Simulation tools for Imaging Atmospheric Cherenkov Telescopes

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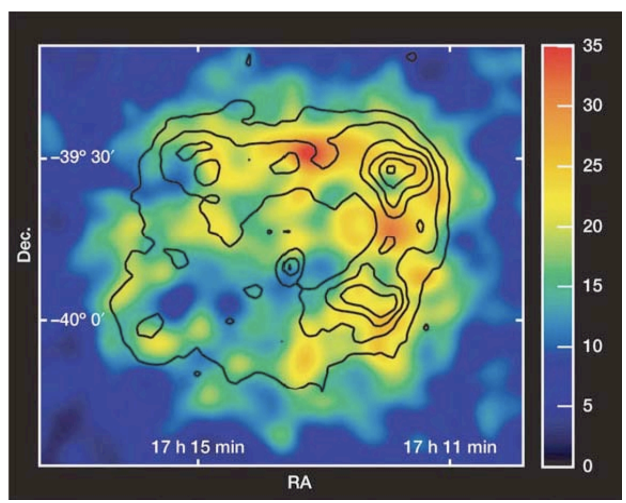


Outline

- Tools for:
  1. Extensive Air Showers simulation
  2. Telescope simulation

General considerations

Any simulation of the IACT technique consists of 2 major steps:

1. the development of extensive air shower (EAS) in the atmosphere and the Cherenkov light emission
   - Done by **CORSIKA** → D.Heck et al. CORSIKA a Monte Carlo code to simulate extensive air showers, Tech. Rep. FZKA 6019, Forschungszentrum Karlsruhe, 1998

2. the response of the telescope (optics, photon detection, electronics)
   - Done by **sim_telarray** → K. Bernloher, Astroparticle Physics 30 (2008) 149-158

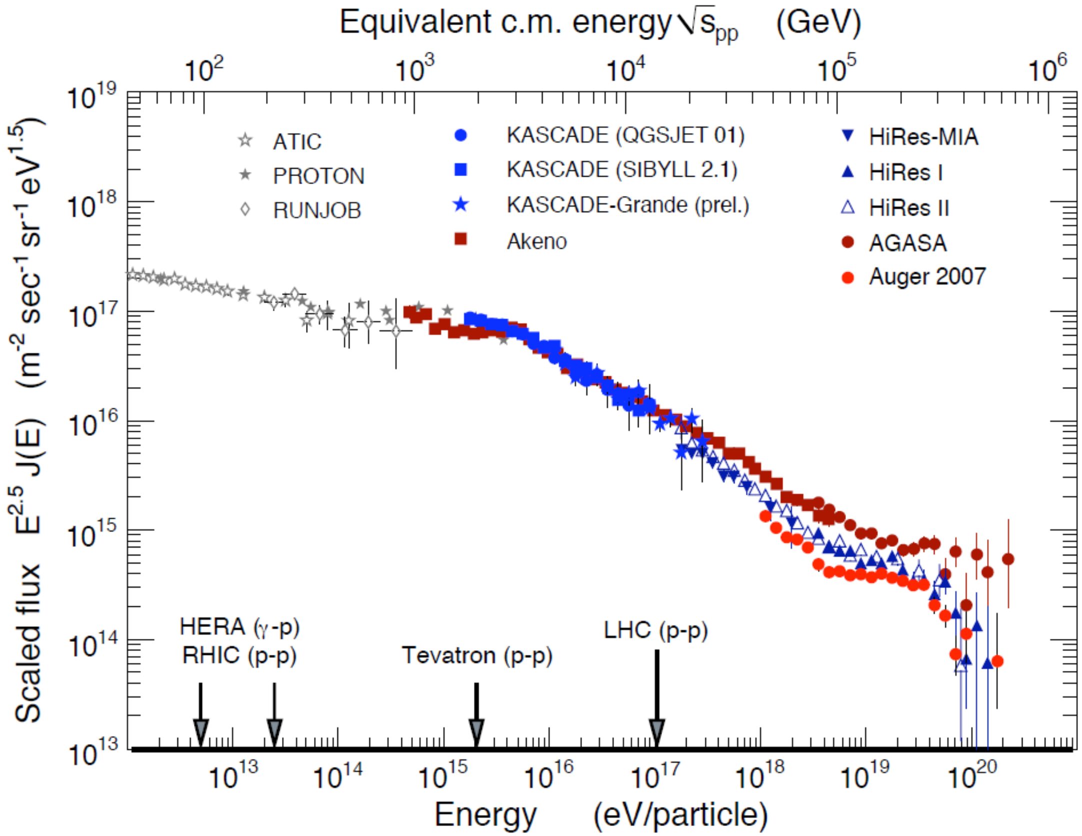
CORSIKA: simulation of EAS

- **CO**smic **R**ay **SI**mulations for **KA**scade
- developed for KASCADE and tested with many EAS experiments
- simulates **interactions** and **decays** of **nuclei, hadrons, muons, electrons,** and **photons** in the atmosphere up to energies of some 10^{20} eV. It gives *type, energy, location, direction and arrival times of all secondary particles* that are created in an air shower and pass a selected observation level

CORSIKA: interaction models

CORSIKA hosts several different models for:

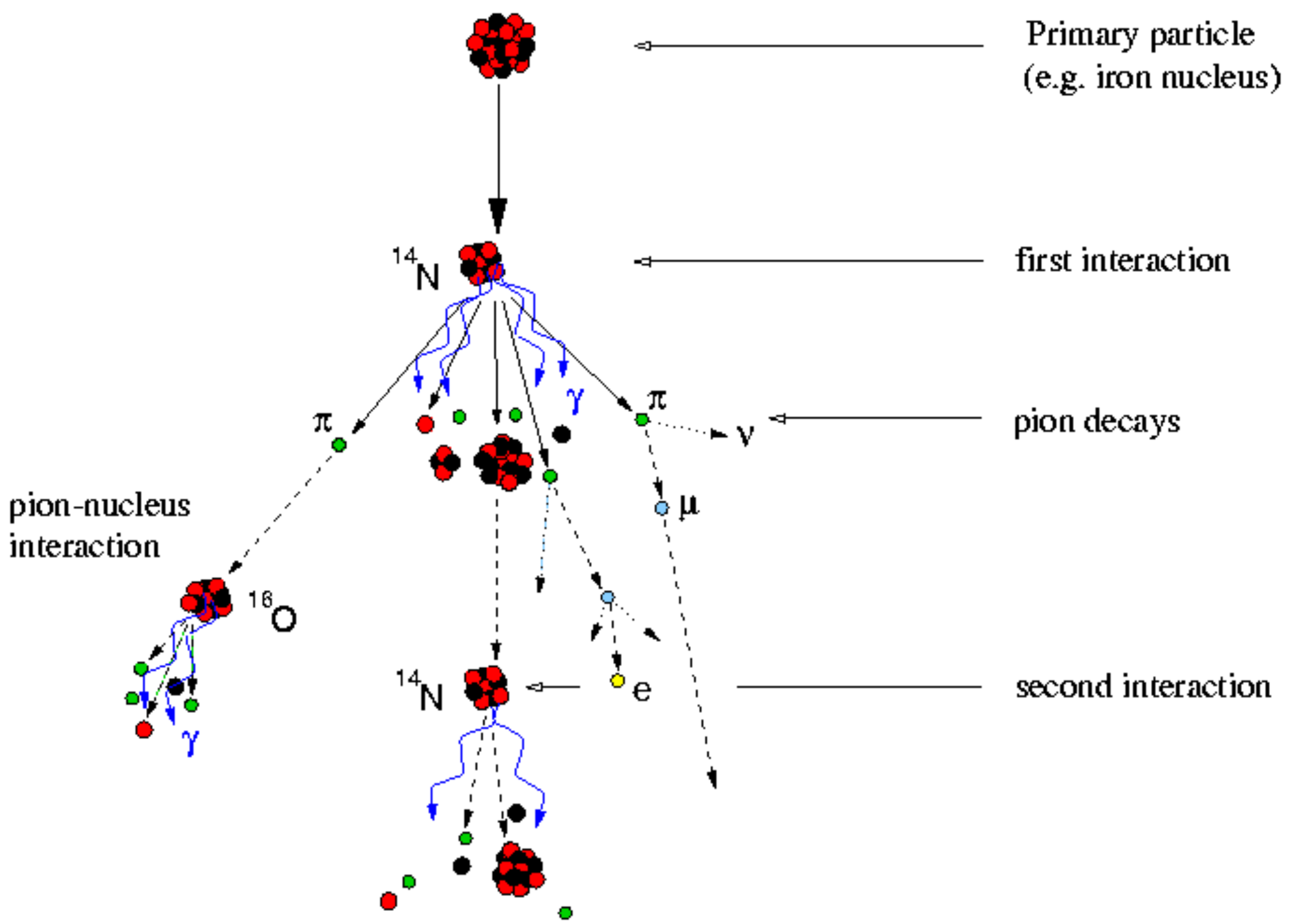
- **high energy hadronic** interactions
  - DPMJET, QGSJET (I e II), SIBYLL, EPOS...
- **low energy hadronic** interactions
  - FLUKA, GHEISHA, UrQMD
- **electromagnetic shower** development
  - EGS4 (following individual particles or analytical NKG or thinning)



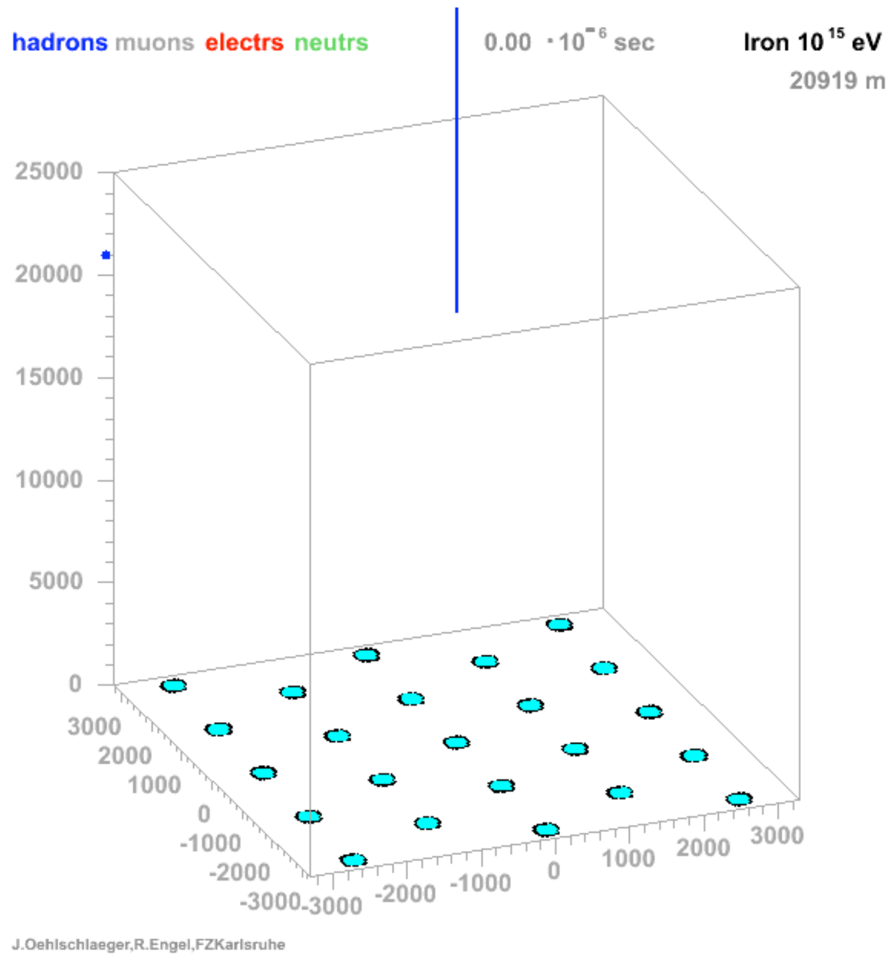
Hadrons are the diffuse background of IACT's measurements.

Hadron-induced shower development

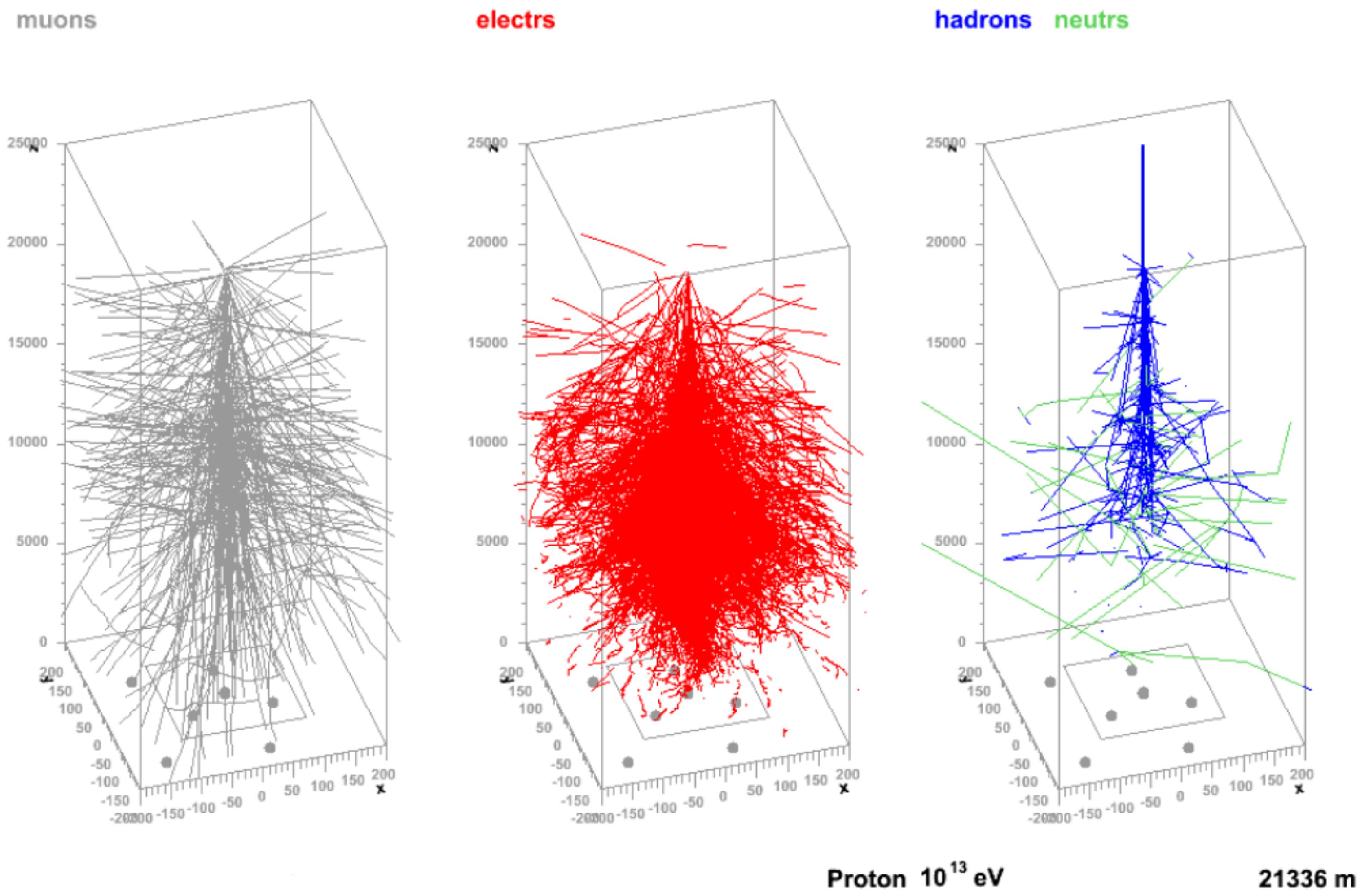
Development of cosmic-ray air showers



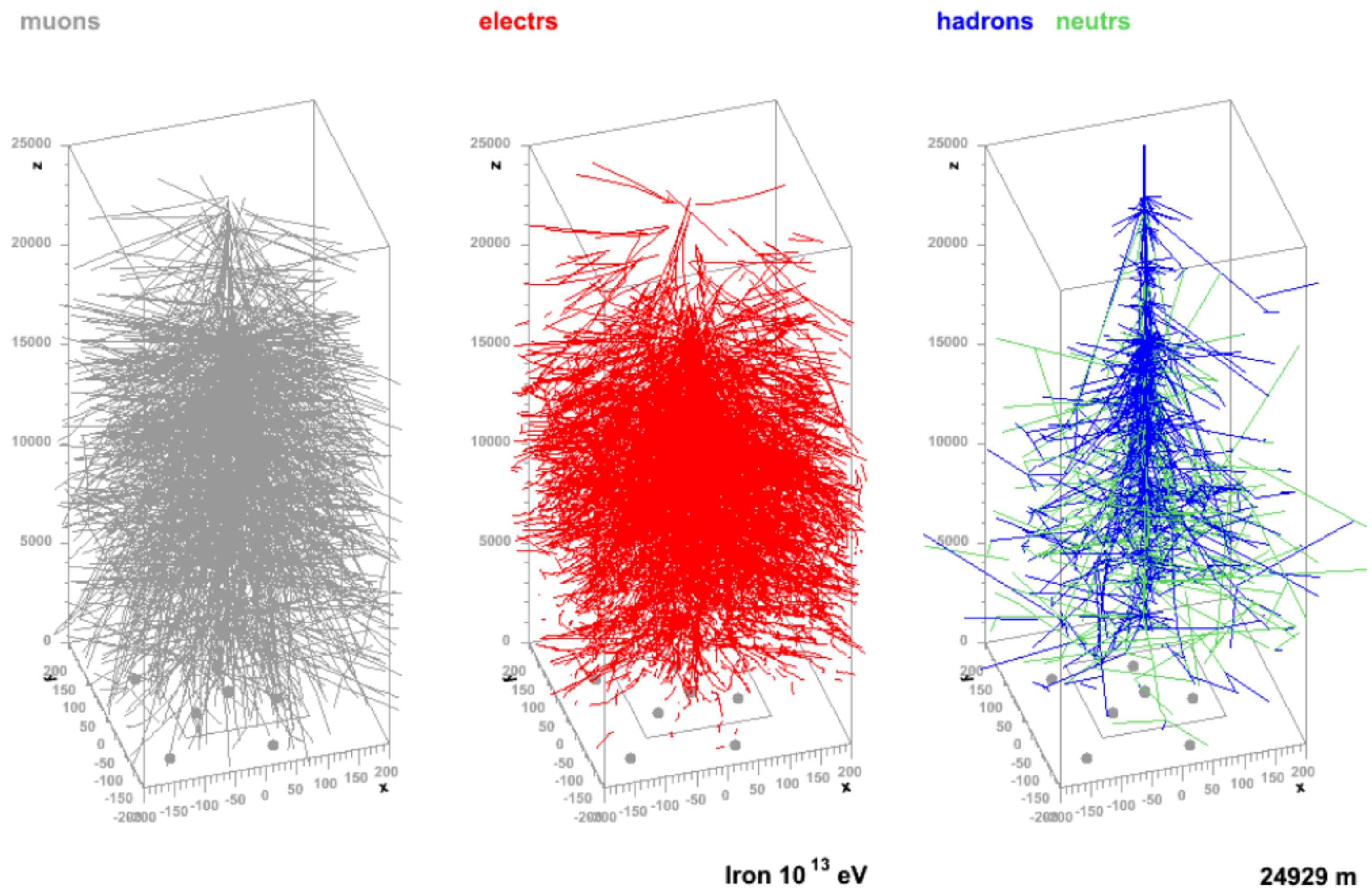
Hadron-induced shower development



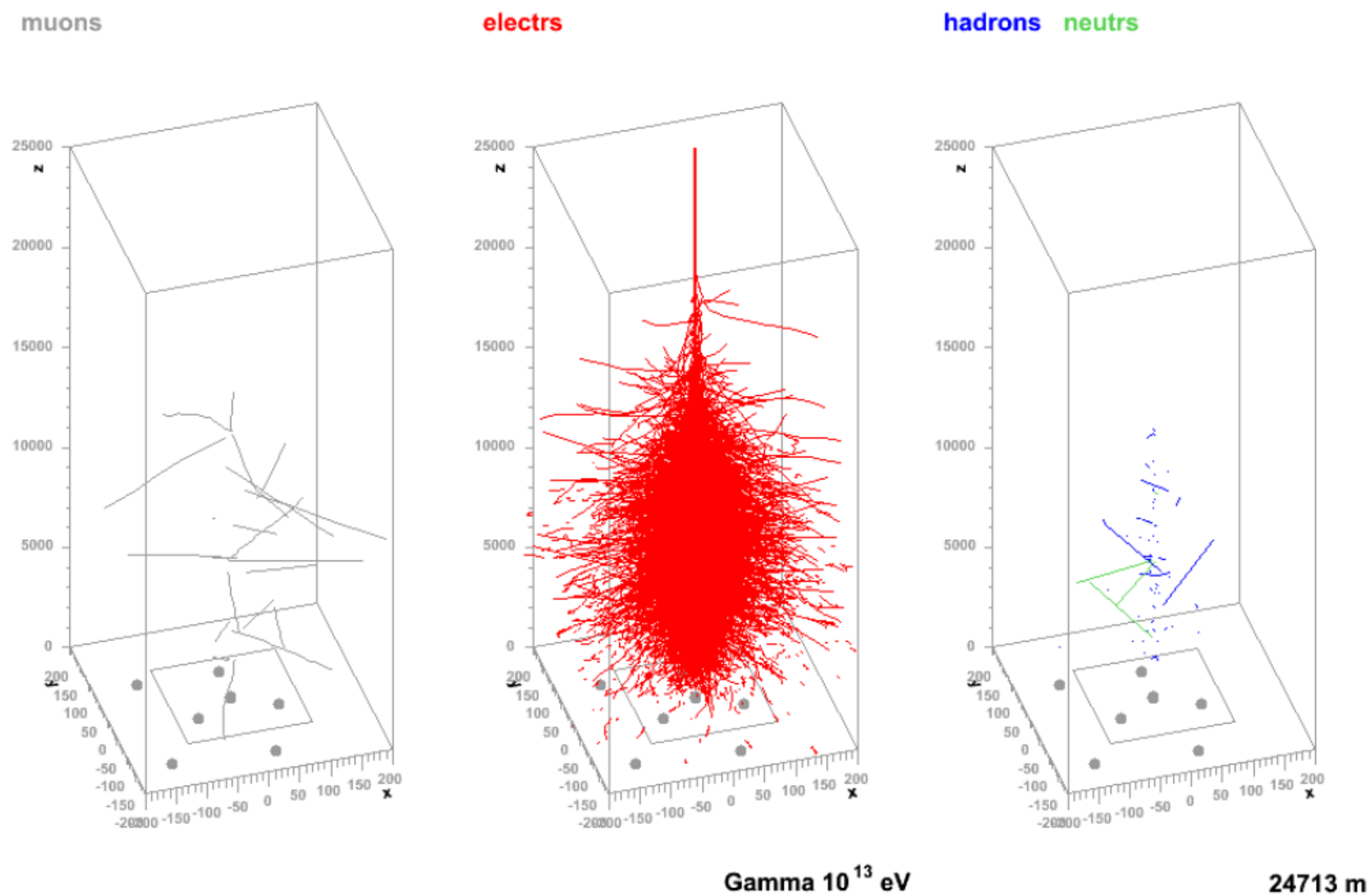
Shower development: proton



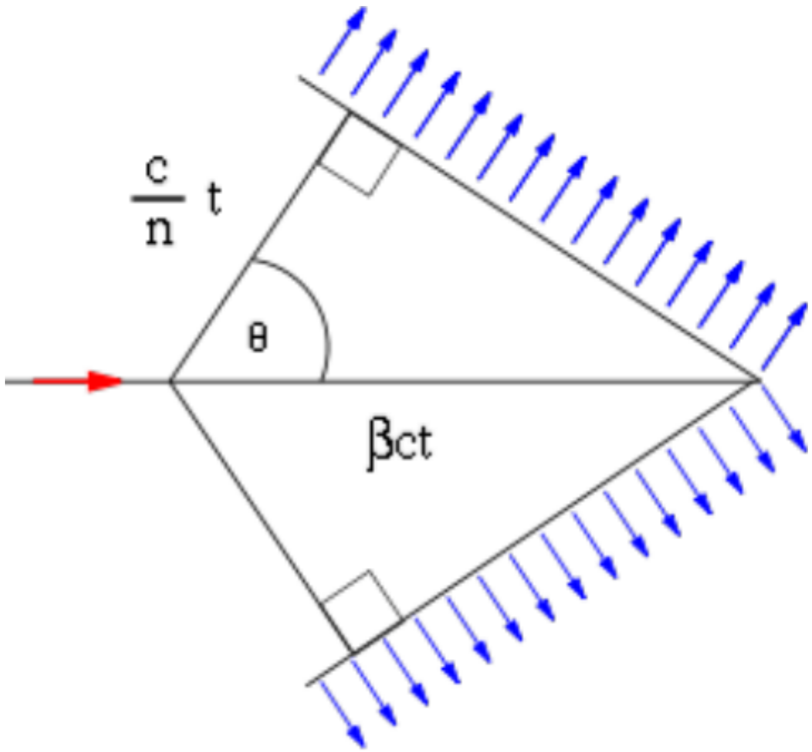
Shower development: iron

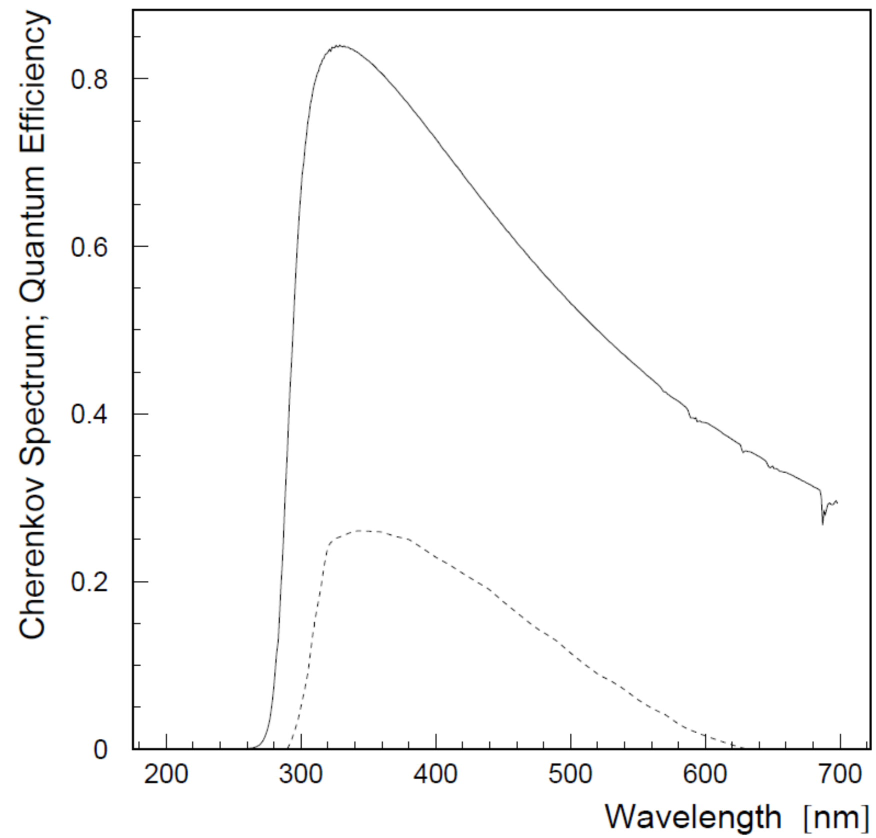


Shower development: photon



Cherenkov light emission: fundamentals





$$\cos è = \frac{1}{ân}$$

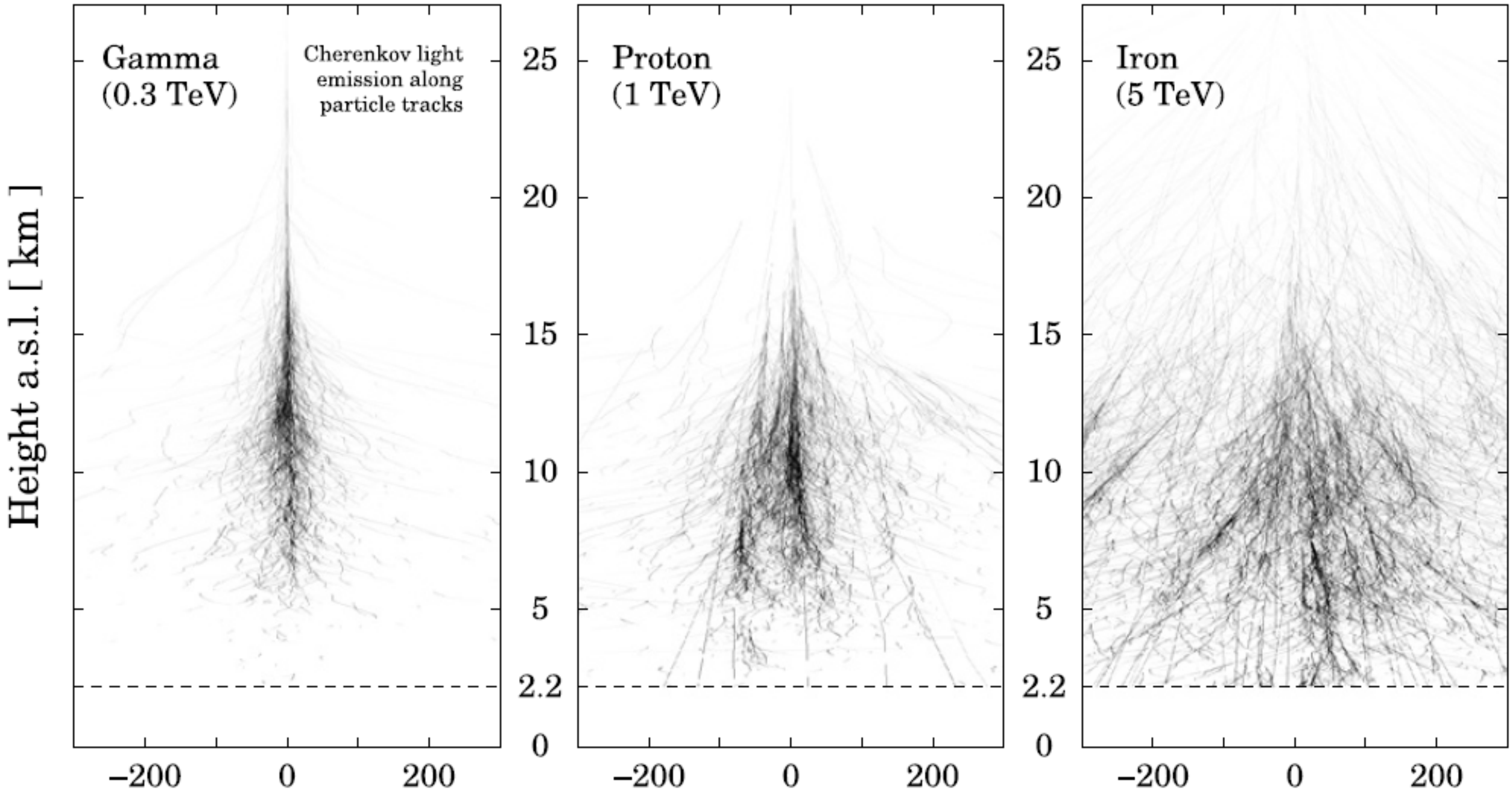
EAS Cherenkov light cone opening angle, from 10 km to sea level ≈ 0.8° - 1.4°

- depends on atmospheric depth

Cherenkov light emission from EAS

movie: Cherenkov.mp4

Cherenkov light emission from EAS



Cherenkov light emission in CORSIKA: *IACT/ATMO*

- Each charged particles is transported down considering: decay, multiple scattering, bending in the geomagnetic field and ionization loss and, if *some options* are switched on, cherenkov light emission;

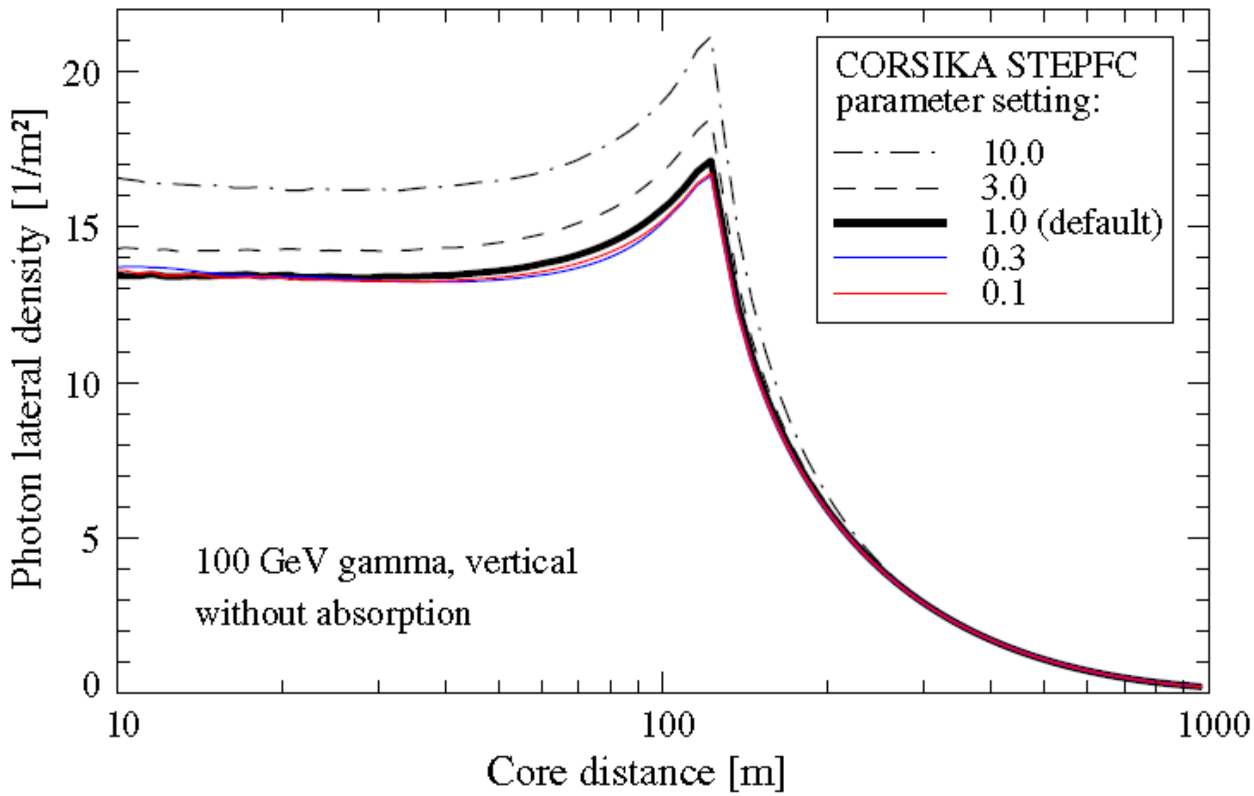
- **Energy thresholds** for particle (when interested in Cherenkov light)
  - e/γ = 20 MeV (Cherenkov thr.)
  - μ/h = 200-300 MeV (lower than their Cherenkov thr. because they may dacay)

- Compilation options specific to Cherenkov simulation:
  - IACT
  - CERENKOV
  - ATMEXT = require tabulated values for the description of the atmosphere (**altitude | density | atm. depth | refraction index**)

  Different atmosphere models (i.e.: tropical, US standard,...)
  - VIEWCONE = for diffuse emission (background or extended/diffuse gamma sources)

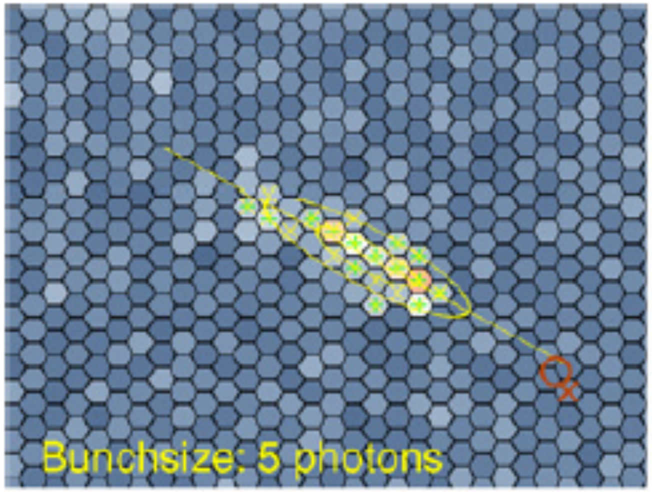
Cherenkov light emission in CORSIKA

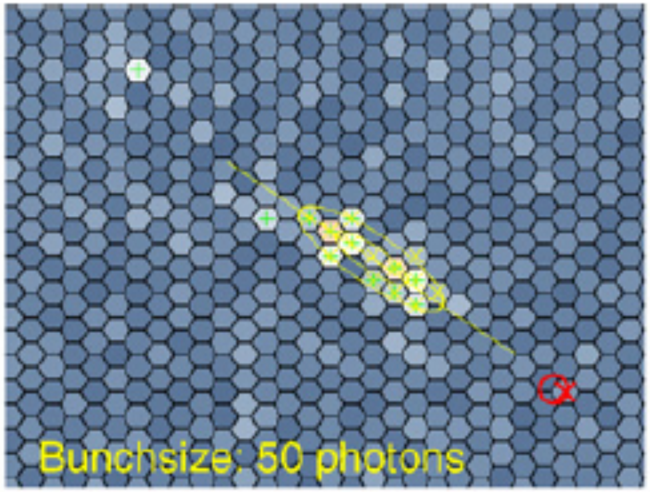
- Both **accuracy** and **efficiency** are important
  - a track is approximated with segments whose length is chosen in order to avoid systematic effects and keeping a good efficiency (STEPFC parameter)

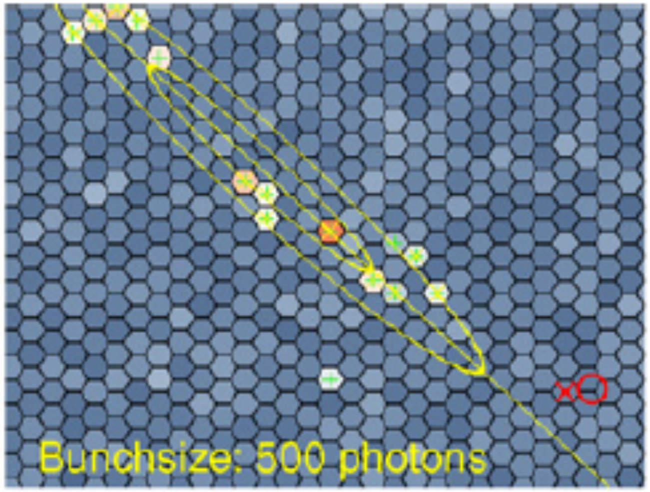


Cherenkov light emission in CORSIKA

- Both **accuracy** and **efficiency** are important
  - photons are not simulated one by one but in ***bunches*** (CERSIZ parameter)
  - CERSIZ = the maximal bunch size

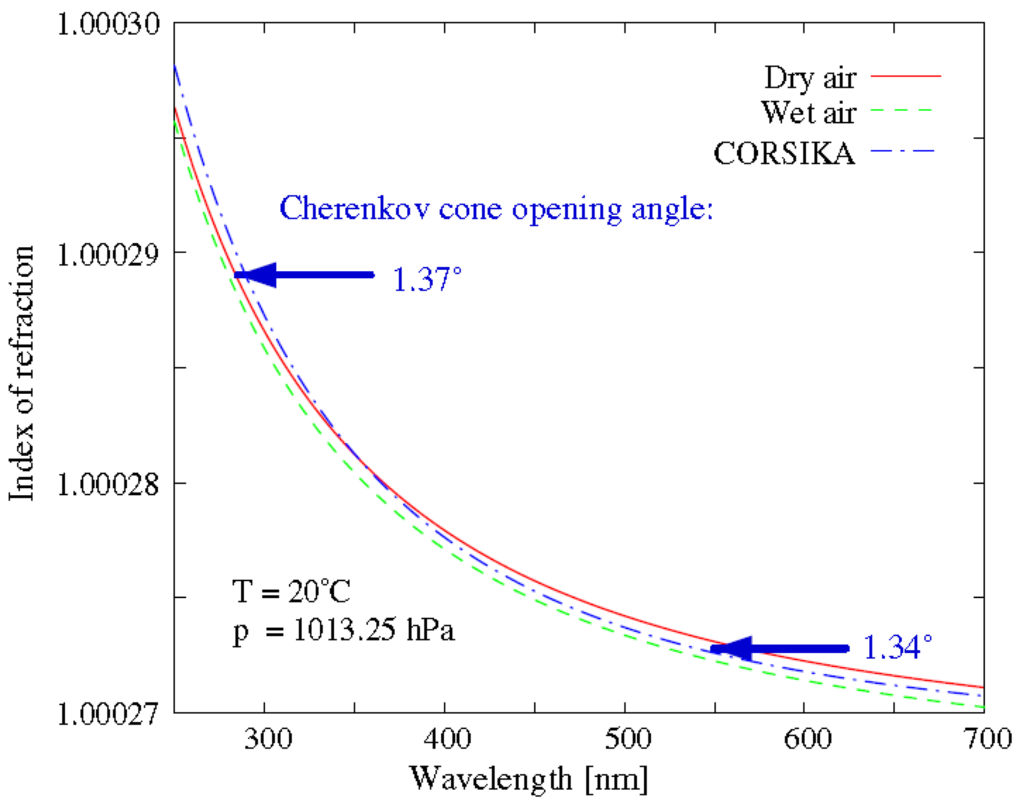






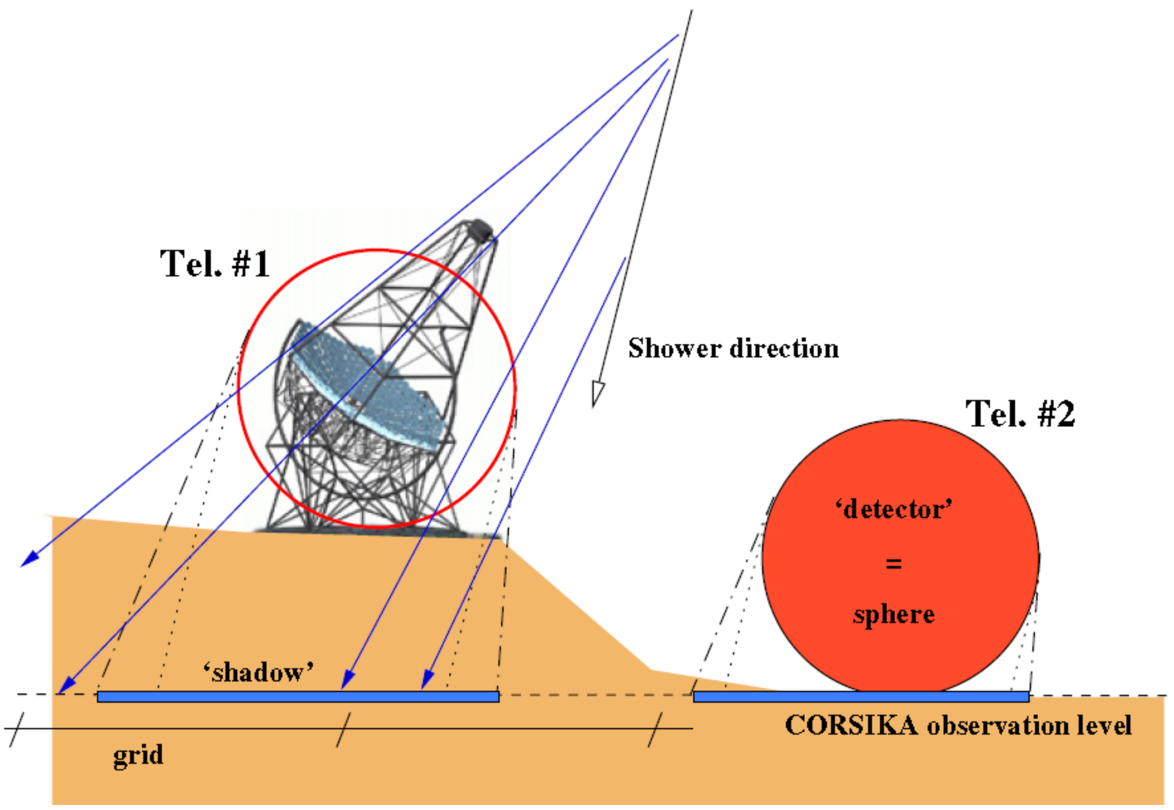
Cherenkov light emission in CORSIKA

- Both **accuracy** and **efficiency** are important
  - CERWLEN = the index of refraction is made wavelength dependent, a wavelength is given to each bunch (shorter λ, larger θ)



Cherenkov light emission in CORSIKA: *telescope*

- an array of telescopes (xi,yi,zi,ri)
- intersection of altitude and azimuth axes, sphere enclosing the dish
- each shower used several times (CSCAT parameter)
- to increase efficiency each sphere is related to a grid at detection level (photon bunches intersection searched only for few spheres)



Telescope simulation: *sim_telarray*

- Developed for HEGRA and HESS (telescope arrays)

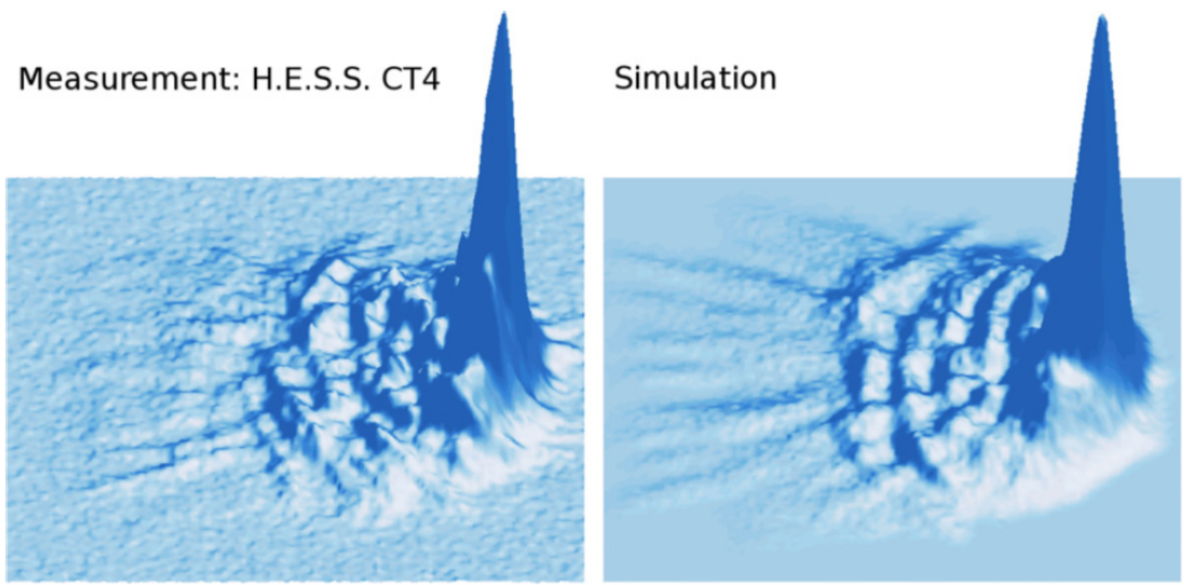
- It allow to simulate and set:
  - optical layout
  - photon sensors
  - electronics and output
  - trigger
  - Night Sky Background

- Each telescope can be individually configured

- Fast with respect to CORSIKA
  - CORSIKA output (photon bunches intersecting the spheres) piped out to several “sim_telarray”;
  - can be also used ”offline” if CORSIKA output can be stored on disk
  - efficiency short-cuts (1st cut: number of photons, 2nd: number of pe)

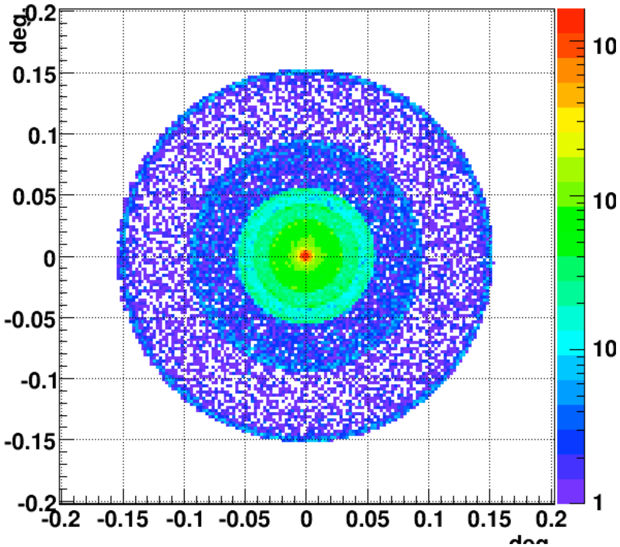
Optics simulation (1)

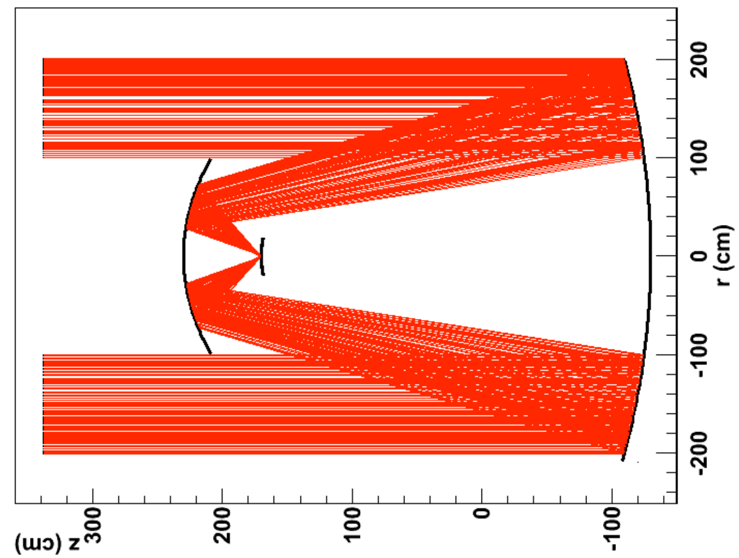
- **Single mirror** (Davies-Cotton or parabolic)
  - segmented: position, shape and focal length of each tiles
- Realistic (measured) optical qualities can be introduced
  - mirror reflection random angle: due to small-scale surface deviations
  - mirror reflectivity (as a function of wavelength)
  - mis-alignments
- **Dual mirror** (Schwarzschild-Couder)
  - mirrors and focal surface described in terms of even polynomials
- **ray-tracing** (including timing) from stars simulated in the FoV and focused on the camera lid (*focus offset* for EAS = $(f^{-1} - D^{-1})^{-1} - f$)

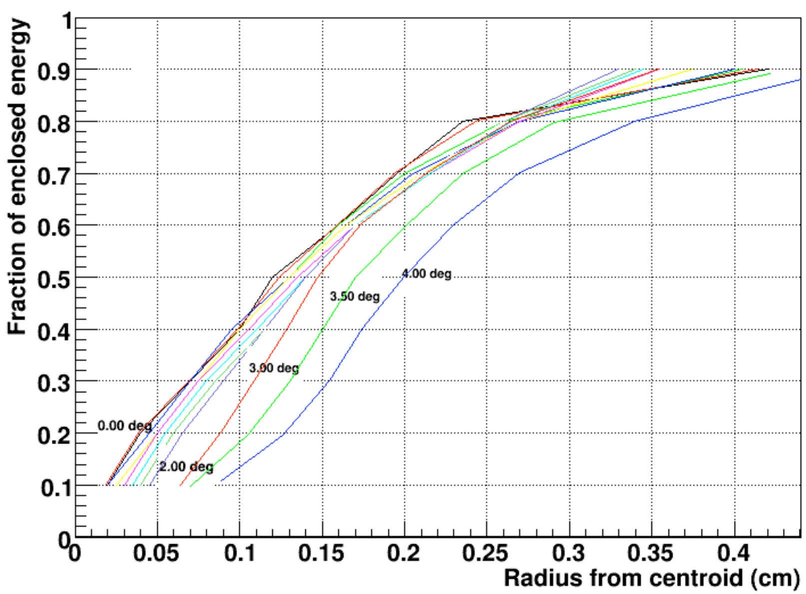


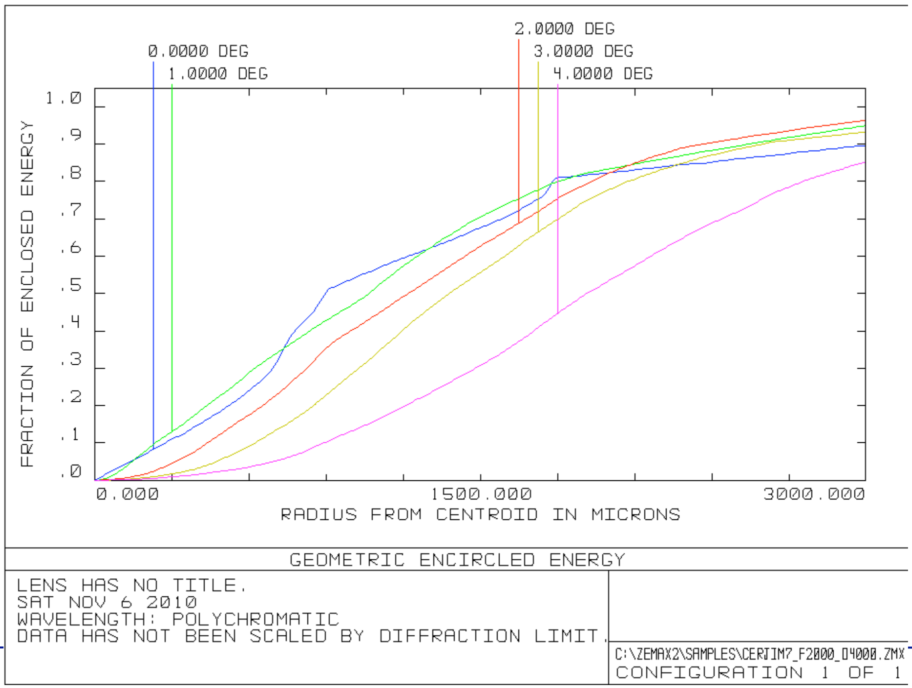
- off-axis = 2.3^{o}
- shown fields =0.4^{o}

Optics simulation: an example (confirmed by Zemax)



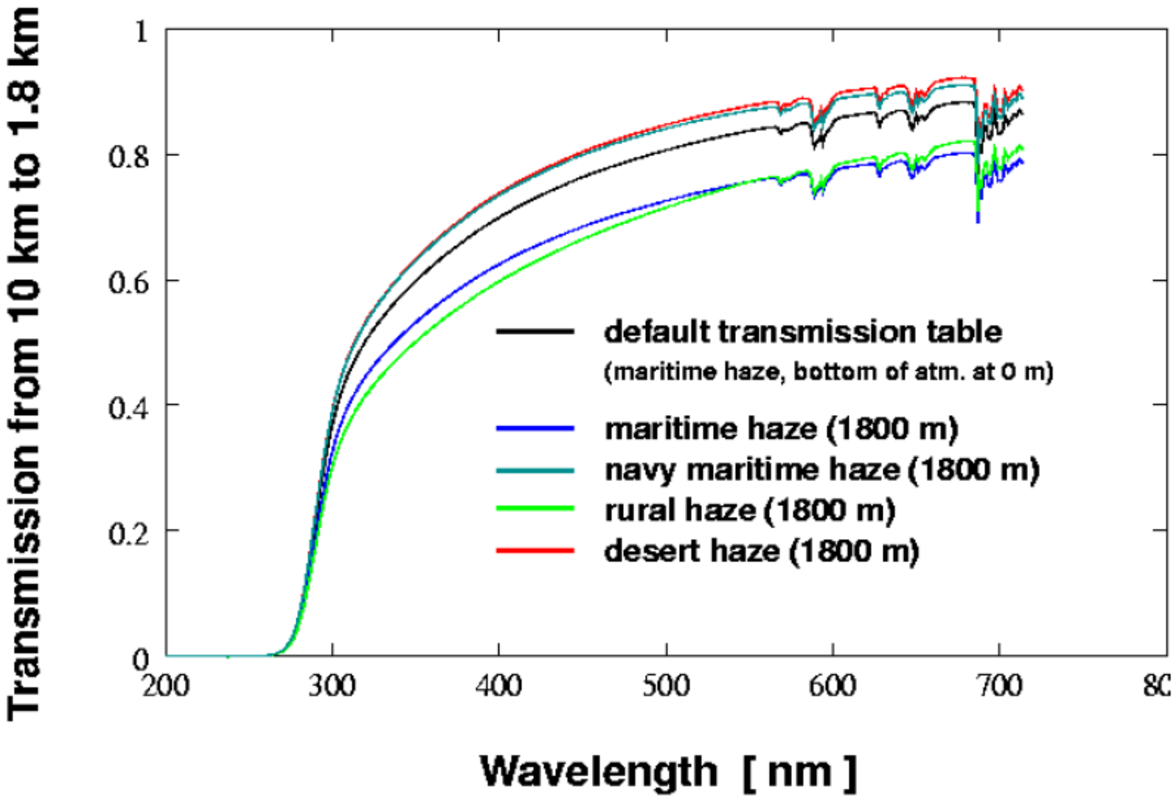






Optics simulation (2)

- **atmospheric transmission** (Cherenkov photons, also available directly in CORSIKA by CEFFIC options)

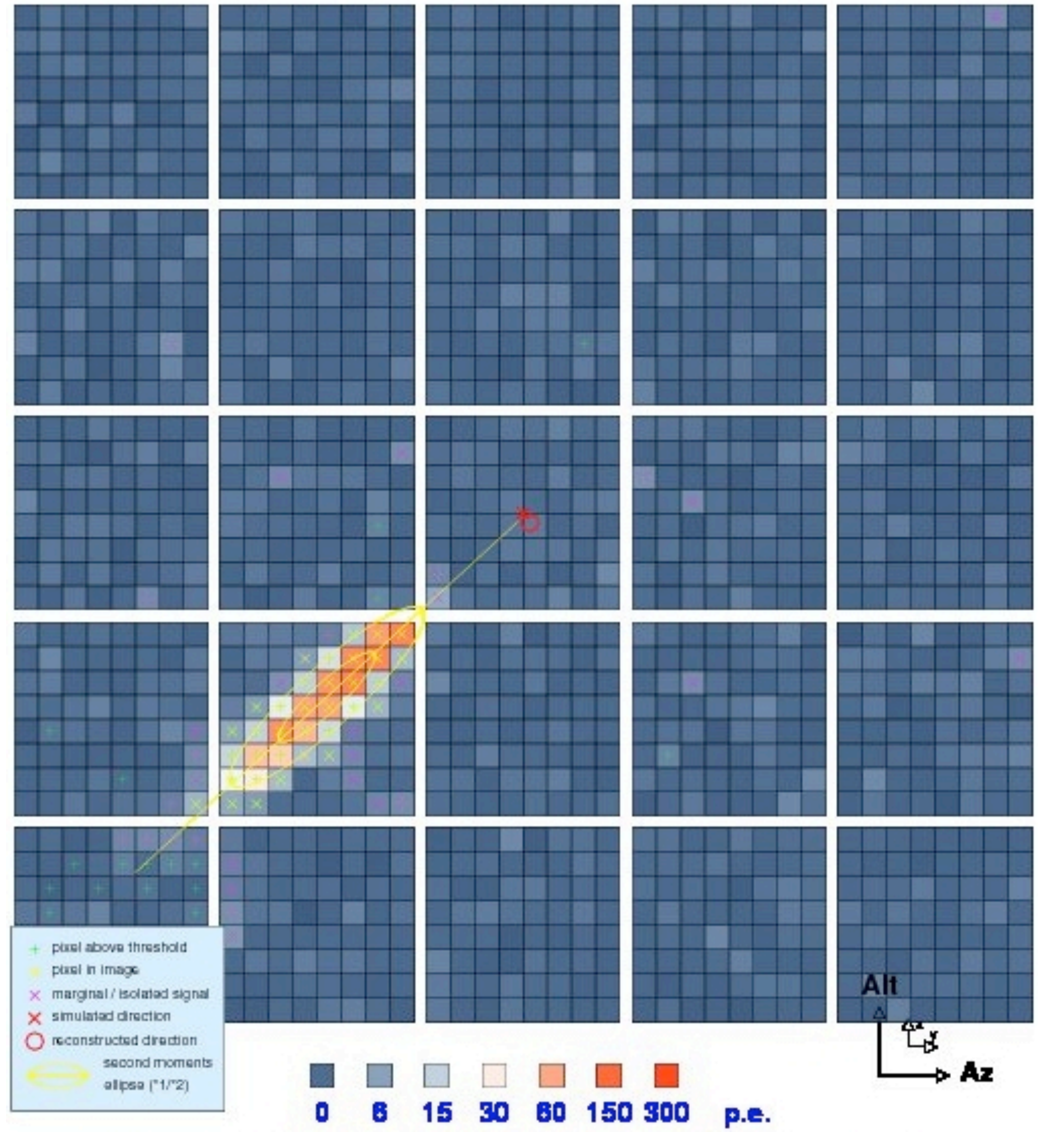


- **shadowing** and **light guides** can be included before the photo-sensors simulation

Camera simulation

- For each pixel it is possible to configure:
  - position
  - dimension
  - shape
- The (simplest) trigger of the camera is organized by pixel multiplets

- In front of each pixel can be simulated a light guide (any size/dimension)

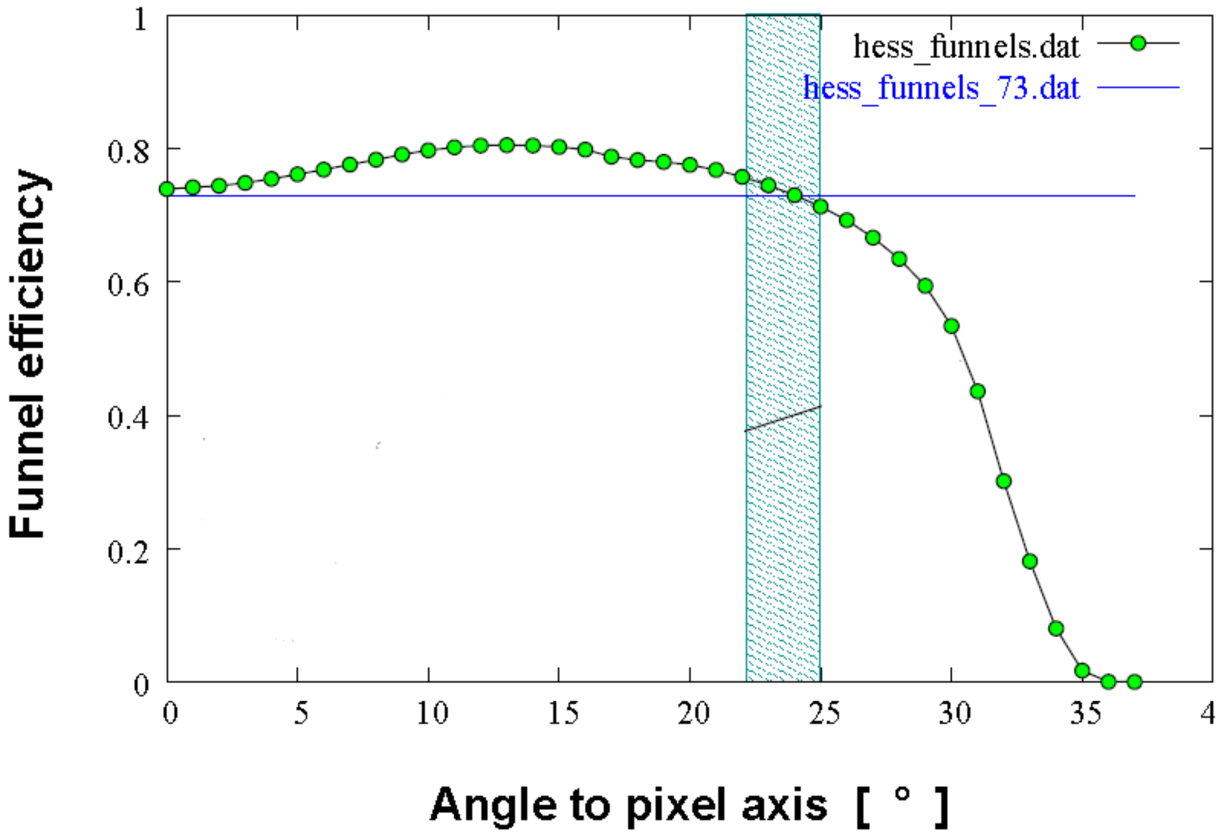


Primary: gamma of 30.000 TeV energy at 223 m distance

Camera for SC, pixel size = 0.2°

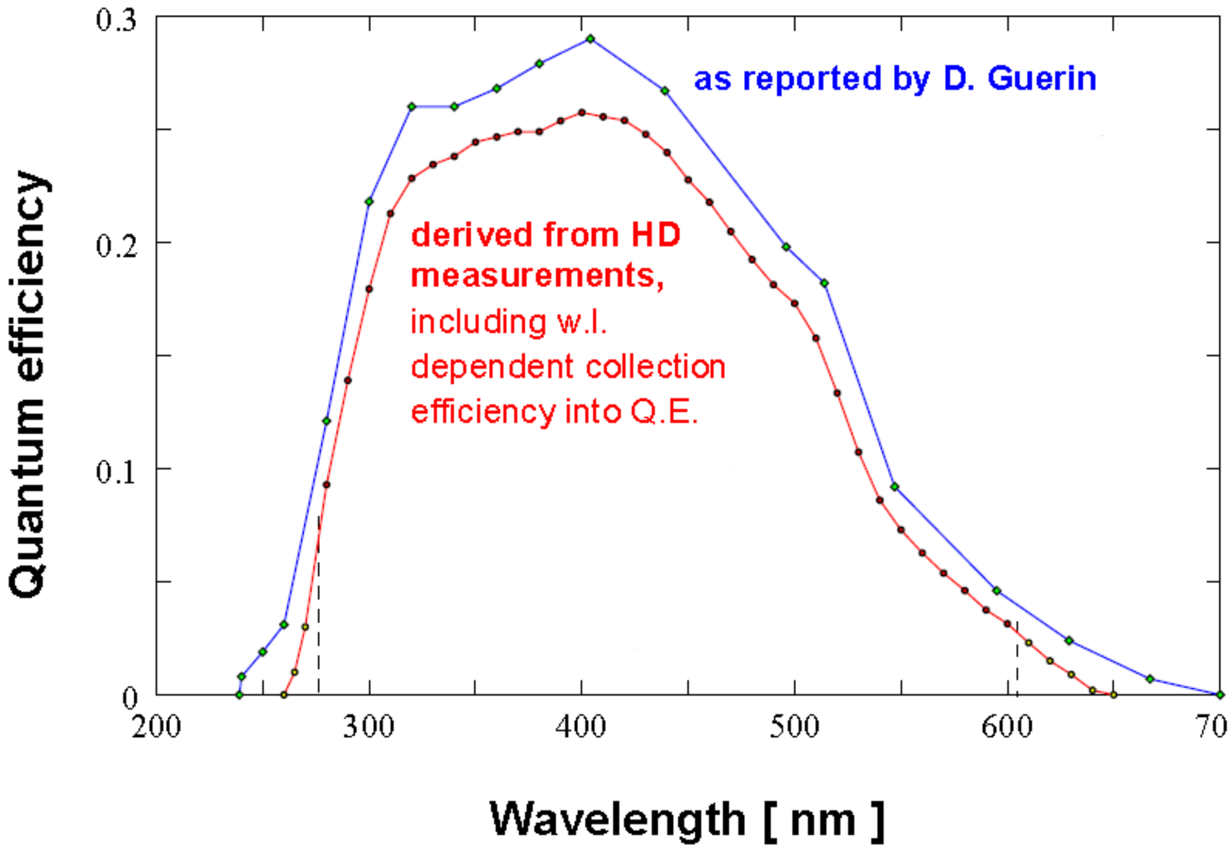
Light guides simulation

In case of the Davies-Cotton a **Winston cone** stands in front of each PMT:



Quantum efficiency

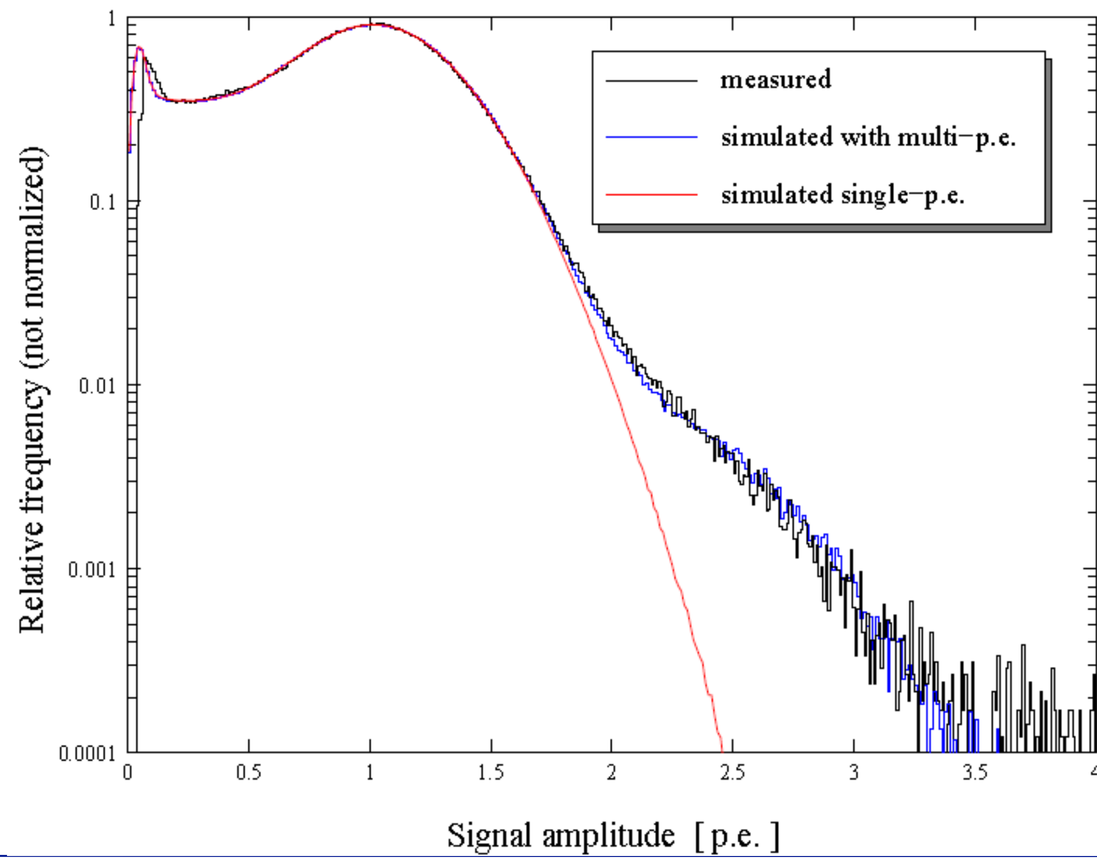
Q.E. = probability, for a photon hitting the cathode, to produce a photo-electron



Single photo-electron response

- **collection efficiency** = probability that a pe actually hits the first dynode and is effectively multiplied rather than elastically scattered

- **afterpulses** = ions in PMT (0(100 ns) after the electron cascade) inducing a signal (for PMT can be high up to ~10 pe)
  - for Cherenkov photons don't matter, whilst matter for NSB

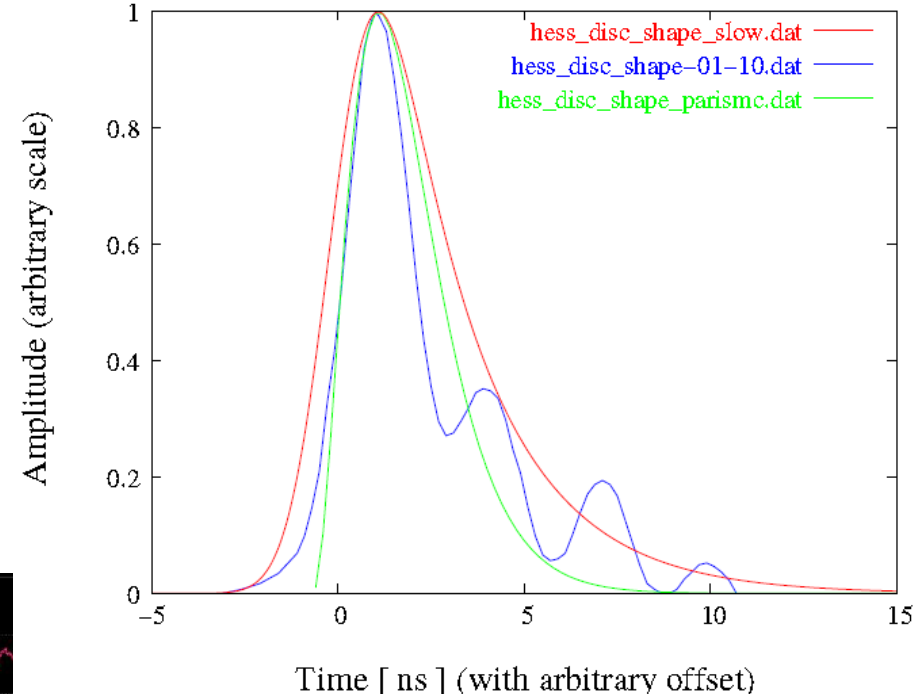


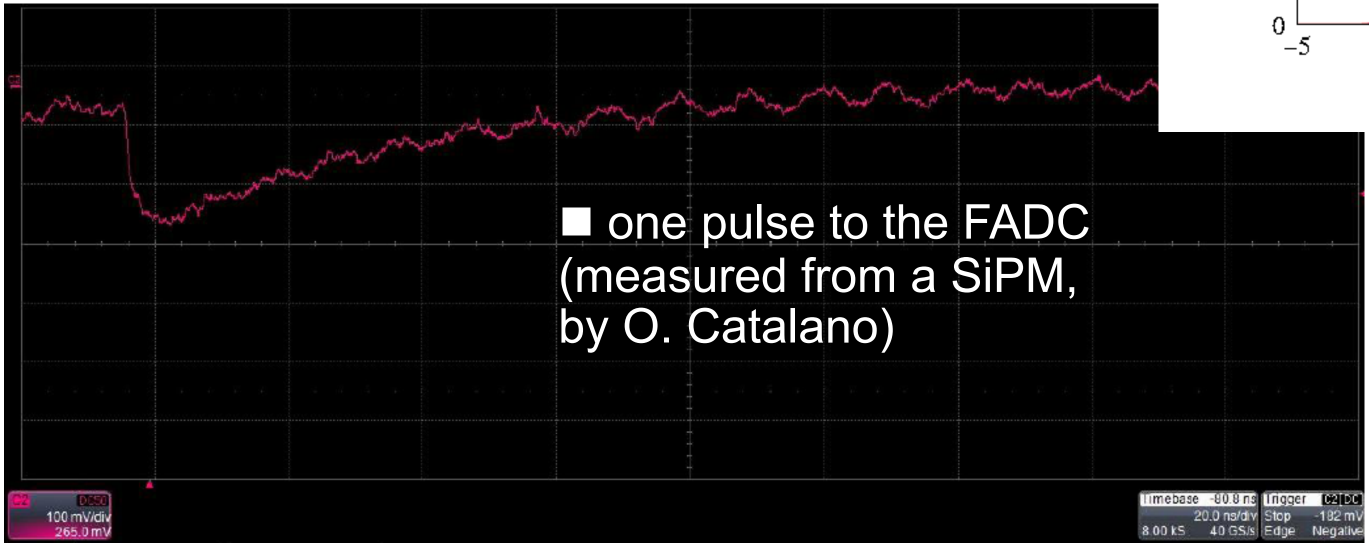
Single photo-electron pulse shapes

• for each pe the pulse shapes are scaled accordingly to random s.p.e. and shifted accordingly to arrival time + random jitter

• all signals from Cherenkov light and NSB are added up

▪ one pulse to the discriminator (sampling ~ 250 ps)



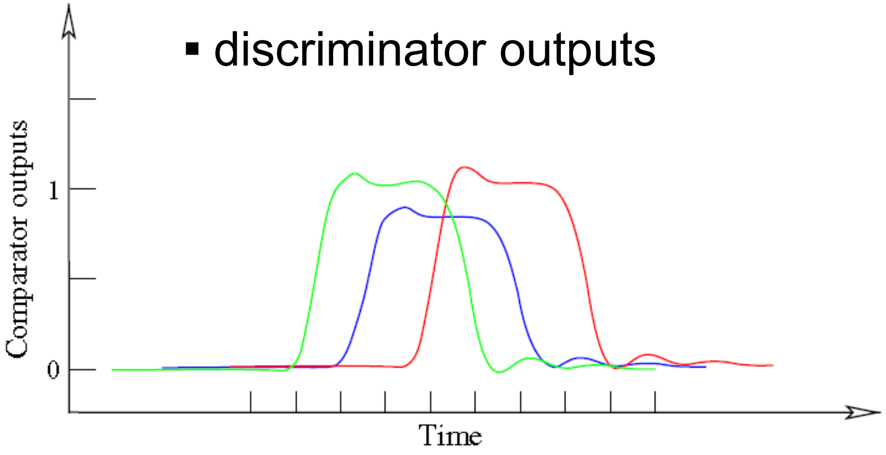


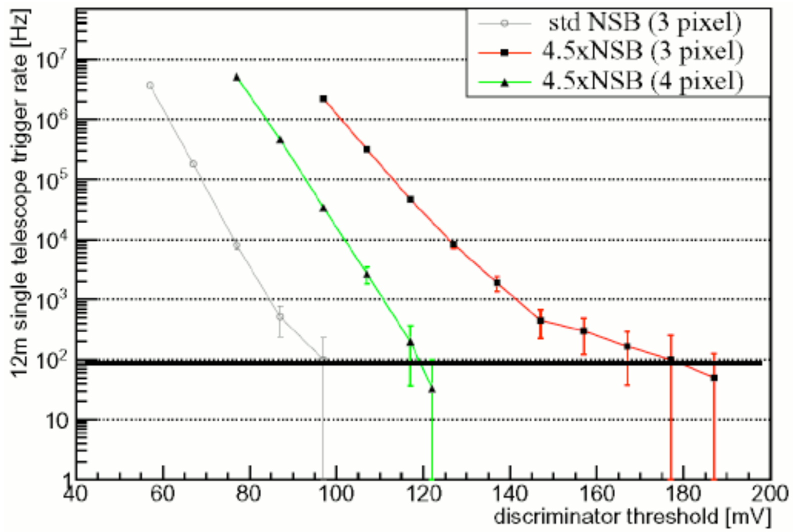
■ one pulse to the FADC (measured from a SiPM, by O. Catalano)

• it is possible to store the **integrated charge** or the full **waveform**

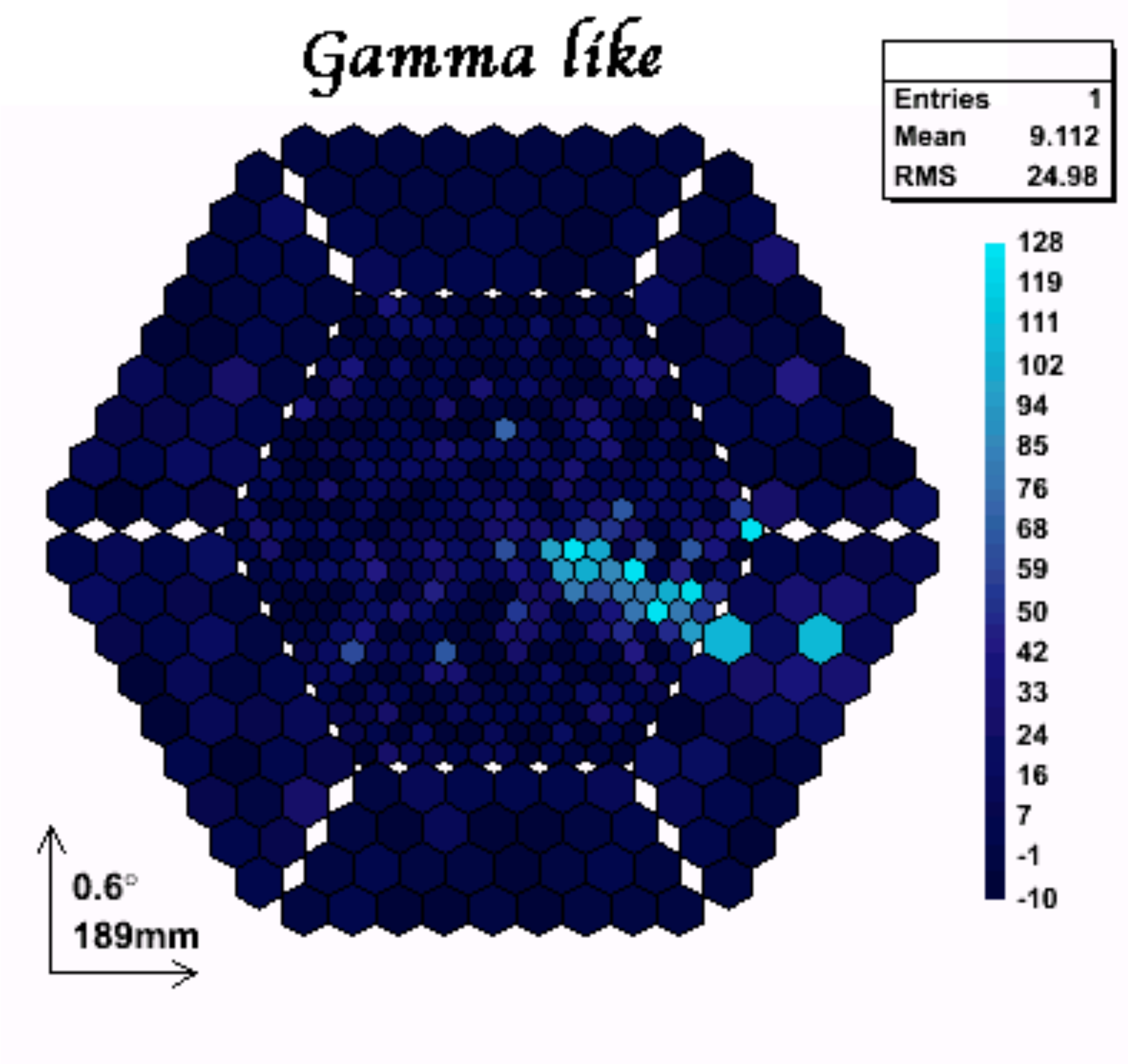
Trigger

- **Pixel** trigger = discriminator threshold
- **Camera** (or telescope) trigger = fully flexible, examples: majority (full camera, trigger cells), analog sum, digital sum
- **Array** = n telescopes of the array within a time window (10-100 ns)
- Trigger rate (discr. thr., pixel size, NSB, trigger logic...)





Camera images



Basic ideas of stereo reconstruction

Conclusions