Towards a Southern gamma-ray wide field-of-view observatory

Ruben Conceição

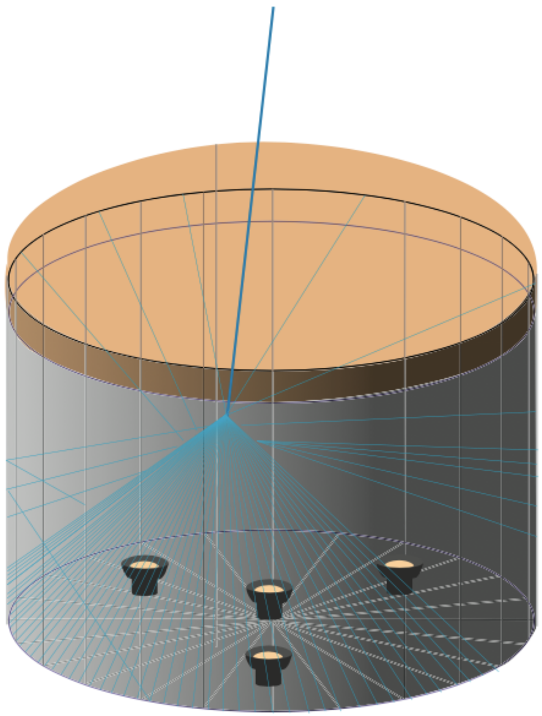
on behalf of the LATTES team

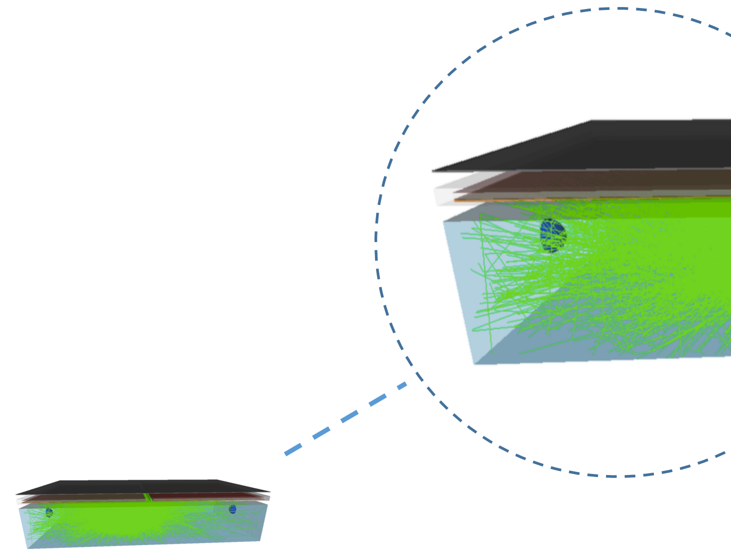
LIP

The requirements

- Access the low energy (~100 GeV)
  - Trigger on shower
    - Few low energy photons
      - **WCD**
  - Geometry shower reconstruction
    - Time resolution better than 2-3 ns
      - **RPC**
  - Hybrid / Autonomous / modular / compact / reduced price

Detector Station



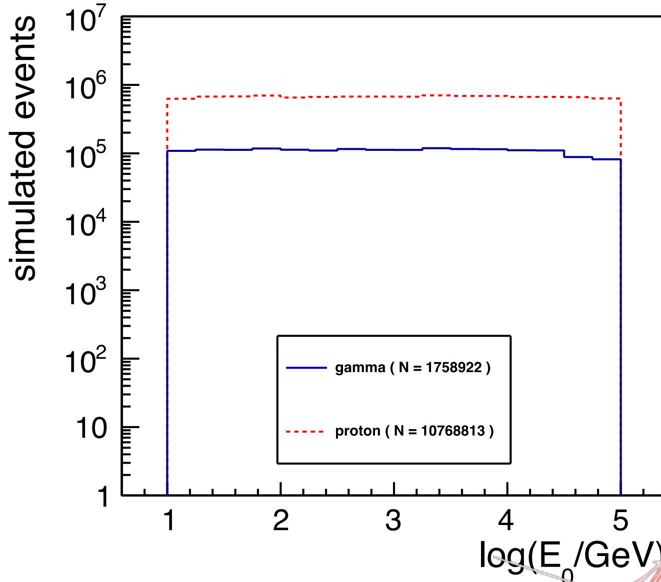


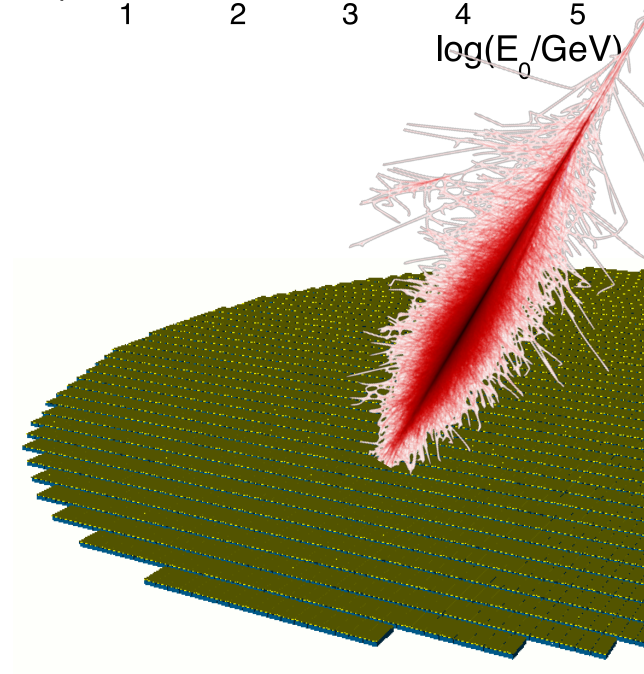
HAWC

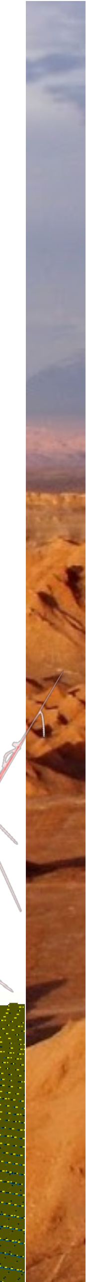
LATTES

Simulation Framework

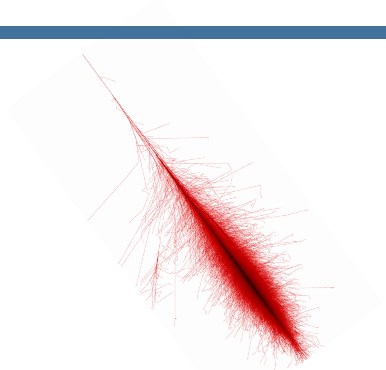
- End-to-end realistic simulation
  - Extensive Air Showers: CORSIKA
    - v7.6400 with Fluka2011.2c
    - More than 100 000 gamma/proton shower simulated randomly between 10 GeV – 300 TeV
    - Gammas have a fixed zenith angle of 10 degrees
    - Observation level at 5200 m of altitude
  - Detector simulation: Geant4
    - v10.1.3
    - Core array 20 000 m²
    - Each shower is resampled 100 times over a big area containing all the array



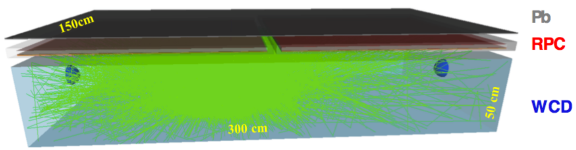




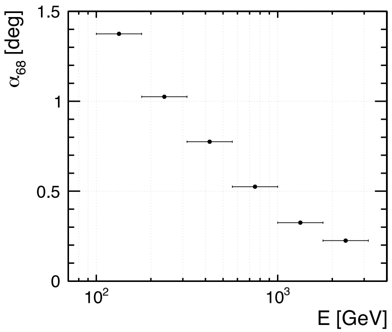
Towards LATTES sensitivity…



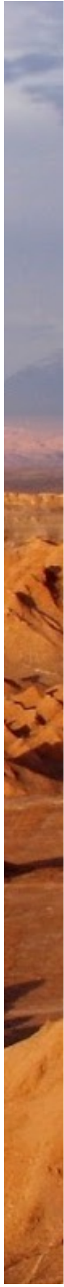
Shower simulation (CORSIKA)



Detector simulation (Geant4)

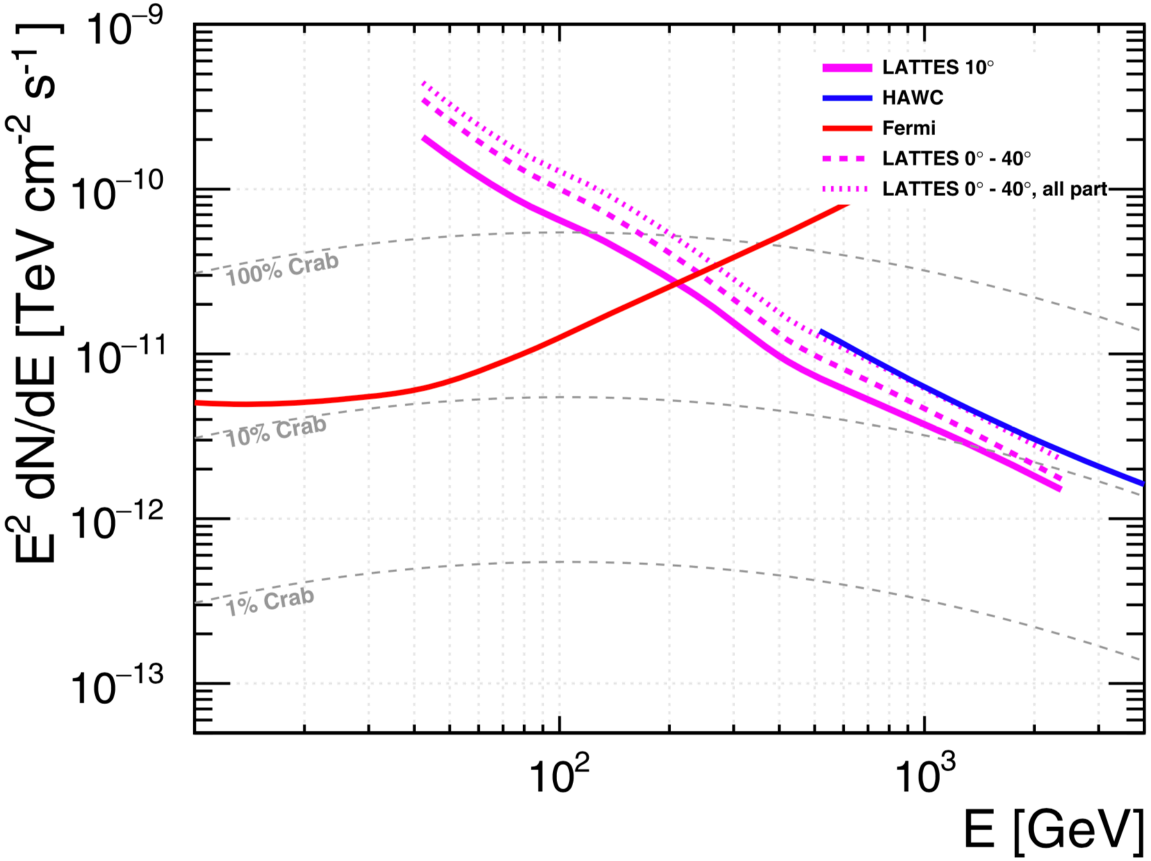


Shower reconstruction (LATTESrec)



Sensitivity to steady sources

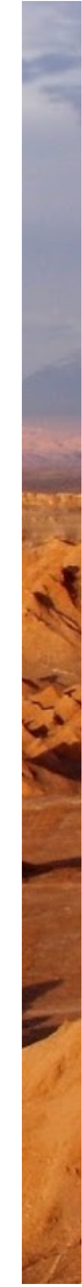
Astroparticle physics 99 (2018) 34-42



✧ *Full line*: full MC calculation for a source at 10 degrees in zenith

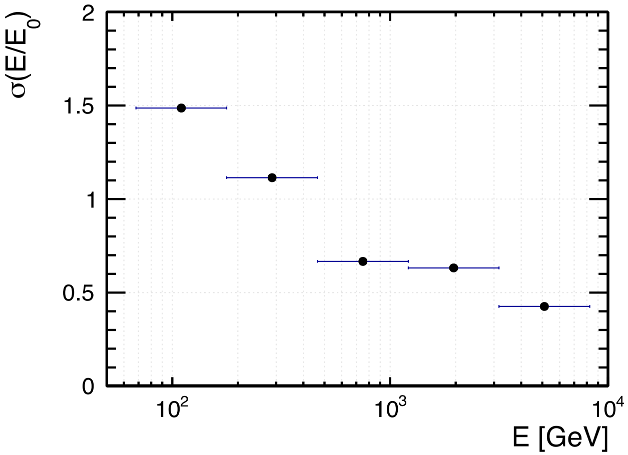
LATTES - works performed

- Trigger and effective area
  - Estimation of accidentals contamination
- Core reconstruction
  - WCD ; Use average LDF with 3 free parameters
- Energy reconstruction
  - WCD ; Total signal calibrated to true energy
- Geometry reconstruction
  - RPCs ; Shower front reconstruction (conic fit)
- Gamma/hadron discrimination
  - WCD ; Steepness/Bumpiness of LDF + Signal far away from shower core (more than 40 m)

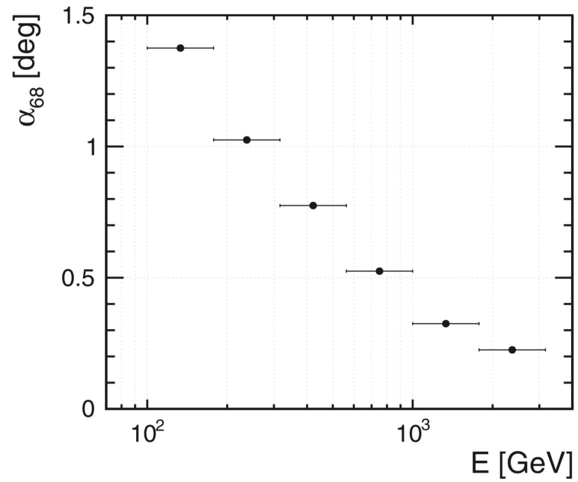


LATTES performance

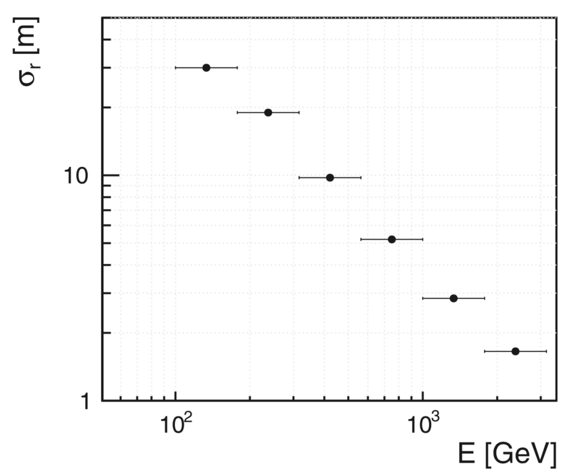
Energy Resolution



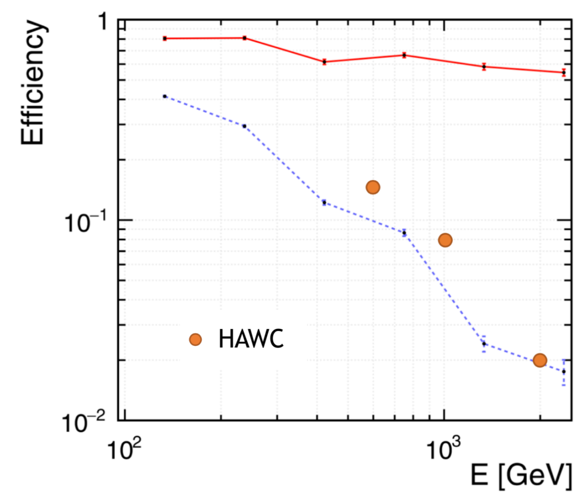
Angular Resolution

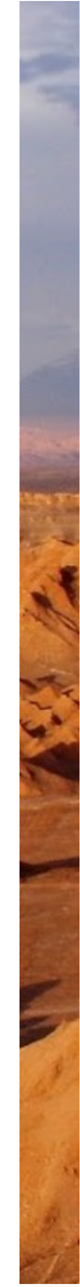


Core Resolution

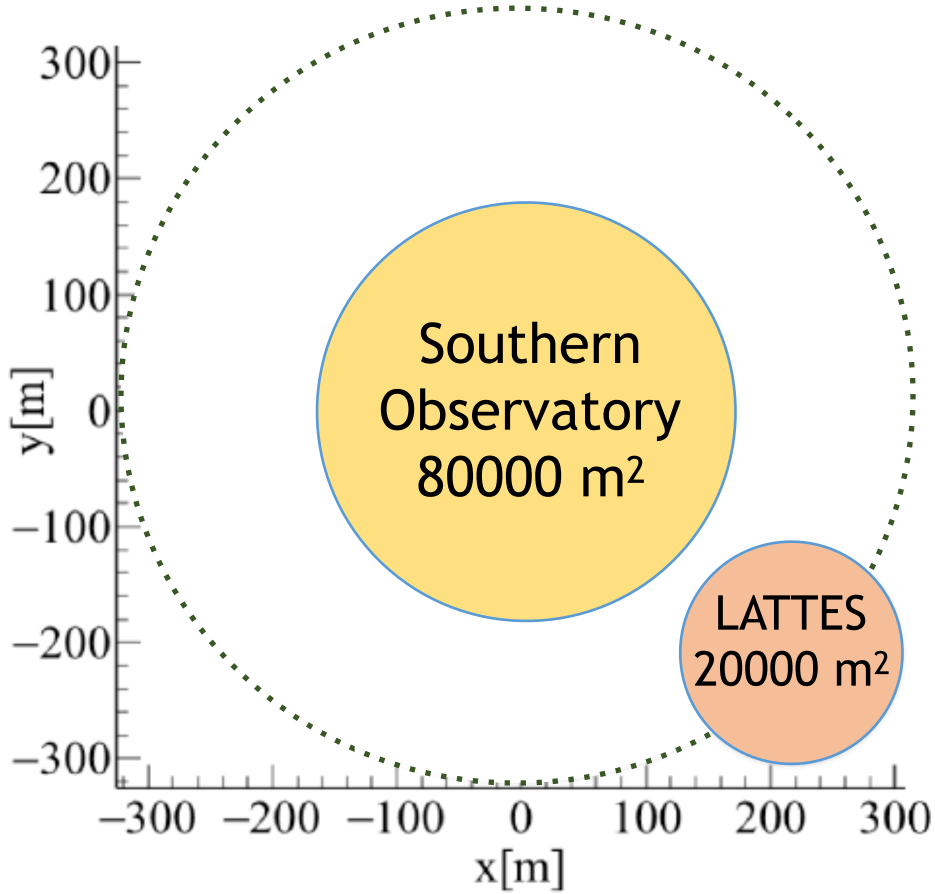


Gamma/Hadron discrimination

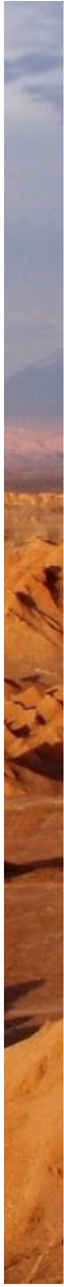




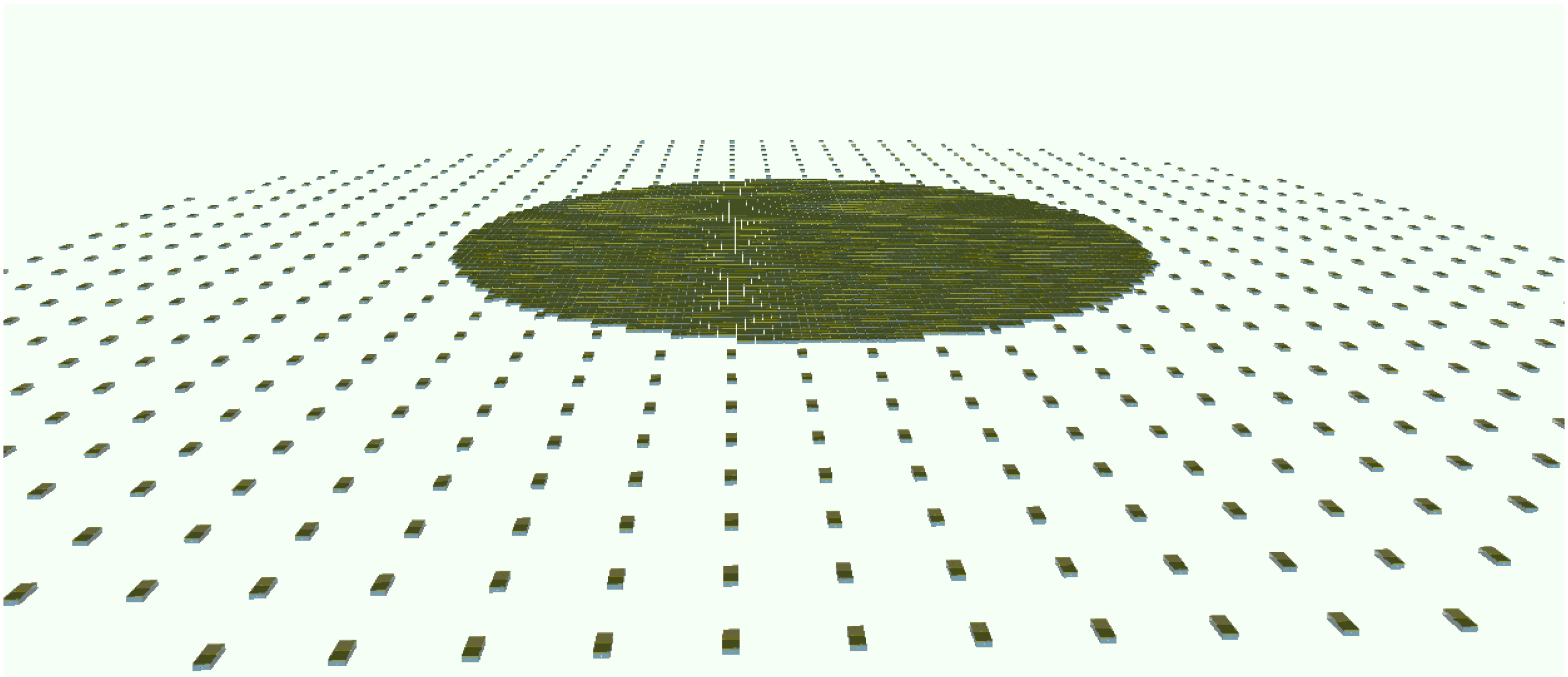
Size matters!

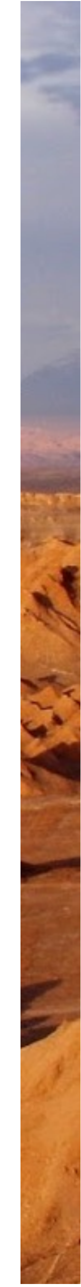


- Preliminary studies on science case at low energies suggests the need for a larger area



New layout?...

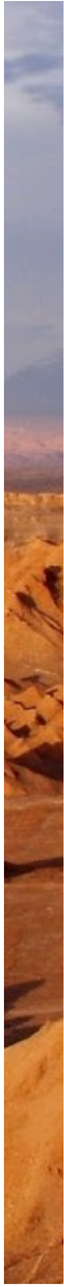




- ✧ Inner core with an area of 80000 m^2
- ✧ WCD with 1 meter height

New challenges

- **Timing**
  - Tank should be white to lower energy threshold!!
- **Gamma/hadron discrimination**
  - Not a problem for lower energies (no muons!)
  - At higher energies muon identification is a powerful discriminant variable



New challenges

- **Timing**
  - Tank should be white to lower energy threshold!!
  - Access Cherenkov direct light on WCD
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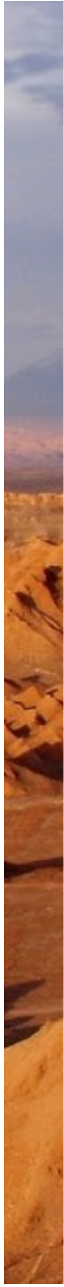
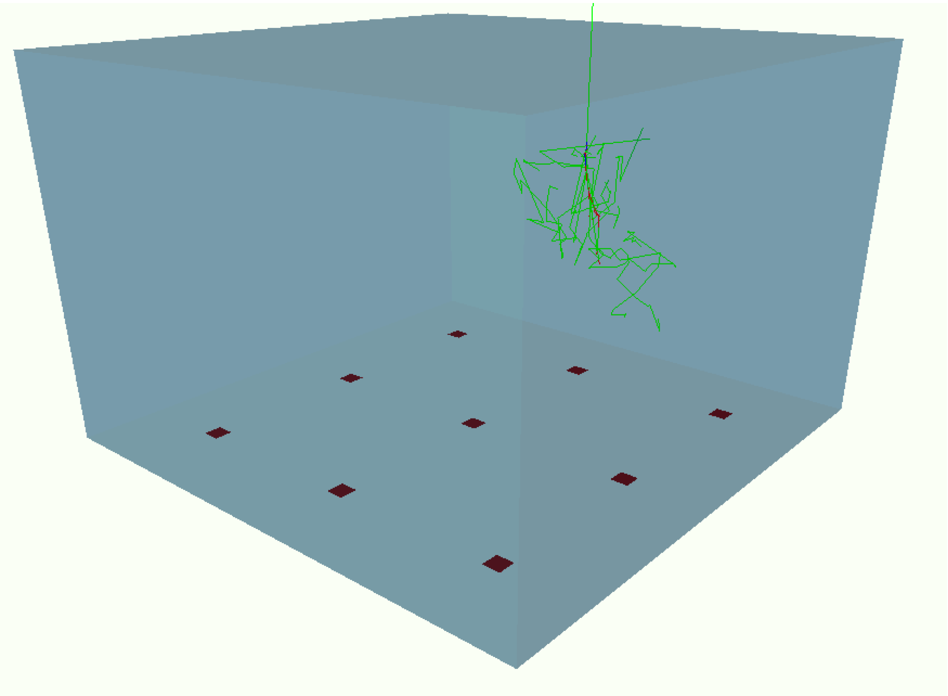


Back to the station level

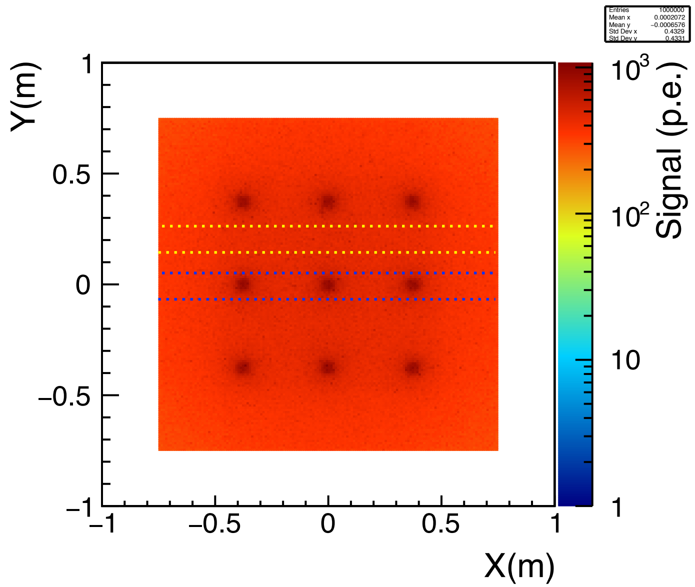


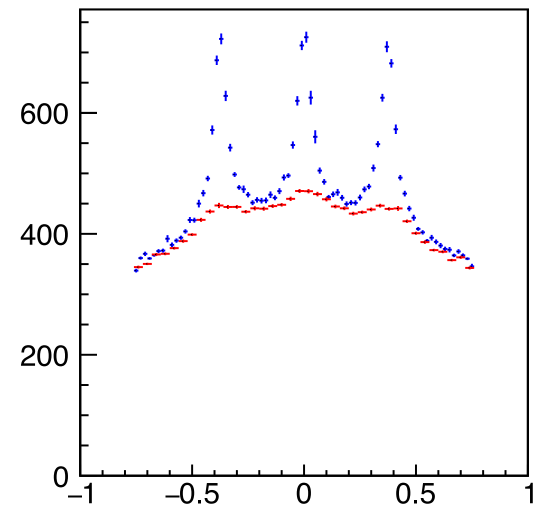
WCD 1.5 x 1.5 x 1 m^3

- Access direct light through 3x3 matrix of SIPM (5x5 cm^2 at the bottom of the WCD

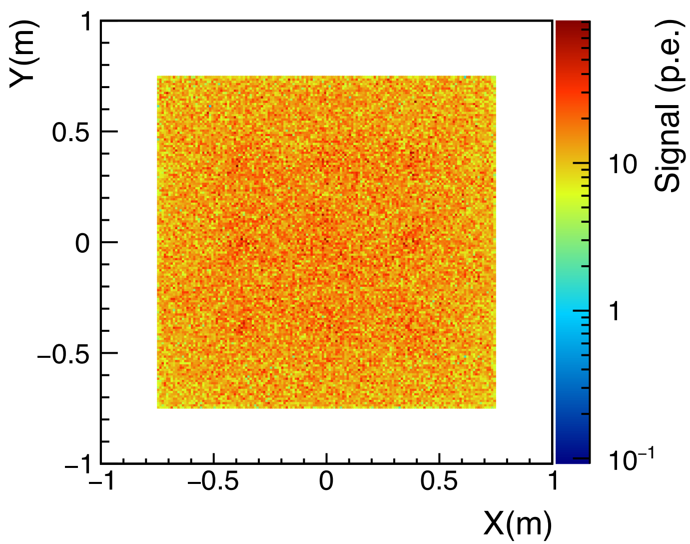
Total signal vs incoming (x,y) for single vertical particles

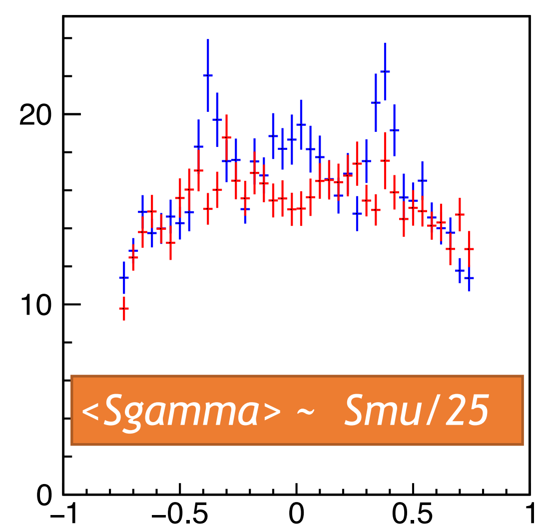
Relativistic muons



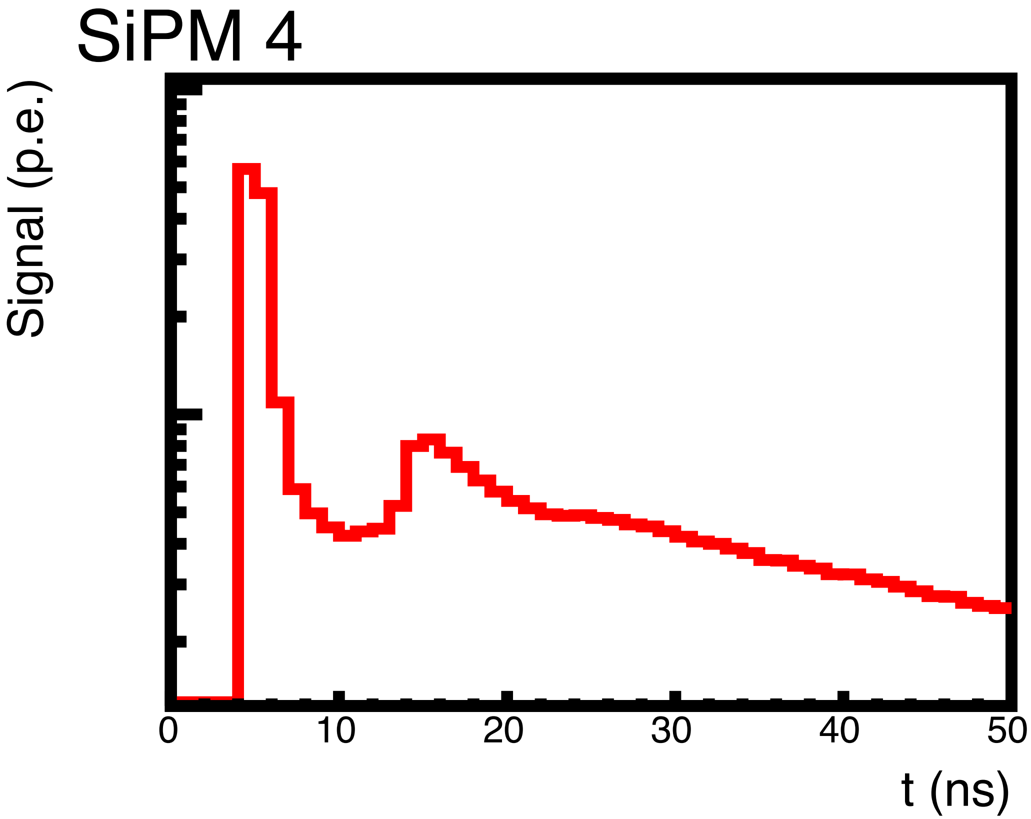


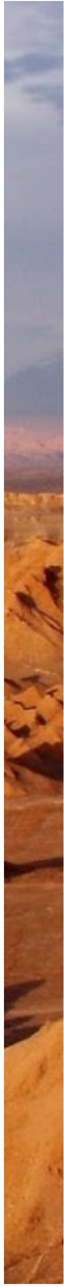
Gammas with spectrum @ ground - r = [40m,500m]





Average traces for photons





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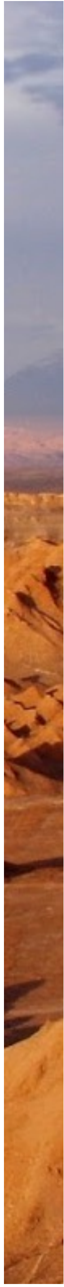
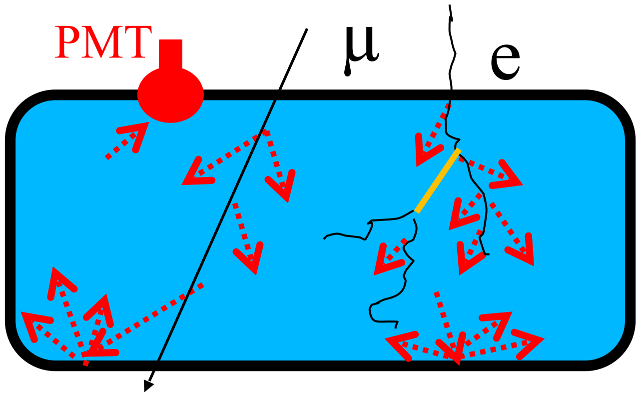
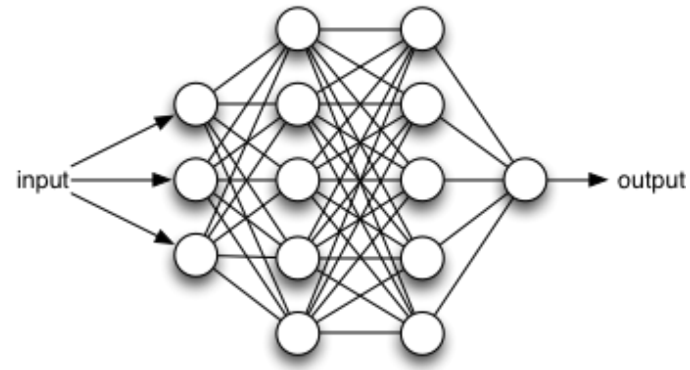
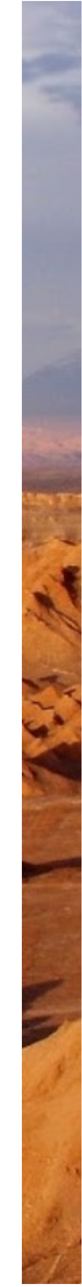


Muon traces from WCDs







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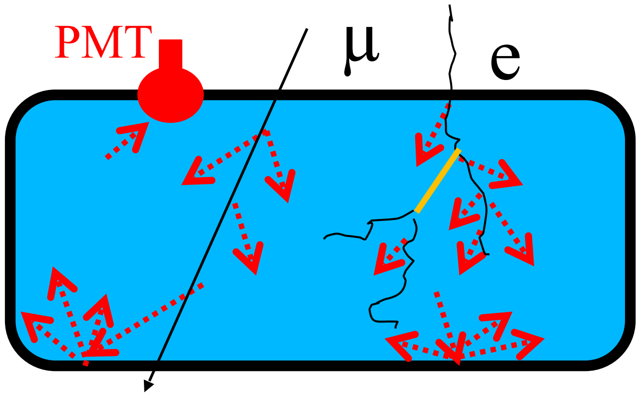
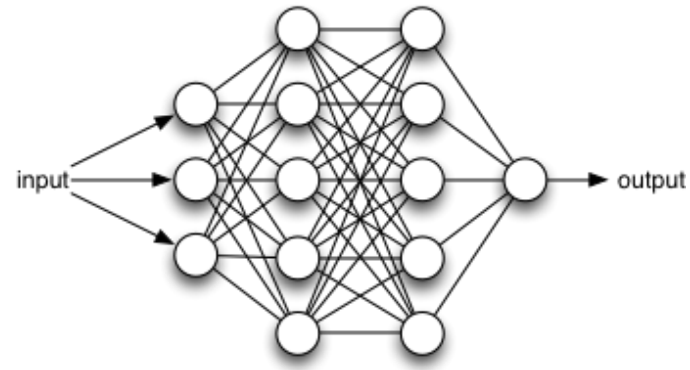
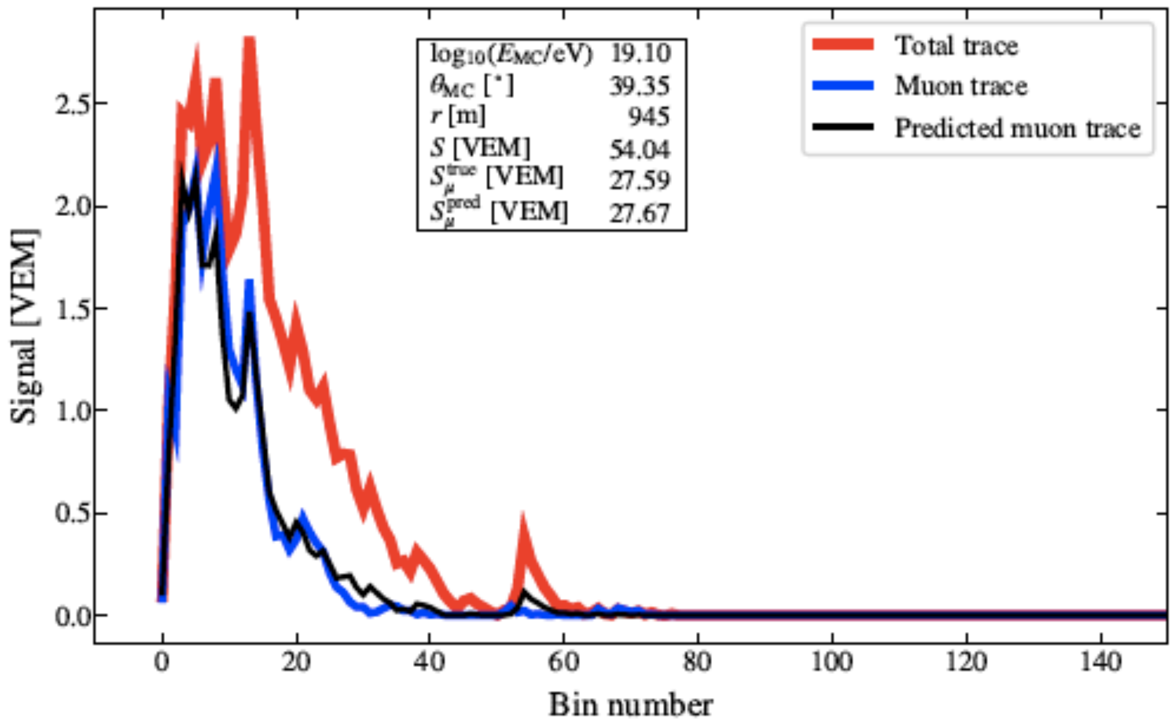
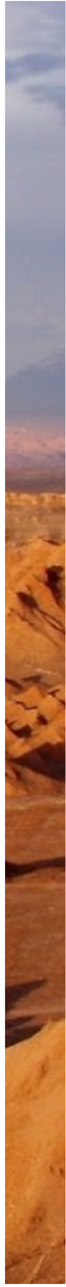






Granada Group

- *A. Bueno*
- *J. M. Carceller*
- *A. Guillén*
- *L. J. Herrera*



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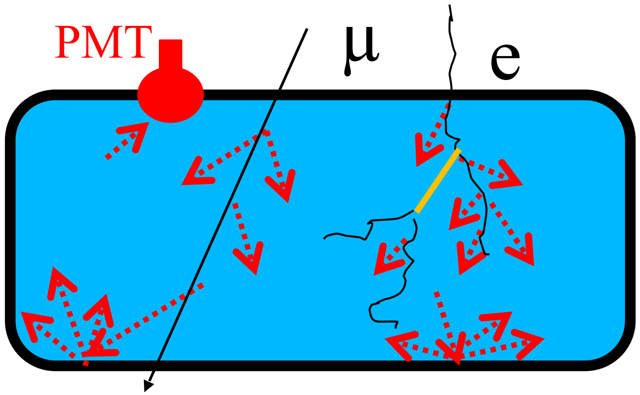
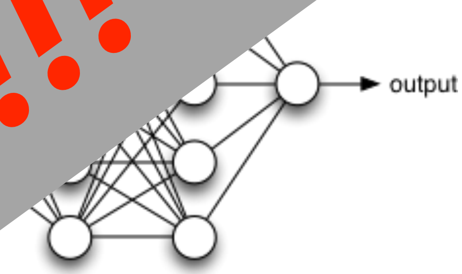
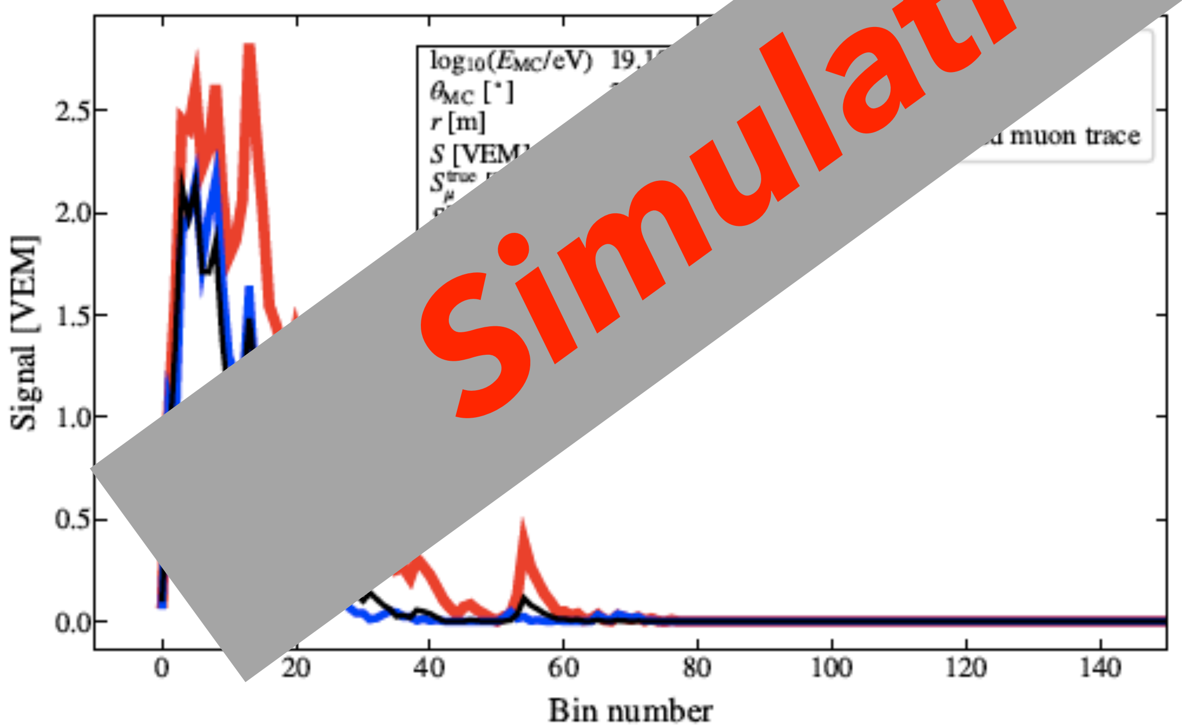




Simulation !!!



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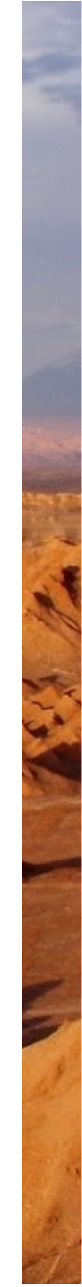
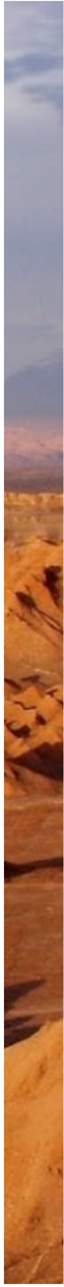
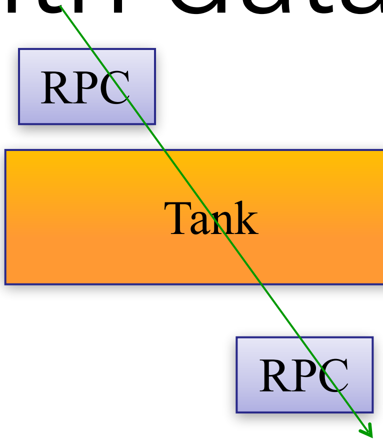


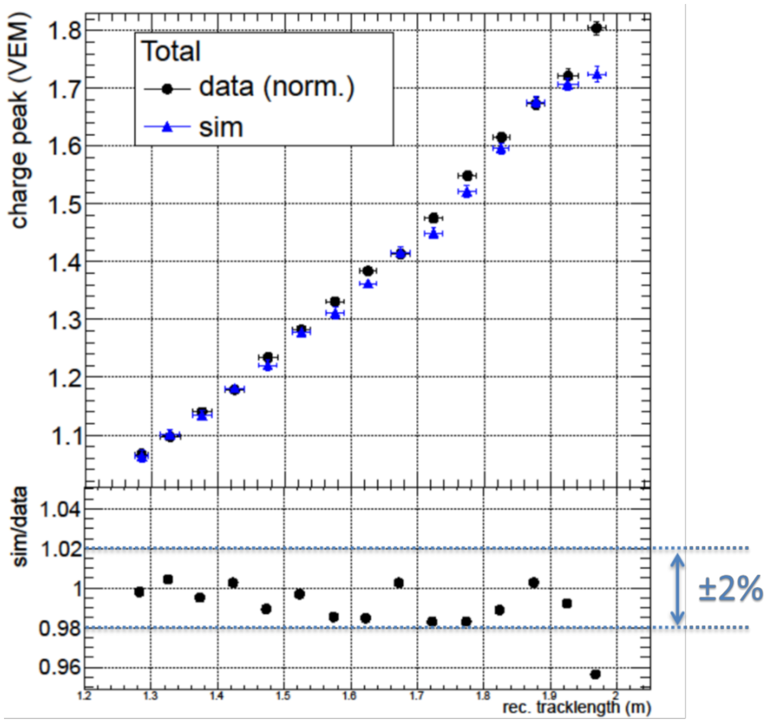
How to train/validate with data?

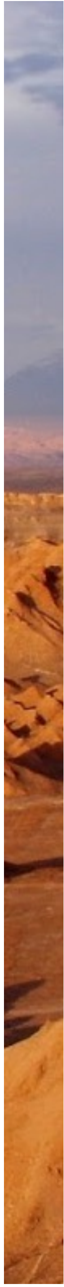


How to train/validate with data?

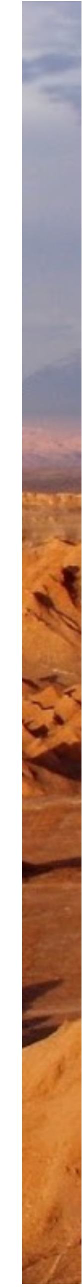
- Test WCD at Auger with at Pierre Auger Observatory





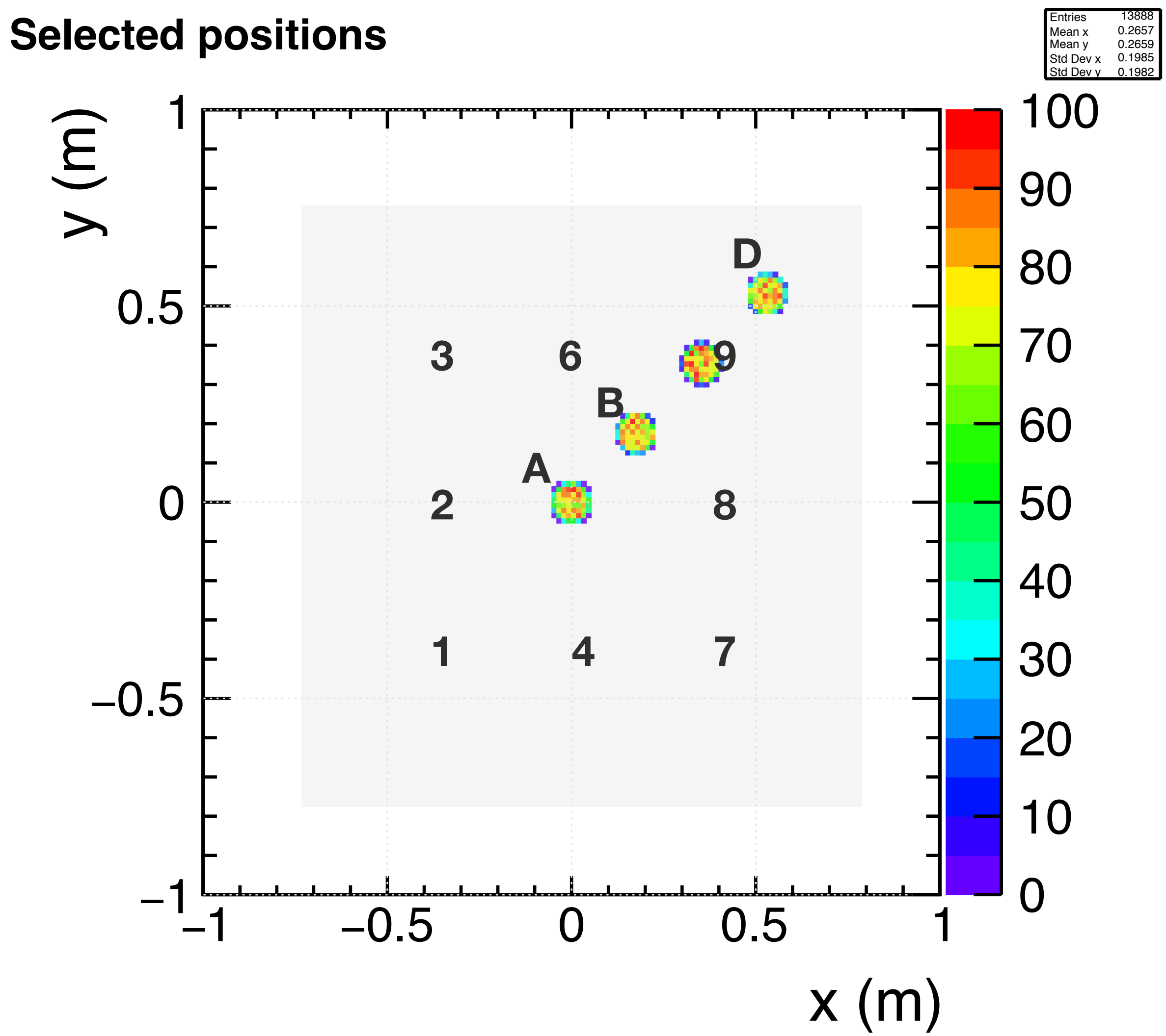


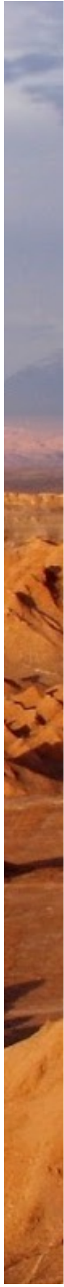
First tests with new WCD station



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

Muons @ position B





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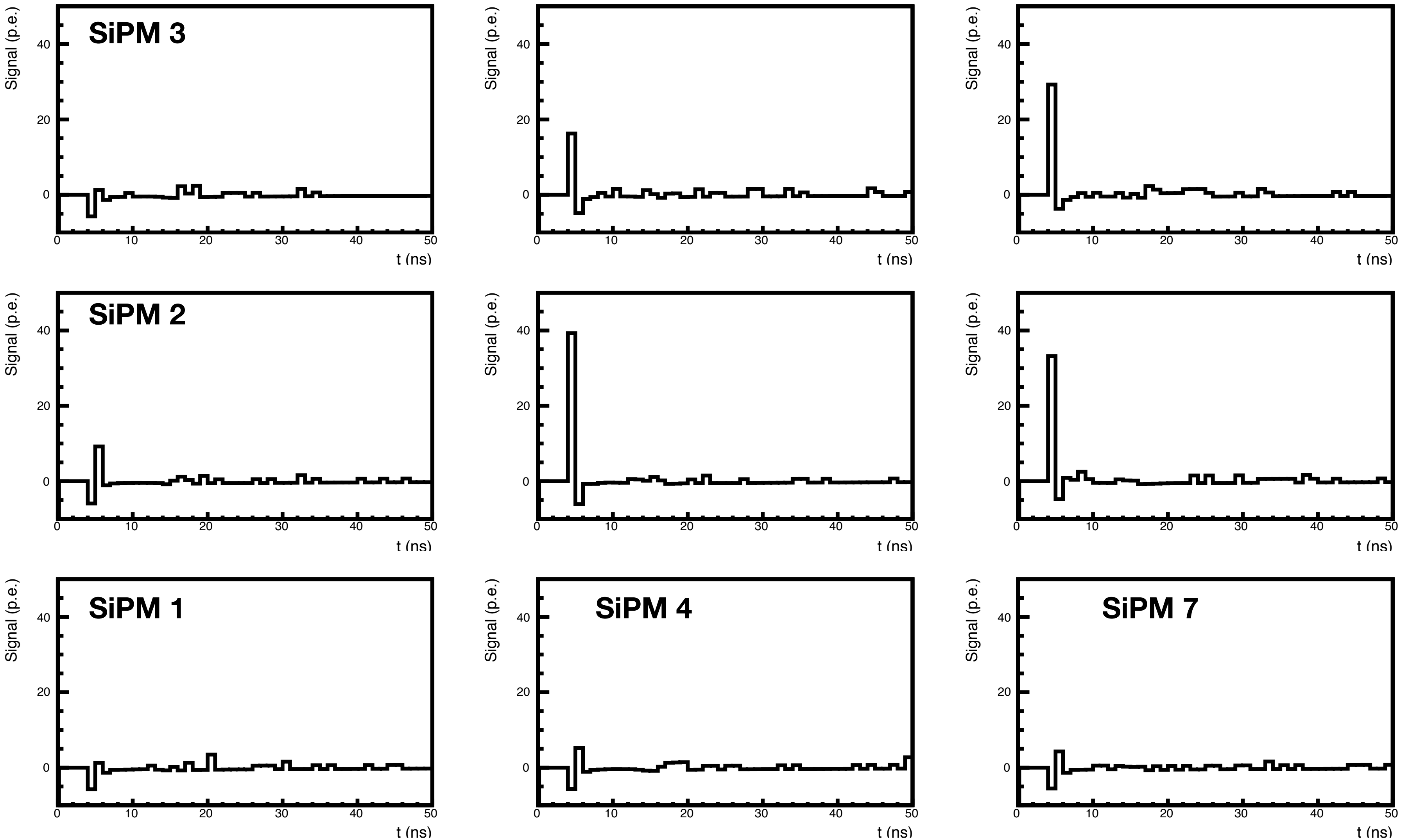

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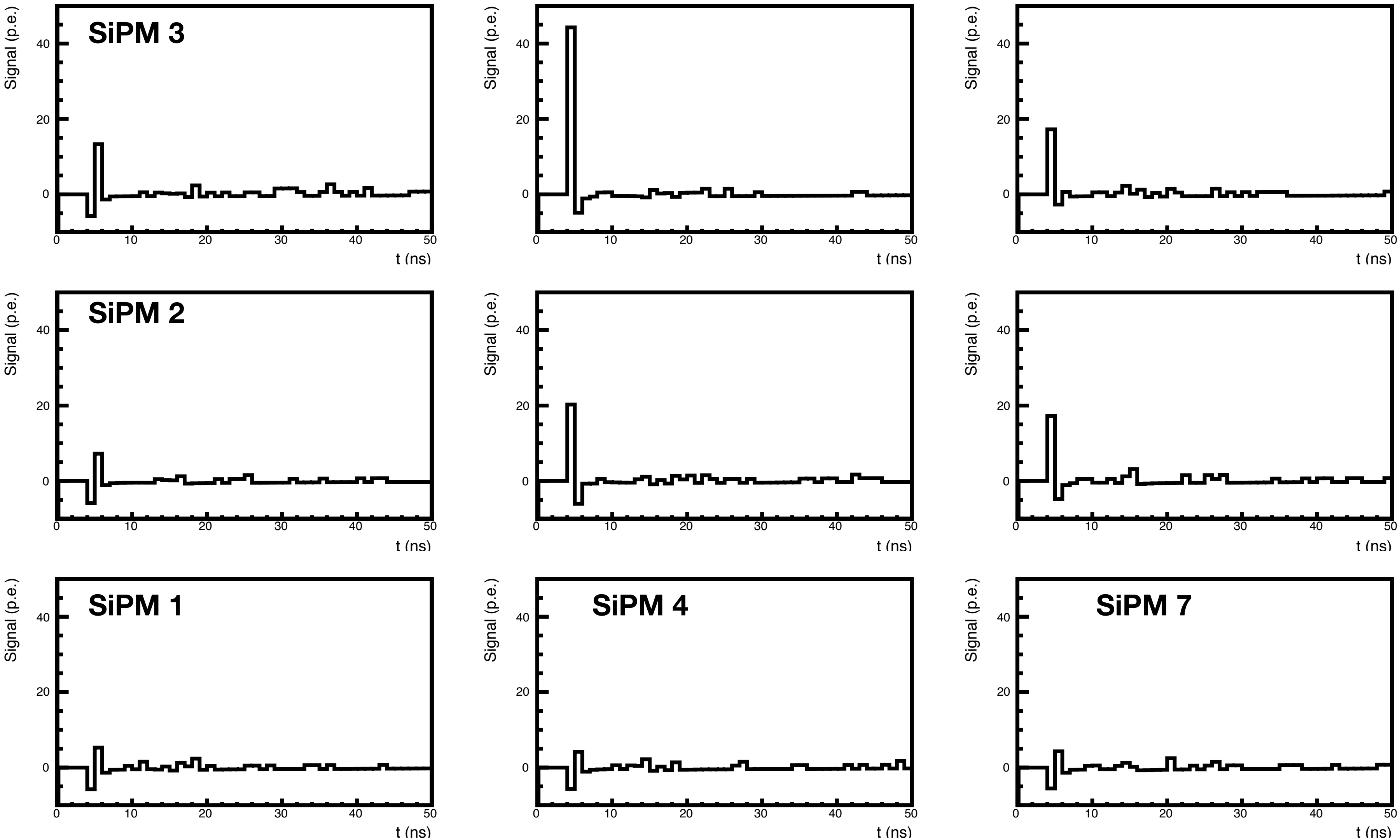
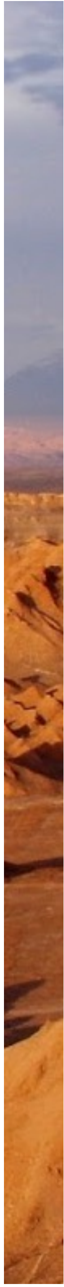
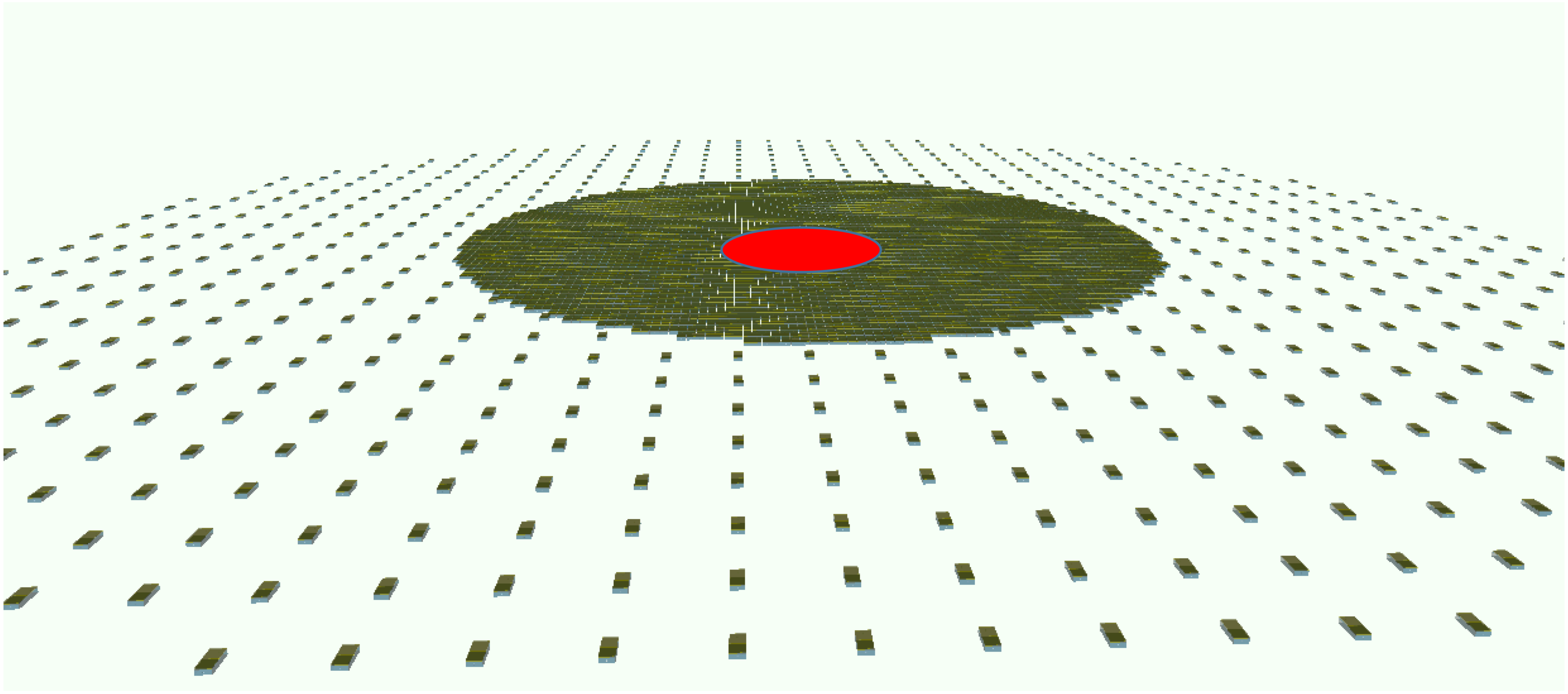


New challenges

- **Timing**
  - Tank should be white to lower energy threshold!!
- **Gamma/hadron discrimination**
  - Not a problem for lower energies (no muons!)
  - At higher energies muon identification is a powerful discriminant variable
    - Use ANN techniques
    - Granada group starting to look into simulations



New layout



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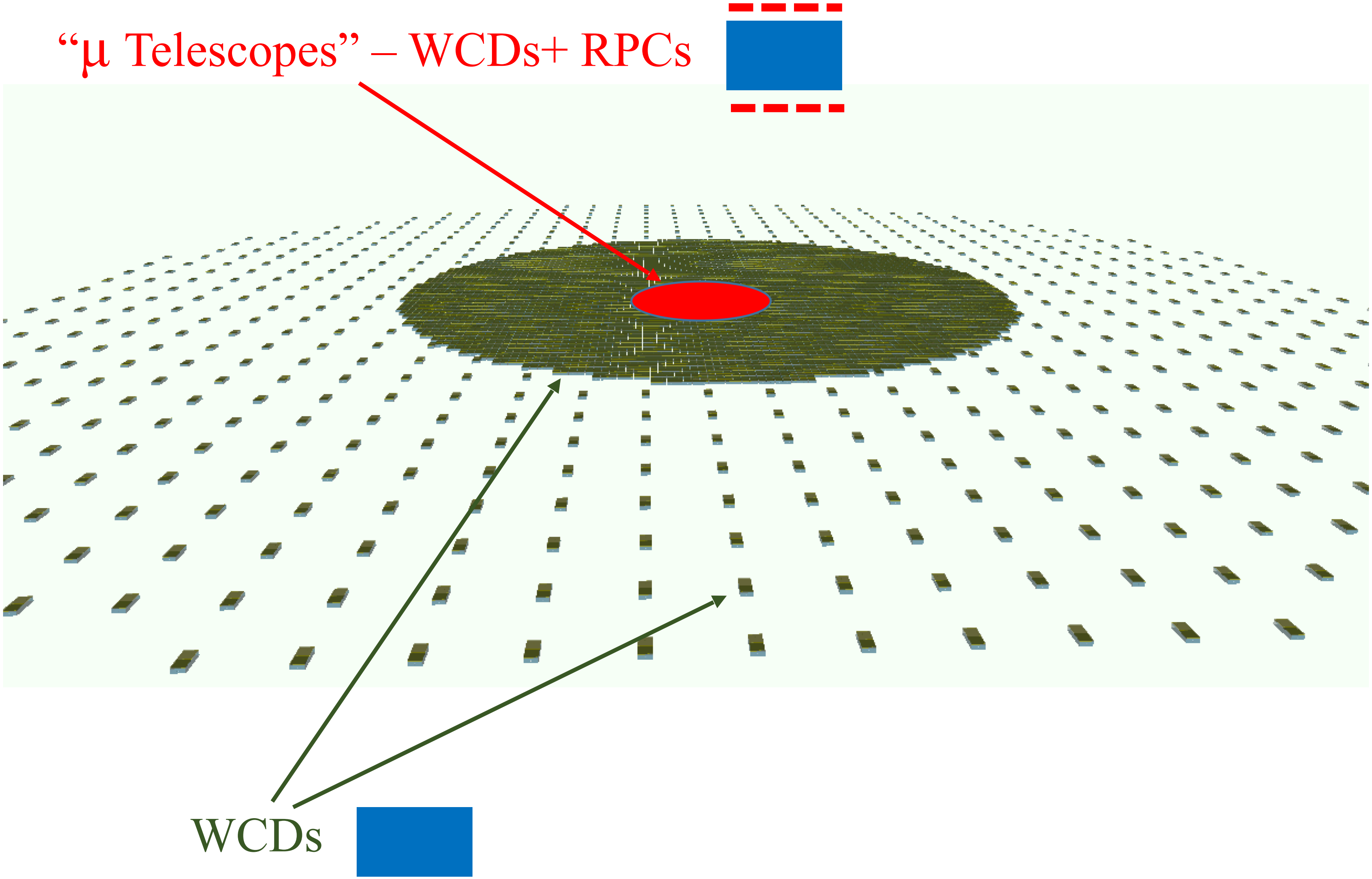
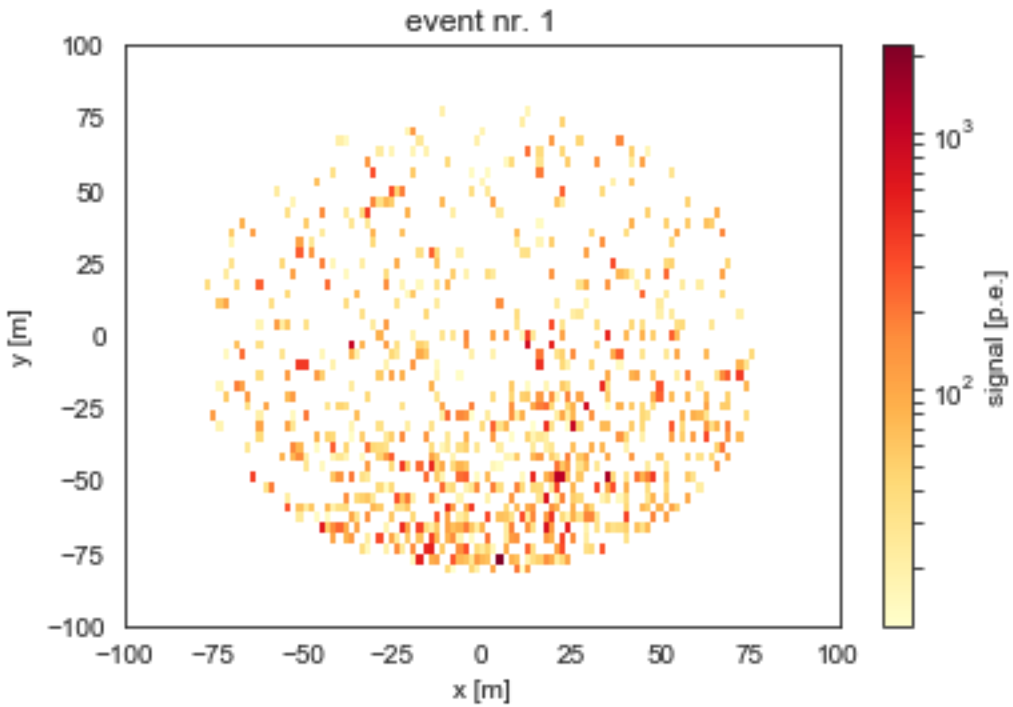


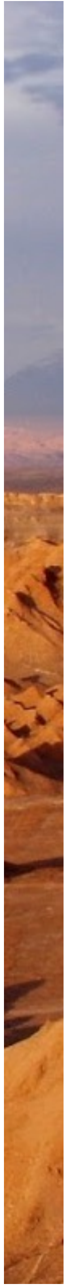
Improve gamma/hadron discrimination

- Study WCD signal patterns at ground as potential discriminator
- Take advantage of Convolution Neural Networks
  - Work being done by computer science group in Coimbra



Summary

- Requirements for the construction of next gamma-ray observatory identified
- Working in a new detector concept that allows to scale to bigger areas
  - Detector based solely on WCDs + SiPM at bottom
  - Small core (about 100 stations) complemented with RPC hodoscopes
  - Take advantage of ANN analyses
  - New ideas? Everything is still open…



Acknowledgements

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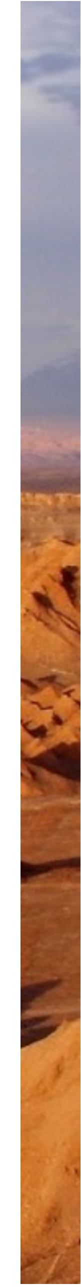
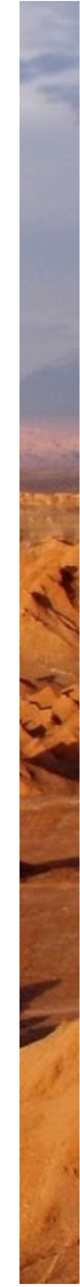
REPÚBLICA
PORTUGUESA

LIP

TÉCNICO
LISBOA



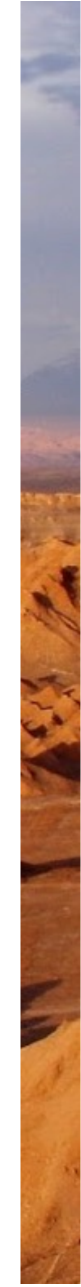
Backup slides



LATTES expected performance

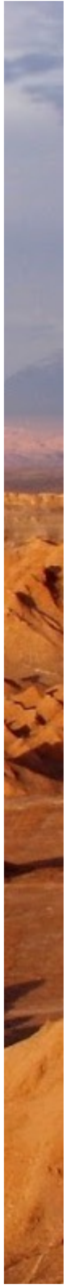
- **Trigger and effective area**
- Core reconstruction
- Energy reconstruction
- Geometry reconstruction
- Gamma/hadron discrimination
- Sensitivity to steady sources

} Effective Area depends with quality cuts



LATTES expected performance

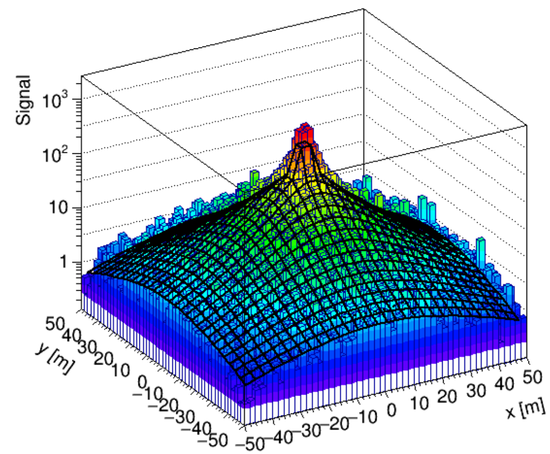
- ✧ Trigger and effective area
- ✧ **Core reconstruction**
- ✧ Energy reconstruction
- ✧ Geometry reconstruction
- ✧ Gamma/hadron discrimination
- ✧ Sensitivity to steady sources



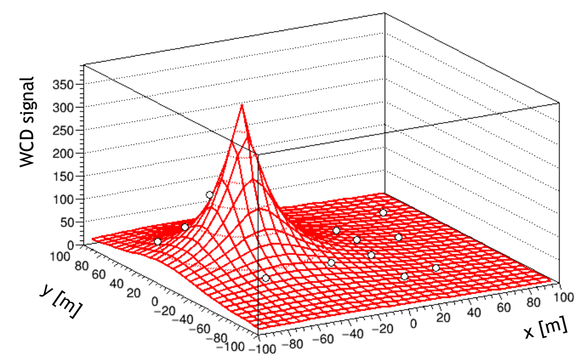
Shower core reconstruction

- Use the WCD signal
- Barycenter
  - Initial guess
  - Works but the core is always reconstructed inside the array
- Fit the WCD LDF
  - Fit photon average LDF to fix the shape
    - Function inspired in HAWC
    - Nearly no evolution with energy
  - Use this form to find the maximum, i.e. the shower core

Average LDF



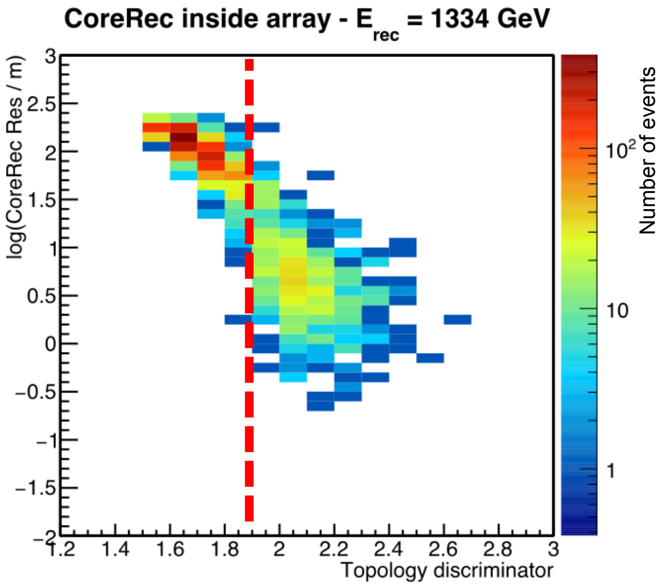
Single event

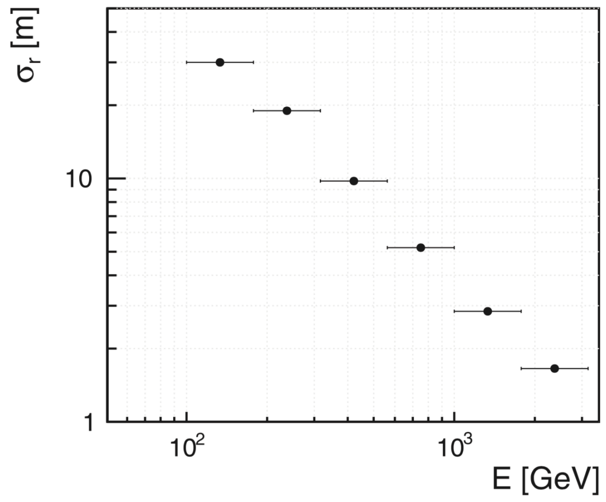


$$S_i = S(A, \vec{x}, \vec{x}_i) = A\left(\frac{1}{2\pi\sigma^2}e^{-|\vec{x}_i-\vec{x}|^2/2\sigma^2} + \frac{N}{(0.5+|\vec{x}_i-\vec{x}|/R_m)^3}\right)$$

Shower core reconstruction

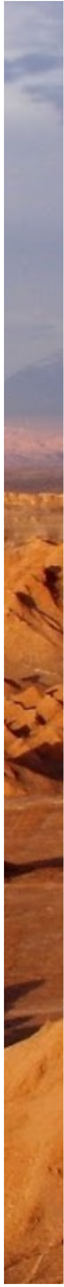
- Test whether the shower is inside/outside the array
  - Explore LDF topology
  - Is maximum observed inside of array?
  - Currently exploring the quality of the fit
  - Fixed cut for all energies
- Resolution better than 10 meters for showers above 300 GeV





LATTES expected performance

- ✧ Trigger and effective area
- ✧ Core reconstruction
- ✧ **Energy reconstruction**
- ✧ Geometry reconstruction
- ✧ Gamma/hadron discrimination
- ✧ Sensitivity to steady sources

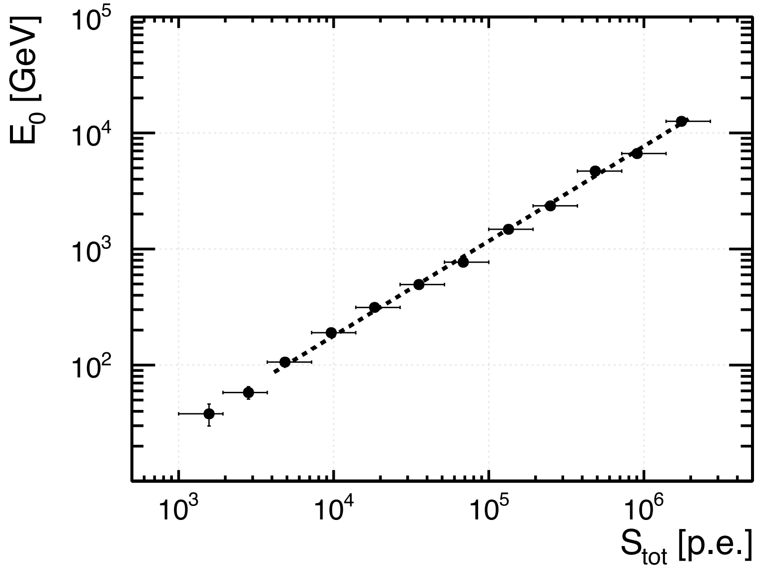


Energy reconstruction

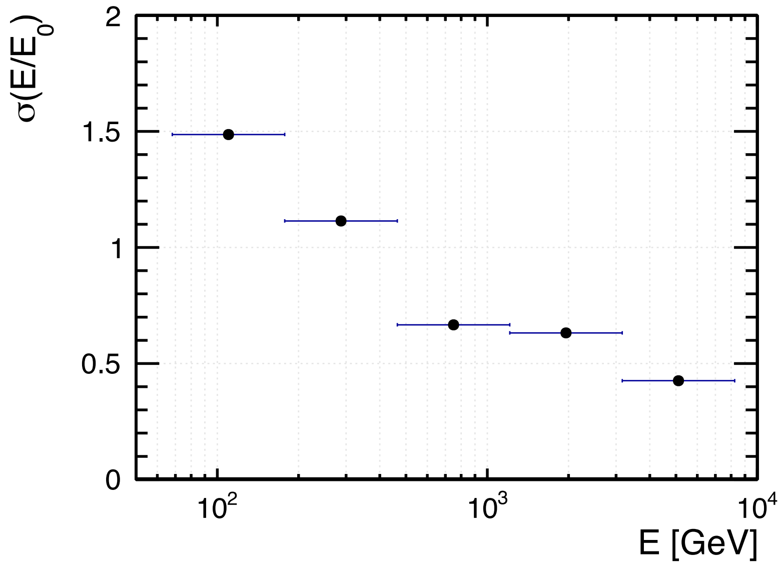
$E_0 \rightarrow$ Simulated energy

$E \rightarrow$ Reconstructed energy

Energy Calibration

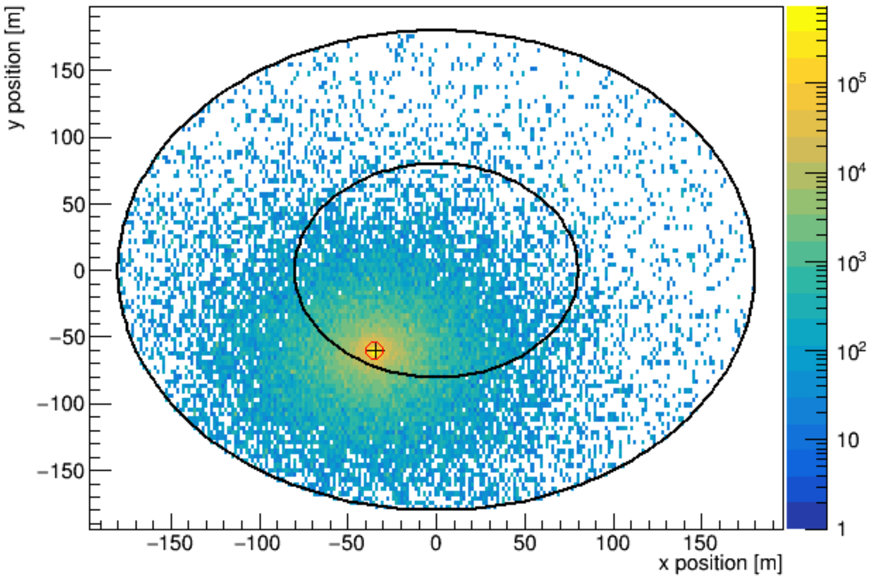


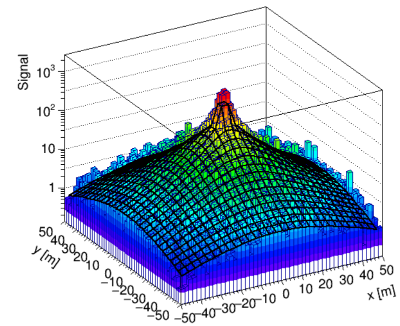
Energy Resolution



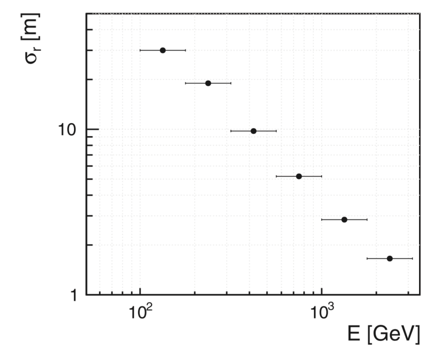
- Use as energy estimator the total signal recorded by WCDs
  - Use only shower cores reconstructed inside array
- Energy resolution at low energy dominated by shower fluctuations

Towards a more sophisticated energy reconstruction

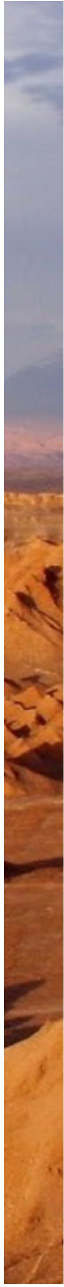




Average LDF



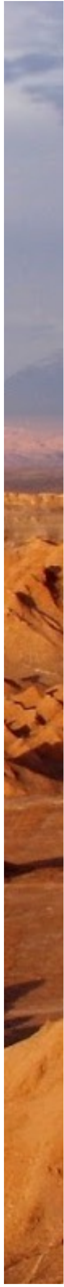
Core resolution



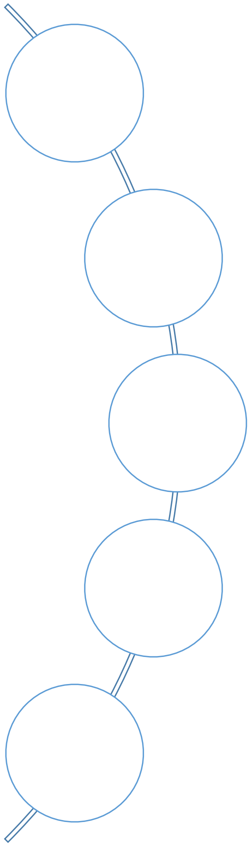
- ✧ Combine the core position with an average LDF to estimate the amount of energy outside of the array

LATTES expected performance

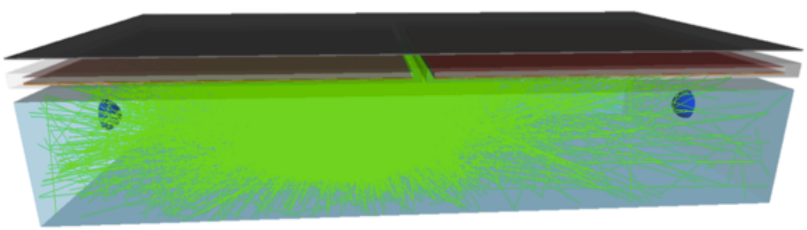
- ✧ Trigger and effective area
- ✧ Core reconstruction
- ✧ Energy reconstruction
- ✧ **Geometry reconstruction**
- ✧ Gamma/hadron discrimination
- ✧ Sensitivity to steady sources



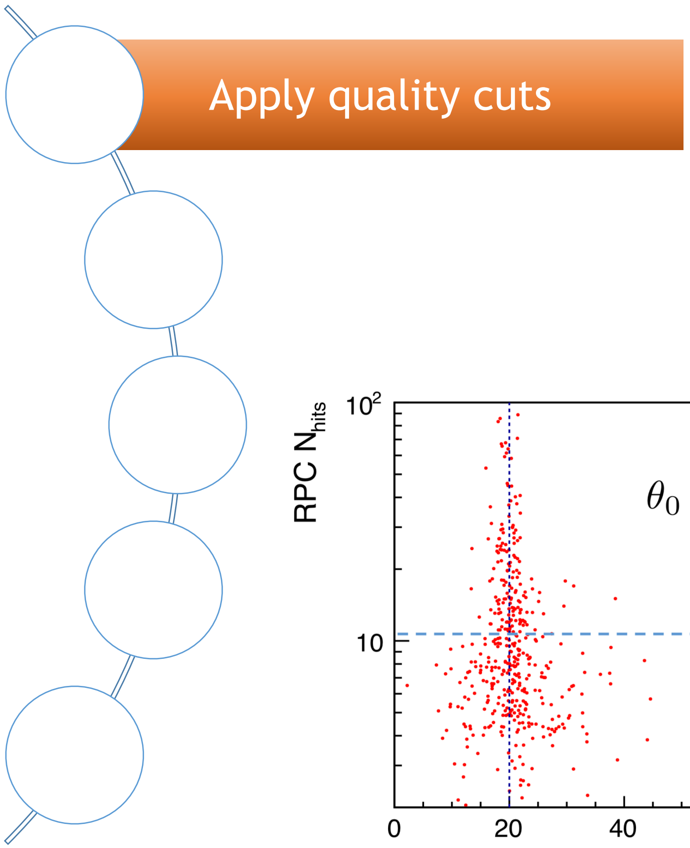
Reconstruction of shower geometry

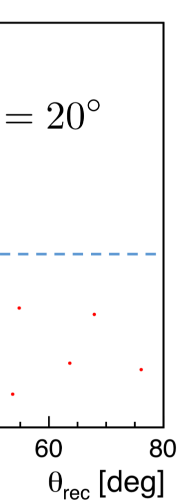


- Use RPC hit time information
  - Take advantage of high spatial and time resolution
  - Used time resolution of 1 ns

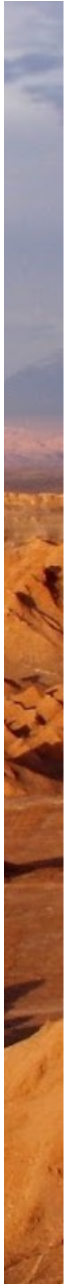


Reconstruction of shower geometry





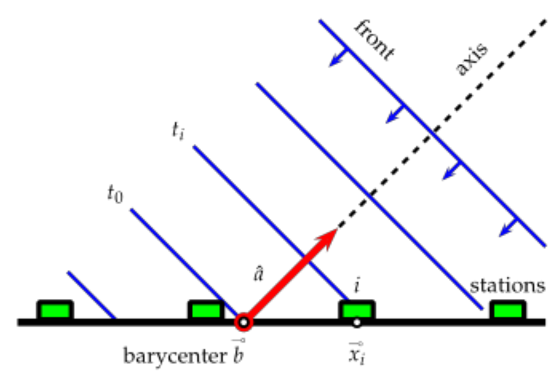
- Use RPC hit time information
  - Apply previous shower rec quality cuts
  - Apply cuts on the number of registered hits on the RPCs
  - Consider only RPCs in triggered WCD stations



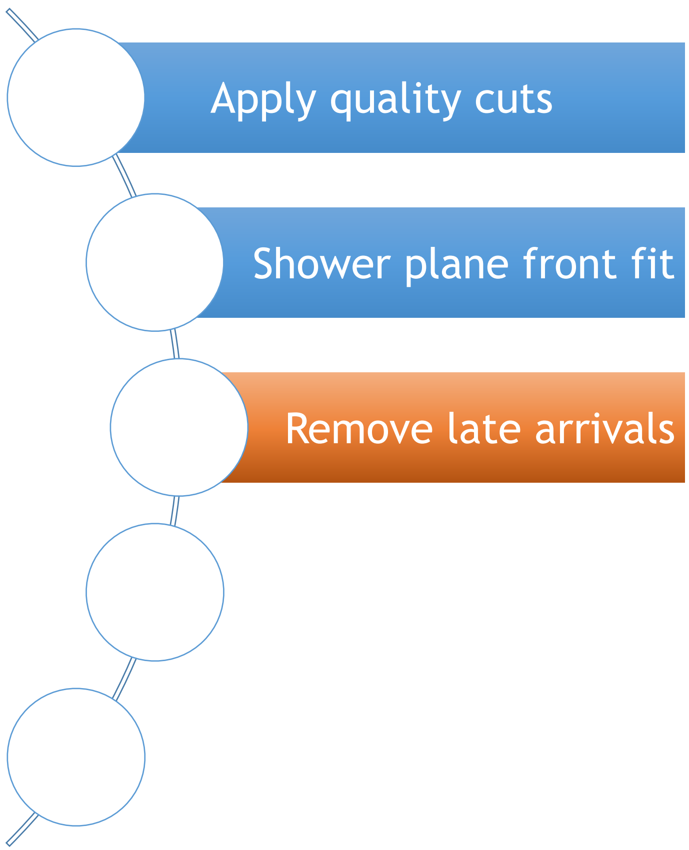
Reconstruction of shower geometry

- Apply quality cuts
- Shower plane front fit

- ✧ Use RPC hit time information
- ✧ Perform shower reconstruction
- ✧ Use shower front plane approximation
- ✧ Analytical procedure



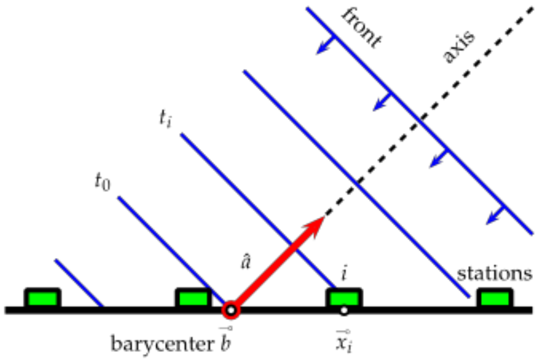
Reconstruction of shower geometry

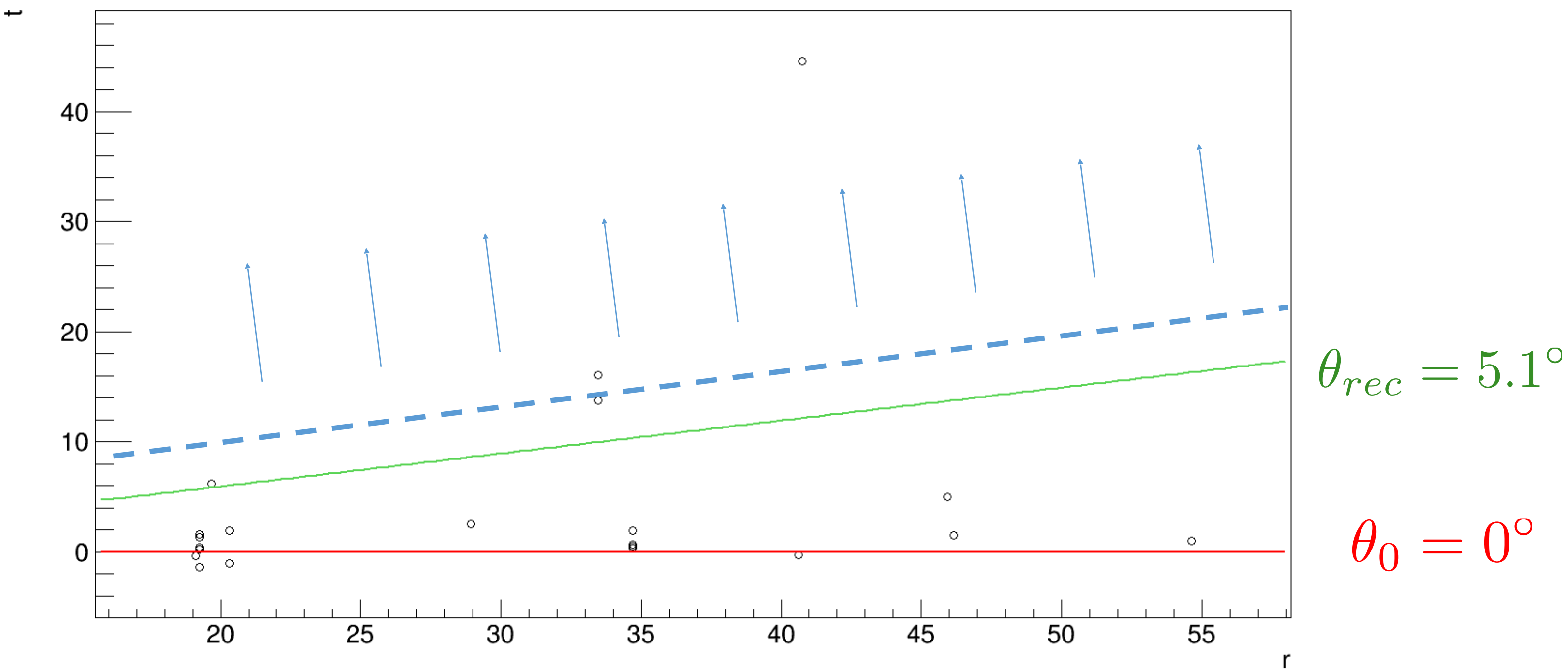


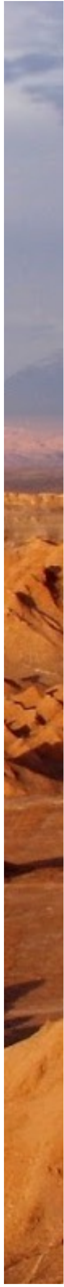
- Use RPC hit time information
  - Identify late arrivals with respect to Rec Shower Front
  - Mainly low energy electrons that lost correlation with shower front

Removal of late arrivals

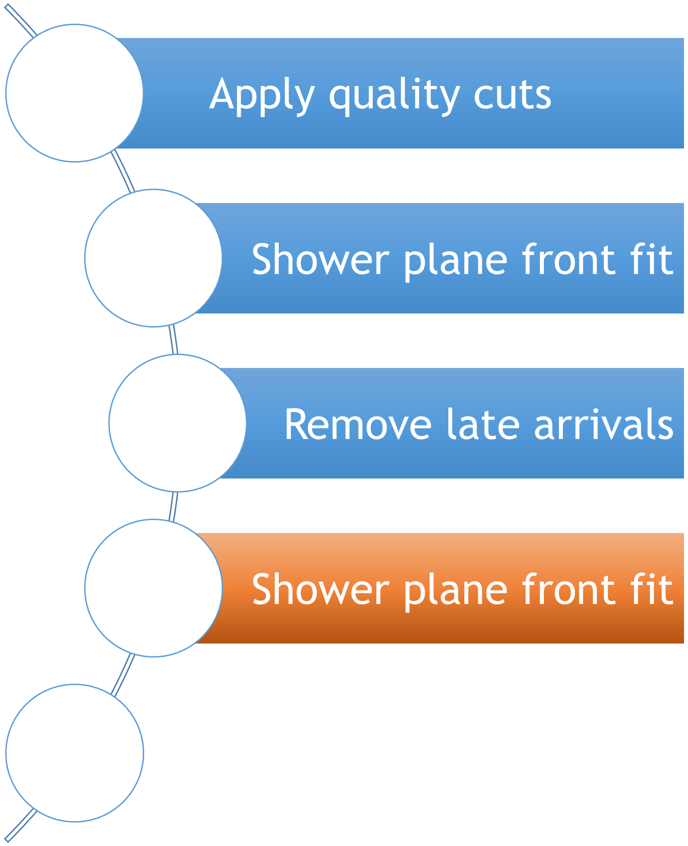
- ✧ Example of a vertical gamma shower
- ✧ Plot depicts arrival time (ns) distance to simulated shower core (m)



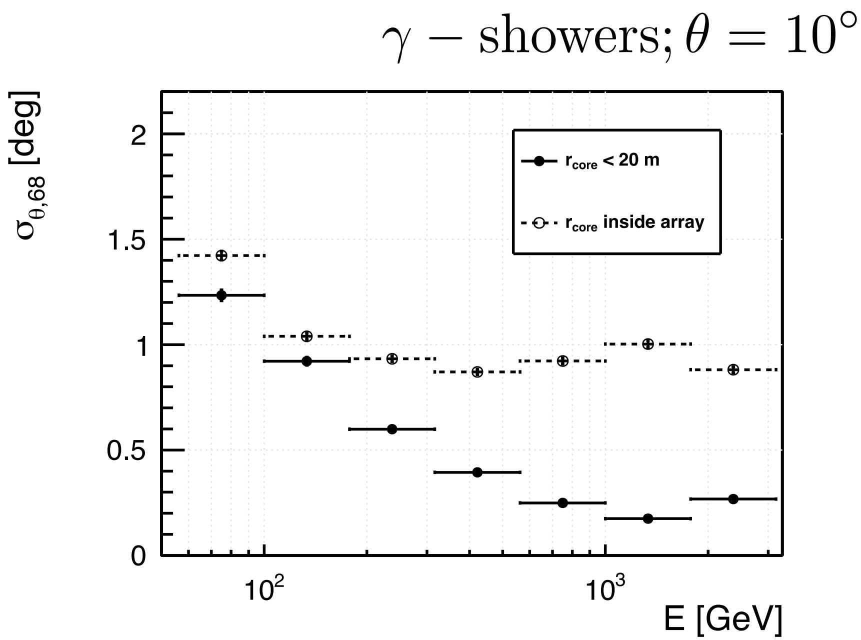




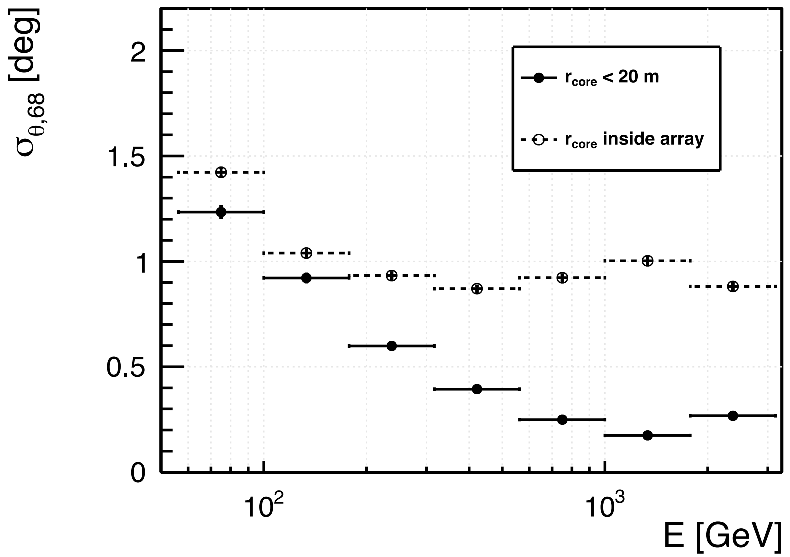
Reconstruction of shower geometry

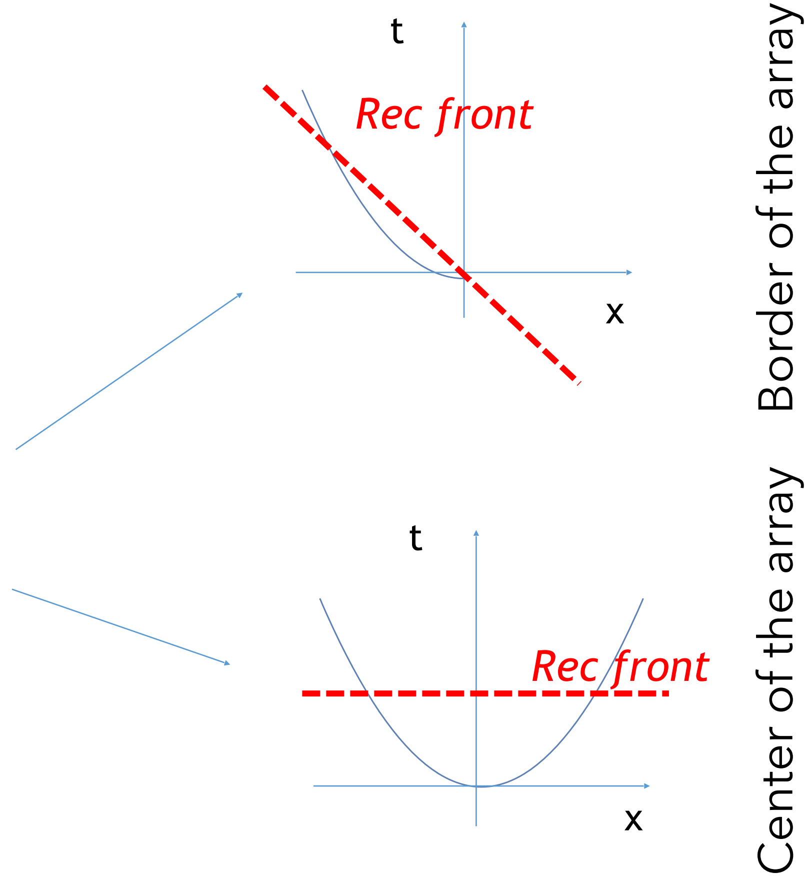


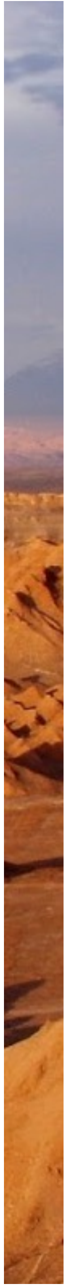
- ✧ Use RPC hit time information
  - ✧ Repeat fit without arrivals
  - ✧ Initial guess for next step



Impact of shower curvature







Solution: implement a conic fit instead of fitting a plane

$$\chi^2 = \sum (c \cdot (T_n - T_0) - X_n \cdot - Y_n \cdot m - R_n \cdot \alpha)^2$$

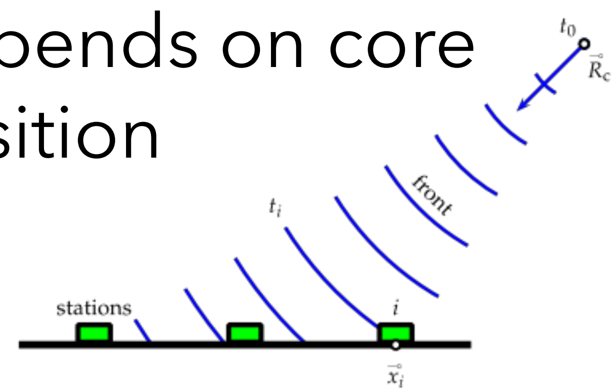
Reconstruction of shower geometry

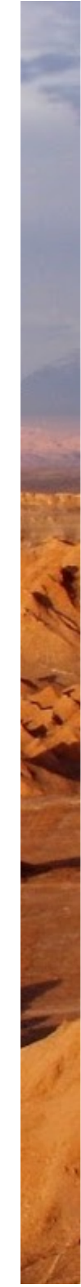
- Apply quality cuts
- Shower plane front fit
- Remove late arrivals
- Shower plane front fit
- Shower conic front fit

✧ Use RPC hit time information

✧ Fit the shower geometry using a shower conic front model

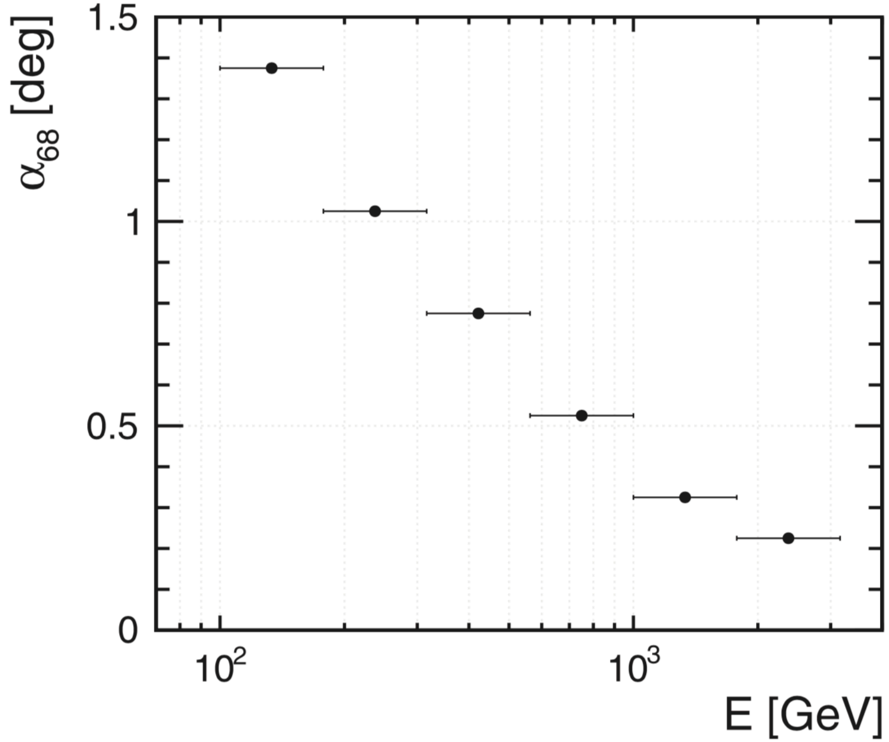
✧ Depends on core position





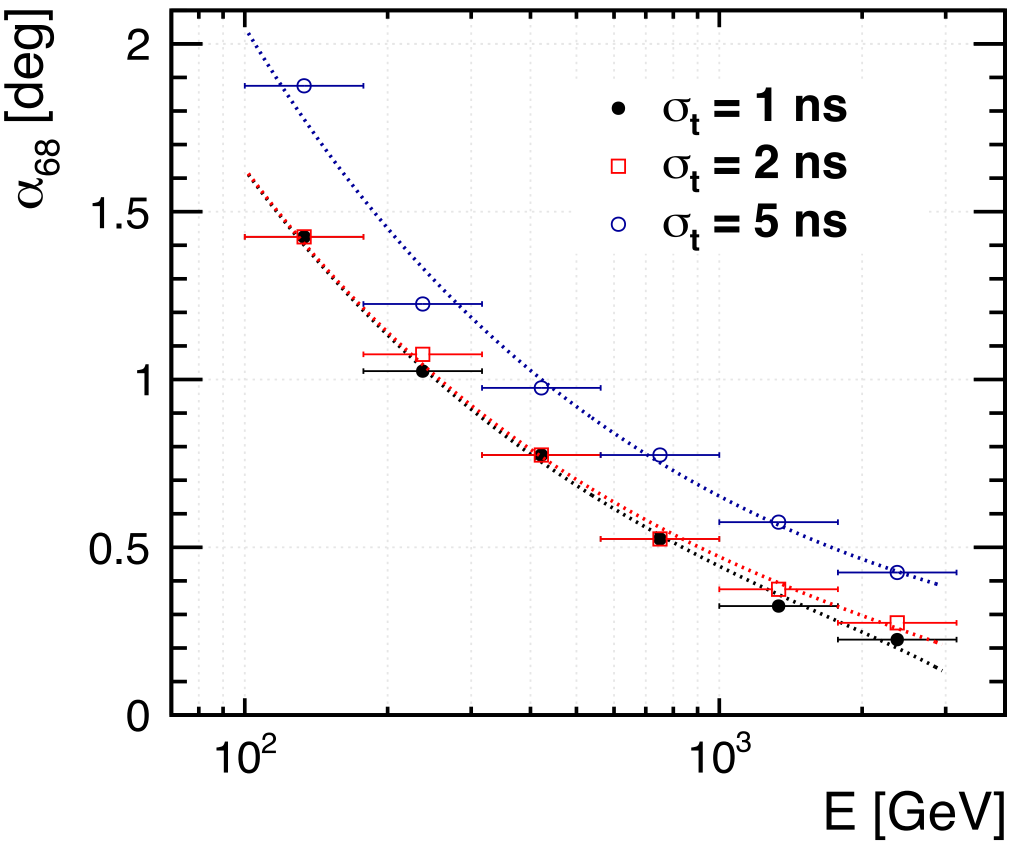
Shower geometry reconstruction

α_{68} = angular distance that contains 68% of the events



A good angular resolution can be achieved for all events reconstructed inside the array

Geom Rec: RPC time resolution



Need of a time resolution of 1-2 ns to obtain a good geometry reconstruction

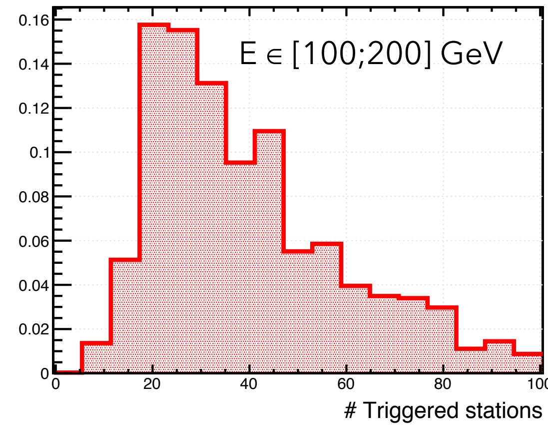
LATTES expected performance

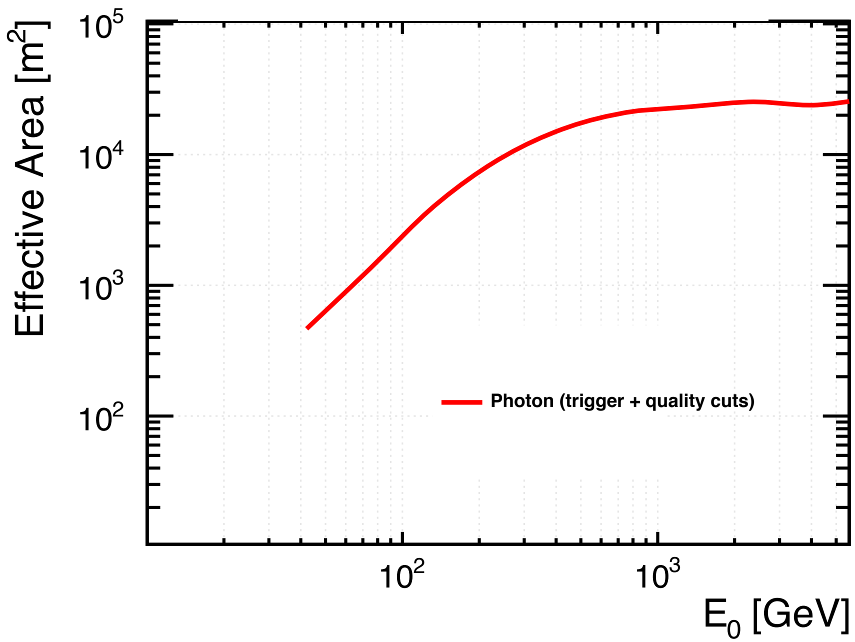
- ✧ Trigger and effective area
- ✧ Core reconstruction
- ✧ Energy reconstruction
- ✧ Geometry reconstruction
- ✧ Gamma/hadron discrimination
- ✧ Sensitivity to steady sources

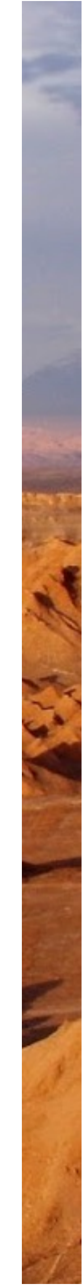
Shower rec quality cuts

Effective Area

- Station Trigger
  - 5 p.e. in each WCD PMT
- Event Trigger
  - 3 stations
- Quality cuts
  - Good core rec
  - Core in array
  - 10 hits in RPCs pads (belonging to active WCDs)
  - Good geom rec
- After applying all quality cuts LATTES gets an effective area of **~1000 m² for E = 100 GeV**

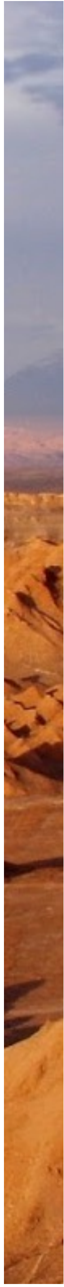




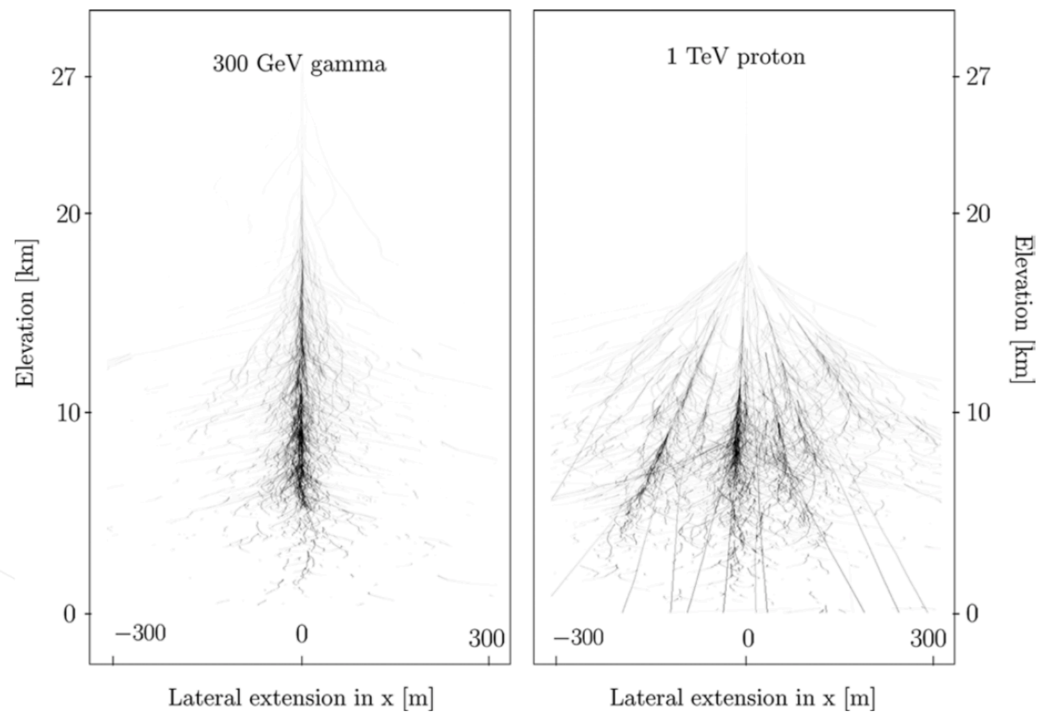


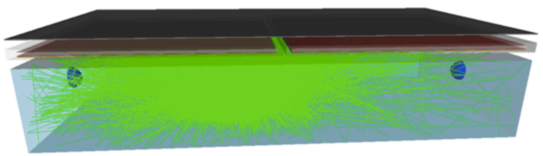
LATTES expected performance

- ✧ Trigger and effective area
- ✧ Core reconstruction
- ✧ Energy reconstruction
- ✧ Geometry reconstruction
- ✧ **Gamma/hadron discrimination**
- ✧ Sensitivity to steady sources



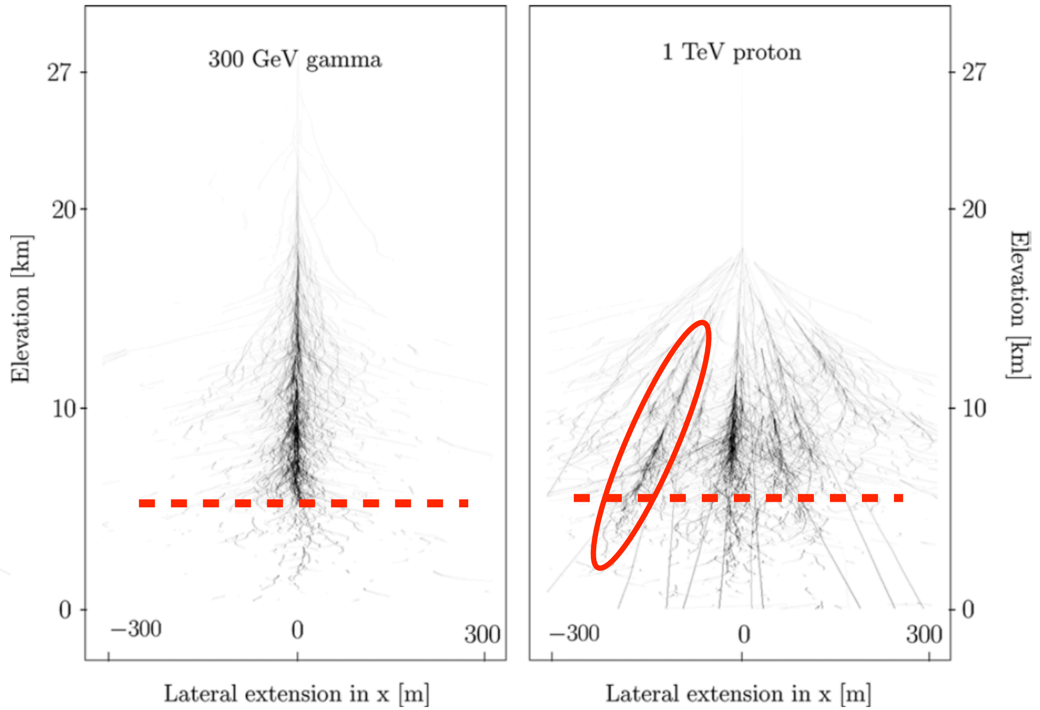
Shower characteristics

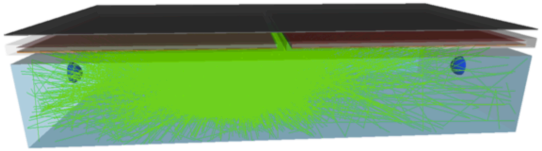




A pure electromagnetic shower (gamma) has distinct features from a shower with an hadronic component (hadron)

Shower characteristics

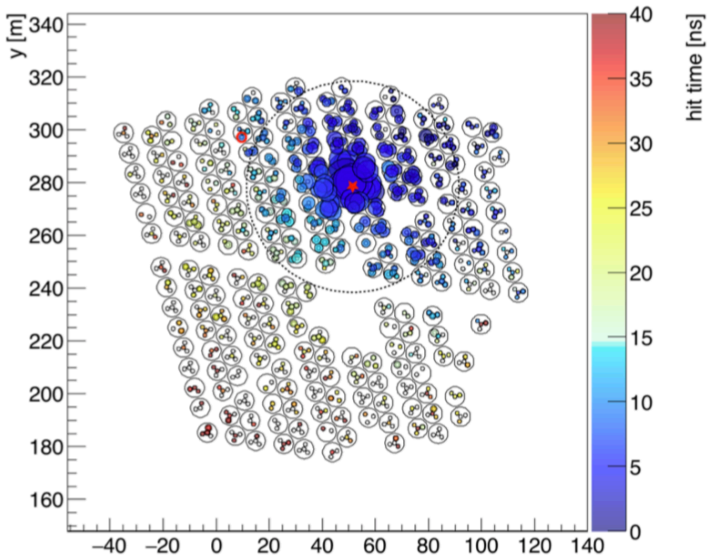




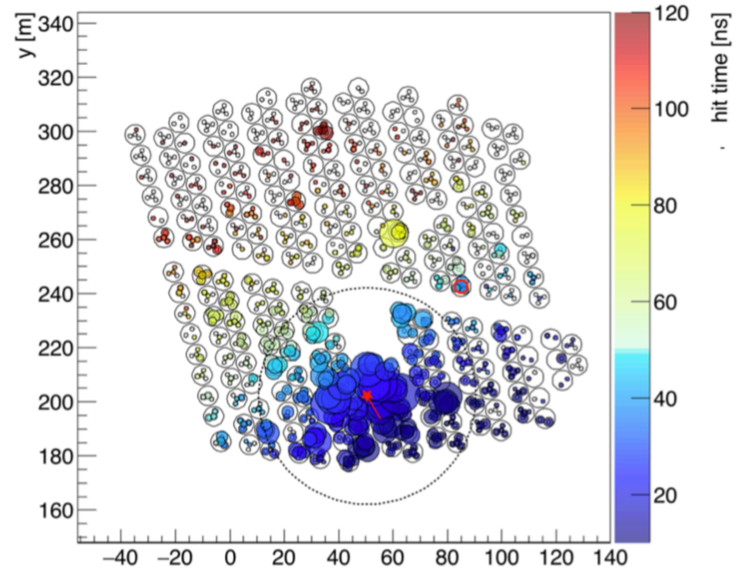
A pure electromagnetic shower (gamma) has distinct features from a shower with an hadronic component (hadron)

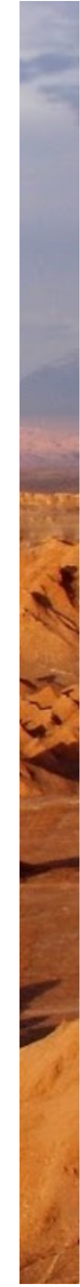
Looking for high-p_T sub-showers

gamma shower



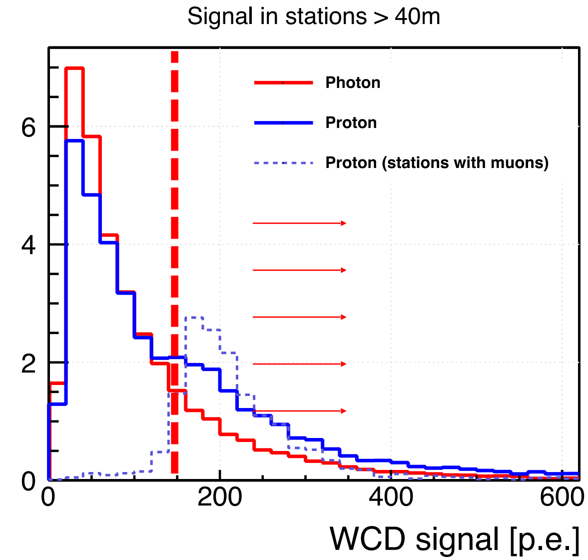
hadron shower

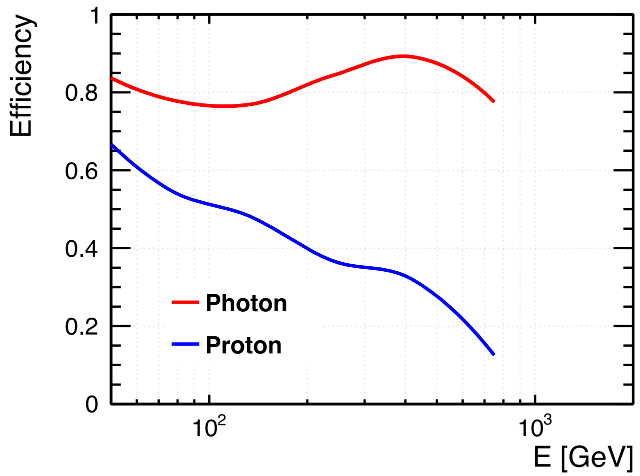




Looking for high p_t sub-showers

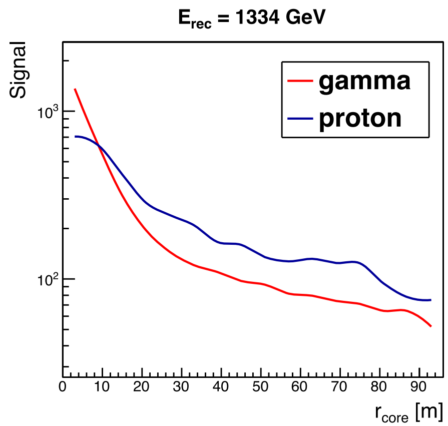
- LATTES g/h discrimination
  - Use only stations with a distance above 40 m
  - $\mathbf{S_{40}}$: sum all WCD stations signal
  - $\mathbf{S_{40\_high}}$: sum all WCD stations that have a signal above the muon energy threshold
  - Compute $\mathbf{S_{40\_high} / S_{40}}$
  - Not optimized…

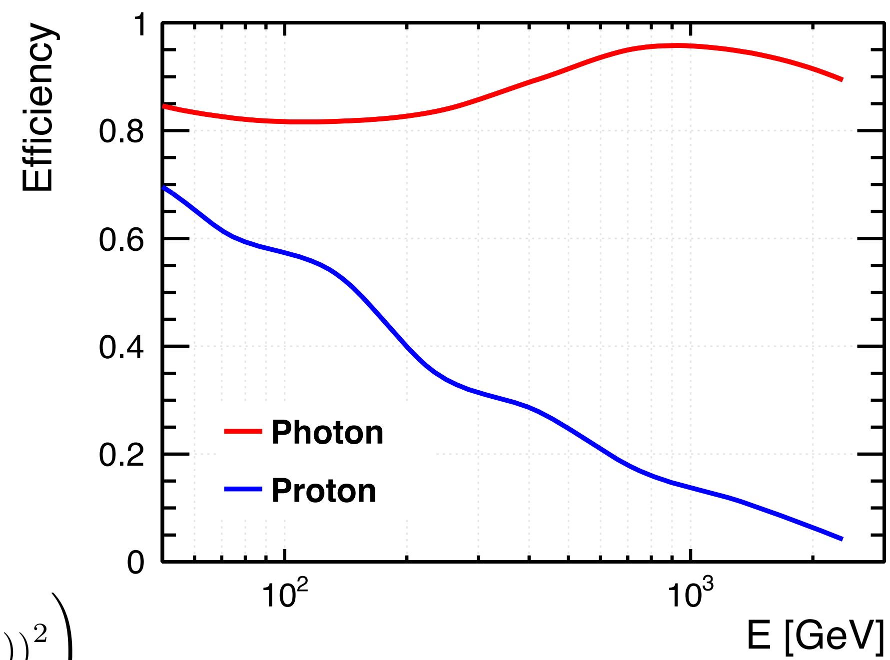




High-energy discrimination strategy

Average LDF

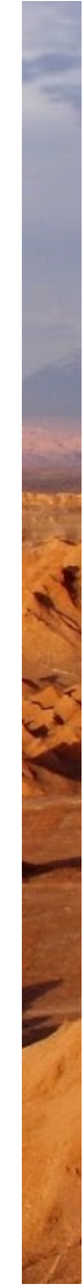




- Compute event-by-event:

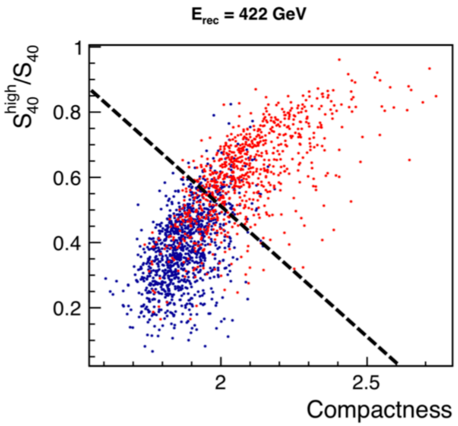
$$\text{Compactness} = \log_{10}\left(\sum_{i}^{n}\left(\langle LDF\rangle(r_i) - y(r_i)\right)^2\right)$$

- Lateral distribution function (LDF)
  - LDF of gamma showers is more steep and less bumpy than the LDF of hadron showers

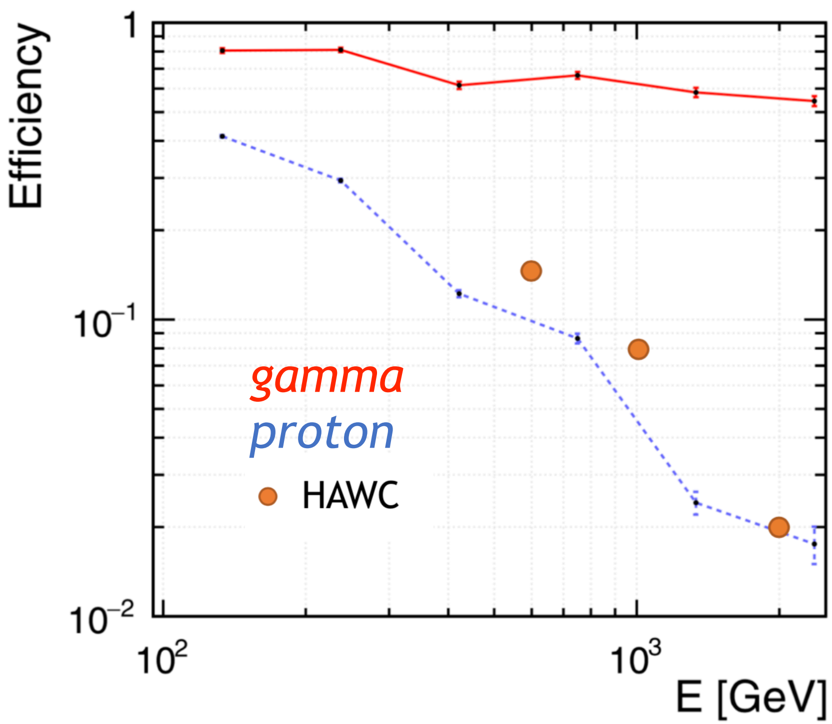


LATTES g/h discrimination

Using only the WCD

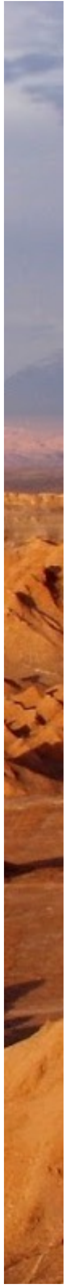


Compactness = LDF steepness
S40 = Signal outside 40 m



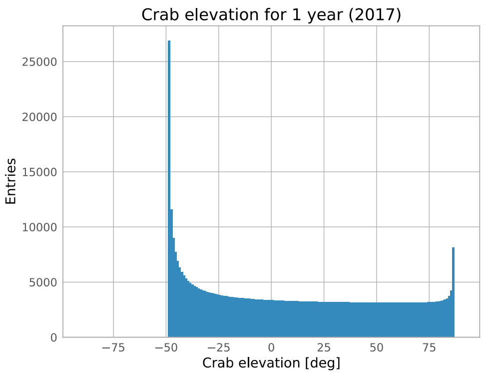
- Although not optimized the gamma/hadron discrimination results are already very encouraging
- Starting to investigate more sophisticated tools (ANN: pattern at ground ; cuts ; …)

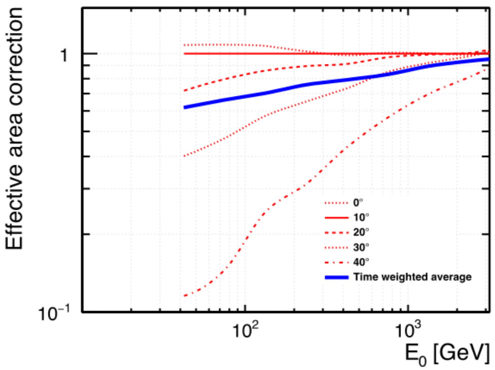
LATTES expected performance



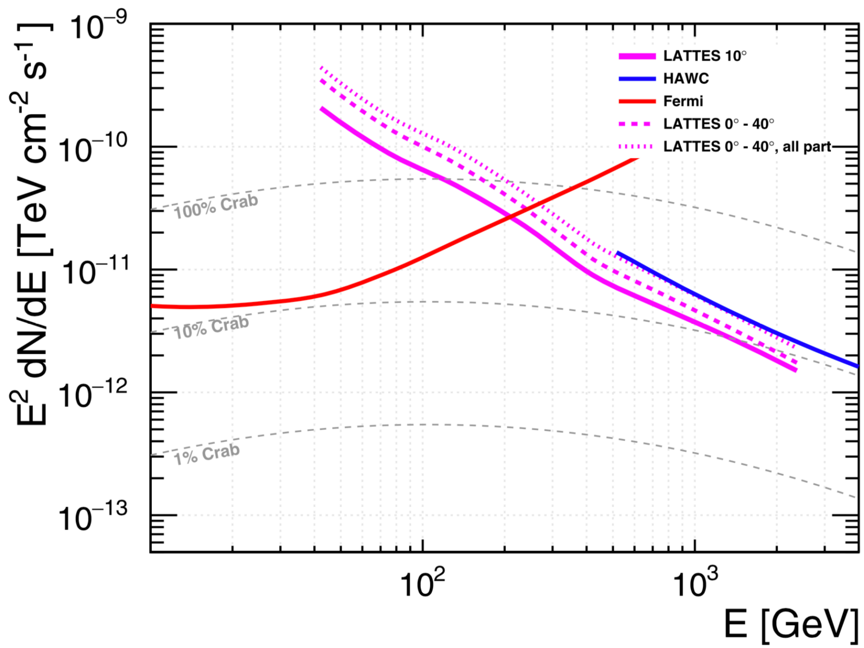
- ✧ Trigger and effective area
- ✧ Core reconstruction
- ✧ Energy reconstruction
- ✧ Geometry reconstruction
- ✧ Gamma/hadron discrimination
- ✧ **Sensitivity to steady sources**

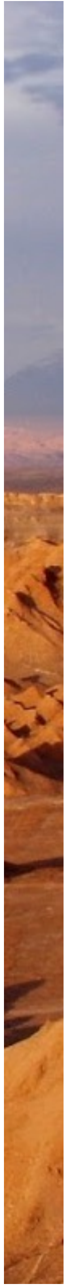
Sensitivity to steady sources





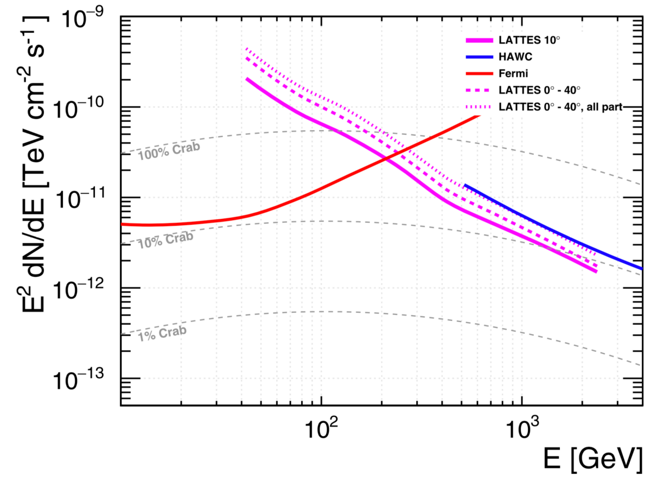
- *Dashed line*: Crab transit as seen by HAWC
  - Degradation of effective area with zenith angle estimated from electromagnetic energy at ground

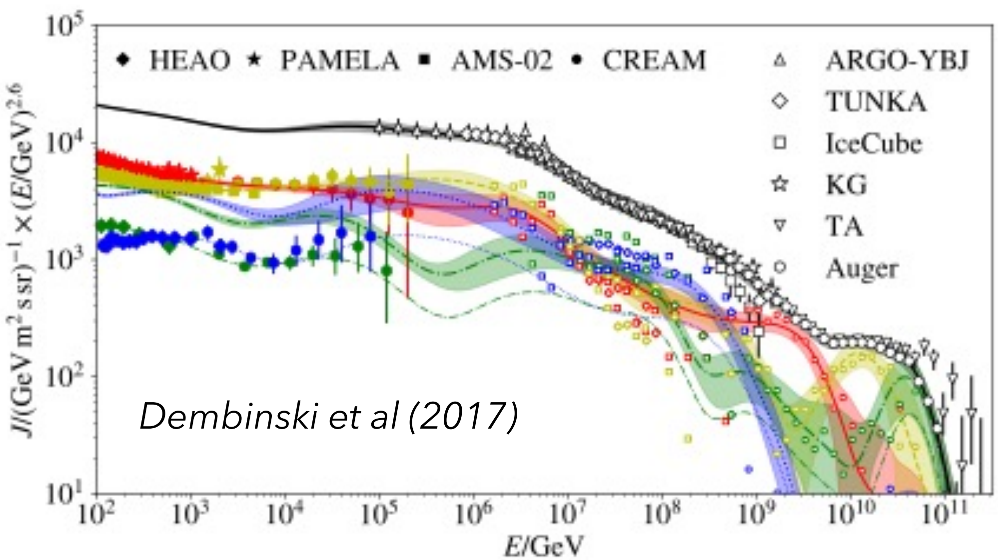


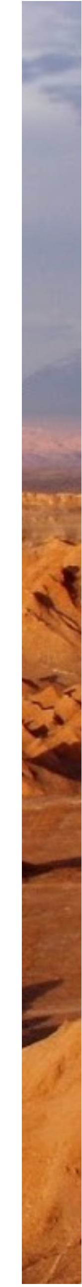


Sensitivity to steady sources

- *Dotted line:* CR all-spectrum
  - Additional elements (He, N, Fe…)
  - Assume that LATTES cannot distinguish gammas from irons



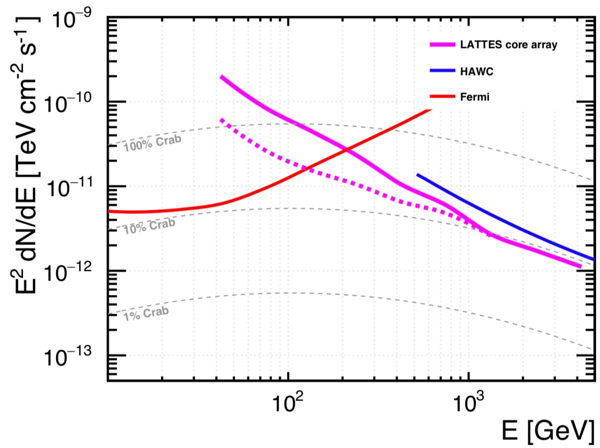


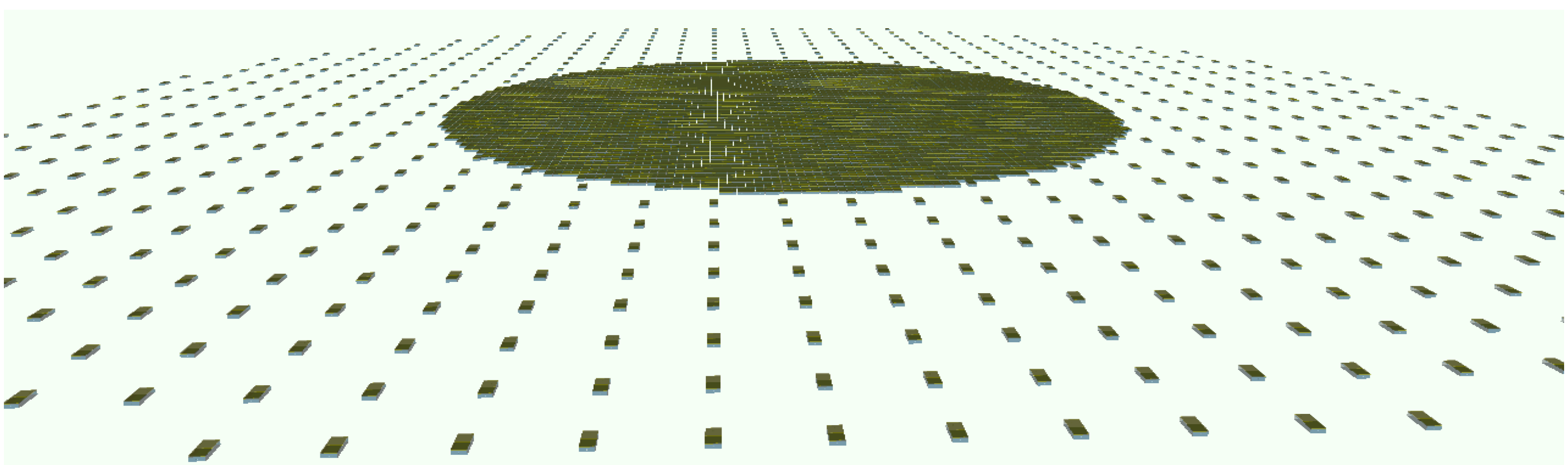


Sparse Array

- Use a sparser array (100 000 m2)
  - Collect more events at higher energies
  - Remove high energy events that fall outside of the core array
- Built LATTES fastsim:
  - Use particle tracklength in water to generate number of photons collected by PMTs

Vetoing showers that fall outside the array

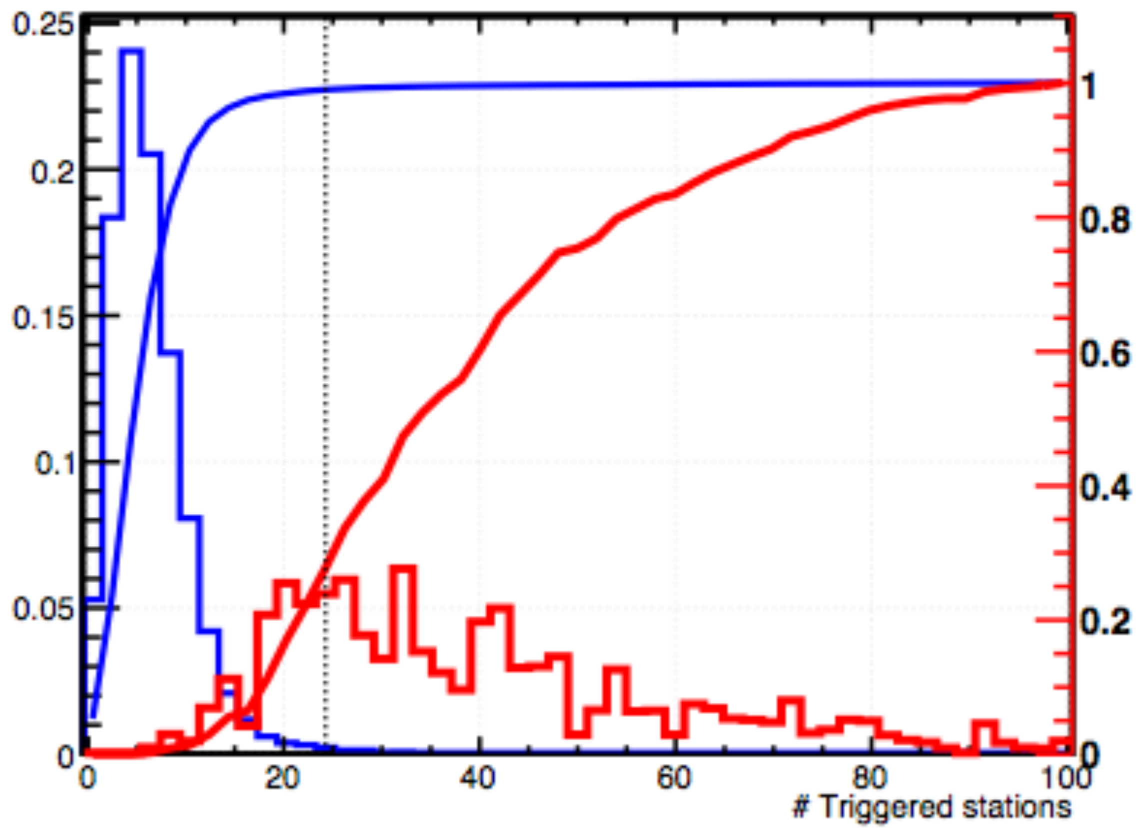




Cosmic rays trigger rate vs photon triggers

Cosmic rays triggered stations

Crab photons with energy in [100 GeV, 200 GeV]



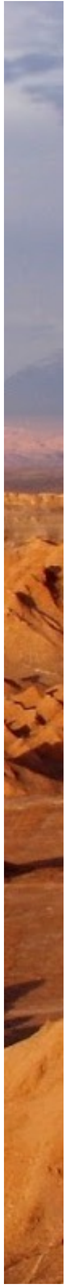
> 18 stations : 98% background rejection (440 kHz) ; 90% photon efficiency

> 25 stations : 99% background rejection (220 kHz) ; 75% photon efficiency

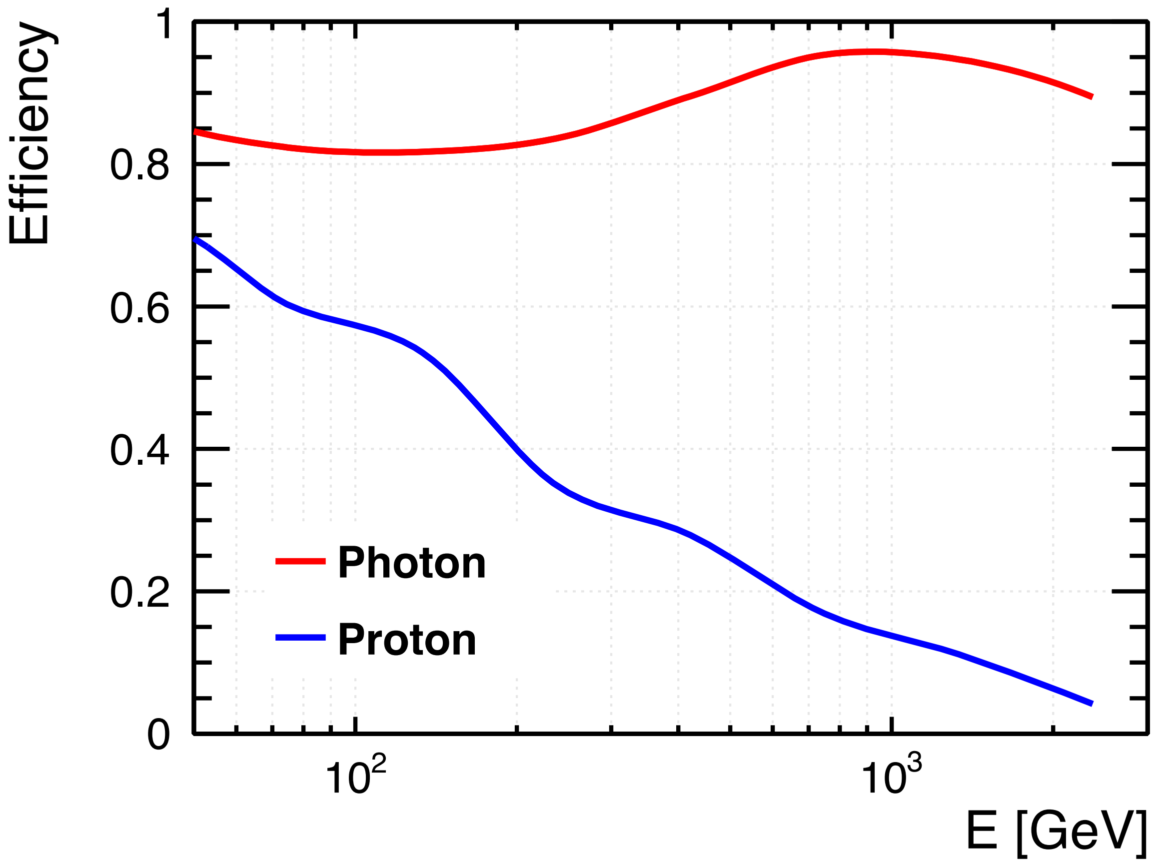
High-energy discrimination strategy

- Get the gamma average LDF for each reconstructed energy bin
- Fit the average LDF to each single event
  - Absorb the normalization factor
- Compute the shower compactness
  - Event LDF “distance” to the gamma average LDF

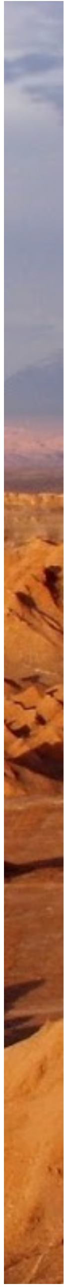
$$\text{Compactness} = \log_{10}\left(\sum_{i}^{n}\left(\left\langle LDF\right\rangle(r_i) - y(r_i)\right)^2\right)$$



High-energy discrimination strategy

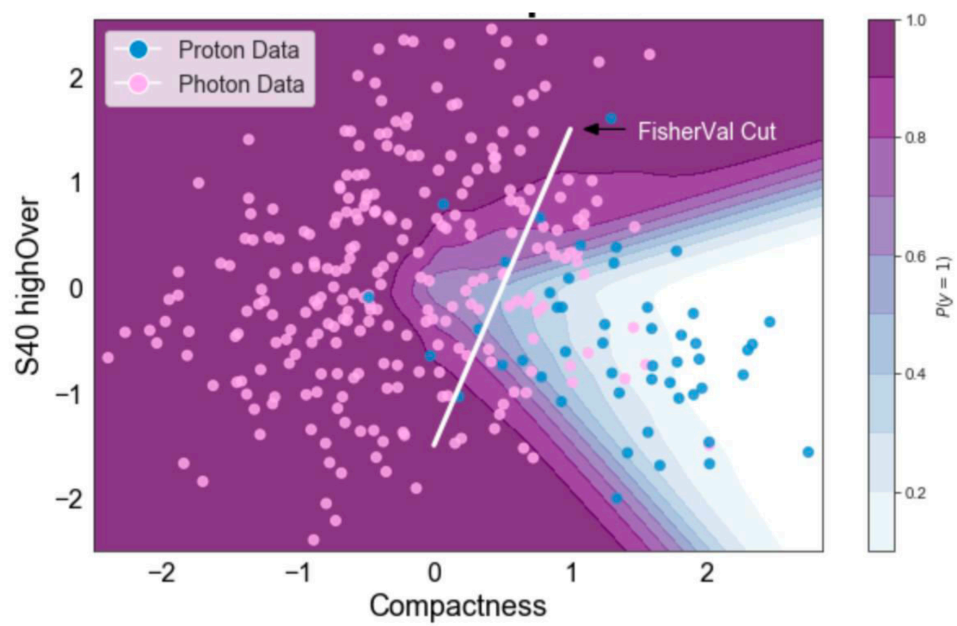


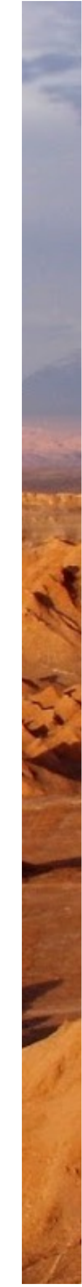
Shower compactness discrimination variable allows for a good background rejection which increases with energy



G/H discrimination and ANN

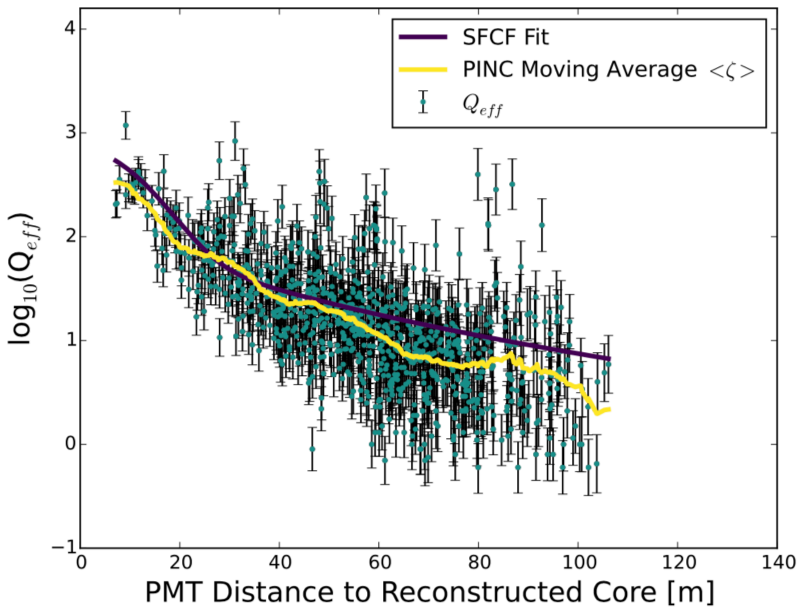
- Linear Discriminante (Fisher) allows a good separation
- Simple artificial neural networs can improve g/h discrimination
- Keras + Scikit-learn + ANN with 5 layers
- More simulation statistics necessary to apply parametric cuts
- Test at lower energies…



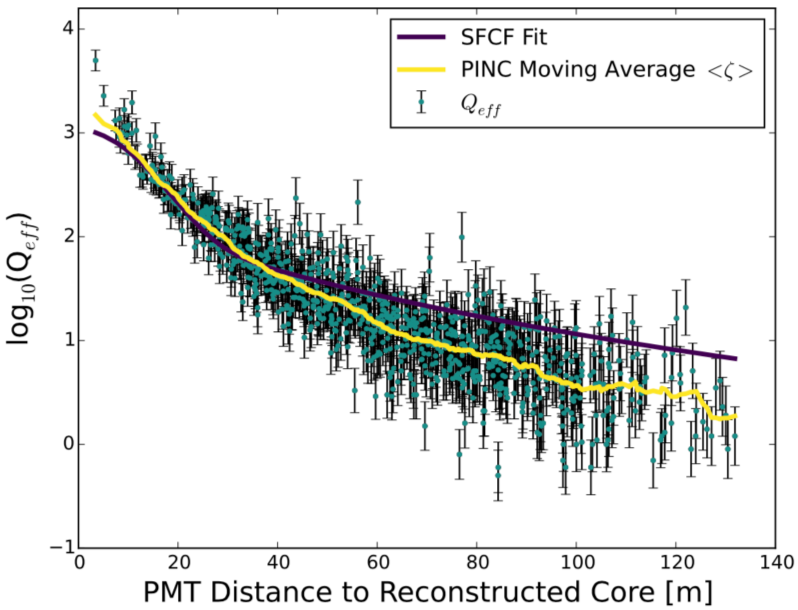


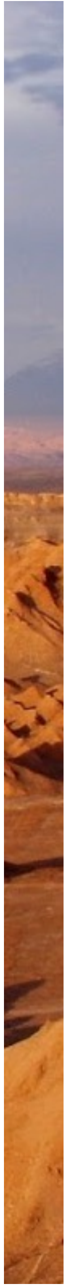
HAWC g/h discrimination

Cosmic ray



Gamma-ray

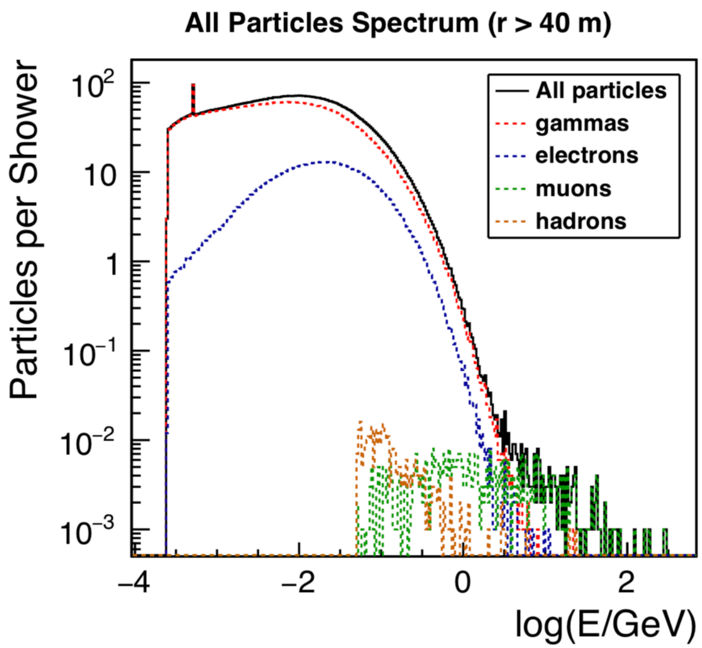




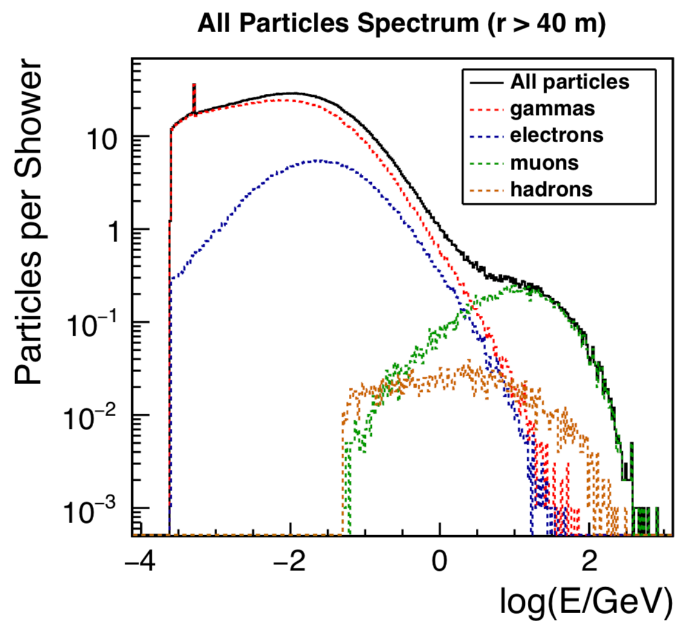
Shower calorimetric information

E=5 TeV

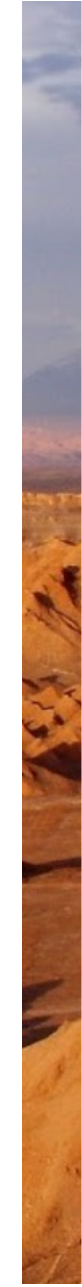
Gamma induced showers



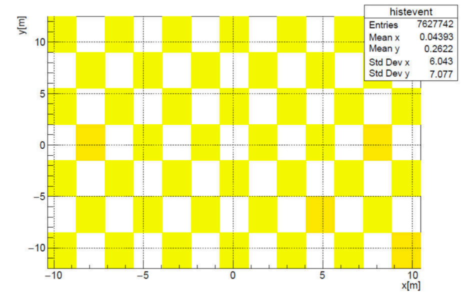
Proton induced showers

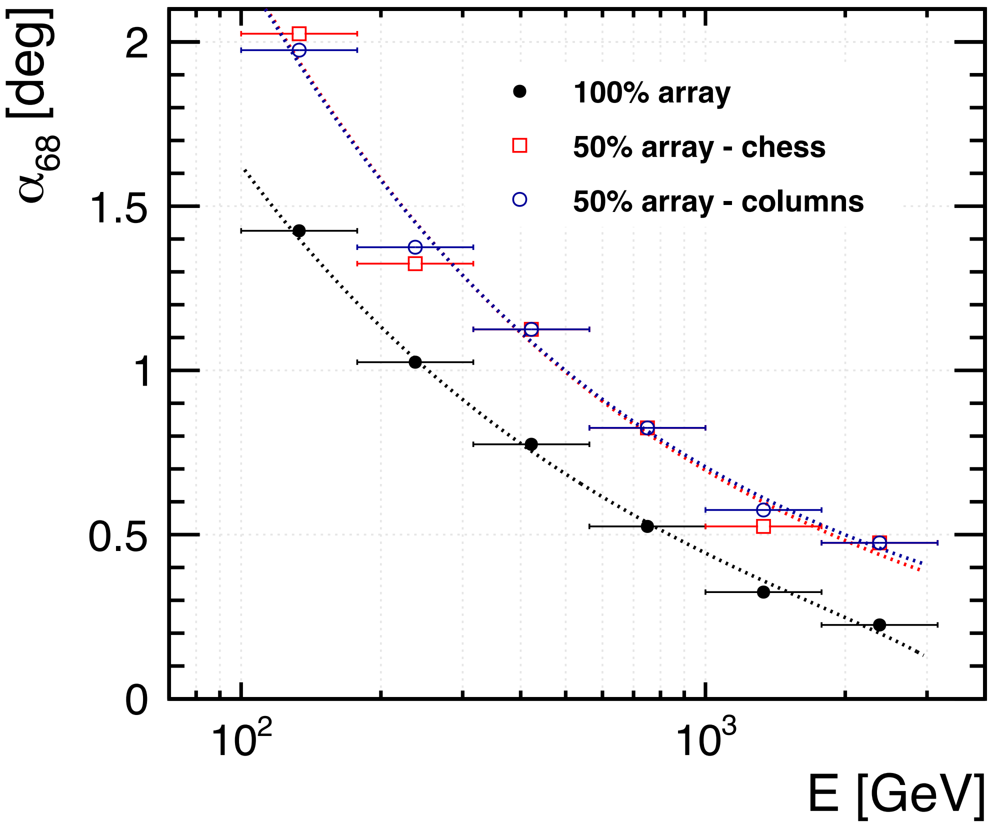


- High pT sub-shower carry large amounts of energy
- Look for energetic clusters far from the shower core (> 40 m)
  - Muons and high-energy photons/electrons

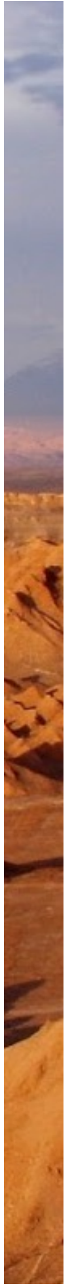


Geom Rec: array configuration

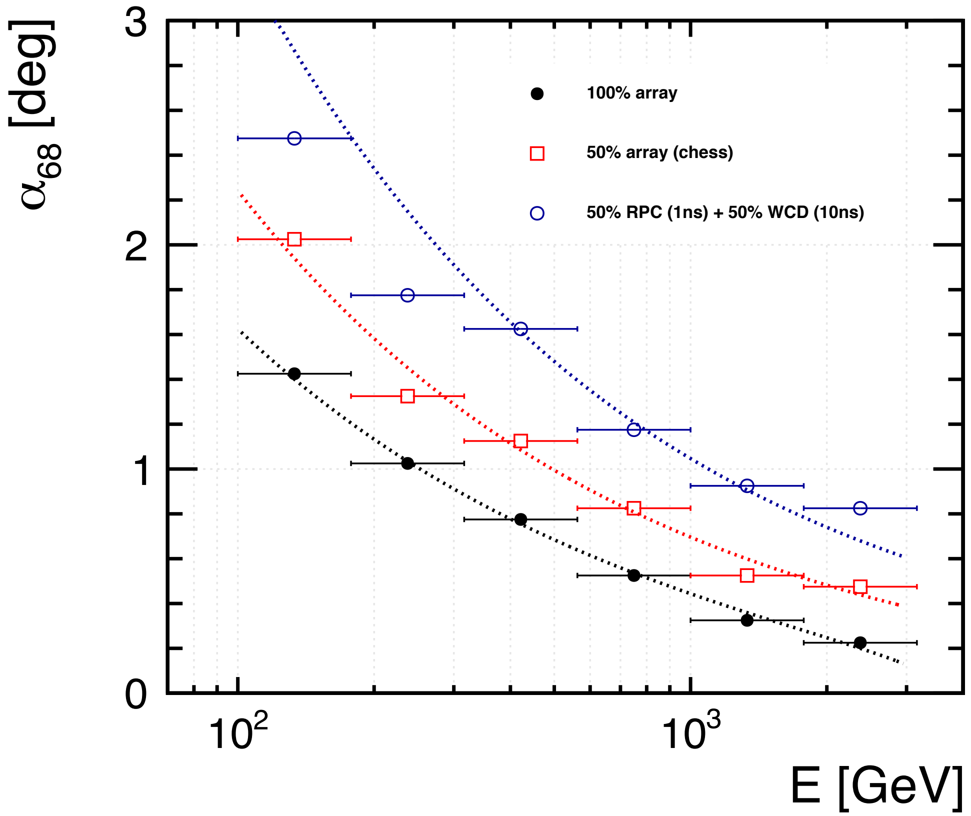




- ✧ It seems important to have RPCs on all stations

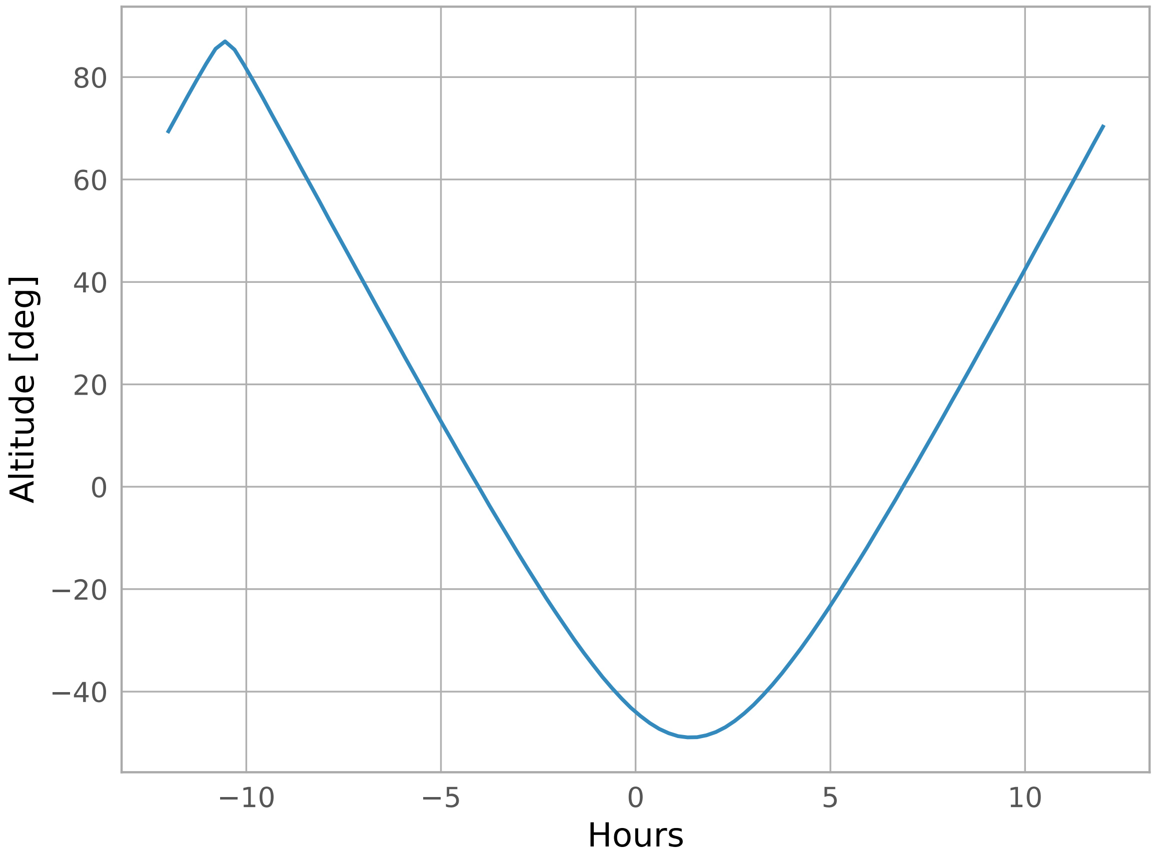


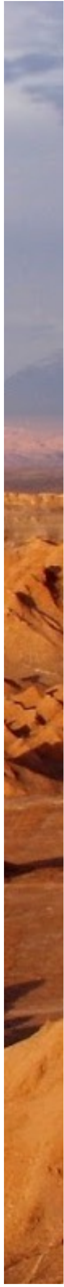
Geom Rec: RPC + WCD



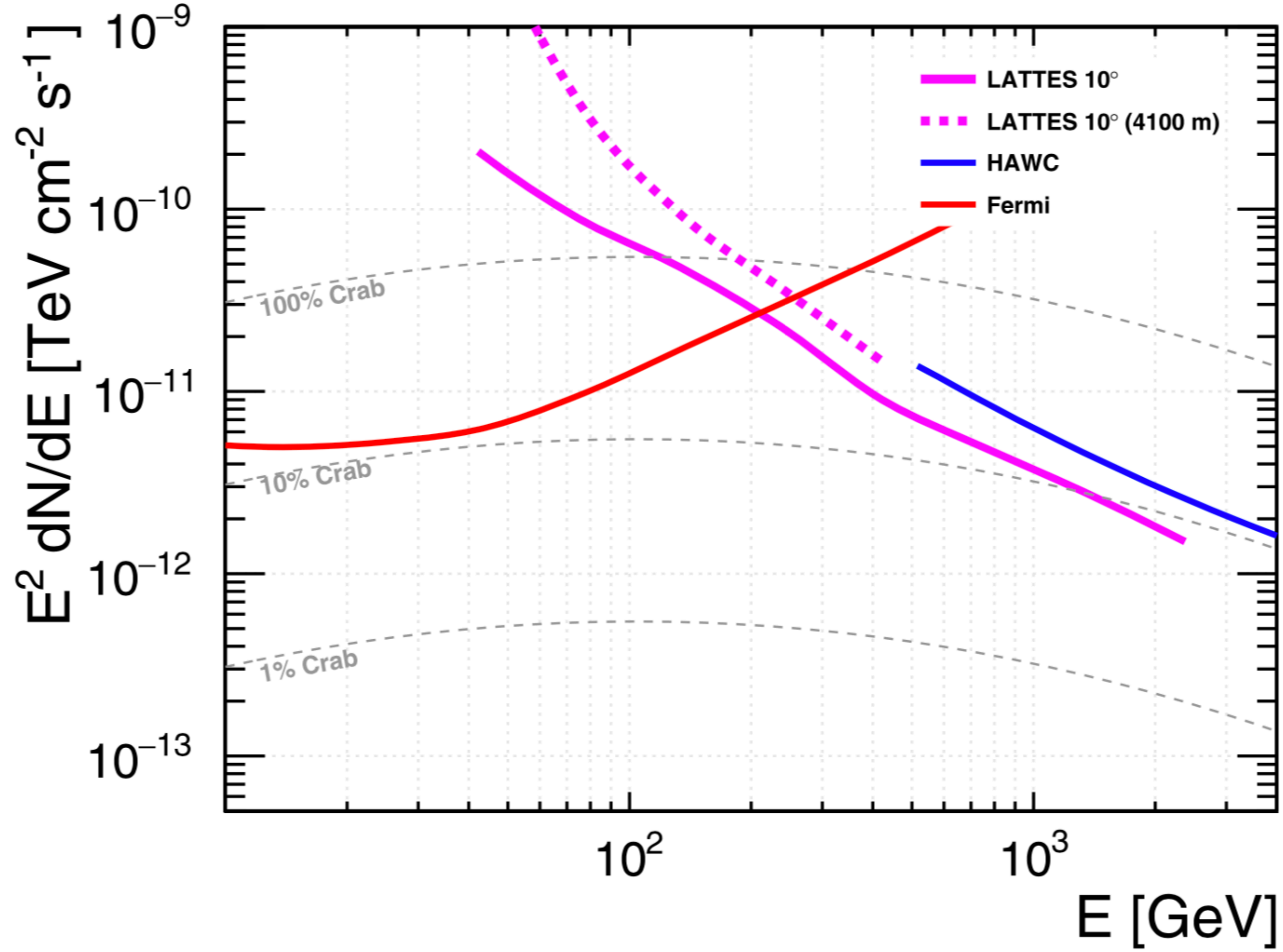
- ✧ Next steps: use only first hit in pad (trade-off between higher correlation with shower front and event statistics)

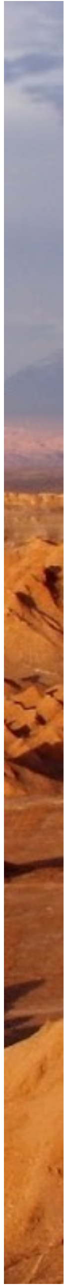
Crab





Impact of altitude

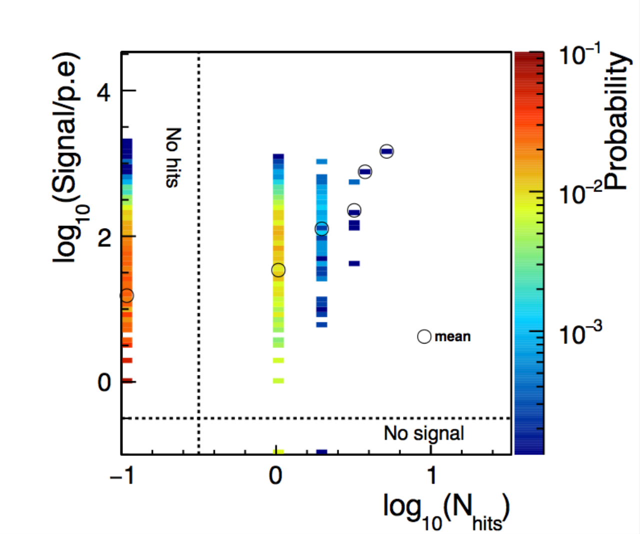


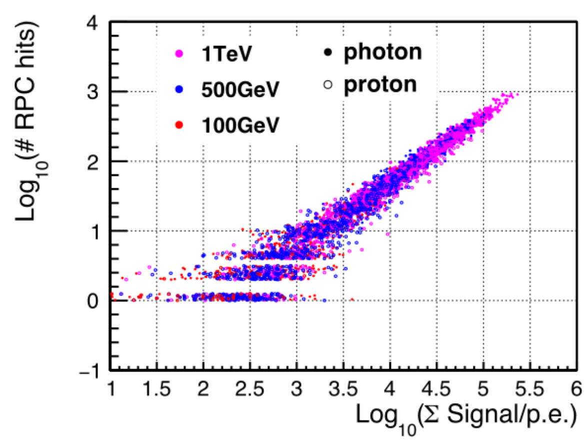


LATTES: a hybrid detector

- Thin lead plate
  - To convert the secondary photons
  - Improve geometric reconstruction
- Resistive Plates Chamber
  - Sensitive to charged particles
  - Good time and spatial resolution
  - Improve geometric reconstruction
  - Explore shower particle patterns at ground
- Water Cherenkov Detector
  - Sensitive to secondary photons and charged particles
  - Measure energy flow at ground
  - Improve trigger capability
  - Improve gamma/hadron discrimination

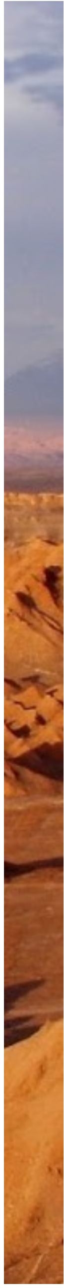
WCD vs RPC (station level)



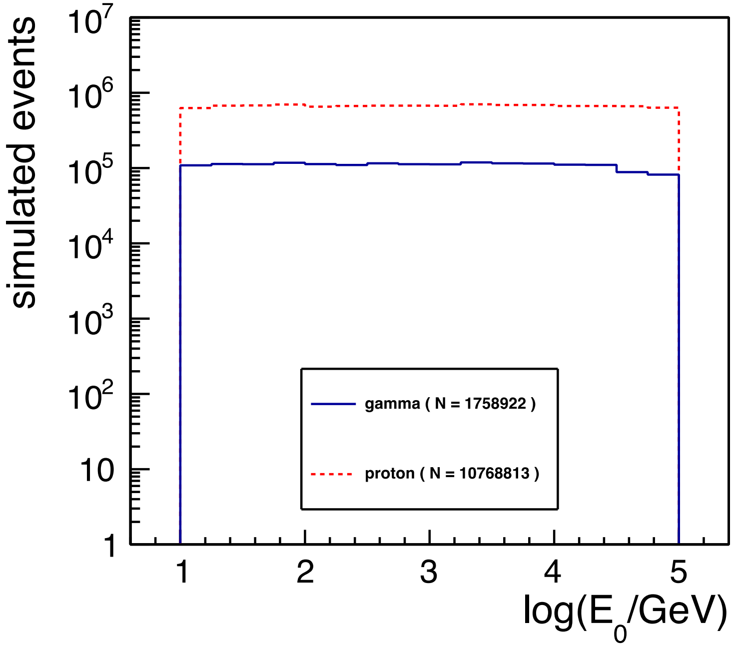


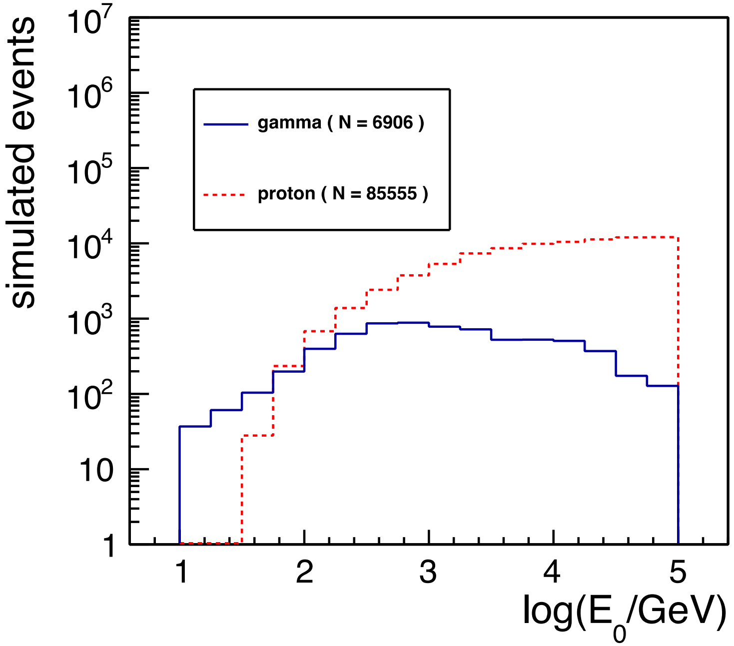
Complementarity

Inter-calibration



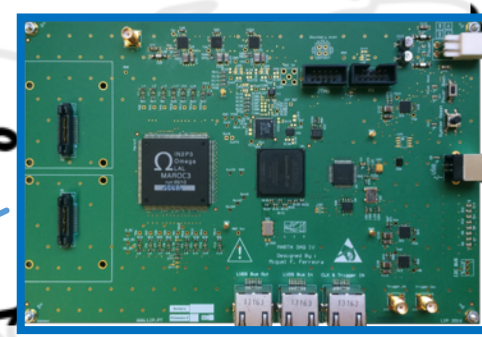
Reconstruction efficiency





Ongoing developments and tests on RPCs, electronics and read-out systems

RPC developments



DAQ Engineering prototype

RPC based muon hodoscope for precise studies of the Auger WCD

Top RPC

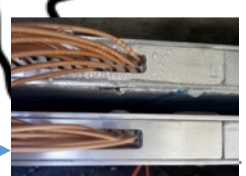
Gianni Navarra WCD

Bottom RPC

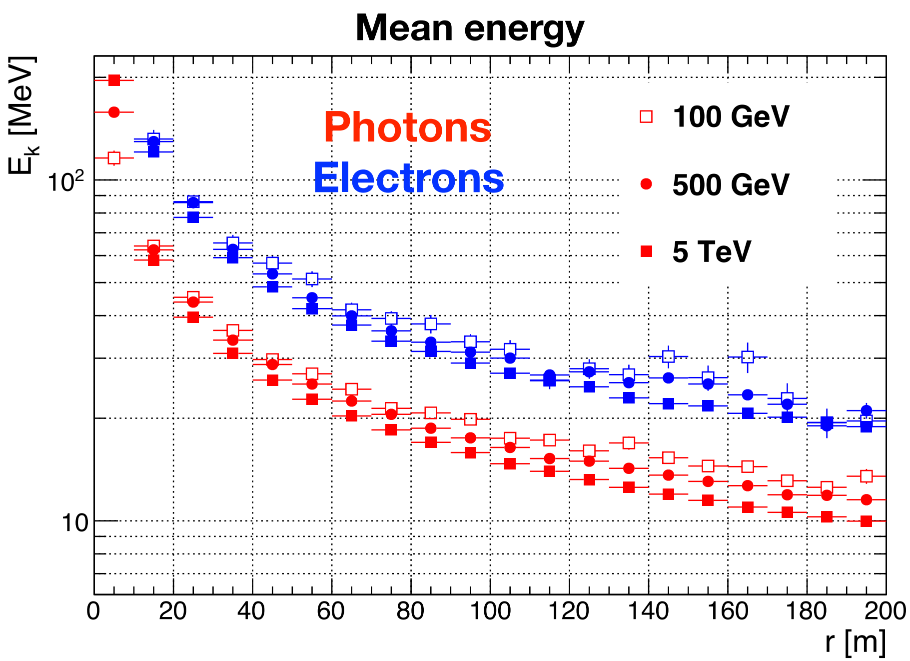
Construction and Assembling

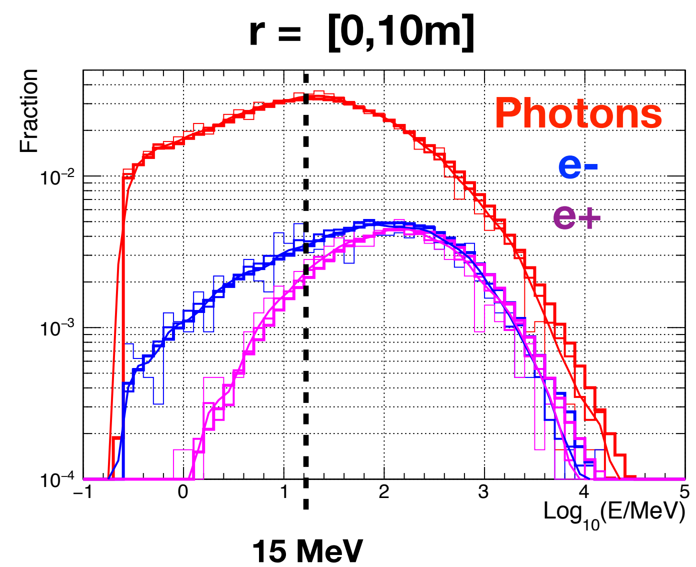
RPC hodoscope

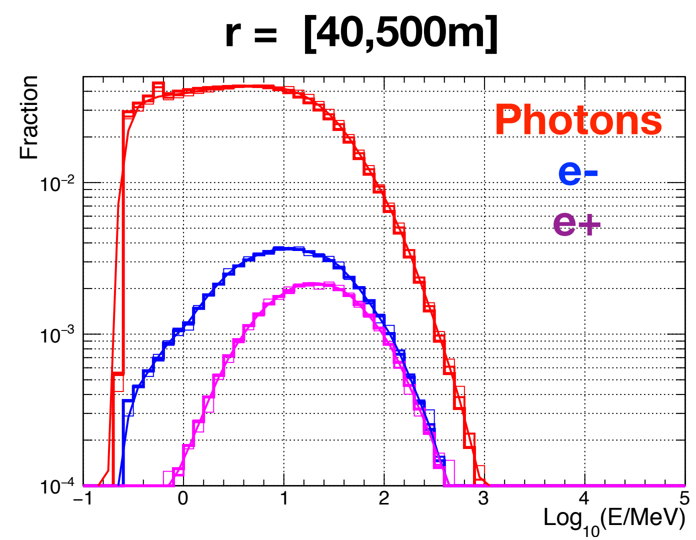
RPCs in the field @ Auger

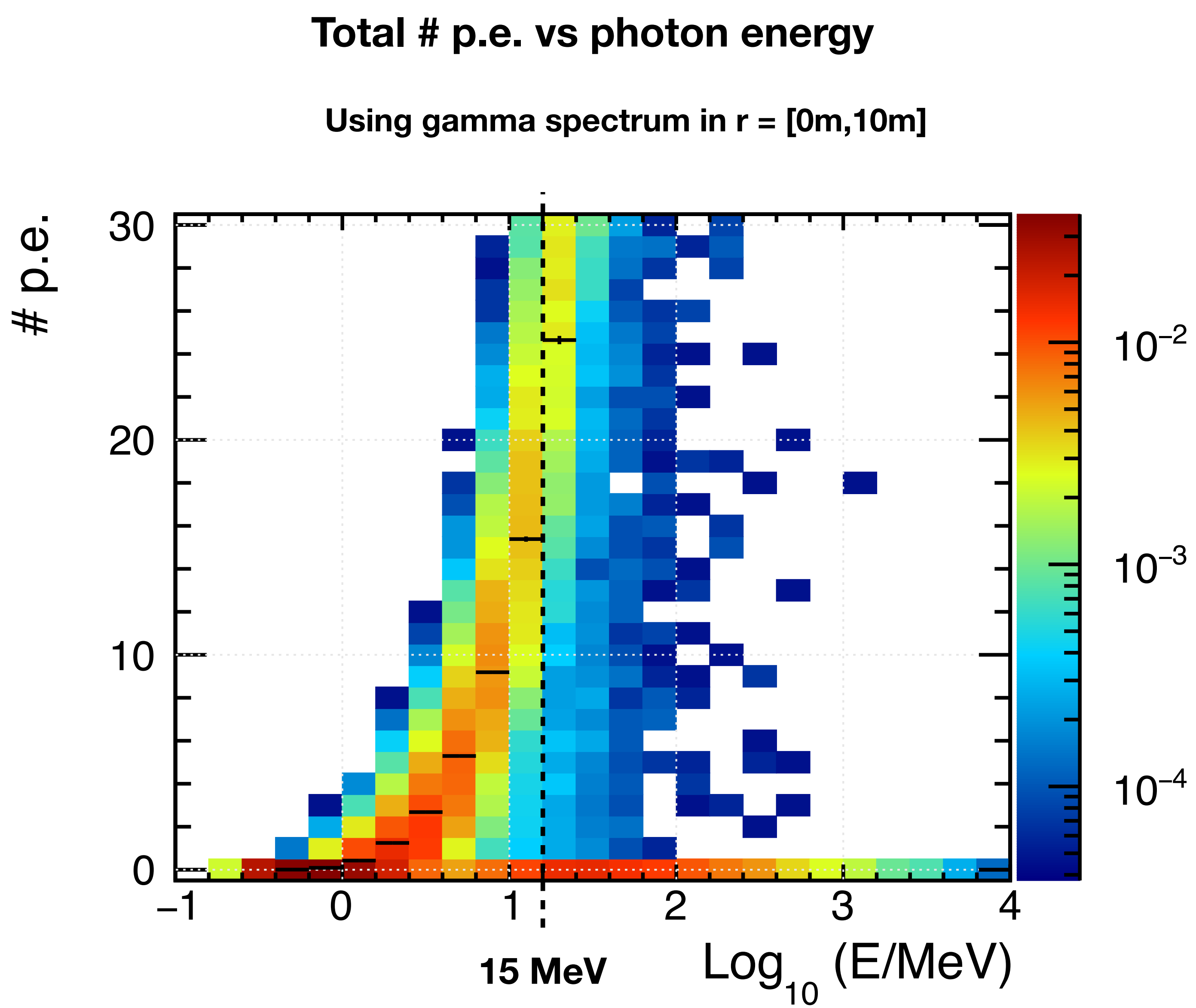


Secondary particle energy at ground gamma showers








Total # p.e. vs photon energy
Using gamma spectrum in r = [0m,10m]
p.e.
30
20
10
0
−1
0
1
2
3
4
15 MeV
Log10 (E/MeV)
10−2
10−3
10−4

~ 20 p.e. @ 15 MeV

Look at muon signal at selected entrance positions
(along diagonal, within R = 5 cm circles)