Cosmic ray simulations - CORSIKA

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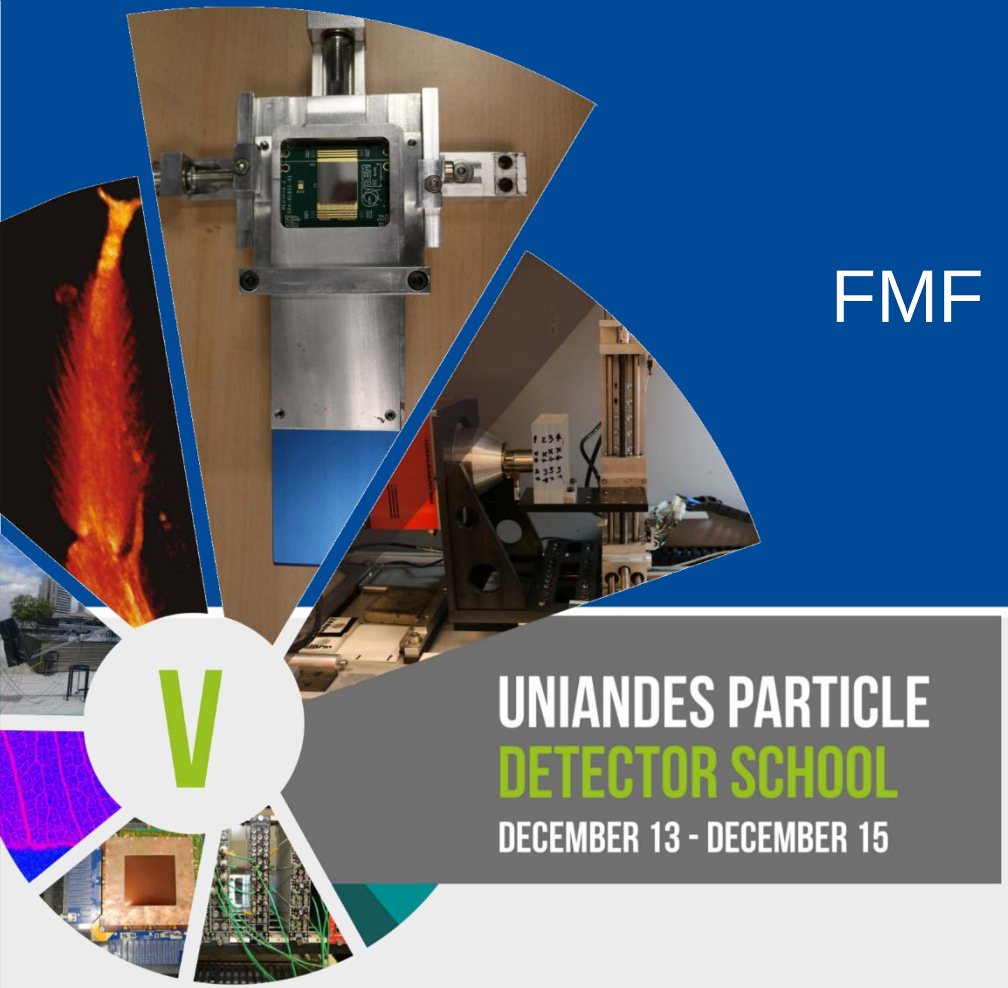


Why do we **measure** cosmic rays?

Study high energy particles interactions

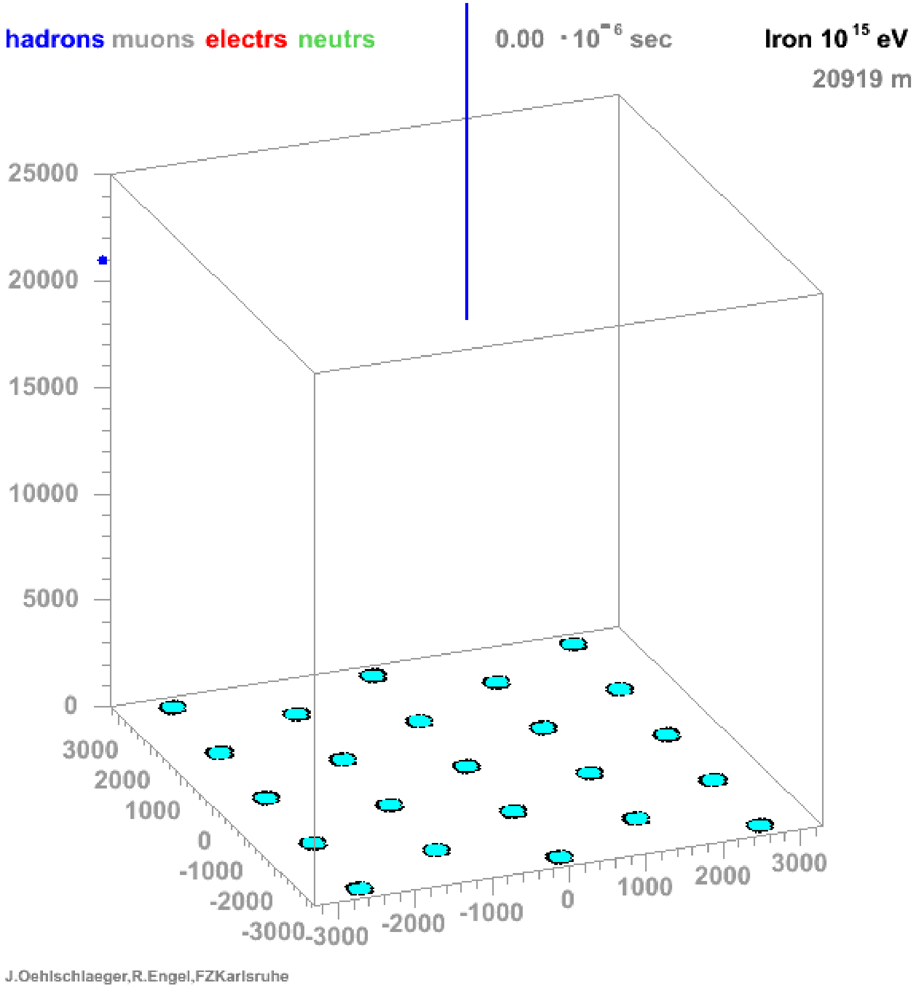
Distinguish between different types of particles (energy dependence)

Measure energy and direction of the primary particle (identification)

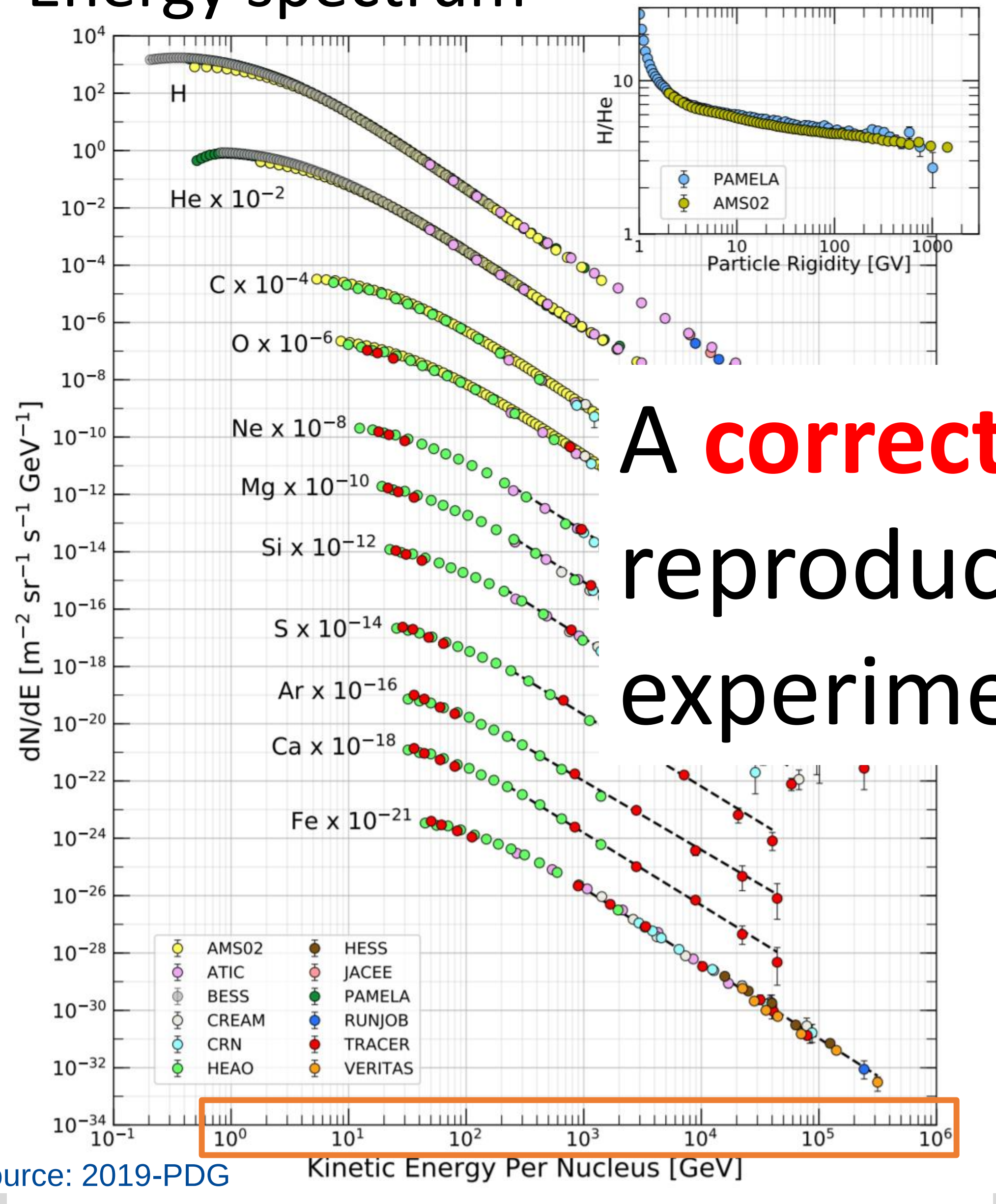
Why do we **simulate** cosmic rays?

The only technique to study cosmic rays is by indirectly measuring the **extensive air showers**

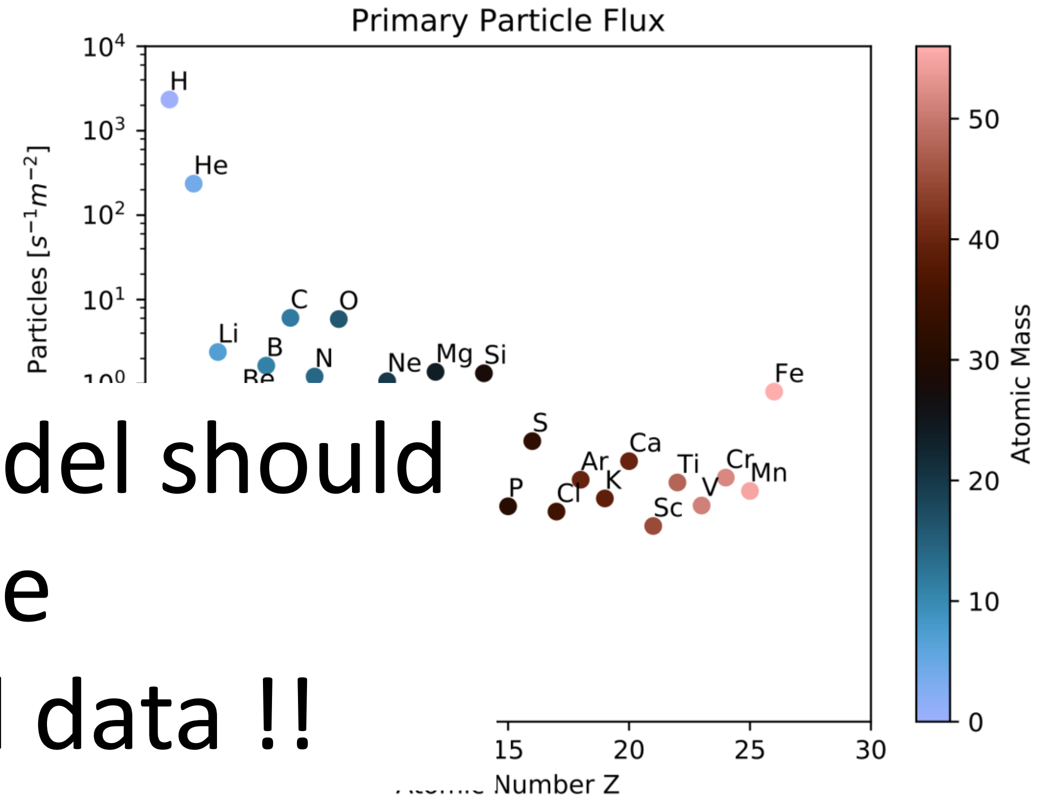
Need a “good” enough model to describe the many inter-dependent sub-processes



Energy spectrum



Source: 2019-PDG



A **correct** model should reproduce the experimental data !!

1 shower of **10^{20}eV:**

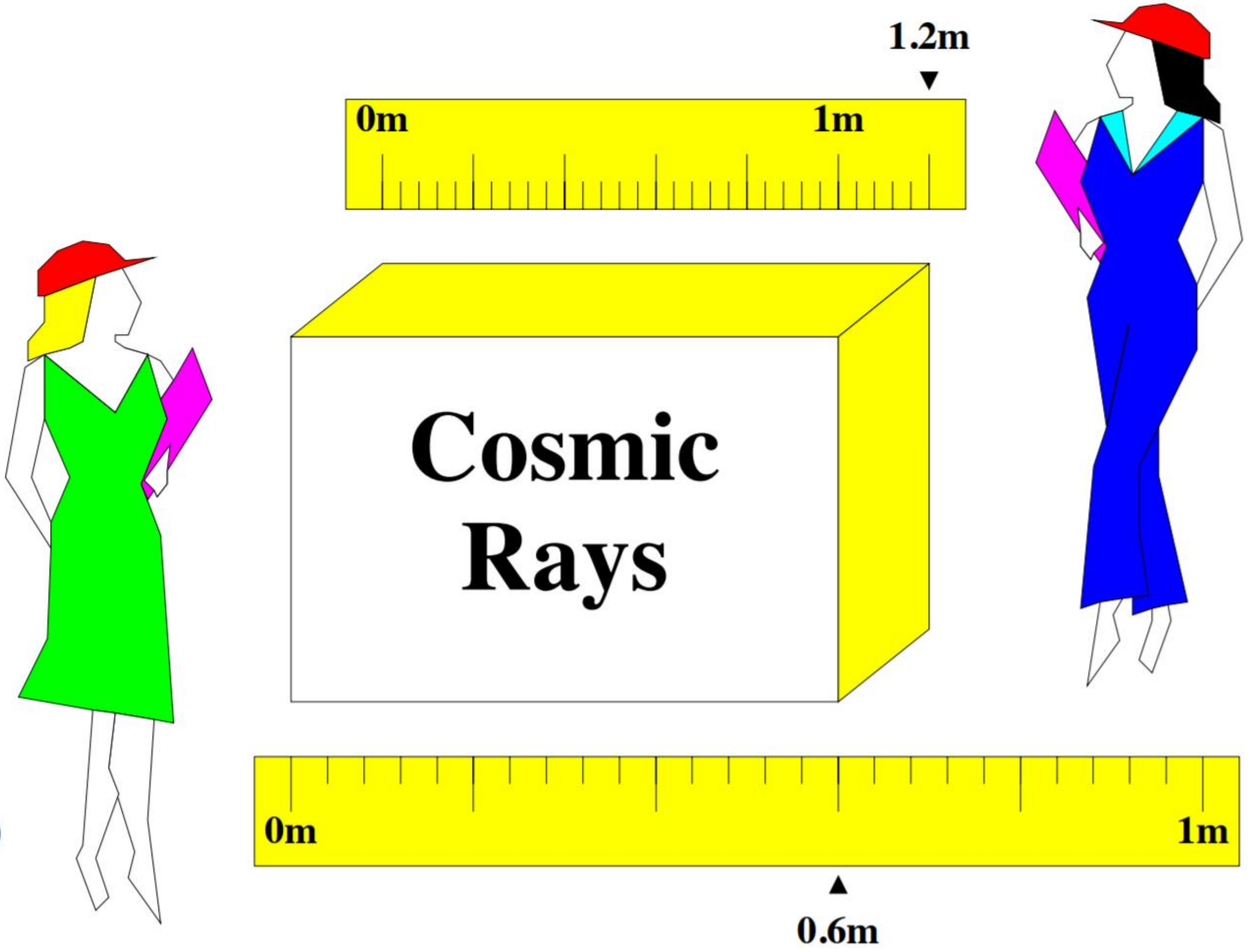
~10 sub-showers of **10^{19}eV**

~10^{6} sub-showers of **100 TeV**

~10^{11} sub-showers of **1 GeV**

1997

$\sim 10^{20} eV$



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

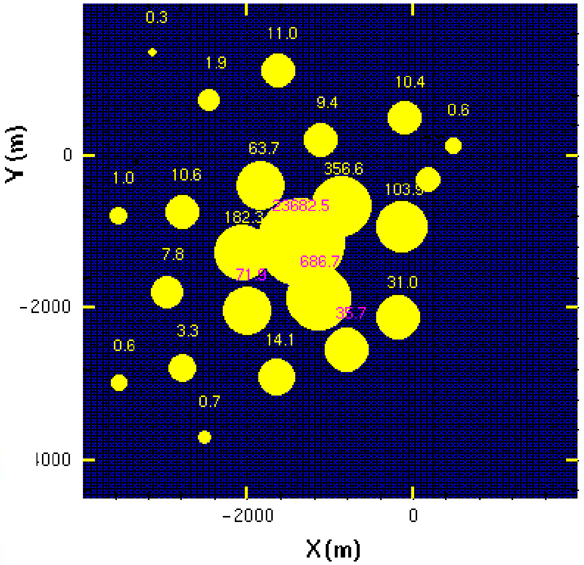
Akeno **G**iant **A**ir **S**hower **A**rray

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

Source: J.Knapp – Air shower simulations with CORSIKA. https://indico.cern.ch/event/719824/timetable/

Some issues

Source: https://www.icrr.u-tokyo.ac.jp/as/project/agasa_org.html



What is needed?

Use the **same ruler** to get consistent results in **different experiments**.

The ruler used should be **reliable** to get **correct results**

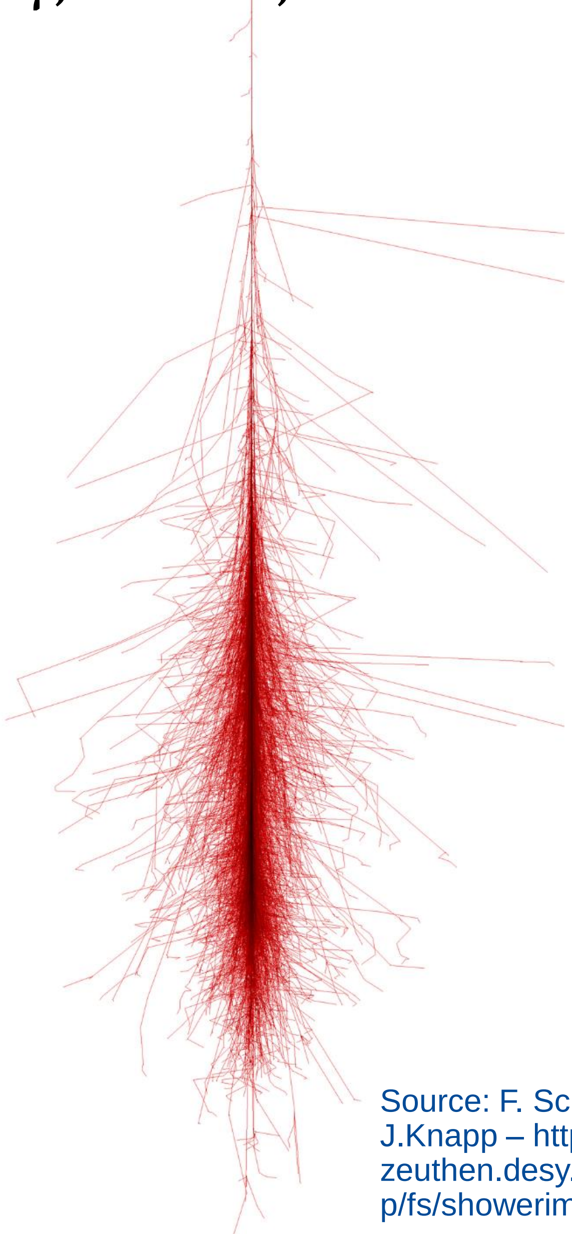
Source: https://www.nature.com/articles/452264b

CORSIKA

Cosmic **R**ay **Si**mulation for **KA**SCADE

KASCADE: an experiment to measure the **composition** of **cosmic rays** in Karlsruhe (Germany) 1997-2009

$\gamma, 50\ GeV, \theta = 0°$



Source: F. Schmidt, J.Knapp – https://www-zeuthen.desy.de/~jknapp/fs/showerimages.html

CORSIKA

"Full" description of a cosmic ray's extensive air shower (4D)

EM model: **EGS4**

Low energy hadronic models:

- **FLUKA**
- **UrQMD**
- **GHEISHA**

High energy hadronic models:

- **QGSJET**
- **EPOS-LHC**
- **DPMJET**
- **SIBYLL**

\+ many extensions:

- **CONEX** (cascade eq.)
- **PARALLEL**
- **CoREAS** (radio signal)
- **COAST** (Corsika data AccesS Tool)

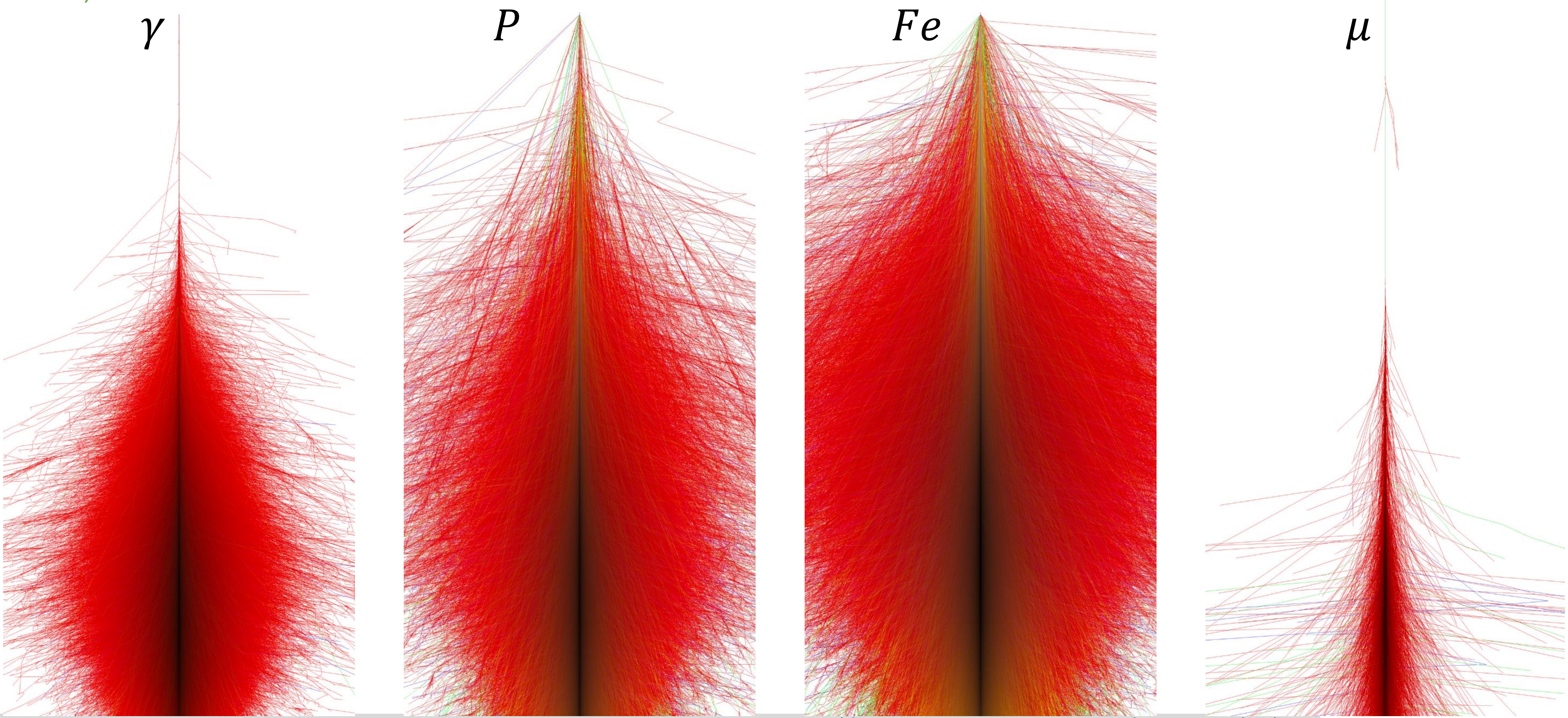
Tuned at collider energies (TeV) and extrapolated to 10^{20} eV

https://www.iap.kit.edu/corsika/index.php

CORSIKA in images

Electrons, positrons, gammas
Muons, hadrons

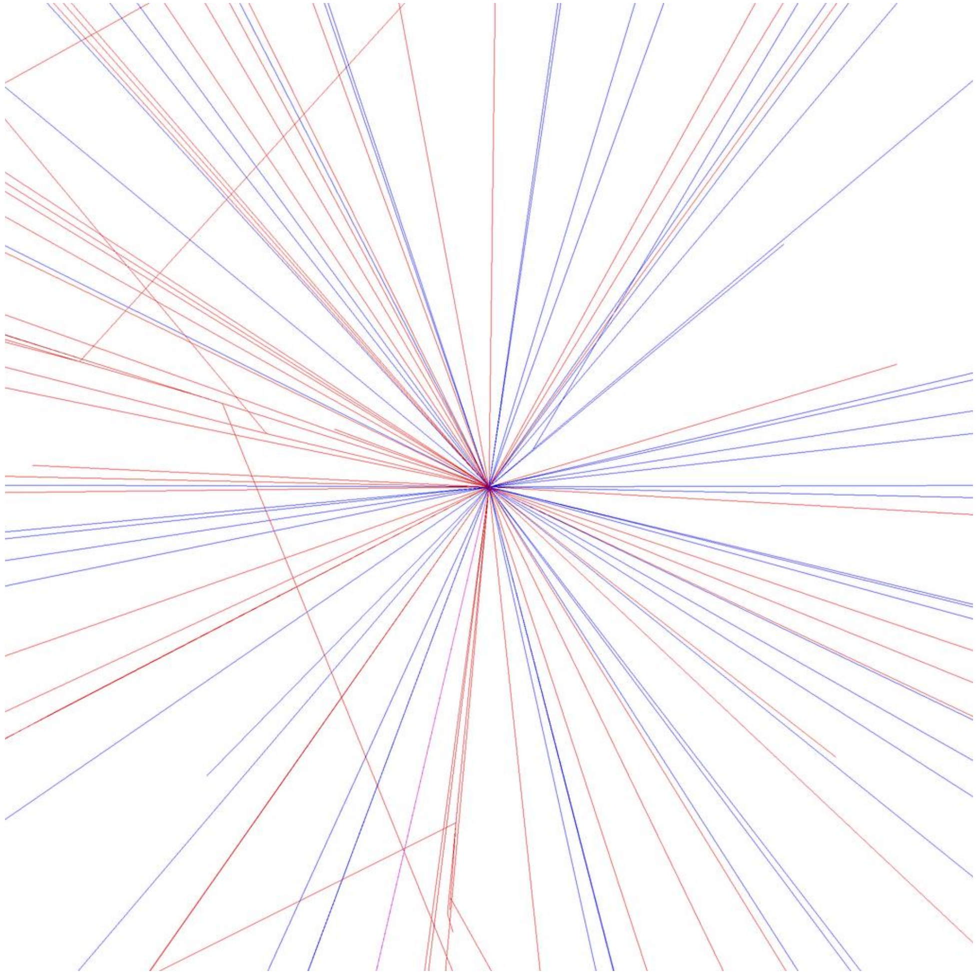
$$E = 10^{15} eV \,, \theta = 0°$$



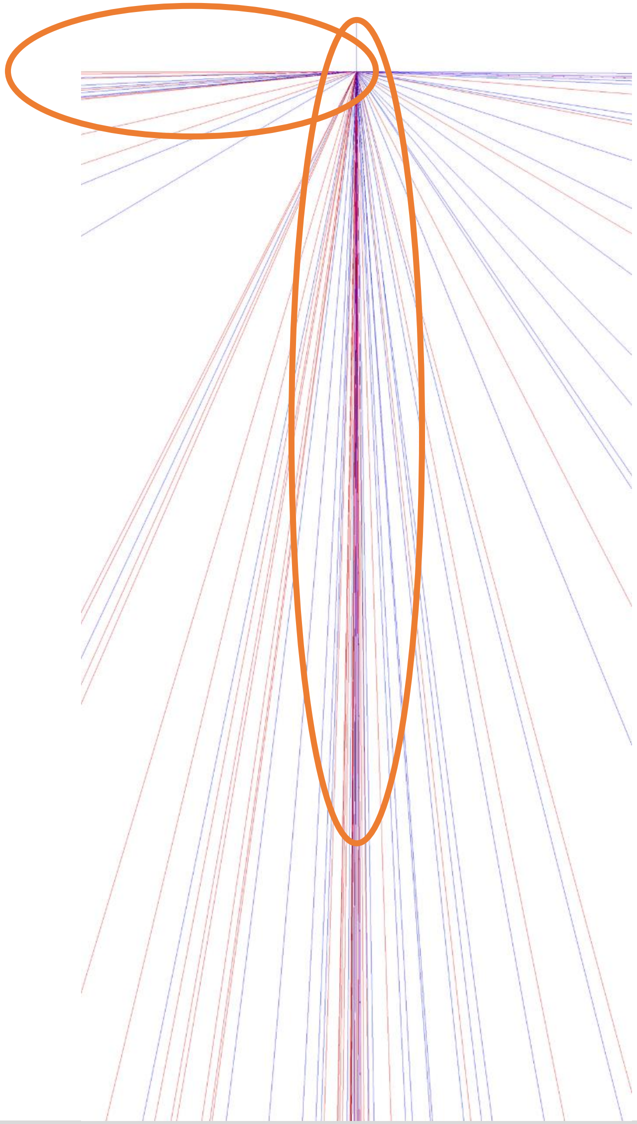
Source: F. Schmidt, J.Knapp – https://www-zeuthen.desy.de/~jknapp/fs/showerimages.html

10^{20}eV Proton interaction

XY Projection



XZ Projection



Isotropic in XY projection

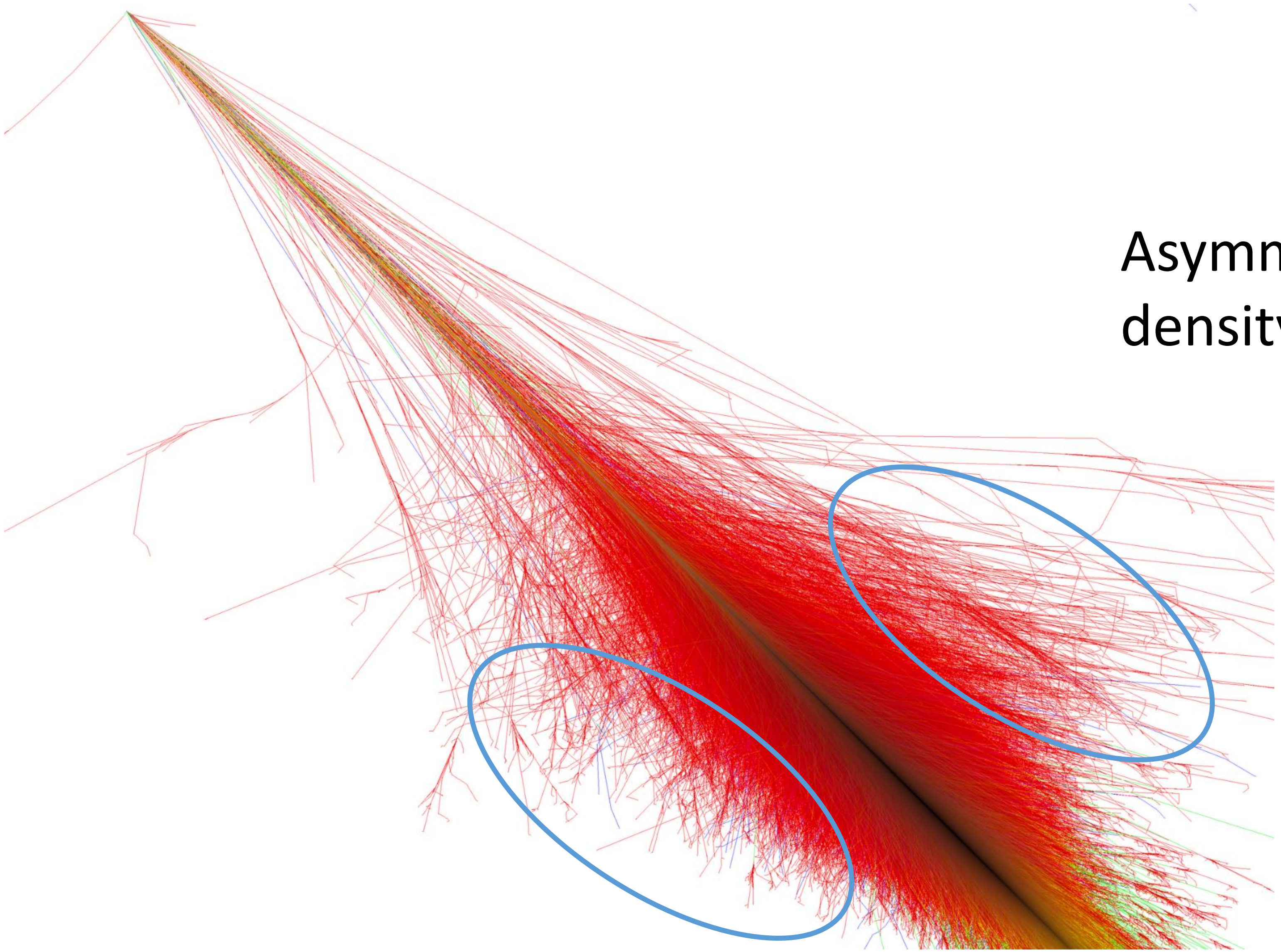
Extreme forward and backward directions

Particles in the backward directions have $\theta \leq\sim 90$

 Source: F. Schmidt, J.Knapp – https://www-zeuthen.desy.de/~jknapp/fs/showerimages.html

Proton interaction

$E = 10^{15} eV, \theta = 45°$

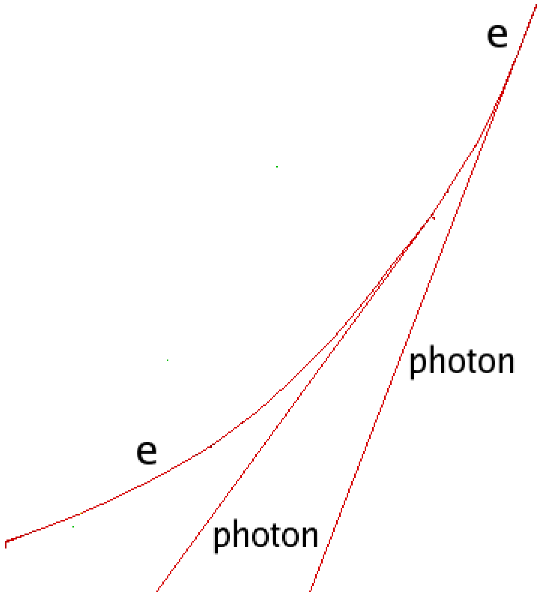


Asymmetry due to air density gradient

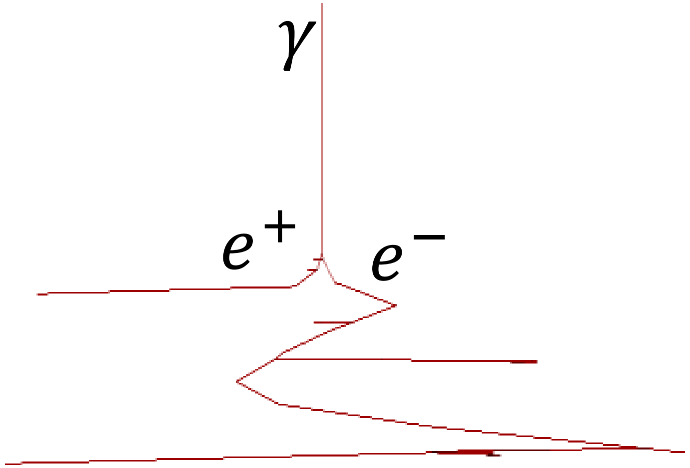
 Source: F. Schmidt, J.Knapp – https://www-zeuthen.desy.de/~jknapp/fs/showerimages.html

Electro-magnetic

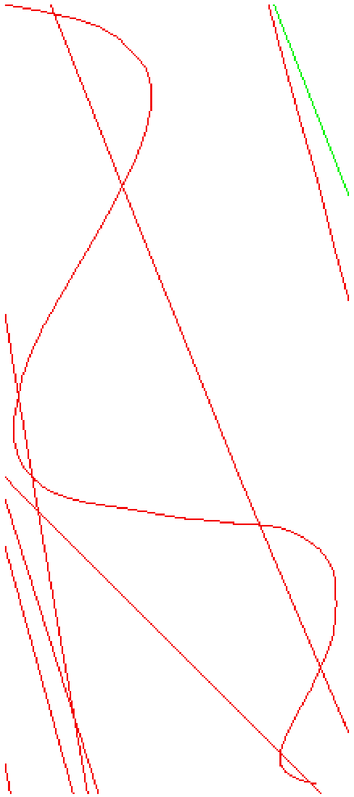
Bremsstrahlung



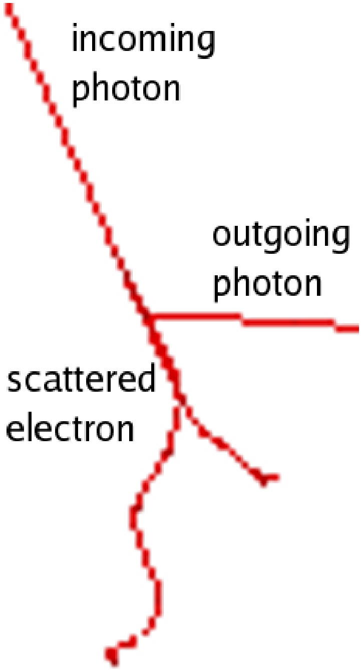
Pair Production



Magnetic deflection



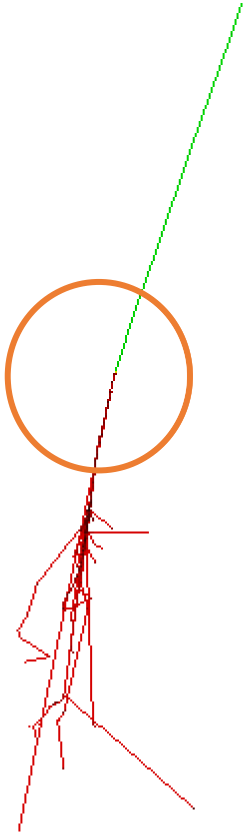
Compton scattering



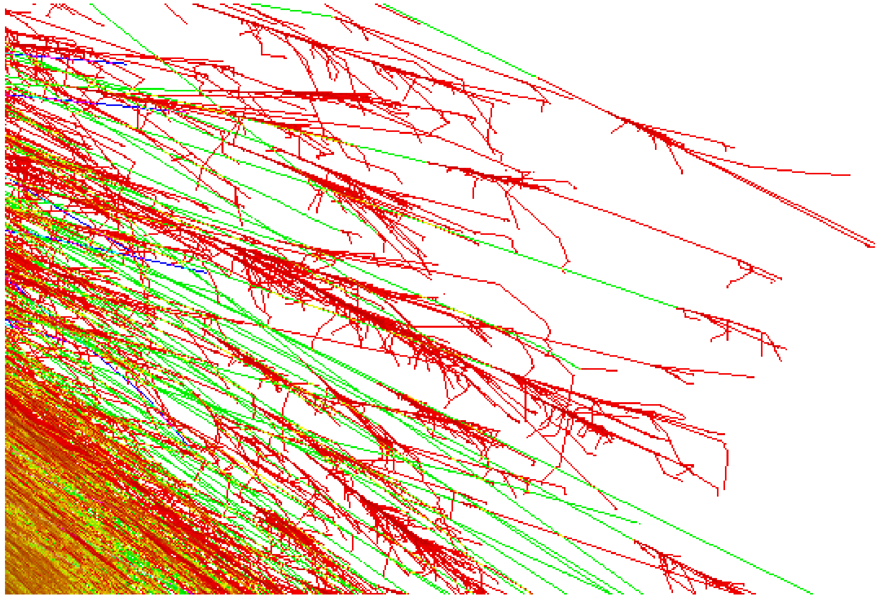
 Source: F. Schmidt, J.Knapp – https://www-zeuthen.desy.de/~jknapp/fs/showerimages.html

Muon Interactions

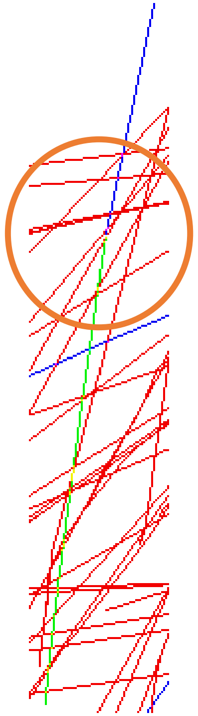
Muon decay



Outer region of shower



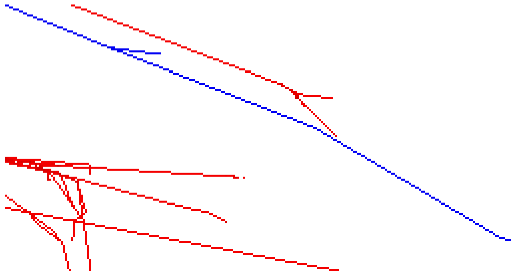
Charged Pion decay



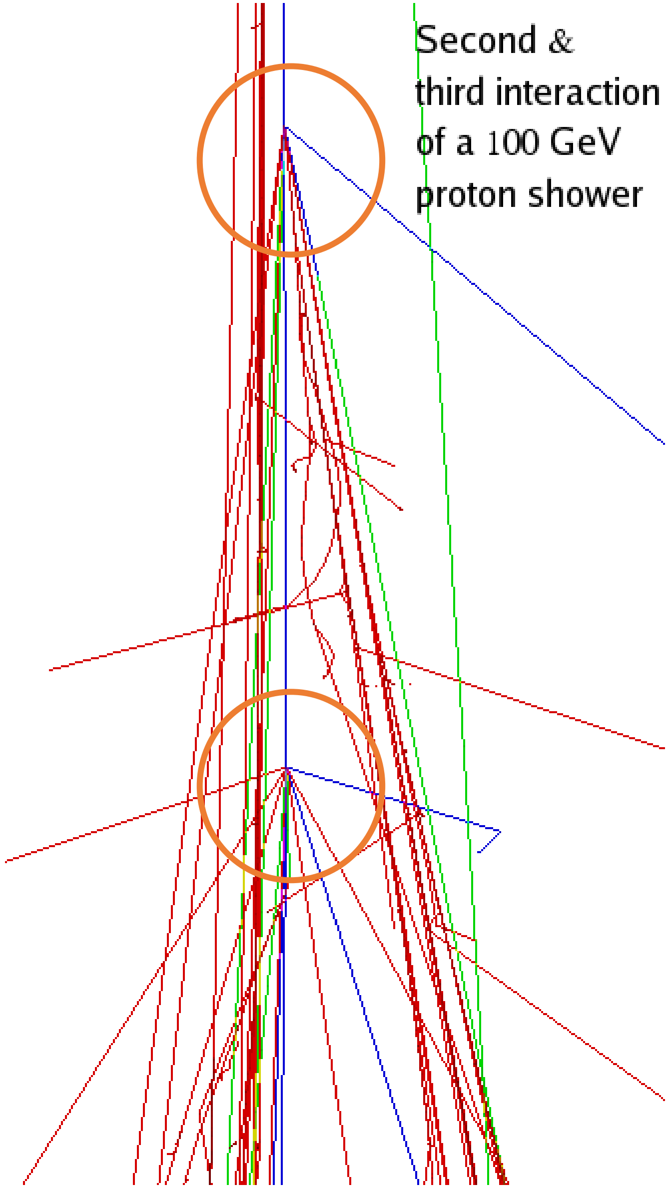
ν_μ ?

Hadron Interactions

Hadron-nucleus interaction



Hadronic decay



How to install ?

Download and unpack the code:

- from: https://web.iap.kit.edu/corsika/download/corsika-v770/
- Unpack using: tar –xvf corsika-77410.tar.gz
- Enter subdirectory: cd corsika-77410

For a “Normal” Linux distribution (gcc and gfortran):

- Execute: ./coconut

Options

After ./cocunut

```
|==========================================================================|
|                        Welcome to COCONUT (v3.1)                         |
|                -- the CORSIKA CONfiguration UTility --                   |
|==========================================================================|
|                                                                          |
|                                                                          |
|           create an executable of a specific CORSIKA version             |
|                                                                          |
|                                                                          |
|        Please read the documentation for a detailed description          |
|                   of the options and how to use it.                      |
|                                                                          |
|             Try './coconut -h' to get some help about COCONUT            |
|    Use './coconut --expert' to enable additional configuration steps.    |
|                                                                          |
| (press 'Enter' to select an option followed by "[DEFAULT]" or "[CACHED]")|
|                                                                          |
|==========================================================================|



*************************************************************************
*  INFO:                                                                *
*        You are using the cached configuration from "include/config.h". *
*        To turn off this you may use the --no-cache option.            *
*************************************************************************


-------------------------------------------------------------------------
Compile in 32 or 64bit mode ?
   1 - Force 32bit mode
   2 - Use compiler default ('-m64' on a 64bit machine) [CACHED]

   r - restart (reset all options to cached values)
   x - exit make

   (only one choice possible):
   SELECTED         : NOM32

-------------------------------------------------------------------------
```

Choosing energy models

```
-------------------------------------------------------------------------
Which high energy hadronic interaction model do you want to use ?
   1 - DPMJET-III (2017.1) with PHOJET 1.20.0
   2 - EPOS LHC
   3 - NEXUS 3.97
   4 - QGSJET 01C (enlarged commons)
   5 - QGSJETII-04
   6 - SIBYLL 2.3d [CACHED]
   7 - VENUS 4.12

   r - restart (reset all options to cached values)
   x - exit make

   (only one choice possible):

   ADDING CHARM

   SELECTED         : SIBYLL


-------------------------------------------------------------------------
```

```
-------------------------------------------------------------------------
Which low energy hadronic interaction model do you want to use ?
   1 - GHEISHA 2002d (double precision)
   2 - FLUKA-CERN
   3 - FLUKA-INFN
   4 - URQMD 1.3cr [CACHED]

   r - restart (reset all options to cached values)
   x - exit make
```

Options

Which detector type to use? → Experiment !!

```
--------------------------------------------------------------------------
Which detector geometry do you have ?
   1 - horizontal flat detector array [CACHED]
   2 - non-flat (volume) detector geometry
   3 - vertical string detector geometry

   r - restart (reset all options to cached values)
   x - exit make

   (only one choice possible):
```

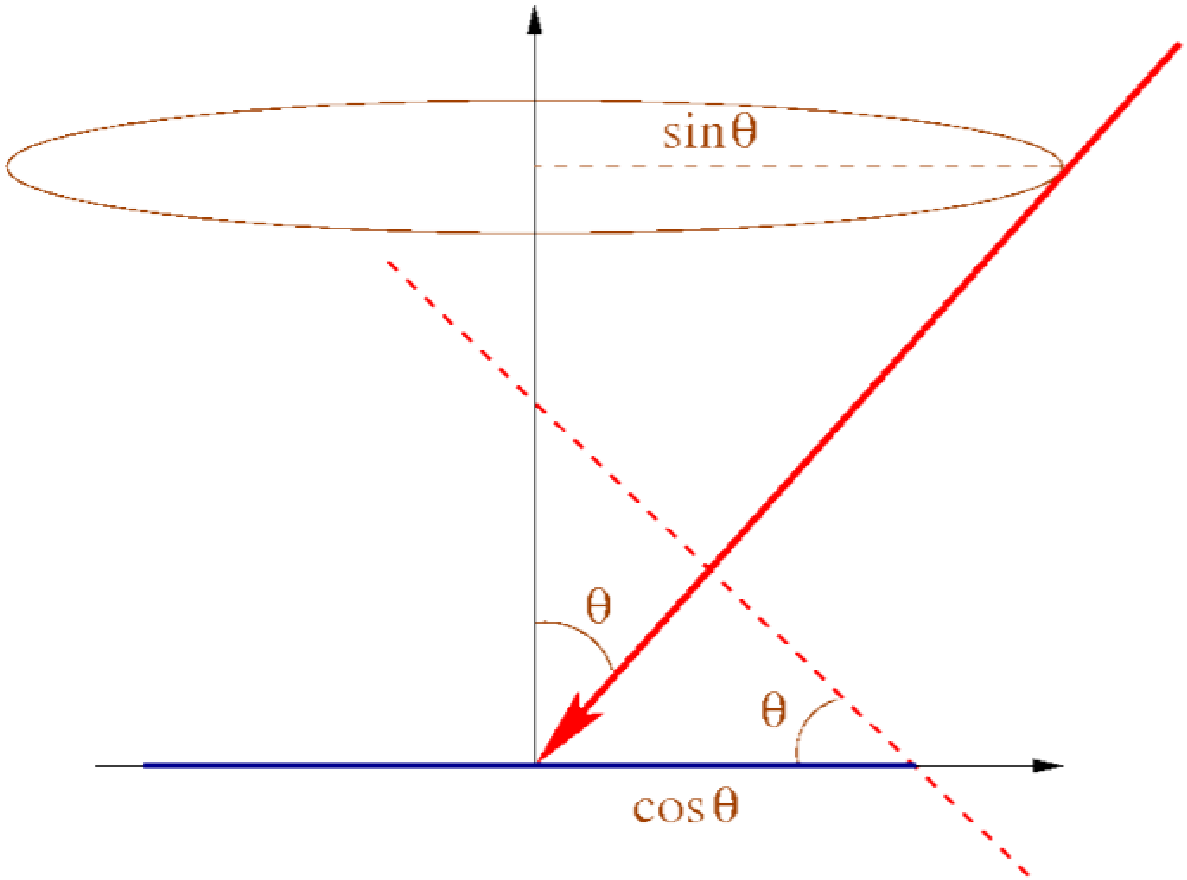
Flat: KASCADE, Pierre Auger Obs

Volume: Magic, HESS

Vertical String: IceCube, Antares

Detector types

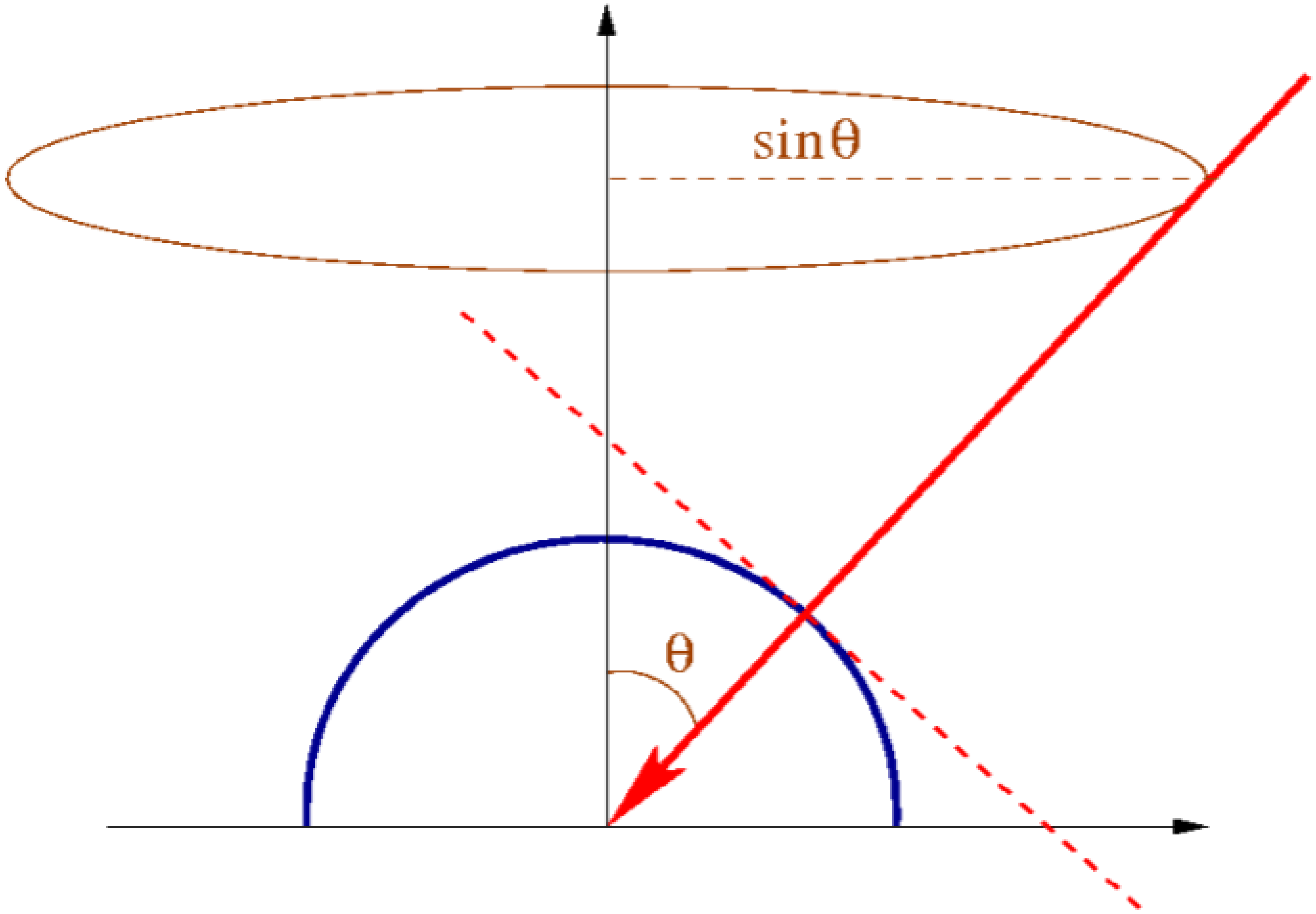
Horizontal flat detector



$$I \propto sin\theta \; cos\theta$$

 Source: T. Pierog – CORSIKA, Physics and technology

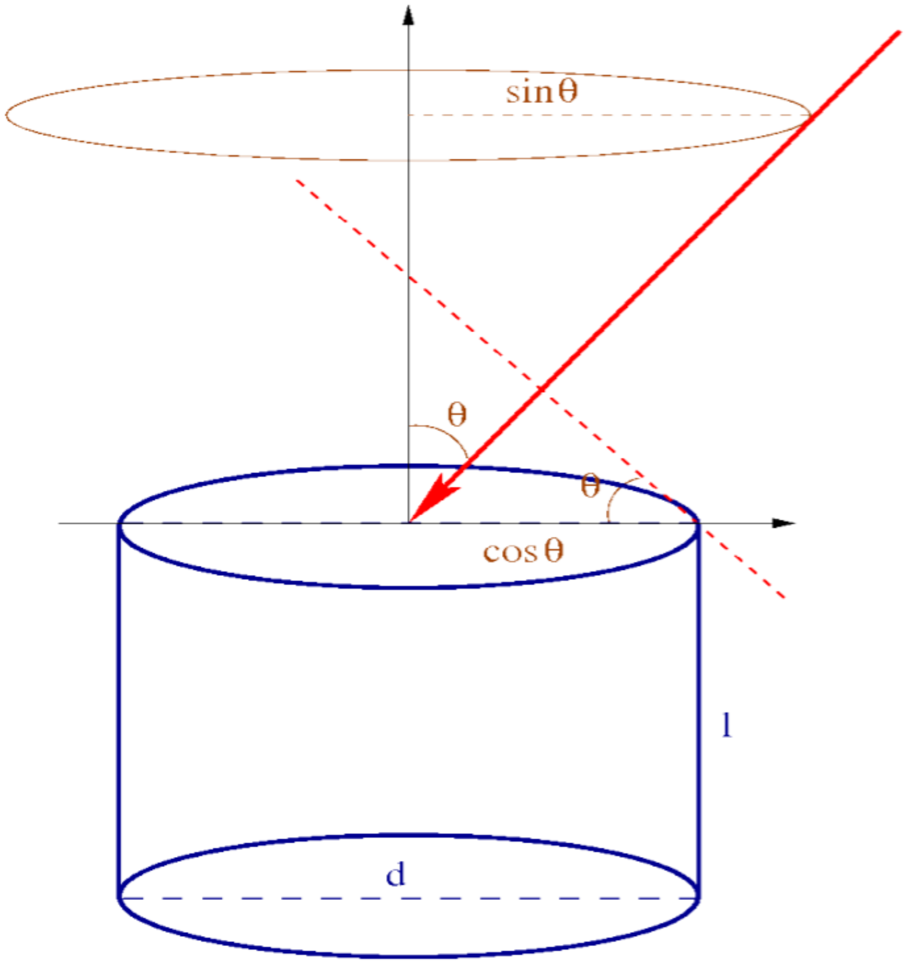
Non-flat (volume) detector



$$I \propto sin\theta$$

Detector types

Vertical string detector



$$I \propto \left(\frac{d}{2}\right)^2 \pi sin\theta(cos\theta + \frac{4ldsin\theta}{\pi})$$

 Source: T. Pierog – CORSIKA, Physics and technology

Options

```
Which additional CORSIKA program options do you need ?
   1a - Cherenkov version
   1b - Cherenkov version using Bernlohr IACT routines (for telescopes)
   1c - apply atm. absorption, mirror reflectivity & quantum eff.
   1d - Auger Cherenkov longitudinal distribution
   1e - TRAJECTory version to follow motion of source on the sky
   2 - LPM-effect without thinning
   2a - THINning version (includes LPM)
   2b - MULTIple THINning version (includes LPM)
   3 - PRESHOWER version for EeV gammas
   4 - NEUTRINO version
   4a - NUPRIM primary neutrino version with HERWIG
   4b - ICECUBE1 FIFO version
   4c - ICECUBE2 gzip/pipe output
   5 - STACK INput of secondaries, no primary particle
   6 - CHARMed particle/tau lepton version with PYTHIA
   6a - TAU LEPton version with PYTHIA
   7 - SLANT depth instead of vertical depth for longi-distribution
   7a - CURVED atmosphere version
   7b - UPWARD particles version
   7c - VIEWCONE version
   8a - shower PLOT version (PLOTSH) (only for single events)
   8b - shower PLOT(C) version (PLOTSH2) (only for single events)
   8c - ANAlysis HISTos & THIN (instead of particle file)
   8d - Auger-histo file & THIN
   8e - MUON-histo file
   9 - external atmosphere functions (table interpolation)
        (using bernlohr C-routines)
   9a - EFIELD version for electrical field in atmosphere
   9b - RIGIDITY Ooty version rejecting low-energy primaries entering Earth-magnetic field
   10a - DYNamic intermediate particle STACK
   10b - Remote Control for Corsika
   a - CONEX for high energy MC and cascade equations
   b - PARALLEL treatment of subshowers (includes LPM)
   c - CoREAS Radio Simulations
   d1 - Inclined observation plane
   e - interaction test version (only for 1st interaction)
   f - Auger-info file instead of dbase file
   g - COMPACT particle output file
   h - MUPROD to write decaying muons
   h2 - prEHISTORY of muons: mother and grandmother
   l - NRREXT enable run number extension
   m - hit Auger detector (steered by AUGSCT)
     - ----------------------------------------
   y - *** Reset selection ***
   z - *** Finish selection *** [DEFAULT]

   r - restart (reset all options to cached values)
   x - exit make

   (multiple selections accepted, leading '-' removes option):
```

Many other options i.e.:

- Cherenkov light
- Faster simulations (THINning)
- Parallelization
- Curved earth
- External atmosphere models
- E-field in atmosphere
- …

Shower Parameters

CORSIKA input file

```
RUNNR    1                                run number
EVTNR    1                                number of first shower event
NSHOW    1                                number of showers to generate
PRMPAR   14                               particle type of prim. particle
ESLOPE   -2.7                             slope of primary energy spectrum
ERANGE   1.E5   1.E5                      energy range of primary particle
THETAP   20.   20.                        range of zenith angle (degree)
PHIP     -180.   180.                     range of azimuth angle (degree)
SEED     1   0   0                        seed for 1. random number sequence
SEED     2   0   0                        seed for 2. random number sequence
OBSLEV   110.E2                           observation level (in cm)
FIXCHI   0.                               starting altitude (g/cm**2)
MAGNET   20.0   42.8                      magnetic field centr. Europe
HADFLG   0  0  0  0  0  2                 flags hadr.interact.&fragmentation
ECUTS    0.3  0.3  0.003  0.003           energy cuts for particles
MUADDI   T                                additional info for muons
MUMULT   T                                muon multiple scattering angle
ELMFLG   T   T                            em. interaction flags (NKG,EGS)
STEPFC   1.0                              mult. scattering step length fact.
RADNKG   200.E2                           outer radius for NKG lat.dens.distr.
LONGI    T  10.   T   T                   longit.distr. & step size & fit & out
MAXPRT   1                                max. number of printed events
DIRECT   ./                               output directory
USER     you                              user
DEBUG    F   6   F   1000000              debug flag and log.unit for out
EXIT                                      terminates input
```

Executing a file:

./corsika_executable < input_file

3 types of controls:

- Shower parameters
- Options parameters
- Output parameters

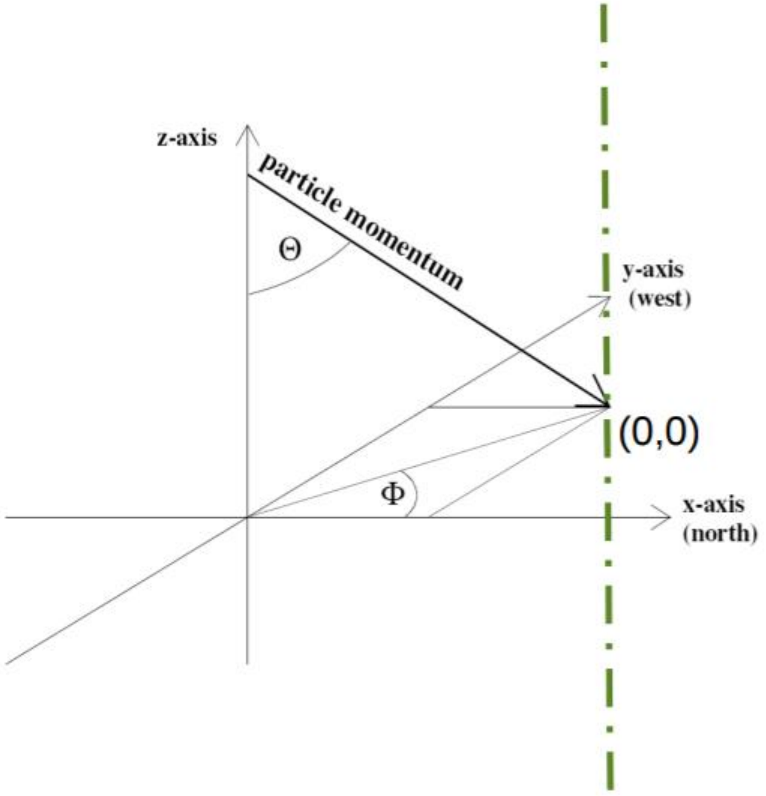
Shower parameters

CORSIKA particle identification

Identification	Particle	Identification	Particle
Particle identifications			
1	γ	50	ω
2	e^+	51	ρ°
3	e^-	52	ρ^+
		53	ρ^-
5	μ^+	54	Δ^{++}
6	μ^-	55	Δ^+
7	π°	56	Δ°
8	π^+	57	Δ^-
9	π^-	58	$\overline{\Delta}^{--}$
10	K_L°	59	$\overline{\Delta}^-$
11	K^+	60	$\overline{\Delta}^\circ$
12	K^-	61	$\overline{\Delta}^+$
13	n	62	$K^{*\circ}$
14	p	63	K^{*+}
15	$\overline{p}$	64	$\overline{K^*}^-$
16	K_S°	65	$\overline{K^*}^\circ$
17	η	66	ν_e
18	Λ	67	$\overline{\nu}_e$
19	Σ^+	68	ν_μ
20	Σ°	69	$\overline{\nu}_\mu$
21	Σ^-		
22	Ξ°	71	$\eta \rightarrow \gamma\gamma$
23	Ξ^-	72	$\eta \rightarrow 3\pi^\circ$
24	Ω^-	73	$\eta \rightarrow \pi^+\pi^-\pi^\circ$
25	$\overline{n}$	74	$\eta \rightarrow \pi^+\pi^-\gamma$
26	$\overline{\Lambda}$	75	μ^+ add. info.
27	$\overline{\Sigma}^-$	76	μ^- add. info.
28	$\overline{\Sigma}^\circ$		
29	$\overline{\Sigma}^+$	85	decaying μ^+ at start[94]
30	$\overline{\Xi}^\circ$	86	decaying μ^- at start[94]
31	$\overline{\Xi}^+$		
32	$\overline{\Omega}^+$	95	decaying μ^+ at end[94]
48	η'	96	decaying μ^- at end[94]
49	ϕ		

Identification	Particle	Identification	Particle
Particle identifications (continued)			
116	D°	155	$\overline{\Xi'_c}^-$
117	D^+	156	$\overline{\Xi'_c}^\circ$
118	$\overline{D}^-$	157	$\overline{\Omega_c}^\circ$
119	$\overline{D}^\circ$		
120	D_s^+	161	Σ_c^{*++}
121	$\overline{D_s}^-$	162	Σ_c^{*+}
122	η_c	163	$\Sigma_c^{*\circ}$
123	$D^{*\circ}$		
124	D^{*+}	171	$\overline{\Sigma_c^*}^{--}$
125	$\overline{D^*}^-$	172	$\overline{\Sigma_c^*}^-$
126	$\overline{D^*}^\circ$	173	$\overline{\Sigma_c^*}^\circ$
127	D_s^{*+}		
128	$\overline{D_s^*}^-$	176	B°
		177	B^+
130	J/ψ	178	$\overline{B}^-$
131	τ^+	179	$\overline{B}^\circ$
132	τ^-	180	B_s°
133	ν_τ	181	$\overline{B_s}^\circ$
134	$\overline{\nu}_\tau$	182	B_c^+
		183	$\overline{B_c}^-$
137	Λ_c^+	184	Λ_b°
138	Ξ_c^+	185	Σ_b^-
139	Ξ_c°	186	Σ_b^+
140	Σ_c^{++}	187	Ξ_b°
141	Σ_c^+	188	Ξ_b^-
142	Σ_c°	189	Ω_b^-
143	$\Xi_c^{\prime +}$	190	$\overline{\Lambda_b}^\circ$
144	$\Xi_c^{\prime\circ}$	191	$\overline{\Sigma_b}^+$
145	Ω_c°	192	$\overline{\Sigma_b}^-$
		193	$\overline{\Xi_b}^\circ$
149	$\overline{\Lambda_c}^-$	194	$\overline{\Xi_b}^+$
150	$\overline{\Xi_c}^-$	195	$\overline{\Omega_b}^+$
151	$\overline{\Xi_c}^\circ$		
152	$\overline{\Sigma_c}^{--}$		
153	$\overline{\Sigma_c}^-$		
154	$\overline{\Sigma_c}^\circ$		
A × 100 + Z	nucleus of Z protons and A − Z neutrons ($2 \leq A \leq 56$)		
$8888jjj$	weights of preceding particle (MULTITHIN option)		
9900	Cherenkov photons on particle output file		

CORSIKA reference system



reference axis used in many experiments

Hands-On !!

Summary

CORSIKA is a good program but not perfect

Cosmic shower simulation is a heavy and long computer task

Wait for CORSIKA 8 with new improvements and more user friendly

Questions?