The next step of ALTO: The Cosmic Multiperspective Event Tracker (COMET)

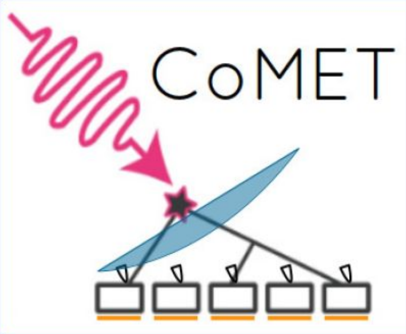
Improving ALTO sensitivity during darkness

Gašper Kukec Mezek[1]

Yvonne Becherini[1], Michael Punch[1,2], Jean-Pierre Ernenwein[3], Satyendra Thoudam[4], Tomas Bylund[1], Mohanraj Senniappan[1], Pat Romano[5], Stefano Vercellone[5], Martin Tluczykont[6], Matteo Cerruti[7]

[1]Linnaeus University, Sweden, [2]AstroParticle and Cosmology, CNRS/IN2P3, France, [3]Aix-Marseille University, France, [4]Khalifa University, United Arab Emirates, [5]INAF-Osservatorio Astronomico di Brera, Italy, [6]Universität Hamburg, Germany, [7]Institut de Ciències del Cosmos, Universitat de Barcelona, Spain

ALTO/COMET: Introduction



COMET is an extension to the ALTO project by adding atmospheric Cherenkov light detectors (μ-HiSCORE). The ALTO/COMET project is dedicated for observing very high energy gamma-ray sources (100 GeV - 10 TeV).

Enlarging the collaboration that is working on ALTO/COMET, by including other institutes.

The key features of ALTO include,

- Regular monitoring → **Observations may be done 24h per day**
- Wide field of view → **~ 2 steradian**
- At high altitude (> 5 km) → **Low threshold E ≥ 200 GeV**
- Excellent timing accuracy → Improved angular resolution (~ 0.1° at few TeV)
- Modular design → Phased construction and easy maintenance
- Simple to construct → Minimize human intervention at high-altitude
- Long duration → Should operate for 30 years
- Open Observatory → Distribute data to the community

Atmospheric Cherenkov light observations only available during clear nights

ALTO/COMET: Motivation

Accessing independent information (X_{max}):

- Extract X_{max} from atmospheric Cherenkov light information
- Better energy resolution and bias
- Improved gamma-ray/hadron separation

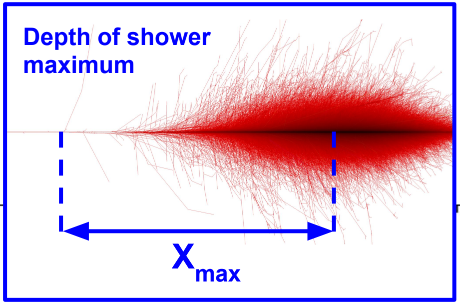
Better source localisation:

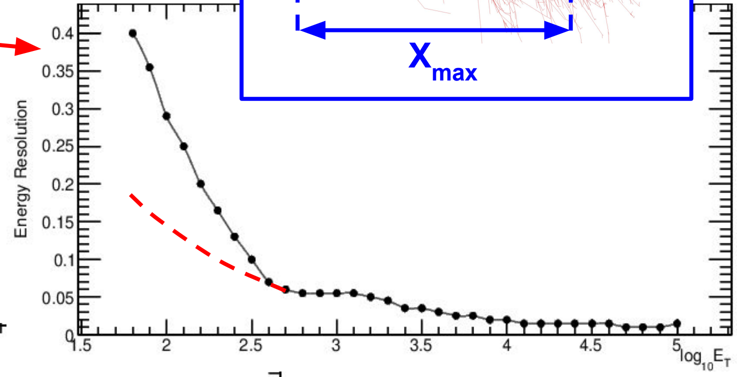
- Adding atmospheric Cherenkov light signals to particle signals

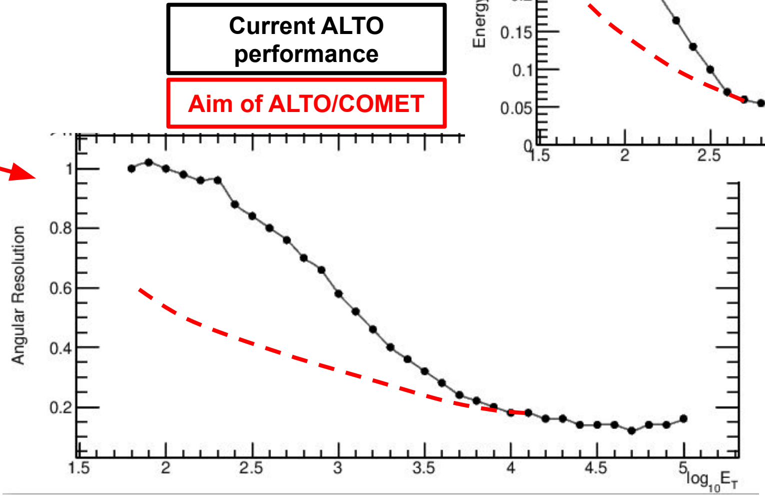
Better sensitivity:

- Energy range focus of ALTO/COMET: 100 GeV - 10 TeV (soft-spectrum sources)

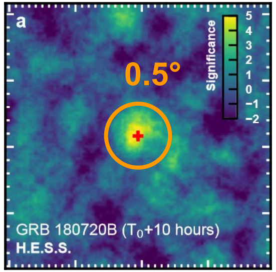
[1] FZKA 6019 (1998)





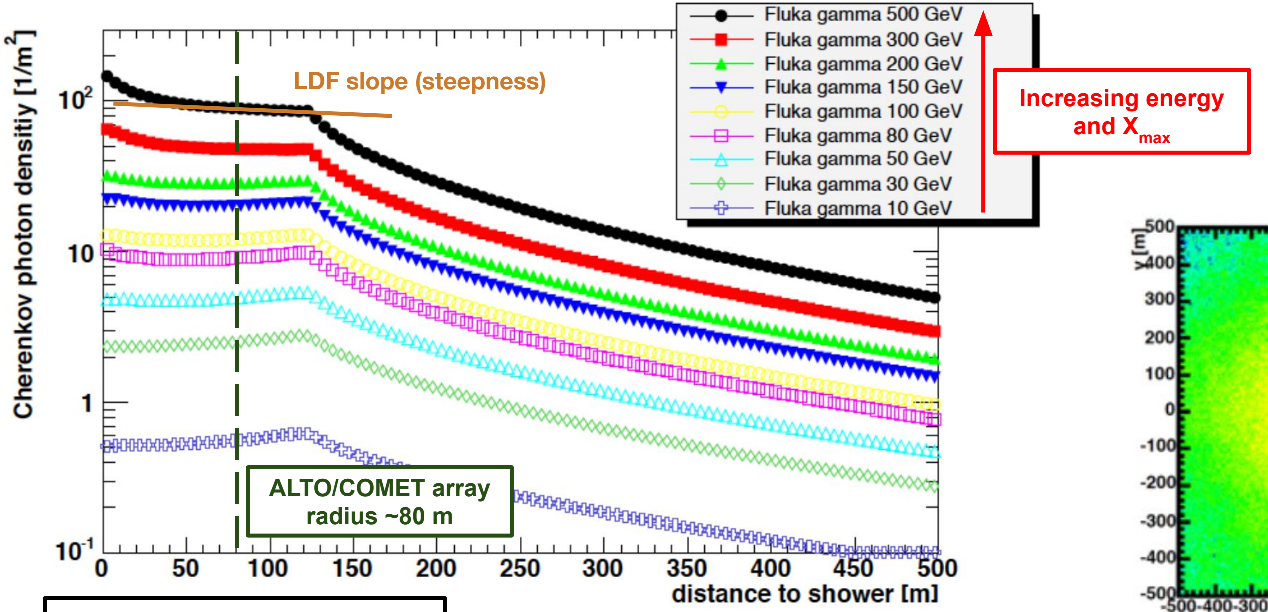


[2] arXiv:1911.08961

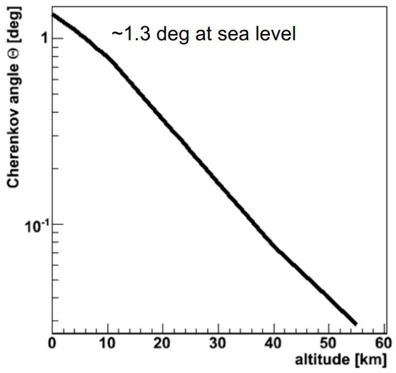


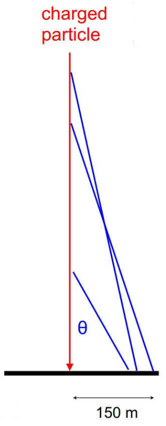
Accessing the depth of shower maximum (X_{max})

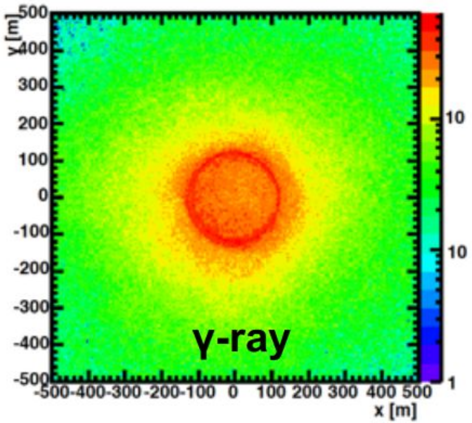
- Cherenkov emission cone angle dependent on height of emission
- Gamma-rays: Flat lateral distribution (ALTO/COMET → up to ~120 m)
- LDF slope carries shower development information (X_{max})



Simulations at 2 km of altitude







[3] G. Maier, Fermi summer school 2011

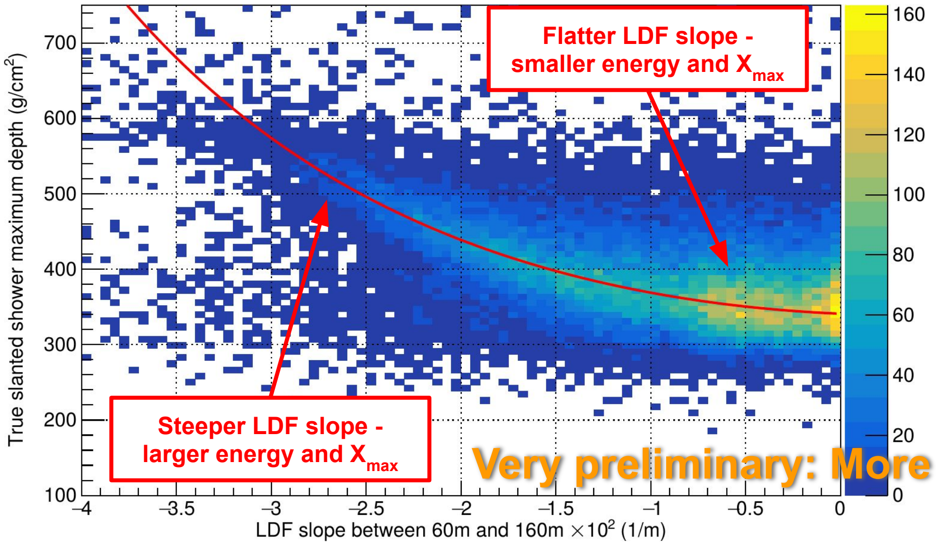
Simulation reconstruction results

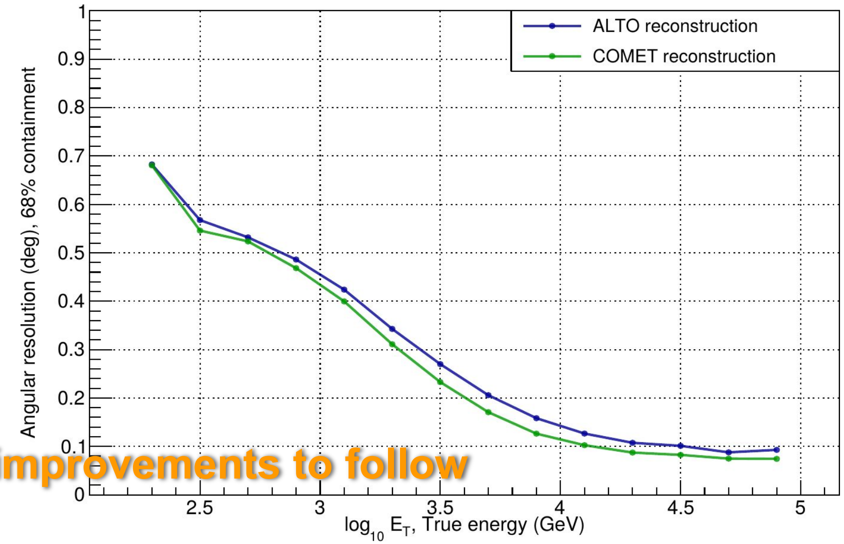
Correlation between X_{max} and LDF slope :

- LDF slope steeper with increasing X_{max}
- At higher energies, the LDF slope is more negative

Better angular resolution:

- Arrival direction from a combined fit of atmospheric Cherenkov light and particle signal peak times





Very preliminary: More improvements to follow

ALTO/COMET detector array

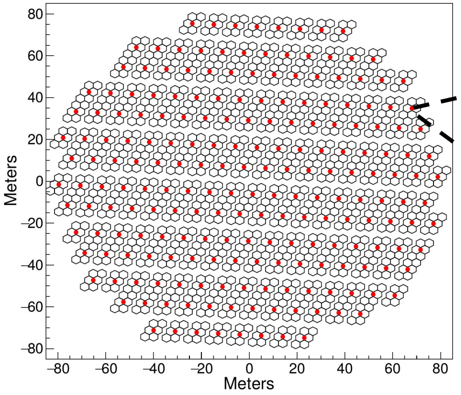
Adding atmospheric Cherenkov light detectors to existing water Cherenkov particle detectors → ALTO/COMET array

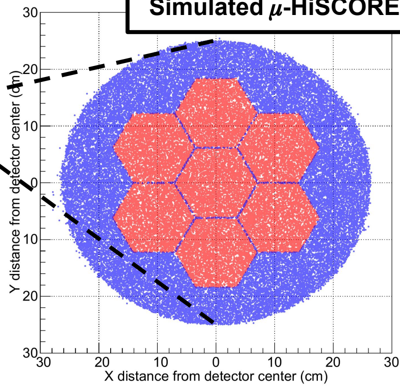
Atmospheric Cherenkov light detectors triggered by coincidence with particle detectors

From HiSCORE to mini-HiSCORE and μ-HiSCORE:

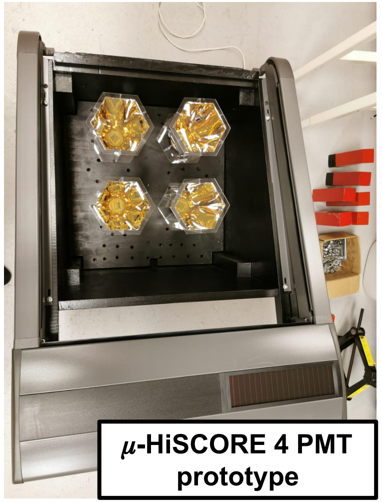
- HiSCORE part of the TAIGA experiment (UHE gamma-rays above 30 TeV):
  - Station consists of four 8-inch PMTs
  - Decagonal Winston cone light guides
- mini-HiSCORE: ¼ of the HiSCORE Cherenkov station
- μ-HiSCORE:
  - Station consists of seven 3-inch PMTs (Hamamatsu R6233, G ≈ 2.5 × 10^6)
  - Hexagonal Winston cone light guides
  - Reduction of background light with a filter

μ-HiSCORE design → Improved sensitivity, reduced night sky background (NSB)





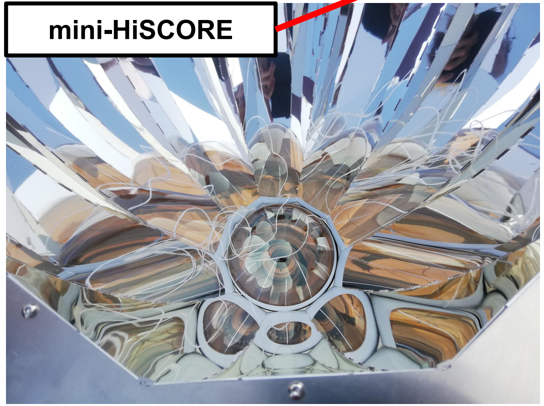
HiSCORE

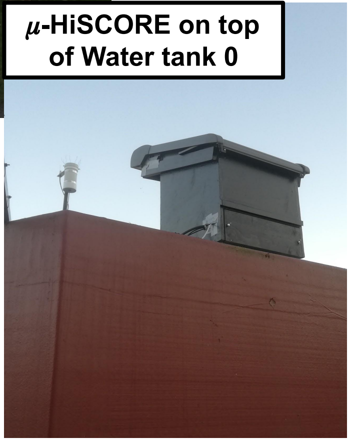


μ-HiSCORE 4 PMT prototype

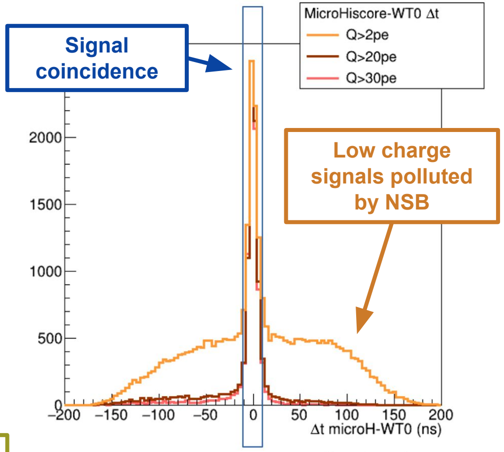
[4] TAIGA-HiSCORE experiment

Prototype activities at Linnaeus University



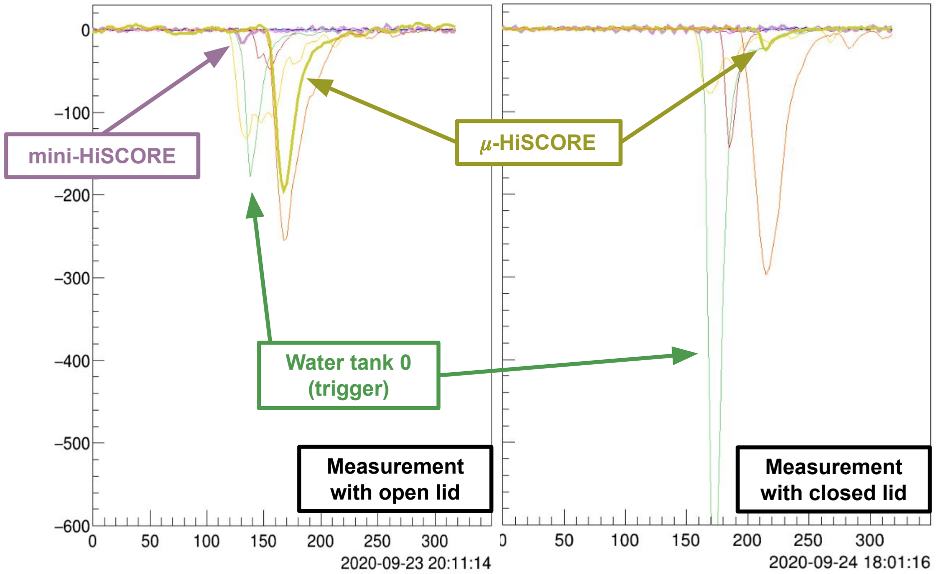


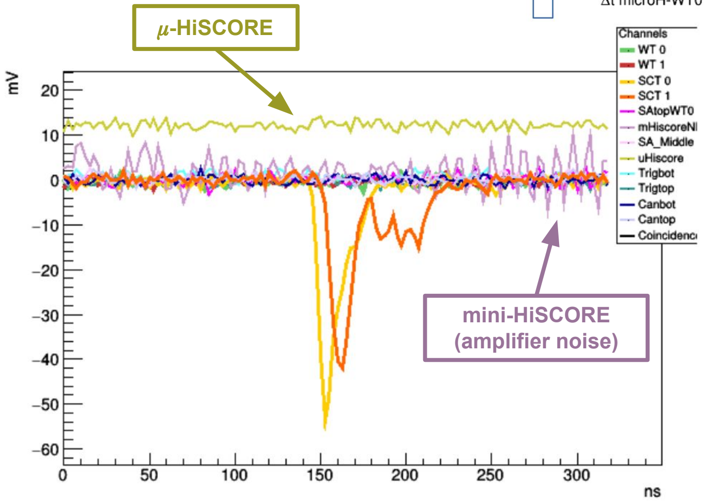
Prototype activities at Linnaeus University



First prototype measurements with μ-HiSCORE (23. and 24. Sep 2020):

- Signals correlated with water Cherenkov particle detectors
- Improved gain and lower noise (compared to mini-HiSCORE)
- Closed vs. open lid measurements show muons passing through the filter (high sensitivity)





Conclusions

- ALTO/COMET dedicated to soft-spectrum sources in the energy range 100 GeV - 10 TeV
- **Key idea:** during darkness couple atmospheric Cherenkov light signals to water Cherenkov signals from atmospheric showers for a better gamma-ray/hadron separation and a better source localisation
- Simulations indicate that adding μ-HiSCORE stations (very preliminary):
  - makes extraction of X_{max} possible
  - improves the angular resolution
- New μ-HiSCORE design has excellent sensitivity and reduced night sky background (NSB)
- Signal of the 4 PMT μ-HiSCORE prototype correlated with the particle detector signal
- More prototype results to follow as weather conditions improve

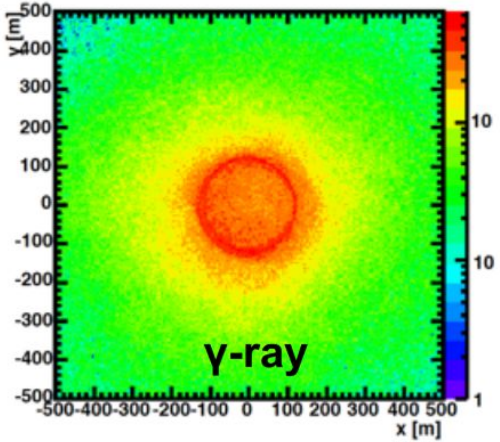
Thank you for your attention

For future updates visit: AstroGamma, Twitter

BACKUP SLIDES

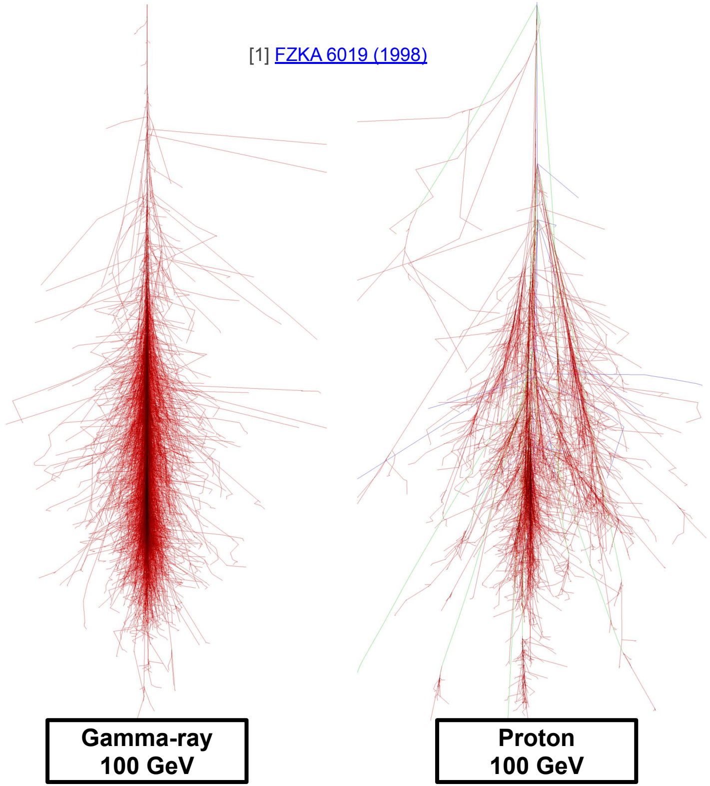
Atmospheric Cherenkov light, particles: Gamma-rays vs. protons

- Protons typically have a non-symmetric shower development (hadronic interactions, production of muons)
- Gamma-rays produce a flatter atmospheric Cherenkov light footprint at the ground, compared to protons



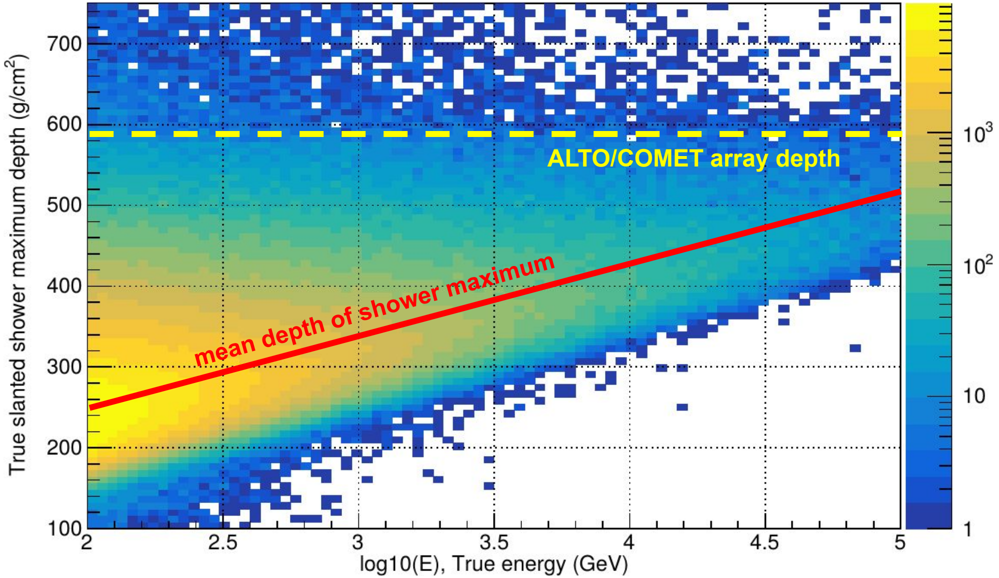
[3] G. Maier, Fermi summer school 2011

[1] FZKA 6019 (1998)



Simulated CORSIKA events

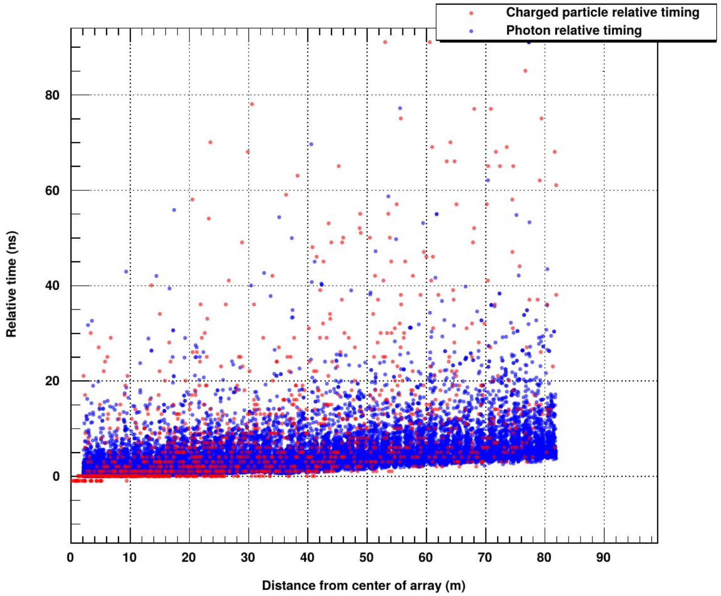
- Gamma-rays simulated with power-law index Γ = 2 ($dN/dE = E^{-\Gamma}$) and zenith angle θ = 18°
- Simulated energy range between 100 GeV and 100 TeV, number of events ~1.7M
- Depth of shower maximum correlated with primary energy:
  - slope ~ 83.8 g/cm^2/decade
  - σ_{Xmax} ~ 65 g/cm^2 (for the complete energy range)

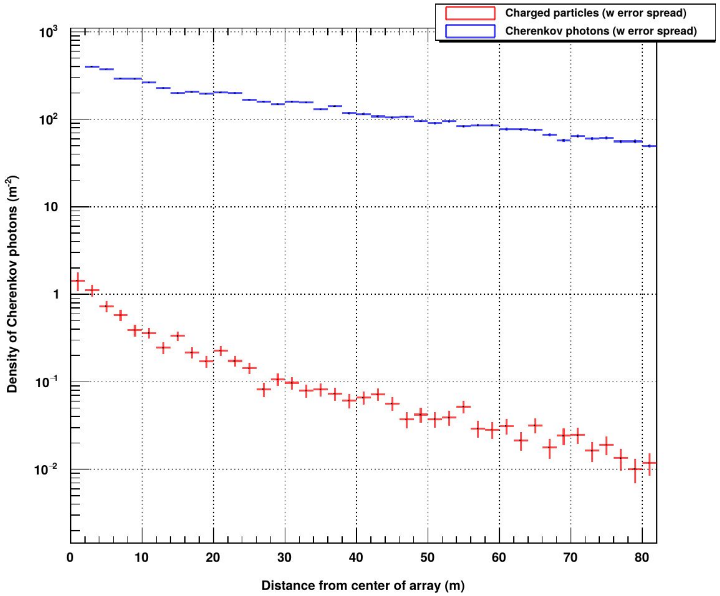


Simulated particles versus atmospheric Cherenkov photons

Examples for timing and density of atmospheric Cherenkov photons (blue) versus particles (red):

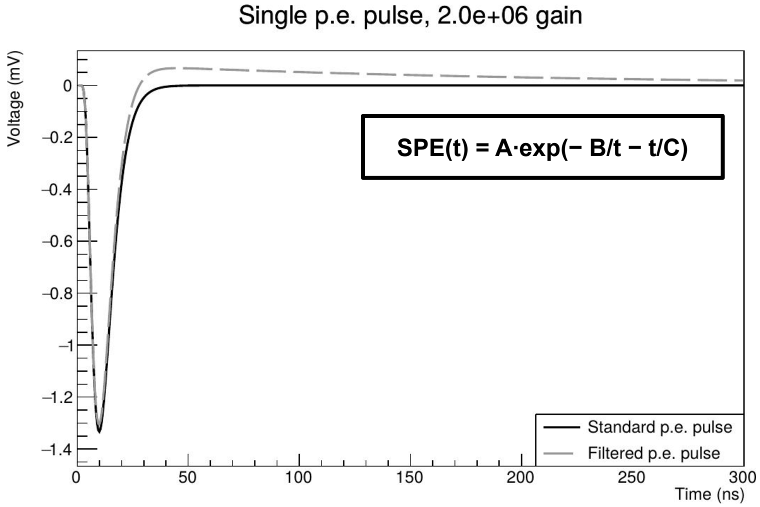
- In both examples, atmospheric showers simulated at zenith angle 0° and energy 3 TeV
- Particles arrive to the ground earlier than atmospheric Cherenkov photons (particularly close to the shower core)
- Higher density of atmospheric Cherenkov photons, compared to particles

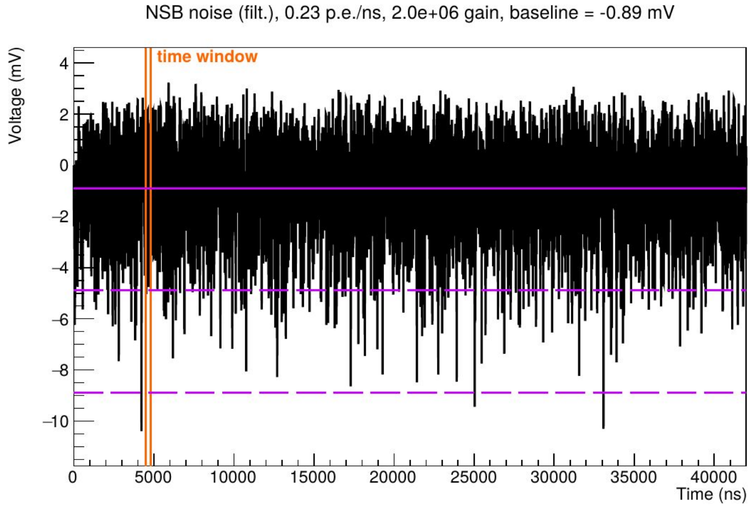




Night Sky Background (NSB) simulations

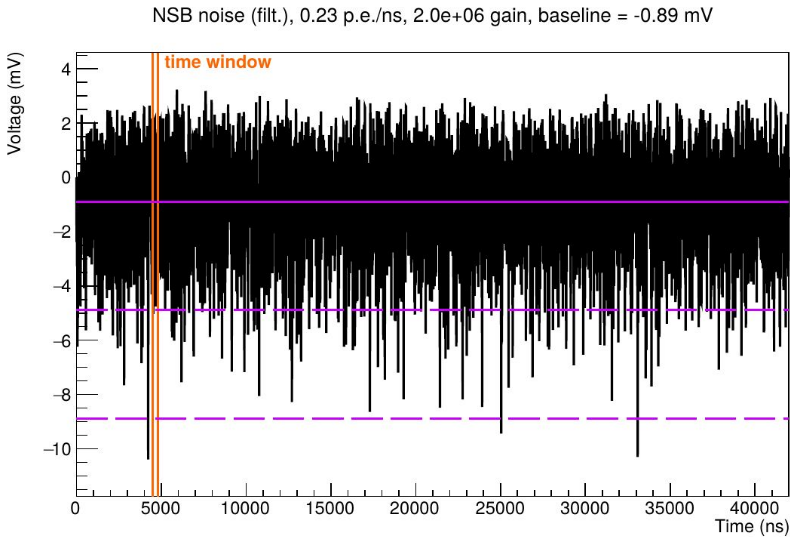
- Assuming NSB rate of 2.3 p.e./ns on a circular area with 40 cm diameter (astro site @La Palma):
  $A_{circle} = \pi R^2 = 0.1257\ m^2$
- Area of one hexagonal pixel of μ-HiSCORE (α = 60°):
  $A_{pixel} = 3R^2 \cdot \cos(\alpha/2) = 0.0127\ m^2$
- Expected NSB rate per pixel about 10x smaller → **0.23 p.e./ns**
- Randomly distribute single p.e. pulses in a large time window (42 μs) according to the expected NSB rate
- Simulate the effect of AC coupling, which filters the single p.e. pulse

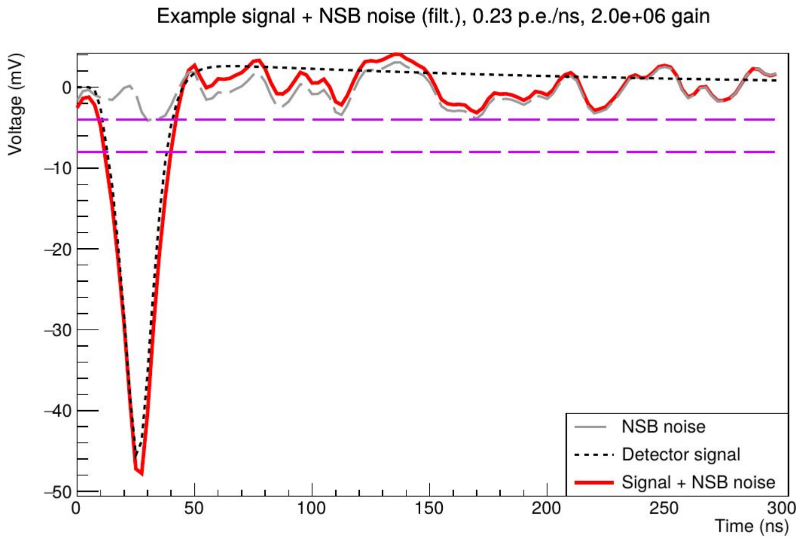




Night Sky Background (NSB) simulations

- A small window of 300 ns is randomly selected to add an example detector signal (height of ≈ 47 mV, gain of $2{\times}10^6$)
- Baseline determined from mean of NSB noise, time rebinned to 2.5 ns intervals
- Example soft signal thresholds of 4 mV and 8 mV (μ-HiSCORE triggered by water Cherenkov detectors)

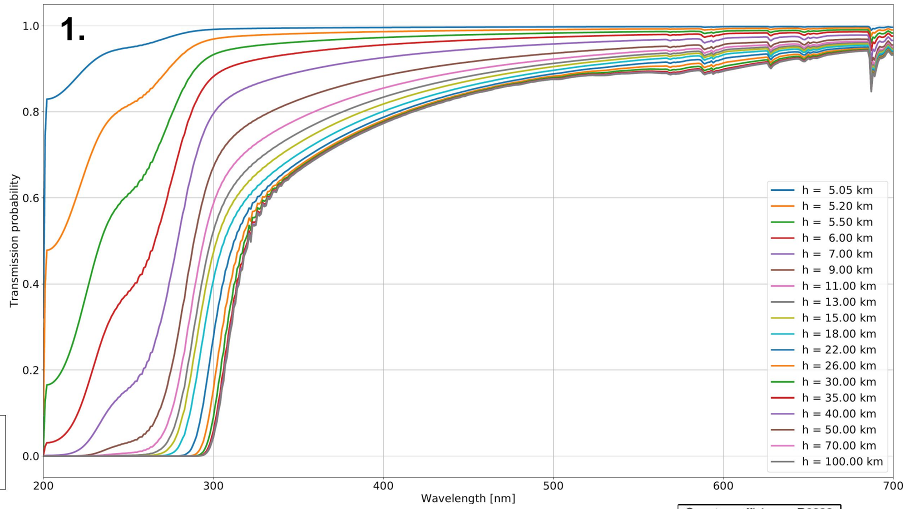


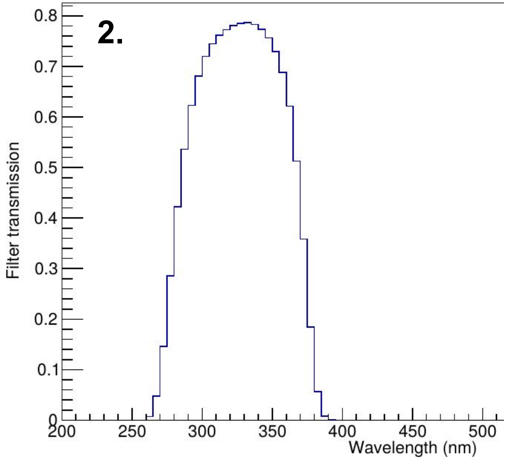


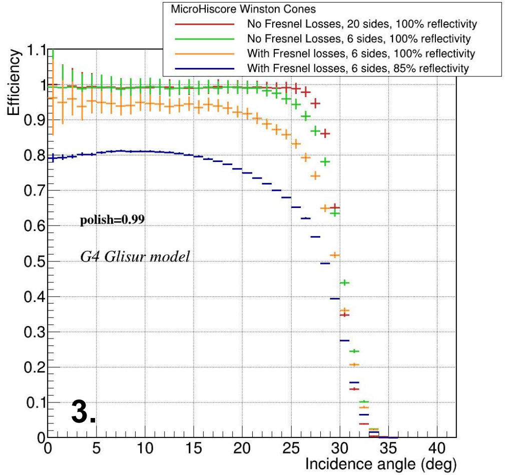
μ-HiSCORE detector simulations

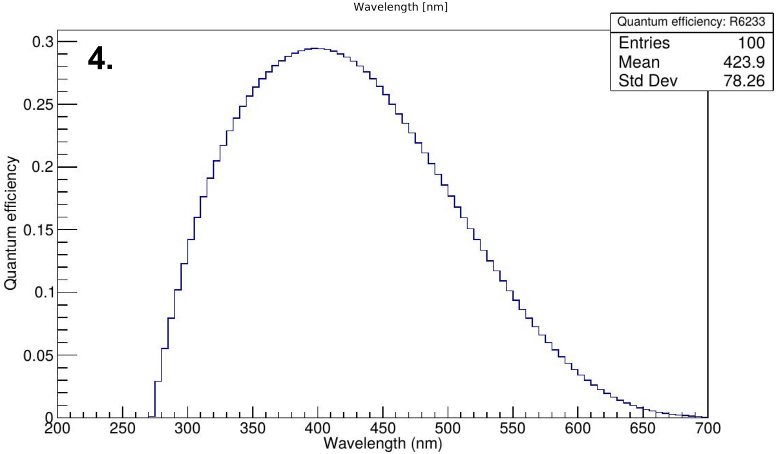
Atmospheric Cherenkov light simulated for:

1. Atmospheric transmission (5 km altitude)
2. Filter (ZWB1 Shijiazhuang Tangsinuo Optoekectronic Technology)
3. Winston Cone transmission
4. PMT quantum efficiency (Hamamatsu R6233)









ALTO/COMET reconstruction strategy

<u>ALTO reconstruction:</u>

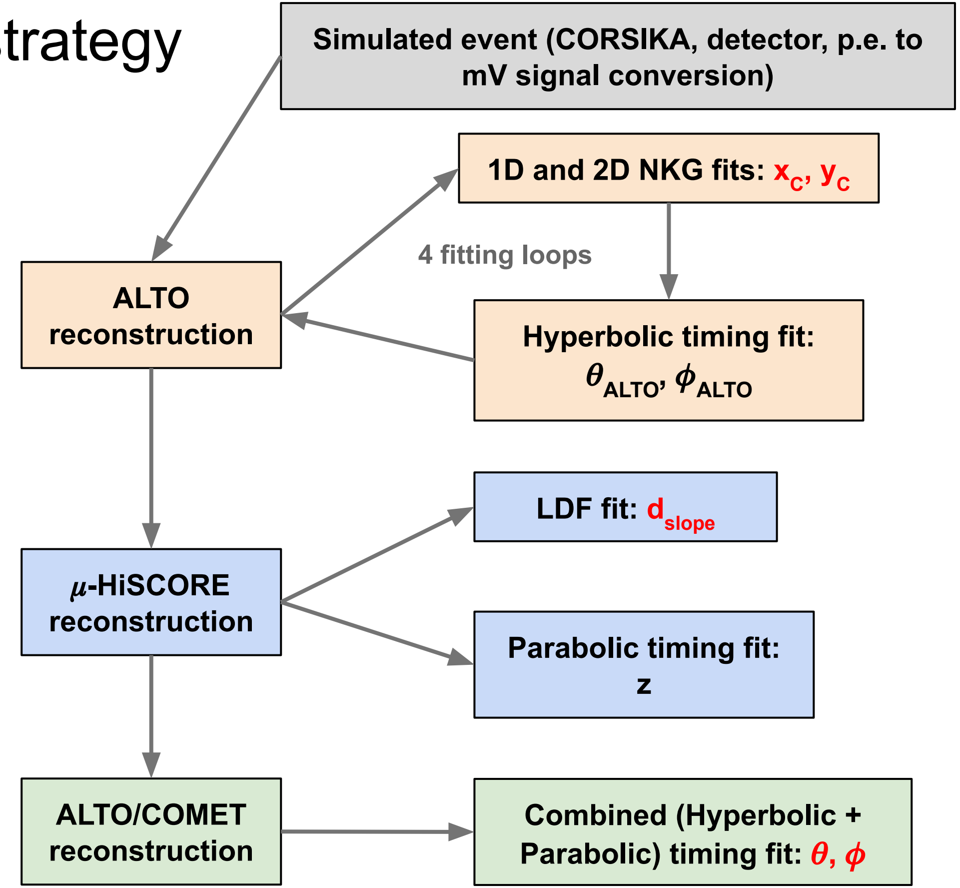
- Core position reconstruction (x_C, y_C)
- Initial estimation of arrival direction (θ_{ALTO}, ϕ_{ALTO})

<u>μ-HiSCORE reconstruction:</u>

- Fixed core position and arrival direction from ALTO
- Shower maximum extraction through LDF slope

<u>ALTO/COMET reconstruction:</u>

- Fixed core position from ALTO
- Arrival direction reconstruction (θ, ϕ)

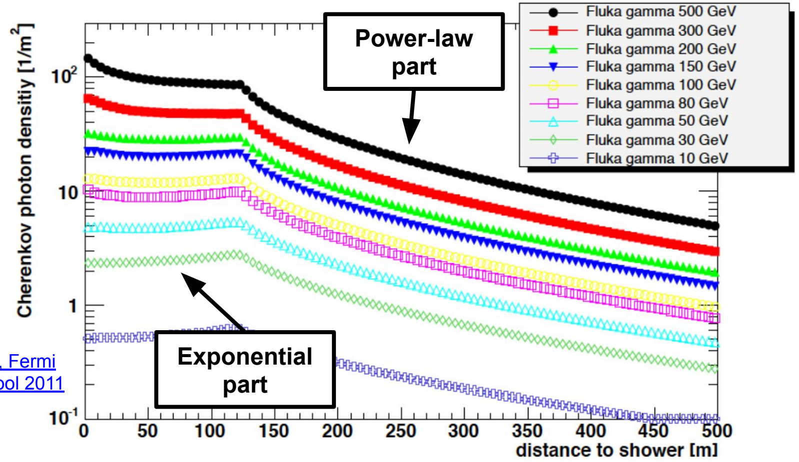


Lateral Distribution Function (LDF) fit

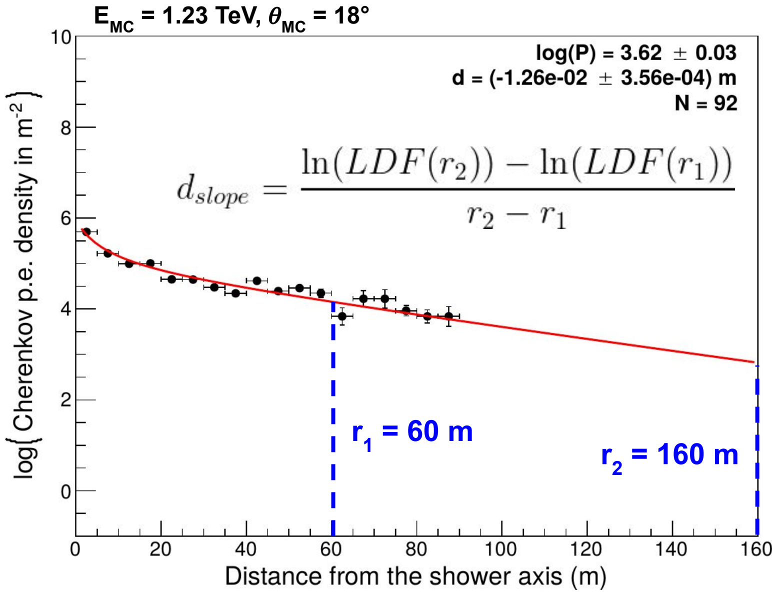
2 fitting parameters: ln(P), d

- LDF - Atmospheric Cherenkov photon density with respect to distance from the shower core
- LDF consists of two parts: The exponential part up to ~120 m and the power-law part beyond that
- ALTO/COMET array only able to see the exponential part
- Behaviour close to the shower core adjusted (A = 0.028846, B = 0.01885)

$$\ln(LDF(r)) = \ln P + d \cdot \left(r + \frac{A + \ln(-d)}{B}\right) \cdot \left(1 + \frac{6.5}{r + 7.5}\right)$$



[3] G. Maier, Fermi summer school 2011

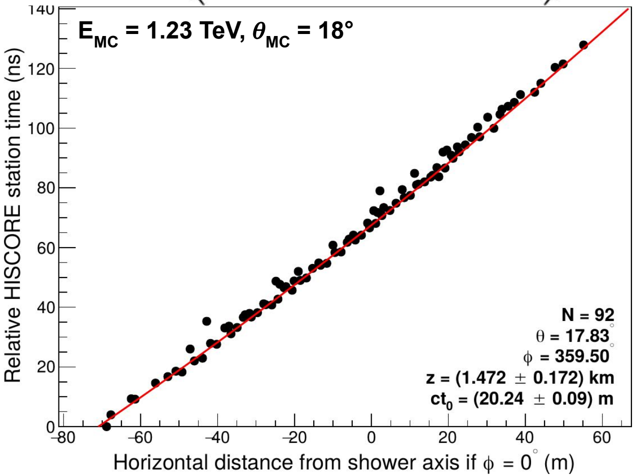


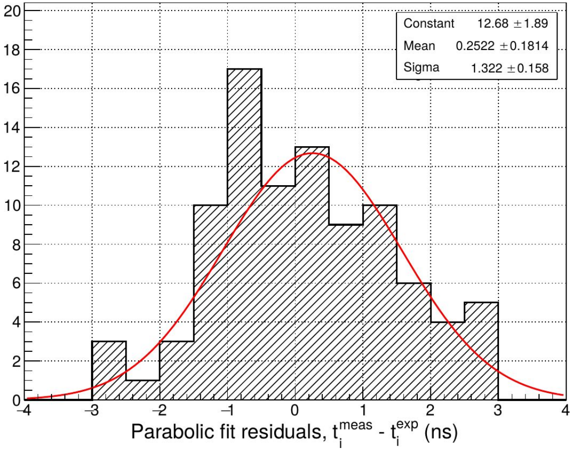
Parabolic timing fit

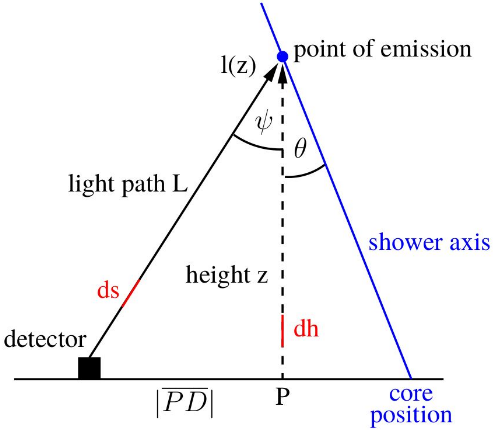
2 fitting parameters:
z, ct_{H0}

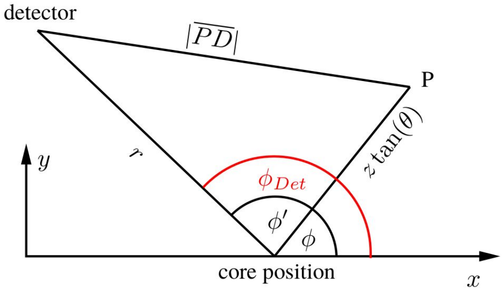
- Timing fit - Determine peak arrival times of atmospheric Cherenkov light signals with respect to detector position
- For a vertical atmospheric shower, the fitting function is parabolic and becomes more planar at larger zenith angles
- Constants from the barometric formula: η_0 = 2.76×10^{-4}, h_0 = 8 km

$$ct_{det}(r) = \left(1 + \frac{\eta_0 h_0 (1 - e^{-z/h_0})}{z}\right) \sqrt{r^2 + \frac{z^2}{\cos^2\theta} - 2rz\tan\theta\cos(\phi_{Det} - \phi)} + ct_0$$







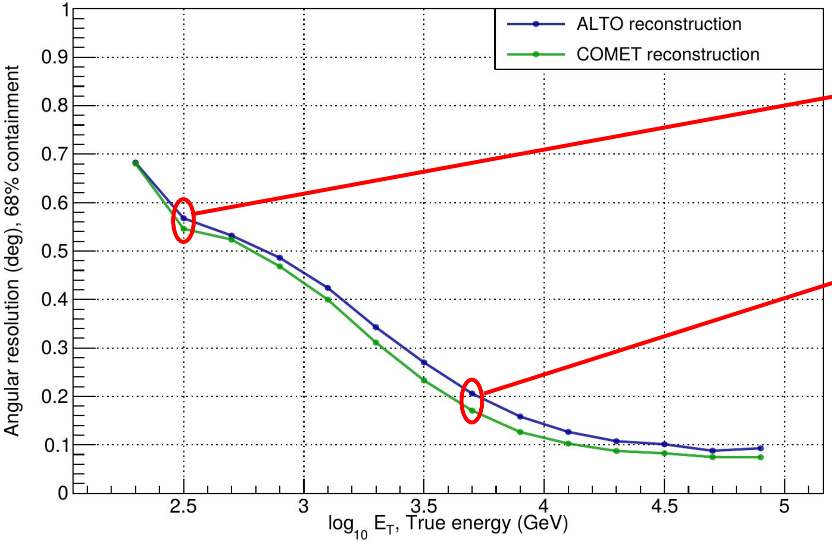


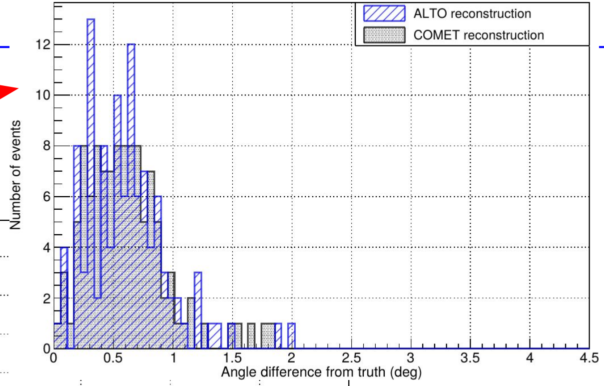
[5] D. Hampf (PhD thesis)

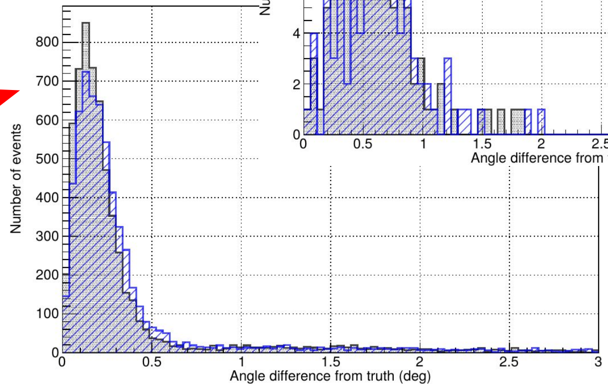
Combined (Hyperbolic + Parabolic) timing fit

7 fitting parameters:
θ, ϕ, z, ct_{H0}, ct_{A0}, α_{cone}, a_{axis}

- Combined ALTO/COMET fit aiming to improve arrival direction reconstruction
- Using timing information from both the atmospheric Cherenkov light and water Cherenkov light signal peak times (Hyperbolic + Parabolic timing fits)
- Fixing core position reconstructed by ALTO NKG fits
- Performing a χ^2-minimization: $\chi^2 = \chi^2_{hyperbolic} + \chi^2_{parabolic}$







Reconstructed event display example

Example of a simulated gamma-ray event with energy **1.42 TeV** and zenith angle **18°**, azimuthal angle **0°** and true core position **(-24.37 m, 9.81 m)**.
Colours designate the number of detected photoelectrons (logarithmic scale for water Cherenkov and scintillation detectors, linear scale for μ-HiSCORE stations)

Reconstructed (ALTO/COMET):

- Zenith angle = **18.32°**
- Azimuth angle = **0.12°**
- Core = **(-23.31 m, 9.95 m)**