Improving CTAO event reconstruction at high energies

CTAO-Australia Spring Meeting 2025

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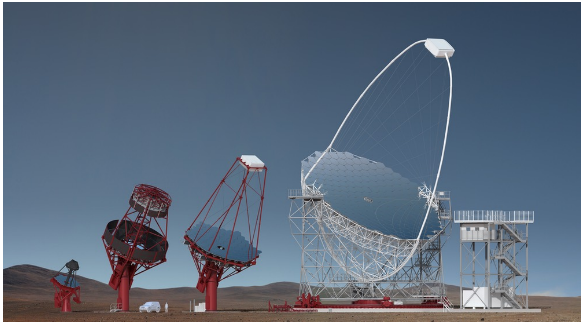
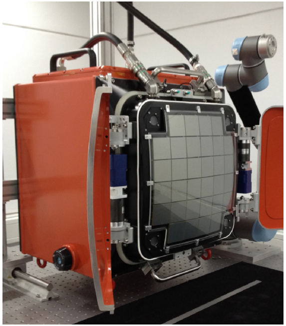
Project aims

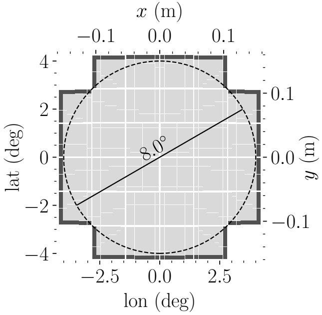
- Optimise the reconstruction, identification, and collection of the highest energy γ-rays.
- High energy events are bright, can trigger from **long distances** ($>$500 m).
- These might be seen by only one telescope (**mono**), or shower images may be **truncated** by edge of FOV of telescopes.
- The Small-Sized Telescopes (**SSTs**) are key to this work.



CTAO telescope scales.
Credit: Gabriel Pérez Diaz (IAC).

The Small-Sized Telescope





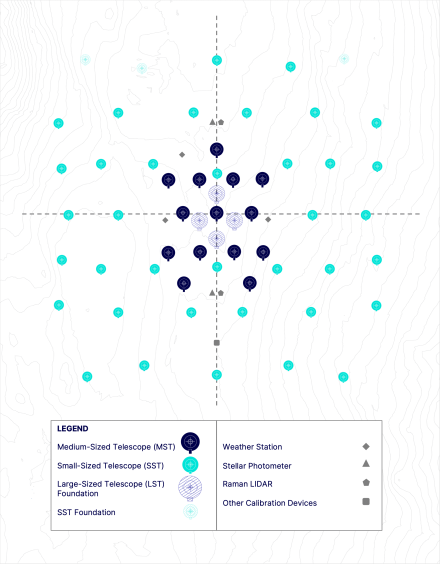
Credits: Akira Okumura (left), J.S. Lapington (middle).

- Effective mirror area: $\sim 5\,\mathrm{m}^2$.
- Optimal energy range: 5 TeV to 330 TeV.
- Silicon photomultipliers (SiPM).
- 2048 square pixels.
- FOV: 8° to 9°.

CTAO-South array

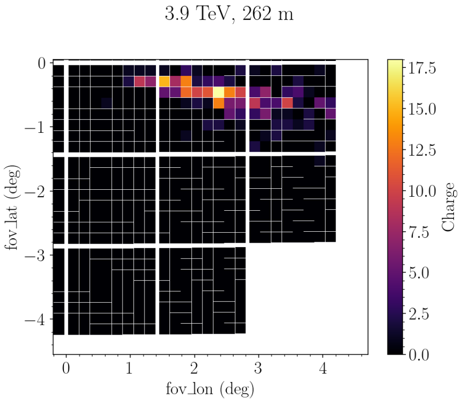
- Located at 2147 m ASL in Paranal, Chile.
- The "Alpha" array layout has 14 MSTs and **37 SSTs**.
- Array footprint is about 1.6 km by 1.6 km.
- Foundations laid for other telescopes, for future upgrades.

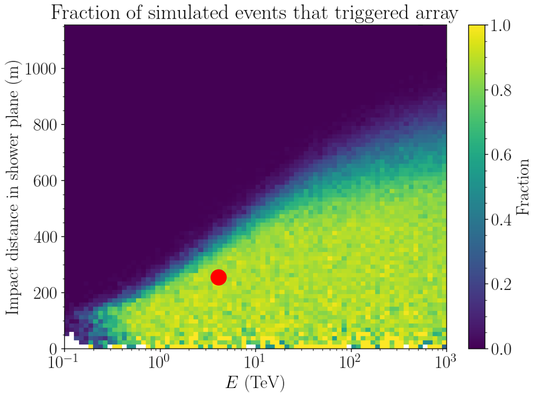
Events will trigger **up to** $\sim$1000 m from each SST (20° zenith).



Air showers in Cherenkov telescopes

- γ-ray events are generally 10s of nanoseconds long.
- SST camera has 1 ns time resolution.
- Air shower images appear elliptical when summed up in time.
  - Shape depends on energy and impact distance.





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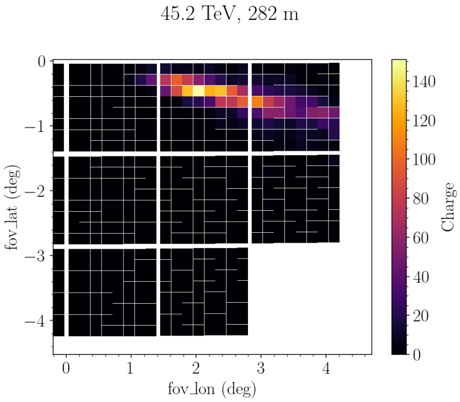

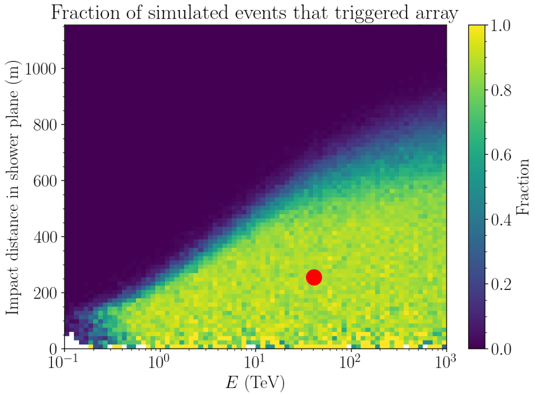

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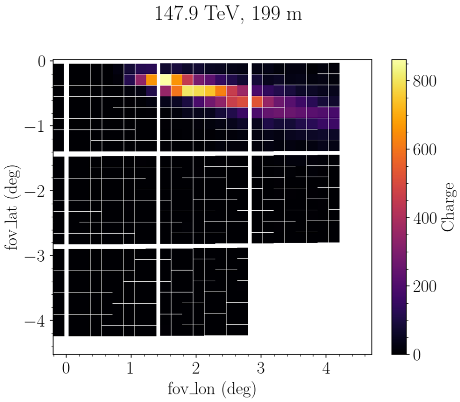

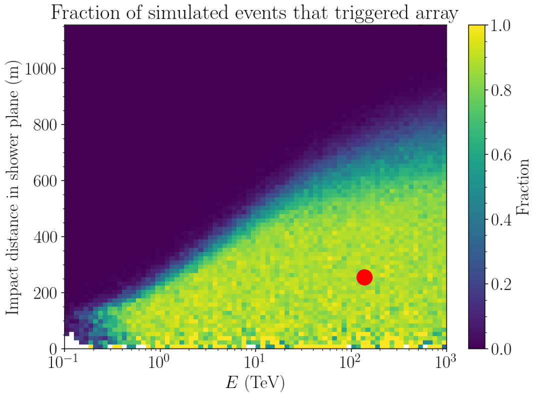

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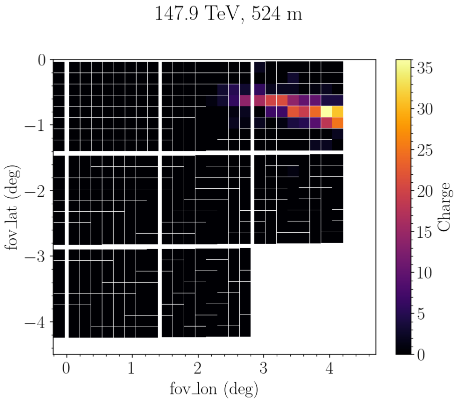

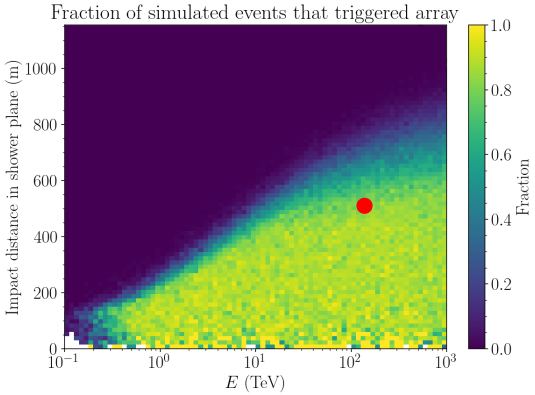

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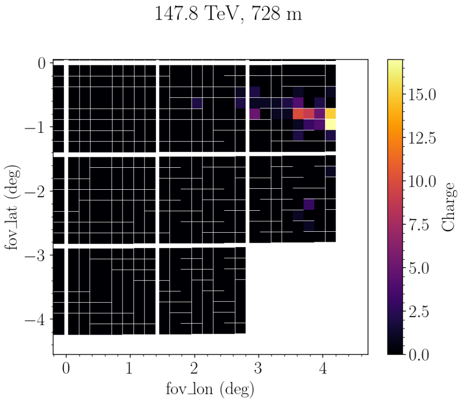
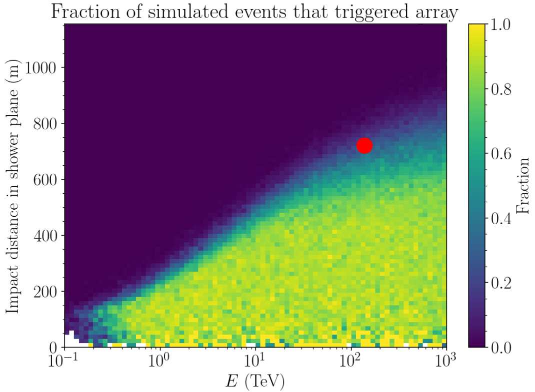
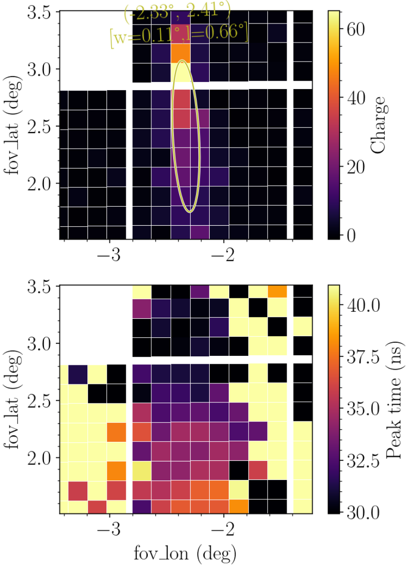




Review of IACT analysis

1. Calibration
2. Signal extraction:
   - Integrate total charge from waveform (trace).
3. Image cleaning:
   - Find signal pixels, remove noise pixels (NSB, electronic).
4. **Feature extraction:**
   - **Hillas parametrisation** (PCA):
     - ⋆ Width, length, asymmetry.
     - ⋆ Intensity, axis angle.
     - ⋆ Centre of gravity (COG).
   - **Time gradient**.
   - Leakage.
   - Concentration.
   - Stereo reconstruction for source/impact position.



Review of IACT analysis

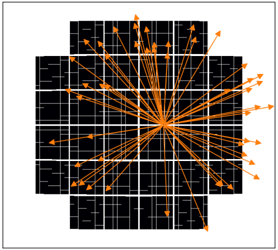
5 Energy regression and γ–h classification:

- Reconstruction is done with machine learning: usually **random forest** (RF).
- RF is trained on Monte Carlo simulations where the truth is known.
  - Provided the *features*, it learns to predict the *energy* or *gammaness*.
- To avoid bias, RF is trained on **diffuse** γ-rays but performance is tested on **point-source** γ-rays.
  - **Real data** is (usually) point-source.

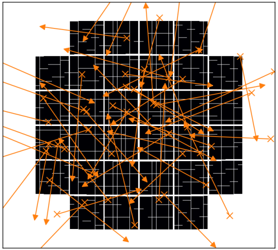
6 Event lists / IRFs

7 Science!

Point-source

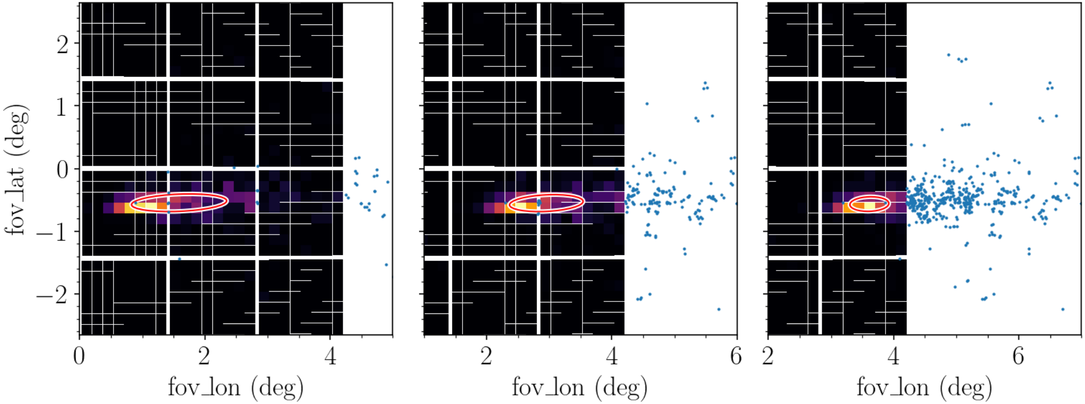


Diffuse



Review of IACT analysis – Truncated images

- Hillas parametrisation becomes distorted as shower image nears edge of camera.
- Intensity also underestimated due to missing charge.



Blue points mark Cherenkov photons that did not land on a pixel.

Handling truncated images

CTAO

- To **quantify** truncation, a variable called **intensity leakage** has typically been used: fraction of total collected charge that landed in edge pixels.
- Can also estimate truncation by **distance from centre of camera to the COG**.
- *Typically*, leakage is used for two things:

Selection cut

- A selection cut may be placed on leakage, to improve reconstruction performance. E.g., leakage < 0.2.
- Can also cut on the radial distance.

RF feature

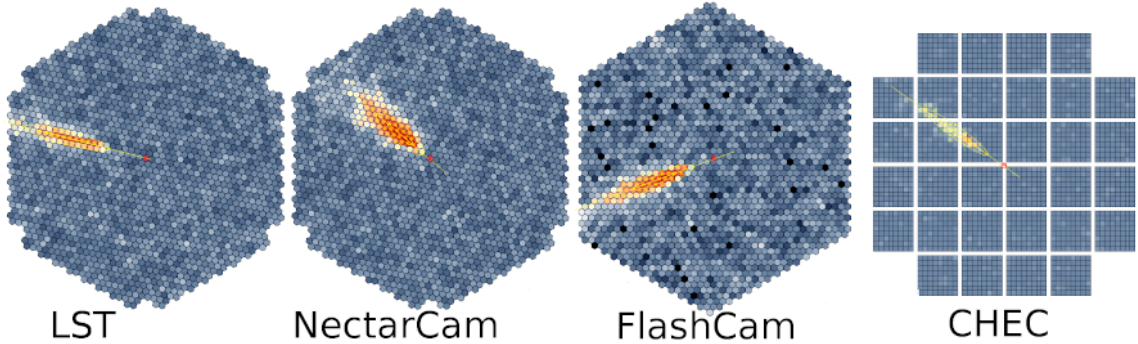
- Leakage is passed to the RF as an image feature to help it learn to "compensate" truncation.
- Radial distance helps this too.

Complications of the leakage definition

1. SST camera has rather unique edge effects that influence leakage.
2. Diffuse γ-rays cross edges at all different angles.

Unique issues for the SST

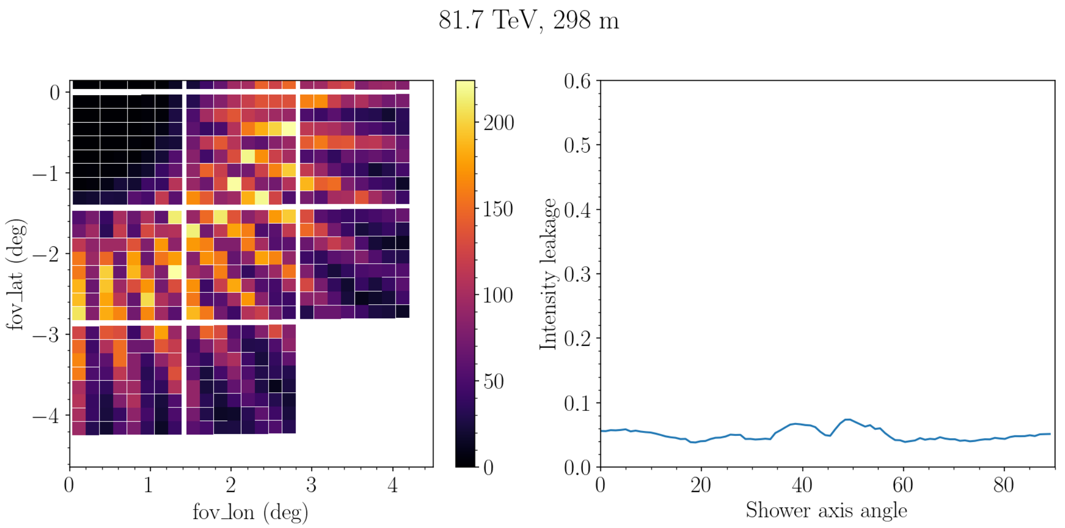
- Cherenkov telescopes typically use hexagonal pixels, arranged in a “circular” fashion.
- The SST camera (CHEC) is unusual in being so square.



Credit: Konrad Bernlöhr (CTAO).

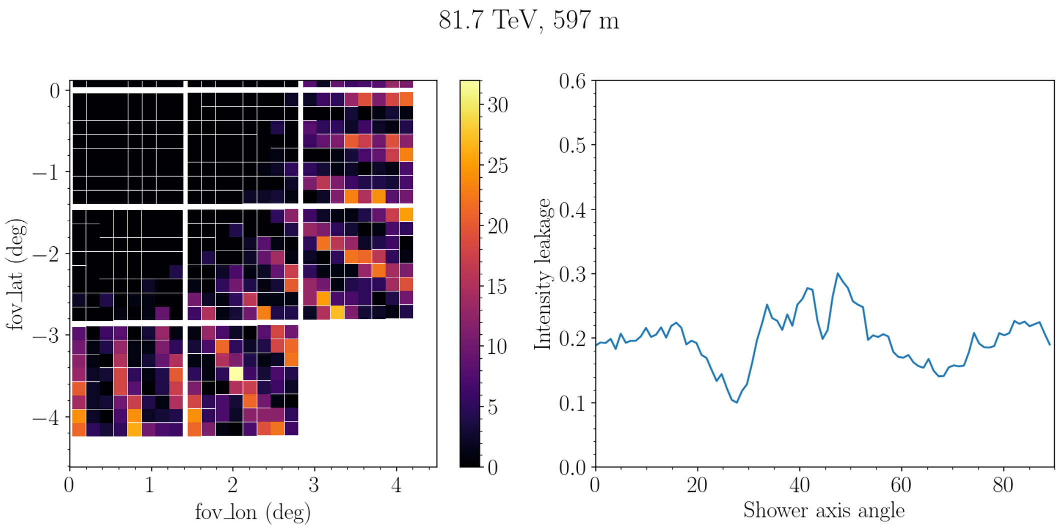
Unique issues for the SST

Same shower at different axis angles.



Unique issues for the SST

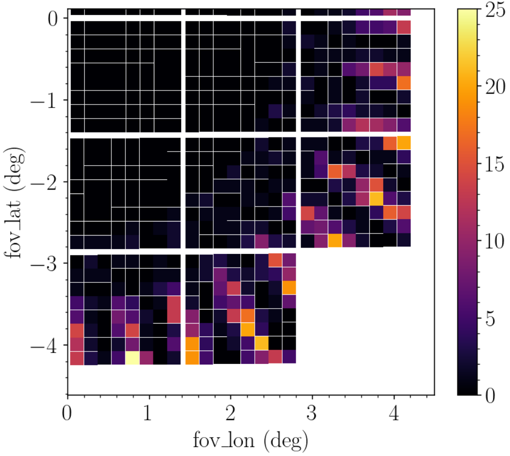
Same shower at different axis angles. Move it to different impact distances... (**2/3**)

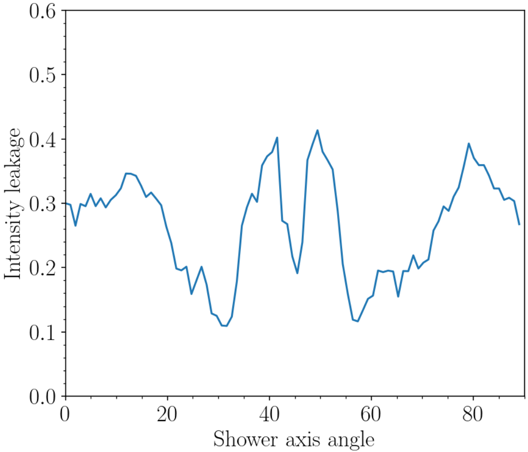


Unique issues for the SST

Same shower at different axis angles. Move it to different impact distances... (**3/3**)

81.7 TeV, 639 m





A new measure of truncation

- Higher leakage events typically have poorer energy reconstruction, hence leakage generally is used for a quality cut.
- Leakage teaches the RF model how to compensate for **missing charge** and **misshapen length and width**.
- However, leakage alone does not *really* map onto how much charge is missing – it's not mathematically motivated or intuitive.

We introduce a **new parameter** that describes the effect of missing charge in a better way.

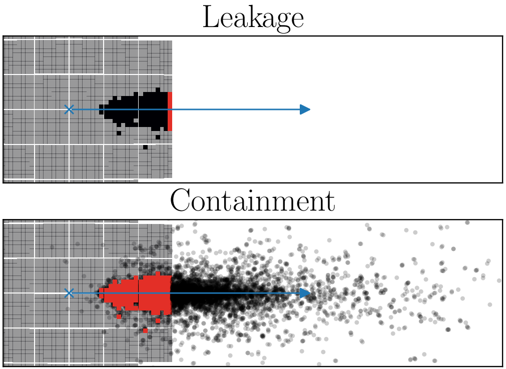
A new measure of truncation

Leakage: Fraction of the total **collected** charge that landed in **edge** pixels.

Containment: Fraction of total **photons** that were **collected**.

(Can only be calculated in MC.)

Containment a better proxy for how much of the shower was seen $\rightarrow$ how good the reconstruction might be.



A new measure of truncation

Containment relates the **observed intensity** to the true shower brightness, and in turn to the true **energy**.

We define "true" containment by

$$\textbf{true containment} = C_{\textbf{true}} = \frac{\textbf{observed intensity (in clean pixels)}}{\textbf{total number of Cherenkov photons}} .$$

After we **reconstruct** the containment, we use it to recover

$$\textbf{true intensity} = \frac{\textbf{observed intensity}}{\textbf{containment}} .$$

Reconstructing the containment

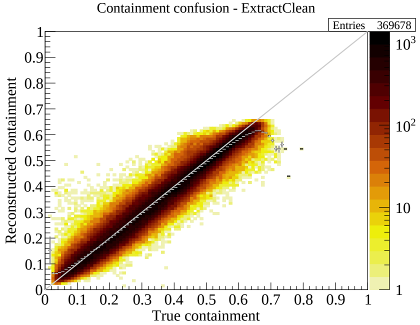
Method:

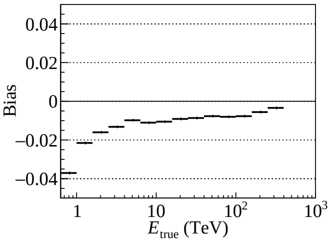
- We use an RF model to **reconstruct** containment.
- Provide all the usual image features.
  - **Leakage** is the most important.

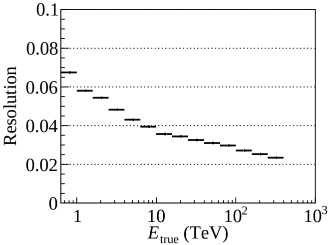
Performance:

- Reconstruction performs very well!
- Maybe not too surprising, though...
  - Energy regressor *normally* does something like this.

The **key point** is that we've made this variable explicit, so we can control it better and even use it as a quality cut.







Using containment to improve reconstruction

Compare performance of a “standard” analysis with our “new” analysis.

“Standard” analysis energy regressor is trained with intensity and leakage as **two separate** features.

For this “new” analysis we **combine** intensity with reconstructed containment to estimate the “true” intensity directly.

Standard feature set

- ln(intensity)
- leakage
- length
- width
- ⋮

New feature set

- ln(intensity/containment)
- containment
- length
- width
- ⋮

Using containment to improve reconstruction

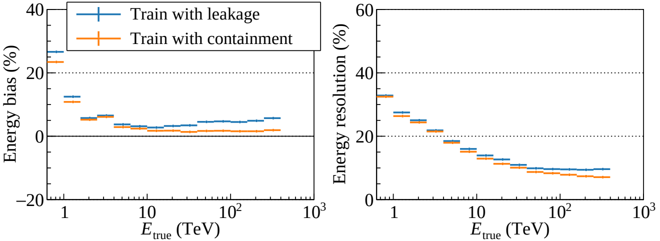
This is mono (single-telescope) performance!

Testing point-source γ-rays at 1° offset.

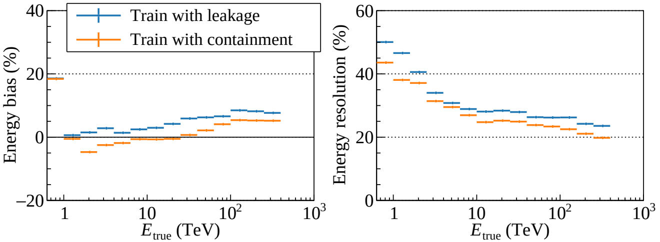
Energy

We achieve modest improvements in both energy bias (left) and resolution (right), for all levels of truncation.

Well-contained events $(C_{\mathrm{true}} > 0.5)$



Truncated events $(0.2 < C_{\mathrm{true}} < 0.4)$



Using containment to improve reconstruction

CTAO

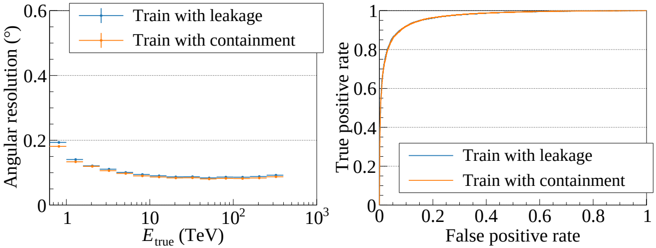
Angular resolution (left)

Some small improvement, for truncated images only.

γ–h classification (right)

No better, no worse.

Well-contained events ($C_{\text{true}} > 0.5$)



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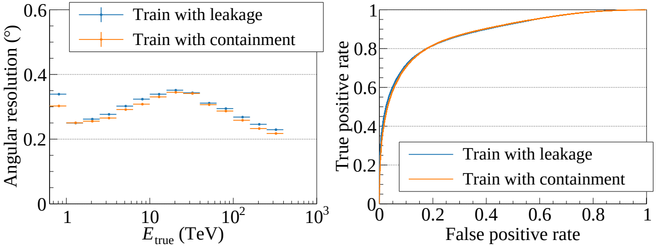


Using containment to improve reconstruction

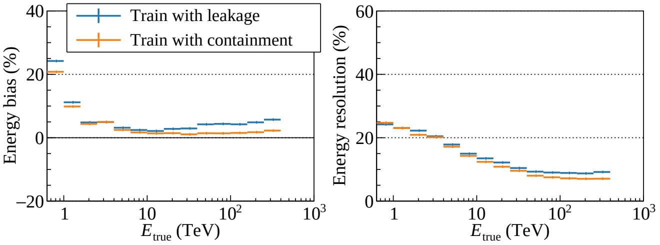
Energy with cuts

Improvements are consistent even if we introduce reasonable (not yet tuned!) cuts such as for a point-source study.

- Off-angle $\Theta < 0.2°$.
- Gamma-score > 0.8.

Mostly improves performance at lower energies.

Well-contained events ($C_{\text{true}} > 0.5$)



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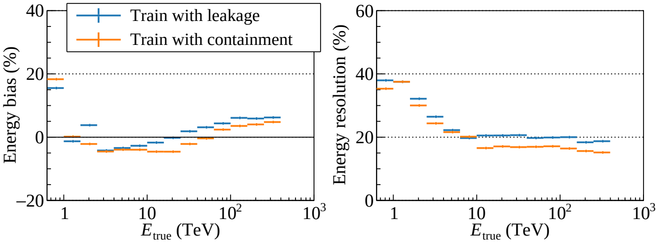
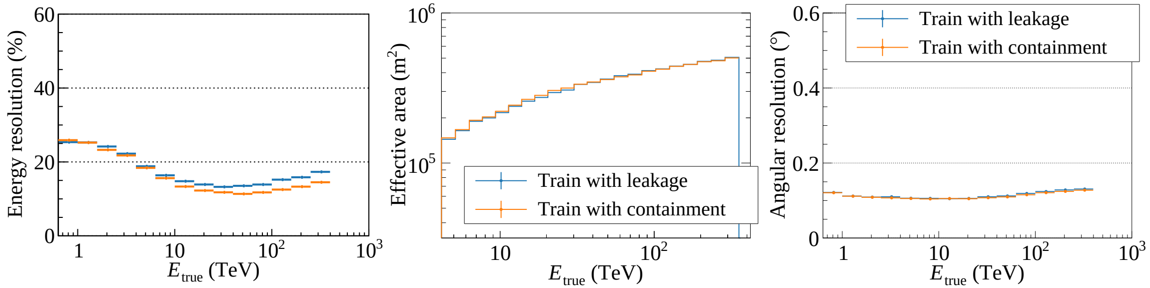


Improving the effective area

Use containment to make a better quality cut than leakage: Here we seek the *most relaxed truncation cut* that gets energy resolution below 10 % above 100 TeV.

This retains the aforementioned cuts on Θ and gamma-score.

Without truncation cut | With leakage $<$ 0.06 or containment $>$ 0.24



By using containment as the cut variable, we get up to a **∼60% higher** effective area, without compromising angular resolution. Useful for **source discovery** or similar studies.

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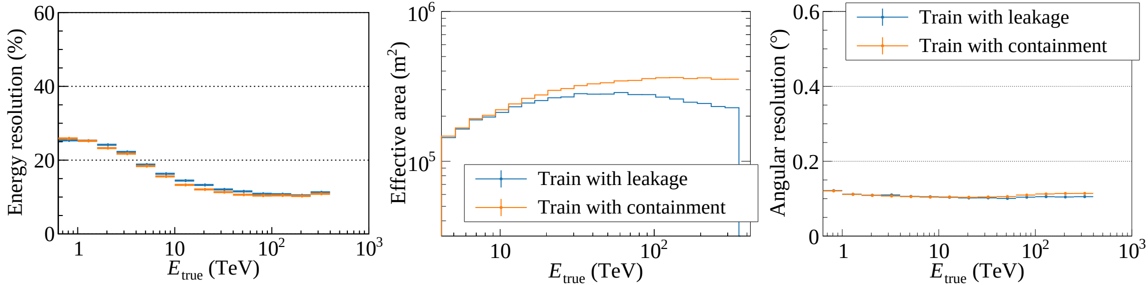


By using containment as the cut variable, we get up to a **~60% higher** effective area, without compromising angular resolution. Useful for **source discovery** or similar studies.

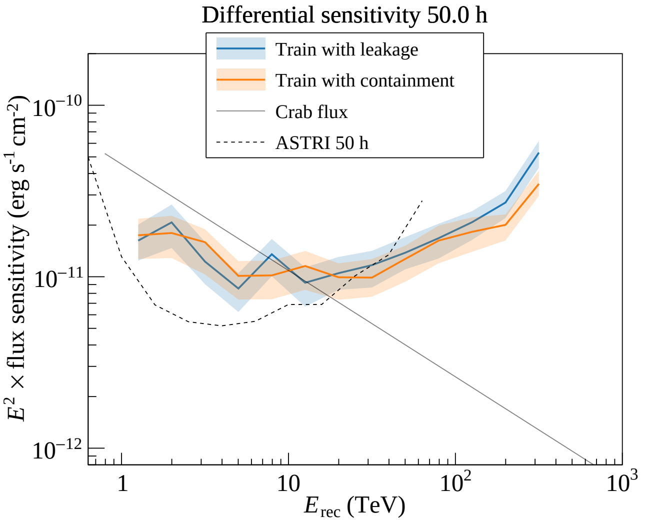
Improving the sensitivity – PRELIMINARY

Point-source sensitivity of a 50 h observation.

Analysis needs further optimisations, but we do see some improvement in the highest energy bin.

Reminder: this is **mono** performance.

Source: ASTRI-1: Early Data and Performance Highlights - ICRC2025.

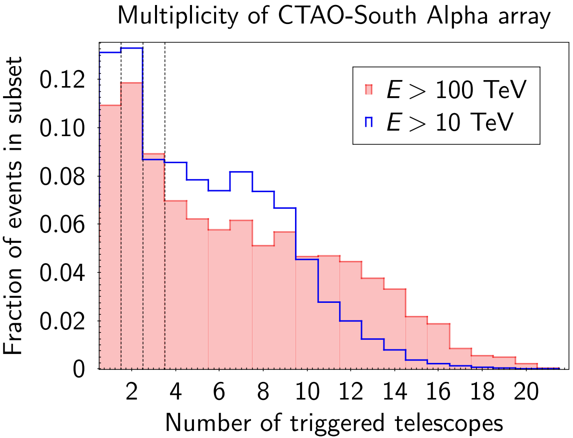


Next steps - stereoscopic reconstruction

- Improvements for monoscopic performance are useful, but CTAO-South will have **37 SSTs**.
- Maybe ∼30 % of point-source γ-rays are mono, or a few telescopes with small stereo angle.
- For events landing outside of the array, best results found by taking the weighted average of mono recons.

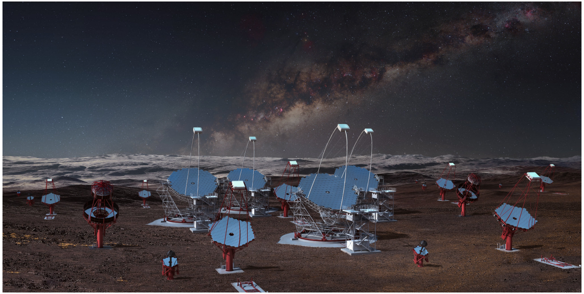
By improving the mono analysis, we help stereo events too.

Next step is to demonstrate this.



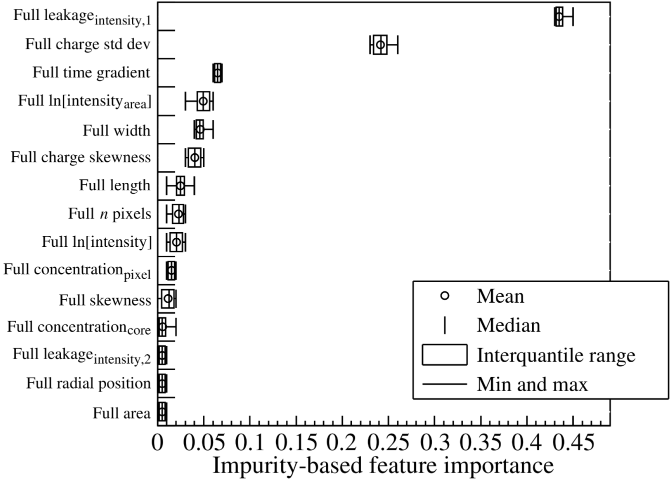
Conclusion

- Highest energy γ-rays are rare and often truncated.
- Existing measure of image truncation is somewhat obscured and sub-optimal.
  - The SST design especially makes for new challenges.
- It already does a decent job, but...
- ...by using containment to parametrise truncation, we can **very cheaply** get further performance improvements.
- Paper in production.



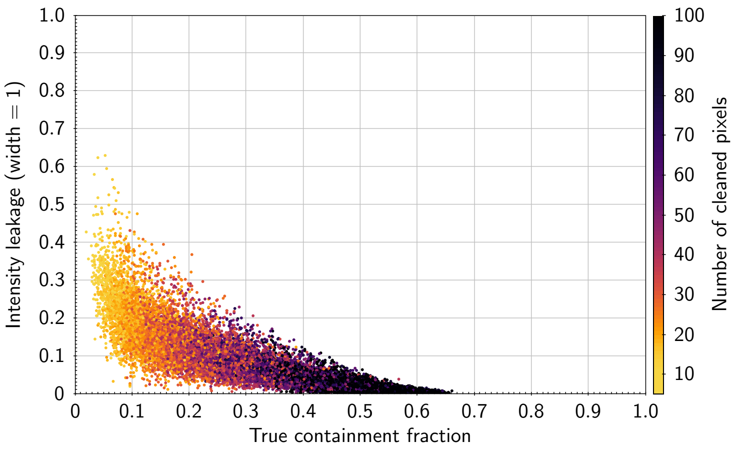
Credit: Gabriel Pérez Diaz (IAC) / Marc-André Besel (CTAO) / ESO / N. Risinger (skysurvey.org).

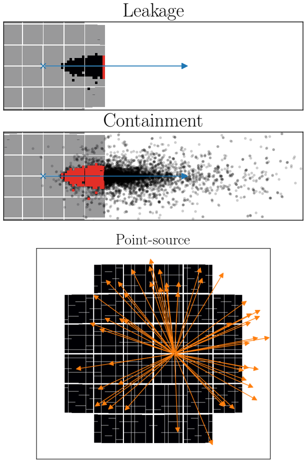
Features relevant to containment reconstruction



Leakage vs containment

- For **point-source** γ-rays, leakage somewhat correlates with containment.
- Scatter due to the corner effects...





Leakage vs containment

- For **diffuse** γ-rays, leakage does not really correlate with containment.
- Leakage is clearly an imprecise parameter on its own.