Neutrino Induced Air Shower Monte Carlo Simulations

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GRAND Workshop, LPNHE, Paris, France

February the 9th 2015

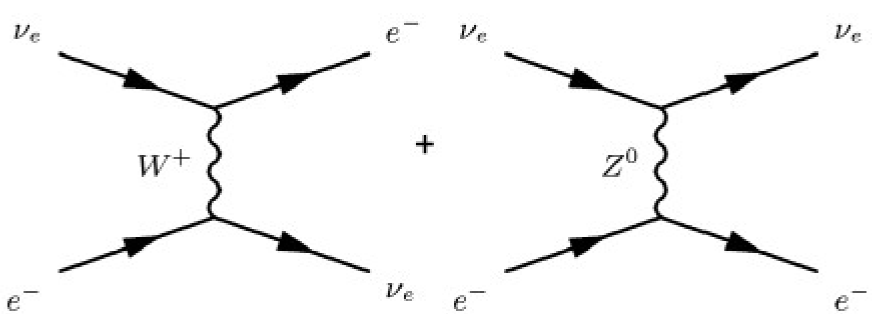
Outline

- **Neutrino induced showers**
  - ➔ energy reconstruction
- **Neutrino and inclined shower in CORSIKA**
- **Large scale air shower simulations**
  - ➔ Parallelization
  - ➔ Cascade equations
- **Summary**

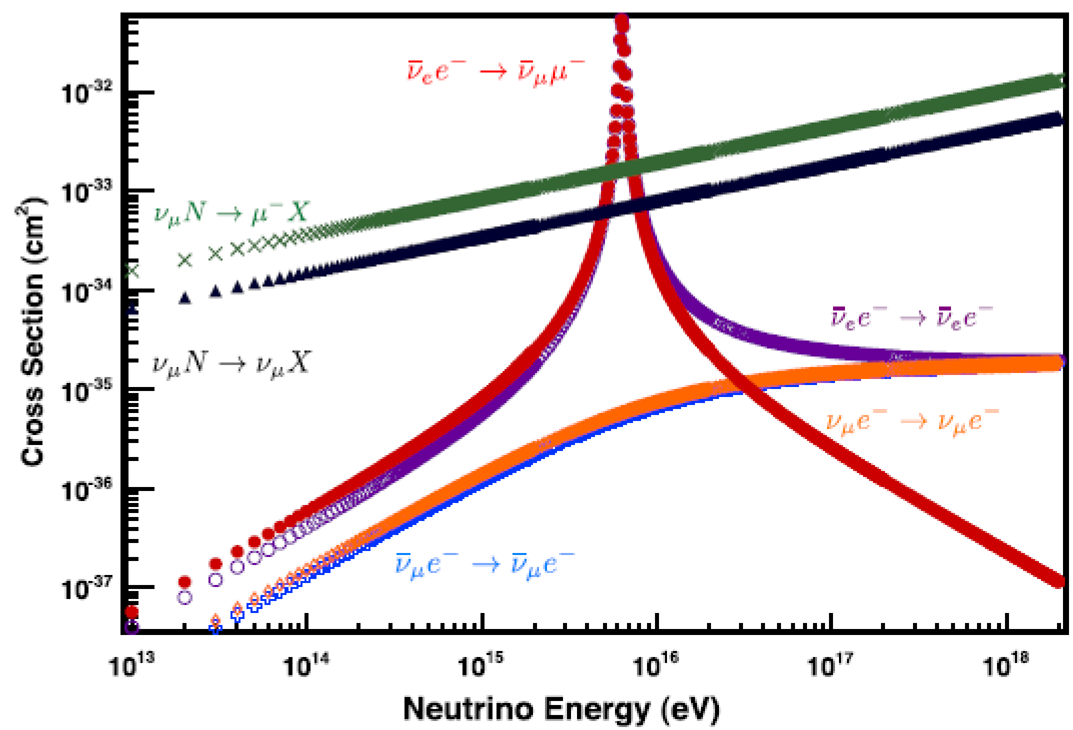
Full energy reconstruction depend on interaction process and parallelization of CORSIKA simulations allows large scale radio simulations.

Neutrino Interaction

- **At high energy neutrino-nucleus interaction via Deep Inelastic Scattering**
  - ➔ exchange of a weak boson ($W^{+/-}$ or Z^0) with a quark in the nucleus :
    - electro-weak cross section well describe by Standard Model
    - depends on parton distribution function with large uncertainty at small momentum fraction x
- **Resonance production at lower energy (~10^{16}eV)**
  - ➔ only lepton scattering



Formaggio & Zeller (2012)



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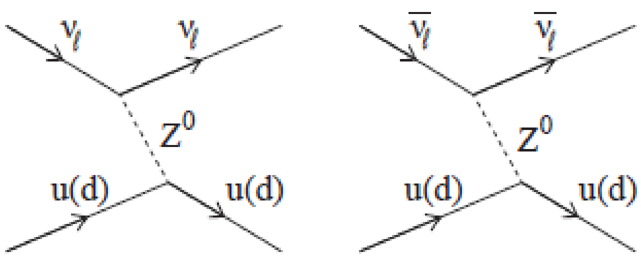
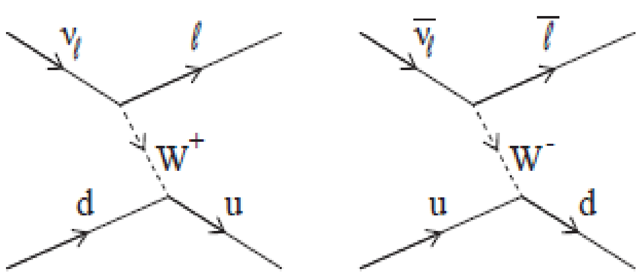
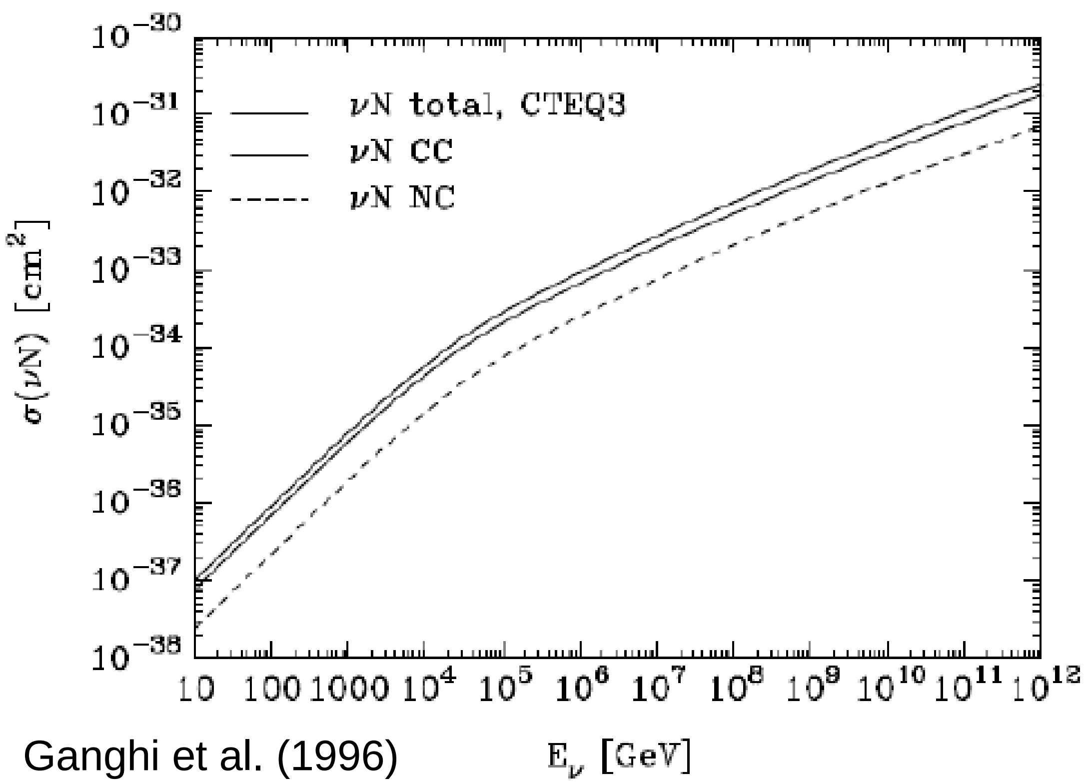
Neutral current (NC)



Charged current (CC)





Ganghi et al. (1996)

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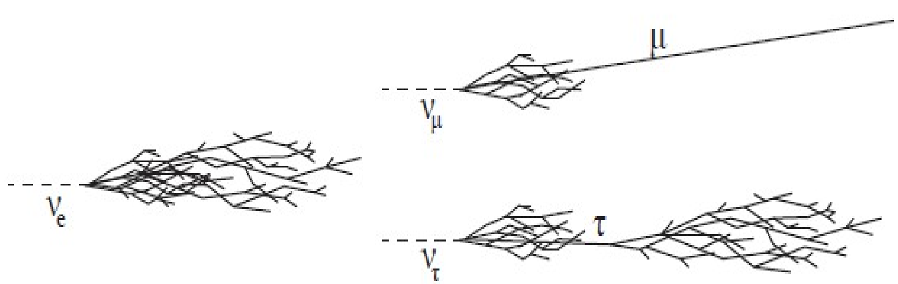
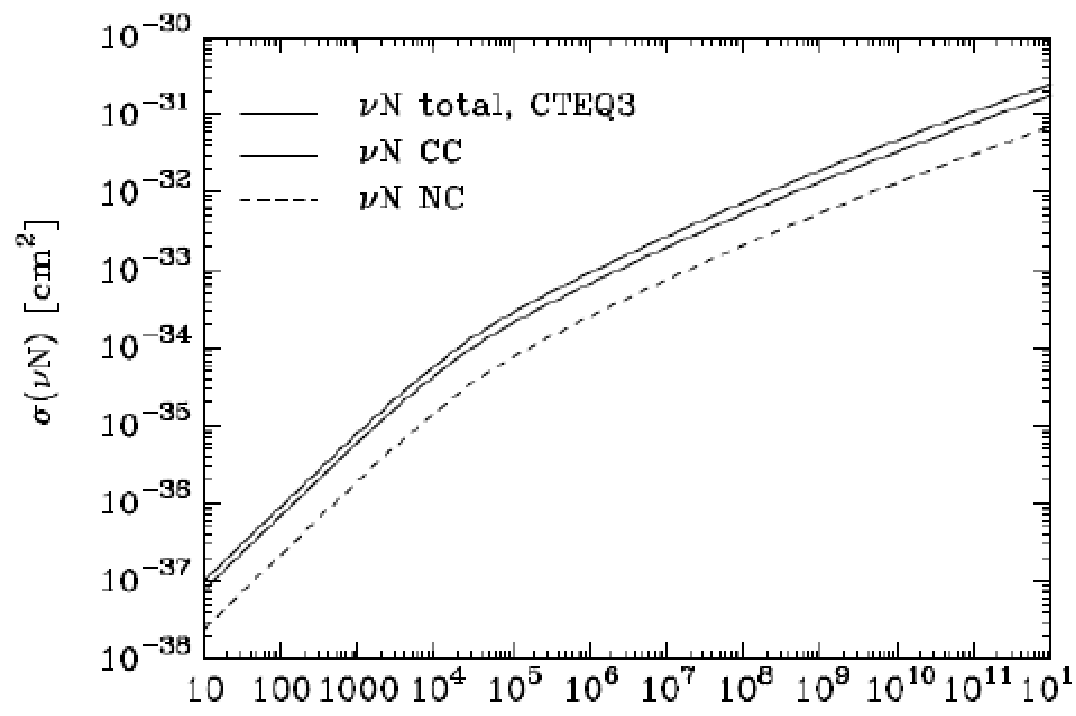




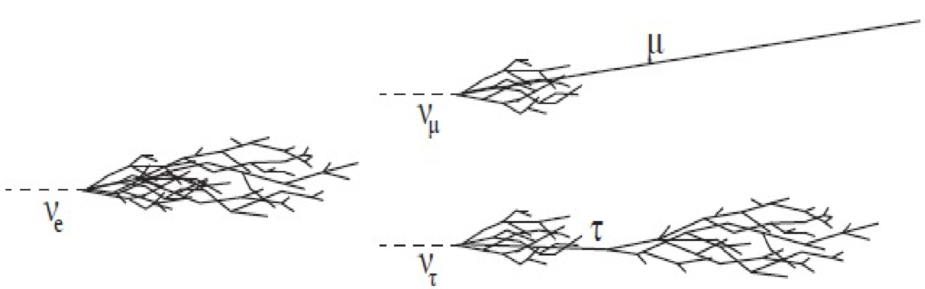
Ganghi et al. (1996) E_ν [GeV]

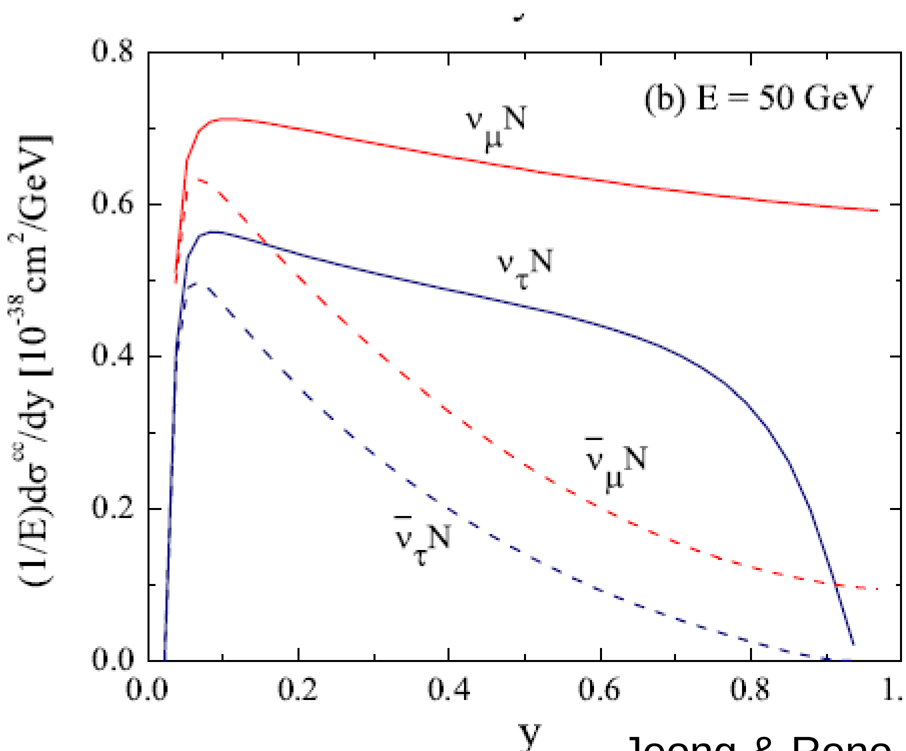
Energy Reconstruction

- **Interaction : ν_ℓ + N → ν/ℓ + X**
  - ➜ $\mathbf{E_\nu = E_\ell + E_X}$ or $\mathbf{E_X = yE_\nu}$ where y is called inelasticity
  - ➜ for all <y>~0.2 but with large spread
  - ➜ Primary Energy known only if $\mathbf{E_\ell}$ can be measured

Neutral current (NC)

Charged current (CC)





Jeong & Reno (2010)

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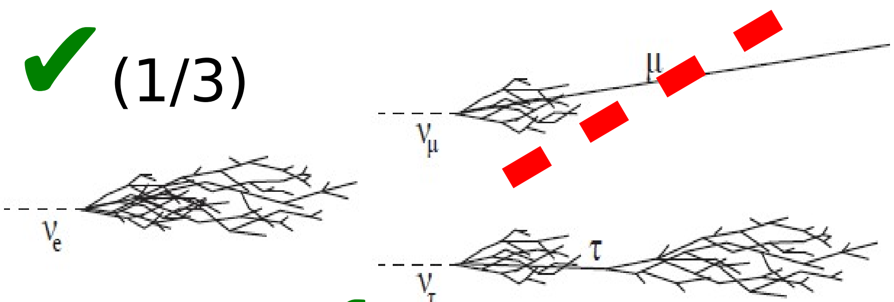
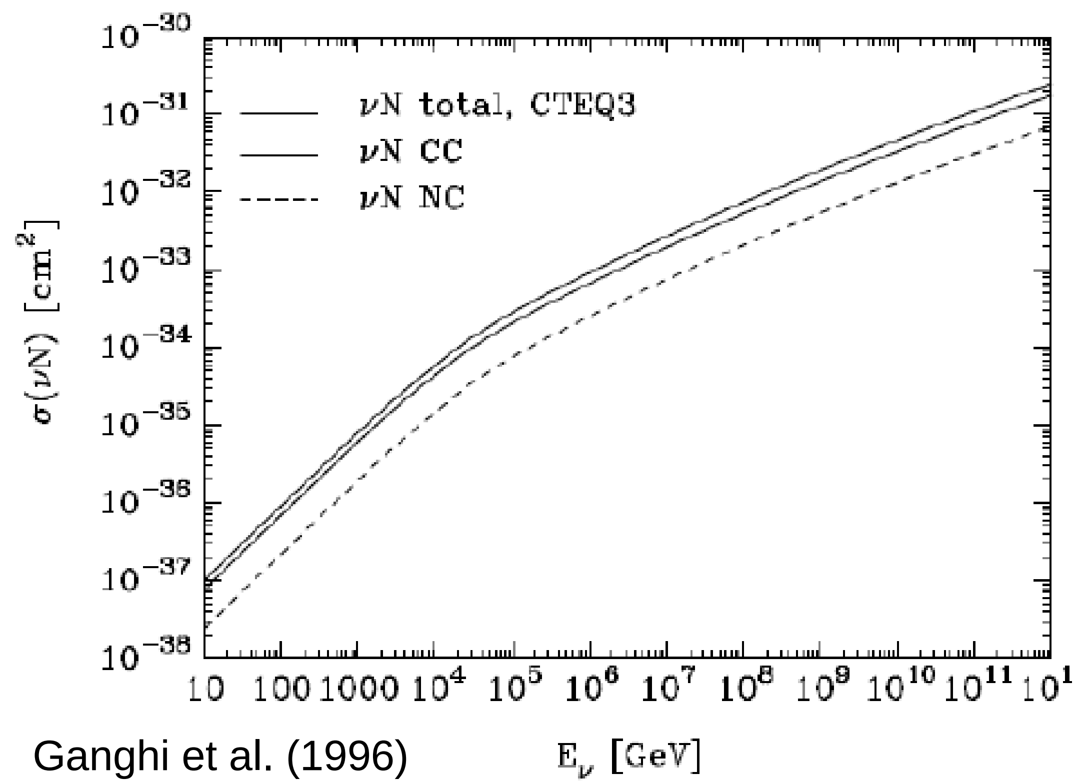
Neutral current (NC 10%)

Charged current (CC 90%)

✔ (1/3)



(✔)(<1/3)



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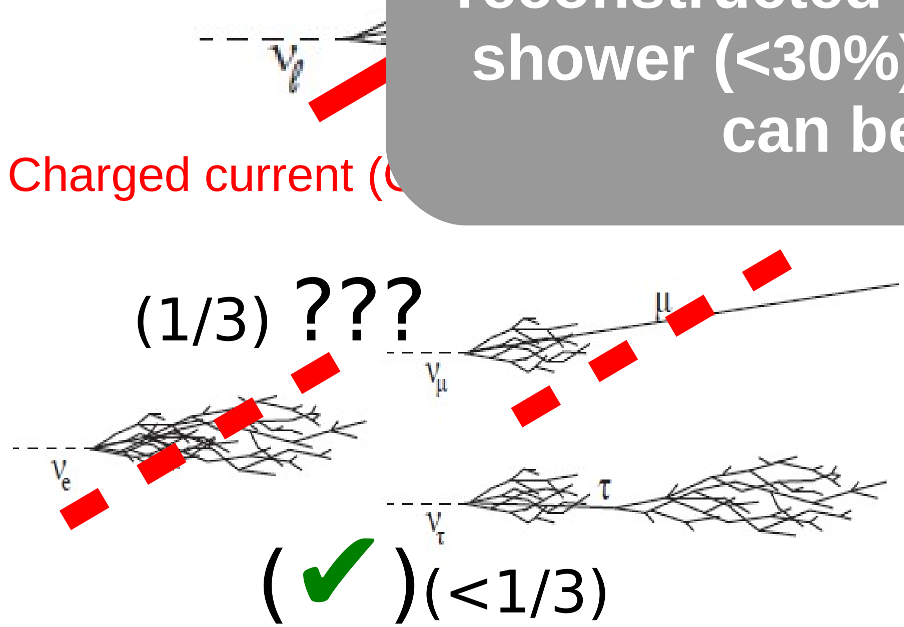
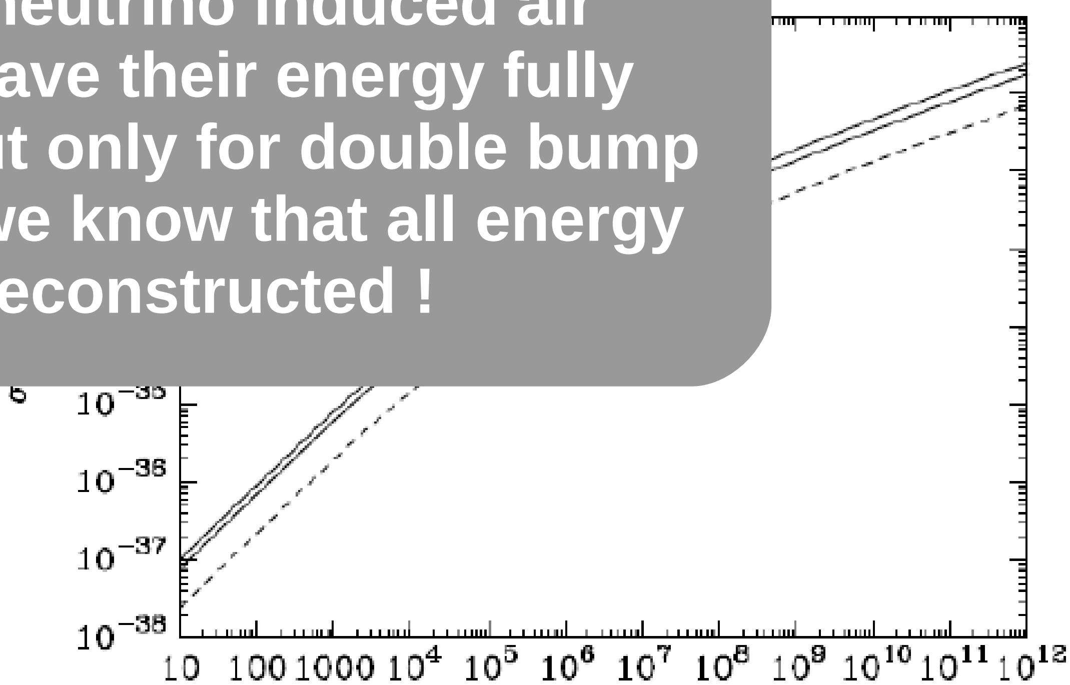


30 to 50% of neutrino induced air showers can have their energy fully reconstructed but only for double bump shower (<30%) we know that all energy can be reconstructed !

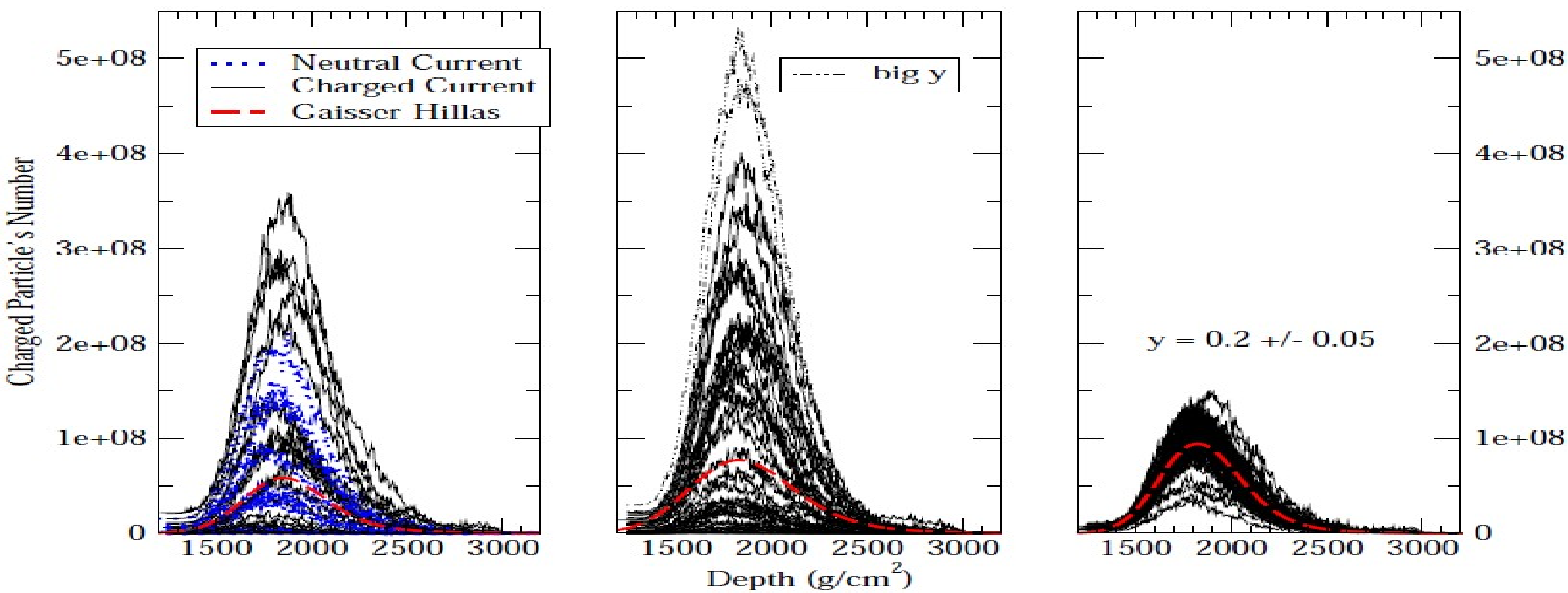


Ganghi et al. (1996)

Neutrino Showers in CORSIKA

- **Primary interaction done by external program**
  - ➔ HERWIG 5.10
- **Possibility to get random interaction or select CC or NC and inelasticity**
- **Neutrino induced EAS are similar to hadron induced EAS but**
  - ➔ large X_{max} due to low cross-section
  - ➔ large N_{max} fluctuations due to varying inelasticity
  - ➔ double bump in case of Tau neutrino

neutrino @ 0.5EeV from Moura & Guzzo (2007)



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no @ 0.5EeV from
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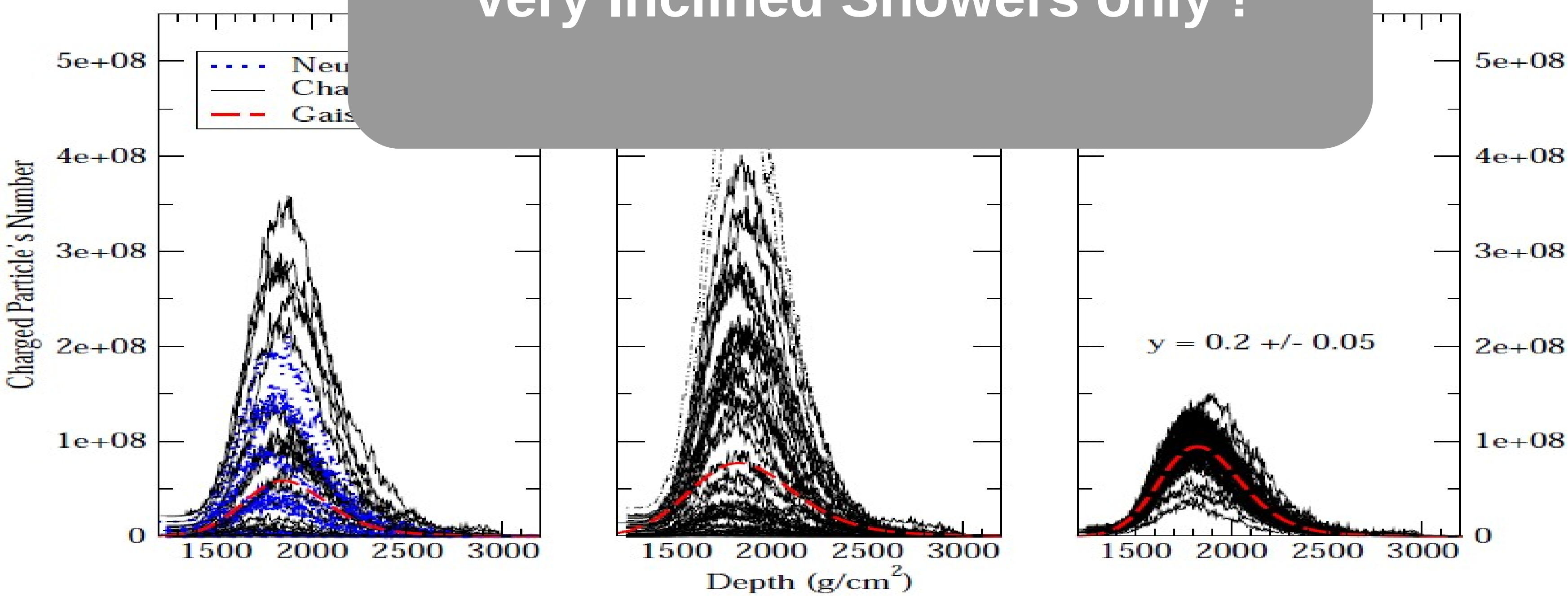
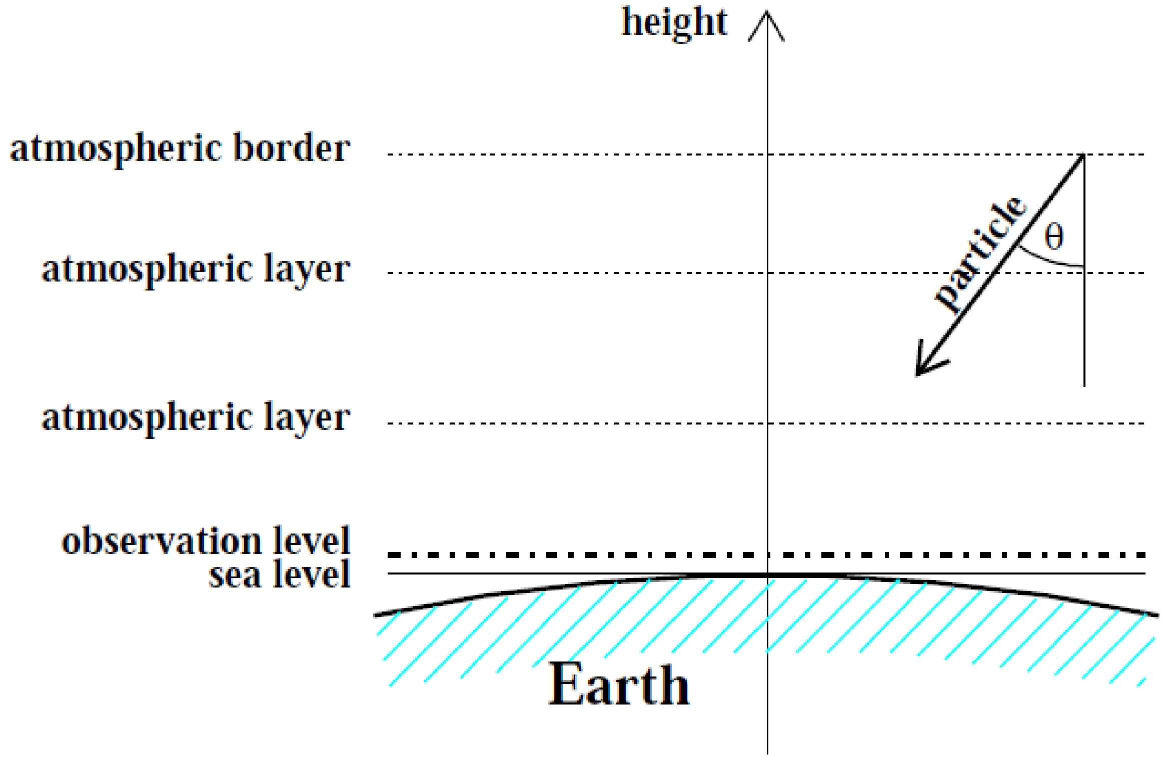
Very Inclined Showers only !



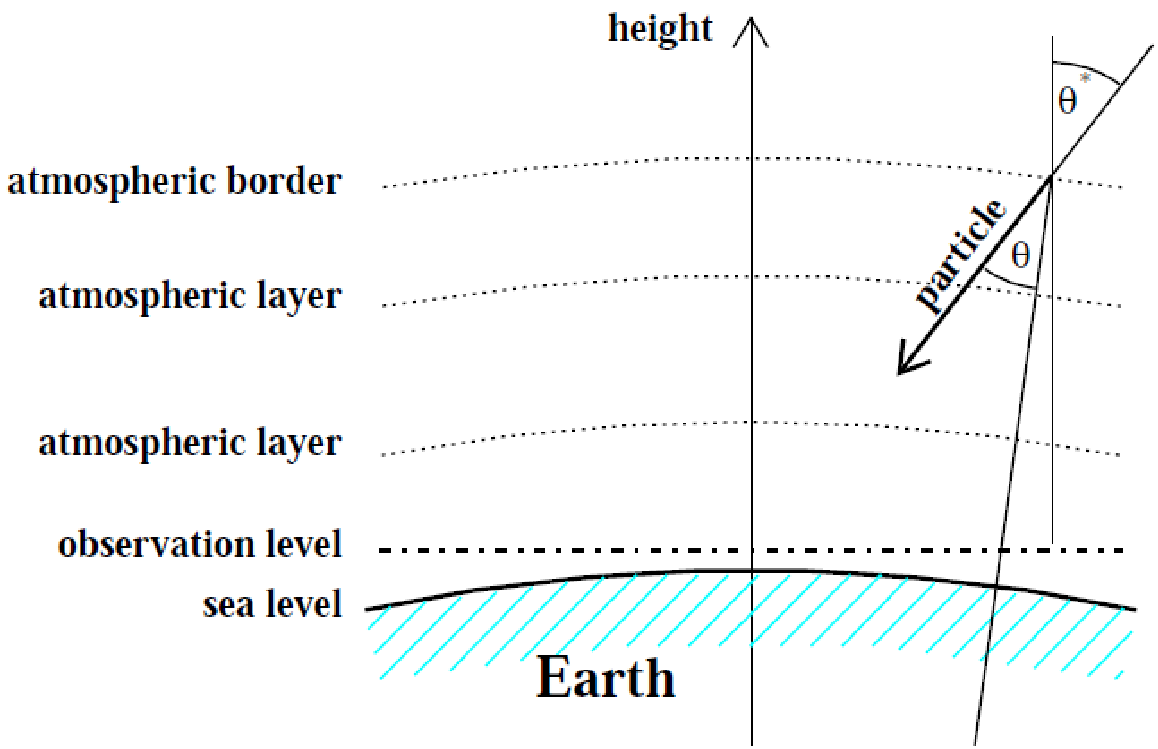
Inclined Showers in CORSIKA

- **Original CORSIKA development for KASCADE experiment**
  - ➜ vertical showers with planar geometry only



Inclined Showers in CORSIKA

- **Original CORSIKA development for KASCADE experiment**
  - ➔ vertical showers with planar geometry only
- **Extension to curved geometry in 2001 for Cerenkov telescopes and neutrino induced showers**
  - ➔ extension of planar geometry



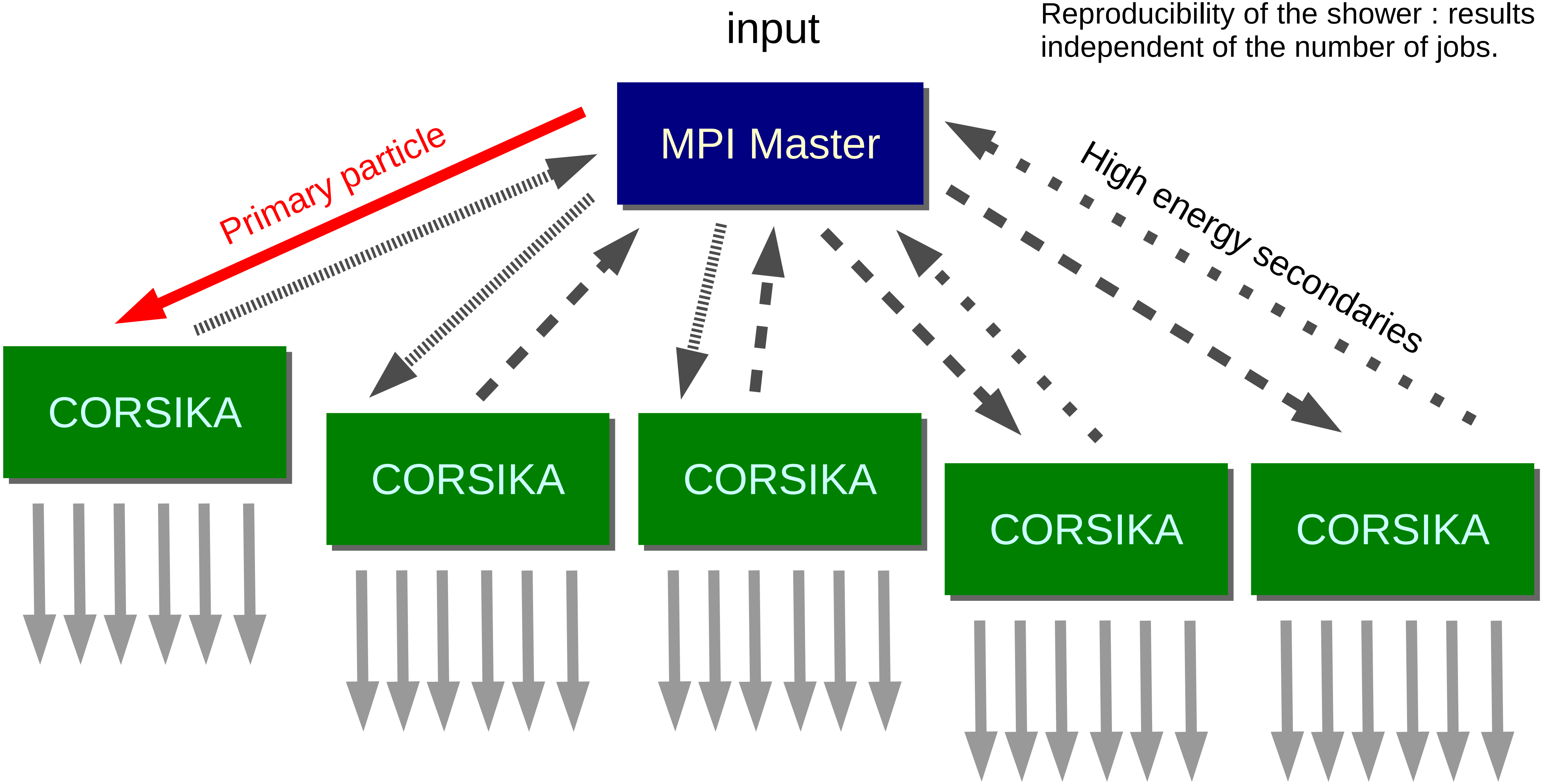
CURVED & UPWARD options

- **For very inclined showers, CURVED option is mandatory**
- **For radio simulations of inclined shower, UPWARD option is necessary**
  - ➡ otherwise particles going upward compared to ground are not tracked

zenith angle degree	planar distance km	planar slant depth g/cm^2	spherical distance km	spherical slant depth g/cm^2
0	112.8	1036.1	112.8	1036.1
30	130.3	1196.4	129.9	1196.0
45	159.6	1465.3	158.2	1463.7
60	225.7	2072.2	220.1	2065.3
70	329.9	3029.4	310.7	3003.9
80	649.8	5966.7	529.0	5765.9
85	1294.6	11887.9	770.9	10572.1
89	6465.0	59367.2	1098.3	25920.4
90	∞	∞	1204.4	36481.8

Parallelization of CORSIKA with MPI

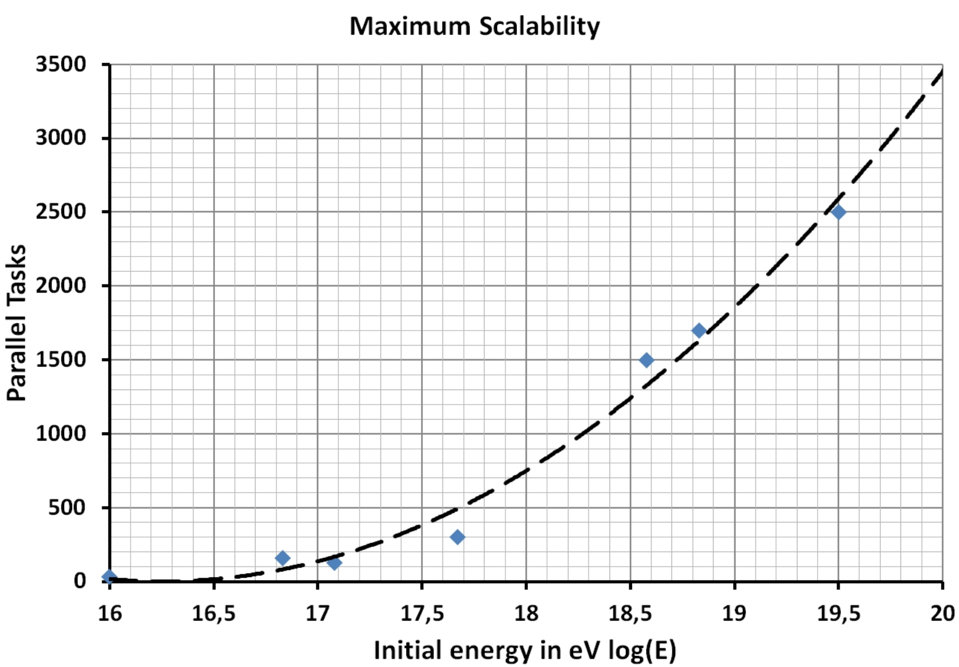
Reproducibility of the shower : results independent of the number of jobs.

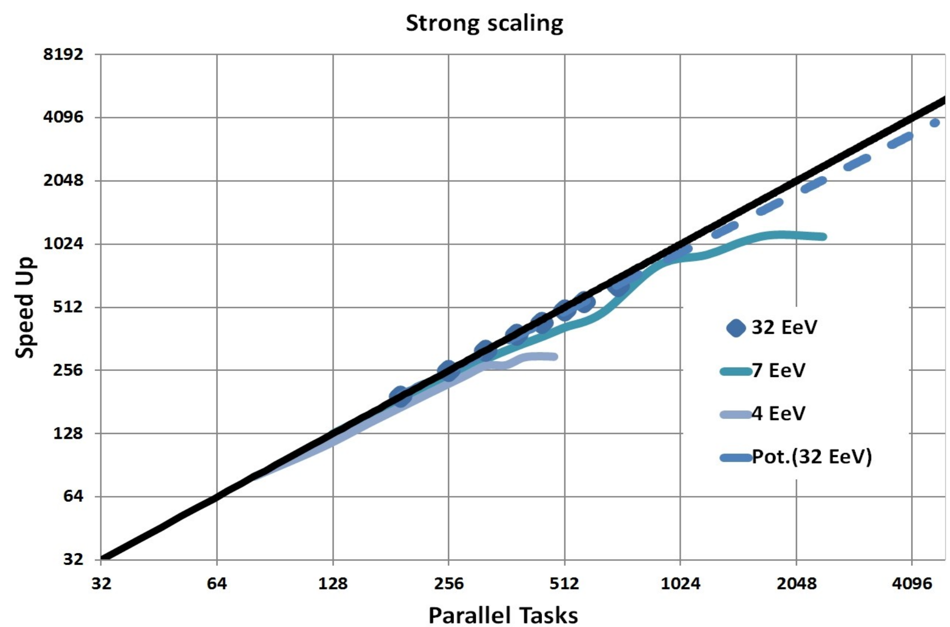


Low energy secondaries down to observation level

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
    - ➜ possible only if simulation time is short
- **solution at high energy : unthinned simulations for each real events**





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

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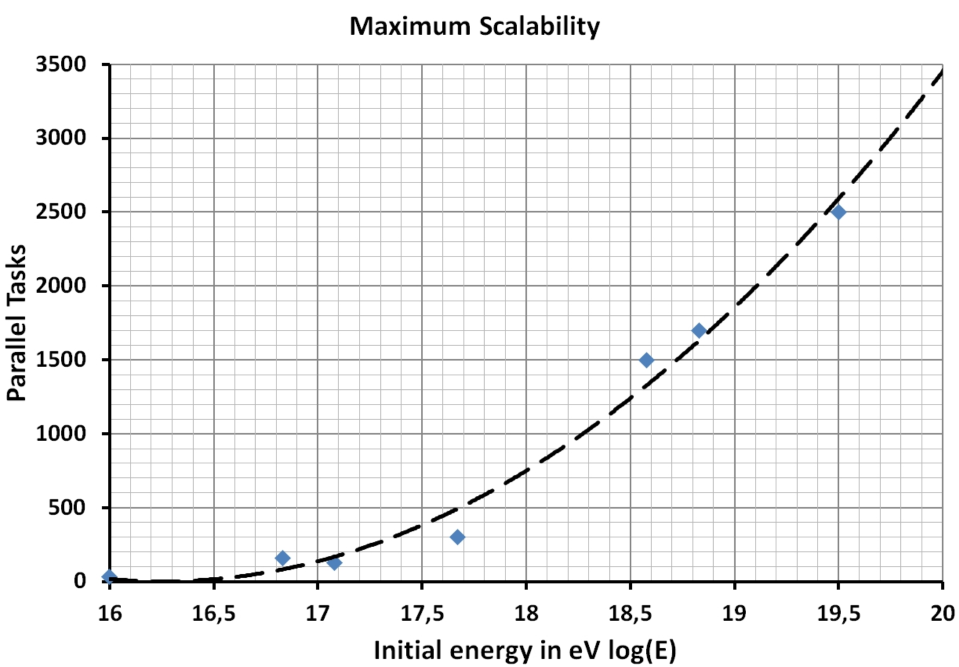
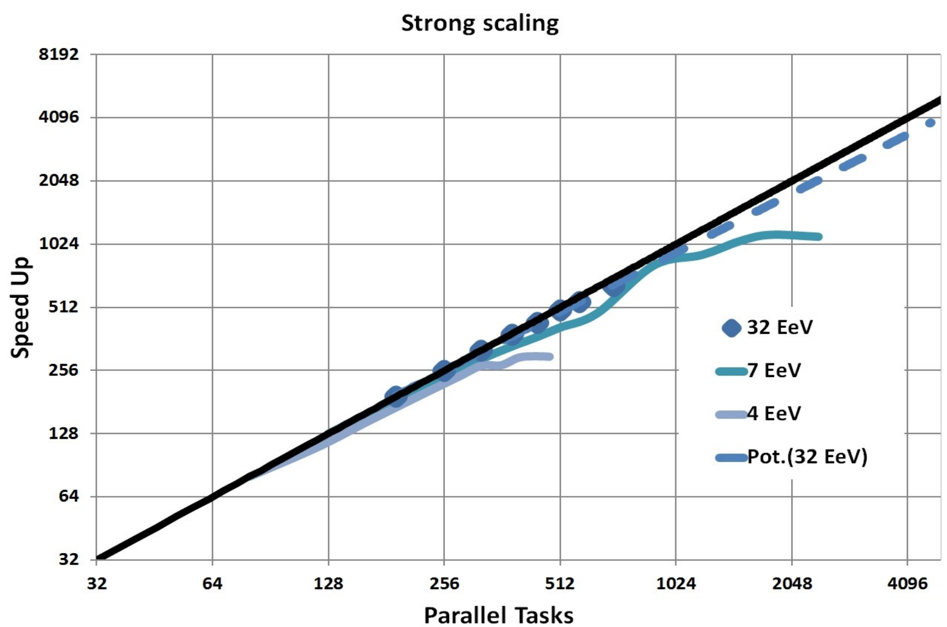
- **solution for large radio antenna array : each antenna signal shared on large number of CPU**





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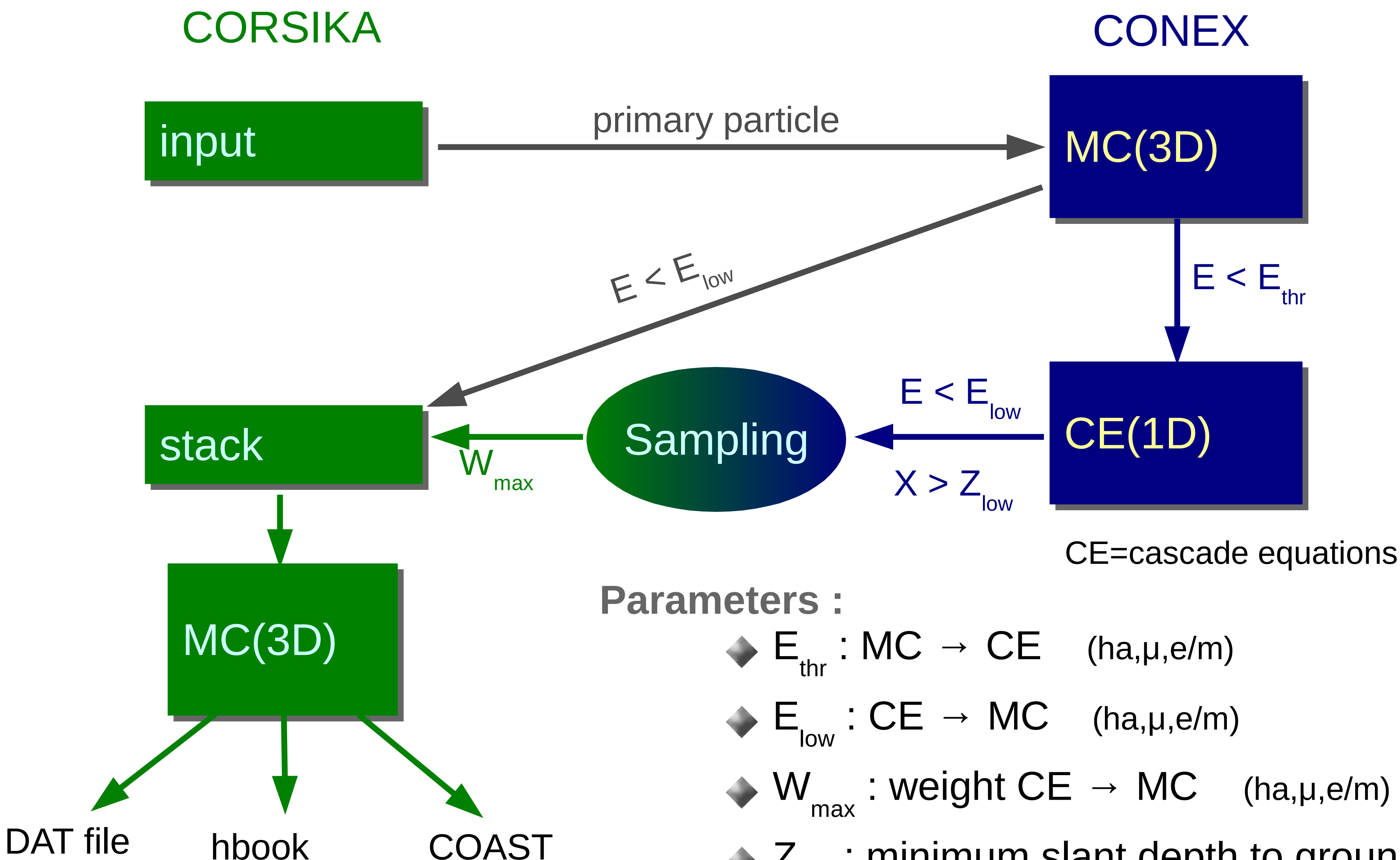
CORSIKA with CONEX



CE=cascade equations

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)

Properties

- **CORSIKA replace part of the CE**
  - First interactions in CONEX independent from E_{low}
    - Event-by-event simulations using first 1D only and then 3D with exactly the same shower (Golden Hybrid, radio)
- **CE replace part of the thinning in CORSIKA**
  - No thinned high energy 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
- **CONEX and CORSIKA are independent**
  - Different media might be used
- **Mean showers can be simulated directly** **(no high energy MC)**
- **Fast Initial condition for macroscopic radio simulations (SELFAS)**

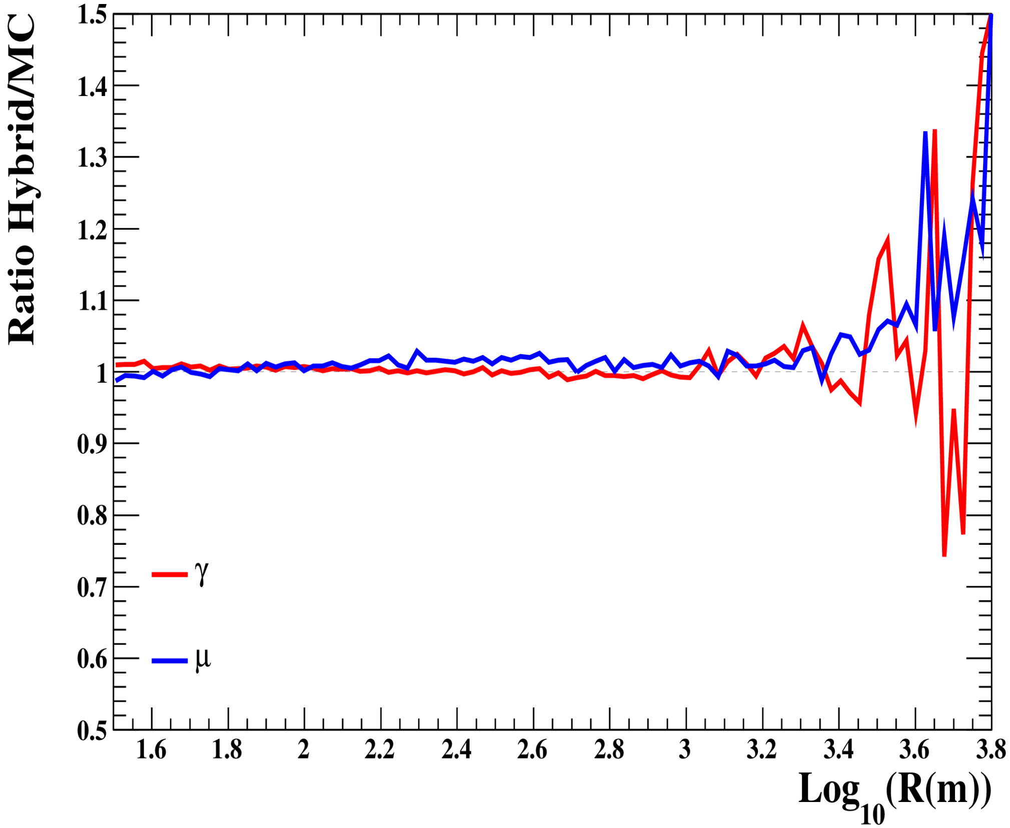
CONEX v4.37 in CORSIKA v7.4

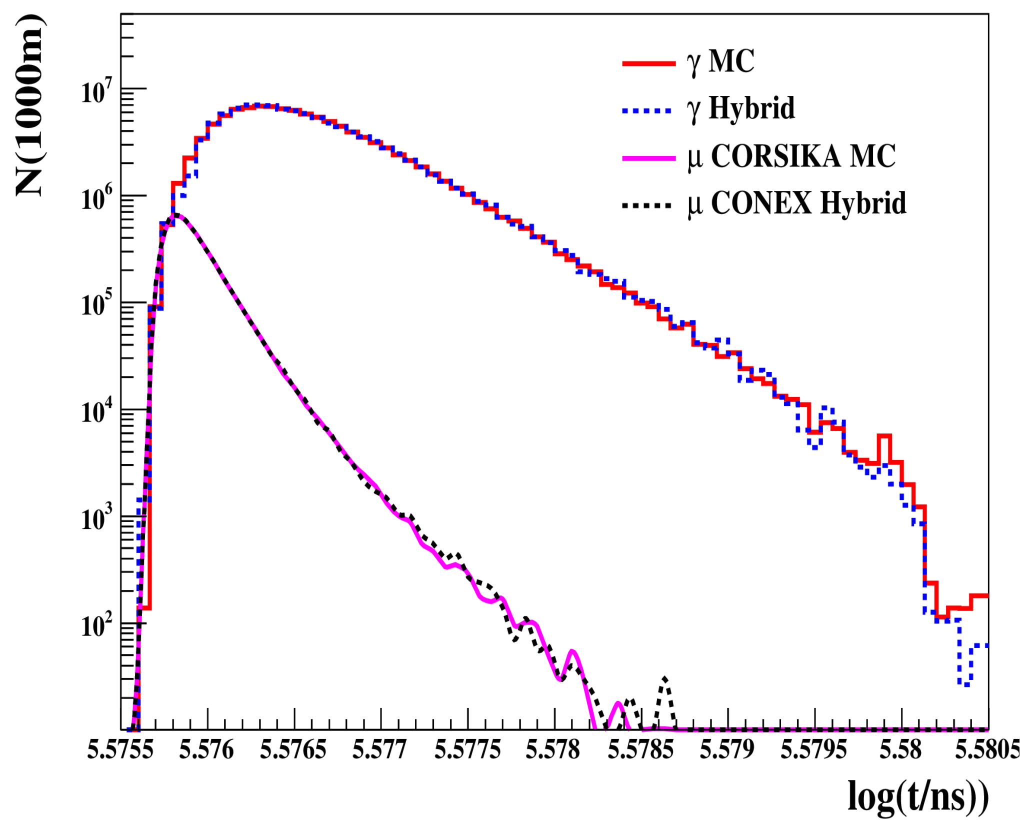
CONEX as an option in CORSIKA

- SENECA like : hybrid type 3D simulation
  - same seed = same shower (1D (fast) or 3D (slow))
- CORSIKA running script and installation
- CORSIKA input
  - one more line in steering file for CONEX parameters
- CORSIKA output
  - no new interface (MC compatible with COAST)
- CORSIKA low energy hadronic interactions models
- CONEX high energy hadronic interaction models
  - EPOS LHC, QGSJET01, QGSJETII-04, SIBYLL 2.1
- NOT COMPATIBLE WITH NEUTRINO PRIMARY YET
  - Possibility to do it if requested

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



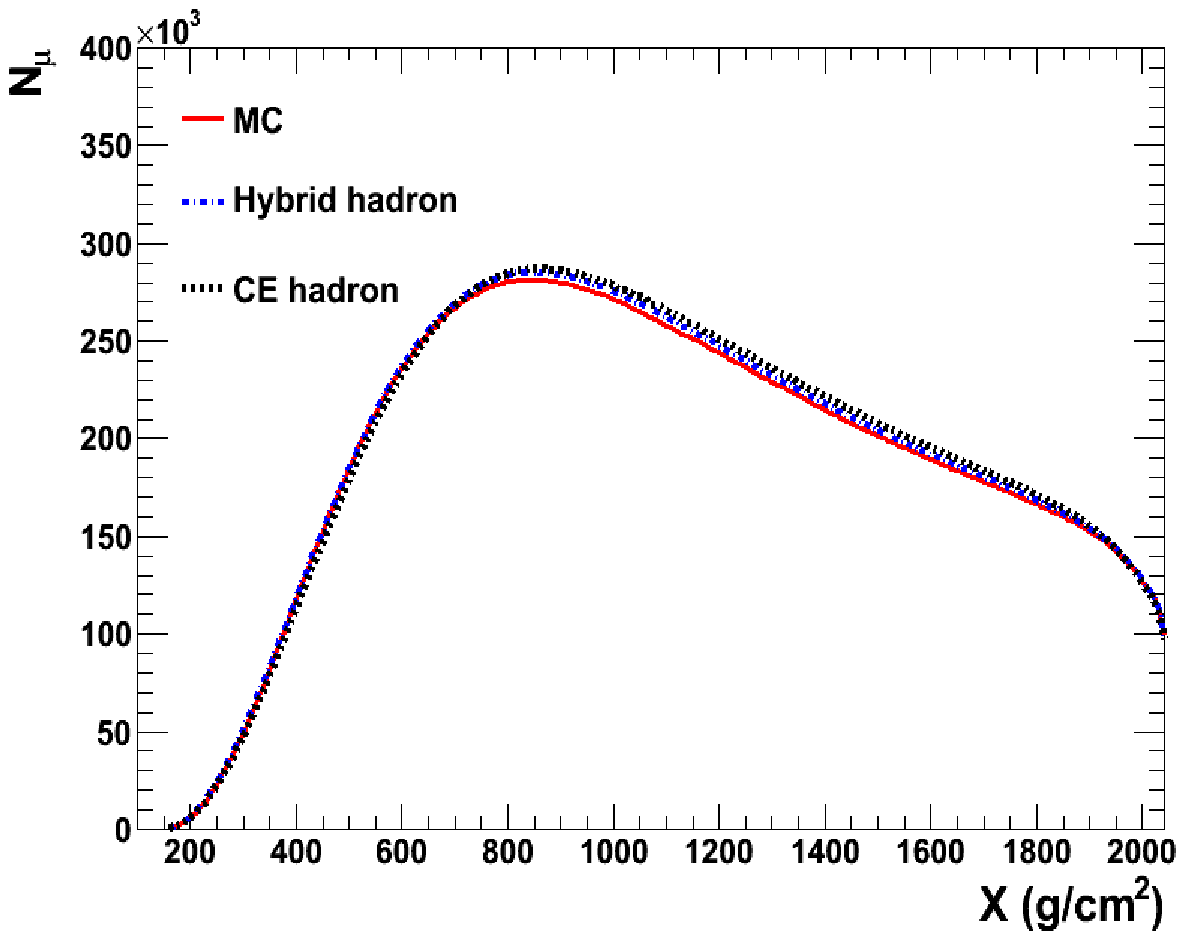


Summary

- **Neutrino interactions**
  - ➔ deep showers with large fluctuations
  - ➔ full energy reconstruction from air showers possible for electron neutrinos and part of tau neutrinos (~50% of neutrino showers) with CC interactions but not for muon neutrinos and NC. But no ambiguity only in case of double bump showers due to Tau neutrino (<30%) ...
- **Air Shower simulations**
  - ➔ Neutrino primary interactions using HERWIG
  - ➔ CURVED and UPWARD for inclined showers
  - ➔ new solutions for fast simulations
    - Parallel calculation : large number of antenna possible with CoREAS on large CPU cluster.
    - CONEX calculation : macroscopic radio simulation

      ➔ new development needed in CORSIKA for neutrino induced showers with CONEX

Example :
1 shower with different thresholds



Same profile within 3%

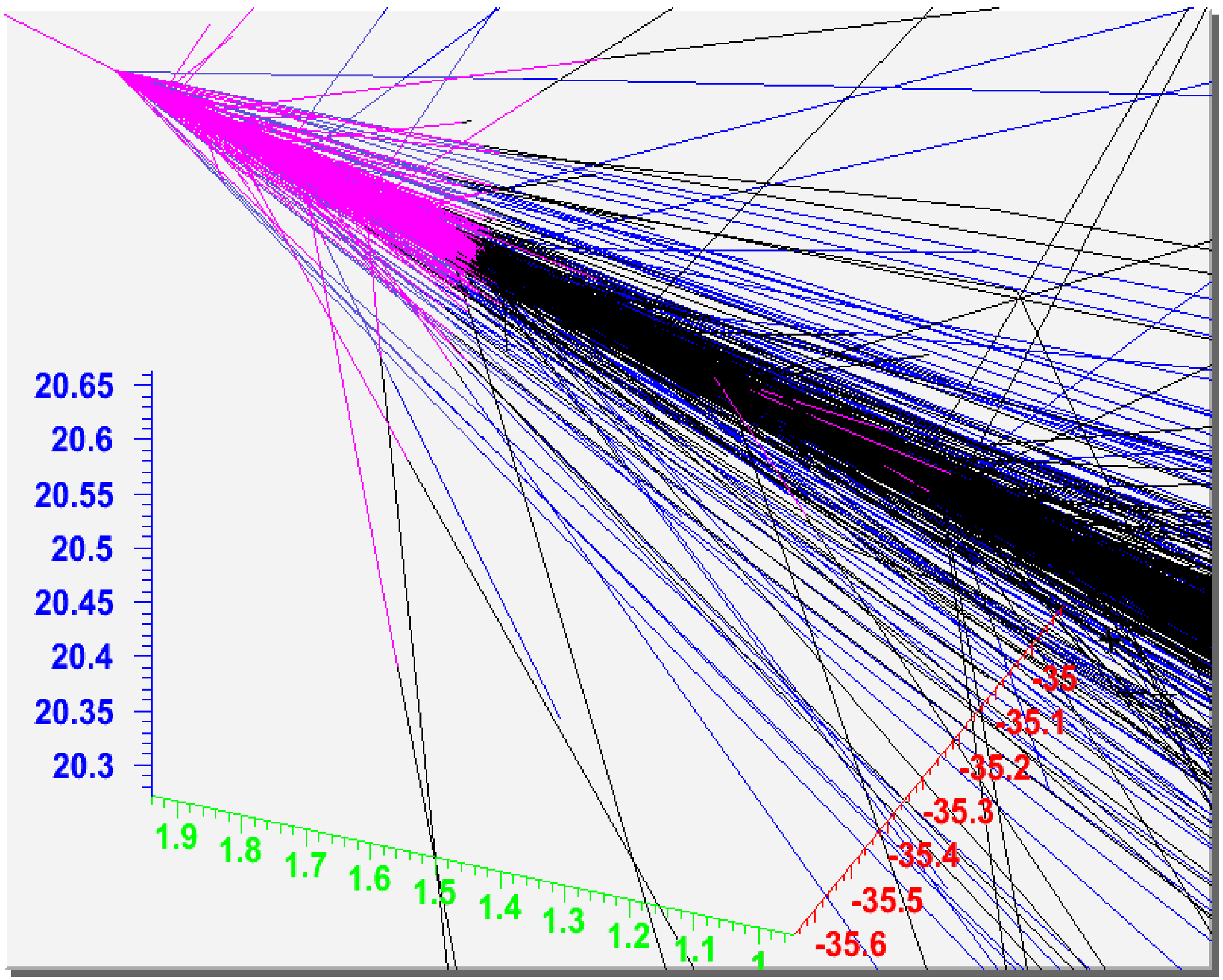
Proton @ 0.1 EeV EGS4 off

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

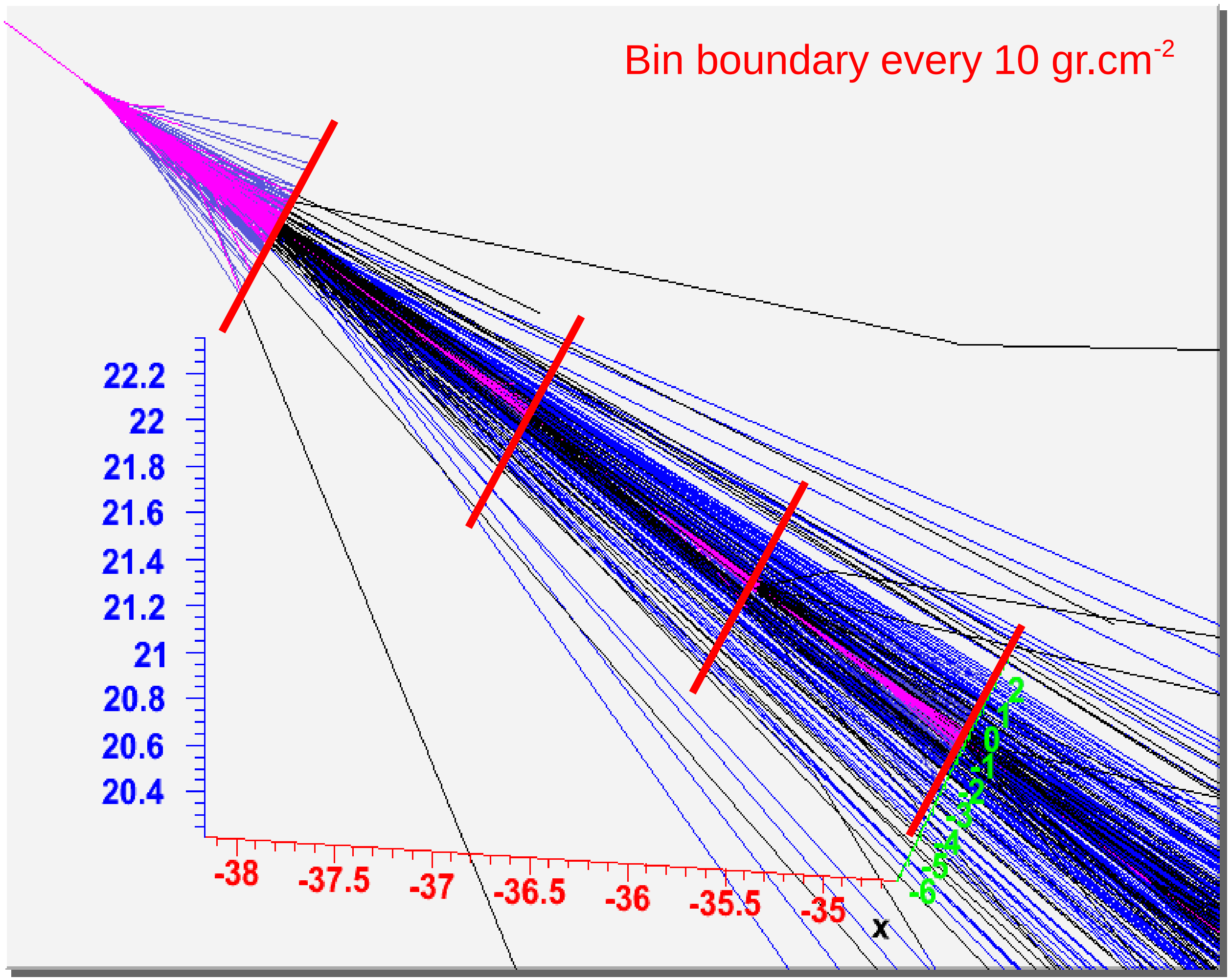
Example :
3D View with COAST



- **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

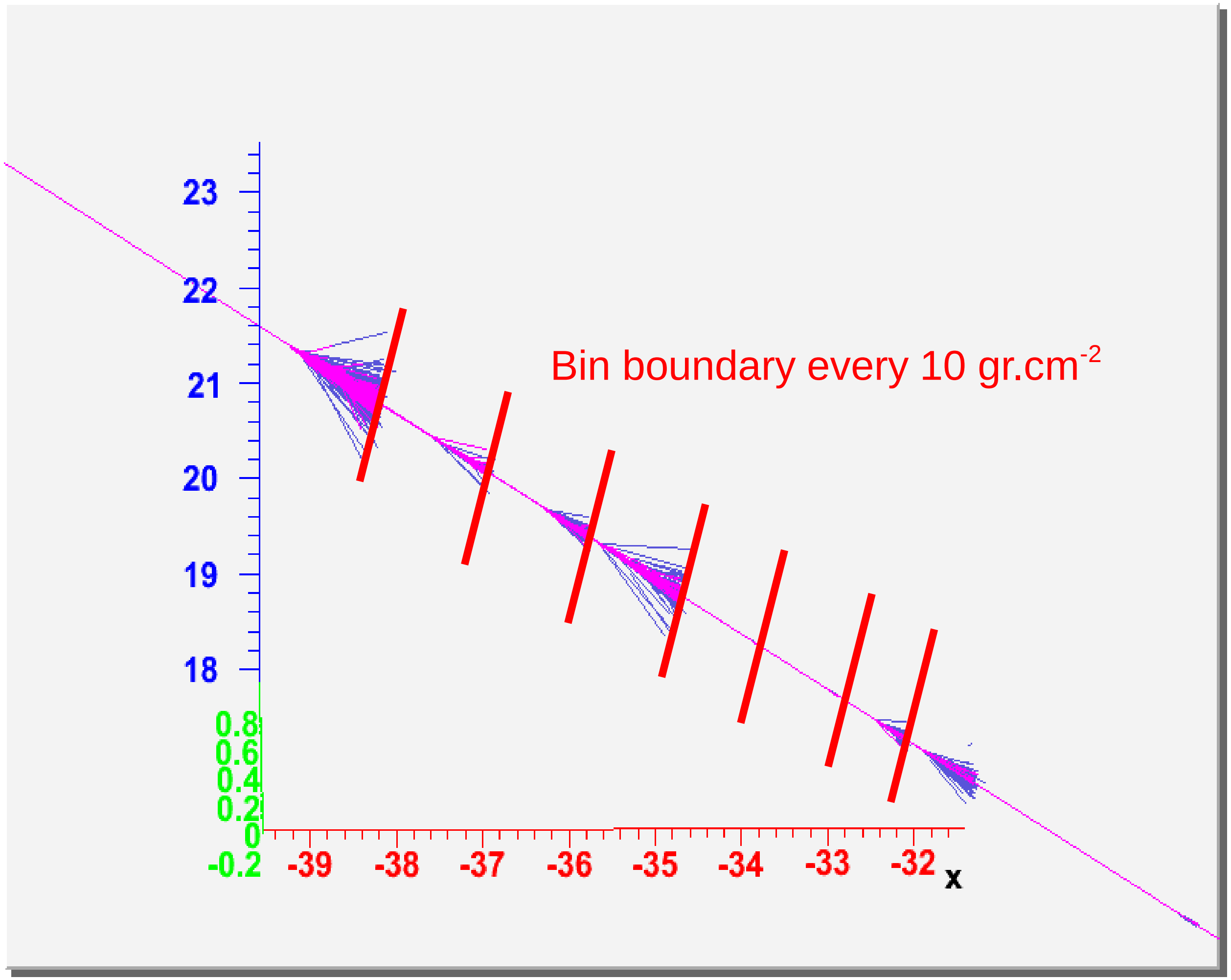
Example :
3D View with COAST



- **Hybrid 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

Example :
3D View with COAST

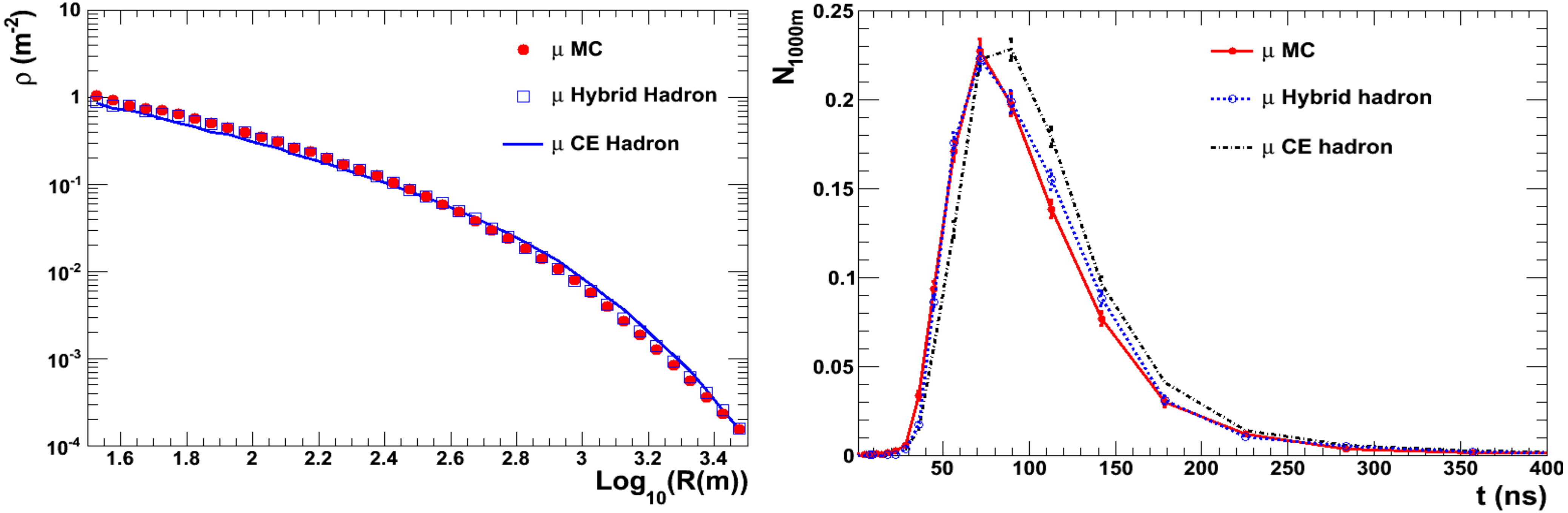


- **Hybrid 1D : Cascade equation only at low energy**
  - Particle track only until bin boundaries
  - Interaction off leading particles

Purple : CONEX hadrons
Dark blue : CONEX muons

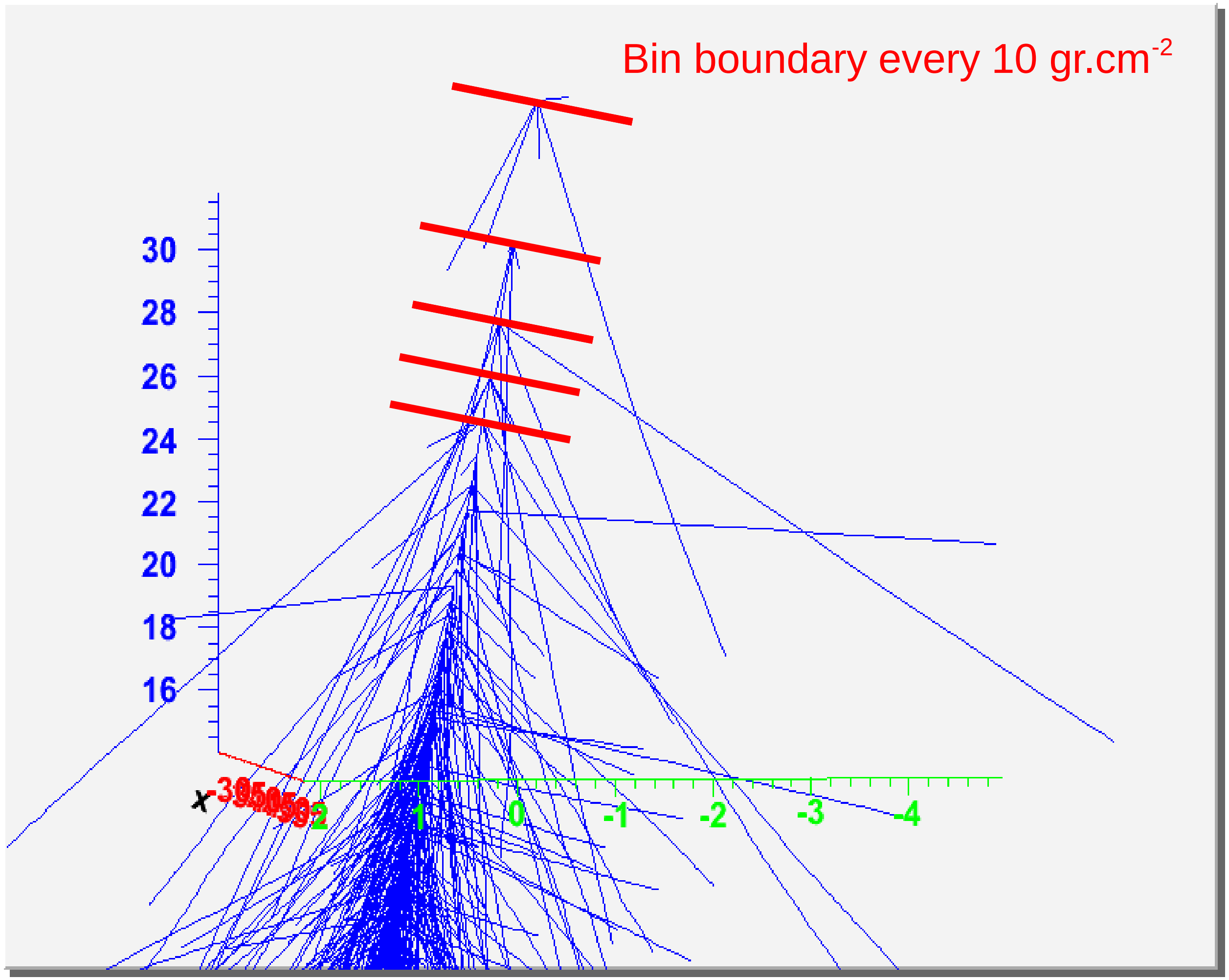
Example :
1 shower with different thresholds

Proton @ 0.1 EeV EGS4 off
QGSJET + GHEISHA



Reasonable results for CE but hadronic MC needed for precise results

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