Friedrich-Alexander-Universität
Erlangen-Nürnberg

GEFÖRDERT VOM
Bundesministerium
für Bildung
und Forschung

Reconstruction of Proton showers using H.E.S.S.

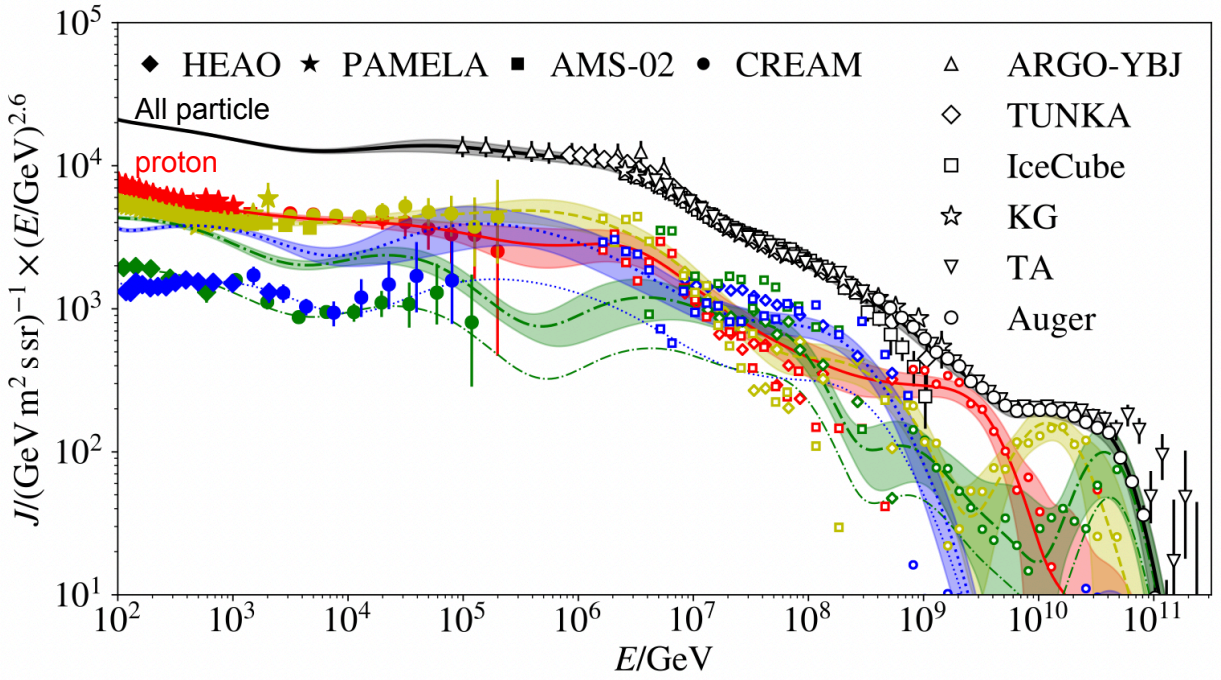
Benedetta Bruno, Jonas Glombitza, Stefan Funk for the H.E.S.S. Collaboration
High-energy astrophysics in the multi-messenger era - Workshop, 08.05.23

About myself…

- Bachelor in Physics @ University of Pisa
- Master in Astrophysics and Cosmology @ University of Bologna
- PhD @ ECAP and working on
  - IRF correction scheme
  - Reconstruction of proton showers

Cosmic Rays

- Over 100 years of research
- Wide variety of potential sources: SNR, AGNs, GRB, etc..
- Space satellite and ground based experiments
- Spectrum observed from Earth largely dominated by protons up to few PeV



arXiv:1711.11432v1

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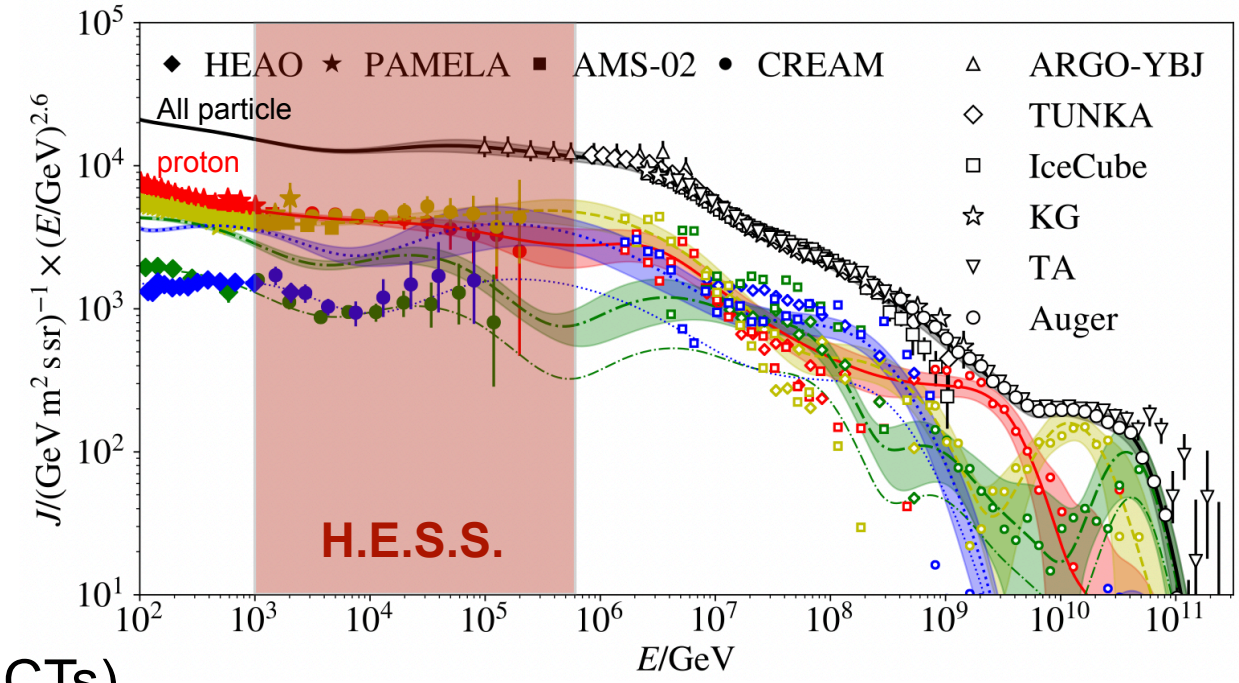


Imaging Atmospheric Cherenkov Telescopes (IACTs)

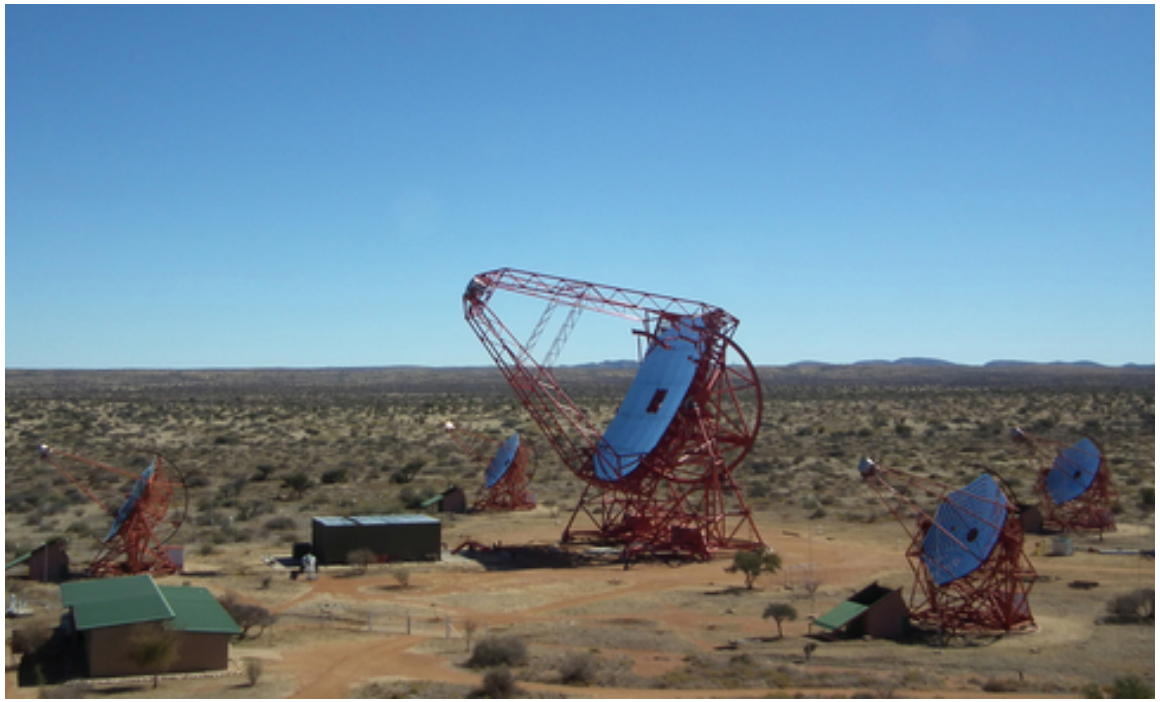
are usually interested in Gamma rays…

bridge between space and ground based CR observatories

arXiv:1711.11432v1

High Energetic Stereoscopic System (H.E.S.S.)

- IACT array located in Namibia
- Observation of gamma rays from 10s of GeV to 10s of TeV
- Protons are dominating background
  - High statistics
- Event reconstruction has to be adapted

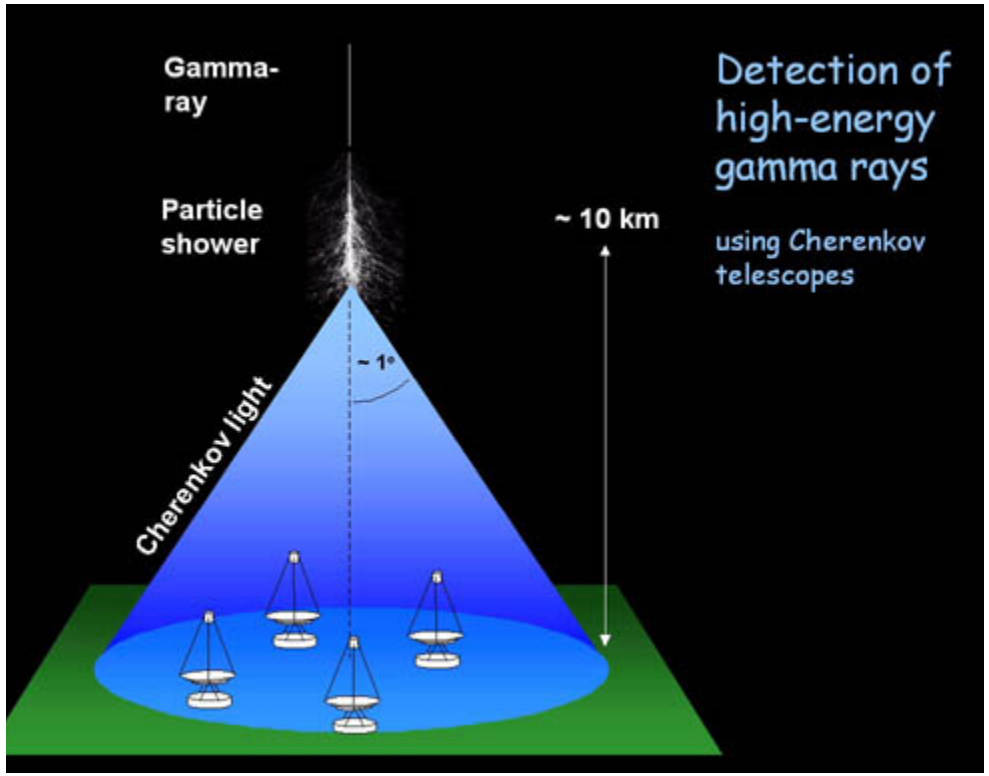


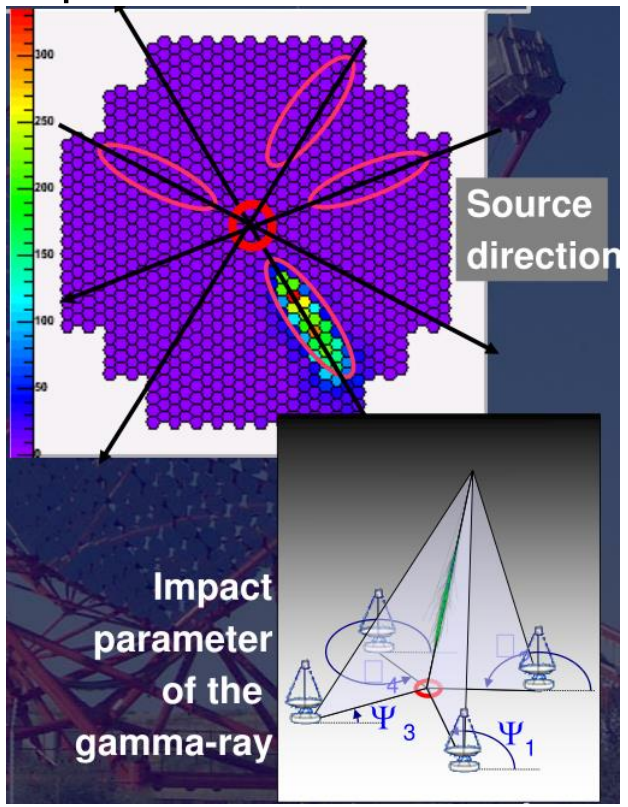
www.mpi-hd.mpg.de

Reconstruction with H.E.S.S.

Standard approach with Hillas parameters

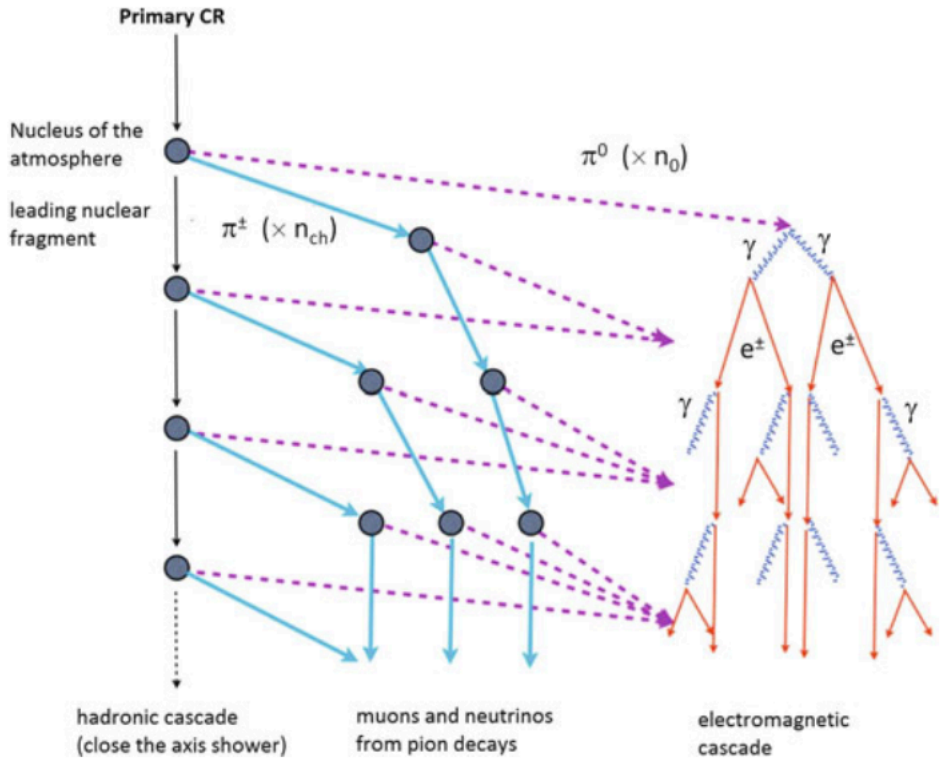
- IACTs detect the Cherenkov light distribution from air showers
- Images are approximated with ellipses
- Energy and shower direction reconstructed through the properties of those ellipses:
  - Integrated intensity → Energy
  - Intersection of major axes → Direction
    - Impact point on the ground





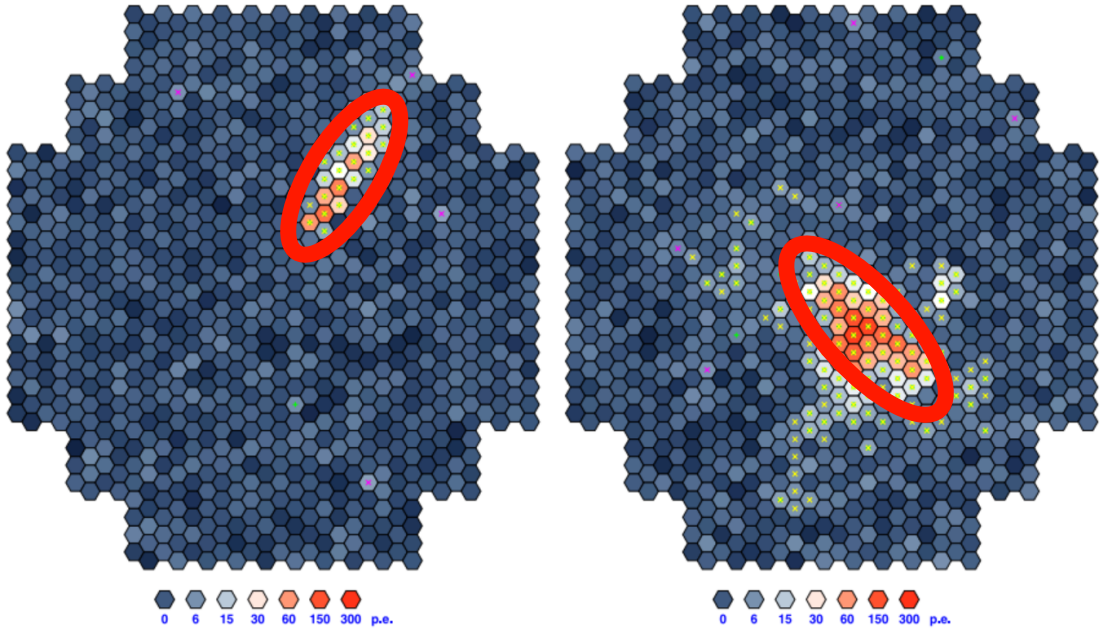
Reconstruction with Hillas parameters

Expected strong bias in the energy reconstruction of ~2/3 because of the hadronic shower component



https://arxiv.org/abs/1103.0031

Proton images are more widely distributed in the camera and residual backgrounds remain still large



1.0 TeV gamma shower

2.6 TeV proton shower

Völk+ 2009 Exper.Astron. 25 173

Reconstruction with Hillas parameters

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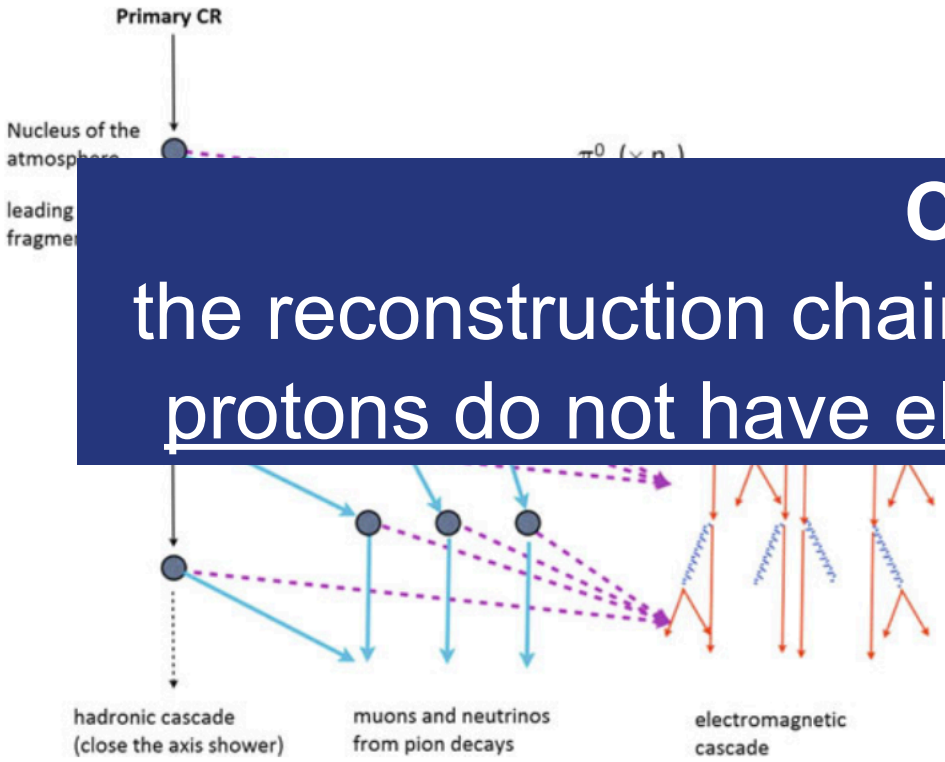

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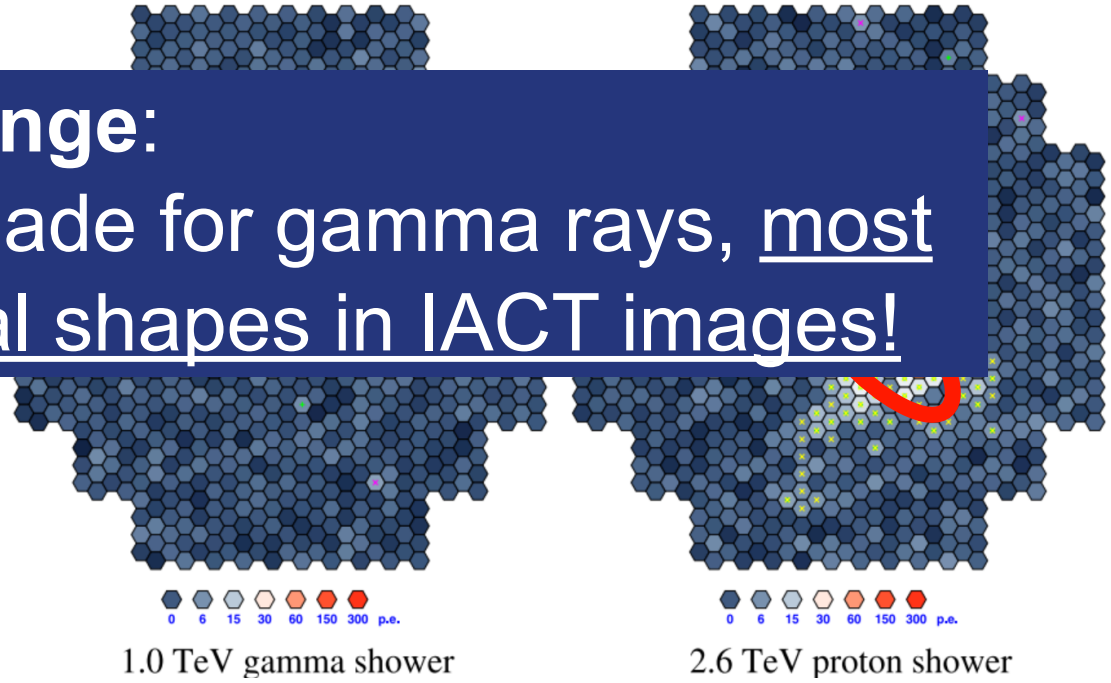


Völk+ 2009 Exper.Astron. 25 173

Challenge:
the reconstruction chain is made for gamma rays, most protons do not have elliptical shapes in IACT images!

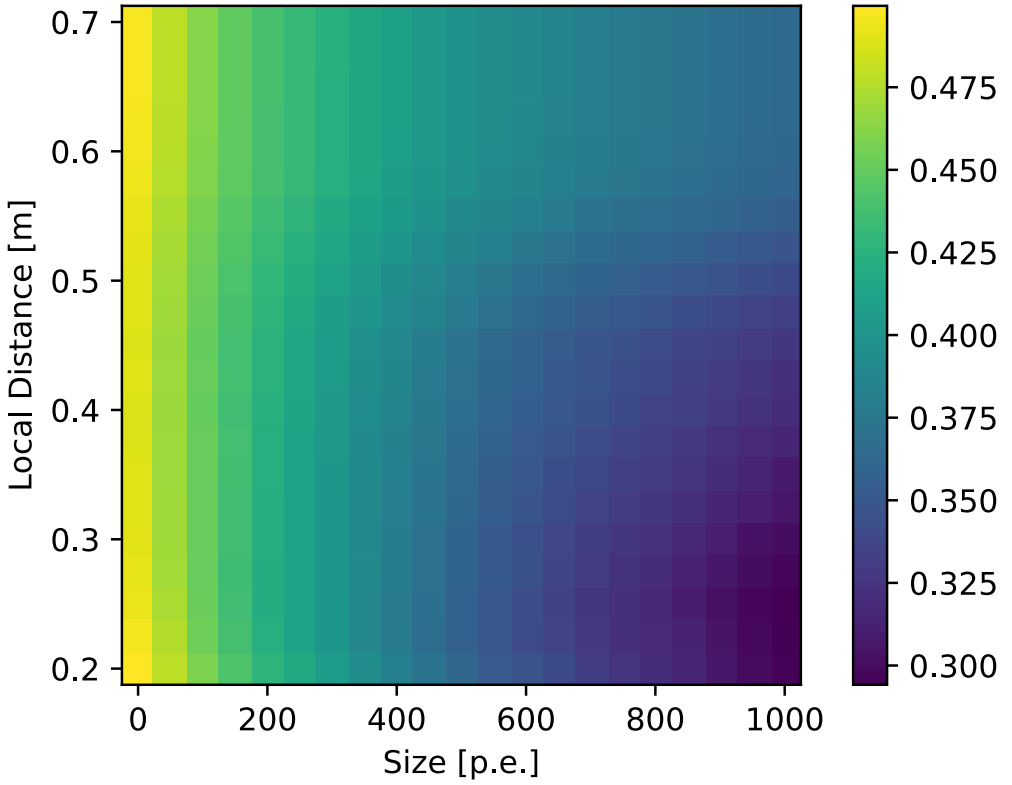
Changes in the reconstruction chain

Optimisation of image amplitude and local distance, analysed together in a 2d grid scan

- Reconstruct protons images that look “gamma-like”
- Energy reconstruction based on MC templates
- Analysis of the reconstructed impact point
- Strict cuts are applied

Selection cut	Allowed values
Multiplicity	4
Image amplitude	$> 300\,\mathrm{p.e.}$
Local distance	$< 0.525\,\mathrm{m}$

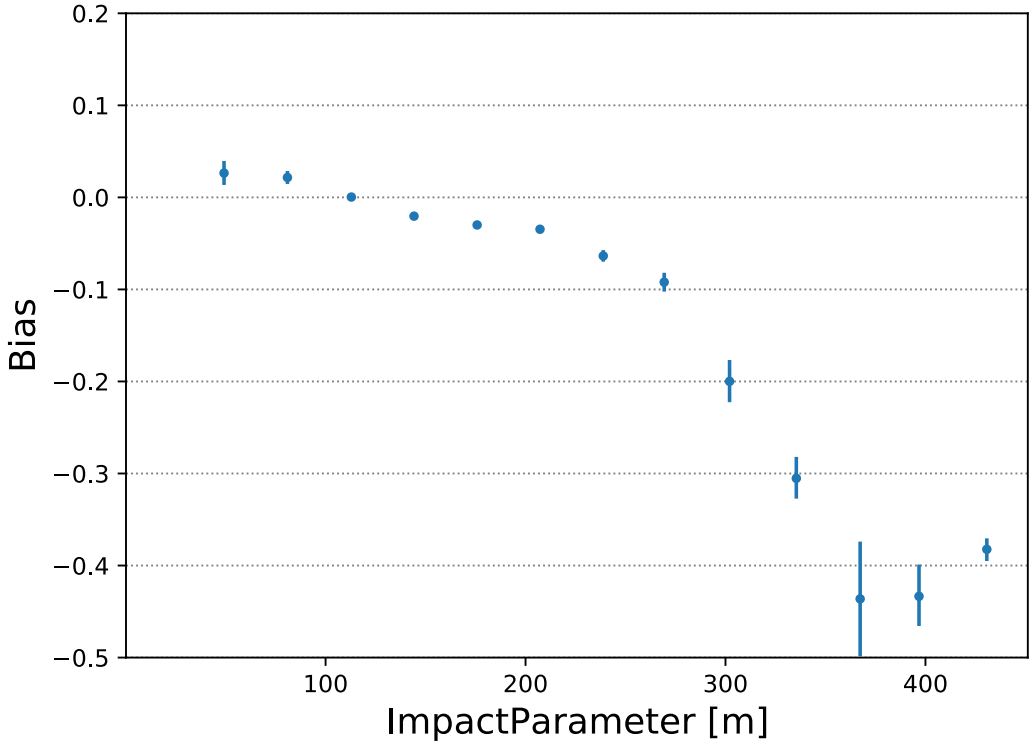
Relative resolution $\left(\frac{\mathrm{Imp_{reco}} - \mathrm{Imp_{true}}}{\mathrm{Imp_{true}}}\right)_{68\%}$ of the reconstructed impact point

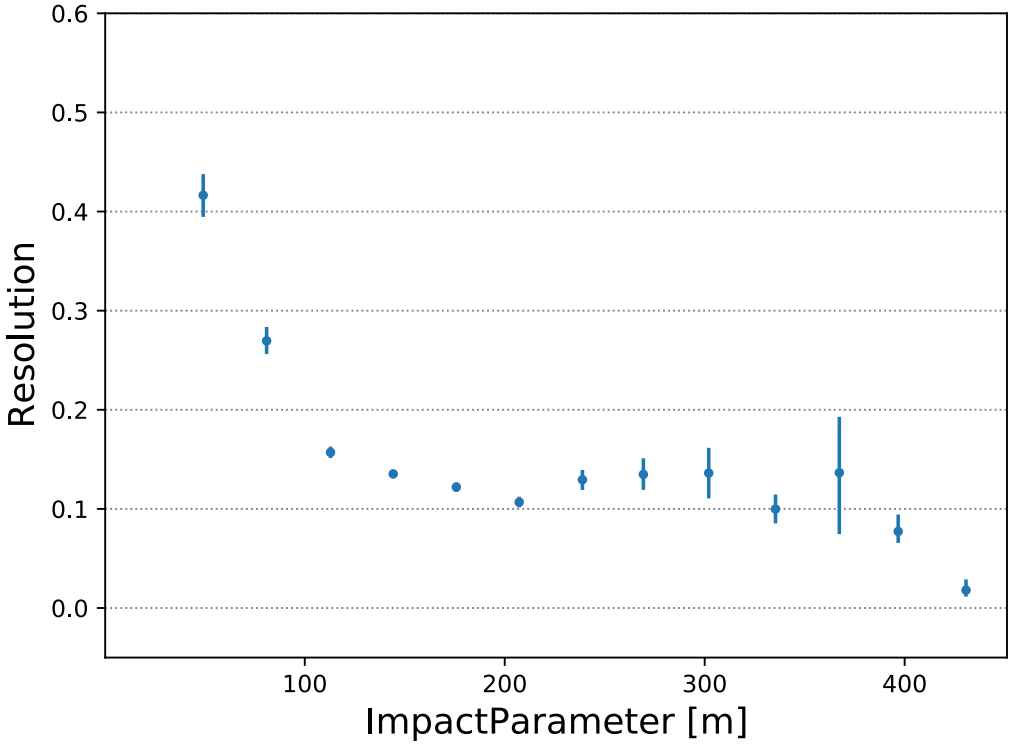


Reconstruction with the proton adapted standard method

Bias and resolution of the Impact Point

Impact parameter bias $< \frac{\mathrm{Imp_{reco}} - \mathrm{Imp_{true}}}{\mathrm{Imp_{true}}} >$ and resolution $\sigma\left(\frac{\mathrm{Imp_{reco}} - \mathrm{Imp_{true}}}{\mathrm{Imp_{true}}}\right)$

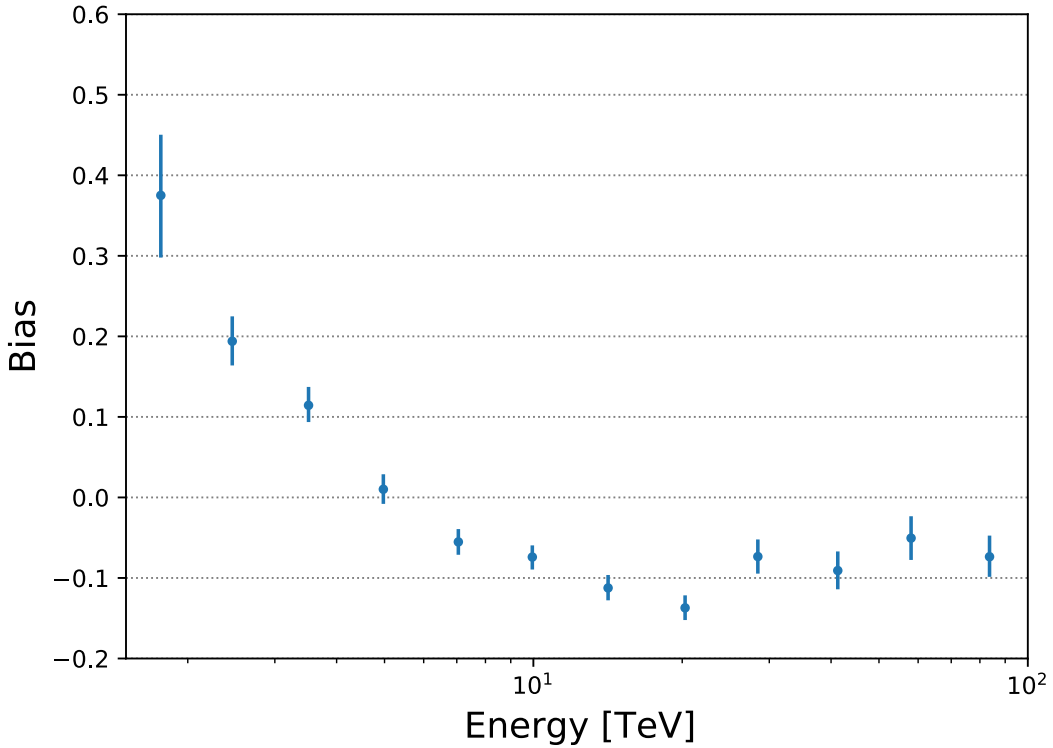


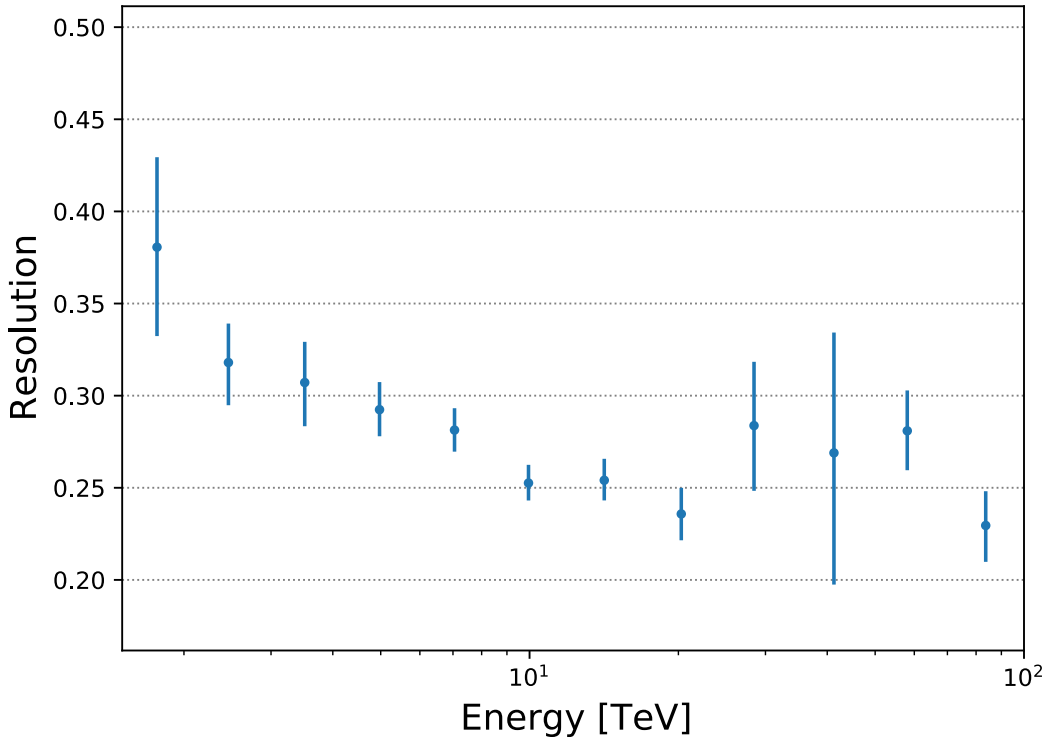


Reconstruction with the proton adapted standard method

Bias and resolution of the Energy

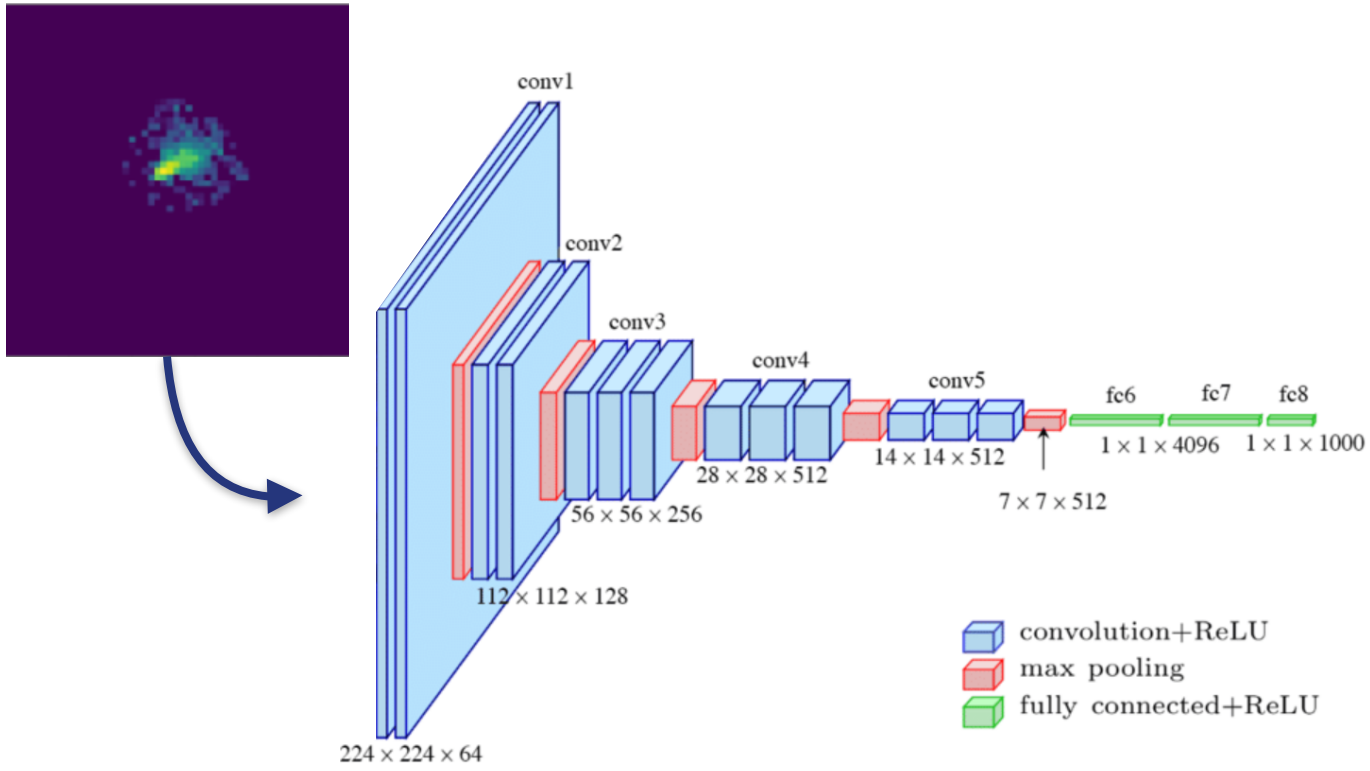
Energy bias $< \frac{E_{reco} - E_{true}}{E_{true}} >$ and resolution $\sigma\left(\frac{E_{reco} - E_{true}}{E_{true}}\right)$





Bias within ~20%, resolution within ~35%

Energy reconstruction with CNN approach



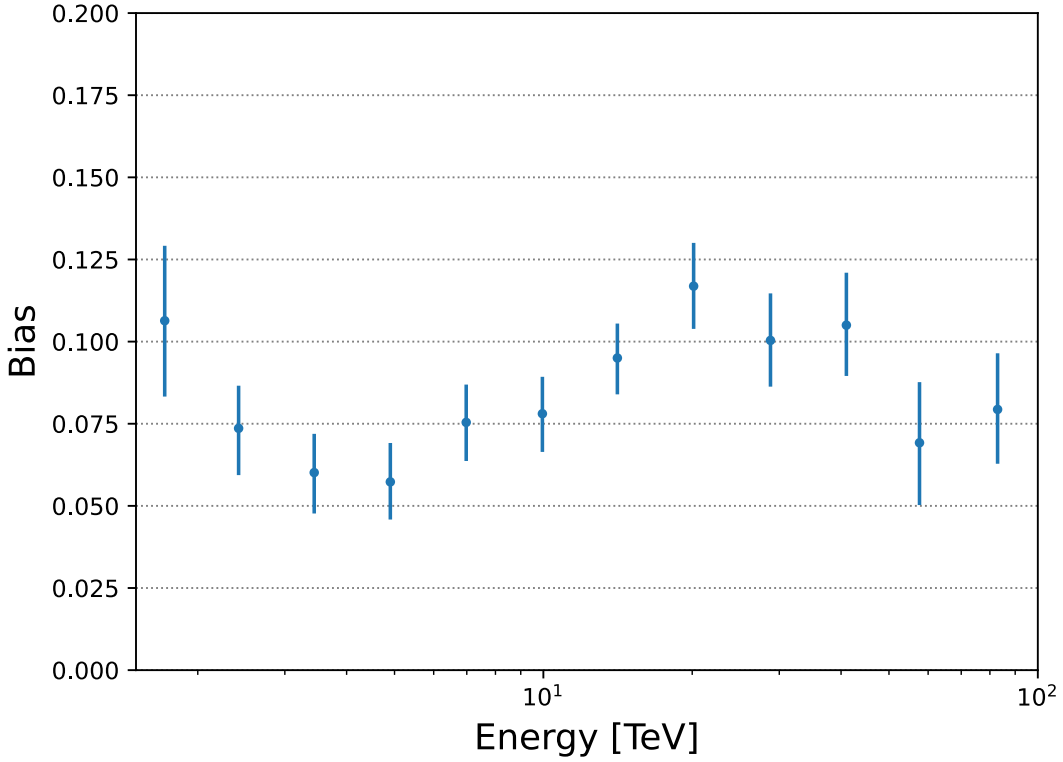
https://arxiv.org/abs/1409.1556v6

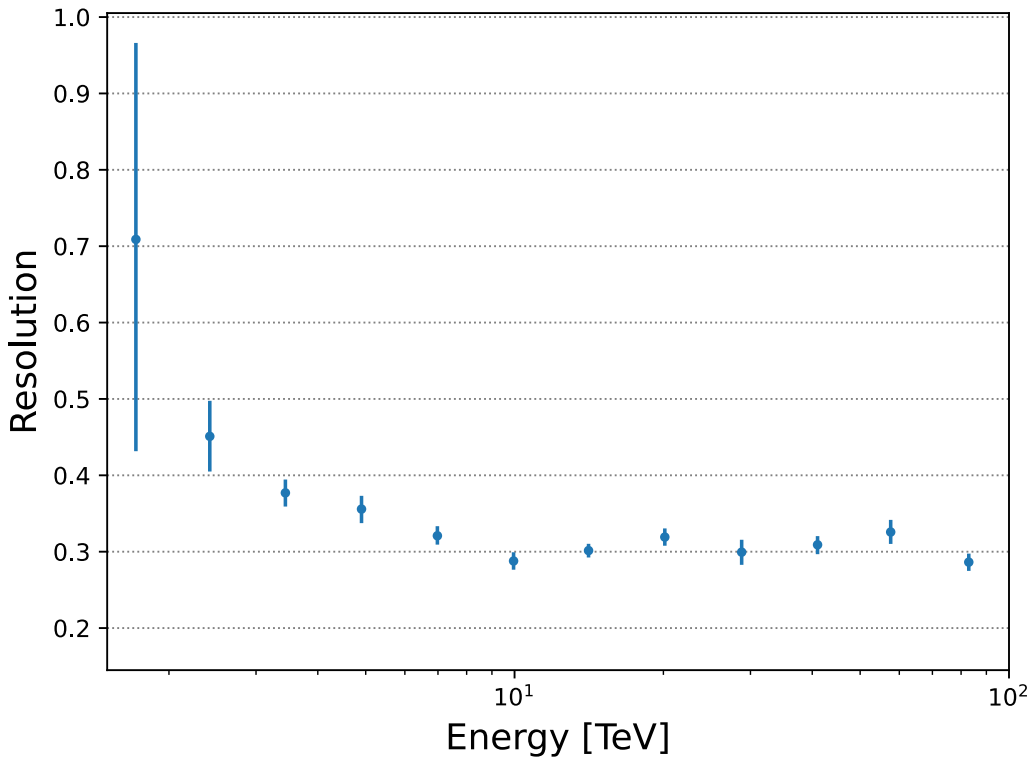
- Current method limited to elliptical image modelling
- Exploit full substructure in proton images by using CNN
  - Significantly increasing statistics
  - Enable to relax cuts
- Detected images are analysed on a telescope-by-telescope basis and merged in fully-connected part
- Method to exploit event stereoscopy ongoing challenge

Reconstruction with CNN approach

Very PRELIMINARY results on energy reconstruction

Energy Bias and Resolution





Bias within 12%, resolution competitive

Summary

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FAU

- **Aim**: reconstruct proton air showers using H.E.S.S.
- **Reconstruction methods**:
  - Modify Hillas protons of gamma ray showers
  - Developed machine-learning-based reconstruction
- **Successful modified**
  - **Good reconstruction of impact point and energy** ✅
- **Promising results for energy reconstruction using CNN** ✅
  - **Enable higher statistics** → more studies needed
- **Next steps**:
  - Increase statistic of simulation and investigate systematic uncertainties
  - Reconstruct the proton spectrum with both approaches

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FAU

Backup slides

Definitions

- The bias of any quantity is defined as

$$\text{bias} = < \frac{q_{reco} - q_{true}}{q_{true}} >$$

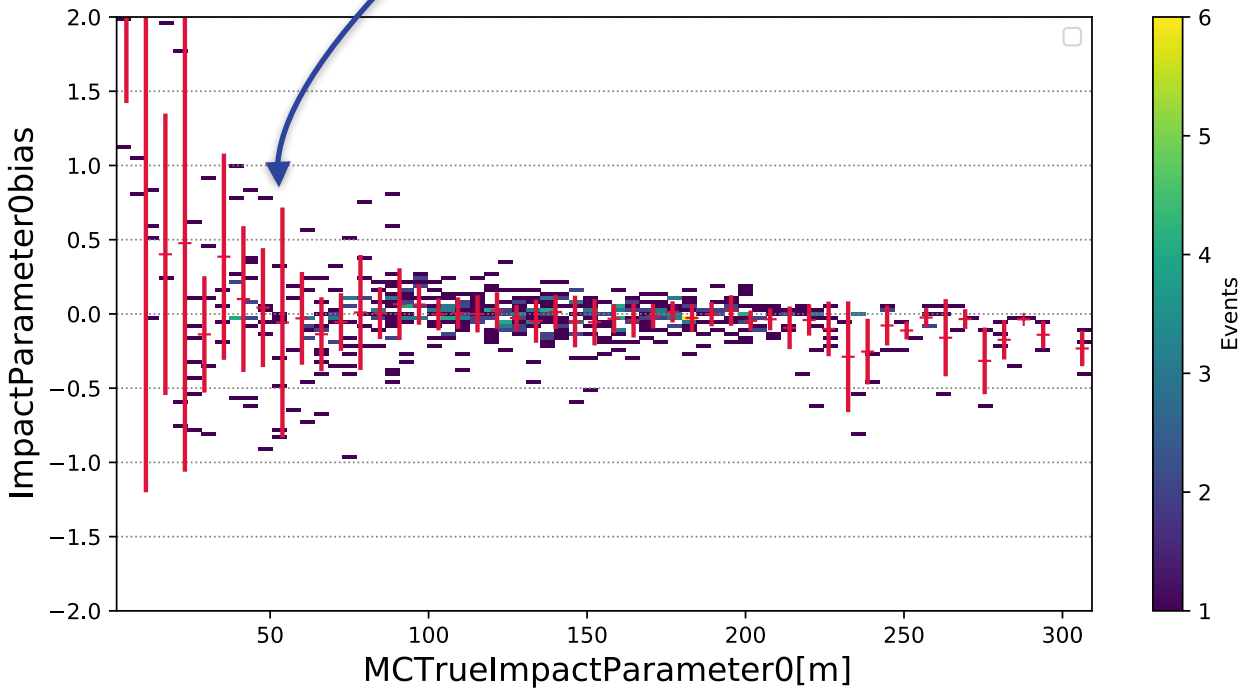
- The resolution of any quantity is defined as

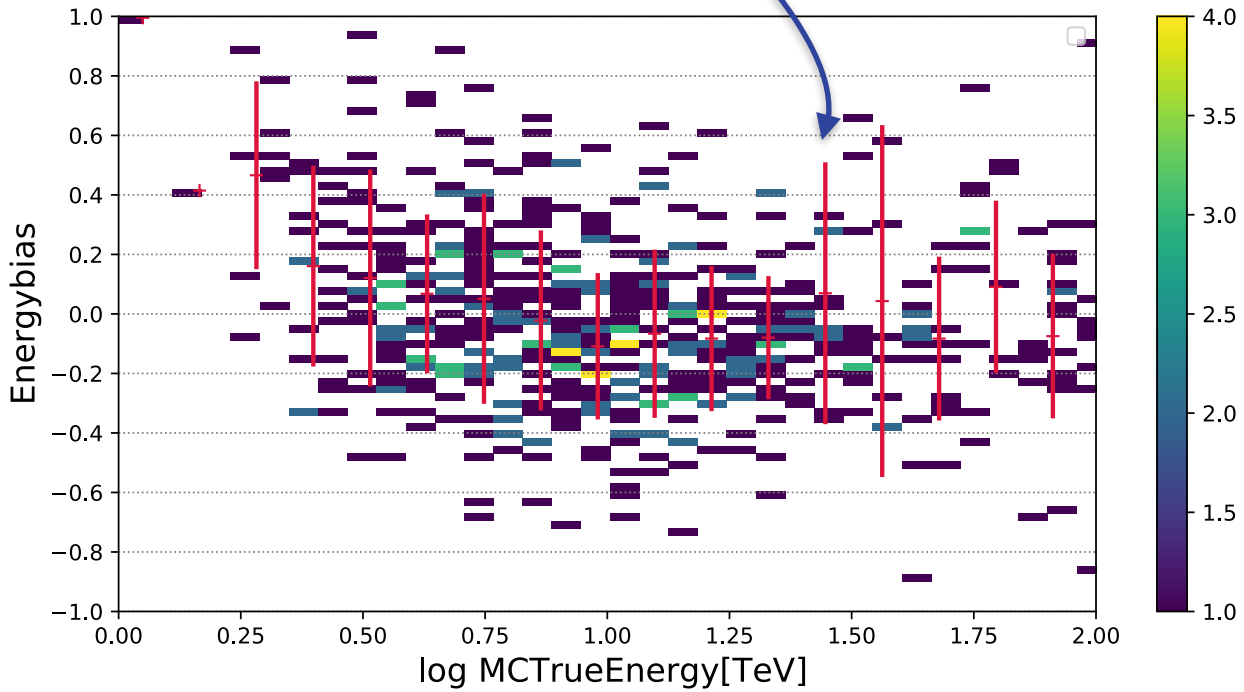
$$\text{resolution} = \sigma\left(\frac{q_{reco} - q_{true}}{q_{true}}\right) \text{ or } \left(\frac{q_{reco} - q_{true}}{q_{true}}\right)_{68\%}$$

Reconstruction with the proton adapted standard method

Hillas analysis with proton lookups

Red datapoints indicate bias and resolution in each impact/energy bin





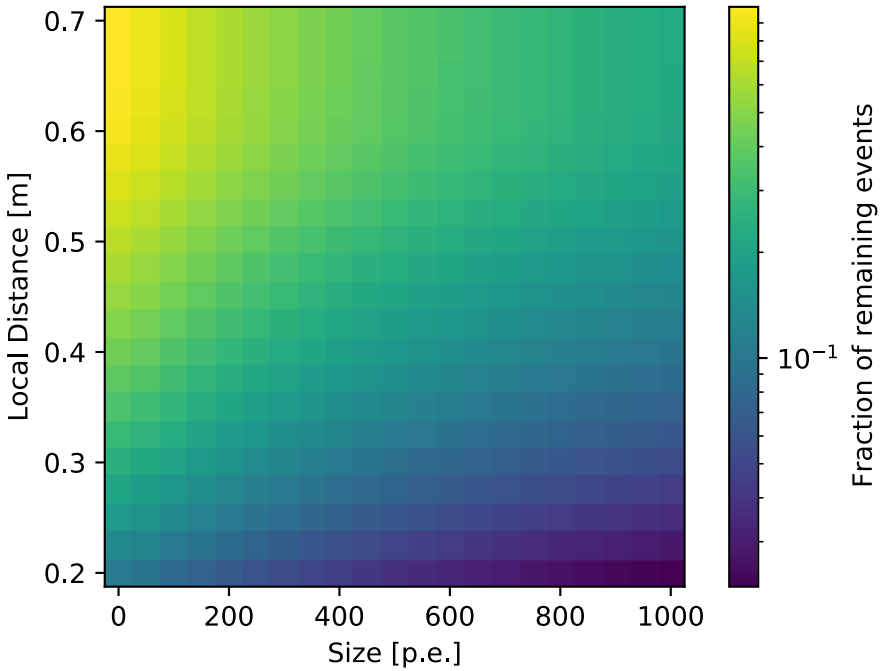
Good impact reconstruction and better resolution above 50m ✅

Small bias in energy reconstruction, using modified chain made for a proton analysis ✅

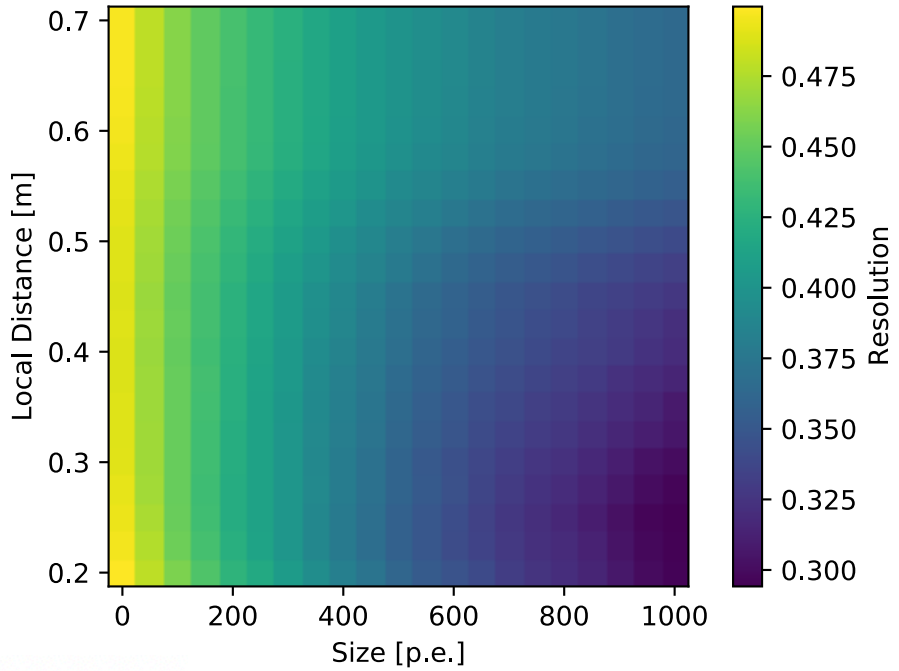
Changes in the reconstruction chain

Optimisation of image amplitude and local distance, analysed together in a 2d grid scan

Remaining events



Resolution of the reconstructed impact point

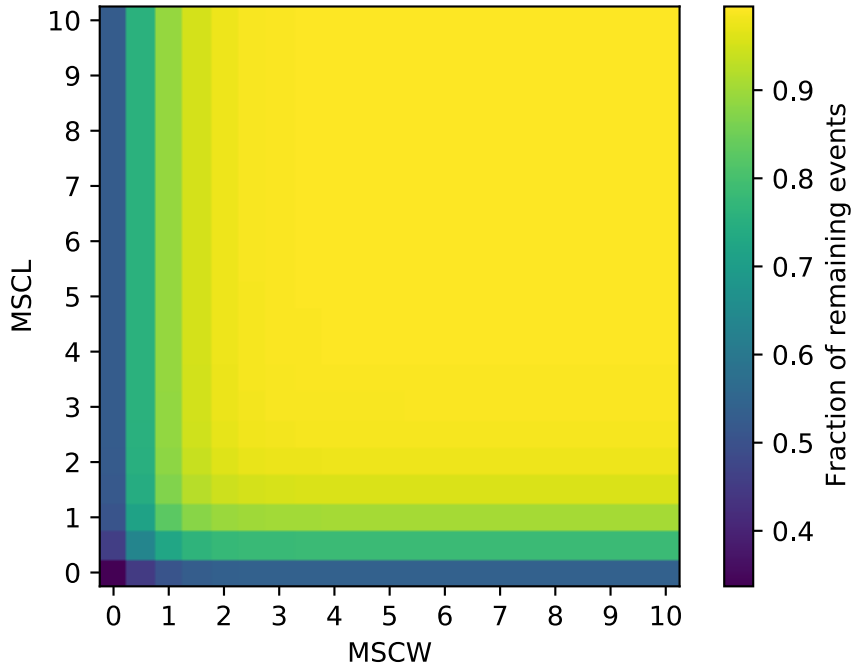


Selection cut	Allowed values
Multiplicity	4
Image amplitude	$> 300\,\mathrm{p.e.}$
Local distance	$< 0.525\,\mathrm{m}$

Changes in the reconstruction chain

Optimisation of MSCW and MSCL, analysed together in a 2d grid scan after applying the previous cut

Remaining events



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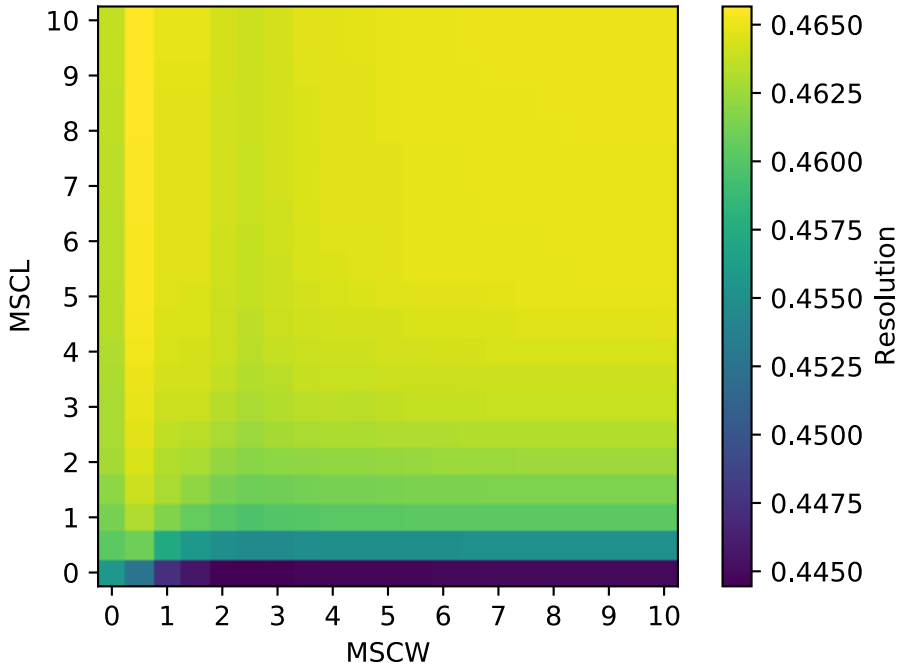

MSCW	[0.0:0.6]	
MSCL	[-6.0:6.0]	Post-
Core distance	$< 200\,\mathrm{m}$	selection
Core goodness	$< 30\,\mathrm{m}$	
Offset	$< 1.5°$	