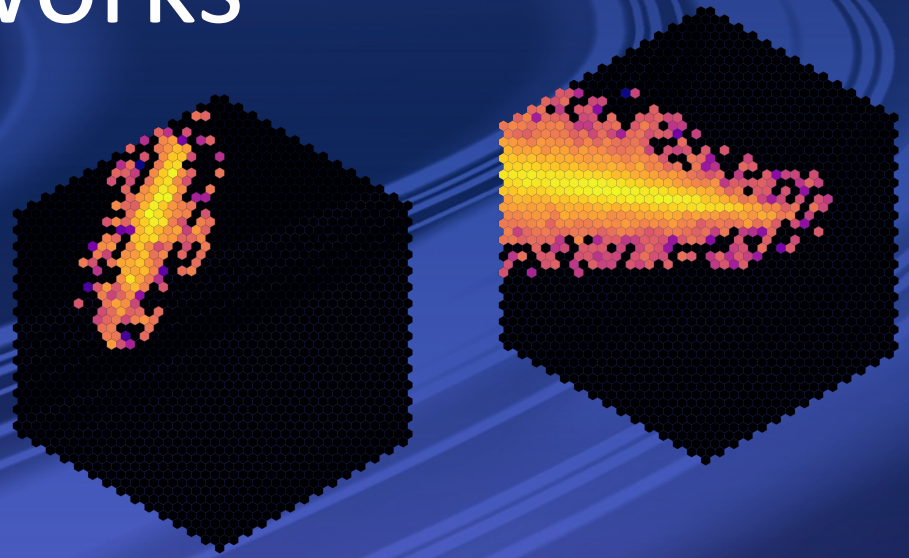
Friedrich-Alexander-Universität
Erlangen-Nürnberg

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

FAU

Ultra-Fast Generation of Air Shower Images for Imaging Air Cherenkov Telescopes using Generative Adversarial Networks

ML4Jets Hamburg



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Erlangen Centre for Astroparticle Physics

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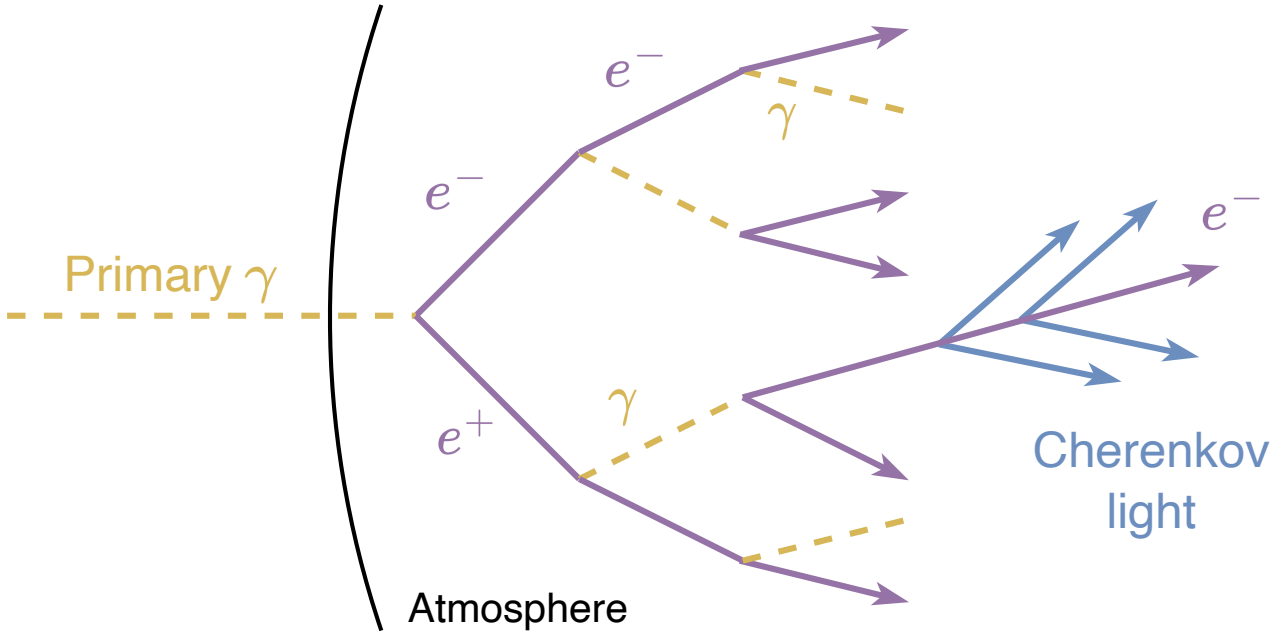
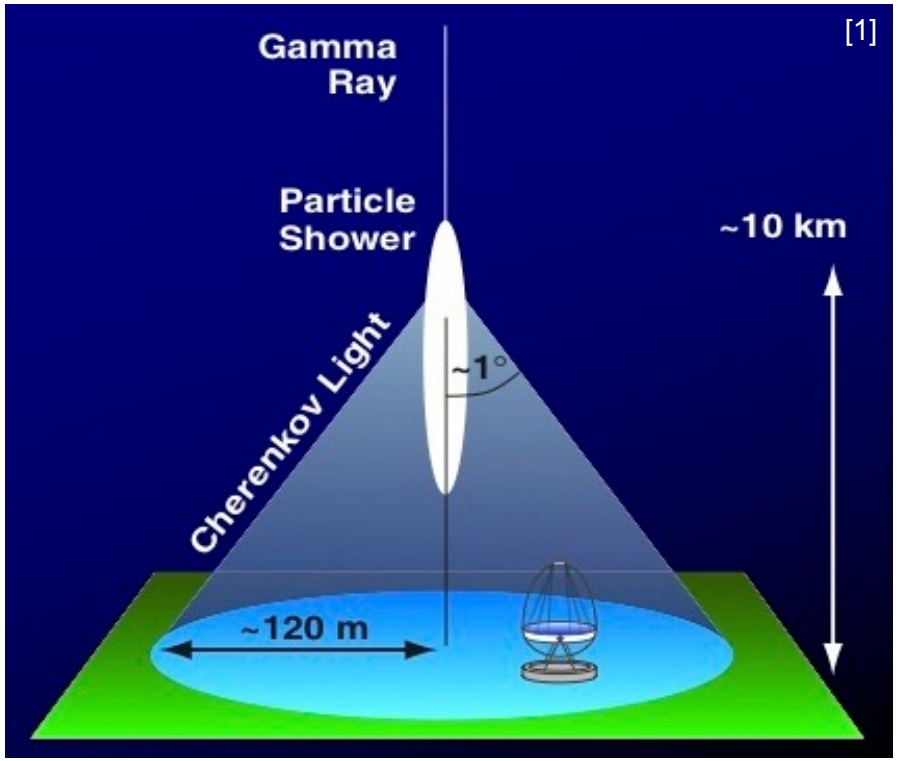
→ Find our paper on arXiv:2311.01385

Air showers in gamma astronomy

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

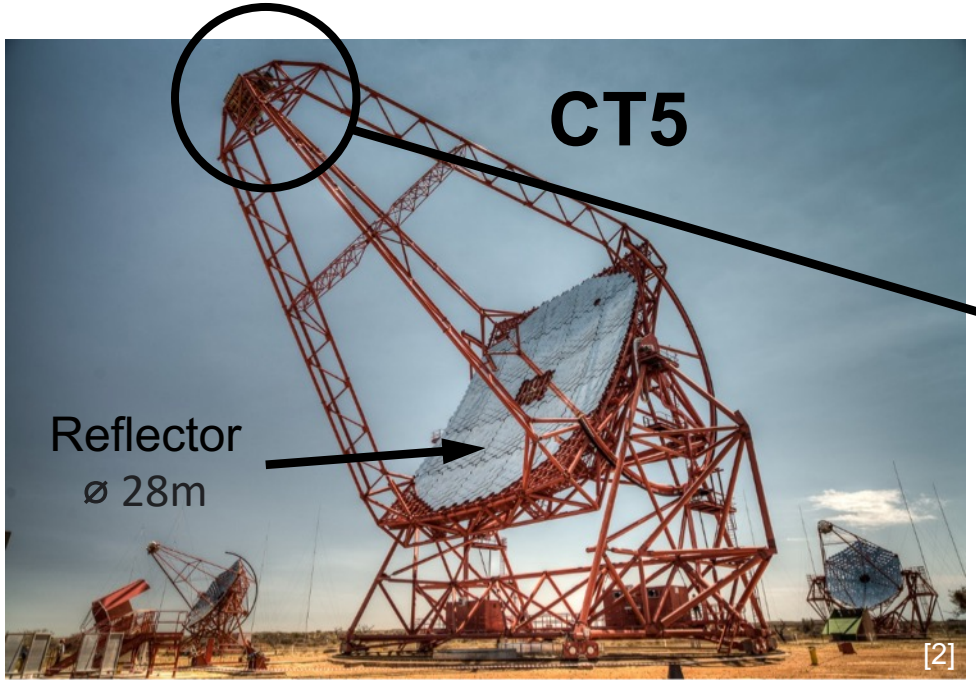




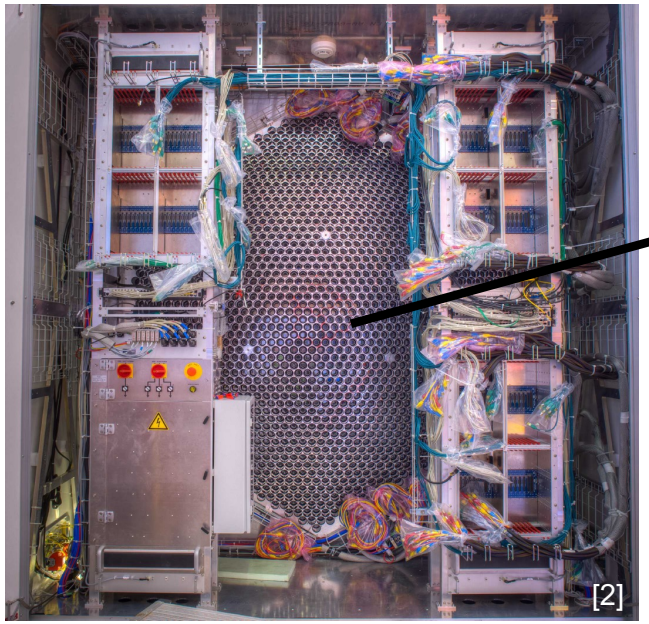
- Detect Cherenkov pool with **I**maging **A**tmospheric **C**herenkov **T**elescopes (H.E.S.S., CTA, …)
- State-of-the-art cameras feature more than thousand pixels

From the air shower to the IACT image

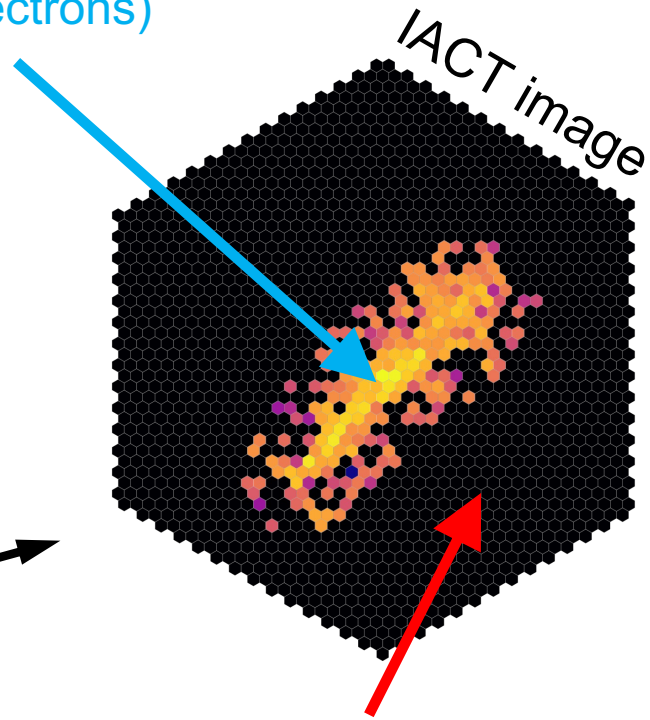
- Detecting Cherenkov light with IACTs like **CT5** from H.E.S.S.
  - Cherenkov light reflected off mirrors onto telescope camera
  - **FlashCam**: camera with 1758 PMTs (pixels)
- IACT image: visualisation of the air shower



FlashCam



Cherenkov signal
(in photoelectrons)

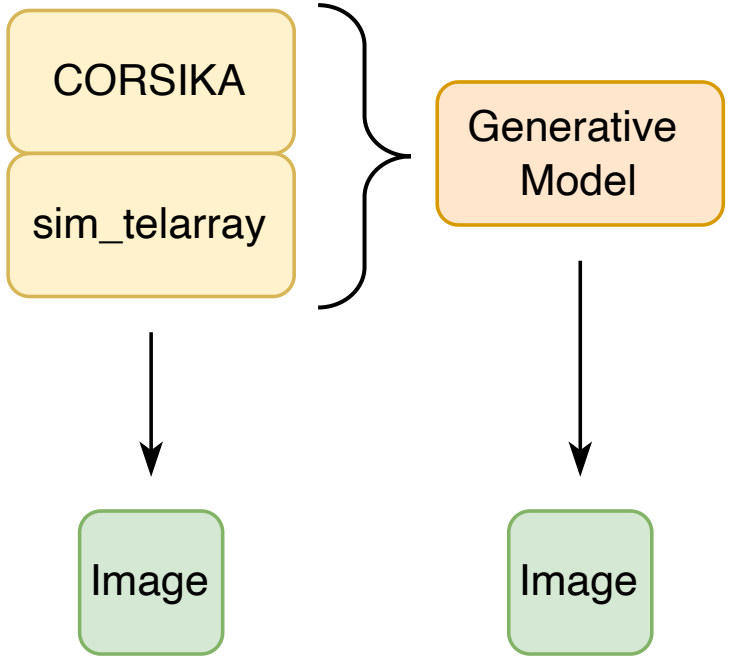


Cleaned pixels
(removed due to
night sky background)

Accelerating the simulation of air shower images

- Simulation of IACT events includes the simulation of
  - Air showers (CORSIKA)
  - Instrument response (sim_telarray)
- Simulations computationally expensive (in particular for CTA)
  - Re-simulated for different observation periods
- Investigate **ML approach (GANs)** for ultra-fast simulation:
  - Memory-efficient storing of model (TB large library within 100 MB)
  - Generate showers with properties not settable in simulations (e.g. X_{max})

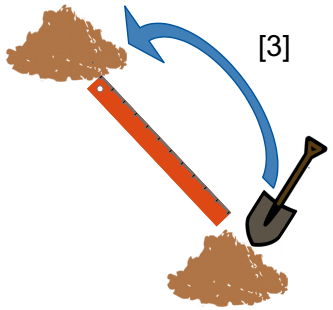
→ Proof of concept: application in astroparticle physics



Generative Adversarial Networks

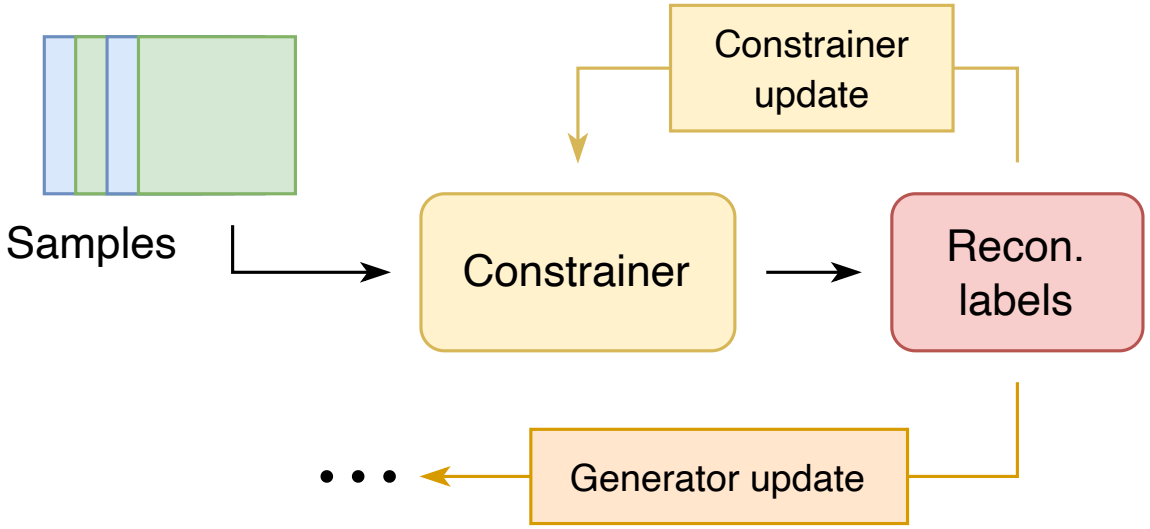
Wasserstein GAN (WGAN-GP):

- Training of GAN delicate and challenging
- WGAN as improvement of GAN
  - Approximate Wasserstein distance with discriminator
  - Sophisticated feedback instead of simple discrimination (yes/no)



Conditioning of physical labels:

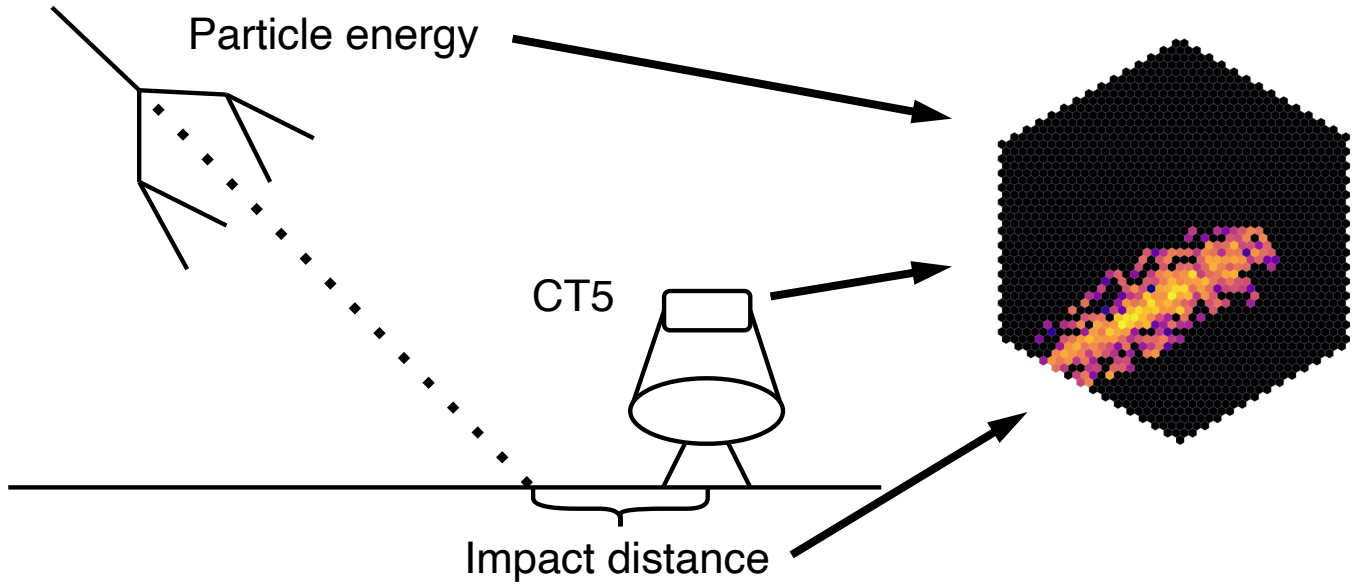
- Enforce representation of physical labels in generated images
- Perform conditioning using constrainer networks



Training data and framework

Simulated data:

- Image, energy and impact point (CT5 mono simulations)
- Training data ~ 360,000 samples
- Analysis of images using test data set with ~ 80000 samples

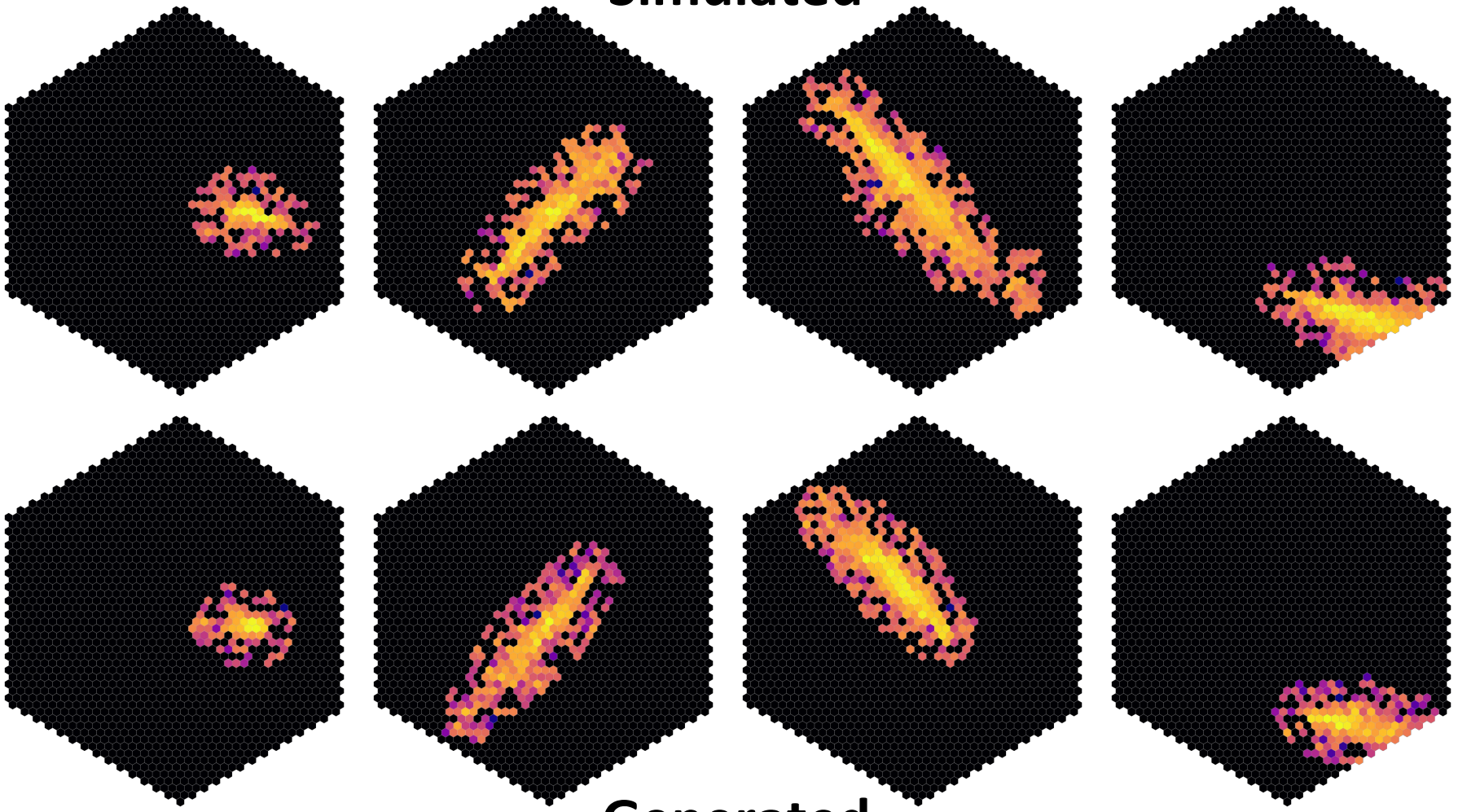


Framework:

- *Critic*, *generator* and *two constrainer networks* (energy and impact point)
- Trained for 1000 epochs (62h) on NVIDIA A100-SXM4-40GB
- Speed-up using WGAN up to 5 orders of magnitude

Method	Hardware	Time	**Speed-up**
Standard simulation	Intel Xeon Gold 6230	70h	-
WGAN framework	AMD EPYC 7713 Milan	86.06s	**x 2930**
WGAN framework	NVIDIA A100-SXM4-40GB	2.34s	**x 108,000**

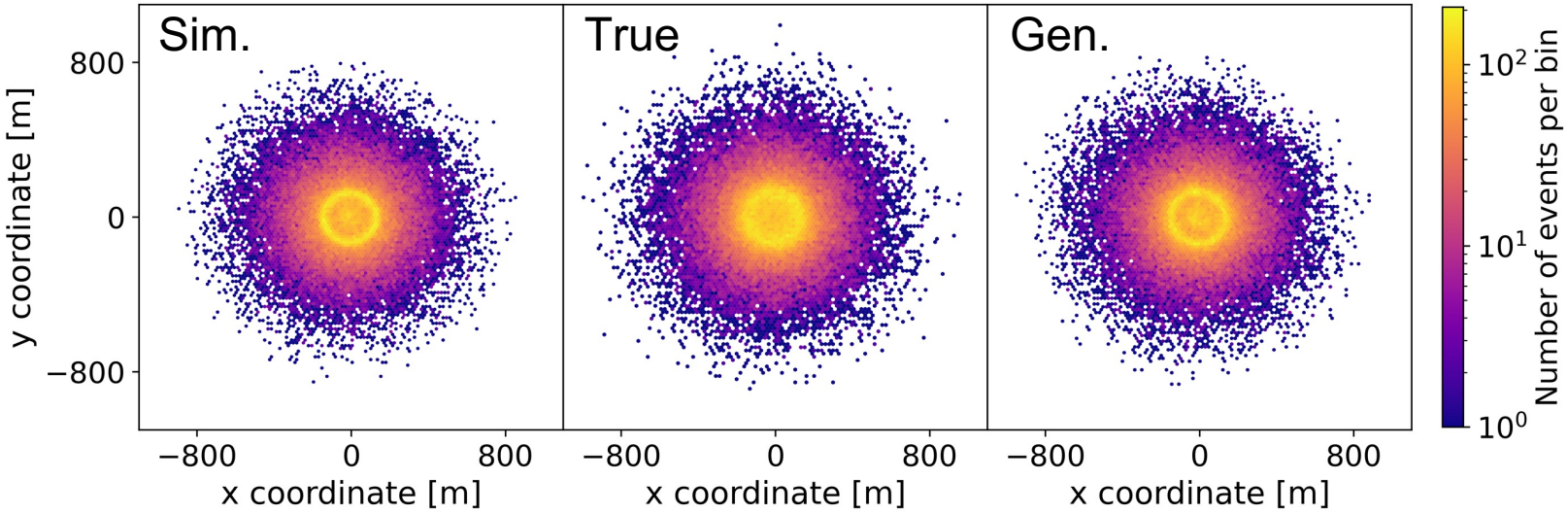
Generation of IACT camera images

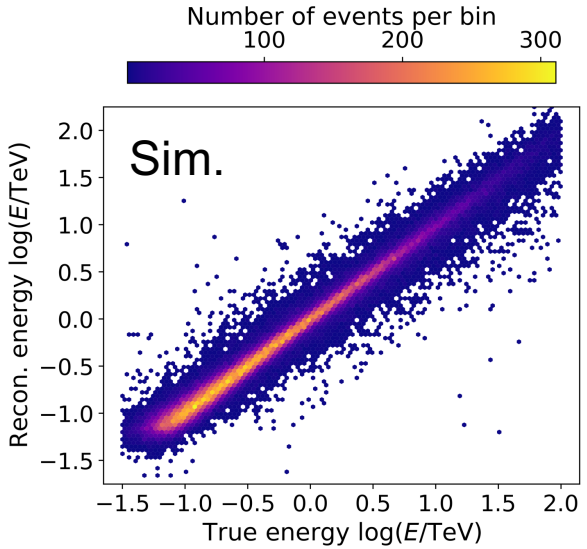


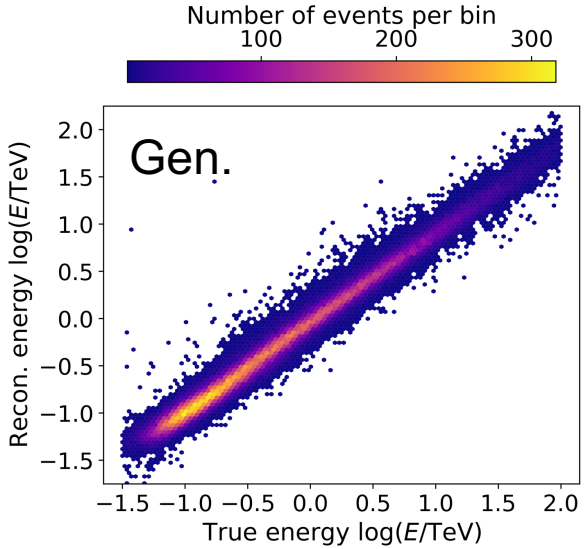
- Various air shower characteristics represented
  - Circular signal
  - Elliptical signal
  - Truncated signal
  - → No mode collapsing
- → Simulated and generated images visually similar

Representation of physics in images

- Test if given energy/impact distance encoded in generated images
  - Reconstruct energy/impact of simulated and generated images using constrainer networks
- Reconstruction performance similar → physics represented in images
  - Less fluctuations for generated images



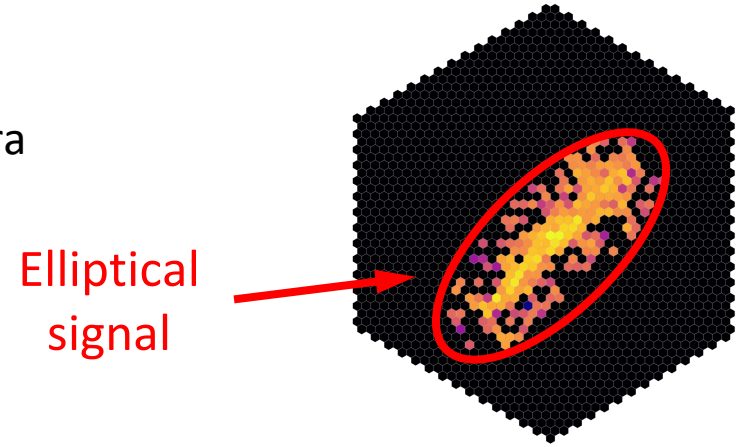


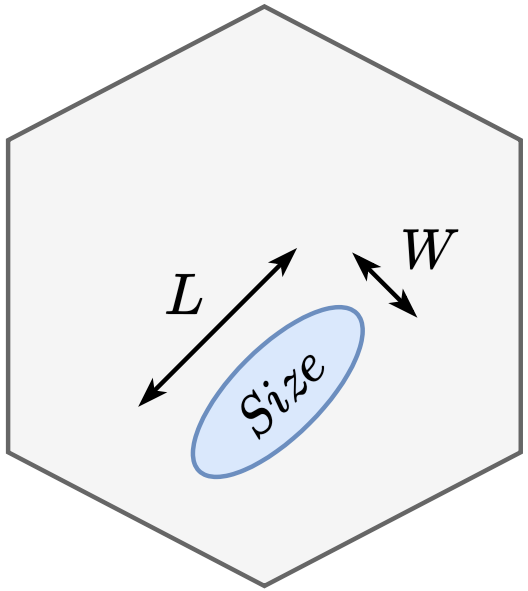


Event analysis using Hillas parameters

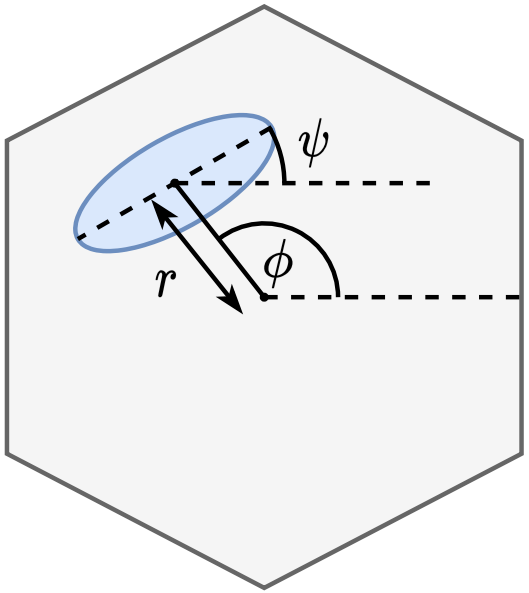
- Hillas parameters introduced for IACT image analysis
  - Elliptical parameterisation of the Cherenkov light distribution on the camera
  - Used for particle identification and event reconstruction

→ Utilized for quantifying shape of generated shower images





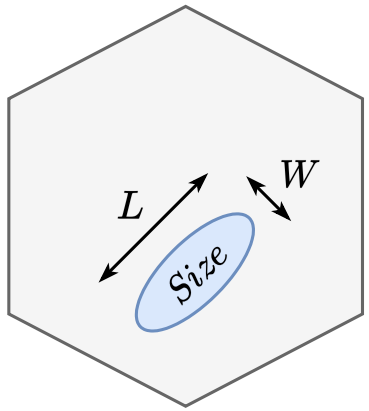
- **Size**: integrated signal
- **Length *L***: spread along major axis
- **Width *W***: spread along minor axis

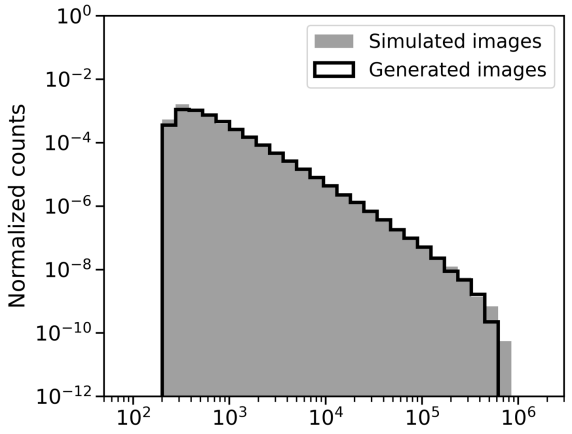


- **Polar coordinate *r*** of ellipsis center
- **Radial coordinate Φ** of ellipsis center
- **Rotation angle Ψ** of ellipsis

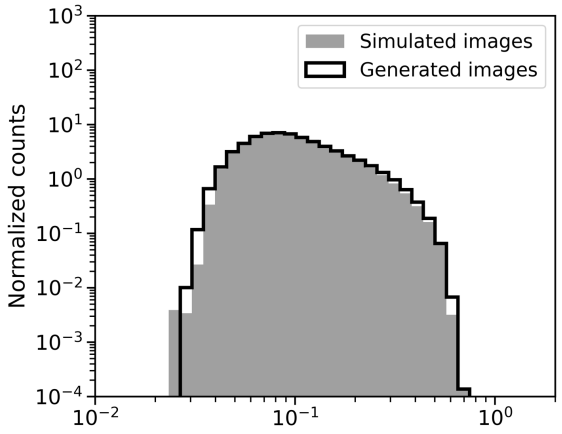
Analysed Hillas parameters

Shape of ellipsis

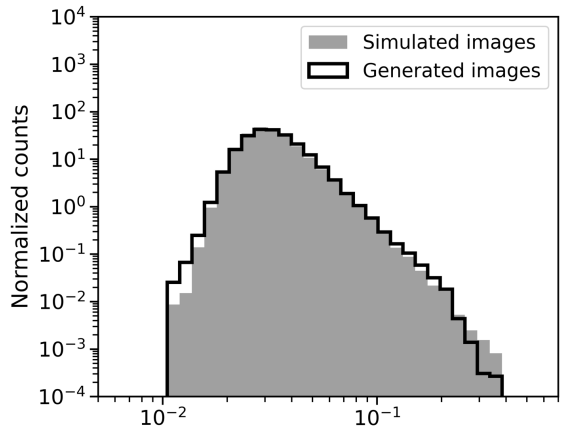




Size

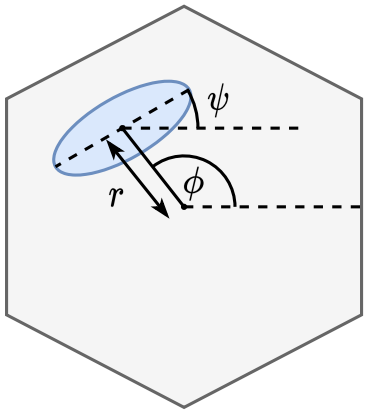


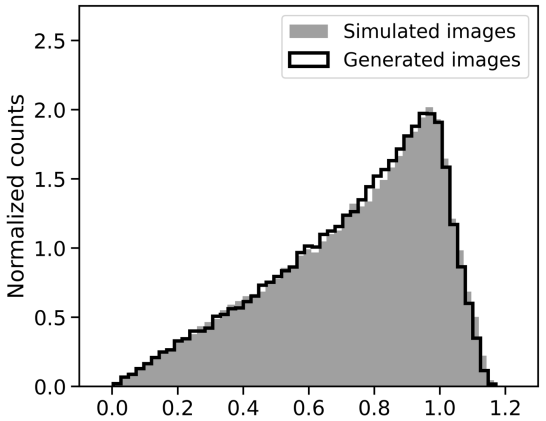
Length



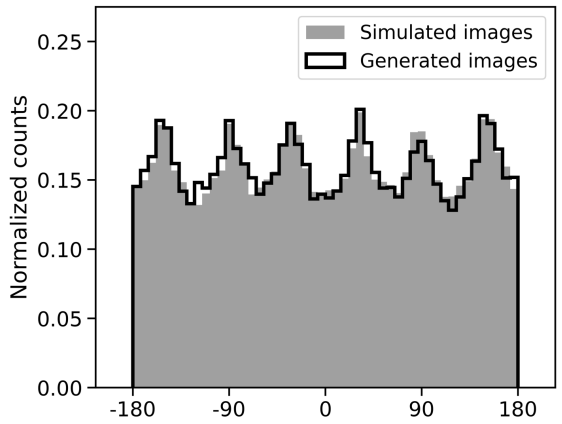
Width

Location of ellipsis

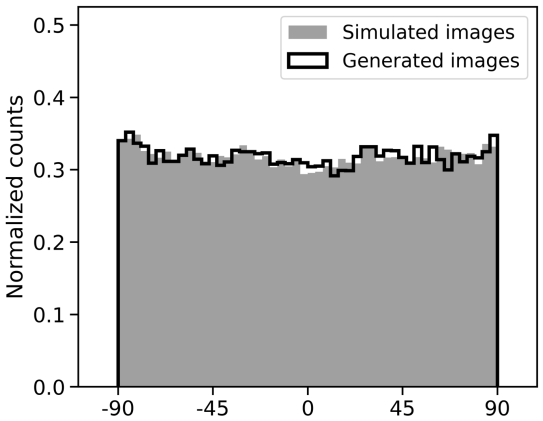




Radial coord.



Polar coord.



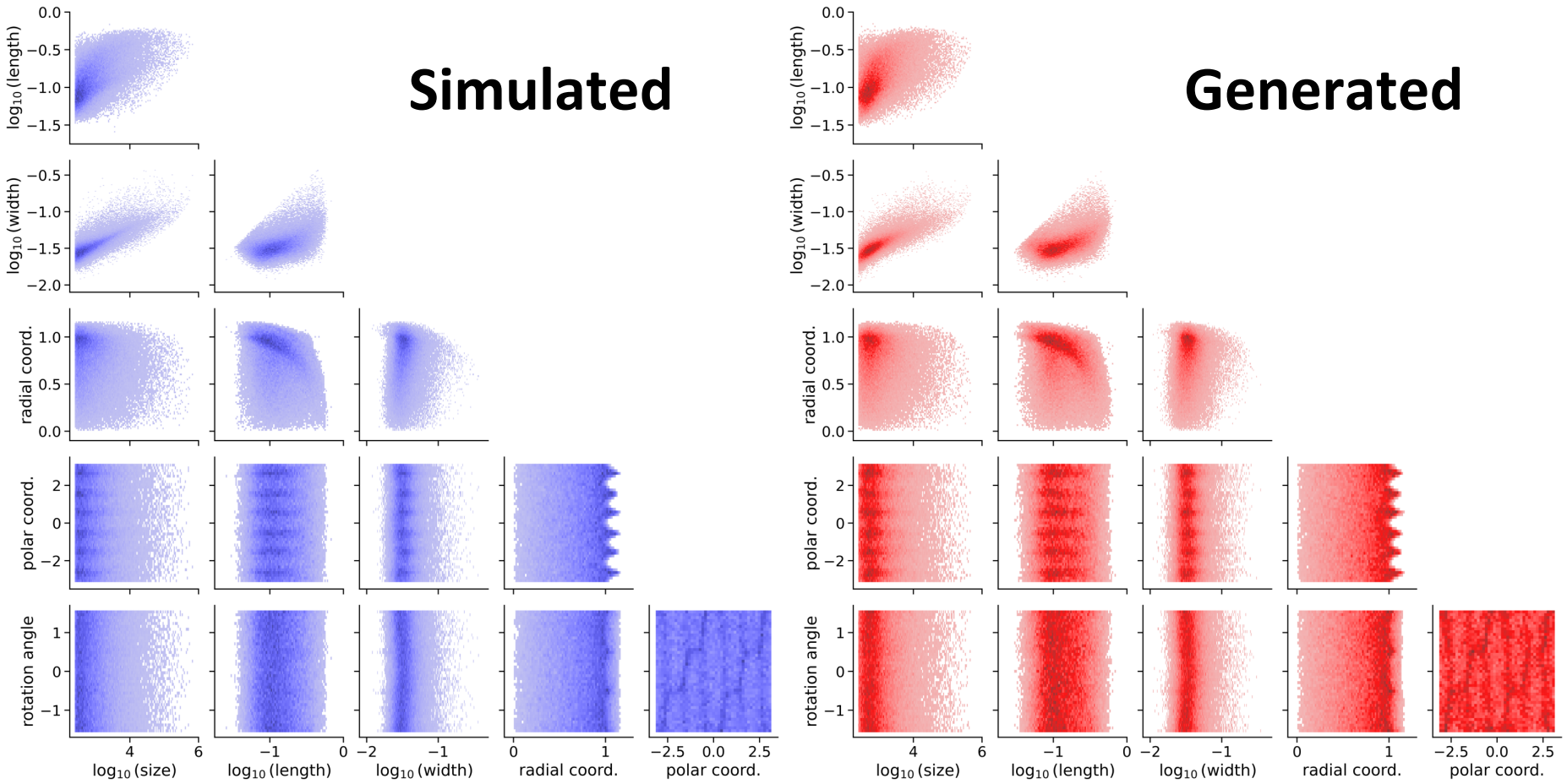
Rotation angle

→ Distributions for simulated and generated images match well over several magnitudes

Correlation of Hillas parameters

- Investigation of encoded physics
  - → Study correlations of high-level parameters
- Minor differences but overall similar
- Fluctuations slightly under-represented

→ WGAN able to pick up complex parameter correlations

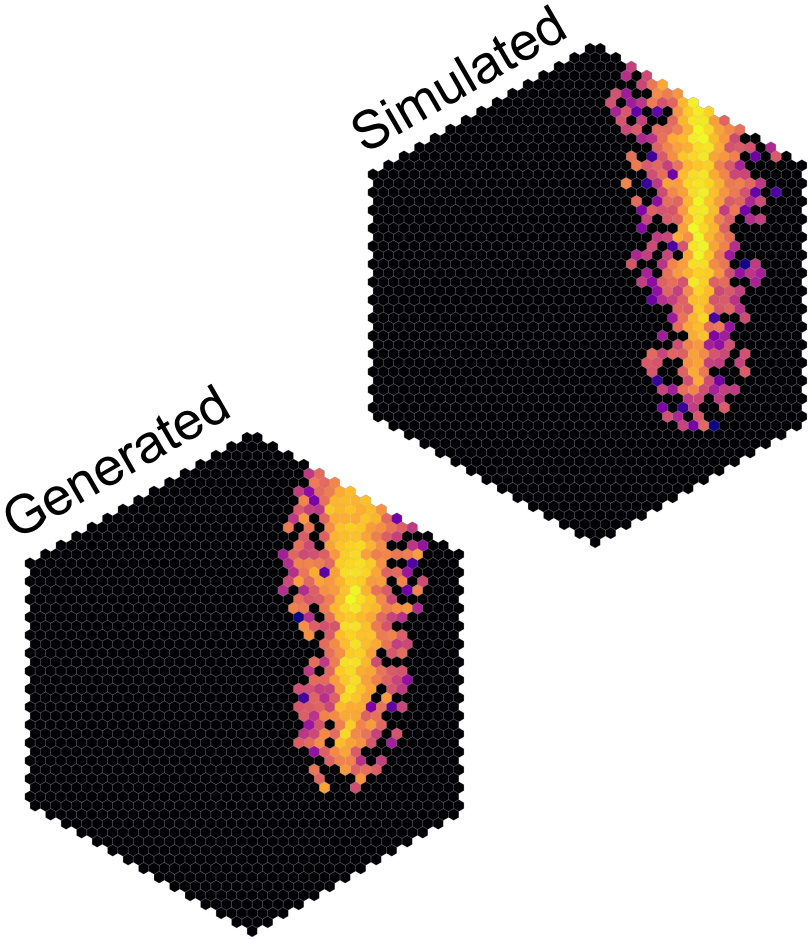


→ **Successful generation of realistic air shower images**

Summary

Ultra-Fast Generation of Air Shower Images (arXiv:2311.01385):

- Simulation of IACT events computationally expensive
  - Investigate fast and memory-efficient approach for event generation
  - Training of WGAN-GP framework (H.E.S.S. CT5 FlashCam)
- Successful generation of realistic images (more than 1500 pixels)
  - Speed-up of five orders of magnitude
- Analysis of Hillas parameters and their correlations
  - Model shows high fidelity in reproducing distributions



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

Backup

Framework for generating air shower images