CORSIKA and CONEX for Air Shower Simulations

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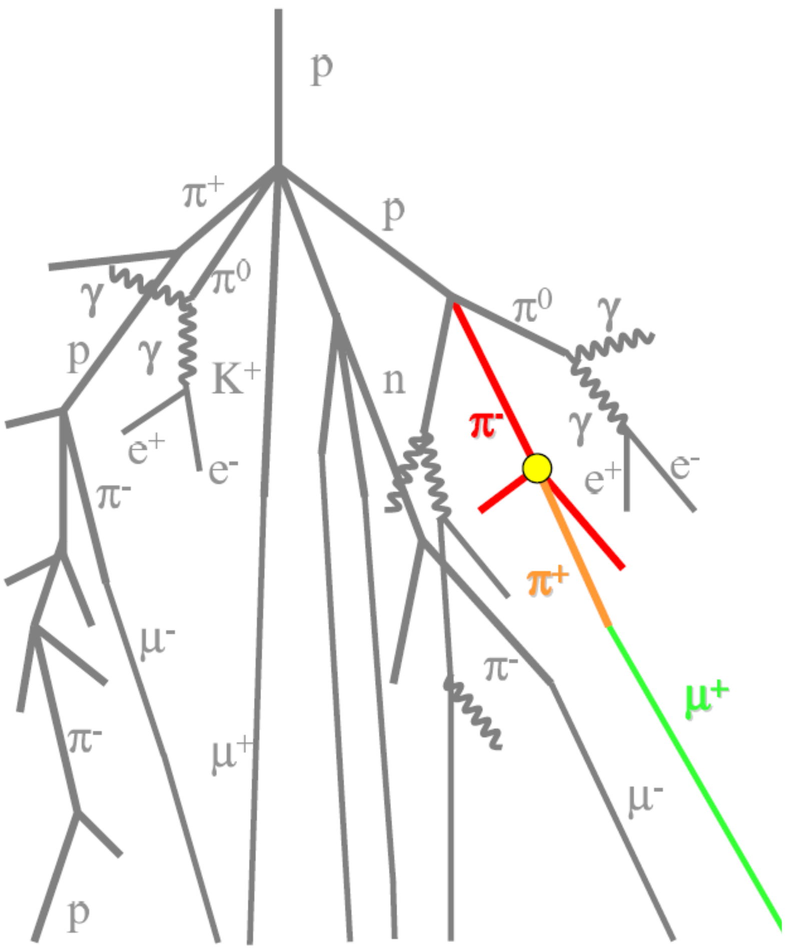
Outline

- Introduction
- Options and outputs
- Faster simulations
- Limitations

Extensive Air Shower



From R. Ulrich (KIT)

$$A + air \rightarrow \text{hadrons}$$
$$p + air \rightarrow \text{hadrons}$$
$$\pi + air \rightarrow \text{hadrons}$$

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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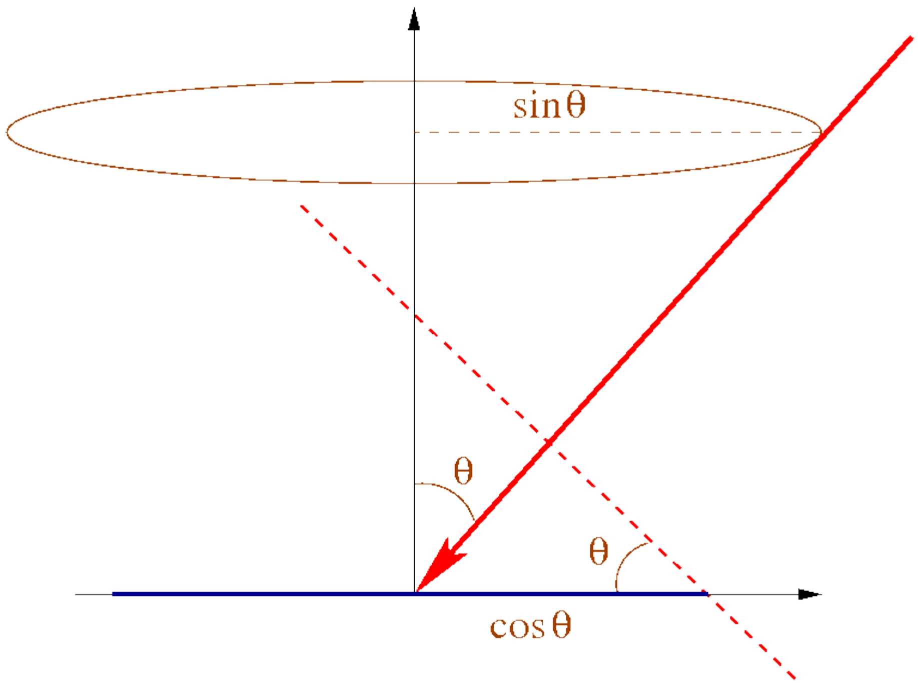
Detector geometry (only change the angular distribution of showers)

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

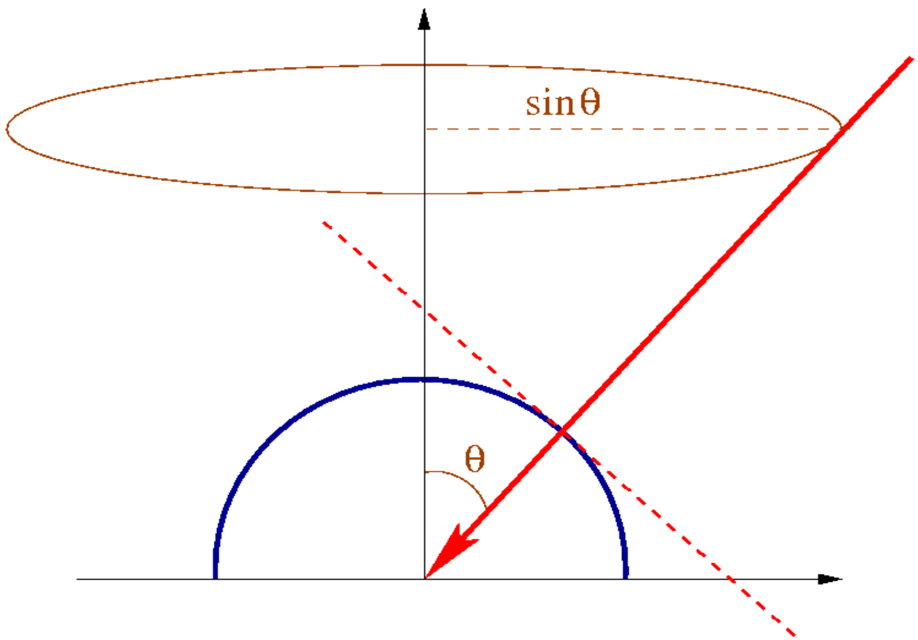
Geometry Selection



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
  (AMANDA, IceCube, Antares, ...)

Geometry Selection



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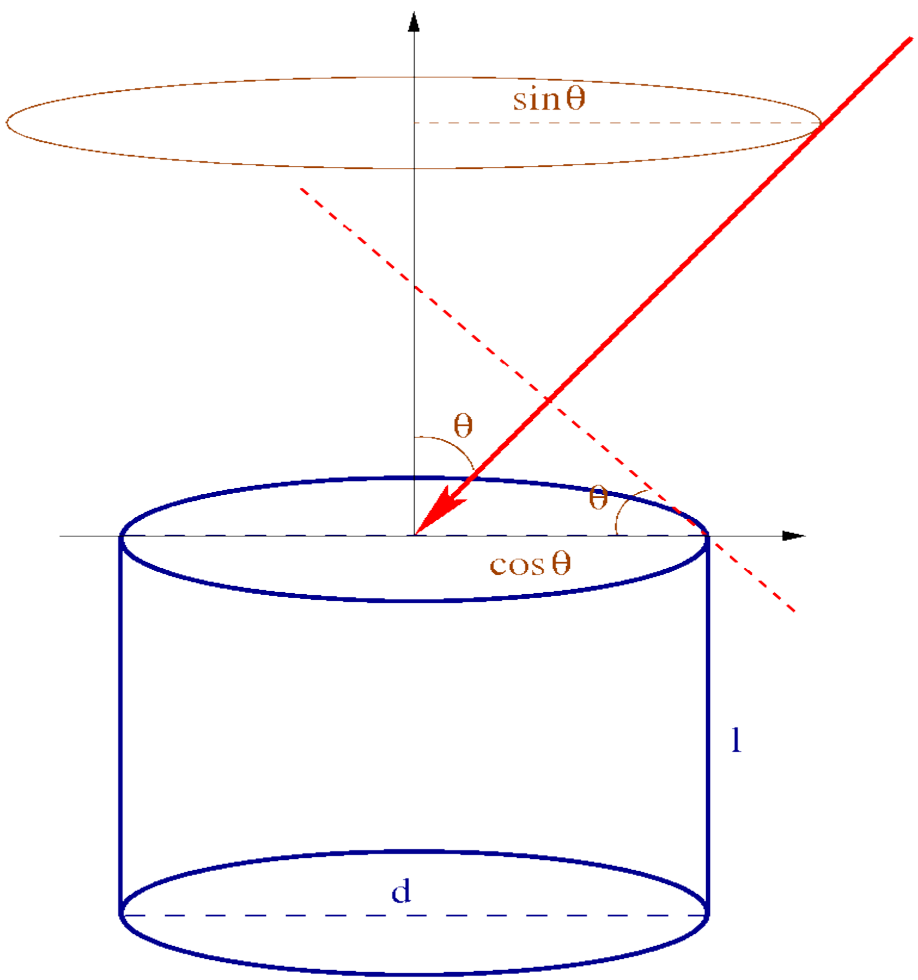

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$$I \propto (d/2)^2 \cdot \pi \cdot sin\theta \cdot (cos\theta + 4/\pi \cdot l/d \cdot sin\theta)$$

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
   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
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   8a - shower PLOT version (PLOTSH) (only for single events)
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   8d - Auger-histo file & THIN
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        (using bernlohr C-routines)
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   10a - DYNamic intermediate particle STACK
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   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)
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   y - *** Reset selection ***
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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)

Options ...

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   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
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   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
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```

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 ?
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   1c - apply atm. absorption, mirror reflectivity & quantum eff.
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   z - *** Finish selection *** [DEFAULT]

   r - restart (reset all options to cached values)
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 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 ?
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   1c - apply atm. absorption, mirror reflectivity & quantum eff.
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   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

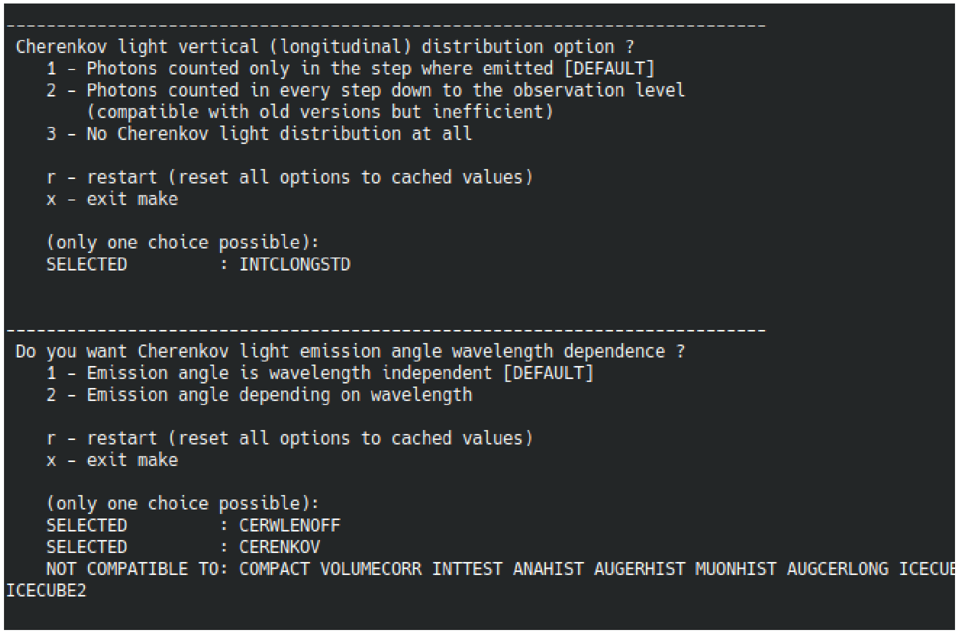
- to get information about mother and grandmother particles of particles arriving at ground
  - MUADDI : muons
  - EMADDI : electrons and photons

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 :

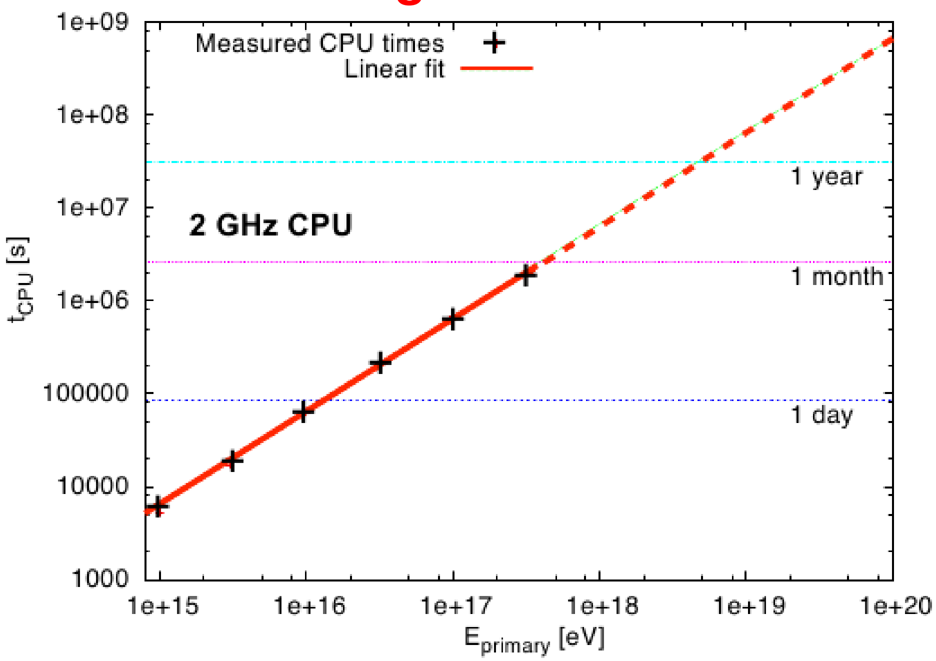
- Using RootOut
  - not recommended because of size and structure limitations
- Using COAST
  - self defined and linked dynamically when information are extracted at running time (all tracks and hadronic interactions available)
- From DAT files (recommended)
  - tools provided to convert the standard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

Limitations in Air Shower Simulations

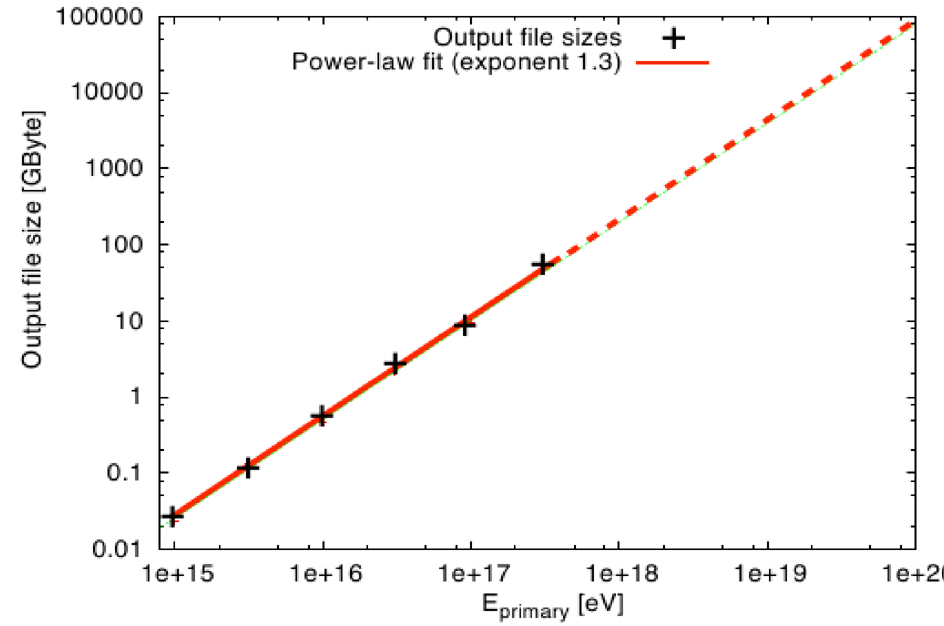
Analysis based on air shower simulations affected by 2 main problems :

- 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

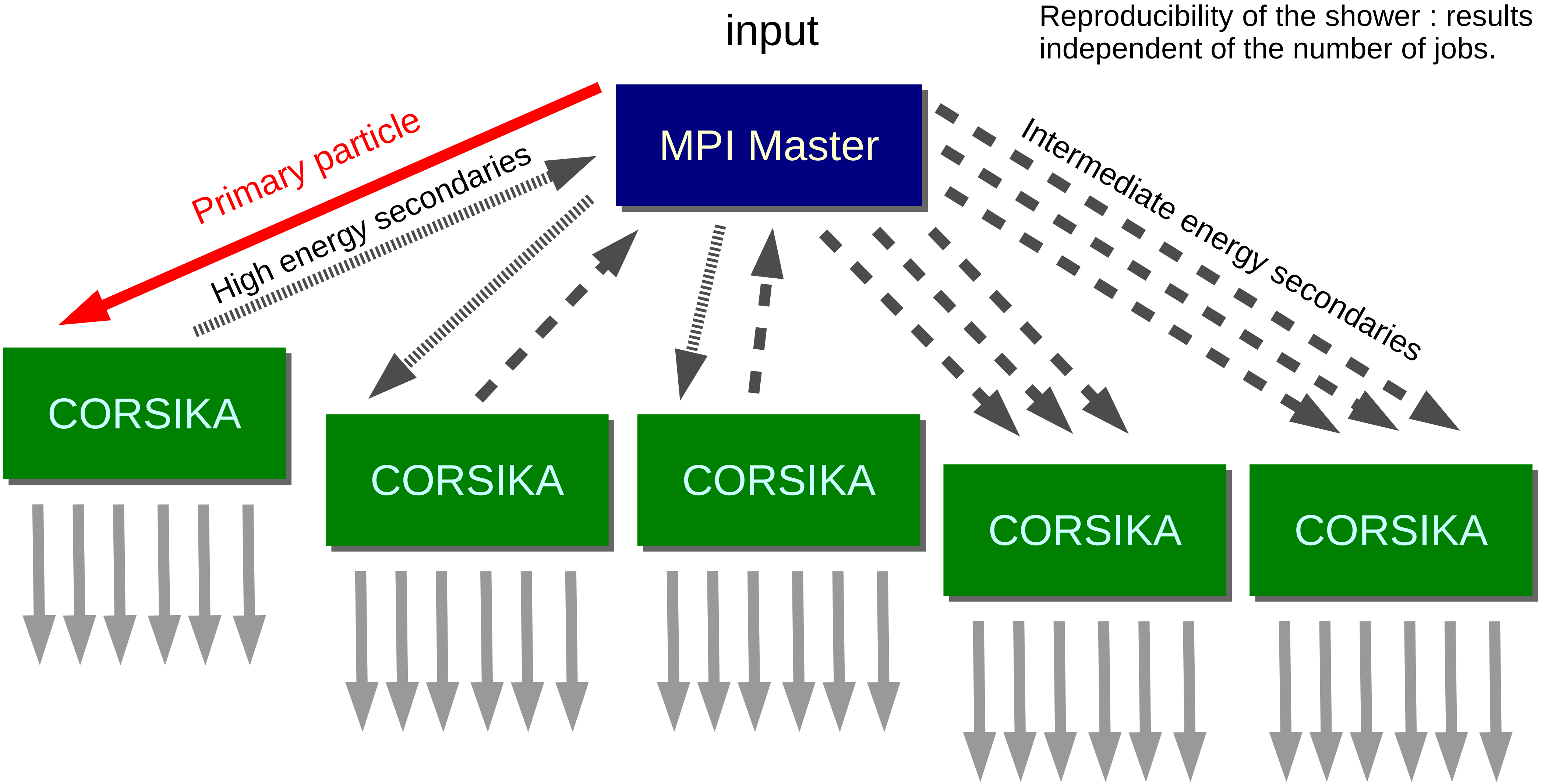
Current Solutions in CORSIKA

- **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.

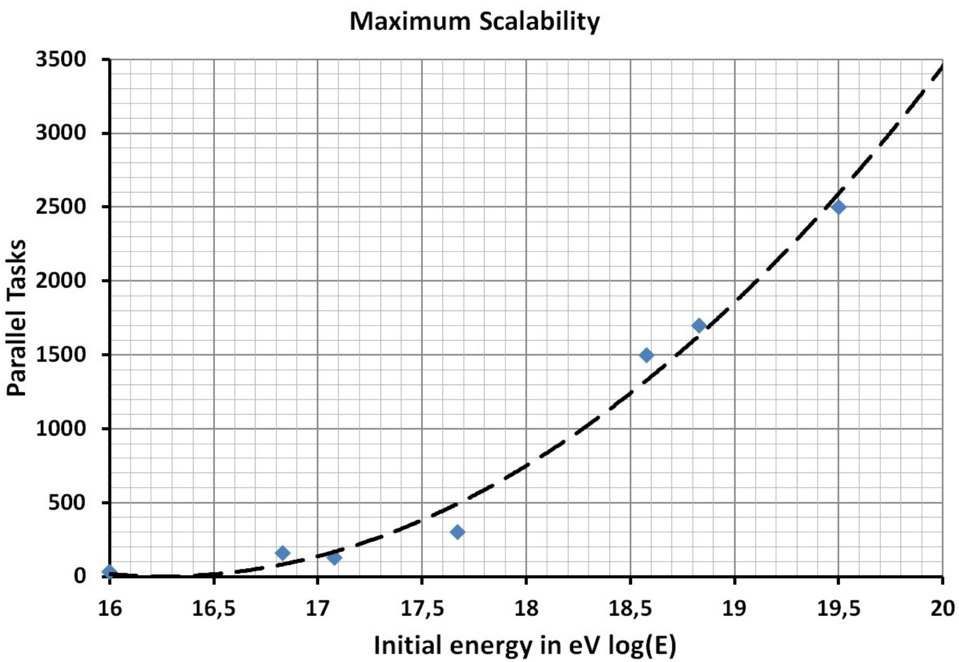


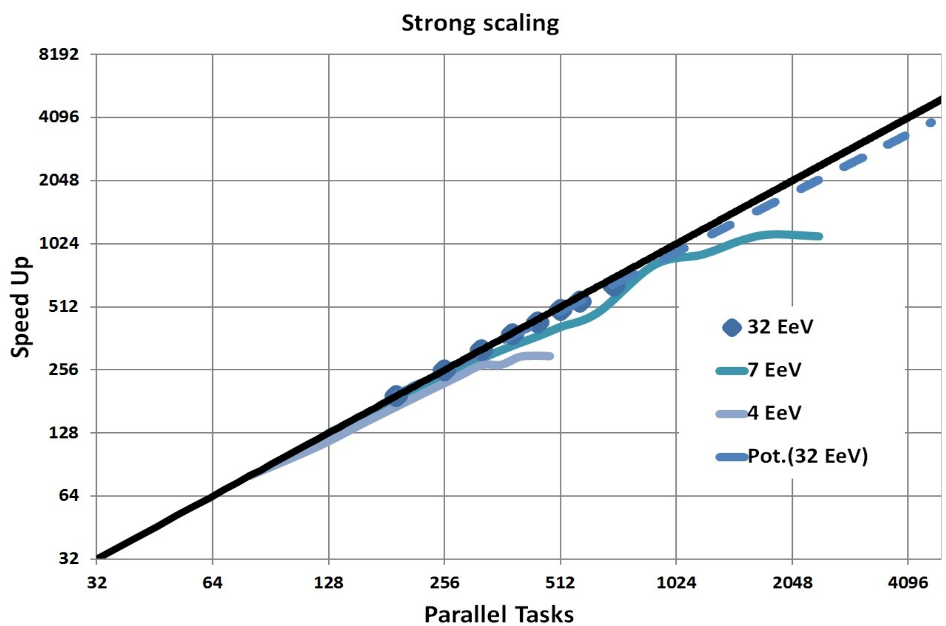
Low energy secondaries down to observation level

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

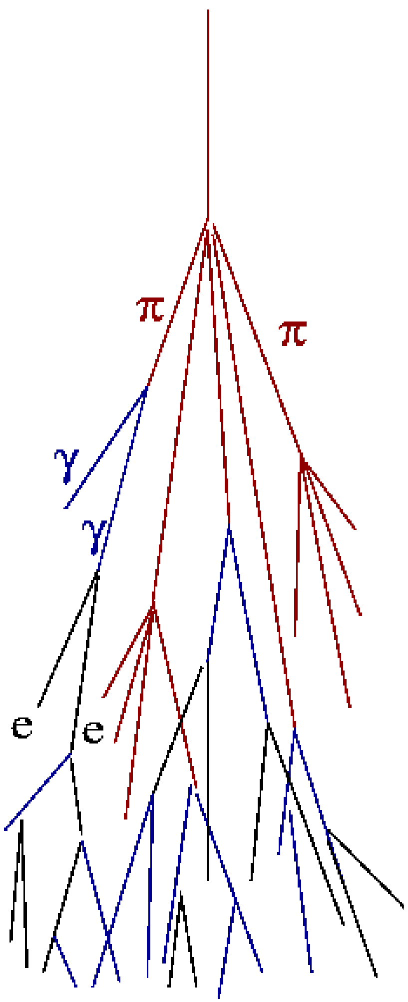
- **solution tested for high energy showers only**
  - ➜ electromagnetic shower not really parallelized ...



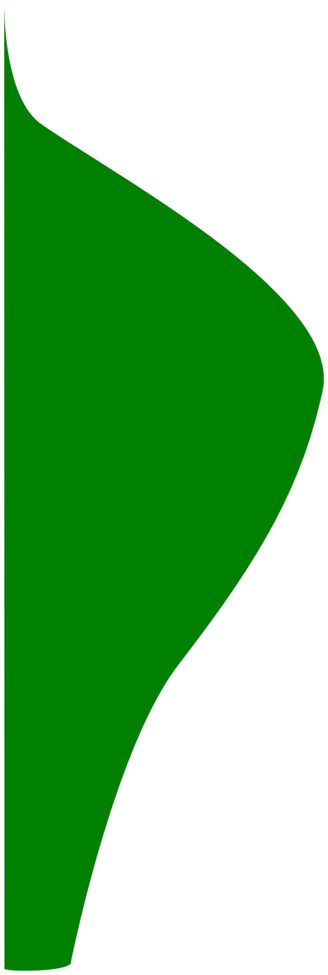


Parallel version tested on HP XC3000 (2.53 GHz CPUs, InfiniBand 4X QDR)

Air Shower Simulations

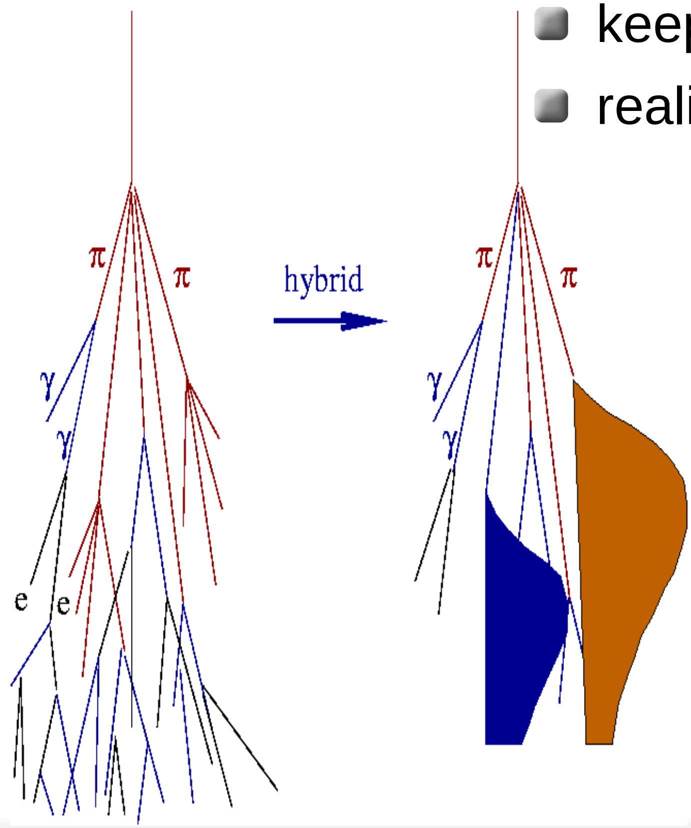


- **Air shower simulations, 2 main methods**
  - Full MC simulations
    - realistic
    - flexible
    - fluctuations
    - slow
  - Cascade Equations (CE)
    - fast
    - mean behavior
    - no fluctuations
    - limited to analytic formula ?
- **Can we have the best of the 2 ?**

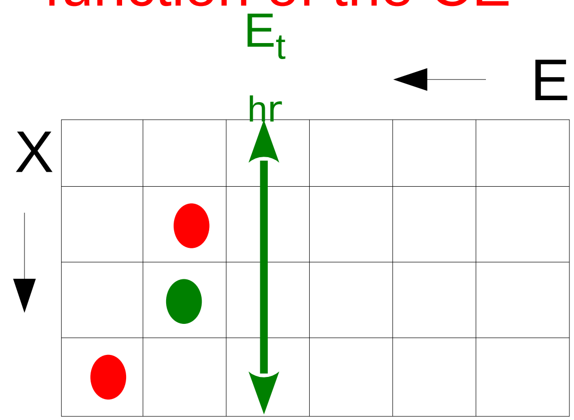


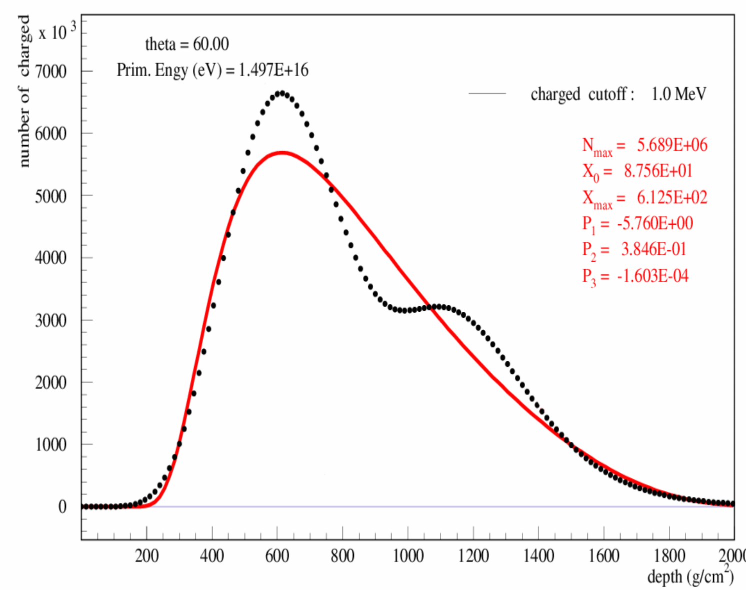
Consistent Hybrid Calculation

- **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)

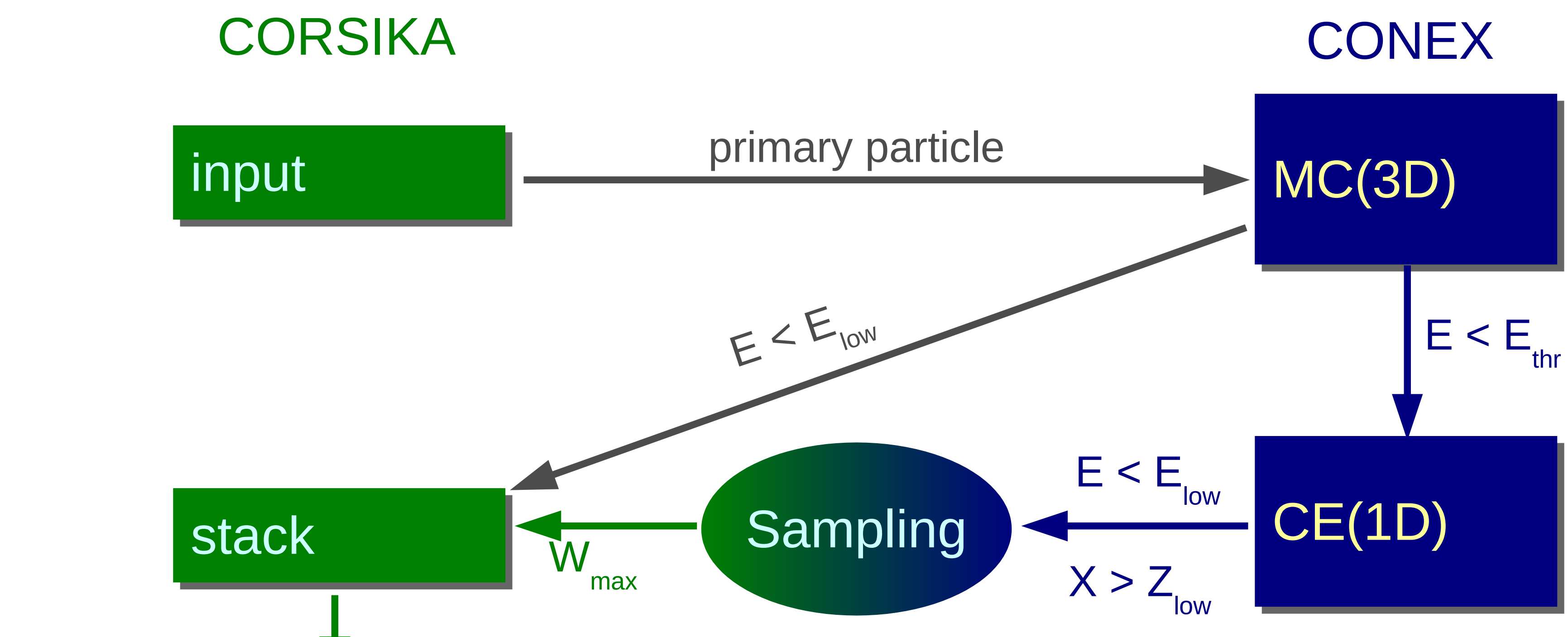


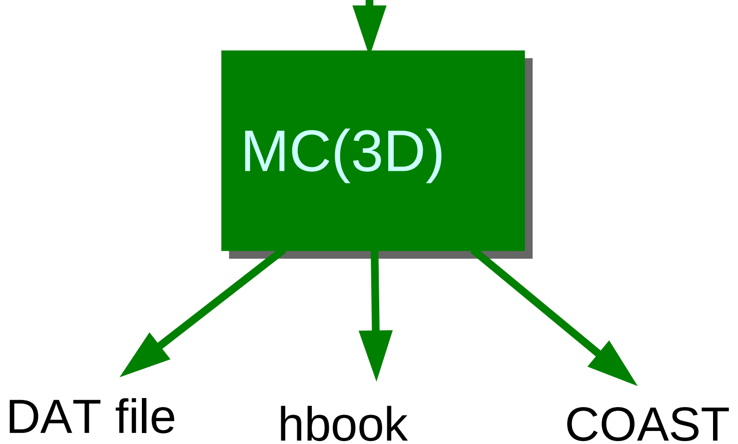
MC fill the source function of the CE





CORSIKA with CONEX

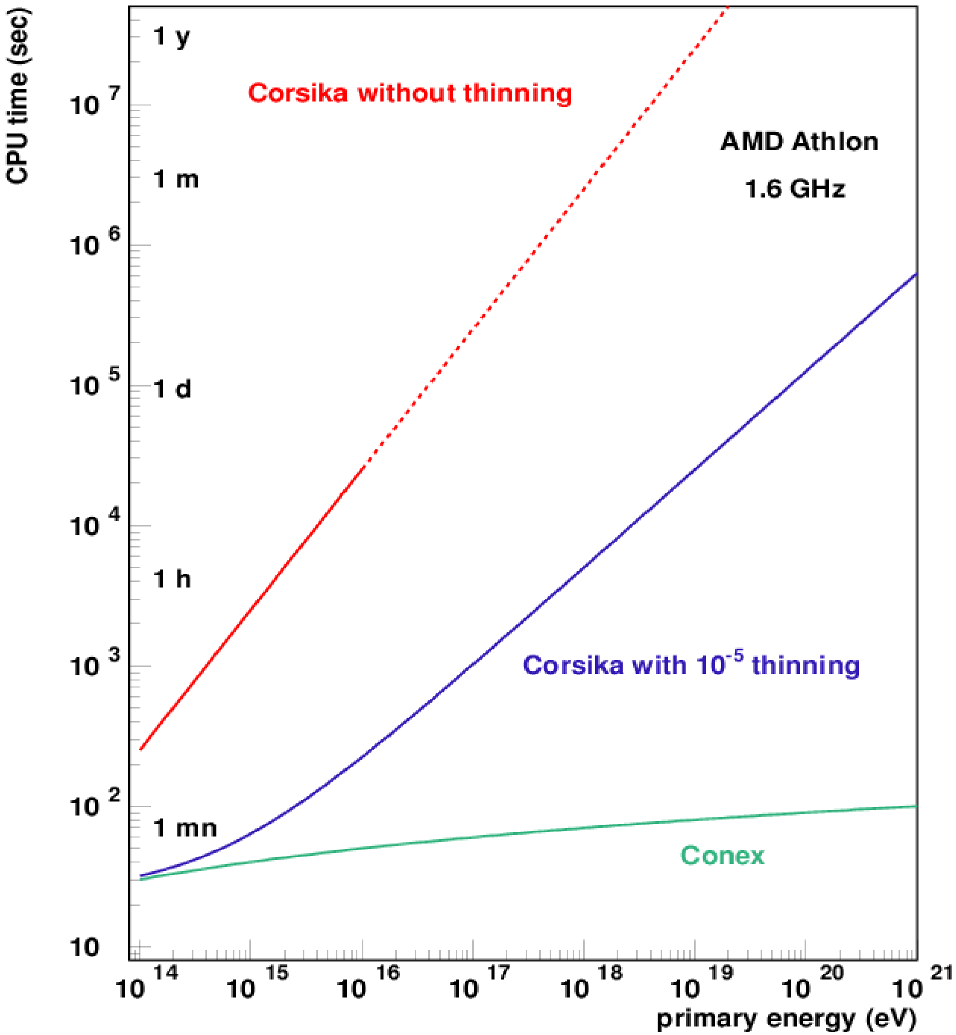




Parameters :

- 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

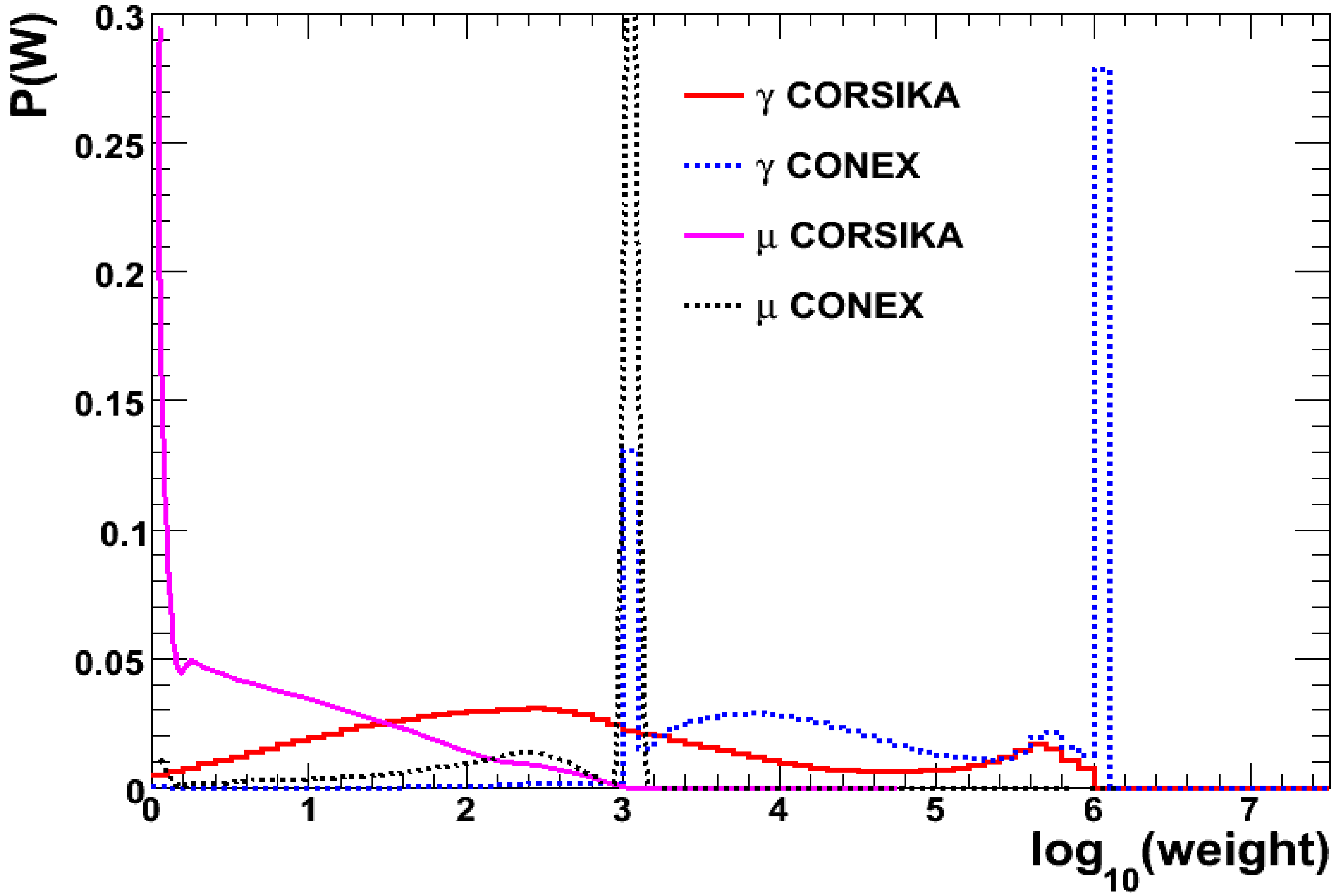


- **1D**
  - CORSIKA : CPU time ∝ Energy
  - CE : CPU time ∝ Log(Energy)
    - <1mn / shower
    - and no artificial fluctuations due to thinning
- **3D**
  - replace thinning
  - 5-10 times faster than thinning for the same maximum weight
  - better weight distribution

Weight distribution R > 100 m

Very narrow weight distribution from sampling

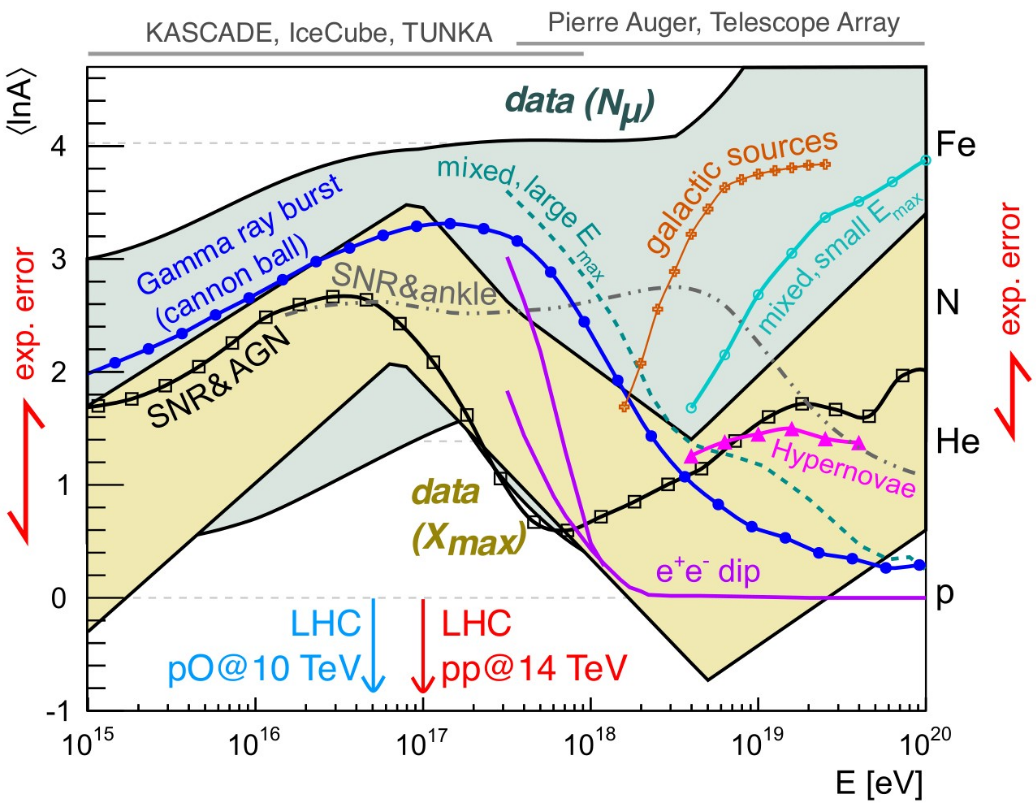
➜ less artificial fluctuations



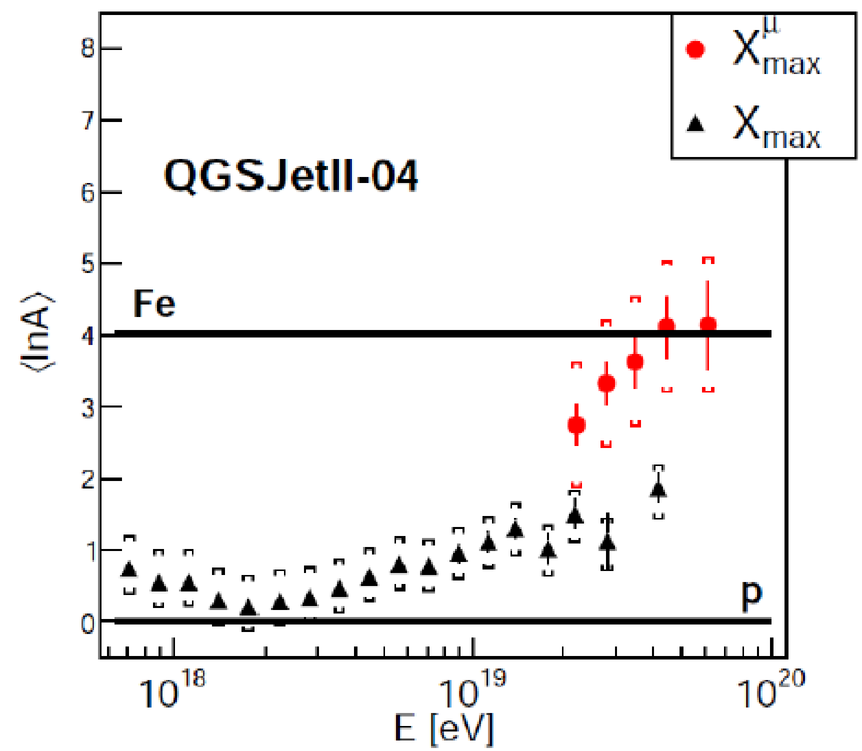
Simulation Inconsistencies

With muons, current CR data are impossible to interpret

- Very large uncertainties in model predictions
- Mass from muon data incompatible with mass from X_{max}



Based on Kampert & Unger, Astropart. Phys. 35 (2012) 660



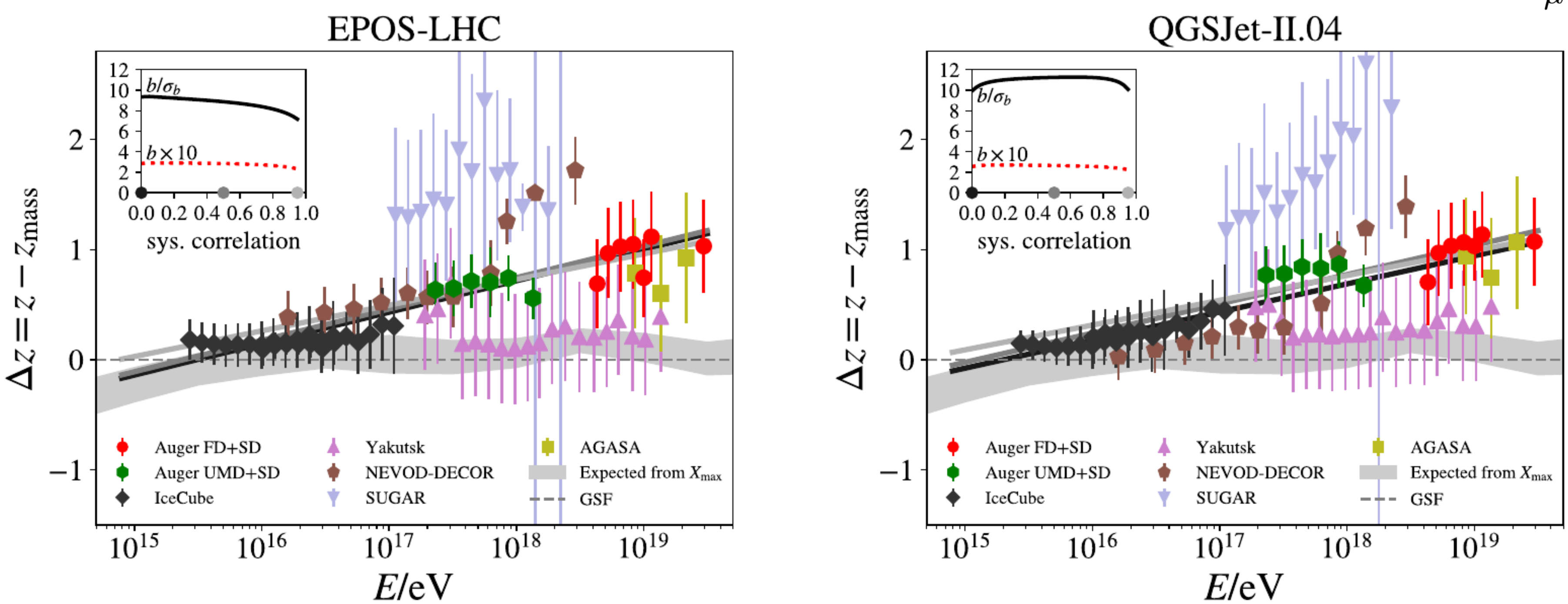
Pierre Auger Collaboration

H. Dembinski UHECR 2018 (WHISP working group)

Global Picture of Muons from EAS

- **Clear muon excess in data compared to simulation : WHISP 2021**
  - Different energy evolution between data and simulations
    - Significant non-zero slope (>8σ)

$$z = \frac{\ln N_\mu^{\text{det}} - \ln N_{\mu,p}^{\text{det}}}{\ln N_{\mu,\text{Fe}}^{\text{det}} - \ln N_{\mu,p}^{\text{det}}}$$

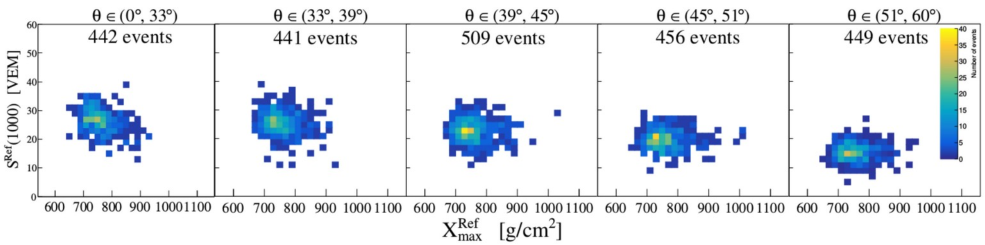


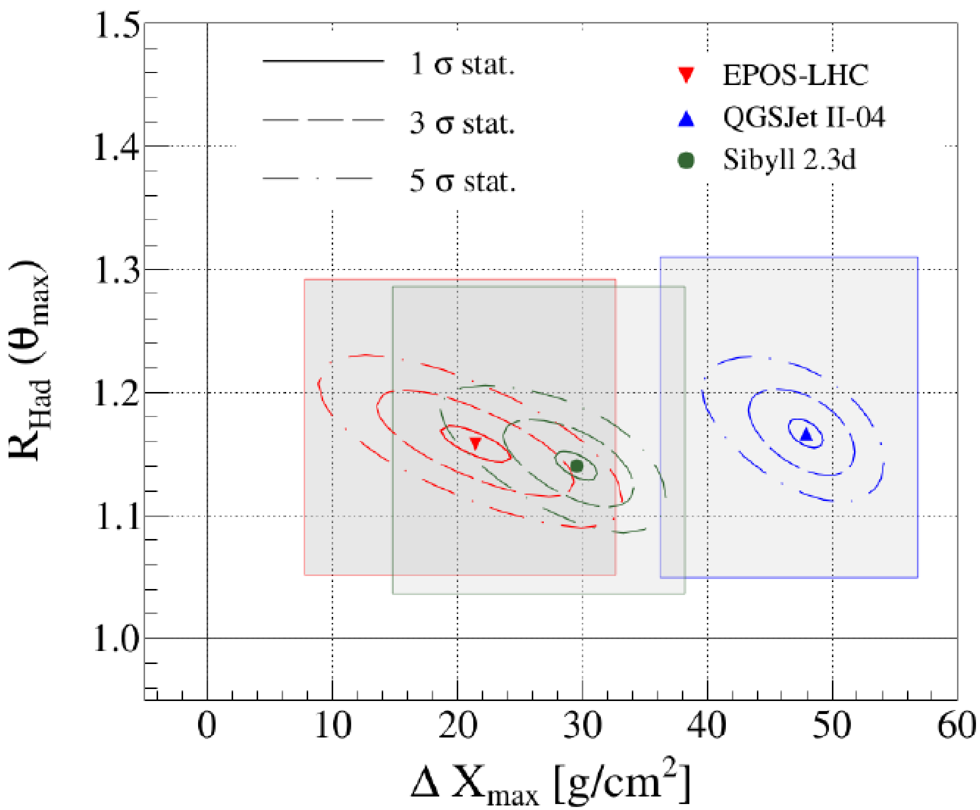
- **Different global energy or mass scale cannot change the slope**
  - Different property of hadronic interactions at least above 10^{16} eV
- **X_{max} (mass) important to get the absolute scale (+energy) !**

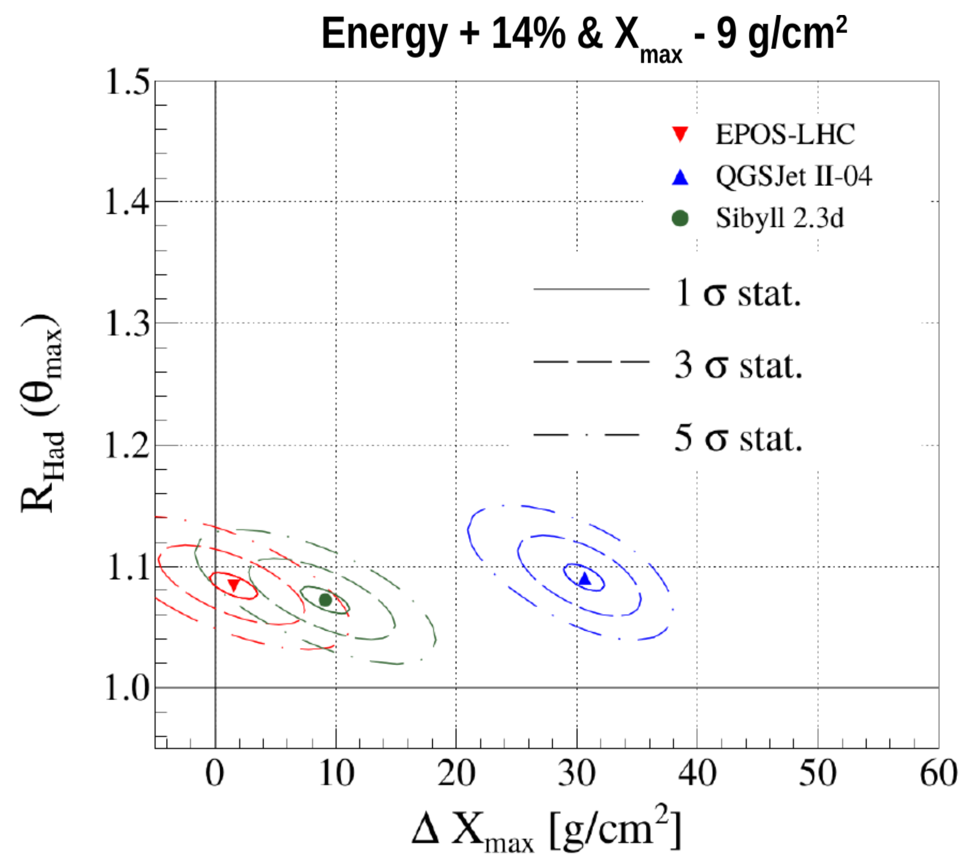
New Analysis from PAO

Best fit of 2D (X_{max}, muon) data for different zenith angle (ICRC2021)

- Allow both X_{max} and muon rescaling
- Data best described by shifting X_{max}
- Indication but large uncertainties







Limitations

Important to keep in mind that simulations are not perfect

- CORSIKA is the best that we can get
  - Limitations mostly due to hadronic interaction models
- Clear problem with the muon production (both number and production height and then timing)
  - Physic based solution on-going …
  - Possibility to test higher number of muons by using higher mass in CORSIKA with EPOS LHC
    (possibility to run very heavy mass (lnA=5 or even 6 with CONEX))
- X_{max} not necessarily perfect neither
  - X_{max} can be shifted artificially using FIXCHI
- Be careful with the detector simulation which might not be perfect neither ...

Conclusion

CORSIKA is a fundamental tool to get accurate simulations of air showers

- Many options
  - Important to read the user guide to select only what is useful
- Various outputs
- Possibility to optimize the running time as a function of what is needed
  - 1D (CONEX) or 3D (CORSIKA)
- Keep in mind the uncertainties due to the hadronic interactions
  - X_{max} could be shifted slitely (within models range)
  - Muons underestimated and produced too late (possibility to test extrapolation with higher mass)
- DNN possibly used to do fast simulations in the future
  - Replacement for cascade equations, unthinning, etc ...