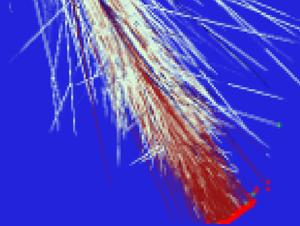


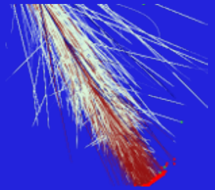
Sparse (“thinned”) sampling in ultra-high energy air shower Monte Carlo simulations

and the modern CORSIKA 8 framework

22.11.2021

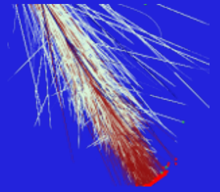
R. Ulrich (IAP) for the CORSIKA 8 Collaboration

Overview

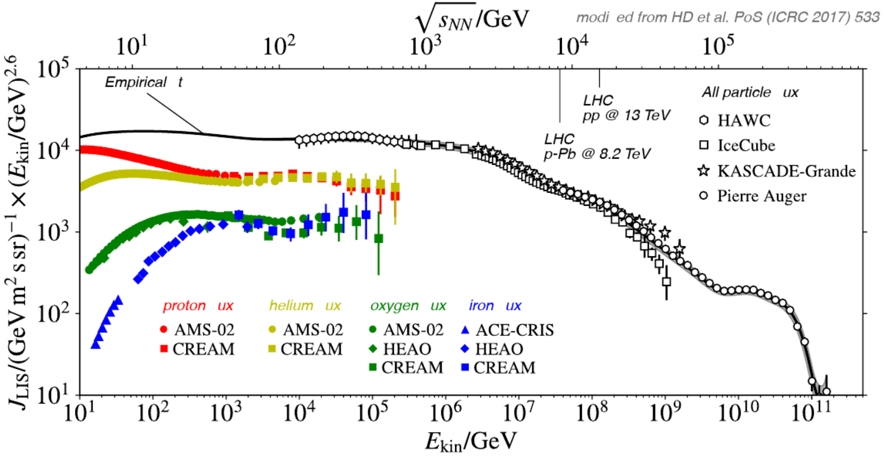


- Context
  - Ultra-high energy cosmic rays
  - Extensive air showers
- CORSIKA 8 as a novel, modern framework
- Comp. resources and sparse sampling: „thinning“
- Thinning as key to economically manage the needs for simulations in the field

Cosmic rays and extensive air showers



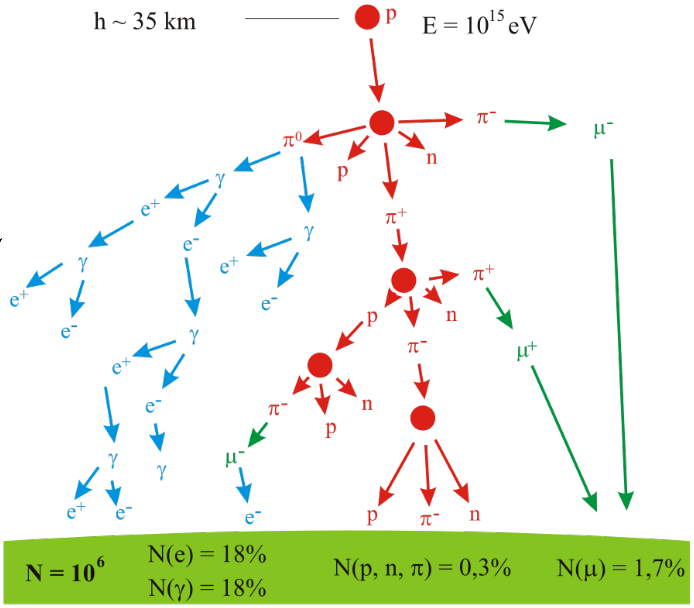
Flux of cosmic rays observed at Earth



Direct measurements with baloons and satellites

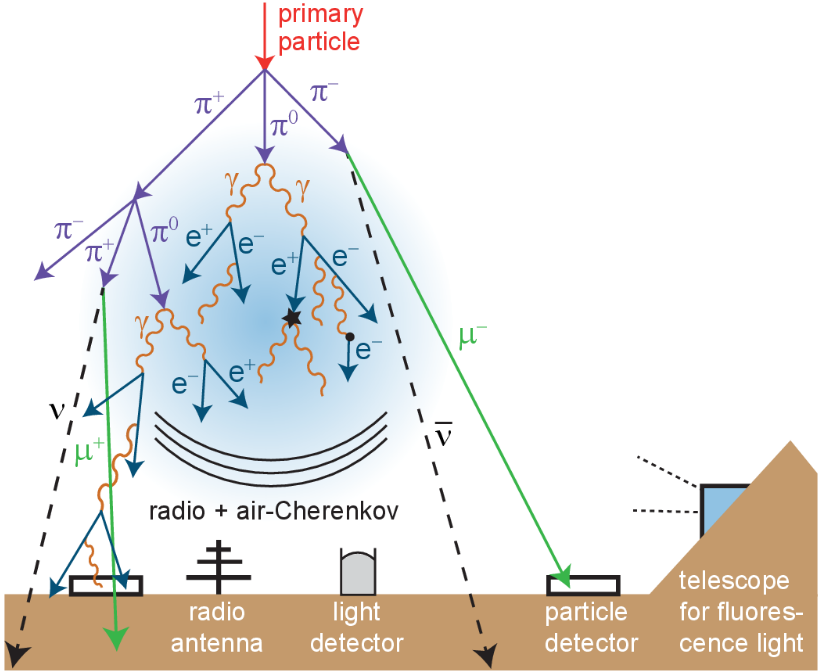
Indirect measurements with sparse detectors on ~sea-level

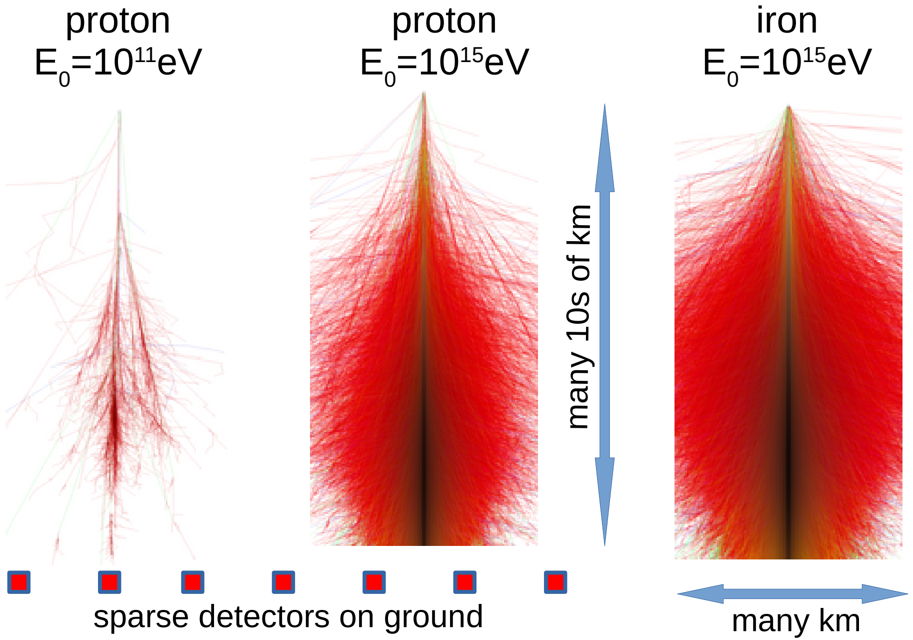
Ultra-high energy (atmospheric) extensive air shower



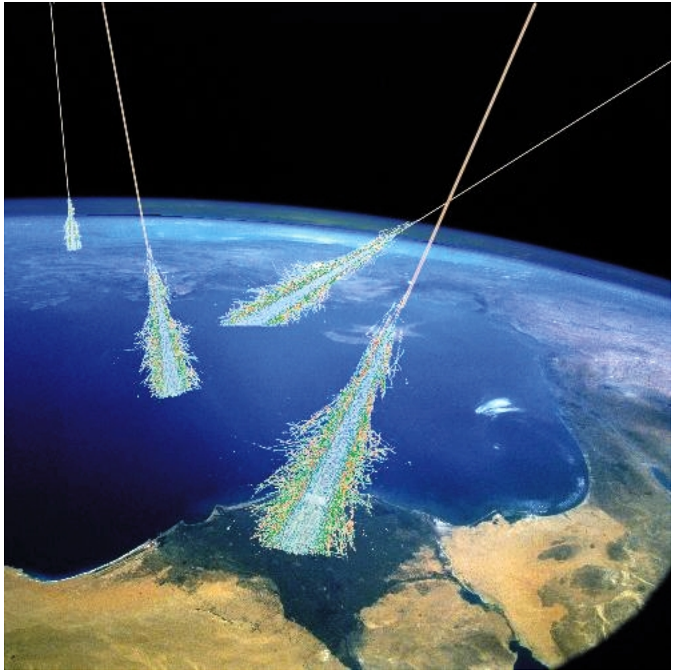
Structure and observation of air showers

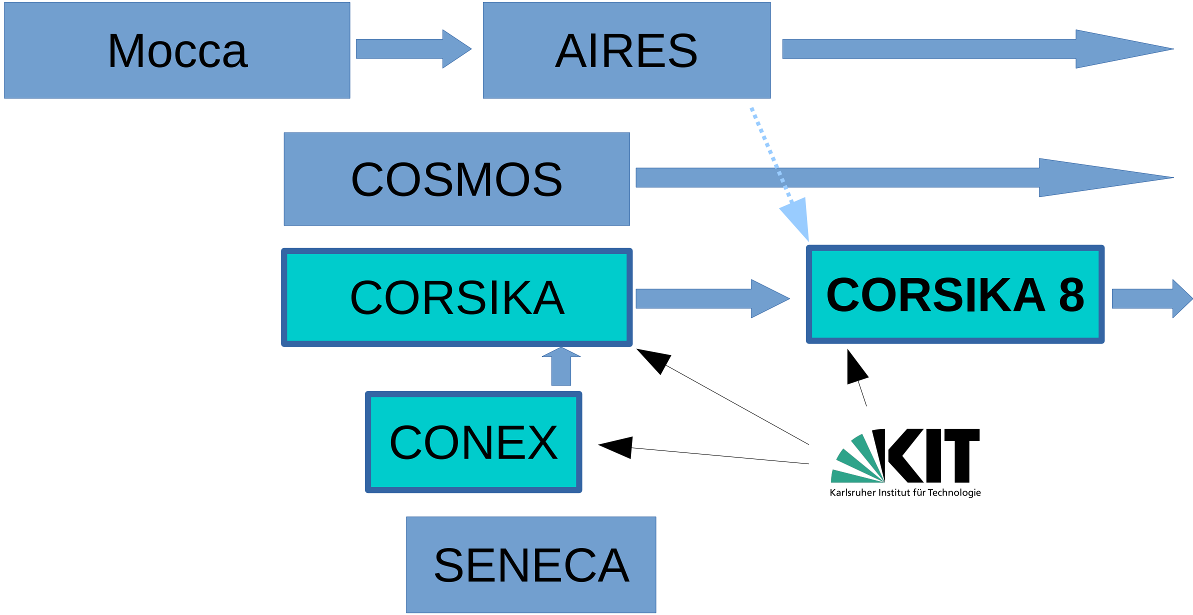
Extensive secondary particle cascades, and their observation





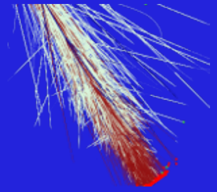
Air shower simulations





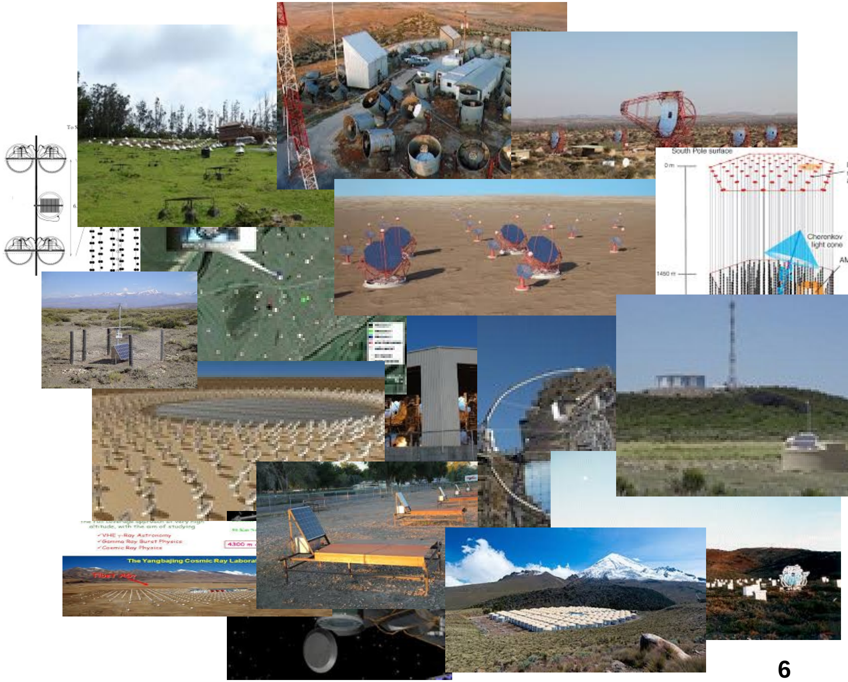
More than 30 years of development history, lots of technology, models, tools.
Fundamental for astroparticle physics, some tools also used at LHC.

CORSIKA 8

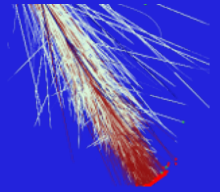


New framework as laboratory to investigate astroparticle physics problems related to secondary particle cascades

- Support future astroparticle physics experiments with solid foundation for simulations and research
- Further improve quality of simulations, and hadronic event generators, reduce and assess modeling uncertainties
- Research of air shower physics, i.e. muon production in air showers, etc.
  - Not enough muons in simulations
  - Spectrum of muons too soft in simulations
  - Closely linked to hadronic shower core



Mathematical formulation of problem



- Highly coupled ODE system
- Various initial conditions
- Evolution of states in several dimensions: E, X, type

$$
\begin{aligned}
\frac{\mathrm{d}n}{\mathrm{d}X} = &-\left(\frac{1}{\lambda_{\mathrm{int},k}(E)} + \frac{1}{\lambda_{\mathrm{dec},k}(E,X)}\right) n(E,X) \\
&- \frac{\mathrm{d}}{\mathrm{d}E}\left(\mu_k(E)\, n(E,X)\right) \\
&+ \sum_\ell \int_E^\infty \mathrm{d}E_\ell\, \frac{c_{\ell\to k}(E_\ell, E)}{\lambda_{\mathrm{int},\ell}(E_\ell)} n_\ell(E_\ell, X) \\
&+ \sum_\ell \int_E^\infty \mathrm{d}E_\ell\, \frac{d_{\ell\to k}(E_\ell, E)}{\lambda_{\mathrm{dec},\ell}(E_\ell, X)} n_\ell(E_\ell, X),
\end{aligned}
$$

Number losses

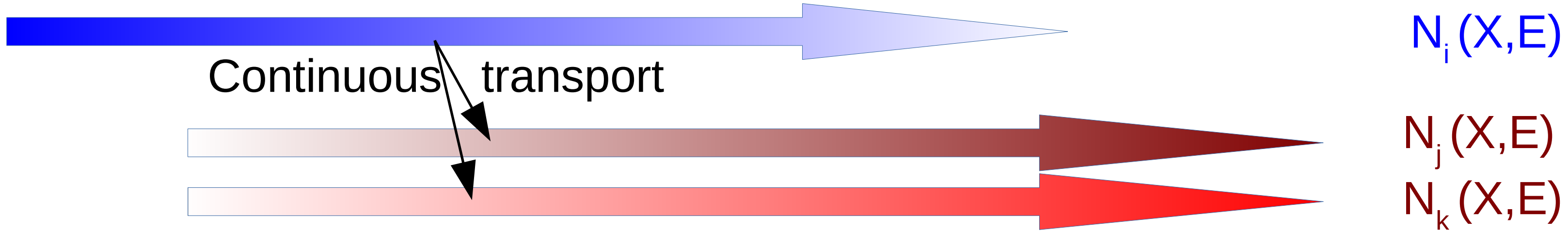
Energy losses

Upstream production

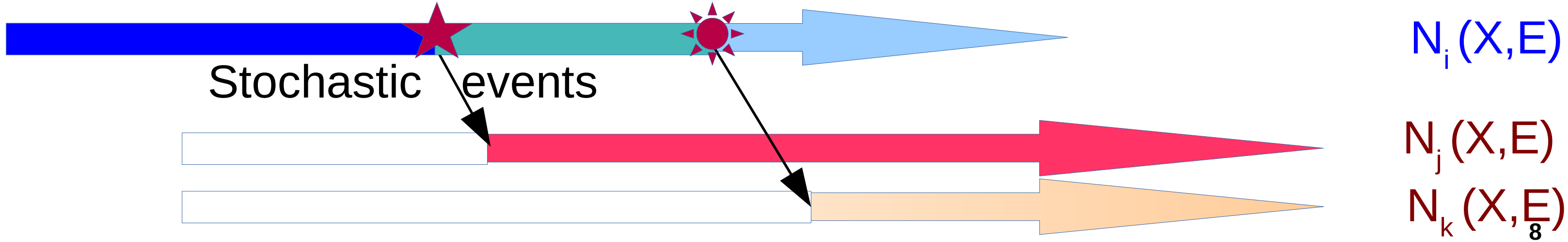
Properties of solution

Depending on scales of interest:

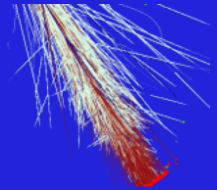
- Solution of ODE system can be completely continuous



- „Explosive“ or „stochastic“ events can play crucial role in evolution and variances.



Ultra-high energy particle cascades



- Energy re-distribution from single ultra-high energy primary particle (or many of them) on O(billions) of secondary particles of all types at low energies.
- Full 4D solution (3D+time) obtained with Monte Carlo simulation: tracking of each particle in magnetic fields and explicit handling of all stochastic events.
- Needed for interpretation and analysis of experimental data.
- Also for design of new experiments.

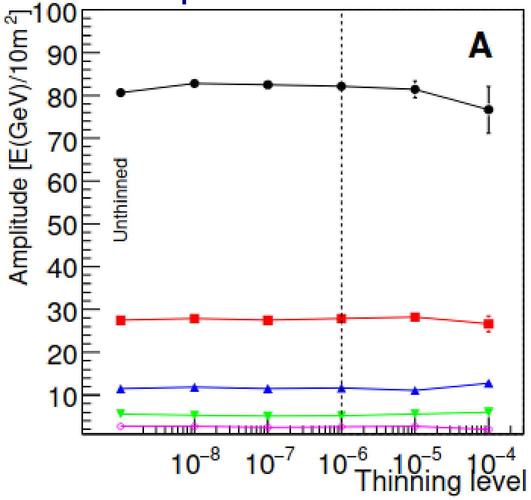
Performance and accuracy are a fundamental (limiting) factors for astroparticle physics.

Example, and introduction of the impact of thinning

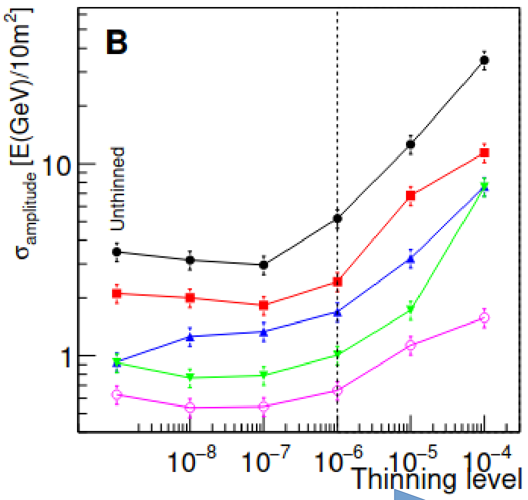
$E_0=10^{19}$eV proton shower: **T=1.5 CPU-years, S=1TB output**

… and T as well as S scale with E_0

Expectation value



Variance

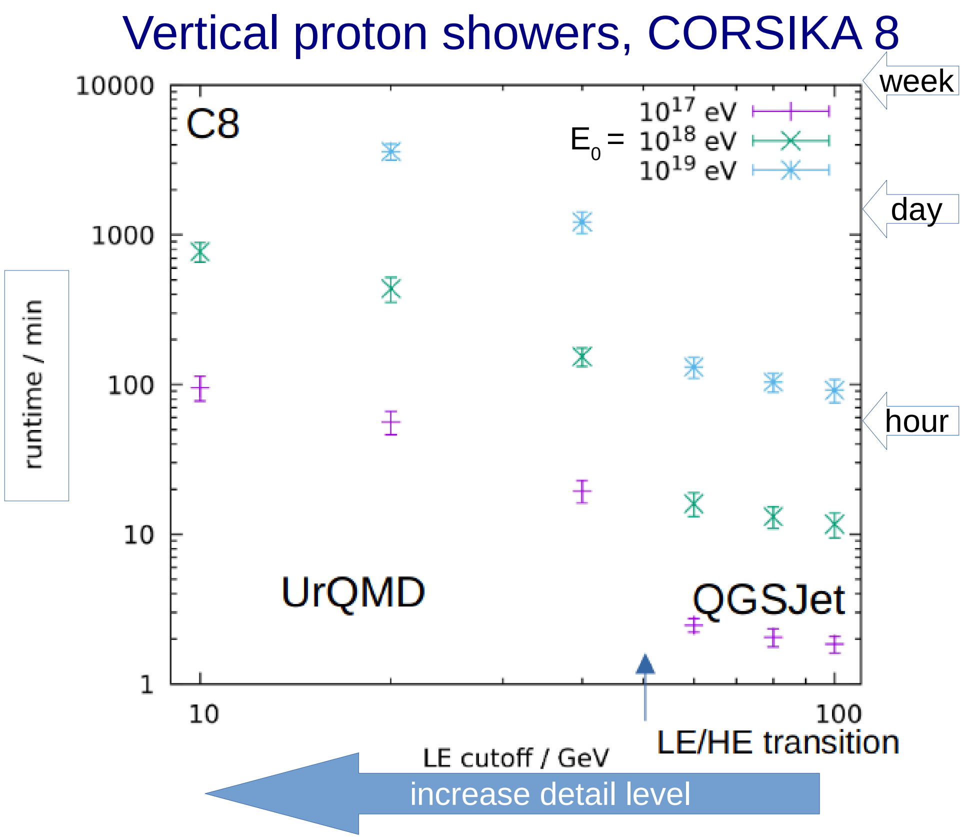


● 600m; ■ 800m; ▲ 1000m; ▼ 1200m; ○ 1400m

Quality decreases

Bruijn, Schmidt, Ilee, Knapp ICRC 2009, http://icrc2009.uni.lodz.pl/proc/pdf/icrc0252.pdf

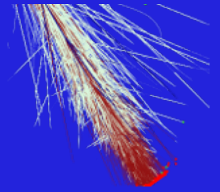
Scaling problem, resource limitations (w/o thinning)

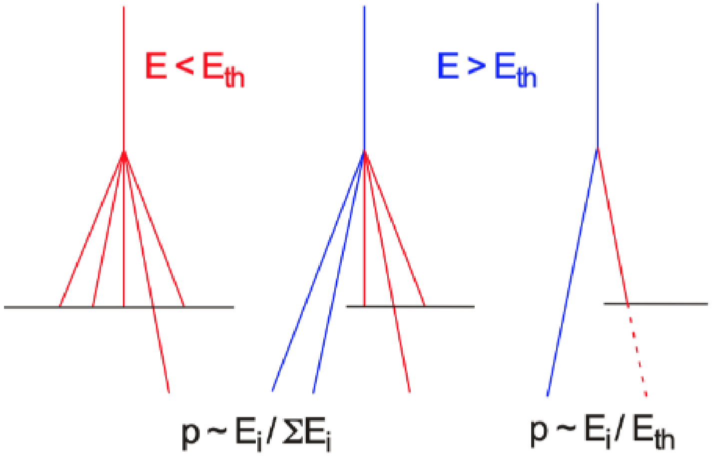


Energy increases by
2 orders of magnitude

… so does runtime

Hillas thinning algorithm





- Select thinning threshold

  $E_{th} = E_0 * eps_{th}$

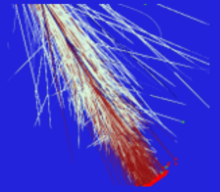
- $E_i > E_{th}$ – follow all particles
- $E_i < E_{th}$ – follow few, but assign weights:

  $w_i = 1/p$

Energy is conserved (by weights).
Computing time and disk space are saved.

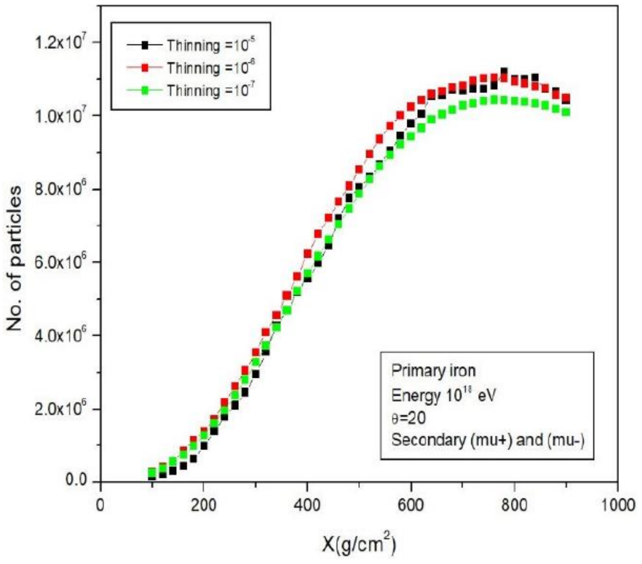
Artificial fluctuations are introduced.

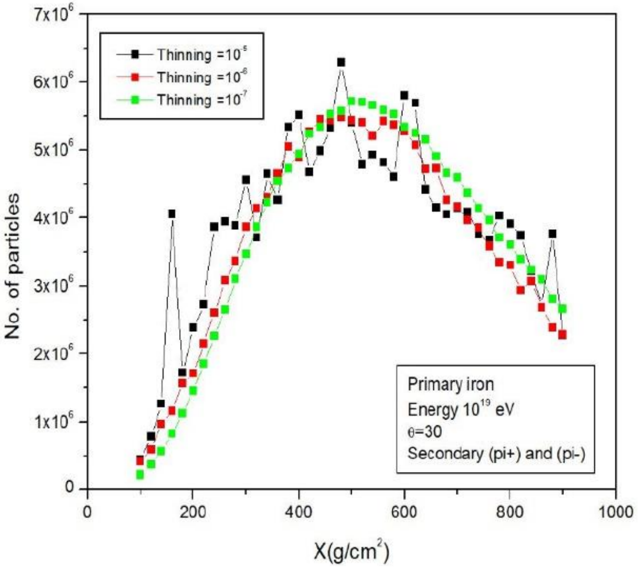
A.M. Hillas, Proc. 19th ICRC, La Jolla, USA, 1(1985)155



Dependence on experimental observable

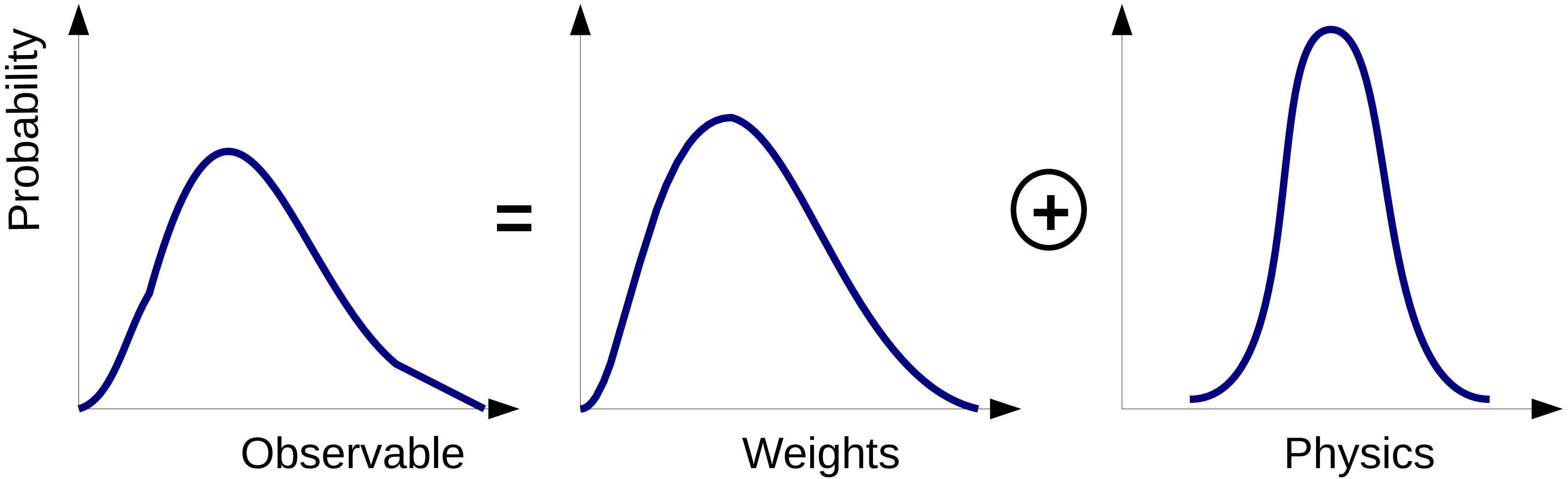
- Significant dependence on choice of experimental observable





Rahman et al. 2020 http://dx.doi.org/10.23851/mjs.v31i3.843

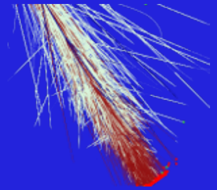
Weights and fluctuations



The distribution of „weights“ contributes artificially to the physics fluctuations

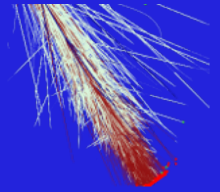
- Difficult to assess, due to expense of simulations
- Any optimization delivers significant returns
- Simple parameter adjustments have shown potential to improve T by factors 10...100

Room for research



- Better understand relation between weights, physics and simulated fluctuations
- Develop thinning algorithms based not simply on „energy“ but on other quantities, like
  - emission angle
  - transverse momentum
  - radial distance
  - geometry
  - ...

Design (CORSIKA 8)

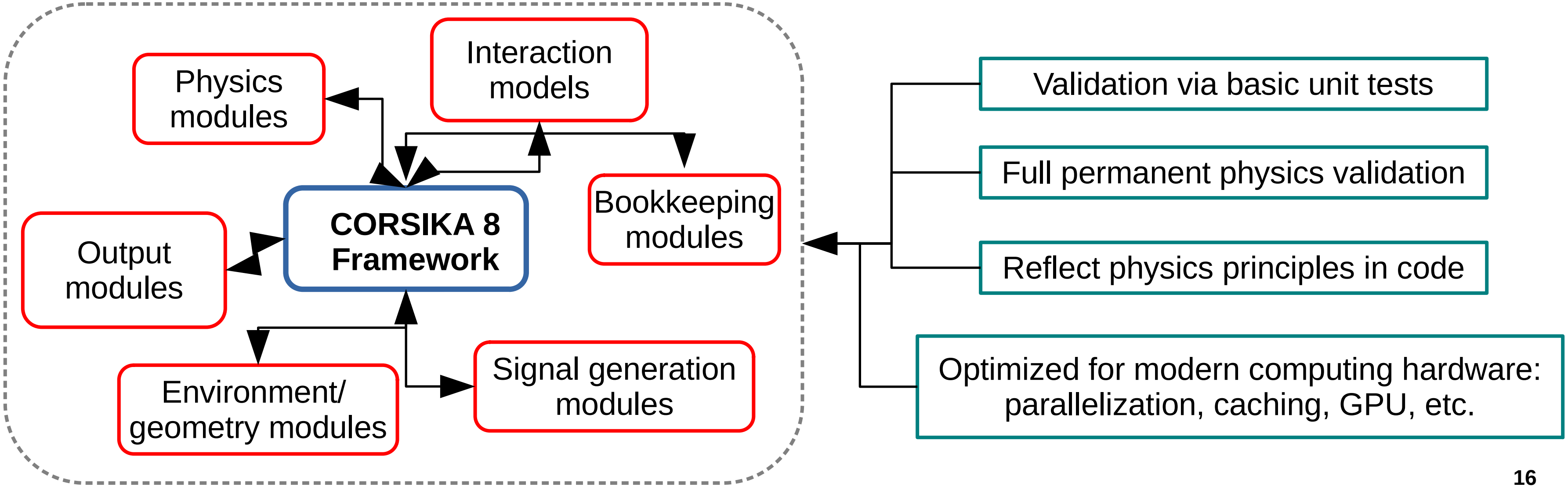


→ **open source, joint community project:**

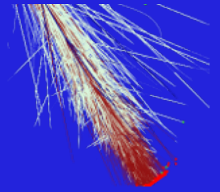
- modular
- flexibility
- completeness

new technology:

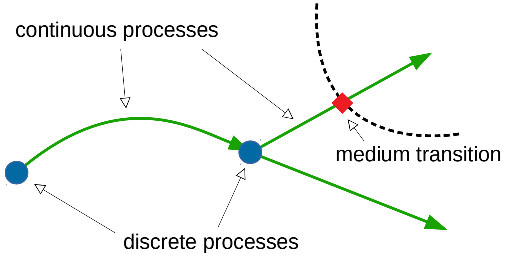
- robustness
- stability
- efficiency



Modularity and Physics (CORSIKA 8)



Physics lists:



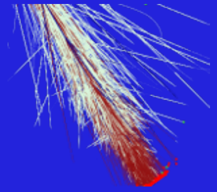
discrete processes:
- collisions
- decays, interactions

continuous processes:
- energy losses
- cherenkov, radio emission

boundary crossing processes:
- observation level
- transition radiation

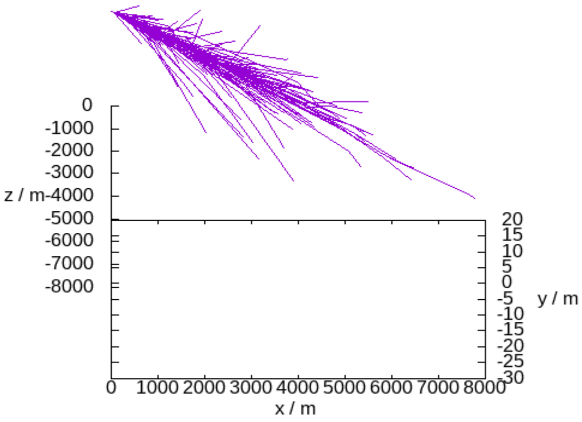
Strictly enforce physics concepts in code:

- Physical units are compile-time and strictly enforced. LengthType dist = 5_km;
- Geometric objects are in well defined reference frames Point{CS, 0_m, 0_m, 0_m};
- Particle data are encoded in unique set of C++ classes and enums, no numeric PID is available. Electron::mass; is_hadronic(Code::Proton); get_pdg(Code::PiPlus);

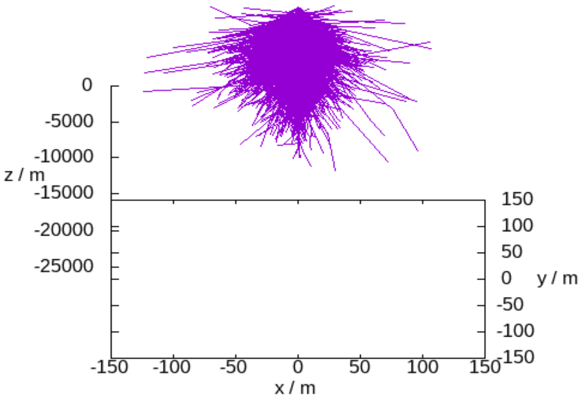


First results, examples (CORSIKA 8)

Proton primary, 100TeV, 45deg

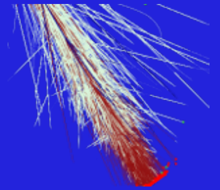


Iron primary, 1PeV, 0deg

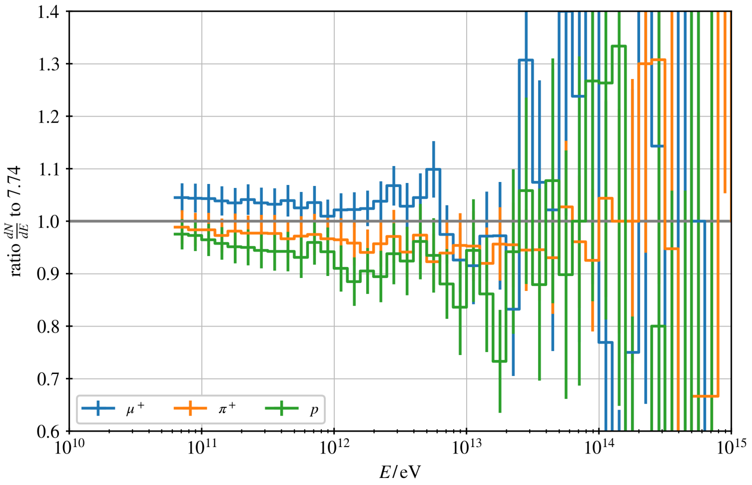


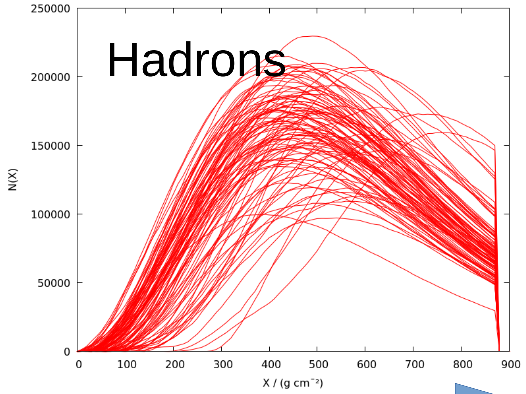

```
…
auto sequence = make_sequence(sibyll, sibyllNuc, decay, cut, trackWriter);
Cascade EAS(environment, tracking, sequence, stack);
EAS.Init();
EAS.Run();
```

Hadron showers, first results (CORSIKA 8)

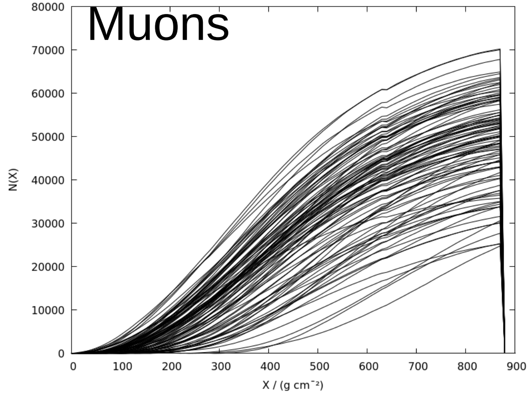


- 50 proton showers @ 1 EeV
- Sibyll 2.3d, E-cut at 60 GeV
- USstd atmosphere, no magnetic field, no e.m.

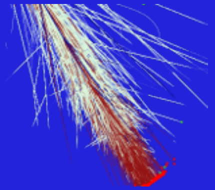




Integrated matter density



Summary



- Air shower simulations are crucial for astroparticle physics
- CORSIKA 8 is the novel, modern, modular tool to serve the community as universal baseline
- KIT is a long-standing, extremely visible and driving actor in developing air shower simulations
- Thinning is a critical mechanism to help tackle high-statistics simulations at energies where they are absolutely needed
- Research on more general thinning algorithms and evaluation of their impact on air shower predictions are extremely promising

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