Introduction to CORSIKA and Historical Review

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Contents

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CORSIKA

The name CORSIKA stands for:

COsmic Ray SImulation for KASCADE

KASCADE = KArlsruhe Shower Core and Array DEtector

Aims of EAS Simulations

Determine measurable EAS parameters:

mean values
fluctuations
correlations

With this knowledge one tries to deduce from the measurements relevant properties of primary particle:

particle type (γ, proton, ... iron, ν, ...)
energy (spectral slope, knee, ankle, GZK-cutoff)
direction (anisotropy, point source)

EAS Simulation

How to simulate an EAS ?

Follow the particles and their fates

Probabilities (transport, interactions):

Decision by random numbers → Monte Carlo method

Random Number Generator

CORSIKA uses the random number generator RMMARD

RMMARD: modification of CERN random generator RM48

with extension to 10 independent sequences

RM48: Combination of Lagged Fibonacci Generator with Linear Congruential Generator

Lagged Fibonacci Generator: $X_i = X_{i-p} \odot X_{i-q}$ p, q lags $\odot$ any binary arithmetic operation

Linear Congruential Generator: $X_i = (a \cdot X_{i-1} + c)$ mod M

Range: 0 $<$ RNDM $<$ 1 uniformly distributed

Precision: 48 significant bits $\rightarrow$ $\approx 4 \cdot 10^{-15}$

Seed: every integer number I with 1 $\leq$ I $\leq$ 900 000 000

starts an independent random number sequence

Sequence length: 2^{144} ($\approx 10^{43}$) random numbers

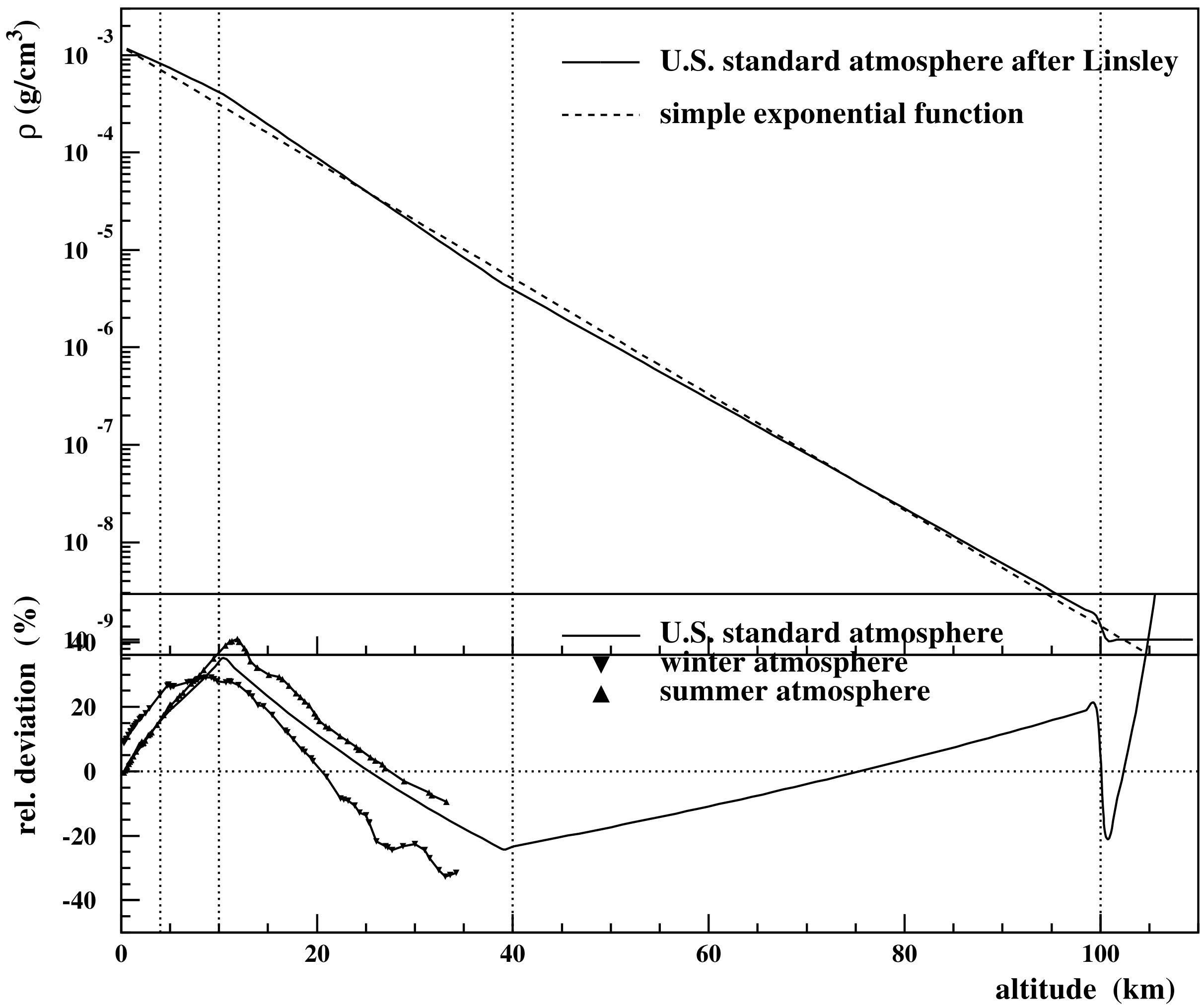
Monte Carlo Simulation of EAS

1. Environment:	atmosphere (composition, density $\propto e^{-h/c}$)
	Earth magnetic field (strength, orientation)
2. Particle:	type, energy, position, direction, time
3. Range estimation:	inelastic cross section σ
	life time τ
4. Particle transport:	ionization energy loss dE/dx
	multiple scattering (for leptons)
	deflection in Earth magnetic field
	particle reaches detector or cut ?

5. Interaction / decay with production of secondaries:

	high-energy hadronic interaction model
	low-energy hadronic interaction model
	particle decay (branching ratio > 1 %)
	electromagnetic interaction (EGS4)
6. Secondary particles:	store particles on stack

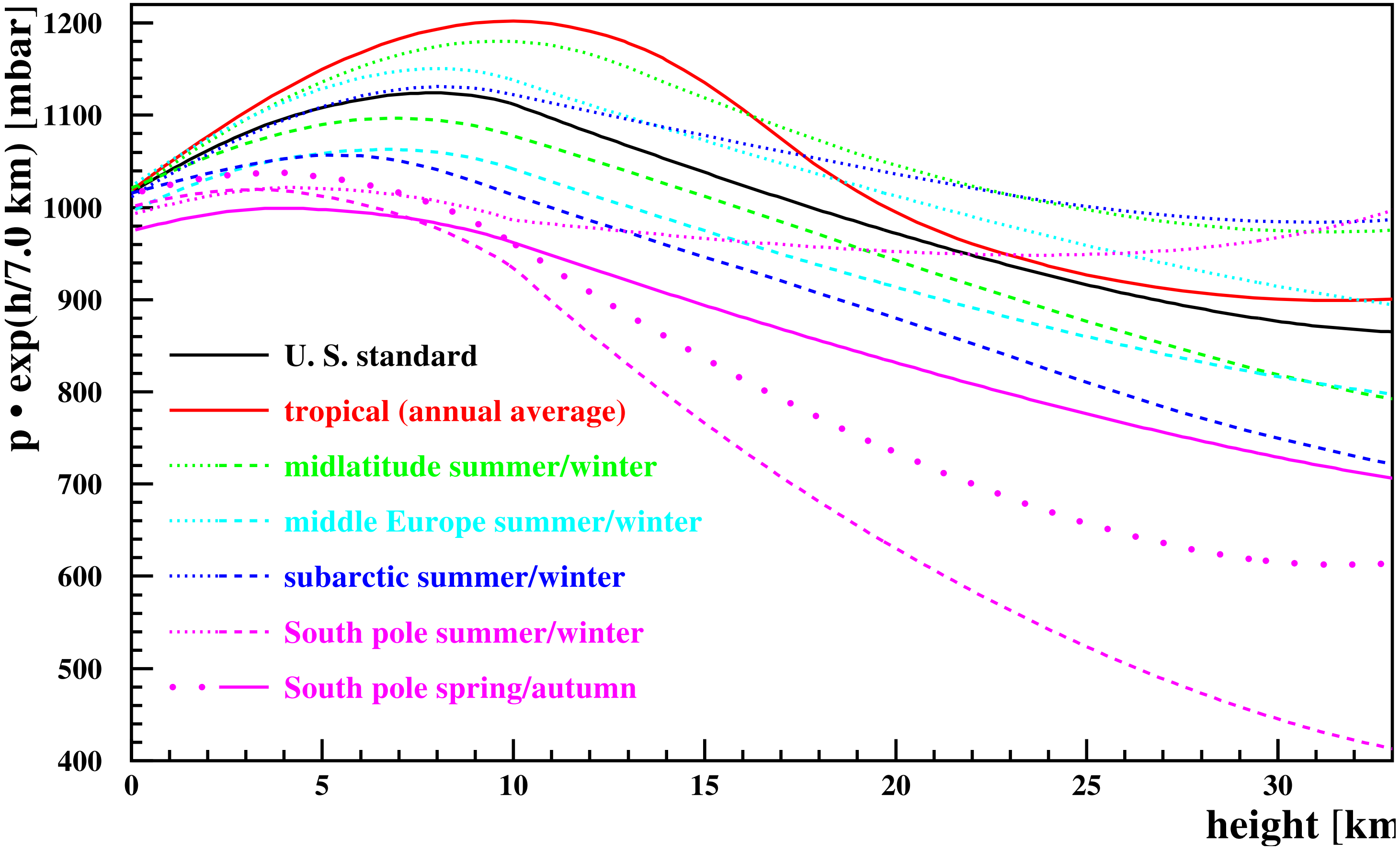
Atmosphere



Atmospheric density vs. altitude (after Knapp).

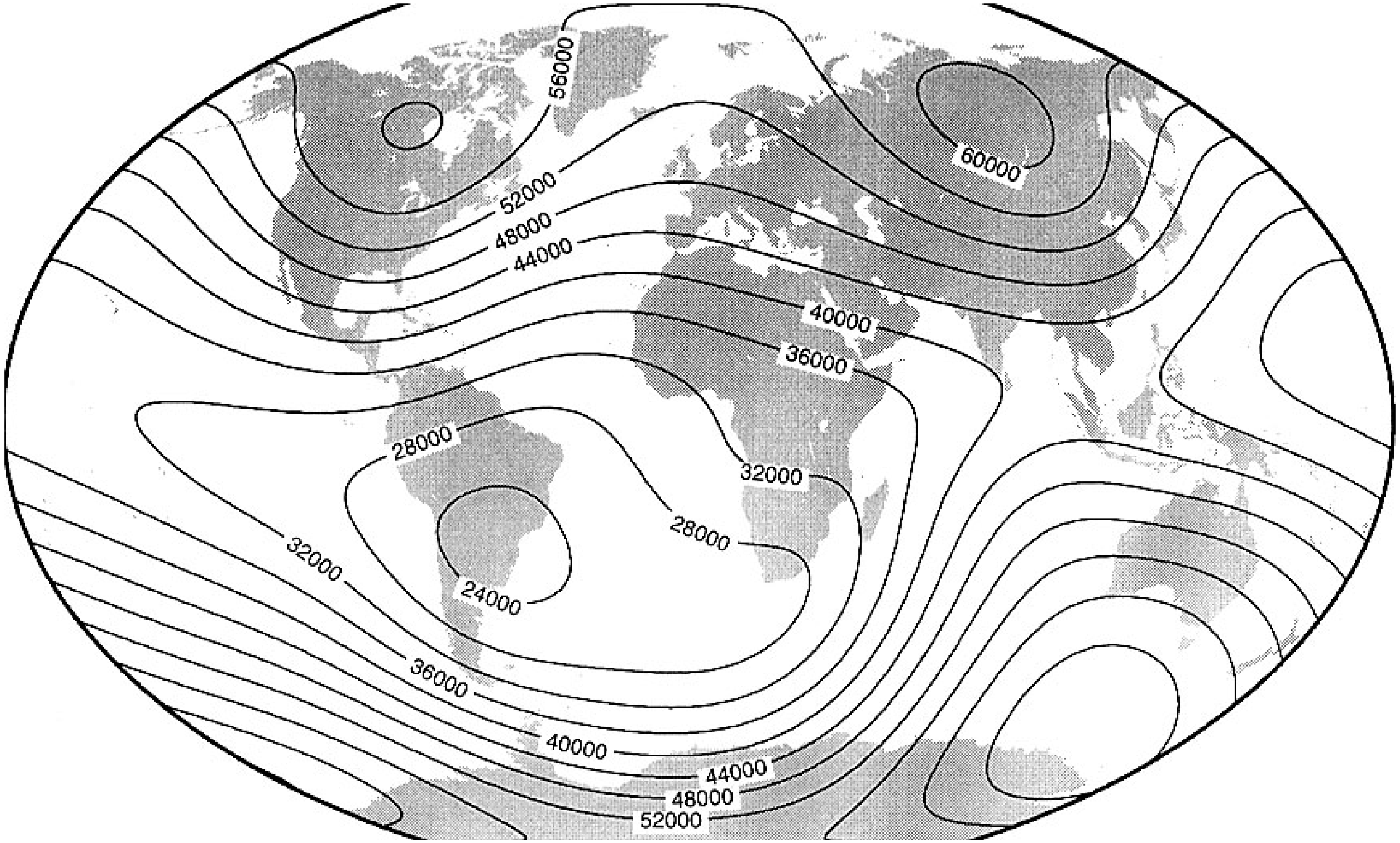
Relative deviation from simple exponential function.

Different Atmospheres



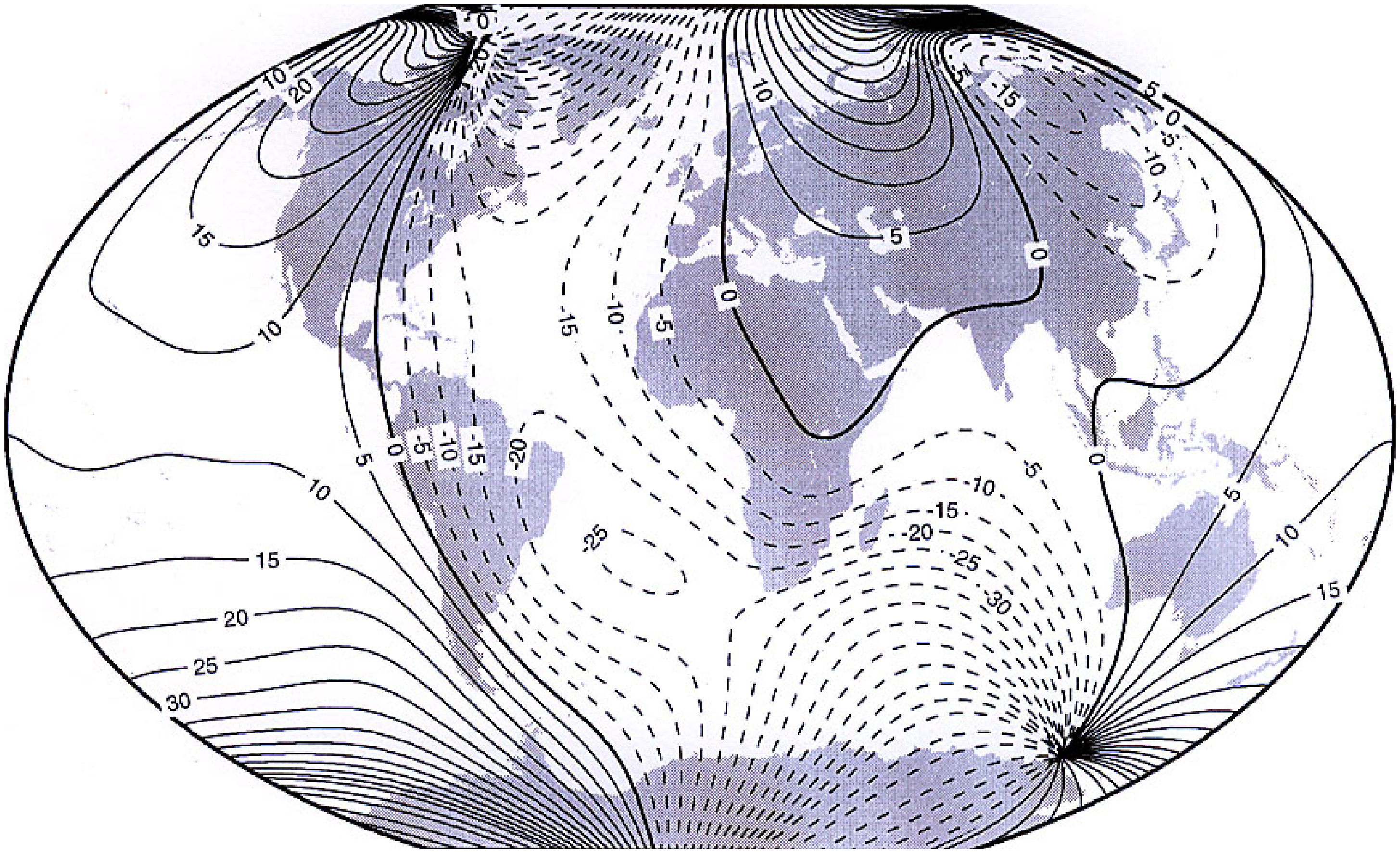
Atmospheric profiles for MODTRAN atmospheres.

Earth Magnetic Field



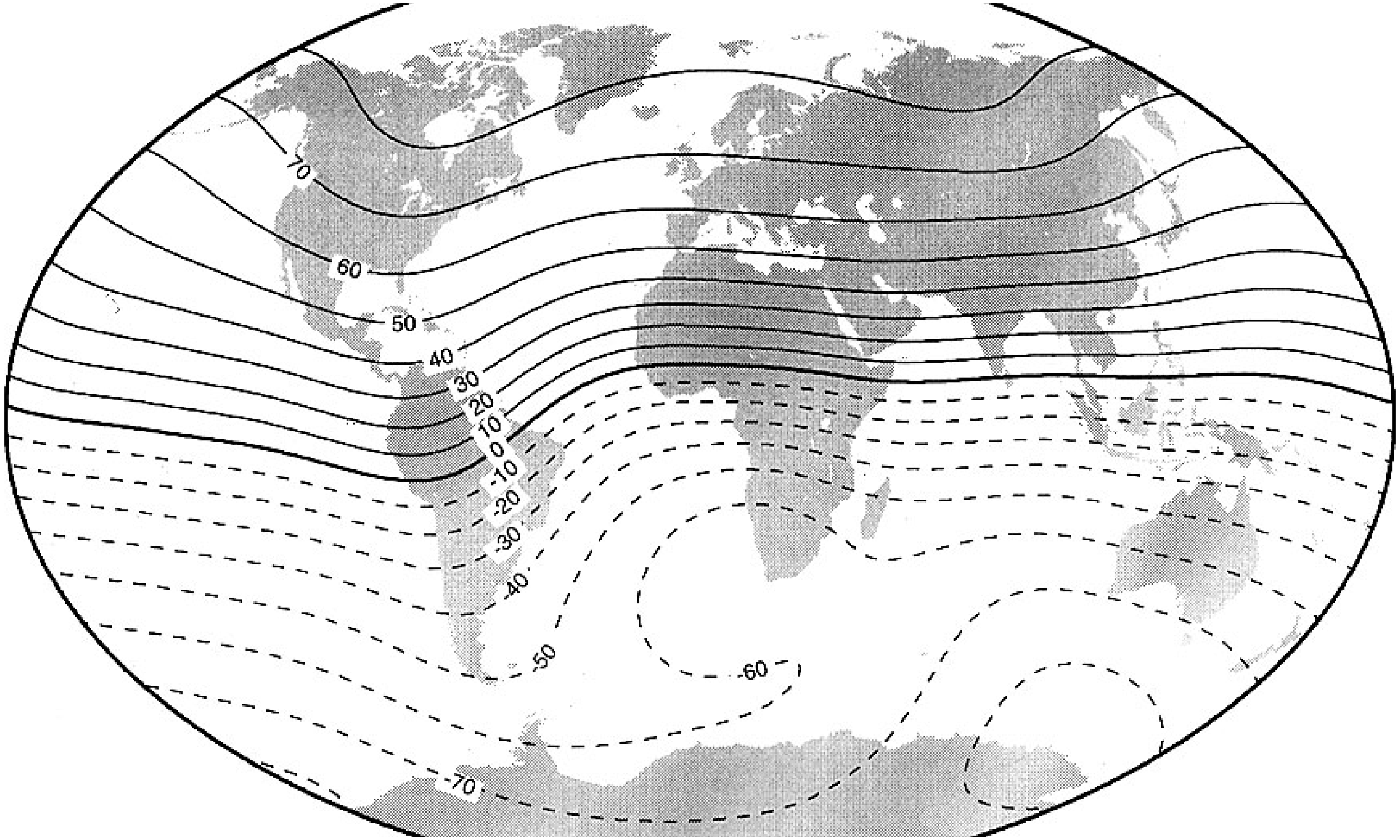
Total strength (nT) of Earth magnetic field for year 2000.

Earth Magnetic Field



Declination (degrees) of Earth magnetic field for year 2000.

Earth Magnetic Field



Inclination (degrees) of Earth magnetic field for year 2000.

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Particles in CORSIKA

Identification	Particle	Identification	Particle	Identification	Particle	Identification	Particle
1	γ	17	η	50	ω	66	ν_e
2	e^+	18	Λ	51	ρ°	67	$\bar{\nu}_e$
3	e^-	19	Σ^+	52	ρ^+	68	ν_μ
		20	Σ°	53	ρ^-	69	$\bar{\nu}_\mu$
5	μ^+	21	Σ^-	54	Δ^{++}		
6	μ^-	22	Ξ°	55	Δ^+	71	$\eta \rightarrow \gamma\gamma$
7	π°	23	Ξ^-	56	Δ°	72	$\eta \rightarrow 3\pi^\circ$
8	π^+	24	Ω^-	57	Δ^-	73	$\eta \rightarrow \pi^+\pi^-\pi^\circ$
9	π^-	25	$\bar{n}$	58	$\bar{\Delta}^{--}$	74	$\eta \rightarrow \pi^+\pi^-\gamma$
10	K°_L	26	$\bar{\Lambda}$	59	$\bar{\Delta}^-$	75	μ^+ add. info.
11	K^+	27	$\bar{\Sigma}^-$	60	$\bar{\Delta}^\circ$	76	μ^- add. info.
12	K^-	28	$\bar{\Sigma}^\circ$	61	$\bar{\Delta}^+$		
13	n	29	$\bar{\Sigma}^+$	62	$K^{*\circ}$	85	dec. μ^+ at start
14	p	30	$\bar{\Xi}^\circ$	63	K^{*+}	86	dec. μ^- at start
15	$\bar{p}$	31	$\bar{\Xi}^+$	64	K^{*-}	95	dec. μ^+ at end
16	K°_S	32	$\bar{\Omega}^+$	65	$\bar{K}^{*\circ}$	96	dec. μ^- at end

Charmed and Bottom Particles in CORSIKA

Identification	Particle	Identification	Particle	Identification	Particle	Identification	Particle
116	D°	133	ν_τ	154	$\overline{\Sigma}_c^{\circ}$	179	$\overline{B}^{\circ}$
117	D^{+}	134	$\overline{\nu}_\tau$	155	$\overline{\Xi}_c^{\prime -}$	180	B_s°
118	$\overline{D}^{-}$			156	$\overline{\Xi}_c^{\prime \circ}$	181	$\overline{B}_s^{\circ}$
119	$\overline{D}^{\circ}$	137	Λ_c^{+}	157	$\overline{\Omega}_c^{\circ}$	182	B_c^{+}
120	D_s^{+}	138	Ξ_c^{+}			183	$\overline{B}_c^{-}$
121	$\overline{D}_s^{-}$	139	Ξ_c°	161	Σ_c^{*++}	184	Λ_b°
122	η_c	140	Σ_c^{++}	162	Σ_c^{*+}	185	Σ_b^{-}
123	$D^{*\circ}$	141	Σ_c^{+}	163	$\Sigma_c^{*\circ}$	186	Σ_b^{+}
124	D^{*+}	142	Σ_c°			187	Ξ_b°
125	$\overline{D}^{*-}$	143	$\Xi_c^{\prime +}$	171	$\overline{\Sigma}_c^{*--}$	188	Ξ_b^{-}
126	$\overline{D}^{*\circ}$	144	$\Xi_c^{\prime \circ}$	172	$\overline{\Sigma}_c^{*-}$	189	Ω_b^{-}
127	D_s^{*+}			173	$\overline{\Sigma}_c^{*\circ}$	190	$\overline{\Lambda}_b^{\circ}$
128	$\overline{D}_s^{*-}$	149	$\overline{\Lambda}_c^{-}$			191	$\overline{\Sigma}_b^{+}$
		150	$\overline{\Xi}_c^{-}$			192	$\overline{\Sigma}_b^{-}$
130	J/ψ	151	$\overline{\Xi}_c^{\circ}$	176	B°	193	$\overline{\Xi}_b^{\circ}$
131	τ^{+}	152	$\overline{\Sigma}_c^{--}$	177	B^{+}	194	$\overline{\Xi}_b^{+}$
132	τ^{-}	153	$\overline{\Sigma}_c^{-}$	178	$\overline{B}^{-}$	195	$\overline{\Omega}_b^{+}$

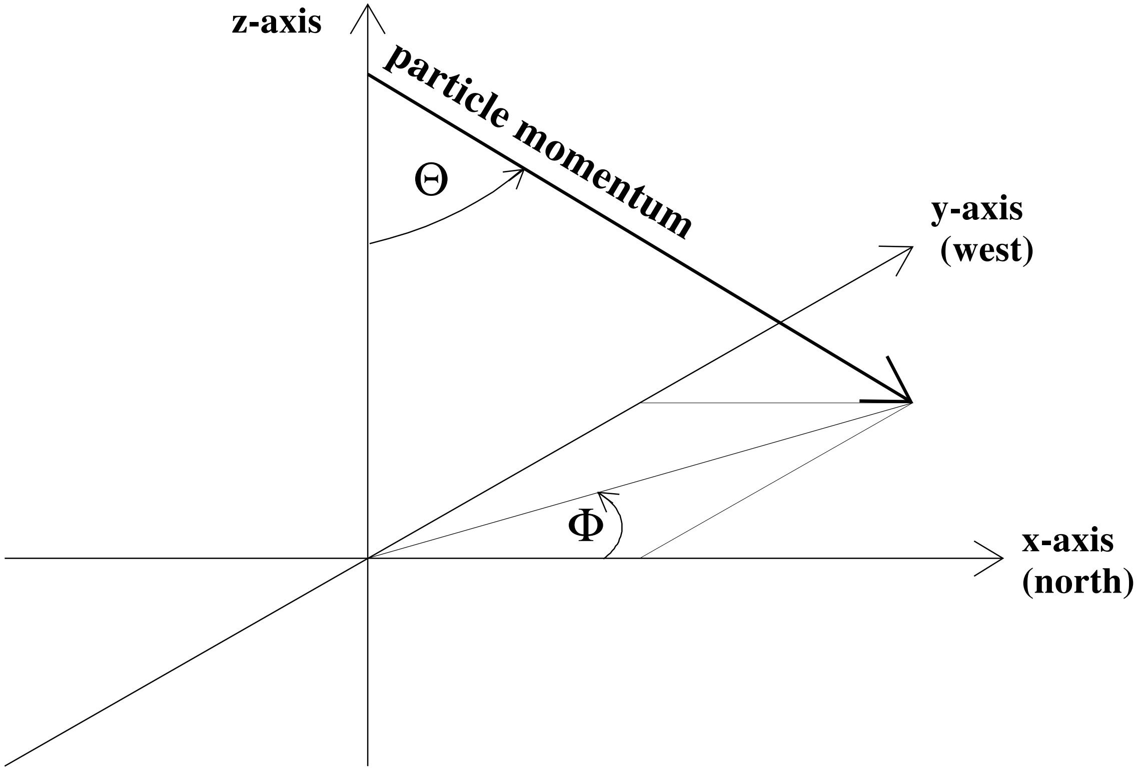
Content of Particle Register

current particle stack position	equivalence	mother particle stack position	grandma particle stack position	meaning
CURPAR(0)	(ITYPE)	CURPAR(17)	CURPAR(28)	particle identifier
CURPAR(1)	GAMMA	CURRAR(18)	CURPAR(29)	γ Lorentz factor (or energy)
CURPAR(2)	COSTHE	CURPAR(19)	CURPAR(30)	$\cos(\theta)$ vertical direction cosine [1]
CURPAR(3)	PHIX	CURPAR(20)	CURPAR(31)	$\sin(\theta)\cdot\cos(\phi)$ horizontal direction cosine [1]
CURPAR(4)	PHIY	CURPAR(21)	CURPAR(32)	$\sin(\theta)\cdot\sin(\phi)$ horizontal direction cosine [1]
CURPAR(5)	H	CURPAR(22)	CURPAR(33)	height [cm]
CURPAR(6)	T	CURPAR(23)	CURPAR(34)	time [sec] (since first interation)
CURPAR(7)	X	CURPAR(24)		horizontal position [cm]
CURPAR(8)	Y	CURPAR(25)		horizontal position [cm]
	(GEN)		CURPAR(35)	generation counter of mother particle
CURPAR(9)	CHI		CURPAR(36)	χ depth to next interaction [g·cm^{-2}]
CURPAR(10)	BETA			β =v/c fraction of speed of light
CURPAR(11)	GCM			γ Lorentz factor in cms-system
CURPAR(12)	ECM			energy in cms-system [GeV]
CURPAR(13)	WEIGHT	CURPAR(26)	CURPAR(37)	weight for thinning (THIN option)
CURPAR(14)	HAPP			apparent height [cm] (CURVED option)
CURPAR(15)	COSTAP			$\cos(\theta^*)$ apparent zenith angle cosine (CURVED option)
CURPAR(16)	COSTEA			$\cos(\theta_E)$ angle at Earth center cosine (CURVED option)
CURPAR(17)				transverse momentum [GeV/c] (INTTEST option)
CUTPAR(18)				random seed (PARALLEL option)
CURPAR(39)				ECT-flag (PARALLEL option)
CURPAR(41 - 46)				weights (MULTITHIN option)

[1] θ = zenith angle, ϕ = azimuth angle

Particle register with extensions for THIN, CURVED, INTTEST, PARALLEL, and MULTITHIN options.

Coordinate System Used in CORSIKA



Definition of Coordinates and Angles in CORSIKA

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Monte Carlo Simulation of EAS

1. **Environment:** atmosphere (composition, density $\propto e^{-h/c}$)
   Earth magnetic field (strength, orientation)
2. **Particle:** type, energy, position, direction, time
3. **Range estimation:** inelastic cross section σ
   life time τ
4. **Particle transport:** ionization energy loss dE/dx
   multiple scattering (for leptons)
   deflection in Earth magnetic field
   particle reaches detector or cut ?
5. **Interaction / decay with production of secondaries:**
   high-energy hadronic interaction model
   low-energy hadronic interaction model
   particle decay (branching ratio $> 1\ \%$)
   electromagnetic interaction (EGS4)
6. **Secondary particles:** store particles on stack

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Range of Particle for Interaction

The probability P_{int} to traverse a layer with thickness χ without interaction is

$$P_{int}(\chi) = \frac{1}{\lambda_{int}} e^{-\chi/\lambda_{int}}$$

The individually traversed matter thickness χ is $\chi = -\ln(\mathrm{RNDM}) \cdot \lambda_{int}$

with random number $0 < \mathrm{RNDM} < 1$

The mean free path λ_{int} is given by $\lambda_{int} = \frac{\sum_{i=1}^{3} n_i A_i}{\sum_{i=1}^{3} n_i \sigma_{i_{int}}}$

with A_i = **atomic weight of component i**

and σ_{int} = **(energy dependent) inelastic cross-section of component i**

The atomic fractions n_i (volume) of air are adopted to

N_2	0.7848	(78.084%)
O_2	0.2105	(20.948%)
Ar	0.0047	(0.934%)

Range of Particle for Decay

The probability P_D to traverse a path ℓ without decay is

$$P_D(\ell) = \frac{1}{\ell_D} e^{-\ell/\ell_D}$$

The individually traversed path length ℓ is $\ell = -\ln(\mathrm{RNDM}) \cdot \ell_D$

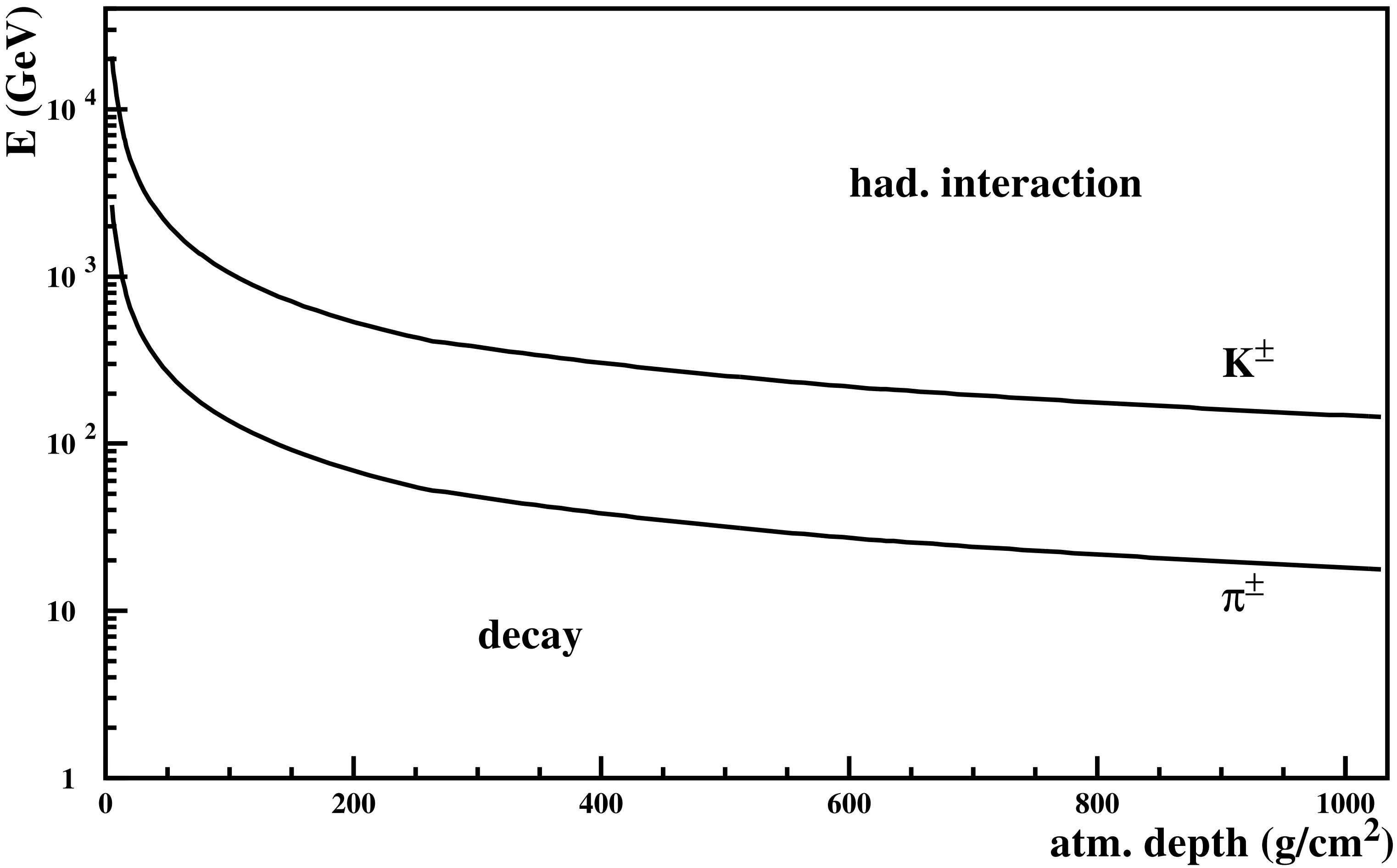
with random number $0 < \mathrm{RNDM} < 1$

The mean free path ℓ_D is given by $\ell_D = c \cdot \tau \cdot \gamma \cdot \beta$

with

- c = **vacuum speed of light,**
- τ = **particle life time at rest,**
- γ = **particle Lorentz factor and**
- β = **particle velocity in units of** c

Interaction or Decay ?



Equal probabilities for decay and interaction of $\pi^\pm$ and $K^\pm$ mesons
(after Knapp).

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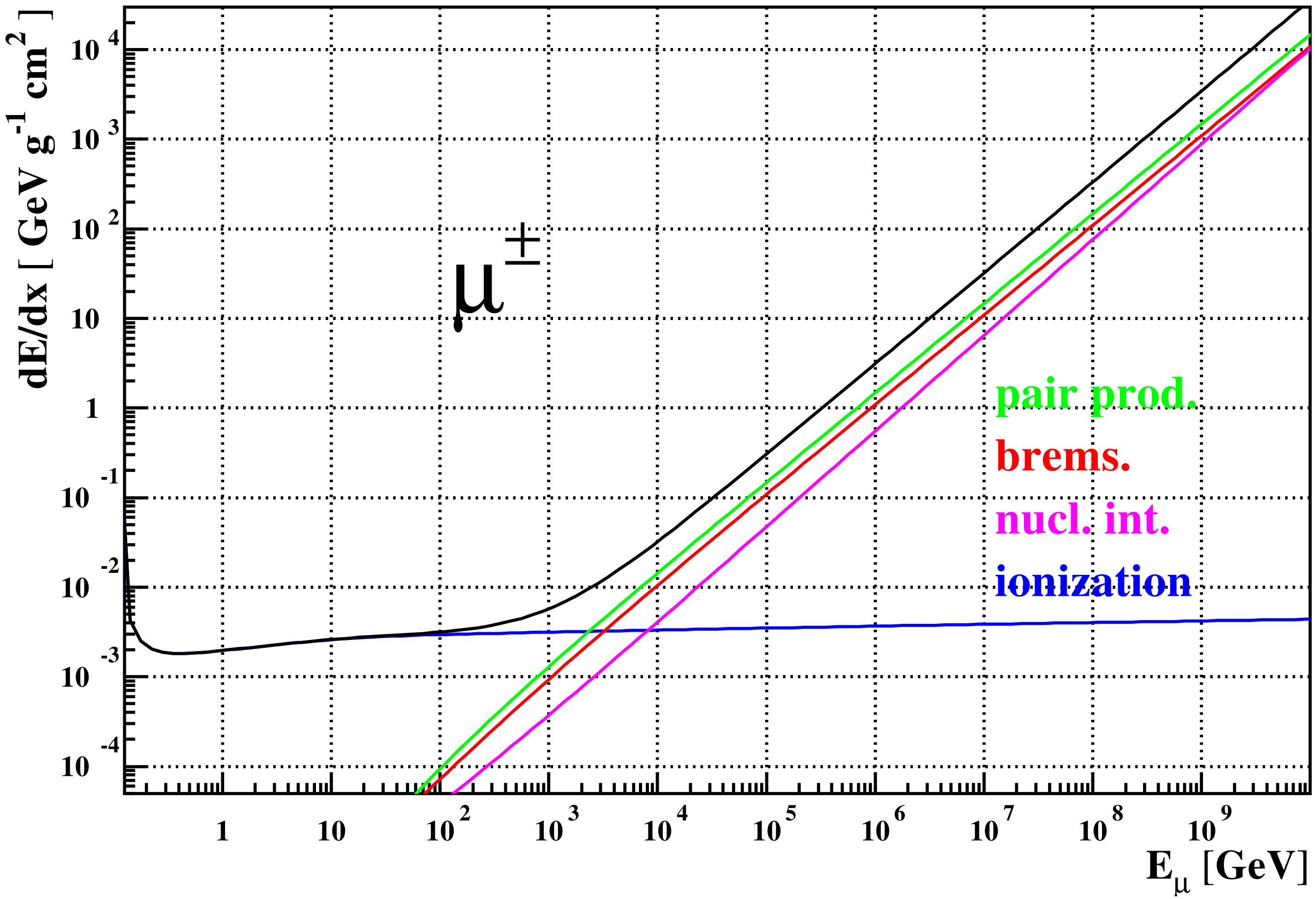
Energy Loss of Muons



Average Muon Energy Loss in Air at Sea Level.

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Monte Carlo Simulation of EAS

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Interaction Models

Why so many hadronic interaction models ?

Different interaction models produce different mean values. Scattering of mean values gives estimation on systematic uncertainty introduced by different extrapolations of accelerator data to high energy and forward direction.

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Particle Registers and Stacks

register / stack name	number of particles	content	located in common/routine
PRMPAR	1	primary particle	common PARPAR
CURPAR	1	current particle	common PARPAR
PROPAR	1	propagated particle	AAMAIN, BOX3, MUTRAC
SECPAR	1	secondary particle	common PARPAR
OUTPAR	1	output / propagated particle	common PARPAR
AMUPAR	1	additional muon info	common MUPART
CUTPAR	1	cutted particle (PARALLEL)	common PARPAR
STACKINT	200 000	intermediate stack for thinning	common STACKINT
STACKI	680 624 (THIN) 512 (CURVED) 50 000 (PARALLEL)	intermediate stack (buffer) for external file	common STACKF
STACKJ	50 000 (PARALLEL)	intermediate stack	common STACKF
(MEXST)	∞	external particle stack	(scratch file)
DATAB	39	output buffer	common BUFFS
(STACKE)	60	em-particle stack	common STACKE

Particle registers and stacks of CORSIKA.

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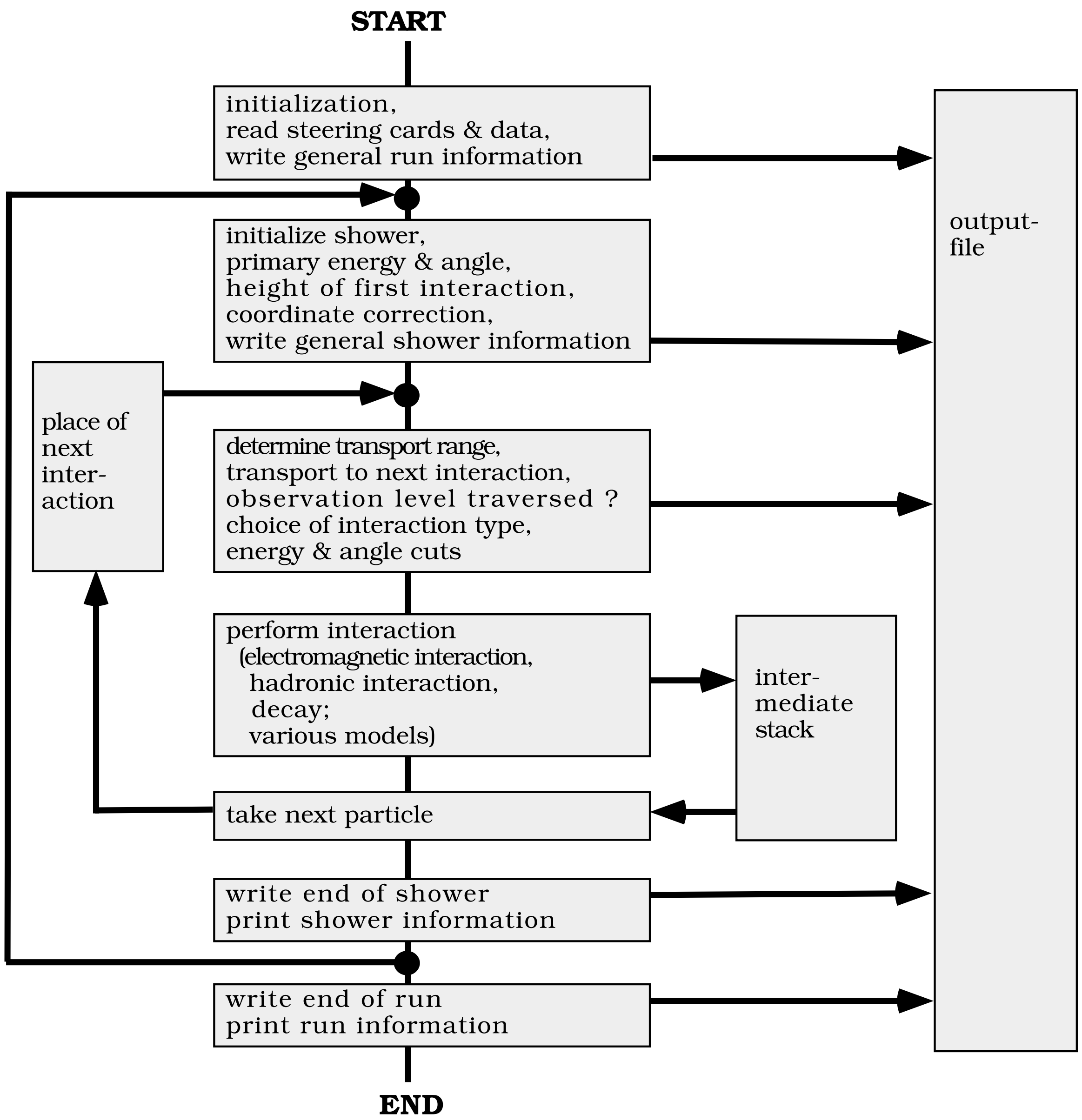
START
initialization,
read steering cards & data,
write general run information
initialize shower,
primary energy & angle,
height of first interaction,
coordinate correction,
write general shower information
place of
next
inter-
action
determine transport range,
transport to next interaction,
observation level traversed ?
choice of interaction type,
energy & angle cuts
perform interaction
(electromagnetic interaction,
hadronic interaction,
decay;
various models)
inter-
mediate
stack
take next particle
write end of shower
print shower information
write end of run
print run information
END
output-
file

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CORSIKA Technical Features

program language (portability): Fortran 77 / 90 + some few C-routines

source code size: ≈ 81 700 lines (without external programs)
≈ 340 routines

optional code: ≈ 60 preprocessor options selectable
during installation with ./coconut

steering input: free format with key words + parameters
≈ 125 key words

availability: download from anonymous ftp: ikp-ftp.ikp.kit.edu
with an internet browser

documentation: physics: FZKA 6019 (1998)
User's Guide: http://www.ikp.kit.edu/corsika/70.php
variables used in COMMONS:
patch VARINDEX (corsika.h) contains list

Contents

1. **Why and how to simulate an Extensive Air Shower (EAS) ?**
2. **Some technical features of the CORSIKA programming**
3. **Historical development of CORSIKA**

Header of First CORSIKA Version

```
C=======================================================================
C
C        OOO          OOO        OOOO         OOOO     OO    O       O         O
C       O   O       O     O     O     O     O     O    OO    O     O          O O
C      O           O       O   O       O   O            OO    O  O           O   O
C      O           O       O   O     O      OOOO     OO    OO            O       O
C      O           O       O   OOOO              O    OO    O  O          OOOOOOO
C       O   O       O     O     O    O     O     O   OO   O     O          O       O
C        OOO          OOO        O      O    OOOO     OO   O       O     O       O
C
C      COSMIC RAY SIMULATION AT KARLSRUHE
C
C
C   A PROGRAM TO SIMULATE EXTENSIVE AIR SHOWERS IN ATMOSPHERE
C
C   BASED ON A PROGRAM OF P.K.F. GRIEDER, UNIVERSITY BERN
C   DUAL PARTON MODEL ACCORDING TO J.N. CAPDEVIELLE, UNIVERSITY BORDEAUX
C   EGS4 AND NKG FORMULAS FOR SIMULATION OF ELECTROMAGNETIC PARTICLES
C
C   INSTITUT FUER KERNPHYSIK
C   KERNFORSCHUNGSZENTRUM AND UNIVERSITY OF KARLSRUHE
C
C   VERSION :   1.0
C   DATE     :  26.  OCTOBER 1989
C
C=======================================================================
```

Origin of CORSIKA

October 26, 1989 CORSIKA Vers. 1.0 merged from:

SH2C-60-K-OSL-E-SPEC (Grieder, 1980):
main structure, isobar model

ESKAR (HDPM) (Capdevielle, 1987):
high-energy hadronic interactions

EGS4 (Nelson et al., 1985):
electron gamma shower

NKG (Capdevielle, 1989):
analytical treatment of EM-subshowers

source code size: $\approx$ 13 000 lines (1/6 of present version 7.6400)

CORSIKA: Development

1994 CORSIKA Vers. 4.06

GHEISHA (Fesefeldt, 1985):
low-energy hadronic interactions

VENUS (Werner, 1993):
high-energy hadronic interactions

CERENKOV (HEGRA Collaboration, 1993):
treatment of Cherenkov radiation

CORSIKA: Development

1997 CORSIKA Vers. 5.20

SIBYLL (Fletcher, Gaisser et al., 1994):
high-energy hadronic interactions

QGSJET (Kalmykov et al., 1993):
high-energy hadronic interactions

DPMJET (Ranft, 1995):
high-energy hadronic interactions

THIN option:
simulate highest energies in reasonable time

CORSIKA: Development

2000 CORSIKA Vers. 6.00

NEXUS (Drescher et al., 2001):
high-energy hadronic interactions

CURVED option (Schröder, 2001):
option for very inclined showers

IACT (Bernlöhr, 2000):
Cherenkov routines incl. telescopes

URQMD (Bleicher et al., 1999):
low-energy hadronic interactions

CORSIKA: Development

2004 CORSIKA Vers. 6.20

PRESHOWER (Homola et al., 2004):
UHE primary gammas

FLUKA (Fassò, Ferrari et al., 2001):
low-energy hadronic interactions

NUPRIM (Ambrosio, Pisanti et al., 2003):
primary neutrinos (HERWIG)

muons (Bottai & Perrone, 2001):
improved muon interactions

SLANT option:
slant depth (instead of vertical depth)

CORSIKA: Development

2007 CORSIKA Vers. 6.60

EPOS (Werner et al., 2005):

high-energy hadronic interactions

QGSJET-II (Ostapchenko, 2006):

improved model for high energies

2009 CORSIKA Vers. 6.900

CHARM option:

PYTHIA treats charmed hadrons

./coconut:

automated installation of CORSIKA

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CORSIKA: Development

2012 CORSIKA Vers. 7.350

CONEX (Bergmann et al., 2007):

hybrid simulation by cascade equations

QGSJET-II-04 (Ostapchenko, 2011):

improved model for highest energies

EPOS-LHC (Pierog et al., 2013):

improved model for highest energies

PARALLEL option:

parallel treatment on multi-CPU cluster

2013 CORSIKA Vers. 7.400

CoREAS (Huege et al., 2013):

coupling with radio emission program

Alternative Programs

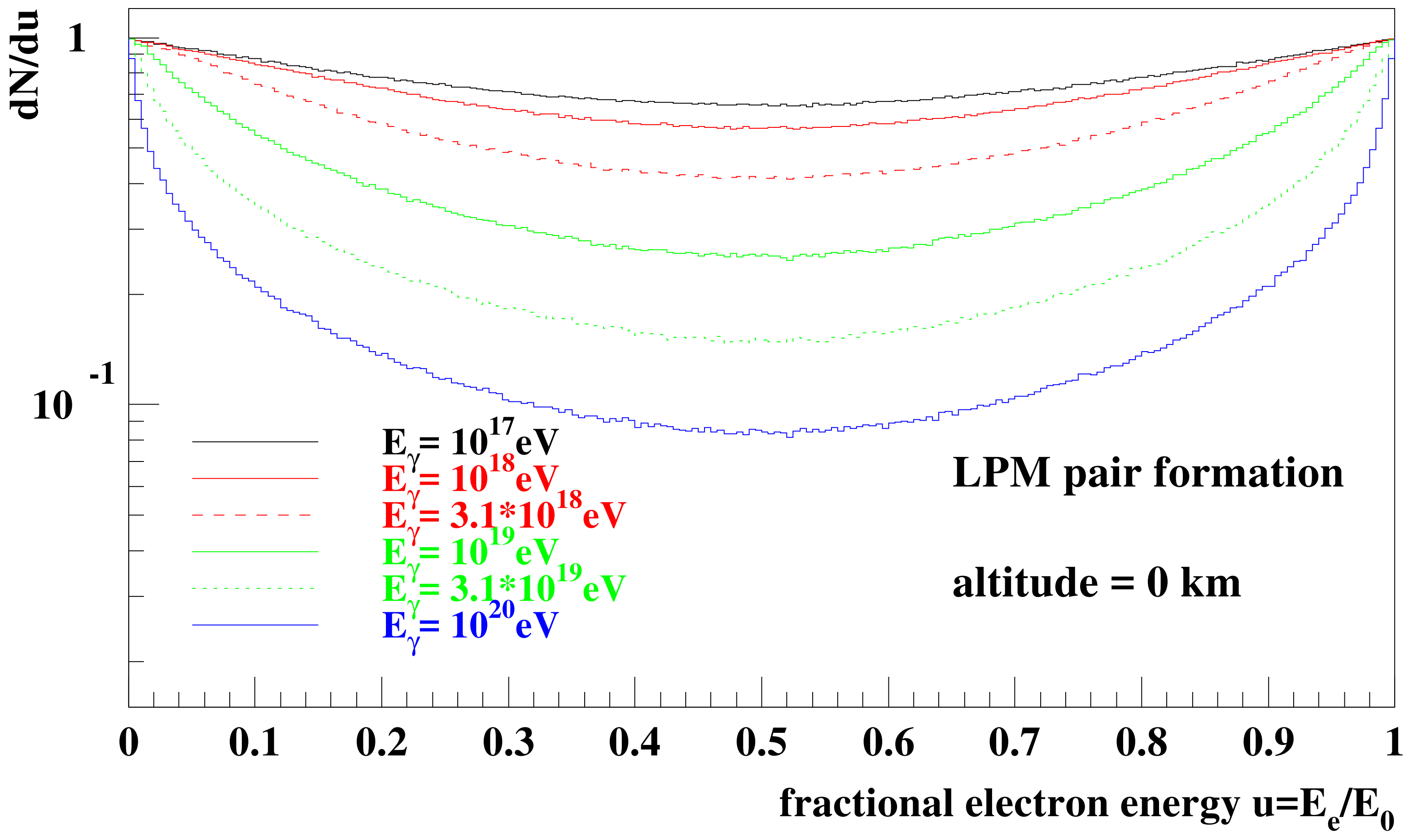
AIRES	**transscript of MOCCA to Fortran (Sciutto)**
CONEX	**hybrid with cascade equations (Kalmykov et al.)**
COSMOS	**hybrid with subshower library (Kasahara et al.)**
FLUKA	**multi-purpose detector MC (Ferrari et al.)**
GEANT 4	**multi-purpose detector MC (CERN)**
HEMAS	**used for MACRO (Battistoni, Forti et al.)**
MOCCA	**split algorithm, thinning, Pascal language (Hillas)**
SENECA	**hybrid with cascade equations (Drescher et al.)**

CORSIKA Users Worldwide

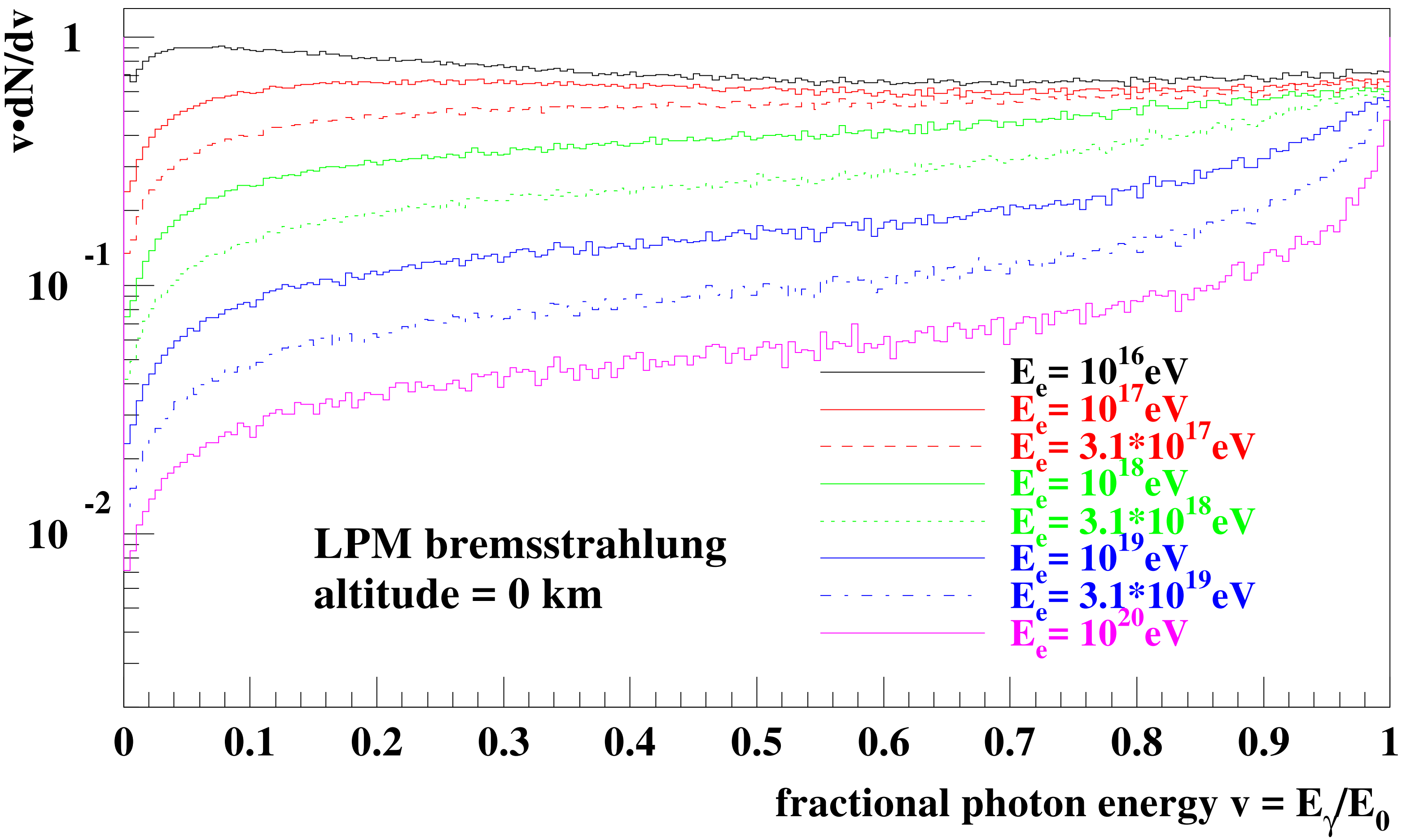
am	=	Armenia	ge	=	Georgia	pe	=	Peru
ar	=	Argentina	gr	=	Greece	pl	=	Poland
at	=	Austria	gt	=	Guatemala	pt	=	Portugal
au	=	Australia	hk	=	Hong Kong	ro	=	Romania
be	=	Belgium	hr	=	Croatia	rs	=	Rep. Serbia
bd	=	Bangladesh						
bg	=	Bulgaria	hu	=	Hungary	ru	=	Russia
bo	=	Bolivia	ie	=	Ireland	sa	=	Saudi Arabia
br	=	Brazil	il	=	Israel	se	=	Sweden
ca	=	Canada	in	=	India	si	=	Slovenia
ch	=	Switzerland	iq	=	Iraq	sk	=	Slovakia
cn	=	China	ir	=	Iran	tj	=	Tajikistan
co	=	Colombia	it	=	Italy	tr	=	Turkey
cz	=	Czech Republic	jp	=	Japan	tw	=	Taiwan
de	=	Germany	ke	=	Kenya	ua	=	Ukraine
dk	=	Denmark	kr	=	South Korea	uk	=	United Kingdom
dz	=	Algeria	kz	=	Kazakhstan	edu/gov	=	USA
es	=	Spain	mx	=	Mexico	ve	=	Venezuela
fi	=	Finland	nl	=	Netherlands	vn	=	Vietnam
fr	=	France	no	=	Norway	za	=	Rep. South Africa

In 58 countries $\approx$ 1270 registered CORSIKA users (outside KIT).

LPM-Effect


dN/du
1
10^-1
E_γ = 10^17 eV
E_γ = 10^18 eV
E_γ = 3.1*10^18 eV
E_γ = 10^19 eV
E_γ = 3.1*10^19 eV
E_γ = 10^20 eV
LPM pair formation
altitude = 0 km
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
fractional electron energy u=E_e/E_0

LPM-Effect



v•dN/dv
1
10^{-1}
10^{-2}
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
fractional photon energy v = E_γ/E_0
LPM bremsstrahlung
altitude = 0 km
$E_e = 10^{16}$eV
$E_e = 10^{17}$eV
$E_e = 3.1*10^{17}$eV
$E_e = 10^{18}$eV
$E_e = 3.1*10^{18}$eV
$E_e = 10^{19}$eV
$E_e = 3.1*10^{19}$eV
$E_e = 10^{20}$eV


WITH THE NEW SIMULATION PROGRAM
WE CAN SIMULATE THE SIMULATION
OF SIMULATION PROCESSES!
OH

Experiments Using CORSIKA

AGASA	Japan	EAS-TOP	Italy	MAGIC	Spain
AMANDA	Antarctica	EAS-1000	Russia	MAKET-ANI	Armenia
ANTARES	France	EUSO	space	MILAGRO	USA
ARGO-YBJ	China (Tibet)	Fly's Eye	USA	NEMO	France
Auger	Argentina	Frejus	France	NESTOR	Greece
Baikal	Russia	GRAAL	Spain	NuTel	USA (Hawaii)
CACTUS	USA	Guwahati	India	PAMIR	Tajikistan
CAKE	USA	Havera Park	UK	Sky-View	Germany (NRW)
CANGOROO	Australia	HEGRA-AIROBICC	Spain	STACEE	USA
CASA-BLANCA	USA	HEGRA-CT	Spain	TA	USA
CASA-MIA	USA	HESS	Namibia	TACTIC	India
CAT	France	HiRes	USA	THEMISTOCLE	France
CELESTE	France	IceCube	Antarctica	TUNKA	Russia
Chacaltaya	Bolivia	KASCADE-Grande	Germany	VERITAS	USA
CORAL	Switzerland	LOPES	Germany	WACT	USA
DECOR	Russia	L3-cosmic	Switzerland	WILLI	Romania
DICE	USA	MACRO	Italy	WHIPPLE	USA

CORSIKA is used for $>$ 50 cosmic ray experiments.