Werner Hofmann

ON PERFORMANCE LIMITS FOR AIR SHOWER ARRAYS

Performance limits

- Assuming a “perfect” detector and a “perfect” analysis, what is the ultimate performance, limited by air shower physics and in particular by fluctuations in air shower development?
- How does performance degrade when various types of detector imperfections are introduced? Which detector characteristics matter most?

Performance Limits for Cherenkov Instruments
W. Hofmann, arXiv:astro-ph/0603076

On angular resolution limits for air shower arrays
W. Hofmann, Astroparticle Physics, Volume 123, article id. 102479

Impact of altitude and Cherenkov photon detection efficiency on the energy threshold of SWGO-like arrays
W. Hofmann, HAP-20-003 (SWGO Internal Note)

Caveats

- Need to simulate a "perfect" detector: easy
- Need to simulated a "perfect" data analysis: very hard

→ The "limiting performance" shown in the following is really a lower limit for the performance that can be obtained with a "perfect detector" – there could always be a better ways to analyze the data

- The models of detectors and in particularly of their imperfections are highly idealized and simplified. These studies aim to provide guidance for detector design but cannot replace detailed simulations of actual detectors.

Performance limits for Cherenkov telescopes

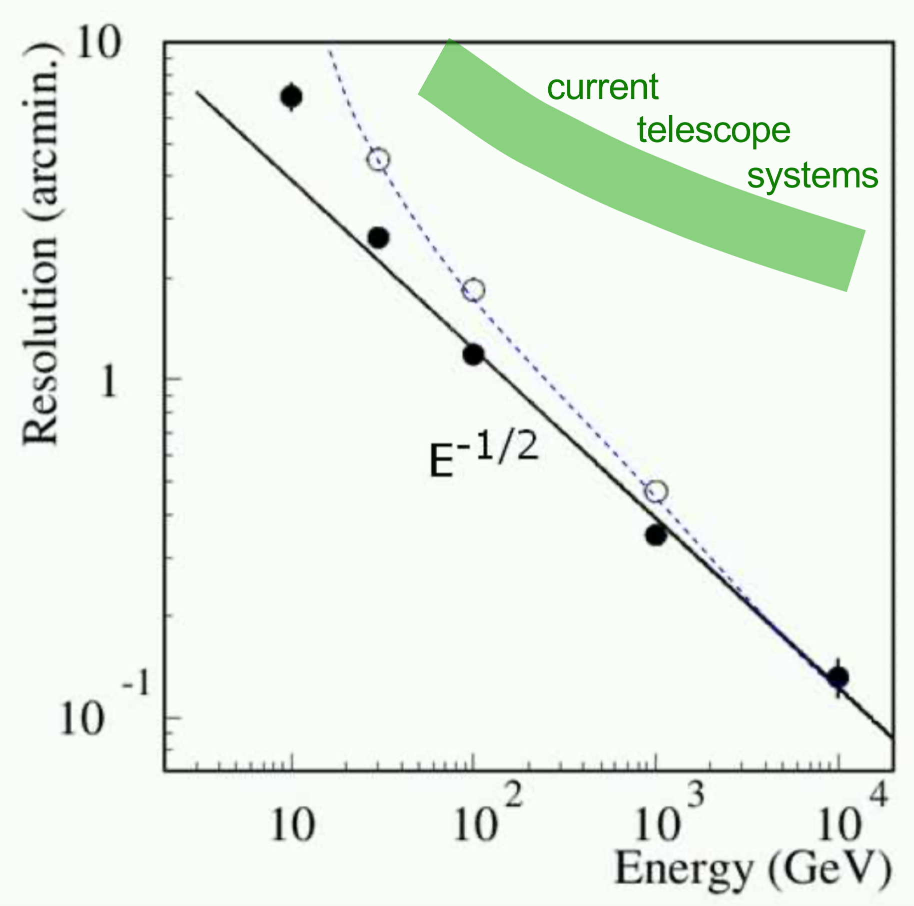
* "Limit" means "can do at least that well"

W. Hofmann
astro-ph/0603076

1) Ideal detector: detects all Cherenkov photons reaching the ground, measures position and direction

2) How well does one need to detect the photons, in order not to spoil this ideal resolution?

– area coverage > few %
– pixel size < 0.05°
– photon impact position < 3-4 m rms



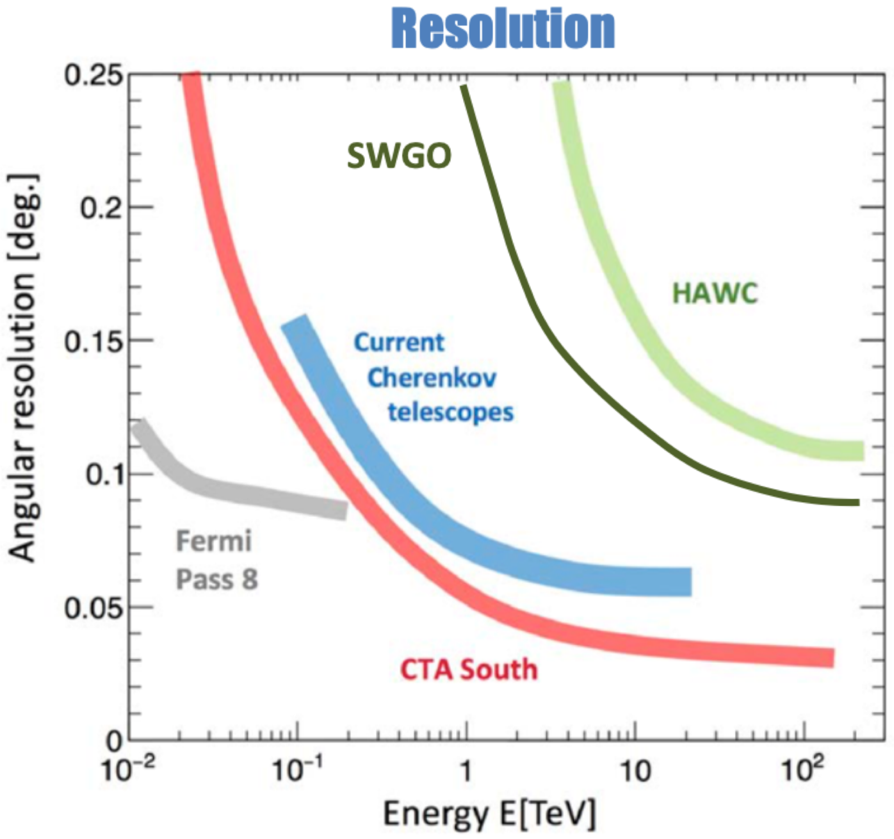
Angular resolution of air shower arrays

Is this the best we can do?

Assume we detect all (e-m) particles reaching the ground, and perfectly measure their

- impact point
- arrival time
- energy

combined with the “perfect” data analysis



Likelihood Fit to all (e.m.) shower particles reaching ground

Particle position

Arrival time

Primary energy

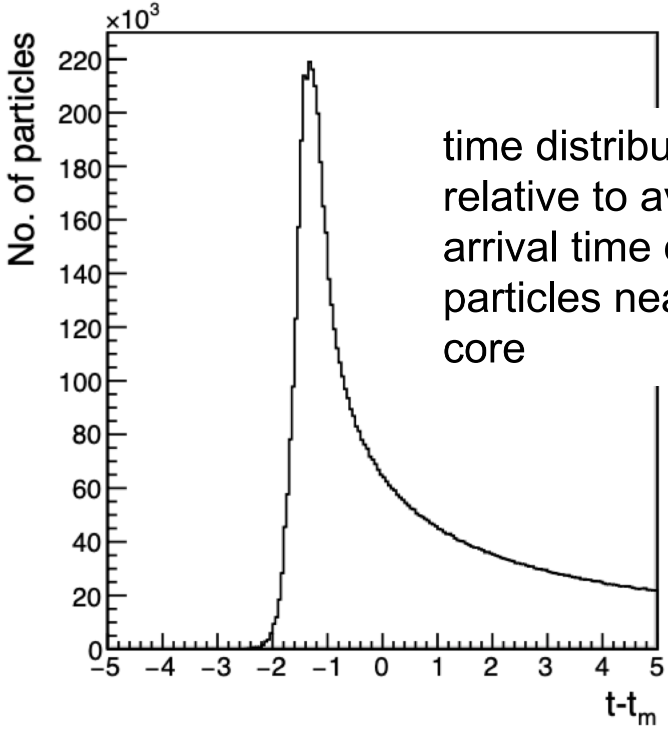
Particle energy

$$\rho(r, t; E_p, \epsilon) = \rho_r(r; E_p, \epsilon)\rho_t(t - t_0; r, E_p, \epsilon)$$

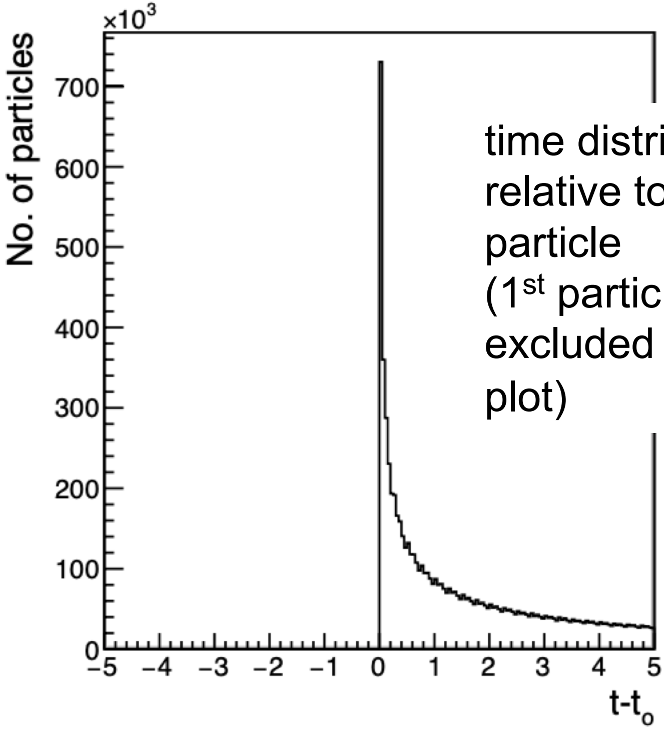
Radial dependence:
modified NKG

Time dependence:
- what is t_0?
- shape

t_0: First particle



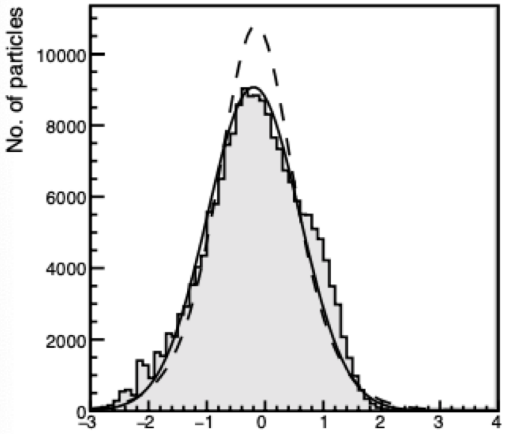
time distribution relative to average arrival time of particles near core



time distribution relative to first particle (1st particle excluded from plot)

Distribution: Log-Normal in t

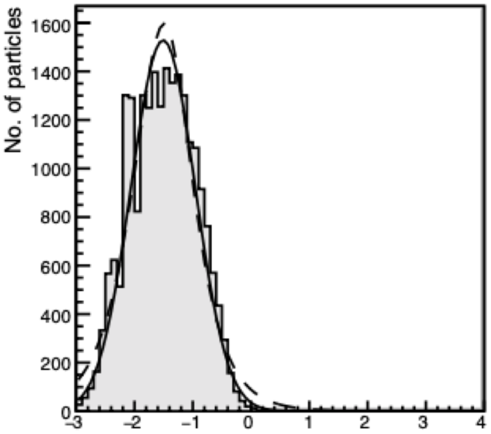
r = 0 - 20 m
ε = 3 - 10 MeV



$\log_{10}(t-t_0)$ [ns]

1 ps 1 ns 1 μs

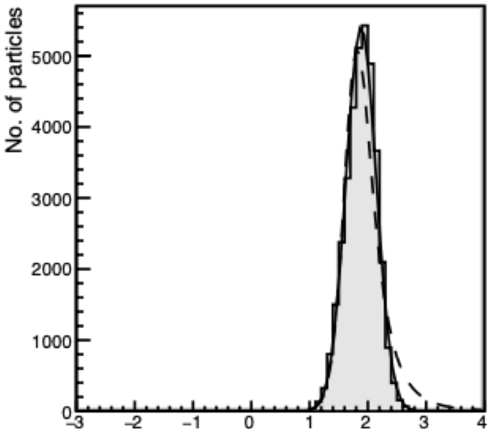
r = 0 - 20 m
ε = 100 - 300 MeV



$\log_{10}(t-t_0)$ [ns]

1 ps 1 ns 1 μs

r = 200 - 220 m
ε = 3 - 10 MeV



$\log_{10}(t-t_0)$ [ns]

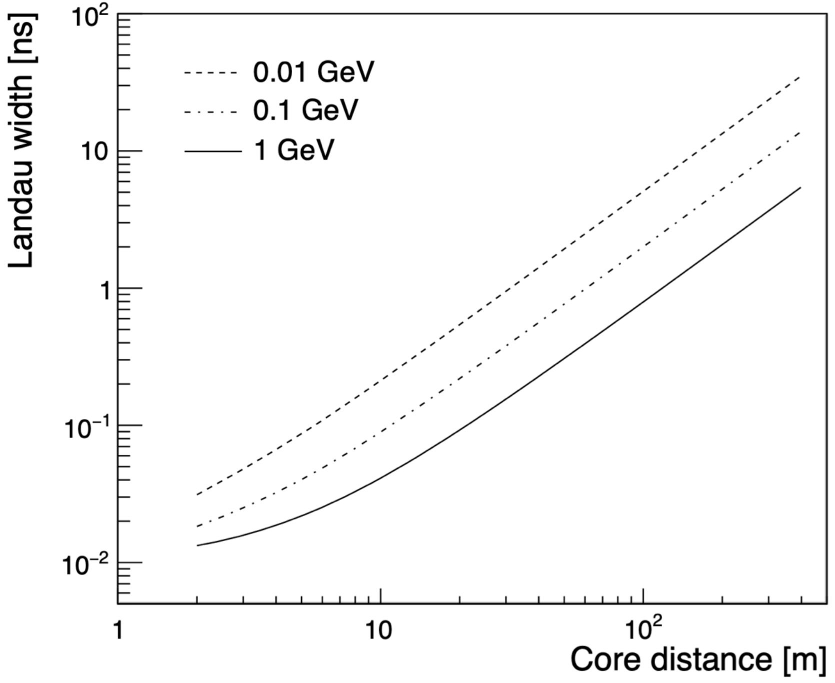
1 ps 1 ns 1 μs

for ease of numerics, use Landau distribution (dashed)

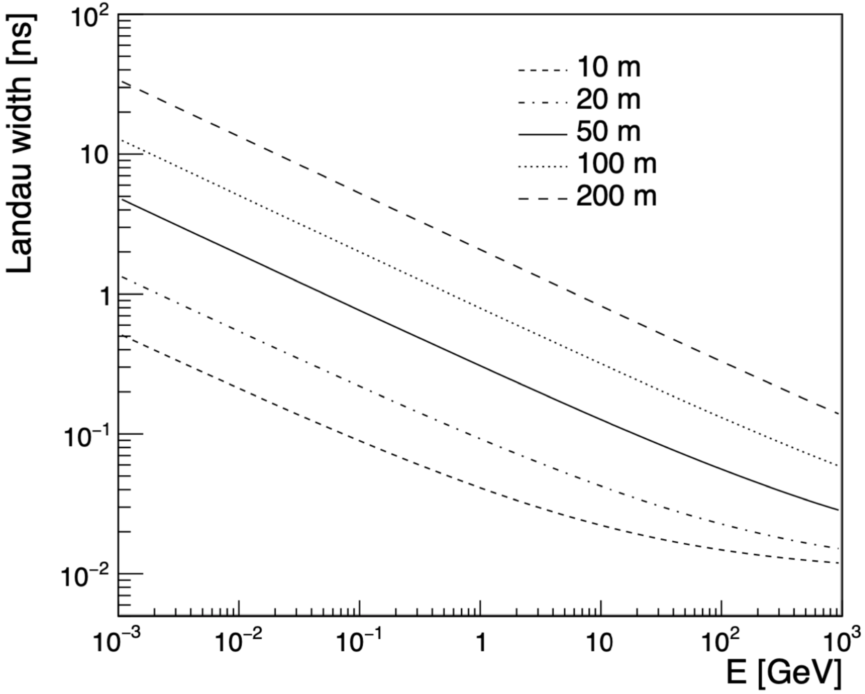
Width of time distribution

Scale parameter of Landau distribution
- not equivalent to Gaussian sigma

versus core distance



versus energy



Width of time distribution

Scale parameter of Landau distribution
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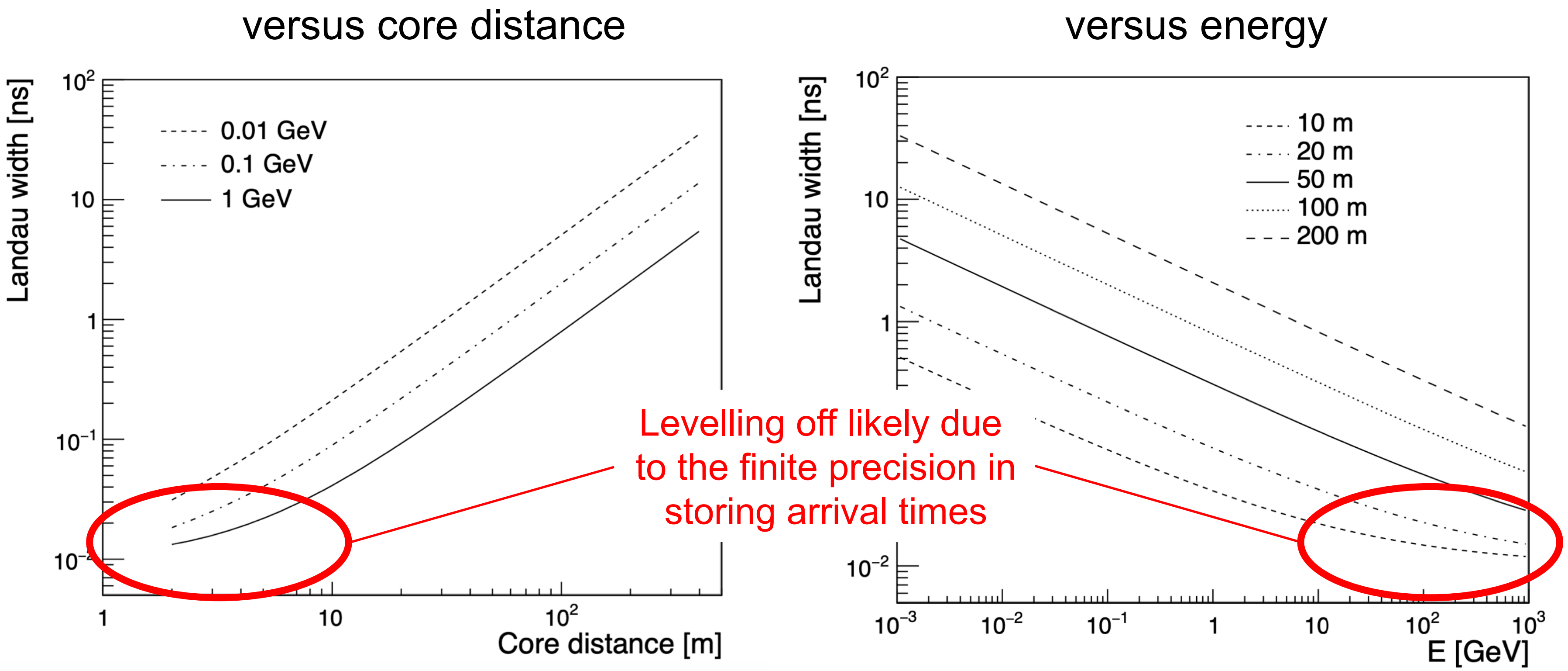
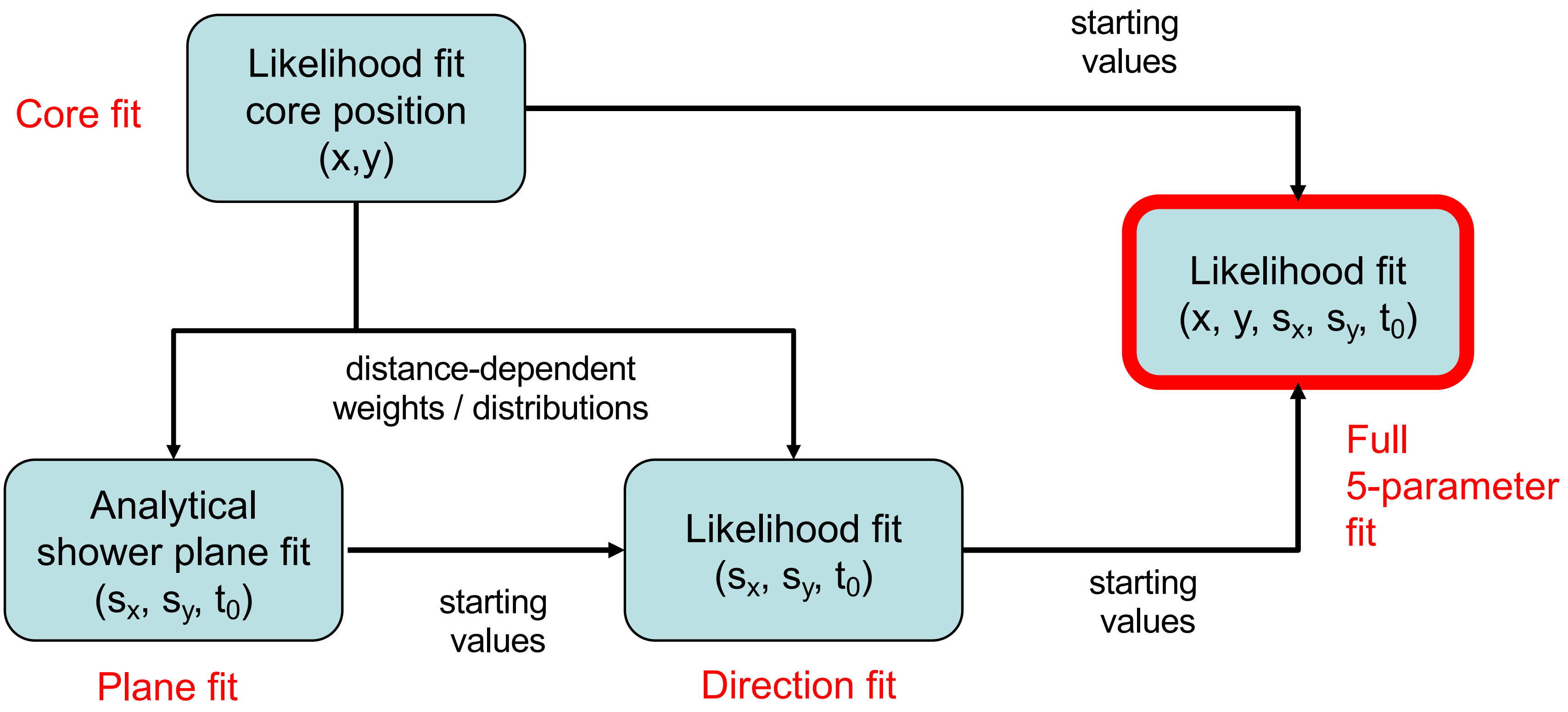
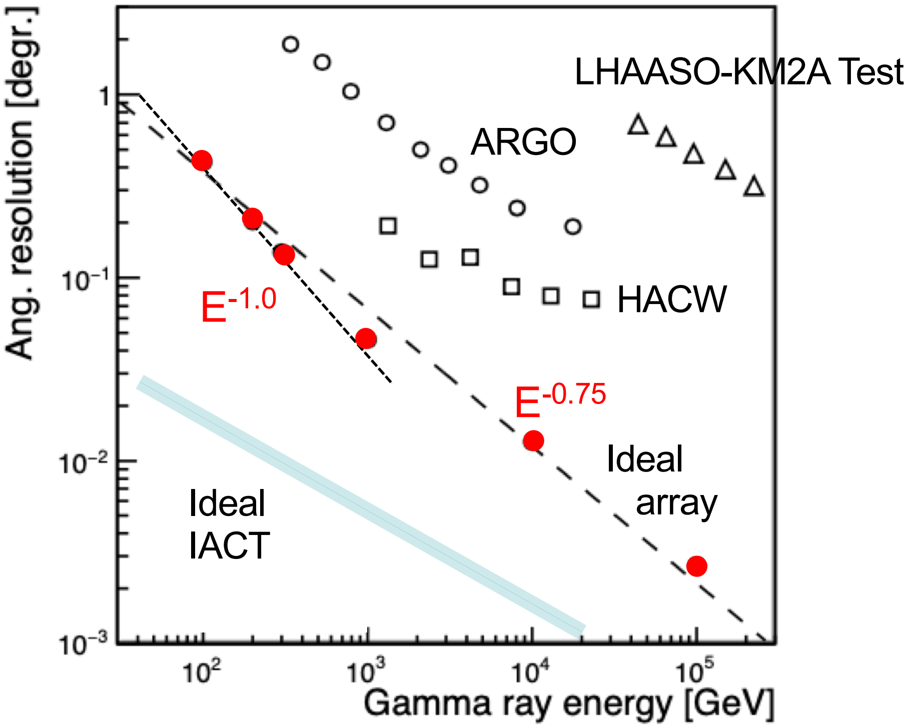


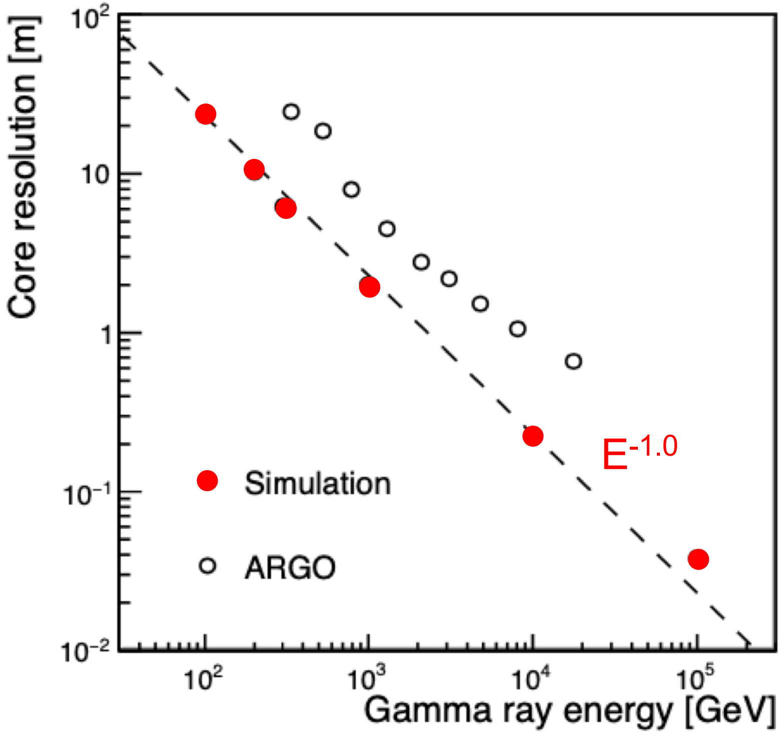
Getting good starting values for the fit



Angular resolution & core resolution

(resolution in projections, multiply by 1.5 for 68% cont.)

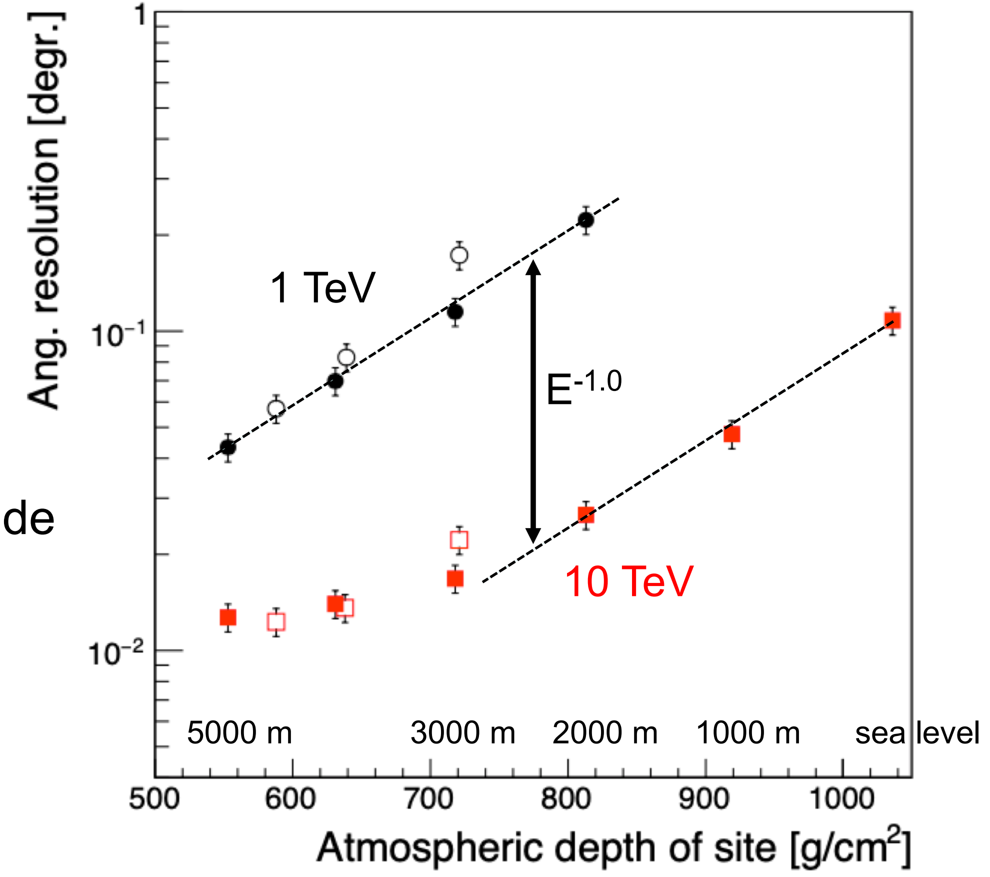




Site elevation & zenith angle

Full points:
vertical incidence, decreasing altitude

Open points:
5000 m, varying zenith angle



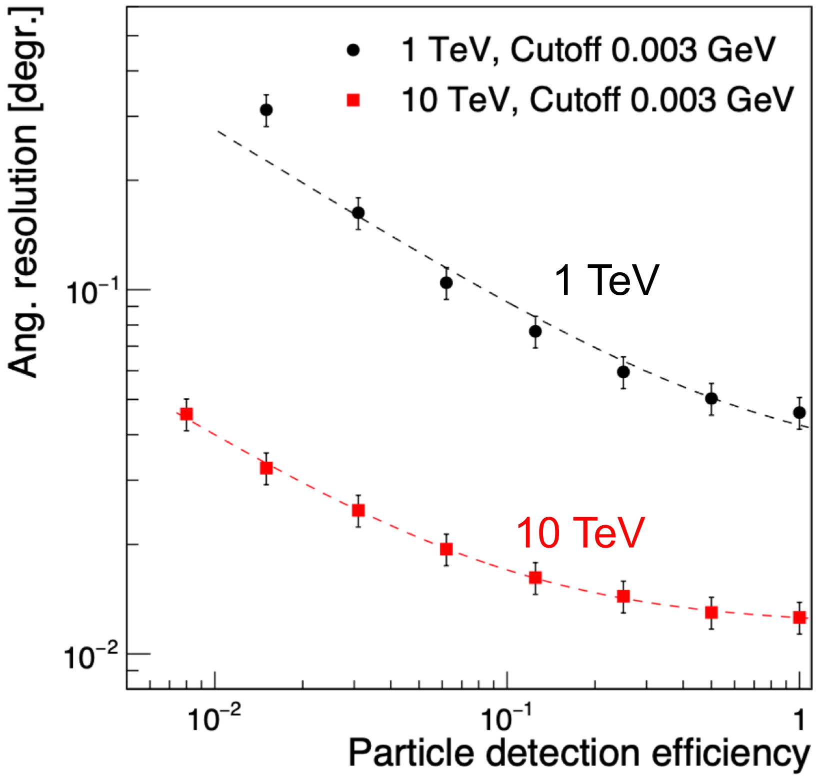
From ARGO to the ideal detector

ARGO plane fit	0.9^o rms proj
Ideal detector at 4300 m asl	0.06^o rms proj
Model with ARGO params, likelihood fit	0.6^o rms proj
… with perfect time res.	0.2^o rms proj
… no edge effects	0.1^o rms proj
… full efficiency for em particles	0.06^o rms proj

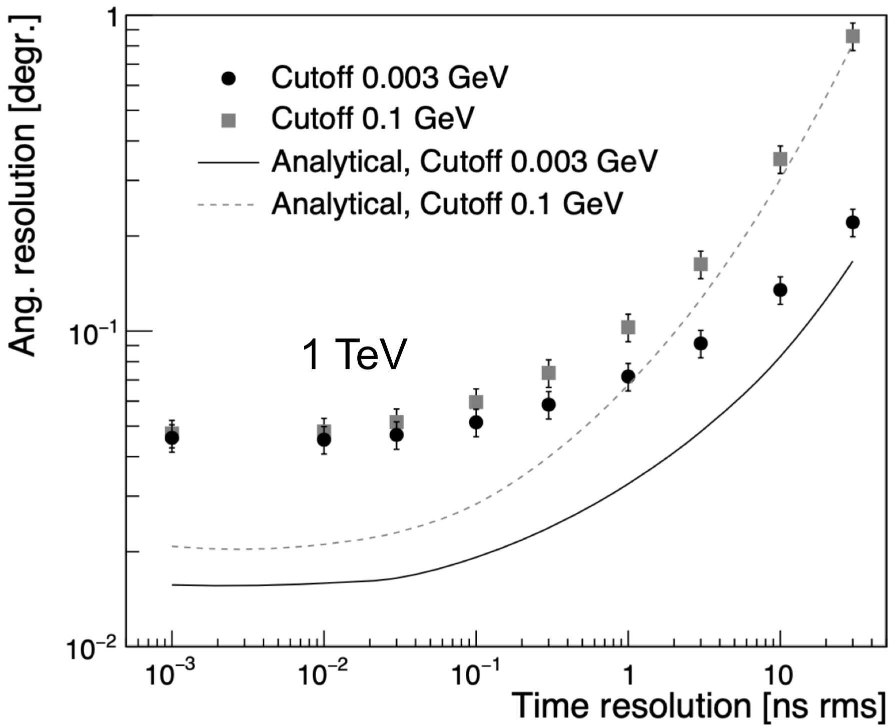
Detector effects

- Particle detection efficiency
- Size of array
- Energy threshold of detection units
- Time resolution of detection units
- Energy resolution of detection units

Detection efficiency - does one need to detect all particles?



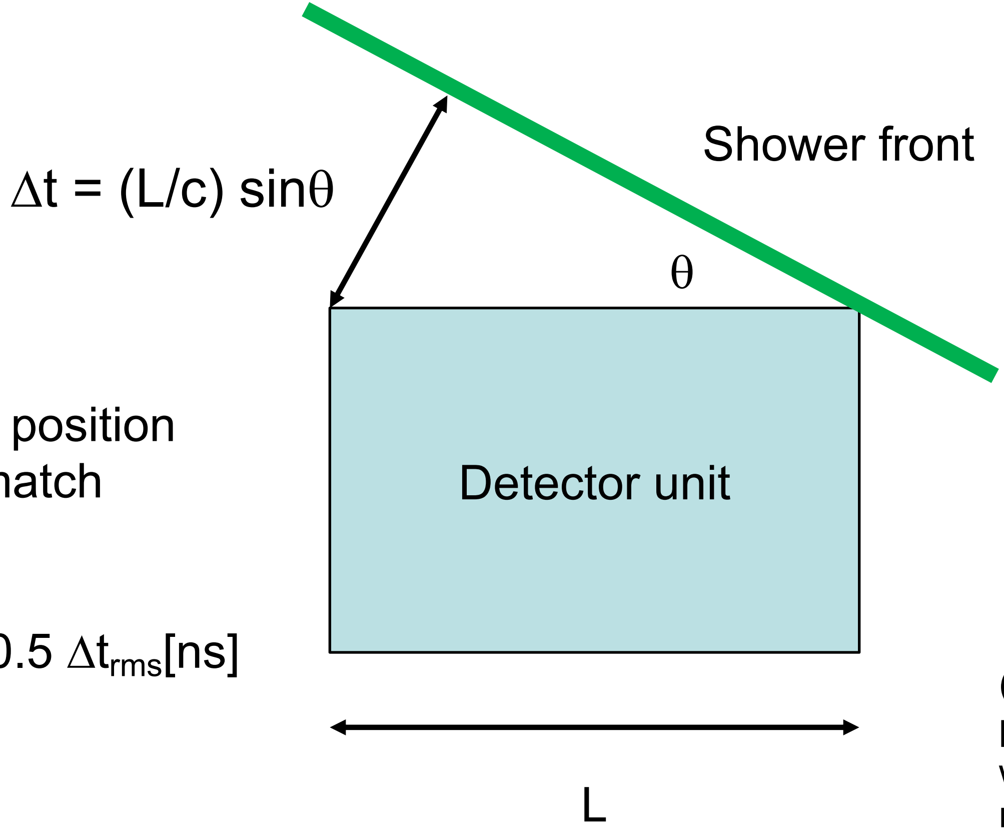
Time resolution (fold Gaussian time resolution with Landau distr.)



particles above 100 MeV detected

particles above 3 MeV detected

Position resolution & time resolution

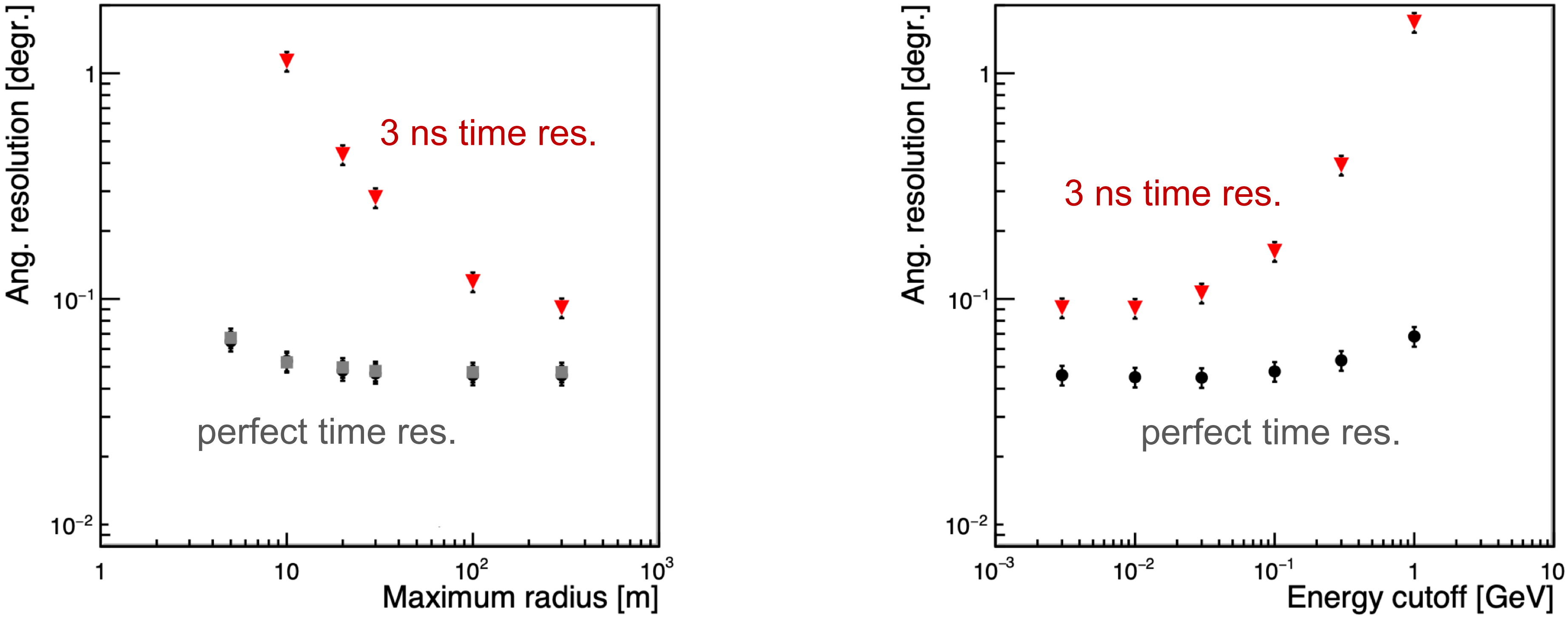


Time resolution and position resolution need to match
$\Delta x \lesssim (c\Delta t)/\sin\theta$

$\Delta x_{rms}[m] \approx L/\sqrt{12} \lesssim 0.5\ \Delta t_{rms}[ns]$

(Improves if many particles hit a detector, which is not the case near threshold)

Size of array and Energy threshold of units



Analytical model for resolution

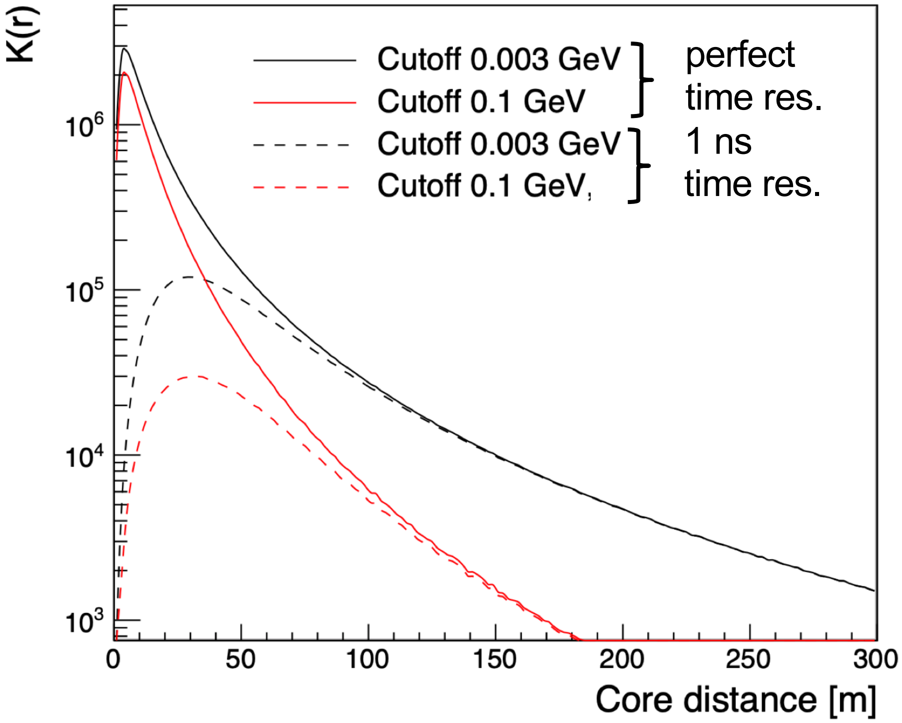
$$\frac{1}{\delta\theta_x^2} \approx \sum \frac{1}{\delta\theta_{x,i}^2} \approx \sum \frac{x_i^2}{c^2\sigma_{t,i}^2}$$

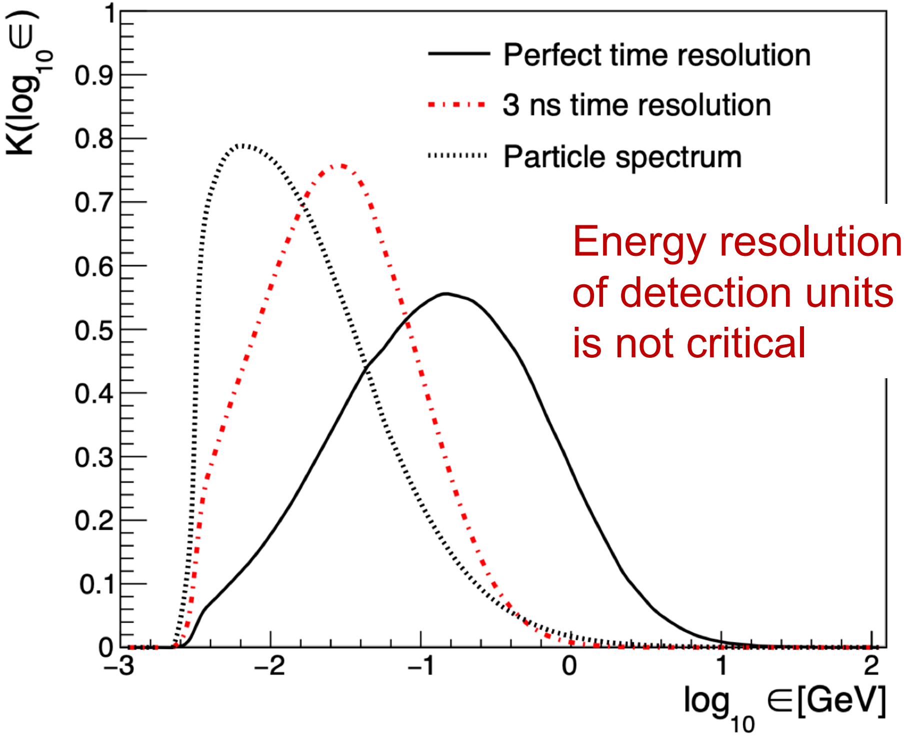
Which particles matter?

Contributions to the sum as function of

- particle radius
- particle energy

Which particles contribute to resolution?





Energy resolution of detection units is not critical

Time resolution of some 10 ps

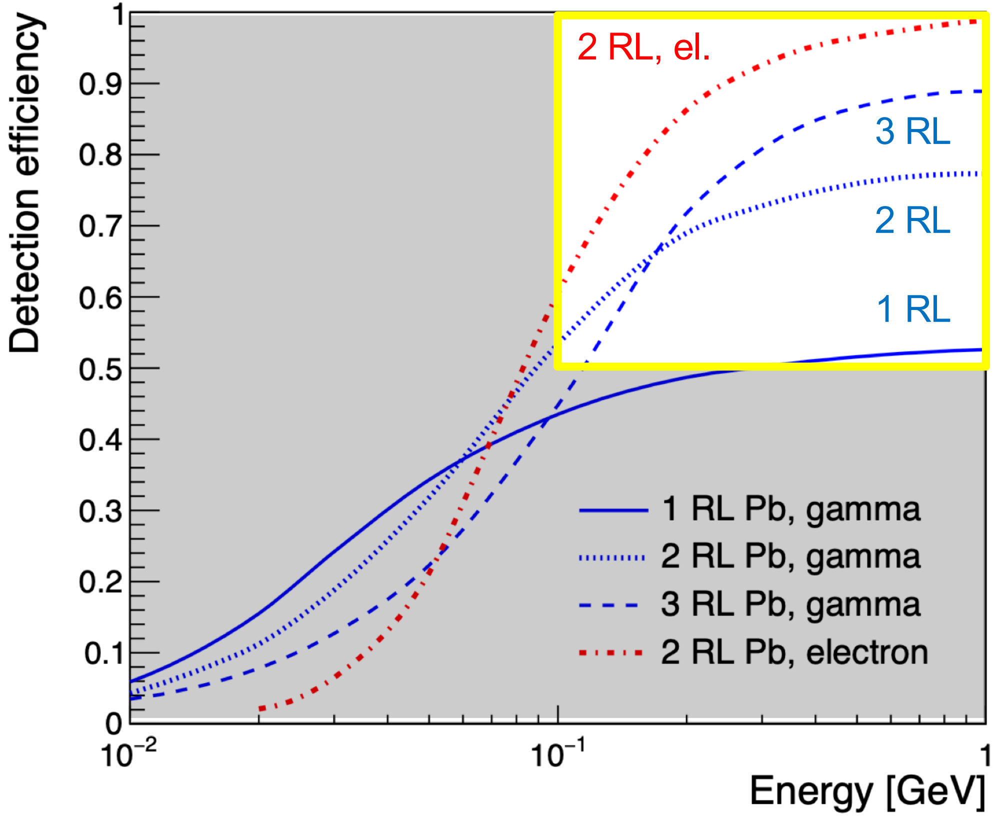
Position resolution of some cm

Detection efficiency for gammas >50% above ~100 MeV

Minimal or no energy resolution

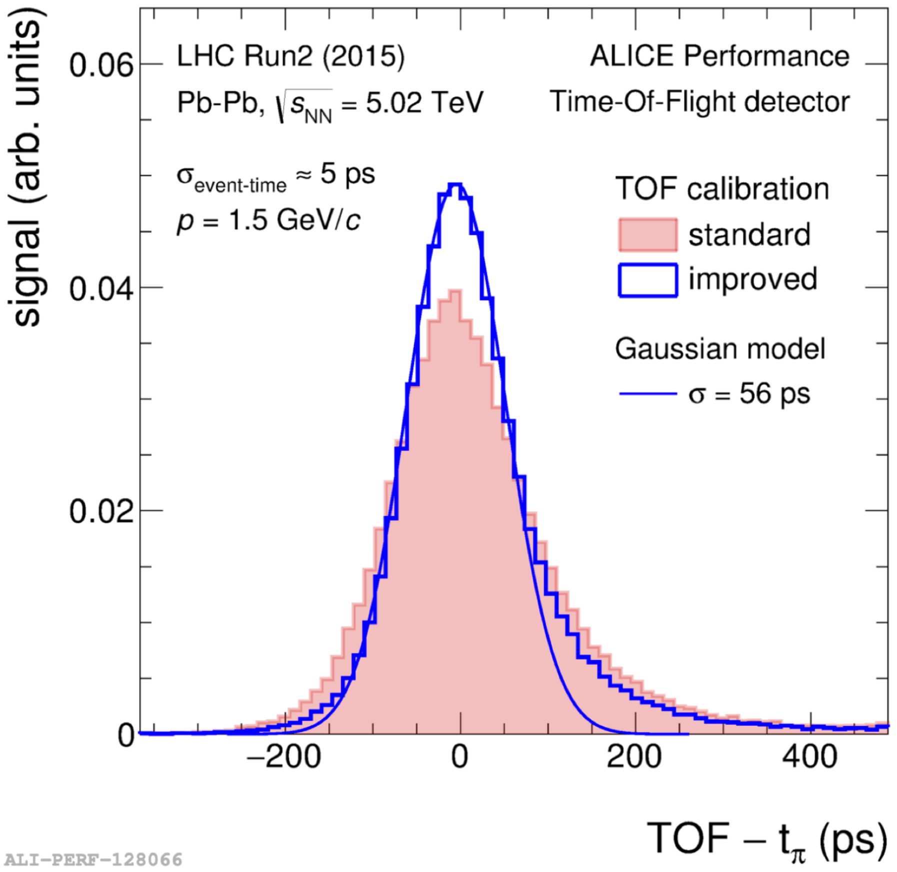
CAN SUCH A DETECTOR BE BUILT?

Charged particle detector behind lead converter



Performance target

Time resolution of RPC TOF systems



IMPACT OF HEIGHT AND PHOTON DETECTION EFF. ON THE ENERGY THRESHOLD OF WC DETECTORS

Energy threshold

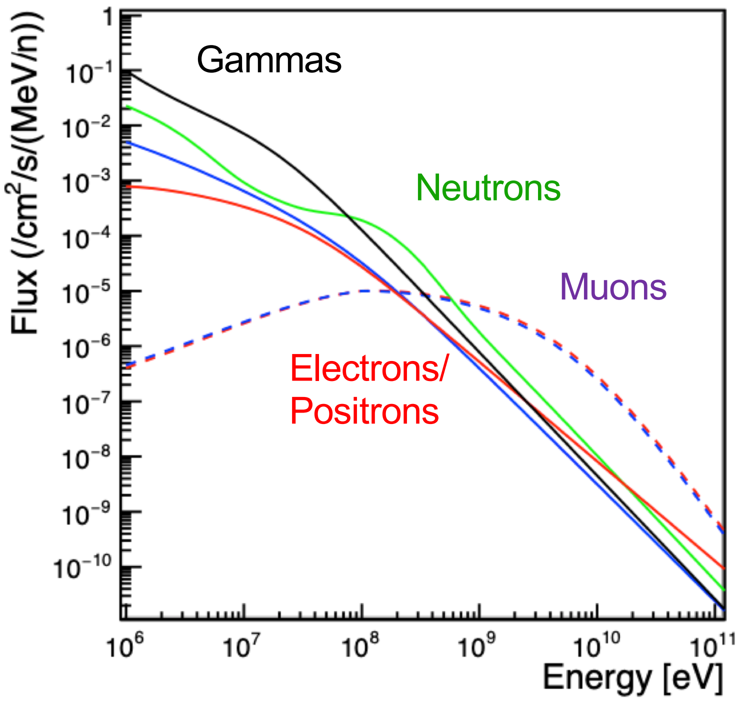
T. Sato, Analytical Model for Estimating Terrestrial Cosmic Ray Fluxes Nearly Anytime and Anywhere in the World: Extension of PARMA/EXPACS, PLOS ONE, 10(12): e0144679

Factors:
- Elevation of site
- Threshold of WC detector unit
  = Photocathode coverage

Assume 100% area coverage

Both factors impact
- Noise rate of detectors
- Number of air shower hits

Adjust array coincidence level such the rate of noise triggers is modest ➜ energy threshold

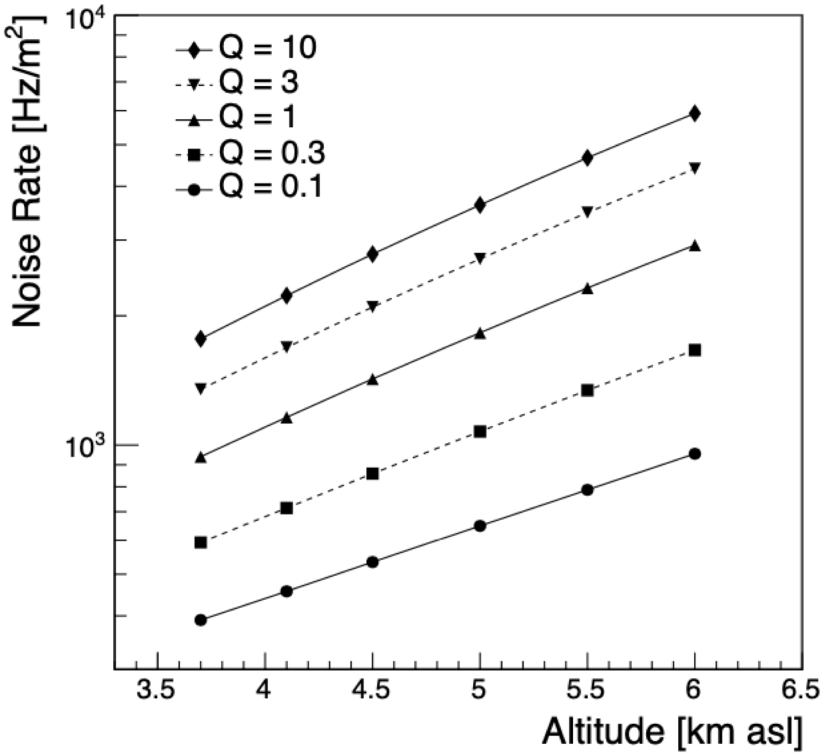


Noise rates

Using background flux from Sato

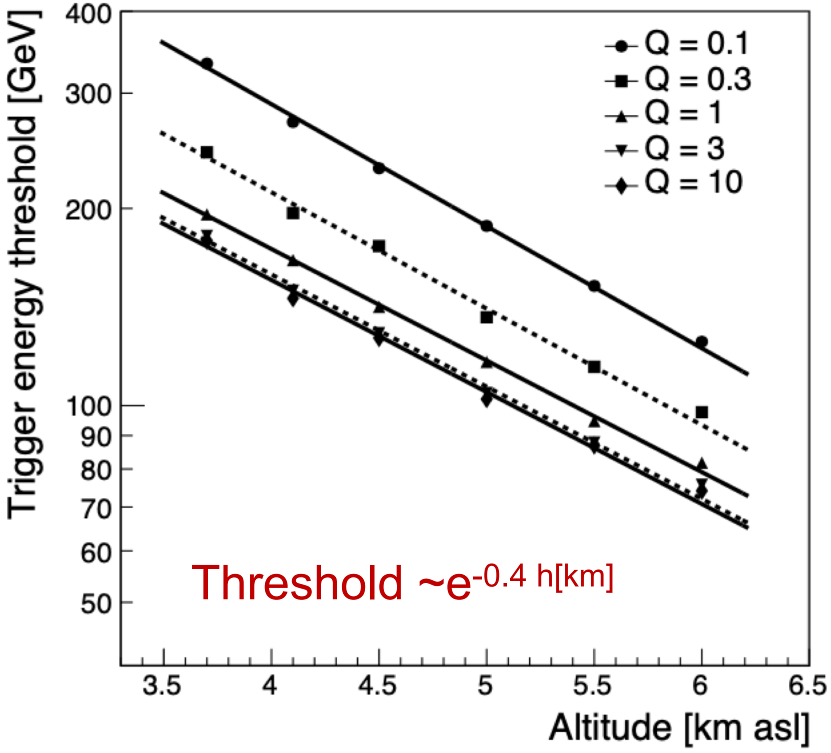
+ very simplified model to estimate yield of Cherenkov photons

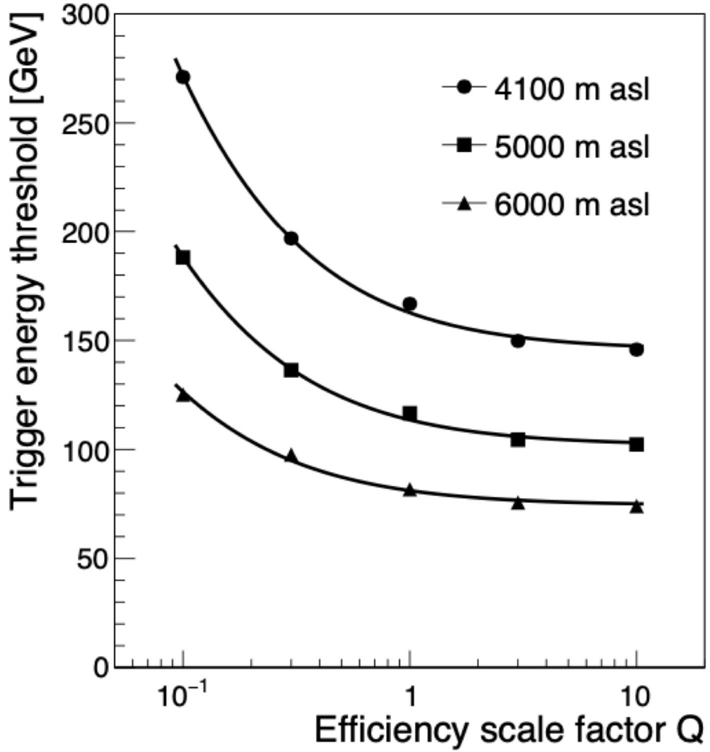
+ efficiency factor Q:
photon detection efficiency relative to HAWC tanks
Q=1: ~50% detection eff for 20 MeV gammas



Energy threshold

used specific definition of threshold
- focus on dependency, not absolute values





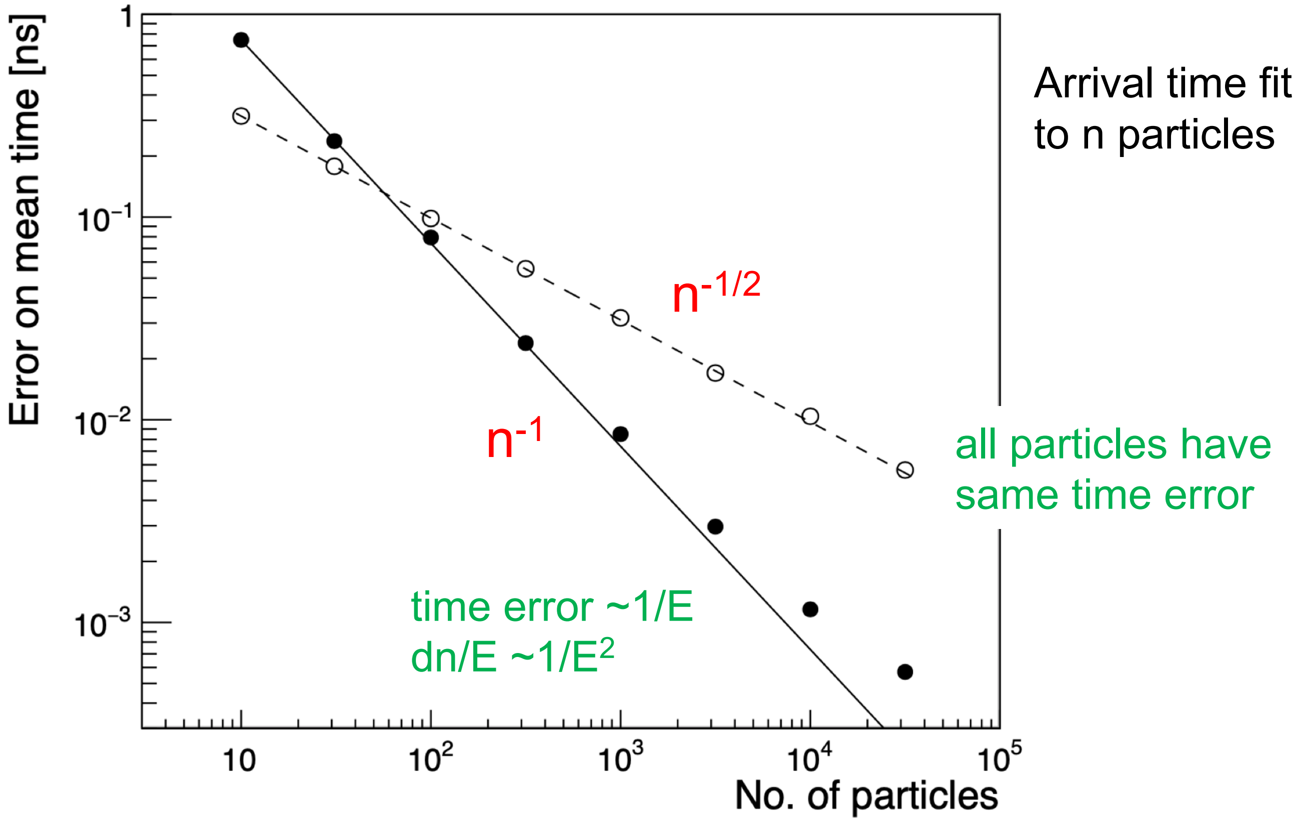
(relative to HAWC)

Conclusion

- Current instruments do not approach the physics limits of ground-based air shower detectors - significant improvements in angular resolution are in principle possible
- Excellent timing of shower particles (in the few 10 ps range) is crucial; implies corresponding spatial segmentation/resolution
- Angular resolution improves significantly with altitude
- With excellent timing, shower time structure can also provide significant gamma/hadron separation
- On energy threshold of WC detectors: height helps (as expected); threshold saturates for high photocathode area

SPARE SLIDES

Statistics does not always follow $n^{-1/2}$



Arrival time fit to n particles

Time resolution