Happy 30th Anniversary

CORSIKA

Cosmic Ray Simulation for KASCADE

Happy 30th Anniversary

1989-2019

Cosmic Ray Simulation for KASCADE

CORSIKA & Particle Physics



J. Knapp CORSIKA Workshop Karlsruhe, June 2019







Astro-Particles

energetic (elementary) particles from space (Sun, Milky Way, distant galaxies) bombard Earth continuously.

Energies from MeV ... PeV ... > 10²⁰ eV 0.1–10 KASCADE range

Astrophysics: with high-energy photons and particles. Particle physics: with probes of astrophysical origin.

What are these cosmic particles?



- + can be accelerated in el.mag. fields
- are deflected in magnetic fields

+ move in straight lines

(good for astronomy)

- secondaries

What are these cosmic particles?





in general: for all particle types

the higher the energy, the lower the flux

the lower the flux, the larger the required detectors



Detector size limits the smallest measurable fluxes.

Large, natural volumes become part of the detectors:

atmosphere,

 $\bullet \bullet \bullet$

instrument (sparsely) to record secondaries produced by particle interactions

understand / monitor the "target"

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

 KASCADE
 10¹⁴-10¹⁶ eV

 KASCADE-Grande
 10¹⁴-10¹⁷ eV



primary particle: E, mass, θ , ϕ

indirect measurement: extensive air showers

transport in atmosphere, hadronic & electromagnetic interactions, detection of shower components

> Energy: Direction: Type:

shower size timing shower shape & particle contents

Schematic Shower Development



p, n, π : near shower axis

....

- μ , e, γ : more widely spread
- e, γ : from el.mag. cascades \approx 10 MeV
- μ : from π^{\pm} , K, decays \approx I GeV

Ne, γ : N $\mu \approx 10 - 100$ varying with core distance, energy, mass, Θ_{r} ...

Details depend on: hadronic and el.mag. particle production, cross-sections, decays, transport, at energies from ≈ 10⁶ ... >10²⁰ eV atmosphere, Earth magnetic field,

Complex interplay with many correlations

Energy Flow in EAS



Hadrons provide energy for muonic and electromagnetic components.
One Way Street for energy transfer into electromagnetic particles.
Details of energy transfer reactions do matter.

Unknown at high energies :

- astroparticle composition
- energy spectrum
- HE nuclear & hadronic interactions

an *impossible* problem??

i.e. CORSIKA

Construct a model based on reliable data & theories at lower energies.

Theory that allows extrapolation to cosmic ray energies.

Find consistent description of all issues together.

(Requires some iteration ...)

COsmic Ray Simulations for KAscade

Model shower development, detection, readout, analysis. Compare measurement and data.

The early beginnings

A new area for the institute after the demise of Nuclear Physics at FZKA.

- 1987 ICRC Moscow: Gerd Schatz gets infected with the Cosmic Ray virus ...
- 1988 preparatory work for an air shower array in Karlsruhe to measure **cosmic ray composition** and for simulation efforts begin...
- 1989 first publications ...

History : as noted down in the Changelog file of the CORSIKA distribution (no date, pre CORSIKA)

"A first version of the simulation program consisted of a program of P.K.F. Grieder for hadronic interactions at energies below 10 GeV, a dual parton model based routine (according J.N. Capdevielle) to simulate high energy hadronic interactions and the NKG formulas for treating gammas from pi 0 decays. The structure of the atmosphere was used in a parametrisation from J. Linsley. To allow for nucleus-nucleus and nucleon-nucleus collisions a simple model was applied based on nuclear densities.

This program (CTG58) was used to simulate a first set of data."

First official mention:

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.



pre 1989

SH2C-60-K-OSL-E-SPEC (Grieder):
main structure,
isobar model for hadronic interactionsthe frameHDPM & NKG (Capdevielle):
high-energy hadronic interactions,
analytic treatment of el.mag.-subshowershadronic
udronicEGS4 (Nelson et al.):
electron gamma showersel.mag.

CORSIKA Vers. I.0 Oct 1989

CORSIKA Version I

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С	DUAL PARTON MODEL ACCORDING TO J.N. CAPDEVIELLE, UNIVERSITY BORDEAUX													
С	EGS4 AND NKG FORMULAS FOR SIMULATION OF ELECTROMAGNETIC PARTICLES													
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22th ICRC, Adelaide, Jan 1990

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AIR SHOWER SIMULATIONS FOR KASCADE

J.N.Capdevielle¹, P.Gabriel, H.J.Gils, P.K.F.Grieder², 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 ¹Laboratoire de Physique Théorique, Université de Bordeaux, F-33170 Gradignan, France ²Physikalisches 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 $E_0 \ge 10^{15} \text{eV}$ can be determined by measuring electrons, muons and hadrons simultaneously with the KASCADE detector.

Forschungszentrum Karlsruhe Technik und Umwelt Wissenschaftliche Berichte FZKA 6019

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

CORSIKA: A Monte Carlo Code to Simulate Extensive Air Showers

D. Heck, J. Knapp, J. N. Capdevielle, G. Schatz, T. Thouw Institut für Kernphysik

Kernforschungszentrum Karlsruhe

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



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.

The Timeline



from Google Scholar:

CORSIKA: a Monte Carlo code to simulate extensive air showers

Authors Dieter Heck, G Schatz, J Knapp, T Thouw, JN Capdevielle

Publication date 1998

- Issue FZKA-6019
- Description CORSIKA is a program for detailed simulation of extensive air showers initiated by high energy cosmic ray particles. Protons, light nuclei up to iron, photons, and many other particles may be treated as primaries. The particles are tracked through the atmosphere until they undergo reactions with the air nuclei or-in the case of instable secondaries-decay. The hadronic interactions at high energies may be described by ve reaction models alternatively: The VENUS, QGSJET, and DPMJET models are based on the Gribov-Regge theory, while SIBYLL is a minijet model. HDPM is a phenomenological generator and adjusted to experimental data wherever possible. Hadronic interactions at lower energies are described either by the more sophisticated GHEISHA interaction routines or the rather simple ISOBAR model. In particle decays all decay branches down to the 1% level are taken into account. For electromagneti the ...

Total citations Cited by 2229



Scholar articles CORSIKA: a Monte Carlo code to simulate extensive air showers D Heck, G Schatz, J Knapp, T Thouw, JN Capdevielle - 1998 Cited by 1367 Related articles All 11 versions

> Upgrade of the Monte Carlo Code CORSIKA to Simulate Extensive Air Showers with Energie [more Than] 1020 EV ***** D Heck, J Knapp - 1998 Cited by 523 Related articles

Report FZKA 6019 (1998) * D Heck, J Knapp, JN Capdevielle, G Schatz, T Thouw - Forschungszentrum Karlsruhe, 1997 Cited by 230 Related articles

FZKA-report 6019 ***** D Heck, J Knapp, JN Capdevielle, G Schatz, T Thouw - Forschungszentrum Karlsruhe,

CORSIKA:

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

tracking, decays, atmospheres, ...

el.mag. EGS4 *

Iow-E.had.* FLUKA * UrQMD *

GHEISHA

high-E.had. ** QGSJET II-4 ** EPOS-LHC ** DPMJET * SIBYLL 2.3

+ many extensions & simplifications

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

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

Tuned at collider energies, extrapolated to > 10²⁰ eV

Sizes and runtimes vary by factors 2 - 40.

Total: >> 10⁵ lines of code

many person-years of development.

What was known then?

Hadron accelerators / colliders:	beam	cm energy			
Intersecting storage ring (ISR) Super proton synchrotron (SPS) Super proton-antiproton Synchrotron (SppS)	Cern Cern Cern	1971-1984 1976- 1981-1991	31 GeV 300400 GeV 100 - 450 GeV	62 GeV 600-800 GeV 200-900 GeV	colliding beams fixed target colliding beams
Tevatron (proton-antiproton)	Fermilab	1987-2011	900 GeV	I.8 TeV	colliding beams
Large hadron collider (LHC), pp	Cern	2009-	8 TeV	I 6 TeV	colliding beams

... cross sections, multiplicities (n_{ch}), p_T-distributions, pseudo-rapidities, ...

Cosmic Ray Projects in Karlsruhe:

KASCADE	1988-2009	10 ¹⁴ -10 ¹⁶ eV	450 GeV - 4.5 TeV
KASCADE Grande	2003-2009	10 ¹⁴ -10 ¹⁷ eV	450 GeV - 14 TeV
Pierre Auger Observatory	1996-	10 ¹⁸ -10 ²⁰ eV	45 TeV - 450 TeV

moderate – big extrapolation in energy and to small angles needed.

How to build an air shower model?

In General

- The detector medium: atmospheric composition, density as function of height
- 2. The beam: p, He, ... Fe, e, γ , ν , exotics ???
 - + all known particles (secondaries)
- 3. Particle Interactions:

cross sections and **particle production** for electromagnetic, weak and **nuclear & hadronic interactions**

4. Particle tracking in magnetic fields, ionisation, energy loss, Cherenkov light, multiple scattering, decays, absorption, ... crucial

In air showers

Projectiles:

p, He, ..., Fe, e, γ , ν + all known particles (secondaries)

Targets:

O, N, Ar in air

Energies:

MeV ... ZeV (all important)

Emission angle:

very forward, small angels to beam "soft interactions"

At accelerators

p, e, A

 \leq 8 TeV (coll. ~10¹⁷ eV) \leq 500 GeV for nuclei and mesons \approx TeV for A–A collisions at LHC

high p_T, large angles to beam "hard interactions" (QCD)

How to build an air shower model?

Hadronic interactions

- I. invent a model for p-p collisions
- 2. tune to reproduce experimental results
- 3. extrapolate to higher energies

add

- 4. diffractive processes
- 5. hard processes
- 6. p-N, π -N and N₁-N₂
- 7. nuclear physics
- 8. string fragmentation into hadrons

Problems arise mostly with 4.-8.

Agreement with p-N, π -N and N₁-N₂ data is usually worse

than with p-p data.

Difficulties for had. models for CRs

CR and HEP cover virtually exclusive kinematic regions.

CR models need predictive power for extrapolation to high energies, small angles and small Q² pure parametrisation likely fail when extrapolated.

Consistent calculation of

cross-sections and particle production in had. interactions

Consistent treatment of

soft, hard, diffractive interactions (no artificial boundaries) all sorts of hadrons and nuclei with nucleons and nuclei over the whole CR energy range from MeV to ZeV

1989:

hadronic models were: rudimentary, qualitative, phenomenological

.... a few examples ...

Electromagnetic Showers: from Toy Model to EGS4



Both reactions have the same scale length (X₀) and have two outgoing particles per incoming particle. Toy Model (one-dimensional, very simplified, yet qualitatively correct):



particle multiplication (x2) in each step (X₀) until $E < E_{crit}$, then particle losses due to ionisation dominant.

$$k = k X_0, \quad k = 1, 2, ...$$

 $N = 2^k \quad E = E_0 / N$

 $k_{max}: = E_0 / 2^{kmax} = E_{crit} \qquad k_{max} = \ln(E_0 / E_{crit}) / \ln(2)$ grows only logarithmically with E_0

$$t_{max} = k_{max} \cdot X_0$$

 $N_{max} = E_0 / E_{crit}$
Measure t_{max} or N_{max}
and estimate E_0 .

Nishimura Kamata Greisen (NKG): Longitudinal Shower Development

analytic description of purely electromagnetic showers:

$$N_{e} = \frac{0.31 \exp(t (1-1.5 \ln s))}{\sqrt{\ln(E_{0}/E_{crit})}} \qquad s = \frac{3t}{t+2 \ln(E_{0}/E_{crit})}$$



Nishimura Kamata Greisen: lateral shower development

purely electromagnetic showers:



$$f_{mol} = X_0 E_s / E_{crit}$$

~ 9.6 g/cm²
~ 78 m at sea level

$$E_{s} = m_{e}c^{2} (4p/a)^{1/2} \sim 21 \text{ MeV}$$

A cylinder around the shower axis with radius rmol contains 90% of the

NKG formalism allows a fast, semi-analytical simulation of electromagnetic sub-showers.

.... but again no fluctuations

A simple hadronic interaction model: the Hillas Splitting Algorithm



```
Originally used in MOCCA: (produces only pions as secondaries)
x, x' uniformly distributed between 0 .... 1
N = 2
```

very símple, very fast, but gíves only a qualitative description of hadronic shower.

A simple example : HDPM ... based on the dual parton mode

Collísíon with colour exchange forms two colour strings which fragment into jets of observable hadrons.

Hadrons from each string form a Gaussian in rapidity space. Parametrize position y_j and width σ as function of Eto reproduce p-p non-diffractive results.

(+ extrapolate S_{tot}

put ín p_{T} , π :K:N, charged/neutral, add 3rd Gaussían for nucleus ín p-A, A-A: superposítíon of índependent p-A collísíons, add díffractíon ...)

ad hoc, Lots of free parameters, no predictive power

Rapidity:

 $y = \frac{1}{2} \ln \frac{E+p_L}{E-p_L}$

Pseudorapidity:

 $\eta = \frac{1}{2} \ln \frac{p + p_L}{p - p_L}$ $\eta = -\ln (\tan(\theta/2))$

η ~ y for high energies (or zero mass) (Pseudo)rapidity

is additive in Lorentz transformation.

dN/dy σ Уi Rapidity y

Fully 4-dim simulation with EGS

of electromagnetic showers in air

Electron Gamma Shower Code Nelson et al. ~1970

ALL processes of electrons and gammas are included.

e: bremsstrahlung,

ionisation, ∂ -electrons, Bhabha & Møller scattering, multiple scattering, annihilation, ...

γ : e⁺e⁻ pair production,

Compton effect, photo effect, Rayleigh scattering, ...

based on QED calculations and is very well checked and verified. EGS gives precise predictions of all sorts of electromagnetic interactions in materials. Important for nuclear radiation calculations, nuclear medicine.

CORSIKA: **EGS 4 (1995)**

Extended by LPM effect (> TeV in dense materials; > 10¹⁸ eV in atmosphere)

EGS 5 2005 maintained by SLAC / KEK collab. http://rcwww.kek.jp/research/egs/egs5.html Theoretical guidelines for soft interactions ?

Yes: Gribov-Regge Theory (GRT) of multi-Pomeron exchange (a relativistic quantum field theory)

successful for elastic scattering total cross-sections

extension to particle production: some uncertainties, relatively few free parameters. seems to work fine up to highest energies.

GRT is the **best theoretical model** we have at the moment for soft hadronic interactions important in air showers.



e.g.

Physics Reports

Volume 232, Issues 2–5, September 1993, Pages 87-299

Strings, pomerons and the VENUS model of hadronic interactions at ultrarelativistic energies * **

K Werner ¹ ⊠

∃ Show more

https://doi.org/10.1016/0370-1573(93)90078-R

Get rights and content

IVSICS REPORT

... a detailed account of hadronic interactions and its implementation in the VENUS code.
(210 pages) Much more complete description of the complex interactions of nucleons and nuclei.

Multiple interactions of multiple nucleons in projectile and target. strings forming, interacting and fragmenting, very time consuming, only possible to simulate with fast modern computers.

Resulting in ...

- Considerable convergence of models since 1990
- Simulations with hadronic interaction models
 - based on Gribov-Regge Theory (very few free parameters)
 - more / better accelerator data
 - more coherent treatment of different interaction types,
- produce showers that look very much like real ones,
 i.e. CORSIKA is not (yet) perfect, but also not far off the truth
- Convergence also with models for soft interactions in particle physics.

Current situation:

Three main had. interaction models are still maintained: (in CORSIKA v 7.69) EPOS LHC QGSJET II 04 Sibyll 2.3

Reasonably good description of inclusive shower observables.

New accelerator data started major new activities in hadronic interaction modelling.

Some shortfalls in reproducing correlations (rel. for CR composition studies) Still mysterious:

Muon production

 X_{max} behaviour not really understood.



Advances in Space Research Available online 12 June 2019 In Press, Accepted Manuscript (?)



High energy interactions of cosmic rays

Sergey Ostapchenko ⊠

E Show more

https://doi.org/10.1016/j.asr.2019.05.050

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Abstract

A discussion of a number of important topics related to modeling of high energy cosmic ray interactions is presented. Special attention is devoted to novel theoretical approaches employed in event generators of hadronic interactions and to the impact of experimental data from the Large Hadron Collider (LHC). In relation to studies of ultra-high energy cosmic rays (UHECRs), differences between various predictions for basic characteristics of UHECR-induced extensive air showers in the atmosphere are analyzed and traced down to differences in the respective treatments of hadronic interactions. Possibilities to discriminate between the alternative approaches, based on LHC and UHECR data, are demonstrated and the relation to UHECR primary composition is outlined. Finally, in relation to direct studies of charged cosmic rays, potential improvements of the treatment of cosmic ray interactions at low and intermediate energies are discussed.

suggests how to reach a coherent picture of UHECR composition:

muon excess, X_{max} vs $\sigma(X_{max})$ mismatch



- Shower simulations are indispensable in high-energy astroparticle physics
- CORSIKA & had. models are approximately correct (and still improving)
- Accelerator data are valuable input
- Tremendous progress in the last 30 years

2019: hadronic models are now: relatively complete, quantitative, theory-based CORSIKA 7.69 is a good starting point for further progress & improvements

Good luck and a long breath for the CORSIKA 8 effort.

CORSIKA: is a well-established "brand"



About 233.000 results (0,56 seconds)

KIT - CORSIKA - Startseite - KIT - IKP

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

CORSIKA (COsmic Ray SImulations for KAscade) is a program for detailed simulation of extensive air showers initiated by high energy cosmic ray particles. You've visited this page 4 times. Last visit: 10/28/18

Documentation

CORSIKA Physics Description. CORSIKA: A Monte Carlo Code ...

Downloads

CORSIKA is available to every scientist free of charge. Please ...

More results from kit.edu »

Visualizations

These shower movies have been established from CORSIKA ...

CORSIKA Schools CORSIKA Schools. ISAPP SCHOOL 2018 Website. LHC ...

CORSIKA Computer software

CORSIKA is a physics computer software for simulation of extensive air showers induced by high energy cosmic rays. It may be used up to and beyond the highest energies of 100 EeV. Wikipedia

<

Available in: Fortran

License: CORSIKA is available to every scientist free of charge (more)

Feedback

[PDF] CORSIKA: A Monte Carlo Code to Simulate Extensive Air Showers

https://publikationen.bibliothek.kit.edu/270043064/3813660

CORSIKA is a program for detailed simulation of extensive air showers initiated by high energy cosmic ray particles. Protons, light nuclei up to iron, photons, and.

CORSIKA - Wikipedia

https://en.wikipedia.org/wiki/CORSIKA -

CORSIKA (COsmic Ray SImulations for KAscade) is a physics computer software for simulation of extensive air showers induced by high energy cosmic rays. It may be used up to and beyond the highest energies of 100 EeV.

Corsika

https://www-zeuthen.desy.de/~jknapp/JK/Corsika.html ▼

Air Shower Simulations With CORSIKA: The CORSIKA program is a versatile tool to simulate in detail

the development of extensive air showers in the ...

CORSICA: also a strong "brand", to compete with...



CORSICA

Images

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About 82.700.000 results (0,62 seconds)

Top things to do in Corsica





Corsica travel guide

Scandola Nature Reserve Nature reserve with



Cap Corse Beach, hiking, fishing, and camping

Lavezzi archipelago

Nature reserve, snorkeling, cliff, and

People also ask	
Is Corsica part of Italy?	~
What language is spoken in Corsica?	~
What country is Corsica in?	~
Is Corsica dangerous for tourists?	~
	Feedback



Corsica

French Region

Corsica, a mountainous Mediterranean island, presents a mix of stylish coastal towns, dense forest and craggy peaks (Monte Cinto is the highest). Nearly half the island falls within a park whose hiking trails include the challenging GR 20. Its beaches range from busy Pietracorbara to remote Saleccia and Rondinara. It's been part of France since 1768, but retains a distinct Italian culture.

Official languages: French

Capital: Ajaccio

Population: 339,178 (2019) INSEE

Plan a trip



3-star hotel averaging €114, 5-star averaging €428

1 h 25 min flight, from €314 \mathbf{T}

Corsica - Wikipedia

https://en.wikipedia.org/wiki/Corsica -

stay with CORSIKA ! (keep the brand)

COsmic Ray Simulation Kit for Astroparticle showers Air Showers

. . . .

Avalanches

of King-sized Avalanches Air showers is Key for Astroparticle physics

... a prize for the best solution?