Faster Simulations in CORSIKA

Tanguy Pierog

Karlsruhe Institute of Technology, Institut für KernPhysik,
Karlsruhe, Germany

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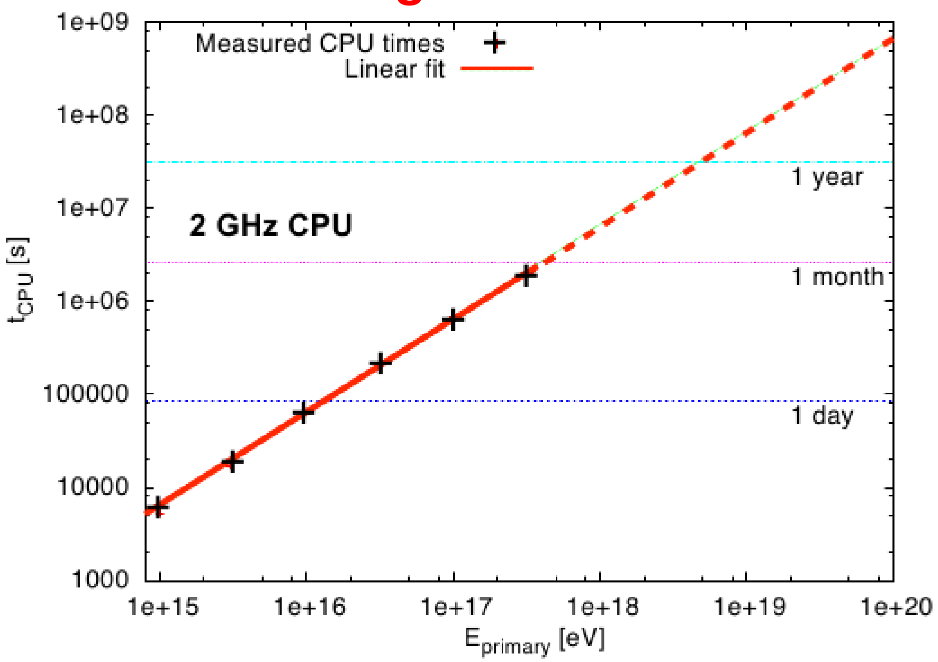
Limitations in Air Shower Simulations

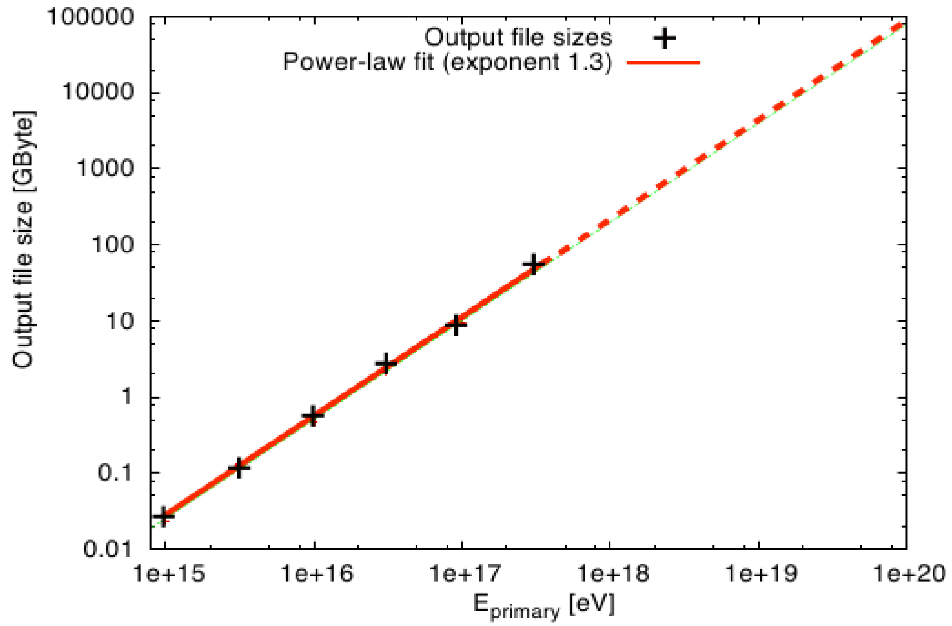
Analysis based on air shower simulations affected by 2 main problems :

- limited statistic due to :

Large CPU time



Large disk space



- same problem for high statistic OR high energy

- uncertainties due to hadronic interactions

  - another topic !

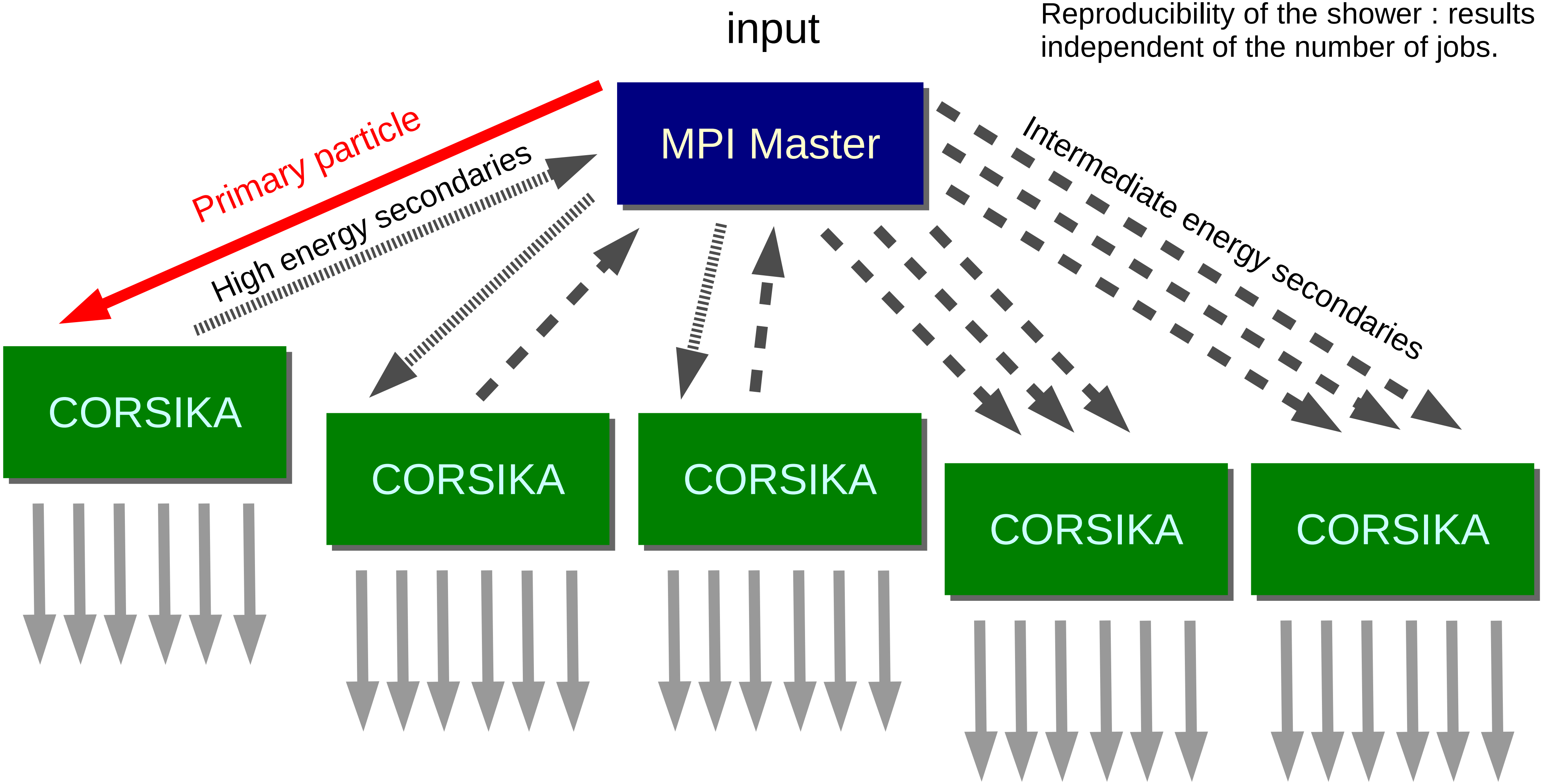
Current Solutions in CORSIKA

- **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.

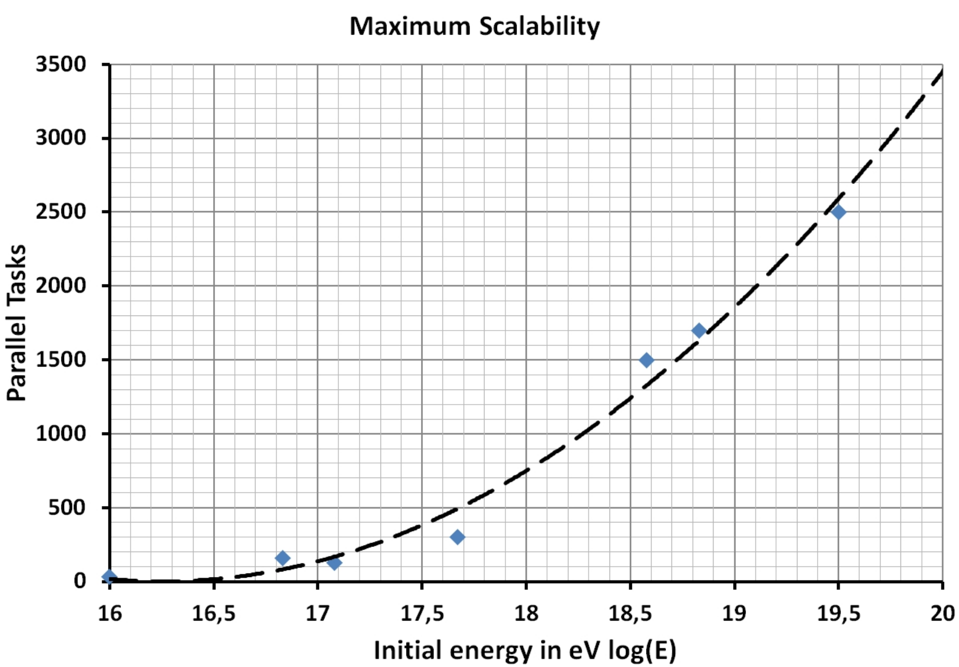


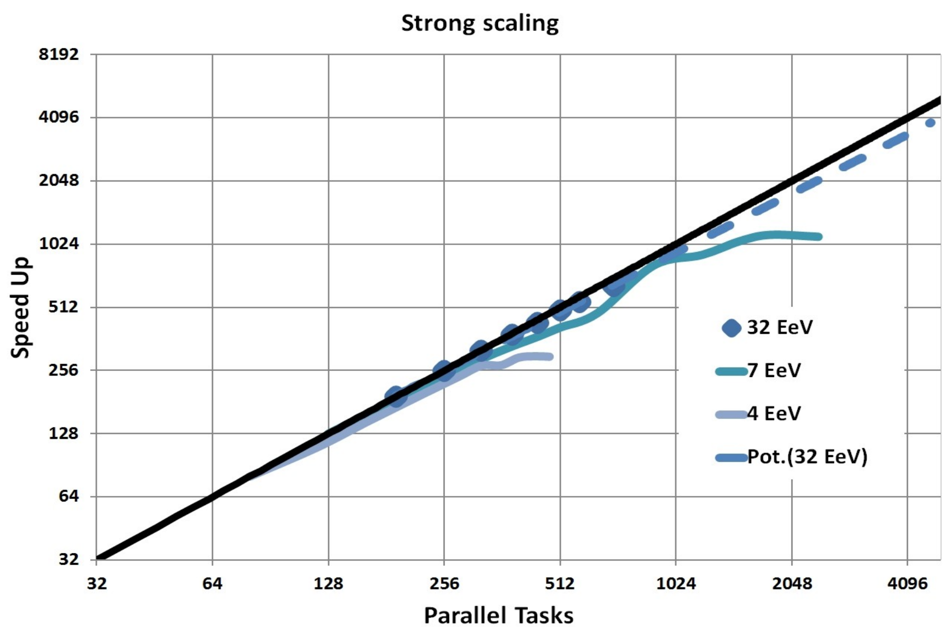
Low energy secondaries down to observation level

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

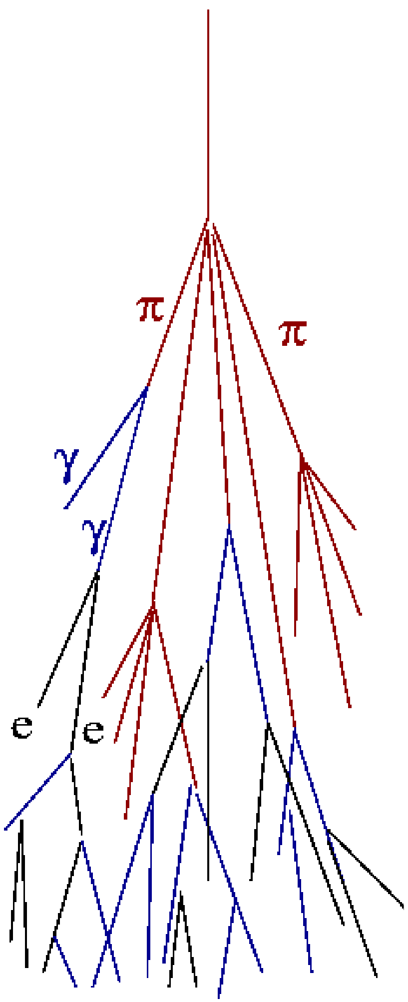
- **solution tested for high energy showers only**
  - ➡ electromagnetic shower not really parallelized ...



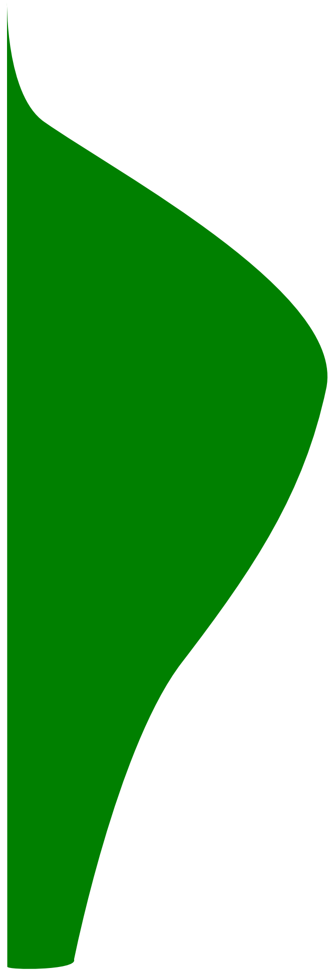


Parallel version tested on HP XC3000 (2.53 GHz CPUs, InfiniBand 4X QDR)

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 ?**

Cascade Equations

- **Can be CE as flexible than MC ?**
  - ➜ electron cascade equations

$$\frac{d\,\phi_e(E)}{dX} = -\sigma_e \phi_e(E) + \int_E^{E_0} \sigma_e \phi_e(\tilde{E})\, P_{e\rightarrow e}(\tilde{E}, E)\, d\tilde{E} + \int_E^{E_0} \sigma_\gamma \phi_\gamma(\tilde{E})\, P_{\gamma\rightarrow e}(\tilde{E}, E)\, d\tilde{E} - \alpha \frac{\partial\, \phi_e(E)}{\partial E}$$

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interaction term

Cascade Equations

- **Can be CE as flexible than MC ?**
  - electron cascade equations

production terms

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interaction term

ionization loss term

Cascade Equations

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- **analytical solution needs simplified distributions**
  - ➡ no analytical function for hadronic production
  - ➡ numerical solution more flexible

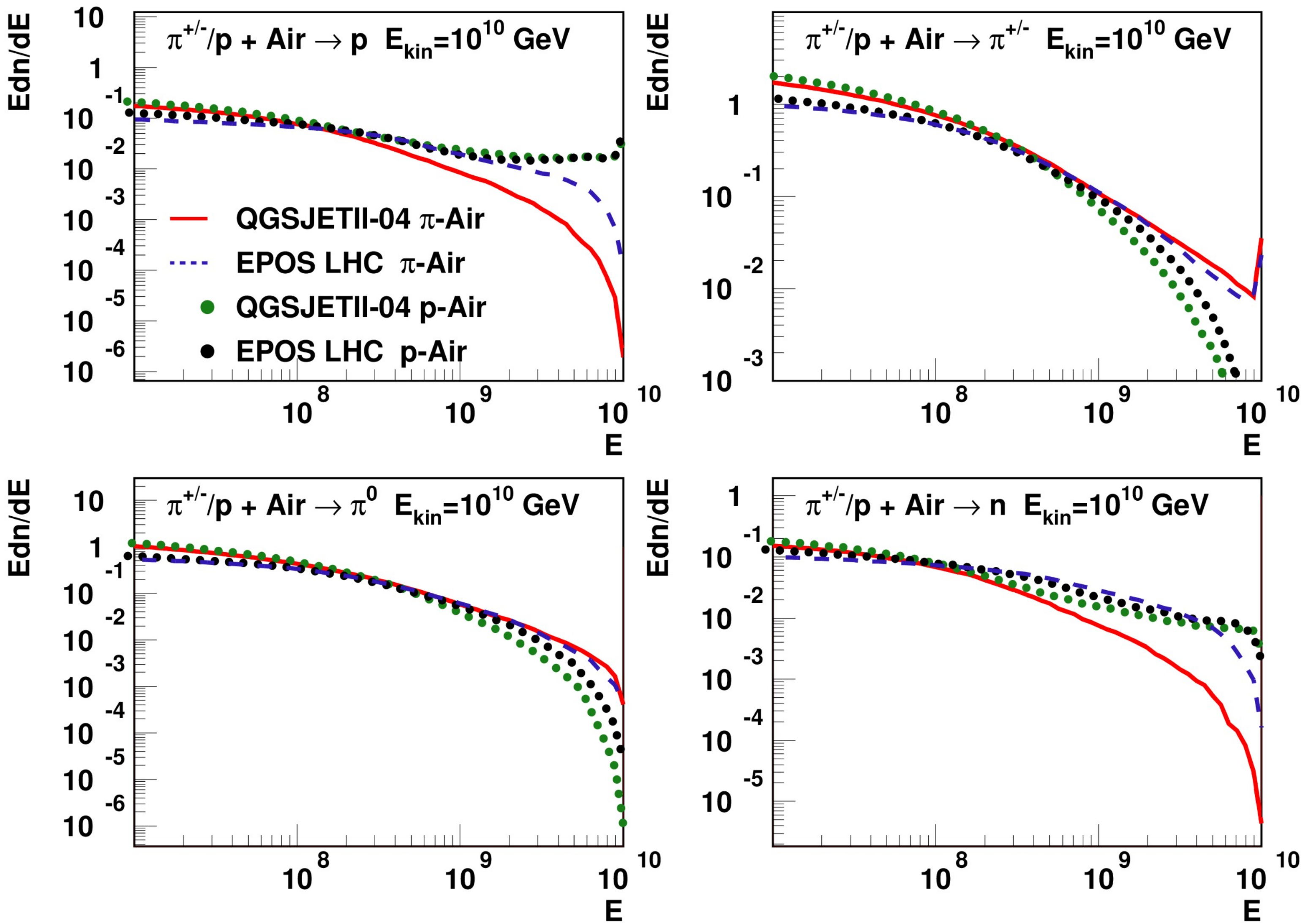
$$\frac{dl_a^i(X)}{dX} = \sum_d \sum_{j=i}^{i_{\max}} \bar{W}_{d\to a}^{ji}\, l_d^j(X) + S_{ai}^{\mathrm{e/m}}(X)$$

Hadronic Particle Spectra (W)

- **Simulations of all type of possible interactions :**
  - $p + Air \rightarrow \pi^{\pm}, p, K^{\pm}, K_L, K_s, n, \gamma, e, \mu$
  - $\pi^{\pm} + Air \rightarrow \pi, p, K^{\pm}, K_L, K_s, n, \gamma, e, \mu$
  - $K^{\pm} + Air \rightarrow \pi, p, K^{\pm}, K_L, K_s, n, \gamma, e, \mu$
  - $K^0 + Air \rightarrow \pi, p, K^{\pm}, K_L, K_s, n, \gamma, e, \mu$
  - $n + Air \rightarrow \pi, p, K, K_L, K_s, n, \gamma, e, \mu$

- **Results stored in tables copied to W**

Hadronic Particle Spectra (W)



- same for decay …

Cascade Equations

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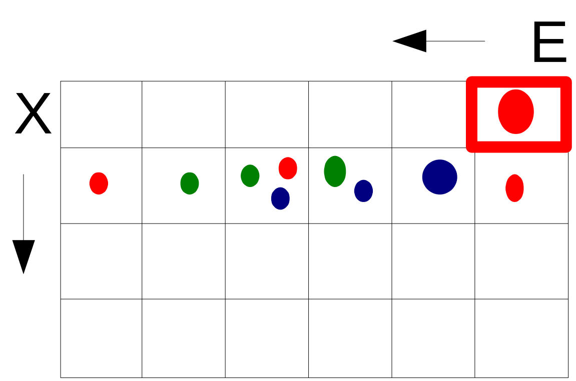

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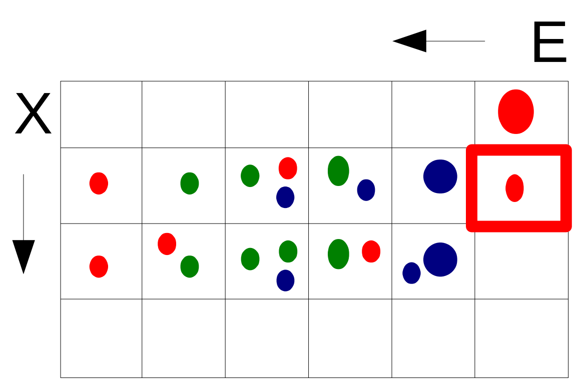

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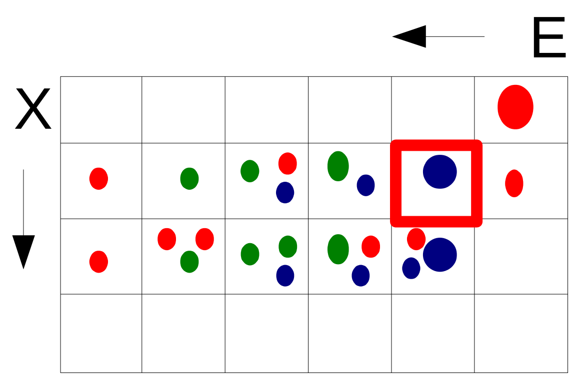
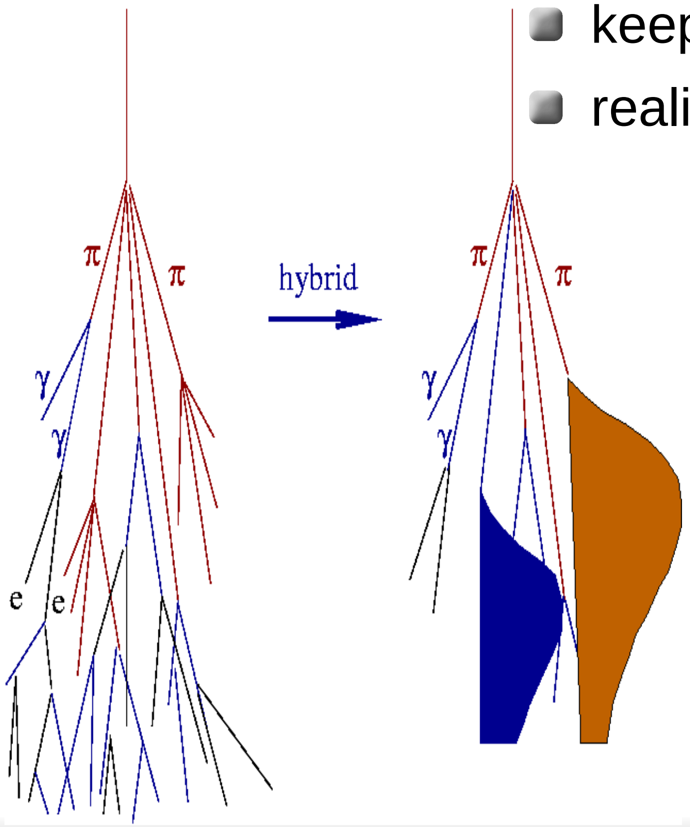
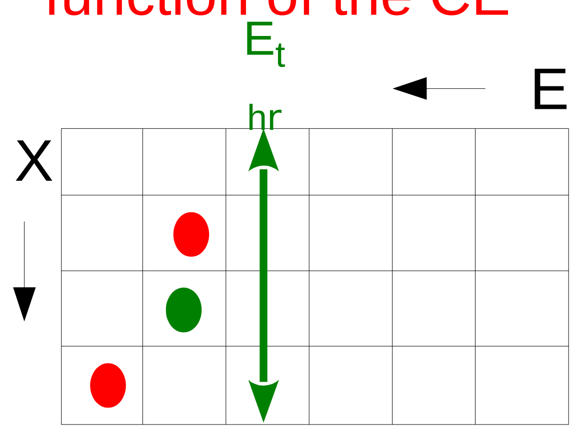


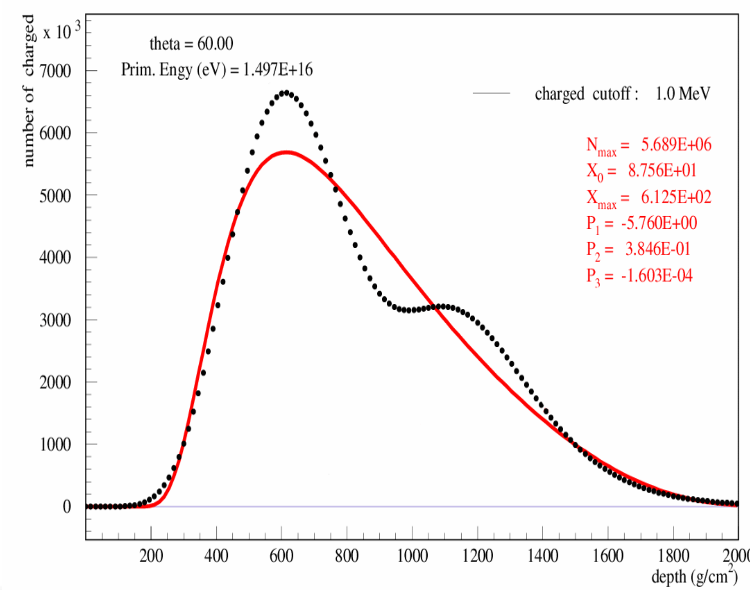
Consistent Hybrid Calculation

- **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

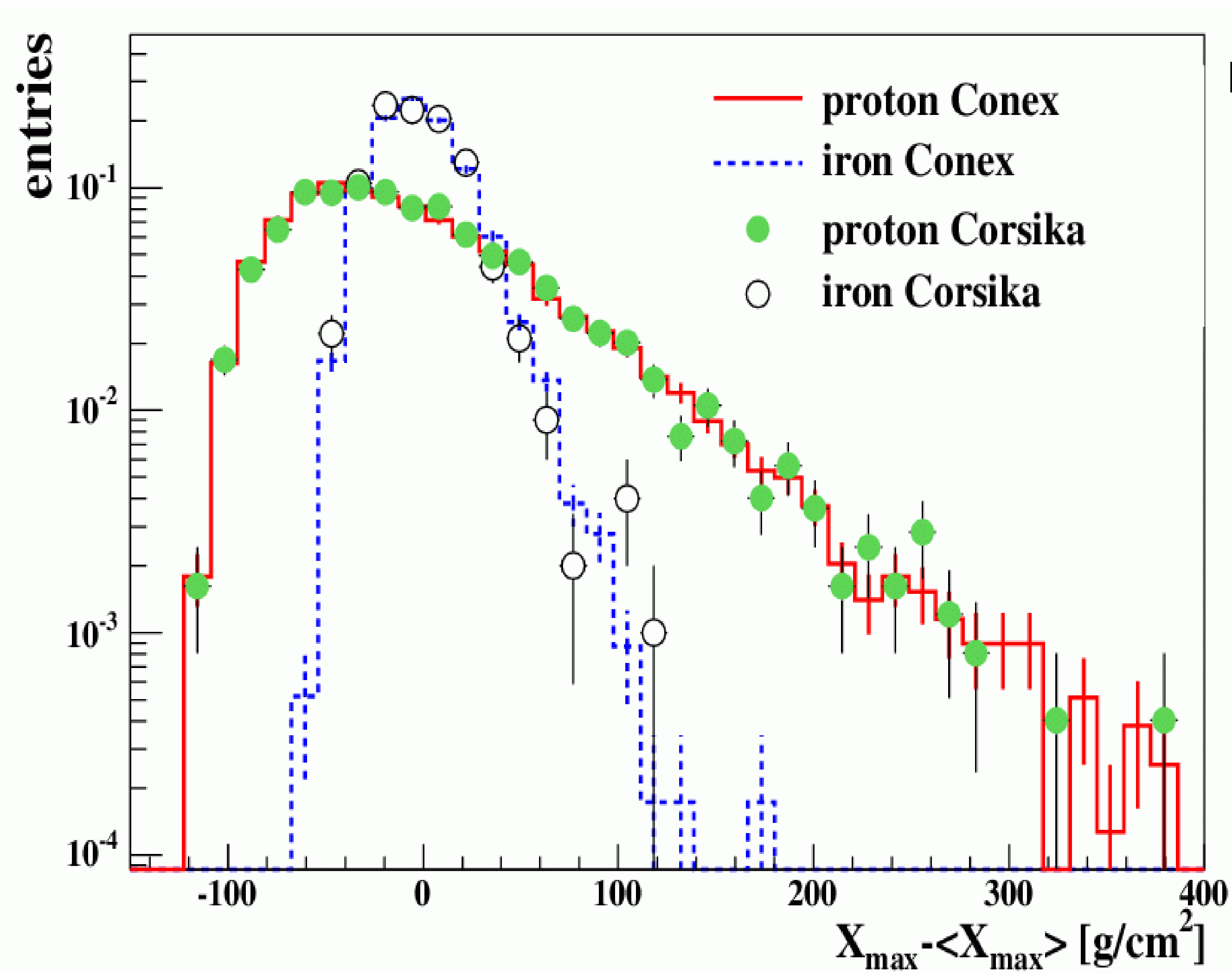




Hybrid vs MC : fluctuations

X_{max} fluctuations

➜ both mean and RMS reproduced



Flat distribution of proton and iron showers from 10^{17} to 10^{20} eV

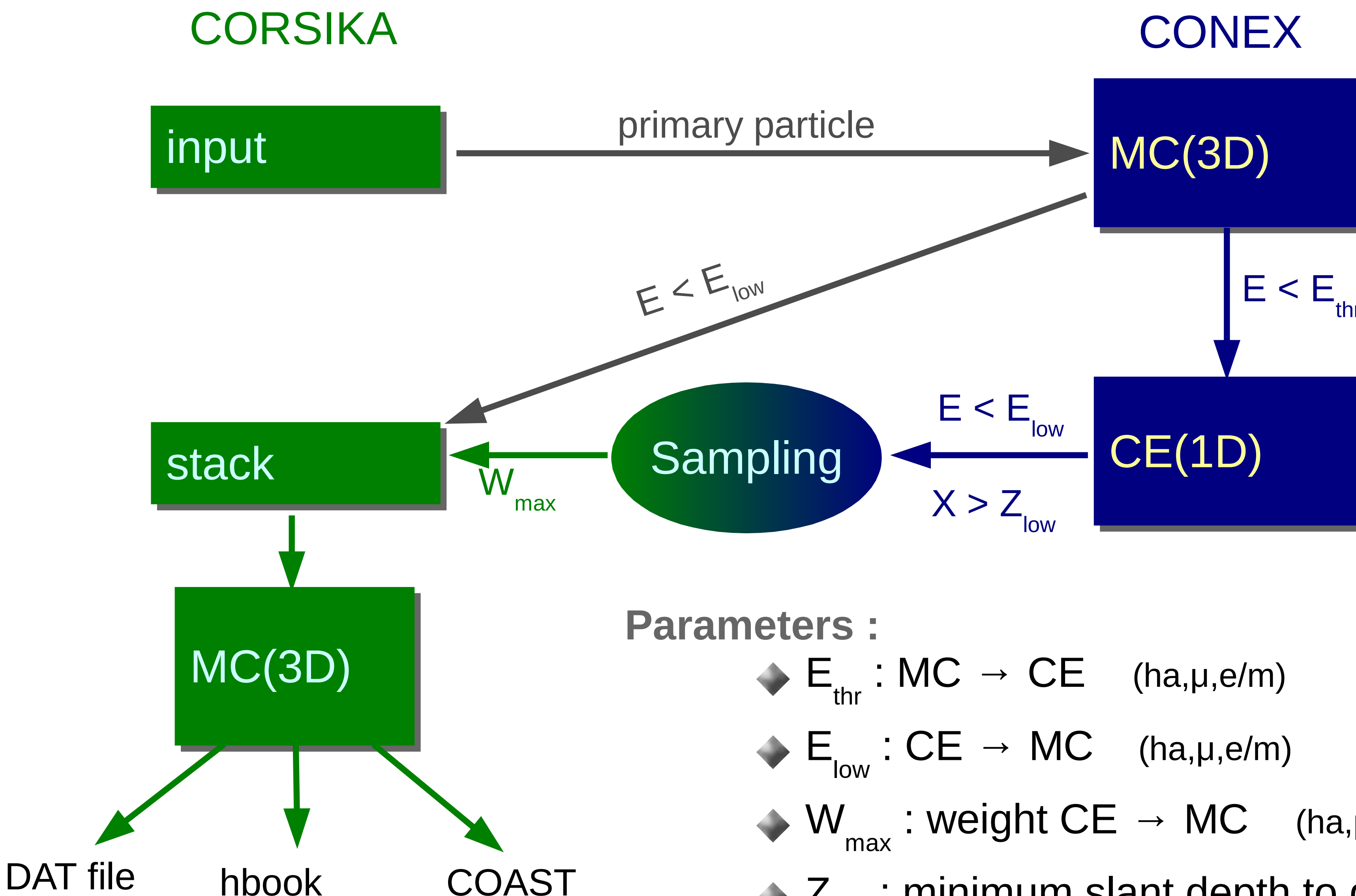
Hybrid Codes

- *L.G. Dedenko et al.*, pioneering work in 1968 (3D, transport equations, Monte Carlo)
- *A.A. Lagutin et al.* (1+1D, transport equations)
- **Bartol code**, *J. Alvarez-Muniz et al.* (1D, pre-simulated shower libraries, muons)
- **SENECA**, *H.J. Drescher & G. Farrar* (3D, 1D transport eqs. for hadrons, 1D em. shower matrix formalism based on EGS)
- **CONEX**, *T. Bergmann, V. Chernatckin, R. Engel, D. Heck, N. Kalmykov, S. Ostapchenko, T. Pierog, K. Werner* (1D Transport equations for hadrons and em with realistic cross section and particle distributions)

Cascade Equations in CORSIKA

- **CE done in CONEX model**
- **CE replace part of CORSIKA Monte-Carlo (MC)**
  - First interactions in CONEX independent from threshold E_{low}
    - Event-by-event simulations using first 1D only and then 3D with exactly the same shower
- **CE replace part of the thinning in CORSIKA**
  - No thinned high energy secondary gammas (stay in CE)
    - No muons from EM particles with very large weight
  - Very narrow weight distributions : less artificial fluctuations
  - No thinning for very inclined shower
    - Only muons and corresponding EM sub-showers in MC
- **Mean showers can be simulated directly** **(no high energy MC)**
- **CE slower than MC at low energy**
  - not efficient for low energy showers

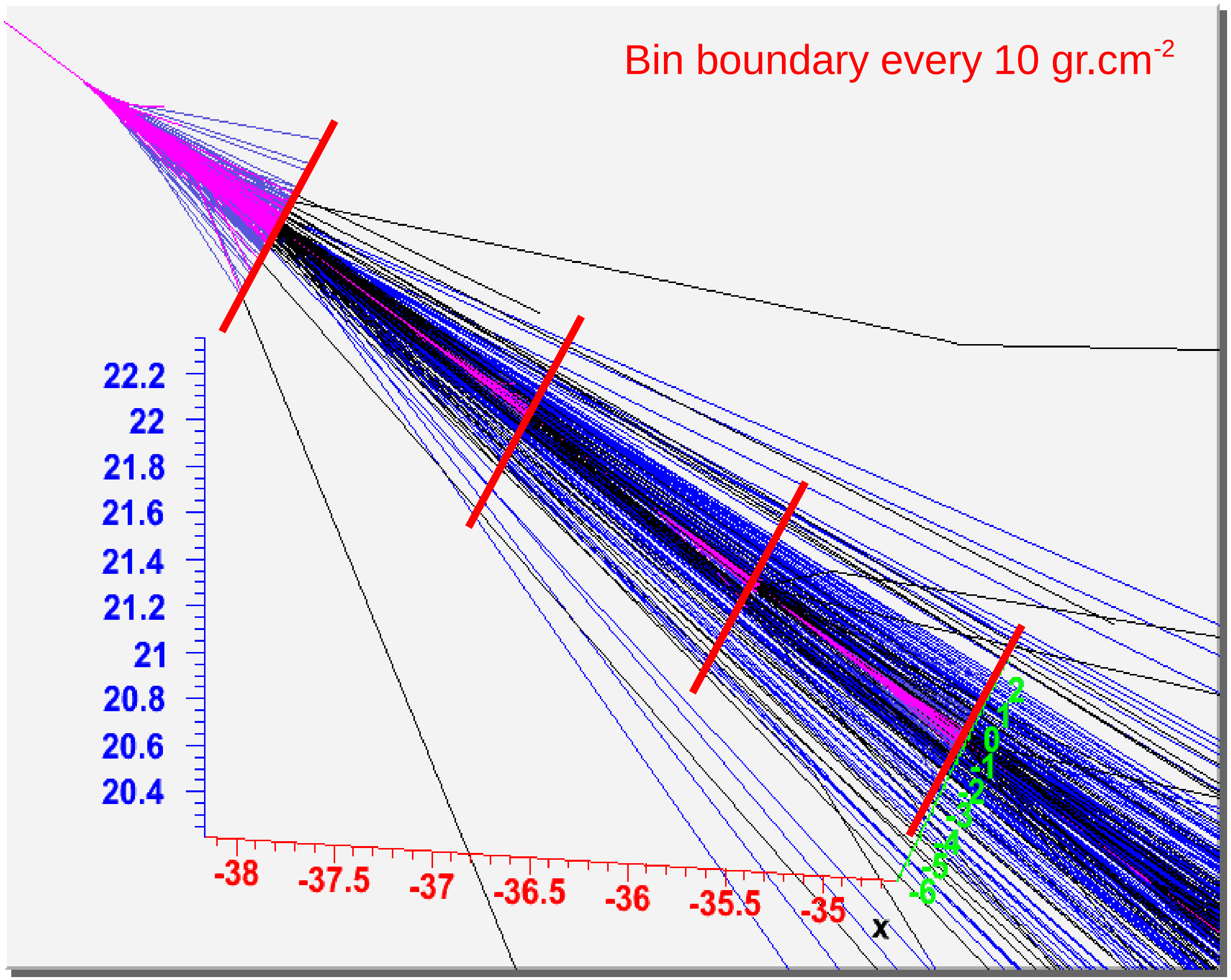
CORSIKA with CONEX



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)

Example :
3D View with COAST

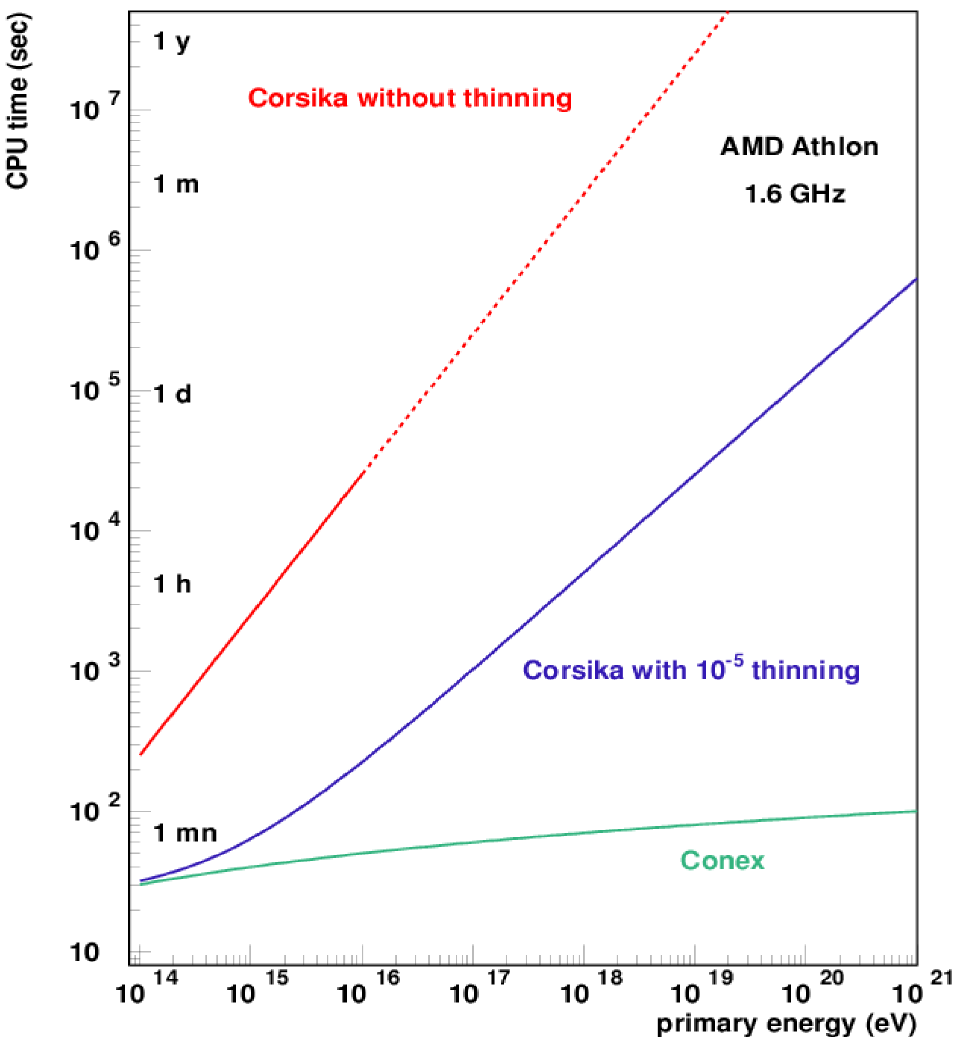


Hybrid 3D : Cascade equation only at intermediate energy

- High energy particle tracks until bin boundaries
- Low energy particle tracks from bin boundaries

Purple : CONEX hadrons
Dark blue : CONEX muons
Dark : CORSIKA hadrons
Blue : CORSIKA muons

CONEX vs CORSIKA : time

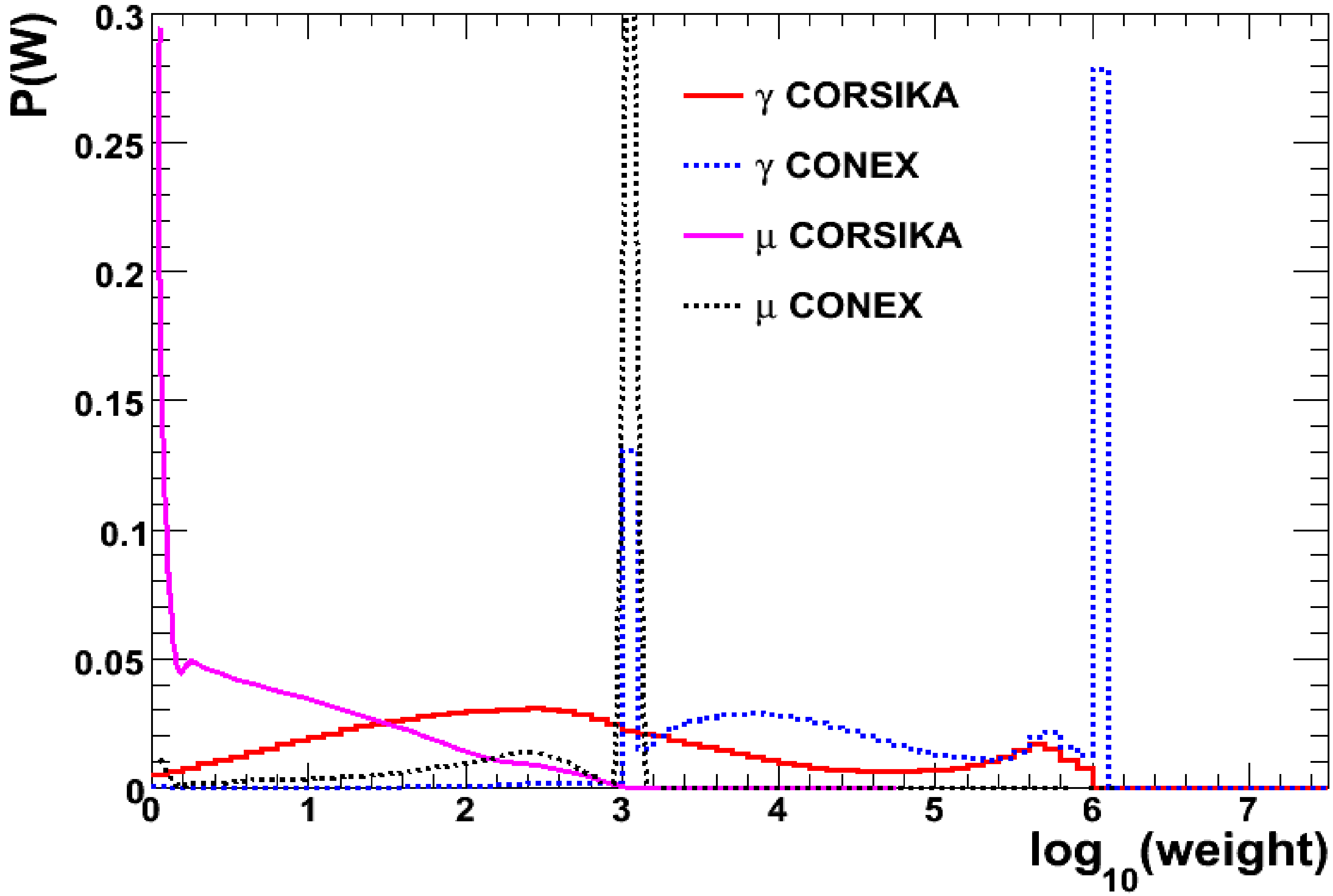


- **1D**
  - CORSIKA : CPU time ∝ Energy
  - CE : CPU time ∝ Log(Energy)
    - <1mn / shower
    - and no artificial fluctuations due to thinning
- **3D**
  - replace thinning
  - 5-10 times faster than thinning for the same maximum weight
  - better weight distribution

Weight distribution R > 100 m

Very narrow weight distribution from sampling

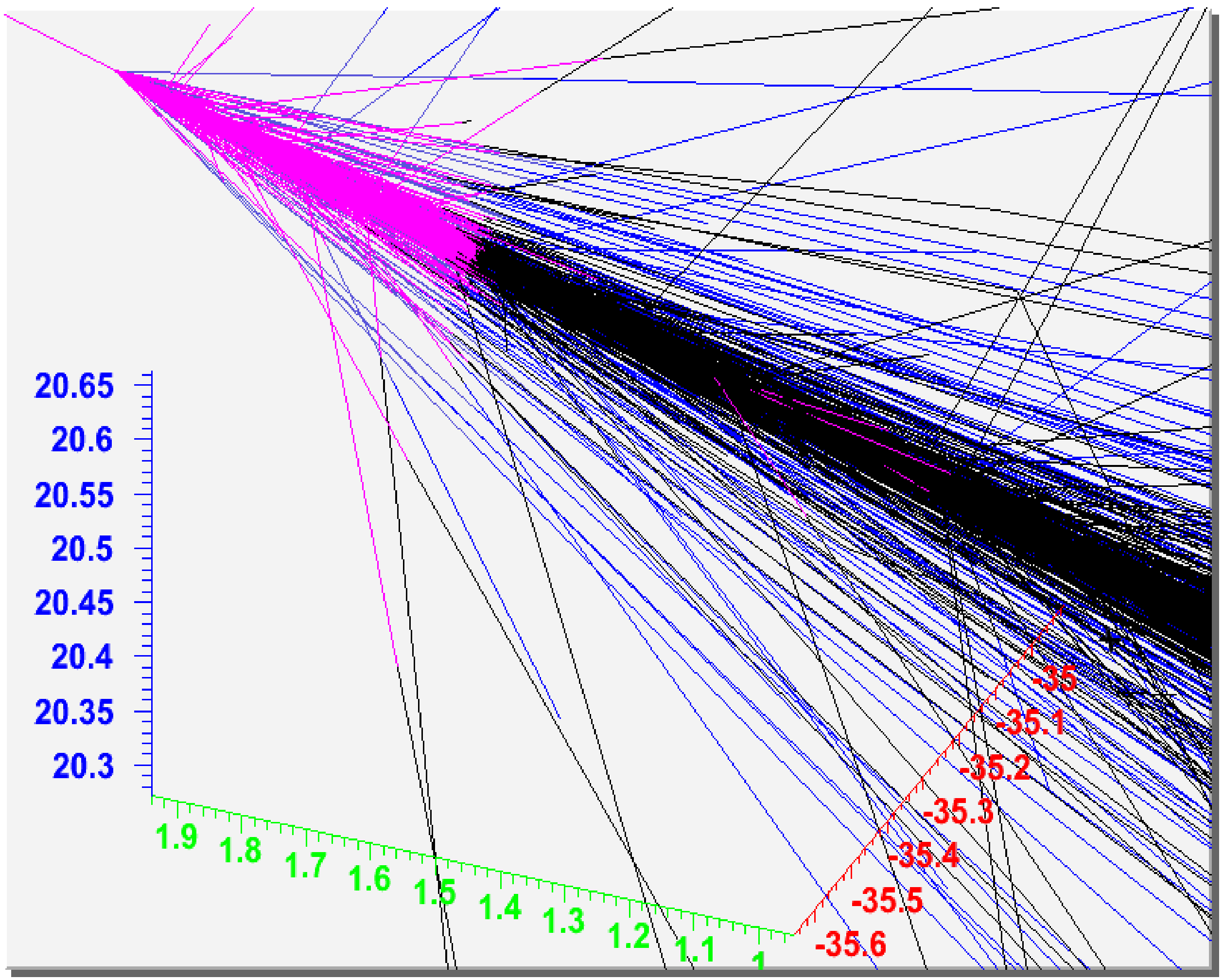
➜ less artificial fluctuations



Possible new Approaches

- **More optimal thinning approach**
- **Cascade Equations part of the new development**
  - ➜ better integration and no redundant code as now with CONEX/CORSIKA
- **MPI type parallelization taken into account from the beginning**
- **Modularity allows parallelization of sub-processes**
  - ➜ GPU based Cherenkov photon calculation
  - ➜ GPU based radio
  - ➜ ...
- **Deep learning based modules for particular processes ? … for the full shower ?**

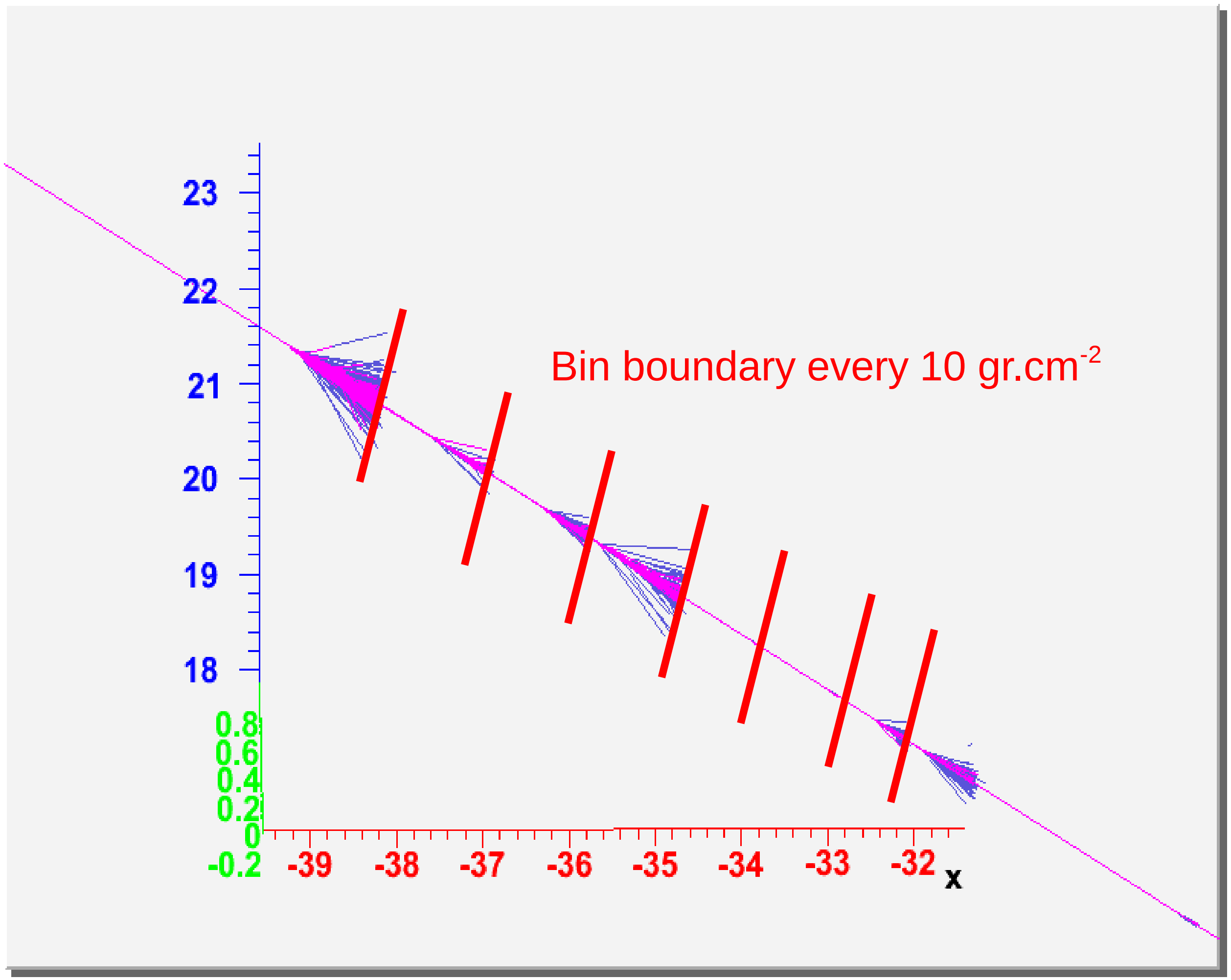
Example :
3D View with COAST



- **MC 3D : no cascade equation**
  - ➡ CONEX MC at high energy
  - ➡ CORSIKA at low energy
  - ➡ Track connection at bin boundary

Purple : CONEX hadrons
Dark blue : CONEX muons
Dark : CORSIKA hadrons
Blue : CORSIKA muons

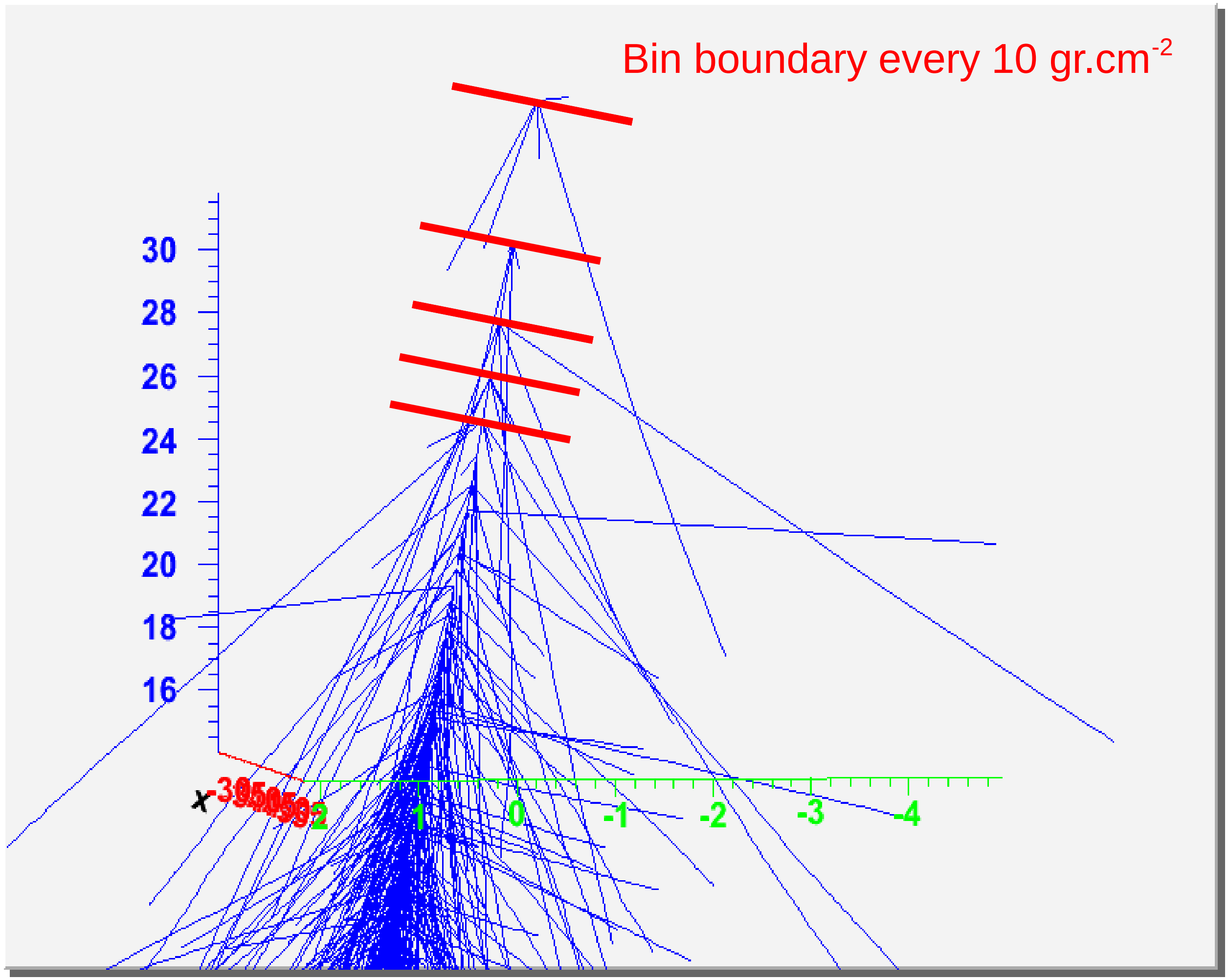
Example :
3D View with COAST



- **Hybrid 1D : Cascade equation only at low energy**
  - Particle track only until bin boundaries
  - Interaction off leading particles

Purple : CONEX hadrons
Dark blue : CONEX muons

Example :
3D View with COAST

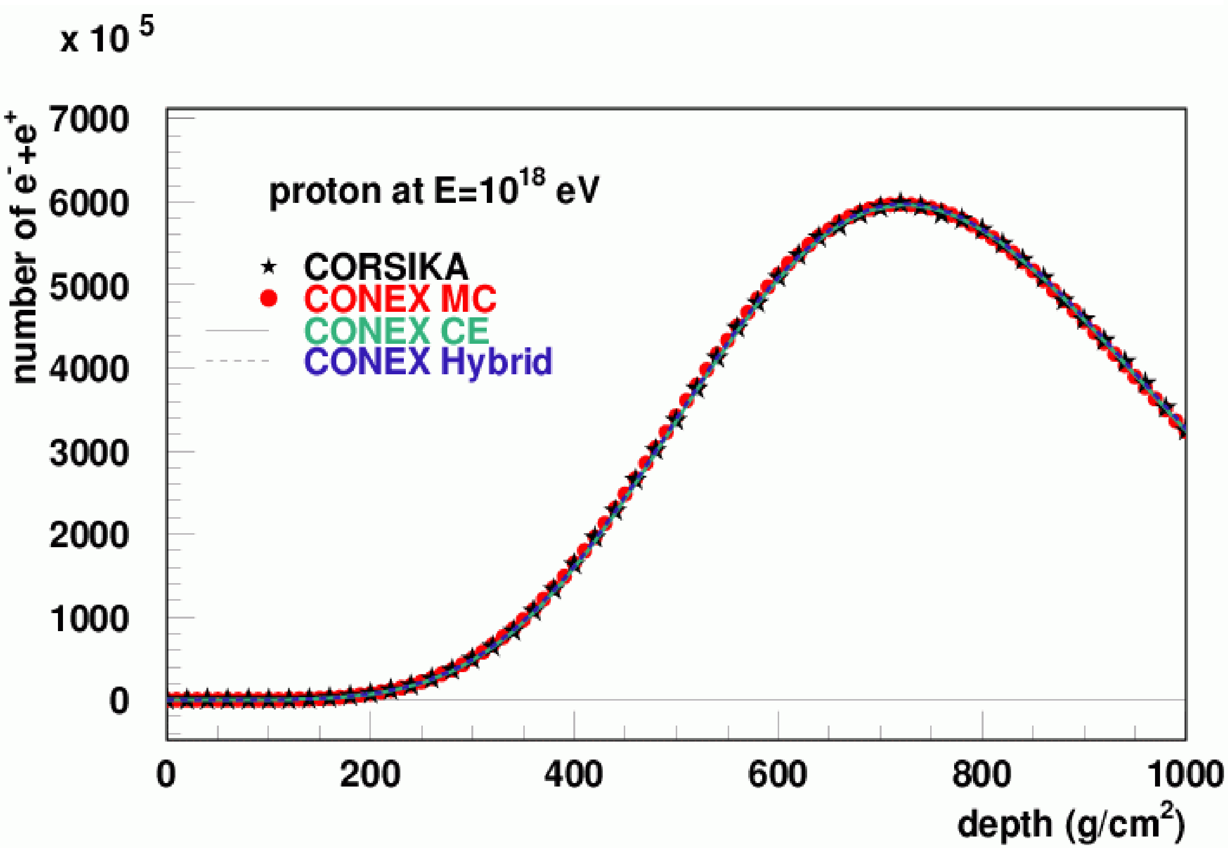


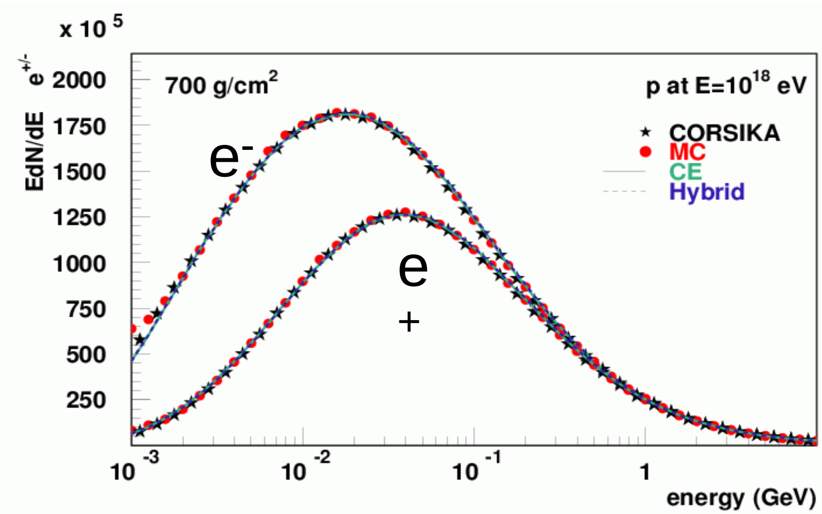
- **3D muons : Cascade equation only for hadrons**
  - Muon tracks start from bin boundaries
  - Muons generated with realistic angular distribution

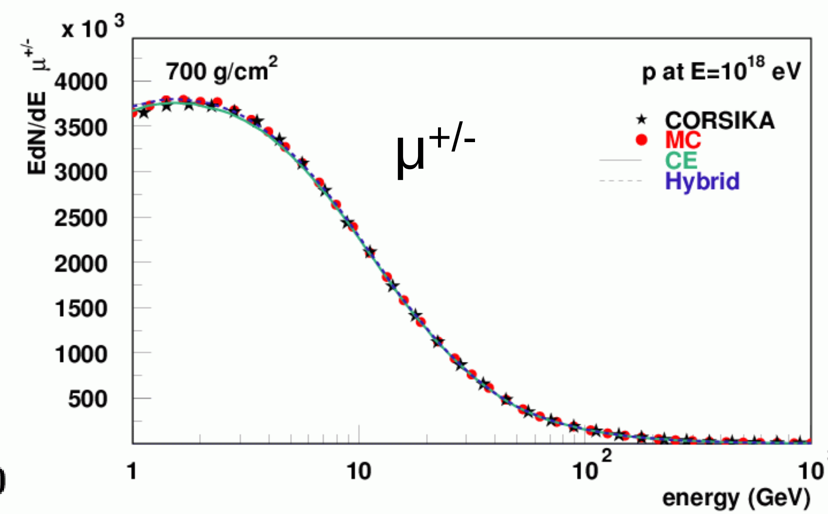
Blue : CORSIKA muons

CORSIKA vs CONEX : particles

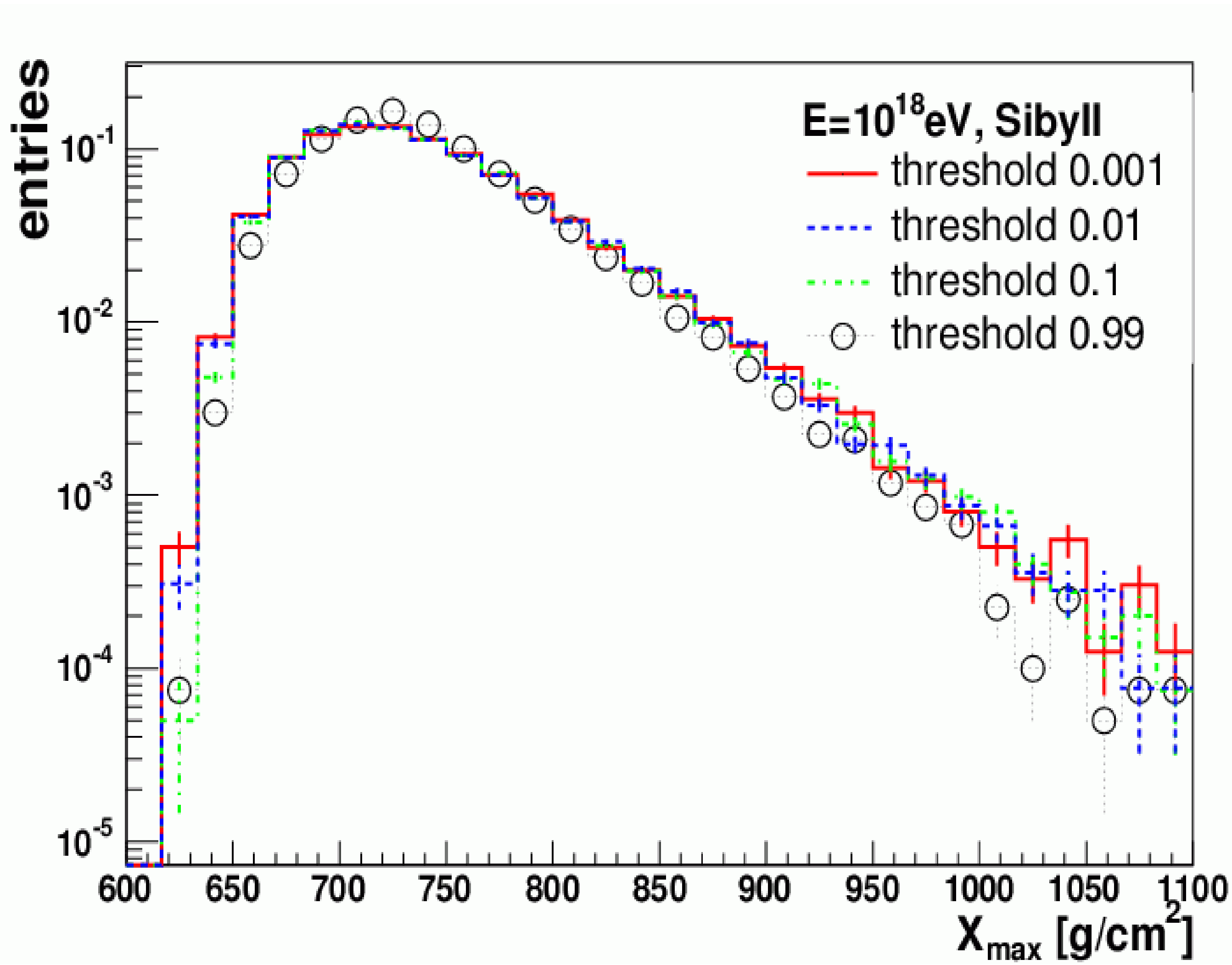
- **Vertical proton induced shower 10^{18}eV :**
  - ➜ Longitudinal distribution
  - ➜ Energy distribution







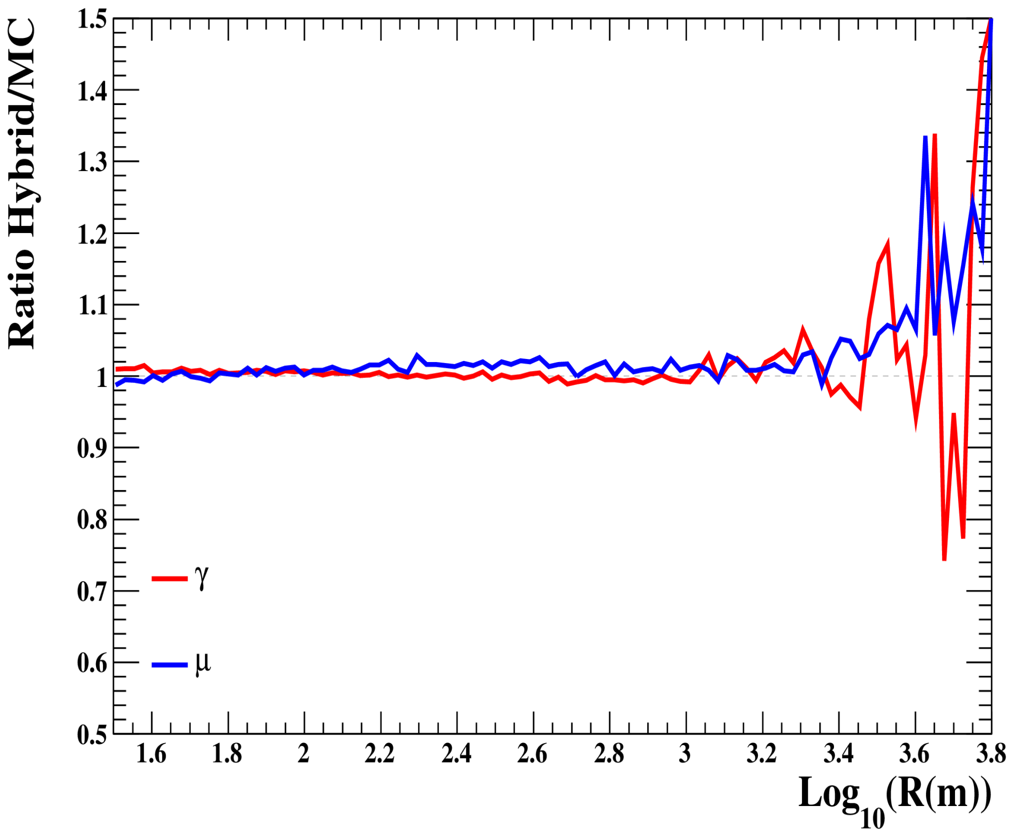
Threshold Effect

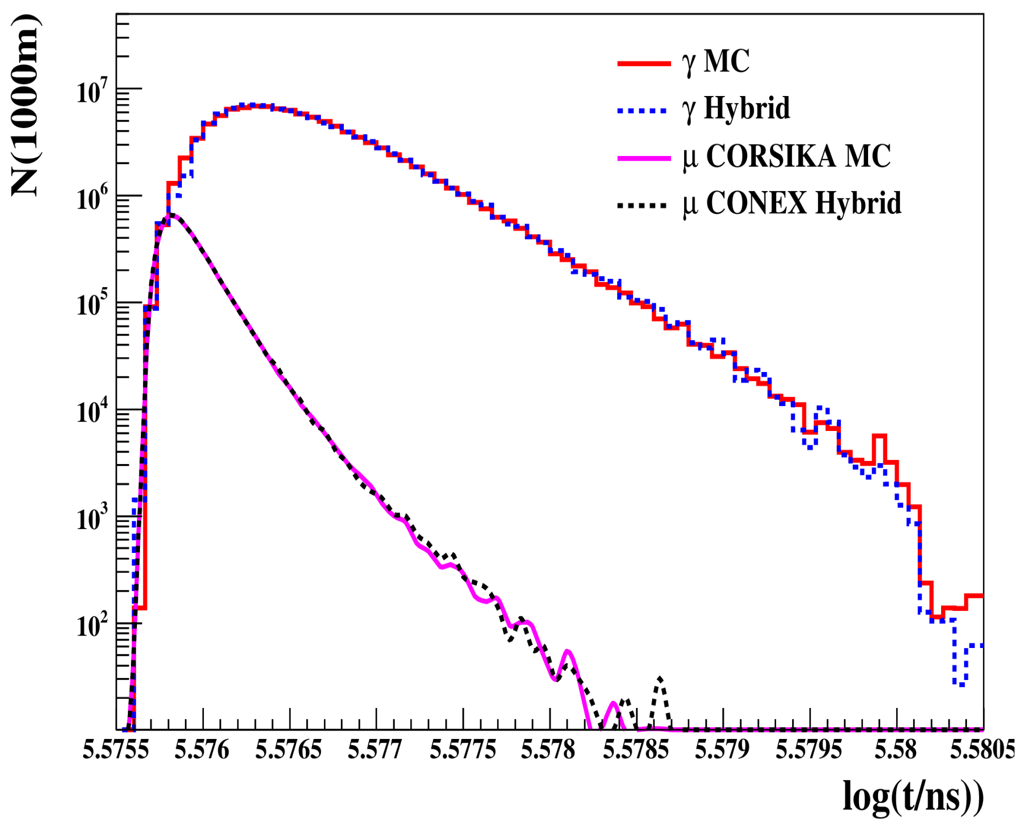


- **Xmax fluctuations :**
  - Probability distribution of Xmax, using SIBYLL model at 10^{18} eV (60°)
  - almost all fluctuations from the first interaction

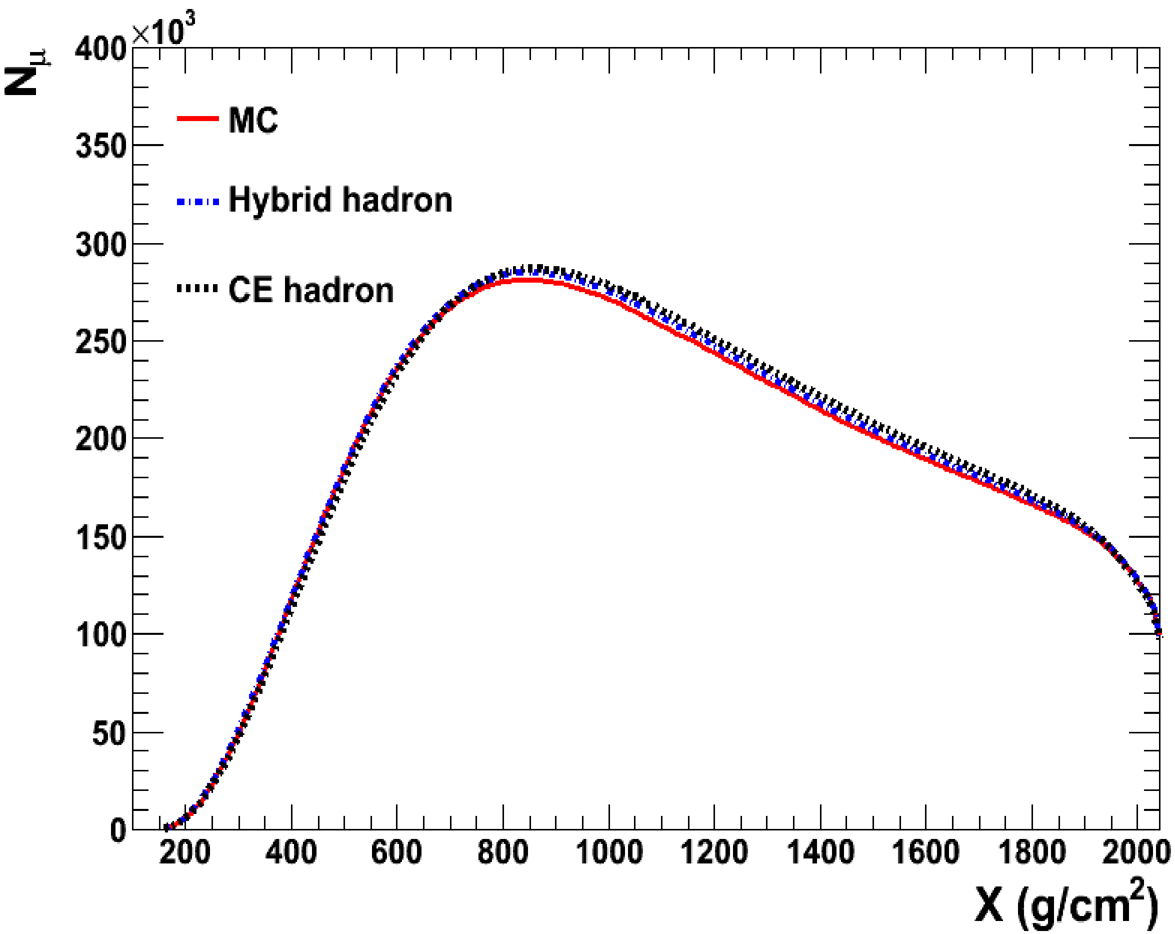
Example

- QGSJET01/GHEISHA Iron shower 10^{19} eV
  - MC : 49h (max weight = 1000(em)/100(had))
  - Hyb : 10h (max weight = 1000(em)/100(had))
- 1 shower (same seed) : X_{max}=670(MC) / 673(Hyb) g/cm^2





Example :
1 shower with different thresholds



Same profile within 3%

Proton @ 0.1 EeV EGS4 off

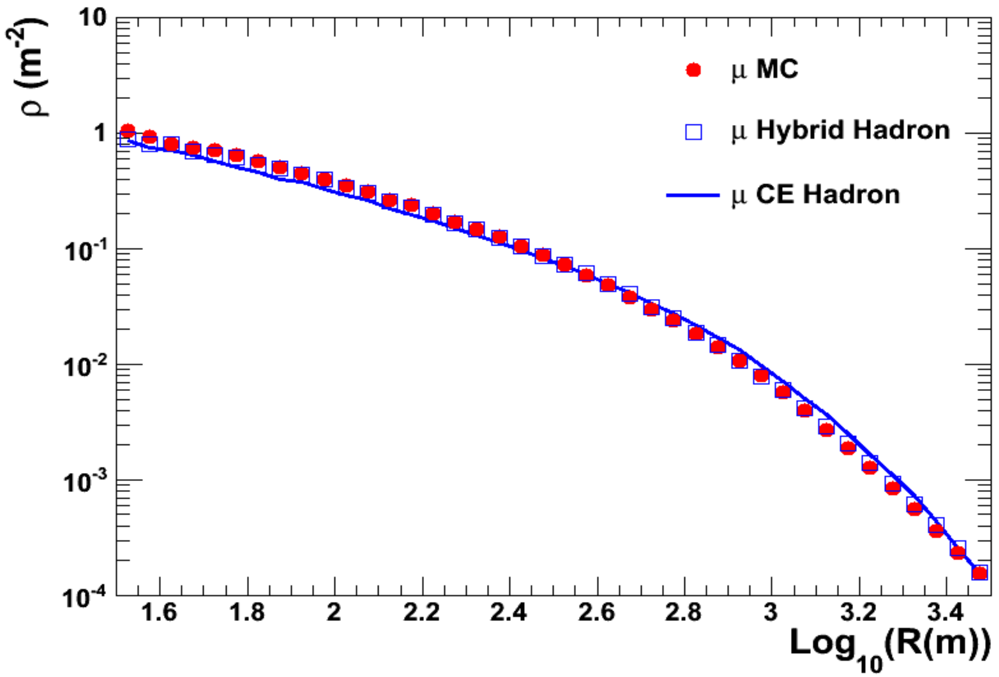
QGSJET + GHEISHA

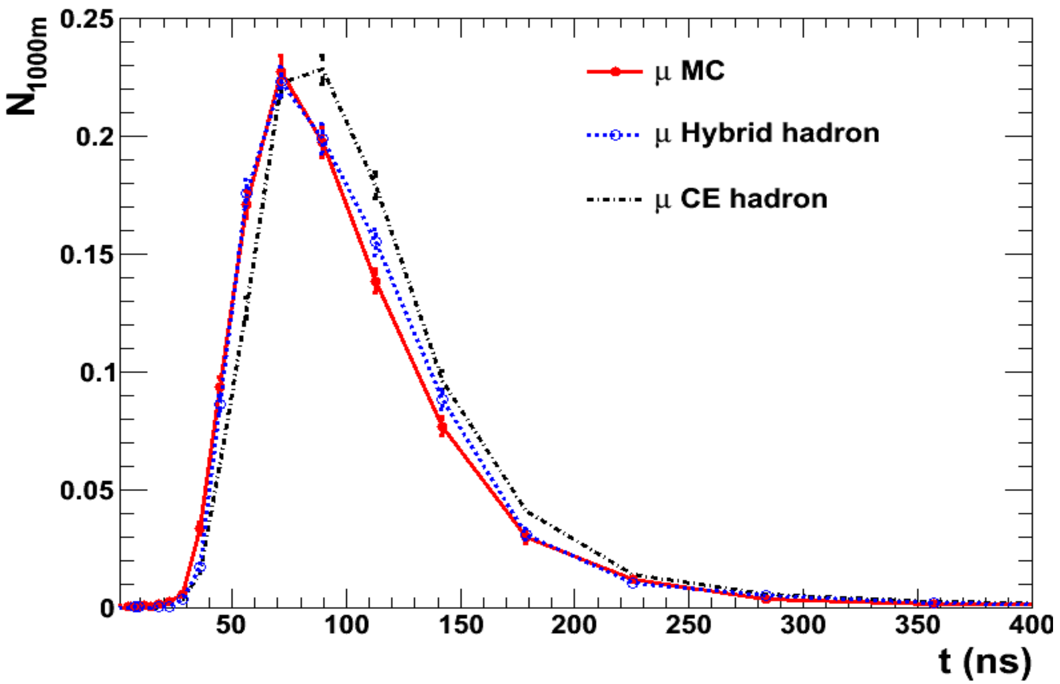
- MC : CONEX MC FOR E > 1 TeV
  CORSIKA FOR E < 1 TeV
- Hybrid hadron : CONEX MC < 1 TeV
  100 GeV < hadronic CE < 1TeV
  CORSIKA < 100 GeV
- CE hadron : CONEX MC < 1 TeV
  CORSIKA only for muons (all E)

One shower, same random numbers

Example :
1 shower with different thresholds

Proton @ 0.1 EeV EGS4 off
QGSJET + GHEISHA





Reasonable results for CE but hadronic MC needed for precise results