

# The Likelihood reconstruction method : The Crab Nebula and BL lacertae flaring state

Uploaded version without WIP paper plots

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CTA Swiss day – 15/12/2022

# Introduction

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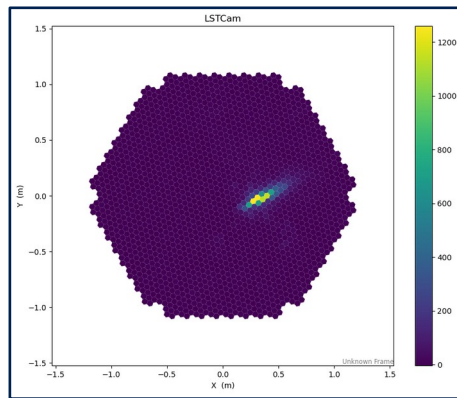
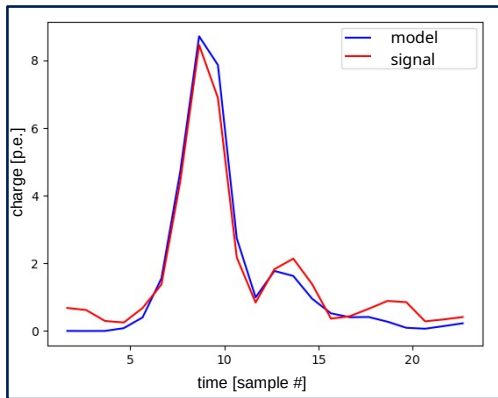


- The method:
  - Model that represent the spatial and temporal signal development convoluted with the pixel response
  - Fit on waveforms
  - Model parameters used to reconstruct/identify photons
  
- Released in cta-1stchain v0.9.8

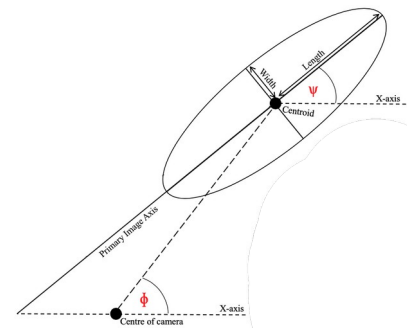
# LH fit Reconstruction pipeline



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

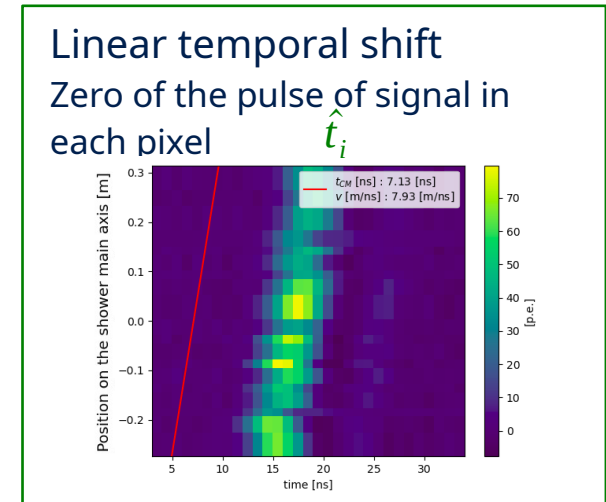
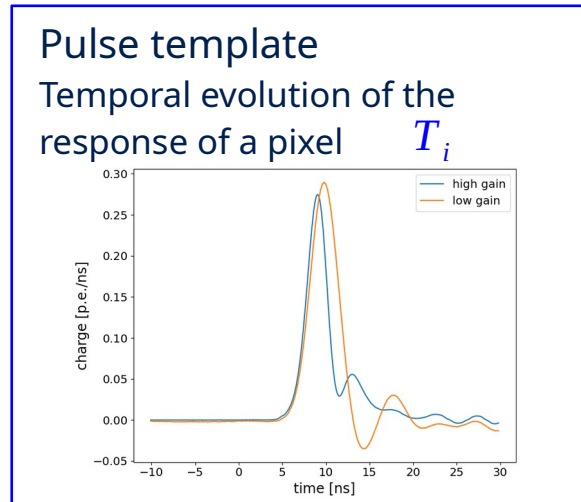
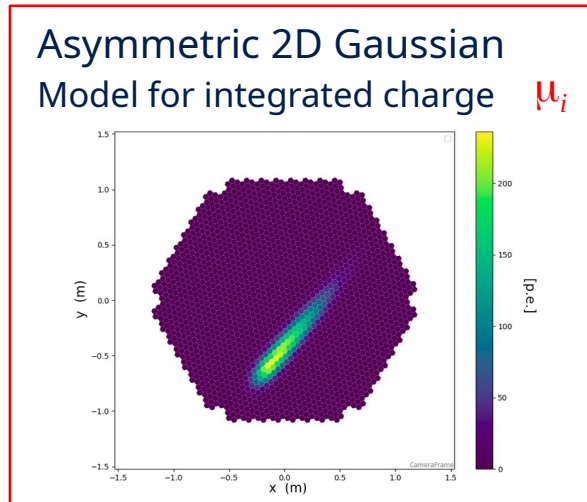


# Spatio-temporal likelihood reconstruction



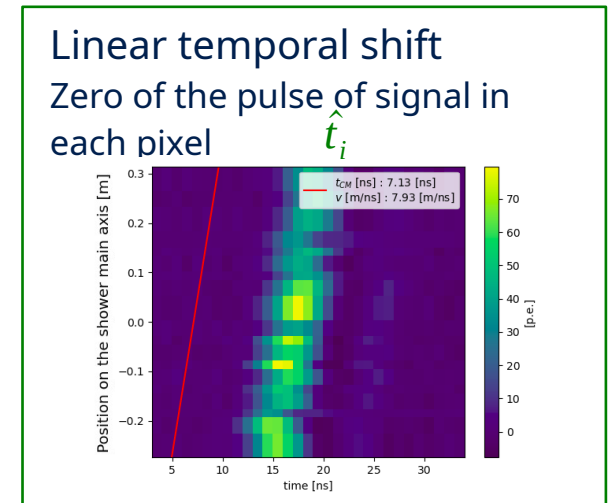
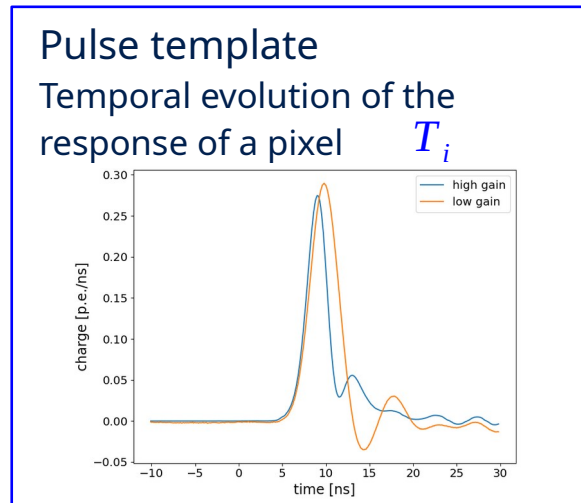
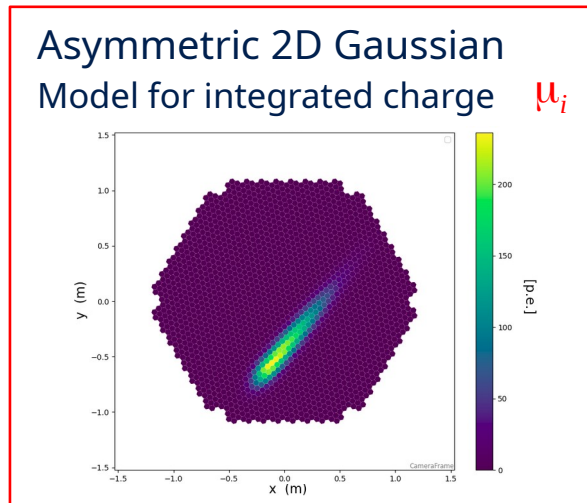
- Use the full waveform recorded by the CTA camera, combined with the knowledge of the instrument response and a space-time EAS image development model
- Fit the model by likelihood maximisation

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



# 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



# Data / MC simulation comparison

Crab nebula from November 2020 to April 2022



- 36 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

Preliminary

Preliminary

# Performance assessment on simulation

## Source independent analysis

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- Performance evaluated on MC test nodes:
  - Zenith angles 10,23,32,43 deg
  - 2 azimuths each
- Cut not optimized for best performance
  - Some event pre-selection
    - e.g. remove faintest signals
  - Energy dependent selections based on photon selection efficiency
  - 70% most gamma like photon events
  - Then 70% angular containment
- - 
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Preliminary

# Performance assessment on simulation

## Source independent analysis



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  - Energy dependent selections based on photon selection efficiency
  - 70% most gamma like photon events
  - Then 70% angular containment
- Improves analysis quality compared to Hillas' parameters
  - 10-20% better angular resolution below 1 TeV
  - Up to 40% better energy resolution and better by at least 10% below 1 TeV



Preliminary





# Application to LST-1 observations

## Crab nebula

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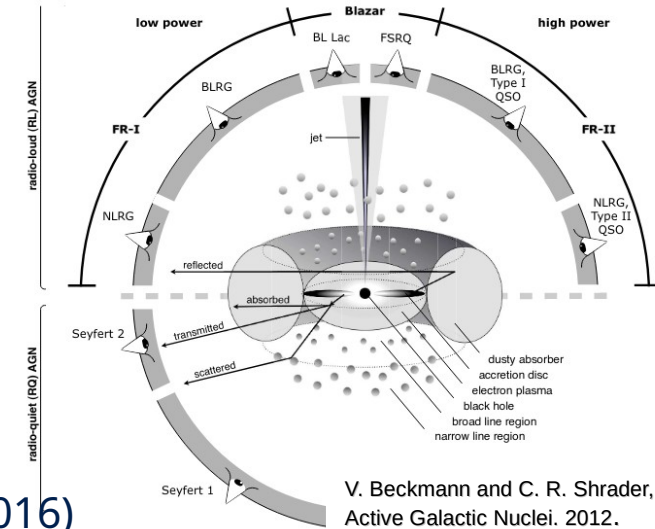
- 36 hours of observation
- Bright, constant source with known spectrum
- Very good agreement with MAGIC SED

Preliminary

# BL Lacertae



- Blazar of the BL lac type object category
  - IBL (intermediate synchrotron peak frequency BL lac object)
  - redshift 0.069
- Not detected by IACTs in low/quiescent state
- Variable :
  - High states detected multiple time by IACTs (e.g. in 2005 and 2016)
  - Multiple high states in 2021
    - Flux increase at the end of July/start of August
      - ATel #14820 : Optical all time maximum
      - MAGIC follow up (ATel #14826) → piggyback observations with LST-1



# Dataset shown today

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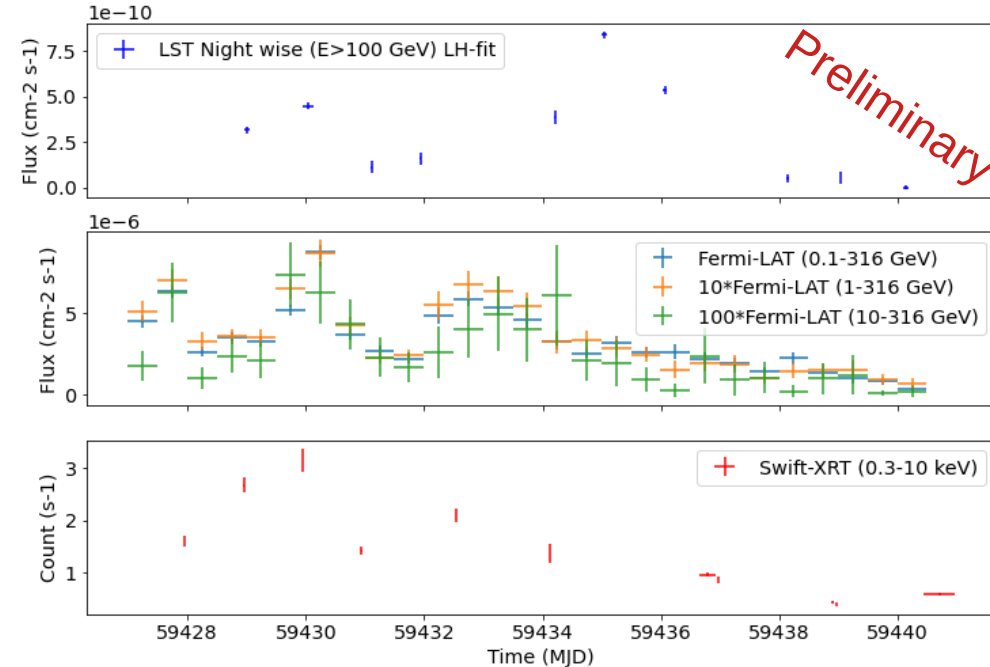
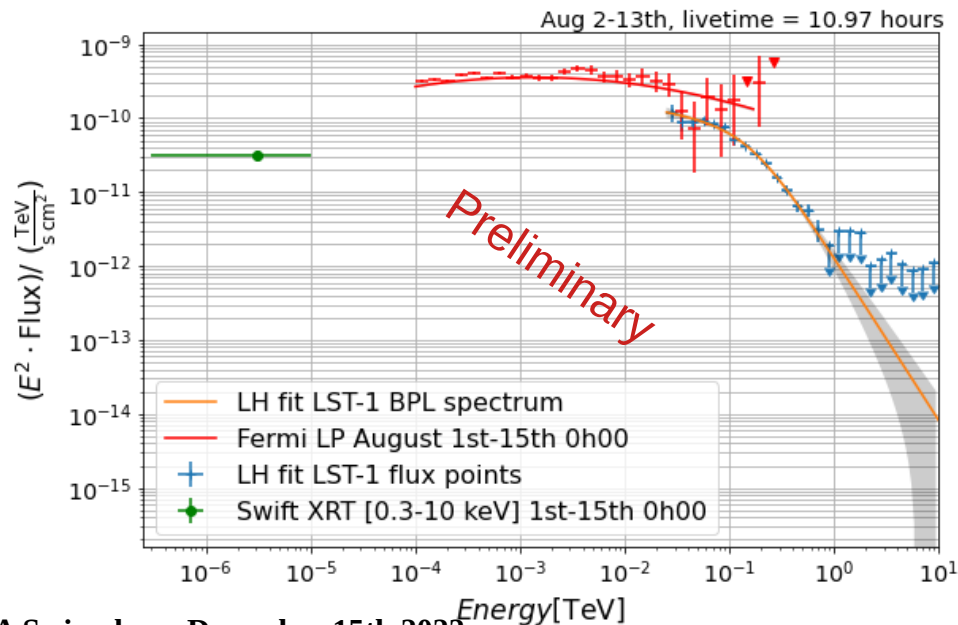
- August 2<sup>nd</sup> to 13<sup>th</sup> : 41 runs for **10.97 hours** of livetime
  - Zenith angle between 13 and 50 degrees
  - Good atmosphere transparency
  - Not the latest run selection
- August 8<sup>th</sup> : 8 runs for **1.87 hours** of livetime
- Also observed by MAGIC, Fermi-LAT, Swift-XRT/UVOT,...
  
- August 2<sup>nd</sup> to 13<sup>th</sup> → older processing with non-optimal MC production and an older code version. Re-processing of the July+August dataset, with all the latest development is ongoing
- August 8<sup>th</sup> → Spectrum produced more recently but will also be updated soon

# BL Lacertae flare observation



## Older analysis

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



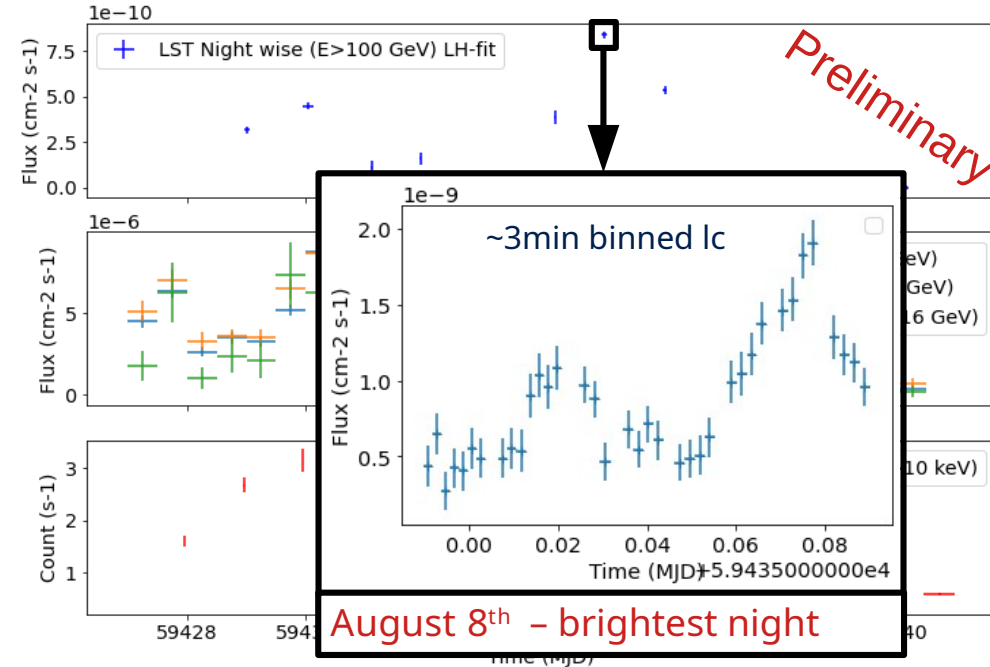
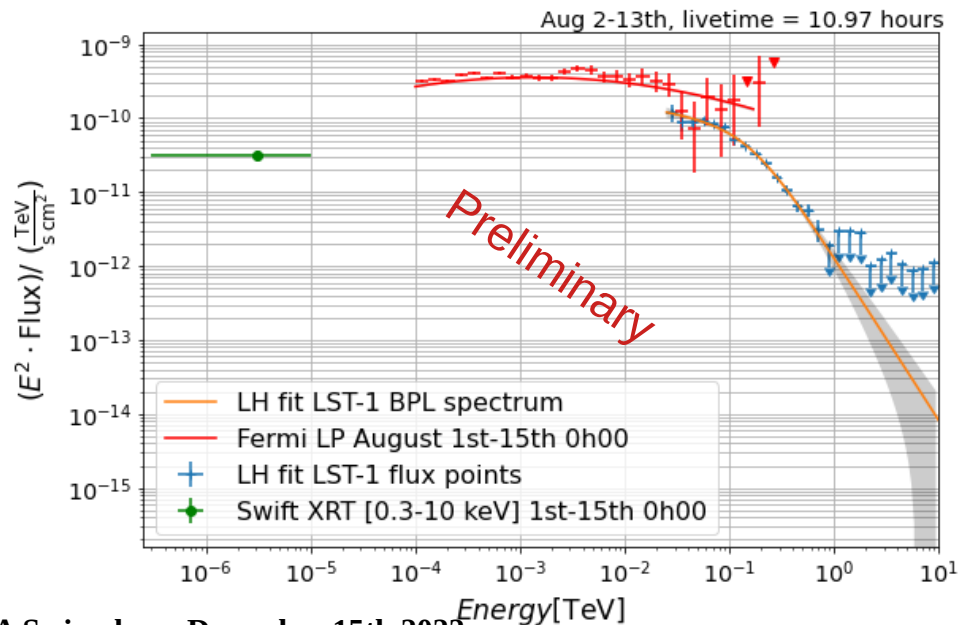
← Spectrum obtained applying uniform event selection :  
fixed gamma likeness threshold and  $\theta < 0.2$   
+ other selections

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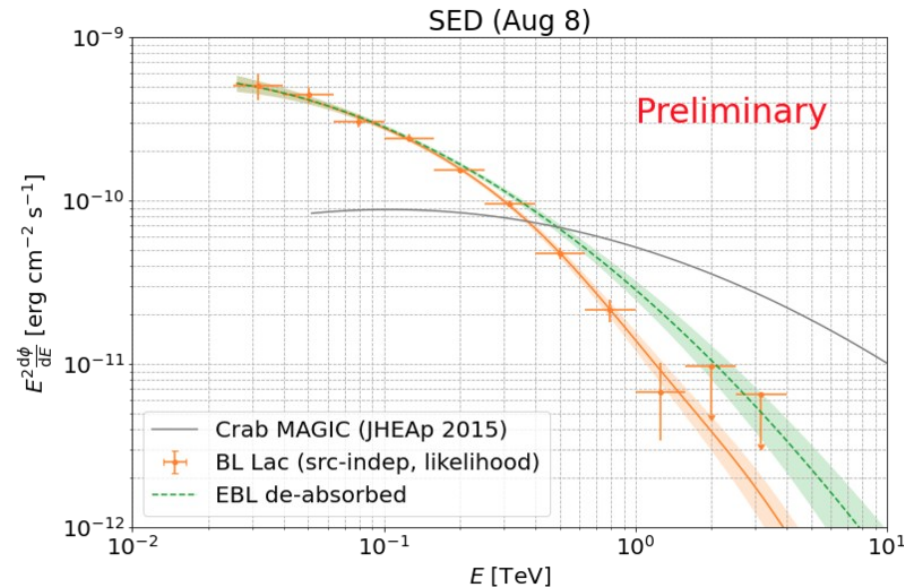
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# BL Lacertae flare observation



## Recent processing and ongoing work

- **August 8<sup>th</sup>** SED obtained with new MC production and energy dependent event selection
  - Significant preference of “curved” spectrum vs simple power law



- Ongoing : New full processing with released LHfit, in source dependent mode and latest configuration. Multi-wavelength modeling and variability study.

# Conclusion

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- The likelihood reconstruction method using the full waveform development of the signal in the camera, shows **improved performance on MC** compared to the standard Hillas reconstruction. Especially **at low energy**.
- Fully implemented in the analysis pipeline for the LST prototype
- Very good results on Crab nebula data
- Interesting variability episode of BL Lacertae analysed
- Ongoing MWL and variability study