Simulation study for the proposed gamma-ray detector array ALTO

Satyendra Thoudam
Yvonne Becherini
Michael Punch

Linnaeus University
Växjö, Sweden

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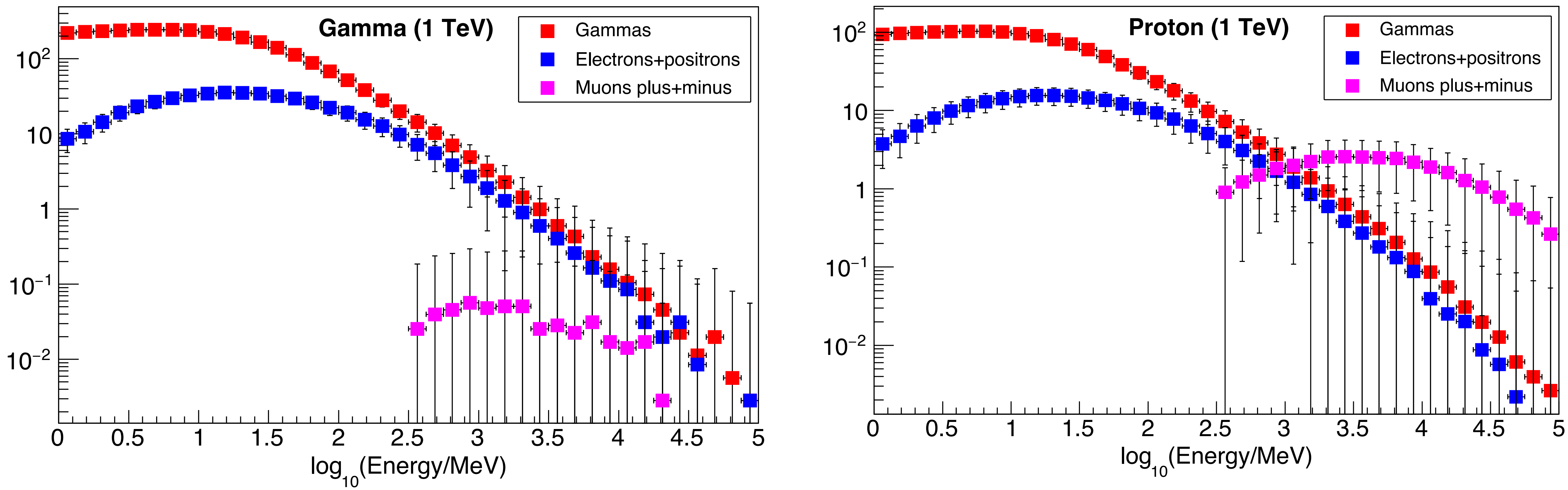
Introduction

- Some properties of air shower particles at high altitude
- Brief description of ALTO detector array
- Monte-Carlo simulation
- Reconstruction of air shower parameters for gammas & protons
- Preliminary estimates of array performance
- To do list ….

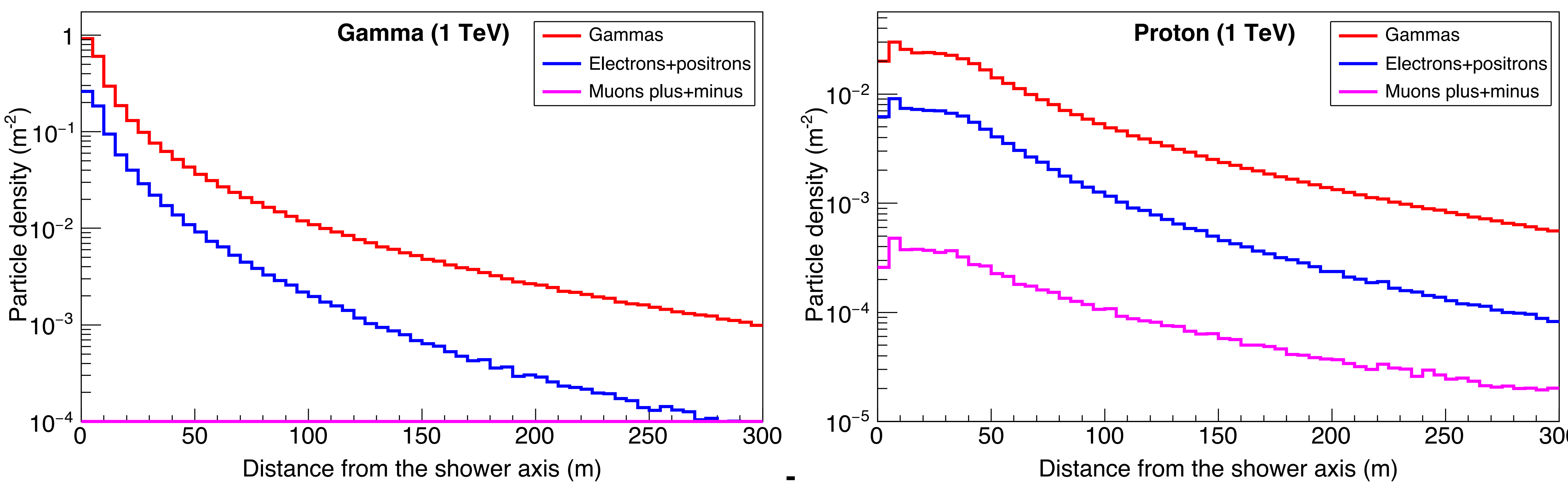
Distribution of air shower particles at the ground

(Primary energy 1 TeV; Altitude 5.1 km a.s.l)

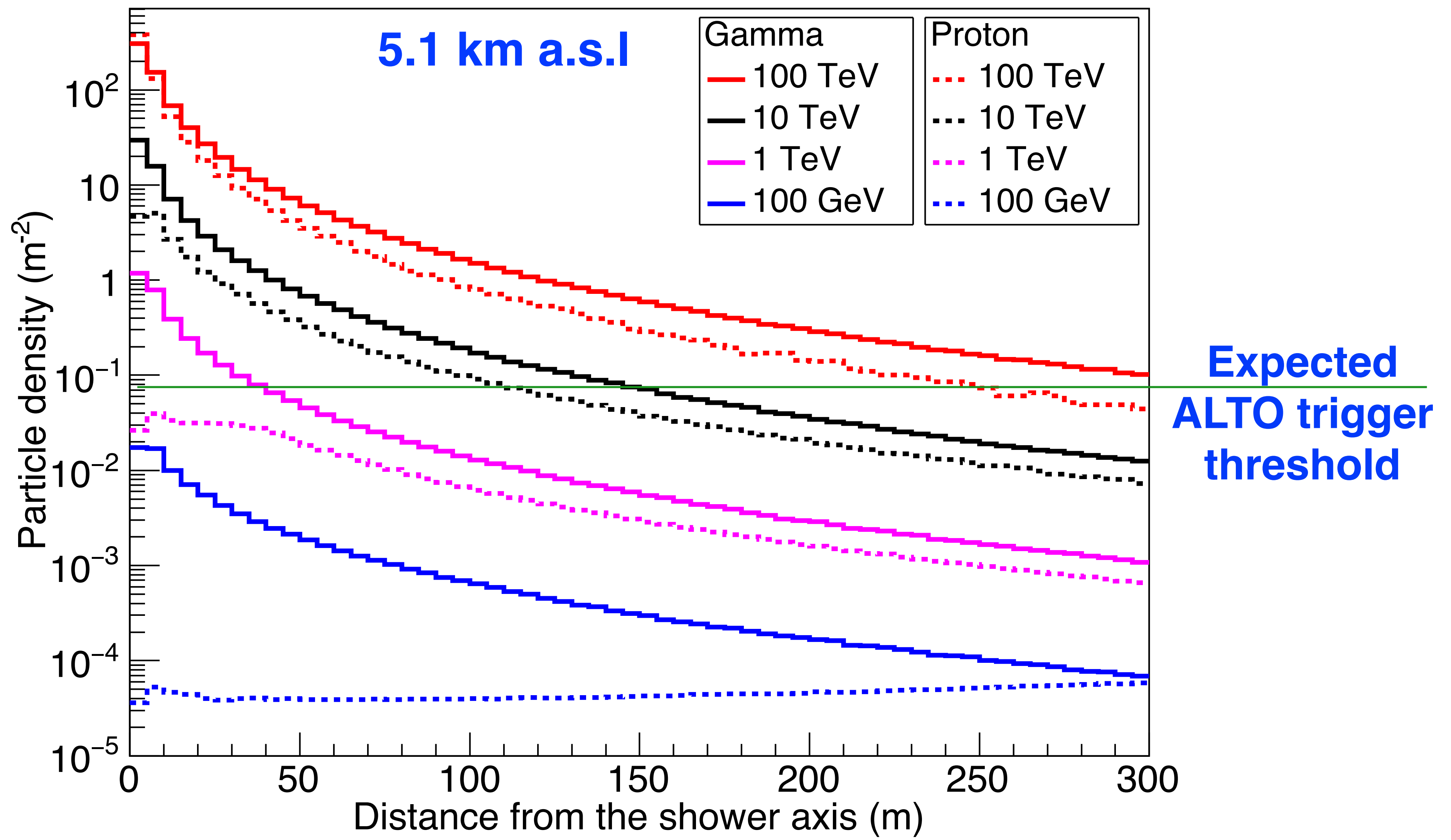
Energy distribution

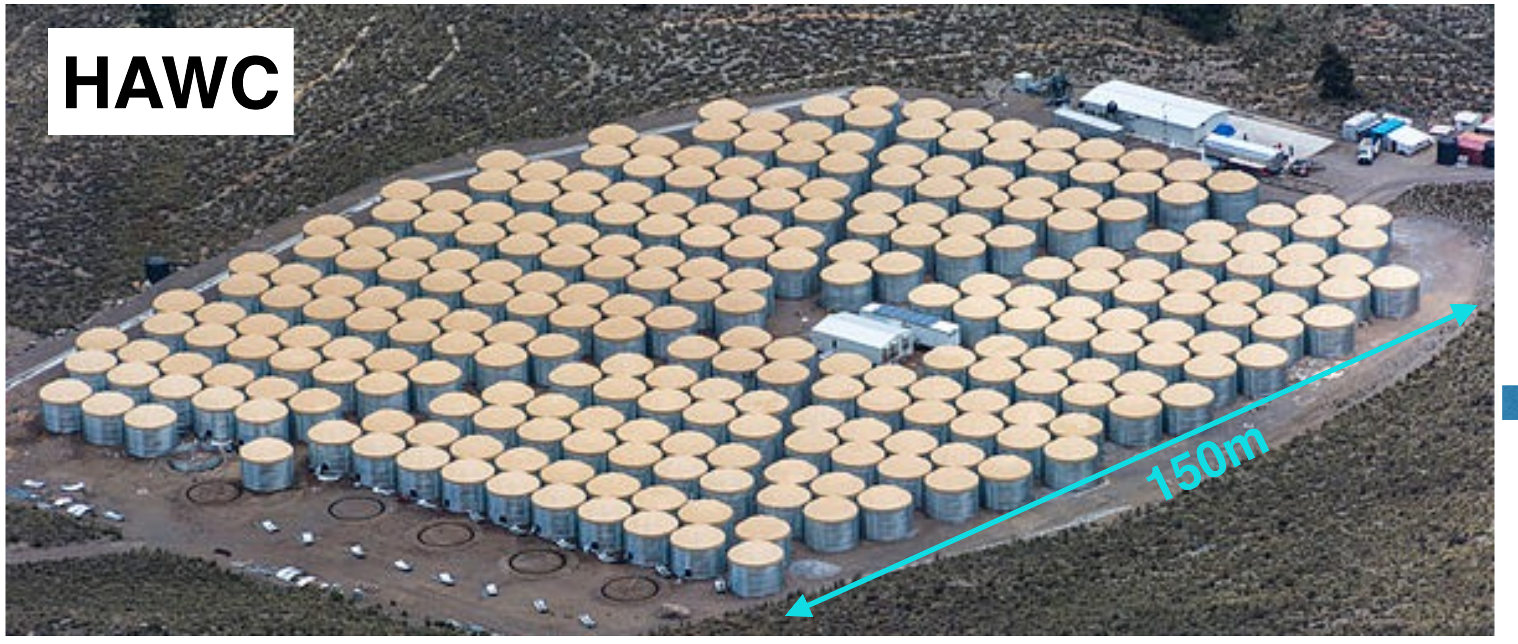


Lateral distribution

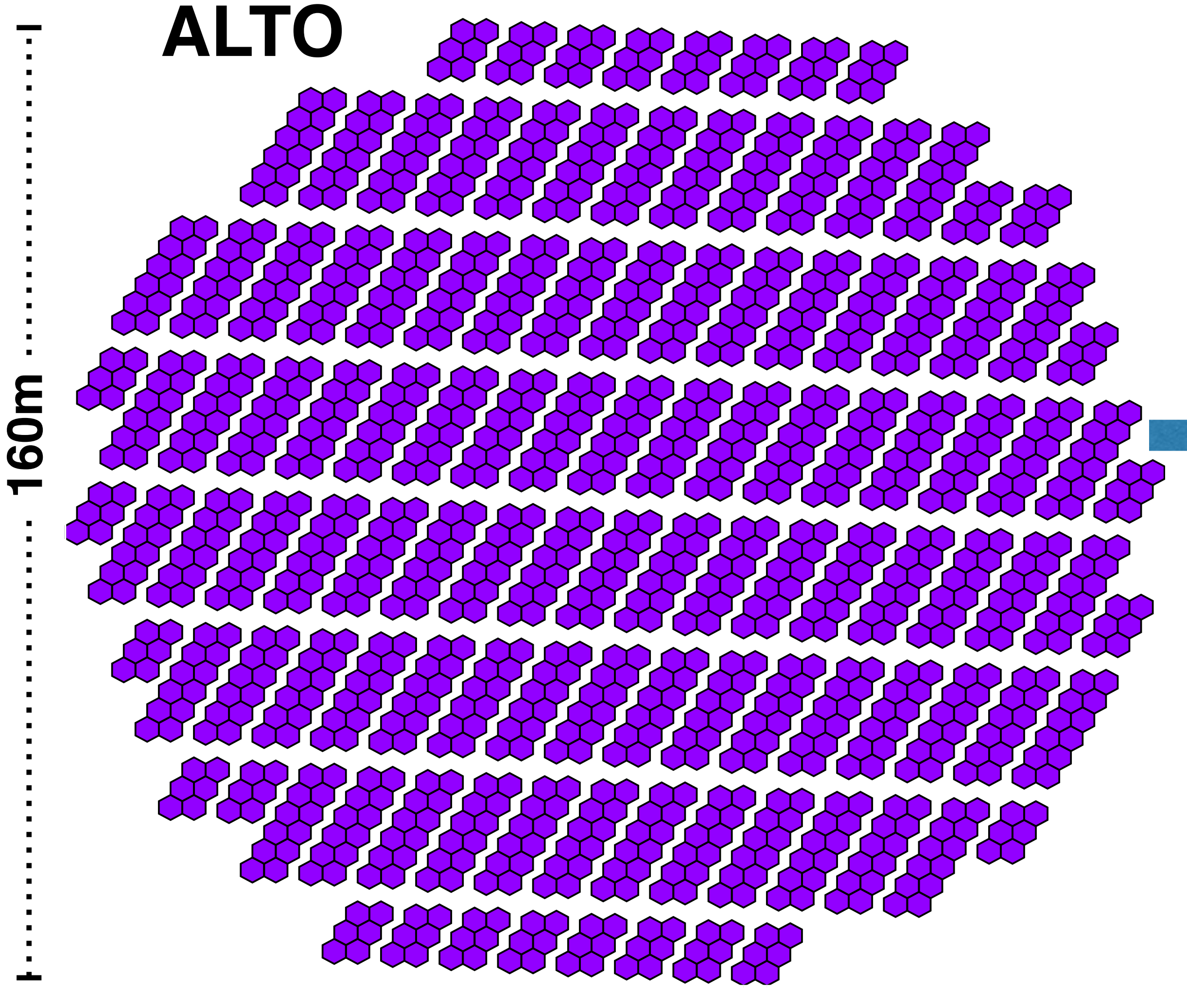


Lateral distribution of air shower particles (Energy>1 MeV)





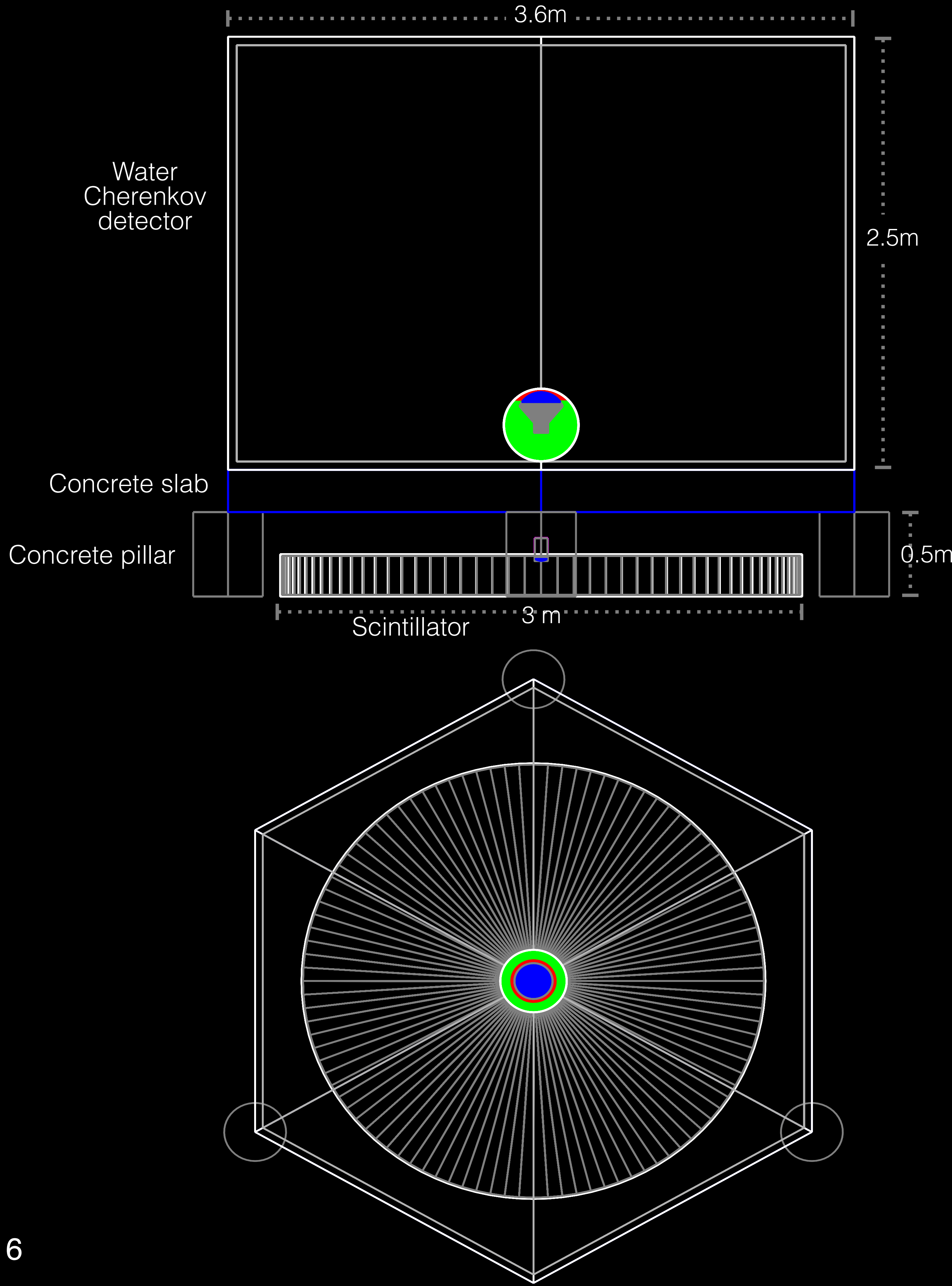
- Altitude 4.1 km a.s.l
- 300 detector units



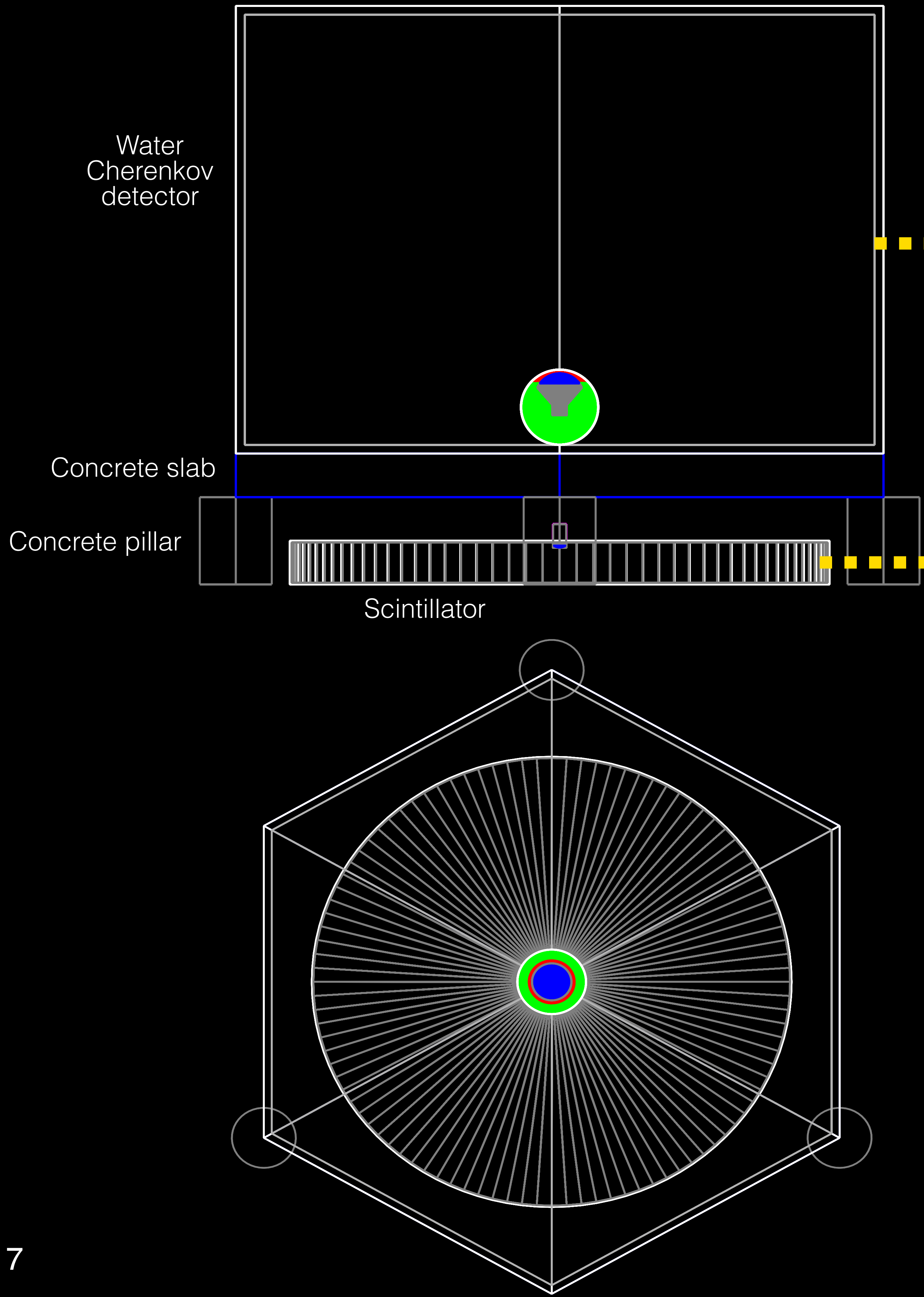
- Altitude 5.1 km a.s.l: Lower threshold
- Sub-ns timing: Better angular resolution
- Small sized detectors
- 1242 units
- Muon detectors

$\left.\right\}$ Better sensitivity

ALTO Detector



ALTO Detector



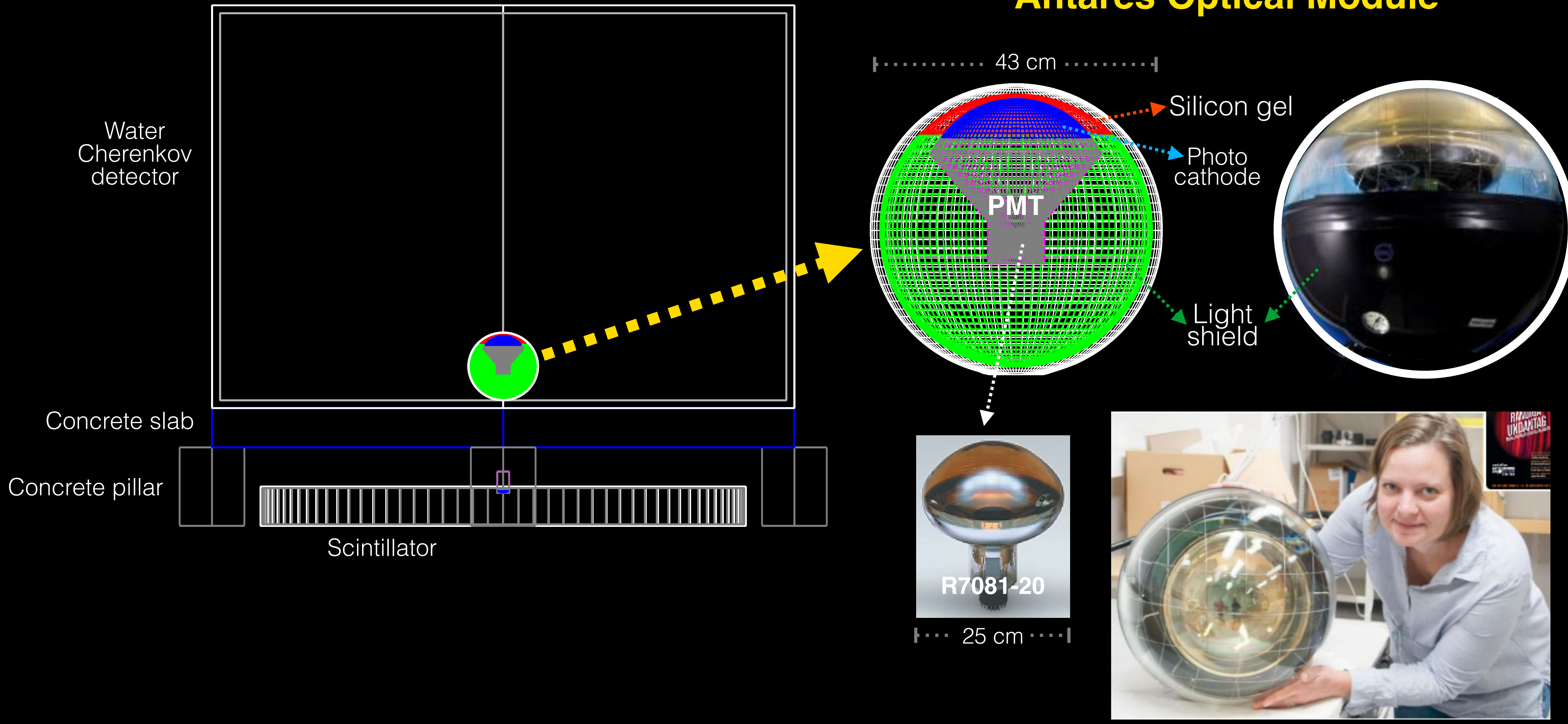
Water Cherenkov detector

- Cover material
  - Polyethylene
  - Thickness: 5 cm
  - Ideally 100% black inside
- Highly purified water

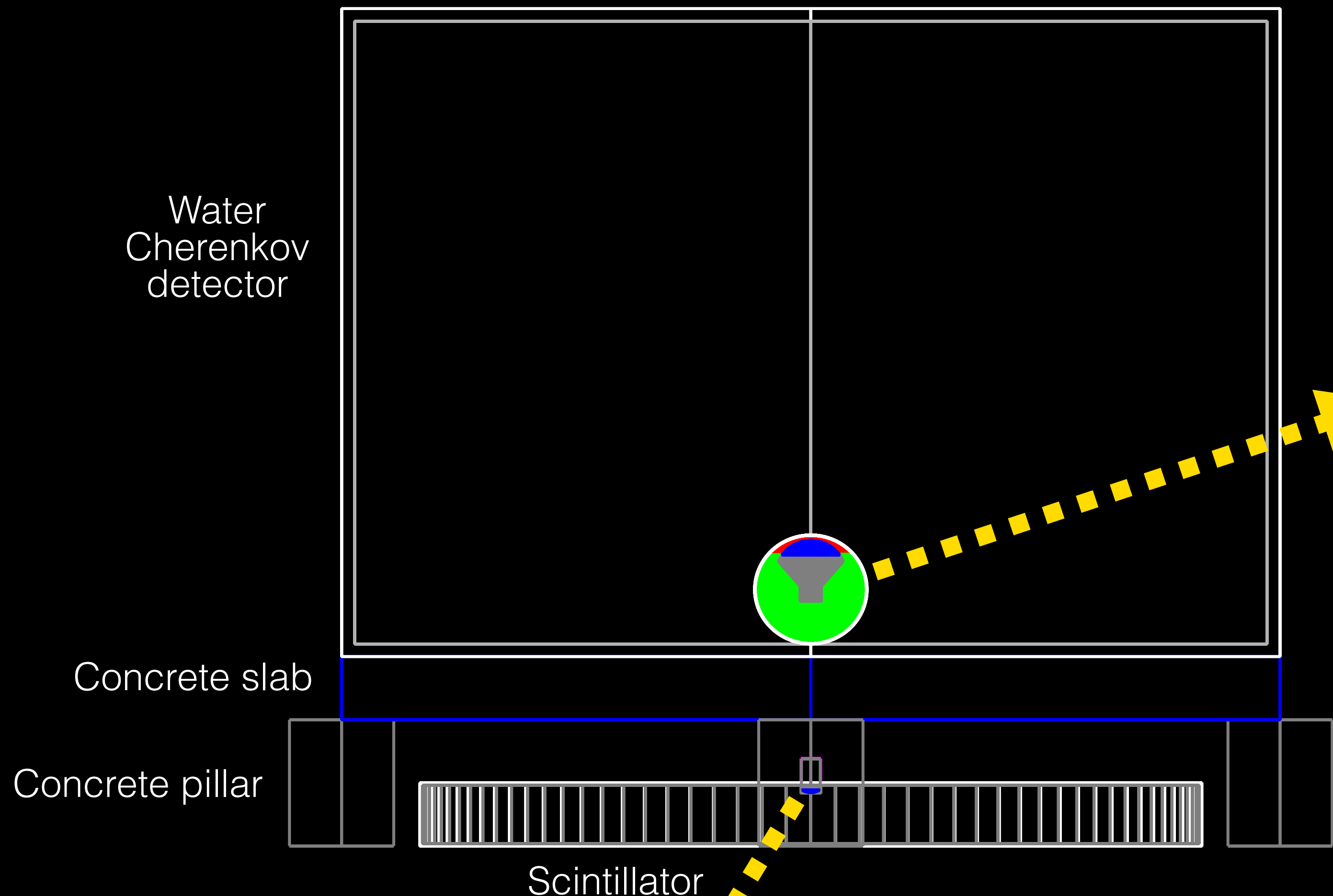
Scintillator

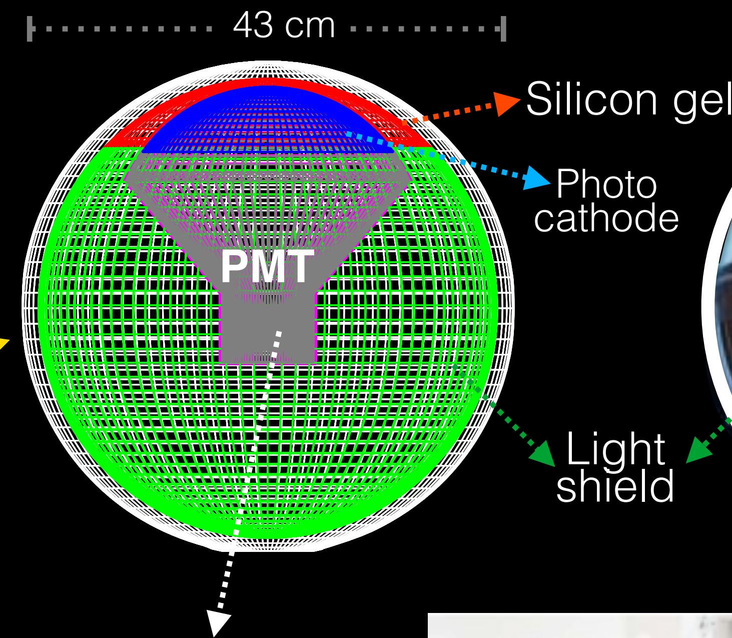
- Cover material
  - Polyethylene
  - Thickness: 1 cm
  - Ideally 100% reflective inside
- Liquid scintillator
  - LAB+5gm/litre of PPO+0.02gm/litre of POPOP

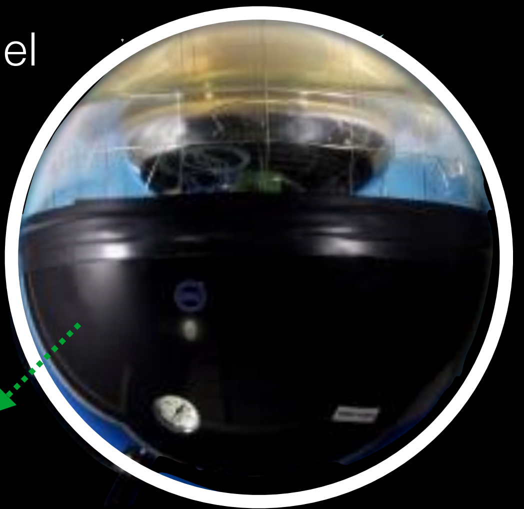
Antares Optical Module

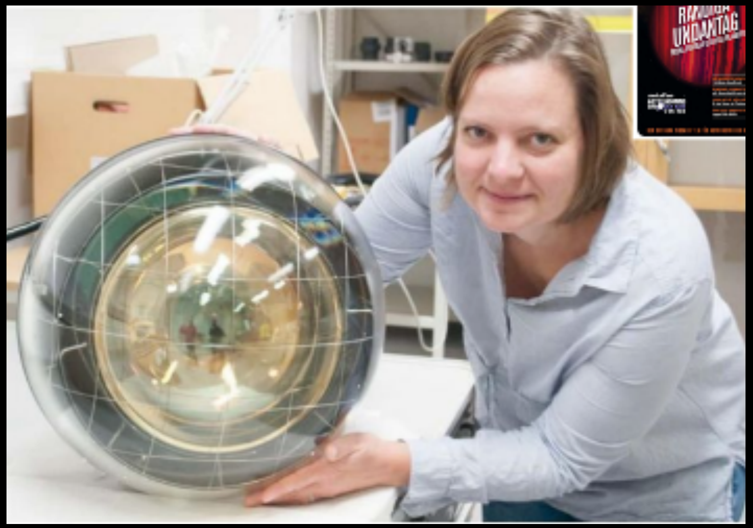


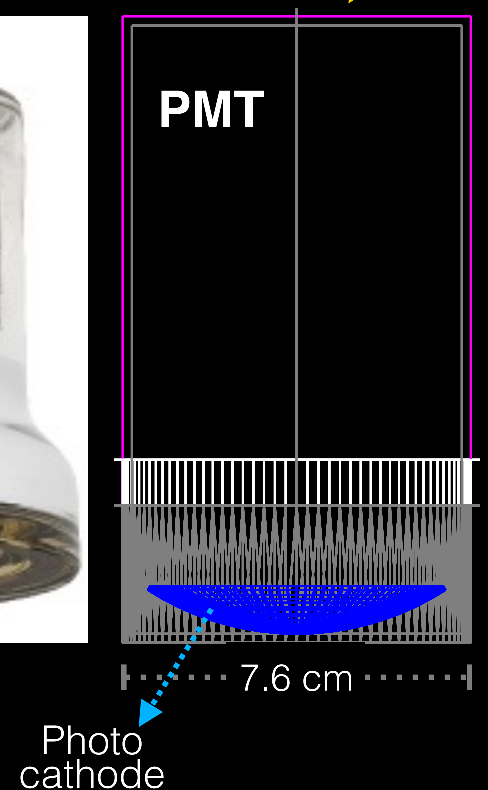
Antares Optical Module



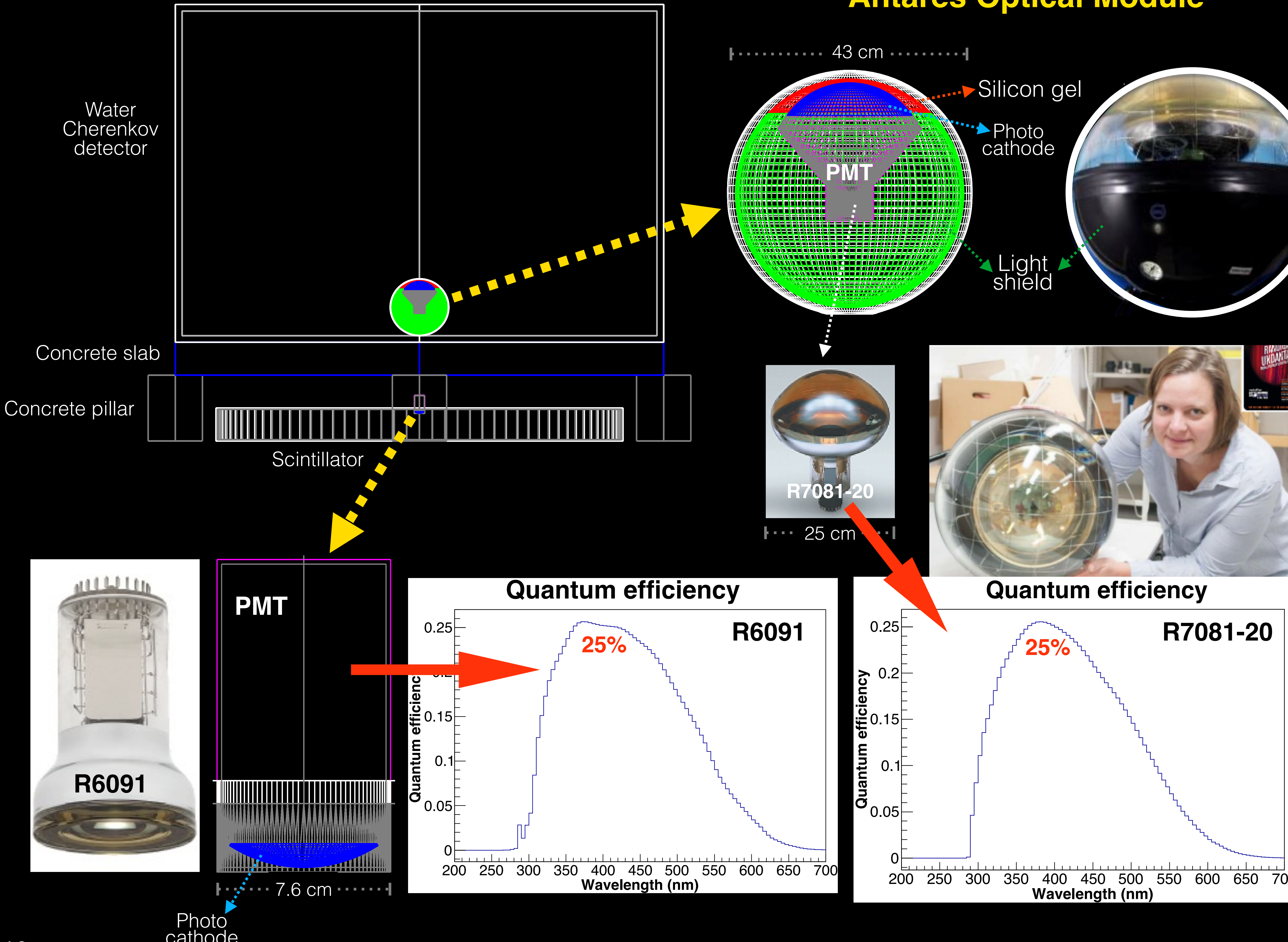








Antares Optical Module

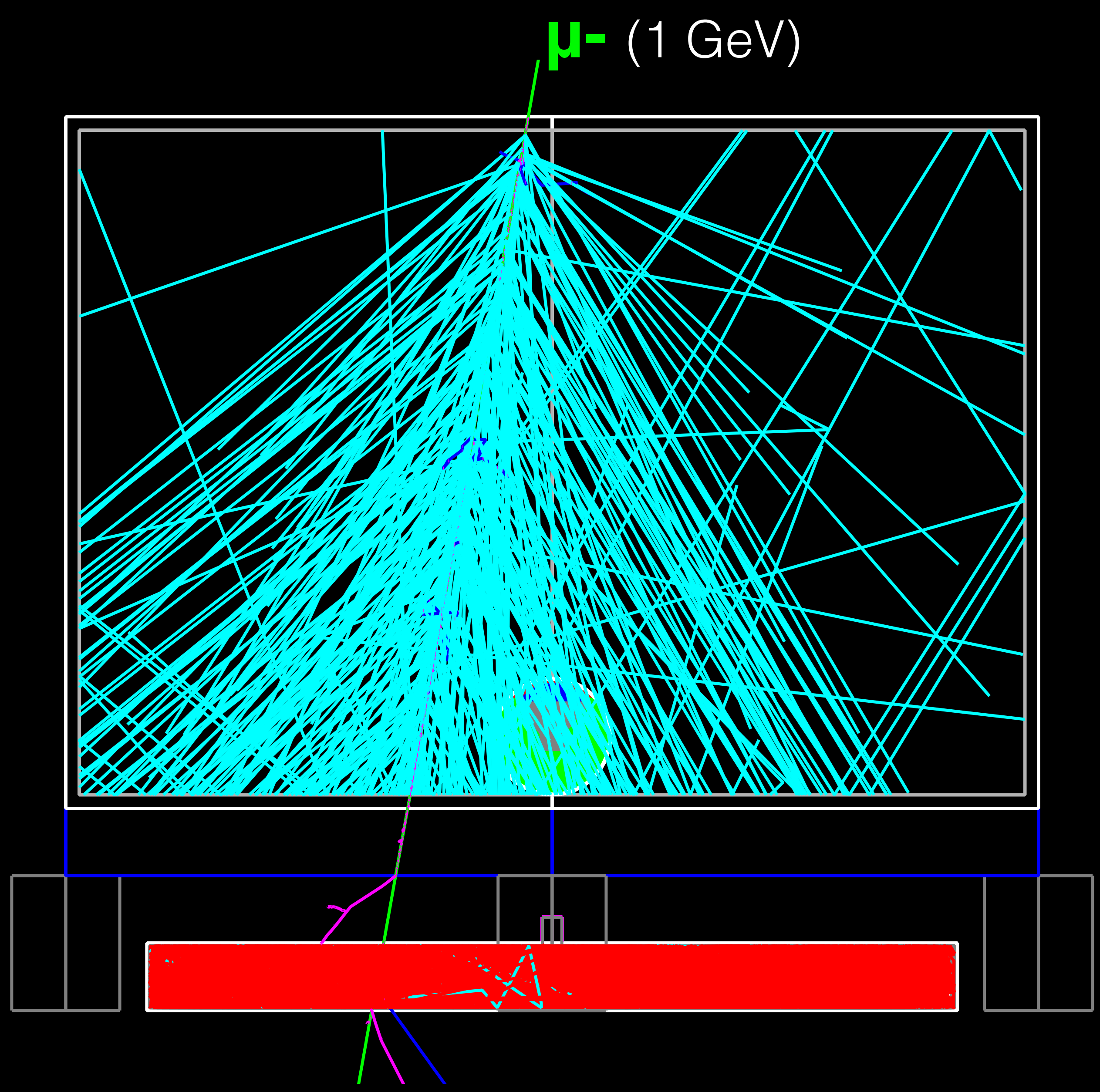


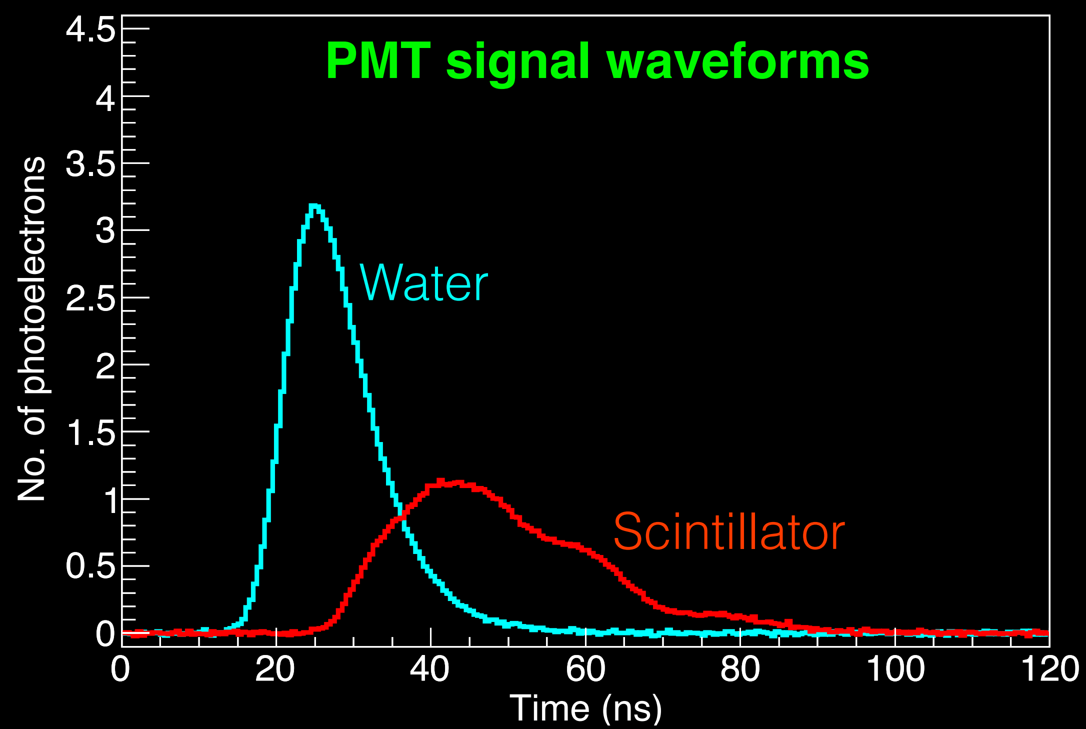
Detector simulation: GEANT4 (version 10.2)

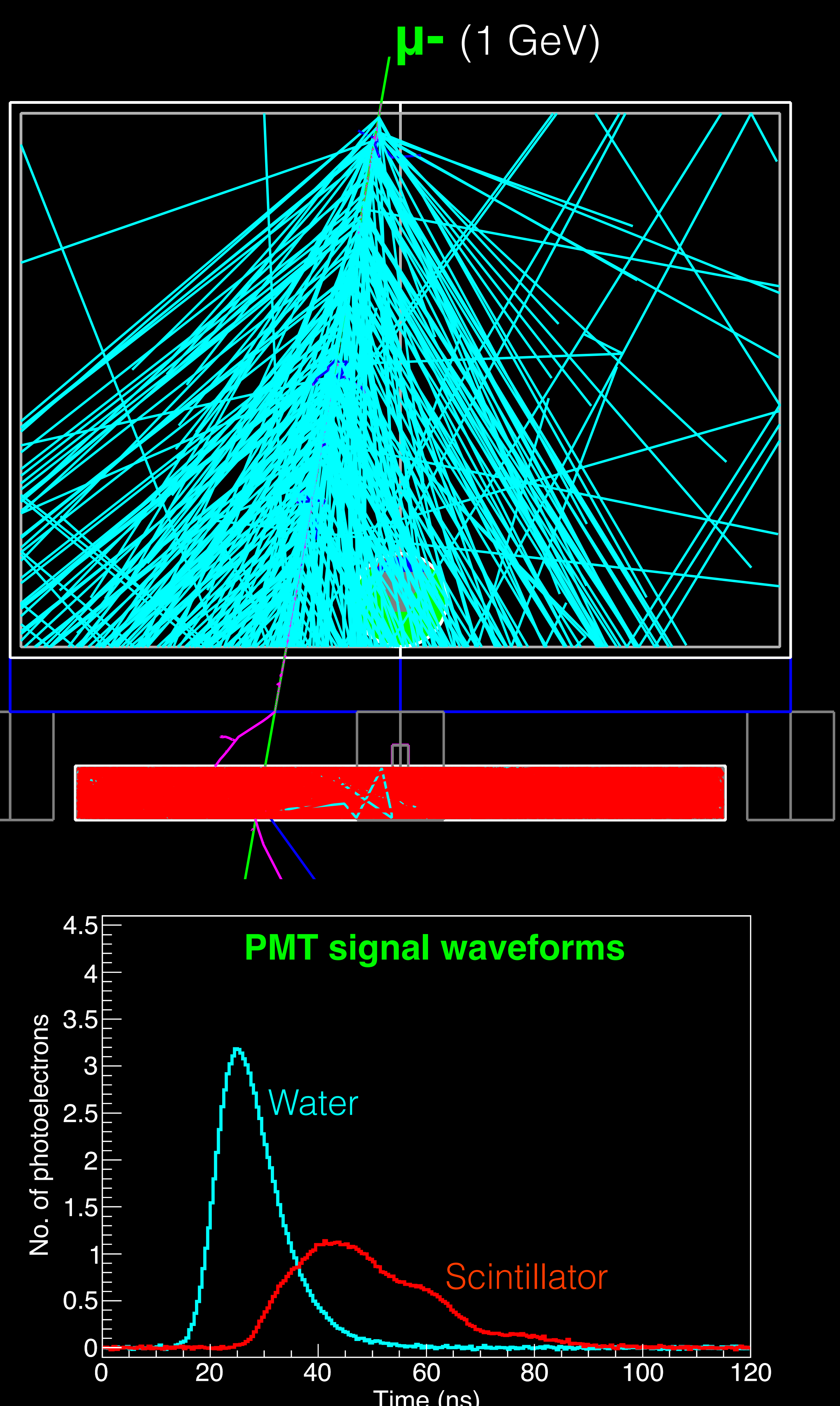
- **All material properties are included**
  - Density
  - Refractive index as function of wavelength
  - Photon reflectivity, absorption and scattering coefficients as function of wavelength

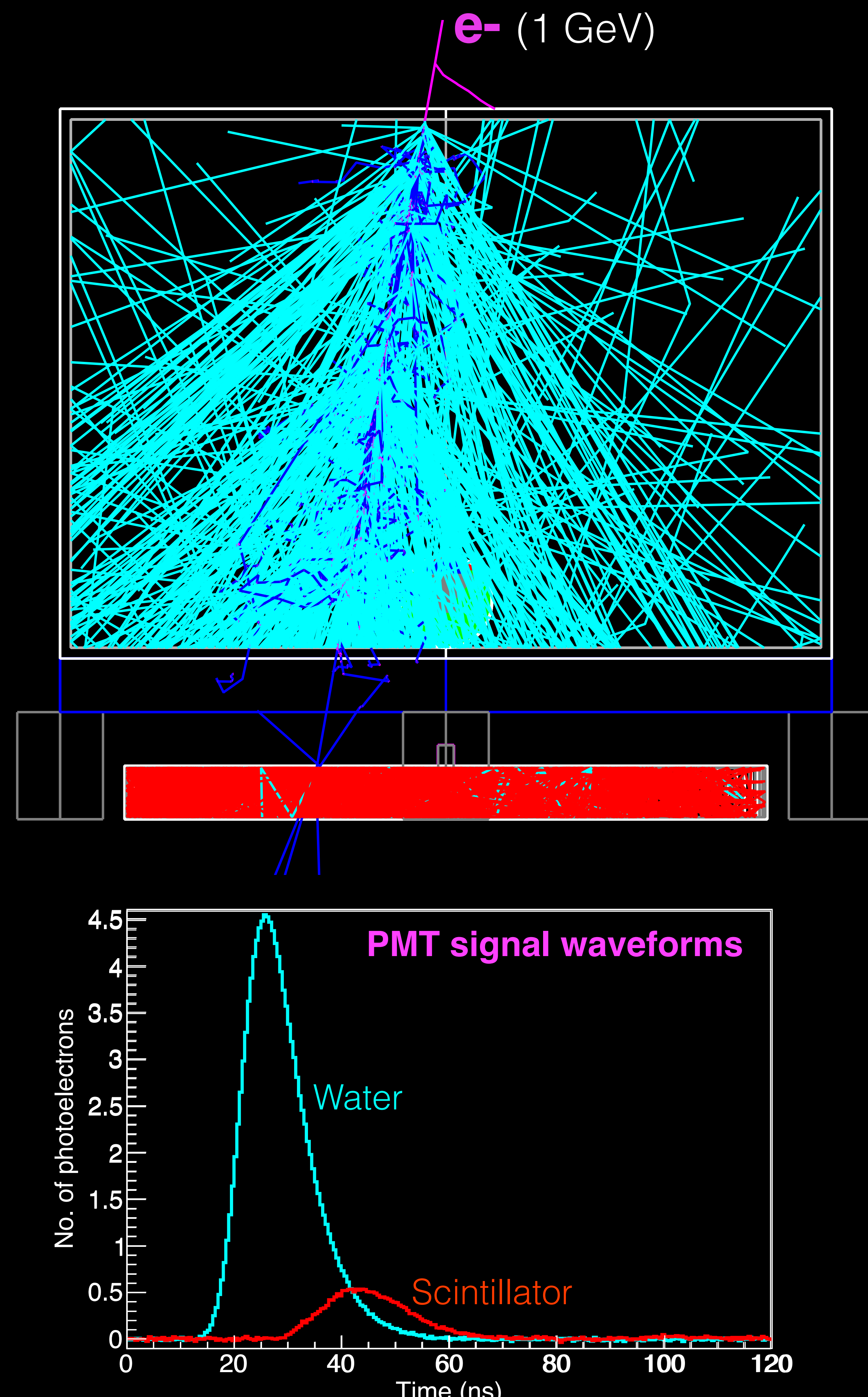
- **All important physical processes are included**
  - **Electro-magnetic processes:**
    - Υ's: Photoelectric effect, Compton scattering, Pair production, Rayleigh scattering
    - $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, nuclei: Multiple scattering, ionisation, bremsstrahlung, annihilation (positrons)
    - Unstable particles: Decay
  - **Optical processes:**
    - Cherenkov photons production
    - Scintillation photons production
    - Absorption, scattering …..

- **Particle tracking**
  - All particles are completely tracked by GEANT4 except for optical photons
  - Optical photons (Cherenkov & scintillation) are produced in million in each tank
    - Almost impossible to track all of them
  - For optical photons inside water tank:
    - Only those that would hit the optical module are allowed to track by GEANT4
    - Rest are killed at the point of emission
  - For optical photons inside scintillator:
    - They are not tracked in the simulation
    - We use a library of PMT signals (waveforms) generated for e-, μ- and Υ as function of their energy, position and incident angle.

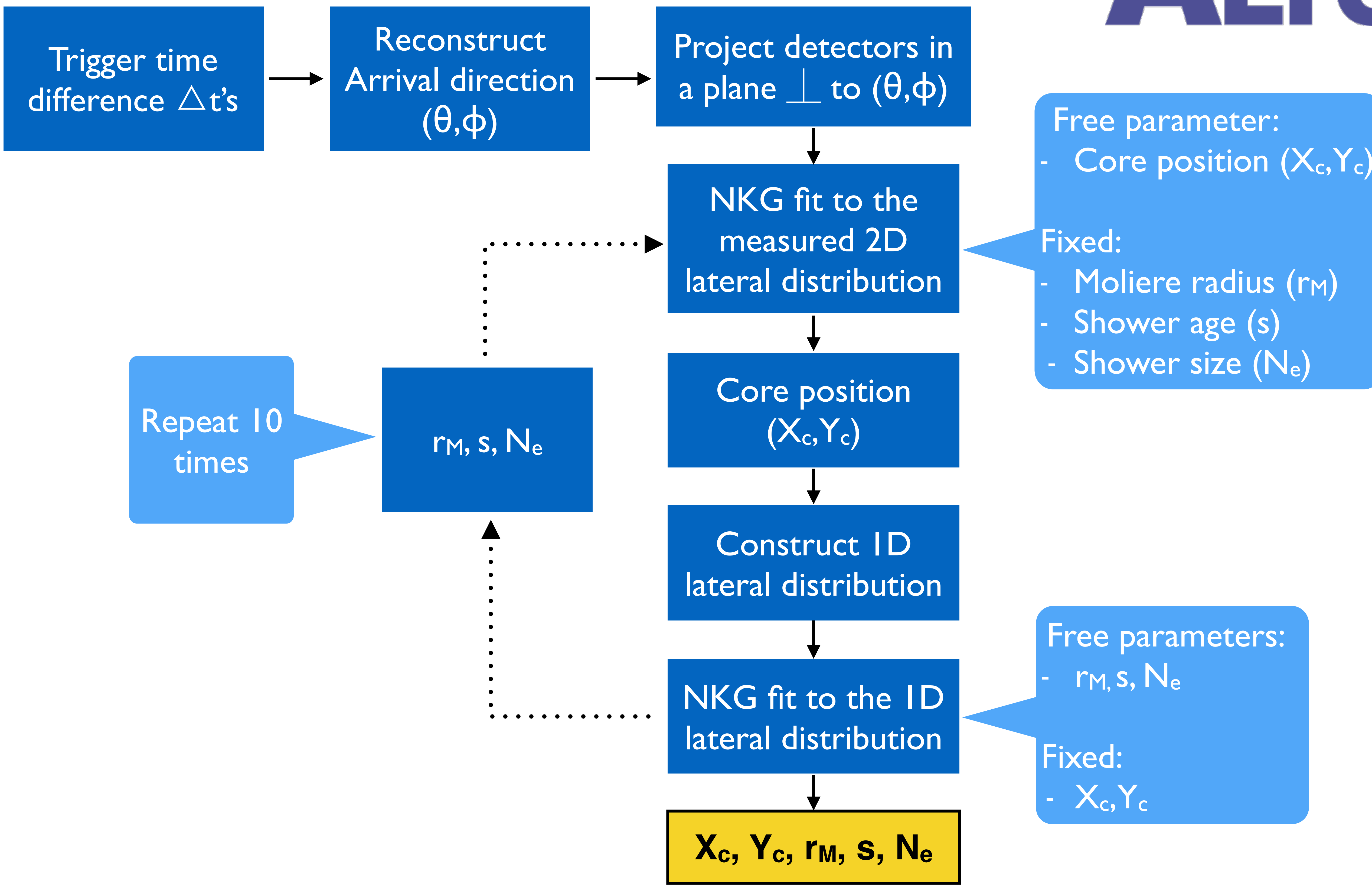

μ- (1 GeV)


PMT signal waveforms
No. of photoelectrons
Time (ns)
Water
Scintillator
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
0
20
40
60
80
100
120


μ- (1 GeV)
PMT signal waveforms
Water
Scintillator
No. of photoelectrons
Time (ns)


e- (1 GeV)
PMT signal waveforms
Water
Scintillator
No. of photoelectrons
Time (ns)

Reconstruction of air shower parameters



Air shower simulation: CORSIKA(version 7.4000)

Parameter	Gamma-rays	Protons
Observation height	5.1 km	Same
Energy	10 GeV-100 TeV	100 GeV-100 TeV
Spectral slope	-2.0	-2.7
Zenith angle	Fixed at 18°	0°-30°
Azimuth angle	Fixed at 180°	0°-360°
Magnetic field	ALMA site	Same
Core position (from the array center)	0-100 m	Same
No. of showers	~17 million	~212 million

Preliminary analysis cuts

Trigger cut

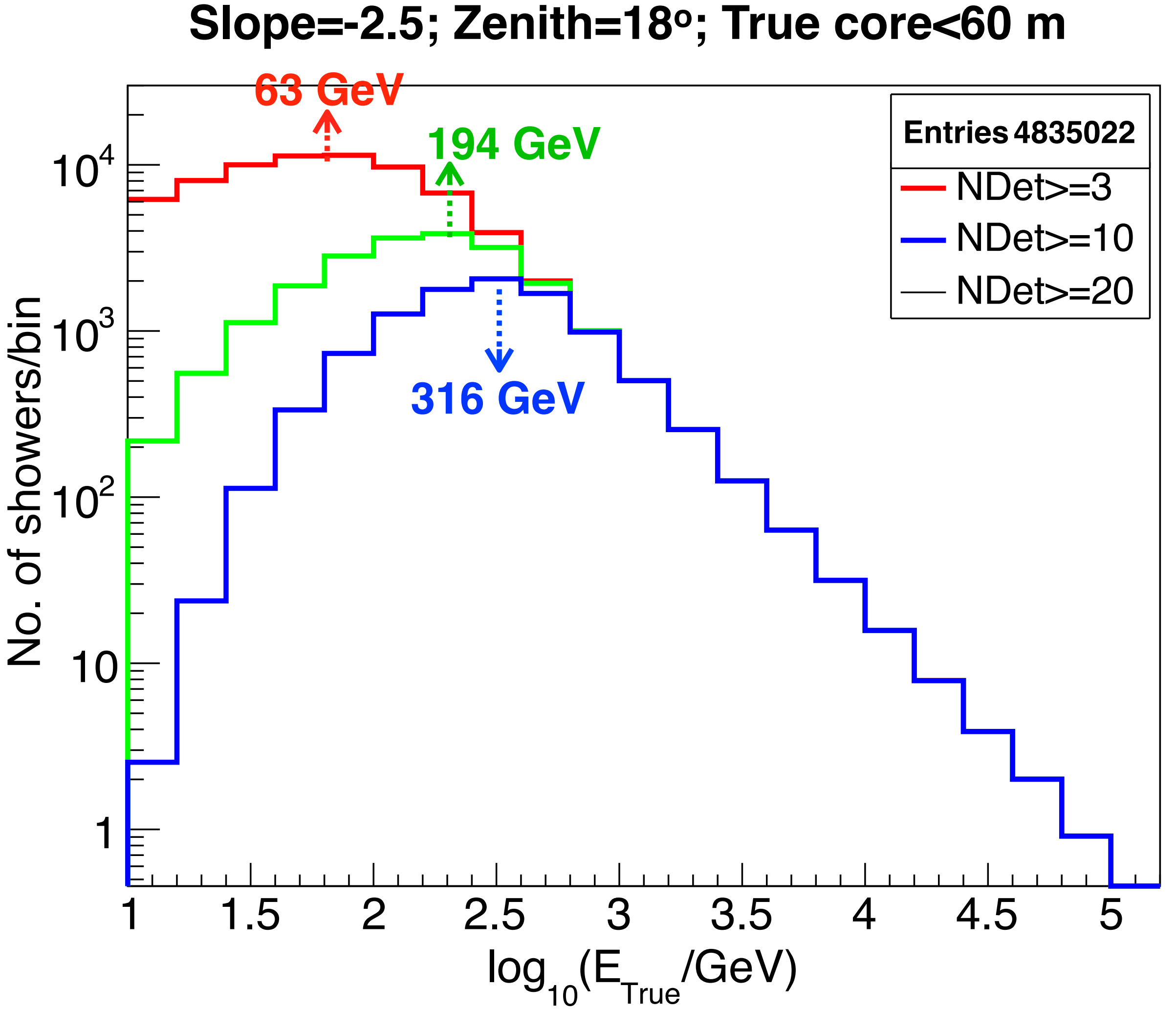
No. of detectors trigger ≥ 3

Reconstruction cut

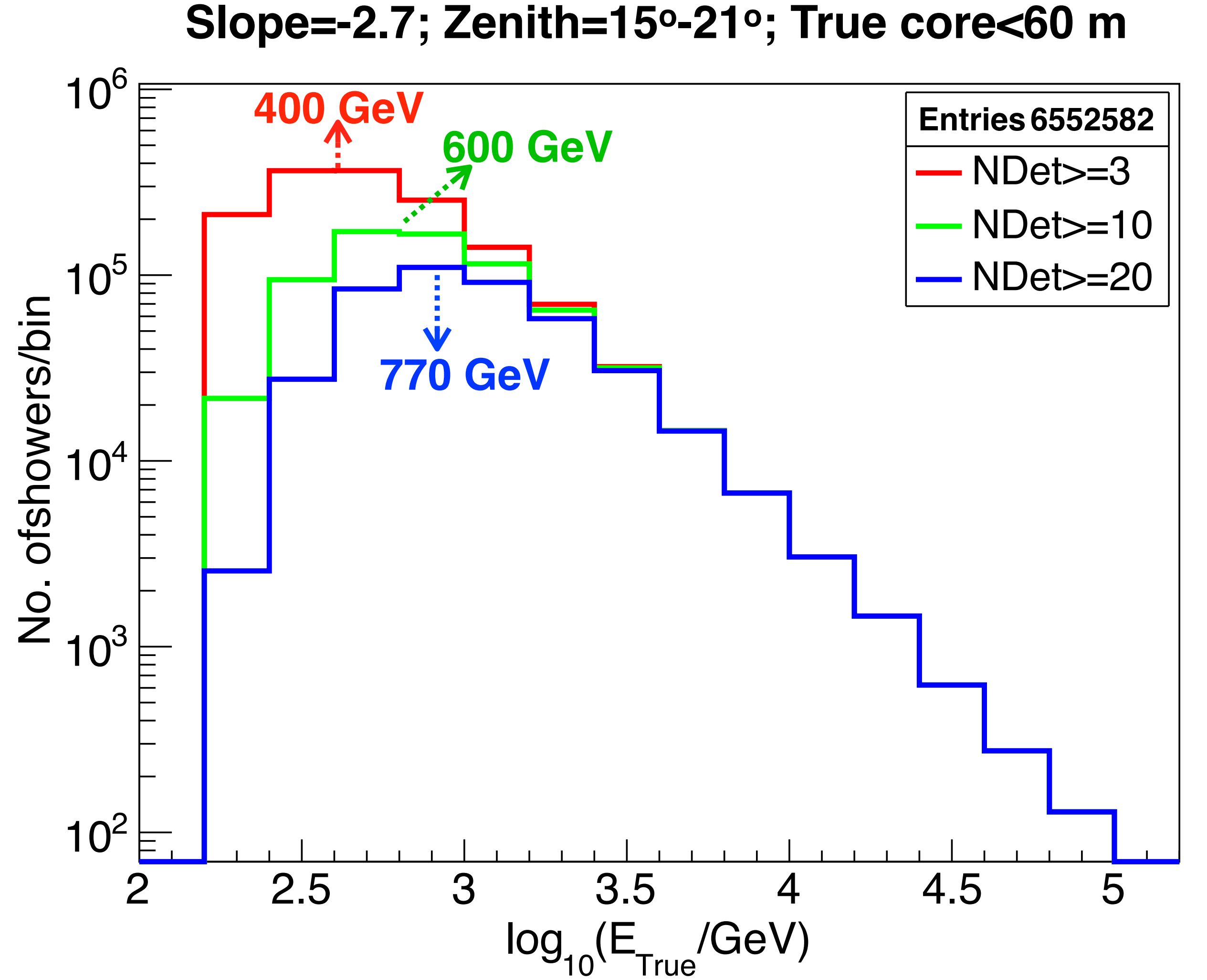
Parameter	Value
No. of detectors trigger	≥20
Recons. shower core position	<60 m
Shower size accuracy, (N_e_err/N_e)	(60-10)% from 10GeV to 100 TeV
Moliere radius, r_M	No cut
Shower age, s	No cut

Energy distribution after different trigger cuts

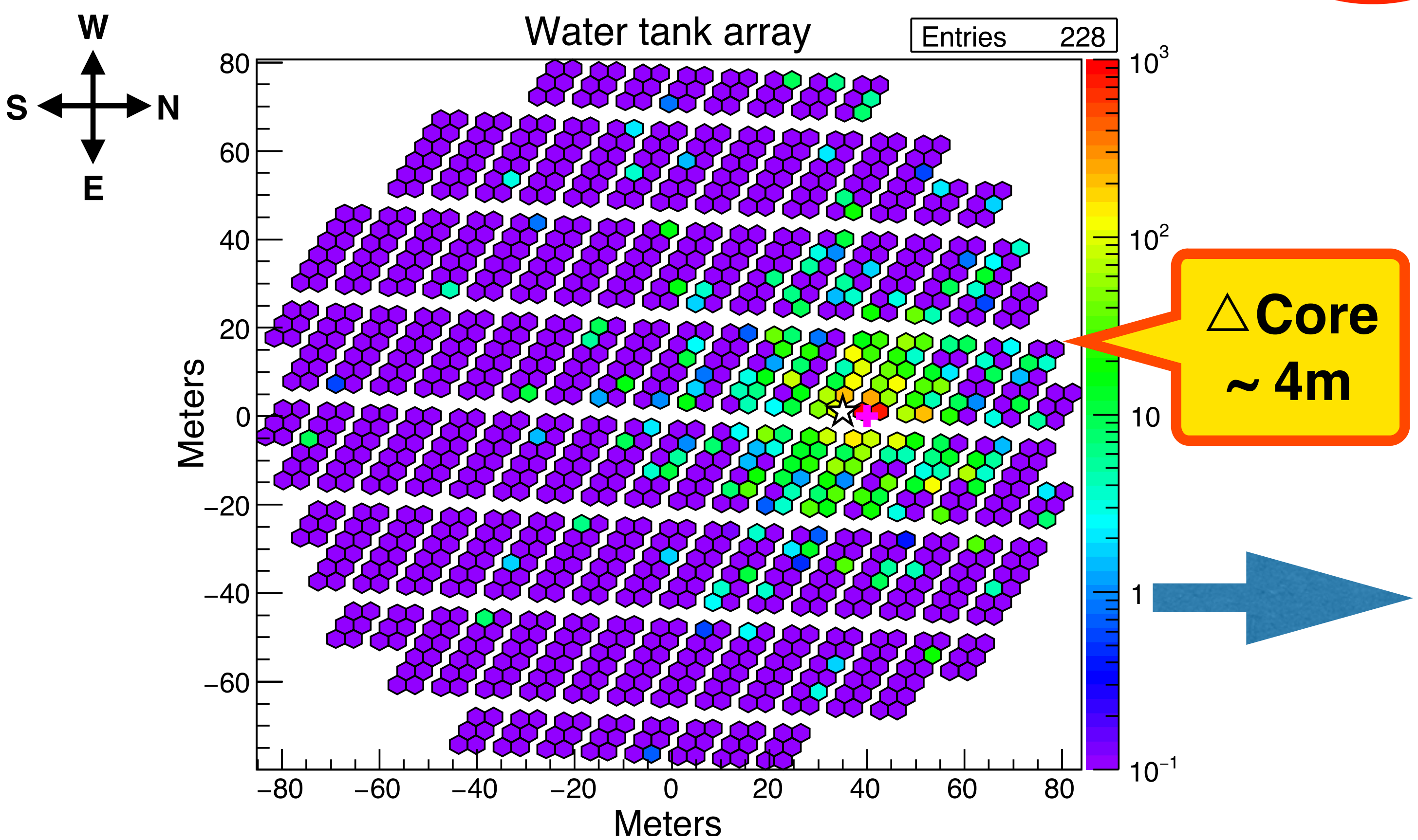
Gamma showers

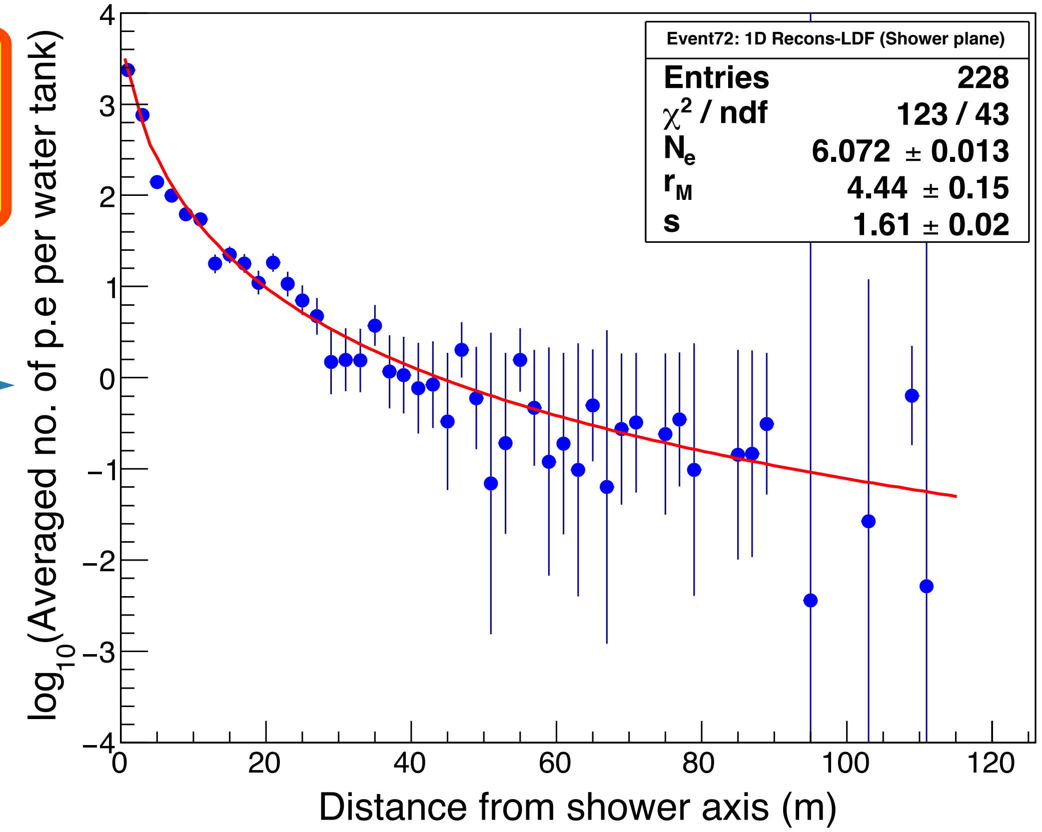


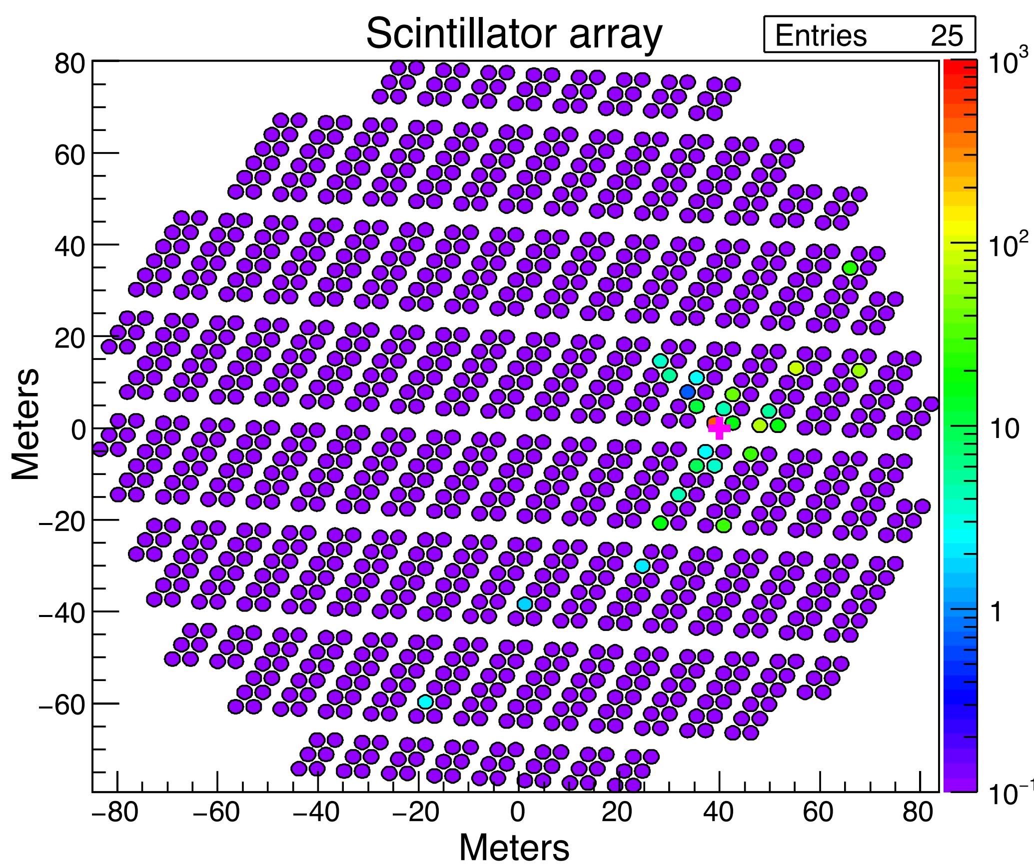
Proton showers



A gamma-ray event (Energy 1 TeV, Zenith 18 deg.)





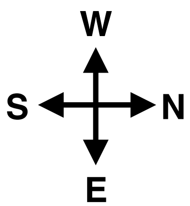


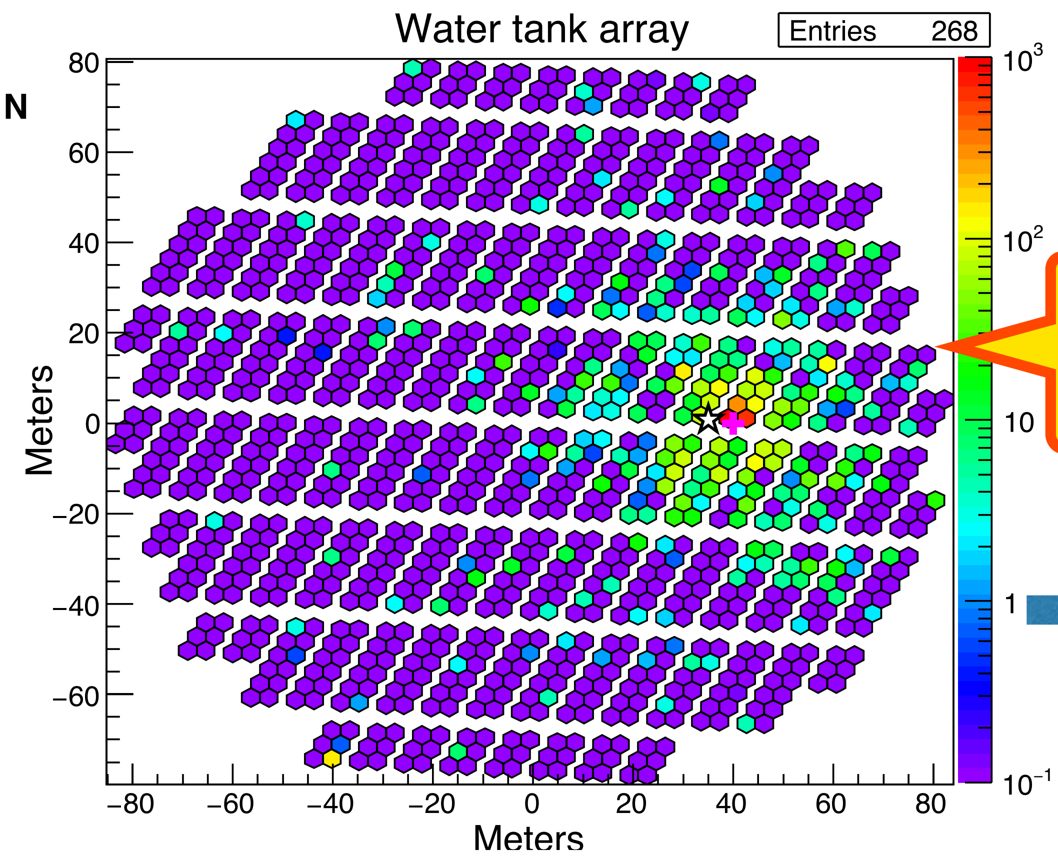
NKG (Nishimura-Kamata-Greisen) function:

$$N(r) = N_{\mathrm{ch}} C(s) \left(\frac{r}{r_{\mathrm{M}}}\right)^{s-2} \left(1 + \frac{r}{r_{\mathrm{M}}}\right)^{s-4.5},$$

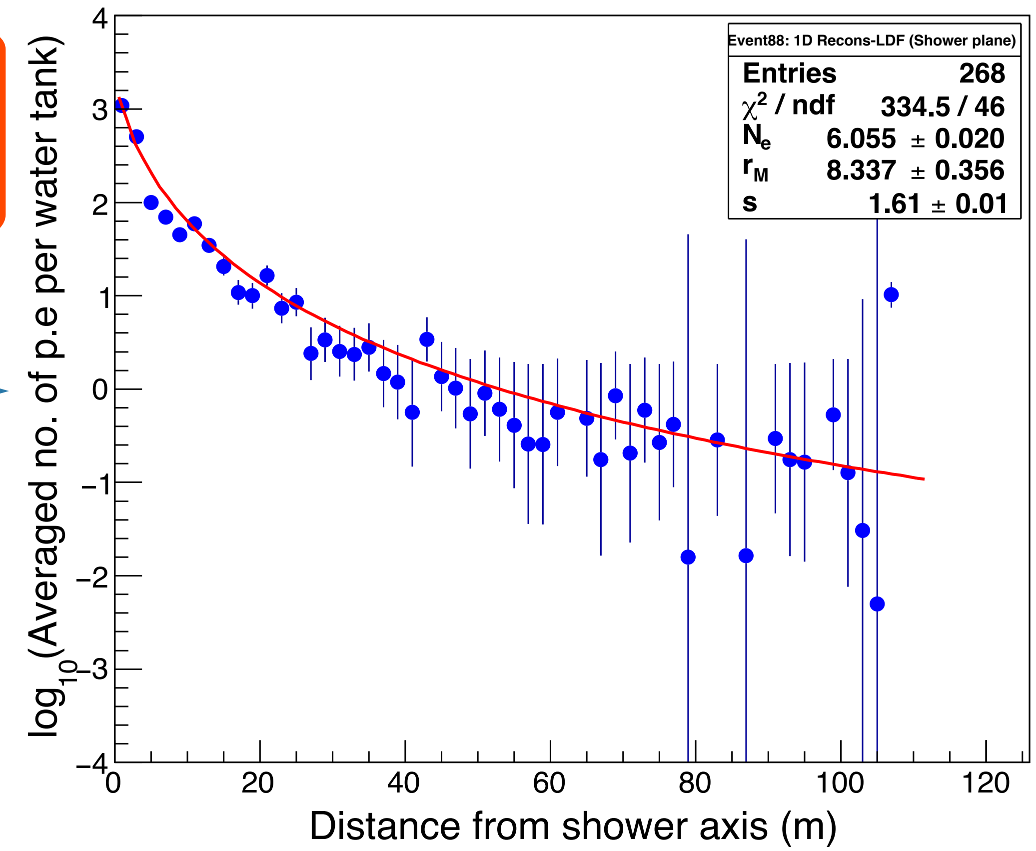
$$C(s) = \frac{\Gamma(4.5 - s)}{2\pi r_{\mathrm{M}}^2 \Gamma(s) \Gamma(4.5 - 2s)}.$$

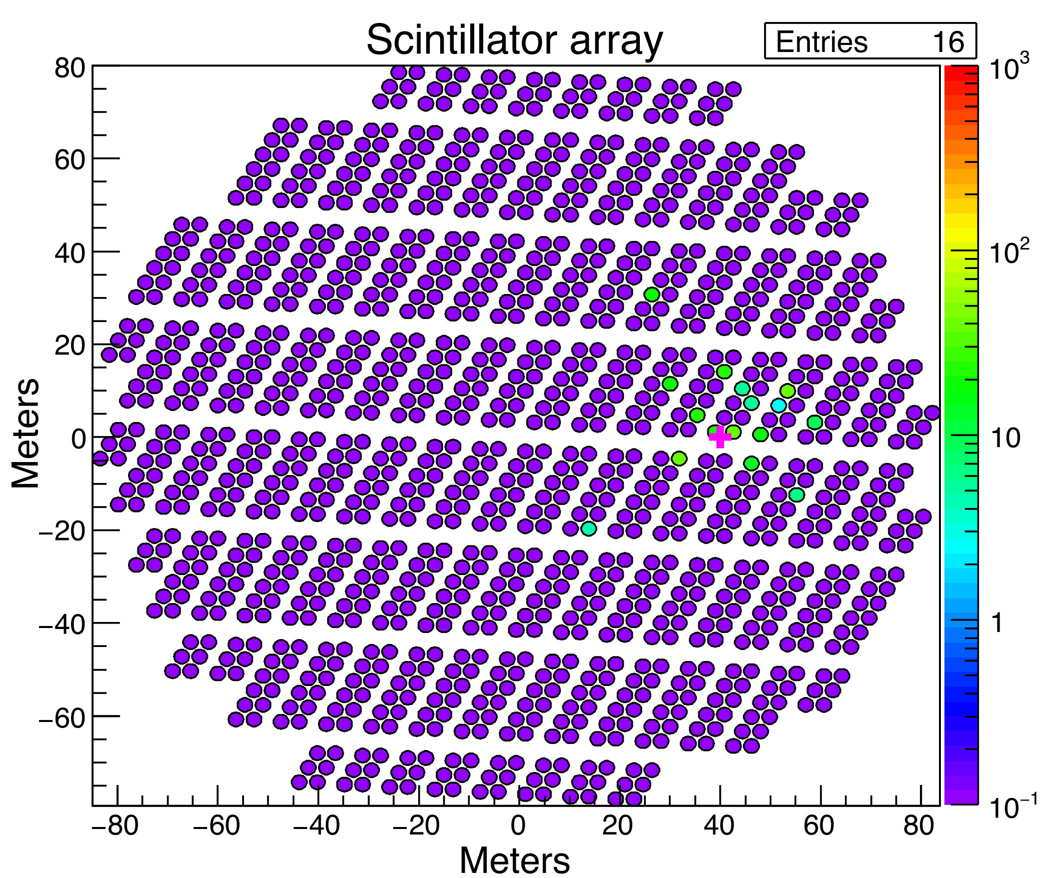
Gamma-ray event 2 (Energy 1 TeV, Zenith 18 deg.)





△Core ~ 4m



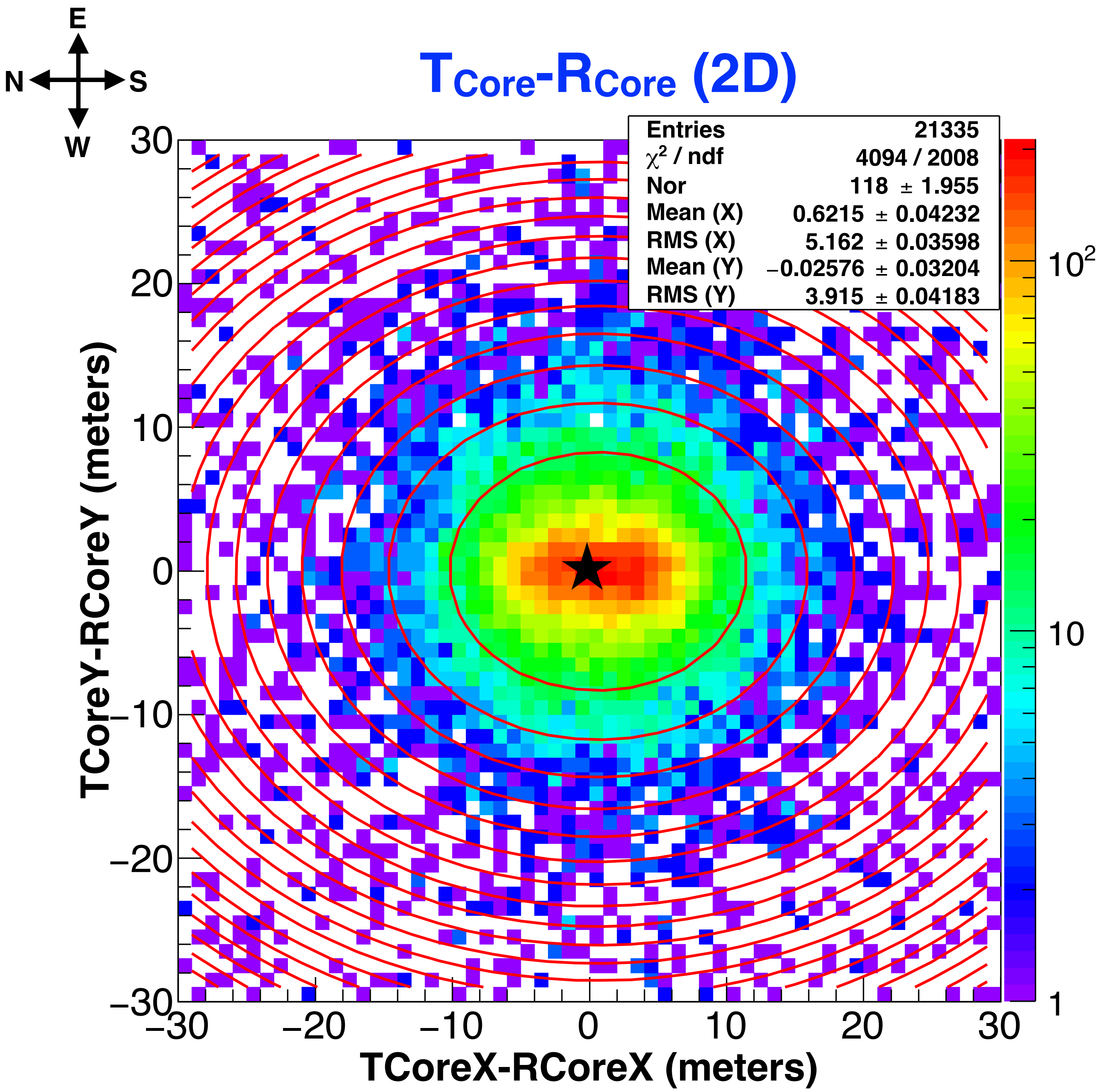


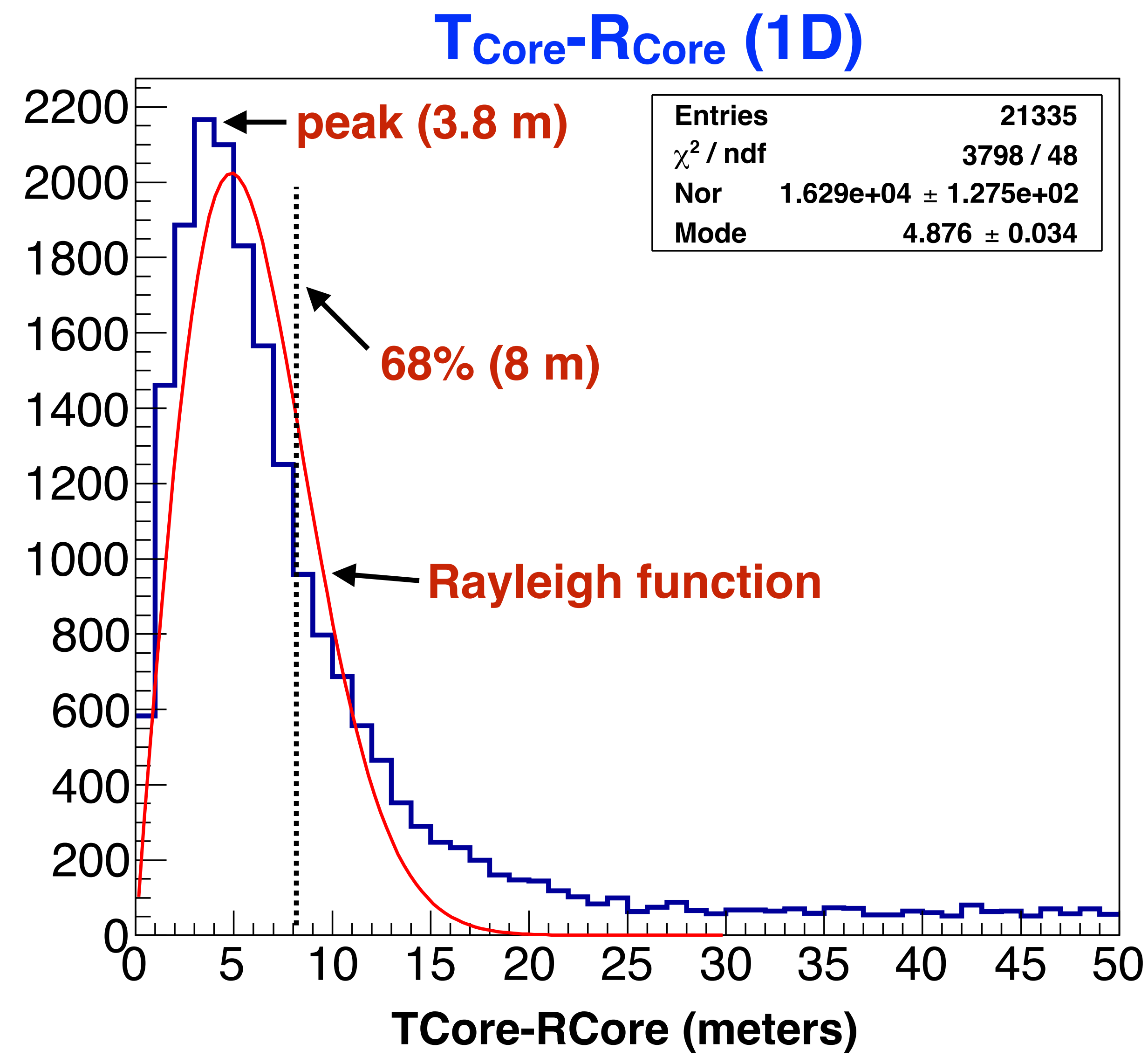
Gamma showers: Core reconstruction accuracy

ALTO

*Energy 1-1.5 TeV; Zenith 18 deg.

*R_{Core}<60 m



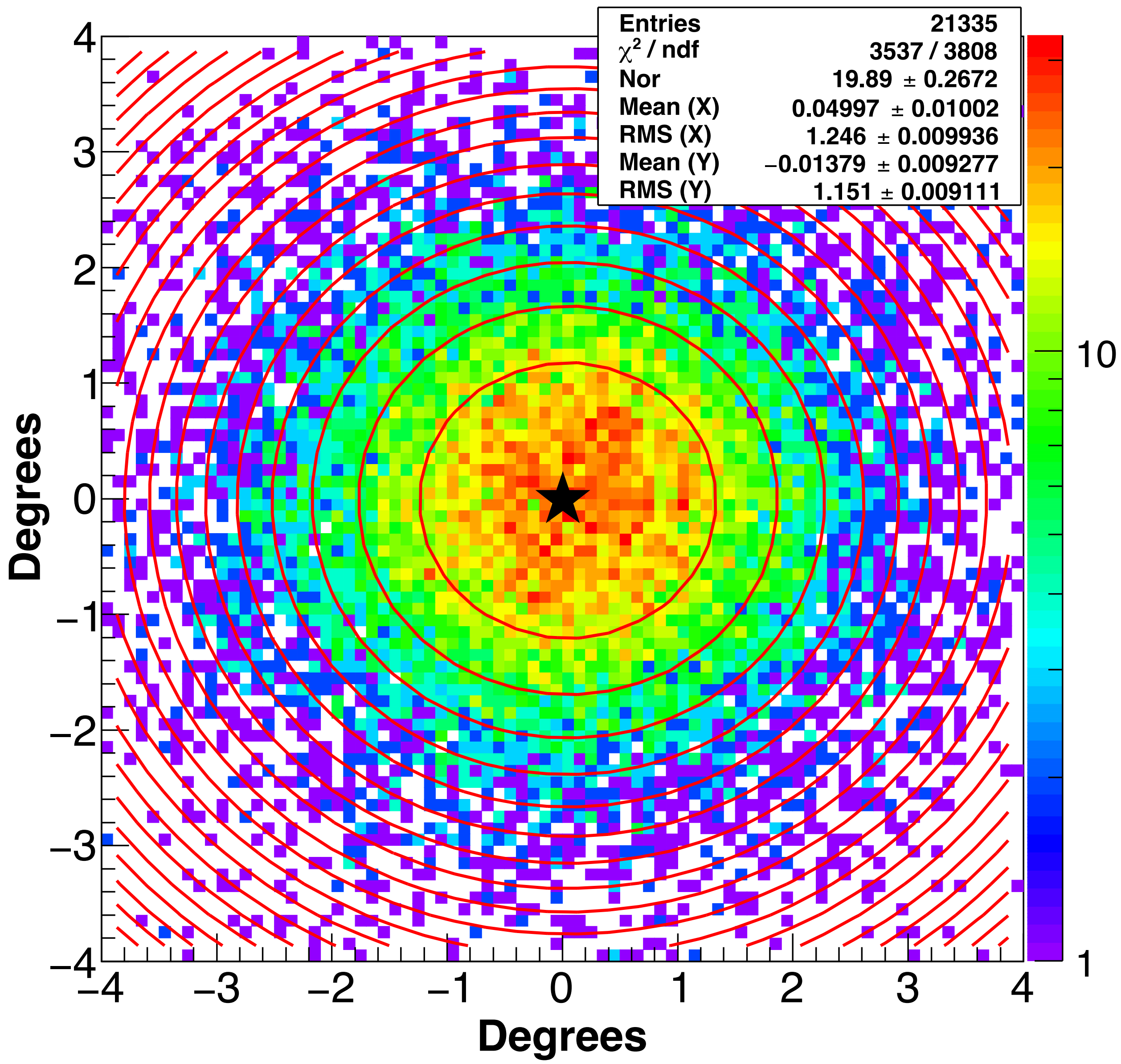


Gamma showers: Direction reconstruction accuracy using plane fit

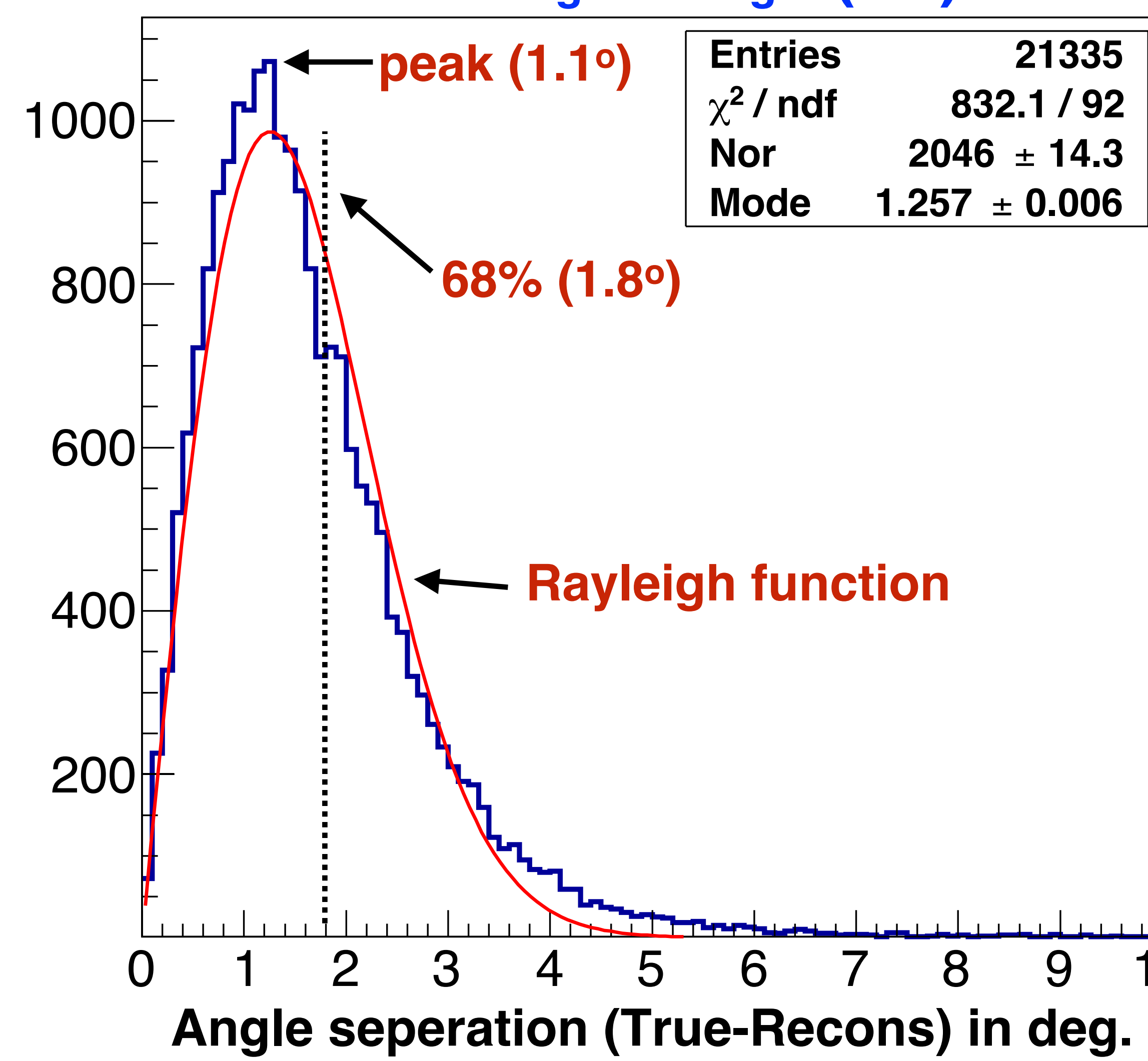
*Energy 1-1.5 TeV; Zenith 18 deg.

*R_{Core}<60 m

T_{Angle}-R_{Angle} (2D)



T_{Angle}-R_{Angle} (1D)



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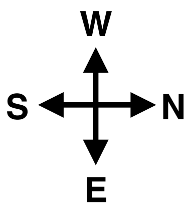
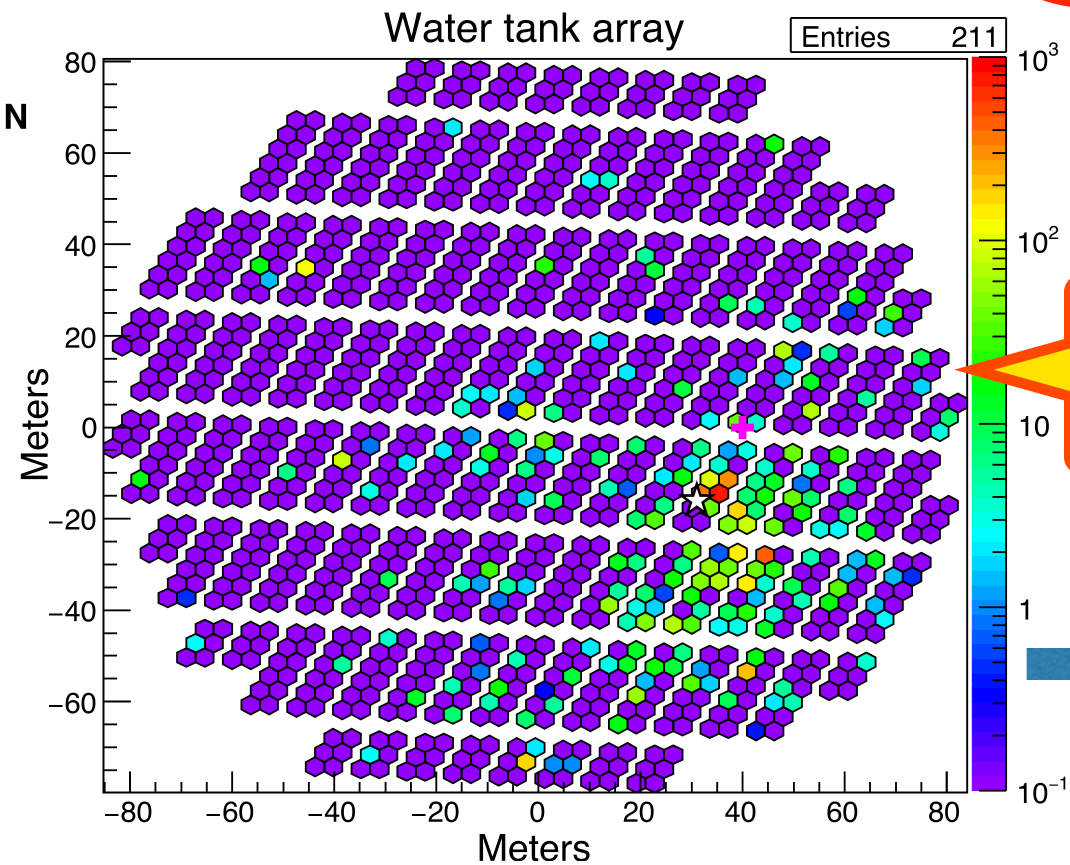
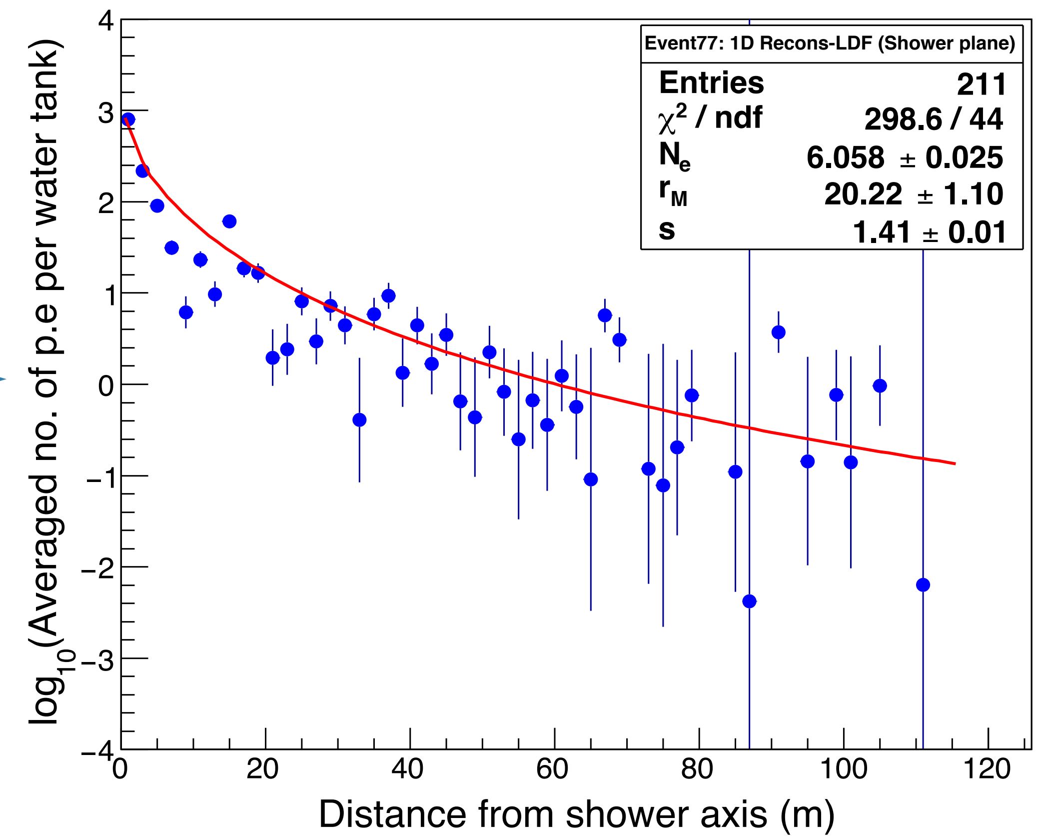
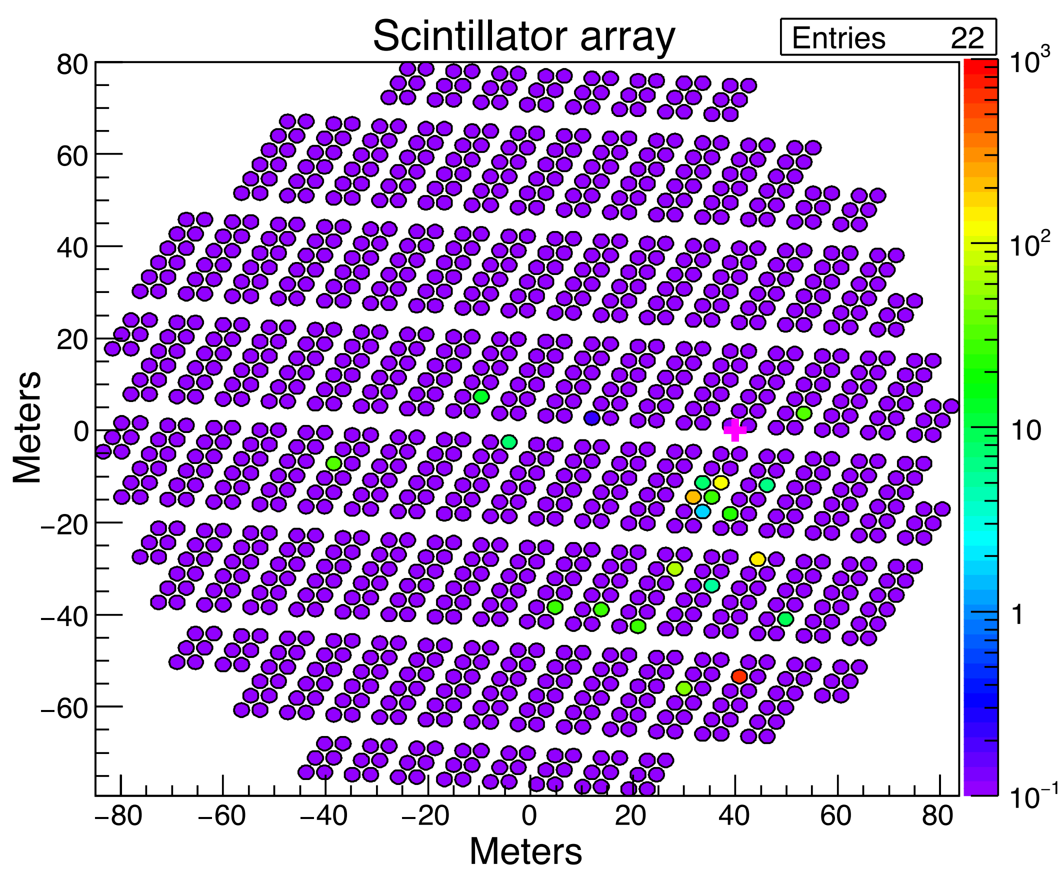
Proton event 1 (Energy 1 TeV, Zenith 18 deg.)



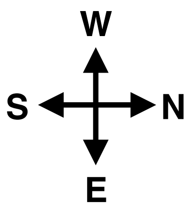


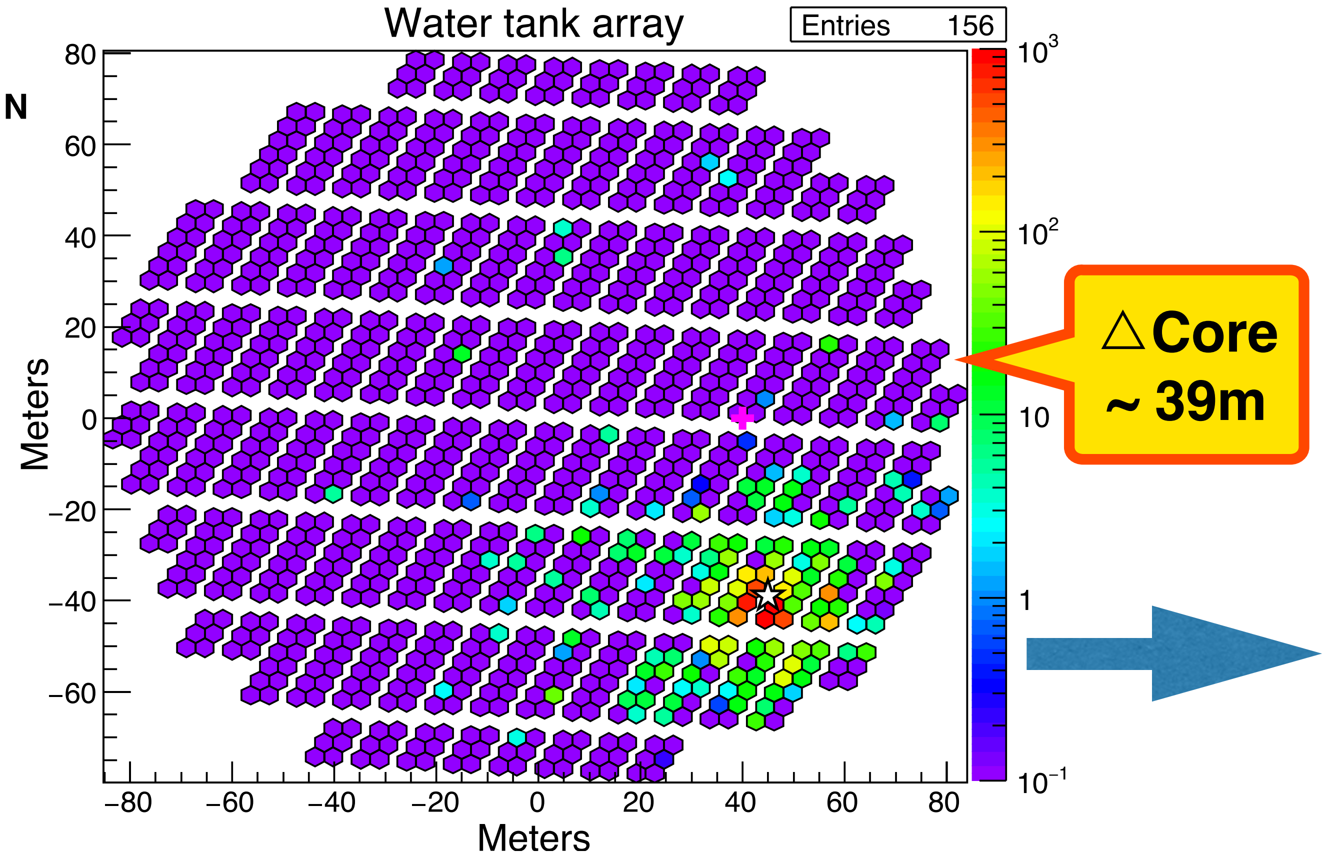
△Core ~ 18m

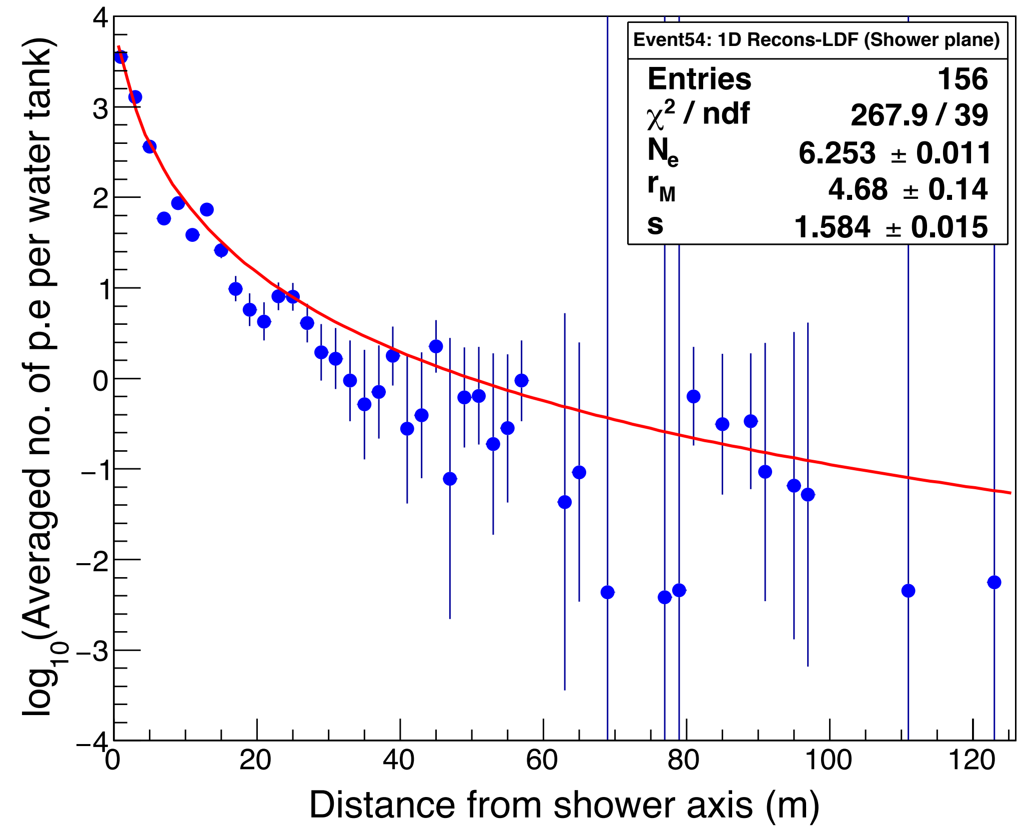


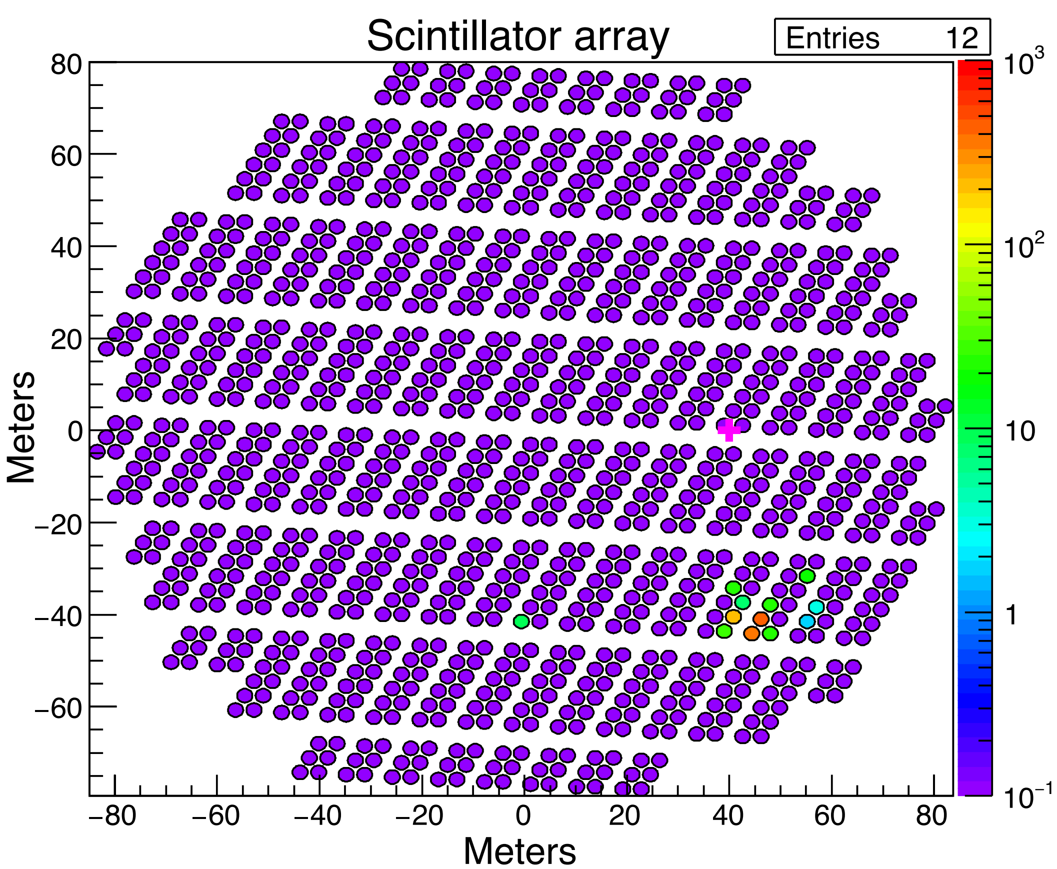


Proton event 2 (Energy 1 TeV, Zenith 18 deg.)

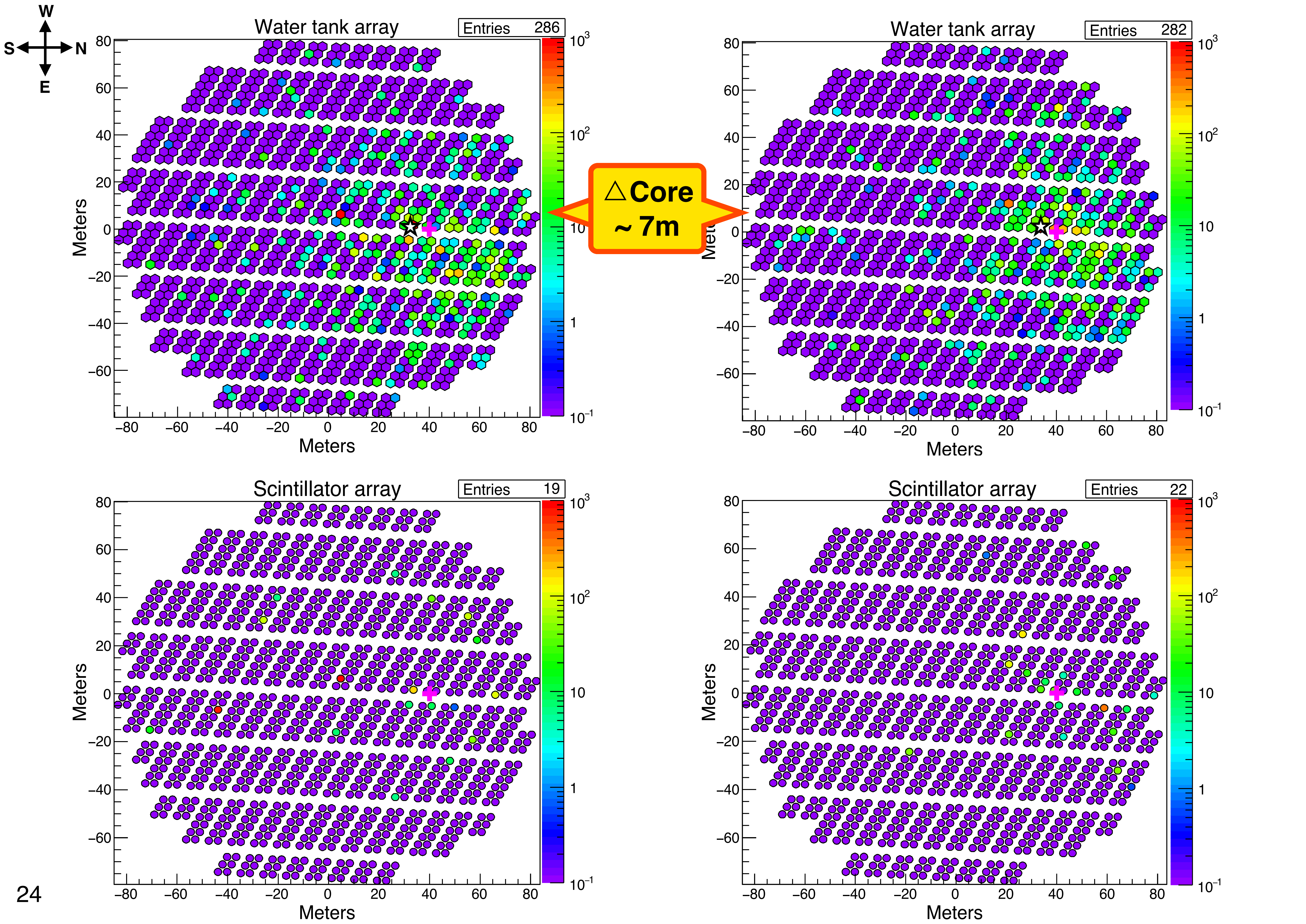






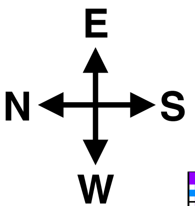


Proton events (Energy 5 TeV, Zenith 18 deg.)

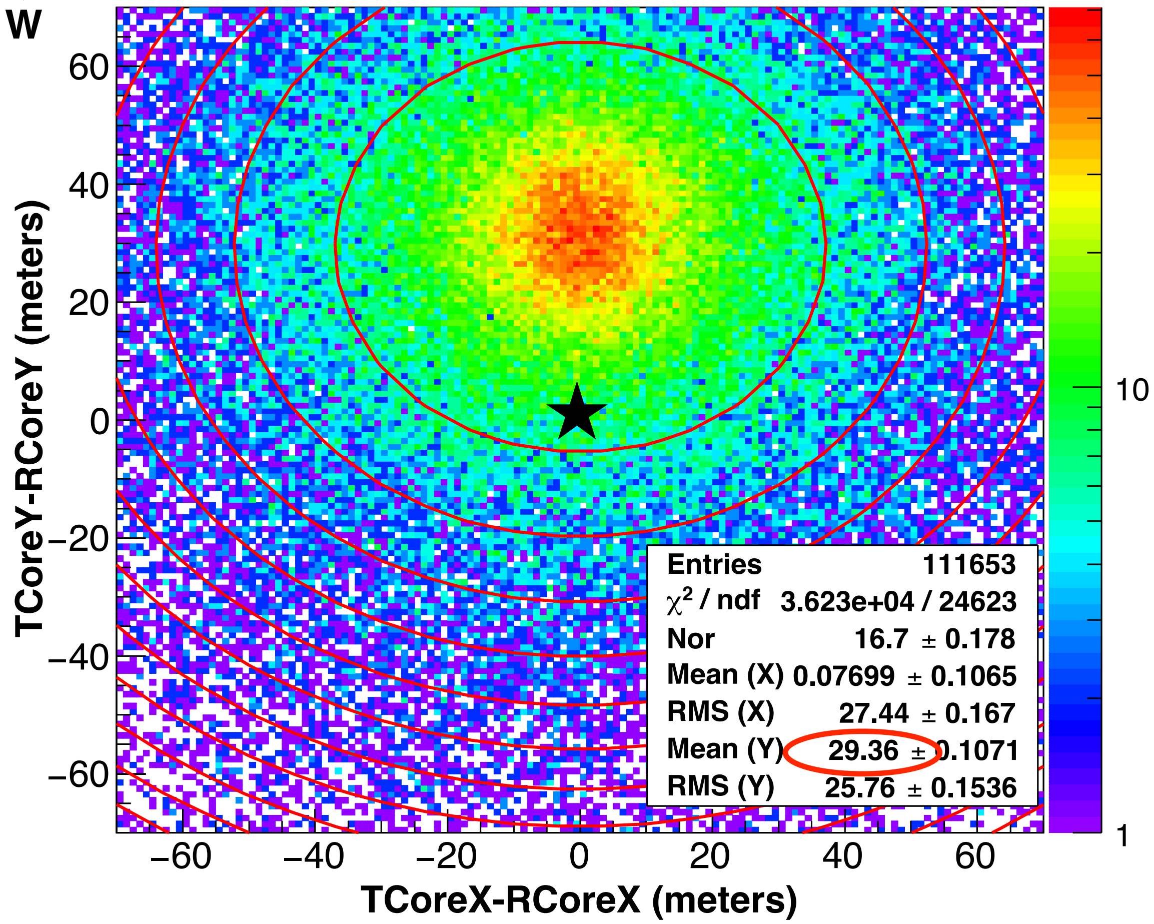


Proton showers: Core reconstruction accuracy

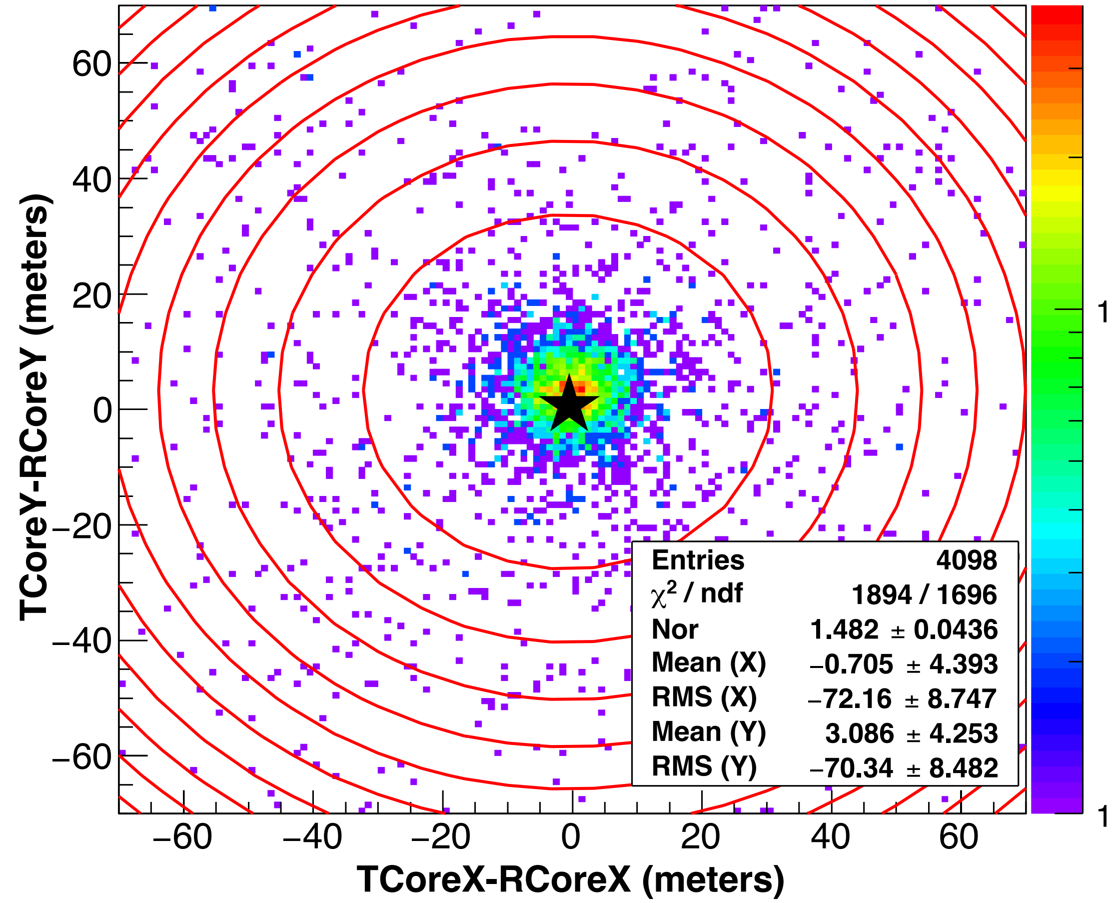
Zenith=15°-21°, R_{Core}<60 m

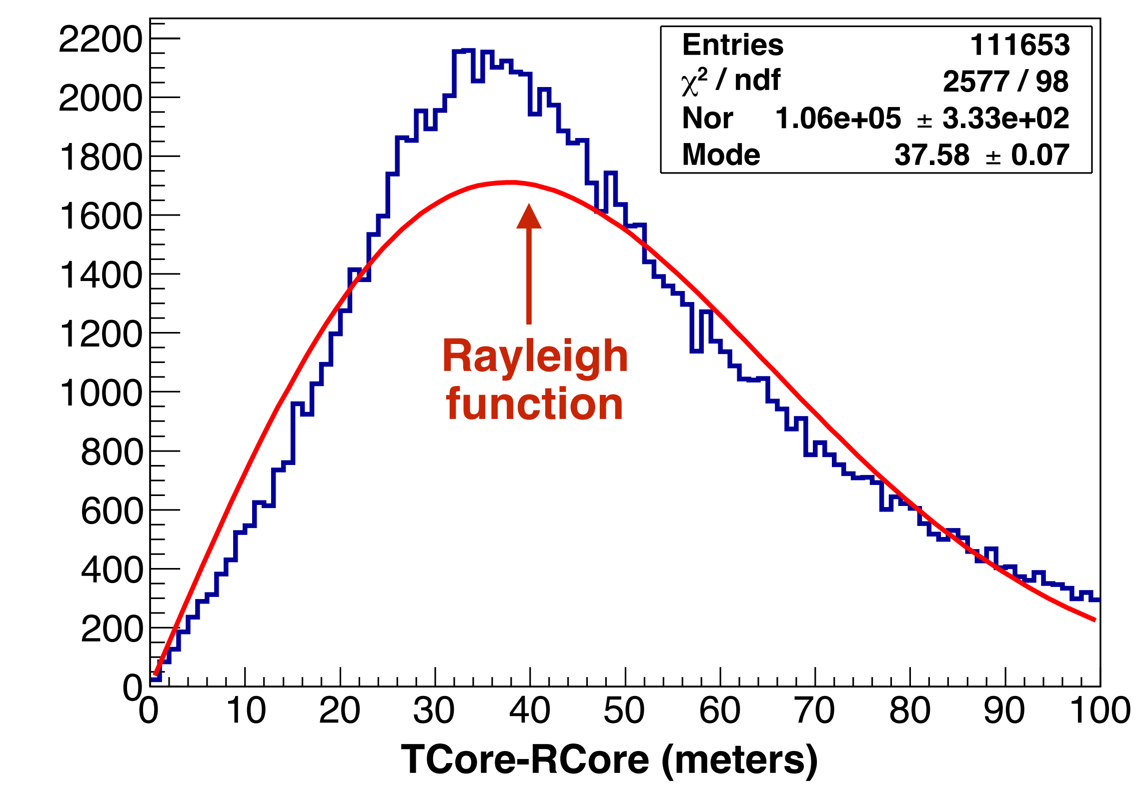


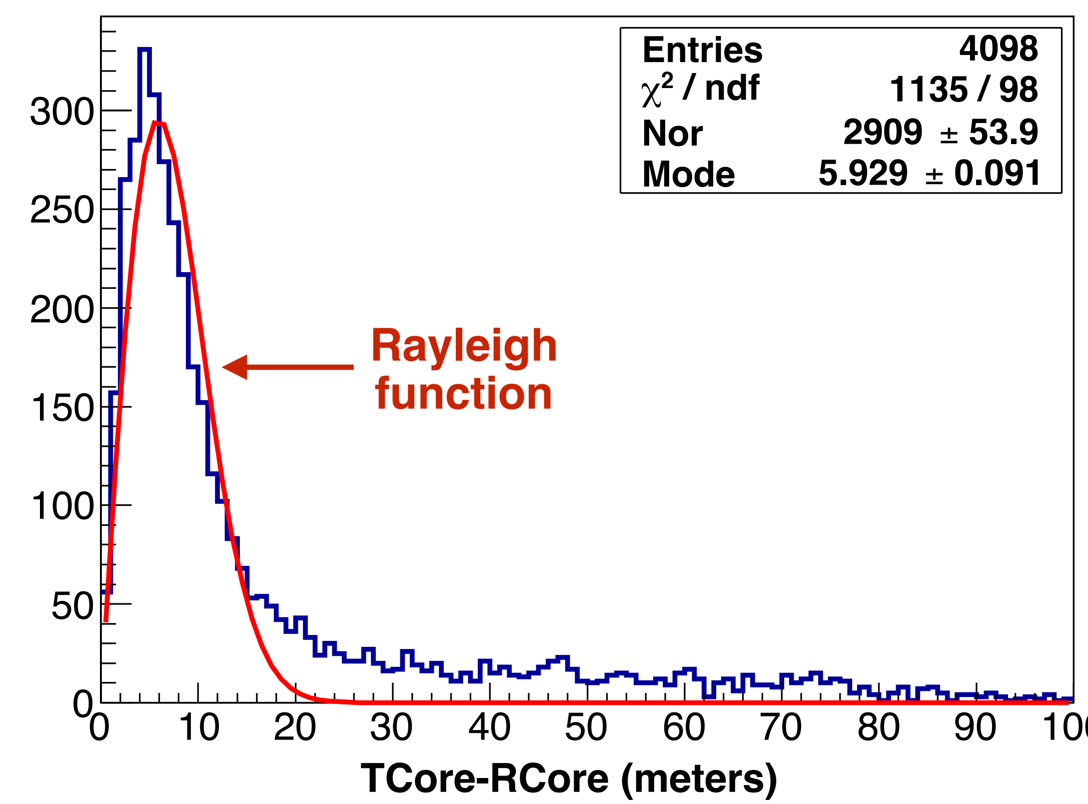
1-1.5 TeV



10-15 TeV

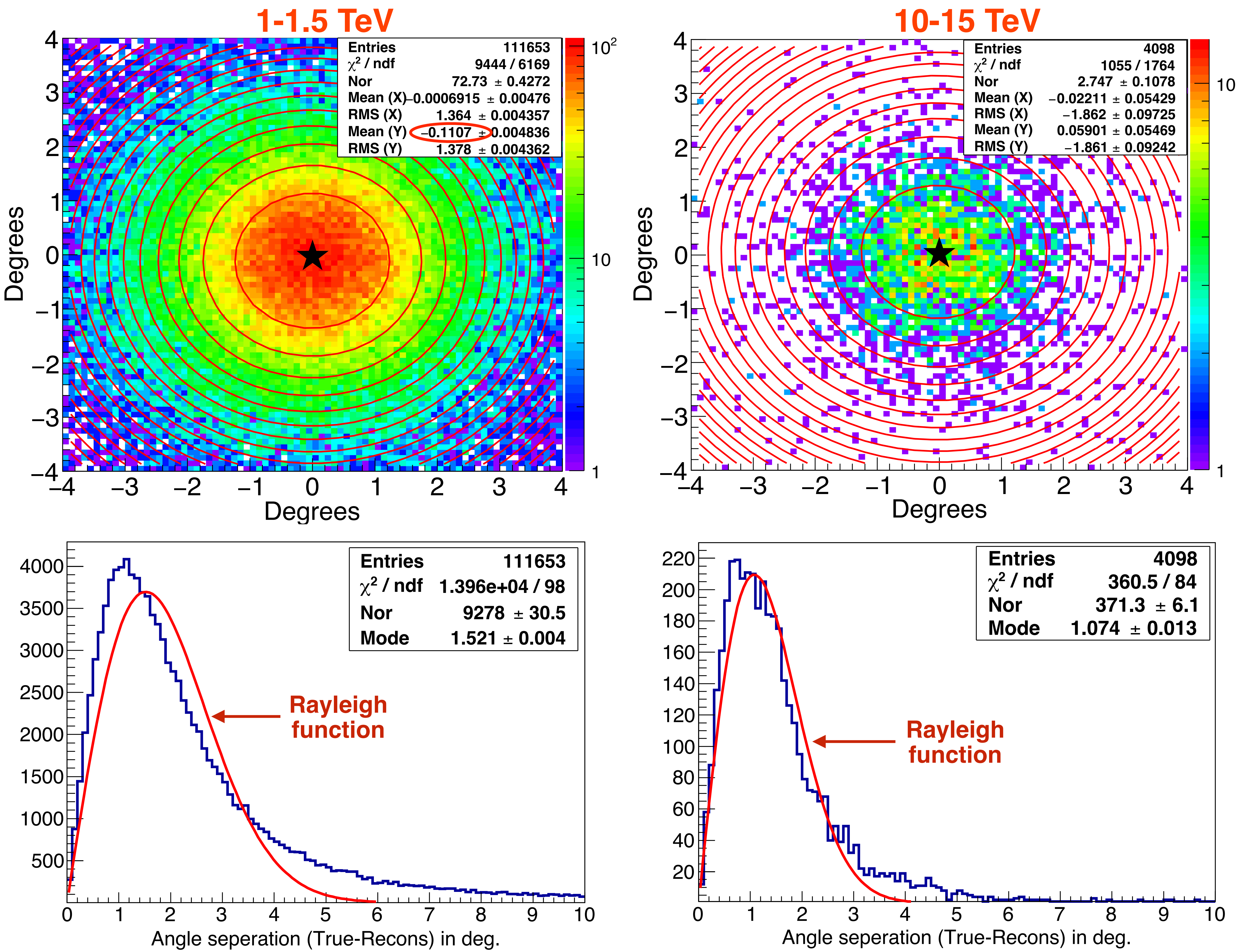






Proton showers: Direction reconstruction accuracy

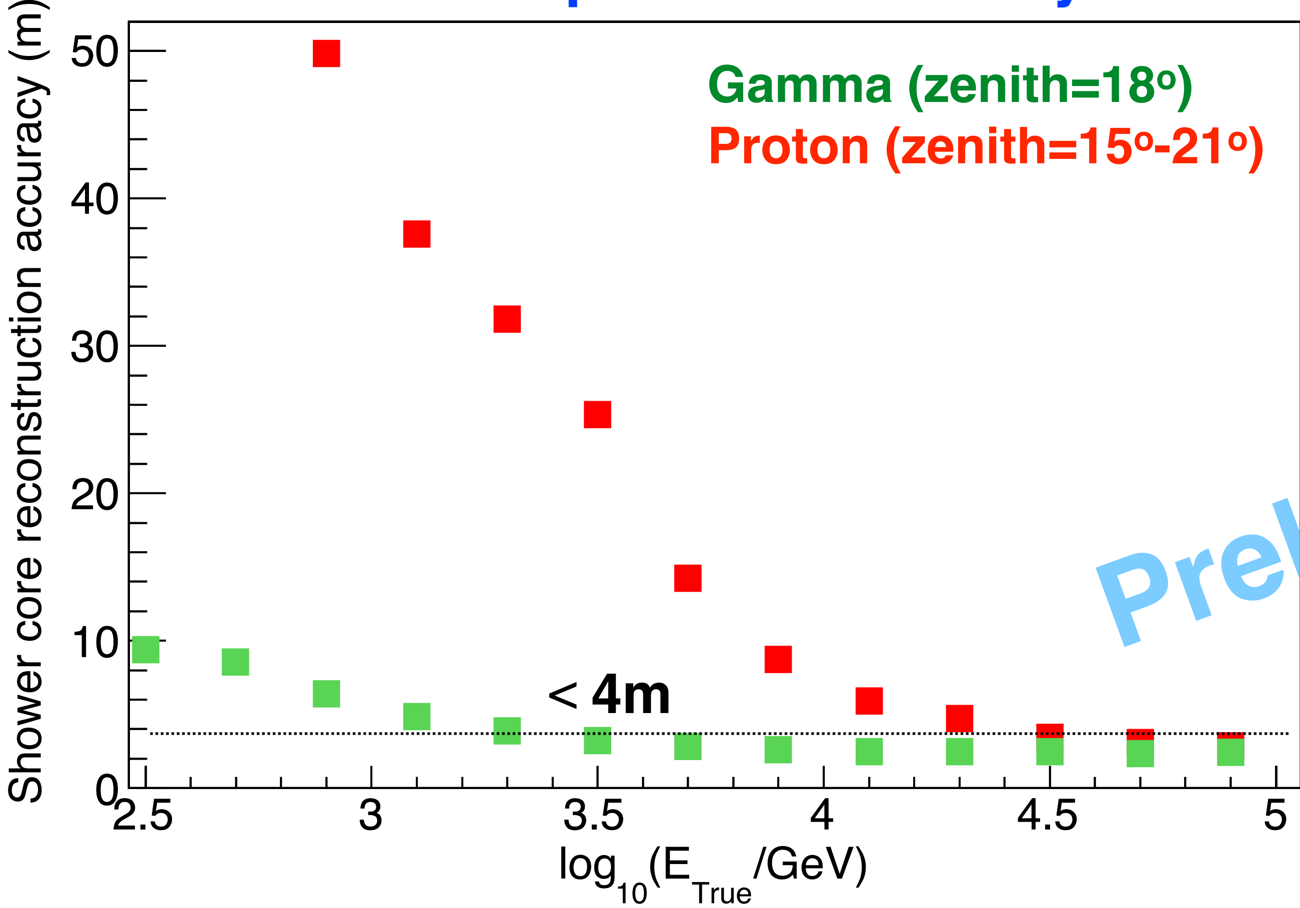
Zenith=15°-21°, R_{Core}<60 m



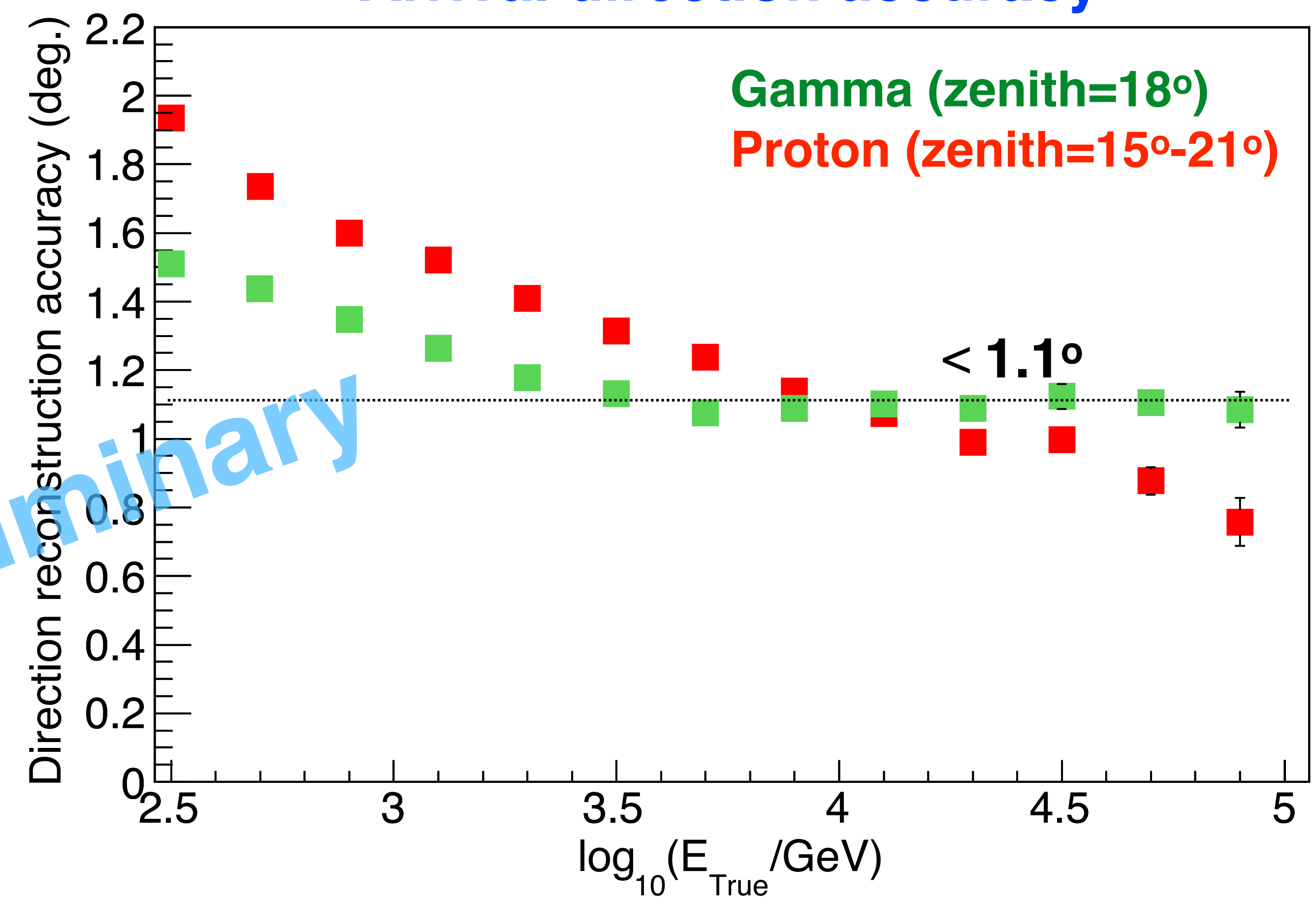
Reconstruction accuracies as function of energy

(RCore<60 m)

Core position accuracy



Arrival direction accuracy



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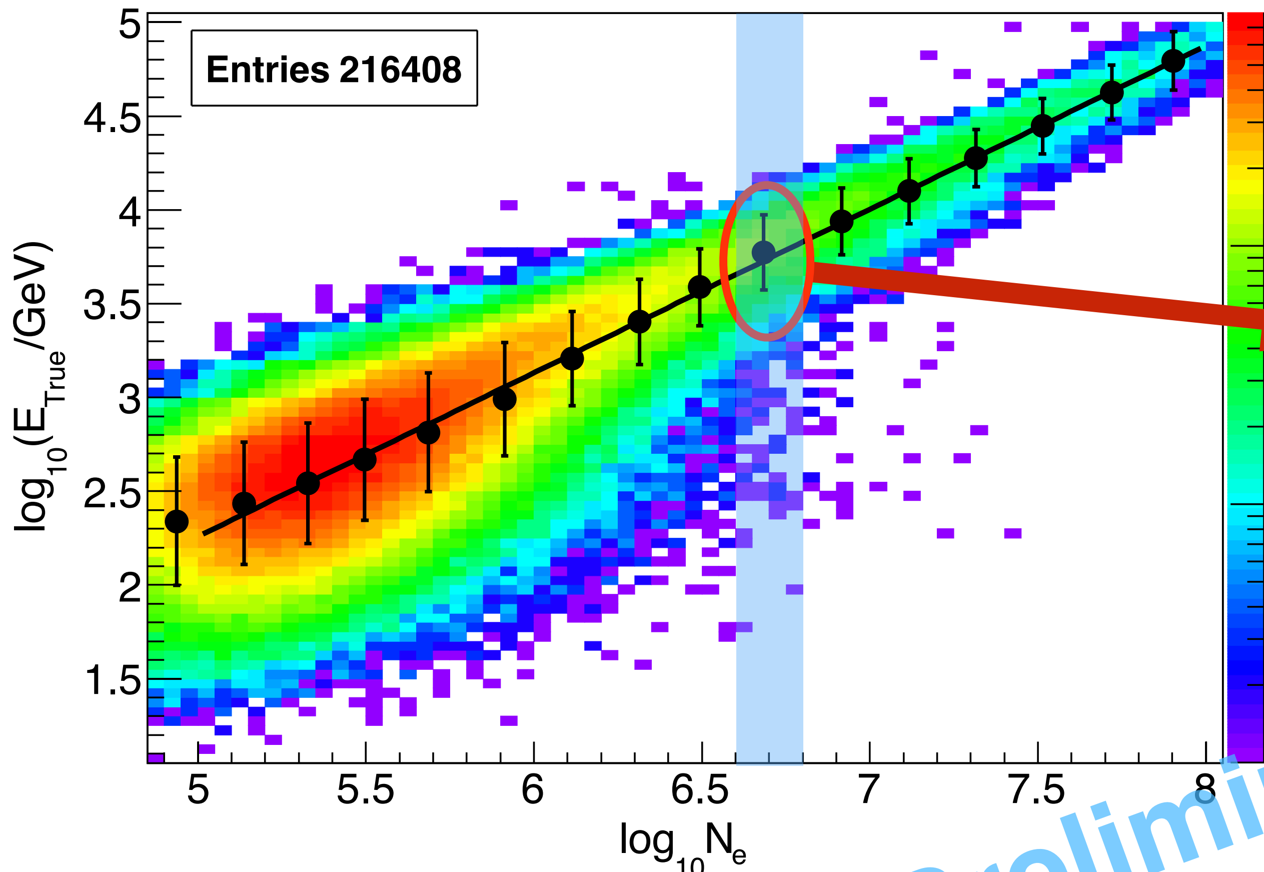
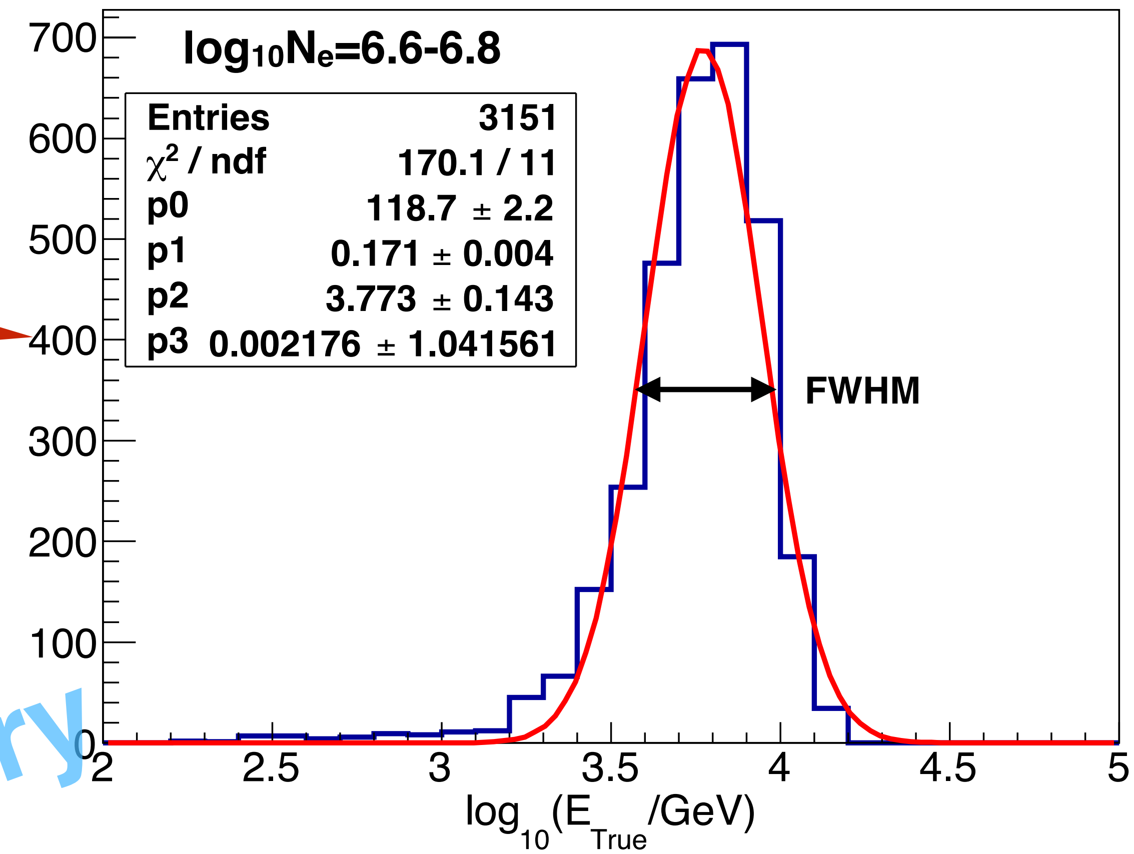
Gamma showers: Energy reconstruction

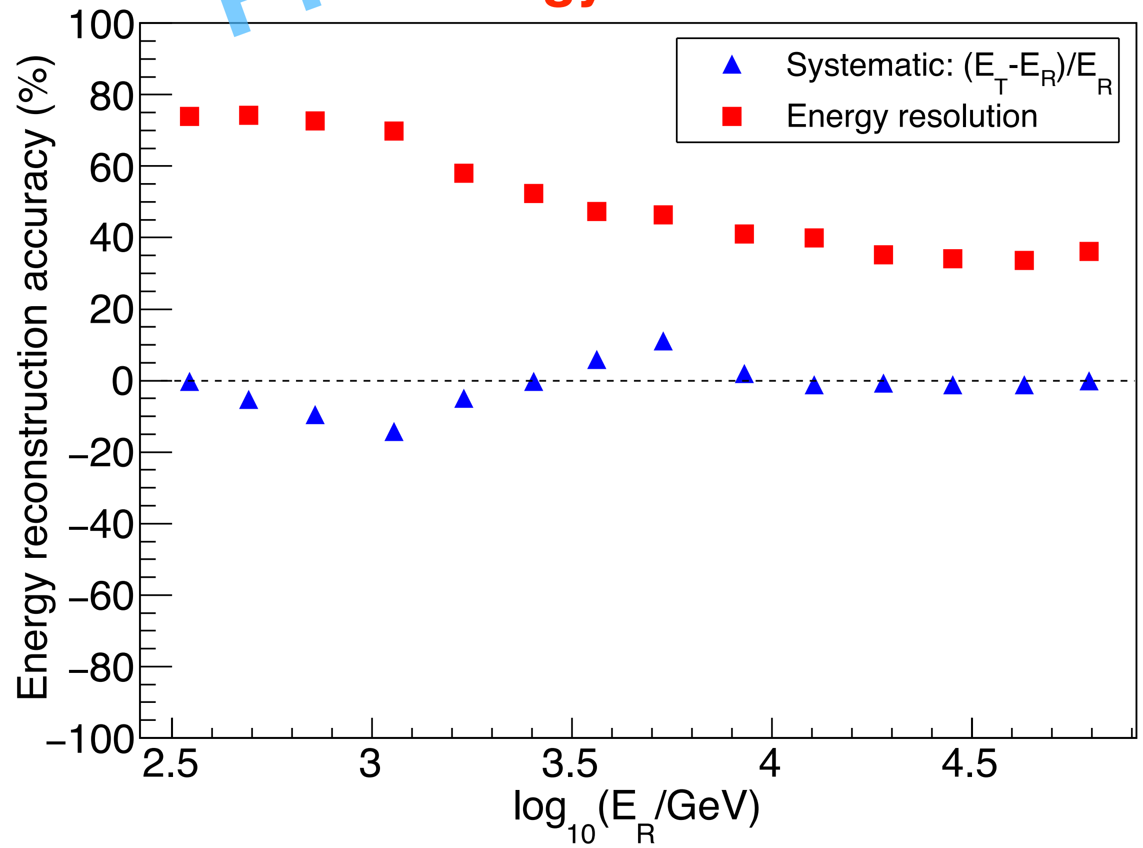
Recons. size VS True Energy



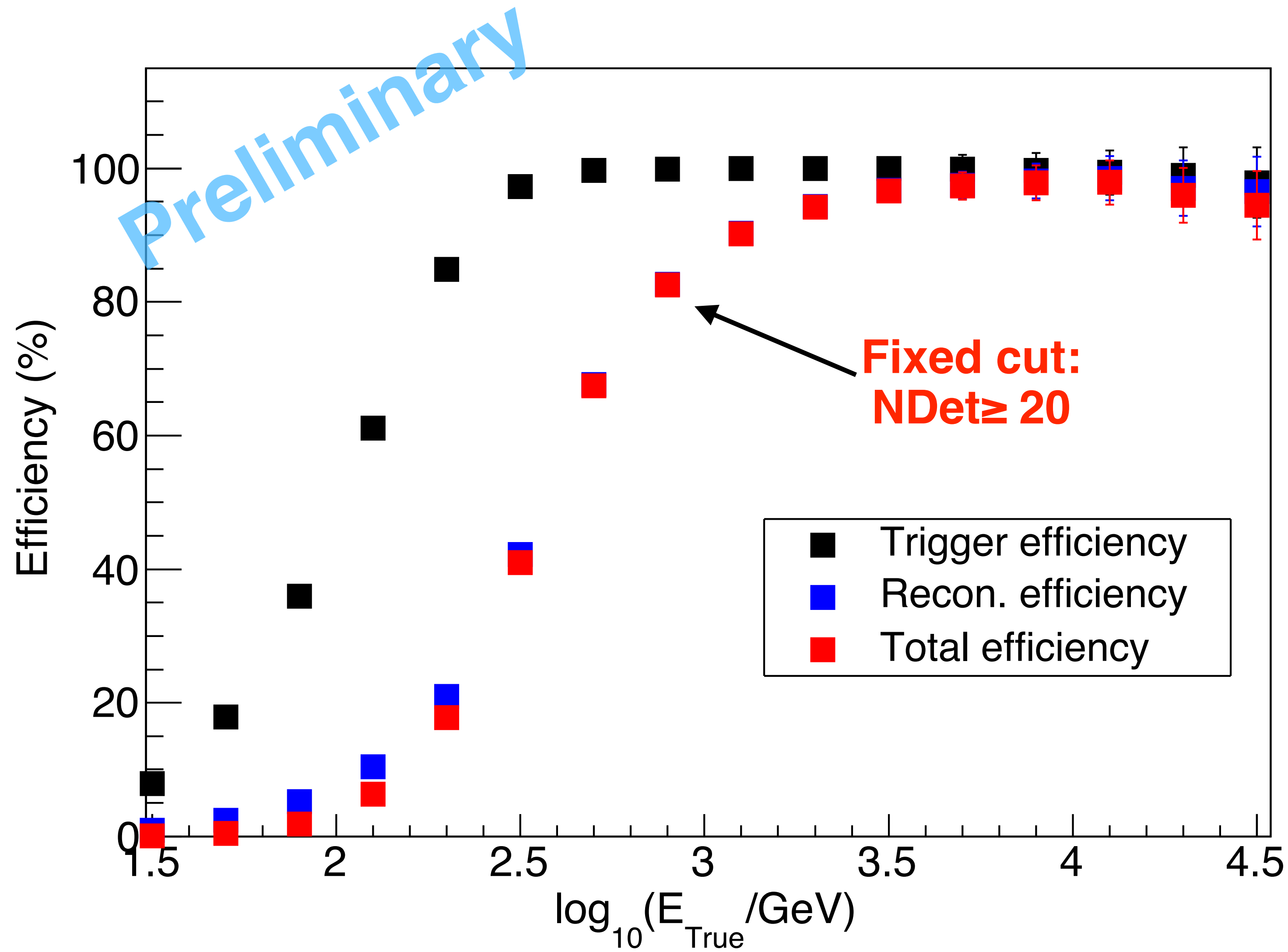


Preliminary

Energy resolution



Gamma showers: Trigger/reconstruction efficiencies



Plans for S/B discrimination

★ Define new discriminating parameters, and use the BDT classification procedure

★ New parameters include scintillator layer signals

★ Cuts optimised per bins in energy, zenith angle, and tank multiplicity

★ Very similar analysis procedure as applied to H.E.S.S:
Astroparticle Physics, 34, 12, July 2011, Pages 858-870

★ 2-month work full-time

★ Expected improvement from baseline sensitivity
- a factor of 2 from scintillator array,
- a factor of 2 from analysis method;

Summary

- We are currently working on a detailed Monte-Carlo simulation of ALTO
- Preliminary results have shown that:
    - A trigger threshold as low as 300 GeV can be reached with proper reconstruction of shower parameters (NDet≥20)
    - Core resolution below 5 m for energy above 1 TeV
    - Angular resolution below 1.2^{o} above 1 TeV
    - Energy resolution ~ 60-32% above 1 TeV

To do list

- Improve arrival direction reconstruction using more realistic assumption for the shower front
- Improve core reconstruction of gamma showers below 1 TeV
- Understand large systematic shift between true and reconstructed core for proton showers below 10 TeV (though no effect on gammas, it seems)
- Determine Gamma/hadron separation cuts using Boosted Decision Tree method
- Sensitivity estimates
- ……..

Thank you for your attention