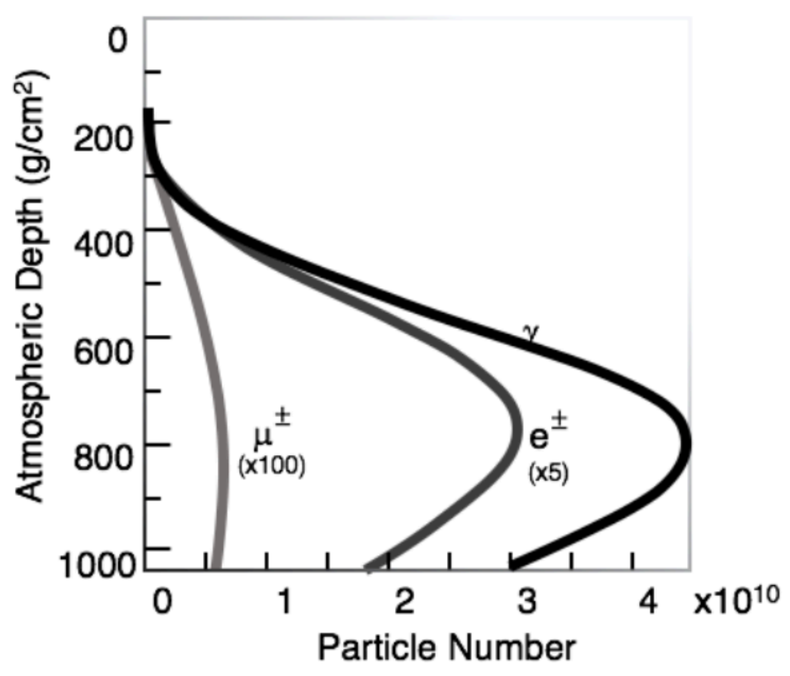
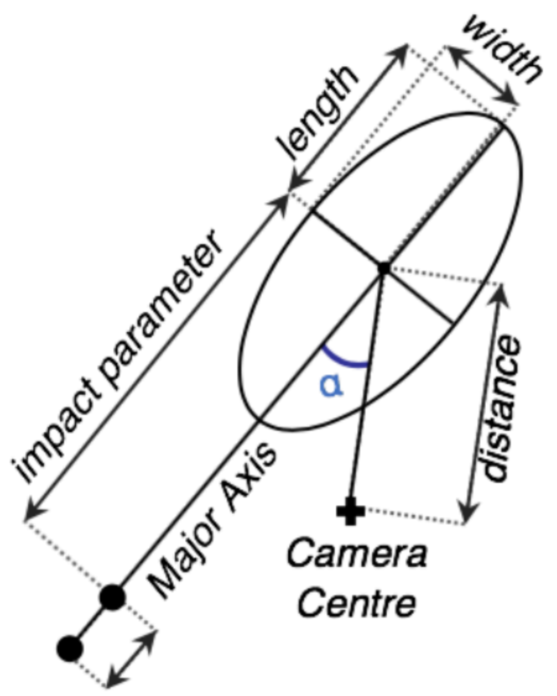
The Legacy of Michael Hillas in Air Shower Simulations.

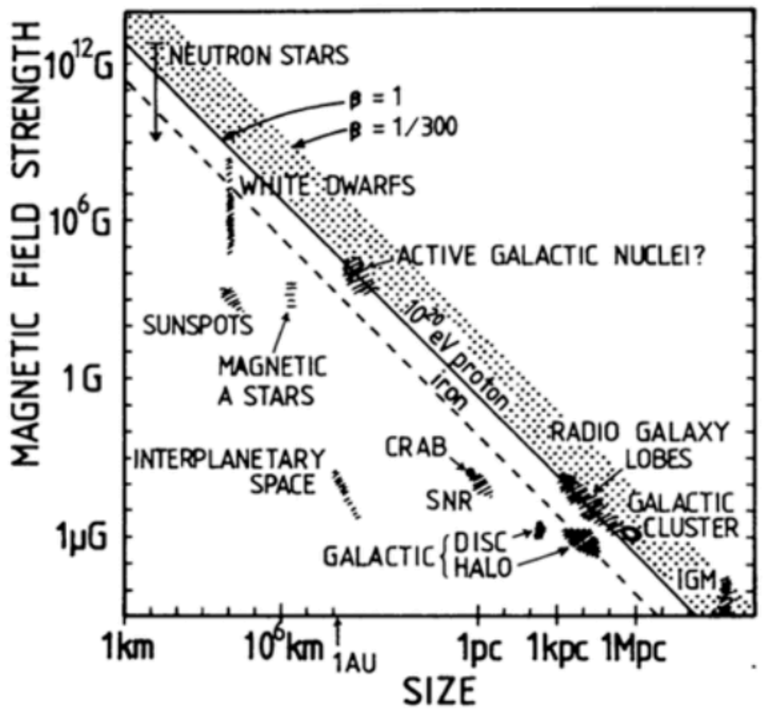
The 2018

HILLAS SYMPOSIUM

Heidelberg, Germany
December 10 - 12







Johannes Knapp, DESY Zeuthen

on Michael:

“**a brilliant mind**”

“**physical insight**, coupled with a flair for **extracting the most from simple numerical calculations**”

“**outstanding talents** as an **experimental physicist** and as a **numerical modeller** of physical phenomena.”

“**unusually penetrating physical insight** with **extraordinary powers of calculation and analysis**”

Many of Michael's results were written down only in contributions to the Proceedings of International Cosmic Ray Conferences. (4 pages each) …

… but in the Age of Digitisation:

These papers are now largely available via ADS
Their citations are counted.
Their impact becomes apparent.

Google Scholar

Antony Michael Hillas

FOLLOW

Professor Emeritus of Physics, U of Leeds
Verified email at desy.de

cosmic rays   air showers   gamma ray astronomy

TITLE	CITED BY	YEAR
The origin of ultra-high-energy cosmic rays AM Hillas Annual review of astronomy and astrophysics 22 (1), 425-444	1587	1984
Detection of TeV photons from the active galaxy Markarian 421 M Punch, CW Akerlof, MF Cawley, M Chantell, DJ Fegan, S Fennell, ... nature 358 (6386), 477	1292	1992
Observation of TeV gamma rays from the Crab nebula using the atmospheric Cerenkov imaging technique TC Weekes, MF Cawley, DJ Fegan, KG Gibbs, AM Hillas, PW Kowk, ... The Astrophysical Journal 342, 379-395	1144	1989
Cerenkov light images of EAS produced by primary gamma AM Hillas	1086	1985
Extremely rapid bursts of TeV photons from the active galaxy Markarian 421 JA Gaidos, CW Akerlof, S Biller, PJ Boyle, AC Breslin, JH Buckley, ... Nature 383 (6598), 319	636	1996
Detection of gamma rays with E> 300 GeV from Markarian 501 J Quinn, CW Akerlof, S Biller, J Buckley, DA Carter-Lewis, MF Cawley, ... The Astrophysical Journal Letters 456 (2), L83	628	1996
Can diffusive shock acceleration in supernova remnants account for high-energy galactic cosmic rays? AM Hillas Journal of Physics G: Nuclear and Particle Physics 31 (5), R95	503	2005
VERITAS: the very energetic radiation imaging telescope array system TC Weekes, H Badran, SD Biller, I Bond, S Bradbury, J Buckley, ...	431	2002

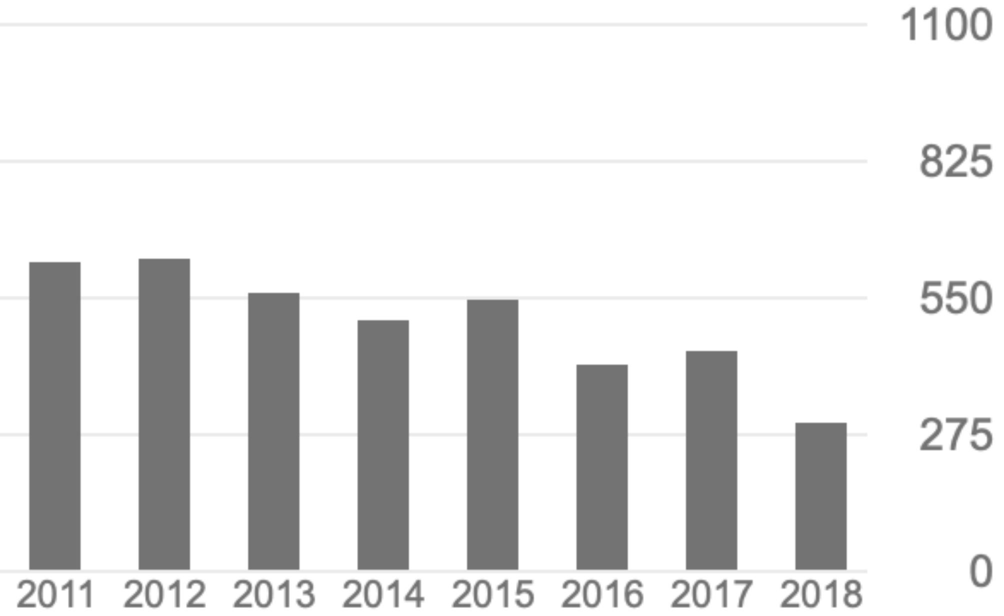
fig 1: Hillas Plot

ICRC 1985, La Jolla
Hillas Parameters

GET MY OWN PROFILE

Cited by   VIEW ALL

	All	Since 2013
Citations	17237	2775
h-index	55	21
i10-index	134	41



Co-authors

- Michael Schubnell — Research Scientist, University of ...
- Giuseppe Vacanti — cosine Science & Computing BV
- James Buckley — Washington University in St. Louis
- John Quinn — University College Dublin
- Valerie Connaughton

Michael's Retirement

Growth of Astroparticle Physics, many "newcomers" discover Michael's work.

Time Line

	EAS up to	gamma rays		Particle Accelerators up to	
Pierre Auger	10^{15} eV		1930	Cyclotrons	10^{6} eV
			1940		10^{8} eV
			1950	Synchrotrons	6×10^{9} eV
John Linsley	10^{20} eV	TeV γ from Crab (prediction)	1960		
			1970		20×10^{9} eV
			1980		
Fly's Eye	3×10^{20} eV	Whipple TeV γ (experimental)	1990	TeVatron	10^{12} eV
			2000		
			2010	LHC	13×10^{12} eV

AMH active

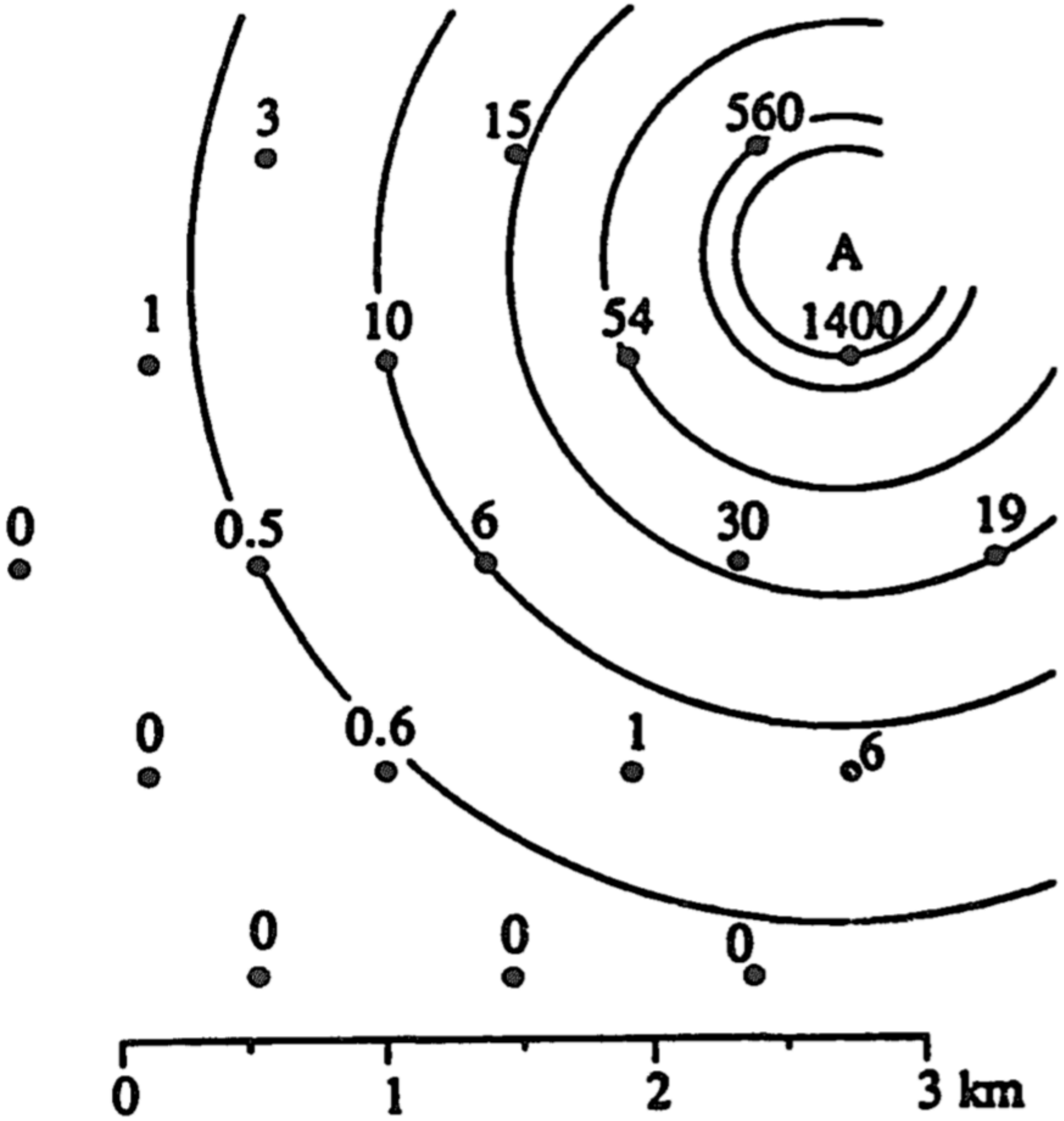
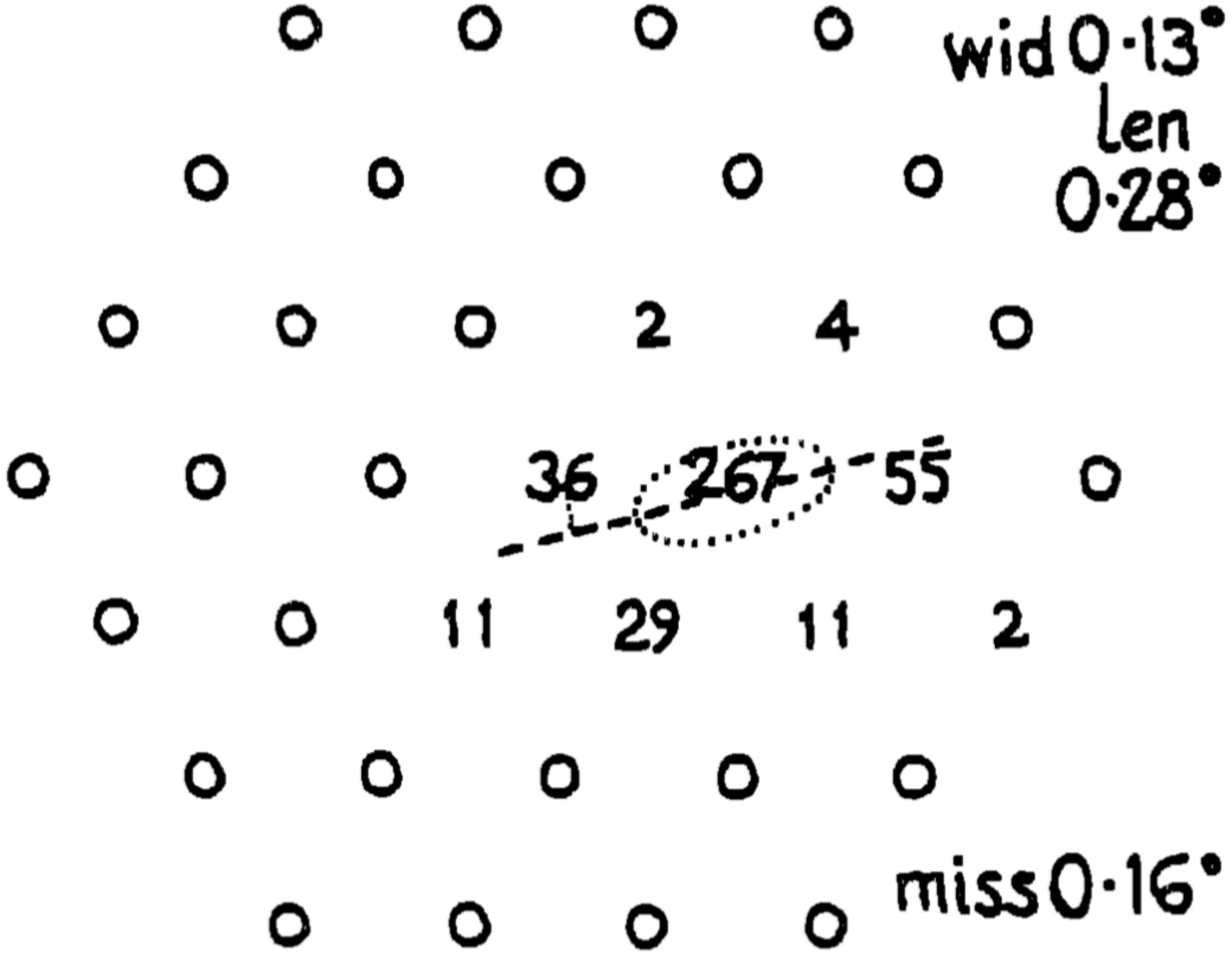


Fig. 5. First event claimed to have an energy of 10^{20}eV

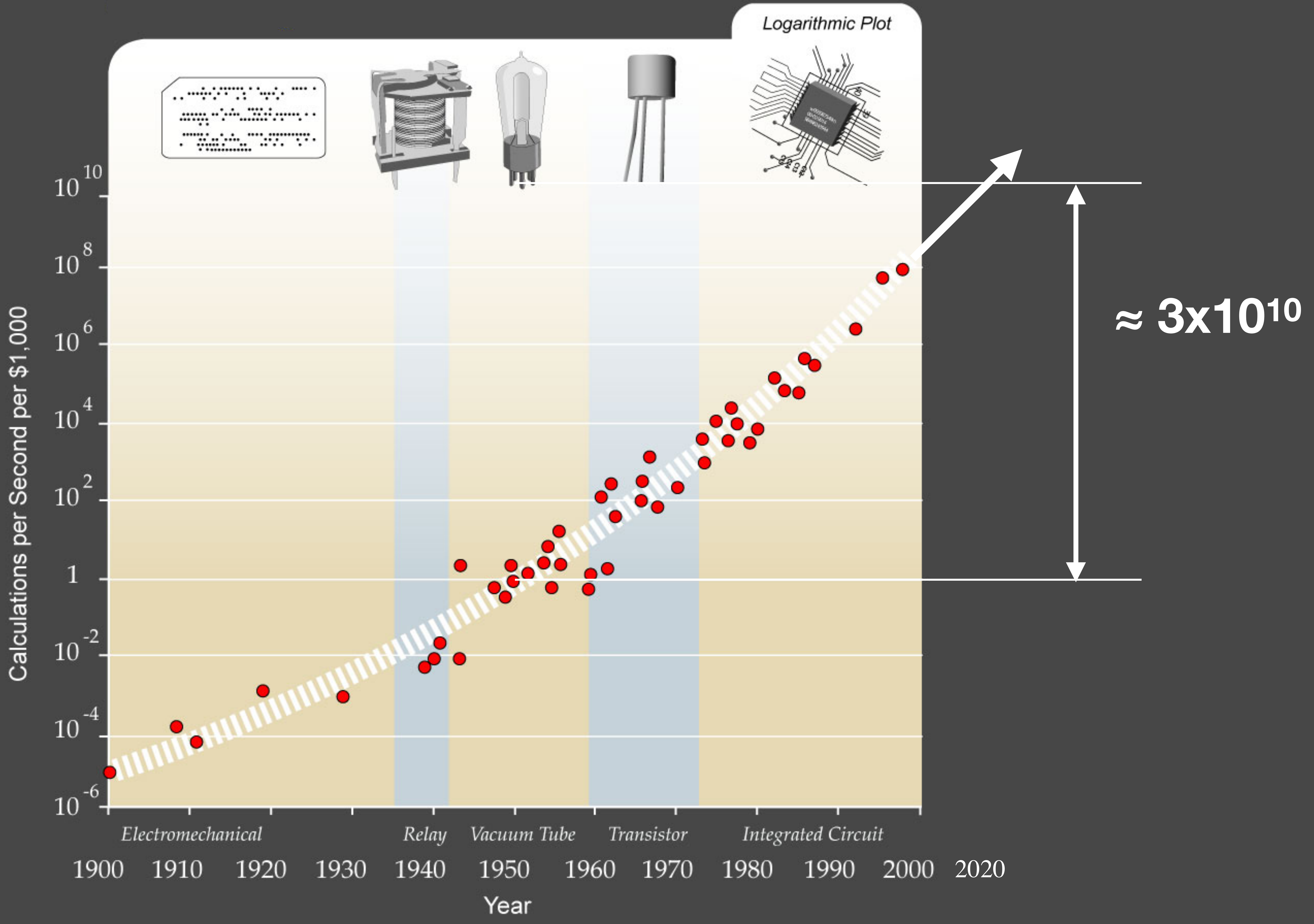
Linsley 1963



2 TeV gamma ray, 30^0, 80 m core distance
for Whipple tel., Thinning below 0.5 GeV
PEs seen in each tube

Cherenkov images of showers
Hillas 1985

Moore's Law



fast sims of complex phenomena,
many cores, parallel computing,
elaborate models, multiple parameters,
neural nets, deep learning ….

early computing
simple problems

Michael used simulations at least since the 1970s

ICRC 1977
Plovdiv

NKG: analytic description of EAS cascades (LDFs) proved inadequate.

Hillas, Lapikens, Marsden made independently simulations, agreed within 5%.

ELECTRON-PHOTON CASCADES IN THE ATMOSPHERE AND IN DETECTORS

A. M. Hillas and J. Lapikens

Physics Department, University of Leeds, Leeds LS2 9JT, U. K.

Detailed Monte-Carlo simulations have been made of electron-photon cascades initiated by photons and electrons of 1, 10 and 100 GeV at various depths in the atmosphere (and for 10 GeV in air of constant density). We confirm the report of Allan et al. that lateral spreads are much less than the Nishimura-Kamata-(Greisen) values, and although our widths are somewhat greater than those of Allan et al., there are now 5 independent calculations which agree to within ~5% on the spread. Examples of the results are given, and other results are available on request. The response of certain detectors has also been calculated.

The aims of the present work have been the following:

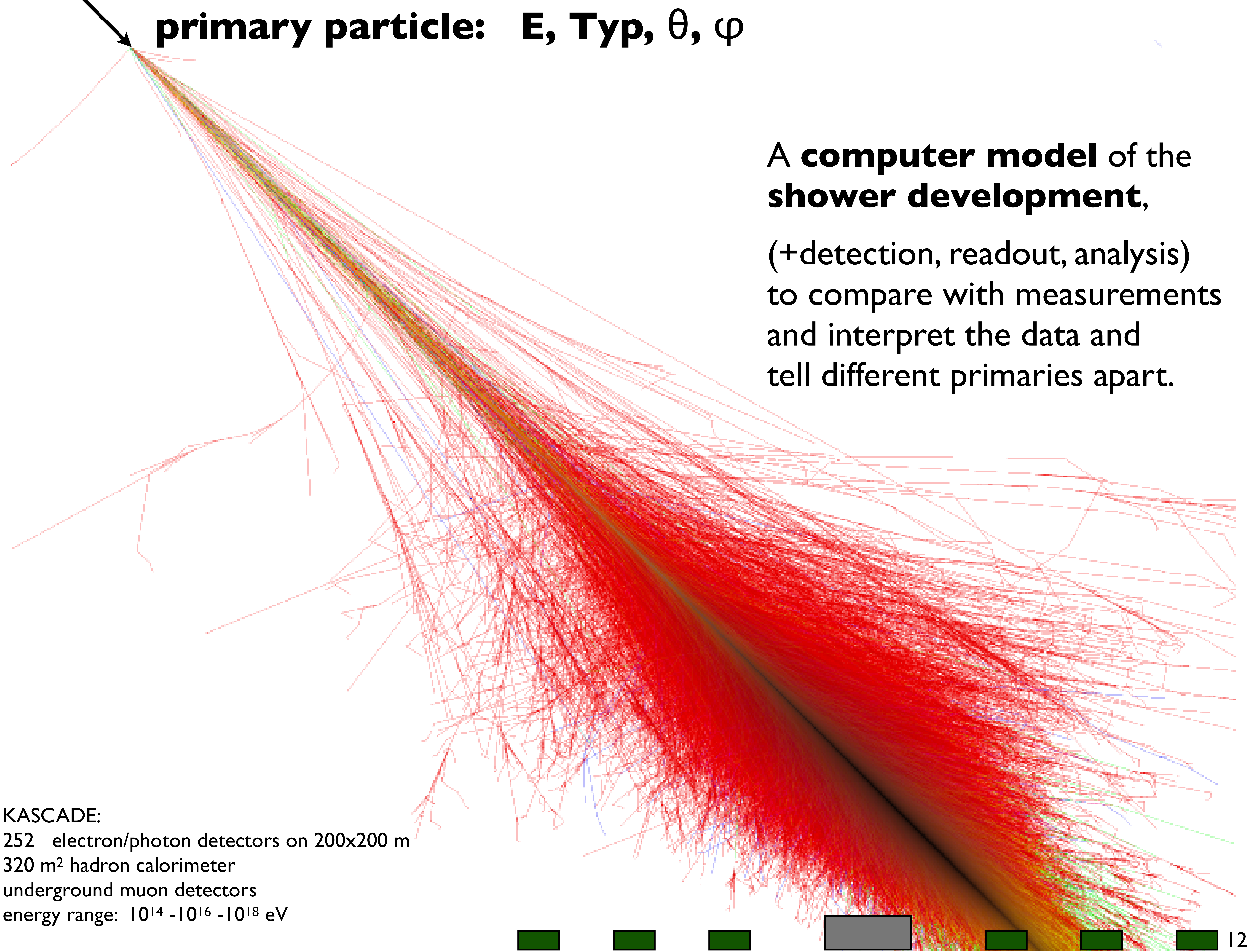
(a) To see whether Allan et al. were correct in stating that the width of electromagnetic cascades should be much less than given by NKG,
(b) To test for consistency between several calculations,
(c) to check for serious errors in the old Haverah Park calculations,
(d) to calculate detector responses in more detail,
(e) to examine the effects of magnetic fields in the atmosphere,
(f) to include smaller effects often omitted from calculations, and to identify the physical assumptions which have an important effect on the density calculated at large distances ($r \gtrsim 500$m), with the aim of ensuring that this very small fraction of the cascade energy is being correctly estimated.
(g) (eventually) to obtain good statistics to test functional forms.

Karlsruhe Shower Core and Array Detector (KASCADE)

to measure cosmic ray spectrum and composition

1987 – first ideas
1997 – first results
2003 – KASCADE-Grande
2009 – End of data taking

primary particle: E, Typ, θ, φ



A **computer model** of the **shower development**,

(+detection, readout, analysis) to compare with measurements and interpret the data and tell different primaries apart.

KASCADE:
252 electron/photon detectors on 200x200 m
320 m^2 hadron calorimeter
underground muon detectors
energy range: 10^{14} - 10^{16} - 10^{18} eV

CORSIKA

Cosmic Ray Simulation for KASCADE

Now the gold-standard for all air shower simulations.

History of CORSIKA

pre 1989

SH2C-60-K-OSL-E-SPEC (Grieder):

main structure,

isobar model for hadronic interactions

HDPM & NKG (Capdevielle):

high-energy hadronic interactions,

analytic treatment of el.mag.-subshowers

EGS4 (Nelson et al.):

electron gamma showers

the frame

hadronic

el.mag.

CORSIKA Vers. 1.0 Oct 1989

First official reference:

Computer Physics Communications 56 (1989) 105–113
North-Holland

A MULTI-TRANSPUTER SYSTEM FOR PARALLEL MONTE CARLO SIMULATIONS OF EXTENSIVE AIR SHOWERS

H.J. GILS, D. HECK, J. OEHLSCHLÄGER, G. SCHATZ and T. THOUW

Kernforschungszentrum Karlsruhe GmbH, Institut für Kernphysik, P.O. Box 3640, D-7500 Karlsruhe, Fed. Rep. Germany

and

A. MERKEL

Proteus GmbH, Haid-und-Neu-Strasse 7–9, D-7500 Karlsruhe, Fed. Rep. Germany

Received 13 July 1989

extended version of EGS4. The program CORSIKA (COsmic Ray SImulations for KASCADE) simulates hadronic showers and has two options differing in their treatment of the electromagnetic subshowers and hence in their requirements of CPU time. It will be described elsewhere [12]. Examples of the computation time

[12] J.M. Capdevielle et al., KfK Report, to be published.

22th ICRC, Adelaide, Jan 1990

HE 7.3–3

AIR SHOWER SIMULATIONS FOR KASCADE

J.N.Capdevielle[1], P.Gabriel, H.J.Gils, P.K.F.Grieder[2], D.Heck, N.Heide, J.Knapp, H.J.Mayer, J.Oehlschläger, H.Rebel, G.Schatz, and T.Thouw

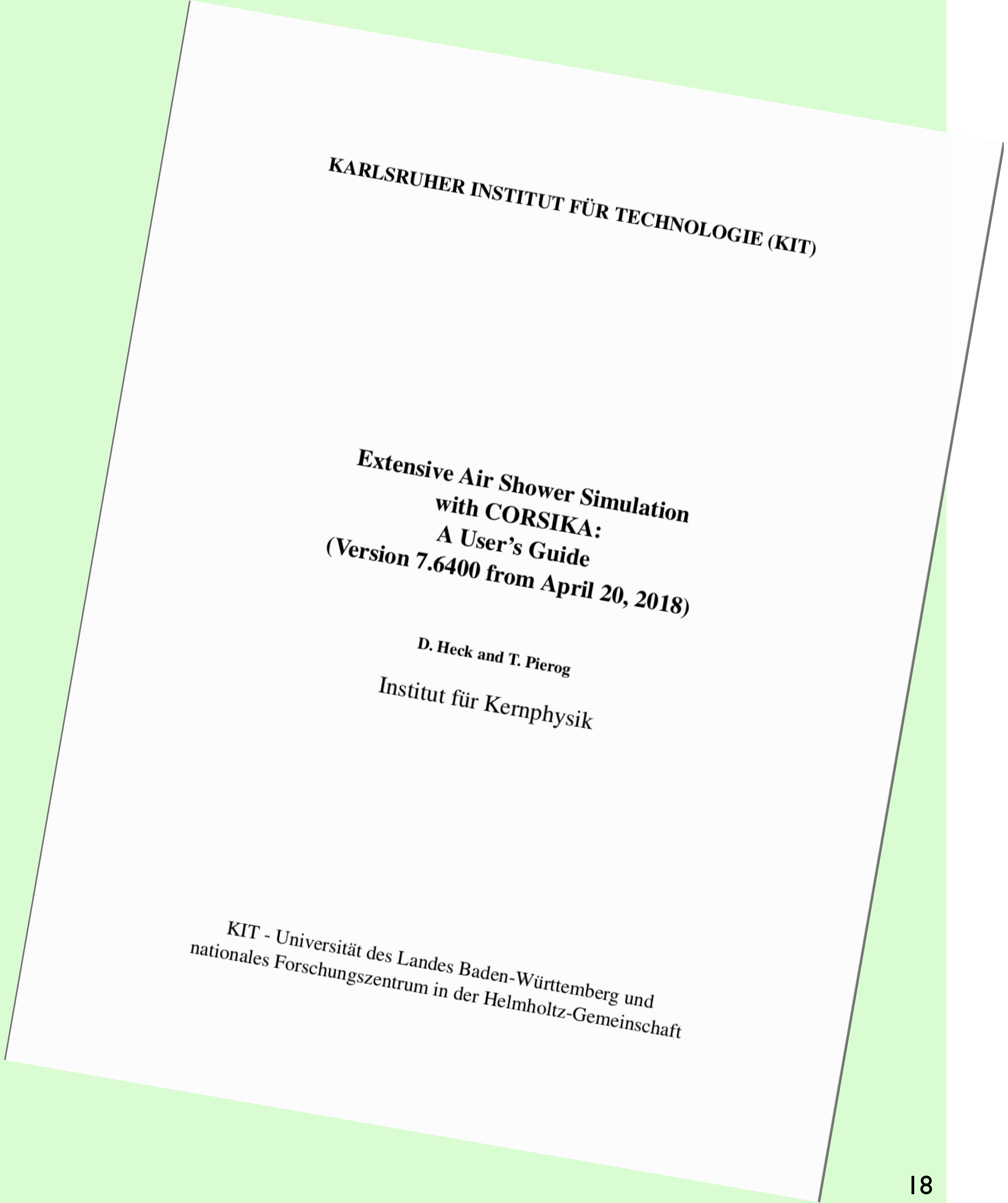
Kernforschungszentrum und Universität Karlsruhe,
D-7500 Karlsruhe, Federal Republic of Germany
[1]Laboratoire de Physique Théorique, Université de Bordeaux,
F-33170 Gradignan, France
[2]Physikalisches Institut der Universität Bern,
CH-3012 Bern, Switzerland

Abstract

A detailed simulation program for extensive air showers and first results are presented. The mass composition of cosmic rays with $E_0 \geqq 10^{15}$eV can be determined by measuring electrons, muons and hadrons simultaneously with the KASCADE detector.


KfK 4998
November 1992
The Karlsruhe Extensive Air Shower Simulation Code CORSIKA
J. N. Capdevielle, P. Gabriel, H. J. Gils, P. Grieder,
D. Heck, J. Knapp, H. J. Mayer, J. Oehlschläger,
H. Rebel, G. Schatz, T. Thouw
Institut für Kernphysik
Kernforschungszentrum Karlsruhe
Forschungszentrum Karlsruhe
Technik und Umwelt
Wissenschaftliche Berichte
FZKA 6019
CORSIKA:
A Monte Carlo Code to Simulate Extensive Air Showers
D. Heck, J. Knapp, J. N. Capdevielle,
G. Schatz, T. Thouw
Institut für Kernphysik
Februar 1998

User’s Manual
(continuously updated)


KARLSRUHER INSTITUT FÜR TECHNOLOGIE (KIT)

Extensive Air Shower Simulation with CORSIKA: A User’s Guide (Version 7.6400 from April 20, 2018)

D. Heck and T. Pierog

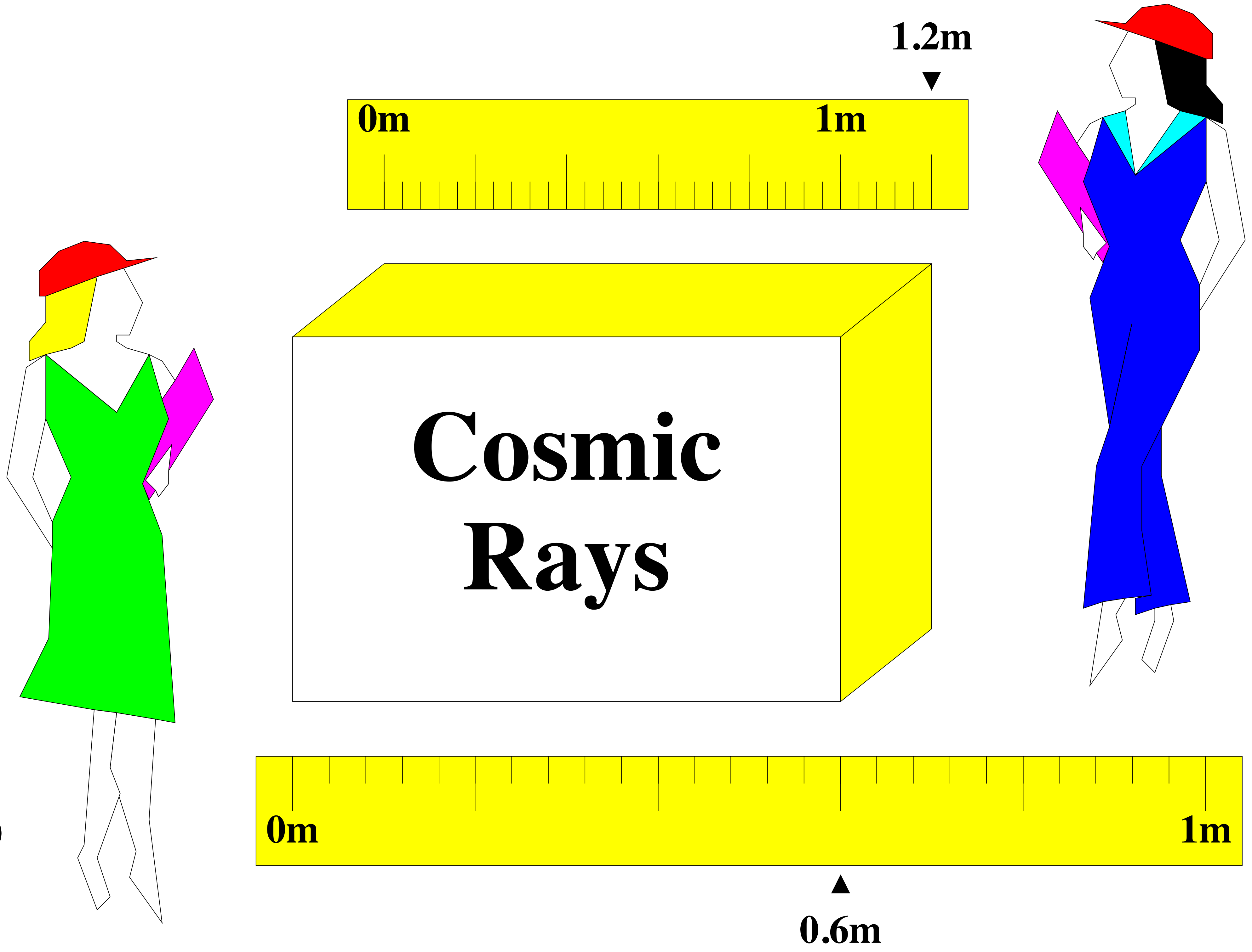
Institut für Kernphysik

KIT - Universität des Landes Baden-Württemberg und nationales Forschungszentrum in der Helmholtz-Gemeinschaft

Preface to KfK 4998 (1992)

Analysing experimental data on Extensive Air Showers (EAS) or planning corresponding experiments requires a detailed theoretical modelling of the cascade which develops when a high energy primary particle enters the atmosphere. This can only be achieved by detailed Monte Carlo calculations taking into account all knowledge of high energy strong and electromagnetic interactions. Therefore, a number of computer programs has been written to simulate the development of EAS in the atmosphere and a considerable number of publications exists discussing the results of such calculations. A common feature of all these publications is that it is difficult, if not impossible, to ascertain in detail which assumptions have been made in the programs for the interaction models, which approximations have been employed to reduce computer time, how experimental data have been converted into the unmeasured quantities required in the calculations (such as nucleus-nucleus cross sections, e.g.) etc.
This is the more embarrassing, since our knowledge of high energy interactions - though much better today than ten years ago - is still incomplete in important features. This makes results from different groups difficult to compare, to say the least. In addition, the relevant programs are of a considerable size which - as experience shows - makes programming errors almost unavoidable, in spite of all undoubted efforts of the authors. We therefore feel that further progress in the field of EAS simulation will only be achieved, if the groups engaged in this work make their programs available to (and, hence, checkable by) other colleagues. This procedure has been adopted in high energy physics and has proved to be very successful. It is in the spirit of these remarks that we describe in this report the physics underlying the CORSIKA program developed during the last years by a combined Bern-Bordeaux-Karlsruhe effort.
We also plan to publish a listing of the program as soon as some more checks of computational and programming details have been performed. We invite all colleagues interested in EAS simulation to propose improvements, point out errors or bring forward reservations concerning assumptions or approximations which we have made. We feel that this is a necessary next step to improve our understanding of EAS.

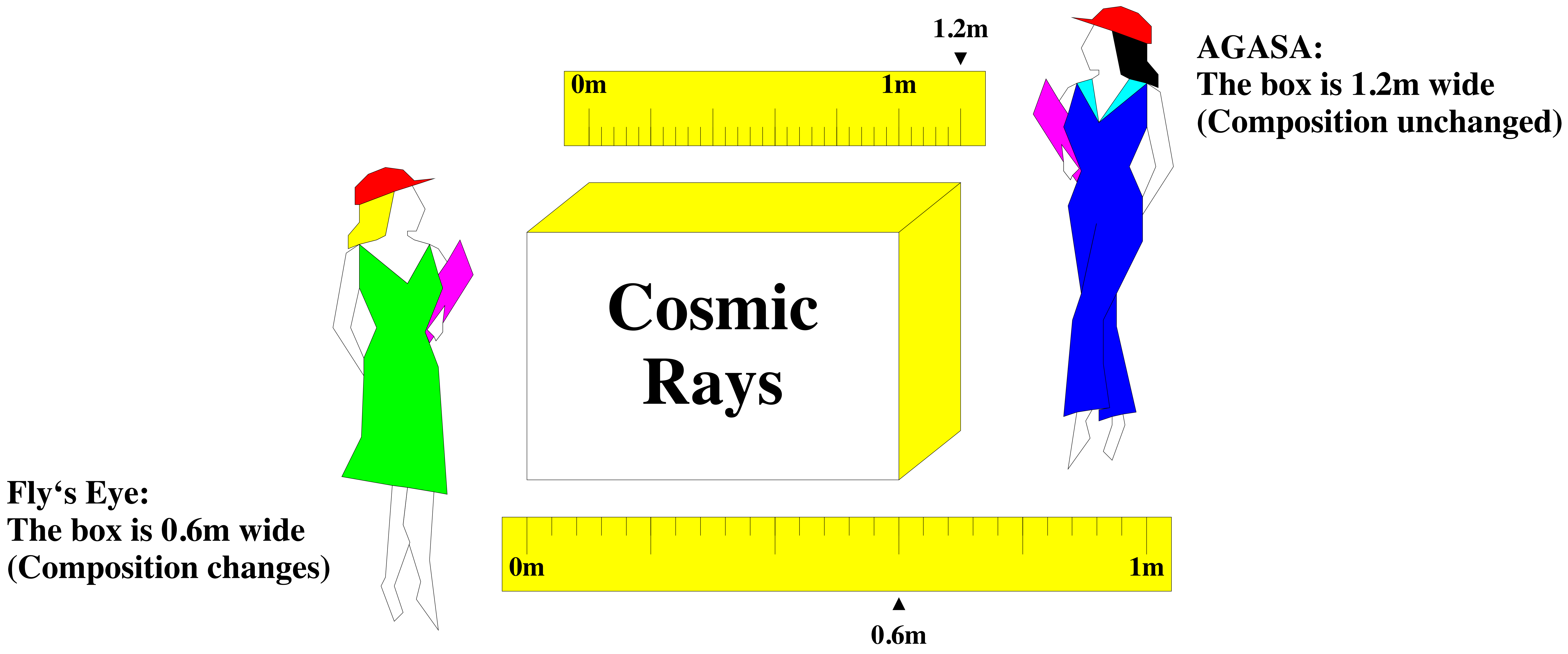
1997



AGASA:
The box is 1.2m wide
(Composition unchanged)

Fly's Eye:
The box is 0.6m wide
(Composition changes)

1997



Use the same yardstick (i.e. Monte Carlo program)
to get consistent results in different experiments.
Use a well-calibrated, reliable yardstick
to get correct results.

CORSIKA:

"as good as possible",
fully 4-dim.

tracking, decays, atmospheres, ...

* recommended
* based on Gribov-Regge theory
* source of systematic uncertainty

el.mag. EGS4 *

low-E.had.* FLUKA *
UrQMD
GHEISHA

high-E.had. ** QGSJET **
EPOS-LHC *
DPMJET *
SIBYLL

Tuned at collider energies, extrapolated to $>10^{20}$ eV

+ many extensions & simplifications

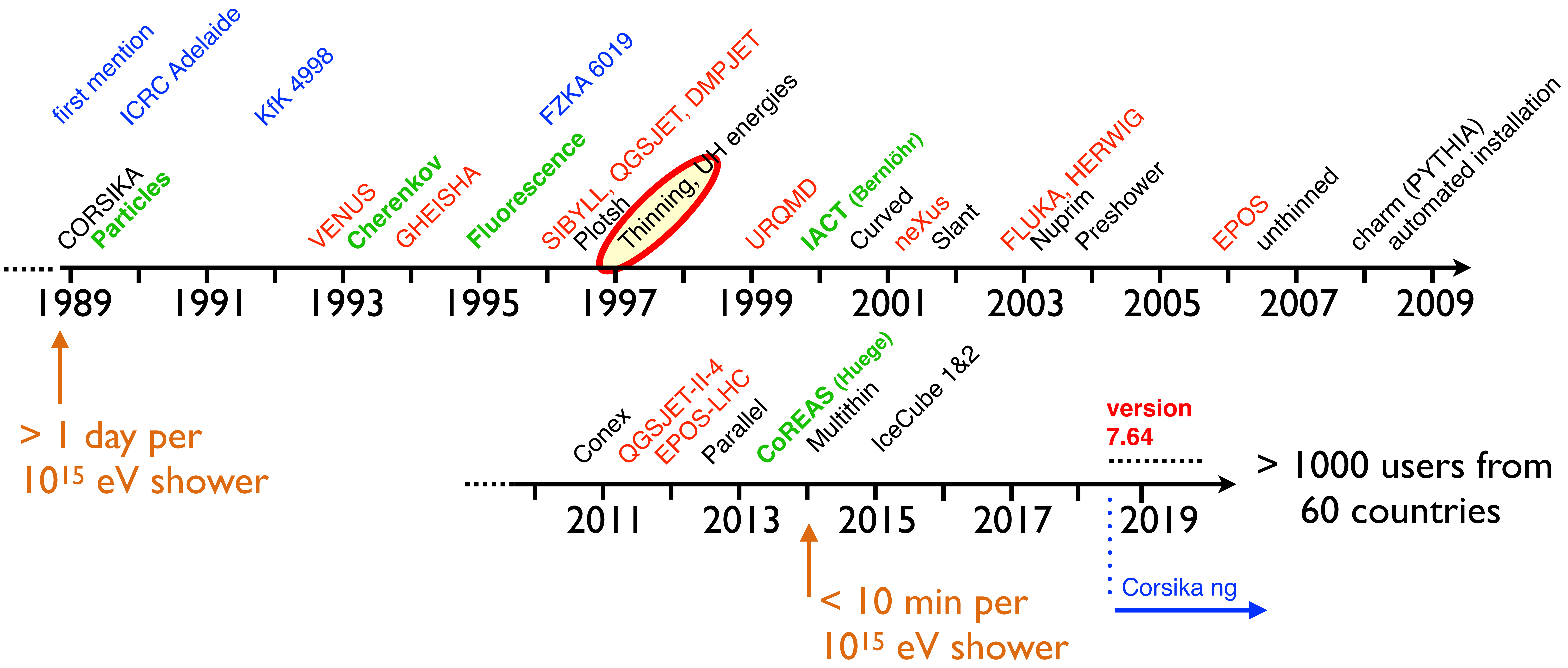
Sizes and runtimes vary by factors 2 - 40.

Total: >> 10^5 lines of code

many person-years of development.

https://www.ikp.kit.edu/corsika/

The Timeline



KfK 4998 + FZKA 6019 ~2300 citations

Google Scholar

by far the most cited work of its authors

(and more citations than all KASCADE papers together)

The Pierre Auger Observatory

Discrepancy between Fly's Eye and AGASA: Cut-off or not ??

1992: First ideas for the Pierre Auger Observatory
1995: 6-months design Workshop: What detectors? What layout? Which site?

Reliable Simulations were urgently needed for UHECR !!

Michael's MOCCA could simulate the UH energies, due to his statistical subsampling
"Thin Sampling" or "Hillas Thinning"

MOCCA was the main sim tool during the Auger Design Phase. ✔✔✔

(used by Jim Cronin, Clem Pryke)

Later:

Hillas Thinning was implemented in CORSIKA, hadronic models were extended to UH energies

A Fortran version of MOCCA was produced (AIRES, by Sergio Sciutto)

Hillas Thinning:

ICRC Paris 1981

1981ICRC....8..193H

T 5-13

TWO INTERESTING TECHNIQUES FOR MONTE-CARLO SIMULATION OF VERY HIGH ENERGY HADRON CASCADES

A. M. Hillas

Physics Department, University of Leeds, Leeds LS2 9JT, UK.

ABSTRACT

An "energy-splitting technique" is described, for simulating the energy spectra of pions produced in hadron collisions in the energy range in which radial scaling holds good. Spectra are generated in the laboratory system of reference, correspon-ding to a given analytic formula while conserving energy in the collisions.

A technique of "thin sampling" which allows pure Monte-Carlo techniques to be used to above 10^{19} eV without requiring greatly increased computer time is briefly outlined.

Hillas Thinning

That's the whole text on thinning in this paper!

4. "Thin sampling" for ultra-high-energy collisions

An extensive air shower may contain 10^8 muons: it does not seem necessary to follow every one of these in order to get a good picture of the shower. Good results have been obtained by selecting a "demarcation energy" D, perhaps $10^{-4} E_{prim}$, and following all particles of energy $E > D$, but only a fraction of particles with $E < D$. Below energy D, particles are subjected to a selection test when they are produced, such that they are only retained with a probability $p = E/D$, but each particle retained is given a "weight" $w = 1/p$, so if only 5% of the particles (of a particular energy) are followed, each one is counted as 20 particles when spectra and lateral distributions are tabulated. When such a particle of weight $w > 1$ itself interacts, its secondaries are retained with probability $p' = E/E_{collision}$, and each one retained is given a weight $w' = w/p'$. These rules satisfy the requirements that

(a) whenever a choice is made in which there is a probability p of retaining the particle, the weight of any retained particle is multiplied by $(1/p)$, (.. to conserve (weighted) particle numbers)

(b) the sum of ($w \times$ Energy) is equal to the energy that would be present if no particles were rejected, (.. so that (weighted) energy is exactly conserved, permitting checks to be made and minimising fluctuations introduced purely by the sampling process)

(c) particles produced in different generations of a cascade but with similar energies have similar weights (approx. D/E), to minimise spurious fluctuations,

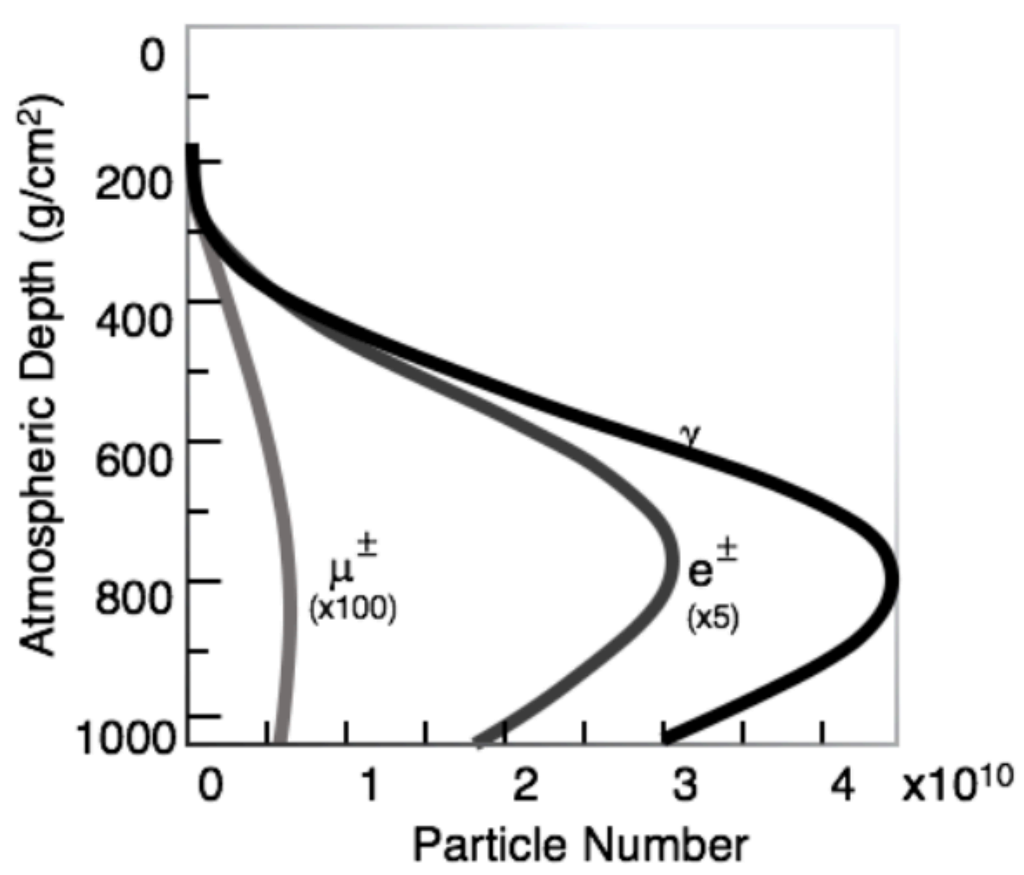
(d) the retention probability has no bias relating to particle type, direction or position.

The result is that the fraction of particles followed, at energies $E < D$, is approximately E/D. The number of particles followed in the cascade will then tend to rise only logarithmically with the total cascade energy, making it practicable to treat even the most energetic air showers.

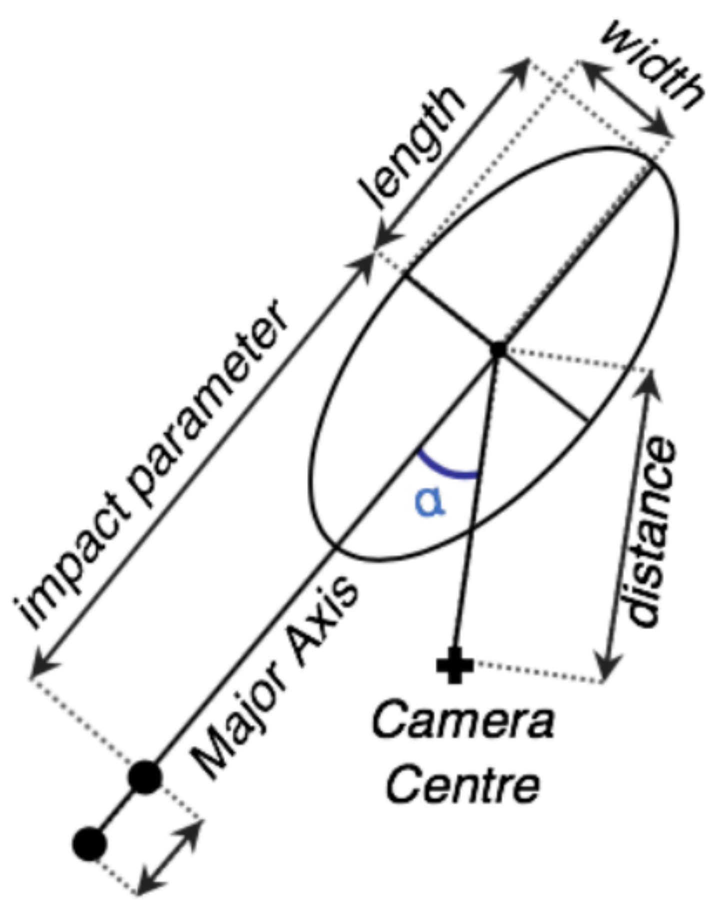
This technique has also been used for electromagnetic cascades.

… and the code was written in PASCAL

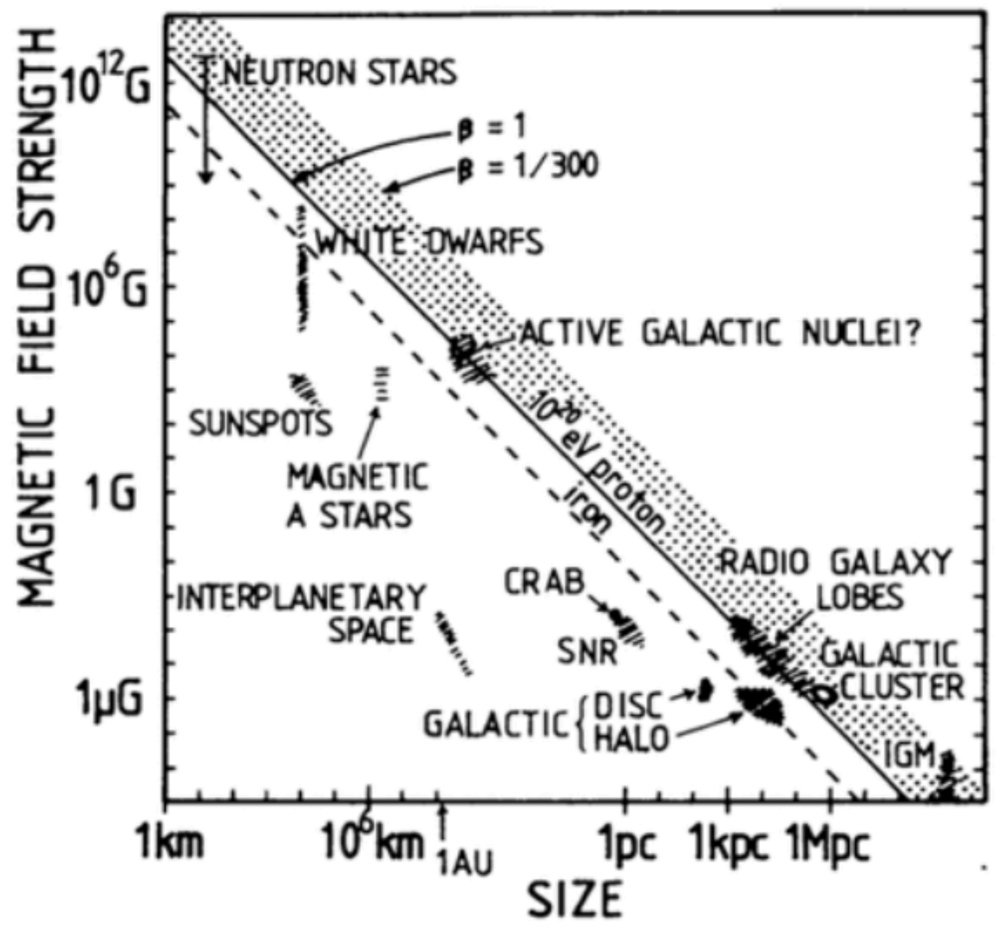
- advanced version of ALGOL 60
- educational; encourages good programming,
- easy to read and understand
- object oriented



Gaisser-**Hillas** curves

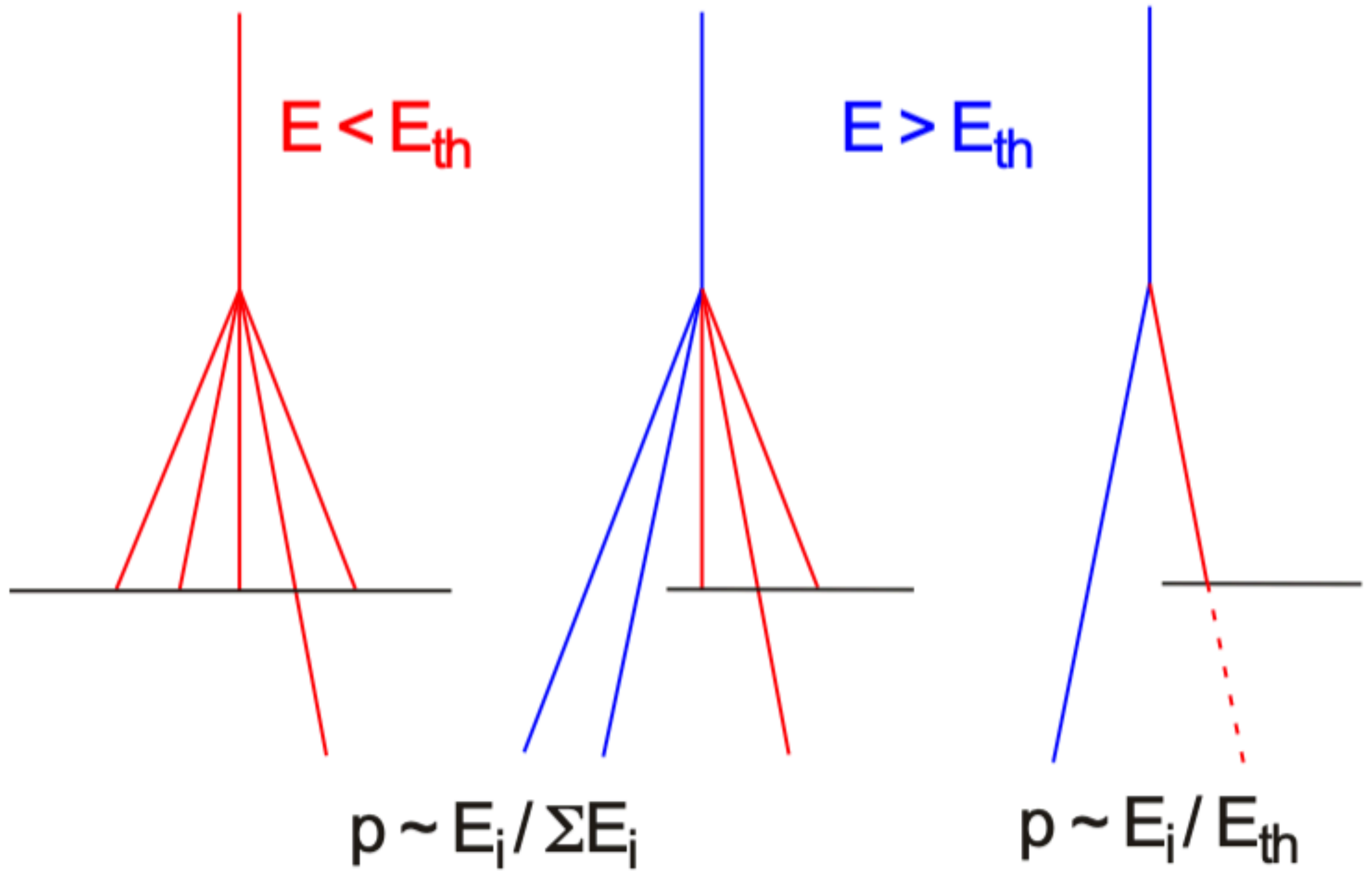


Hillas parameters



Hillas Plot

but also: **Hillas** thinning

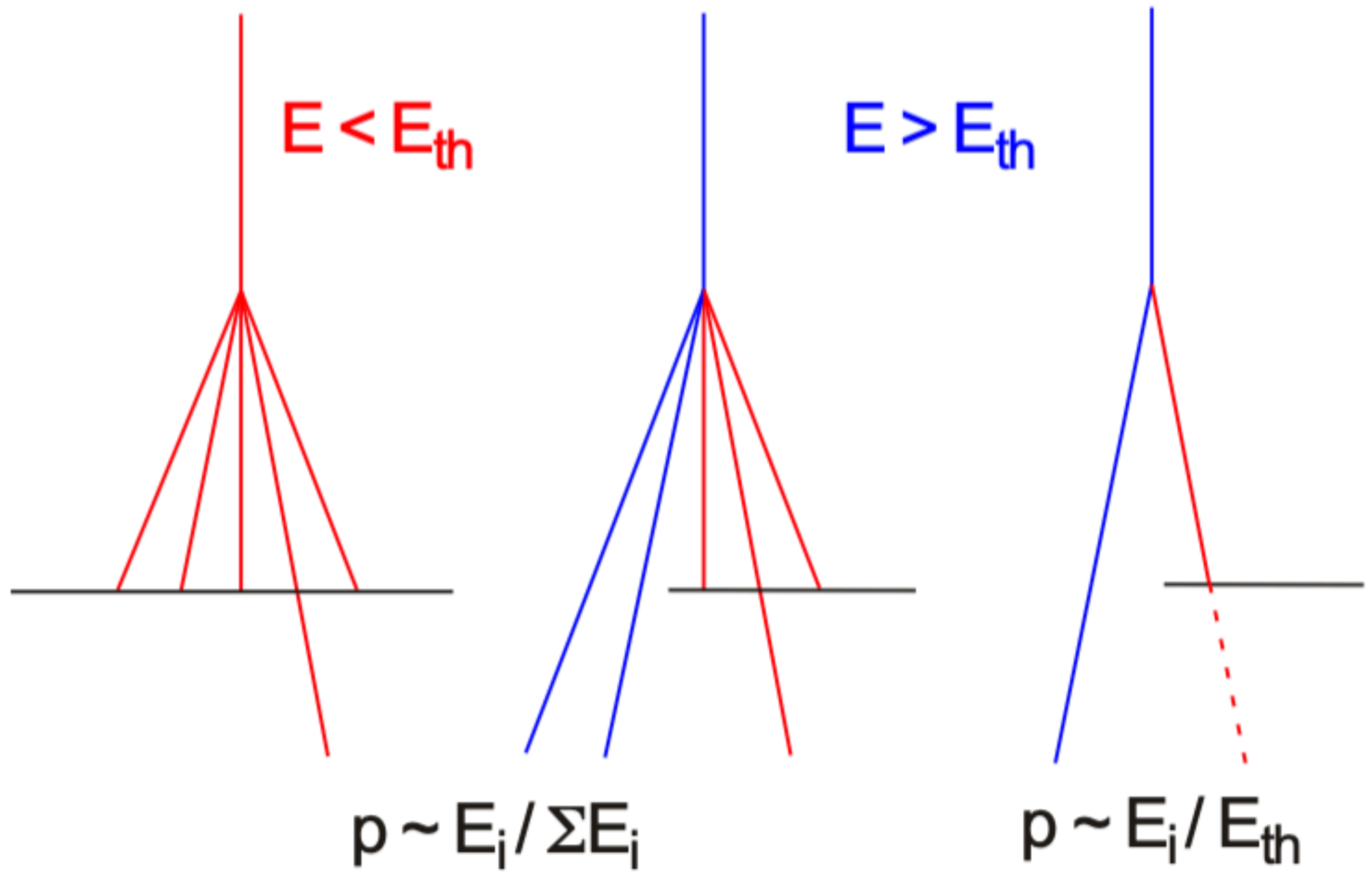


Simulation Speed-Up

Computing time $\approx$ 1h x E/10^{15} eV   Disk space $\approx$ 300 MB x E/10^{15} eV   per shower.

At 10^{20} eV: > 10^{11} secondaries, $\approx 10^5$ h = 11 years $\approx$ 30 TB

No way (no need?) to follow all particles.   Follow a statistical subsample: "thinning"



Hillas Thinning:

define a thinning threshold $E_{th} = E_0 \times \varepsilon_{th}$

e.g. 10^{-6}

The smaller ε_{th}, the better the shower is modelled.

$E > E_{th}$: follow every particle

$E < E_{th}$: follow only one (or few) but give it a weight w' = w / p to account for discarded particles

+ Energy is conserved
+ Number of particles of a species is conserved
+ Computing time and disk space largely reduced.

– Artificially enlarged fluctuations

What is the right thinning level ?

Longitudinal Development N(t): very many particles in the shower core,
can tolerate heavy thinning / large thinning levels (e.g. $E_{th} = 10^{-4}\, E_0$)

Particle far from shower core (e.g. S(r) for Auger): very many particles in the shower core,
small particle densities require very little thinning (e.g. $E_{th} < 10^{-7}\, E_0$)

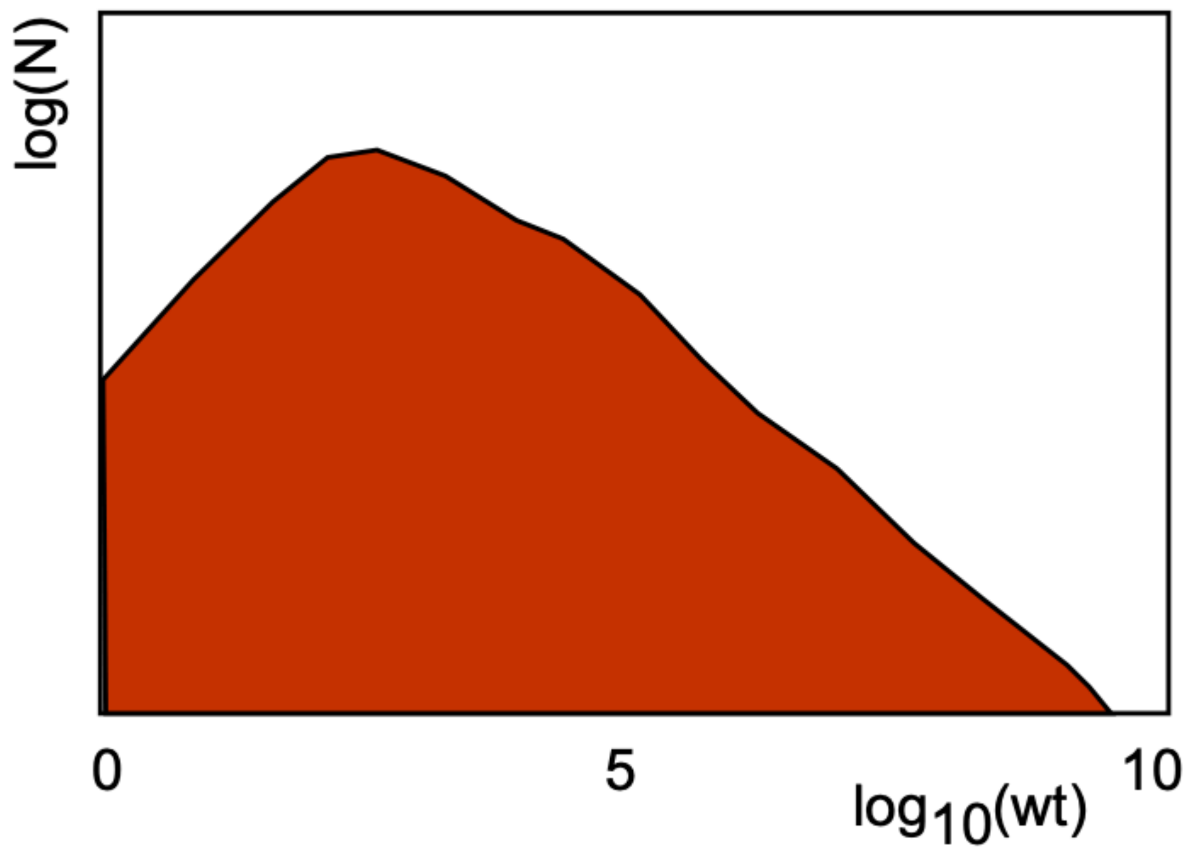
Artificial fluctuations due to thinning should be smaller than intrinsic shower fluctuations.

Computing time, disk space are largely reduced, but still grow proportional to E_0.

Particle weights can become rather large: $w_{max} = E_{th} / E_{min}$ **e.g.** $10^{20} \times 10^{-6} / 10^{5} = 10^{9}$

start end of thinning; (E_{min} = low energy cut-off)

High weights are problematic for subsequent detector simulations and analysis.
How to avoid them?



Weight limitation and optimum thinning

Set a maximum allowed weight, e.g. $w_{max} = 10^5$

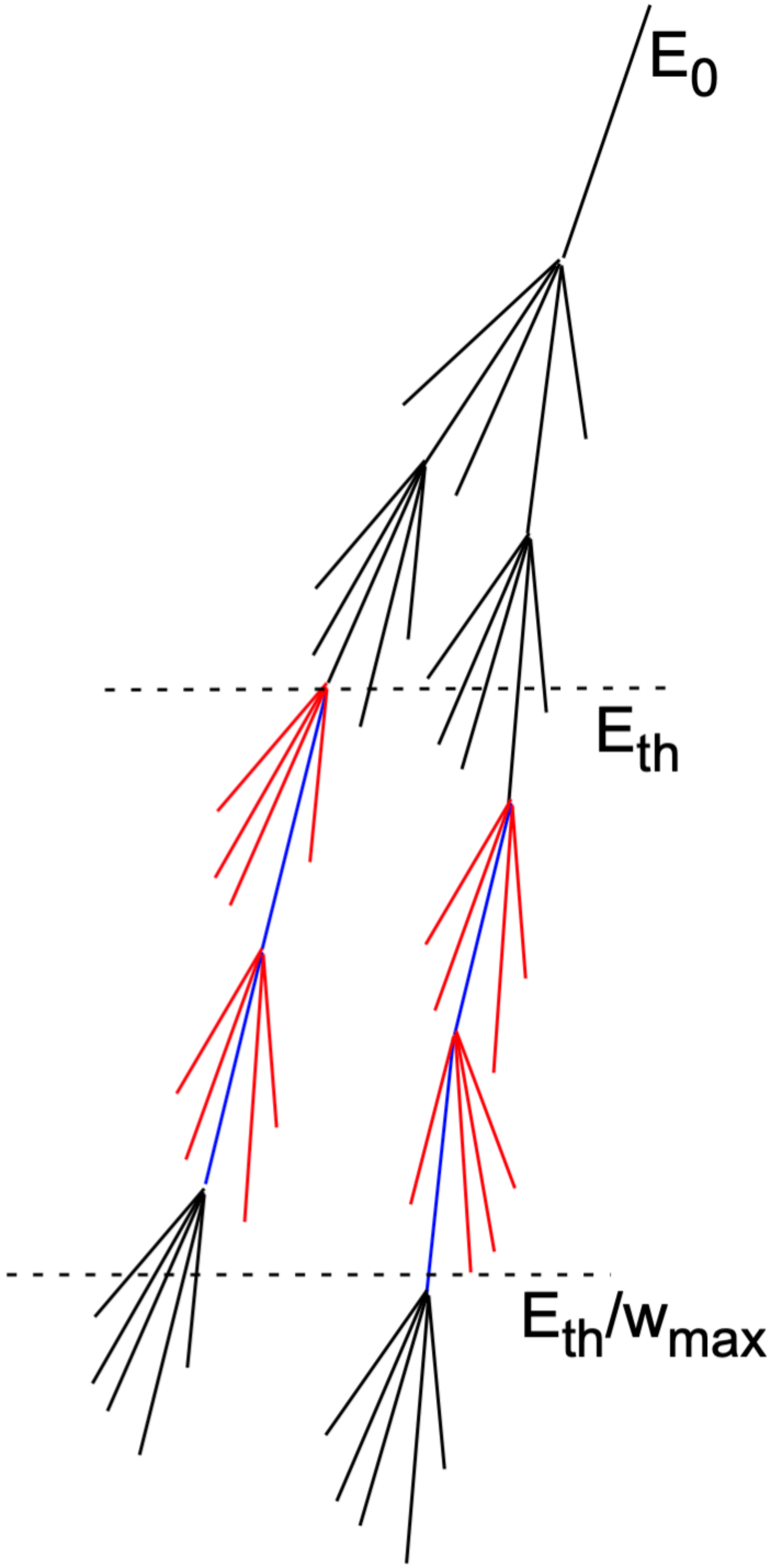
If weights get larger, follow all particles again.

Best setting: minimises statistical error for a given run time:

10^{18} eV	$\varepsilon_{th} = 10^{-6}$	$w_{max} = 10^3$
10^{19} eV	$\varepsilon_{th} = 10^{-6}$	$w_{max} = 10^4$
10^{20} eV	$\varepsilon_{th} = 10^{-6}$	$w_{max} = 10^5$

Run time depends now only on ε_{th}, no longer on E_0

10^{-5} "Optimum Thinning" is about as good as
10^{-7} "Thinning" without weight limitation.



In 1996:

CORSIKA (Fortran)	MOCCA (Pascal)	= MOnte Carlo CAscade successfully used for >15 years, (Haverah Park, SPASE, Whipple, …)
~7 MB	~0.4 MB	

Michael's thinning was introduced in CORSIKA in 1996
and kept basically unchanged since then.

Thanks to Moors's Law,
in 2005 the first un-thinned shower of 5×10^{18} eV was simulated.
(by running sub showers on many processors in parallel.)

Now, (few) unthinned showers at 10^{20} eV can be simulated.

But it's still unpractical for larger shower libraries.

Thus, thinning is still of paramount importance at the highest energies.

A true child of MOCCA:

AIRES

A system for air shower simulations

User's guide and reference manual

Version 2.2.0

S. J. Sciutto

Departamento de Física
Universidad Nacional de La Plata
C. C. 67 - 1900 La Plata
Argentina
`sciutto@fisica.unlp.edu.ar`

November 15, 1999

Summary

The present version of AIRES (2.2.0) represents a new release of the Air Shower Simulation System where many new features and algorithm improvements have been added to it. The most important additions are: An improved parameterization of the electron and positron continuous energy losses; a *resampling algorithm* complements the thinning to achieve important reduction of the output compressed files; and a new interface for processing special primary particles not directly propagated by AIRES internal engine.

It is important to mention that many of the algorithms for particle propagation included in the present release of the AIRES system are based on the corresponding procedures of the widely known **MOCCA** program developed by A. M. Hillas. MOCCA has been the primary reference used to develop the first version of AIRES (1.2.0, May 1997). As a consequence, results coming from this first version are concordant with MOCCA's output when invoked with similar initial conditions. Later versions of AIRES do include procedures independently developed and so a strict equivalence between both programs is no longer maintained.

ELSEVIER

Nuclear Physics B (Proc. Suppl.) 52B (1997) 29–42

NUCLEAR PHYSICS B
PROCEEDINGS
SUPPLEMENTS

Shower Simulation: Lessons from MOCCA

A.M. Hillas[a]

[a]Department of Physics and Astronomy, University of Leeds, Leeds, LS2 9JT, UK

The paper describes one approach to the Monte-Carlo simulation of extensive air showers of energy in the range 10^{12} to 10^{21} eV, using thin sampling for particles of energy much below the energy of the primary particle. Experience of this approach using the MOCCA program is outlined. Also, it is argued that only a few features of hadronic interactions are important in determining shower properties, and that the far plateau region of particle production is of little importance, and hence a simplified hadron interaction algorithm, as employed in MOCCA, is useful. Methods of demonstrating the contribution of different features of the interactions to observable aspects of showers are illustrated. The importance of secondary spectra from pion-air collisions in influencing the depth of maximum is highlighted.

The simulation program MOCCA (= MOnte Carlo CAscade) was developed to study such cascades, with the objectives of (a) following particles down to very low energies (well below 1 MeV) from an arbitrarily high primary energy, (b) avoiding the use of analytical expressions at large distances, (c) permitting changes in the calculation to be made readily - both to investigate the possible significance of features of very energetic interactions that are not yet well understood (in particular investigating to which apparently minor features the results were very sensitive and therefore uncertain), (d) in a short computing time – so that questions could be readily investigated by making several runs.

2. Thin Sampling

3. What details of hadronic interactions are "important"?

4. Representation of hadronic interactions in MOCCA-92

(i.e. The Hillas splitting algorithm)

The algorithm used in MOCCA to describe hadronic interactions appears absurdly simple in comparison with those described by many contributors to this meeting, and one cannot claim for it the same status or theoretical backing as these much more detailed treatments. So why give it any attention? There are three reasons.

1. **no good hadronic model yet,**
   only few feature are important
2. **Find the simplest model with adequate match to data**
3. **was used for earlier TeV and PeV analyses.**
   check its features and limitations.

MOCCA:

Emphasis on simplicity and flexibility, to gain insight and understanding.

rather than
a complicated “Black Box”

perhaps this aspect is somewhat lacking in CORSIKA

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Evolution of ground-based gamma-ray astronomy from the early days to the Cherenkov Telescope Arrays

… on the Cygnus X-3 hype (in the 1980s)

Several of the Cygnus X-3 reports seemed absurd…

many observations did not demonstrate an actual excess of counts from that direction, but only a periodic modulation …

A discussion by G. Chardin and G. Gerbier in 1989 of the statistical inconsistencies and underestimated effects of selection, re-scaling and special choices of orbital ephemeris concluded that

…. **none of the observations was statistically convincing.**

“When one considers the incredible 4.8-h periodicities extracted even in underground experiments, I am made to remember my Harwell mentor, T.E. Cranshaw, who once explained to me that a

physicist’s apparatus gradually learns what is expected of it.

This is the best explanation I know of for this episode (and happily convenient, blaming **the apparatus for a dog-like desire to please**).”

Also Michael’s simulations are a “physicist’s apparatus” that seemingly learned what was expected of it.

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But his great physical insight and intuition

- made him expect the right things,
- prevent him from going astray, and
- led him to his outstanding results.

Also Michael’s simulations are a “physicist’s apparatus” that seemingly learned what was expected of it.

But his great physical insight and intuition

- made him expect the right things,
- prevent him from going astray, and
- led him to his outstanding results.

Lessons to be learned:

aim for understanding the basic features of a system,
take your time to think.

Michael Hillas (1932-2017)

A kindly man he was,
who loved his work in physics.
A great scholar, teacher, gentleman,
An example to us all.