Results of a new reconstruction likelihood method

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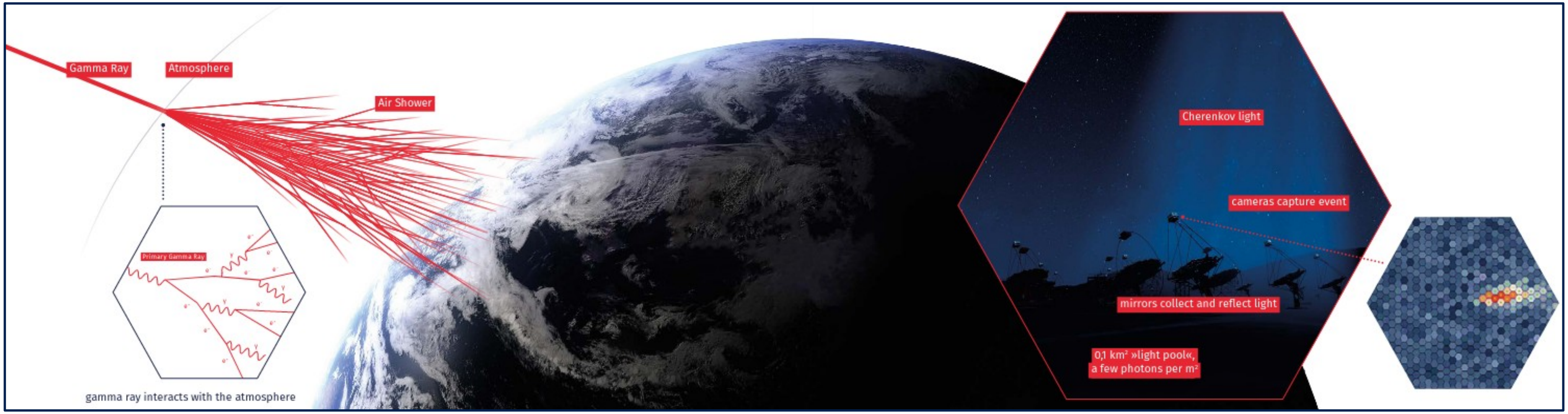
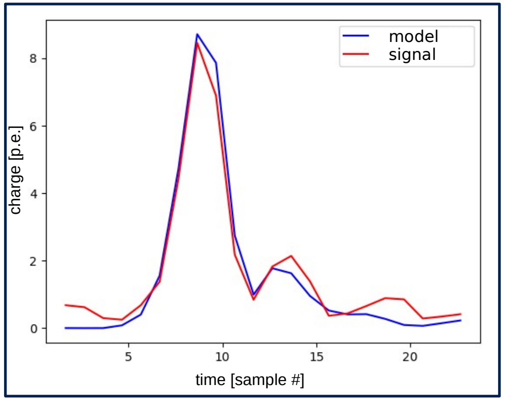
CTA Swiss day 2022

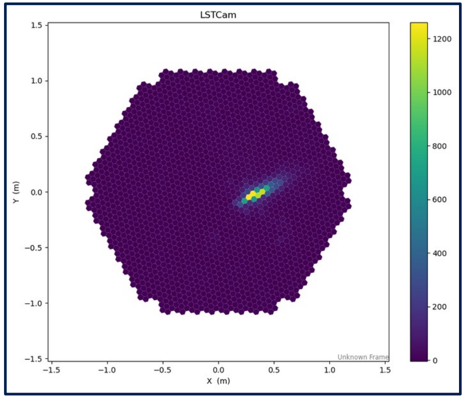
Imaging Atmospheric Cherenkov Telescopes
Observations and classical reconstruction



- 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
- Signal : photons reaching the camera pixels
  - Photo-multiplier tubes (in LST-1) → convert a photon to a cascade of electrons
  - Electronics measure these electrons

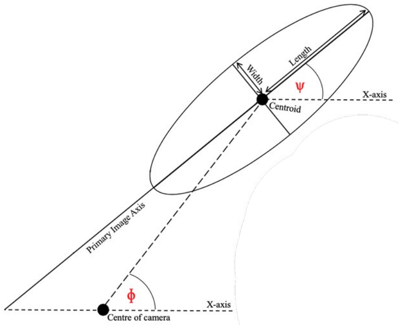
LH fit Reconstruction pipeline

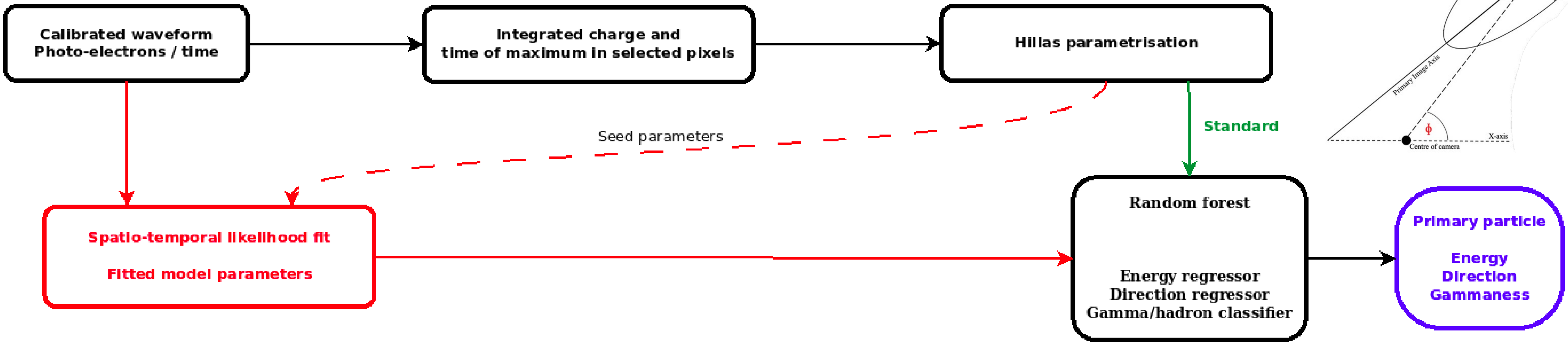




LH fit
Standard

- Inputs to the fit:
  - Calibrated waveforms as signal
  - Seeds derived from the standard reconstruction + some modifications
- Physical primary properties obtained with random forest





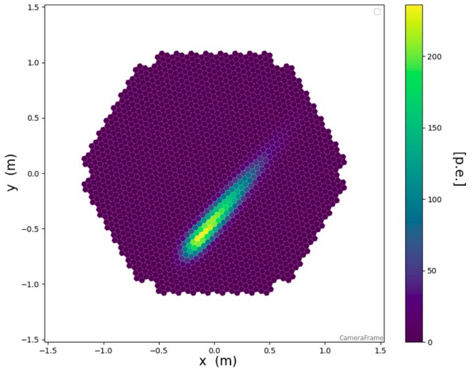
Spatio-temporal likelihood reconstruction

- Use the **full waveform** recorded by the CTA camera, combined with the knowledge of the instrument response and a space-time EAS image development model
- Fit the model by likelihood maximisation

$$\ln L = \sum_i^{pixels} \sum_j^{times} \ln\left(\sum_{k=0}^{+\infty} Poisson(k|\mu_i) \times Gaussian(\mathbf{W_{ij}}|k, T_i, \hat{t}_i)\right)$$

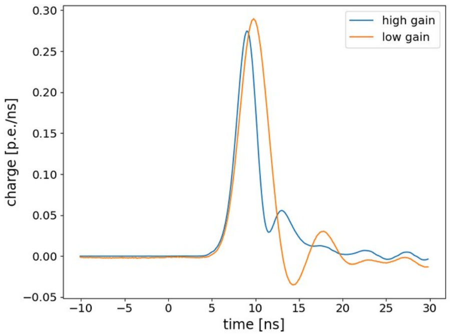
Asymmetric 2D Gaussian

Model for integrated charge μ_i



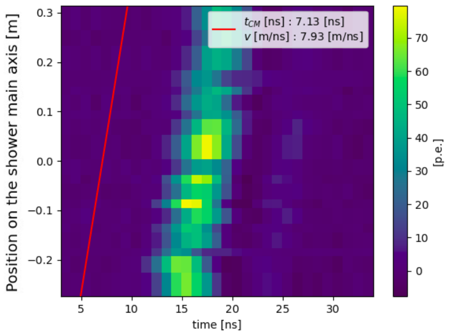
Pulse template

Temporal evolution of the response of a pixel T_i



Linear temporal shift

Zero of the pulse of signal in each pixel $\hat{t}_i$

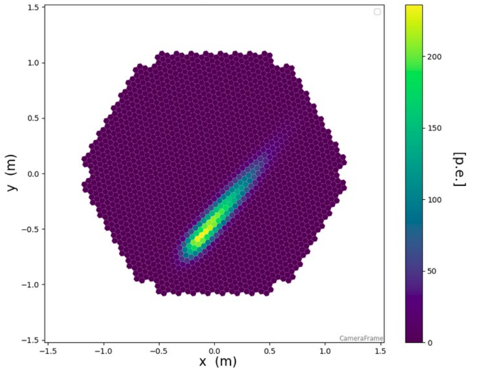


Spatio-temporal likelihood reconstruction

- Approximations :
  - Finite sum over relevant Poisson terms at low signal
  - Gaussian approximation at high signal
  - Common pulse template for all pixels
  - No temporal widening of the pulse

Asymmetric 2D Gaussian

Model for integrated charge μ_i



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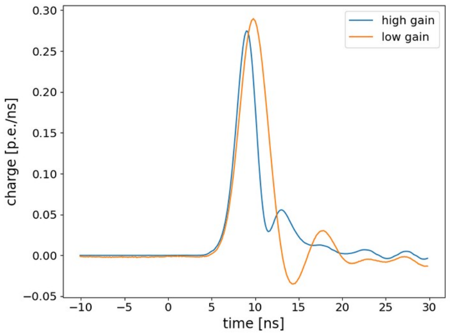

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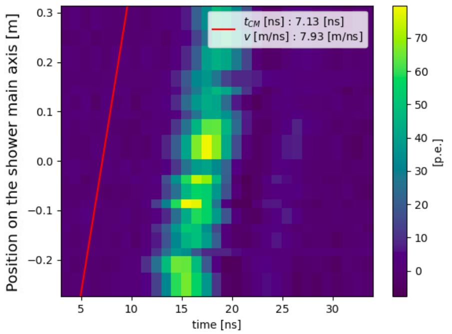
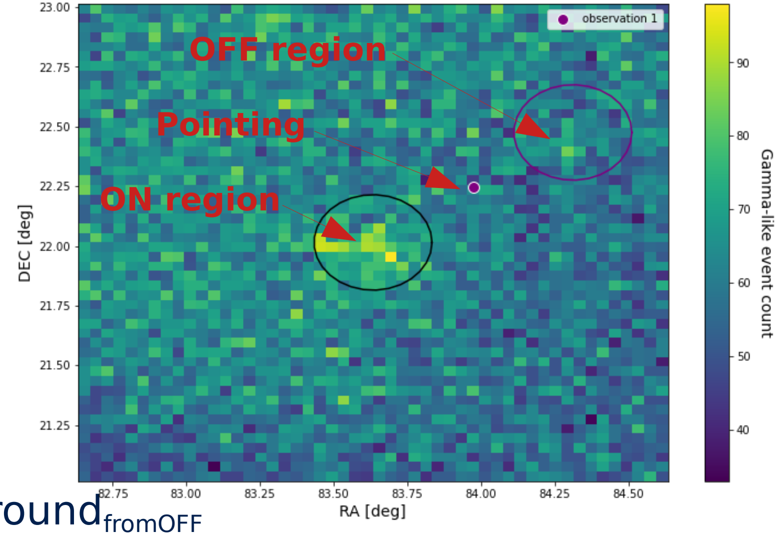


ON-OFF analysis

Case of the reflected background region in wobble mode observations

IACT : Large background contamination

- Identify signal (gamma-rays) from background (hadrons, electrons) → gammaness
  - imperfect → contamination remains
- Estimate remaining contamination : **ON/OFF**
  - ON region
    - source position
    - **signal** and **background**
  - OFF regions
    - **only background**
  - Excess : $(\text{signal}_{ON} + \text{background}_{ON}) - \text{estimated\_background}_{fromOFF}$



- **Wobble** mode : pointing with offset from the source at alternating positions
- **reflected background** : OFF regions = rotation of the ON region around the pointing direction

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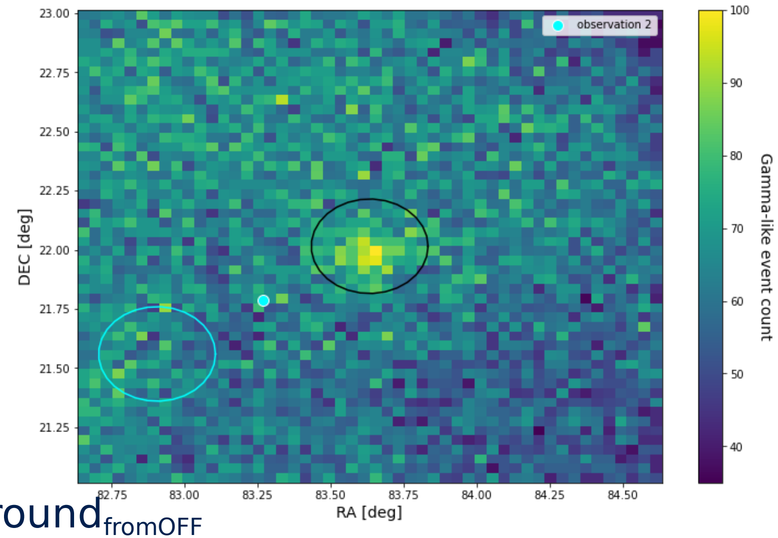

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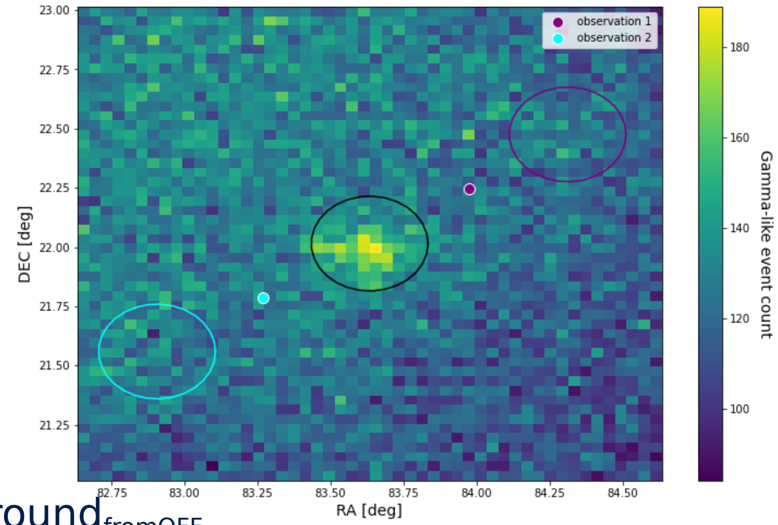

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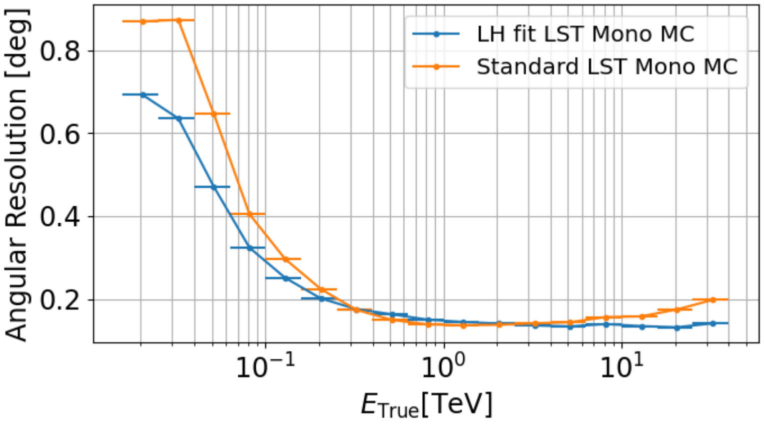
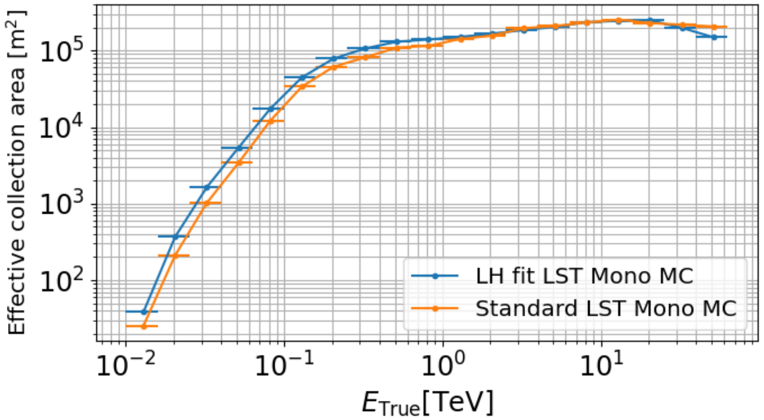
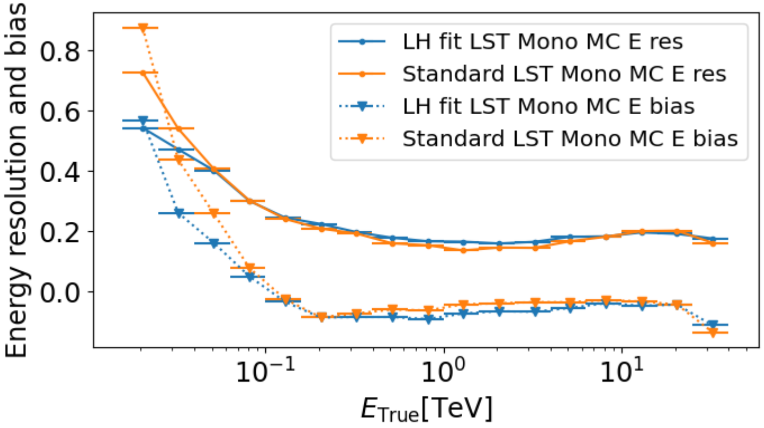
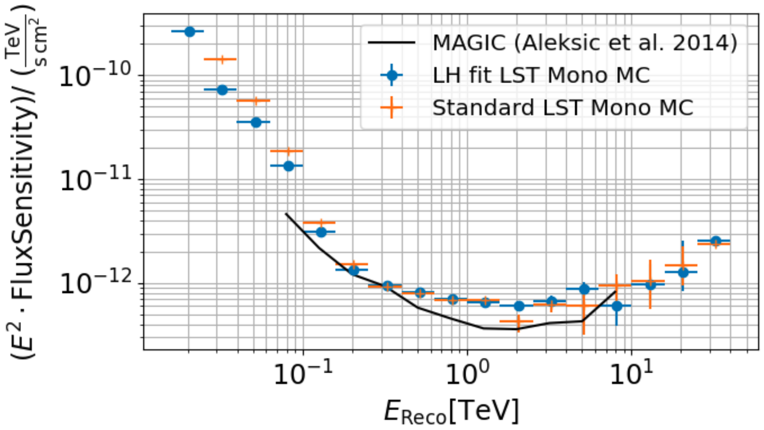
Performance assessment on simulated Crab-like source
Source independent analysis in wobble mode

- Standard : Hillas-based reconstruction
- Sensitivity : CTA criteria
- Event selection :
  - Not too faint
  - Most signal in the camera
  - Energy dependent maximum direction deviation and minimum photon identifying variable value
- **Improvements at low energy** using the likelihood reconstruction





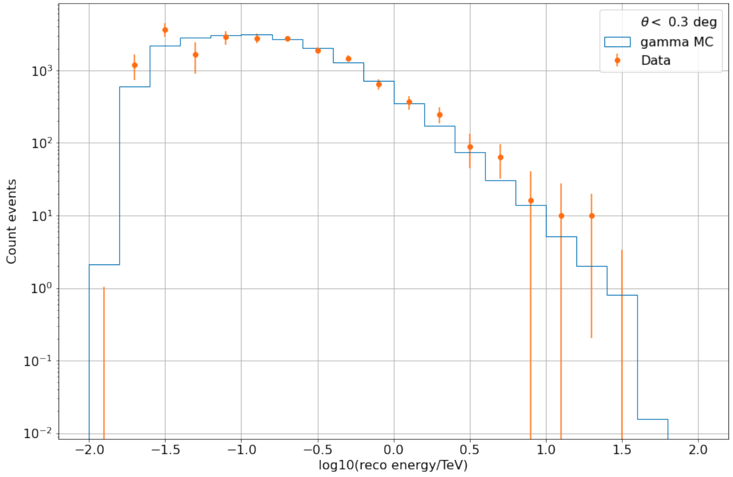


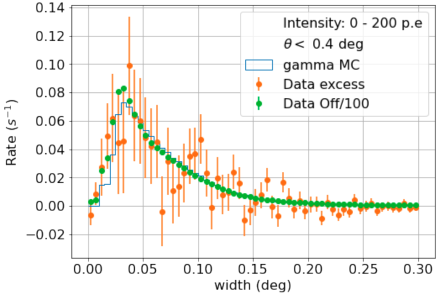


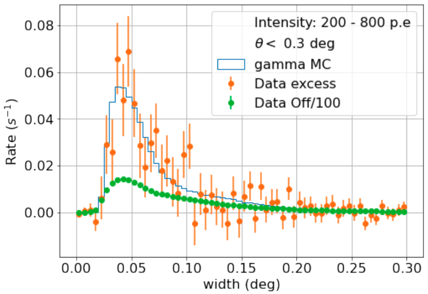
Data / MC simulation comparison

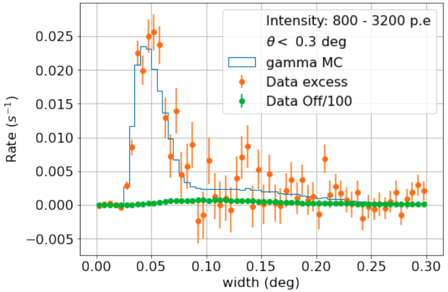
Crab nebula 20th November 2020

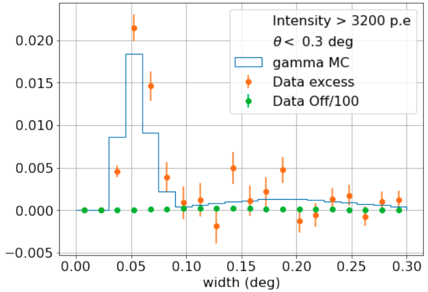
- 3.5 hours of observation
- Bright, constant source with known spectrum
- Agreement for signal of fitted quantities (e.g. width, length, time_gradient) and primary quantities (here energy) distribution is good at all image intensities
  - Some bias are seen at high intensity

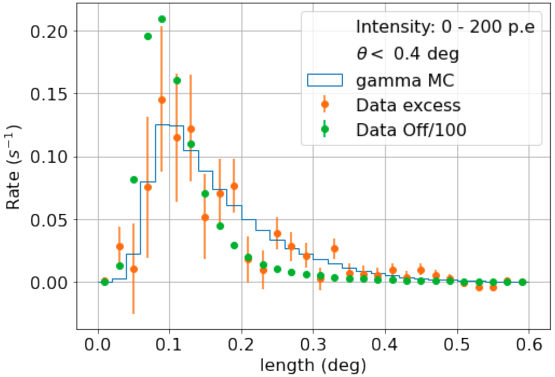


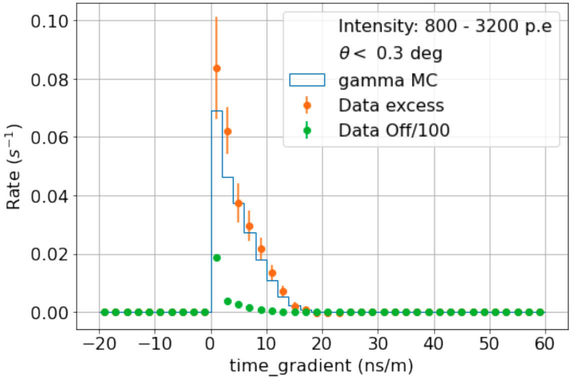












Application to LST-1 observations

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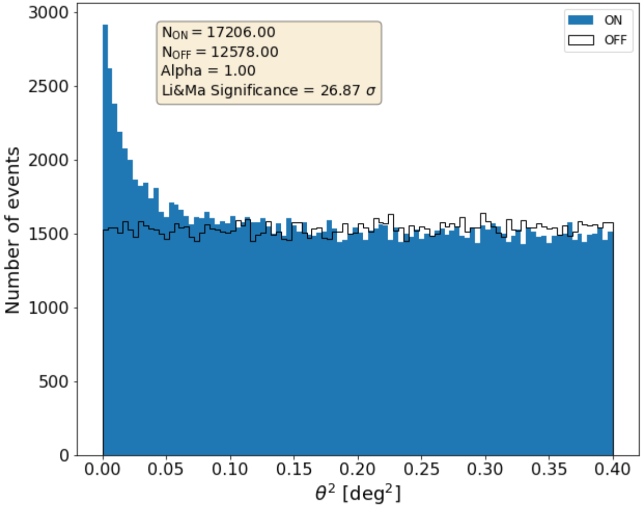
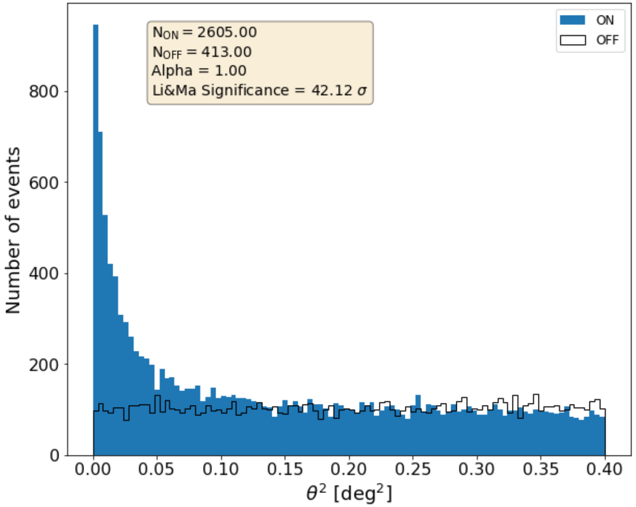
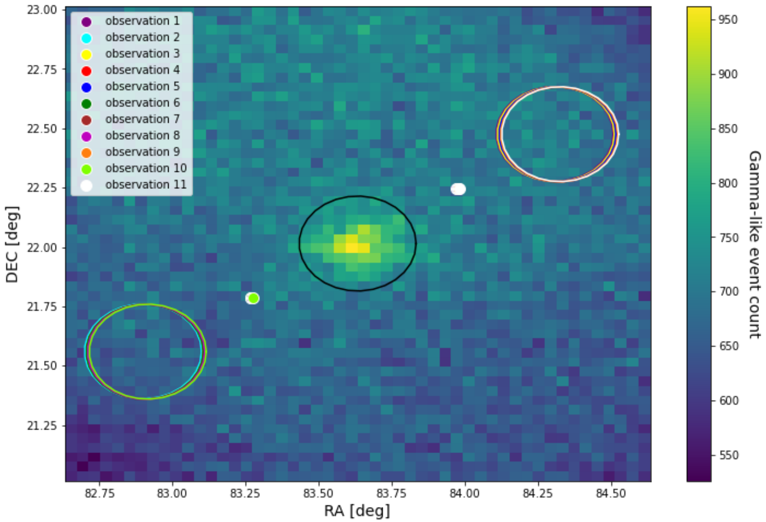


E_{Reco} 0.05-25 TeV



E_{Reco} 0.2-25 TeV

Cumulative sky map of gamma-like events (γ-ness>0.7)

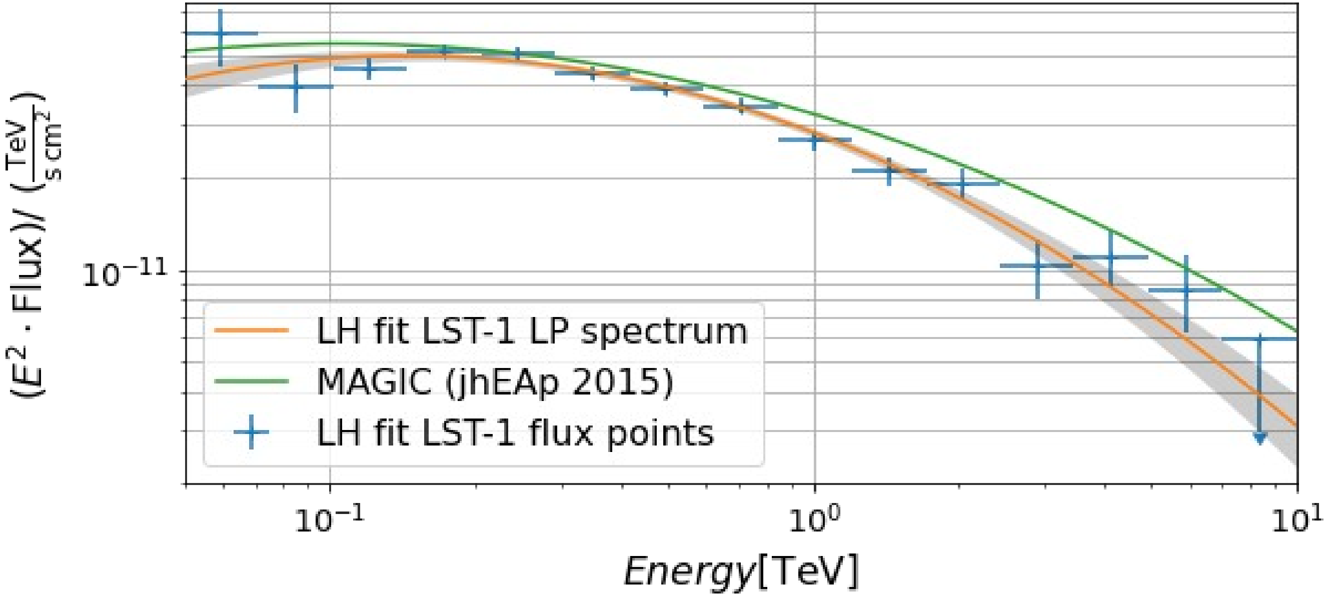


← θ^2 obtained applying energy dependent γ-ness cuts optimised on MC

Application to LST-1 observations

Crab nebula 20th November 2020

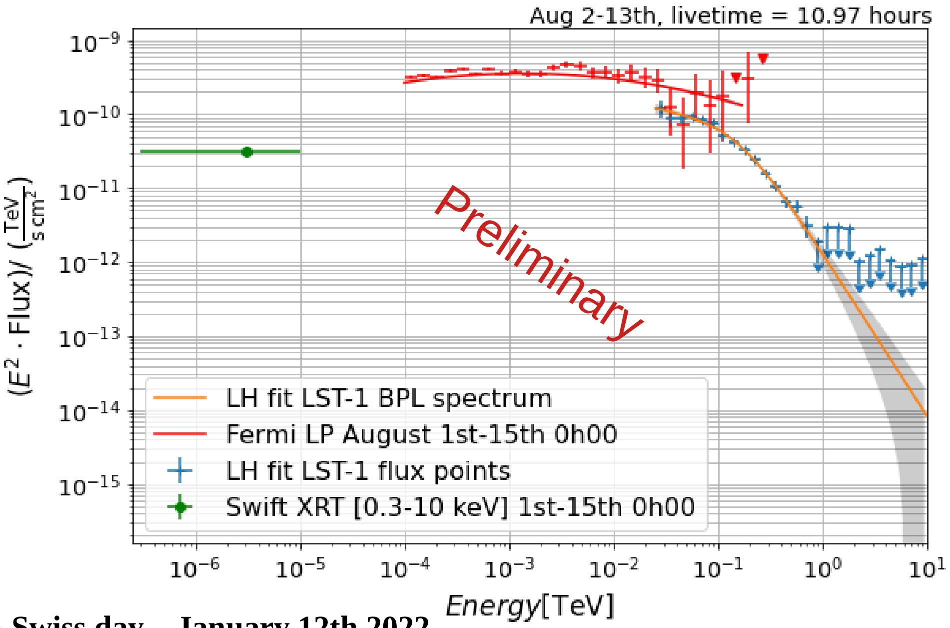
- Spectral agreement is quite good (fit between 50 GeV and 10 TeV) but not perfect. 50 GeV used here since it is the threshold for the MAGIC spectrum.

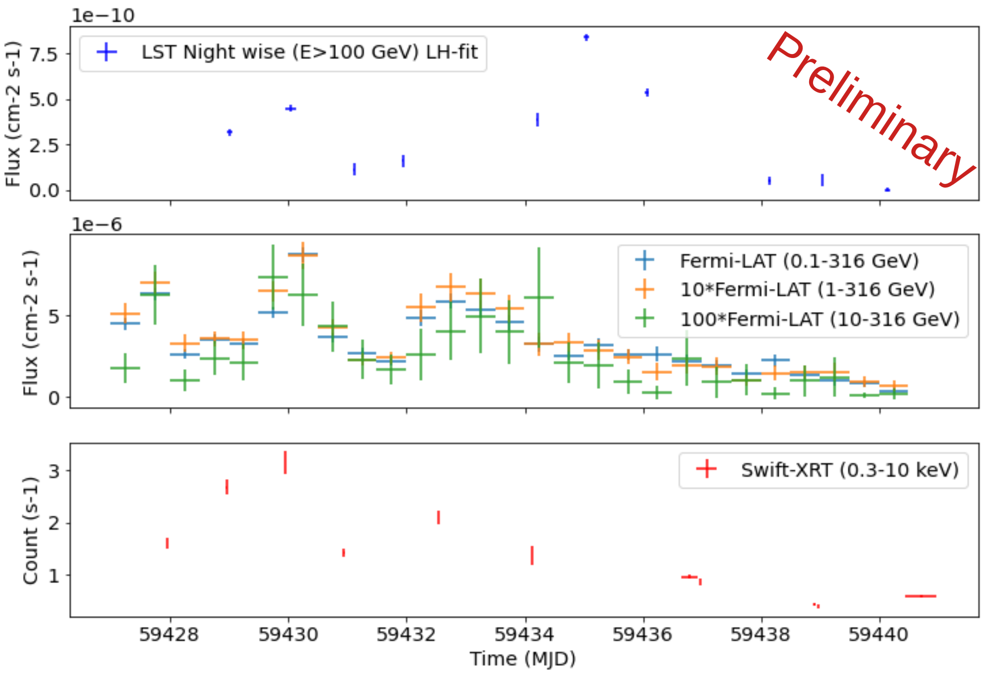


← Spectrum obtained applying uniform event selection : γ-ness>0.7 and θ < 0.2 + other selections

BL Lacertae flare observation

- Blazar of the BL lac type object category
  - redshift 0.069
- Not detected by IACTs in low/quiescent state
- Variable
- **August 2nd to 13th** : 41 observations, 10.97 hours
- **Multi-wavelength data** – non simultaneous





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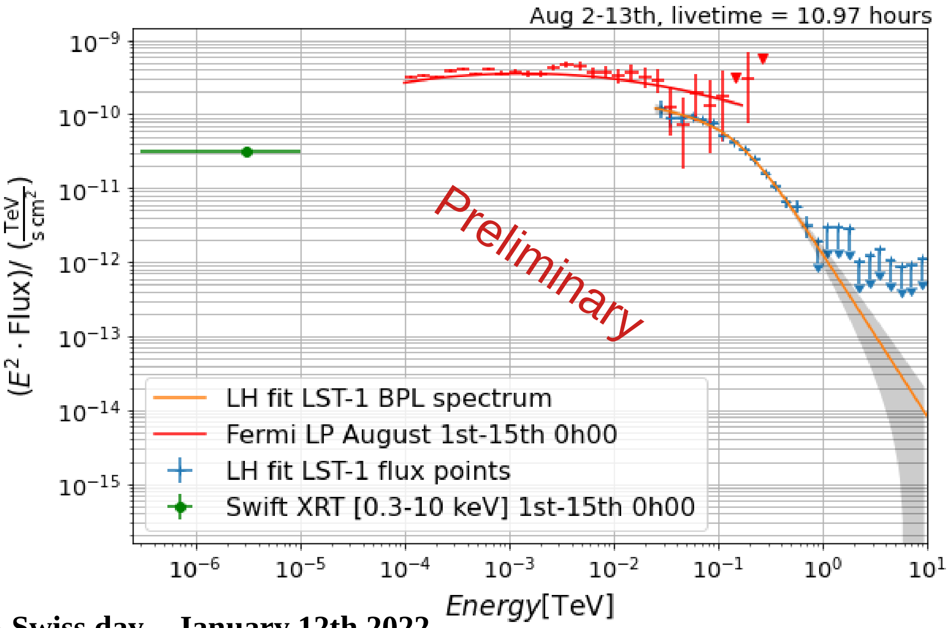

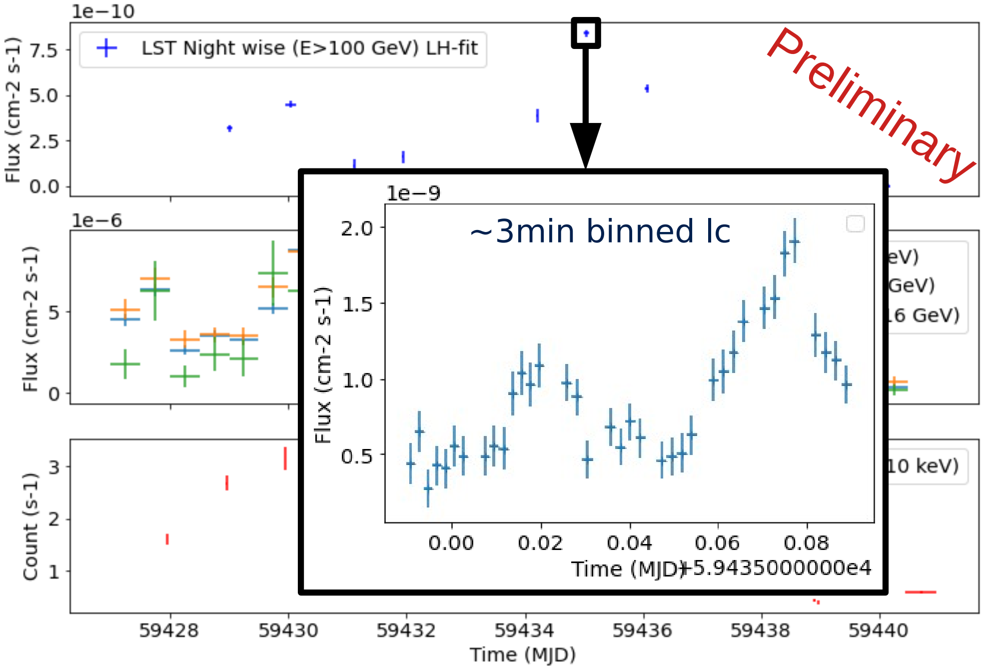

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Conclusion

- The likelihood reconstruction method using the full waveform development of the signal in the camera, shows improved performance compared to the standard Hillas reconstruction. Especially at low energy.
- Realistic results on **Crab nebula** data
  - Spectral agreement should improve with LH-fit independent developments to the subsequent analysis steps
- Interesting variability episode of **BL lacertae** analysed
- Implemented in the analysis pipeline for the LST prototype
- Work is ongoing to improve the code and model
  - Possible further performance improvements
  - Code acceleration
- Plans to extend the method to a stereoscopic reconstruction