# Performance of joint LST-1 + MAGIC analysis chain

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on behalf of CTA-LST Project,
on behalf of MAGIC Collaboration

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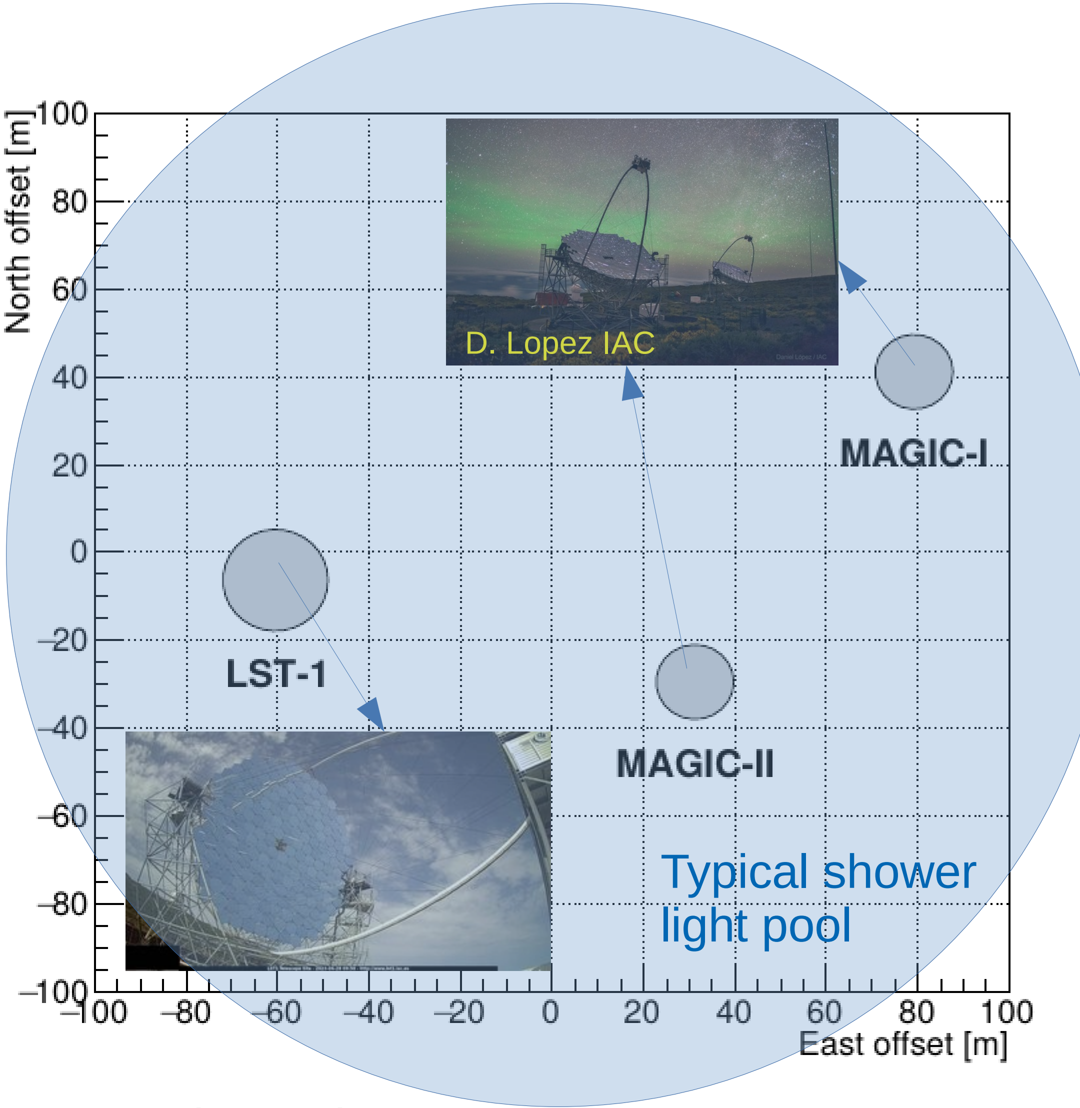
# MAGIC and LST-1

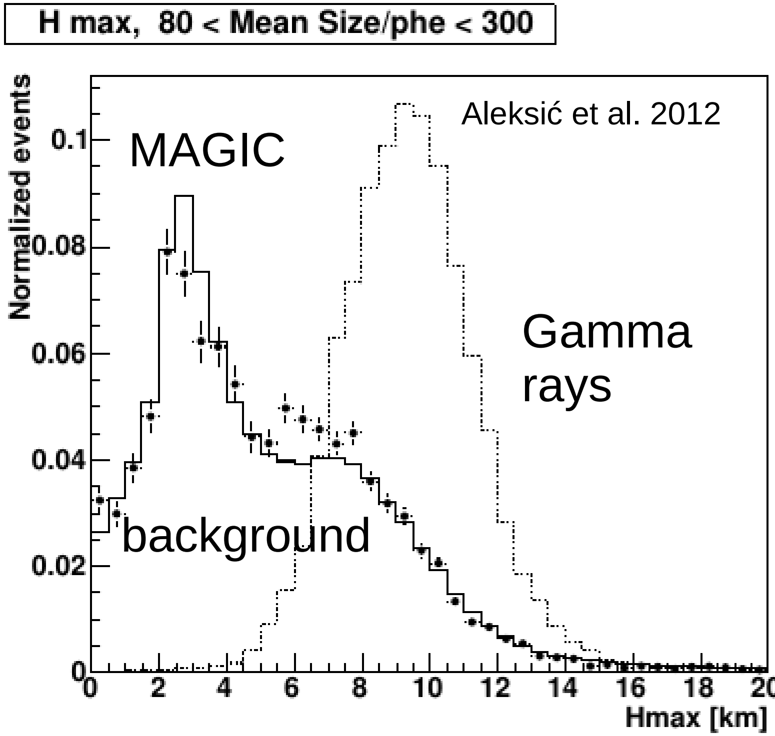
- MAGIC:
  - 17m diameter
  - two telescopes
- LST-1:
  - 23m diameter
  - the first of the CTAO’s largest telescopes
- The instruments are located just 100m one from another. The proximity allows common analysis of the same gamma-ray showers.



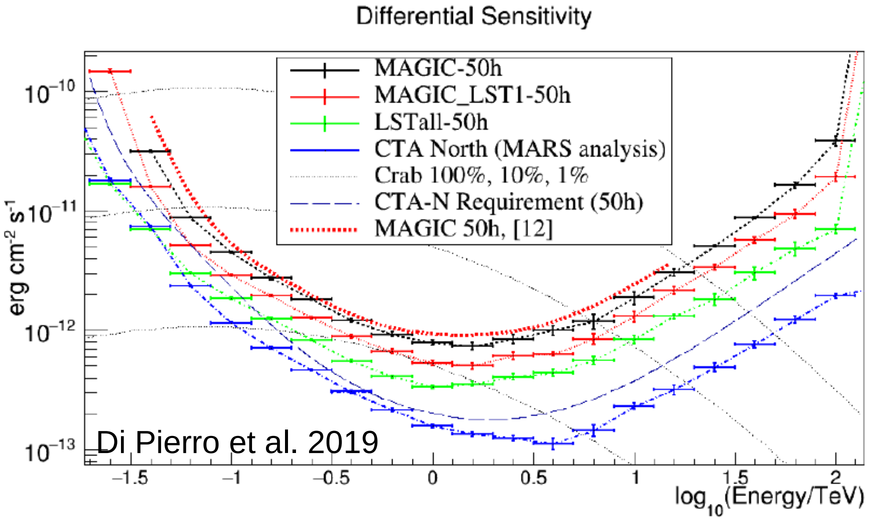
Size of the grey circles represent the mirror diameters

# Why joint analysis?

- LST are next generation instruments with an excellent energy threshold, but currently there is only LST-1.
- A single telescope is burdened with a large background at low energies, which limits the current low-energy performance
- The early MC studies showed that joint observations provide better sensitivity, bringing the performance half the way towards 4 x LST



Aleksić et al. 2012



Di Pierro et al. 2019

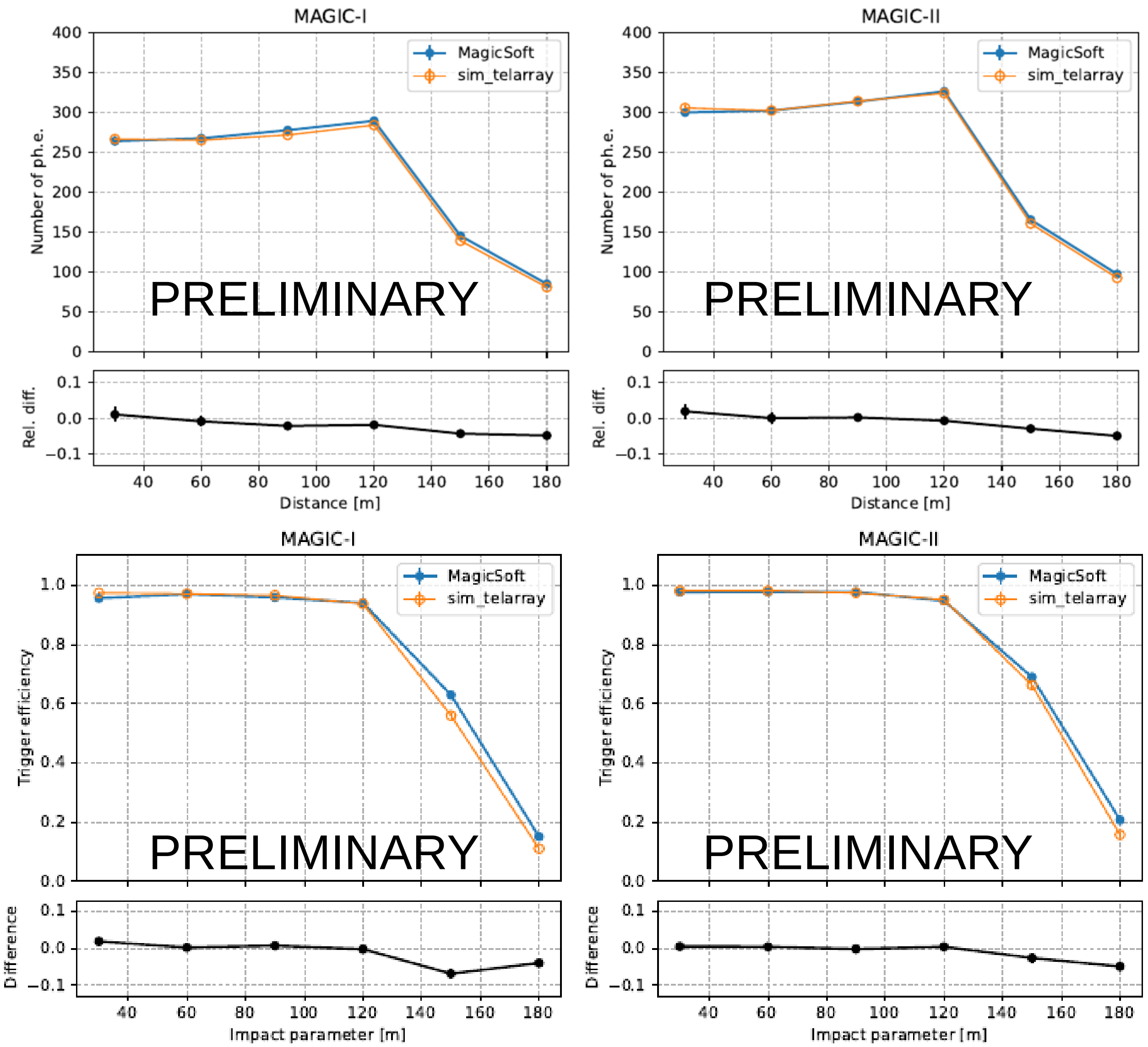
# Two instruments, two MCs, two analysis chains...

- LST(-1) is using
  - “regular” Corsika
  - telescope response simulated with sim_telarray
  - ctapipe-based lstchain (Python) for analysis
- MAGIC is using
  - Customized Corsika (*mmcs*)
  - *MagicSoft* to simulate telescope response
  - Dedicated MARS software (C++)

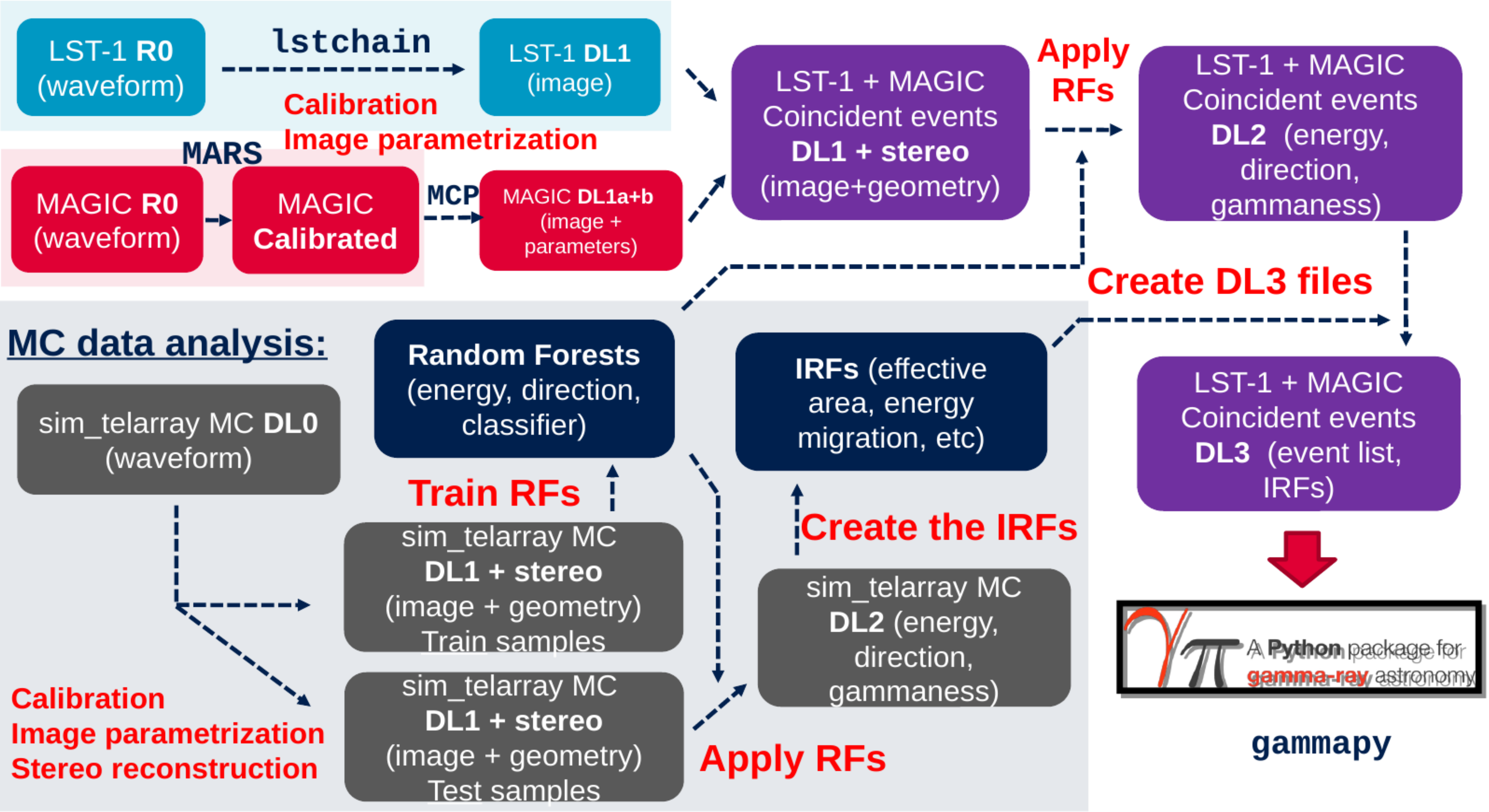
**Need common simulation and analysis framework – “MAGIC ctapipe” (MCP)**

# Validation of MAGIC part of MCs

- 100 GeV gamma rays were generated at fixed impacts of 30m, 60m, 90m, … with both chains
- Good agreement in the reconstructed true number of p.e. and trigger efficiency was obtained



# Pipeline in a glance



LST-1 **R0** (waveform)

`lstchain`

**Calibration**

**Image parametrization**

LST-1 **DL1** (image)

**MARS**

MAGIC **R0** (waveform)

MAGIC **Calibrated**

**MCP**

MAGIC **DL1a+b** (image + parameters)

LST-1 + MAGIC Coincident events **DL1 + stereo** (image+geometry)

**Apply RFs**

LST-1 + MAGIC Coincident events **DL2** (energy, direction, gammaness)

**Create DL3 files**

LST-1 + MAGIC Coincident events **DL3** (event list, IRFs)

A **Python** package for **gamma-ray** astronomy

**gammapy**

**MC data analysis:**

sim_telarray MC **DL0** (waveform)

**Calibration**
**Image parametrization**
**Stereo reconstruction**

**Random Forests** (energy, direction, classifier)

**Train RFs**

sim_telarray MC **DL1 + stereo** (image + geometry) Train samples

sim_telarray MC **DL1 + stereo** (image + geometry) Test samples

**Apply RFs**

**IRFs** (effective area, energy migration, etc)

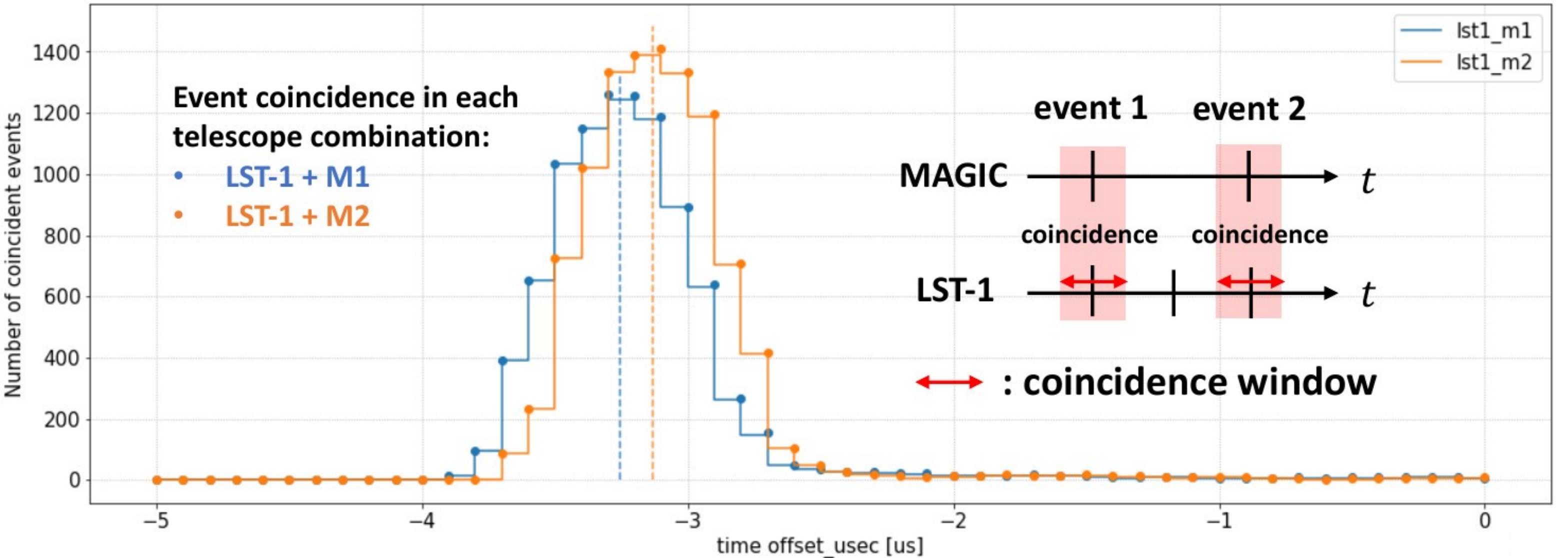
**Create the IRFs**

sim_telarray MC **DL2** (energy, direction, gammaness)

MAGIC data start from calibrated images, LST-1 from image parameters, simulations from waveforms

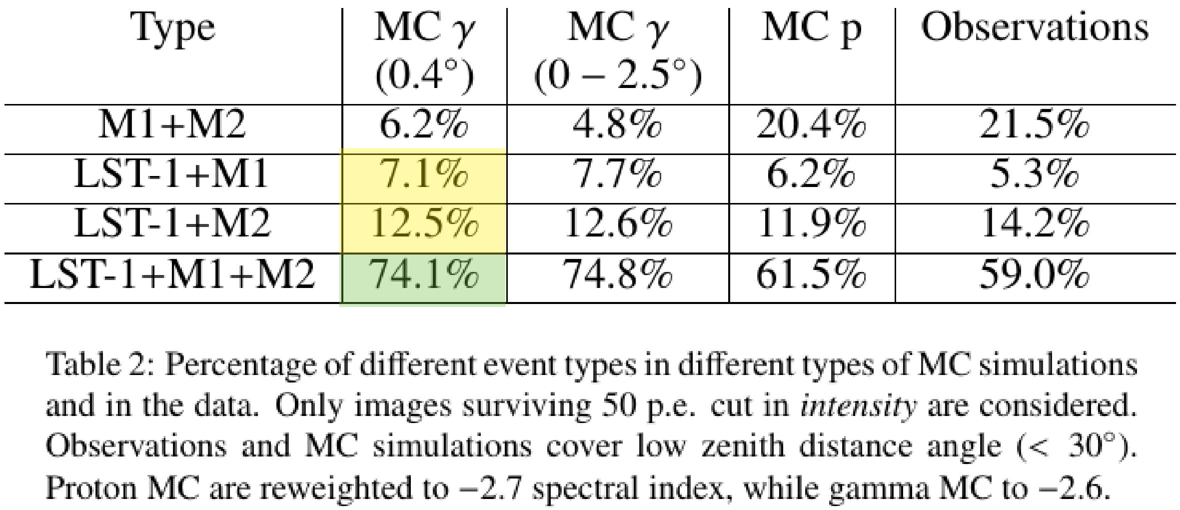
# Matching MAGIC and LST-1 events

- MAGIC-I and MAGIC-II events are matched by a common stereo trigger number from the MAGIC stereo trigger system
- MAGIC and LST-1 operate as independent systems, but joint observations can be taken in semi-automatic mode in which the current MAGIC pointing direction is provided to LST-1
- Hardware stereo trigger is currently in development for MAGIC+LST-1 observations, but GPS clocks can be used to match the events by their time stamps
- There are both constant (related to cable lengths) and variable (mostly dependent on the pointing direction) delays, hence the optimal delay between LST-1 and MAGIC is derived for each subrun from a scan.



# What’s in the data?

- Performance studies are done using MC simulations and 4hrs of Crab Nebula data
- LST-1 is triggering most of the gamma-ray events that MAGIC sees
- A fraction of MAGIC-only events is much higher for background – such events are best to exclude



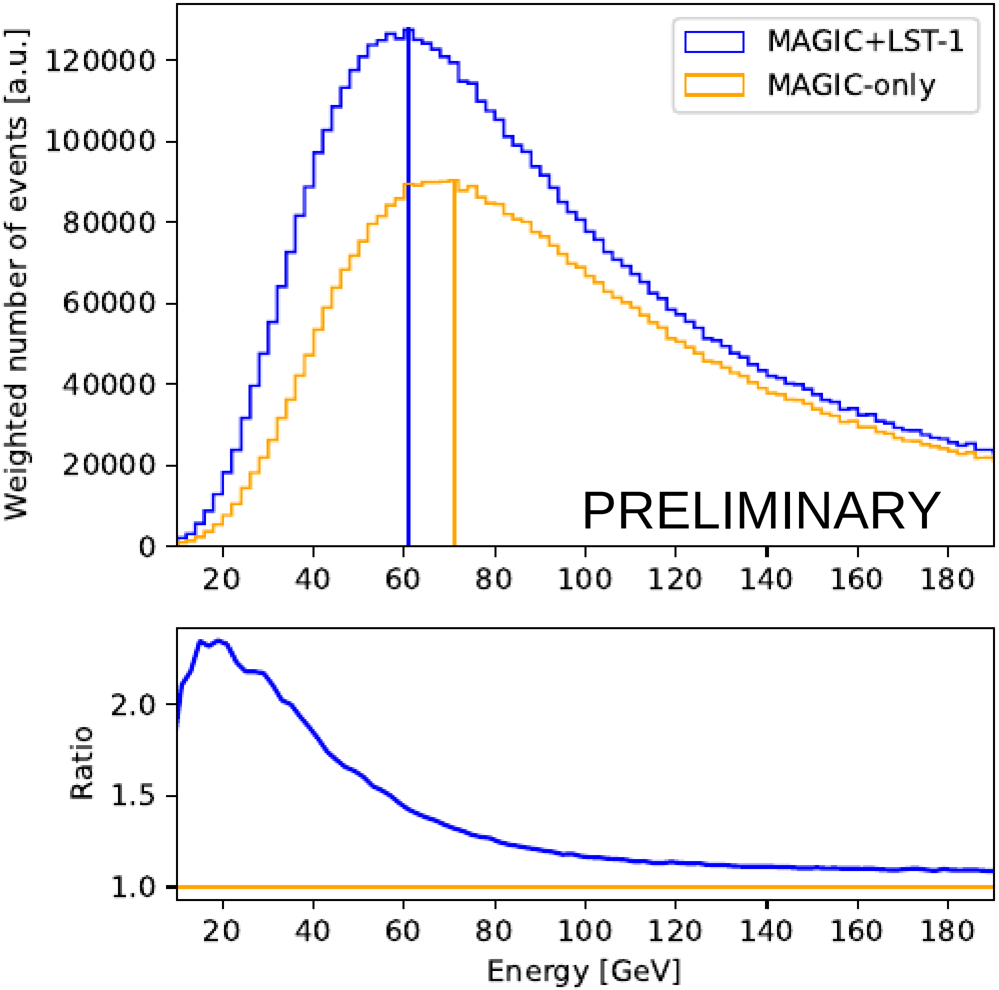
| Type | MC $\gamma$ (0.4°) | MC $\gamma$ (0 – 2.5°) | MC p | Observations |
|---|---|---|---|---|
| M1+M2 | 6.2% | 4.8% | 20.4% | 21.5% |
| LST-1+M1 | 7.1% | 7.7% | 6.2% | 5.3% |
| LST-1+M2 | 12.5% | 12.6% | 11.9% | 14.2% |
| LST-1+M1+M2 | 74.1% | 74.8% | 61.5% | 59.0% |

Table 2: Percentage of different event types in different types of MC simulations and in the data. Only images surviving 50 p.e. cut in *intensity* are considered. Observations and MC simulations cover low zenith distance angle (< 30°). Proton MC are reweighted to −2.7 spectral index, while gamma MC to −2.6.

- The joint analysis requires that the event is triggered by LST-1 and **both** MAGIC telescopes, but one of MAGIC images might not survive image cleaning or intensity cut.
- **Despite the lack of hardware trigger MCP can provide a higher analysis-level collection area**

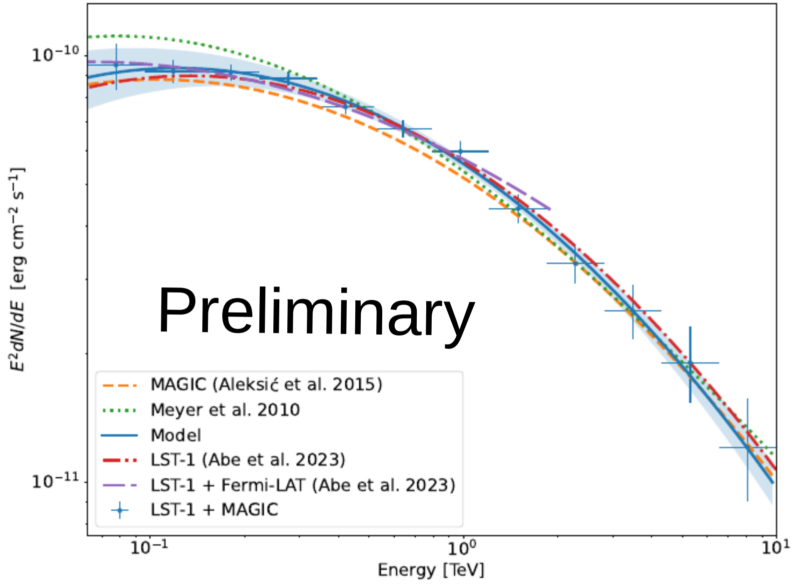
# Energy threshold

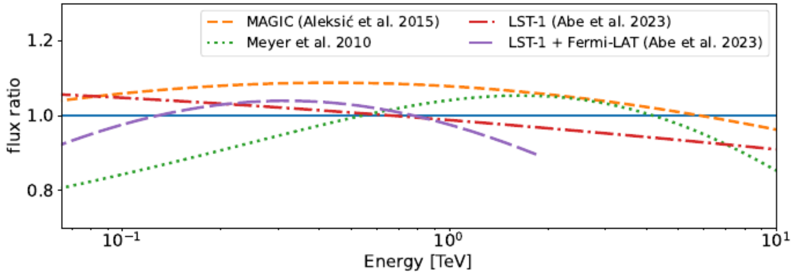
- Differential rate plot for a -2.6 slope source at the analysis level (intensity > 50 p.e.) assuming zd<30$^{o}$
- 15% improvement in the threshold w.r.t. MAGIC
- A factor of 2 improvement in the collection area at 30 GeV

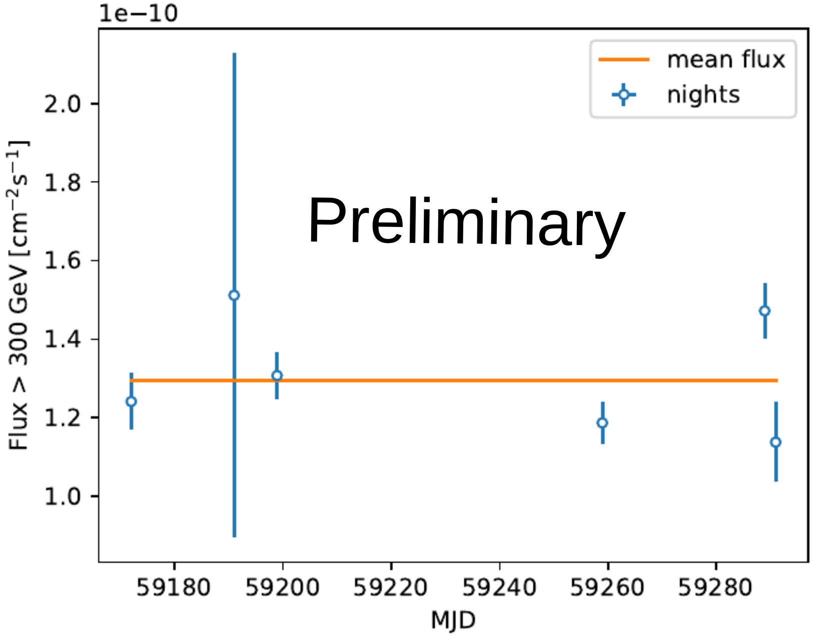


# Flux reconstruction

- The data sample is mostly at medium zenith distance, so the spectrum can be reconstructed starting from 80 GeV point
- In agreement with MAGIC and LST-1 curves within 10%
- Due to high signal from the Crab Nebula we can test the systematic uncertainties by investigating stability of the flux – it is comparable to the MAGIC-only and LST-1-only analysis

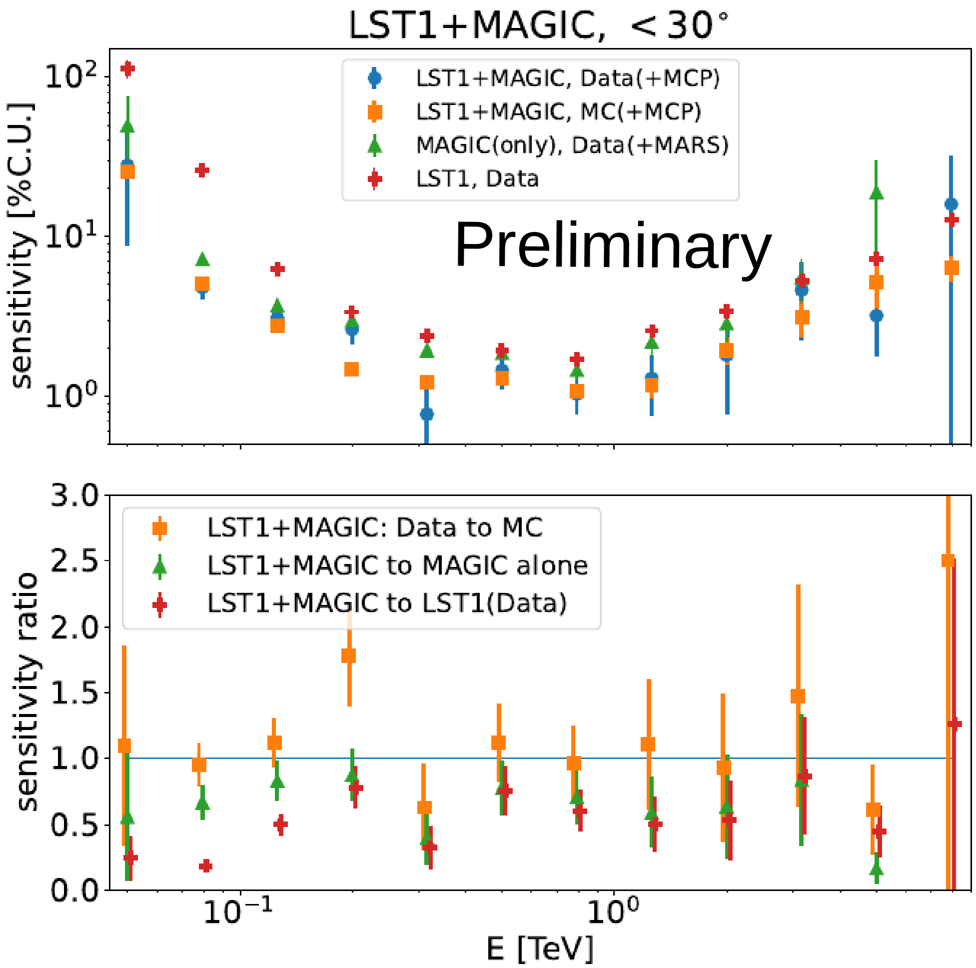






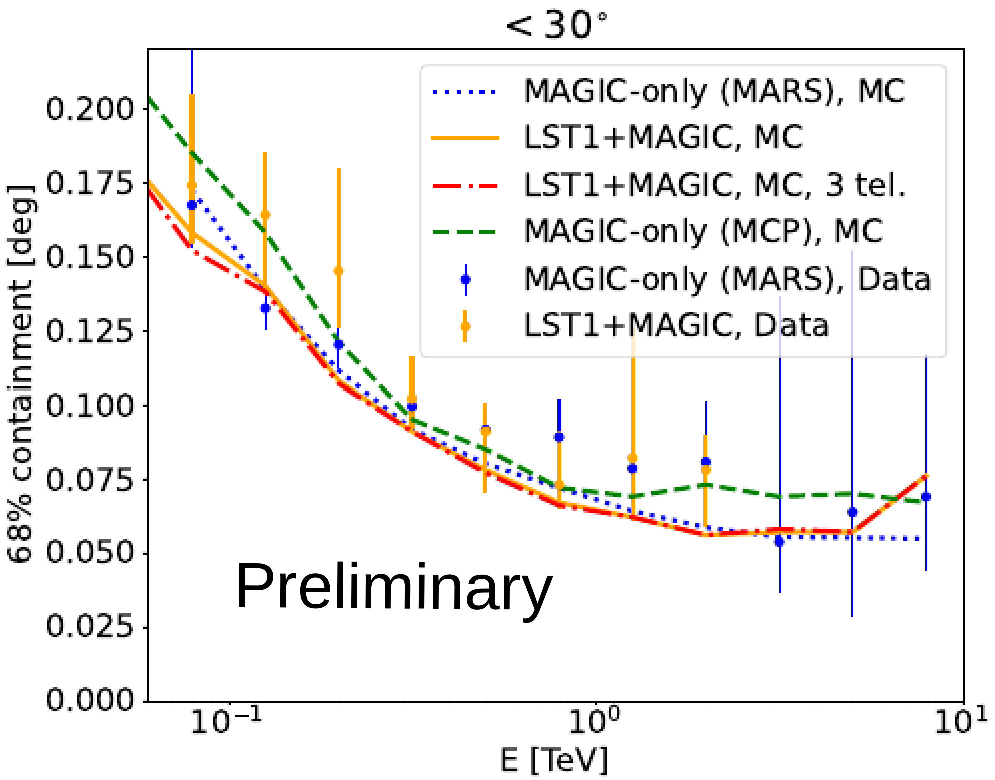
# Differential sensitivity (low Zd)

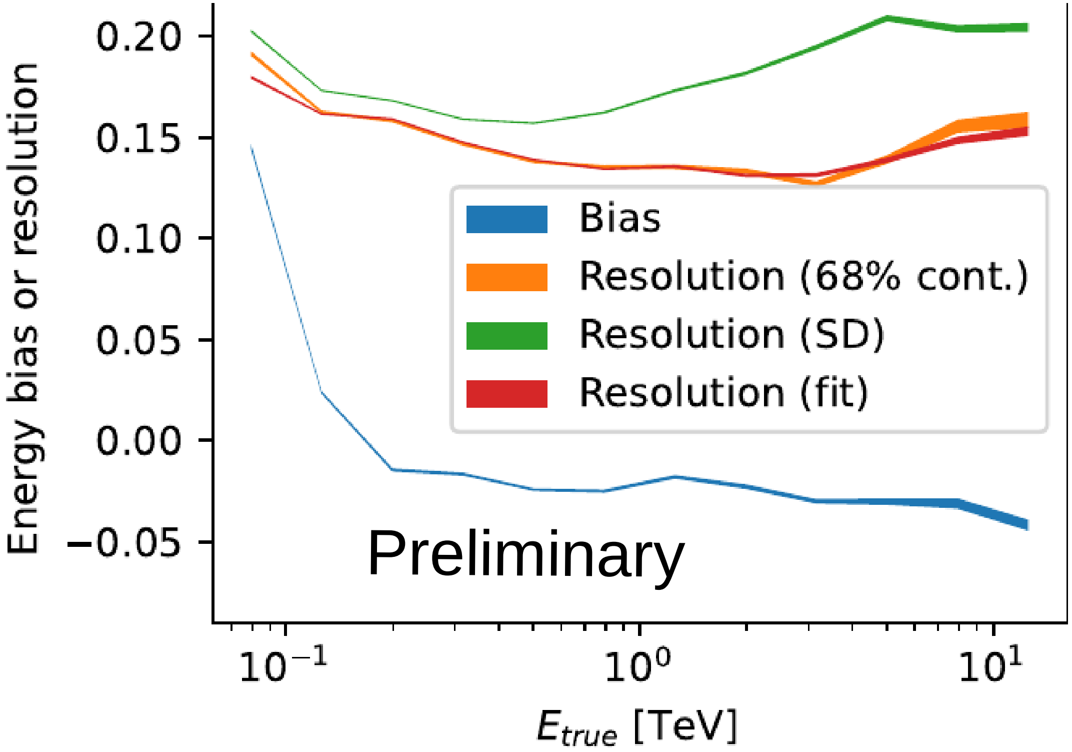
- Joint observations allow detection of 30% (40%) lower flux than MAGIC-alone (LST-1-alone).
- This corresponds to the detection of the same flux in twice (nearly three times) shorter time.
- **MAGIC and LST-1 work together better than each instrument alone**



# Energy & angular resolutions

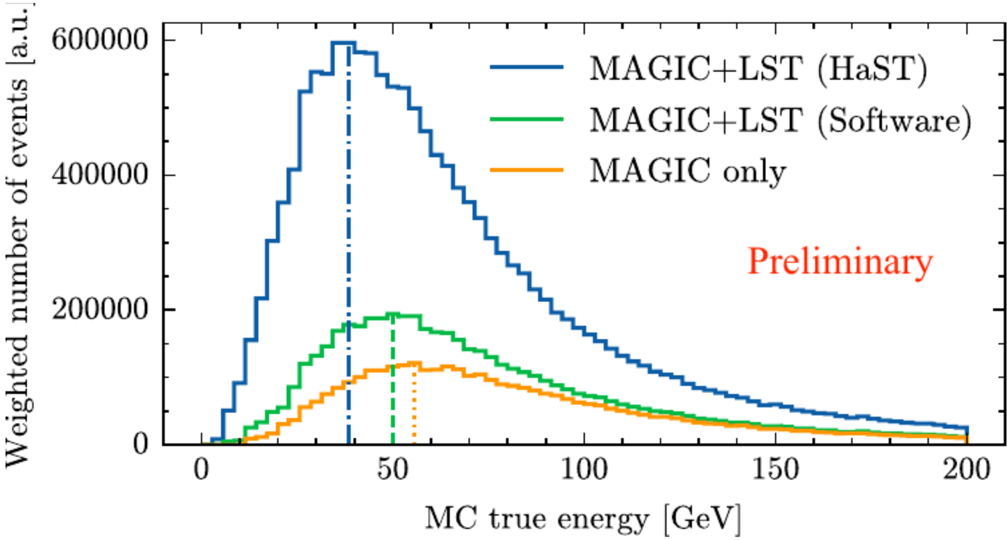
- MCP chain provides slightly better angular resolution for joint observations than for MAGIC-only observations, however the angular resolution is still comparable to the one obtained with dedicated MARS analysis of MAGIC-only data.
- With further optimization improved performance can be achieved (at the price of collection area)





# How to make it even better? Hardware stereo trigger

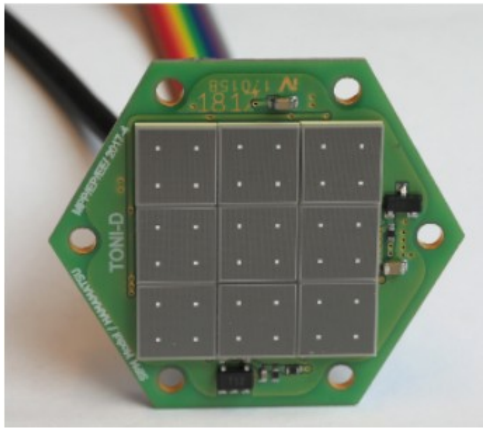
- Hardware trigger greatly enhances the collection area (especially at the lowest energies)
- The first data with HaST have been already taken (however now it is only available for a part of the sky)



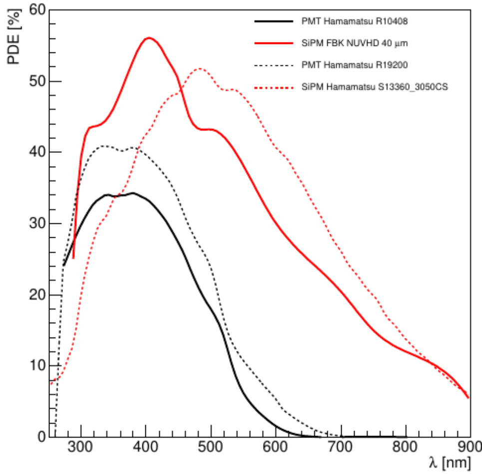
Baxter et al. ICRC 2023

# How to make it even better? SiPMs in MAGIC cameras?

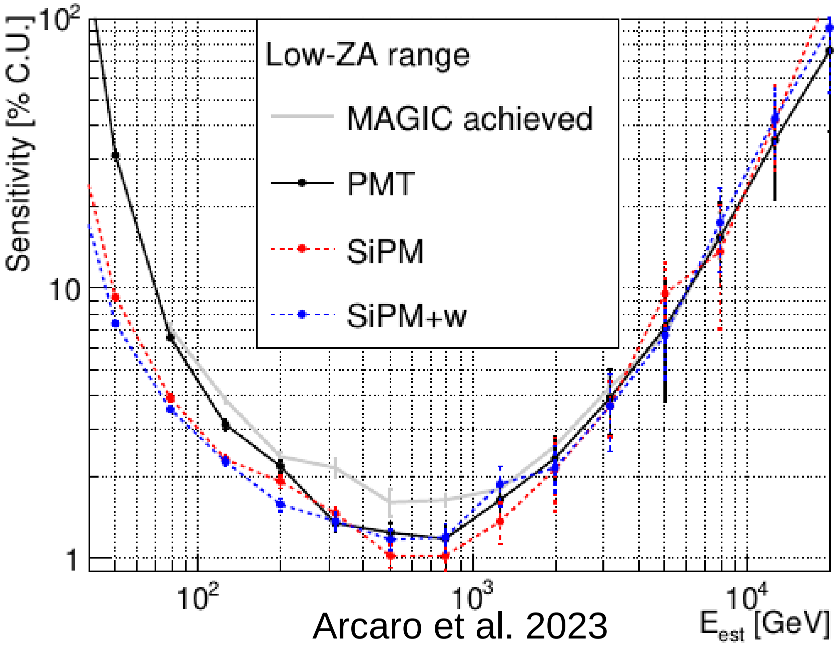
- Due to larger mirror area and newer PMTs LST-1 is gathering 2.6 – 3 times more light than each of MAGIC telescopes.
- With a SiPM-based camera MAGIC can get 2.2 times light more, making it comparable to LST-1
- MC studies show that SiPM camera would results in a considerable improvement in the MAGIC sensitivity at the lowest energies
- **MAGIC with a SiPM camera can be a good partner for joint observations for more than one LST**
- **Would the performance gain justify the cost in view of upcoming further LST (and MST) telescopes?**



Hahn et al. 2019



Arcaro et al. 2023



Arcaro et al. 2023

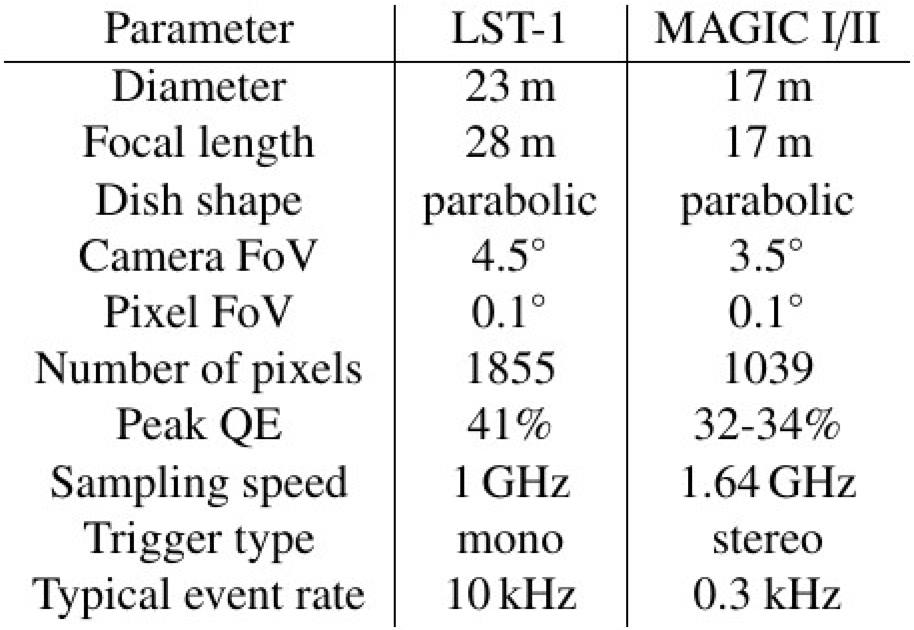
# Summary

- A joint simulation and analysis chain has been implemented for MAGIC+LST-1 observations.
- The joint observations provide major boost in sensitivity (30% lower fluxes can be detected than with MAGIC), making the two instruments more efficiently working together than separate.
  **(MAGIC+LST-1) > (MAGIC) + (LST-1)**
- Hardware stereo trigger and/or upgrade of MAGIC camera can make the joint observations desirable also when multiple LSTs are in place.

# Backup

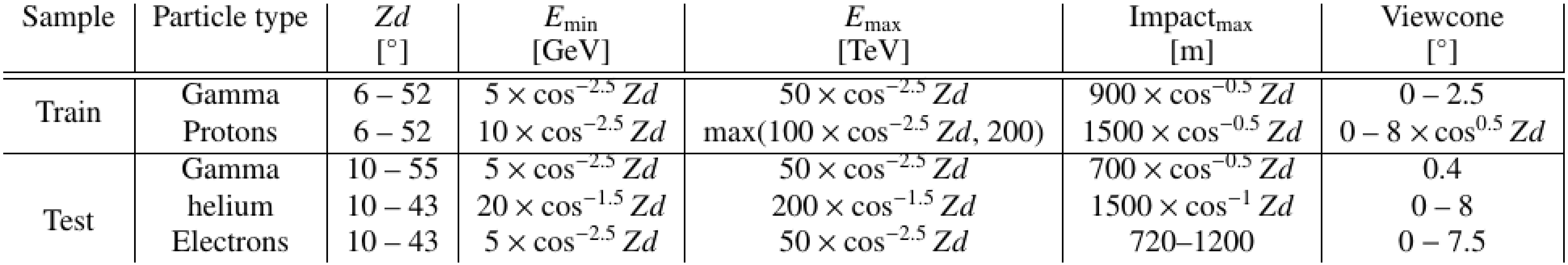
# MAGIC and LST-1

- LST-1 design follows the general one of MAGIC, but with a number of significant improvements
- The larger mirror area and novel PMTs result in over twice larger light yield in the case of LST-1, but LSTs are still more similar in light yield to MAGIC than to MSTs
-



| Parameter | LST-1 | MAGIC I/II |
|---|---|---|
| Diameter | 23 m | 17 m |
| Focal length | 28 m | 17 m |
| Dish shape | parabolic | parabolic |
| Camera FoV | 4.5° | 3.5° |
| Pixel FoV | 0.1° | 0.1° |
| Number of pixels | 1855 | 1039 |
| Peak QE | 41% | 32-34% |
| Sampling speed | 1 GHz | 1.64 GHz |
| Trigger type | mono | stereo |
| Typical event rate | 10 kHz | 0.3 kHz |

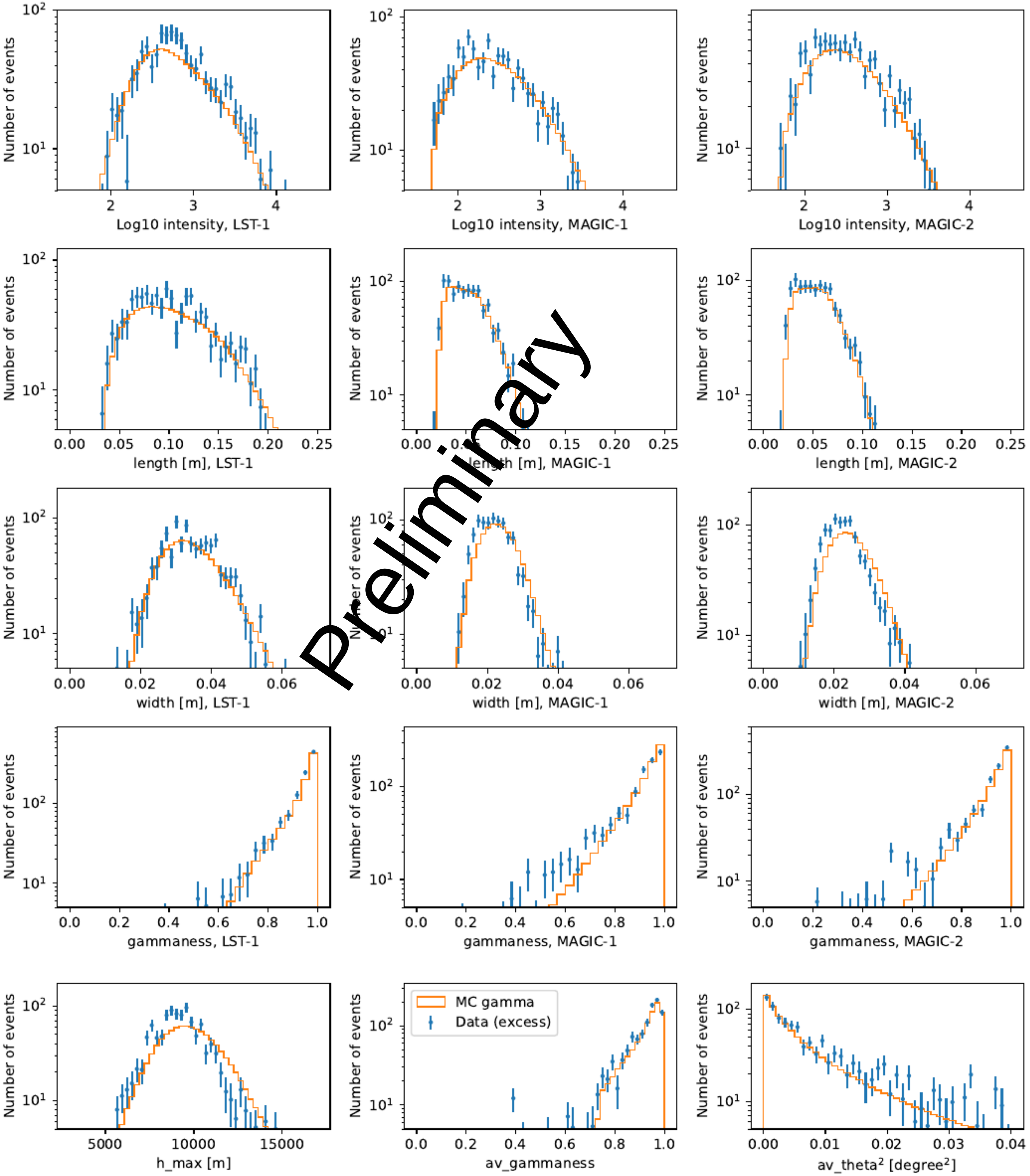
# Simulations



| Sample | Particle type | $Zd$ [°] | $E_{\mathrm{min}}$ [GeV] | $E_{\mathrm{max}}$ [TeV] | $\mathrm{Impact}_{\mathrm{max}}$ [m] | Viewcone [°] |
|---|---|---|---|---|---|---|
| Train | Gamma | $6 - 52$ | $5 \times \cos^{-2.5} Zd$ | $50 \times \cos^{-2.5} Zd$ | $900 \times \cos^{-0.5} Zd$ | $0 - 2.5$ |
| | Protons | $6 - 52$ | $10 \times \cos^{-2.5} Zd$ | $\max(100 \times \cos^{-2.5} Zd, 200)$ | $1500 \times \cos^{-0.5} Zd$ | $0 - 8 \times \cos^{0.5} Zd$ |
| Test | Gamma | $10 - 55$ | $5 \times \cos^{-2.5} Zd$ | $50 \times \cos^{-2.5} Zd$ | $700 \times \cos^{-0.5} Zd$ | 0.4 |
| | helium | $10 - 43$ | $20 \times \cos^{-1.5} Zd$ | $200 \times \cos^{-1.5} Zd$ | $1500 \times \cos^{-1} Zd$ | $0 - 8$ |
| | Electrons | $10 - 43$ | $5 \times \cos^{-2.5} Zd$ | $50 \times \cos^{-2.5} Zd$ | 720–1200 | $0 - 7.5$ |

# Comparison with gamma

- We compare MC simulations of gamma rays with the gamma-ray excess obtained from the data
- Most of the parameters agree rather well
- Small differences in $H_{max}$ and MAGIC-2 width distributions, but **gammaness and theta distribution are matching relatively well**



# Collection area

- MC simulation at zenith distance of 10 degree
- Above ~80 GeV most of the MAGIC events survive stereoscopic reconstruction