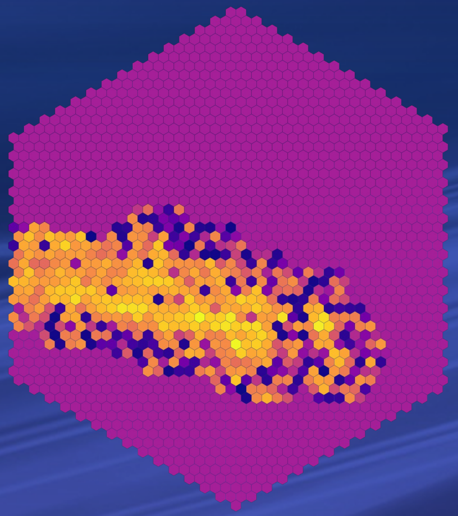
Friedrich-Alexander-Universität
Erlangen-Nürnberg

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

Ultra-Fast Generation of Air Shower Images for Imaging Air Cherenkov Telescopes using a score-based diffusion model



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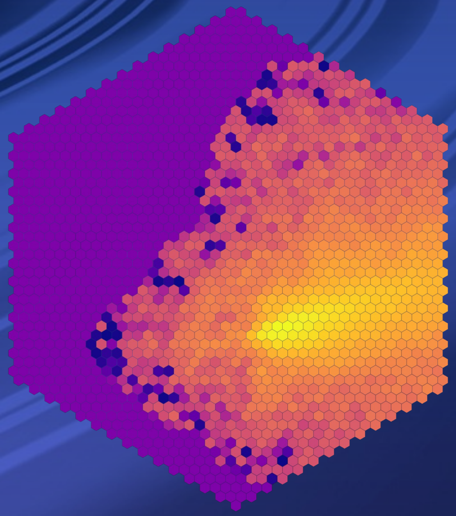
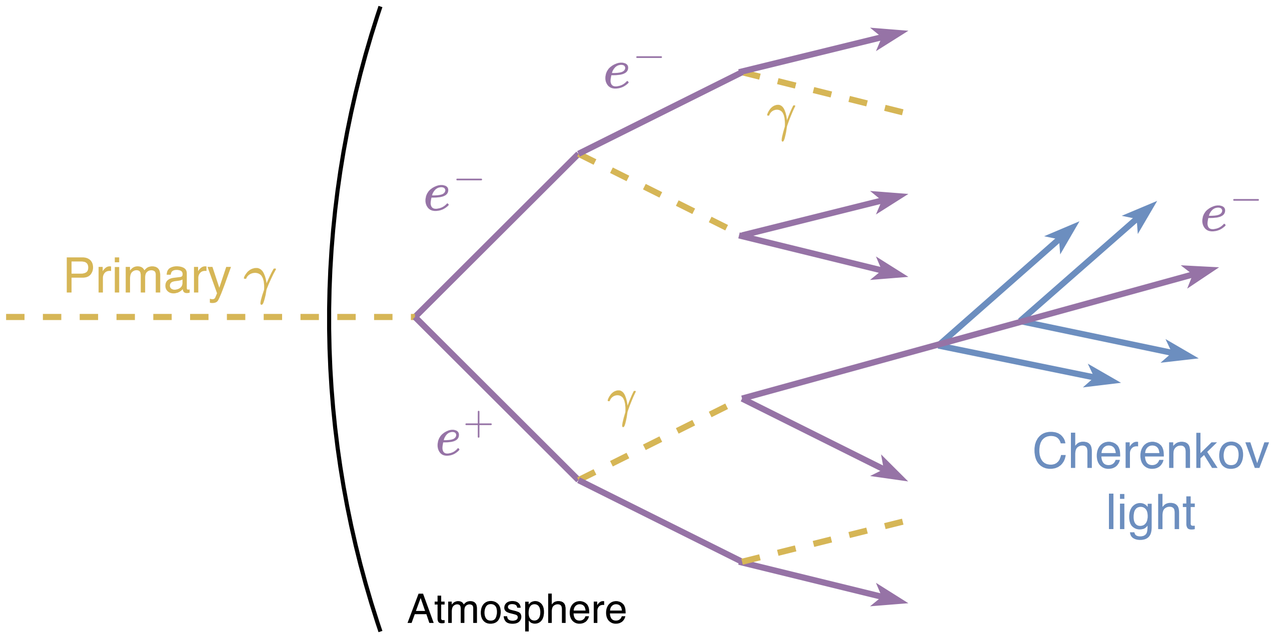
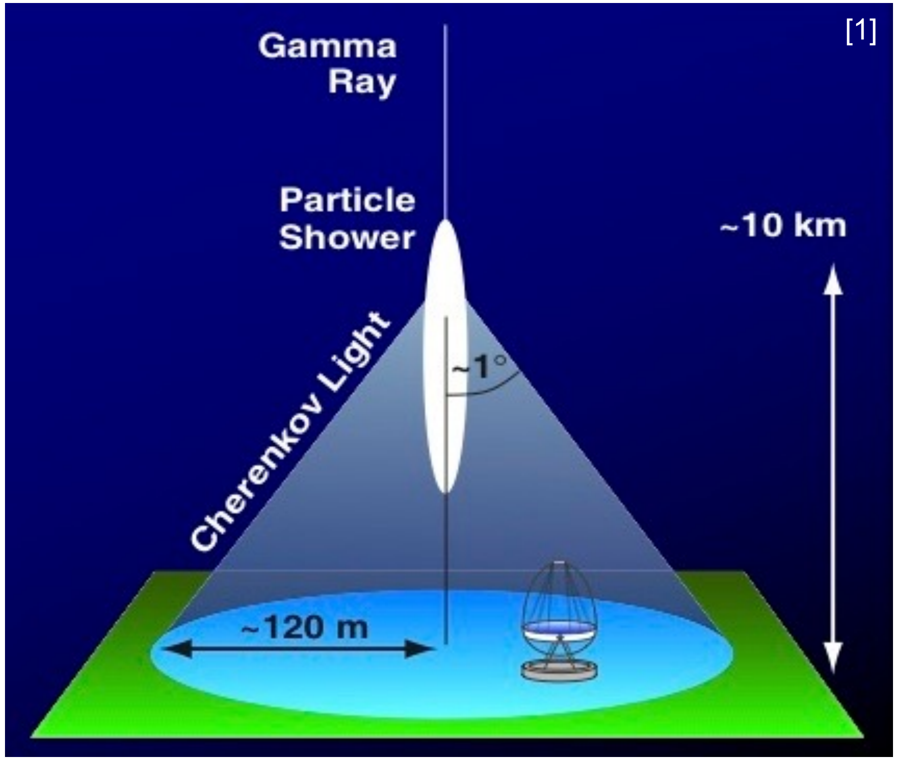


Air showers in gamma astronomy

- Study of astrophysical sources using cosmic gamma rays
- Extensive air showers induced by cosmic particle

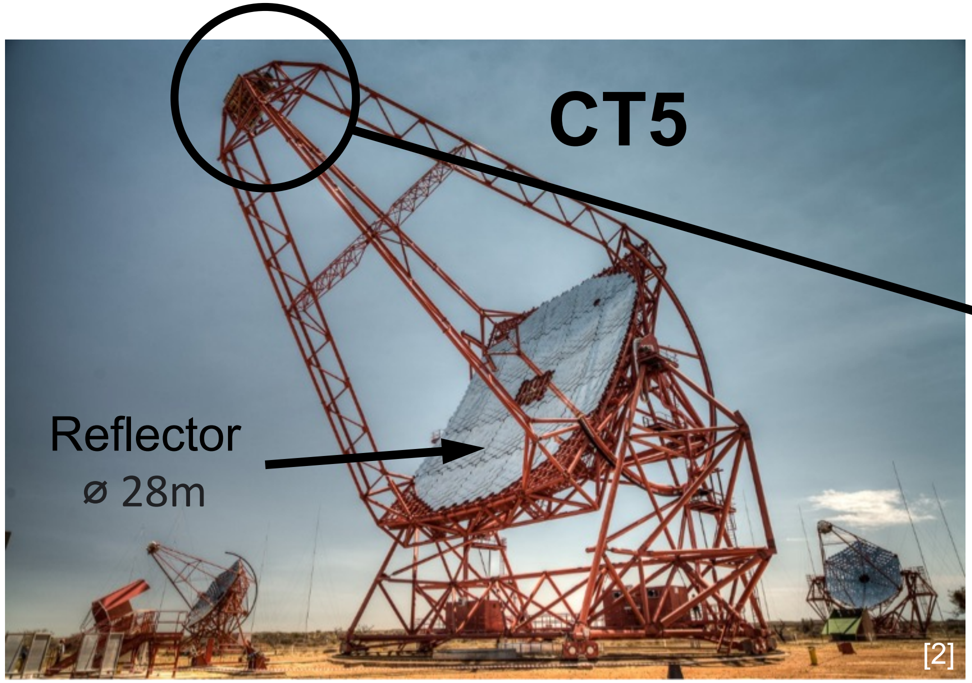




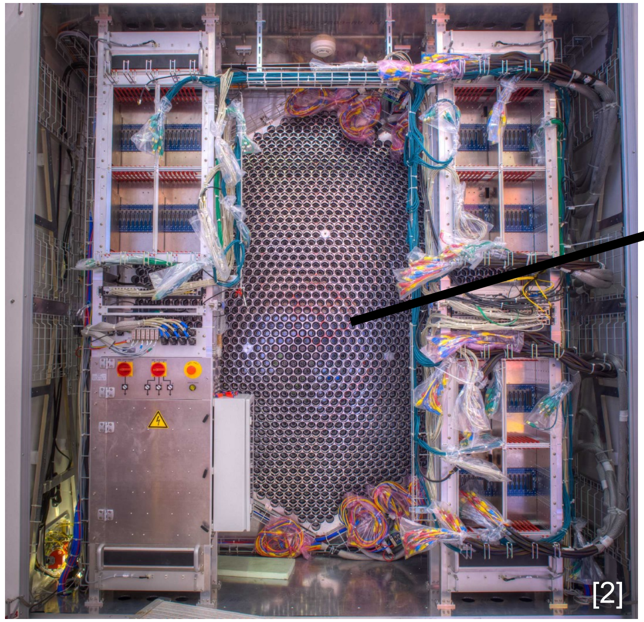
- Detect Cherenkov pool with **I**maging **A**tmospheric **C**herenkov **T**elescopes (H.E.S.S., CTA, …)
- State-of-the-art cameras feature more than thousand pixels

From the air shower to the IACT image

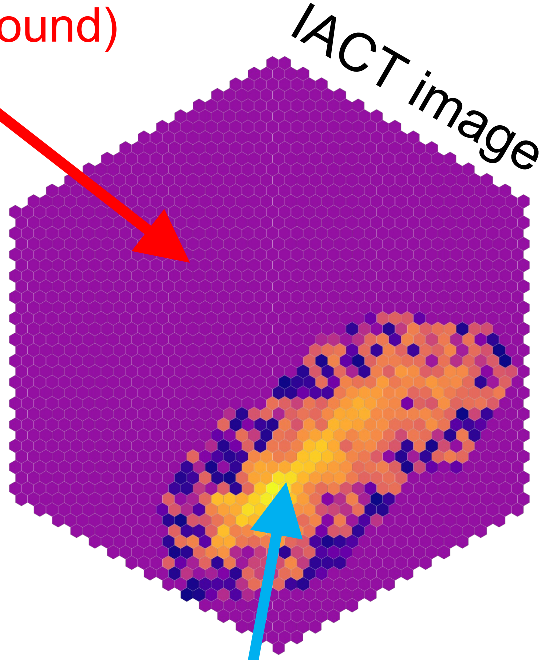
- Detecting Cherenkov light with IACTs like **CT5** from H.E.S.S.
  - Cherenkov light reflected off mirrors onto telescope camera
  - **FlashCam**: camera with 1758 PMTs (pixels)
- IACT image: visualisation of the air shower



FlashCam



Cleaned pixels (removed due to night sky background)



Cherenkov signal (in photoelectrons)

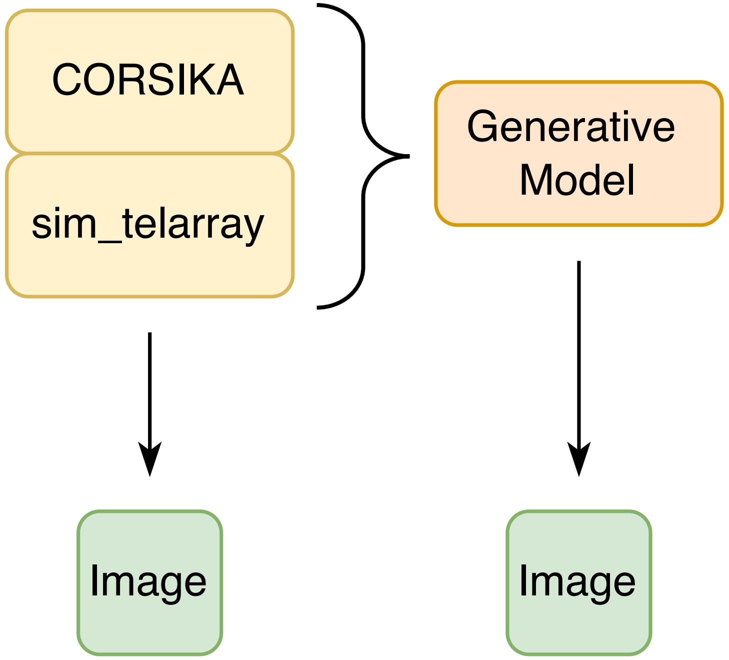
Accelerating the simulation of air shower images

- Simulation of IACT events includes the simulation of air showers (CORSIKA) and instrument response (sim_telarray)
- Especially simulation of background computationally expensive
  - Up to 10000 background cosmic rays for every gamma ray
  - Air shower development much more complex for cosmic rays

→ **Goal**: speed up air shower simulation and keep simulation accuracy

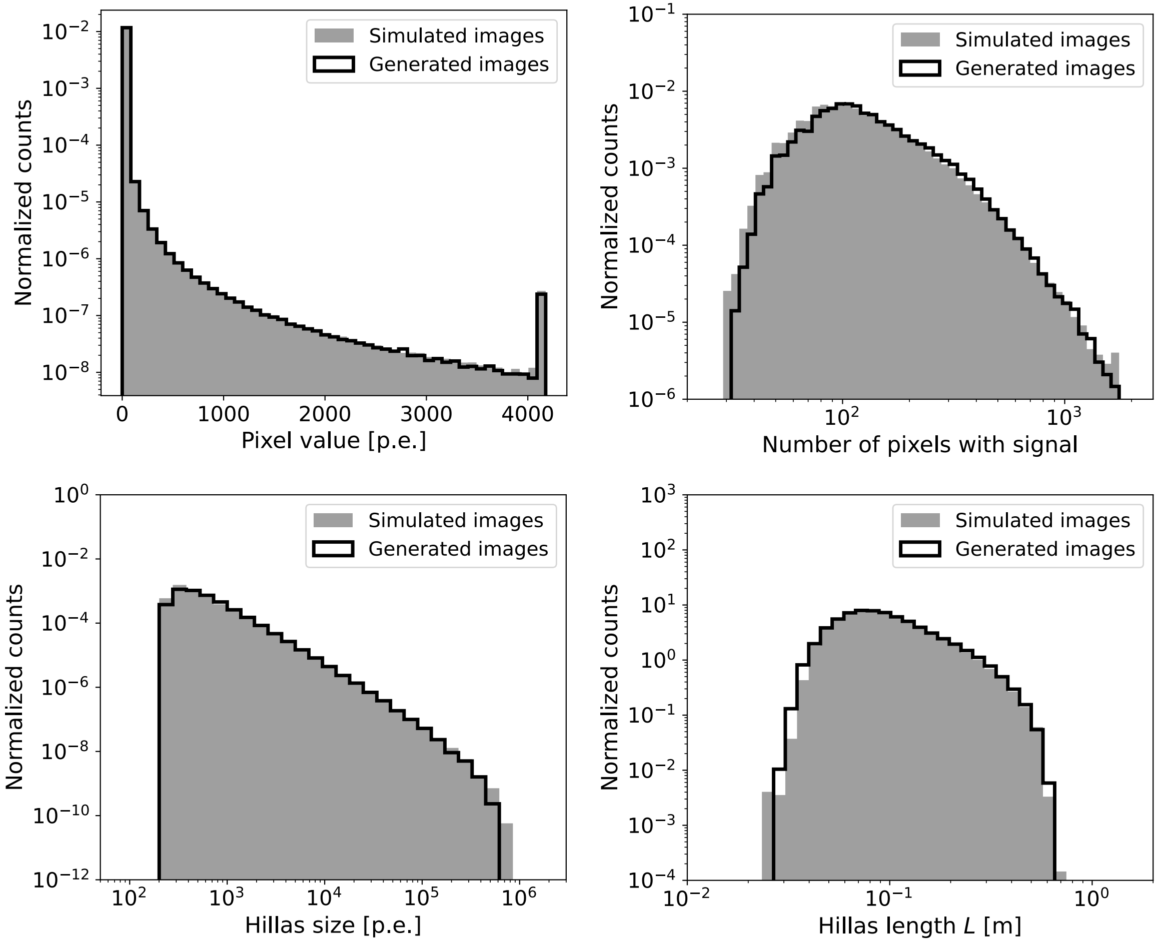
- Investigate **ML approach (Diffusion Model)**:
  - Memory-efficient storing of model (TB large library within 100 MB)
  - Generate showers with properties not settable in simulations (e.g. $X_{\max}$)

→ **Proof of concept**: application in astroparticle physics

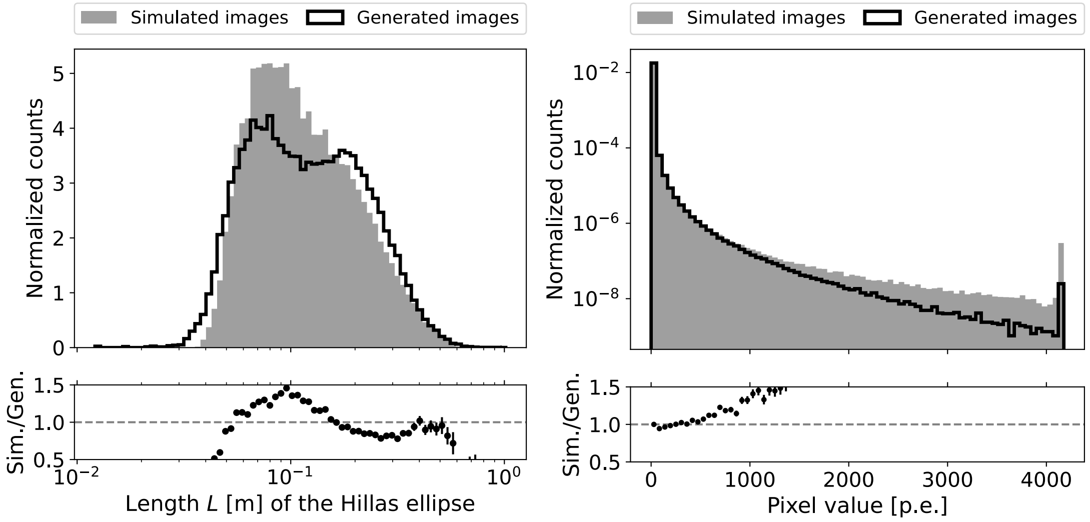


Previous work on IACT image generation

- Successful generation of IACT **gamma** images using a conditional WGAN (our paper: [arxiv:2311.01385](https://arxiv.org/abs/2311.01385))



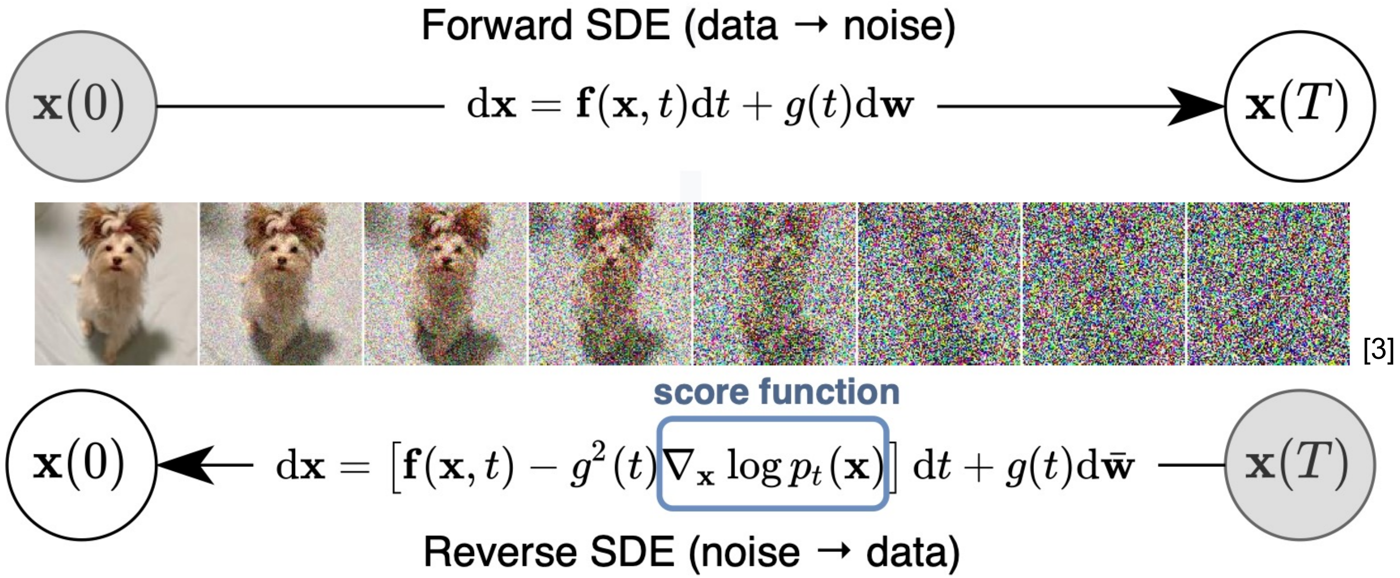
- However: significantly worse results for **proton** images

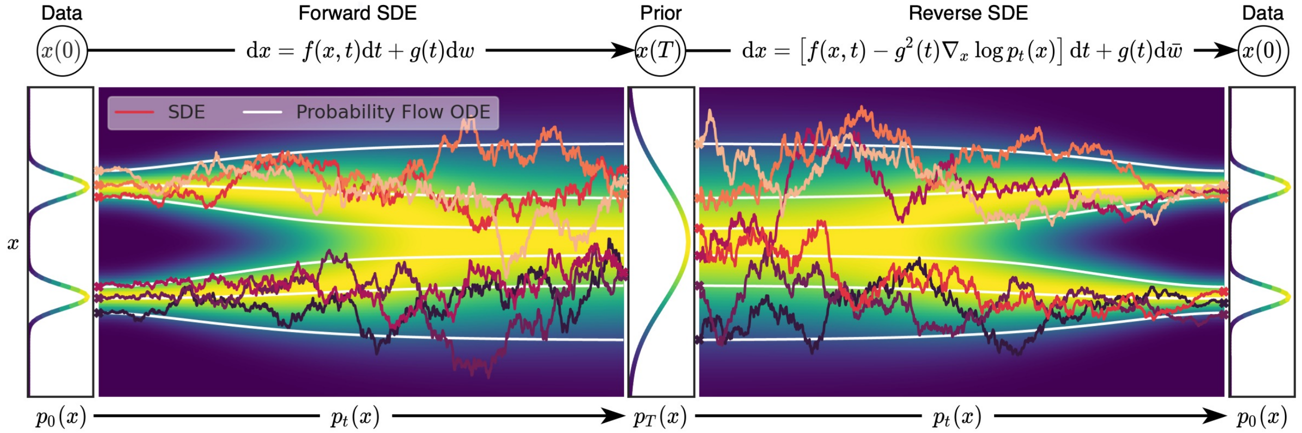


→ **Use of state-of-the-art diffusion models known for their accurate generation**

Score-based diffusion model

- Diffusion model: state-of-the-art generative model
- Corruption of the initial image through the addition of noise (data → noise)
- Addition of noise described by Stochastic Differential Equation
- Prediction of score function by the neural network
- Removal of noise through SDE and predicted score (noise → data)





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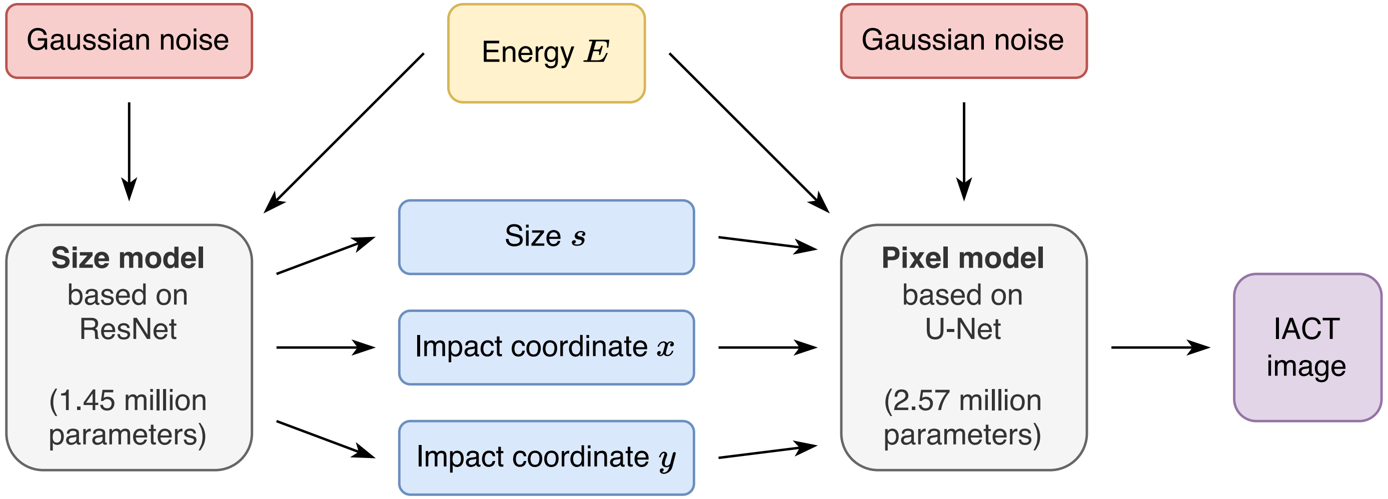
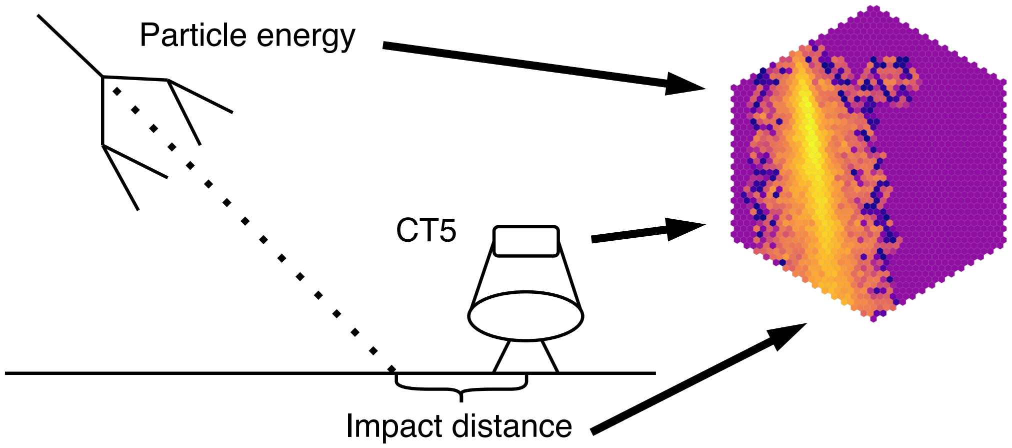
Training data and framework

Simulated data:

- Proton images, energy and impact point (CT5 mono simulations)
- Images contain 1764 pixels
- Training data ~ 350,000 samples
- Analysis of images using test data set with ~ 80000 samples





Framework:

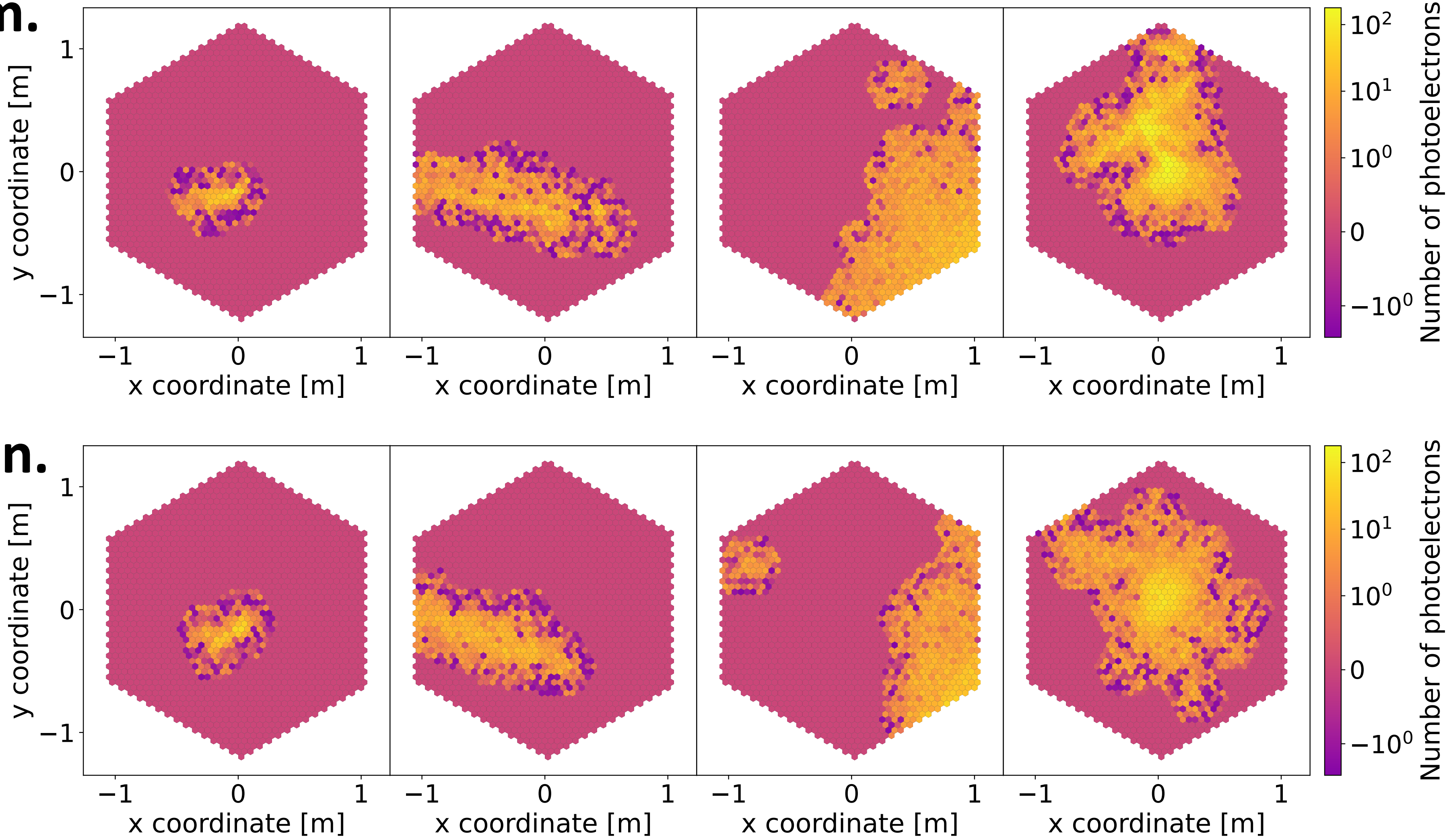
- Score-based diffusion model based on CaloScore (arxiv:2308.03847)
- Size model: ResNet predicting size and impact coordinates from energy
- Pixel model: U-Net predicting image from energy, size, and impact coordinates

Generation of IACT proton images

Work in progress

Sim.

Gen.



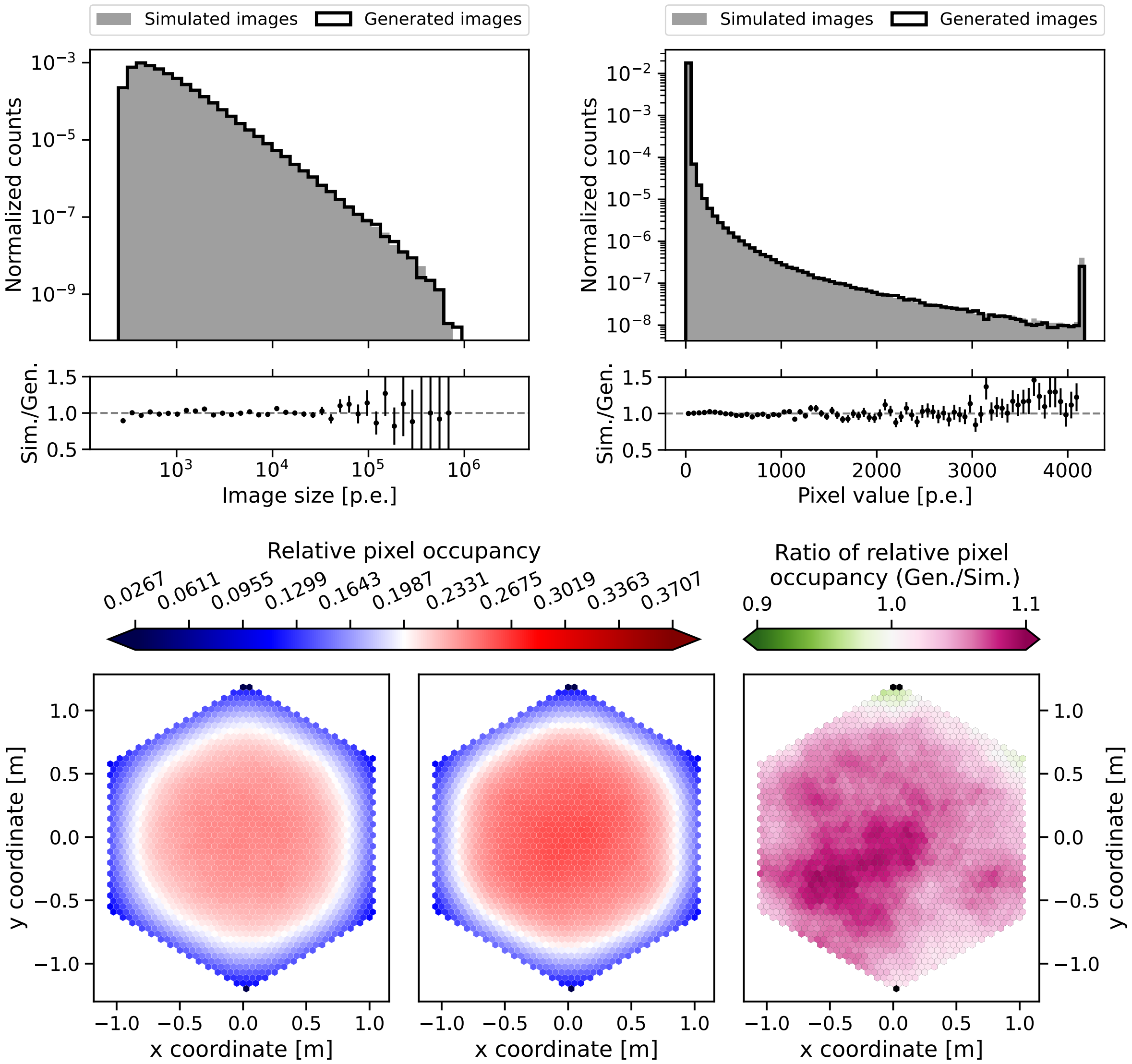
- Various air shower characteristics represented
  - Circular signal
  - Elliptical signal
  - Truncated signal
  - Hadronic substructure

→ Simulated and generated images visually similar

Investigation of pixel parameters

Work in progress

- Investigation of low-level image parameters
- Distributions of simulated and generated data sets match well
- Slightly more pixels occupied in generated images



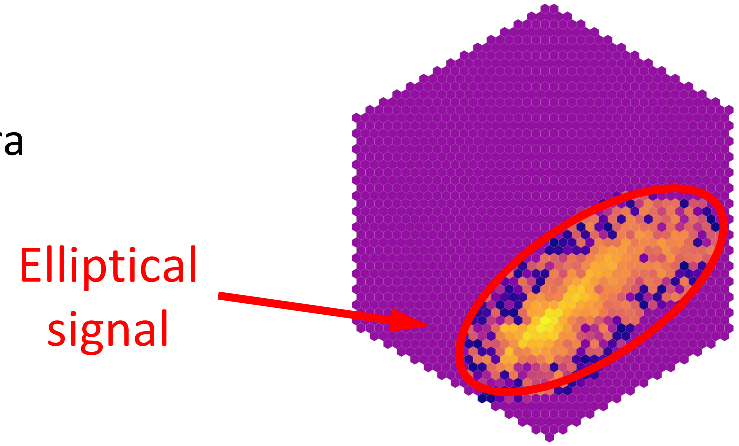
→ Pixel parameters represented in generated images

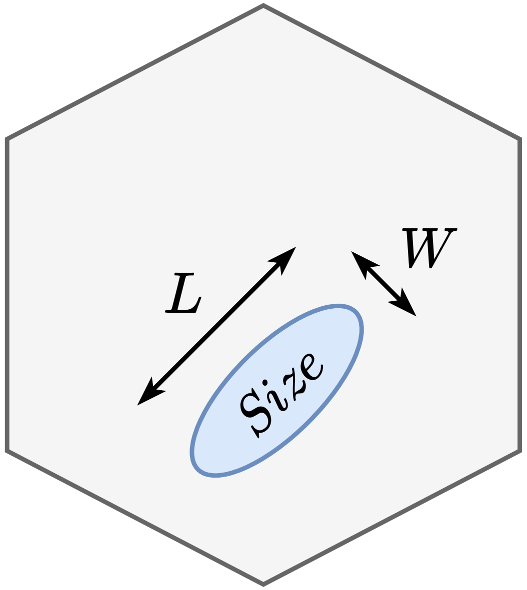
- Minor improvements still needed

Event analysis using Hillas parameters

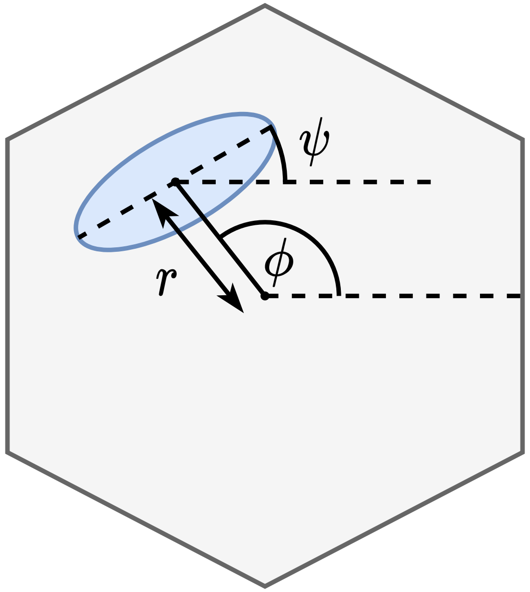
- Hillas parameters introduced for IACT image analysis
  - Elliptical parameterisation of the Cherenkov light distribution on the camera
  - Used for particle identification and event reconstruction

→ Utilized for quantifying shape of generated shower images





- **Size**: integrated signal
- **Length *L***: spread along major axis
- **Width *W***: spread along minor axis

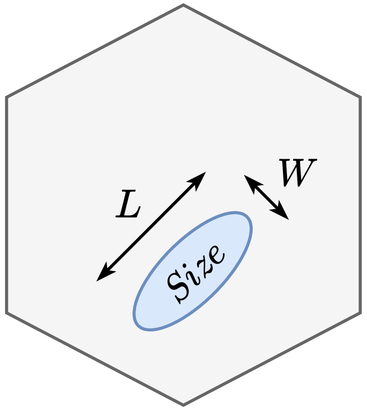


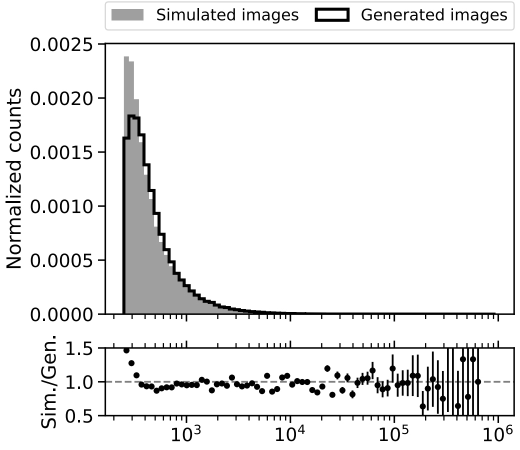
- **Polar coordinate *r*** of ellipsis center
- **Radial coordinate Φ** of ellipsis center
- **Rotation angle Ψ** of ellipsis

Analysed Hillas parameters

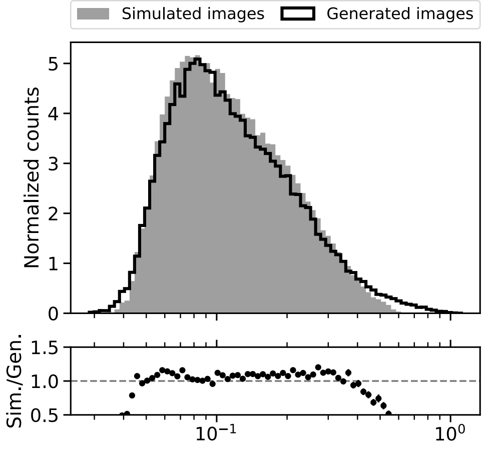
Work in progress

Shape of ellipsis

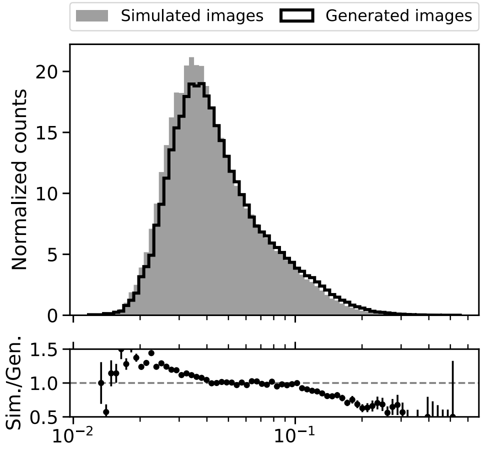




Size

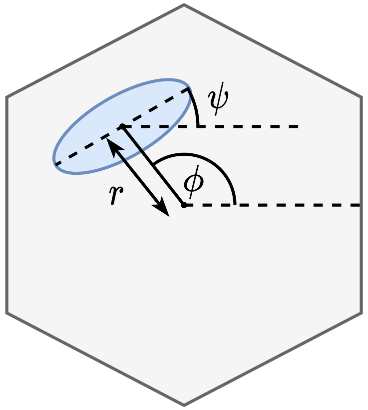


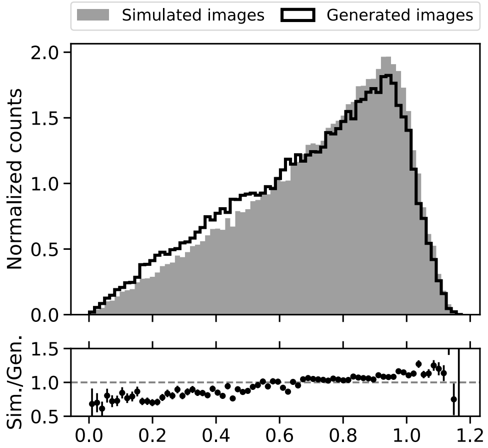
Length



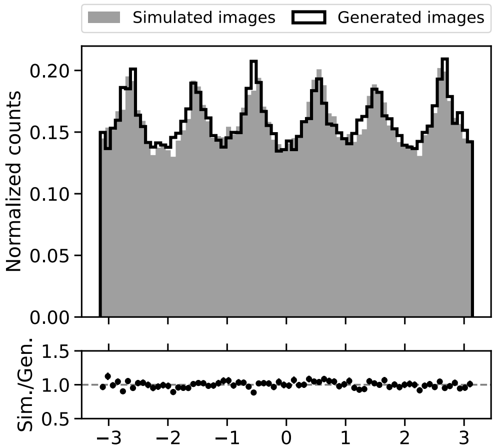
Width

Location of ellipsis

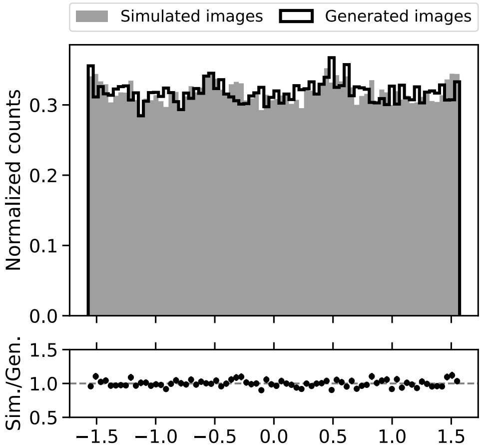




Radial coord.



Polar coord.



Rotation angle

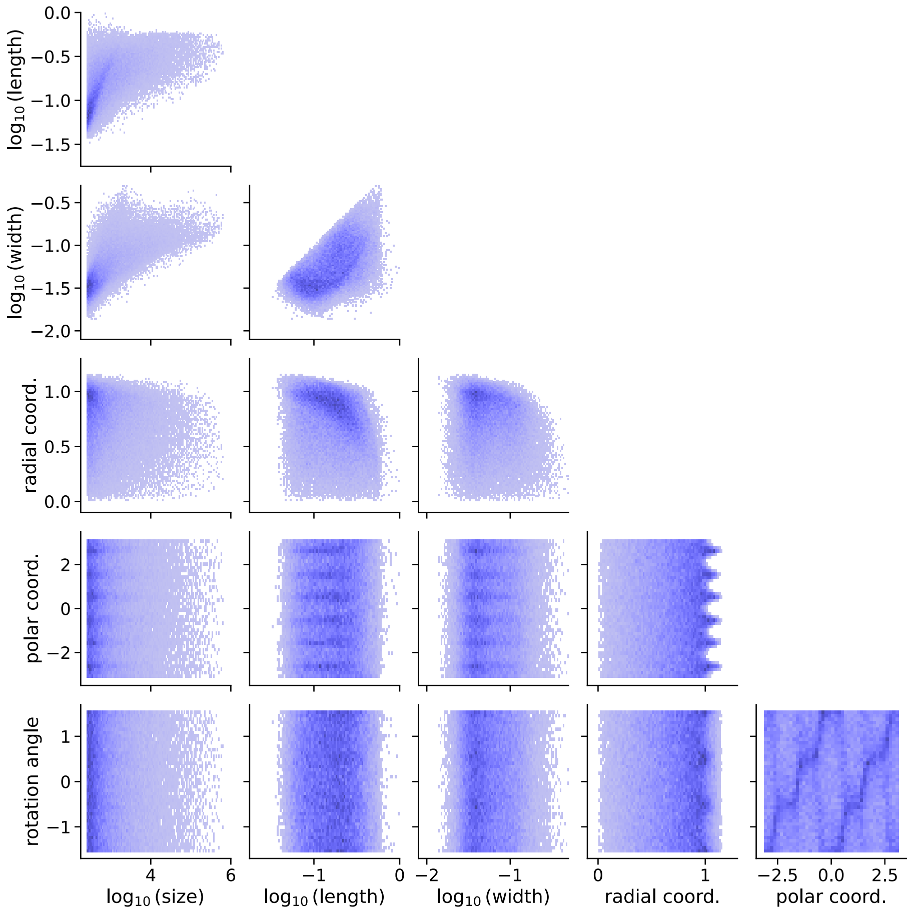
→ Already good match of distributions, but improvements are still needed for most parameters

Correlation of Hillas parameters

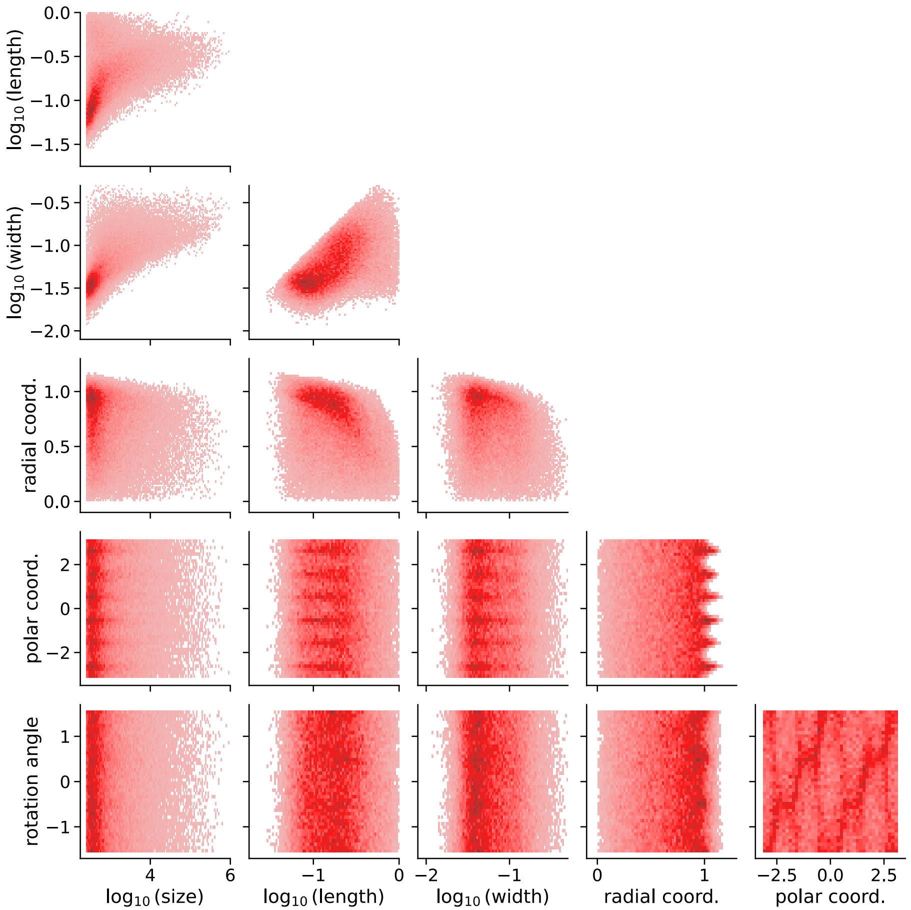
Work in progress

- Investigation of encoded physics
  → Study correlations of Hillas parameters
- Minor differences but overall similar

→ Diffusion model able to pick up complex parameter correlations



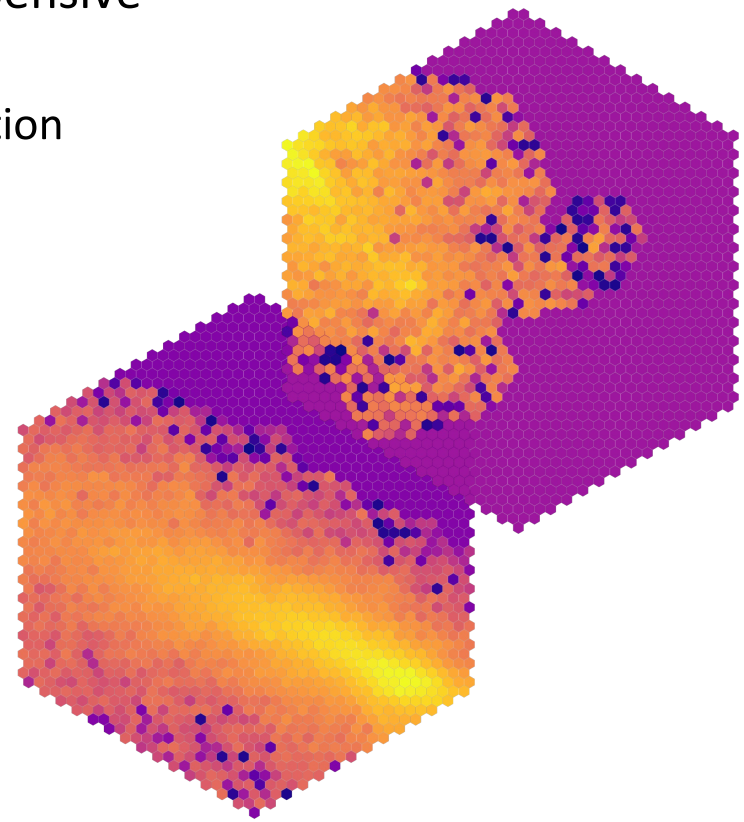
Simulated



Generated

Summary and Outlook

- Simulation of IACT events, especially cosmic rays, computationally expensive
  - Investigate fast, accurate, and memory-efficient approach for event generation
  - Training of a score-based diffusion model (H.E.S.S. CT5 FlashCam)
- Successful generation of realistic images (more than 1500 pixels)
- Analysis of Hillas parameters and their correlations
  - Reproduction of distributions despite minor differences
- Speed-up of generation process still work in progress



→ **Promising prospects for accelerating simulations in astroparticle physics with generative models**

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Backup

Additional information

- **cWGAN-GP:** Critic, generator, energy constrainer and impact constrainer
- **Score-based diffusion model:** size model and pixel model

	Training time	Number of A100 GPUs for training	Generation time (100k images)
MC simulation	-	-	~ 70 h (1 CPU)
WGAN	~19 h	4	~ 2 s (1 GPU)
Diffusion model	~18 h	8	~ 33.5 h (1 GPU)

→ **Outlook:** improving of speed and accuracy of DM and accuracy of WGAN