LATTES: simulated performance

Ruben Conceição

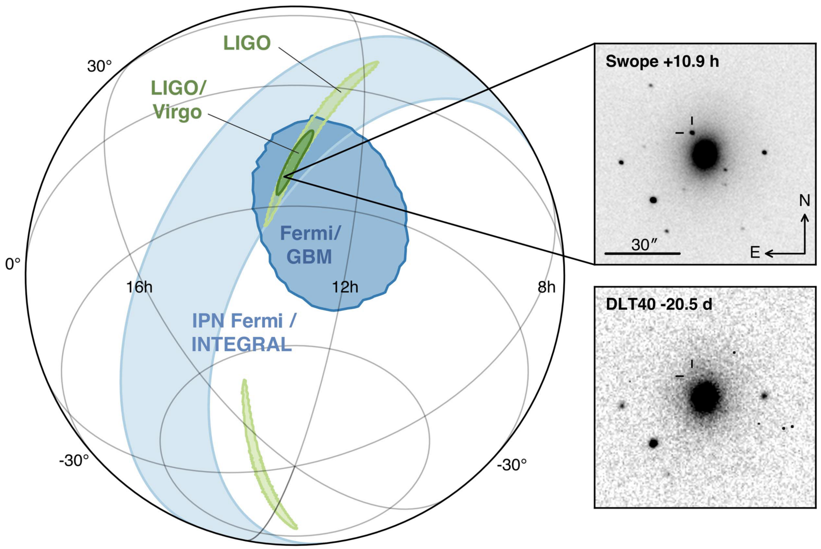
on behalf of the LATTES team

LIP

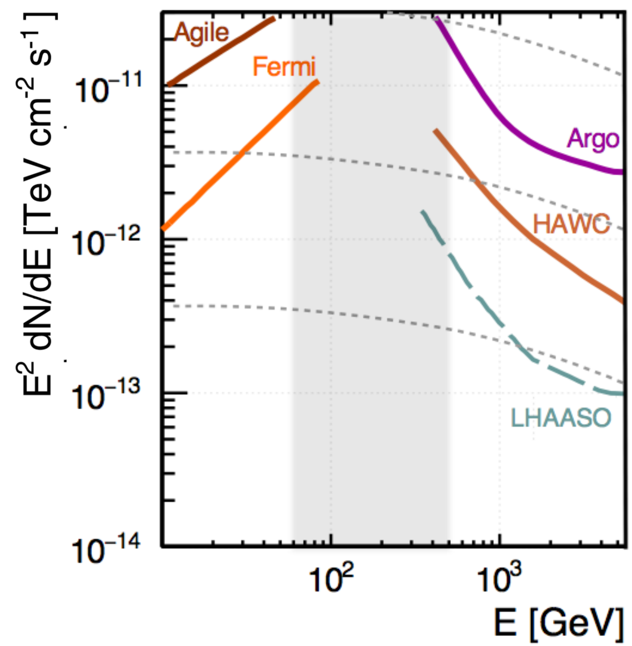
The era of multi-messenger observations

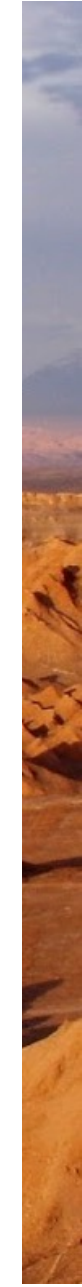
physicsworld
BREAKTHROUGH OF THE YEAR 2017

Joint publication of LIGO, VIRGO, INTEGRAL, Fermi, IceCube, Pierre Auger …



Current wide FoV gamma-ray observatories

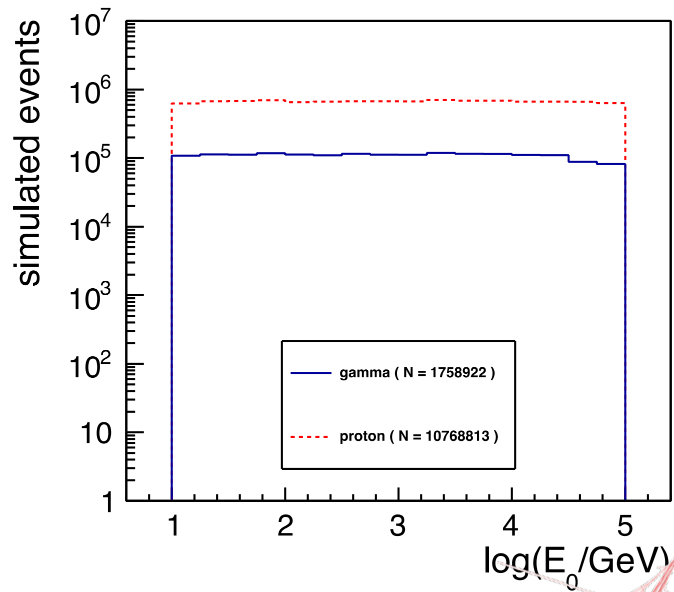


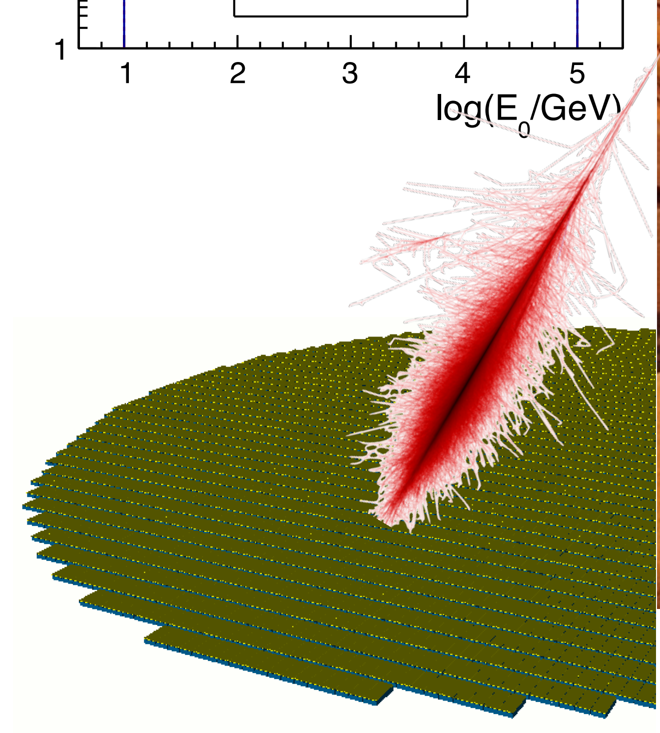


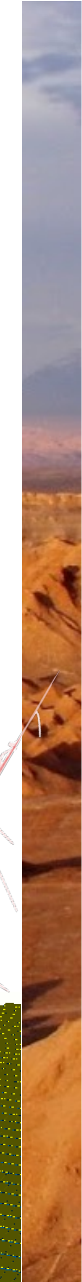
- Simultaneous observation of a Gravitational Wave + electromagnetic counterparts
- Study of transient phenomena in all energy windows is one of the main ingredients

Simulation Framework

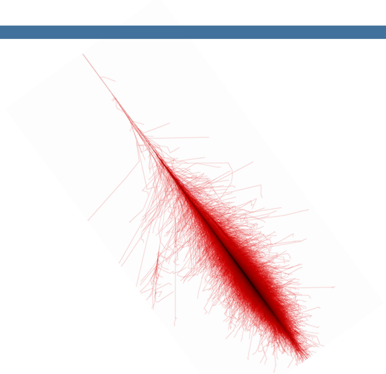
- End-to-end realistic simulation
  - Extensive Air Showers: CORSIKA
    - v7.6400 with Fluka2011.2c
    - More than 100 000 gamma/proton shower simulated randomly between 10 GeV – 300 TeV
    - Gammas have a fixed zenith angle of 10 degrees
    - Observation level at 5200 m of altitude
  - Detector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



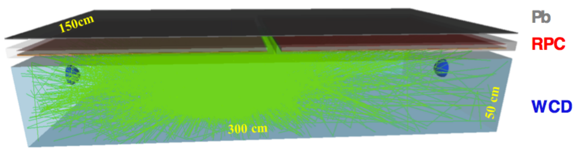




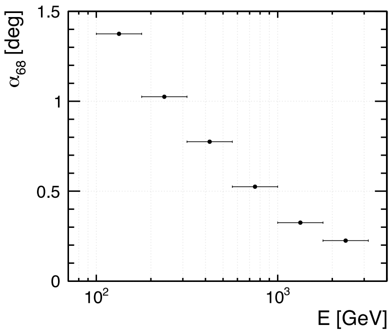
Towards LATTES sensitivity…



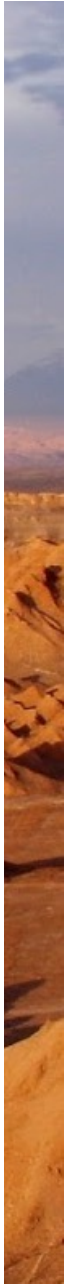
Shower simulation
(CORSIKA)



Detector simulation
(Geant4)

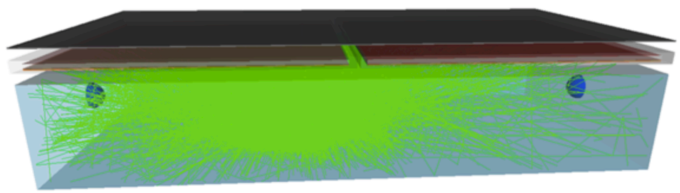


Shower reconstruction
(LATTESrec)

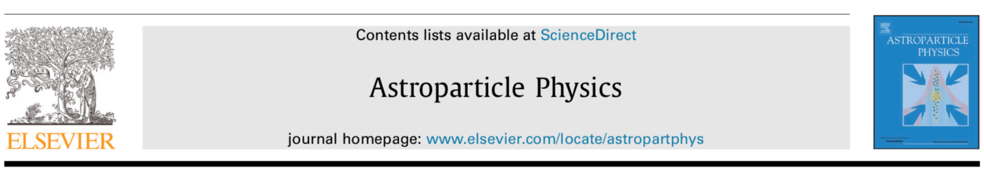


Simulation Framework

- Reconstruction
  - First order analyses with little optimization only to demonstrate principle



- Performance and sensitivity



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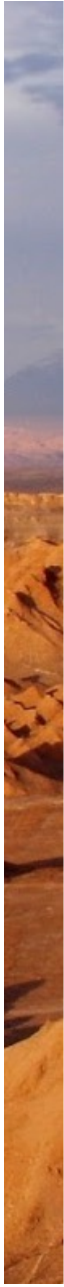
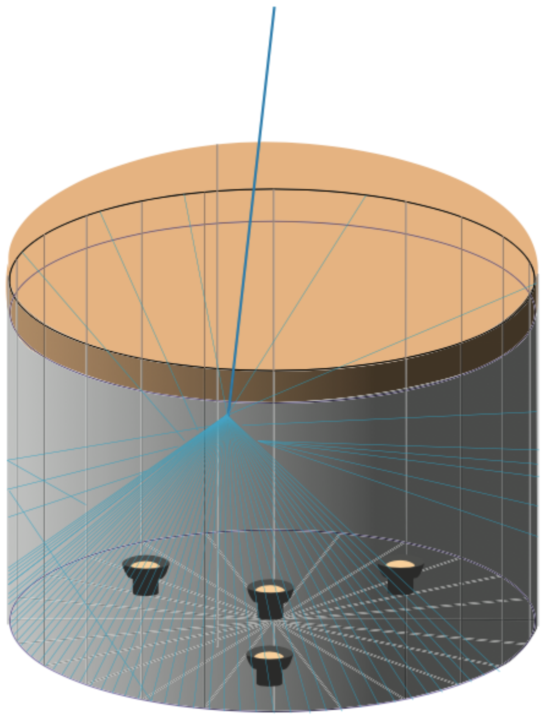
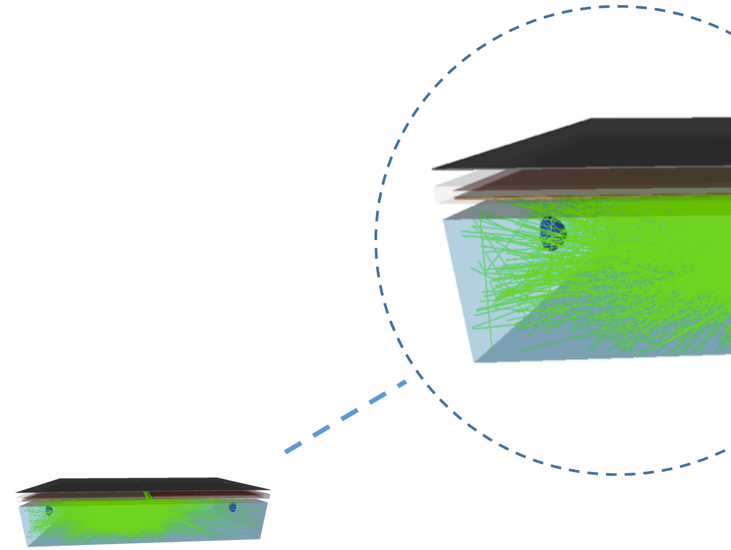
Design and expected performance of a novel hybrid detector for very-high-energy gamma-ray astrophysics

P. Assis[a,b], U. Barres de Almeida[c], A. Blanco[d], R. Conceição[a,b,*], B. D'Ettorre Piazzoli[e], A. De Angelis[f,g,b,a], M. Doro[h,f], P. Fonte[d], L. Lopes[d], G. Matthiae[i], M. Pimenta[b,a], R. Shellard[c], B. Tomé[a,b]



Detector Station



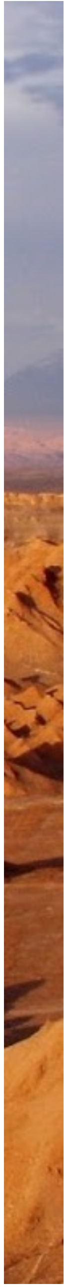


HAWC

LATTES

LATTES expected performance

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



LATTES expected performance

- **Trigger and effective area**
- Core reconstruction
- Energy reconstruction
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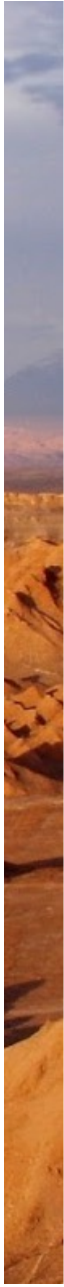
- Sensitivity to steady sources

Effective Area depends with quality cuts



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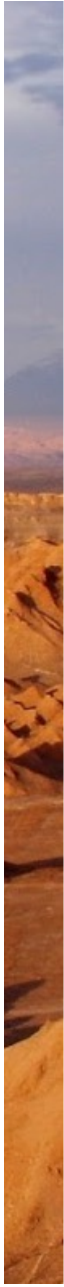
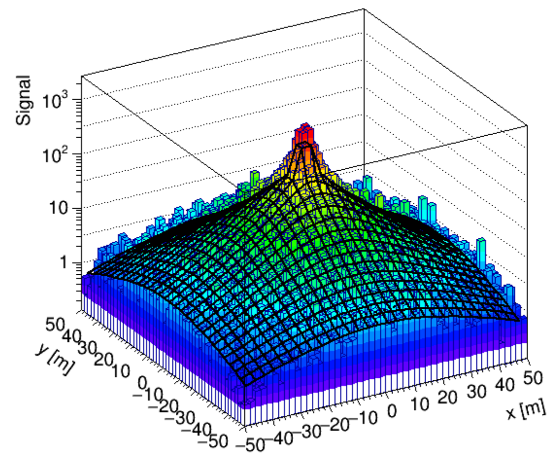


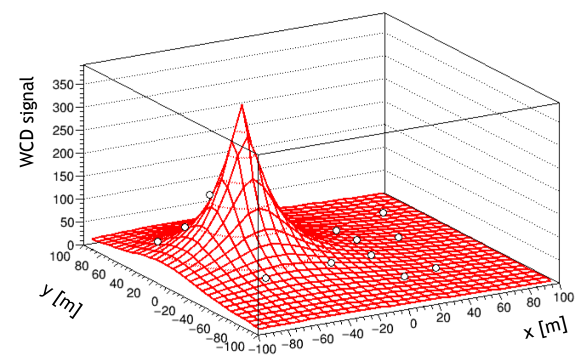
Shower core reconstruction

- 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

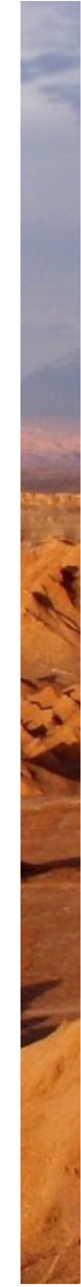
Average LDF



Single event

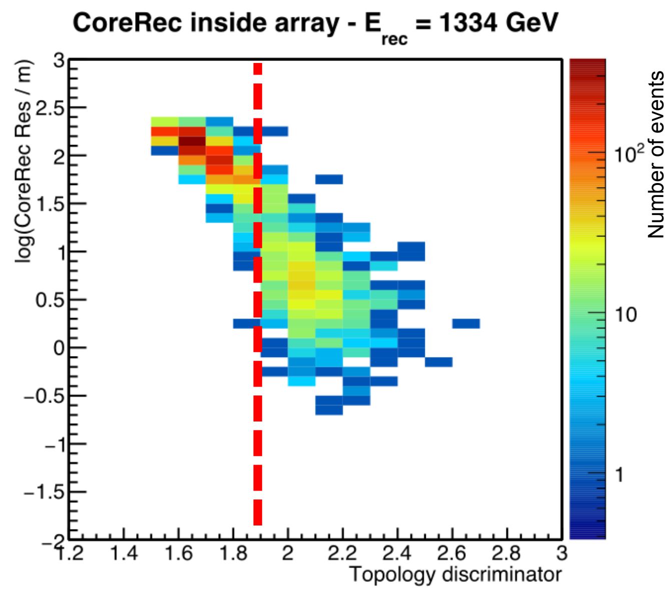


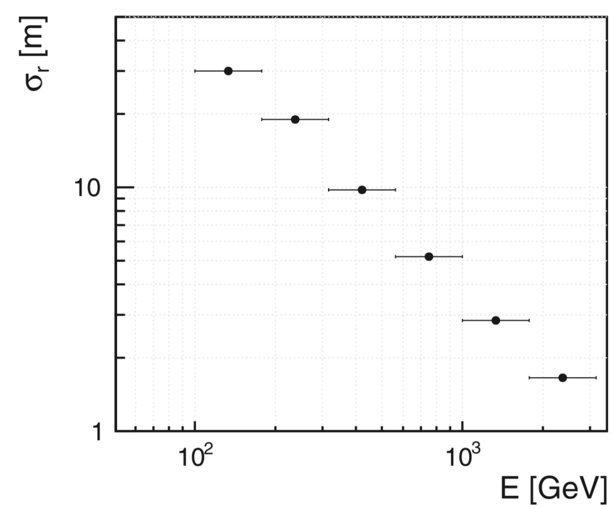
$$S_i = S(A, \vec{x}, \vec{x}_i) = A\left(\frac{1}{2\pi\sigma^2} e^{-|\vec{x}_i - \vec{x}|^2/2\sigma^2} + \frac{N}{(0.5 + |\vec{x}_i - \vec{x}|/R_m)^3}\right)$$



Shower core reconstruction

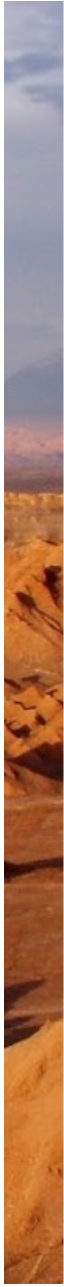
- Test whether the shower is inside/outside the array
  - Explore LDF topology
  - Is maximum observed inside of array?
  - Currently exploring the quality of the fit
  - Fixed cut for all energies
- Resolution better than 10 meters for showers above 300 GeV





LATTES expected performance

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

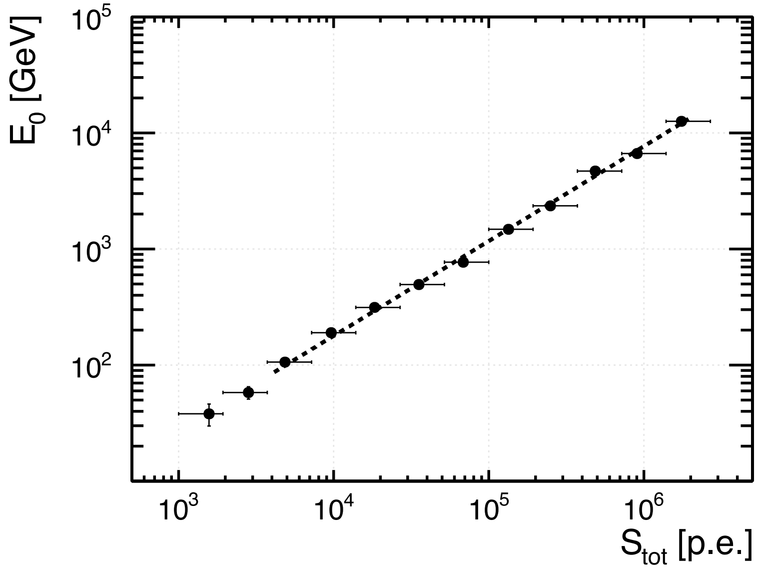


Energy reconstruction

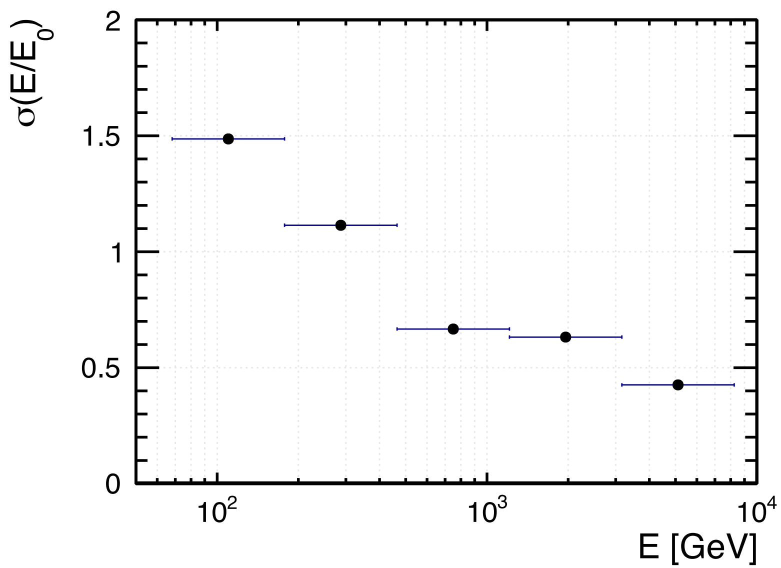
$E_0 \rightarrow$ Simulated energy

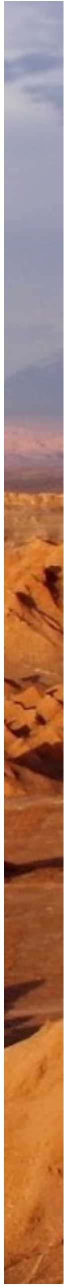
$E \rightarrow$ Reconstructed energy

Energy Calibration



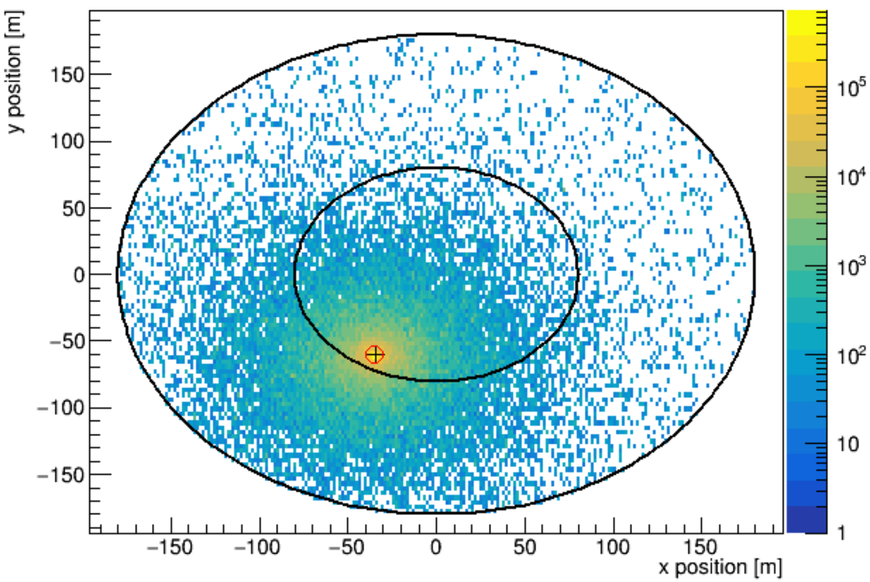
Energy Resolution

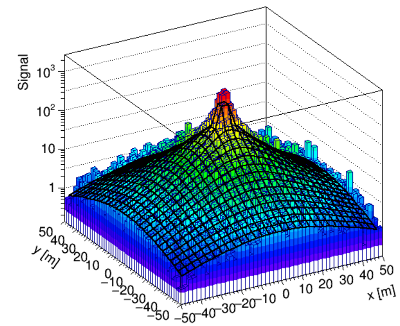




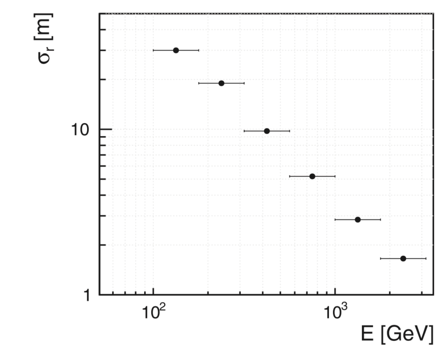
- Use as energy estimator the total signal recorded by WCDs
  - Use only shower cores reconstructed inside array
- Energy resolution at low energy dominated by shower fluctuations

Towards a more sophisticated energy reconstruction





Average LDF

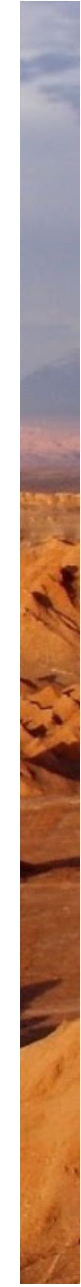


Core resolution

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

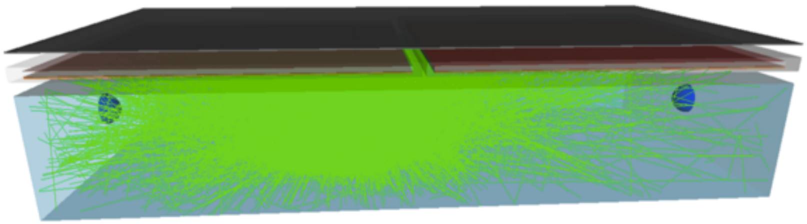
LATTES expected performance

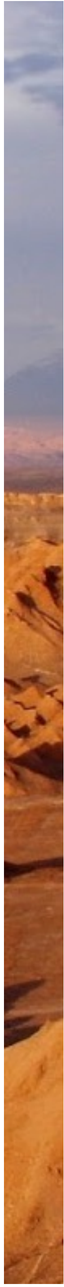
- ✧ Trigger and effective area
- ✧ Core reconstruction
- ✧ Energy reconstruction
- ✧ **Geometry reconstruction**
- ✧ Gamma/hadron discrimination
- ✧ Sensitivity to steady sources



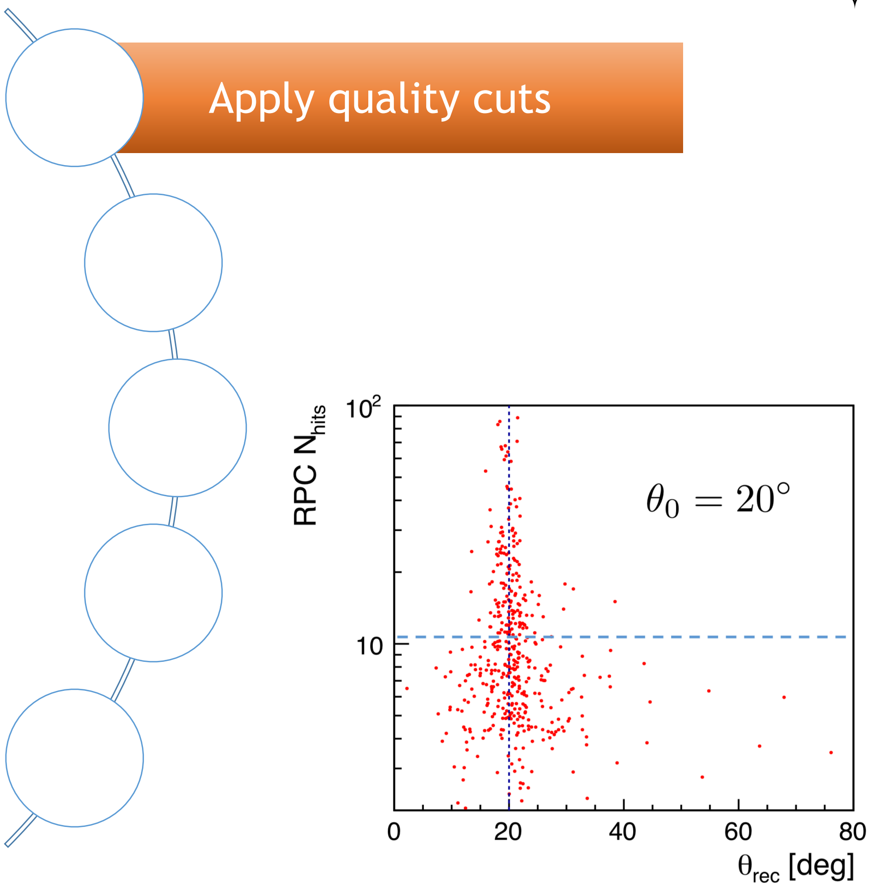
Reconstruction of shower geometry

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



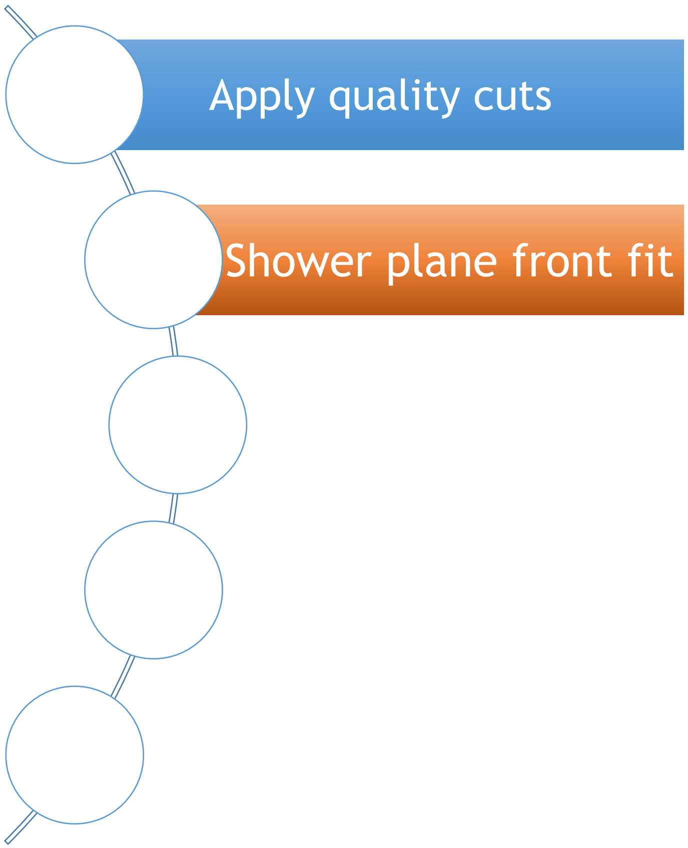


Reconstruction of shower geometry

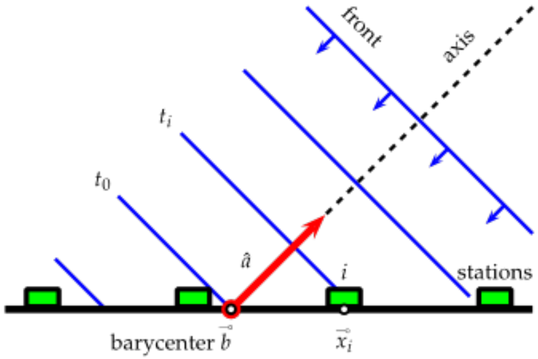


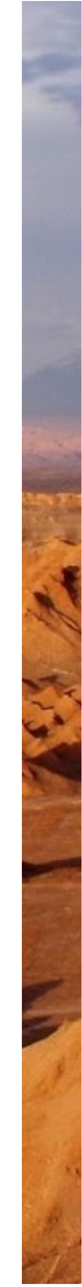
- Use RPC hit time information
  - Apply previous shower rec quality cuts
  - Apply cuts on the number of registered hits on the RPCs
  - Consider only RPCs in triggered WCD stations

Reconstruction of shower geometry



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

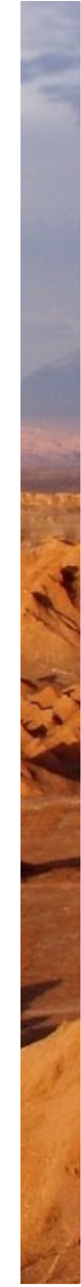




Reconstruction of shower geometry

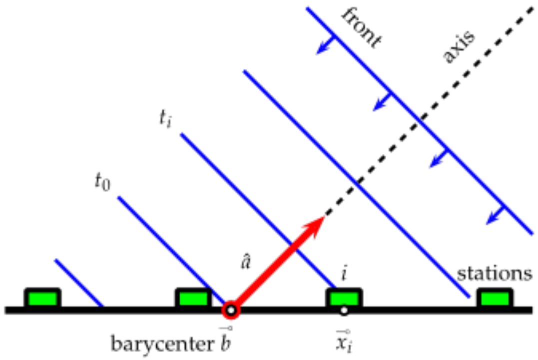
- Apply quality cuts
- Shower plane front fit
- Remove late arrivals

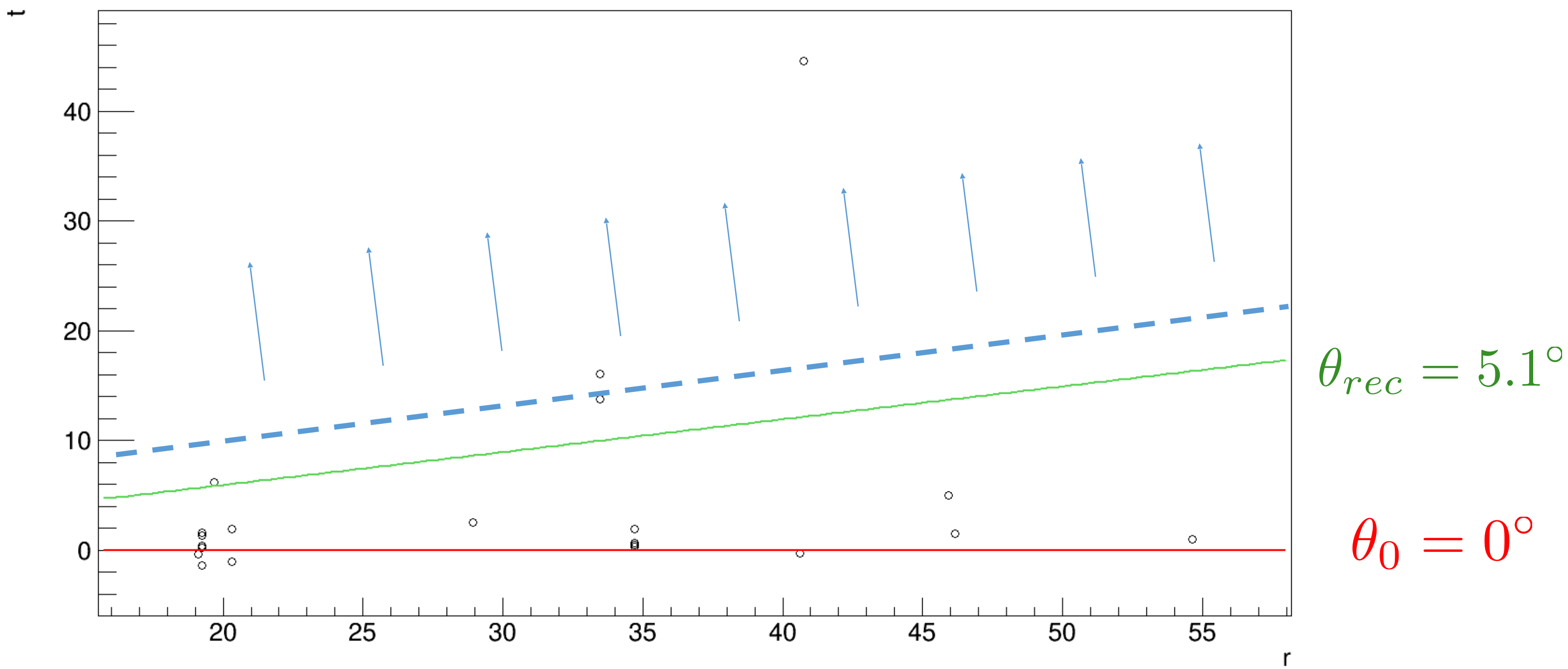
- Use RPC hit time information
  - Identify late arrivals with respect to Rec Shower Front
  - Mainly low energy electrons that lost correlation with shower front

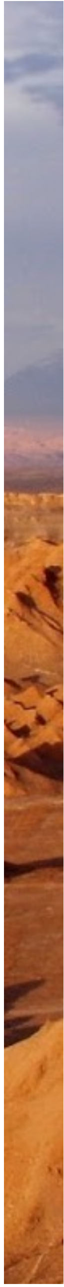


Removal of late arrivals

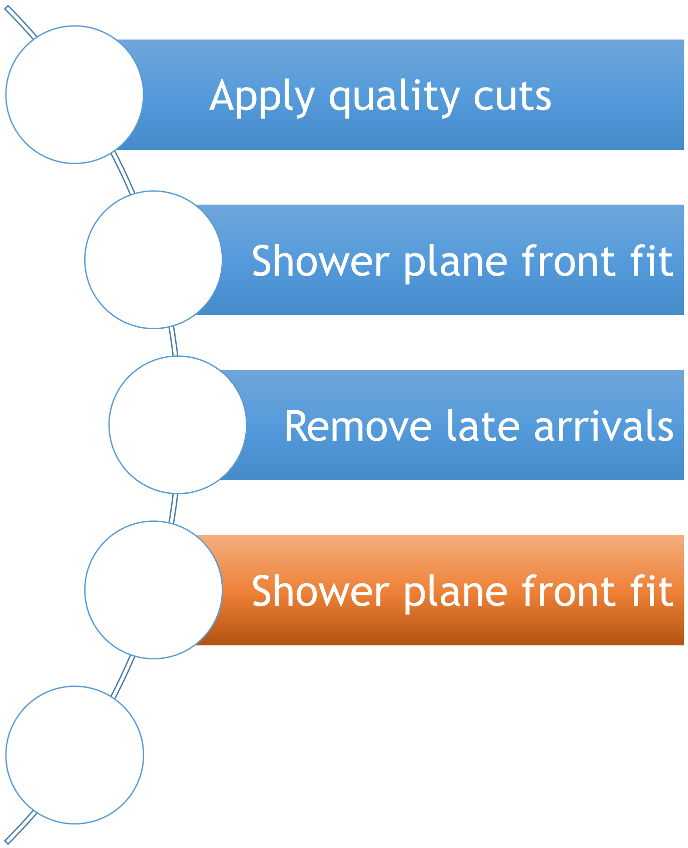
- ✧ Example of a vertical gamma shower
- ✧ Plot depicts arrival time (ns) distance to simulated shower core (m)



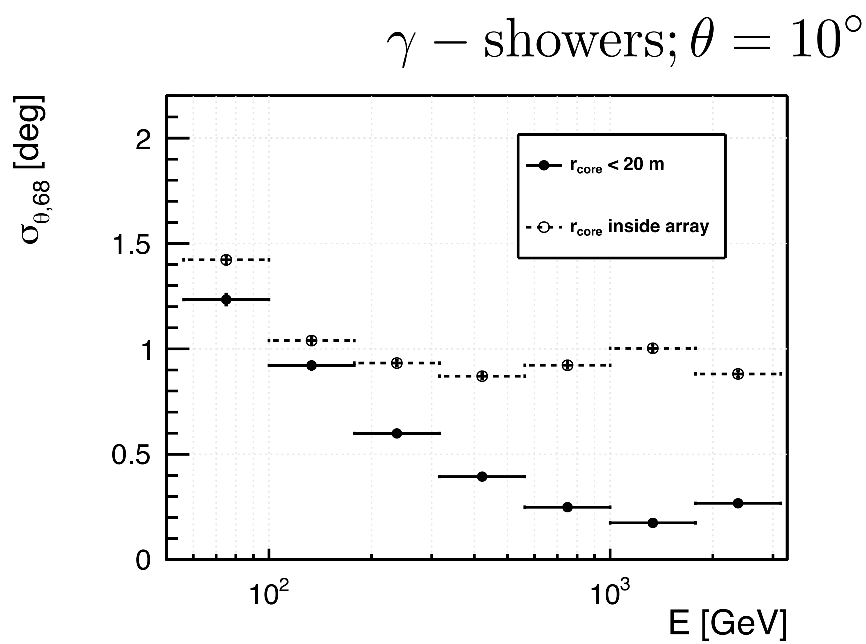


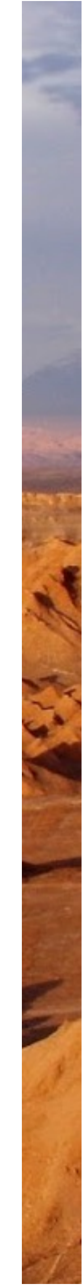


Reconstruction of shower geometry

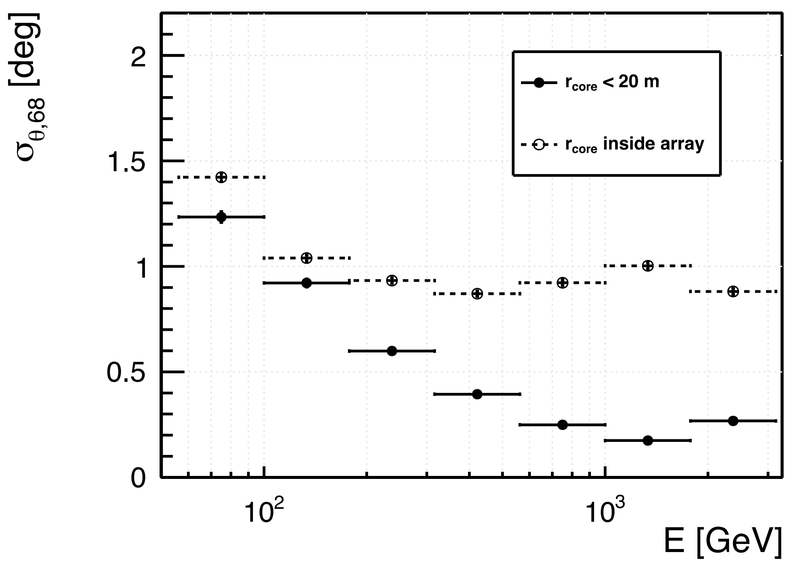


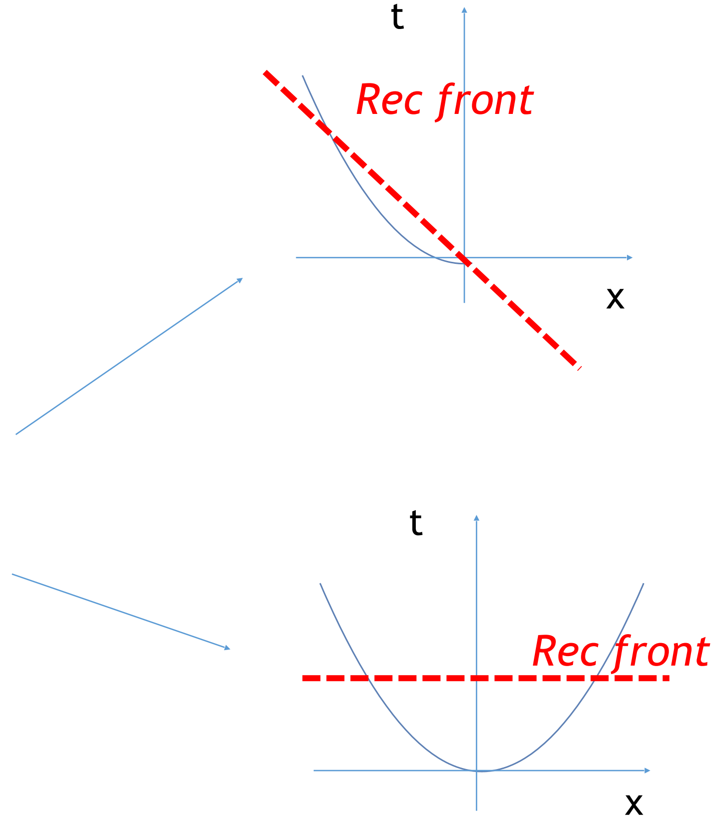
- Use RPC hit time information
  - Repeat fit without arrivals
  - Initial guess for next step





Impact of shower curvature



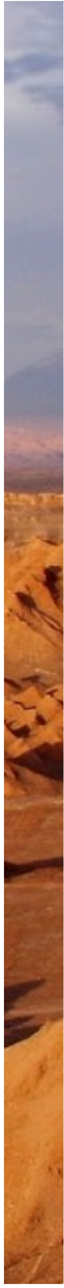


Border of the array

Center of the array

Solution: implement a conic fit instead of fitting a plane

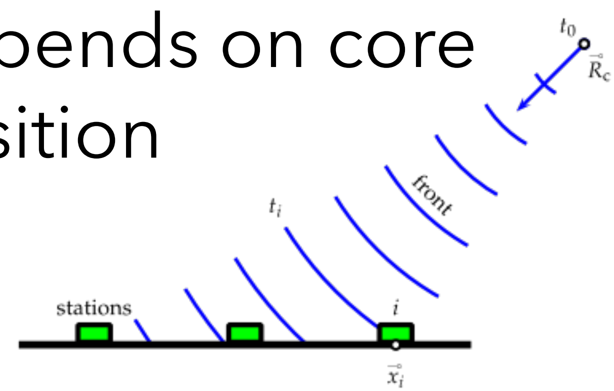
$$\chi^2 = \sum (c \cdot (T_n - T_0) - X_n \cdot -Y_n \cdot m - R_n \cdot \alpha)^2$$

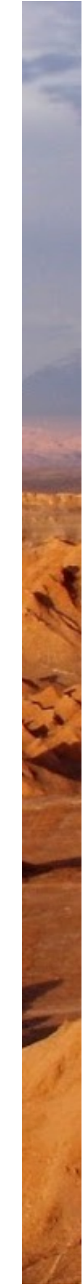


Reconstruction of shower geometry

1. Apply quality cuts
2. Shower plane front fit
3. Remove late arrivals
4. Shower plane front fit
5. Shower conic front fit

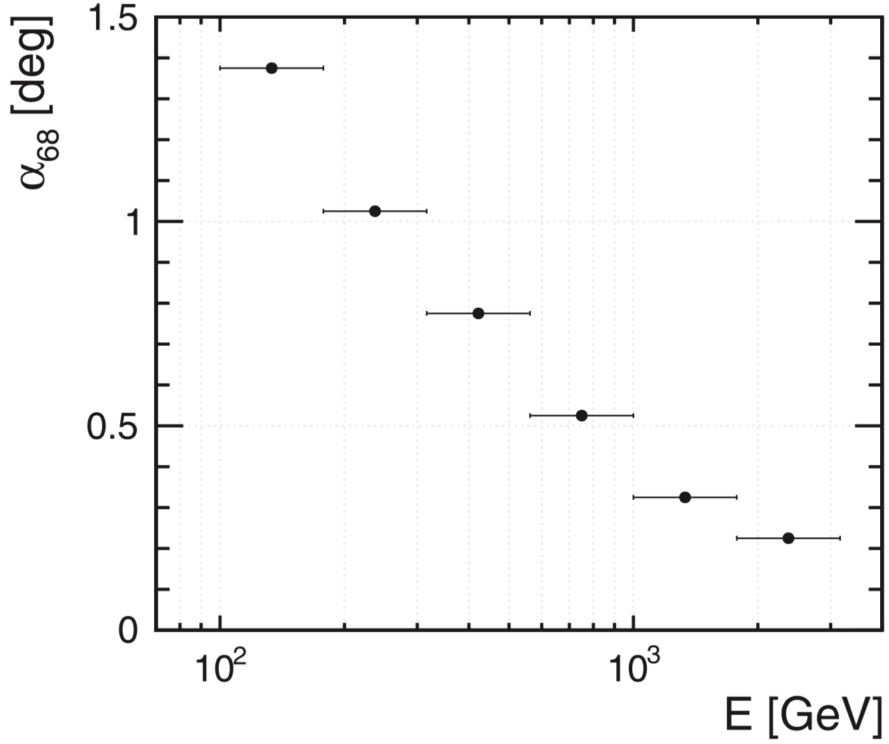
- Use RPC hit time information
- Fit the shower geometry using a shower conic front model
- Depends on core position



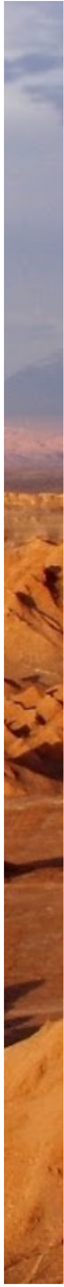


Shower geometry reconstruction

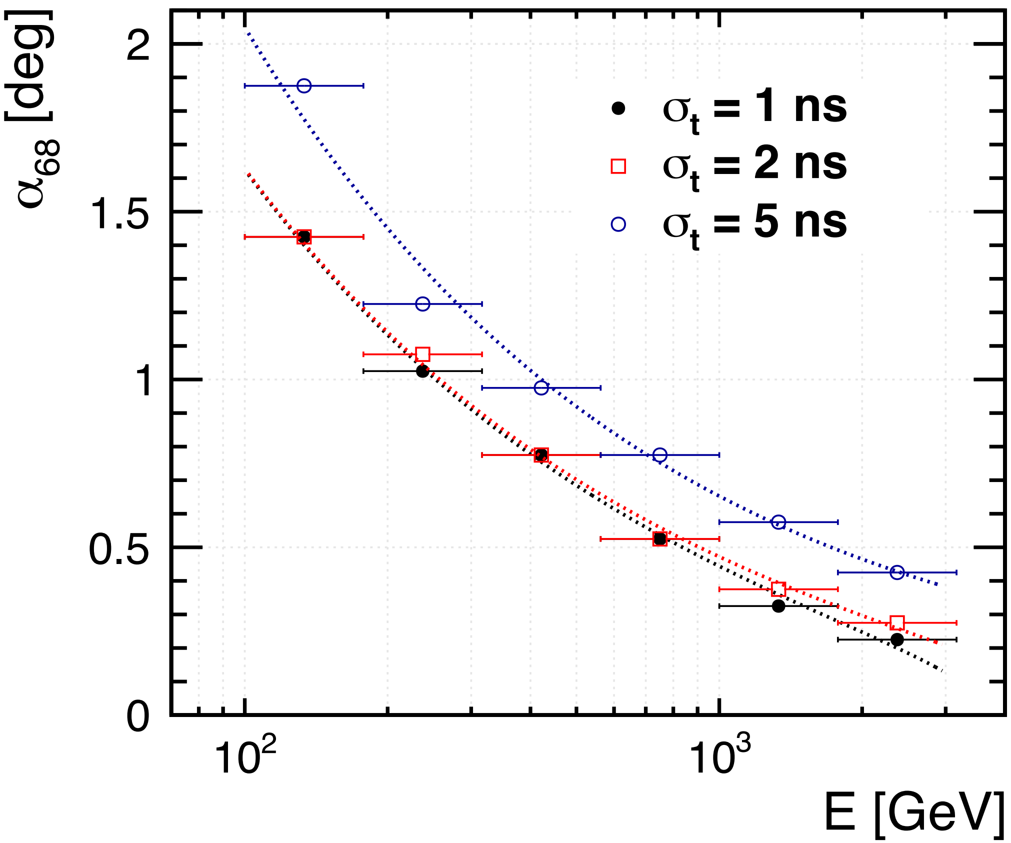
α_{68} = angular distance that contains 68% of the events

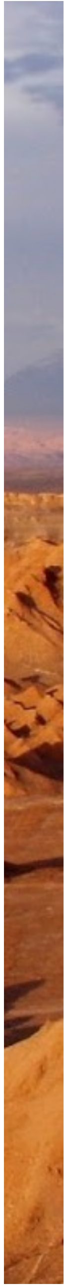


A good angular resolution can be achieved for all events reconstructed inside the array



Geom Rec: RPC time resolution



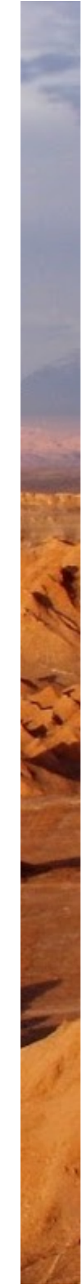


Need of a time resolution of 1-2 ns to obtain a good geometry reconstruction

LATTES expected performance

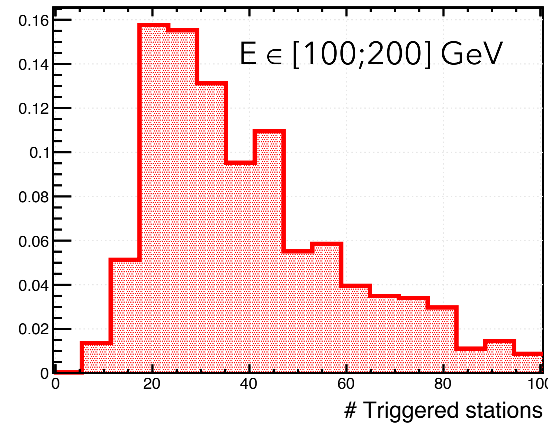
- ✧ Trigger and effective area
- ✧ Core reconstruction
- ✧ Energy reconstruction
- ✧ Geometry reconstruction
- ✧ Gamma/hadron discrimination
- ✧ Sensitivity to steady sources

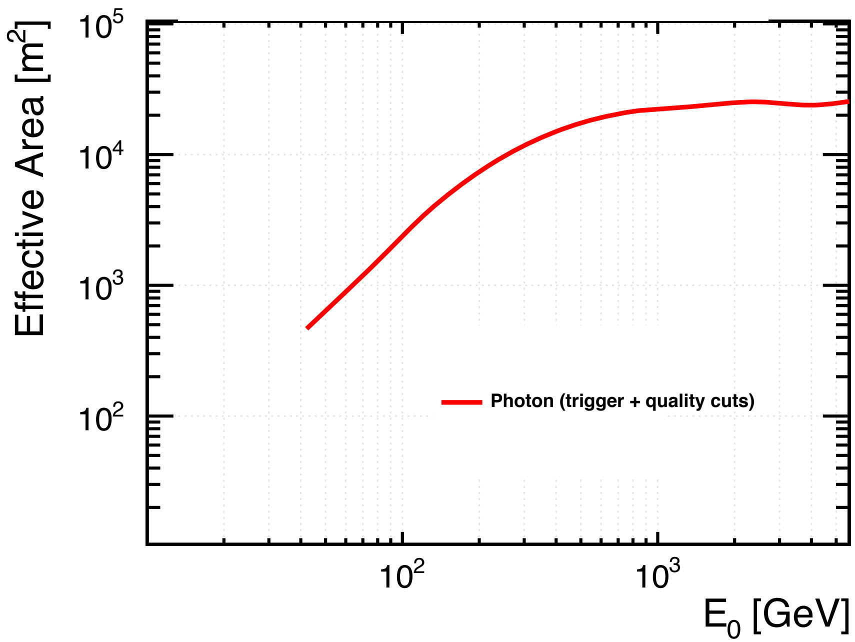
Shower rec quality cuts

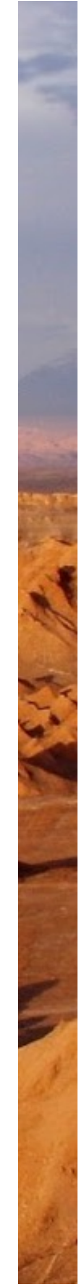


Effective Area

- 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**







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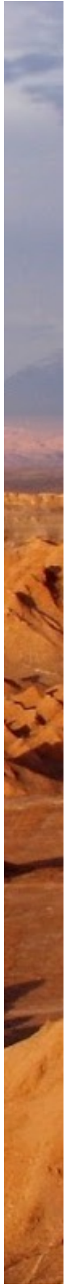
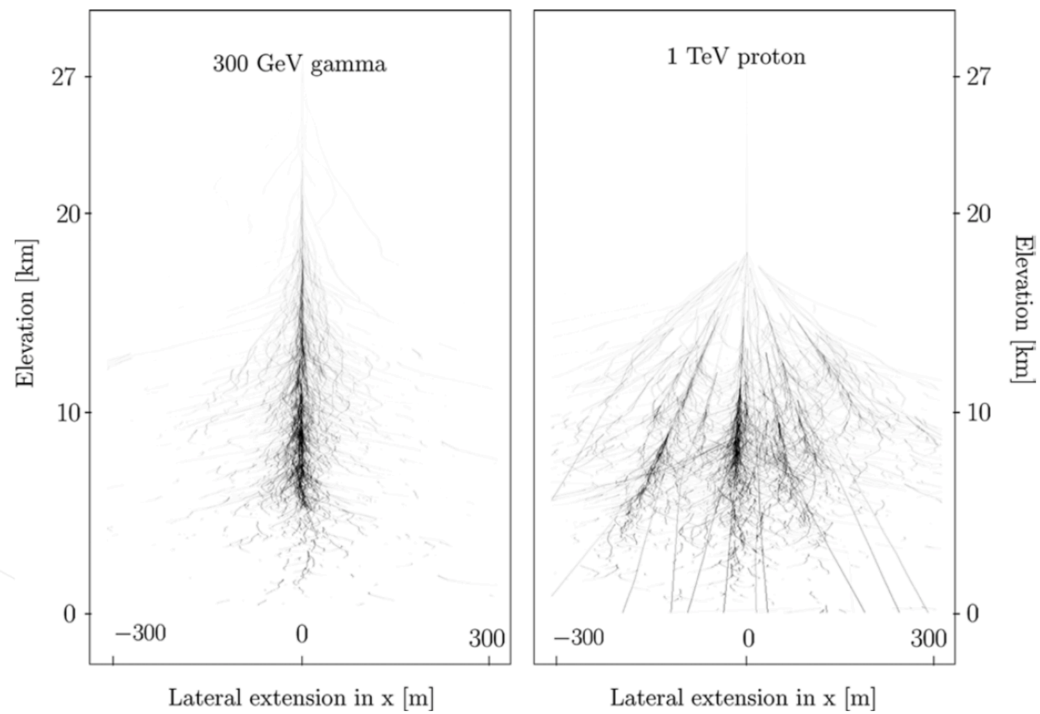
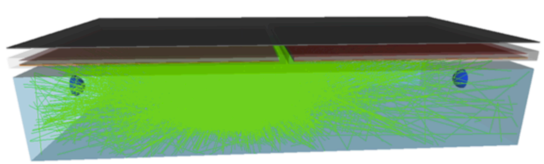
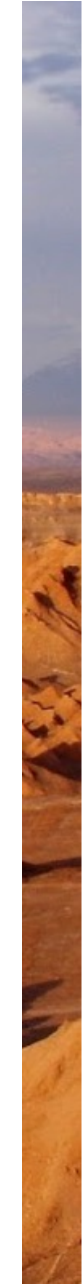


Shower characteristics

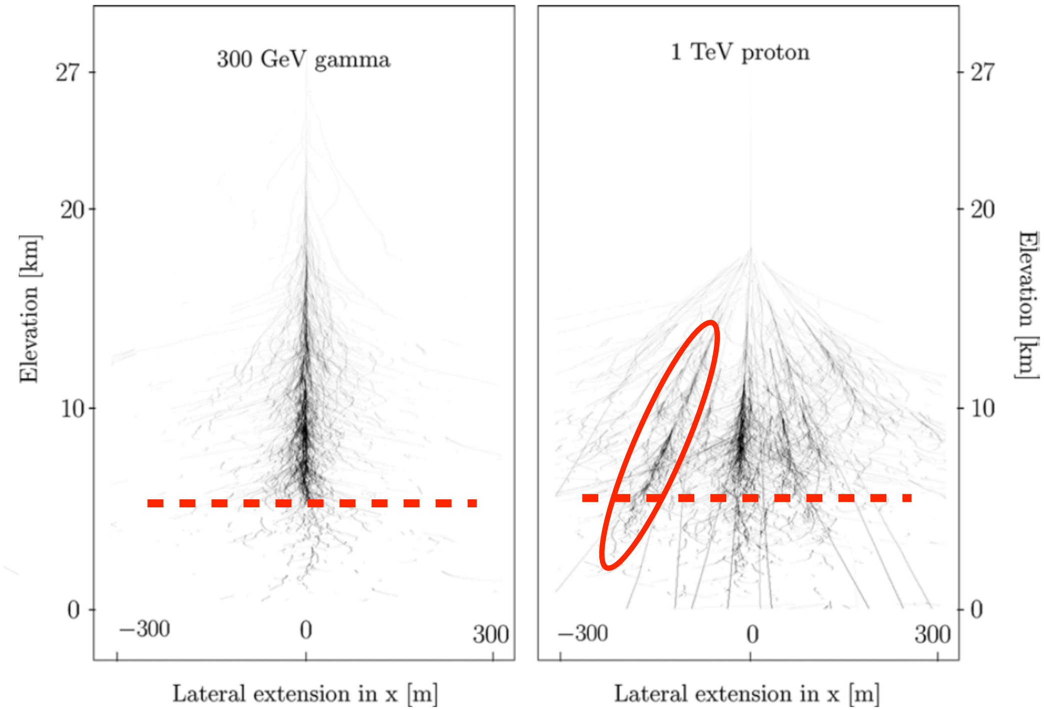


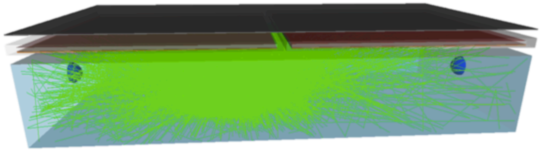


A pure electromagnetic shower (gamma) has distinct features from a shower with an hadronic component (hadron)

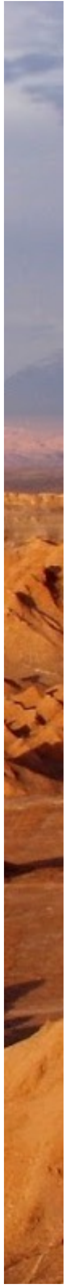


Shower characteristics



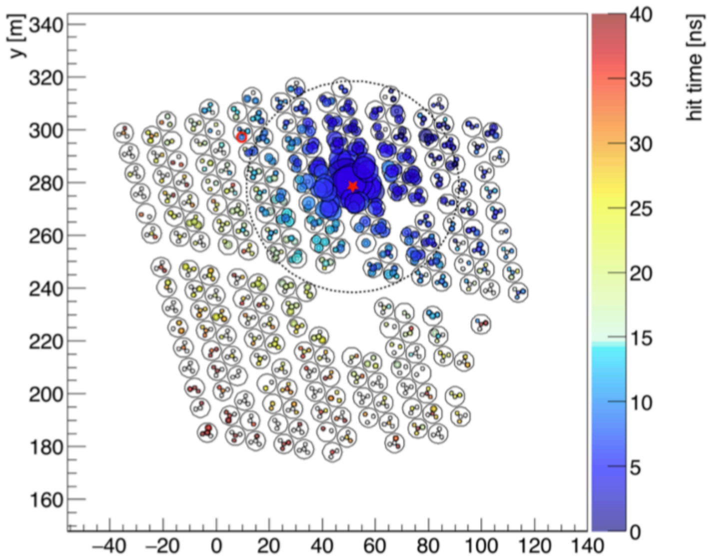


A pure electromagnetic shower (gamma) has distinct features from a shower with an hadronic component (hadron)

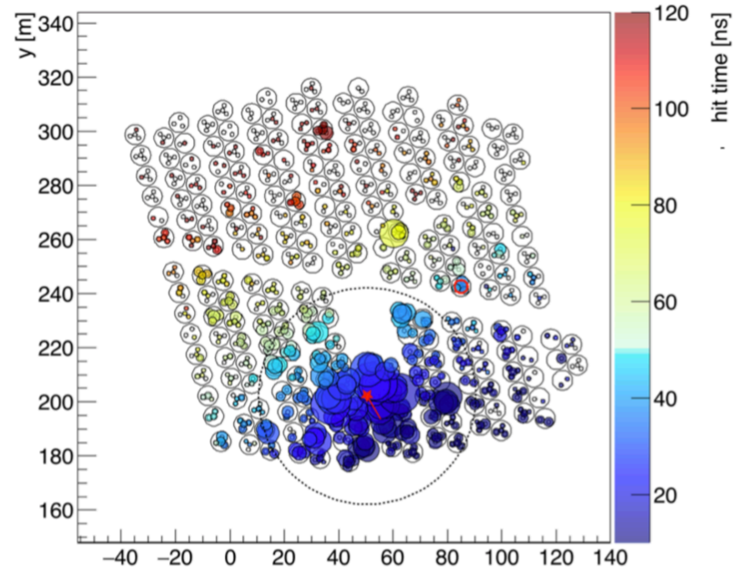


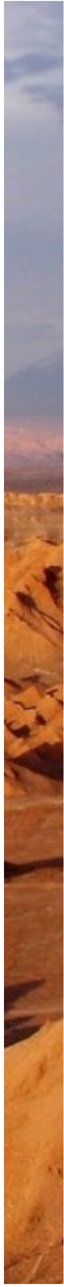
Looking for high-p_T sub-showers

gamma shower



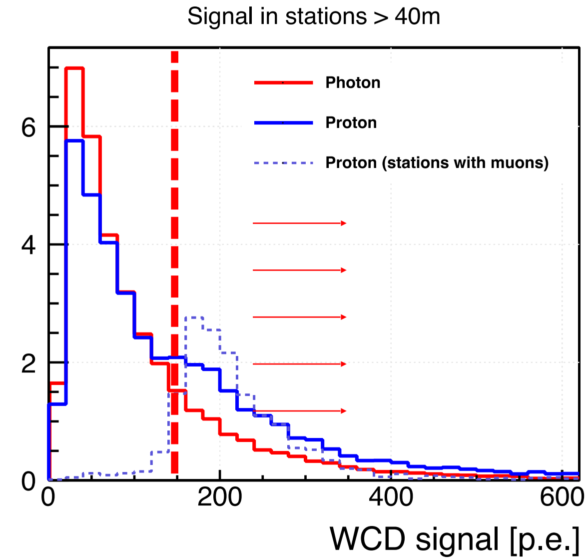
hadron shower

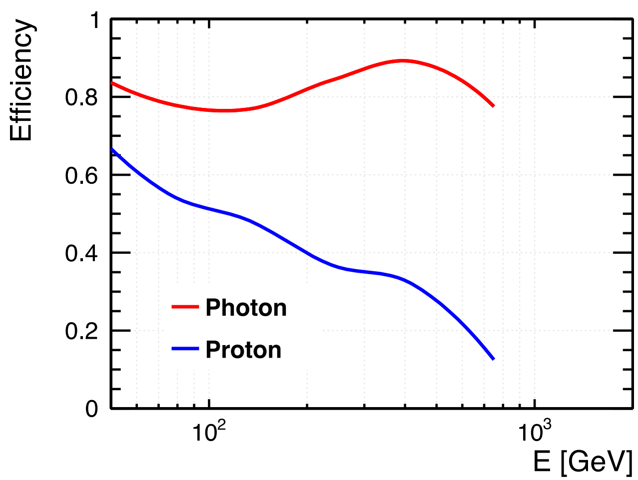




Looking for high p_t sub-showers

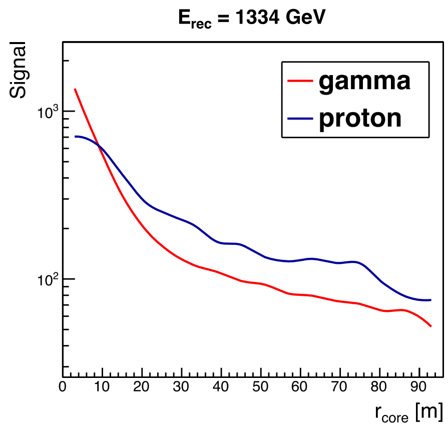
- LATTES g/h discrimination
  - Use only stations with a distance above 40 m
  - $\mathbf{S_{40}}$: sum all WCD stations signal
  - $\mathbf{S_{40\_high}}$: sum all WCD stations that have a signal above the muon energy threshold
  - Compute $\mathbf{S_{40\_high} / S_{40}}$
  - Not optimized…

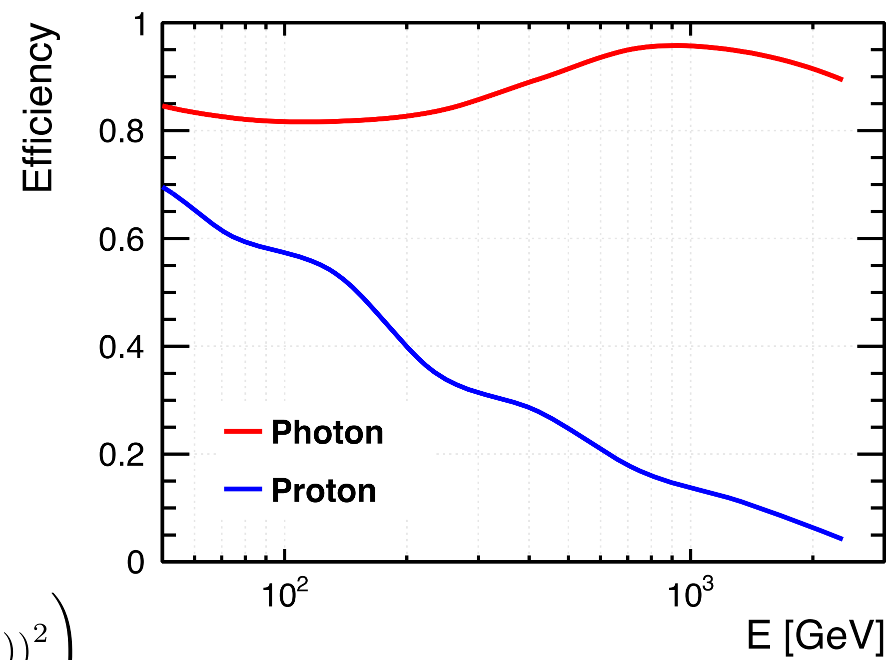




High-energy discrimination strategy

Average LDF

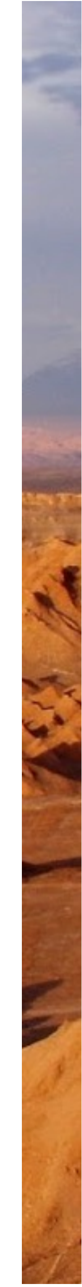




- Compute event-by-event:

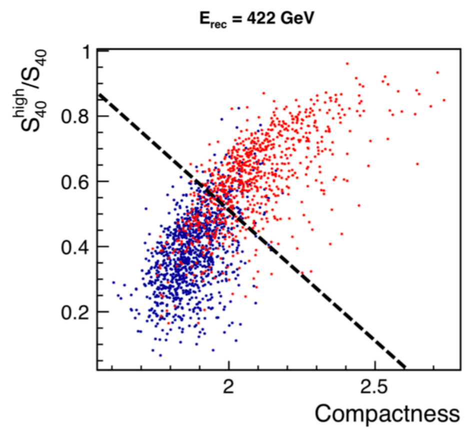
$$\text{Compactness} = \log_{10}\left(\sum_{i}^{n}\left(\langle LDF\rangle(r_i) - y(r_i)\right)^2\right)$$

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

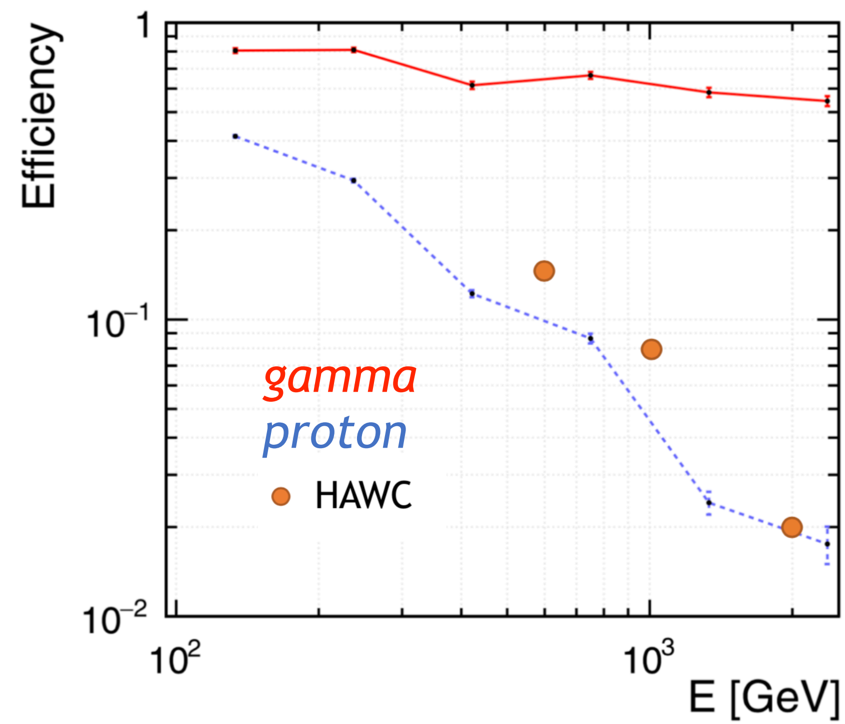


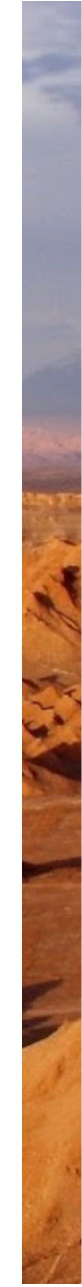
LATTES g/h discrimination

Using only the WCD



Compactness = LDF steepness
S40 = Signal outside 40 m

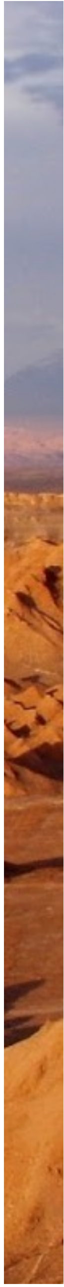




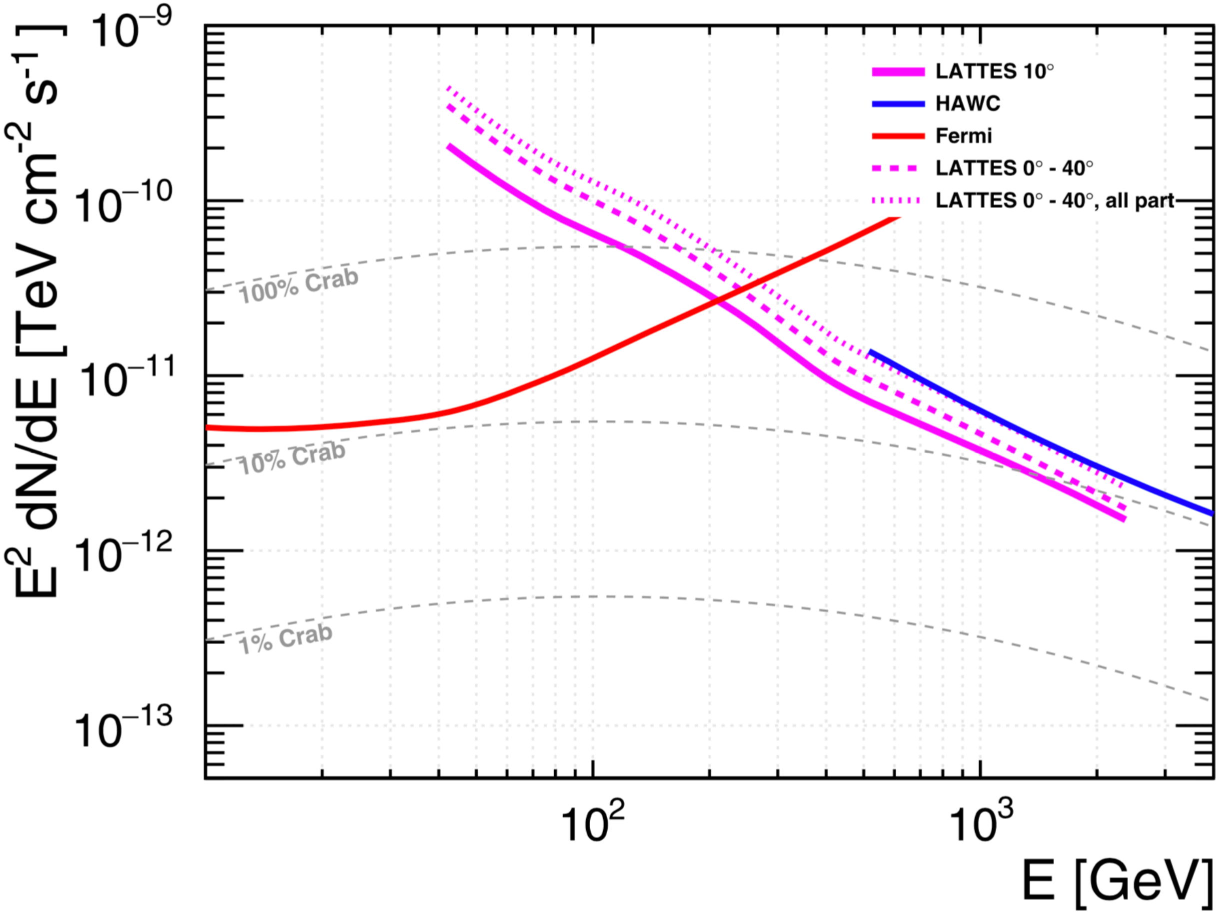
- Although not optimized the gamma/hadron discrimination results are already very encouraging
- Starting to investigate more sophisticated tools (ANN: pattern at ground ; cuts ; …)

LATTES expected performance

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

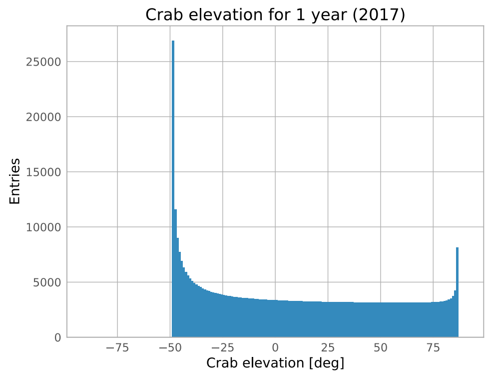


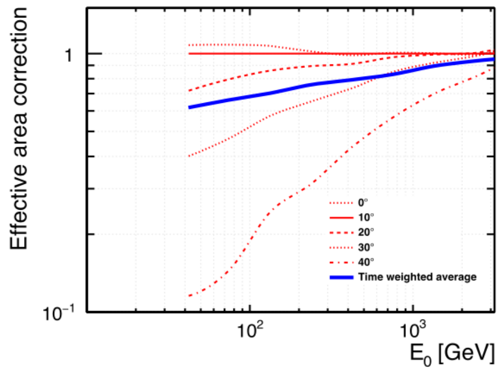
Sensitivity to steady sources



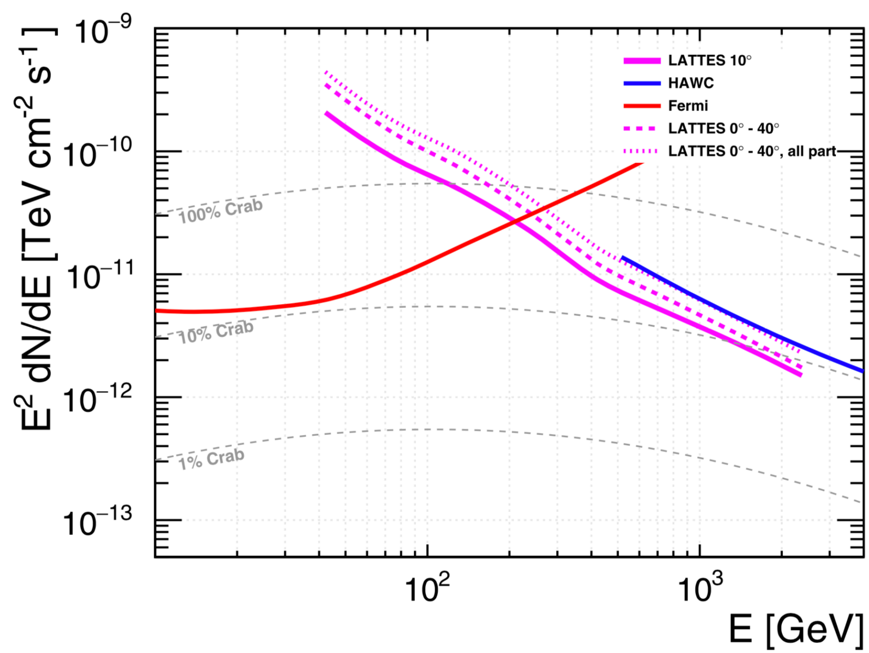
✧ *Full line*: full MC calculation for a source at 10 degrees in zenith

Sensitivity to steady sources





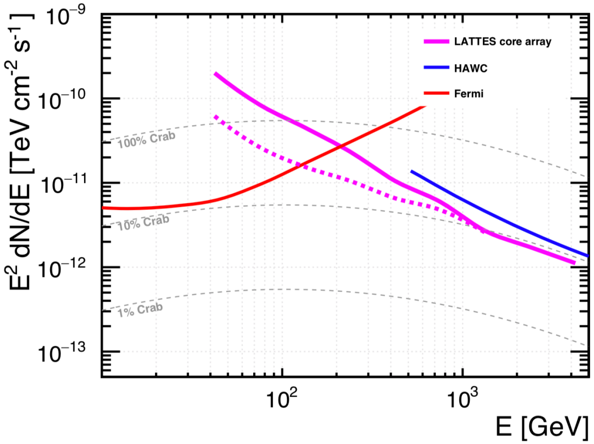
- *Dashed line*: Crab transit as seen by HAWC
  - Degradation of effective area with zenith angle estimated from electromagnetic energy at ground

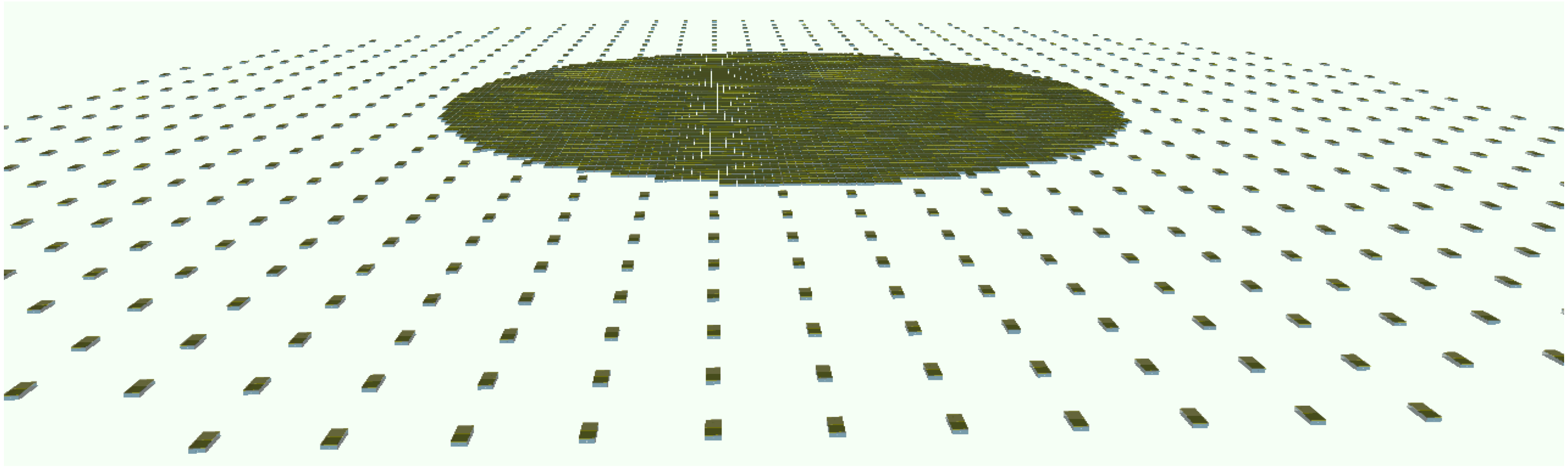


Sparse Array

- 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

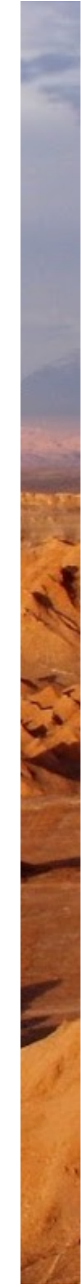




Summary

- LATTES shower reconstruction performance has been evaluated yielding very good results
  - Shower trigger (effective area)
  - Shower core reconstruction
  - Shower energy reconstruction
  - Shower geometry reconstruction
  - Gamma/hadron discrimination

- LATTES capabilities are far from being fully explored
  - Possible improvements already identified
    - Sparse array to veto far away high-energy showers (main background source)
    - Use RPC patterns to discriminate g/h
    - Better assess LATTES ability to reconstruct
      - Inclined showers
      - Heavier primaries induced showers
    - …



Acknowledgements

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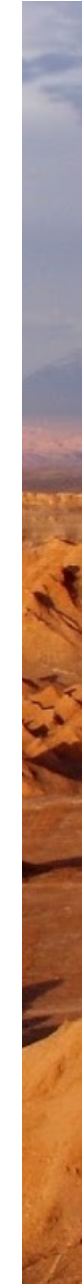
MINISTÉRIO DA EDUCAÇÃO E CIÊNCIA

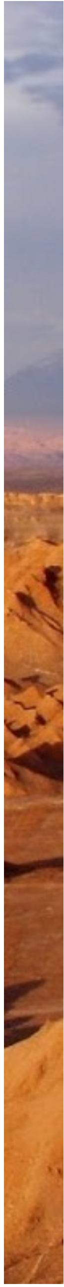
REPÚBLICA PORTUGUESA

LIP

TÉCNICO LISBOA

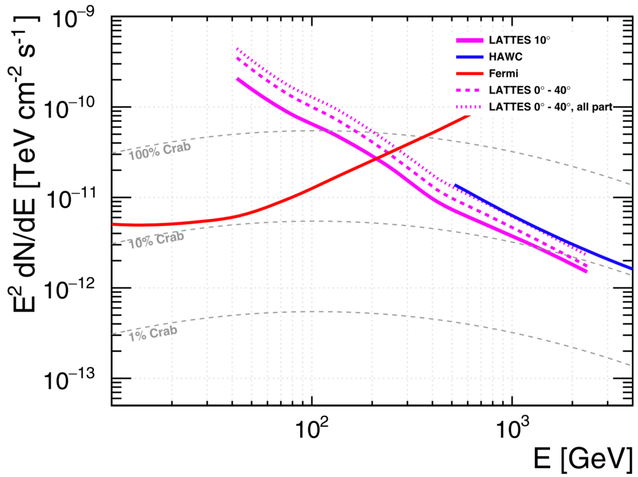


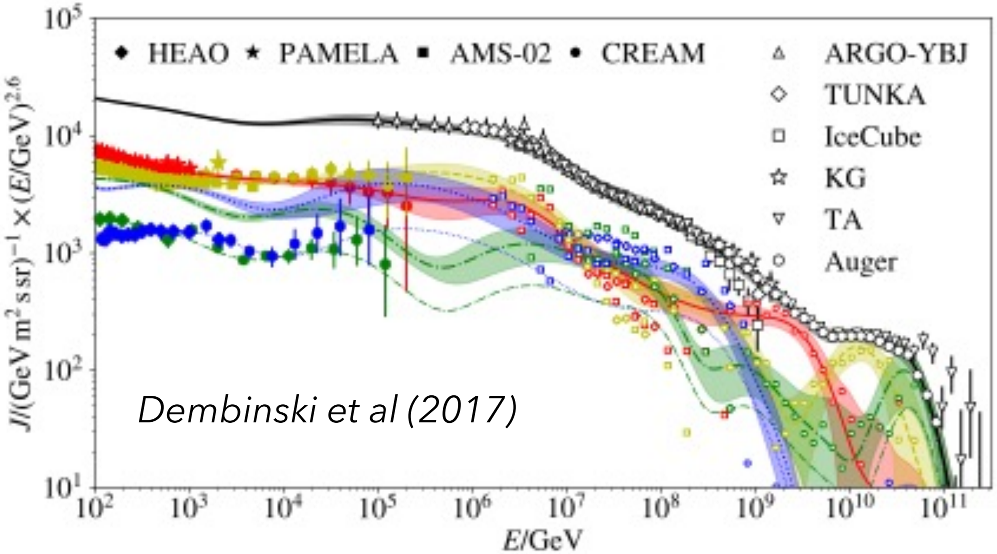
Backup slides



Sensitivity to steady sources

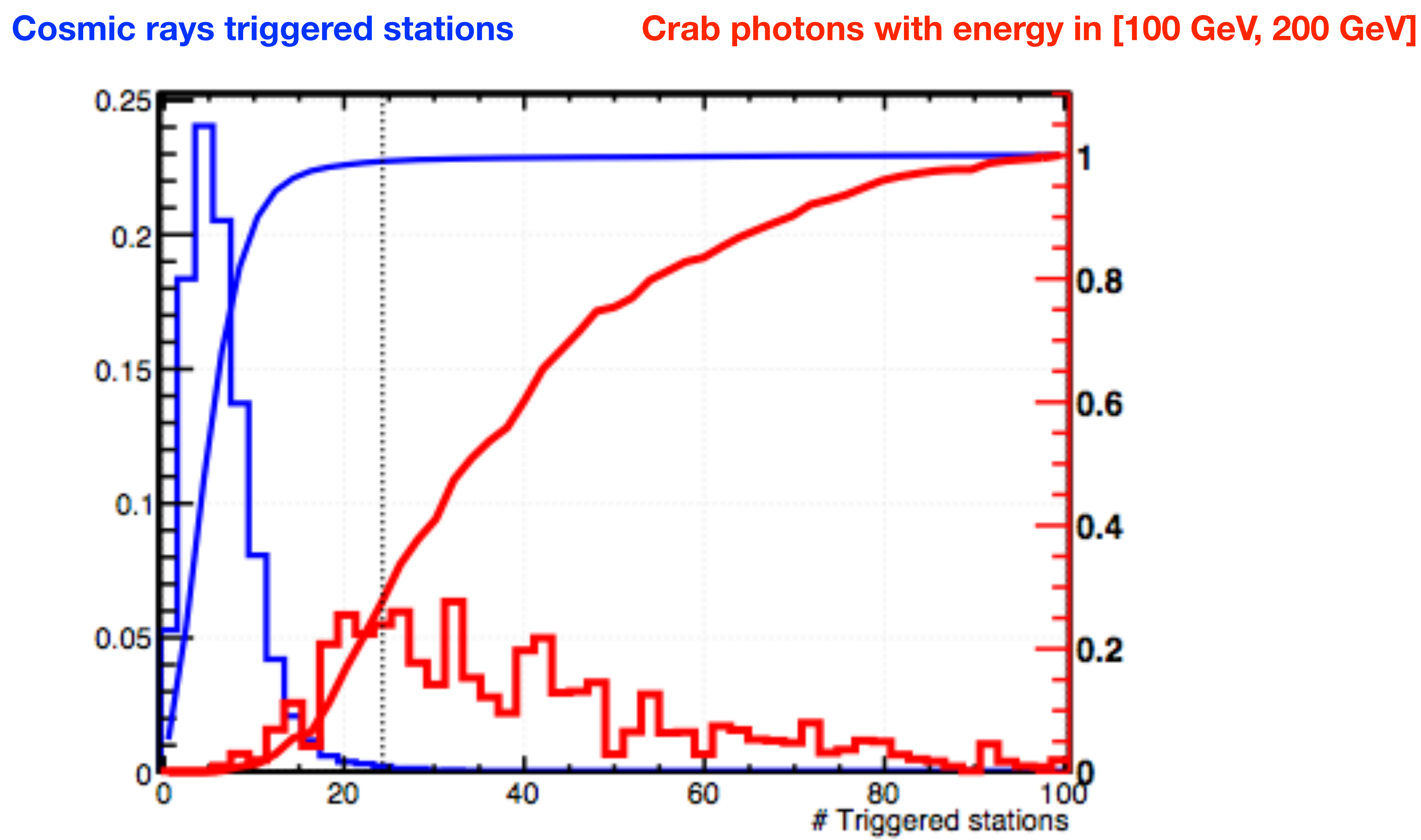
- *Dotted line:* CR all-spectrum
  - Additional elements (He, N, Fe…)
  - Assume that LATTES cannot distinguish gammas from irons





Dembinski et al (2017)

Cosmic rays trigger rate vs photon triggers



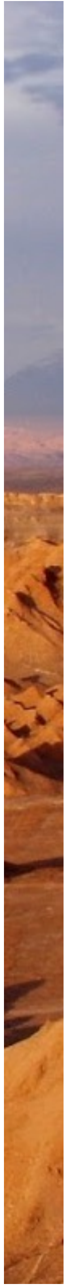
> 18 stations : 98% background rejection (440 kHz) ; 90% photon efficiency

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

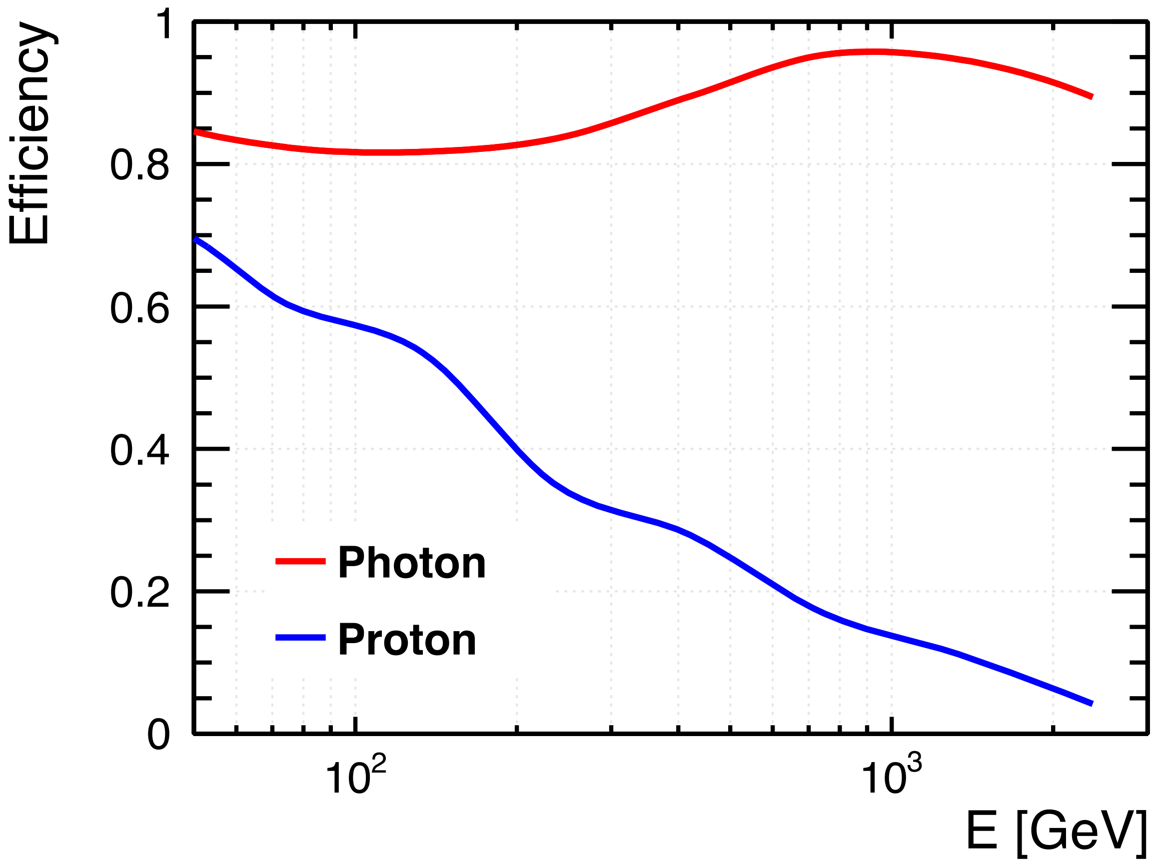
High-energy discrimination strategy

- 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

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



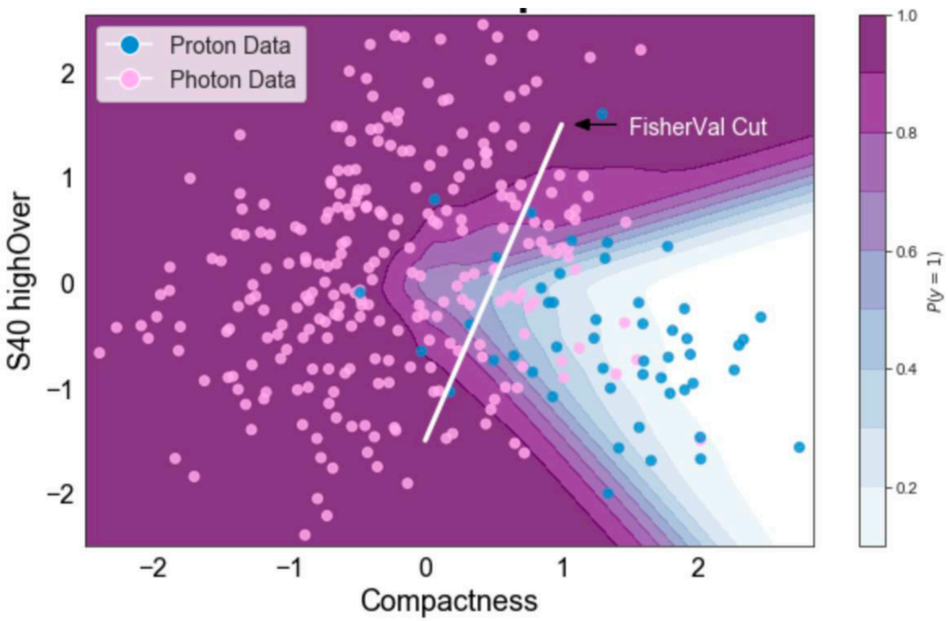
High-energy discrimination strategy



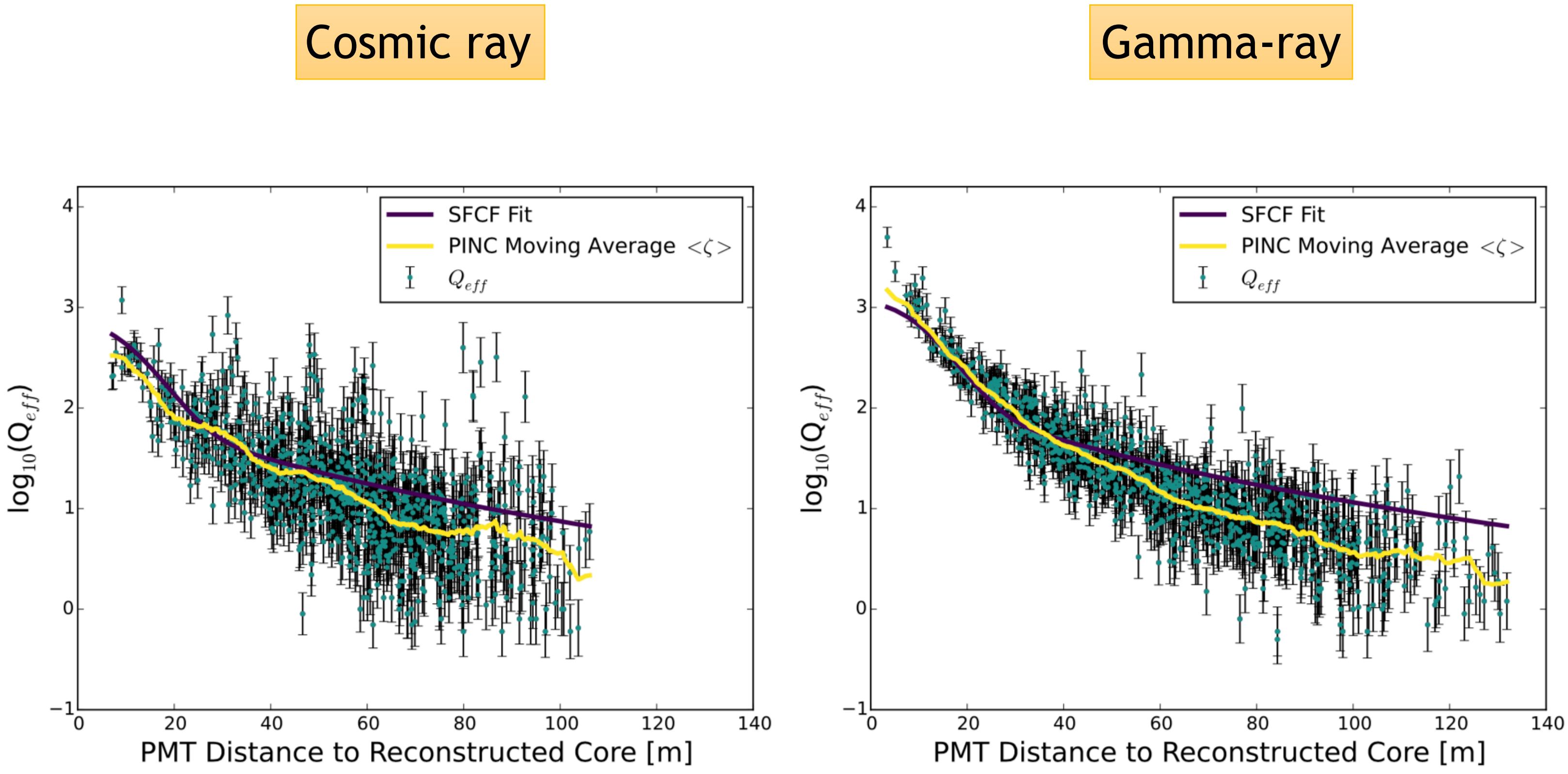
Shower compactness discrimination variable allows for a good background rejection which increases with energy

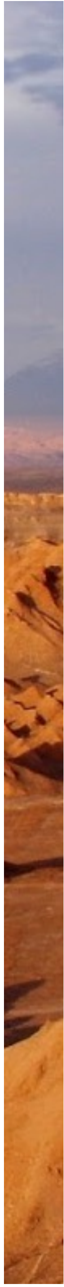
G/H discrimination and ANN

- 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

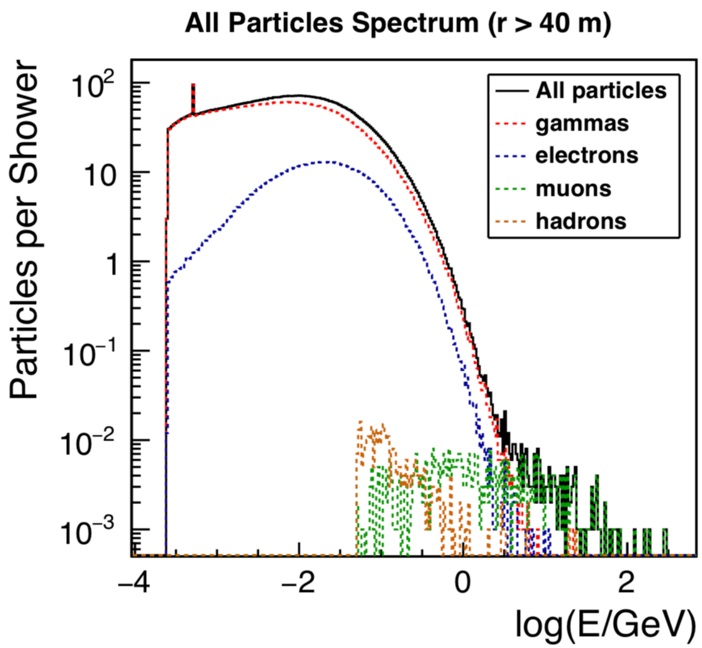




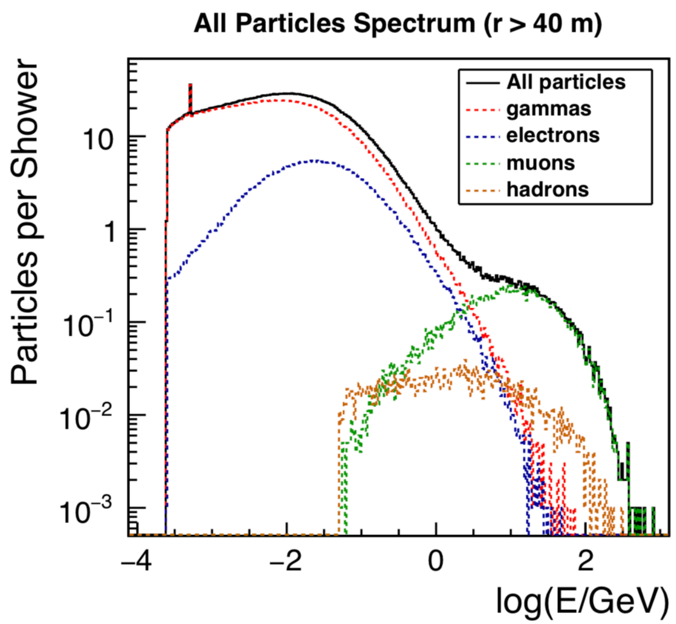
Shower calorimetric information

E=5 TeV

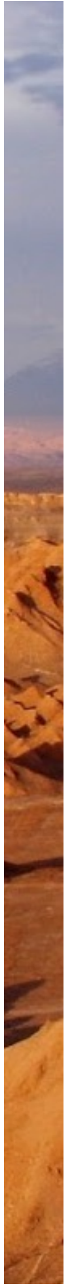
Gamma induced showers



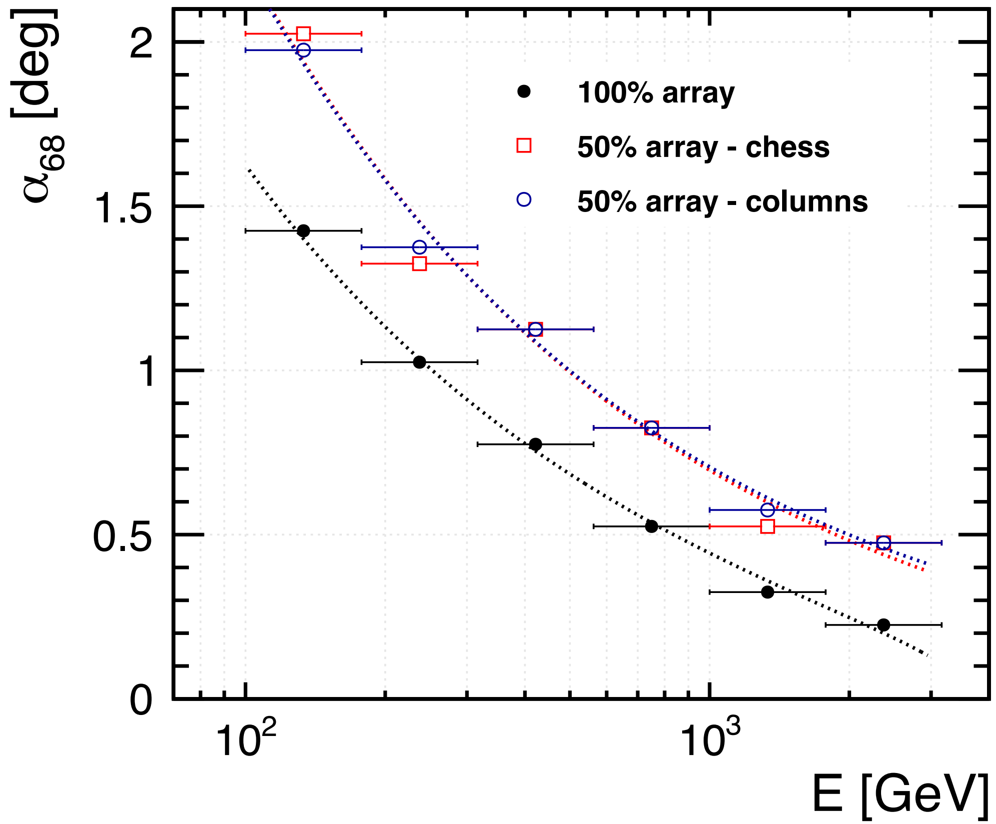
Proton induced showers

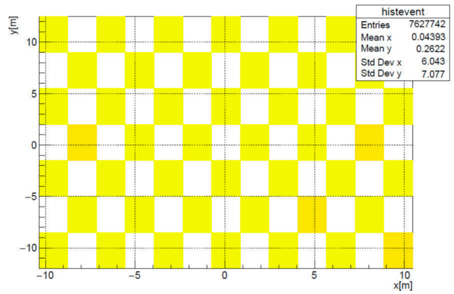


- High pT sub-shower carry large amounts of energy
- Look for energetic clusters far from the shower core (> 40 m)
  - Muons and high-energy photons/electrons



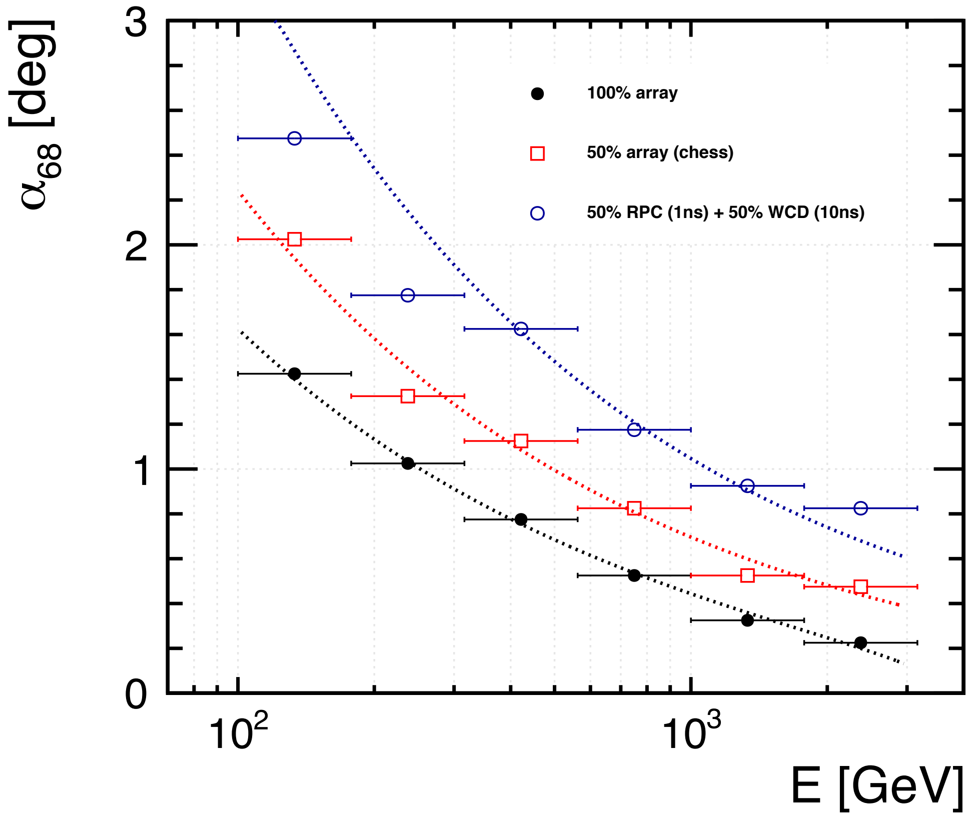
Geom Rec: array configuration





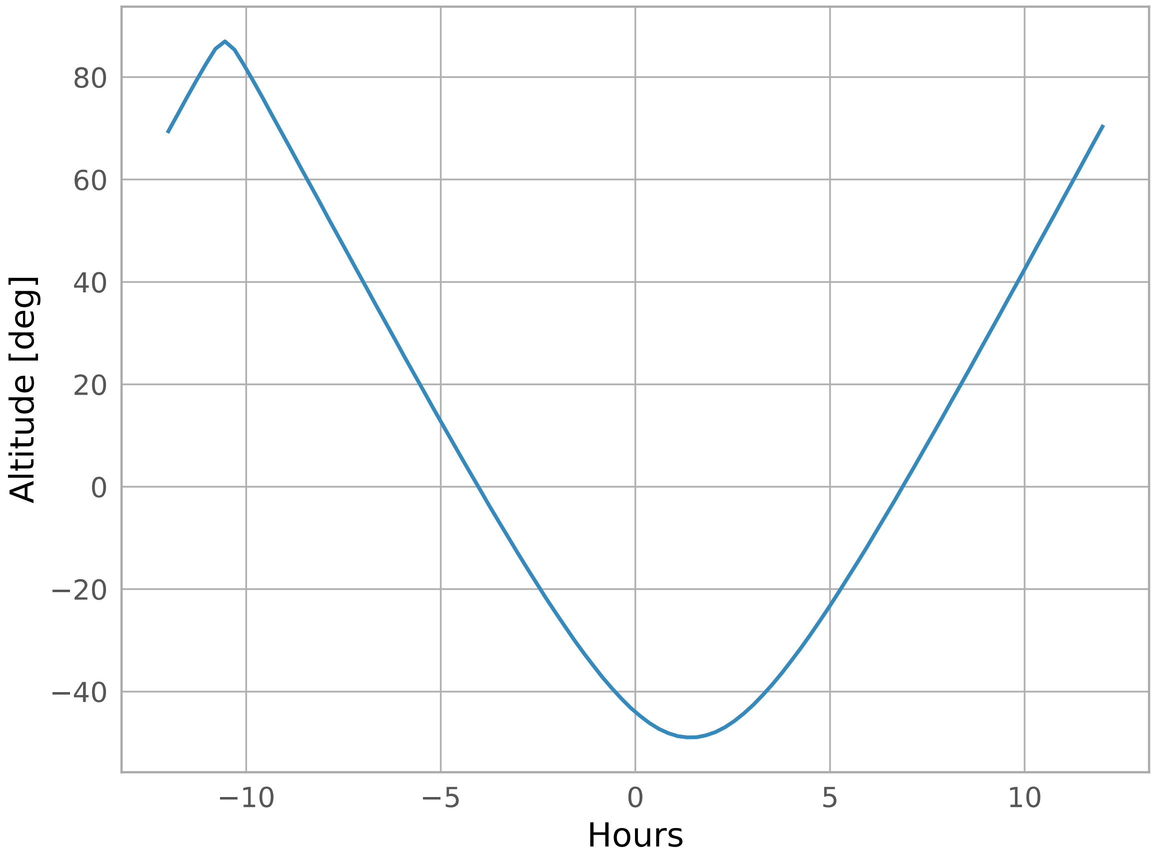
- It seems important to have RPCs on all stations

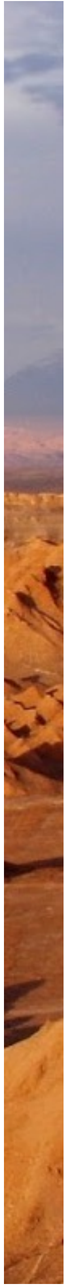
Geom Rec: RPC + WCD



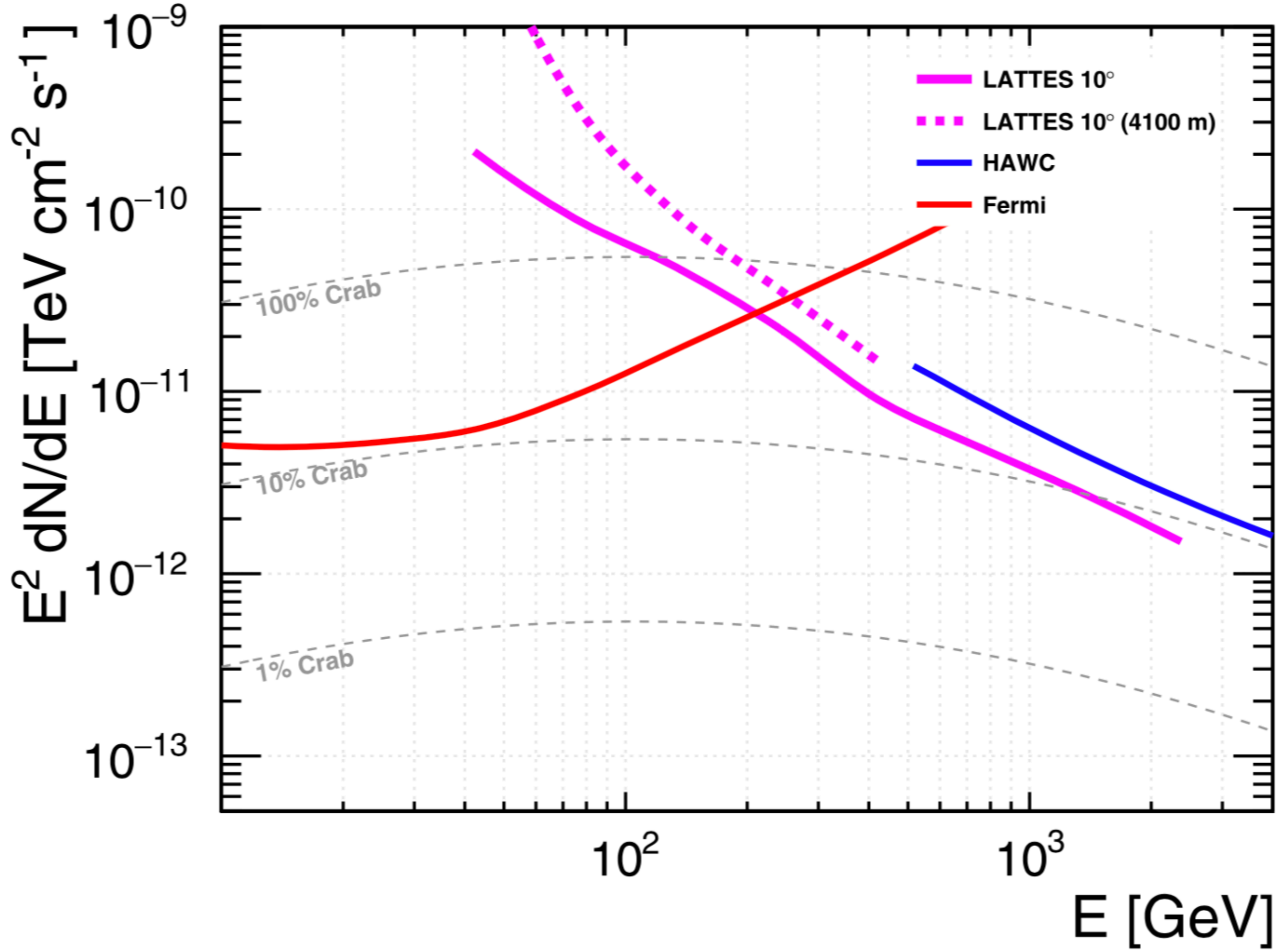
- ✧ Next steps: use only first hit in pad (trade-off between higher correlation with shower front and event statistics)

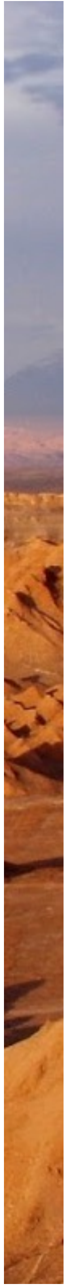
Crab





Impact of altitude

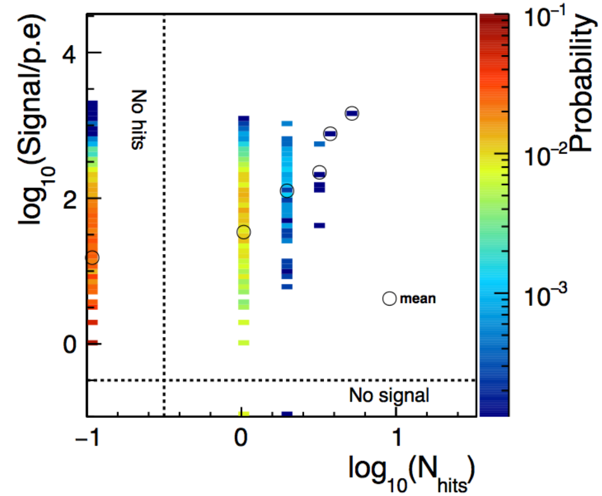


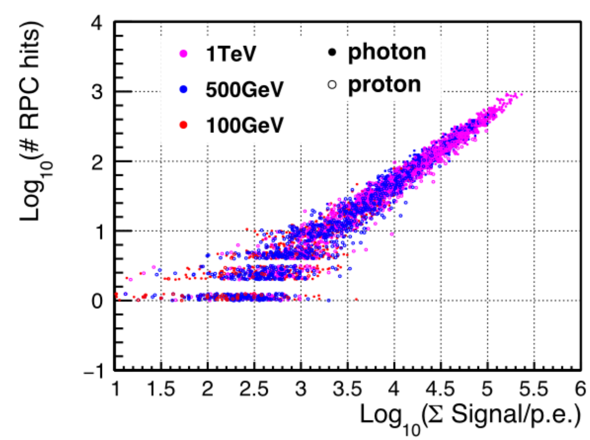


LATTES: a hybrid detector

- ✧ **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

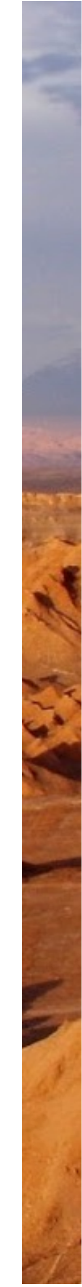
WCD vs RPC (station level)



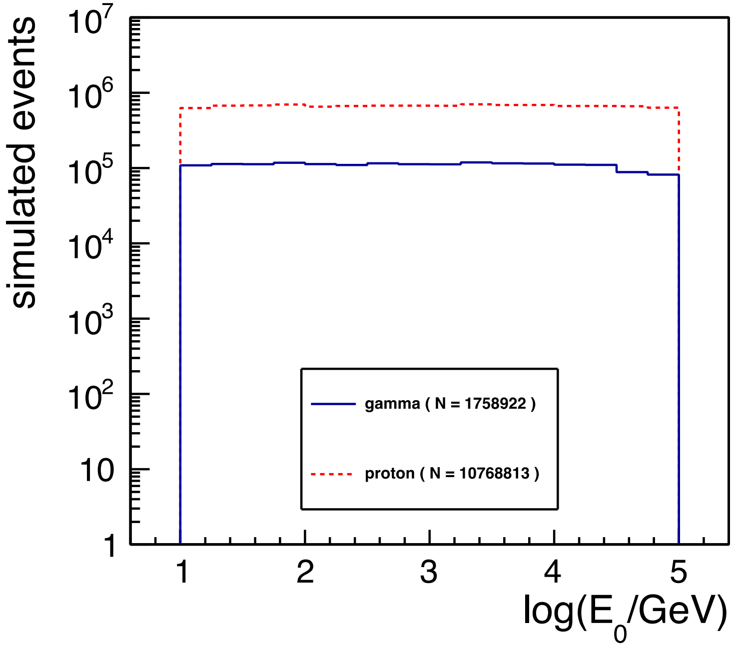


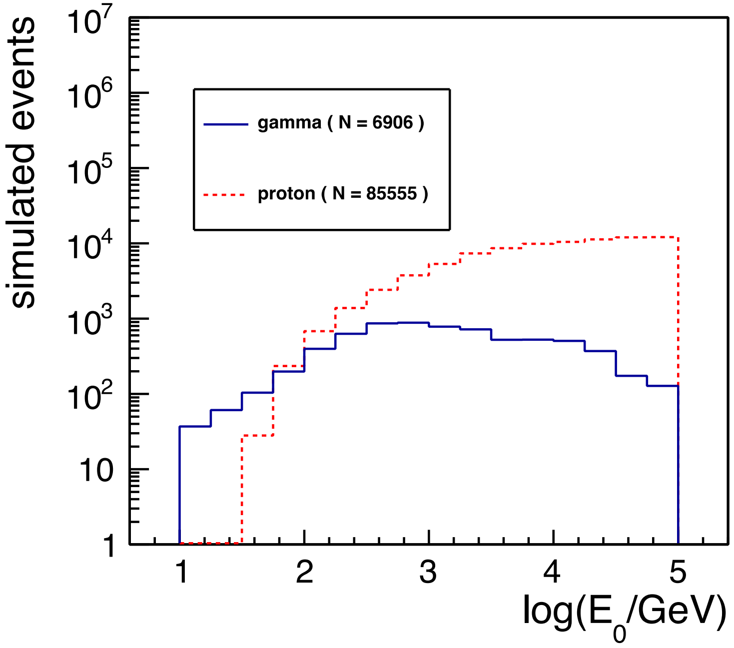
Complementarity

Inter-calibration



Reconstruction efficiency





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