Air Shower Simulations with CORSIKA.

The first 30 years

ISAPP School 2018
LHC meets Cosmic Rays

Johannes Knapp, DESY Zeuthen
Energy scale:

meV ... eV ... keV ... MeV ... GeV ... TeV ... PeV ... EeV ... ZeV

$10^{-3} ... 1 \ldots 10^3 \ldots 10^6 \ldots 10^9 \ldots 10^{12} \ldots 10^{15} \ldots 10^{18} \ldots 10^{21} eV$

Photons: astronomy (Light)

charged: p, He, .... Fe, ... completely ionised nuclei electrons

Neutrinos:

the range of astroparticle physics

non-thermal processes

radio IR visible light UV X rays Y rays
Cosmic rays, gamma rays and neutrinos come likely from the same sources

only charged particles can be accelerated in el.mag. fields

B, inv. Compton

reactions with fields, gas, dust

p, He, ... Fe e

π±

π0

μ± + νμ
e± + νe + νμ
gγ
difficult to detect
easy to detect

“multi-messenger astrophysics”

but gamma rays are currently the most “productive” messengers.

γ,ν

point back to sources (good for astronomy) but serious backgrounds
primary particle:  $E$, Typ, $\theta$, $\varphi$

The only detection technique for high energy particles (low fluxes).

Indirect measurement: extensive air showers

Measure the shower to identify the primary

Energy: shower size
Direction: arrival timing
Type: shower shape & particle contents
needed in all experiments where showers of astroparticles are measured:

**gamma rays** \((E \geq 50 \text{ GeV})\) \text{ in air}  

distinguish \(\gamma\)s from hadrons (cosmic rays)

**cosmic rays** \((E \geq 1 \text{ TeV})\) \text{ in air}  

distinguish p, He, O, … Fe, \(\gamma\), electrons

**neutrinos** \((E \geq 10 \text{ TeV})\) \text{ in air, ice, water, earth}  

distinguish neutrinos from penetrating muons and identify \(\nu_e, \nu_\mu, \nu_\tau\)  

and measure energy and direction of primary particle.
many inter-dependent sub-processes (from $10^6 \ldots >10^{20}$ eV) to form one large and complex process: Extensive Air Showers

with:
- dependencies of observables on $E, \theta, r, \ldots$
- correlations between them,
- statistical fluctuations,
- ....

(similarly: simulation for detector, electronics, trigger, readout, & reconstruction)
A shower of $10^{20}$ eV contains:

$\sim 10$ sub-showers of $10^{19}$ eV

$\ldots$

$\sim 10^6$ sub-showers of 100 TeV

$\ldots$

$\sim 10^{11}$ sub-showers of 1 GeV

A **correct** shower model reproduces experimental data for **all** primaries and energies, at **all** altitudes and zenith angles.
Simulation:

“*Imitating the behaviour* of some situation or process by means of a suitably analogous situation or apparatus”
(e.g. with a computer program)

Model:

“A *simplified or idealised* description or conception of a particular system, situation, or process, as a basis for theoretical or empirical understanding, or for calculations, predictions, etc.;

*A conceptual* representation of something.”
Simulation:

Large and complex problems can usually be broken down in smaller and simpler, but inter-dependent, sub-problems.

Simulation is the **numerical convolution** of many individual, but inter-dependent, parts to a greater and more complex whole.

(“do on the computer what nature does”)

If the sub-processes are known in **all** details,
then the simulation produces the **correct** result,
with all **correlations, biases, selection effects ....**
even with new features emerging from the complex interplay of the various sub-processes.

**e.g.**

Sims (on computer) are cheaper than real crashes, but initially real crashes are needed to test whether sims are correct (good enough)
Models:

simplified, conceptual

If not all details are known (i.e. most common case), or it is impractical to do a full simulation,
then Models of reality are used (i.e. simplifications, assumptions, approximations, ...)

but simplifications come at a cost:
The more simplification - the easier to obtain a result, but
- the smaller the “confidence level”
- the more verification is needed

crucial: Is the model good enough (for the specific purpose) ?
When do simplifications start to affect the results ?

e.g.
assume: well-known velocity, no air resistance,
then: trajectories are parabolas, easy to calculate
In Practice

> the precise and complete simulation of a complex problem may be impossible (or at least very difficult / costly).

> Usually, “Simulation” and “Model” are mixed in various degrees find a good compromise:

The complexity of the simulation should reflect the complexity of the problem.

> interplay between sub-parts (and emergence) still qualitatively correct, even if some of the ingredients are not right.

> statistical nature of particle interactions and transport makes Monte-Carlo simulations (with random numbers) the tool of choice.

(The names “Simulation” and “Model” are often wrongly used synonymously.)
CORSIKA

Cosmic Ray Simulation for KASCADE

KASCADE: an experiment to measure cosmic ray composition in Karlsruhe (Germany)
first ideas: 1987, first data ~1997,
KASCADE-Grande ~2003
end data taking 2009
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 m² hadron calorimeter
underground muon detectors
energy range: $10^{14}$ - $10^{16}$ eV

primary particle: $E$, Typ, $\theta$, $\varphi$
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

CORSIKA  Vers. 1.0        Oct 1989
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

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and

A. MERKEL


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

AIR SHOWER SIMULATIONS FOR KASCADE


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Abstract

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

Institut für Kernphysik

Kernforschungszentrum Karlsruhe

November 1992

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 1996
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

User's Manual (continuously updated)
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.
Fly's Eye:
The box is 0.6m wide
(Composition changes)

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

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

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

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, ...

el.mag.  EGS4 *
low-E.had.*  FLUKA *
           UrQMD
           GHEISHA
high-E.had.  **  QGSJET **
            EPOS-LHC *
            DPMJET *
            SIBYLL

+ many extensions & simplifications

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

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

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/
KfK 4998 + FZKA 6019
~2300 citations
by far the most cited work of its authors
(by more citations than all KASCADE papers together)

Google Scholar
ICRC Adelaide
KfK 4998
First mention
1 day per 10^15 eV shower
< 10 min per 10^15 eV shower

Particles
GHEISHA
VENUS
Cherenkov
Fluorescence

SIBYLL, QGSJET, DMPJET
Preshower

IACT (Bernlöhr)
Curved neXus

FLUKA, HERWIG
Preshower

Multithin

Thinning, UH energies

Conex
QGSJET-II-4
EPOS-LHC
Parallel

CoREAS (Huege)
Mulithin
IceCube 1&2

EPOS
unthinned

charm (PYTHIA)

automated installation

> 1000 users from 60 countries

> 2017

version 7.64

IceCube 1&2

conex
QGSJET-II-4
Parallel

2019

EPOS
unthinned

charm (PYTHIA)

automated installation

> 1000 users from 60 countries
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 unstable 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 electromagnets the ...

Total citations  Cited by 2294

Scholar articles

CORSIKA: A Monte Carlo code to simulate extensive air showers
Cited by 1284  Related articles  All 11 versions

report FZKA 6019 *
Cited by 458  Related articles

Upgrade of the Monte Carlo code CORSIKA to simulate extensive air showers with energies> 10** 20-eV *
D Heck, J Knapp - 1998
Cited by 417  Related articles  All 3 versions

Report FZKA 6019 (1998) *
Cited by 229  Related articles

100/yr (av.)
CORSIKA flow diagram

Initialization of shower

Where is next interaction or decay?

Steering cards: ID, E, θ,ϕ
sim. parameters
random numbers
Cross sections
for had & em
interactions
atm parameters

internal particle stack

get first particle
or next particle
from stack

apply cuts,
put secondaries
onto stack

decays

interactions

passed
observation level?

tracking to int. point:
multiple scattering
energy loss
defl. in mag field
Cherenkov light

QGSjet
SIBYLL
DPMJET
neXus
...

Gheisha2002
FLUKA
UQMD
...

EGS4
NKG
...

El.mag.

Particle output
Examples of emerging features in detailed simulations:

Cherenkov light:

- gamma 300 GeV
- proton 90 GeV
- iron 50 GeV
asymmetric due to air density gradient
Signal and Timing as function of $\theta$, $\phi$, mass, ... - change in a complex way, - are correlated, and this is important for analysis

This behaviour and correlations emerge automatically, qualitatively and quantitatively, as consequence of convolution of basic transport & interaction processes of particles in an air shower.

Many such effects in EAS physics. Therefore:

detailed simulation (rather than simplified modelling)
are so important.
Simulations vs Data:

Result: fair agreement from $10^{12} - 10^{20}$ eV

Simulated showers look very much like measured ones.
– Considerable convergence of models since 1990

– Simulations with hadronic interaction models

- based on Gribov-Regge Theory
- tuned to accelerator data (mainly pp, pA, < TeV)
- extrapolated to all energies $10^6$ .... $>10^{20}$ eV ...
  all particles p, n, nuclei, π, K, Λ, ...
  heavy mesons, baryons ....

produce showers that look very much like real ones,

i.e. CORSIKA is not far off the truth.

(uncertainties < 30% for most observables)
– Considerable convergence of models since 1990

– Simulations with hadronic interaction models
  - based on Gribov-Regge Theory
  - tuned to accelerator data (mainly pp, pA, < TeV)
  - extrapolated to all energies $10^6 \ldots >10^{20}$ eV ...
    all particles p, n, nuclei, $\pi$, K, $\Lambda$, ...
    heavy mesons, baryons ....

produce showers that look very much like real ones,
i.e. CORSIKA is not far off the truth.
(uncertainties < 30% for most observables)

– much better agreement at lower energies
  (where collider data constrain extrapolations)

– for highest energies ($>10^{18}$ eV)
  considerable extrapolation beyond collider data is needed.
Without firm theoretical guidelines as to how
to extrapolate, uncertainties are exploding.
Pure phenomenology is not good enough.
Current limitations:

\[ X_{\text{max}} \quad \text{Auger: composition} \]

\[ \text{RMS}(X_{\text{max}}) \]

Model dependent interpretation

If one trusts the models, then composition turns heavier

(but the two plots are not consistent)

\((10^{19} \text{ eV} < E < 4 \times 10^{19} \text{ eV})\)
Composition data: transition to heavier primaries

\[
\langle X_{\text{max}} \rangle \approx \langle X_{\text{max}}^p \rangle - D_p \langle \ln A \rangle
\]

\[
\sigma(X_{\text{max}})^2 \approx \langle \sigma_i^2 \rangle + D_p^2 \sigma(\ln A)^2
\]

\(\langle \ln A \rangle\): Transition from medium → light → heavy

\(\sigma(\ln A)\): Transition from proton dominated or mixed → approx. pure

Differences between models, inconsistencies between \(\langle \ln A \rangle\) and \(\sigma(\ln A)\)
Are the EAS models right?

- Match the long. shower profile (as seen in FD) of a measured event with p and Fe simulations.
- Models underestimate ground signal by 1.5 - 2x.
- Same simulated events have less signal in SD than the measured ones.
- \( \mu \) content rises with \( \theta \).
where varying amounts of energy being transferred to the EM and

In addition, the maximum-likelihood fit is also performed for this analysis. The variance in the contributions to the 411, which are observed with two FD eyes whose initiated showers and 4% for iron initiated showers.

to the uncertainty in the calorimetric energy measurement, and iii) the uncertainty in the ground signal for a given LP, to limitations in reconstructing and simulating the shower, in independent of composition.

The signal size is determined by calculating the variance in the signal as a function of zenith angle, for stations at 1 km from the shower core, in simulated 10 EeV proton air showers. It is illustrated for QGSJET-II-04. The signal size is measured in units of vertical equivalent muons (VEM), the calibrated unit of SD signal size.

The resultant model of the 411, which is observed with two FD eyes whose initiated showers and 4% for iron initiated showers.

The systematic uncertainties in the event reconstruction, is the extension of the analysis by shifting the reconstructed central values by their sigma statistical uncertainty region in the simulations. The ellipses show the one-sigma statistical uncertainties, for the journal version of this analysis.

The values of the uncertainties as described in the text; these will be refined in a journal version of this analysis.

The best-fit values of the systematic uncertainties in the event reconstruction, is the extension of the analysis by shifting the reconstructed central values by their sigma statistical uncertainty region in the simulations. The ellipses show the one-sigma statistical uncertainties, for the journal version of this analysis.

Finally, the variance of the 411, which are observed with two FD eyes whose initiated showers and 4% for iron initiated showers.

The uncertainty in the reconstruction of the ground signal for a given LP, contains i) the uncertainty in the reconstruction of the ground signal for a given LP, ii) the uncertainty in the reconstruction of the ground signal for a given LP, and iii) the uncertainty in the reconstruction of the ground signal for a given LP, due to the uncertainty in the reconstruction of the ground signal for a given LP, and energy.

in all models muon number is 30-60% too small
More muons in air shower data than expected

No consistency between different observables can be achieved

→ Interaction physics in air shower models still not accurate
Something is still wrong

Air shower models require modifications:

hadronic model ?
fluorescence yield ?

LHC results on cross-sections and particle production (in very forward range) provide very helpful constraints.

Auger is doing
Particle physics at $>10^{19}$ eV with cosmic rays !!
Note: an air shower model must work well for all energies from MeV to $10^{20}$ eV (as in a shower interactions occur at all energies) for all primaries at all angles and altitudes.

Good agreement at one energy / primary / angle / altitude is no guarantee for good agreement at another one. Need to tune models always with all available sets of data:

- air showers, direct CR measurements,
- colliders, fixed target expts., underground muons, …

… a long and tedious process
Educational Images
Visualise and understand what is going on ...

... as with early bubble and cloud chamber photos.
proton shower \(10^{12}\) eV
photon shower $10^{12}$ eV
proton shower $10^{14}$ eV
proton shower  $60^\circ$  $10^{15}$ eV
proton $10^{15}$ eV

1st interaction

electrons/photons
muons
hadrons
2\textsuperscript{nd} interaction

3\textsuperscript{rd} interaction

π decay in \( \mu \)
Muon decays
Magnetic deflection:
charged particles spiral around
Earth magnetic field.

e^+ e^- pair production
electrons/photons
muons
hadrons

various hadronic interactions
photon induces electromagnetic sub-shower

protons (or neutrons) are absorbed

electron slowed down and absorbed
2 TeV gamma shower, bottom view

Development of a 2 TeV Gamma Ray Shower from first interaction to the Milagro Detector

Viewed from below the shower front -
Color coded by Particle Type

This movie views a CORSIKA simulation of a gamma ray initiated shower. The purple grid is 20 m per square and is moving at the speed of light in vacuum. The height of the shower above sea level is shown at the bottom of the screen.

Blue - electrons and gammas
Yellow - muons
Green - pions and kaons
Purple - protons and neutrons
Red - other, mostly nuclear fragments
2 TeV gamma shower, bottom view

Development of a 2 TeV Gamma Ray Shower from first interaction to the Milagro Detector

Viewed from below the shower front - Color coded by Particle Type

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- Blue - electrons and gammas
- Yellow - muons
- Green - pions and kaons
- Purple - protons and neutrons
- Red - other, mostly nuclear fragments
Development of a 2TeV Proton Shower from first interaction to the Milagro Detector

Viewed from below the shower front - Color coded by Particle Type

This movie views a CORSIKA simulation of a proton initiated shower. The purple grid is 20m per square and is moving at the speed of light in vacuum. The height of the shower above sea level is shown at the bottom of the screen.

Blue - electrons and gammas
Yellow - muons
Green - pions and kaons
Purple - protons and neutrons
Red - other, mostly nuclear fragments
Development of a 2 TeV Proton Shower from first interaction to the Milagro Detector

Viewed from below the shower front -
Color coded by Particle Type

This movie views a CORSIKA simulation of a proton initiated shower. The purple grid is 20m per square and is moving at the speed of light in vacuum. The height of the shower above sea level is shown at the bottom of the screen.

Blue - electrons and gammas
Yellow - muons
Green - pions and kaons
Purple - protons and neutrons
Red - other, mostly nuclear fragments
Shower from a vertical 2TeV Gamma Ray Primary
Side View

Note the penetration of the shower core almost to the second layer of detectors (6m) and the formation of the bowl and ring structure by the shower core. The ring is the classic Cherenkov radiation pattern, and the bowl is formed by multiple scattering - many small rings from highly scattered particles adding up to form a bowl. In the Milagro pond the probability density of Cherenkov light emission from an entering particle is in this bowl-ring distribution.

- Red - electrons and positrons
- Green - secondary gammas
- Blue - Cherenkov Photons
Shower from a vertical 2TeV Gamma Ray Primary
Side View

Note the penetration of the shower core almost to the second layer of detectors (6m) and the formation of the bowl and ring structure by the shower core. The ring is the classic Cherenkov radiation pattern, and the bowl is formed by multiple scattering - many small rings from highly scattered particles adding up to form a bowl. In the Milagro pond the probability density of Cherenkov light emission from an entering particle is in this bowl-ring distribution.

Red - electrons and positrons
Green - secondary gammas
Blue - Cherenkov Photons
2 TeV gamma shower onto Milagro, bottom view
2 TeV gamma shower onto Milagro, bottom view

Shower from a vertical 2TeV Gamma Ray Primary
Bottom View

This shower is seen from below the Milagro pond. Note the small Cherenkov rings from the peripheral particles and the prominent bowl and ring structure formed by the core. The boxes are the same size, but the white box is at the water surface, and the purple box moves with the shower front.

Red - electrons and positrons
Green - secondary gammas
Blue - Cherenkov Photons
2 TeV proton shower onto Milagro, side view

Shower from a vertical 2 TeV Proton Primary
Side View

At this energy proton showers tend to have many fewer particles hitting the pond - as seen by the wide particle spacing in this relatively strong proton shower. Notice the very distinctive Cherenkov cone left by a muon.

Red - electrons and positrons
Green - secondary gammas
Yellow - muons
Blue - Cherenkov Photons
2 TeV proton shower onto Milagro, side view

Shower from a vertical 2 TeV Proton Primary
Side View

At this energy proton showers tend to have many fewer particles hitting the pond - as seen by the wide particle spacing in this relatively strong proton shower. Notice the very distinctive Cherenkov cone left by a muon.

Red - electrons and positrons
Green - secondary gammas
Yellow - muons
Blue - Cherenkov Photons
200 MeV electrons onto Milagro, side view

In this movie the shower reference plane color has been changed from red to purple, and two white planes representing the upper and lower layers of photodetectors in the Milagro pond have been added (1.5m and 6.15m depths respectively). Note the delayed refraction of the showerfront due to the penetration of gamma ray photons into the Milagro Pond. The gammas are produced by Bremsstrahlung in the air and water. See the movie 20dE200MeVNC to clearly observe the separation by particle type that occurs.

Red - electrons and positrons
Green - secondary gammas
Blue - Cherenkov Photons
200 MeV electrons onto Milagro, side view

Plane of 200MeV Electrons at 20°
Side View

In this movie the shower reference plane color has been changed from red to purple, and two white planes representing the upper and lower layers of photodetectors in the Milagro pond have been added (1.5m and 6.15m depths respectively). Note the delayed refraction of the showerfront due to the penetration of gamma ray photons into the Milagro Pond. The gammas are produced by Bremsstrahlung in the air and water. See the movie 20dE200MeVNC to clearly observe the separation by particle type that occurs.

Red - electrons and positrons
Green - secondary gammas
Blue - Cherenkov Photons
Extensive air showers are complicated.

Monte Carlo simulations (based on random numbers) are the right tool for simulating EAS.

Beware the details:
  The more details are simulated,
    the more reliable / correct is the result,
  but also
    the longer it takes / the more it costs.
Summary:

Shower simulations are **indispensable** in high-energy astroparticle physics.

Accelerator data & theory provide valuable constraints.

Weak point: hadronic interactions @ high energies. The higher the energy the larger the uncertainties.

CORSIKA & its models are reasonably correct (on the 10-50% level) and improving...
CORSIKA @ 30

- a great success, has revolutionised the field.
- prime tool of astroparticle physics
  (helps to understand shower formation in subtle detail)
- the **gold standard**, work horse for CR related physics,
- essentially all experiments are using it,
- a great and lasting legacy of the KASCADE project.

... and we want to keep it like this.
The future

CORSIKA is needed for at least another 30 years:

Auger, TA, LHAASO, EUSO, …
HESS, MAGIC, VERITAS, HAWC, CTA, Taiga, …
IceCube, KM3Net, VLVND, …
Lofar, ANITA, ARIANNA, ARA, SKA, …

A serious upgrade is underway:
clearer structure, better description, modern software technology,
remove historical baggage, re-write with many improvements,
easier to understand, debug, maintain, extend, (less of a black box)
diagnostics, diagnostics, diagnostics, … of all aspects of simulations
ensure the availability of the best possible simulation tool.
Needs also progress on the hadronic interactions!

Next Generation CORSIKA Workshop, KIT, June 2018
https://indico.scc.kit.edu/event/426/

“Towards the next generation of CORSIKA:
A framework for the simulation of particle cascades in astroparticle physics”
CORSIKA (COsmic Ray SImulations for KAscade) 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 several reaction models alternatively: The VENUS, QGSJET, and DPMJET models are based on the Gribov-Regge theory, while SIBYLL is a minijet model. The neXus model extends far above a simple combination of QGSJET and VENUS routines. The most recent EPOS model is based on the neXus framework but with important improvements concerning hard interactions and nuclear and high-density effect. HERWIG is inspired by findings of the Dual Parton Model and tries to reproduce relevant kinematical distributions being measured at colliders.