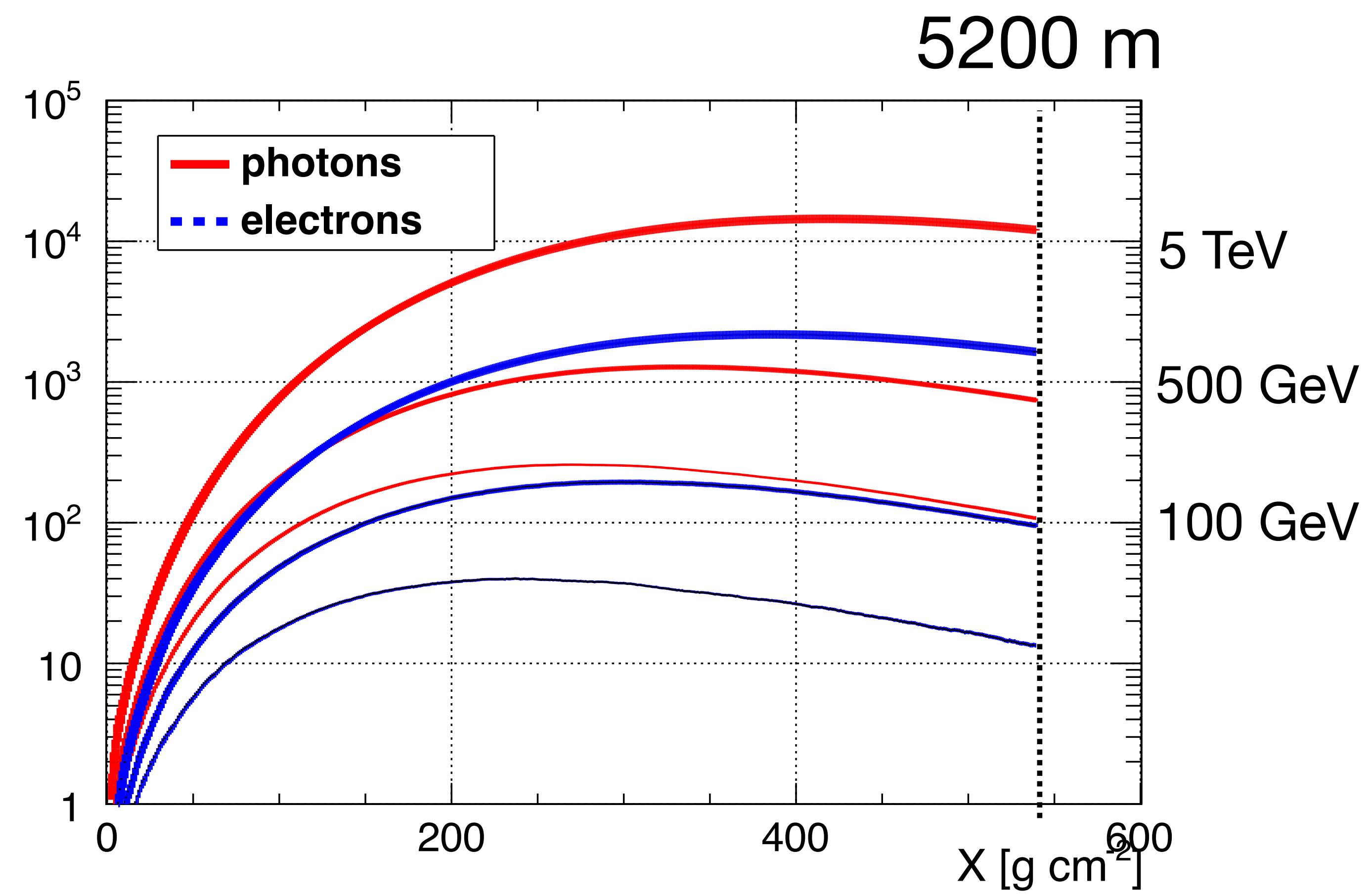
Ruben Conceição, Giovanni La Mura, Cédric Perennes, Mário Pimenta, Bernardo Tomé

LIP
TÉCNICO LISBOA

Wide field-of-view gamma-ray observatory in the Southern hemisphere, Lisboa, May 20th -22nd , 2019

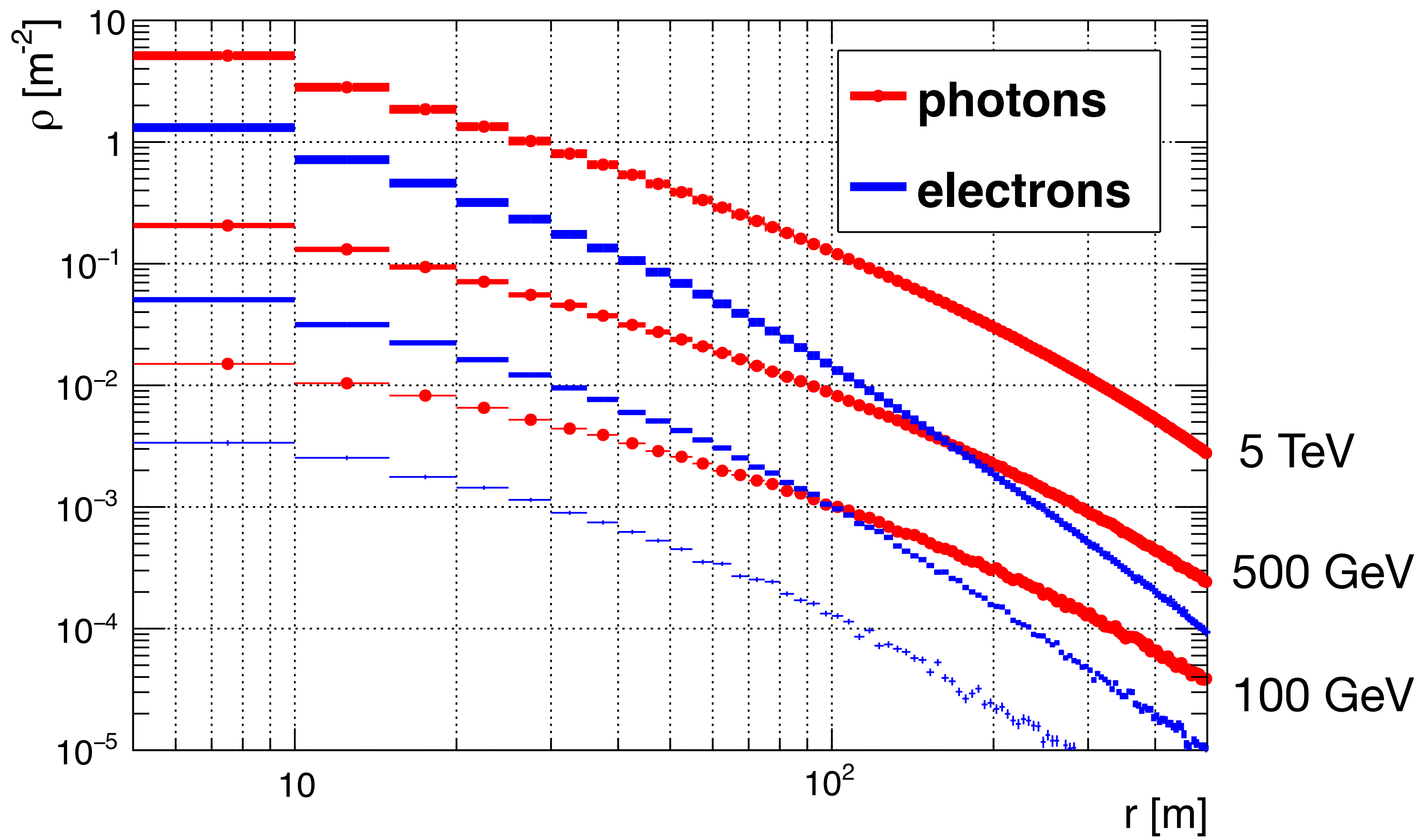
The low energy challenge





- Even at high altitudes (reasonable!) low energy photon showers are still detected at > 5 X_0 below X_{max}
- For E = 100 GeV vertical showers, ~ 100 e.m. particles reach the ground at ~ 5000 m a.s.l
- ~ 90% of the shower secondaries are photons

Mean LDF at 5200 m altitude

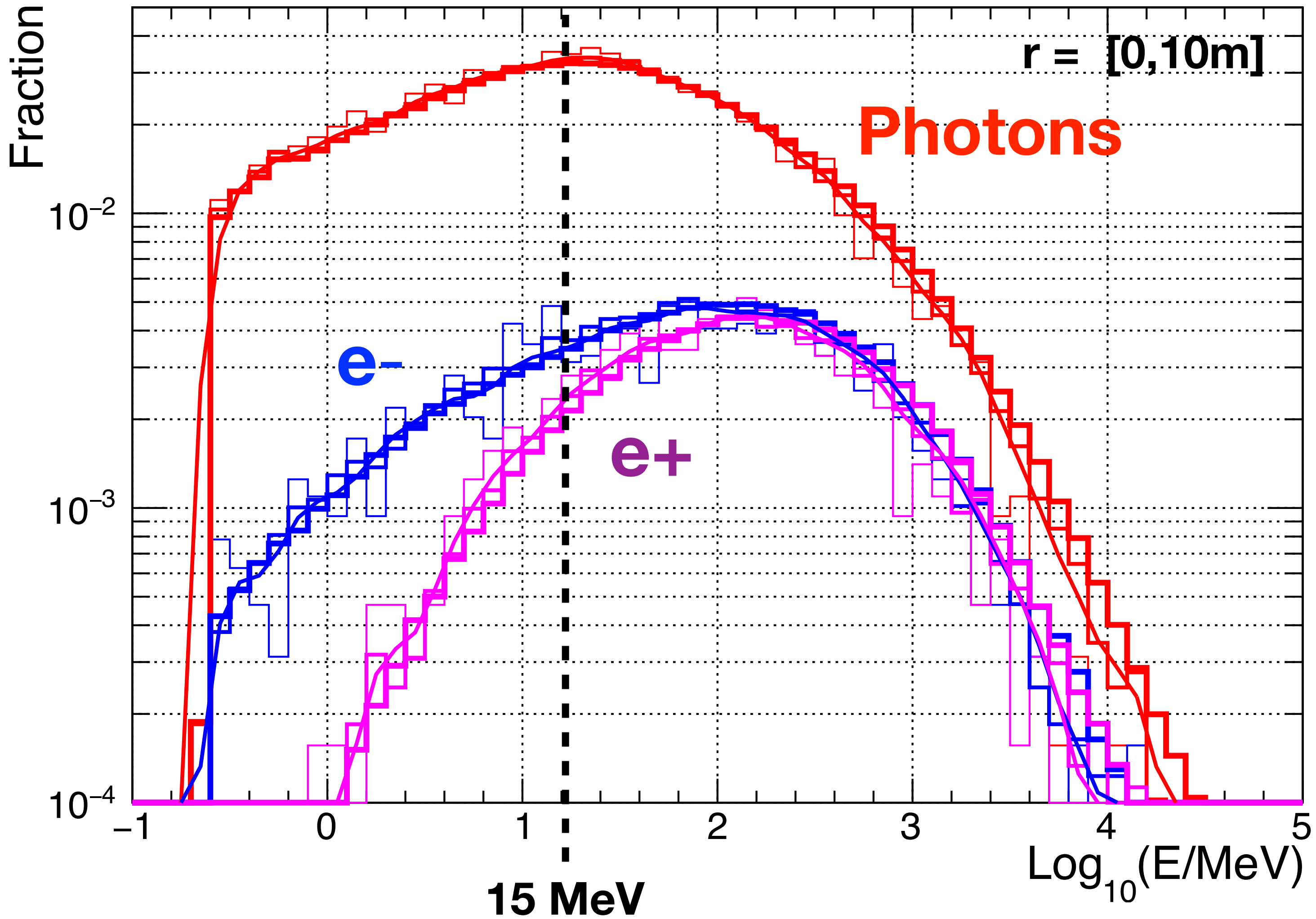


@ 100 GeV :

- r = 100 m —> <ρ> ~ 0.001 photons/m2
- r = 10 m —> <ρ> ~ 0.015 photons/m2
- Increasing the station area does not help to increase the individual station signal…

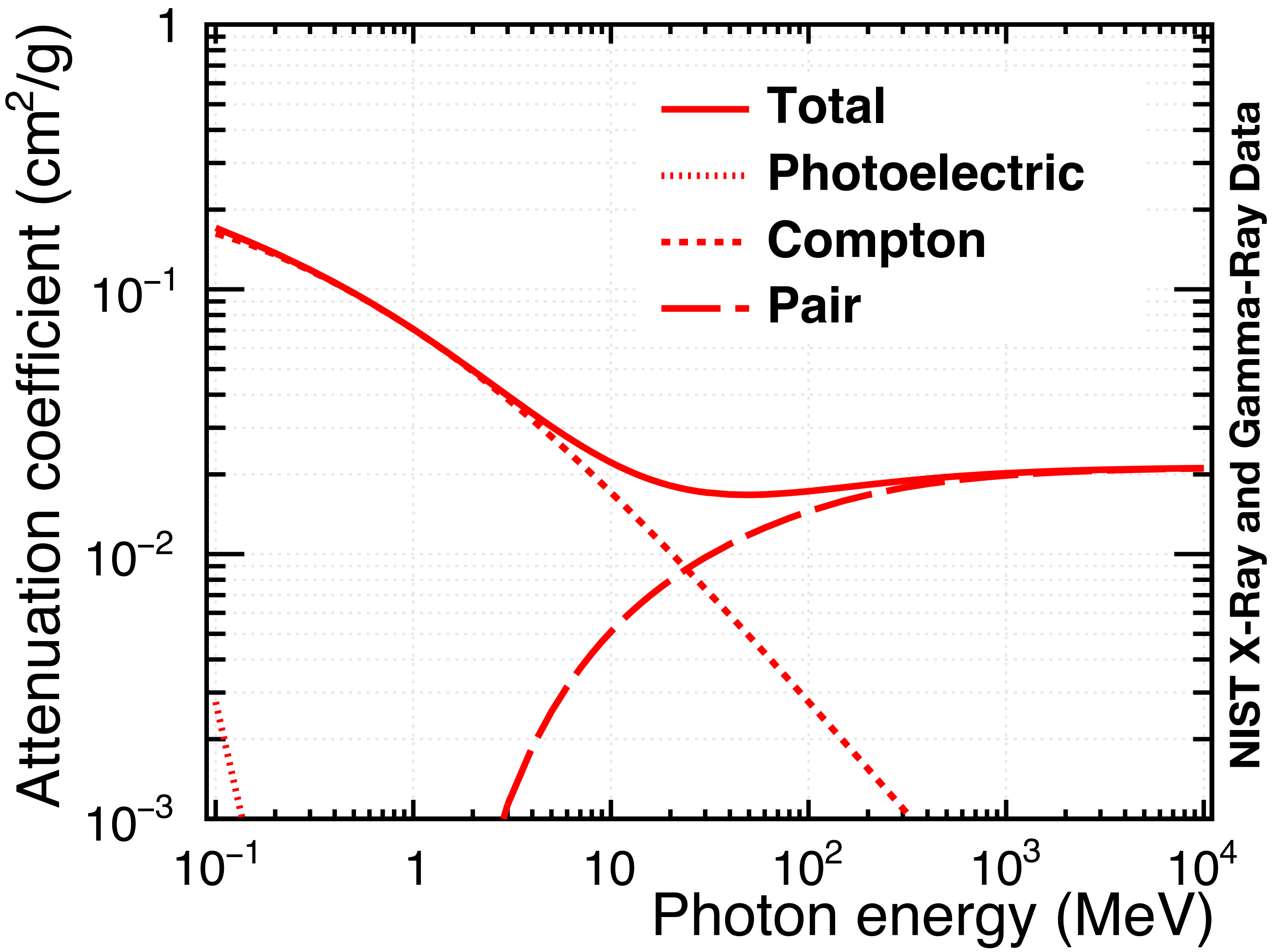
Need single-particle station sensitivity !

Secondary particle spectra @ 5200 m altitude



- WCD sensitivity to single ~ 10 MeV - 15 MeV photons is a challenge !

Photon interactions in H_2O



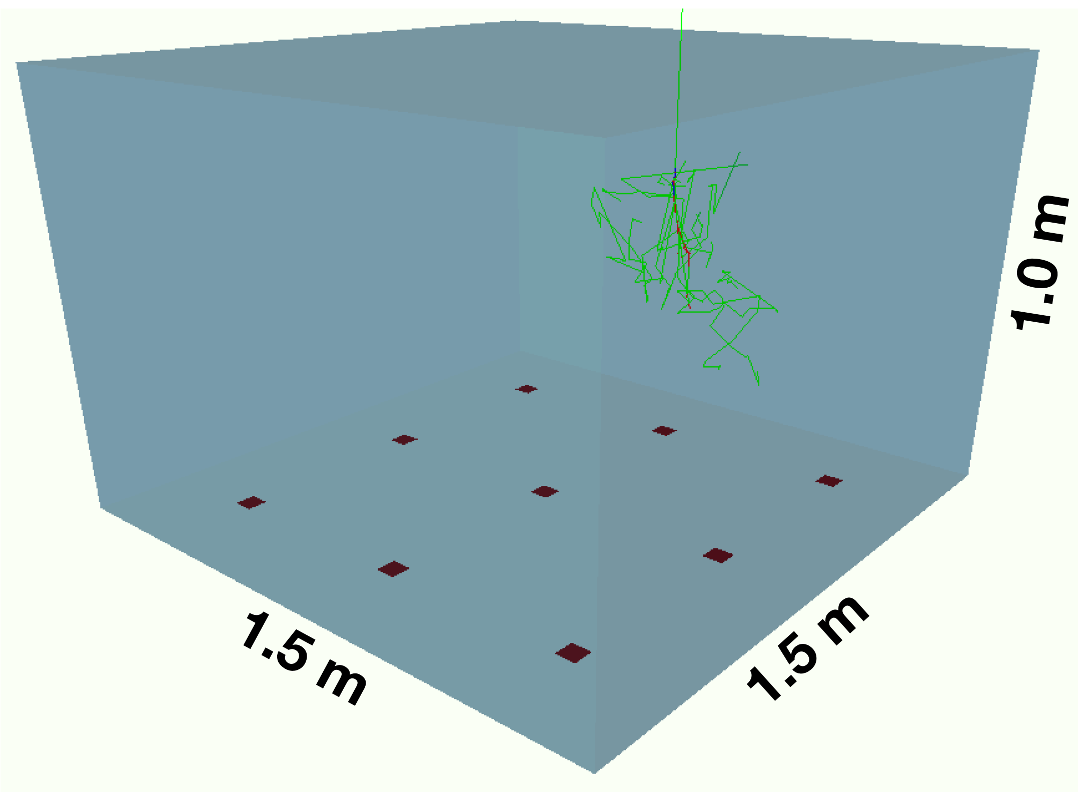
- At > 10 MeV : $L_{Compton} + L_{Pair}$ ~ 50 g/cm2 (~9/7 X_0)
- 1 m H_2O —> P_{int} = 0.86; 2 m H_2O —> P_{int} = 0.98
- 2 x water depth increases the interaction probability by 1.14 …

A compact WCD concept

Addressing new (and old…) challenges

- **Station signal**
  - WCD should be white to lower energy threshold!
- **Timming**
  - Access direct Cherenkov light pulse
- **Gamma/hadron discrimination**
  - WCD signal patterns at ground as potential discriminator
  - At higher energies muon identification is a powerful discriminant variable
    - Explore timming characteristics to enhance muon id

Station layout

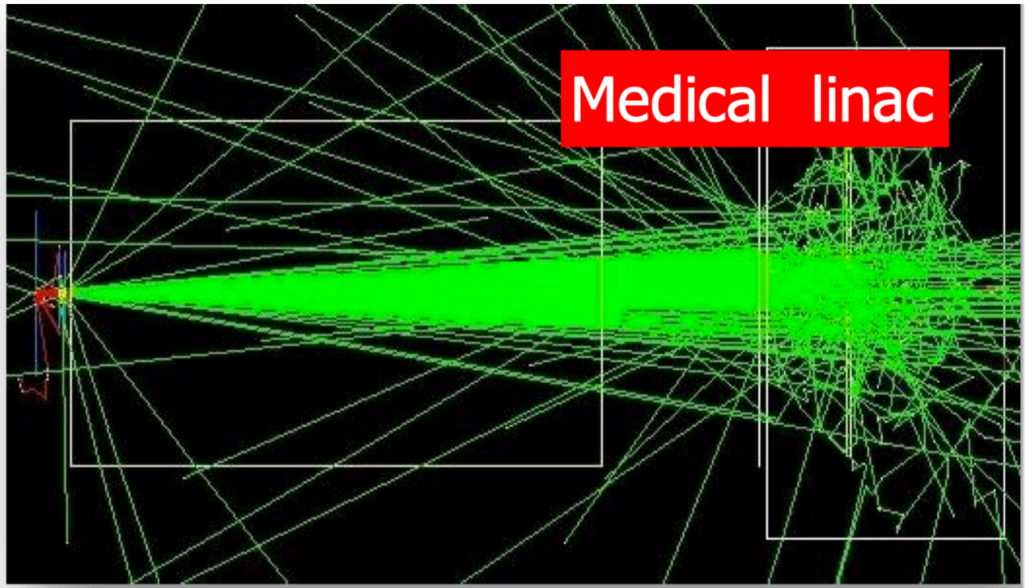


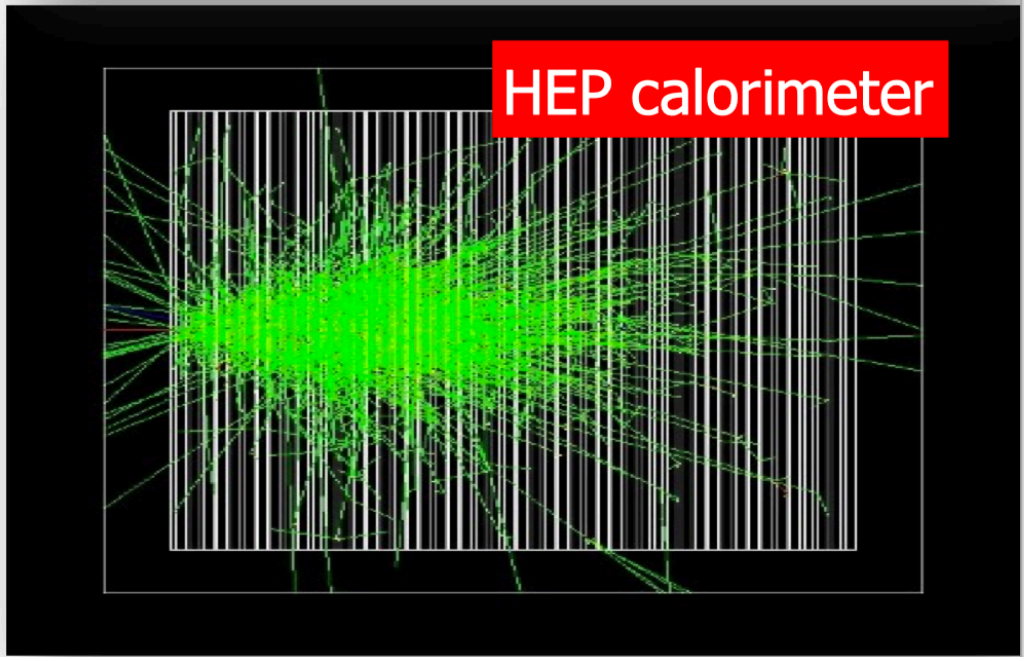
- Water Cherenkov Detector
- 1.5 x 1.5 x 1 m3
- 3 x 3 matrix of SiPMs @ WCD bottom
- 3x3cm^2 SiPMs
- Inner walls covered with white diffusing Tyvek

Geant4 simulation toolkit

- Geant4 provides a wide variety of physics components for use in simulation

- Photon processes
  - γ conversion into e+e- pair
  - Compton scattering
  - Photoelectric effect
  - Rayleigh scattering
  - *Gamma-nuclear interaction in hadronic sub-package*
- Electron and positron processes
  - Ionisation
  - Coulomb scattering
  - Bremsstrahlung
  - Positron annihilation
  - Production of e+e- pairs
  - *Nuclear interaction in hadronic sub-package*
- Suitable for HEP & many other Geant4 applications with electron and gamma beams





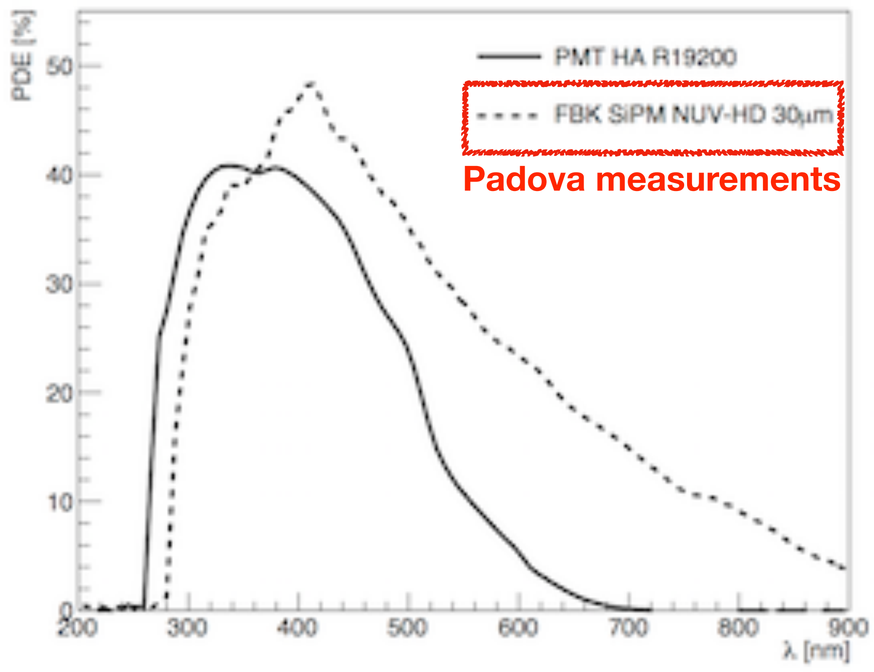
\+ equivalent processes for μ; + hadronic processes, …

WCD simulation using Geant4

- Explore Geant4 functionalities to simulate **optical photon production and propagation :**
  - Cherenkov emission, refraction and reflection at boundaries, bulk absorption, Rayleigh scattering, etc.

- **λ dependence** of all the relevant optical processes and material properties also implemented :
  - transmission efficiencies, dielectric constants, surface properties, photodetection efficiency,…

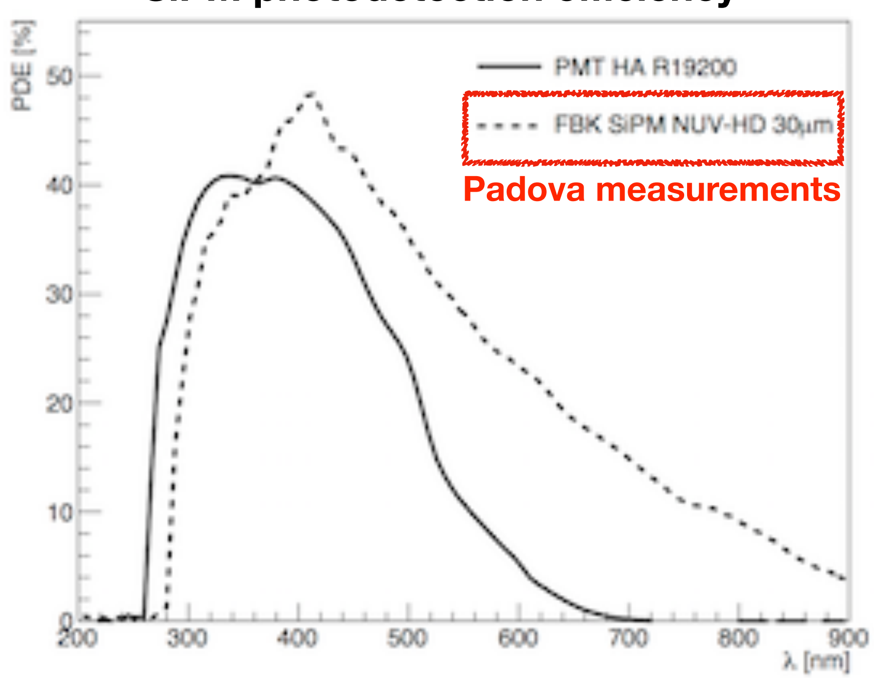
SiPM photodetection efficiency



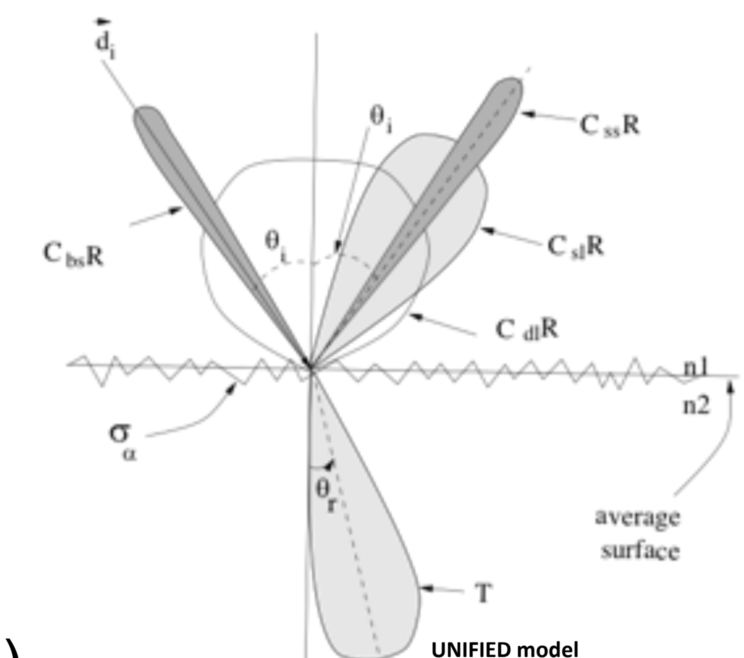
WCD simulation using Geant4

- Explore Geant4 functionalities to simulate **optical photon production and propagation :**
  - Cherenkov emission, refraction and reflection at boundaries, bulk absorption, Rayleigh scattering, etc.
- **λ dependence** of all the relevant optical processes and material properties implemented :
  - transmission efficiencies, dielectric constants, surface properties, photodetection efficiency,…

SiPM photodetection efficiency



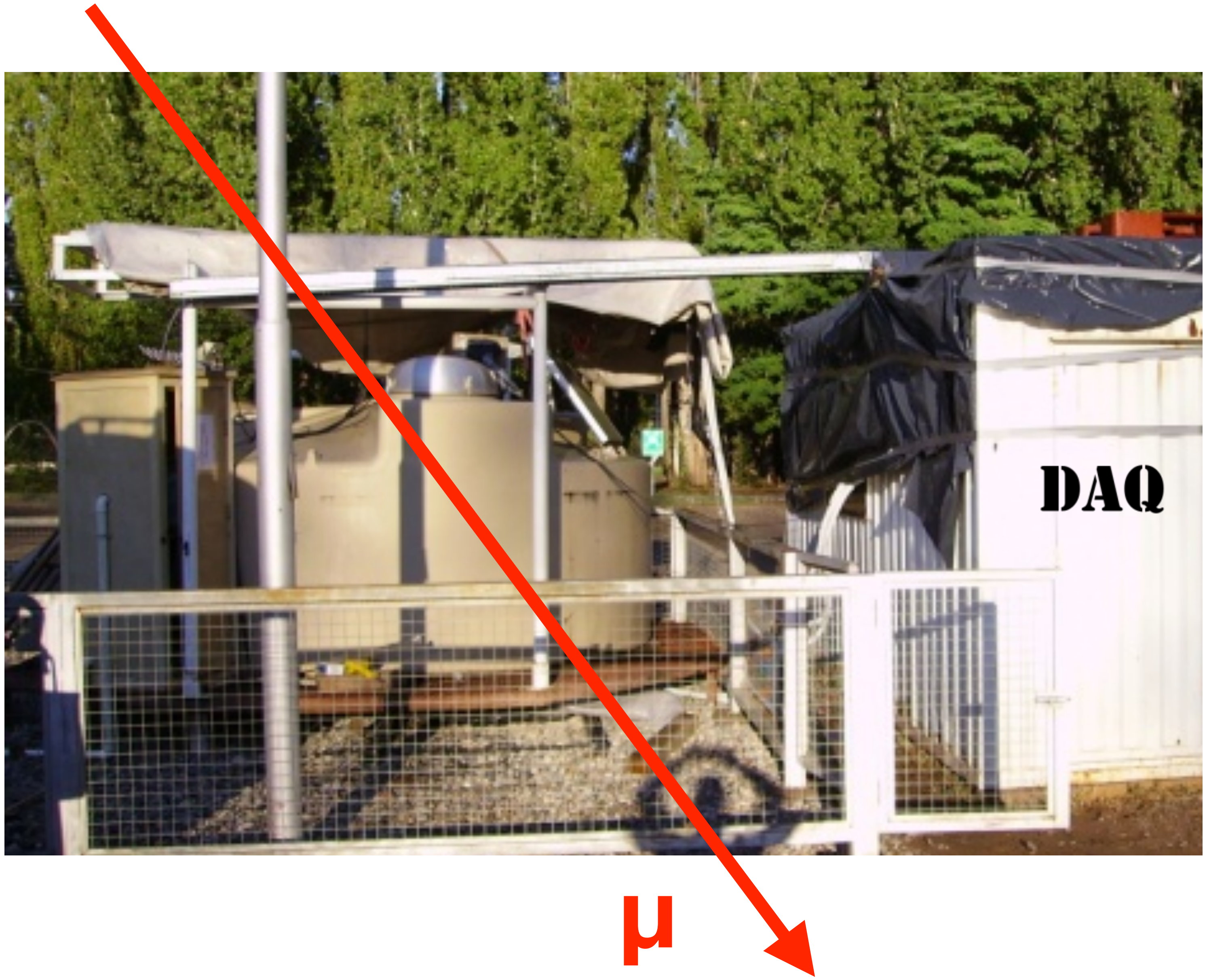
- **Tyvek**
  - Described using the **G4 UNIFIED optical model;**
  - Specular and diffusive properties;
  - R ~ 95%, for λ > 450 nm
    - 80% of which is diffusively reflected;
    - 20% is reflected around the specular reflection direction, with $\sigma_\alpha \sim 0.2^o$

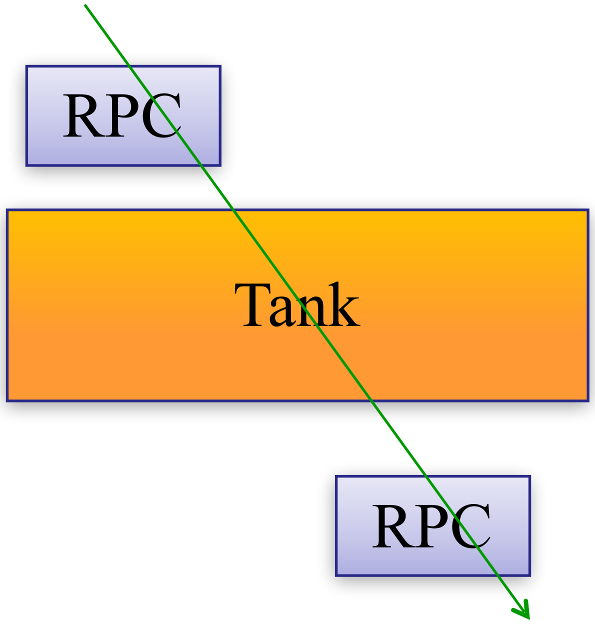


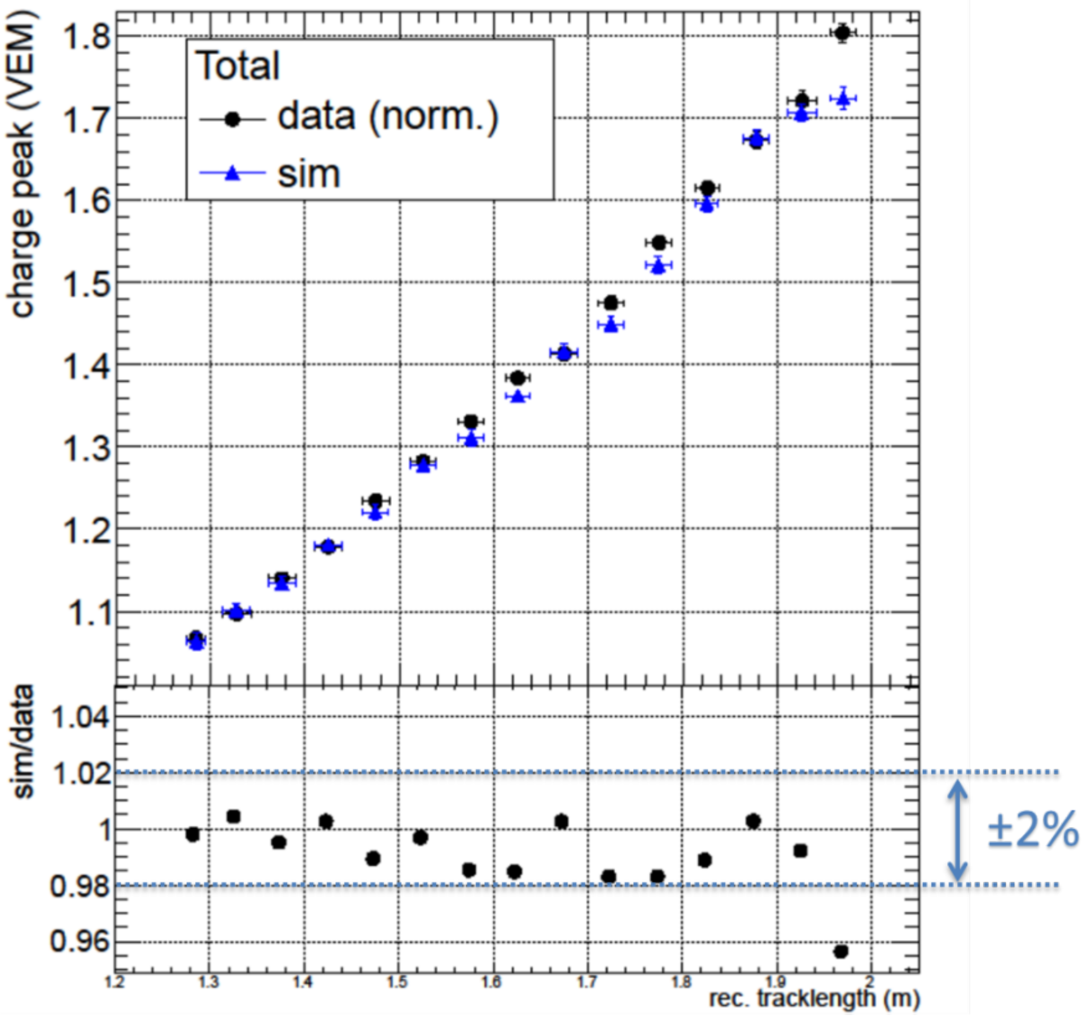
UNIFIED model (A. Levin and C. Moisan)

- Tyvek properties "inspired" in Auger simulation parameters :-)

RPC based μ-hodoscope in a test WCD at Auger Observatory







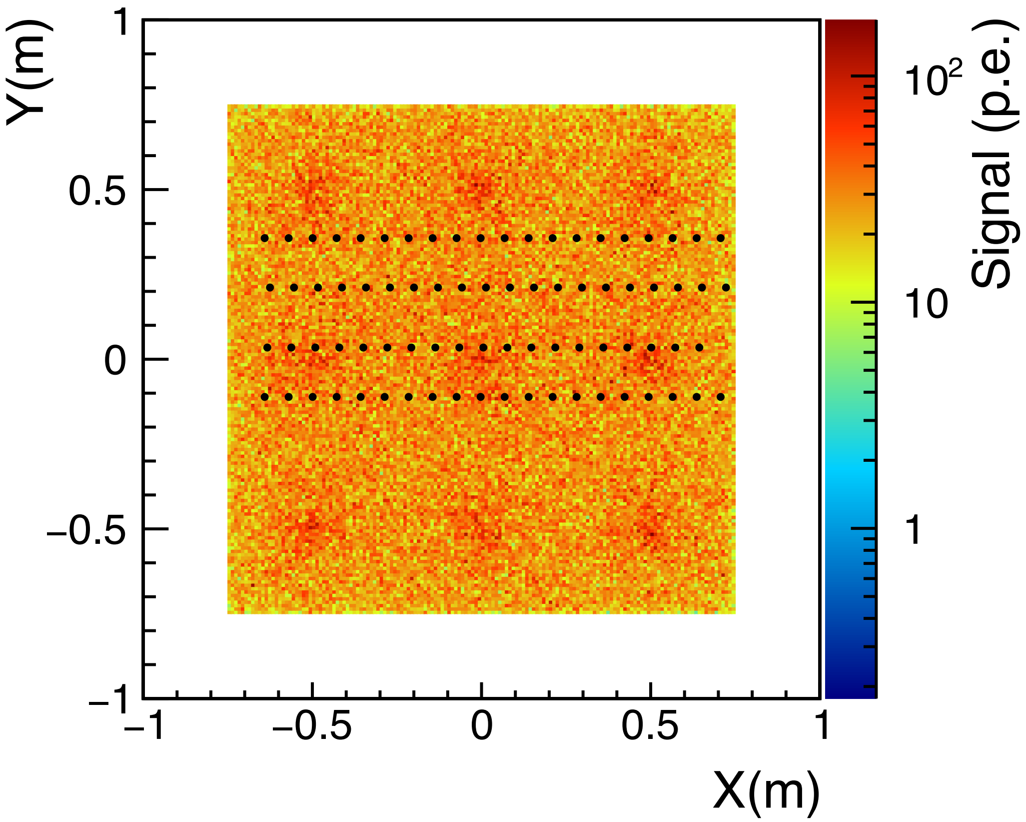
Data/Simulation agreement at % level !

First simulation studies

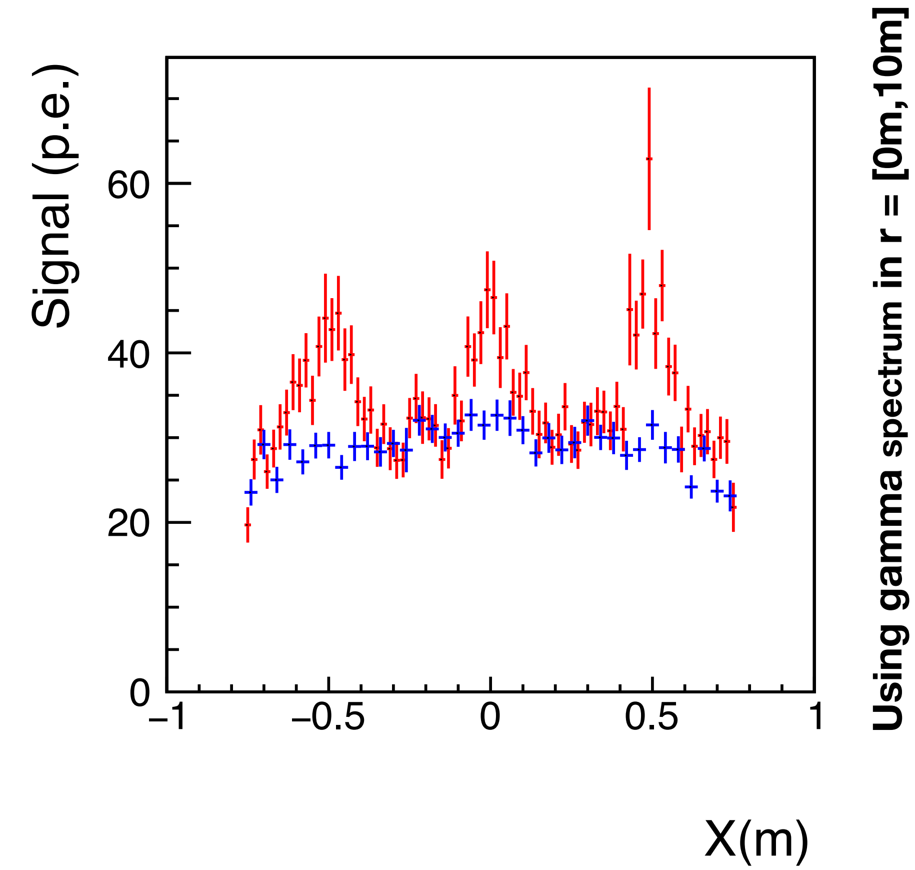
- **Standalone Geant4**
  - Single particles uniformly injected at top surface
  - Photons with fixed energy and with shower energy spectra
- Shower simulations

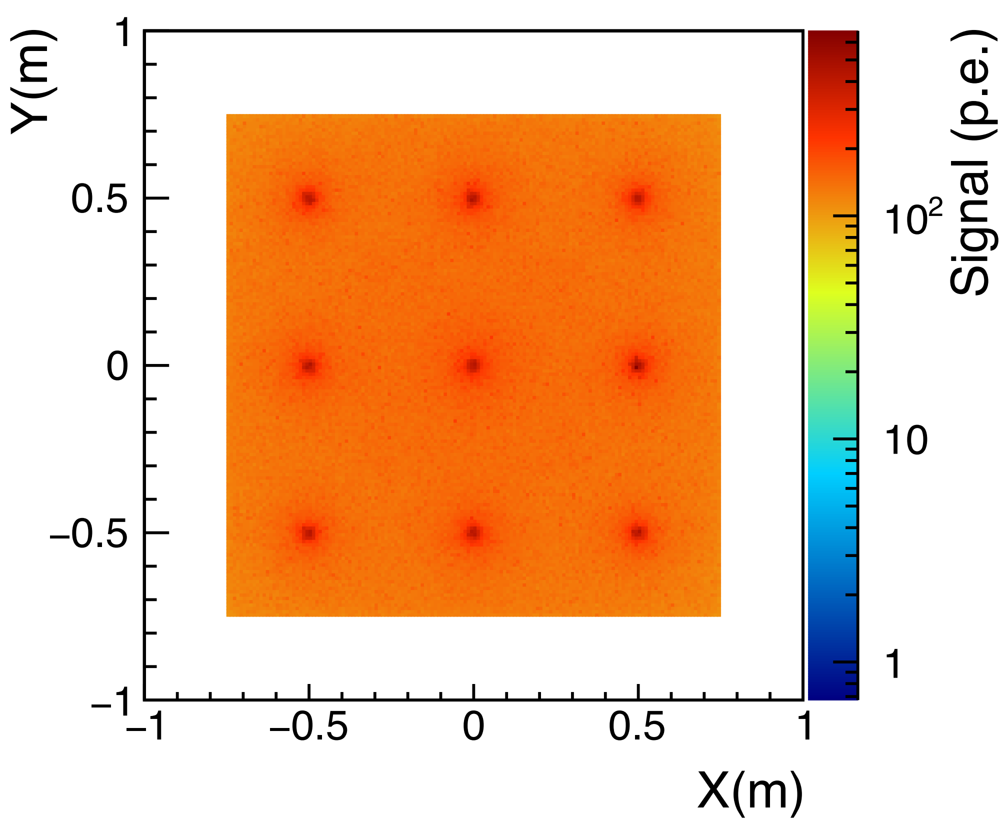
Signal size and uniformity

Vertical incidence

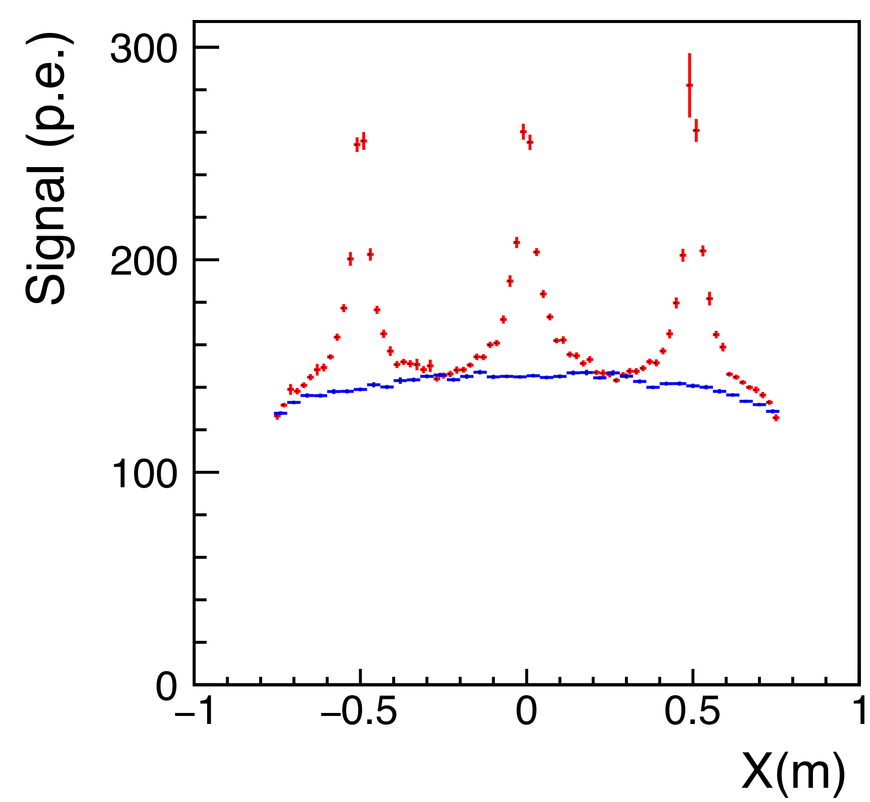


Photons



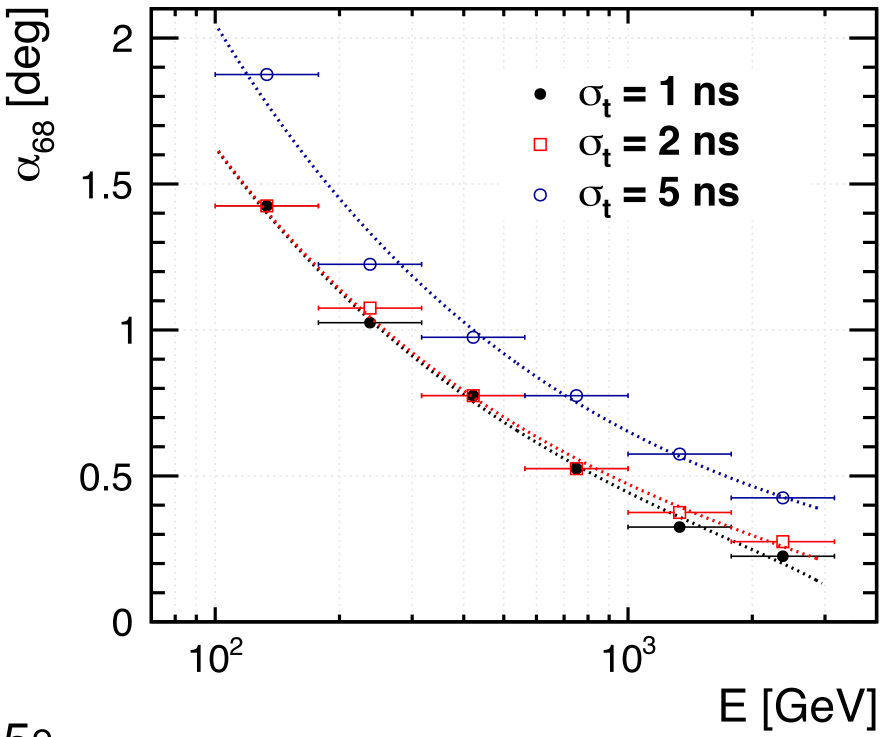


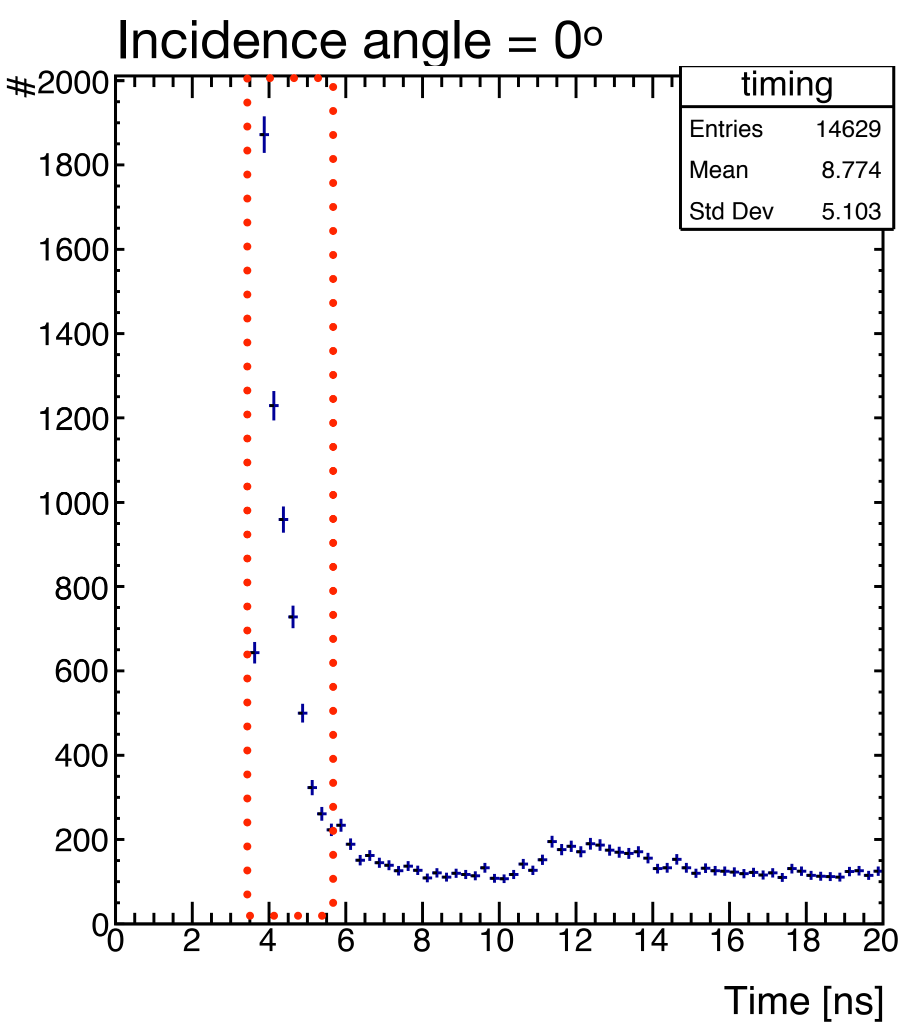
Muons

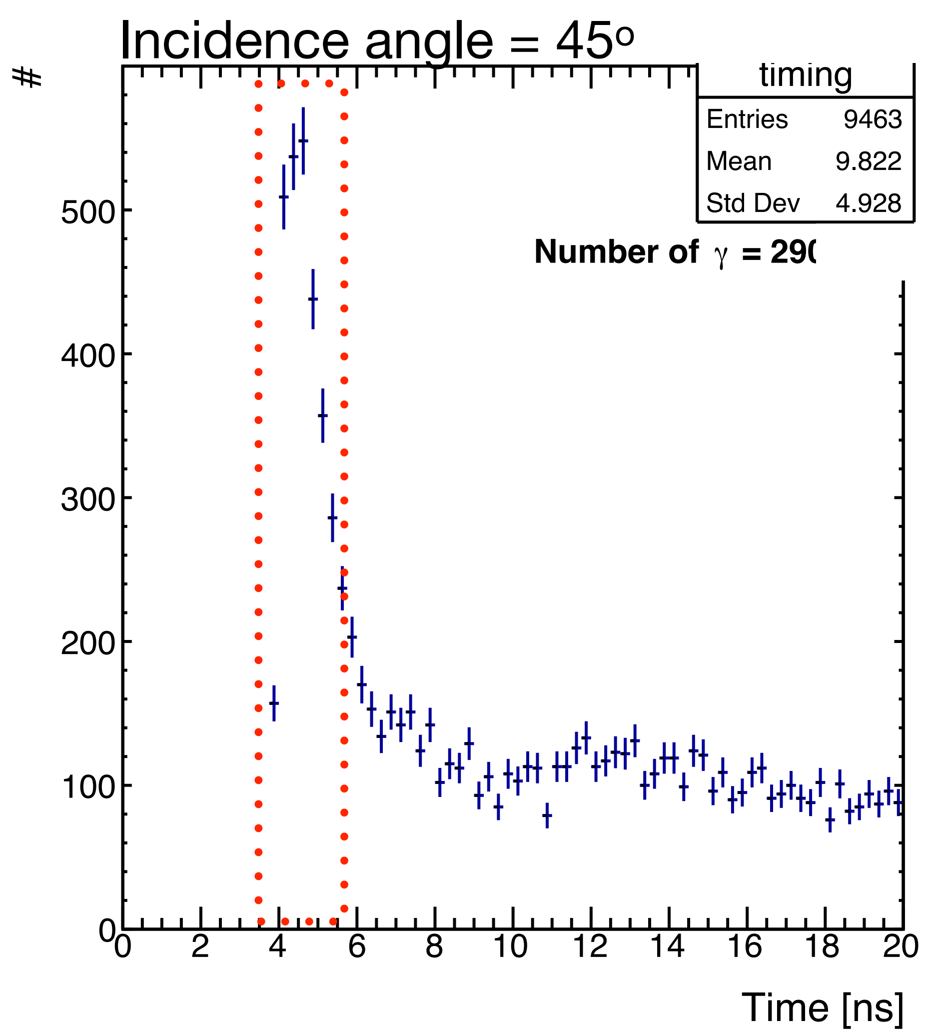


Station time trace

Photons with E = 15 MeV





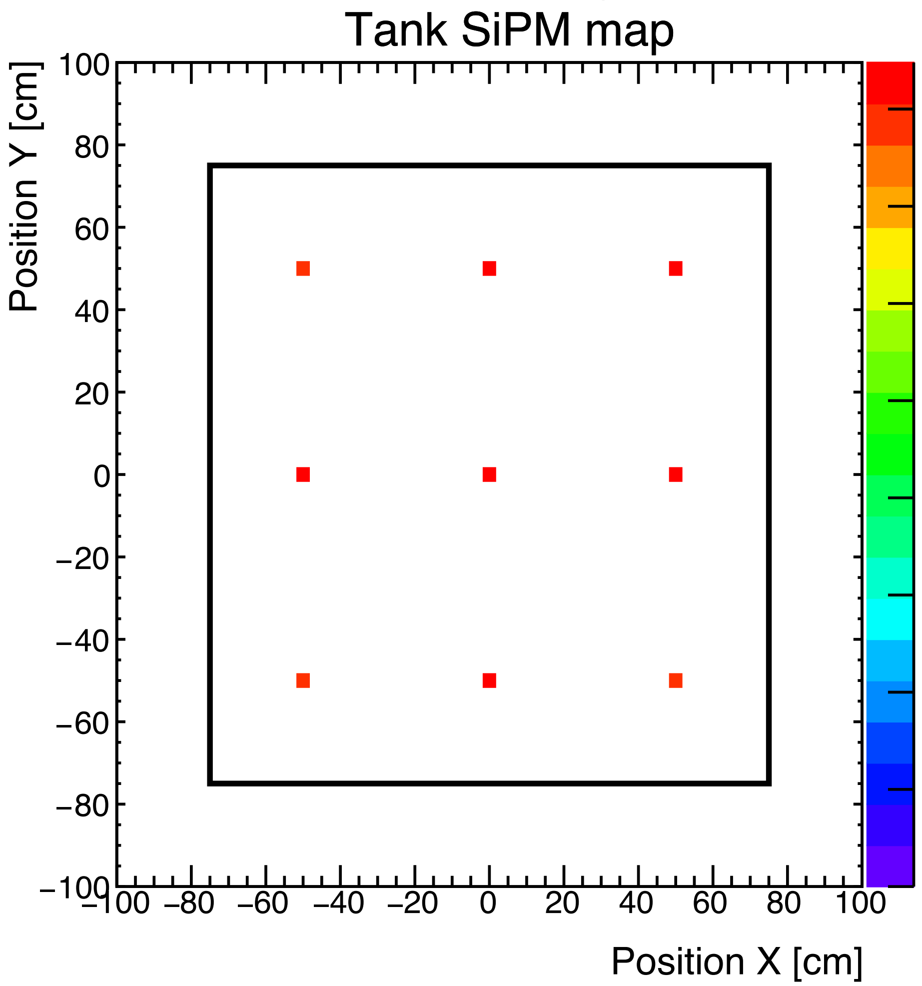


The fast, direct light pulse, arrives within 2 ns !

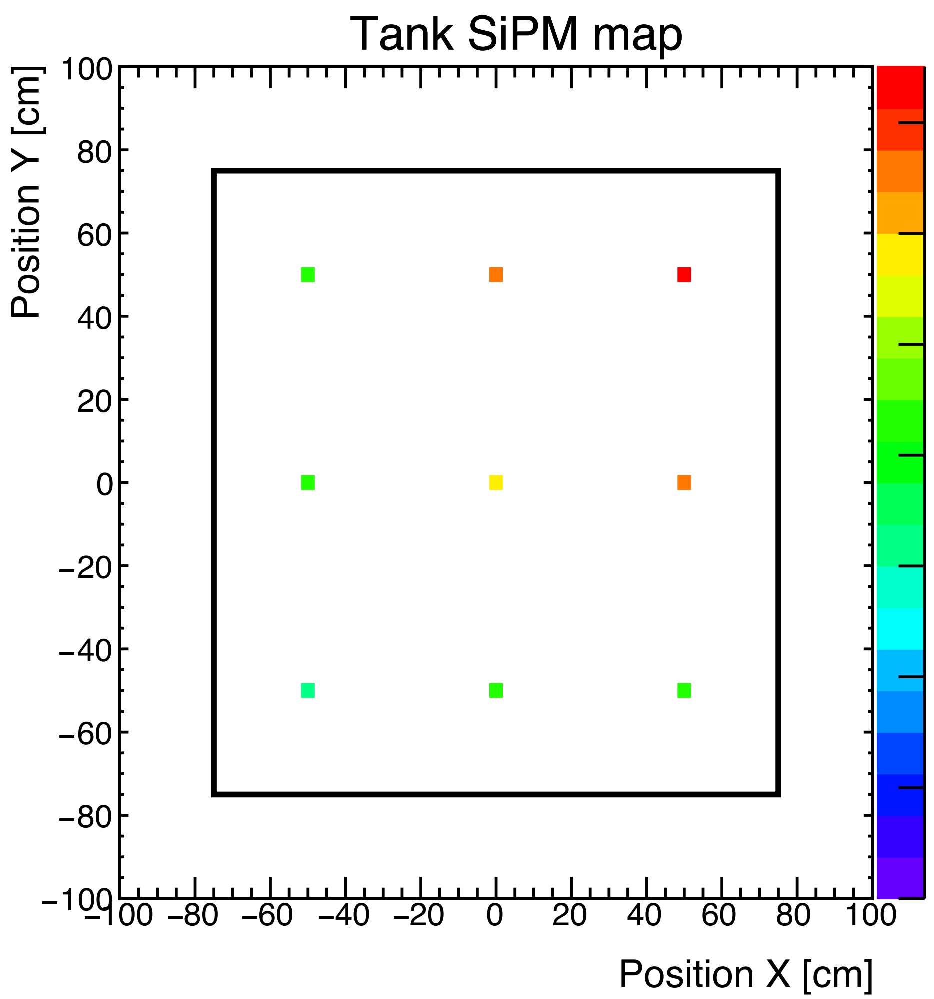
SiPM signal vs angle

Photons with E = 15 MeV

Incidence angle = 0°

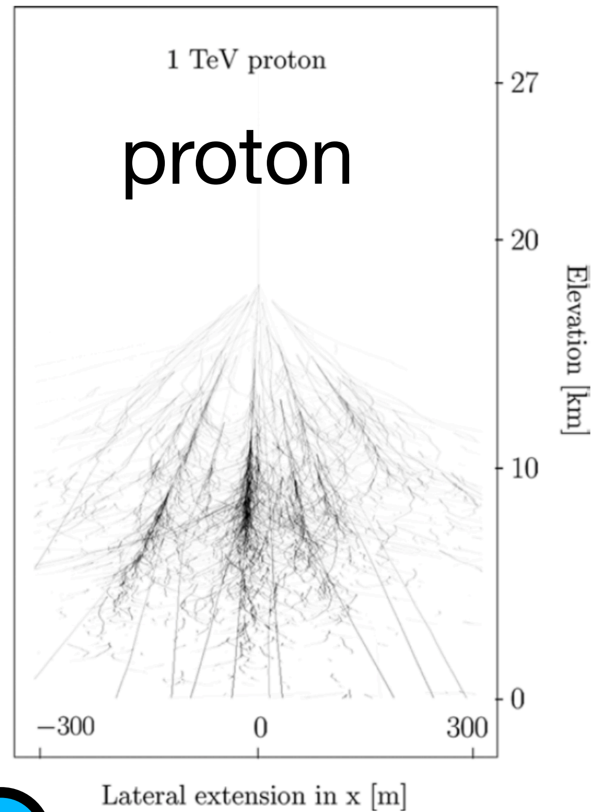


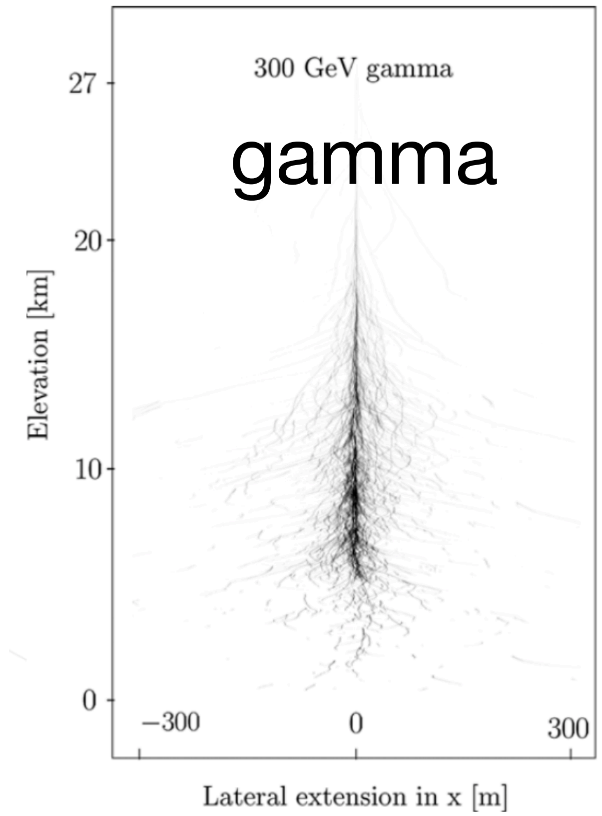
Incidence angle = 45°

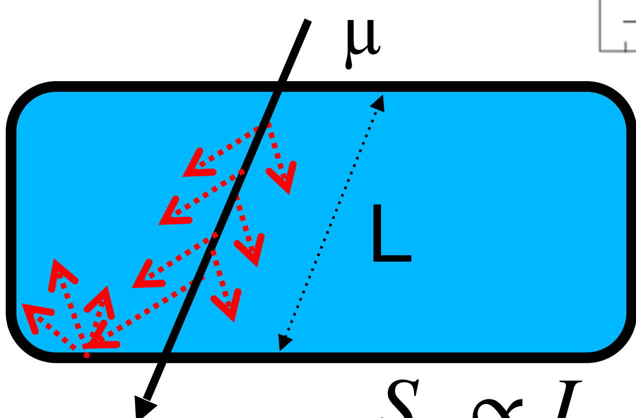


SiPM signal asymmetry gives additional information; to be explored ?

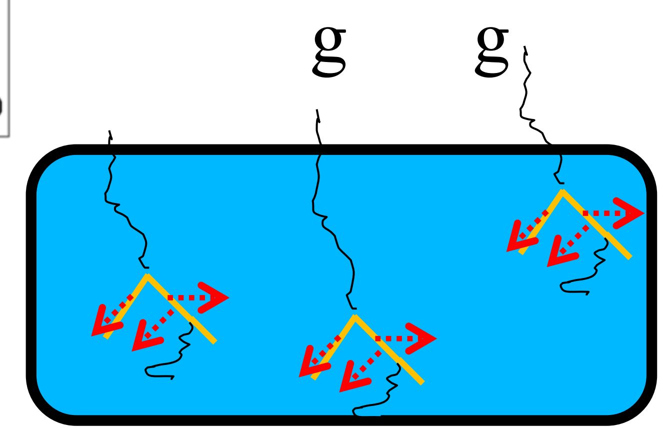
γ/h separation through muon id







$S_\mu \propto L$



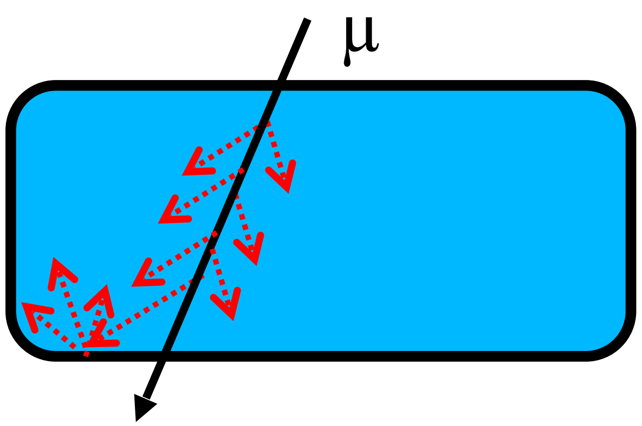
$S_{em} \propto (\rho_{em} \times A_{station} \times < E_{em} >)$

- At high energies muon counting is a powerful gamma/hadron discriminator;
- Muon id is usually based on its large Cherenkov signal in the WCD;
- Increasing Sμ/Sem :
  - Increase muon track length L; reduce station area $A_{station}$
  - Consider only stations at large distances to shower core : ρ_{em} and $<E_{em}>$ decrease with r_{Core}

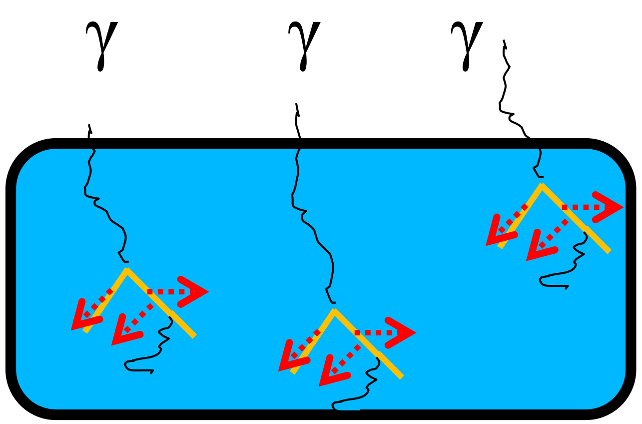
Muon id in a compact WCD

Exploring the timming and topological characteristics :

- Fast direct Cherenkov light pulse of a **single muon** is seen mainly in only a part of the readout matrix



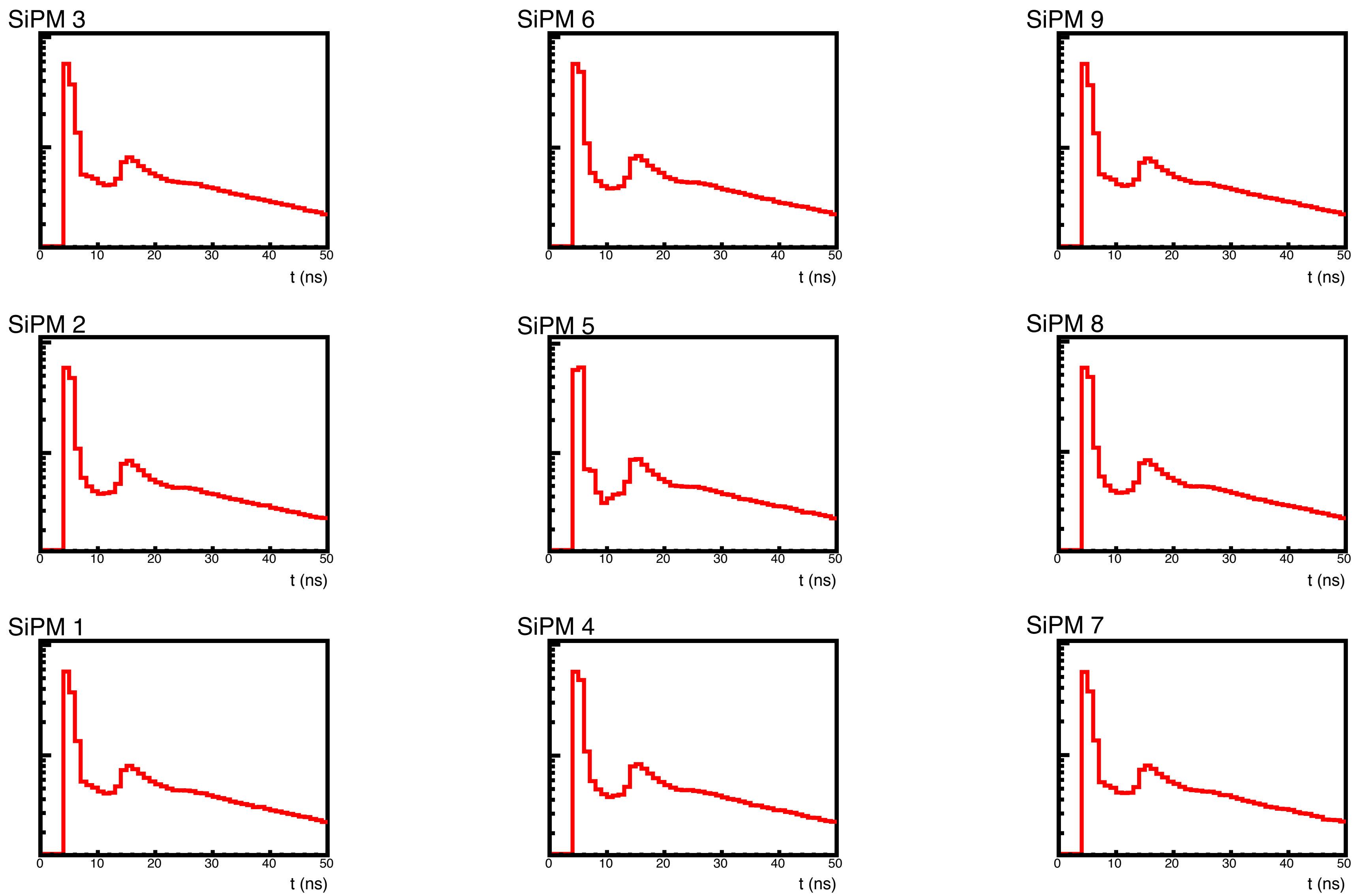
- The spreaded signal of **several photons/electrons** entering at random positions in the WCD is seen across the whole readout matrix



First tests …

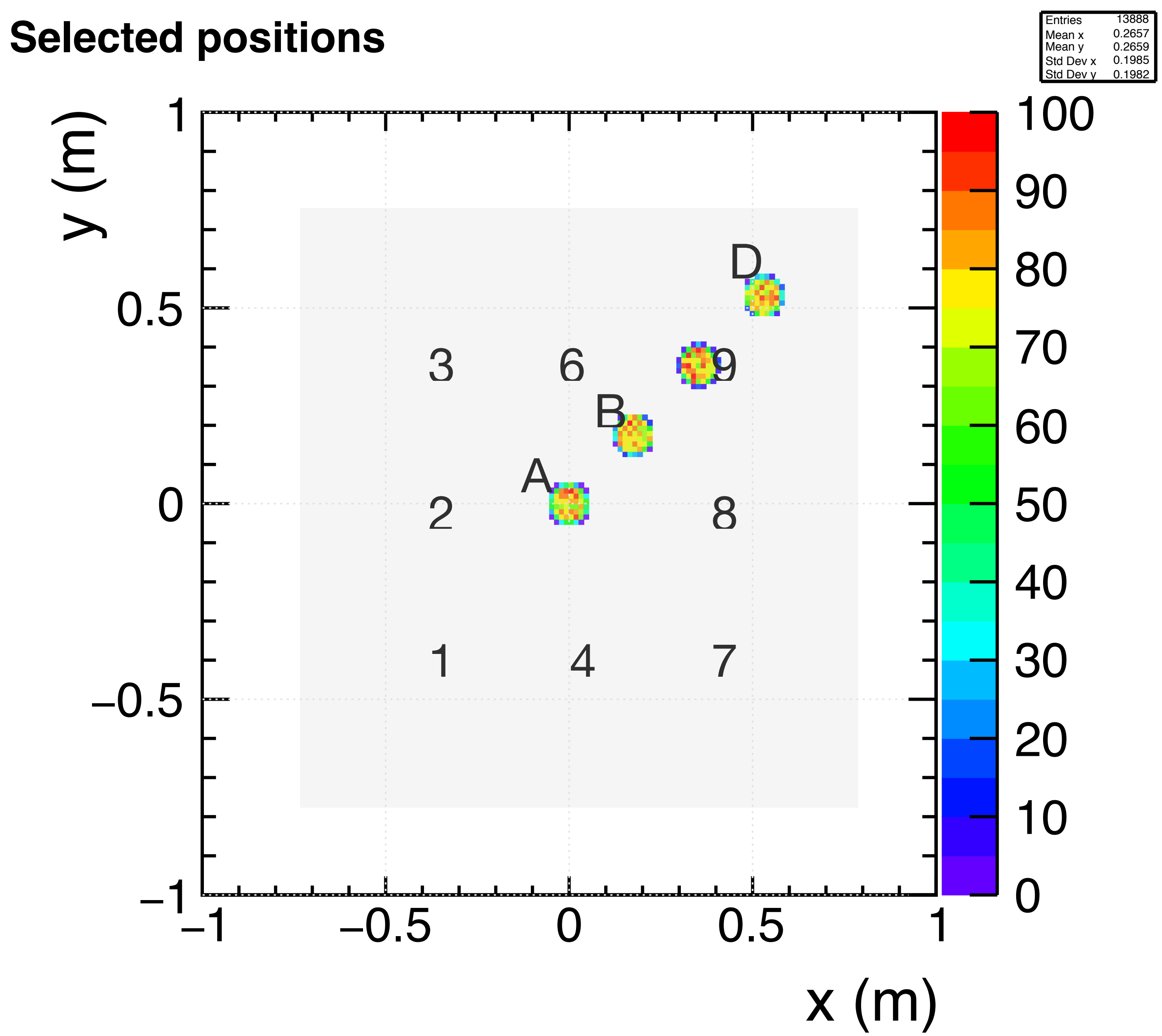
- For r > 40 m : $S_\mu \sim 25 \times S_\gamma$
- Each "photon event" consists of 25 photons injected uniformly in the WCD;
- Total signal ~ signal from a single muon

Average traces for photons



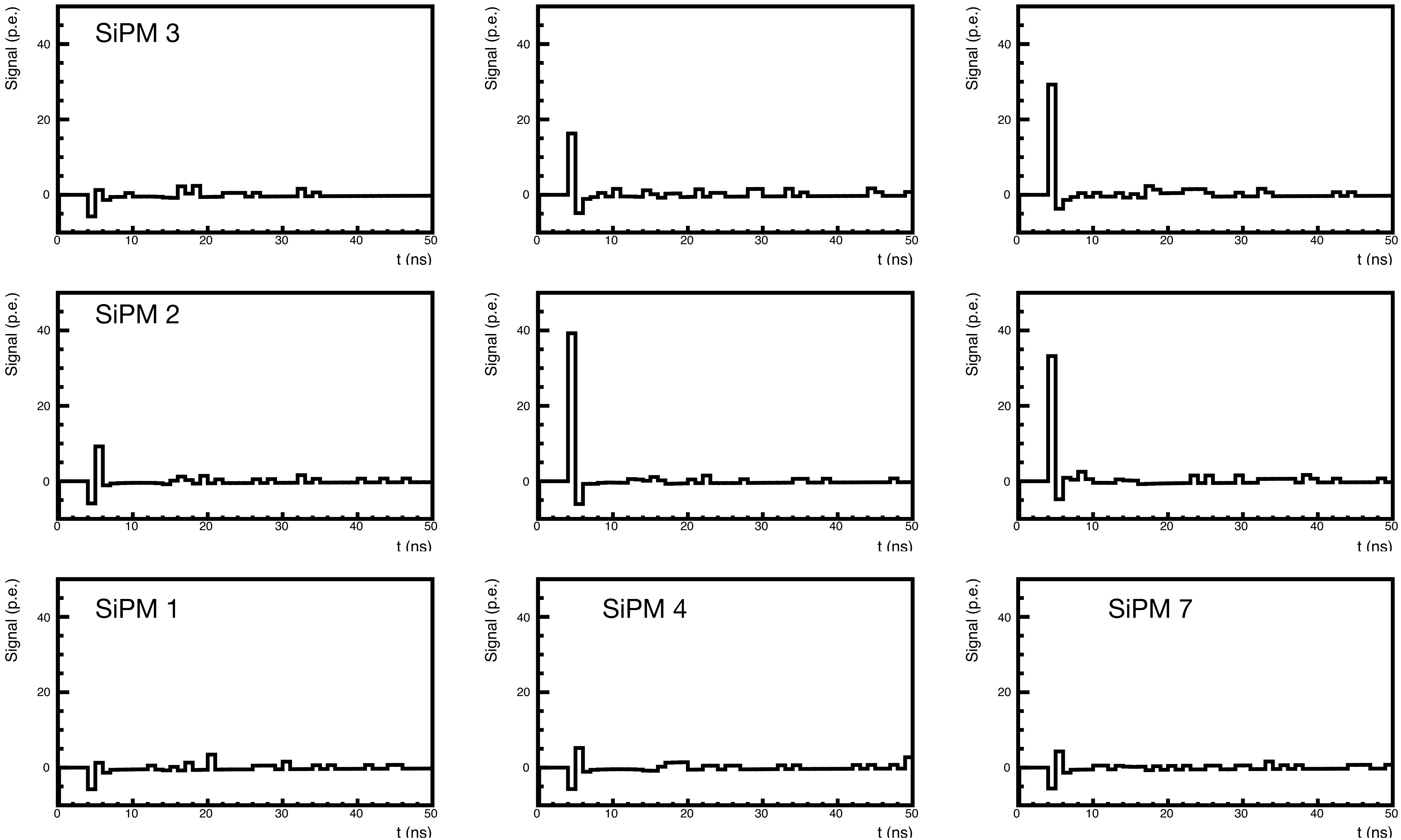
First tests …

Compute *event by event differences of traces:* **muon - <gamma25>**

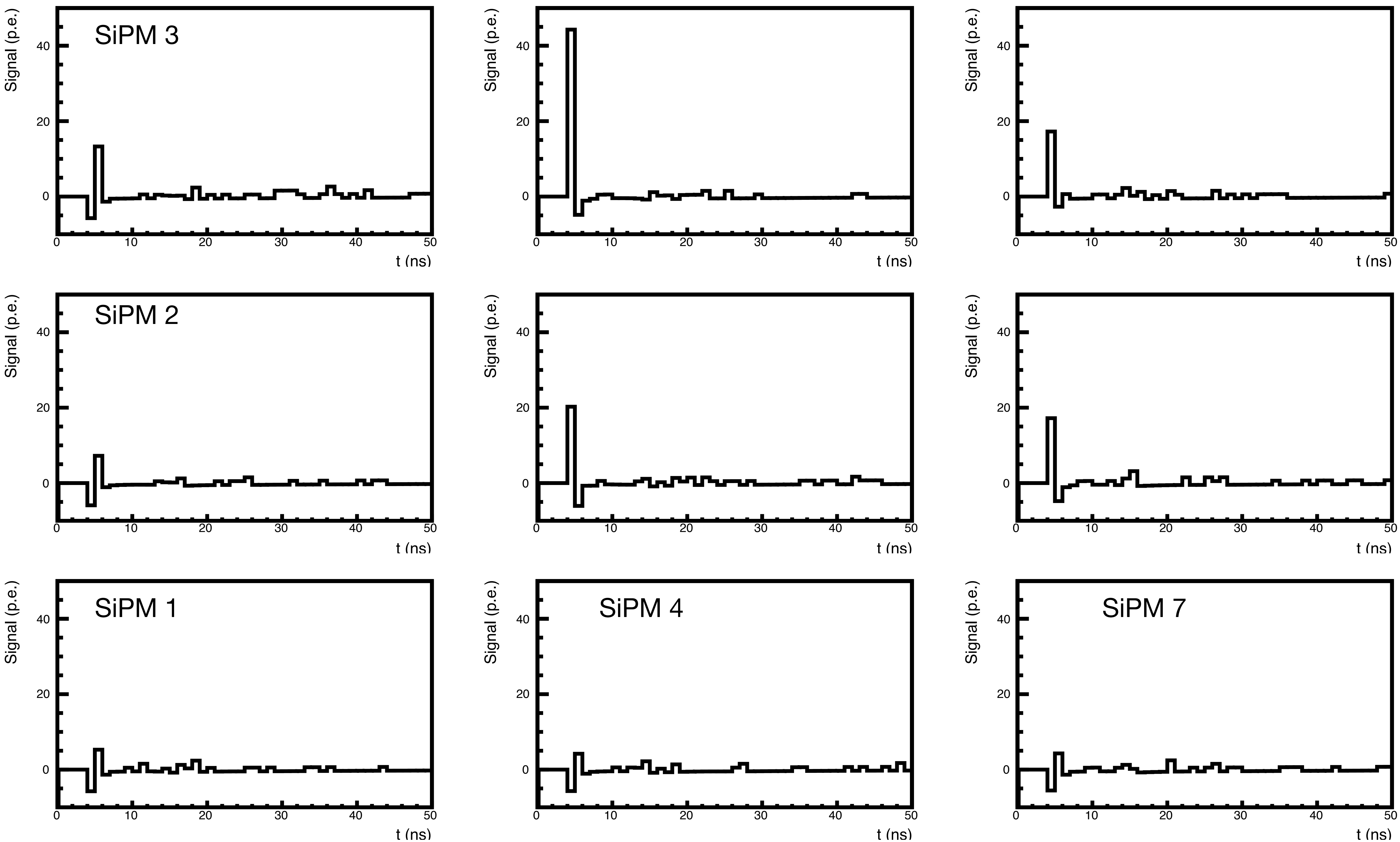


Single muons @ position B —>

Differences of traces : muon - <gamma25>

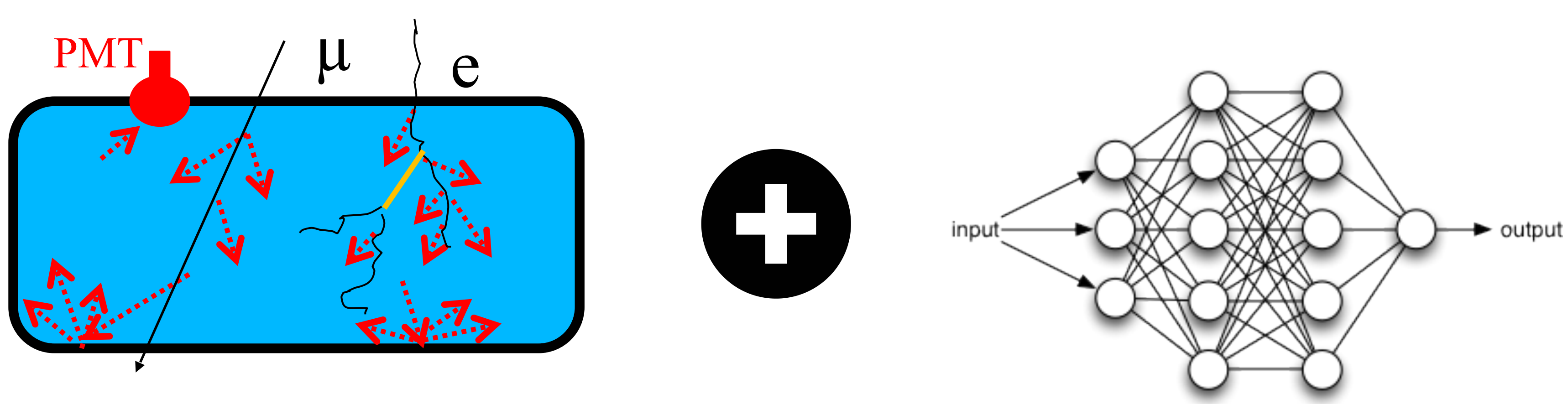


Differences of traces : muon - <gamma25>



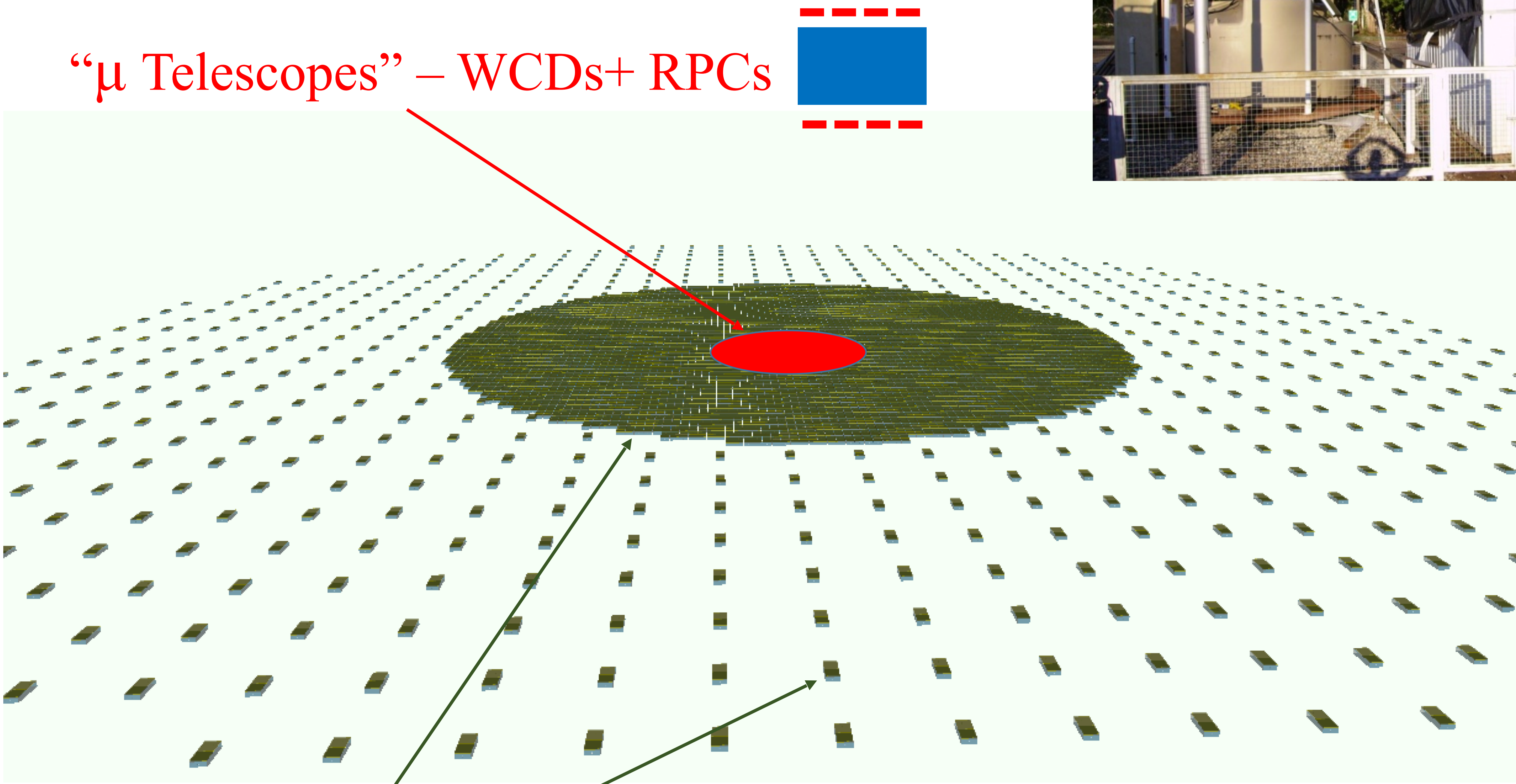
Towards Muon id with a compact WCD

- Preliminary, single-station, assessment quite promising
- Starting studies with shower events
  - Explore ANN techniques
  - Granada group starting to look into simulations
- Stations close to the shower core could also be used ? …



New layout

RPC hodoscope in test WCD at Auger Observatory



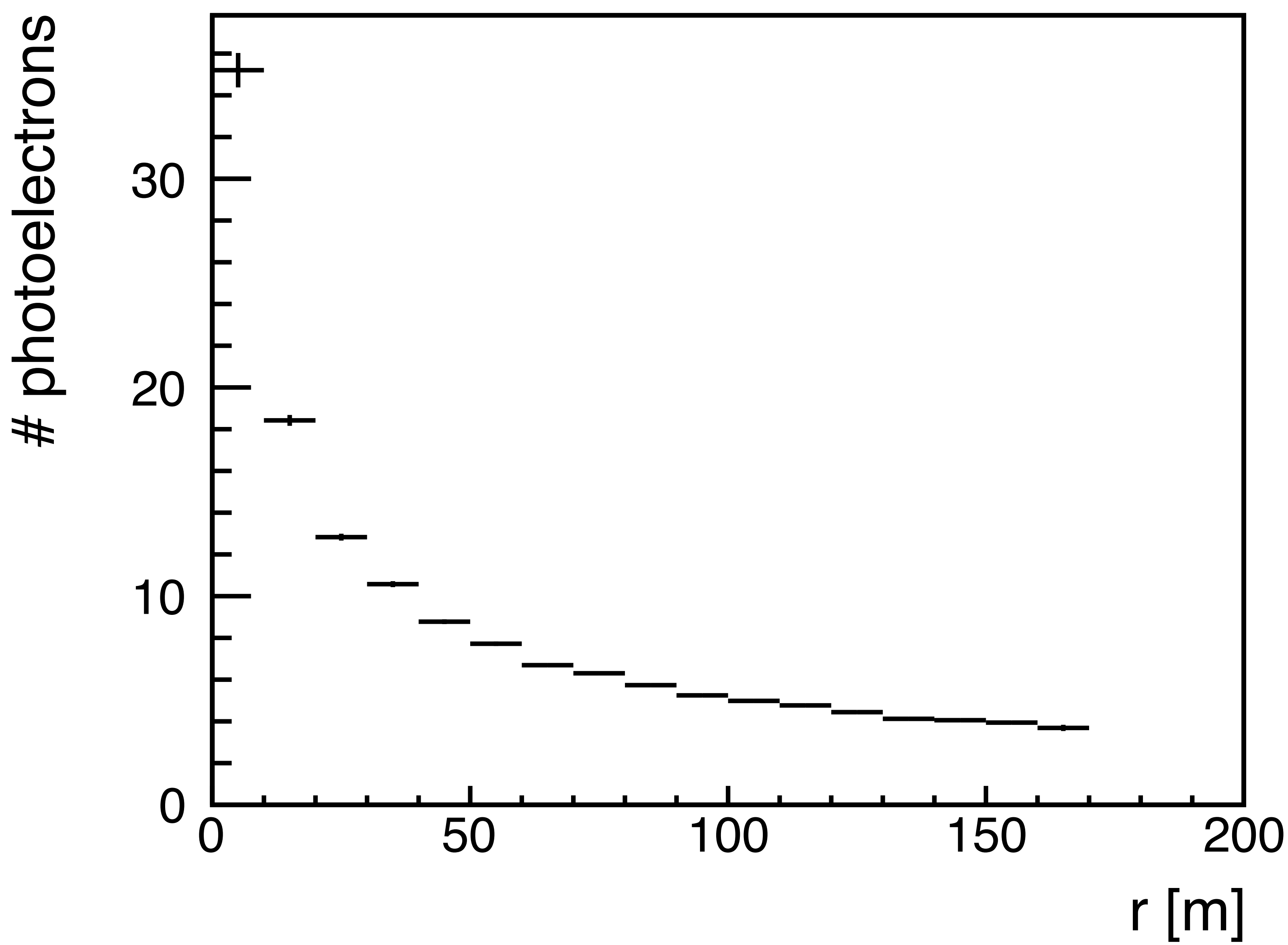
WCDs

- Train and validate ANN techniques with data
- Study + monitor + calibrate WCD response

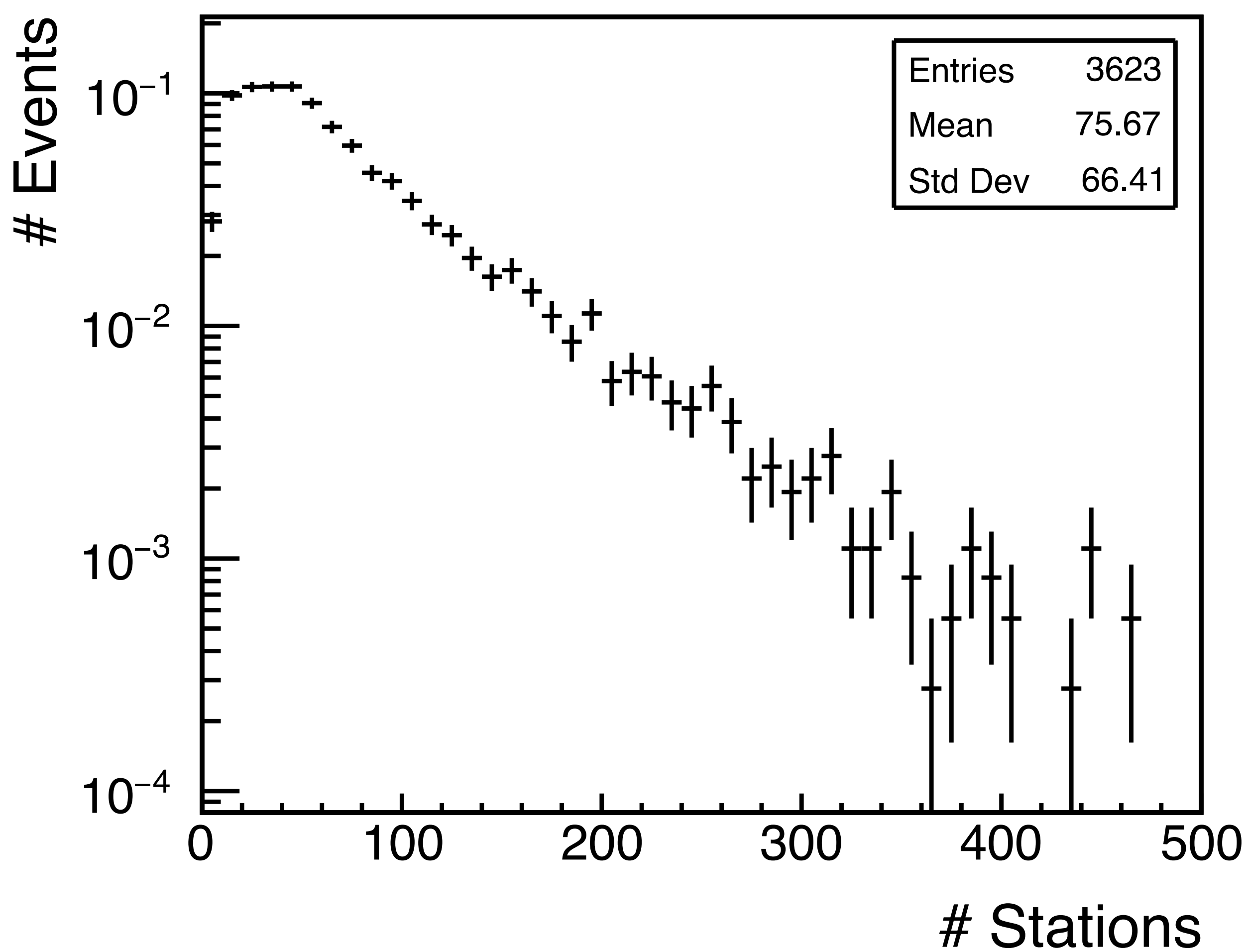
First simulation studies

- Standalone Geant4
  - Single particles uniformly injected at top surface
  - Photons @ fixed E and with shower energy spectra
- **Shower simulations**
  - Circular array with R = 160 m (80000 m^2) @ 5200 m altitude
  - Corsika showers @ LogE in [2.0,2.2] ; $\theta = 10^o$

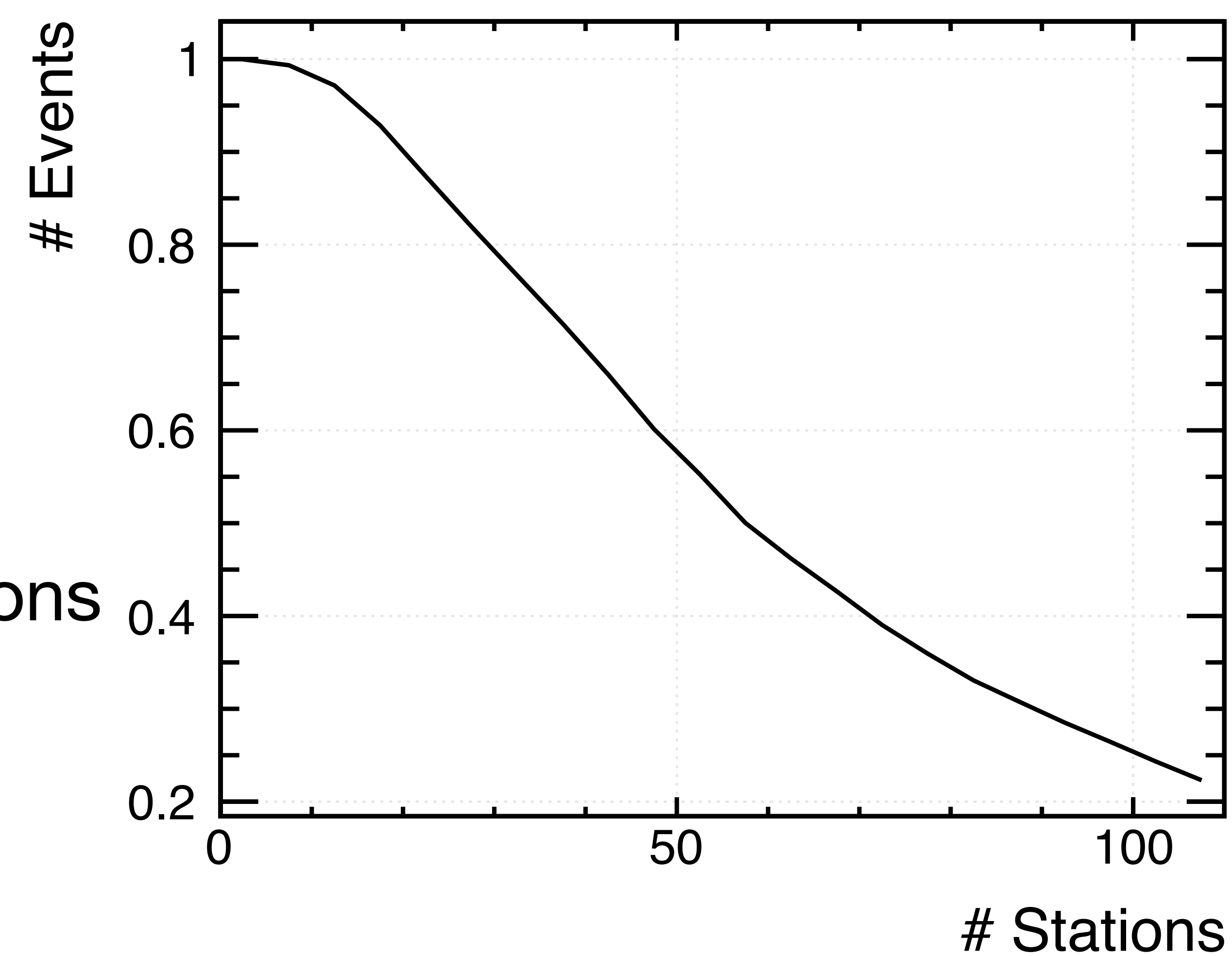
Station signal mean LDF
@ 100 GeV



Stations with detected signal

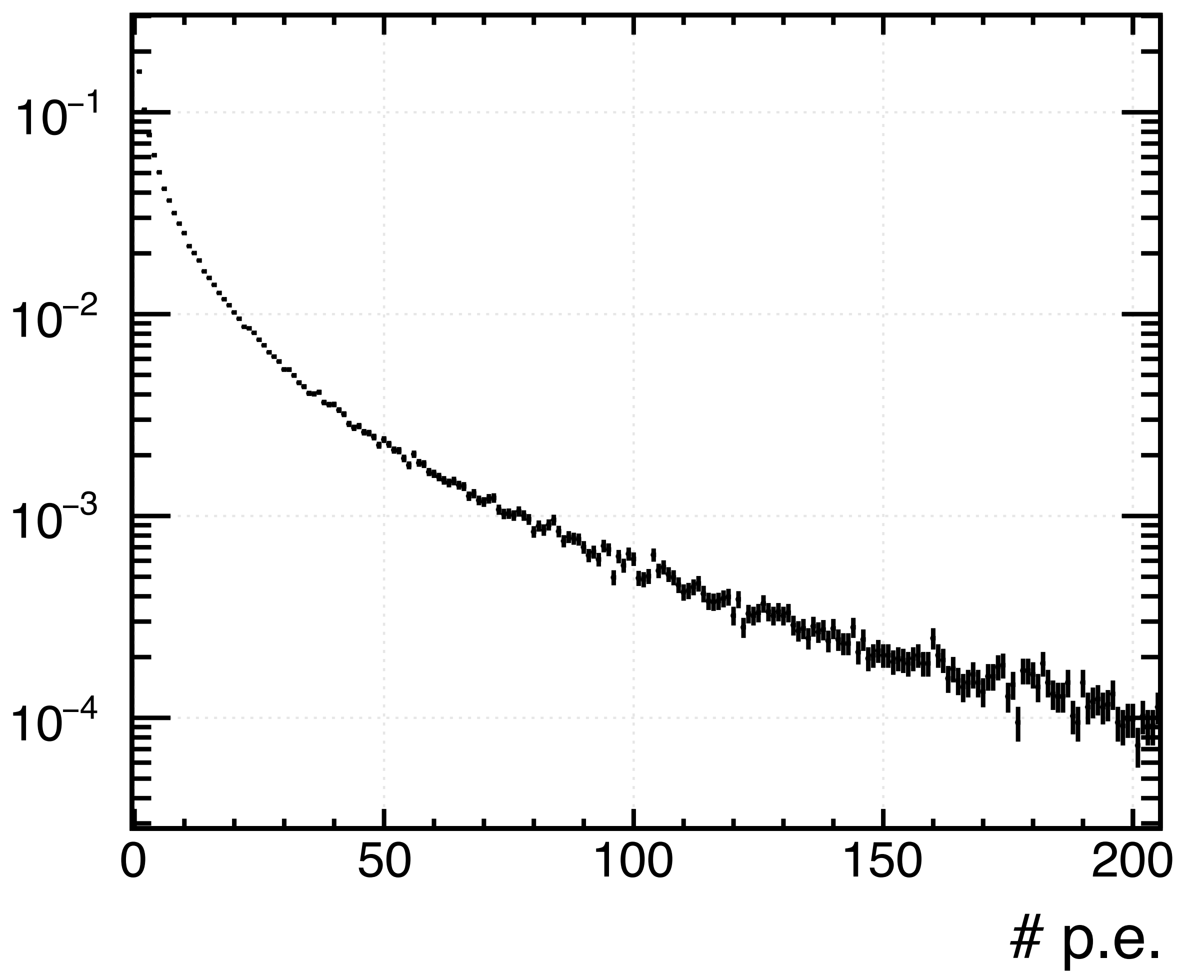


@ 100 GeV

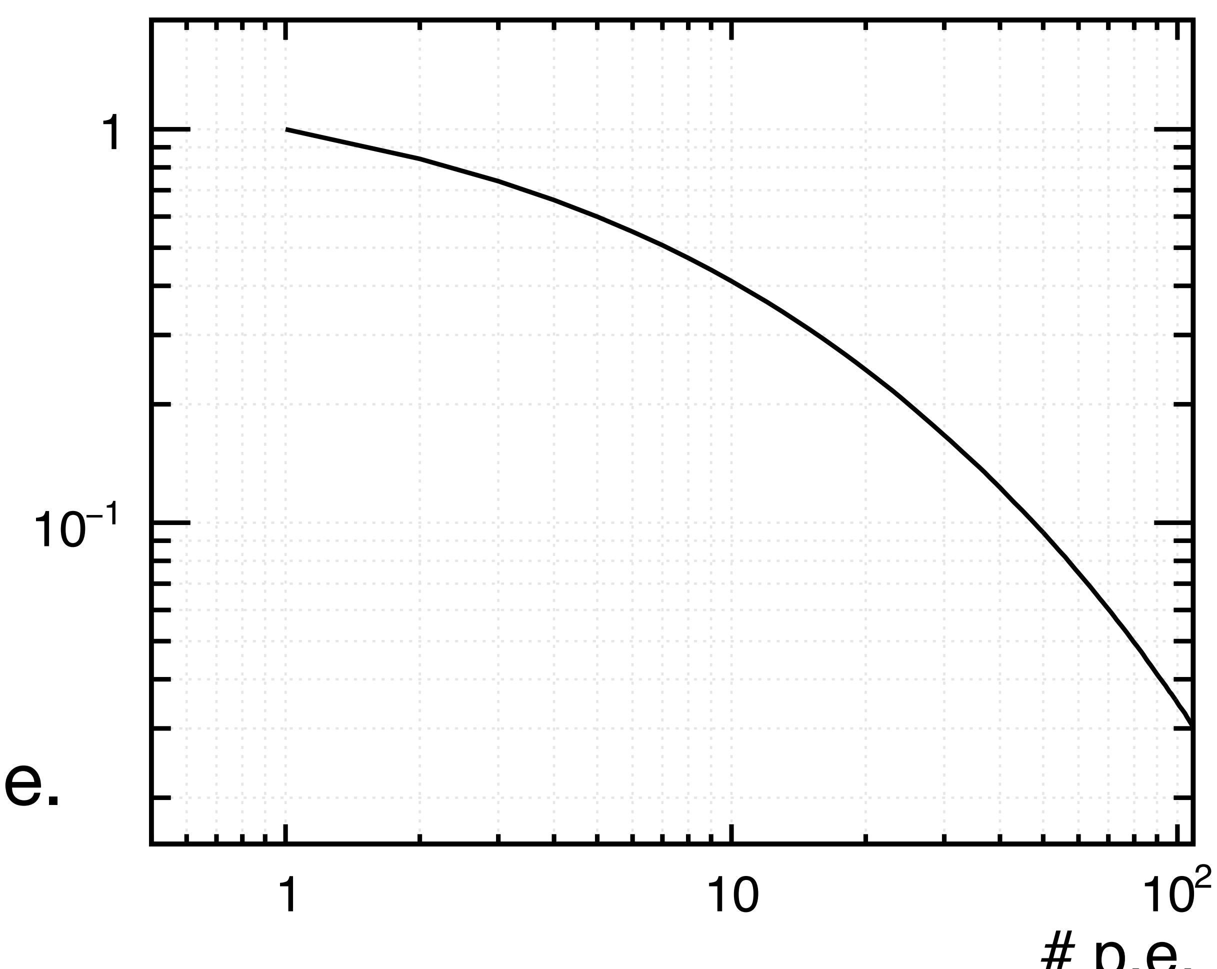


90% of the events have > 20 active stations

Station signal

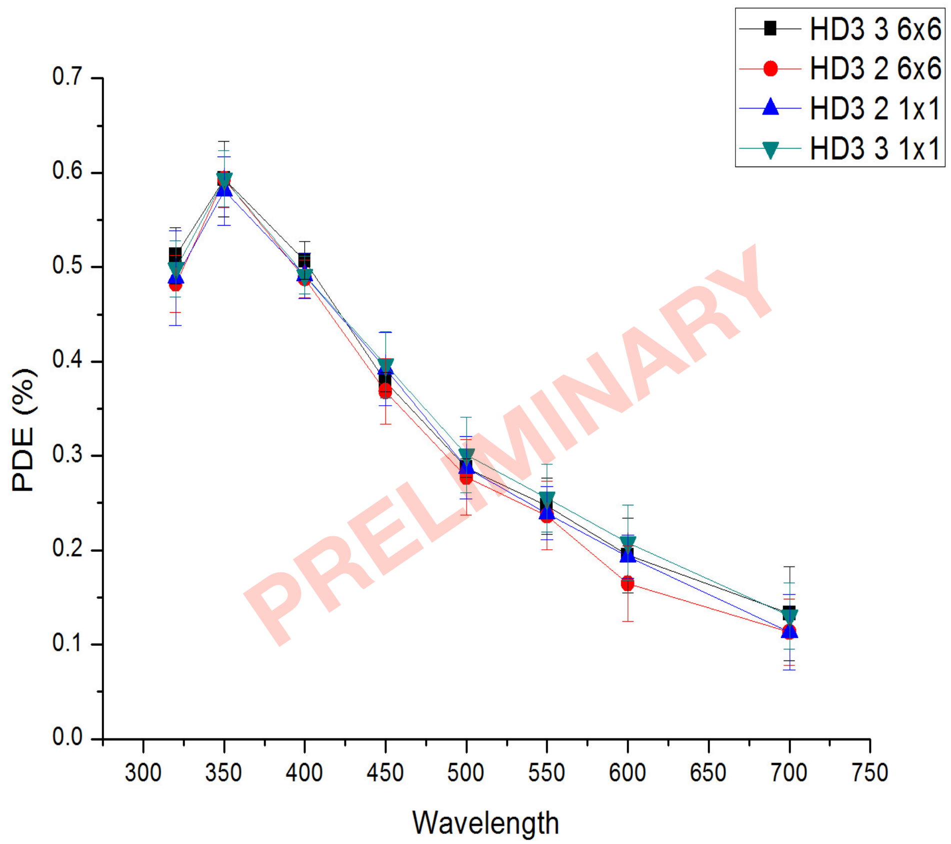


@ 100 GeV



~ 40% of the active stations have > 10 p.e.

- All simulations based on an old SiPM PDE curve;
- Recent measurements by the Padova group on new SiPMs show better performance, namely towards small wavelenghts;
- Simulations to be updated with new PDE curve…



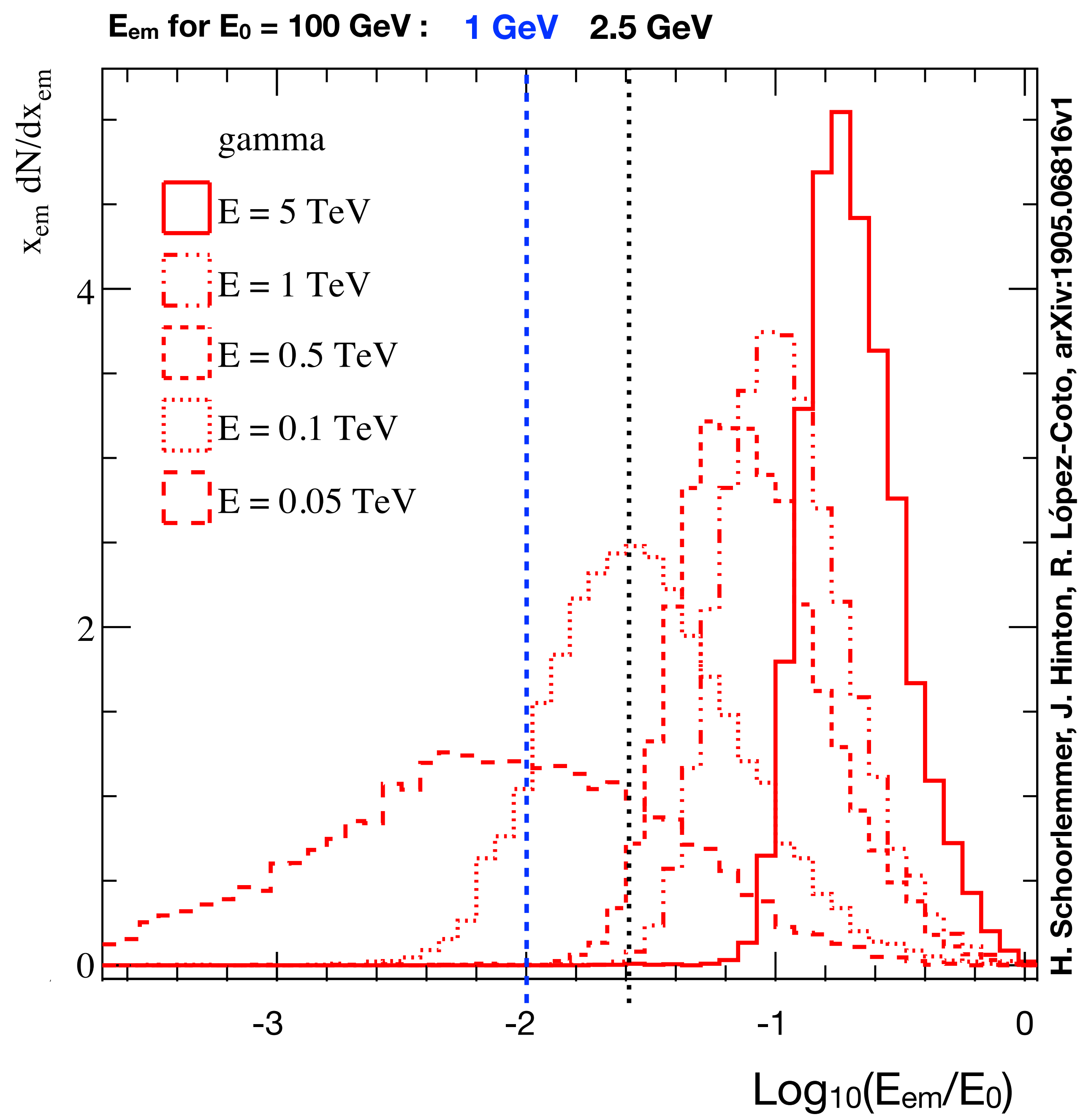
Summary

- First considerations on a **compact WCD with SiPM readout**
- Triggering at **100 GeV** difficult, but may be achievable…
- Timing, using fast direct light pulse, at the level of 2 ns
- Muon id exploring time trace and using ANN is promising

  –> Small core (about 100 stations) complemented with RPC hodoscopes
- Nothing yet optimised… WCD dimensions, light readout, …

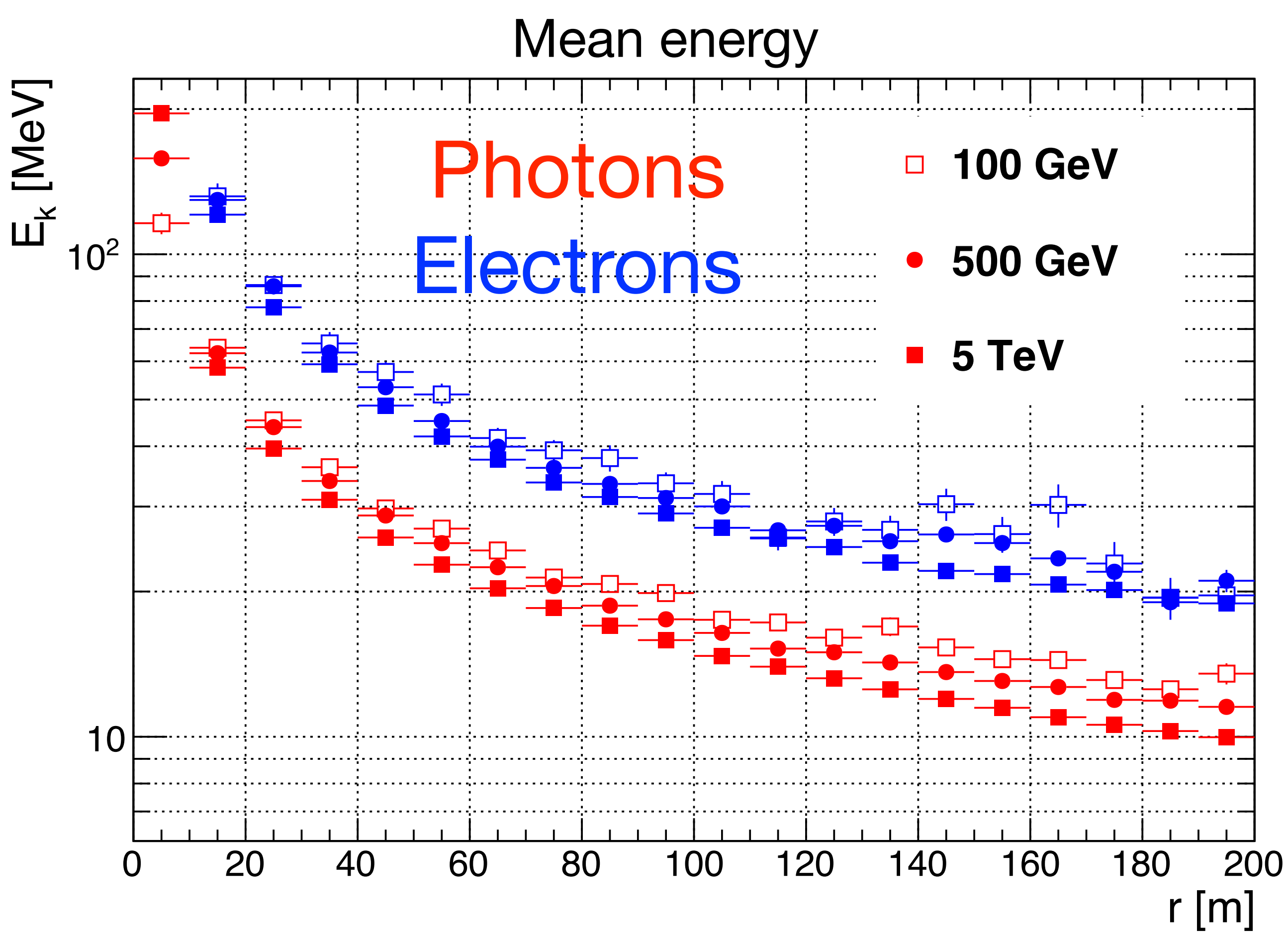
END

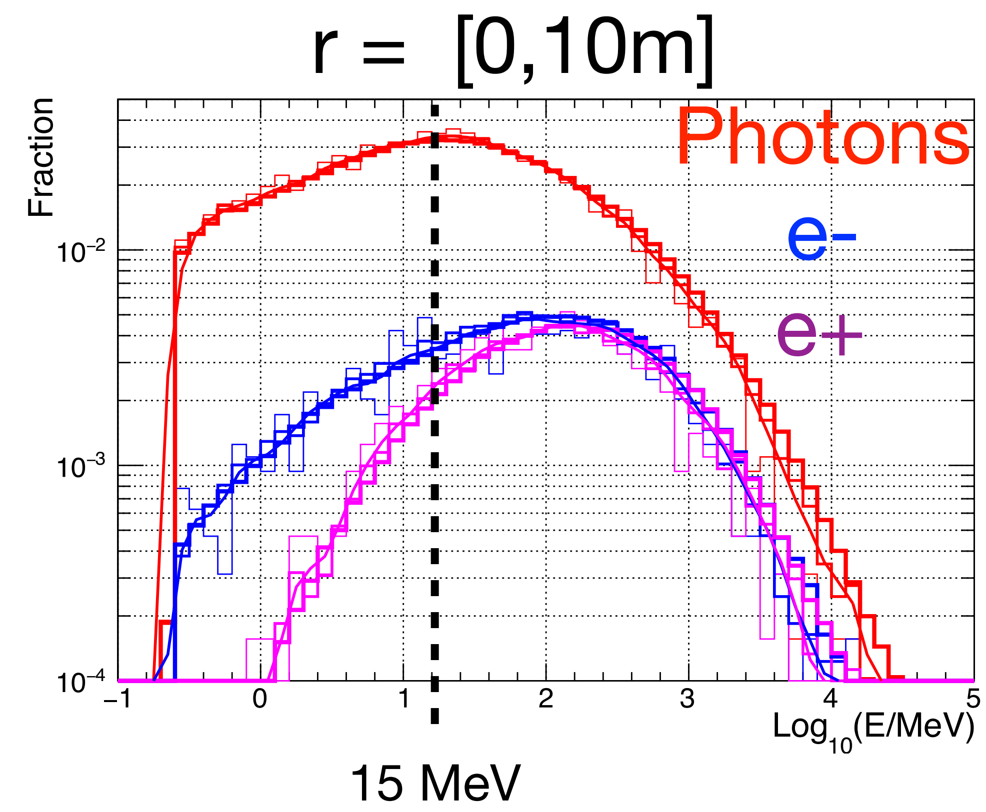
EM energy @ 5000 m

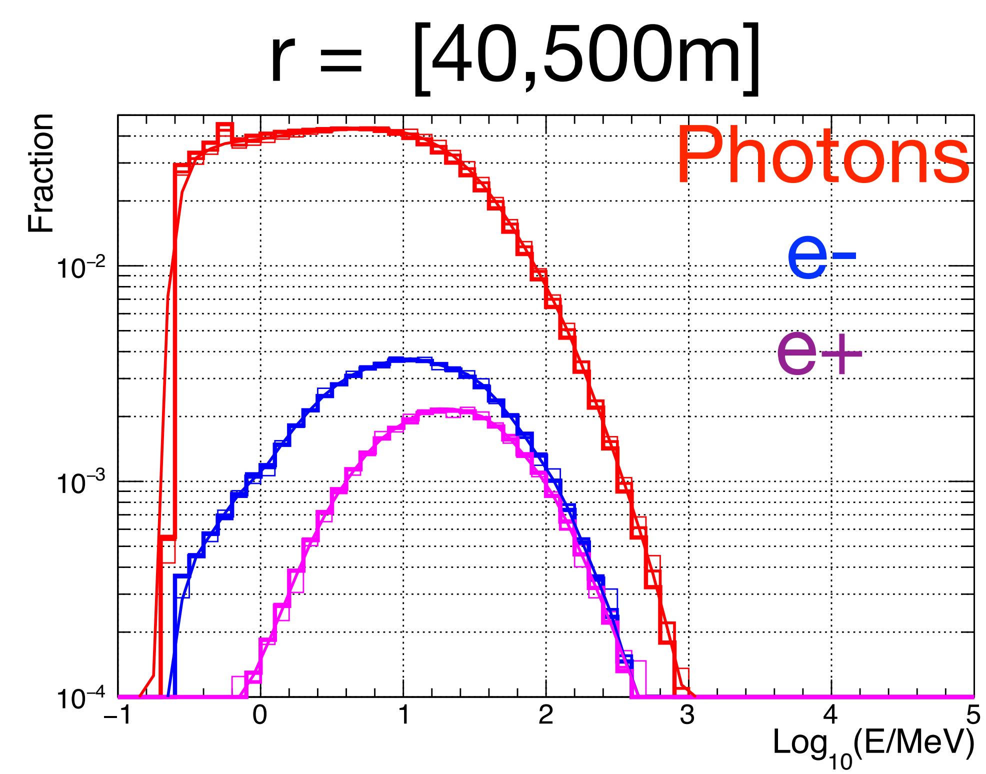


- For E_{em} ~ 1 GeV —> ~ 100 photons @ ground, each with a typical energy of 10 MeV - 15 MeV
- WCD sensitivity to single ~ 10 MeV photons is a challenge !

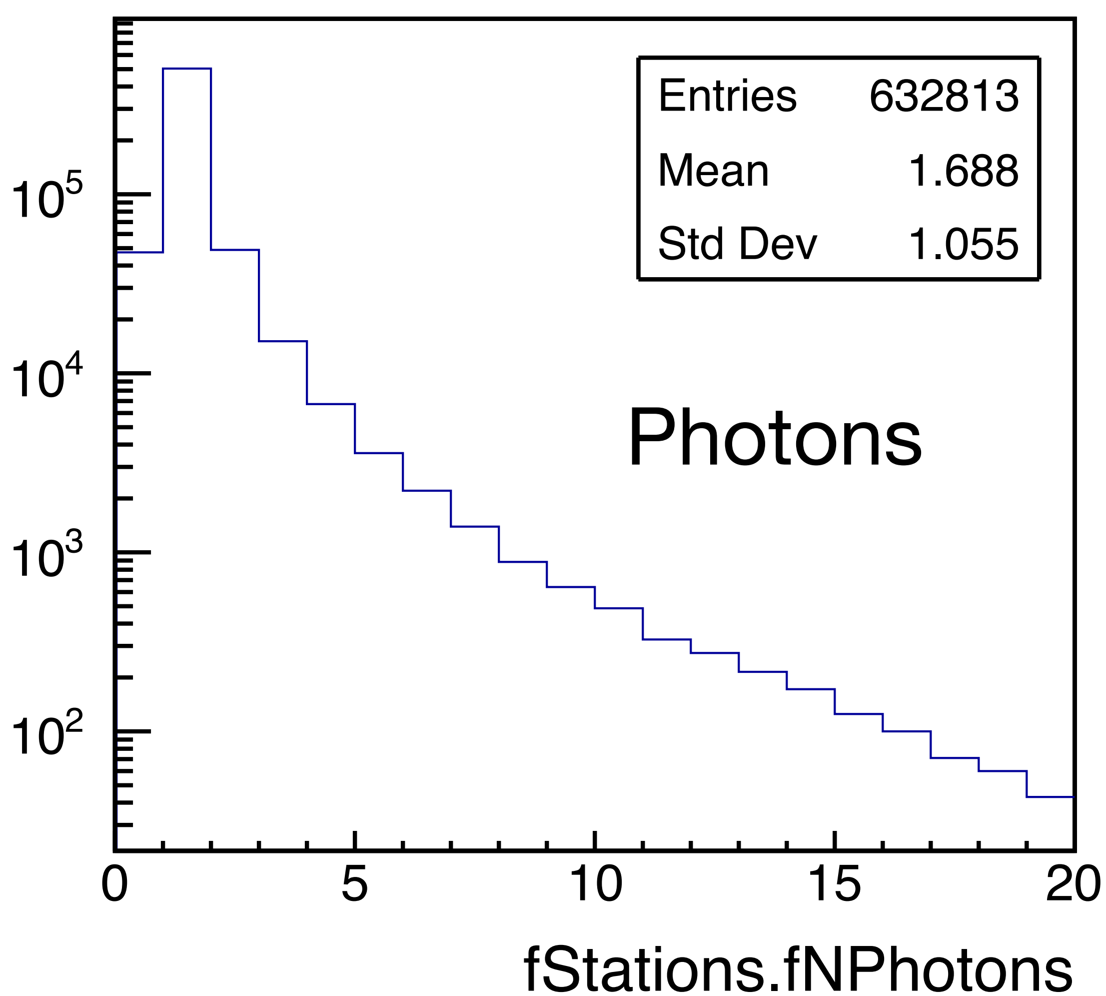
Secondary particle energy at ground (5200m) for gamma showers

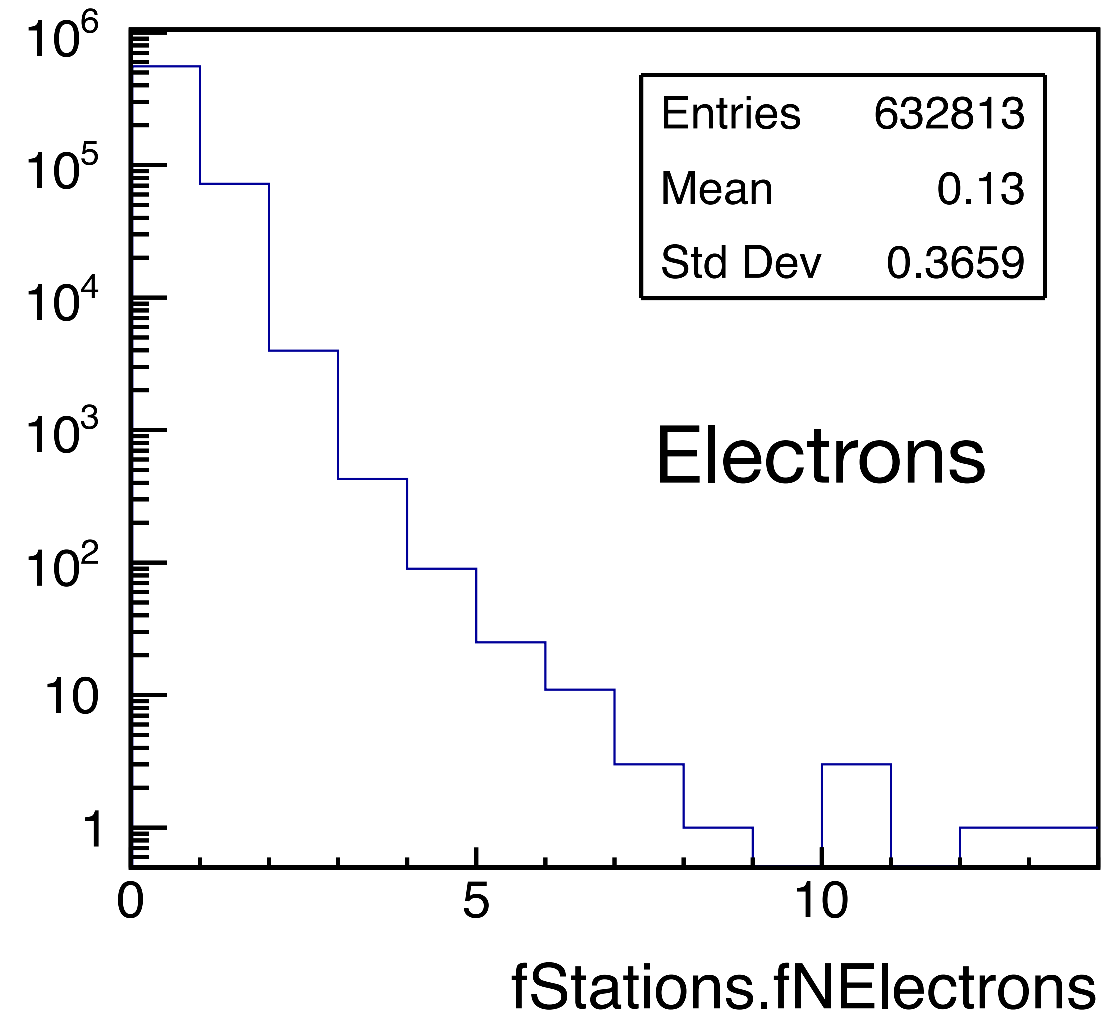






particles per station
@ 100 GeV





~ 80% of the stations have only 1 photon