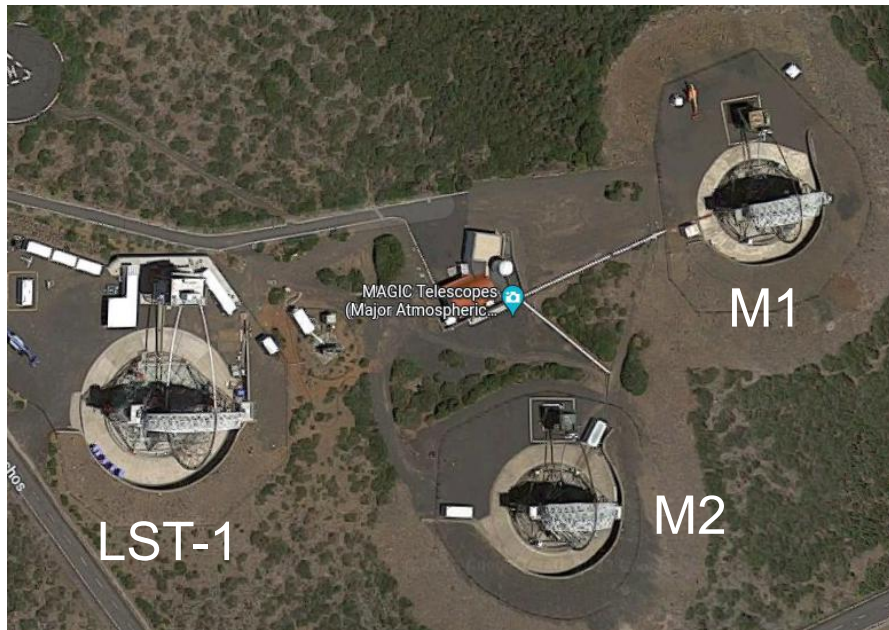


Performance of joint observations with LST-1 and MAGIC

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on behalf of the CTA-LST Project
and the MAGIC Collaboration

TeVPA 2023, September 2023

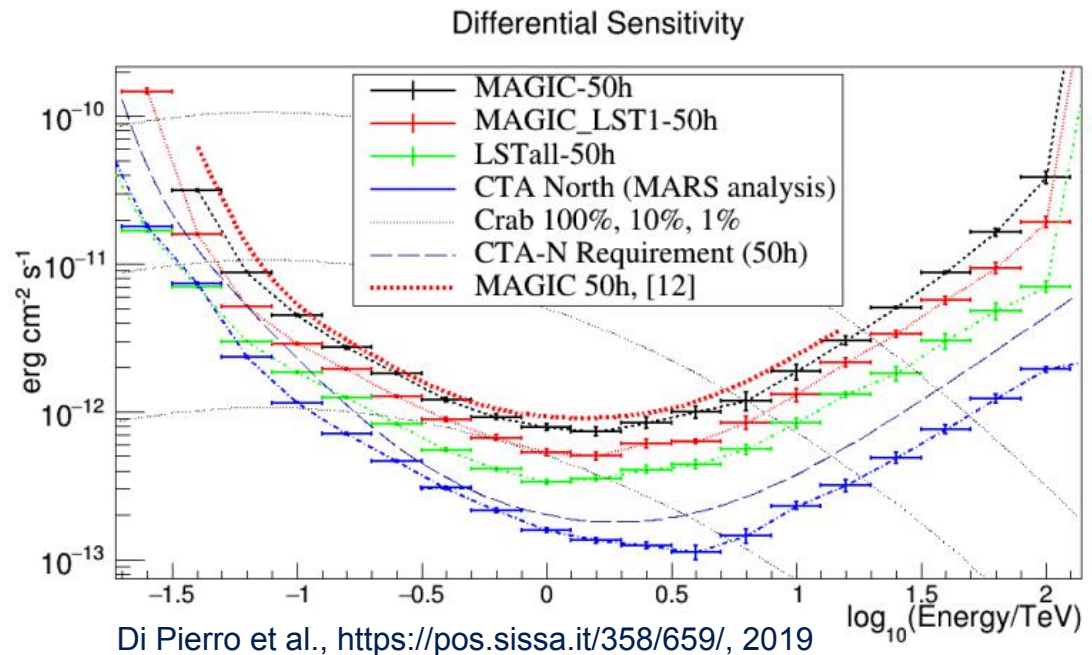
MAGIC and LST-1



- MAGIC has two 17m Cherenkov telescopes, operating since 20 years (~14 in stereoscopic mode)
 - LST-1 is the first LST (Large-Sized Telescope) prototype of the upcoming CTAO
 - Both MAGIC and LST-1 are located in the ORM (Observatorio del Roque de Los Muchachos)
-
- Separation between telescopes is ~100m
 - similar to radius of the Cherenkov pool, so events can trigger all three telescopes --> JOINT ANALYSIS
 - possible cross-calibration between the instruments

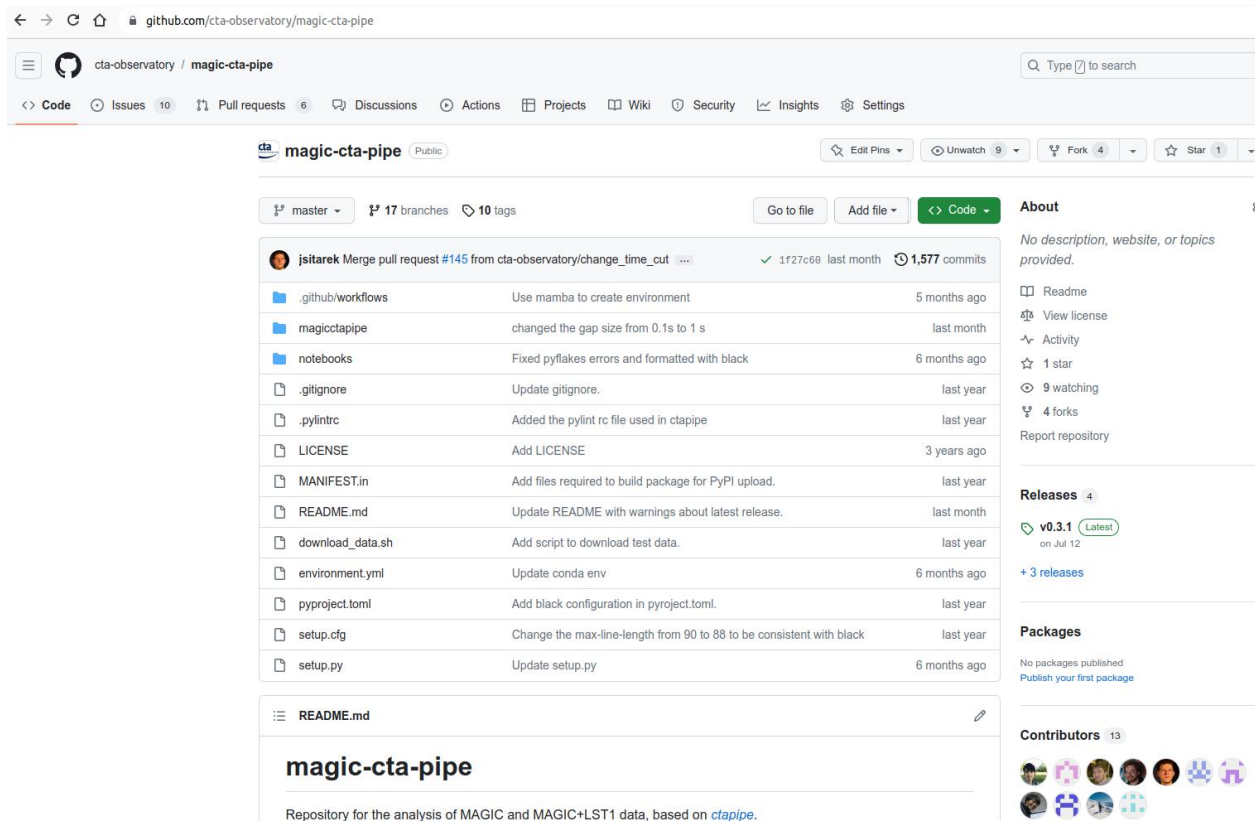
Why joint observations?

- The low-energy performance of a single Cherenkov telescope, like LST-1 at this moment, is limited by large background: stereoscopic reconstruction greatly reduces the background
- Previous studies on simulations showed a ~ 1.5 factor of improvement in sensitivity for MAGIC+LST-1, compared to MAGIC alone
- Therefore, clear advantage in having MAGIC+LST-1 observations
- Also, precursor of stereo analysis of CTAO telescopes



Common simulation and analysis framework

- **CORSIKA+sim_telarray** for MonteCarlo simulations (same as used in CTA/LST-1)
- a pipeline called **magic-cta-pipe** (aka [MCP](#), public repository), based on *ctapipe*, for the data analysis



The screenshot shows the GitHub repository page for `cta-observatory/magic-cta-pipe`. The repository is public and has 17 branches and 10 tags. The main branch is `master`. The repository contains a `.github/workflows` directory, `magicctapipe` directory, `notebooks` directory, `.gitignore`, `.pylintrc`, `LICENSE`, `MANIFEST.in`, `README.md`, `download_data.sh`, `environment.yml`, `pyproject.toml`, `setup.cfg`, and `setup.py` files. The repository is described as a repository for the analysis of MAGIC and MAGIC+LST1 data, based on *ctapipe*. The repository has 1 star, 9 watchers, and 4 forks. The latest release is `v0.3.1` on Jul 12. The repository is also listed as a contributor to the `cta-observatory` organization.

| File | Description | Last Commit |
|--------------------------------|--|--------------|
| <code>.github/workflows</code> | Use mamba to create environment | 5 months ago |
| <code>magicctapipe</code> | changed the gap size from 0.1s to 1 s | last month |
| <code>notebooks</code> | Fixed pyflakes errors and formatted with black | 6 months ago |
| <code>.gitignore</code> | Update gitignore. | last year |
| <code>.pylintrc</code> | Added the pylint rc file used in ctapipe | last year |
| <code>LICENSE</code> | Add LICENSE | 3 years ago |
| <code>MANIFEST.in</code> | Add files required to build package for PyPI upload. | last year |
| <code>README.md</code> | Update README with warnings about latest release. | last month |
| <code>download_data.sh</code> | Add script to download test data. | last year |
| <code>environment.yml</code> | Update conda env | 6 months ago |
| <code>pyproject.toml</code> | Add black configuration in pyproject.toml. | last year |
| <code>setup.cfg</code> | Change the max-line-length from 90 to 88 to be consistent with black | last year |
| <code>setup.py</code> | Update setup.py | 6 months ago |

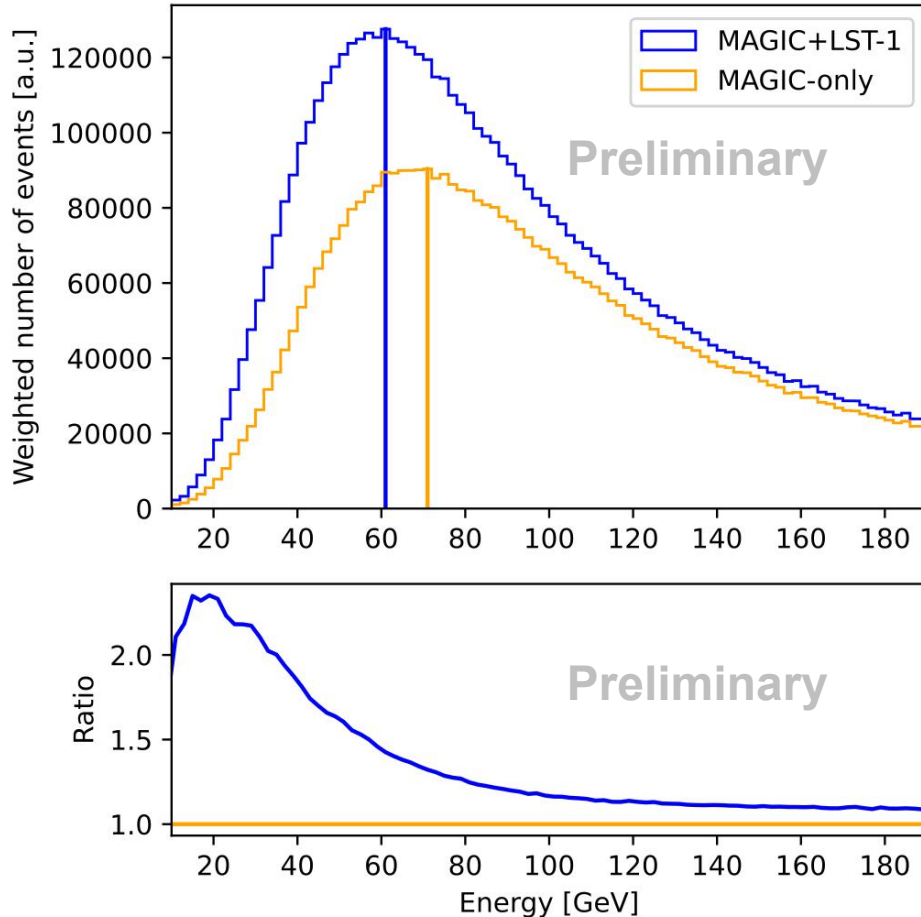
MAGIC+LST-1 coincident events

- No hardware trigger available yet: coincidence of events is performed offline via software using the events GPS timestamp

| Type | MC γ (0.4°) | MC γ (0 – 2.5°) | MC p | Data |
|-------------|-----------------------|---------------------------|-------|-------|
| 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% |

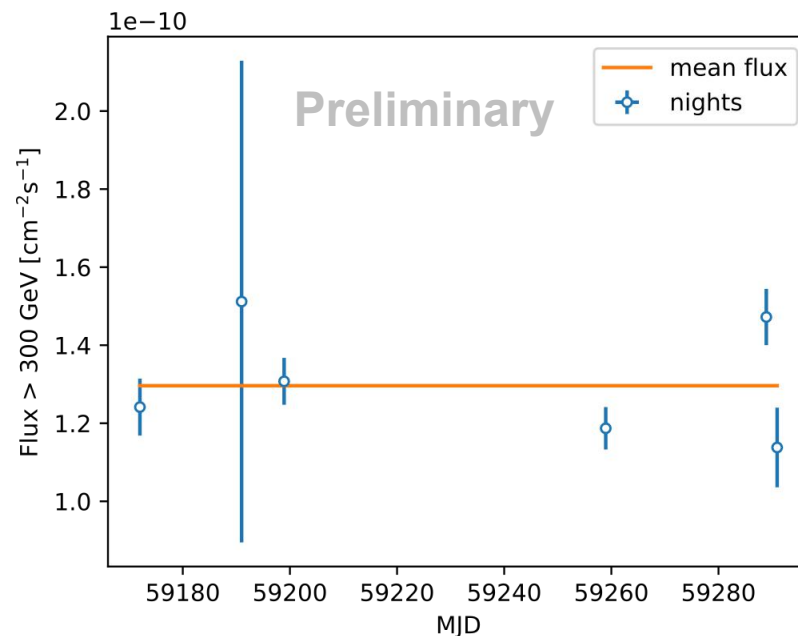
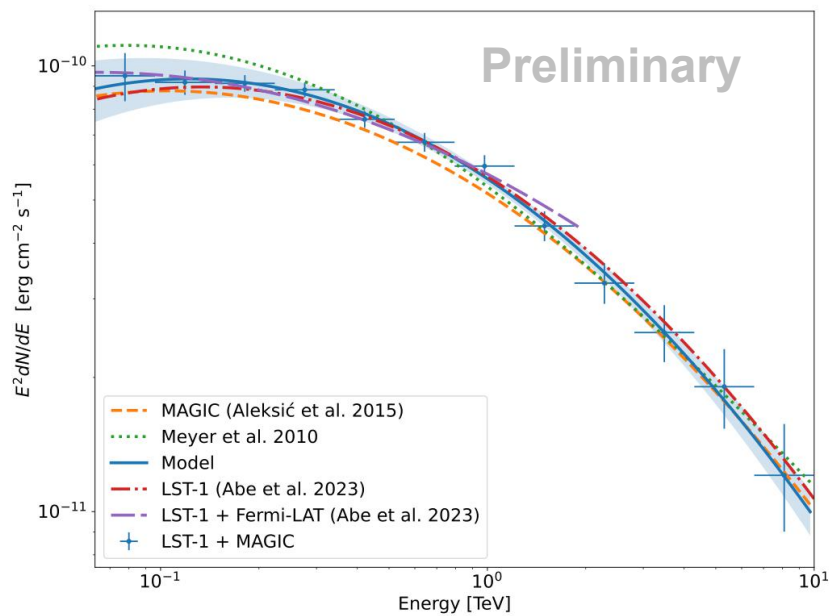
- Three-telescopes events are the dominating fraction and LST-1 sees most of the events that MAGIC sees
- MAGIC-only events in 3-telescope analysis are mostly background --> removing them improves background rejection!
- Recovering events that in MAGIC-only analysis would be rejected because they do not pass the selection (i.e. too dim images) in one of the two MAGIC telescopes --> increase in collection area!

Energy threshold (reconstruction level)



- The energy threshold, considering events with at least two images, goes down from 70 GeV (MAGIC-only) to 60 GeV (MAGIC+LST-1)
- The collection area is also higher, especially at low energies
 - factor ~ 2 at 30 GeV
 - factor ~ 1.5 around 50 GeV
 - factor ~ 1.2 around 100 GeV

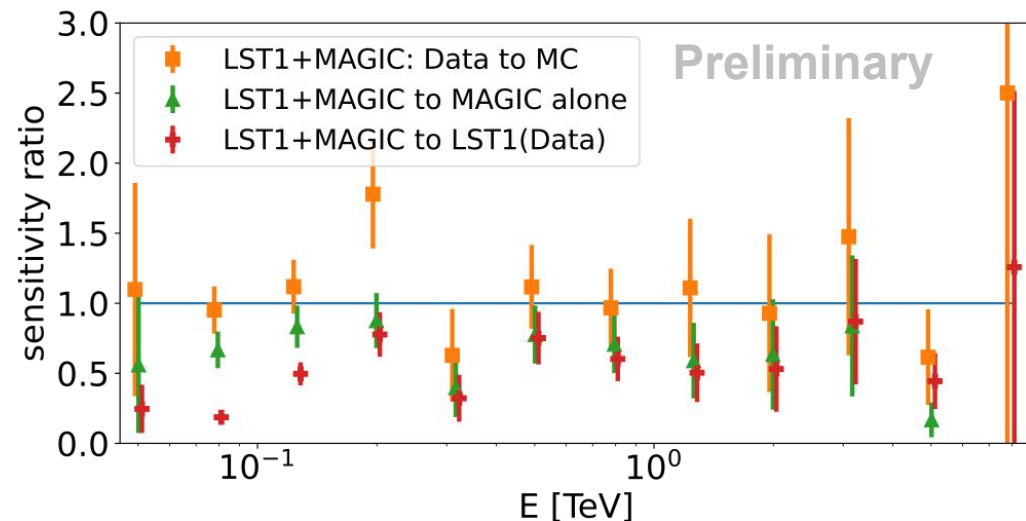
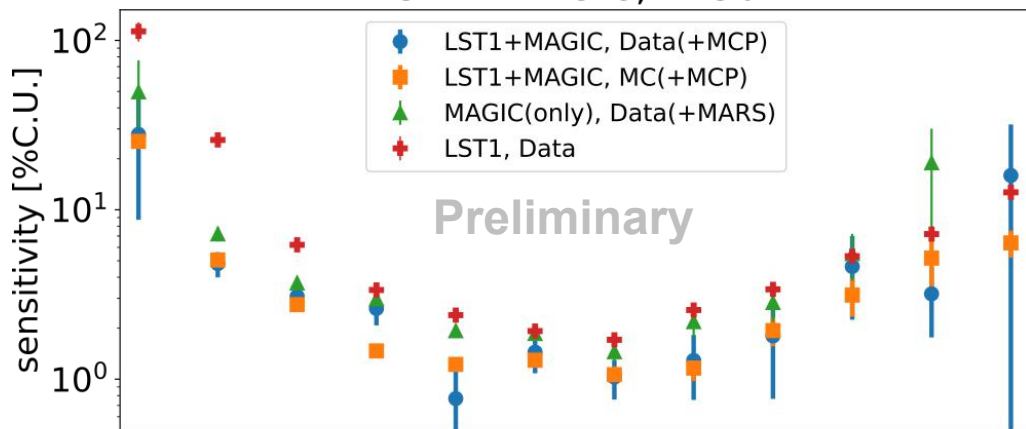
Crab Nebula spectrum and light curve



- Using ~4h of data from the Crab Nebula (period: October 2020-March 2021)
- Spectrum is consistent within ~10% with previous measurements
- Light curve shows some flux instability, probably related to systematics --> ~12% (8%) systematic uncertainty needed for run-by-run (night) analysis to be consistent with a constant flux (similar to MAGIC studies)

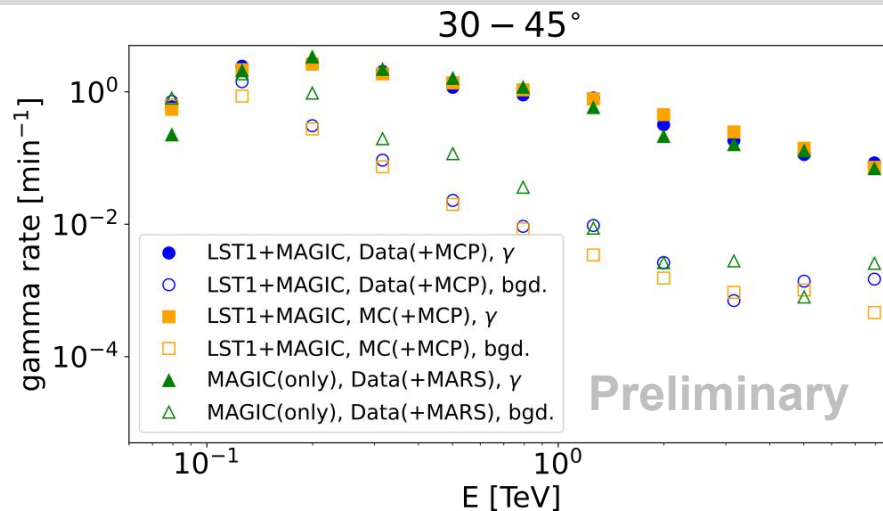
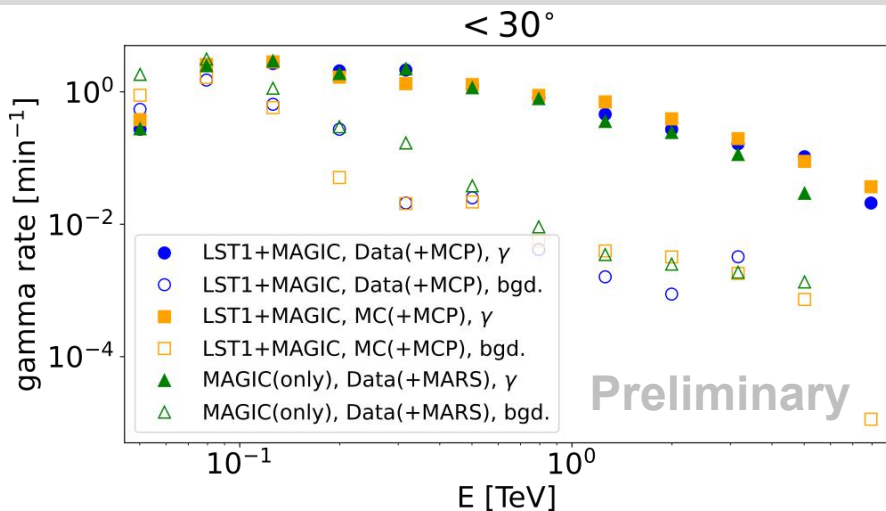
Differential flux sensitivity

LST1+MAGIC, $< 30^\circ$



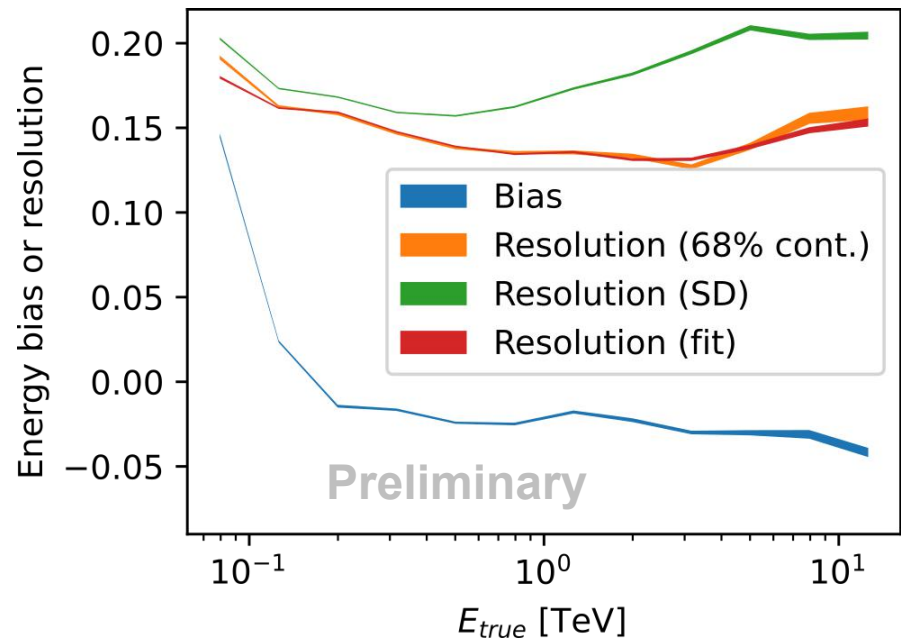
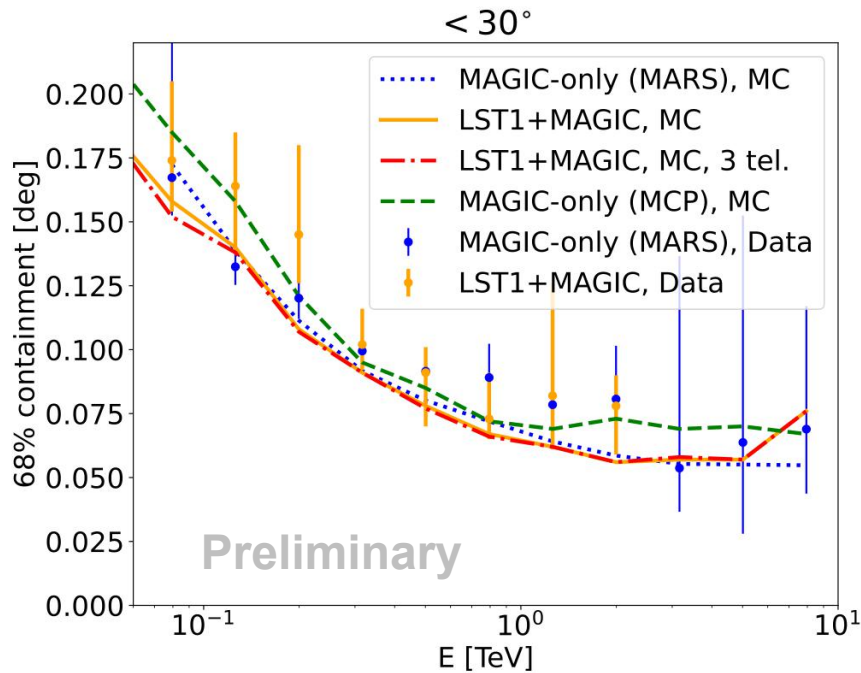
- Joint observations allow detection of 30% (40%) lower fluxes than MAGIC alone (LST-1 alone)
- Main reason is the better background rejection (see next slide)
- Increased sensitivity translates in less observation time to detect the same flux level

Gamma/background rates comparison



- Better background rejection across almost all the energy range, which improves the sensitivity
- Some improvement of gamma-ray rate at multi-TeV energies: either the cuts can be relaxed, or additional high impact events are reconstructed

Angular and energy resolution



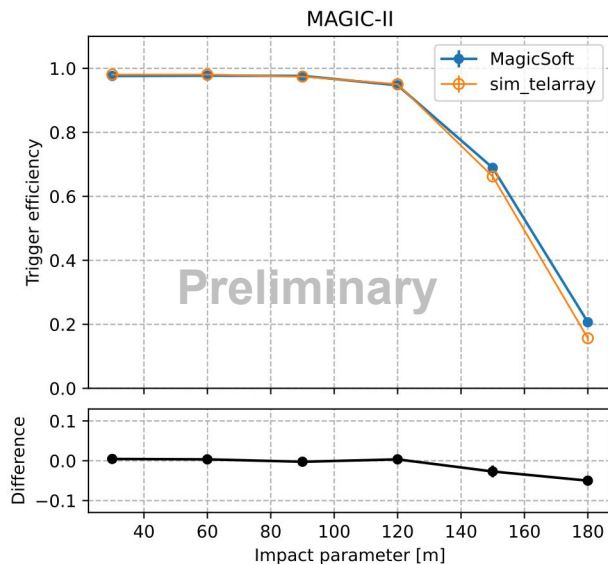
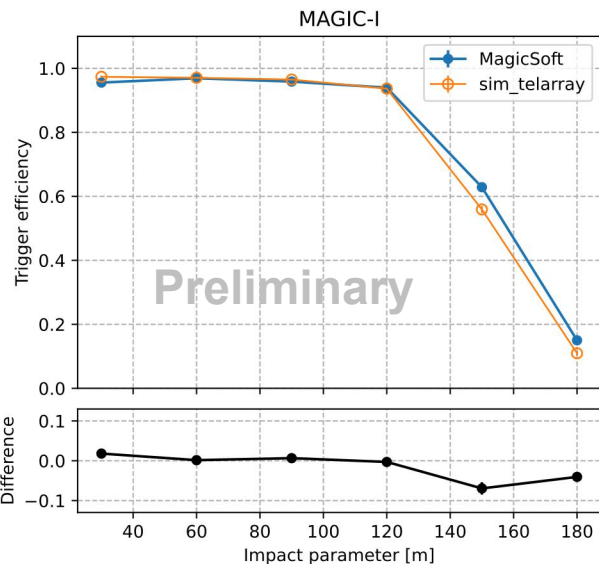
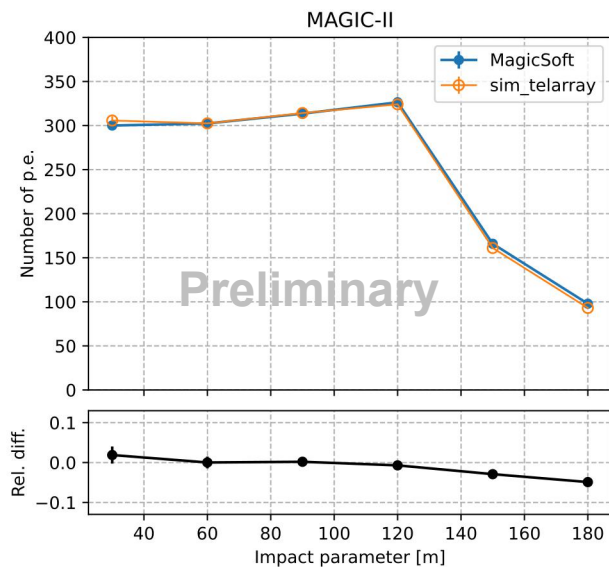
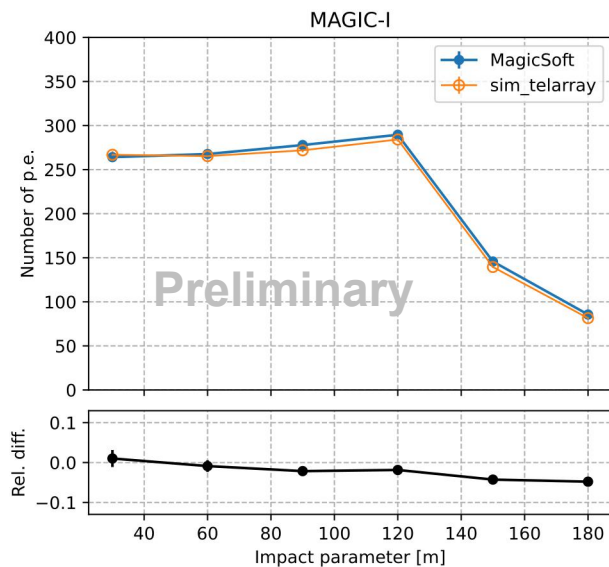
- Angular and energy resolution show only slight improvements wrt MAGIC-only: probably due to optimized methods used in MAGIC-only analysis and not implemented in MAGIC+LST-1
- Some data/MC mismatches at high energies for angular resolution

Summary

- Proximity of MAGIC and LST-1 makes joint analysis possible
 - a pipeline was developed for this specific purpose
 - first study of stereoscopic analysis scheme applied to the data taken with a prototype of a CTA telescope
- Good match between the MAGIC+LST-1 reconstructed Crab Nebula spectrum and previous measurements
- Joint observations allow detection of 30% (40%) lower fluxes than MAGIC alone (LST-1 alone)
 - mainly better background rejection
 - less observation time!
- “Performance paper” under review: stay tuned for the final publication!

BACKUP

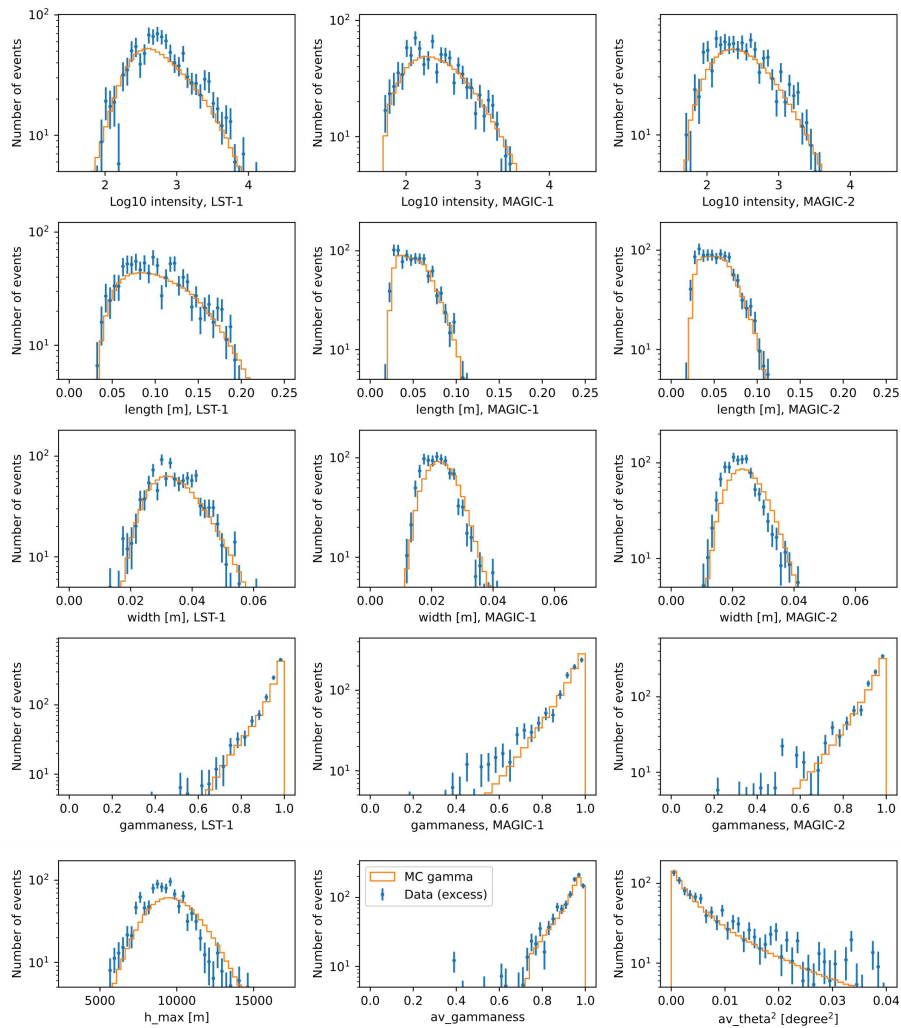
Simulation validation



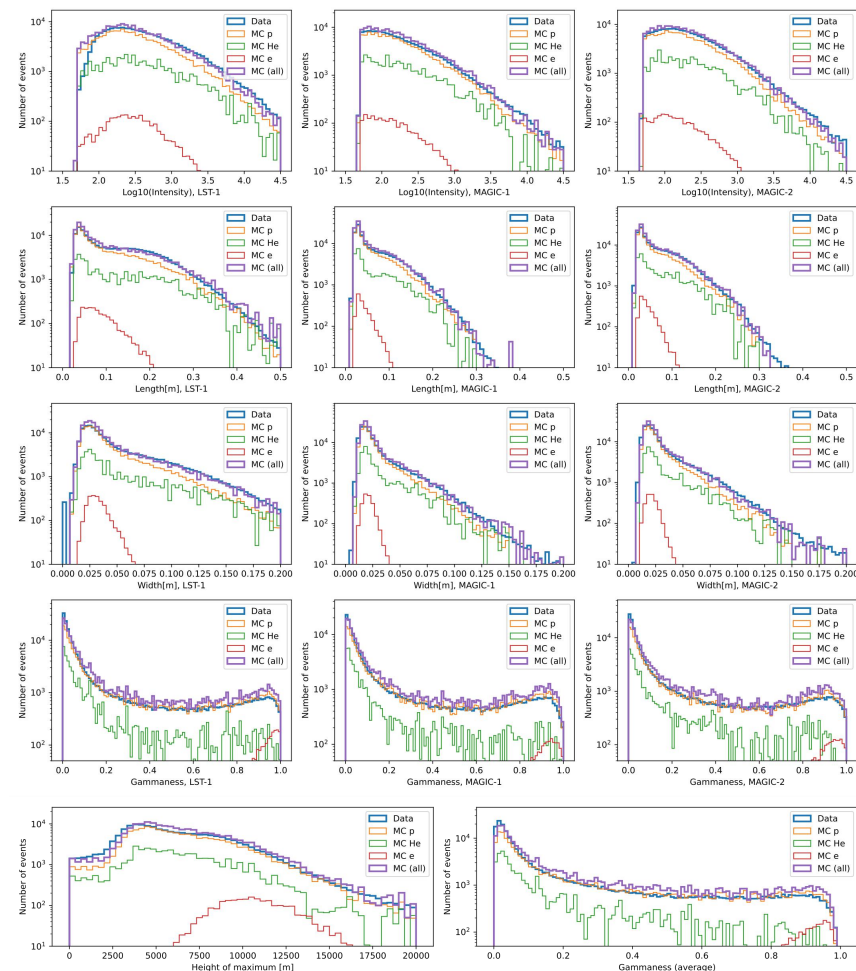
- Validated sim_telarray simulation of MAGIC telescopes with 100 GeV vertical gamma-ray showers, at different fixed impact parameter
- Compared the reconstructed true number of p.e. and trigger efficiency, agreement at few % level

Data-MC comparisons

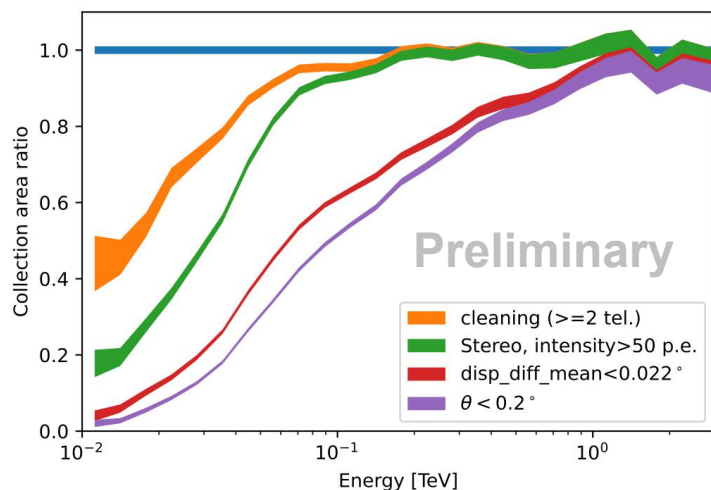
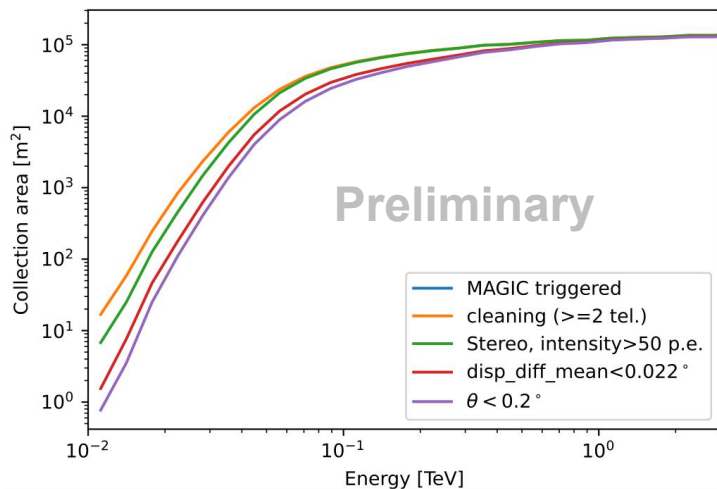
MC gamma-rays and gamma-ray excess from data



MC (p, He, e) and data

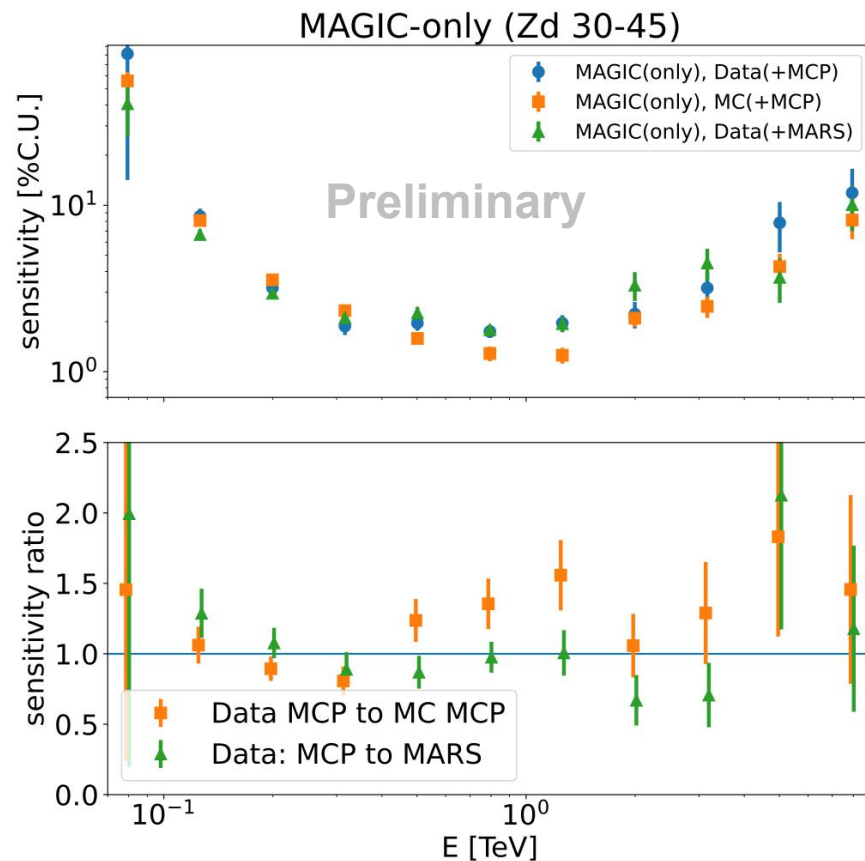
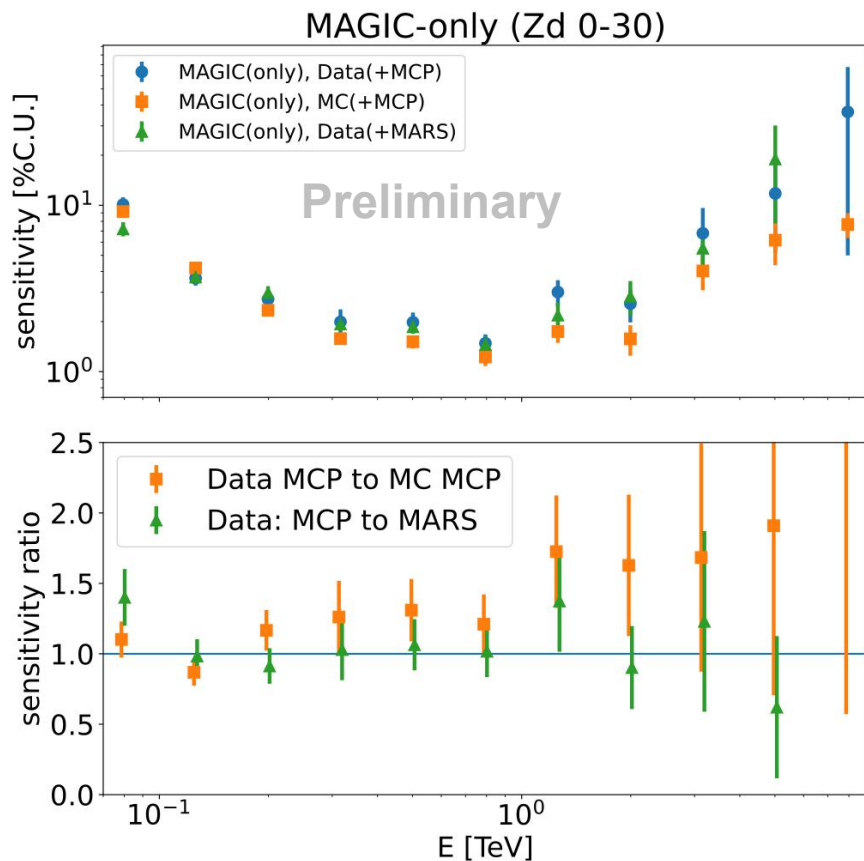


Effective area



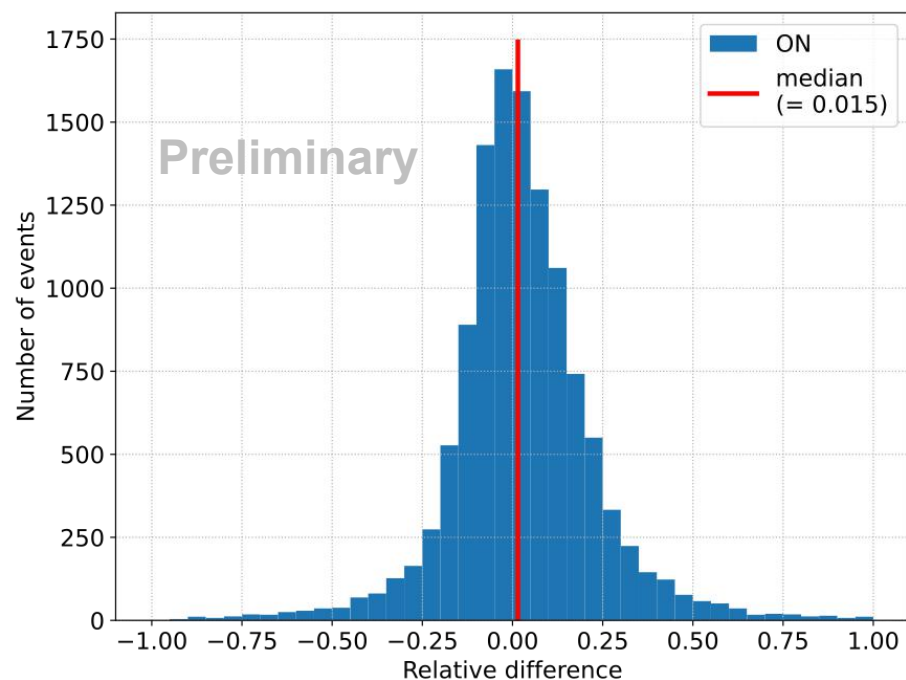
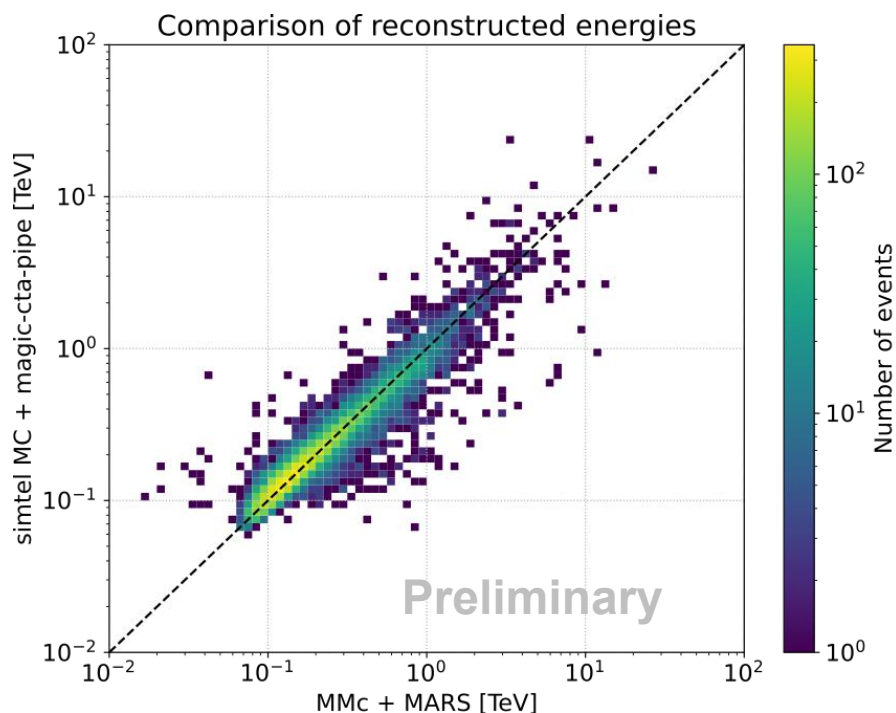
- Collection area for simulated gamma rays, for zenith=10 degrees and different level analysis stages
- For energies above 80 GeV, most MAGIC events survive stereoscopic reconstruction
- Drop when requiring agreement between the reconstructed position in different telescopes

MAGIC-only sensitivity



Good agreement, especially in medium energy range, between sensitivities obtained on MAGIC-only data analyzed with MARS and MCP

Energy reconstruction



Comparing the energy estimation of the same gamma-like events for MAGIC-only events reconstructed with MARS and MCP, consistency around 2%