Improving CTAO event reconstruction at the highest energies

CTAO-Australia Autumn Meeting 2025

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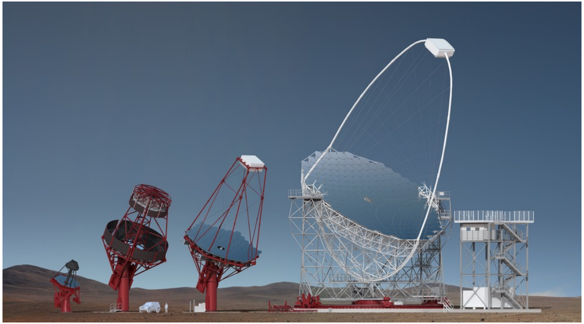
Project aims

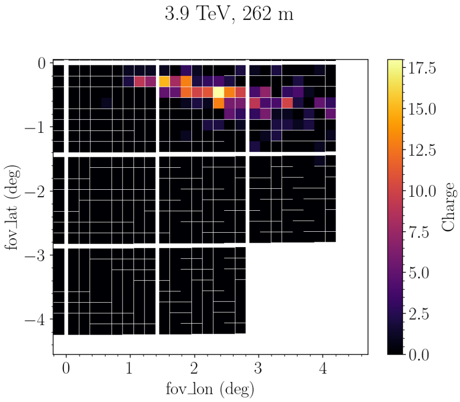
- Optimise the reconstruction/identification of the highest energy γ-rays.
- When within or near the array, existing stereoscopic techniques should handle well.
- However, being very bright, many events will trigger from **long distances** ($>$500 m).
- These might be seen by only one telescope ("**mono**"), or shower images may be "**truncated**" by edge of FOV of telescopes.
- The Small-Sized Telescopes (**SSTs**) are key to this work.
  - Effective mirror area: $\sim$5 m^2.
  - FOV: 8.8°.
  - Energy range: 5 TeV to 330 TeV.

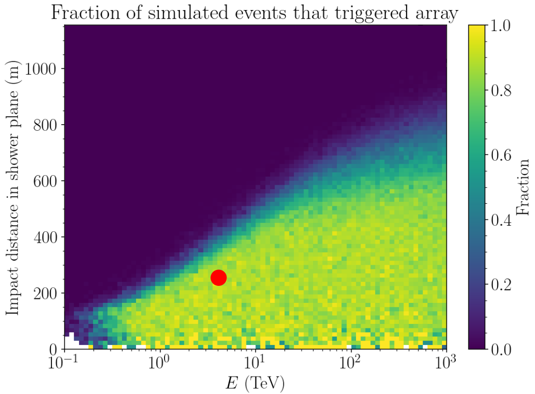


CTAO telescope scales.
Credit: Gabriel Pérez Diaz (IAC).

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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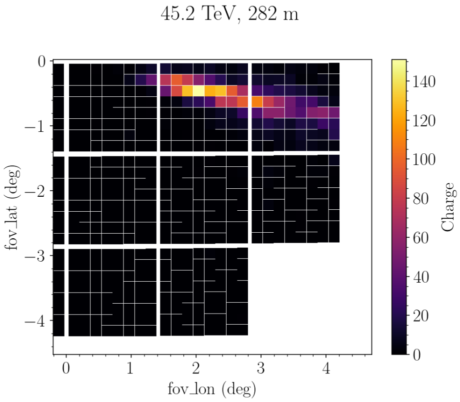

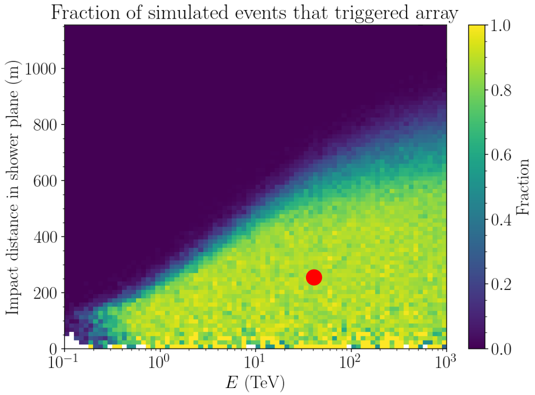

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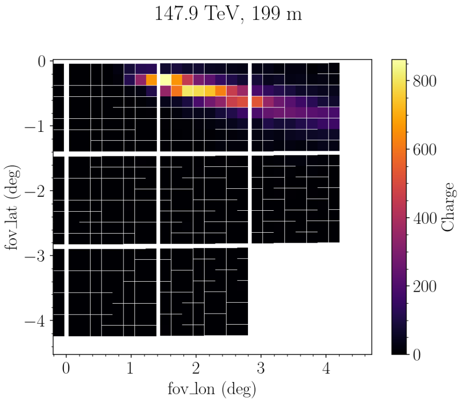

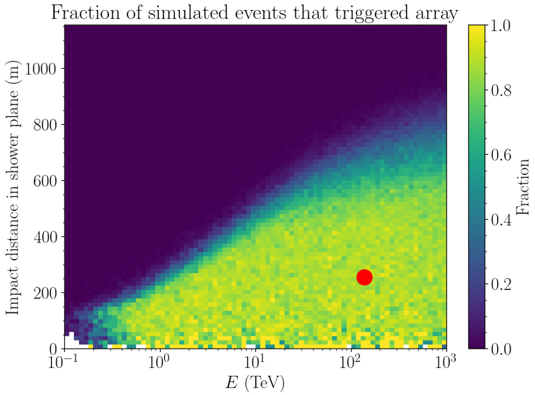

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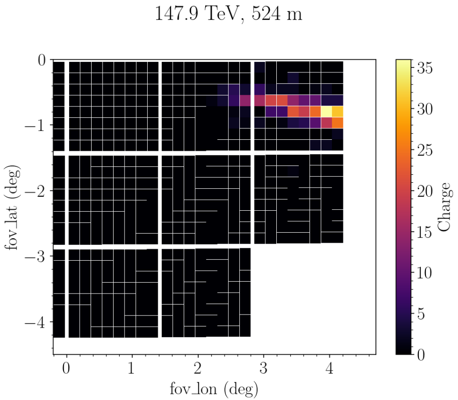

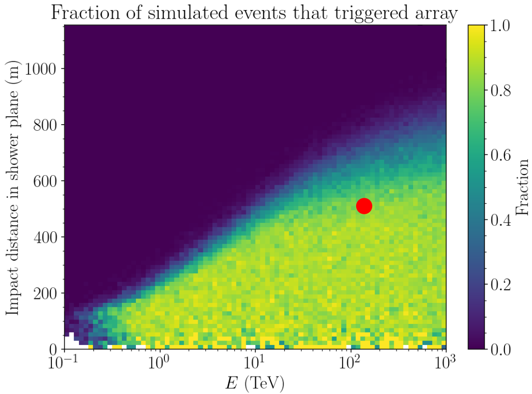

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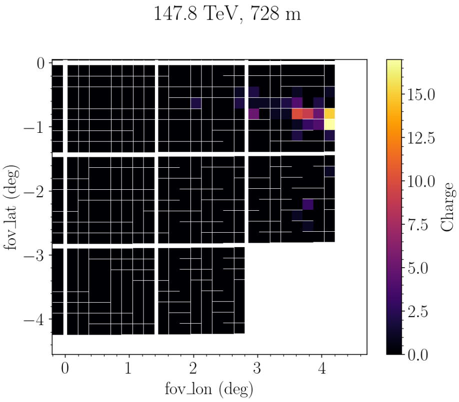
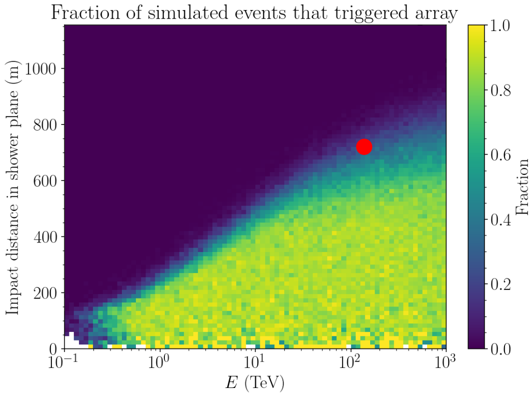
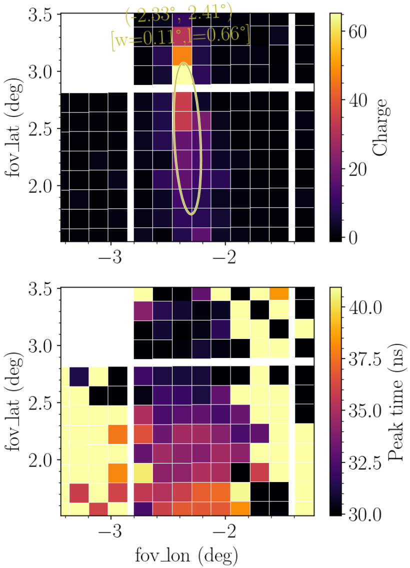




Review of IACT analysis

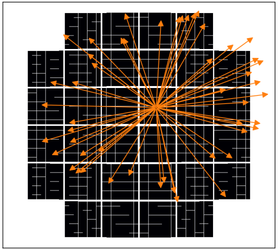
1. Calibration
2. Signal extraction:
   - Integrate total charge from waveform (trace).
3. Image cleaning:
   - Find signal pixels, remove noise pixels (NSB, electronic).
4. **Feature extraction:**
   - **Hillas parametrisation** (PCA):
     - ★ Width, length, asymmetry.
     - ★ Intensity, axis angle.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



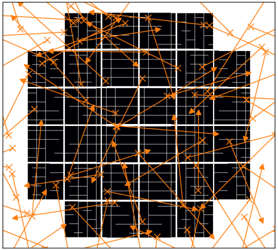
Review of IACT analysis

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

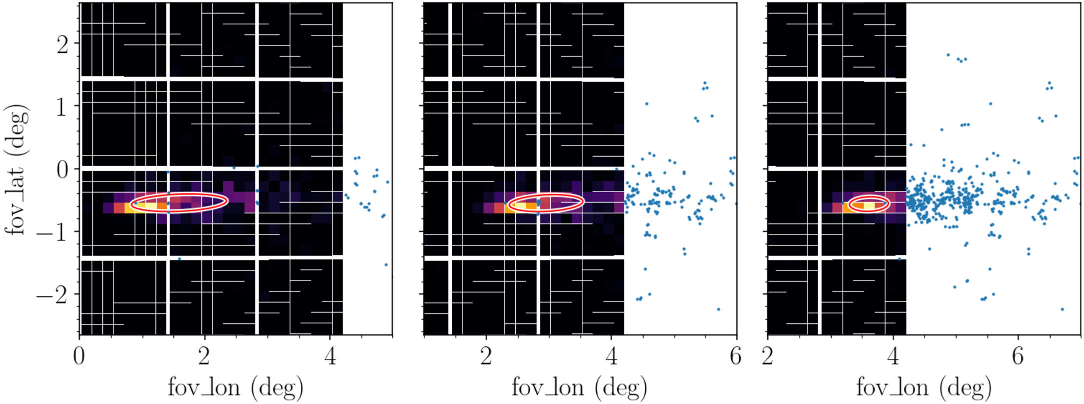


Diffuse



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.

Typical handling of truncated images

- To **quantify** truncation, a variable called **intensity leakage** is used: fraction of total collected charge that landed in edge pixels.
- No standardised approach... But similar practices between IACT experiments.
- *Typically*, leakage is used for two things:

Selection cut

- A selection cut is placed on the leakage.
- E.g., typical cut is leakage < 0.2.

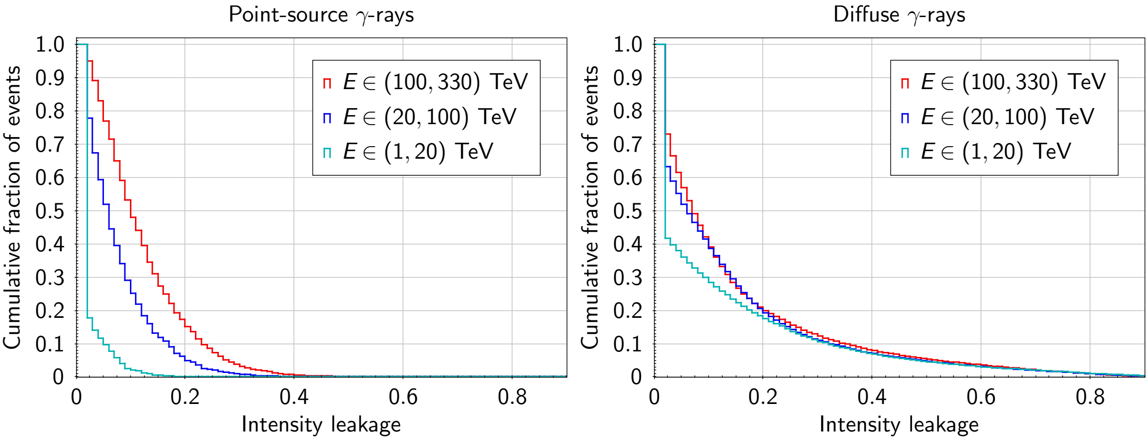
RF feature

- Leakage is also passed to the RF as an image feature.

Let's look closer at the consequences of both of these.

Typical handling of truncated images

What fraction of events are discarded by a cut at 0.2?



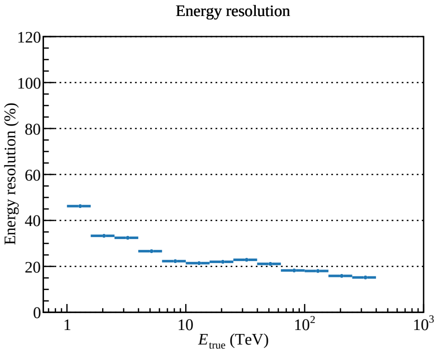
Depends if γ-rays are point-source or diffuse, but up to 20 % of the highest energy events may be discarded!

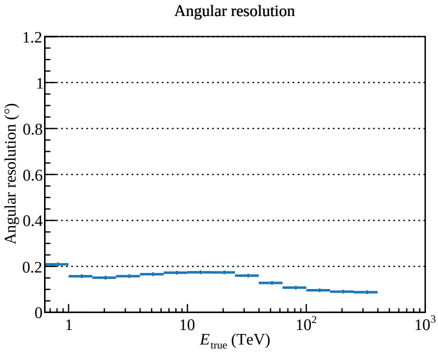
Typical handling of truncated images

How do truncated images perform in the RF analysis?

Mono reconstruction (i.e., one telescope), tested on point-source γ-rays.

leakage $\approx$ 0





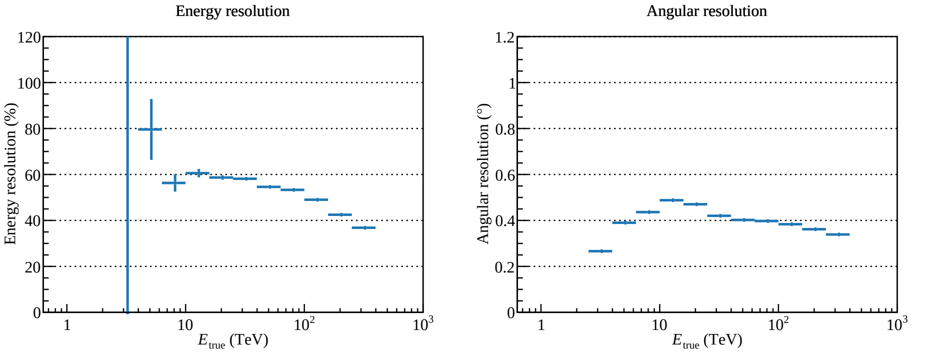
Energy assignment deteriorates but angular resolution still reasonable. The RF is good at compensating for truncation.

Typical handling of truncated images

How do truncated images perform in the RF analysis?

Mono reconstruction (i.e., one telescope), tested on point-source γ-rays.

$0.1 < \text{leakage} < 0.2$



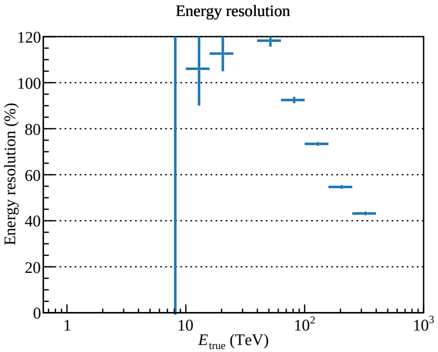
Energy assignment deteriorates but angular resolution still reasonable. The RF is good at compensating for truncation.

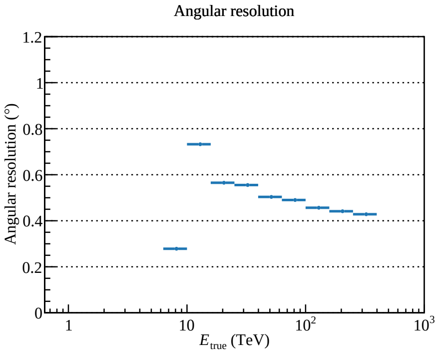
Typical handling of truncated images

How do truncated images perform in the RF analysis?

Mono reconstruction (i.e., one telescope), tested on point-source γ-rays.

$0.2 < \text{leakage} < 0.4$





Energy assignment deteriorates but angular resolution still reasonable. The RF is good at compensating for truncation.

Complications of the leakage definition

Reminder: intensity leakage $=$ fraction of total collected charge that landed in edge pixels.

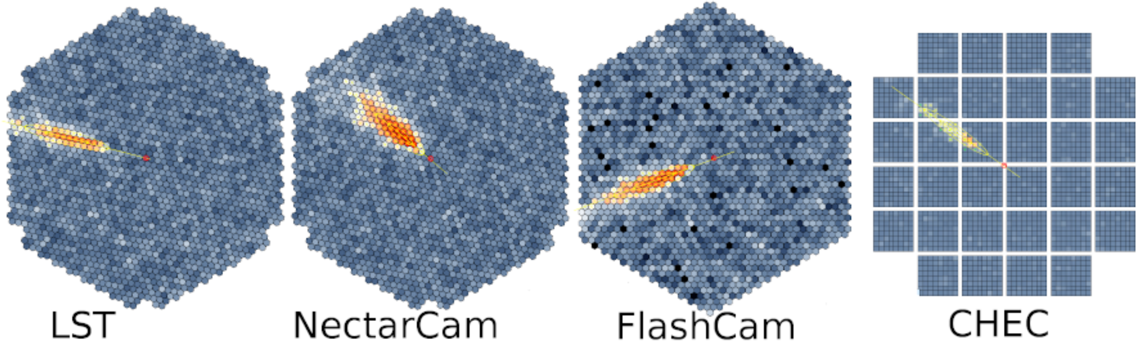
What we've learnt: This definition of leakage has some problems.

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

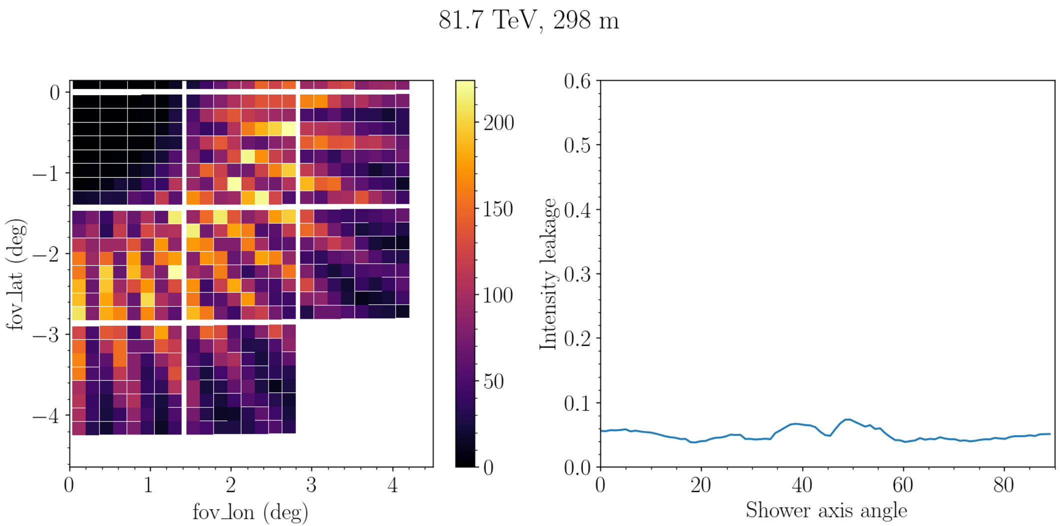
- Cherenkov telescopes typically use hexagonal pixels, arranged in a “circular” fashion.
- The SST camera (CHEC) is a rarity in being so square.



Credit: Konrad Bernlöhr (CTAO).

Unique issues for the SST

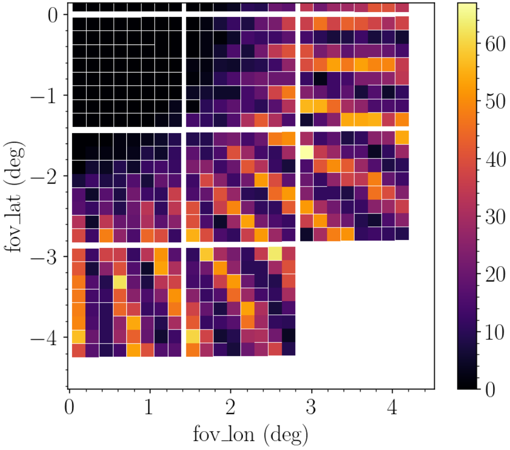
Same shower at different axis angles.

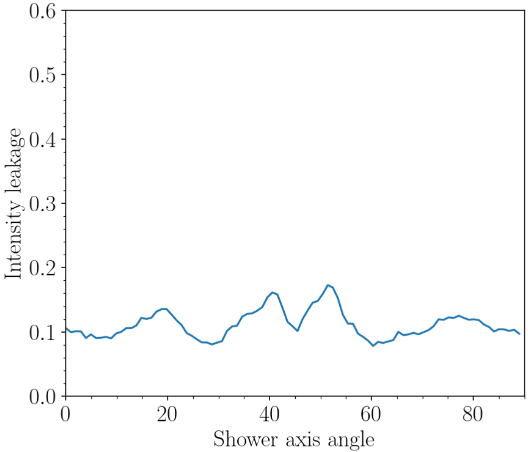


Unique issues for the SST

Same shower at different axis angles. Move it to different impact distances... (2/6)

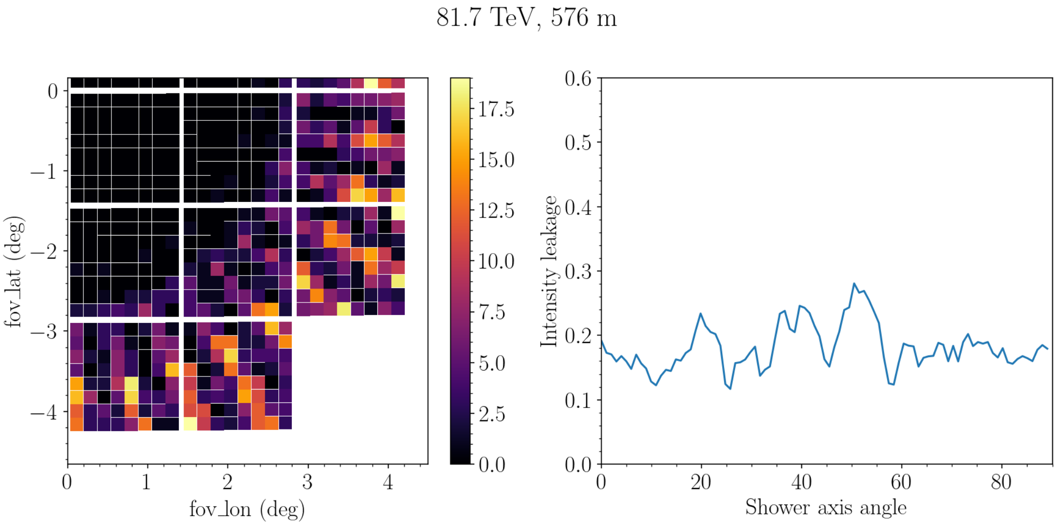
81.7 TeV, 420 m





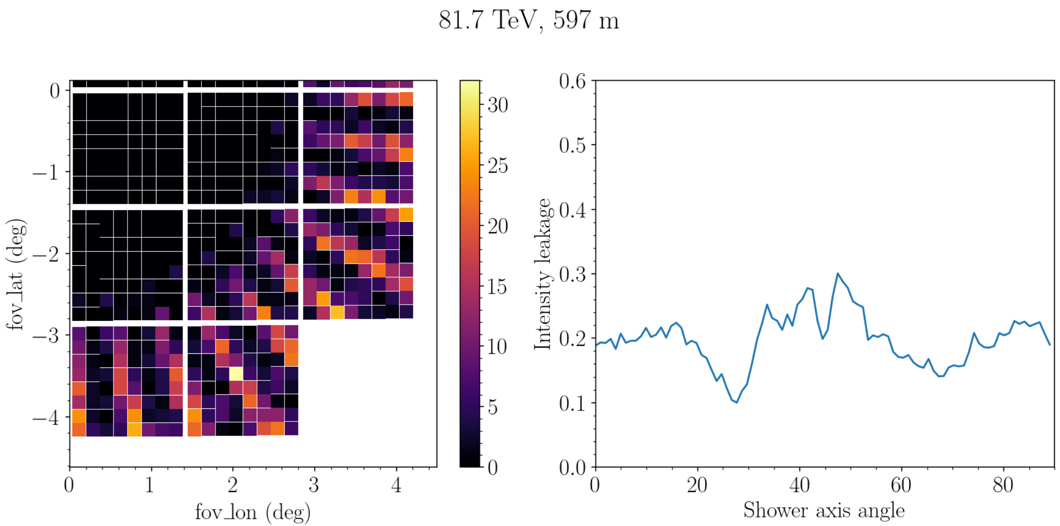
Unique issues for the SST

Same shower at different axis angles. Move it to different impact distances… (**3/6**)



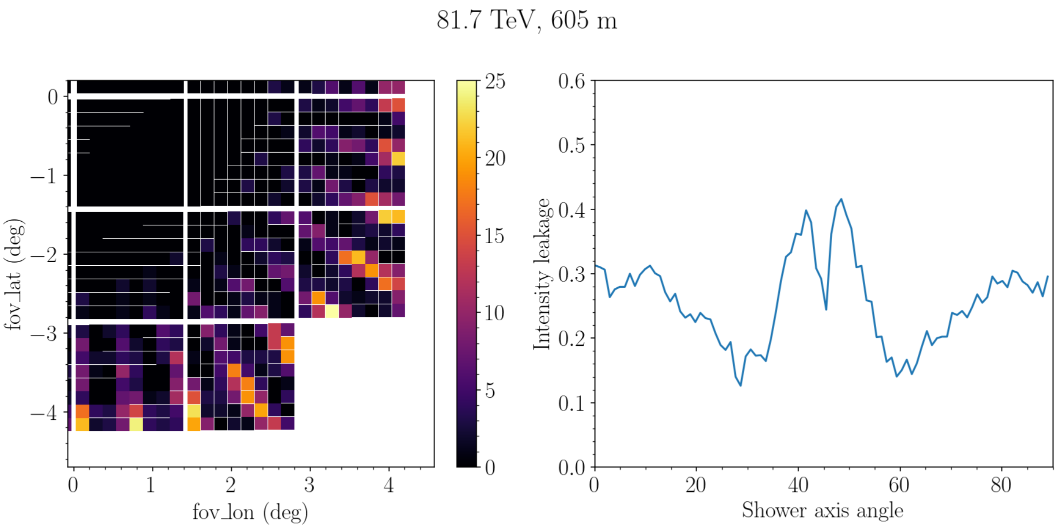
Unique issues for the SST

Same shower at different axis angles. Move it to different impact distances... (4/6)



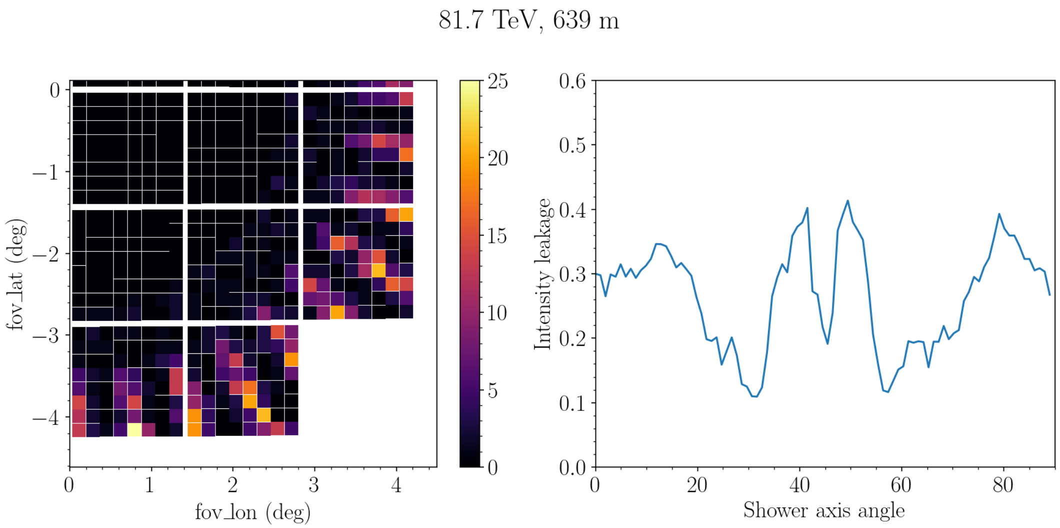
Unique issues for the SST

Same shower at different axis angles. Move it to different impact distances… (5/6)



Unique issues for the SST

Same shower at different axis angles. Move it to different impact distances... (6/6)



A new measure of truncation

- As shown, higher leakage events have poorer energy reconstruction.
- This is why leakage is generally used as 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 *intuitive*.

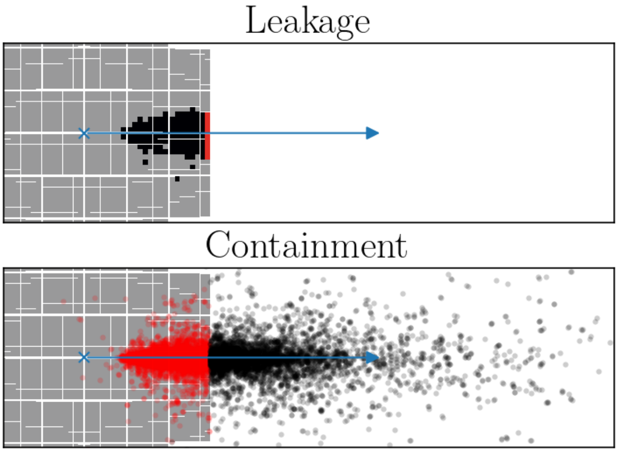
We introduce a **new parameter** that describes the effect of missing charge in a better way.

A new measure of truncation

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

Containment: Fraction of total charge that was collected.
(Can only be calculated in MC.)

Containment a better proxy for how much charge we collected → how good the reconstruction might be.



A new measure of truncation

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

We define “true” containment by

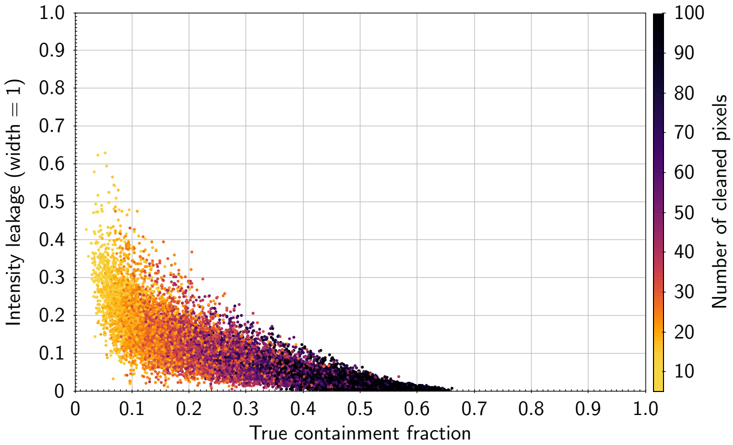
$$\textbf{containment} = \frac{\textbf{observed shower intensity}}{\textbf{true shower intensity}} .$$

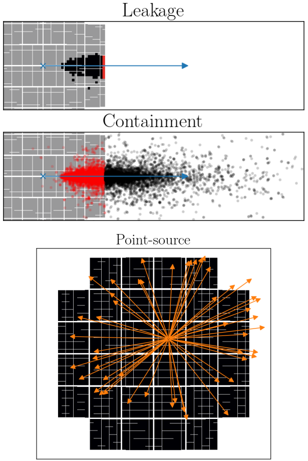
After we **reconstruct** the containment, we use it to recover

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

A new measure of truncation

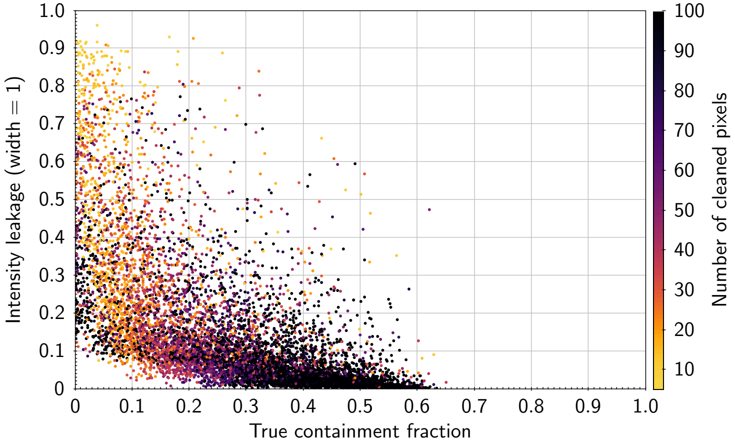
- For **point-source** γ-rays, leakage somewhat correlates with containment.
- Scatter due to the corner effects...

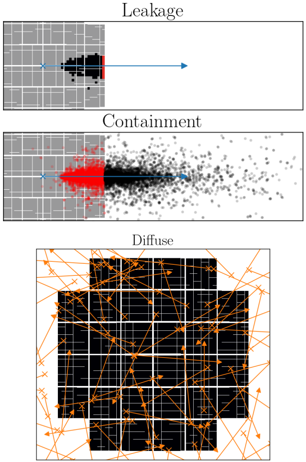




A new measure of truncation

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



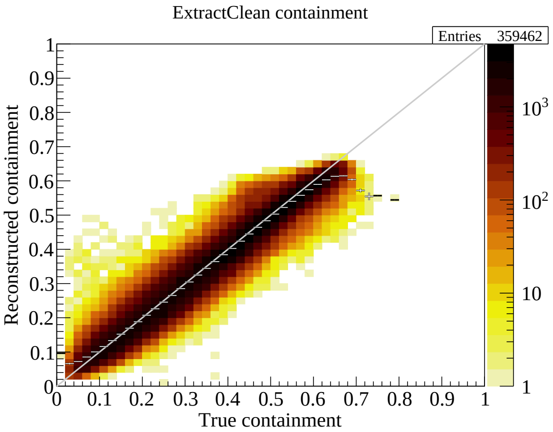


Reconstructing the containment

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 energy

"Standard" method is to train energy regressor with the intensity and leakage as **two separate** features.

For our "new" method we **combine** intensity with reconstructed containment to estimate the "true" intensity directly.

Standard feature set

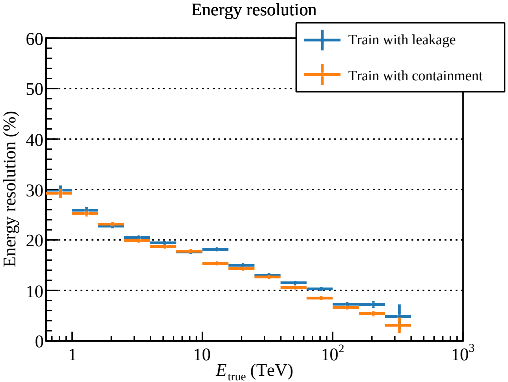
- ln(intensity)
- leakage
- length
- width
- ⋮

New feature set

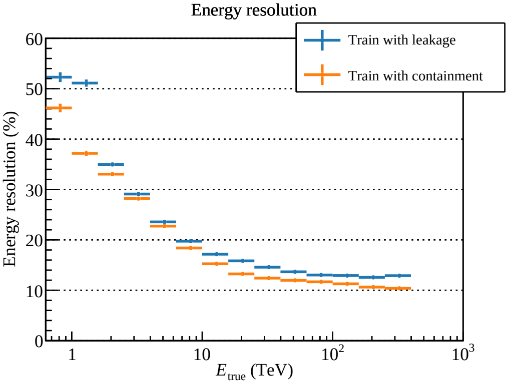
- ln(intensity/containment)
- containment
- leakage
- length
- width
- ⋮

Using containment to improve energy

Well-contained events



Truncated events



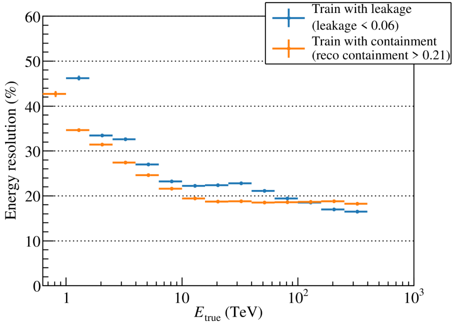
We achieve an improvement in energy resolution over the standard method.

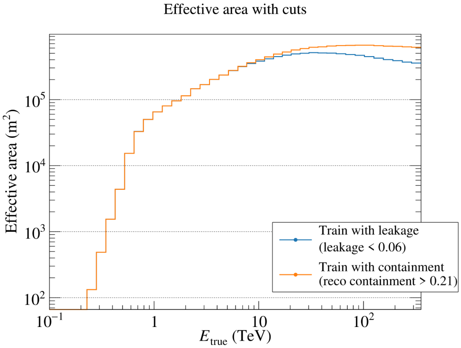
The increased overhead of this technique is small, with only one additional RF to train and evaluate.

Improving the effective area – PRELIMINARY

Use containment to make a better quality cut than leakage: Here we seek the **most relaxed quality cut** that keeps energy resolution below 20 % above 100 TeV.

We can equivalently keep leakage < 0.06 or containment > 0.21.

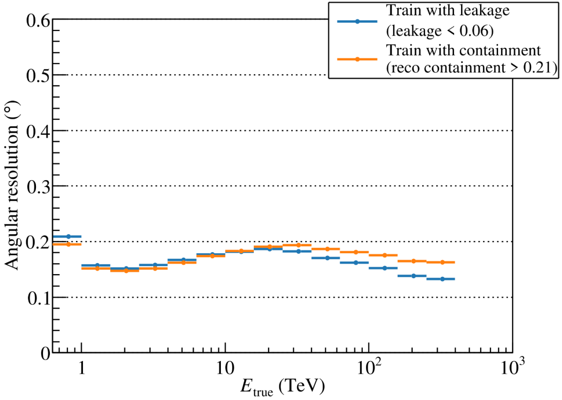




By using containment as the cut variable, we get a $\sim$**50 % increase** in effective area at the highest energies. Useful for **source discovery** or similar studies.

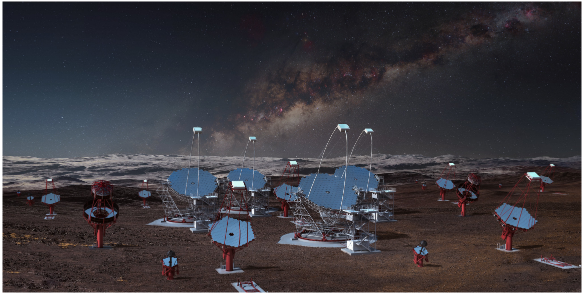
Improving the effective area – PRELIMINARY

The trade-off is a slight worsening of angular resolution, as the events we gain are all truncated and this affects the axis angle.



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.
- Despite this, it does a good job – random forest model performance with truncated events is decent on its own.
- By using containment to parametrise leakage, we can **very cheaply** get further performance improvements.
- **Next steps:** Check out γ–h classification.



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