Hands-on high-energy shower modelling: CORSIKA and CONEX for Air Shower Simulations

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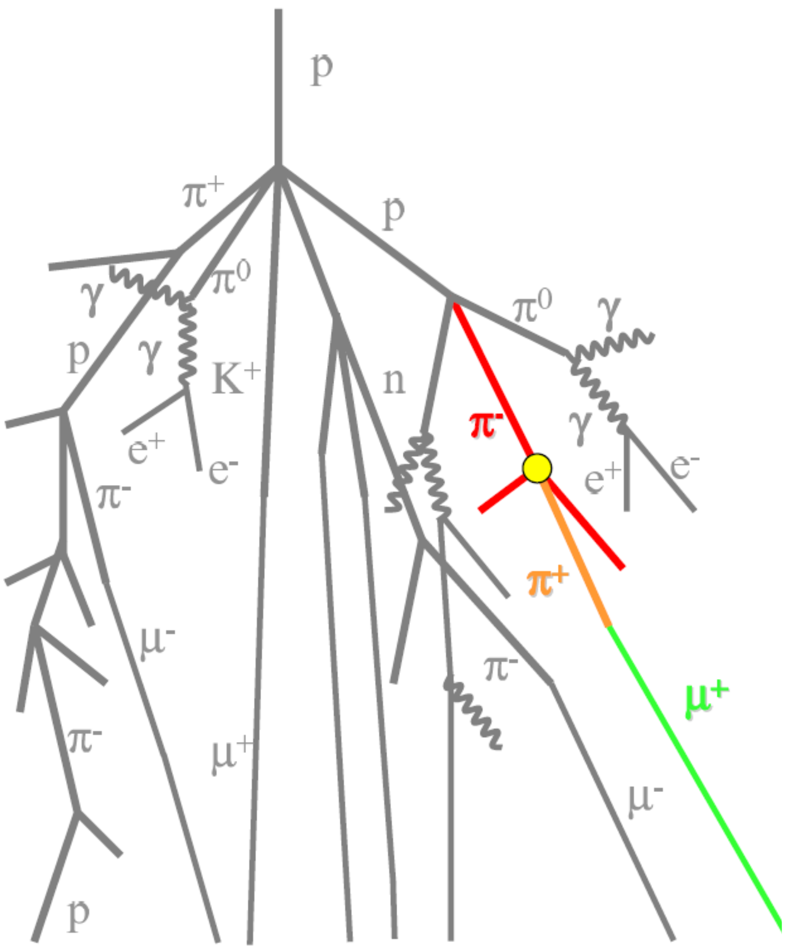
Outline

- Introduction
- Options and outputs
- Faster simulations
- Hands-on

Extensive Air Shower



From R. Ulrich (KIT)

$A + air \rightarrow$ hadrons
$p + air \rightarrow$ hadrons
$\pi + air \rightarrow$ hadrons
intial γ from π^0 decay

main source of uncertainties

$e^{\pm} \rightarrow e^{\pm} + \gamma$
$\gamma \rightarrow e^{+} + e^{-}$

well known

$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_\mu / \bar{\nu_\mu}$

Cascade of particle in Earth's atmosphere

Number of particles at maximum

- 99,88% of electromagnetic (e/m) particles
- 0.1% of muons
- 0.02% hadrons

Energy

- from 100% hadronic to 90% in e/m + 10% in muons at ground (vertical)

Origin

30+ years of development …

- Reminder : COsmic Ray SImulations for KASCADE

- 1989 : original design optimized for vertical showers on a flat array detector using monte-carlo technique
- 1994< : extension to different type of experiments
  - Cherenkov, fluorescence light, inclined showers, ...
- 2010< : extension to new type of simulations
  - cascade equations, parallelization, different media ...

Technicalities

source code :

- ~ 83 300 lines (without external programs) ~ 300 routines
- optional code : ~ 50 preprocessor options to be chosen during installation with ./coconut
- program language (portability) : Fortran 77 / 90 + some few C-routines

steering input :

- free format with key words + parameters
- ~ 100 key words

documentation :

- physics: FZKA 6019 (1998)
- Webpage (documentations) : <https://www.iap.kit.edu/corsika/>

availability:

- download from web : <https://web.iap.kit.edu/corsika/download/>
- Access by registration to our new mailing list (by email)
- Last release : v7.7410 (30.04.2021)

Models Selection

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

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

    (only one choice possible):
Use program EPOS LHC for linking
    SELECTED         : EPOS
    NOT COMPATIBLE TO: CHARM


--------------------------------------------------------------------------
 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 [DEFAULT]

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

    (only one choice possible):
Use program UrQMD 1.3c for linking
    SELECTED         : URQMD


--------------------------------------------------------------------------
 Which detector geometry do you have ?
    1 - horizontal flat detector array [DEFAULT]
    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):
    SELECTED         : HORIZONTAL


--------------------------------------------------------------------------
  options:   TIMEAUTO URQMD EPOS HORIZONTAL
```

First selection is the high energy hadronic interaction model :

- See other talks on models to select the most suitable for your application
  - up-to-date:
    - EPOS LHC, QGSJETII-04 and SIBYLL 2.3d
    - DPMJETIII.17-1 has problem at very high energies
  - Reference:
    - EPOS LHC
  - special use:
    - others

Low energy hadronic interaction model

- FLUKA, Gheisha, UrQMD

Geometry Selection

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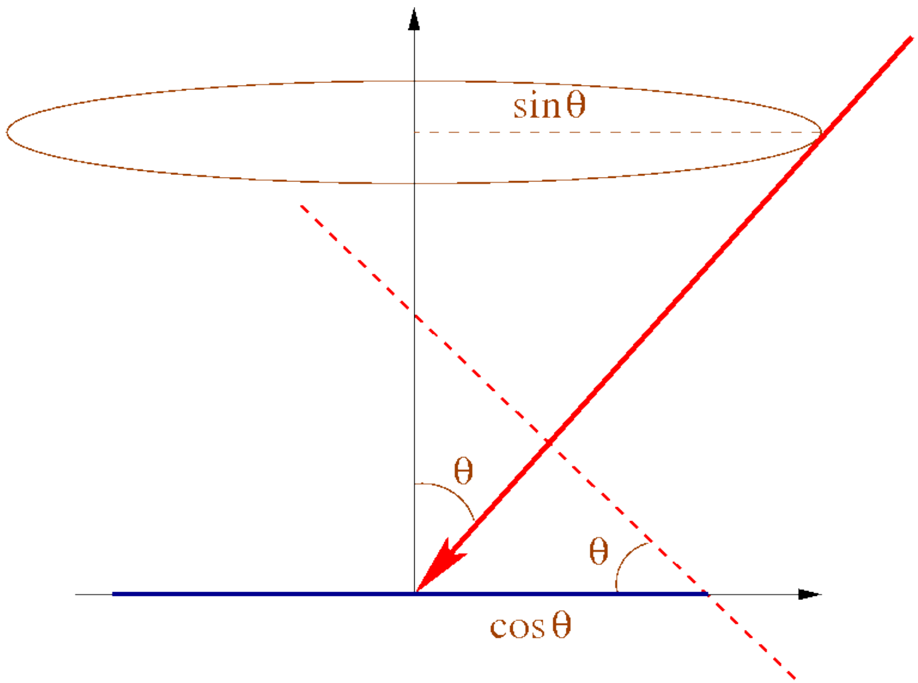
Detector geometry (only change the angular distribution of showers)

- Horizontal flat detector
  (KASCADE, Pierre Auger Obs,...)
- Non-flat (volume) detector
  (Magic, HESS,...)
- Vertical String detector
  (AMANDA, IceCube, Antares, ...)

Geometry Selection



Detector geometry (only change the angular distribution of showers)

- Horizontal flat detector
  (KASCADE, Pierre Auger Obs,...)
  - $I \propto sin\theta \cdot cos\theta$
- Non-flat (volume) detector
  (Magic, HESS,...)
- Vertical String detector
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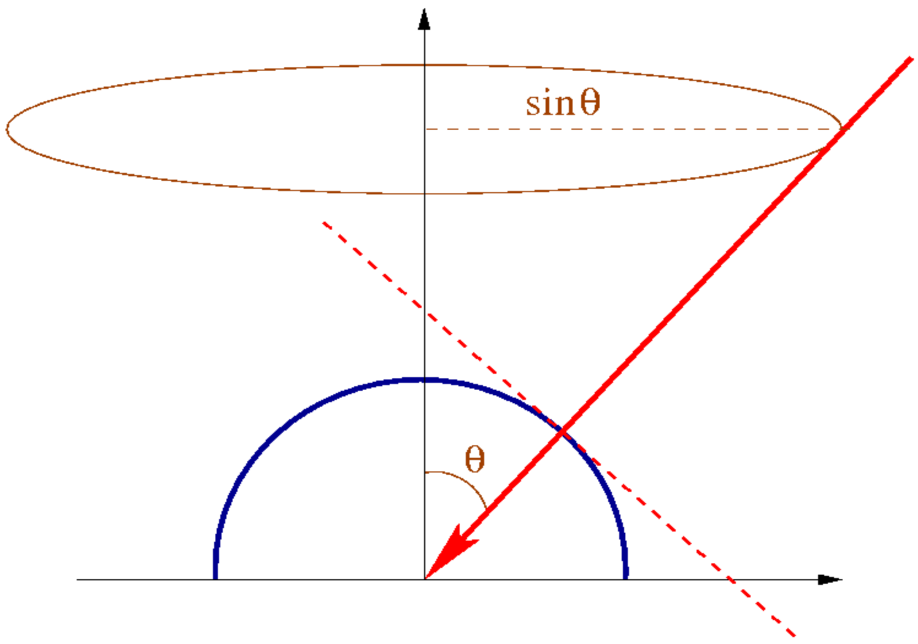
Geometry Selection



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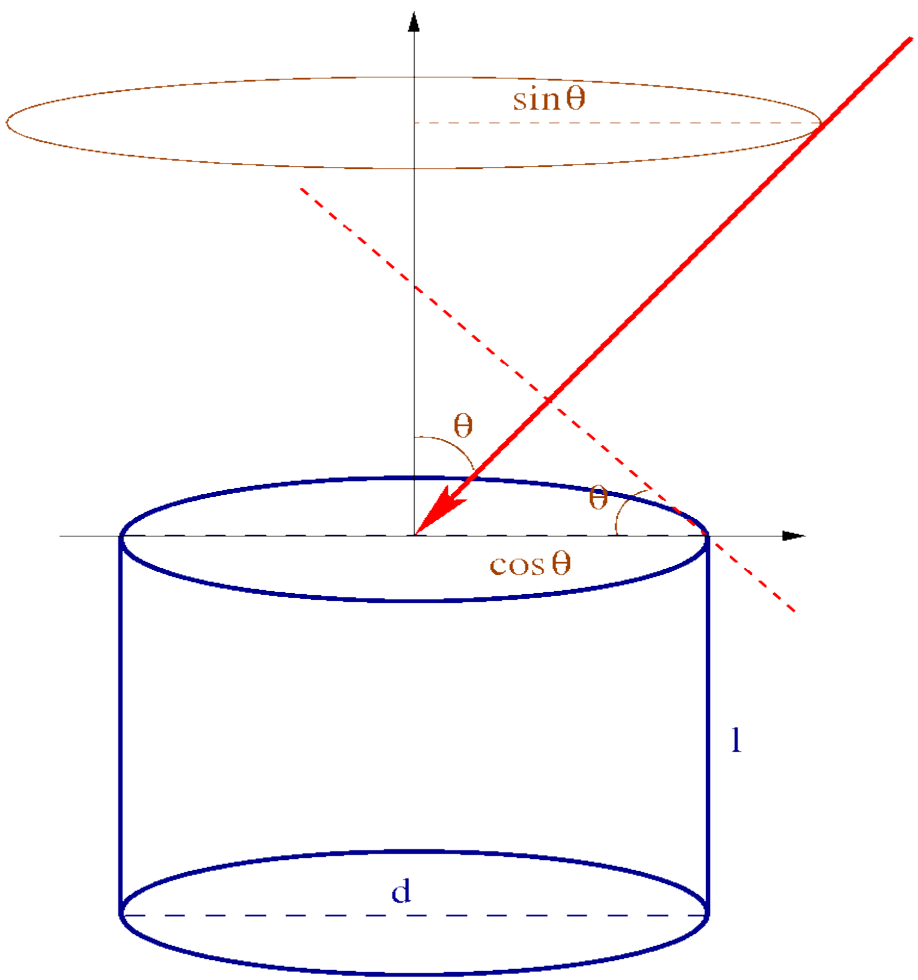

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$$I \propto (d/2)^2 \cdot \pi \cdot sin\theta \cdot (cos\theta + 4/\pi \cdot l/d \cdot sin\theta)$$

Cherenkov Light

```
Which additional CORSIKA program options do you need ?
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   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
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   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
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   10a - DYNamic intermediate particle STACK
   10b - Remote Control for Corsika
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   b - PARALLEL treatment of subshowers (includes LPM)
   c - CoREAS Radio Simulations
   d - Use an external COAST user library (COrsika data AccesS Tool)
   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
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```

1a – Cherenkov for rectangular grid

- cherenkov array at ground

1b – Cherenkov for det. system (IACT)

- HESS, Magic ...
  - with extension for more informations on particles

1c – atmospheric corrections (CEFFIC)

- suppression of part of the cherenkov photons (use to speed-up simulations)
  - light absorption in atmosphere
  - mirror reflectivity
  - quantum efficiency

Options ...

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```

1d – Auger Cherenkov long. prof.

- not full simulation but time consuming

1e – Trajectory

- follow motion of source on the sky

2 – LPM effect

- only if no thinning and high energy showers (with thinning, LPM included)

2a – Thinning

- Needed for high energy simulations to save time and disk space

2b – MULTIple THINning

Options ...

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```

3 – PRESHOWER

- preshowering of gamma primary before atmosphere

4 – Neutrino version

- add neutrino into list of particle

4a – NUPRIM

- use HERWIG to have neutrino as primary particle
  - only primary neutrino will interact

4b – ICECUBE1 (fifo)

4c – ICECUBE2 (pipe output)

5 – STACKIN

- start shower with a list of particle

Options ...

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6 – CHARM

- track and decay (using PYTHIA) charmed particles produced by QGSJET01 or DPMJET 2.55

6a – TAULEP

- for Tau lepton propagation and decay (using PYTHIA)

7 – Slant

- longitudinal profile as a function of slant depth and not vertical depth (default)

7a – Curved

- use a curved atmosphere instead of flat (default)
  - needed for large angles (>70°)

Options ...

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7b – Upward

- track particle going upward
- allows upward going showers

7c – View-cone

- restrict primary angle generation to a cone around a given direction
  - to be used for atmospheric cherenkov detectors.

8a – PLOTSH

- only to make a “picture” of the shower

8b – PLOTSH2

- more compact output for PLOTSH (need some special library)

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8c – ANAHIST

- plot various particle distributions from air shower in hbook file
    - Longitudinal prof, LDF, time, weight, ...

8d – Auger-histos

- hbook file but with many layers

8e – MUON-histo

- hbook file for muon production depth and muon distribution study

9 – External atmosphere

- Using Bernlohr C-routines.

9a – Efield

9b – RIGIDITY (Grappes)

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   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
   d - Use an external COAST user library (COrsika data AccesS Tool)
   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):
 Are you sure you want to continue with these current option selection:

   yes or no ? (default: yes) >
```

10a – DYNSTAC

10b – REMOTE control

a – CONEX

- use cascade equations to reduce simulation time
  - various option for 1D or 3D

b – PARALLEL

- parallel calculation
  - shell script or MPI

c – CoREAS

- radio signal emission from air shower
  - needs more input files

COAST 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
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   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):
 Are you sure you want to continue with these current option selection:

   yes or no ? (default: yes) >
```

d1 – Inclined

- arbitrary direction for obs. level

(d2 – ROOTOUT)

- produce the DAT file in ROOT

(d3 – COASTUSERLIB)

- appear only if COAST is installed
- to use COAST as external package for shower analysis

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
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   8c - ANAlysis HISTos & THIN (instead of particle file)
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   9a - EFIELD version for electrical field in atmosphere
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   10a - DYNamic intermediate particle STACK
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   a - CONEX for high energy MC and cascade equations
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   c - CoREAS Radio Simulations
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   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):
 Are you sure you want to continue with these current option selection:

   yes or no ? (default: yes) >
```

e – Interaction test

- only first interaction to plot particle distributions (hbook)

f – Auger info file

- special output file on generated showers (primary parameters)

g – COMPACT output

- compact output file to be used for low energy showers with few particles at ground

h – MUPROD

- write in particle list produced muons which do not reach observation level

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)
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   8a - shower PLOT version (PLOTSH) (only for single events)
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   8c - ANALysis HISTos & THIN (instead of particle file)
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   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):
 Are you sure you want to continue with these current option selection:

   yes or no ? (default: yes) >
```

h2 – preHISTORY

- to get information about mother and grandmother particles of particles arriving at ground
  - MUADDI : muons
  - EMADDI : electrons and photons

l – NRREXT

- Extended the number of digit for the run number to 999999999

l – Auger Hit

If Cherenkov

```
--------------------------------------------------------------------------------
Cherenkov light vertical (longitudinal) distribution option ?
   1 - Photons counted only in the step where emitted [DEFAULT]
   2 - Photons counted in every step down to the observation level
       (compatible with old versions but inefficient)
   3 - No Cherenkov light distribution at all

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

   (only one choice possible):
   SELECTED         : INTCLONGSTD


--------------------------------------------------------------------------------
Do you want Cherenkov light emission angle wavelength dependence ?
   1 - Emission angle is wavelength independent [DEFAULT]
   2 - Emission angle depending on wavelength

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

   (only one choice possible):
   SELECTED         : CERWLENOFF
   SELECTED         : CERENKOV
   NOT COMPATIBLE TO: COMPACT VOLUMECORR INTTEST ANAHIST AUGERHIST MUONHIST AUGCERLONG ICECUE
ICECUBE2
```

Che. longitudinal distribution

- differential (prod. per bin)
- integrated (sum in bin)
- none

Che. light emission

- refraction index wavelength independent
- refraction index wavelength dependent
  - emission angle change at low energy

Output Types

4 different types of output files :

- Control output (text file)
- Particle list (binary files)
  - DAT file for secondary particles of shower
  - CER file for Cherenkov photons
- Histograms
  - LONGitudinal profile and energy deposit (ASCII)
  - ANAHIST (CERNLIB)
  - AUGERHIST (CERNLIB)
  - MUONHIST (CERNLIB)
  - First Interaction (CERNLIB)
  - COAST (with or withoutROOT)
- Infos on shower production
  - DBASE
  - INFO (Auger)

ROOT Outputs

ROOT output files :

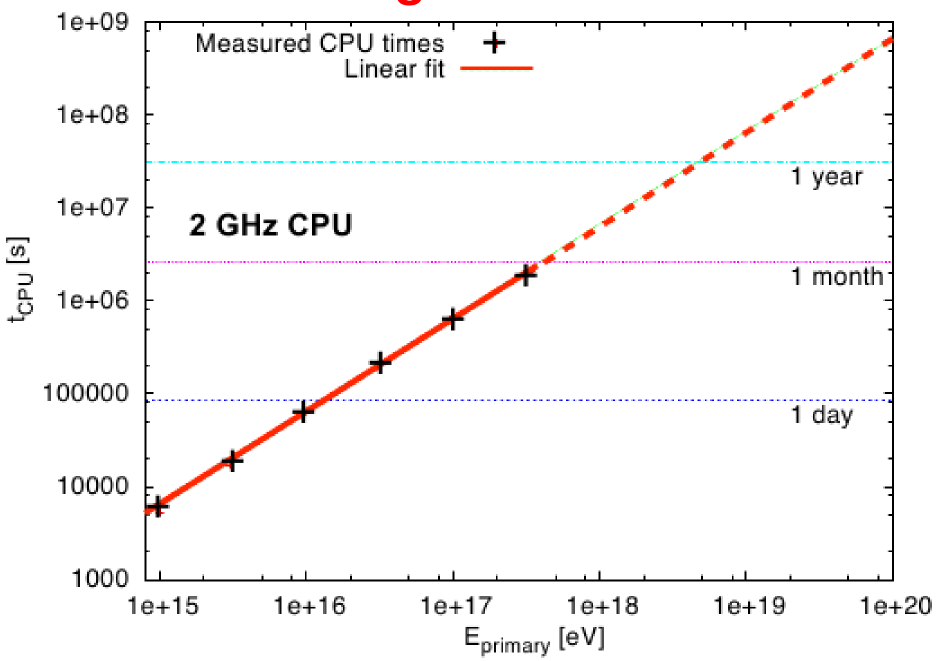
- Using RootOut
  - not recommended because of size and structure limitations
- Using COAST
  - self defined and linked dynamically when information are extracted at running time (all tracks and hadronic interactions available)
- From DAT files (recommended)
  - tools provided to convert the standard DAT file into ASCII or ROOT file with self defined structure

Limitations in Air Shower Simulations

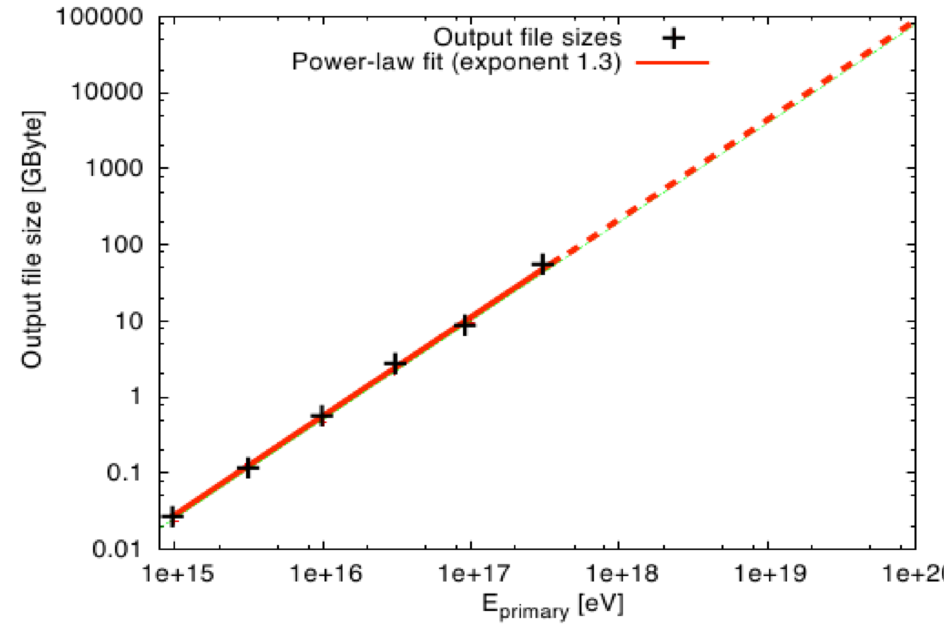
Analysis based on air shower simulations affected by 2 main problems :

- limited statistic due to :

Large CPU time



Large disk space



  - same problem for high statistic OR high energy

- uncertainties due to hadronic interactions
  - See later

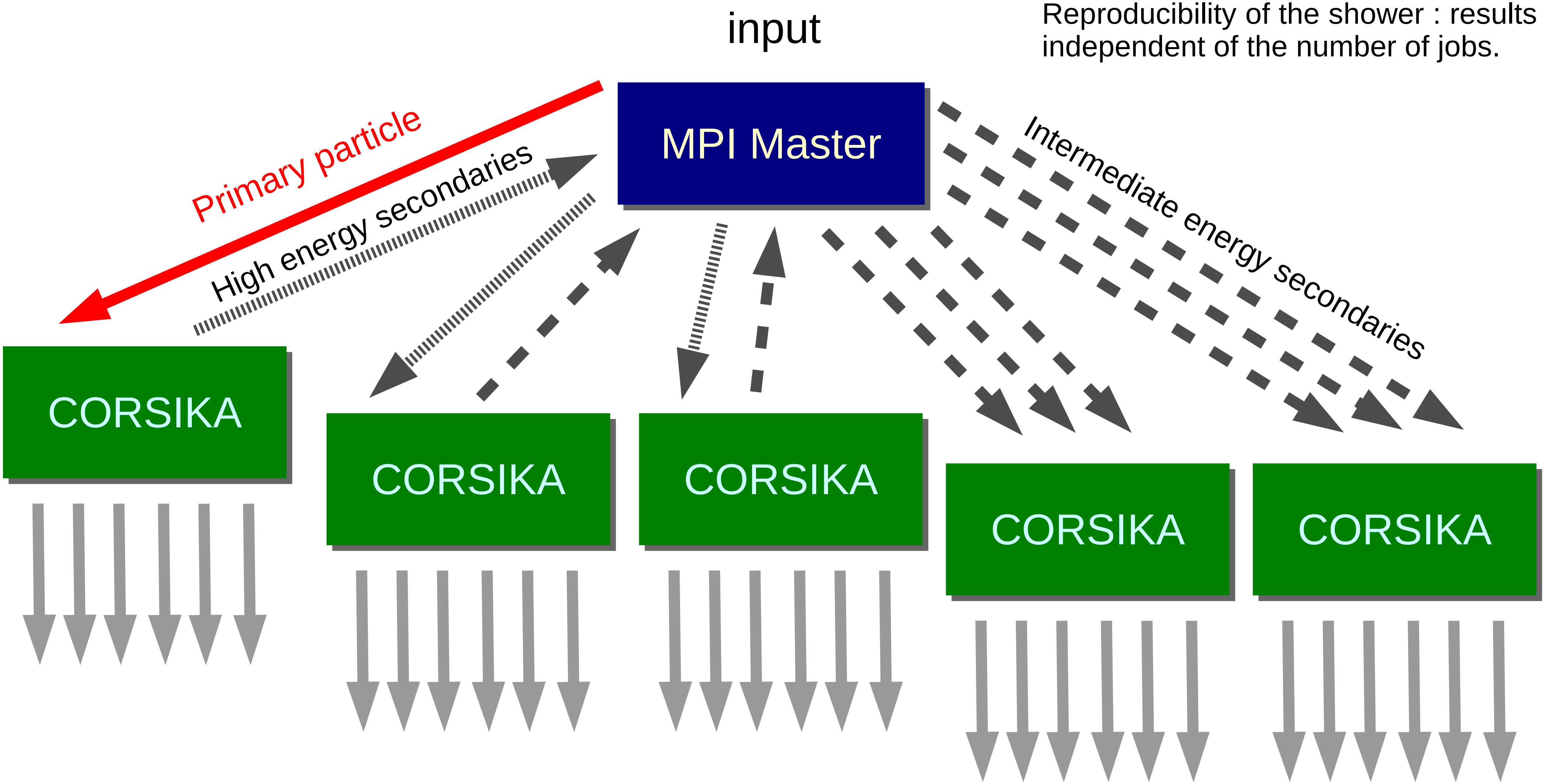
Current Solutions in CORSIKA

- **Most commonly used : thinning**
  - number of particles reduced by introducing weight
  - after each interaction only one particle kept
    - weight to conserve energy (not particle number)
  - introduce artificial fluctuations
    - particles with large weight
  - limited effect using maximum weight

- **Alternative solutions for high energy showers**
  - parallelization
  - use of numerical solution of cascade equations (CE)

Parallelization of CORSIKA with MPI

Reproducibility of the shower : results independent of the number of jobs.

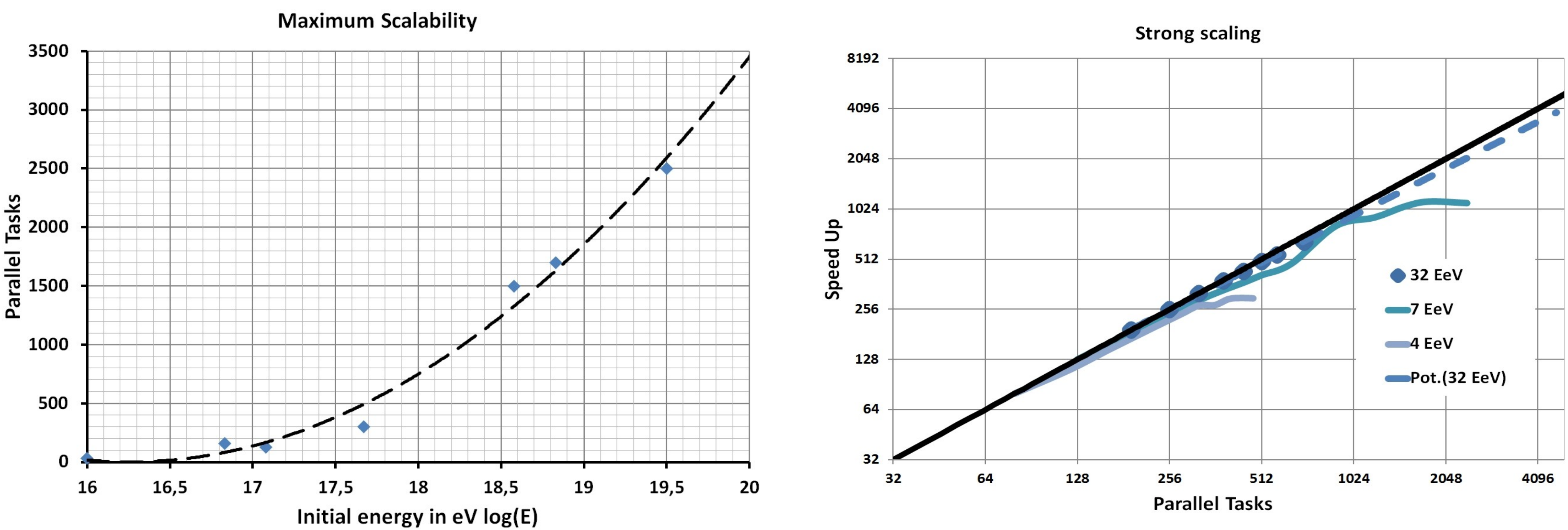


Low energy secondaries down to observation level

Parallelization of CORSIKA

- **Each shower is simulated on a large number of CPU**
  - ➜ Simulation time reduction limited by the number of machines
  - ➜ Disk space problem solved by saving particles in detectors only

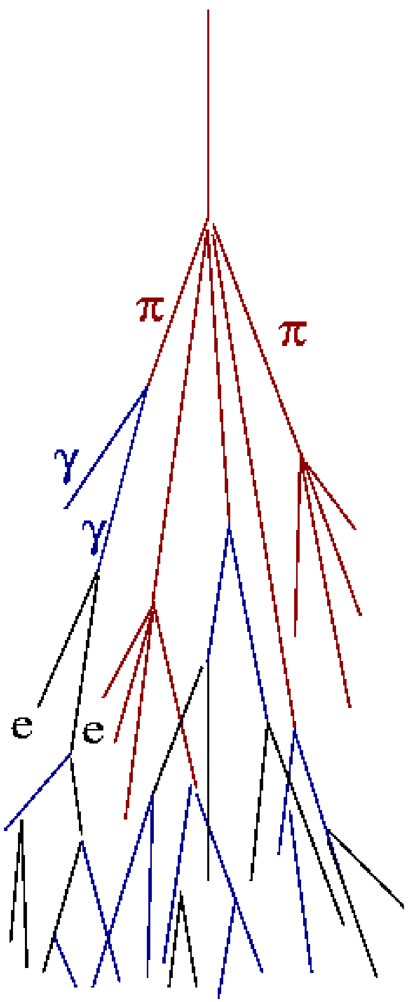
- **solution tested for high energy showers only**
  - ➜ electromagnetic shower not really parallelized ...

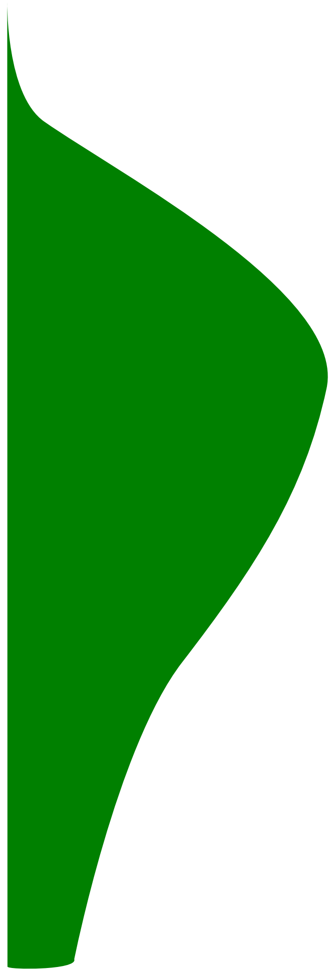


Parallel version tested on HP XC3000 (2.53 GHz CPUs, InfiniBand 4X QDR)

Air Shower Simulations

- **Air shower simulations, 2 main methods**
  - ➡ Full MC simulations
    - realistic
    - flexible
    - fluctuations
    - slow
  - ➡ Cascade Equations (CE)
    - fast
    - mean behavior
    - no fluctuations
    - limited to analytic formula ?

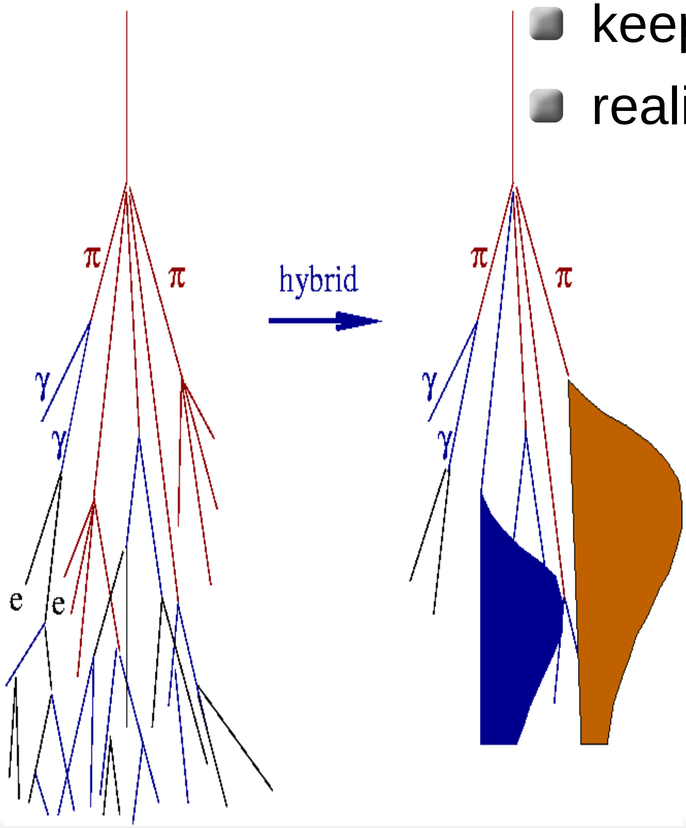




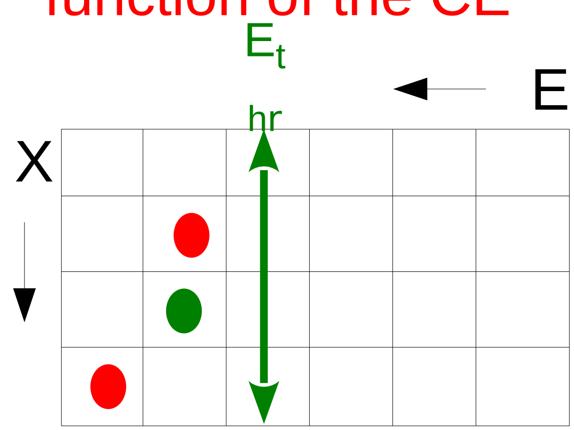
- **Can we have the best of the 2 ?**

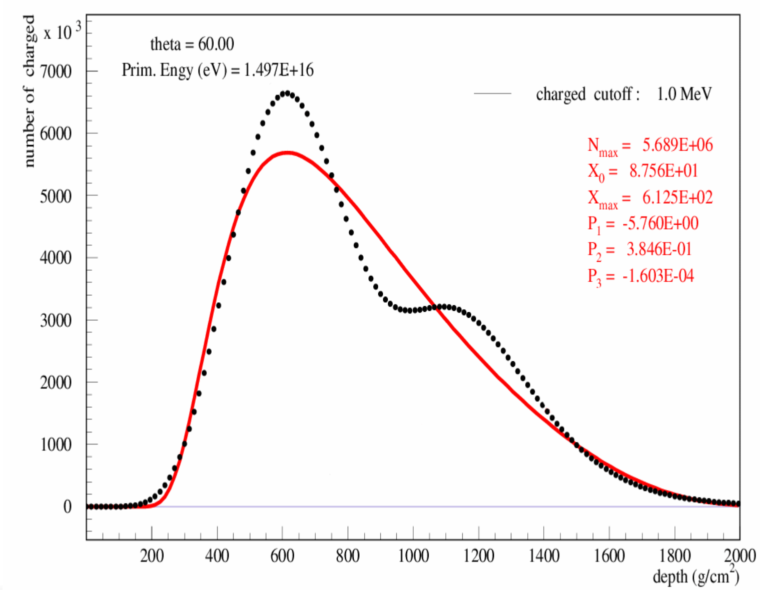
Consistent Hybrid Calculation

- **Numerical solution of cascade equations**
  - same cross-section, atmosphere, models for CE and MC
    - mixing possible : hybrid simulation
  - CE replace MC when number of particles is large ($E<E_{thr}$)
    - save lot of time
    - keep fluctuations
    - realistic 1D simulations (longitudinal profiles)

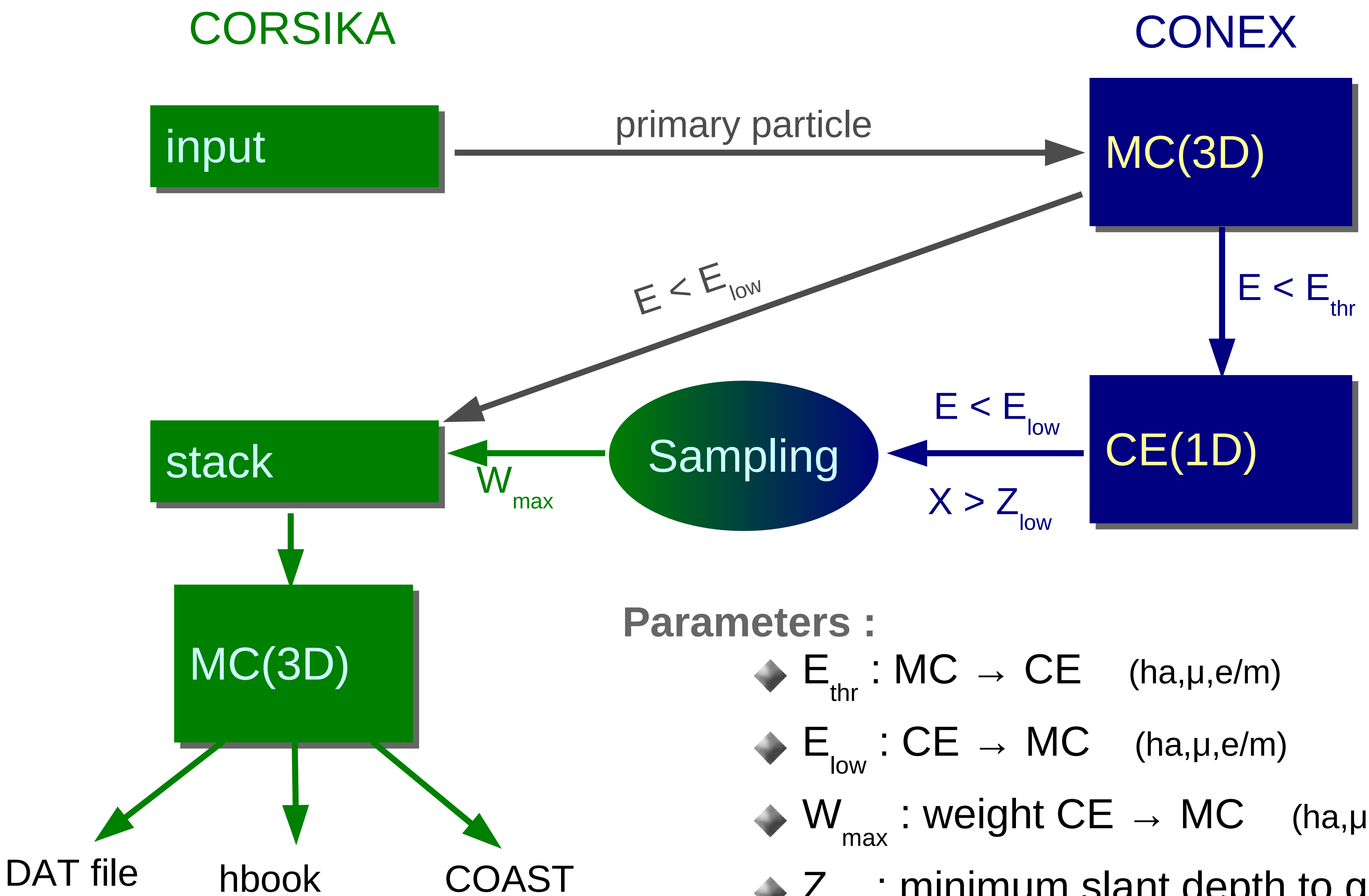


MC fill the source function of the CE





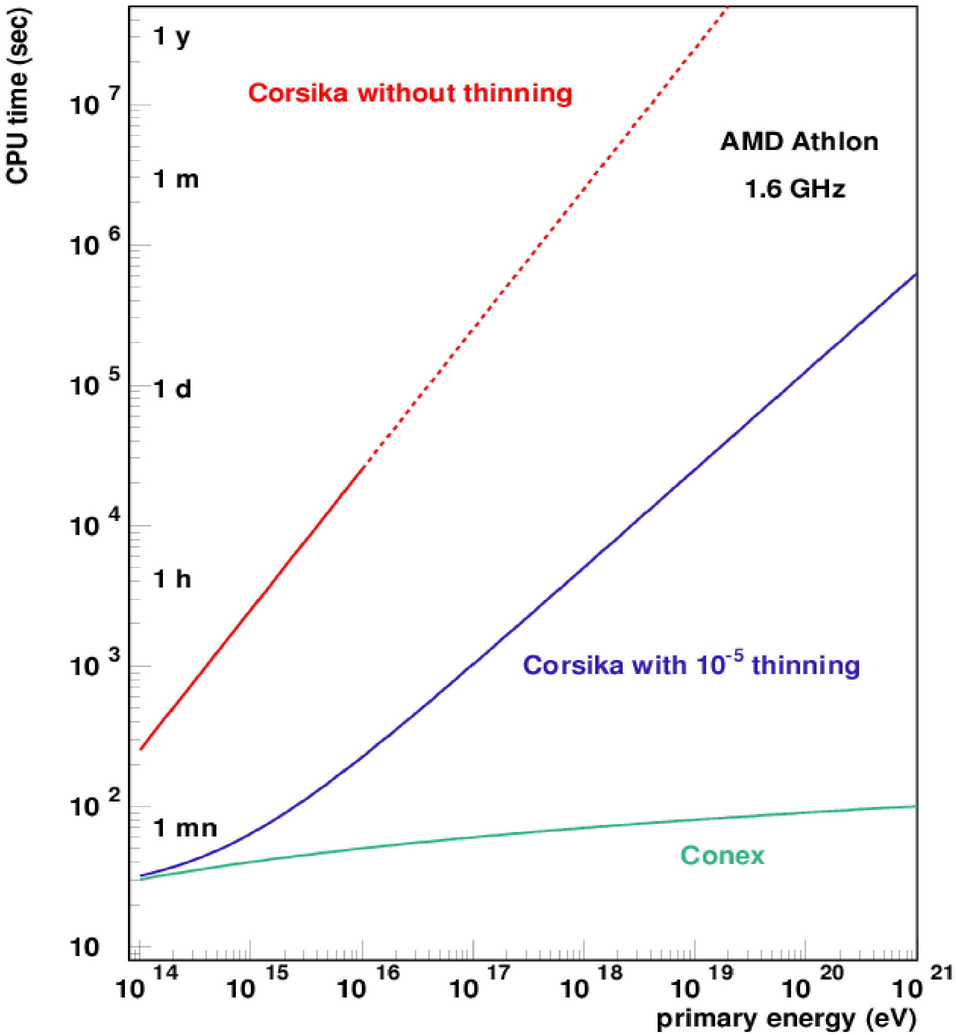
CORSIKA with CONEX



Parameters :

- E_{thr} : MC → CE (ha,μ,e/m)
- E_{low} : CE → MC (ha,μ,e/m)
- W_{max} : weight CE → MC (ha,μ,e/m)
- Z_{low} : minimum slant depth to ground for CE → MC (only e/m)

CONEX vs CORSIKA : time

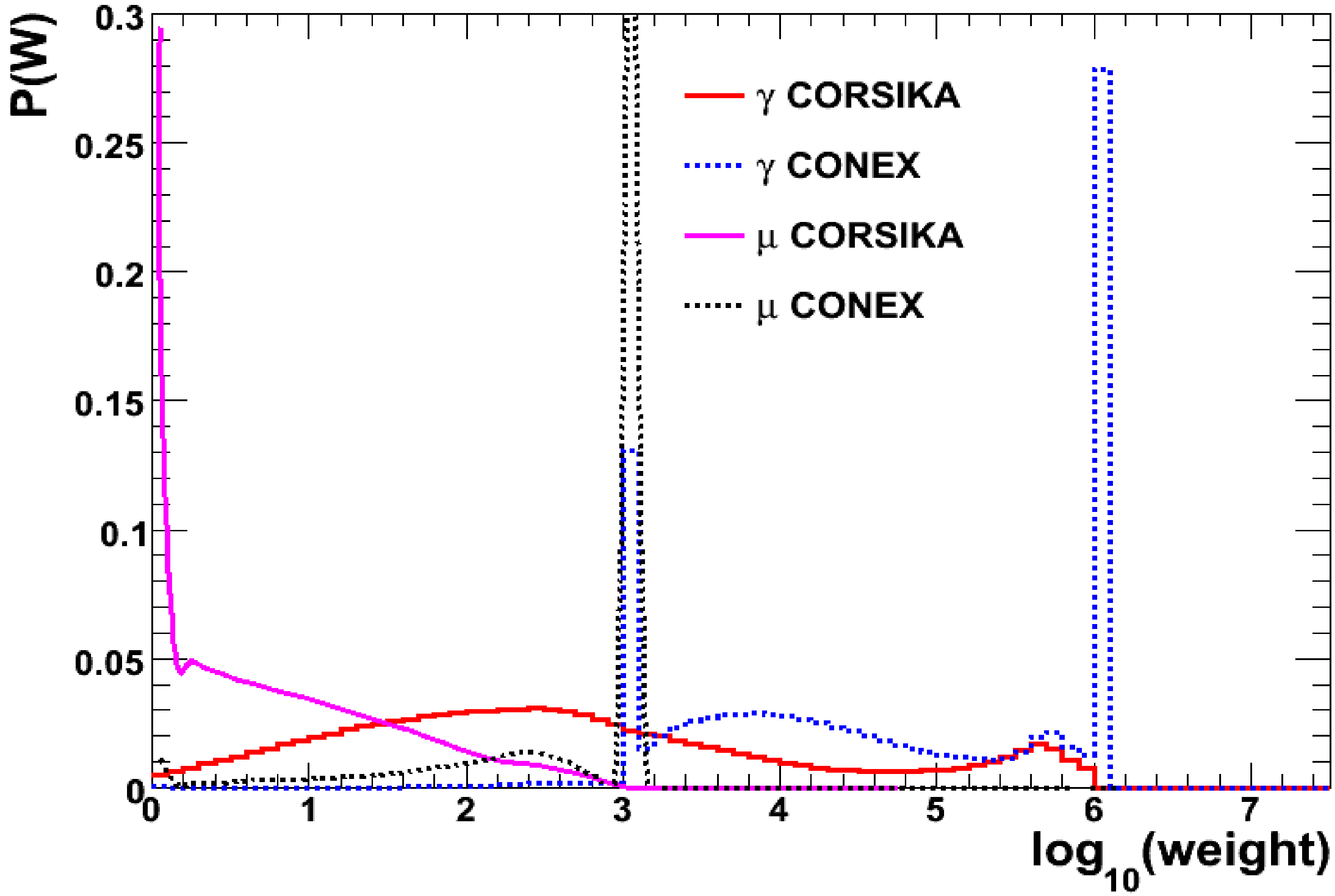


- **1D**
  - ➜ CORSIKA : CPU time ∝ Energy
  - ➜ CE : CPU time ∝ Log(Energy)
    - <1mn / shower
    - and no artificial fluctuations due to thinning
- **3D**
  - ➜ replace thinning
  - ➜ 5-10 times faster than thinning for the same maximum weight
  - ➜ better weight distribution

Weight distribution R > 100 m

Very narrow weight distribution from sampling

- ➜ less artificial fluctuations



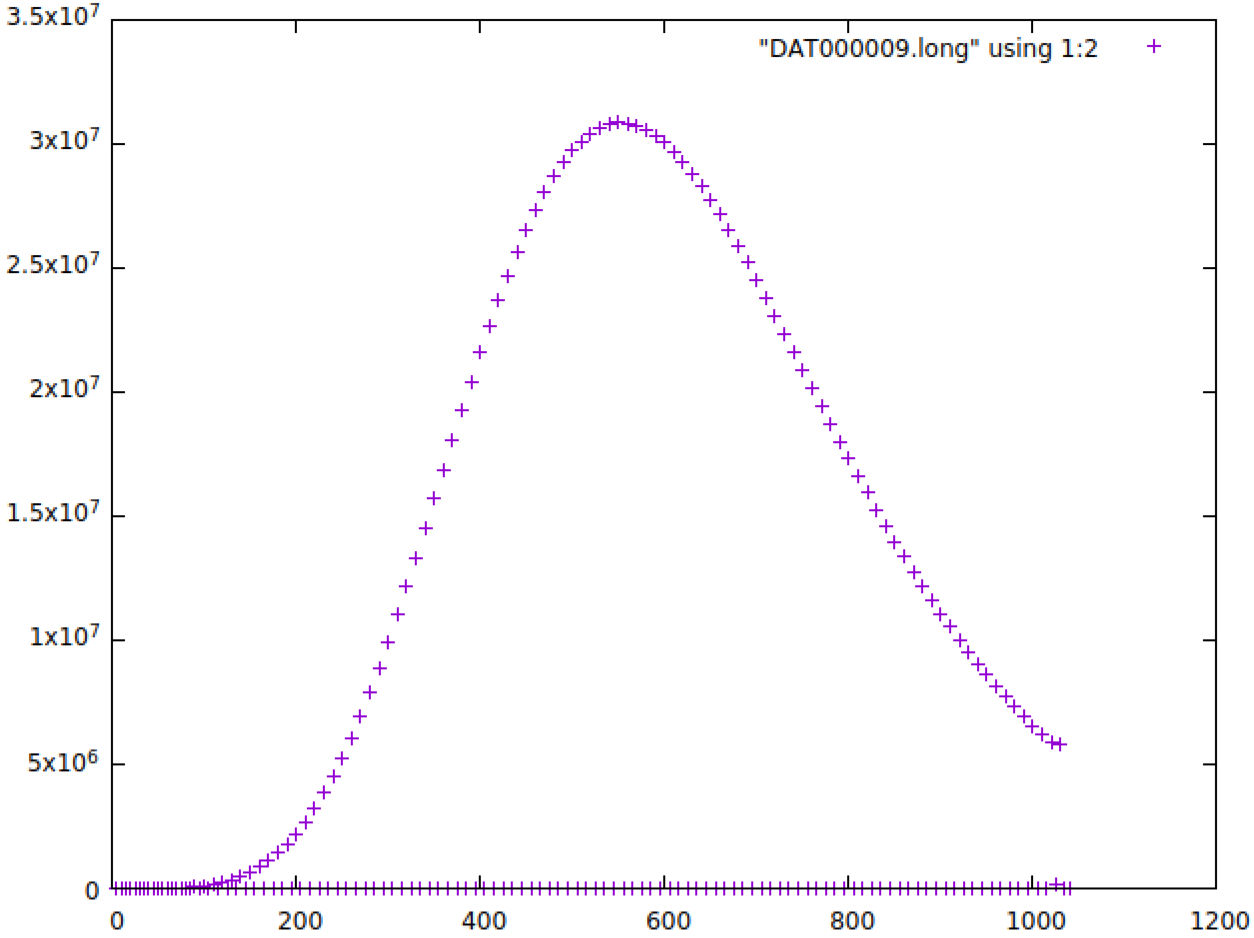
Hands-on

Make sure the followings are present on you computer :

- CORSIKA :
  - git clone https://gitlab.iap.kit.edu/AirShowerPhysics/corsika-legacy/ISAPP/corsika7.7410.git
  - User : isapp
  - Password : Orsay2022
    (temporary account, if you plan to use CORSIKA, please register here following ...)
- Fortran compiler
  - gfortran
- Some plotting tools
  - Gnuplot, Python, ROOT ...
- Hopefully already done…
  - No problem on LINUX, OK on OSX, no way with Windows

Longitudinal profile

1st exercise: compile CORSIKA with CONEX option and plot the longitudinal profile of gammas



Longitudinal profile

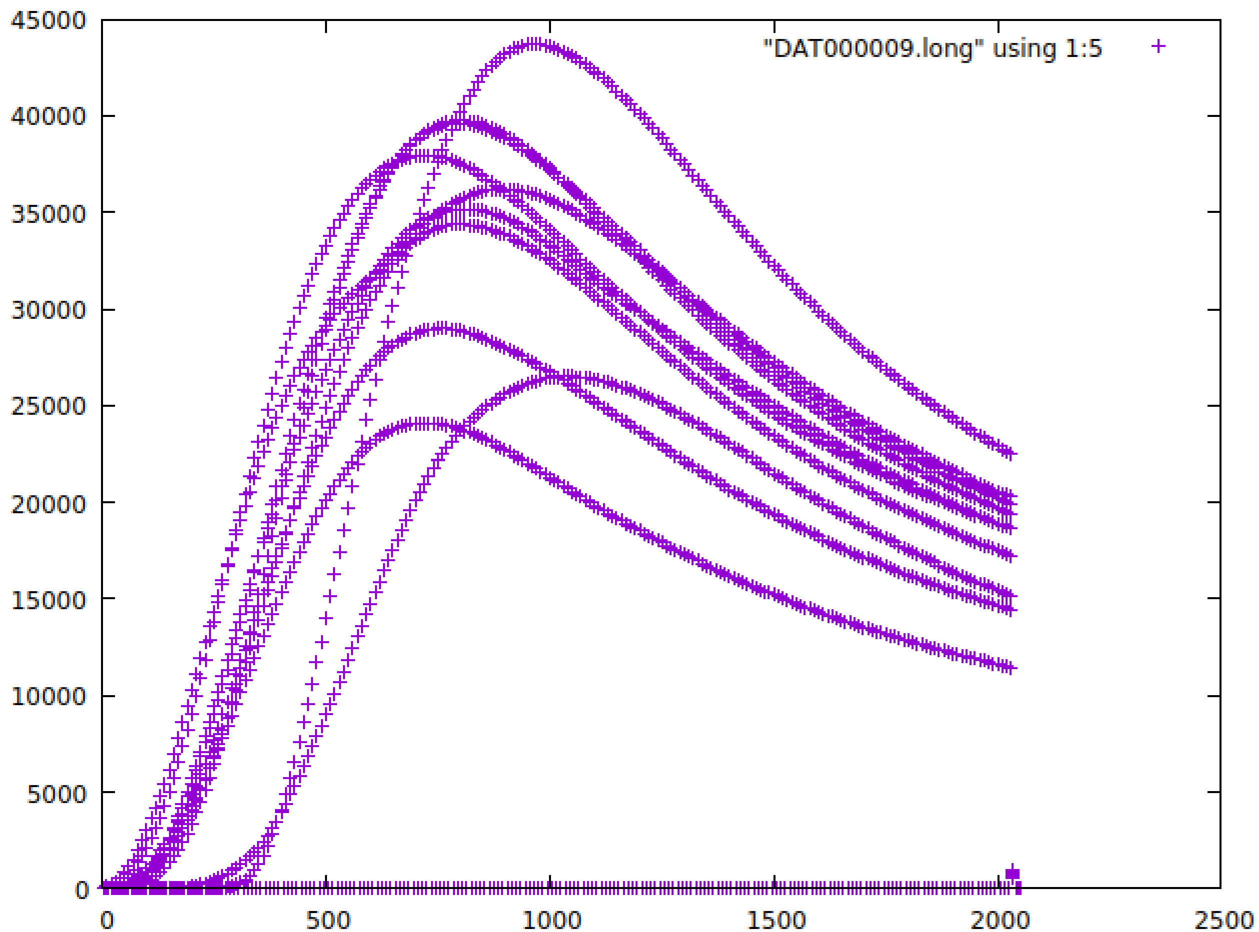
1st exercise: compile CORSIKA with CONEX option and plot a longitudinal profile

- Compile CORSIKA using ./coconut with default option + CONEX
- Run the default example “conex-epos-input”
  - ./corsika77410Linux_EPOS_urqmd_thin_conex < conex-epos-inputs
- Plot one distribution from file “DAT000009.long”
  - With gnuplot : plot “DAT000009.long” using 1:2

```
 LONGITUDINAL DISTRIBUTION IN   104 SLANT    STEPS OF   10. G/CM**2 FOR SHOWER       1
 DEPTH       GAMMAS    POSITRONS   ELECTRONS         MU+         MU-     HADRONS     CHARGED      NUCLEI   CHERENKOV
    10.0 3.62734E+02 2.19830E+01 2.19450E+01 3.70000E+01 3.70000E+01 2.18000E+02 3.06928E+02 0.00000E+00 0.00000E+00
    20.0 9.34499E+02 1.21170E+02 1.58487E+02 1.14376E+02 1.14376E+02 2.55394E+02 7.20026E+02 1.70530E-13 0.00000E+00
    30.0 2.46582E+03 3.37706E+02 4.33546E+02 1.92688E+02 1.92688E+02 3.79289E+02 1.45919E+03 0.00000E+00 0.00000E+00
    40.0 5.60164E+03 8.14010E+02 1.02320E+03 3.55774E+02 3.55774E+02 7.73047E+02 3.17762E+03 0.00000E+00 0.00000E+00
    50.0 1.09839E+04 1.64012E+03 2.10030E+03 5.61064E+02 5.61064E+02 1.06707E+03 5.71469E+03 3.63798E-12 0.00000E+00
    60.0 2.05090E+04 3.00148E+03 3.91294E+03 8.52340E+02 8.52340E+02 1.64047E+03 9.94326E+03 0.00000E+00 0.00000E+00
    70.0 3.53634E+04 5.15638E+03 6.80506E+03 1.20929E+03 1.20929E+03 1.97462E+03 1.59431E+04 0.00000E+00 0.00000E+00
```

Longitudinal profiles

2nd exercise: plot the longitudinal profile of positive muons for 10 showers at 60°



Longitudinal profiles

2nd exercise: plot the longitudinal profile of positive muons for 10 showers

- Edit “conex-epos-input” to increase the number of showers and the run number

```
-RUNNR   9                                       run number
-NSHOW   1                                       number of showers to generate
+RUNNR   10                                       run number
+NSHOW   10                                       number of showers to generate
 PRMPAR  14                                      prim. particle (1=gamma, 14=proton, ...
 ESLOPE  -1                                    slope of primary energy spectrum
 ERANGE  1.E7  1.E7                              energy range of primary particle (GeV)
-THETAP  0.  0.                                  range of zenith angle (degree)
+THETAP  60.  60.                                  range of zenith angle (degree)
 PHIP    -180.  180.                                range of azimuth angle (degree)
```

- Run the default example “conex-epos-input”
  - ./corsika77410Linux_EPOS_urqmd_thin_conex < conex-epos-inputs
- Plot distributions from file “DAT000010.long”
  - With gnuplot : plot “DAT000010.long” using 1:5

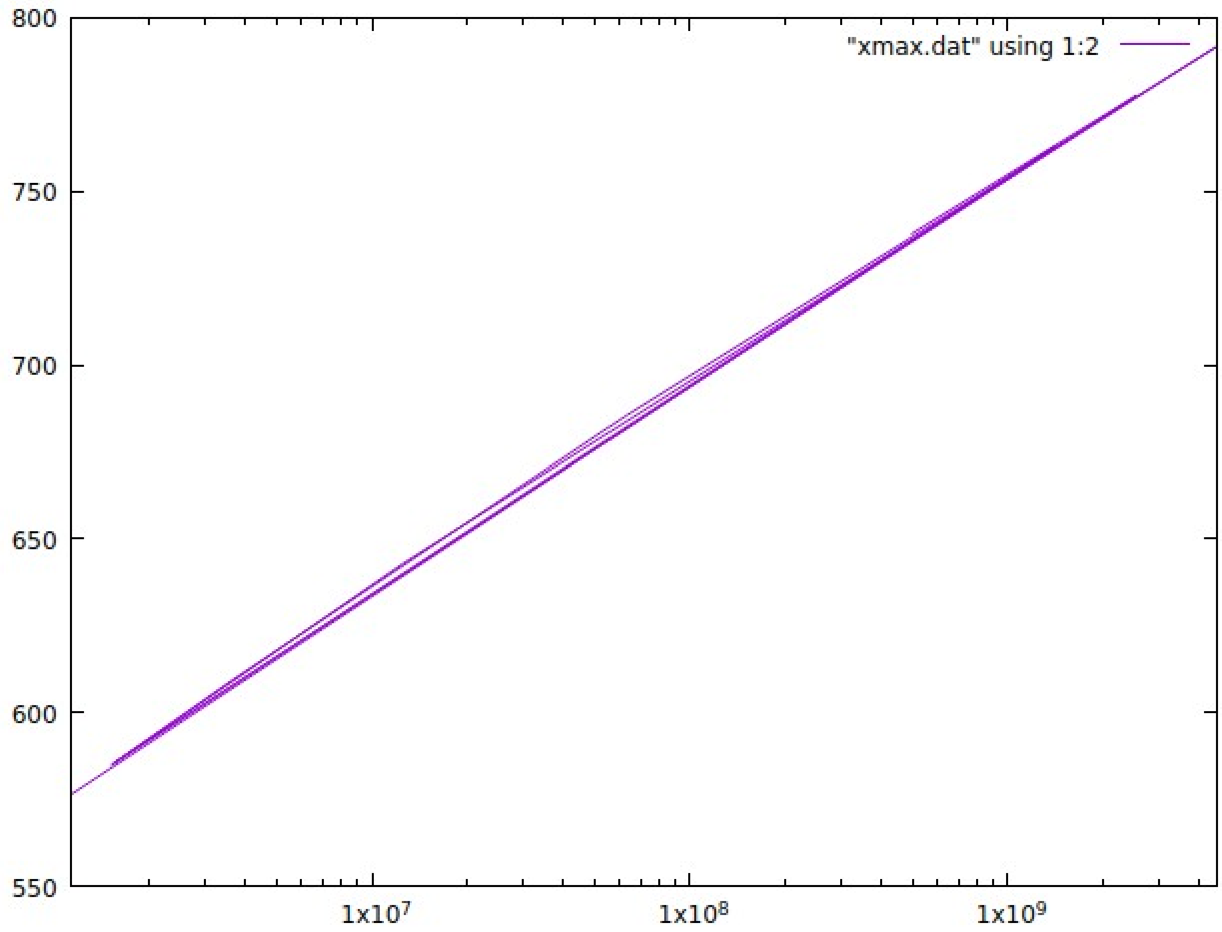
Longitudinal profiles

Ralph’s exercises: plot the longitudinal profile of positive muons for 10 showers

- Edit “conex-epos-input” to change energy and/or primary
  - PRMPAR : 14=proton … 5628=iron (A*100+Z)
  - ERANGE in GeV
  - Use different run number not to overwrite files (like 20 and 21)
- Run the example “conex-epos-input” for different cases
  - ./corsika77410Linux_EPOS_urqmd_thin_conex < conex-epos-inputs > output.txt
- Plot distributions from file “DAT000020.long” and “DAT000021.long”
  - plot “DAT000020.long” using 1:2
  - replot “DAT000021.long” using 1:2

Elongation rate

3rd exercise: plot the evolution of Xmax with energy



Elongation rate

3rd exercise: plot the evolution of Xmax with energy

- Edit “conex-epos-input” to set energy range, speed and output

```
@@ -1,9 +1,9 @@
-RUNNR   9                                       run number
-NSHOW   1                                       number of showers to generate
+RUNNR   11                                       run number
+NSHOW   10                                       number of showers to generate
 PRMPAR  14                                      prim. particle (1=gamma, 14=proton, ...)
-ESLOPE  -1                                    slope of primary energy spectrum
-ERANGE  1.E7  1.E7                              energy range of primary particle (GeV)
-THETAP  0.  0.                                  range of zenith angle (degree)
+ESLOPE  -1.                                    slope of primary energy spectrum
+ERANGE  1.E6  1.E10                              energy range of primary particle (GeV)
+THETAP  60.  60.                                  range of zenith angle (degree)
 PHIP    -180.  180.                                range of azimuth angle (degree)
```

```
 CASCADE T T T
+CONEX 1. 1. 1.
 MUADDI  T                                 additional info for muons
 MUMULT  T                                 muon multiple scattering angle
 ELMFLG  F    T                            em. interaction flags (NKG,EGS)
 STEPFC  1.0                               mult. scattering step length fact.
 RADNKG  200.E2                            outer radius for NKG lat.dens.distr.
 ARRANG  0.                                rotation of array to north
-LONGI   T   10.   F   T                   longit.distr. & step size & fit & out
+LONGI   T   10.   T   T                   longit.distr. & step size & fit & out
 ECTMAP  1.E5                              cut on gamma factor for printout
-MAXPRT  0                                 max. number of printed events
+MAXPRT  10                                 max. number of printed events
```

```
 USER    you                               user
-PAROUT F F
+PAROUT T F
 * URQMD T 2
 DEBUG   F  6  F  1000000                  debug flag and log.unit for out
 EXIT                                      terminates input
```

Elongation rate

3rd exercise: plot the evolution of Xmax with energy

- Edit “conex-epos-input” to set energy range, speed and output
- Create a file “xmax.dat” with energy and Xmax
  - Easy way : extract information out of “DAT000011.long”

```
========== SHOWER NO          1 ============================================

PRESENT TIME : 31.03.2022  13:00:41 UTC
AND RANDOM NUMBER GENERATOR AT BEGIN OF EVENT :        1
SEQUENCE =  1  SEED =         1  CALLS =         1  BILLIONS =         0
SEQUENCE =  2  SEED =         2  CALLS =         0  BILLIONS =         0
SEQUENCE =  3  SEED =         3  CALLS =         0  BILLIONS =         0
SEQUENCE =  4  SEED =         4  CALLS =         0  BILLIONS =         0
SEQUENCE =  5  SEED =         5  CALLS =         0  BILLIONS =         0
SEQUENCE =  6  SEED =         6  CALLS =         0  BILLIONS =         0
SEQUENCE =  7  SEED =         3  CALLS =         0  BILLIONS =         0
SEQUENCE =  8  SEED = 987170455  CALLS =         0  BILLIONS =         0
PRIMARY ENERGY =    495899825.52870762       GEV
PRIMARY ANGLES ARE: THETA =  1.0472 RAD, PHI = -2.5506 RAD
```

Energy

```
FIT OF THE HILLAS CURVE   N(T) = P1*((T-P2)/(P3-P2))**((P3-P2)/(P4+P5*T+P6*T**2)) * EXP((P3-T)/(P4+P5*T+P6*T**2))
TO LONGITUDINAL DISTRIBUTION OF                ALL CHARGED PARTICLES
PARAMETERS         =   2.8938E+08 -6.7917E+00  7.3758E+02  1.0081E+02 -6.7750E-02  3.3338E-05
CHI**2/DOF         =  1.5091E+04
AV. DEVIATION IN % =  8.8713E+01


  END OF SHOWER NO          1
```

Xmax

Elongation rate

3rd exercise: plot the evolution of Xmax with energy

- Edit “conex-epos-input” to set energy range, speed and output
- Create a file “xmax.dat” with energy and Xmax
  - Easy way : extract information out of “output.txt”
  - Proper way : use “src/utils/coast/CorsikaRead”
- Edit “CorsikaRead.cc” to print out energy and Xmax
- Follow instruction in README to compile (won’t work on OSX)
- Use on output binary file
  - Copy “CorsikaReader” in “run/”
  - CorsikaReader DAT000011 > xmax.dat
  - In gnuplot : set log scale x ; plot “xmax.dat” using 1:2 w l

Nmu vs Xmax

4th exercise: plot the correlation between Xmax and number of muons

- Add a column in “xmax.dat” with Nmu
  - Easy way : extract information out of “output.txt”
  - Proper way : use “src/utils/coast/CorsikaRead”
- Possibility to compare 2 models ...