Reconstruction of extensive air shower images of the Large Size Telescope prototype of CTA using a novel likelihood technique

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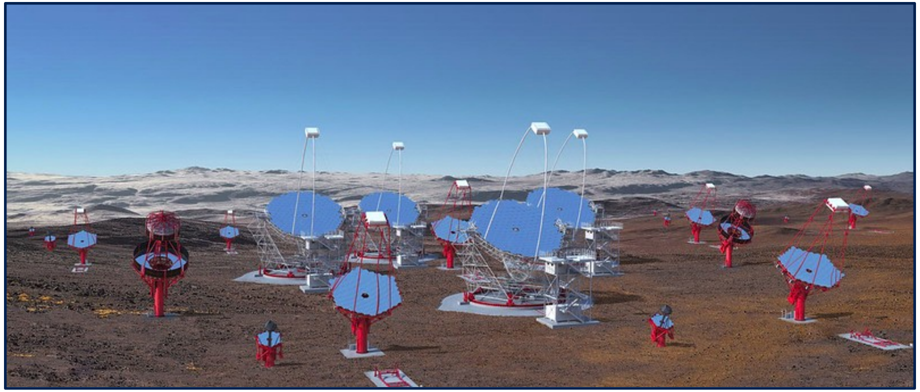
CTA and the Large Size Telescope prototype

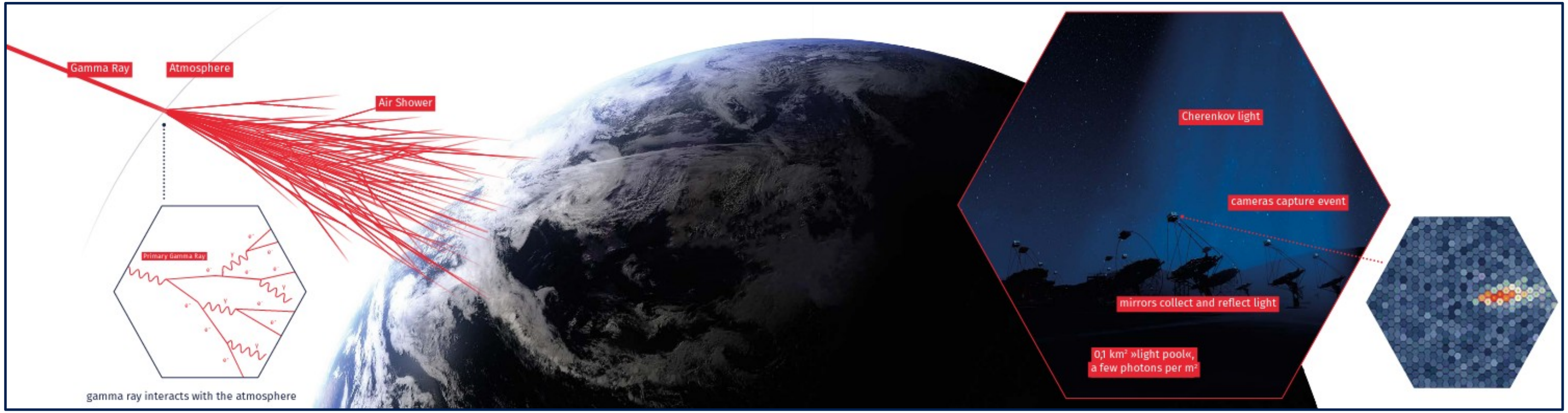
- CTA : Two arrays of IACTs
  - Combined energy range of all 3 telescopes sizes : tens of GeV → ~300 TeV
  - Large performance improvements
  - Near full sky coverage
- LST – 1 : First working CTA telescope

Large Size Telescope prototype
North site of CTA (La Palma)
credit : Daniel López / IAC

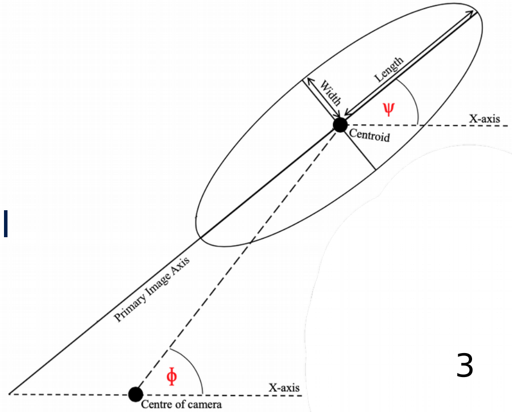


CTA south rendering
credit : Gabriel Pérez Diaz, IAC
Marc-André Besel, CTAO

Imaging Atmospheric Cherenkov Telescopes Observations and classical reconstruction



- IACTs collect the Cherenkov light from extensive air shower
  - Indirect information on the primary over a large effective area
  - Large background over gamma-ray signal of interest
- Standard reconstruction : Characterise the primary with a set of image parameters from the integrated charge and time of maximum per pixel
  - Hillas' parameters : Extraction of the image momenta
  - Temporal development : spatial gradient of the time of arrival of the signal

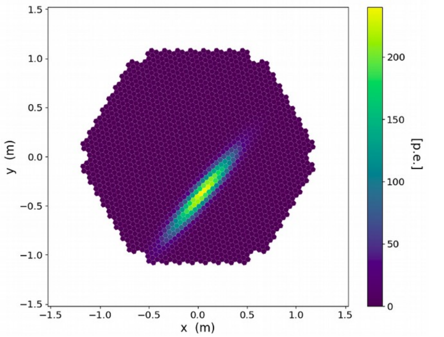


Spatio-temporal likelihood reconstruction

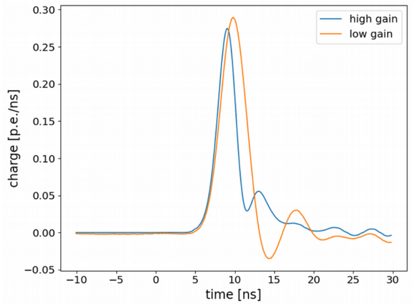
- Use the **full waveform** recorded by the CTA camera, combined with the knowledge of the instrument response and a space-time gamma image model
- Fit the model by likelihood maximisation to extract image or primary properties

$$\ln L = \sum_i^{pixels} \sum_j^{\text{times}} \ln\left(\sum_{k=0}^{+\infty} \frac{\mu_i^k}{k!} e^{-\mu_i} \times \frac{1}{\sqrt{2\pi}\sigma_{k_i}} \exp\left(- \frac{(\boldsymbol{W_{ij}} - k T_i (t_{ij} - \hat{t}_i))^2}{2\sigma_{k_i}^2} \right) \right)$$

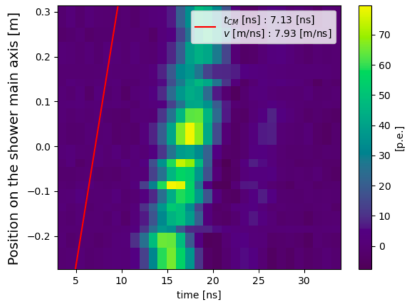
Symmetric 2D Gaussian
Model integrated charge μ_i



Pulse template
Temporal evolution of the response of a pixel T_i



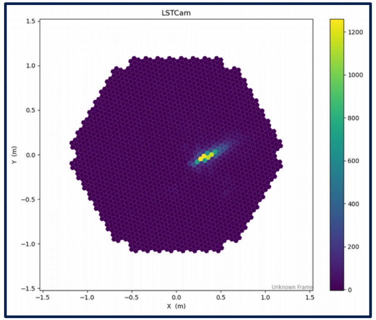
Linear temporal shift
Zero of the pulse of signal in each pixels $\hat{t}_i$



Reconstruction pipeline

- Model parameter fitted using
  - Calibrated waveforms as signal
  - Seeds derived from the standard reconstruction
- Physical primary properties from random forest
  - Not needed if the model gives them directly

Integrated charge image



Raw waveform
Signal strength [ADC]

Baseline substraction
Calibrations
Corrections

Calibrated waveform
Photo-electrons

Peak finding
Charge integration
Cleaning

Integrated charge and
time of maximum in selected pixels

Hillas parameters
Time gradient

Standard pipeline

Seed parameters

Spatio-temporal likelihood fit

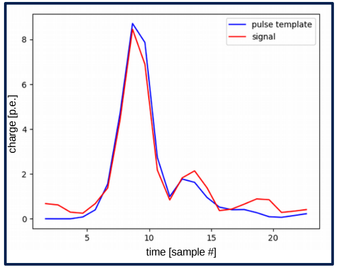
Fitted model parameters

Random forest

Energy regressor
Direction regressor
Gamma/hadron classifier

Primary particle

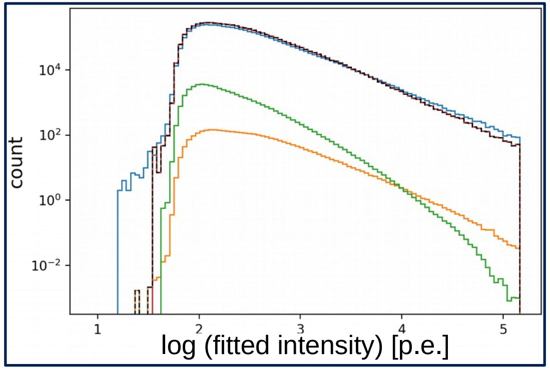
Energy
Direction
Gammaness

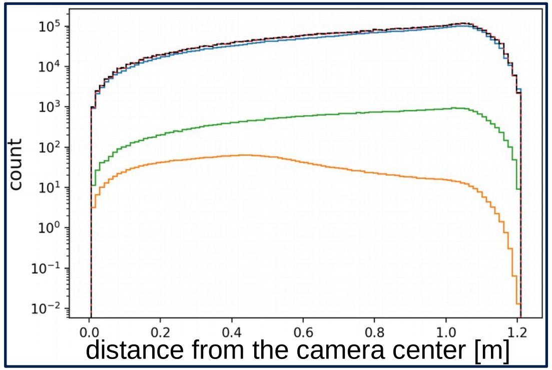


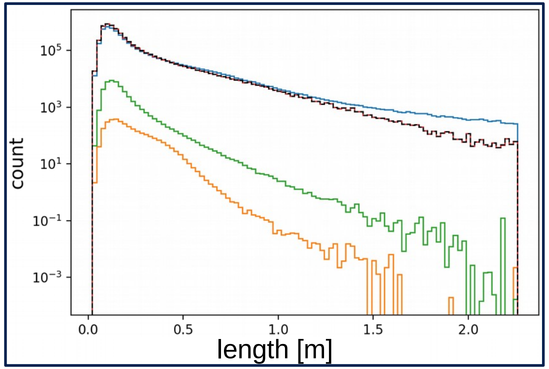
Calibrated waveform and fitted model for one pixel

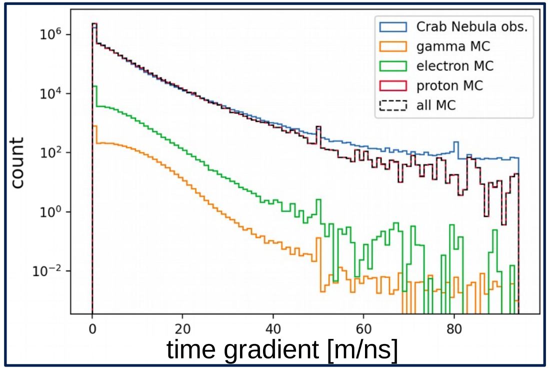
LST-1 data and Monte-Carlo simulation : Comparison of extracted features

- Distribution of features extracted using the likelihood method for MC and data from the LST-1 :
  - 20 minutes of Crab Nebula observation
  - MC gammas scaled to the spectrum from MAGIC (JhEAp 2015)
  - MC protons/electrons using spectra from the PDG scaling protons with the all hadrons spectrum
- A good agreement is found
  - With some divergences in the tails of some distributions
  - Fully dominated by protons





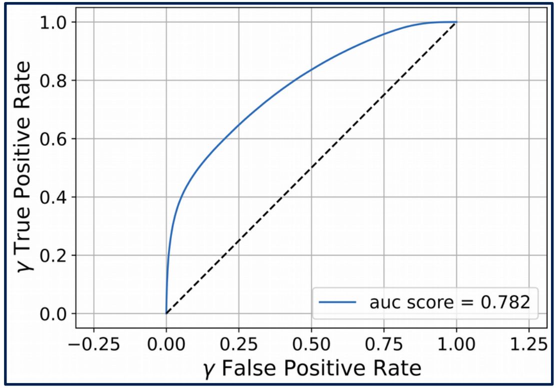




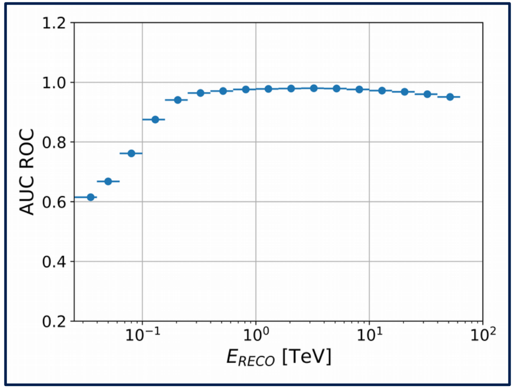
NB : Low intensity events cut out to remove star contamination

Performance from Monte-Carlo simulations
Source independent analysis

- Random forest trained on diffuse gammas and protons for the likelihood method
  - tested on point source gammas and diffuse protons
- Analysis performances evaluated on point source gammas and diffuse protons and electrons
  - Rejection of events with low intensity or high fraction of the signal at the edge of the camera optimised globally for best sensitivity
  - Gamma/hadron separation and angular size of the signal extraction region optimised for best sensitivity per energy bin



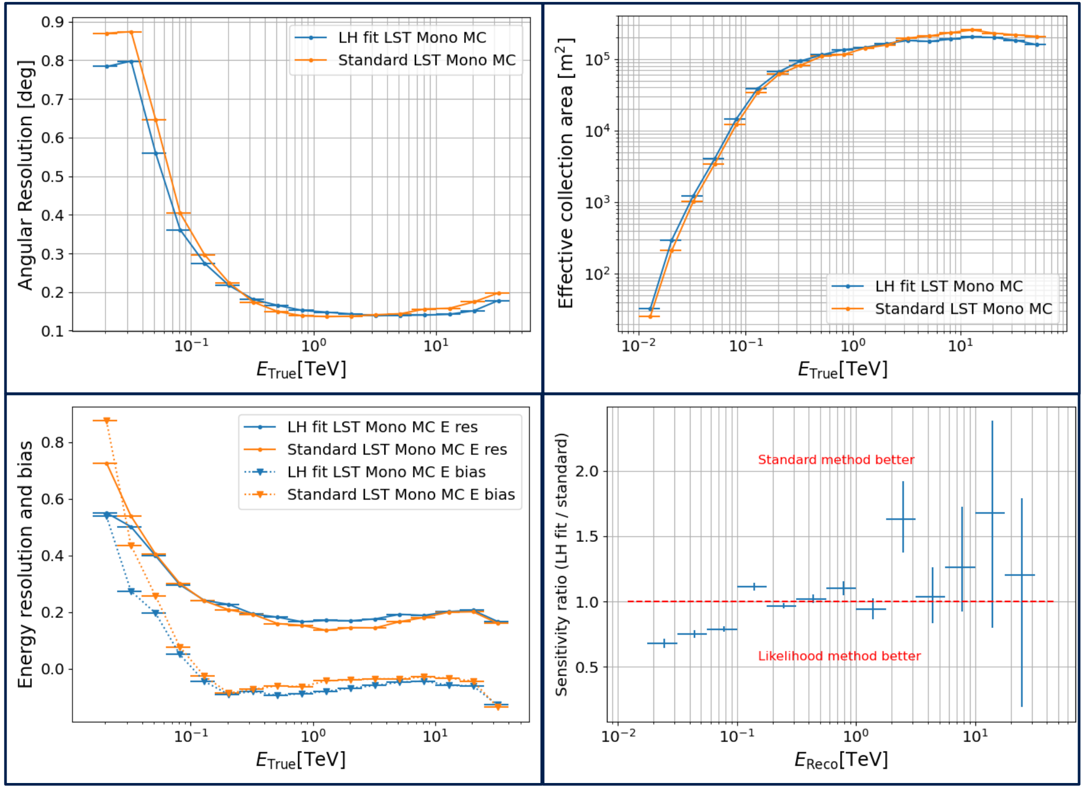
ROC curve



Area under curve (AUC) of the ROC curve versus energy

Analysis performance
Source independent analysis

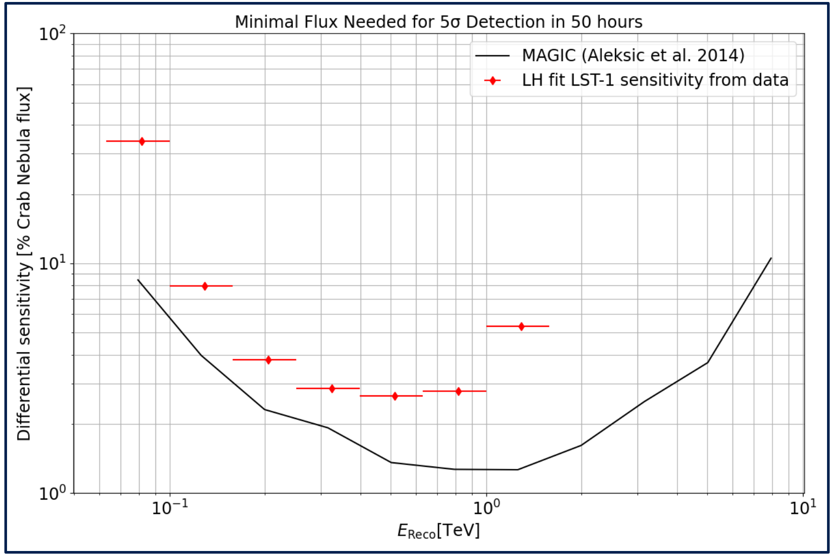
- Comparison with the standard reconstruction with the same analysis pipeline
- Improvement at low energy :
  - ~30% better sensitivity at 25 GeV
  - Energy resolution ~15% lower at 25 GeV
  - Angular resolution close to 0.1 degree lower at 25 GeV
- Similar between 100 GeV and 1 TeV
- Worse above 1 TeV?
  - Not clear



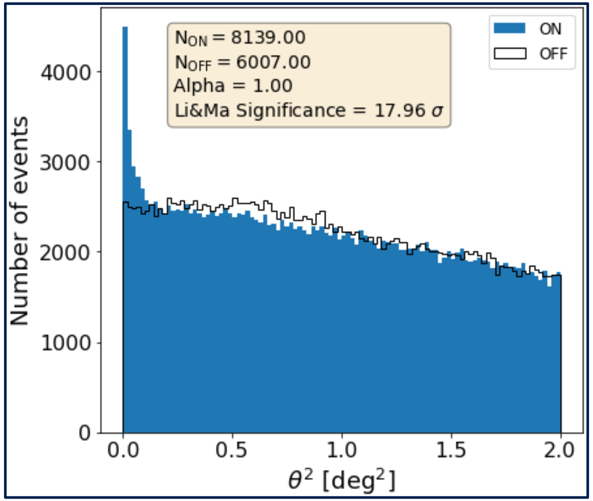
Performance from MC : comparison with the standard reconstruction

Crab Nebula analysis

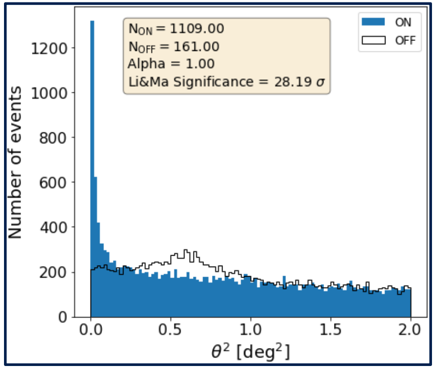
- Crab Nebula observed with LST-1
  - 118 minutes
  - Pointing between 10° and 27° from the zenith
  - Two wobble offsets of 0.4 degrees
- Signal extraction applying optimised cuts



Differential sensitivity from Crab Nebula observation



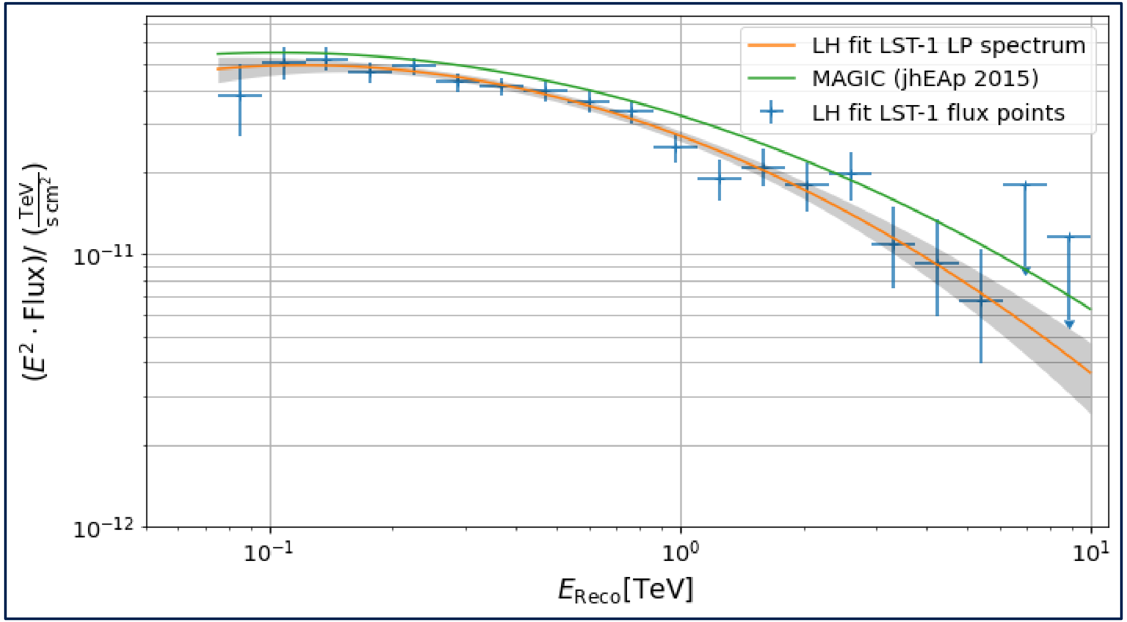
Signal distribution vs angular distance Θ
ON : source position
OFF : control regions
alpha^{-1} : #OFF regions
E_{reco} [50 GeV – 25 TeV]



Energy range with better gamma/hadron separation
E_{reco} [200 GeV - 2 TeV]

Crab Nebula analysis

- Spectral analysis using fixed cuts
- A log-parabola is fitted and compared to the spectrum measured by MAGIC



Log-parabola spectrum

Conclusion

- A reconstruction method for IACT images exploiting the time resolved images from the CTA telescopes cameras is introduced.
- Implemented in the analysis pipeline for the LST prototype
- First performance evaluated on simulations and application to observations were shown. Performance on MC indicates an improvement compared to the standard pipeline in the lower energies.
- Considered future improvements:
  - More realistic model : spatial asymmetries, dispersion of photon arrival time, multiple p.e. pulse shape, ...
  - Further improved treatment of the detector calibration
  - Adjustments to the RF feature set
  - Model using the primary properties as parameters