Simulating penetrating atmospheric leptons in IceCube

Challenges, efficiency-boosting tricks, and a wish list

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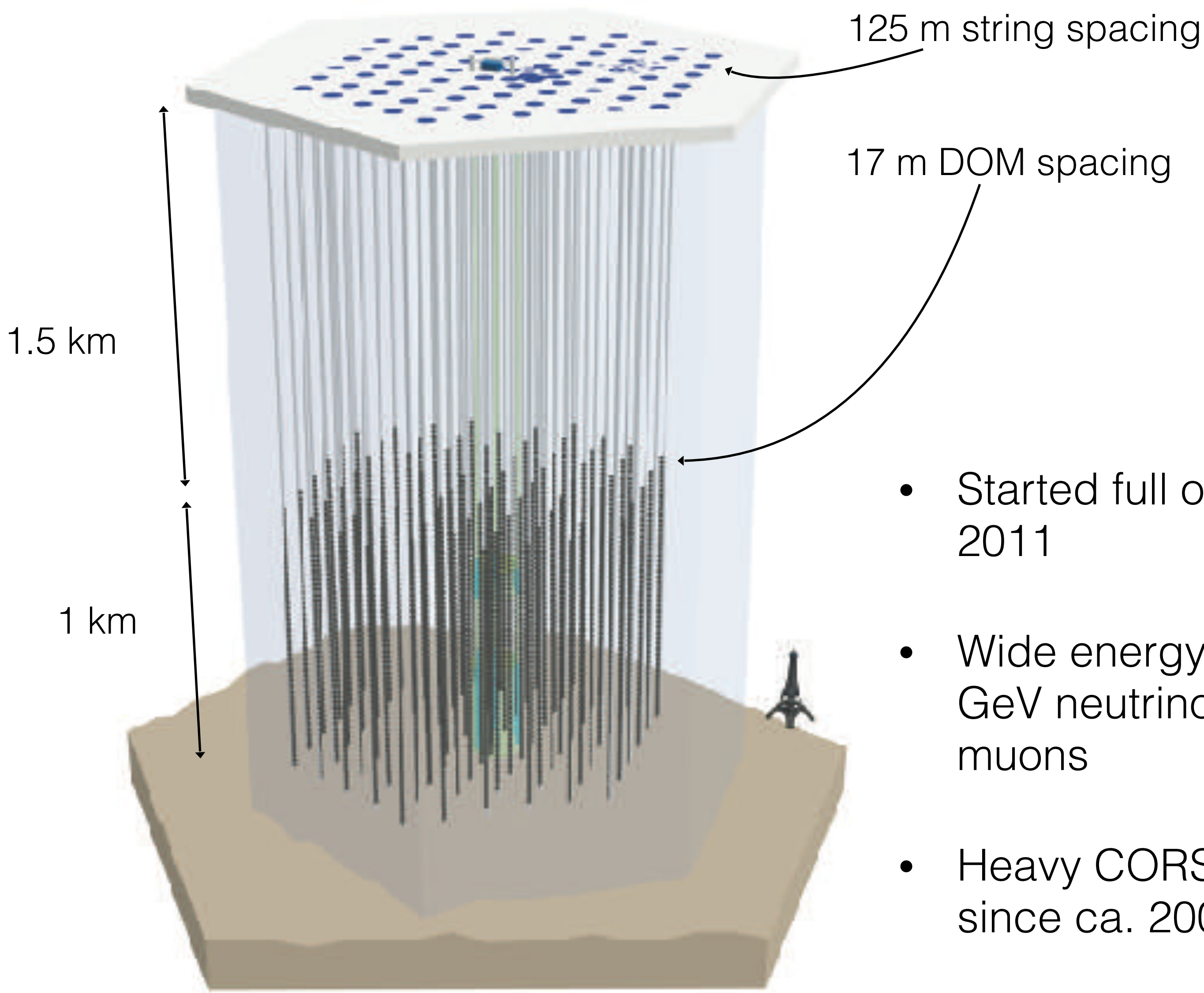
Karlsruhe, 2018-06-26

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

IceCube

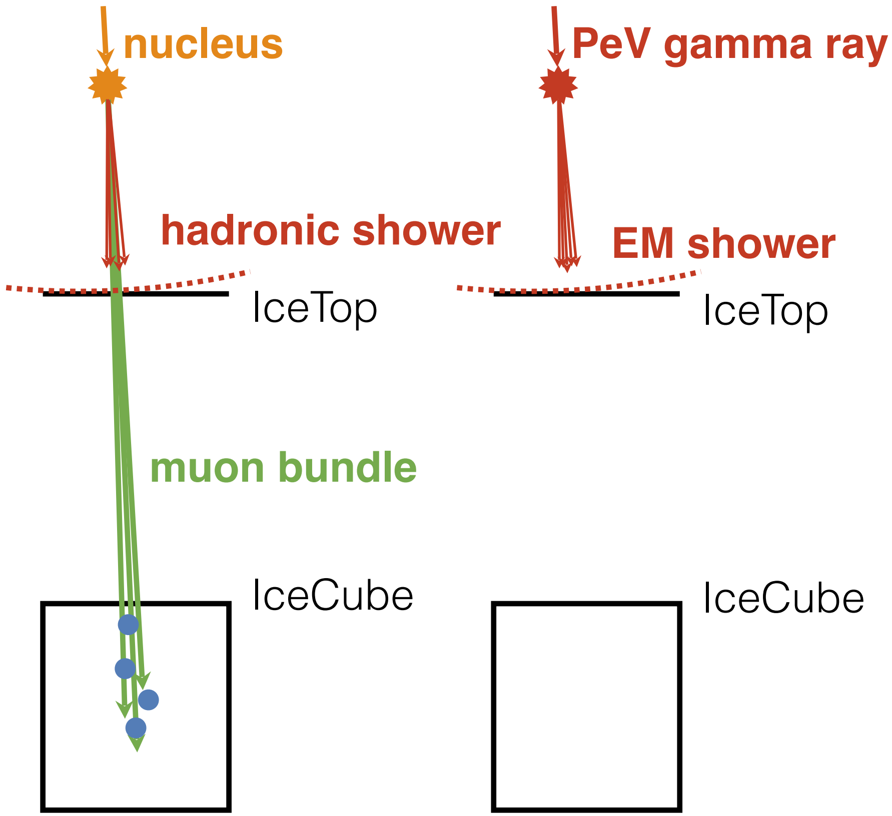
an optical Cherenkov detector in the deep Antarctic ice



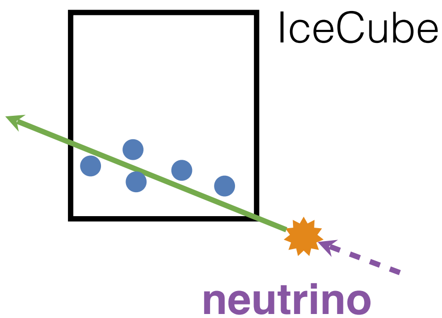
- Started full operation in 2011
- Wide energy range: ~30 GeV neutrinos to PeV muons
- Heavy CORSIKA users since ca. 2002

CR, gamma, and neutrino detection

Cosmic rays

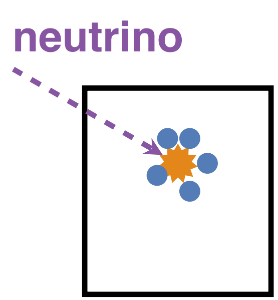


Neutrinos



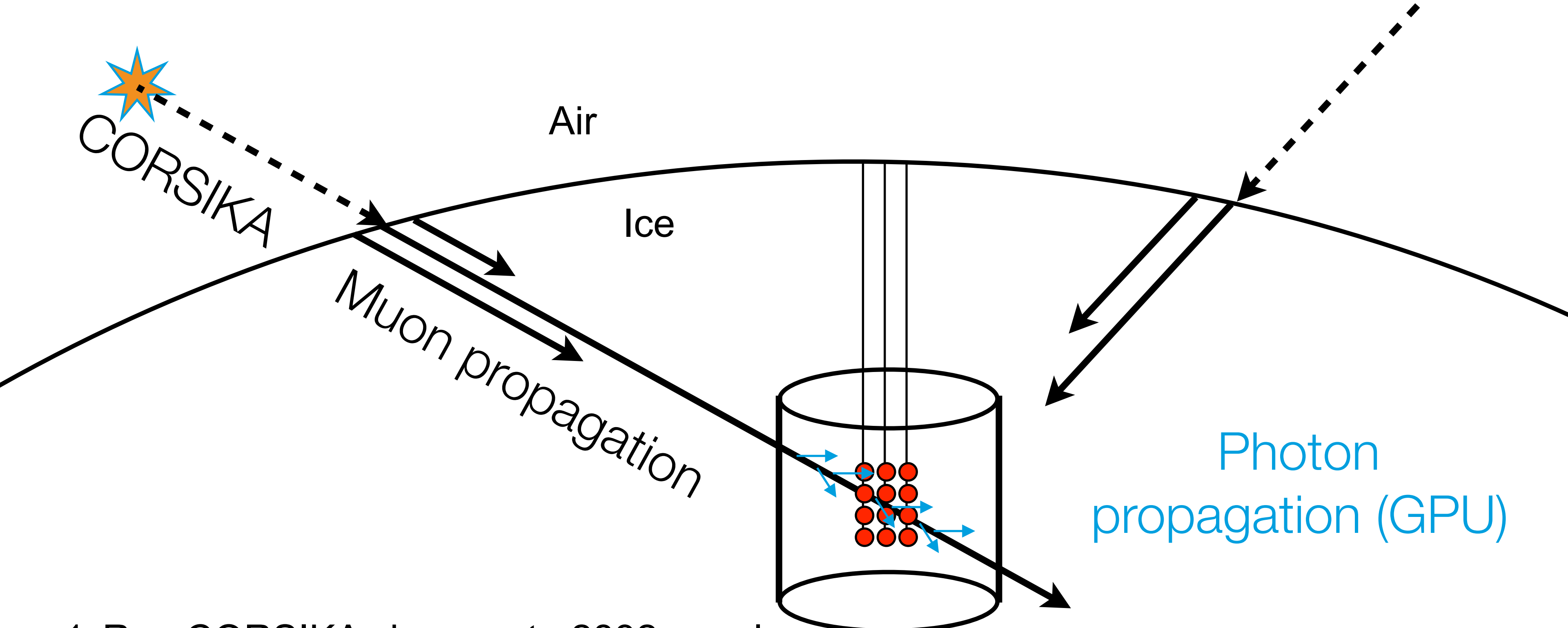
- Earth stops penetrating atmospheric muons
- Up-going muon tracks are neutrino events

- IceCube detects incoming muons
- Starting events are neutrino events



Trickiest backgrounds: rare showers dominated by single high-energy muon or neutrino

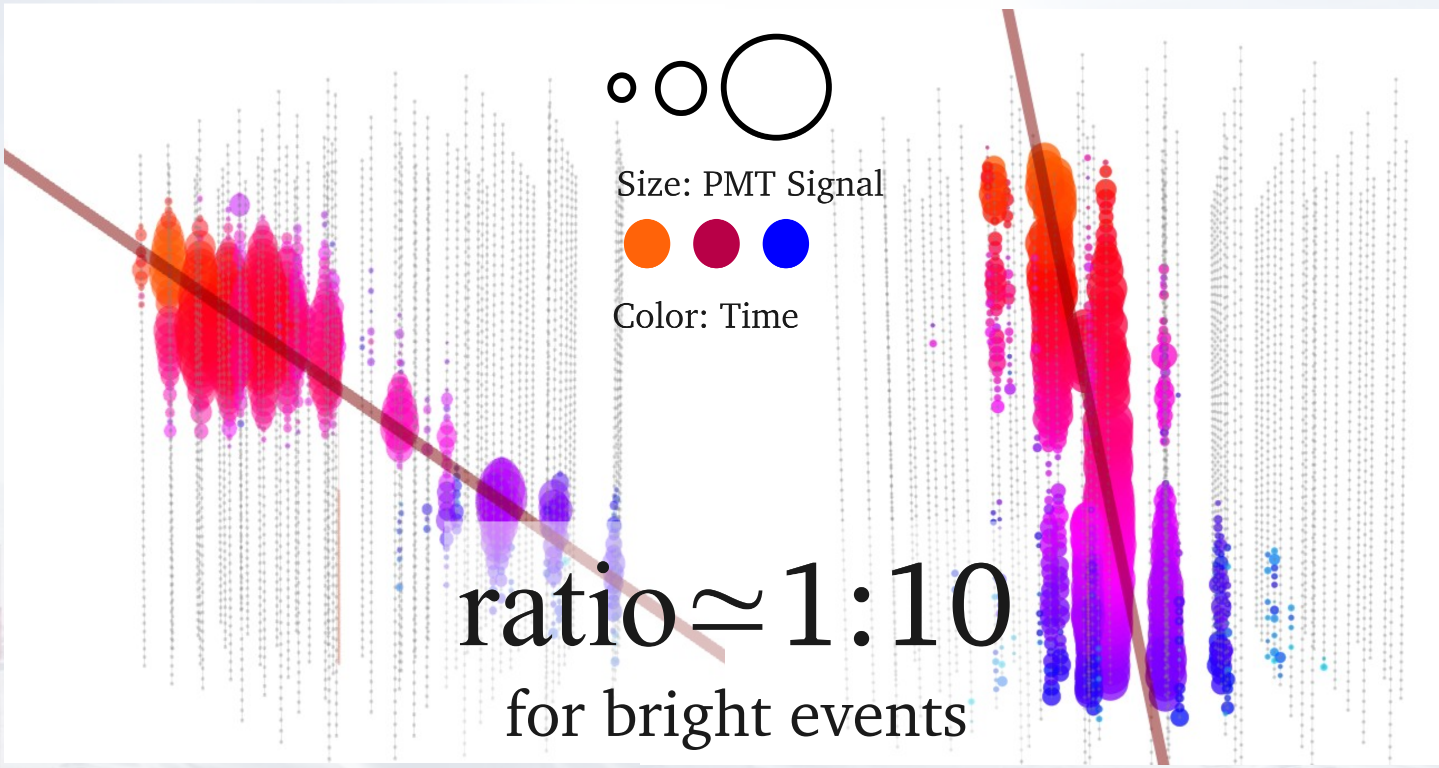
CORSIKA in IceCube



1. Run CORSIKA showers to 2832 m asl
2. Propagate muons to instrumented volume, simulation stochastic losses
3. Propagate photons to DOMs
4. Simulate detector response

IceCube detects ~1e11 air showers per year. We need to **choose which showers to simulate**. (Even with SIBYLL)

Muon Event Types in Volume Detector



ratio$\simeq$1:10

for bright events

High Energy Muon

Energy Spectrum follows **Nucleons**

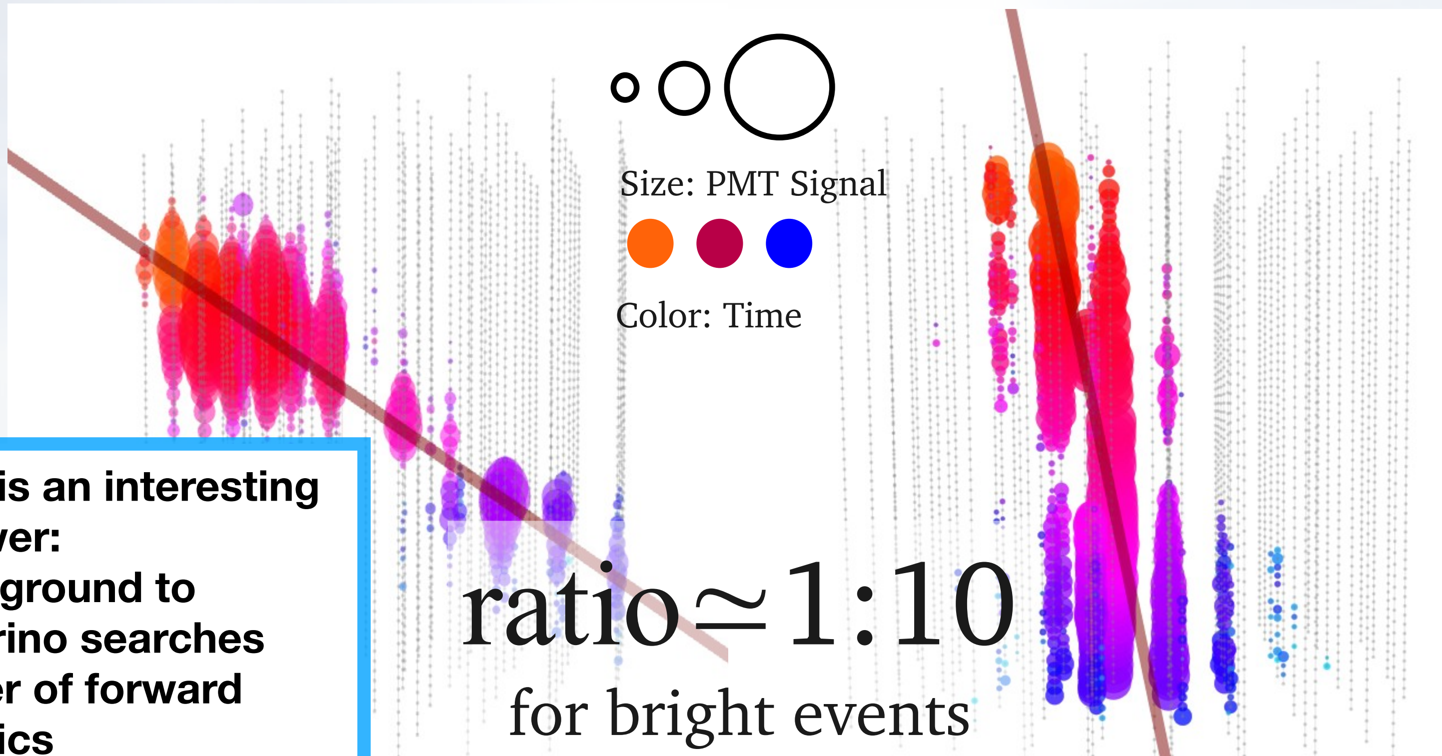
-same as Neutrinos!

High Multiplicity Bundle

Energy Spectrum follows **Nuclei**

Patrick Berghaus, 2012

Muon Event Types in Volume Detector



This is an interesting shower:

- **background to neutrino searches**
- **tracer of forward physics**

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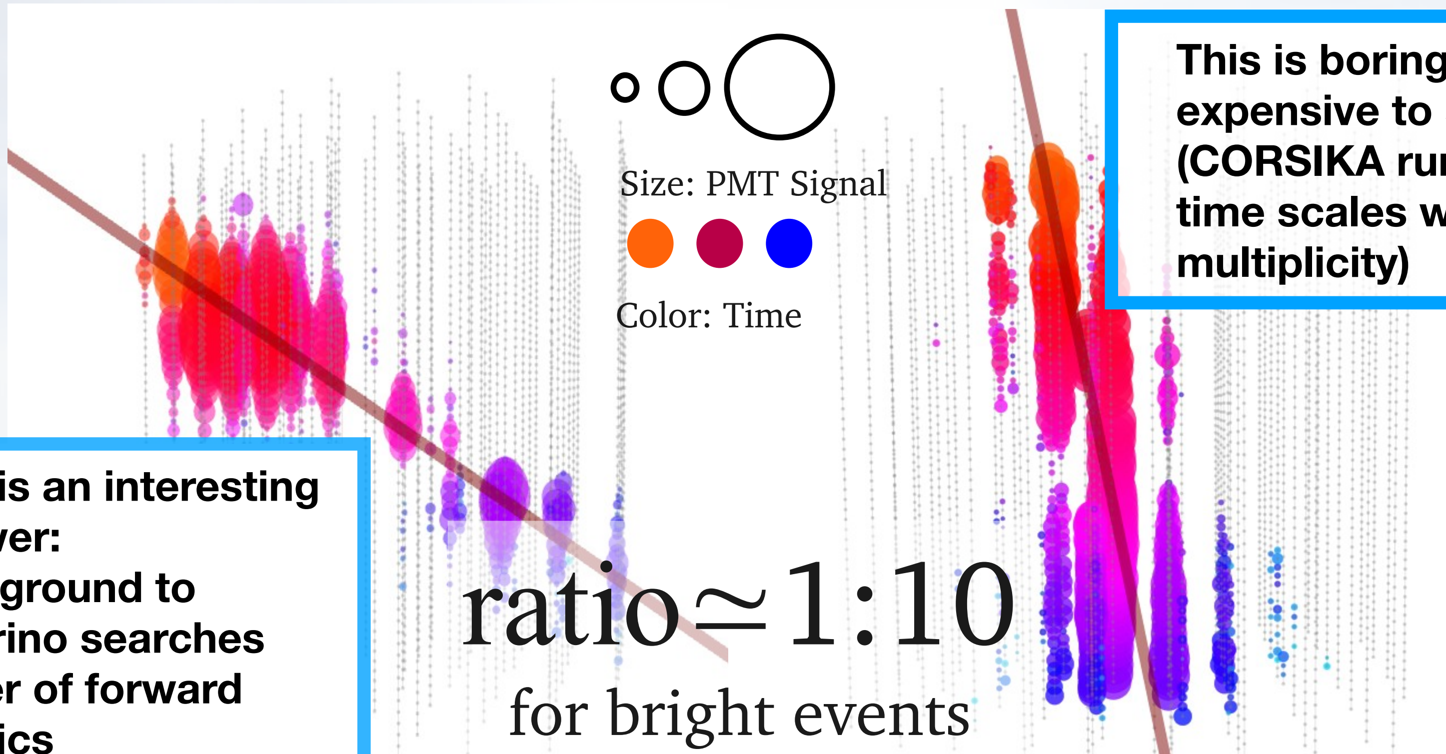
Patrick Berghaus
Muon Multiplicity Spectrum

3

Patrick Berghaus, 2012

DESY.

Muon Event Types in Volume Detector



This is boring, and expensive to simulate (CORSIKA running time scales with multiplicity)

This is an interesting shower:
- background to neutrino searches
- tracer of forward physics

High Energy Muon

Energy Spectrum follows **Nucleons**
-same as Neutrinos!

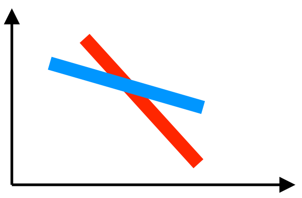
High Multiplicity Bundle

Energy Spectrum follows **Nuclei**

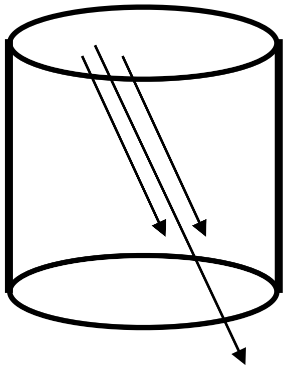
Patrick Berghaus, 2012

Simulating interesting showers

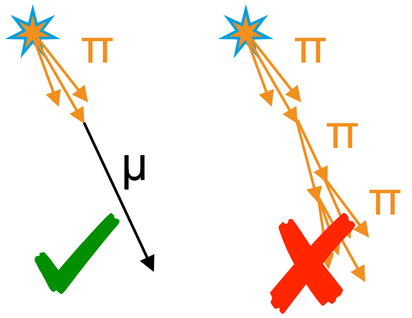
- Carefully tune injected energy spectrum & mass composition to avoid simulating excessively high-multiplicity showers. **Only accounts for average shower behavior.**



- Sample from a parameterization of the muon flux at depth (MUPAGE/MuonGun). **Parameterization loses information for > 1 muon.**

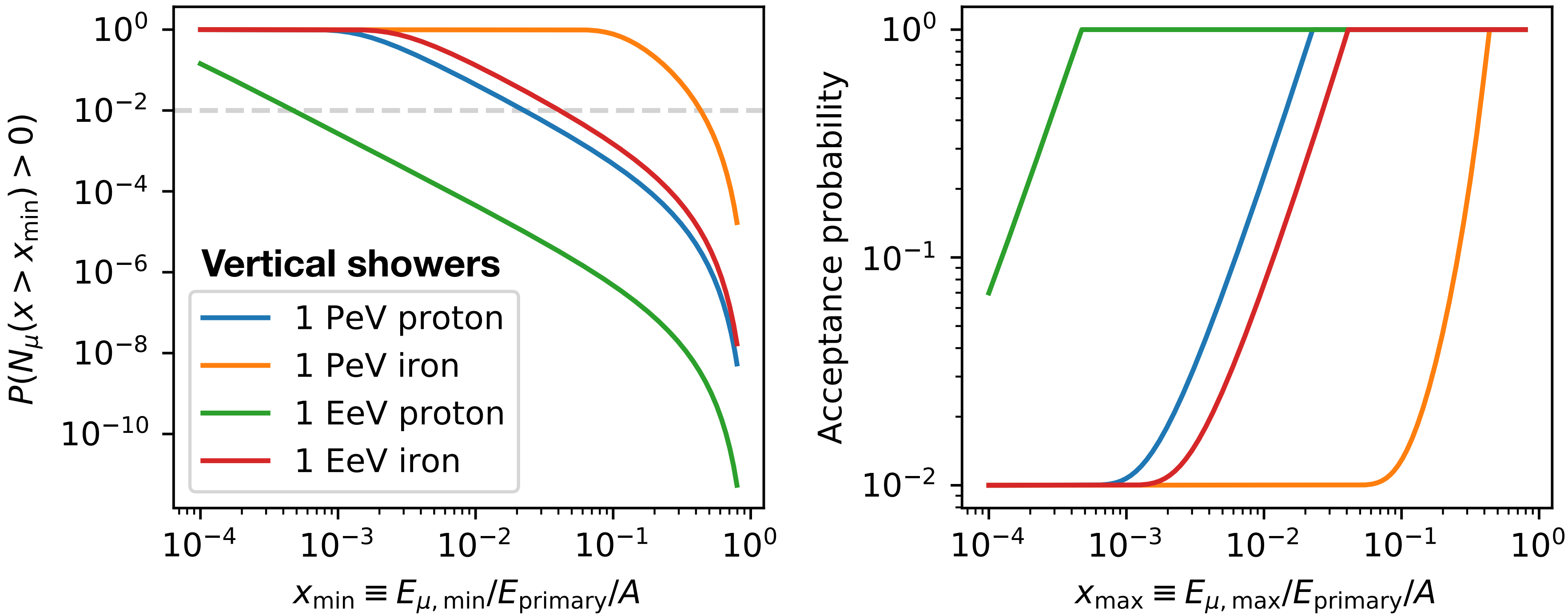


- Apply a known bias by aborting boring showers as quickly as possible. **Used to require mucking about in CORSIKA internals (ICECUBE1 option from v7.50); now significantly easier with D. Baack's dynamic stack.**



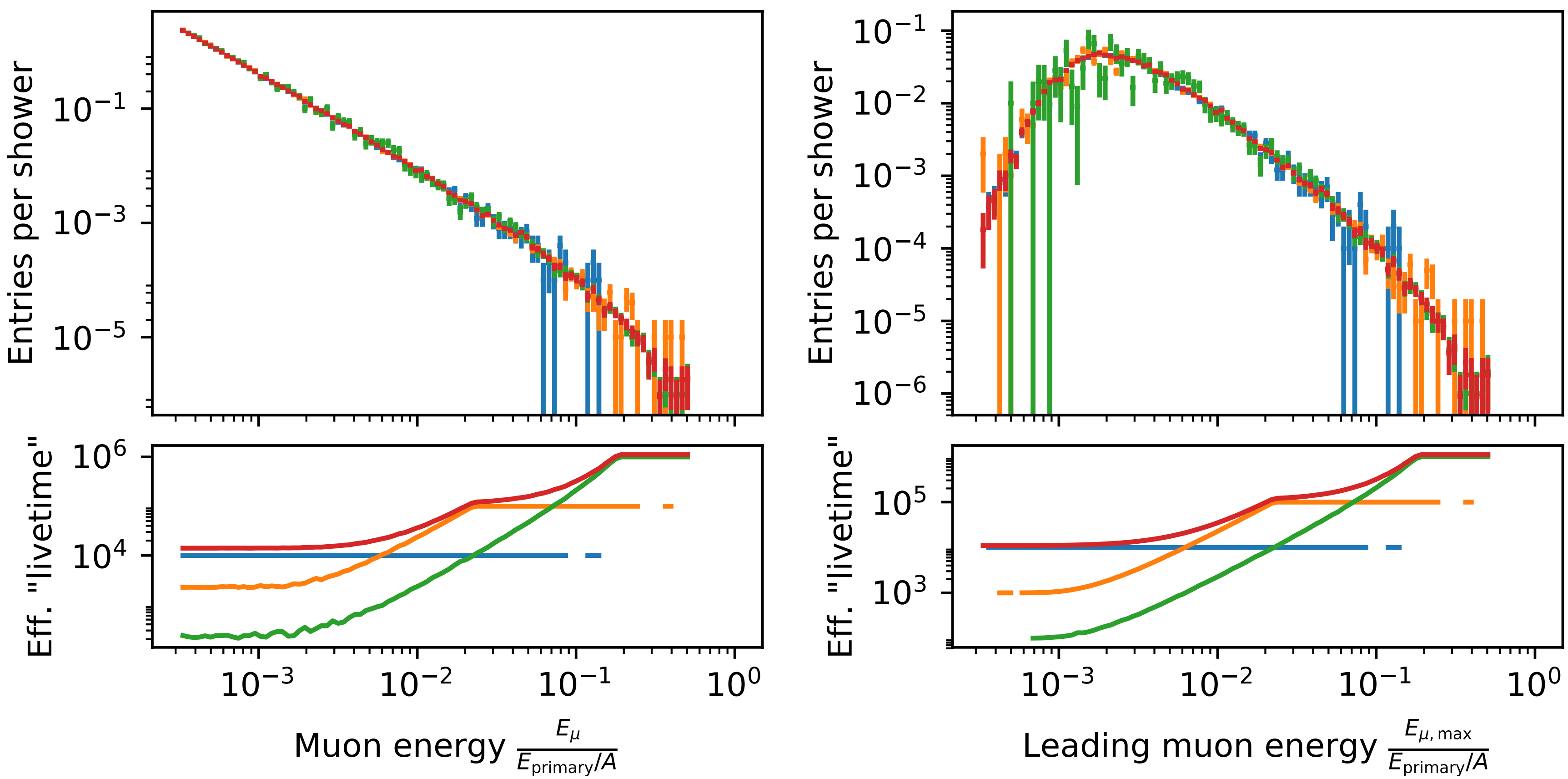
Biasing scheme for single-like showers

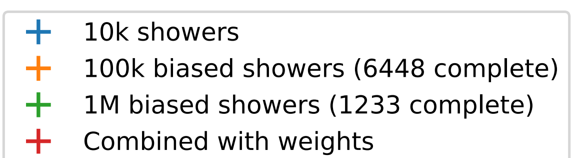
- **User specifies a target fraction of showers to accept ("bias factor," e.g. 0.01)**
- **Plugin uses the Elbert formula to pick a muon energy threshold for each shower**



- Shower is killed with a probability **(always < 1!)** based on the highest-energy muon in the shower
- Kill probability increases monotonically with energy, so shower can be killed before the first muon is produced.

Demo: vertical proton showers





Showers	Bias factor	Killed	Interactions killed	Interactions complete	Time per shower
1e4	1	0	N/A	937	169 + 0.5 ms
1e5	1e-2	93552	40	954	20 + 0.5 ms
1e6	1e-4	998767	6	867	2 + 0.5 ms

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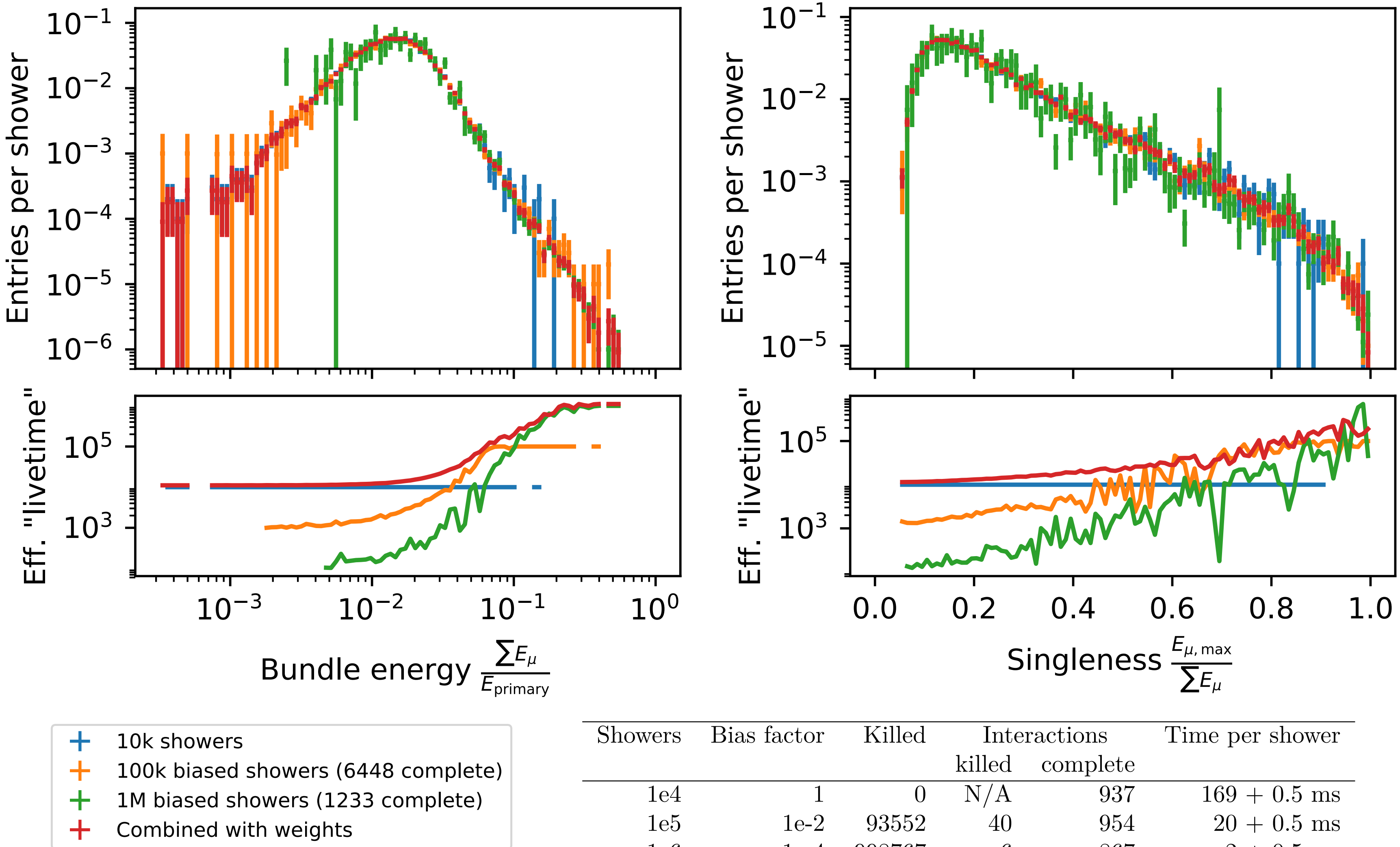

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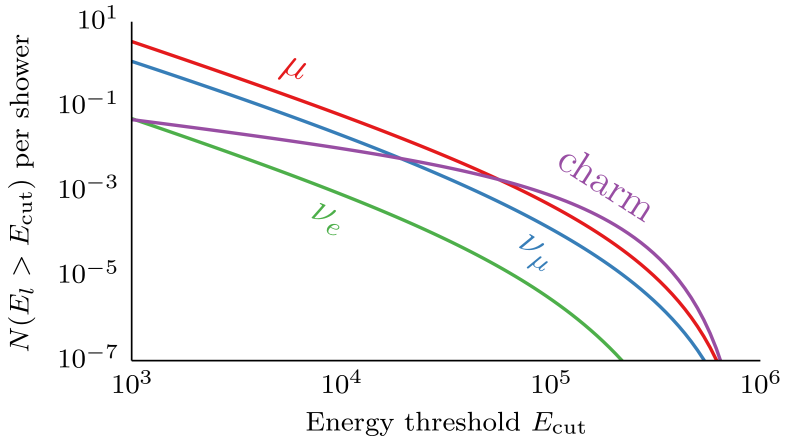
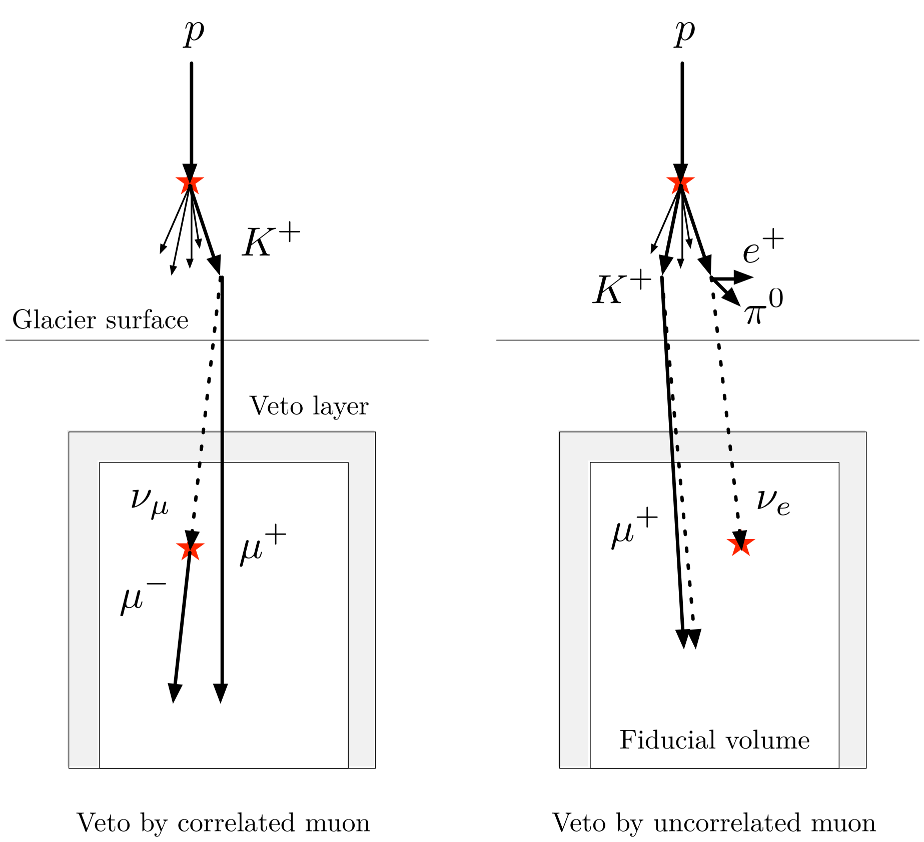
Down-going atmospheric neutrinos

- Majority of high-energy neutrinos are embedded in high-multiplicity muon bundles.
- Showers dominated by a single high-energy neutrino are rare. **Same energy-based biasing scheme** efficiently produces interesting showers.





Other possible applications

- **Combined IceTop-IceCube events:** defer EM shower until hadronic core turns into something interesting
- **CTA:** efficiently simulate gamma-like proton showers
- Any other situation where you need complete showers in a small corner of your phase space (and where the probability of landing in that corner decreases monotonically in the order in which you propagate particles)

Variety of useful manipulations possible simply by having control over the order in which particles leave the stack. DynStack is critical to efficient rare-background simulation today, and similar functionality needs to exist in next-generation CORSIKA.

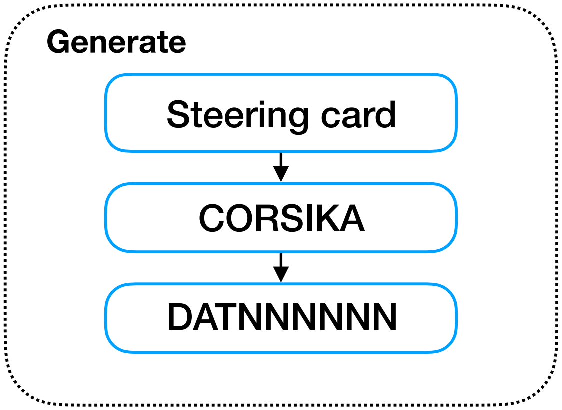
Wish list for next-generation CORSIKA

In order of priorities

1. **Open development:** version control makes it much easier to follow core changes and contribute useful patches. **Also for CORSIKA Classic!**
2. **Modularity:**
    1. **Extensions:** Experiment-specific extensions should be able to exist separate from the mainline distribution, and rely on relatively stable interfaces.
    2. **Output:** Everyone has their favorite output format (row-oriented table, column-oriented in-memory table, shared-memory queue, zmq socket, etc.). These should be largely interchangeable, and users should be able to provide their own.
3. **Automated testing** makes it easier to contribute patches that don't break everything.
4. **CORSIKA as a library:** it should be possible to control shower initialization, random number generation, and simulation stepping from client code.
5. **Unique particle IDs.** Every particle needs a unique (per shower) ID.
6. **Flexible history:** not everyone has the same definition of interesting history. Client code should be able to reconstruct the complete particle graph and calculate its own.

Backup: CORSIKA as a Service

simprod CORSIKA + I3CORSIKAReader



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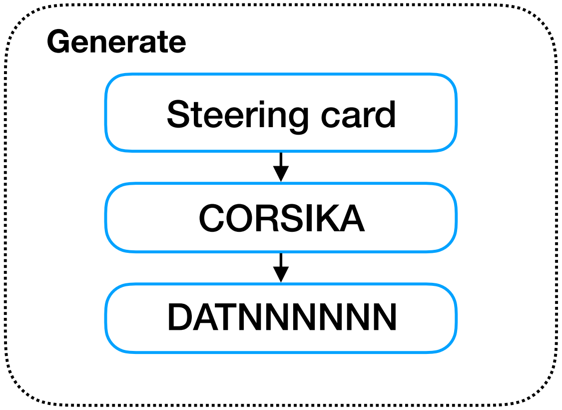

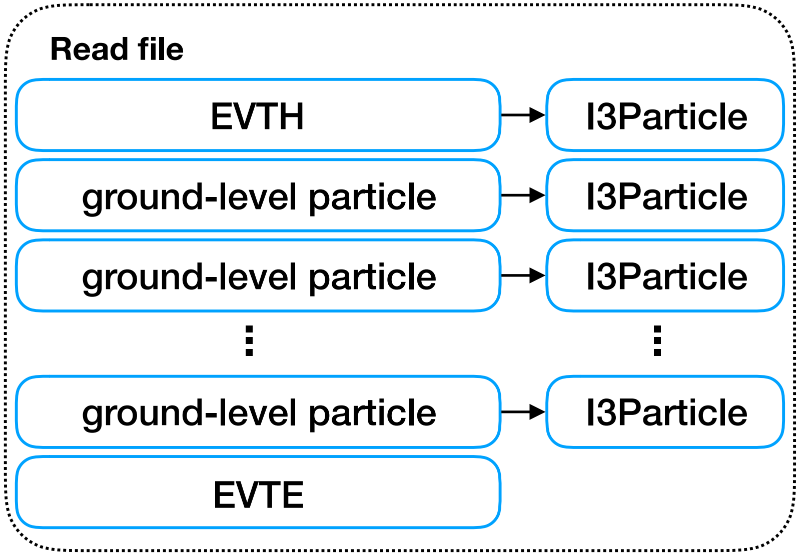

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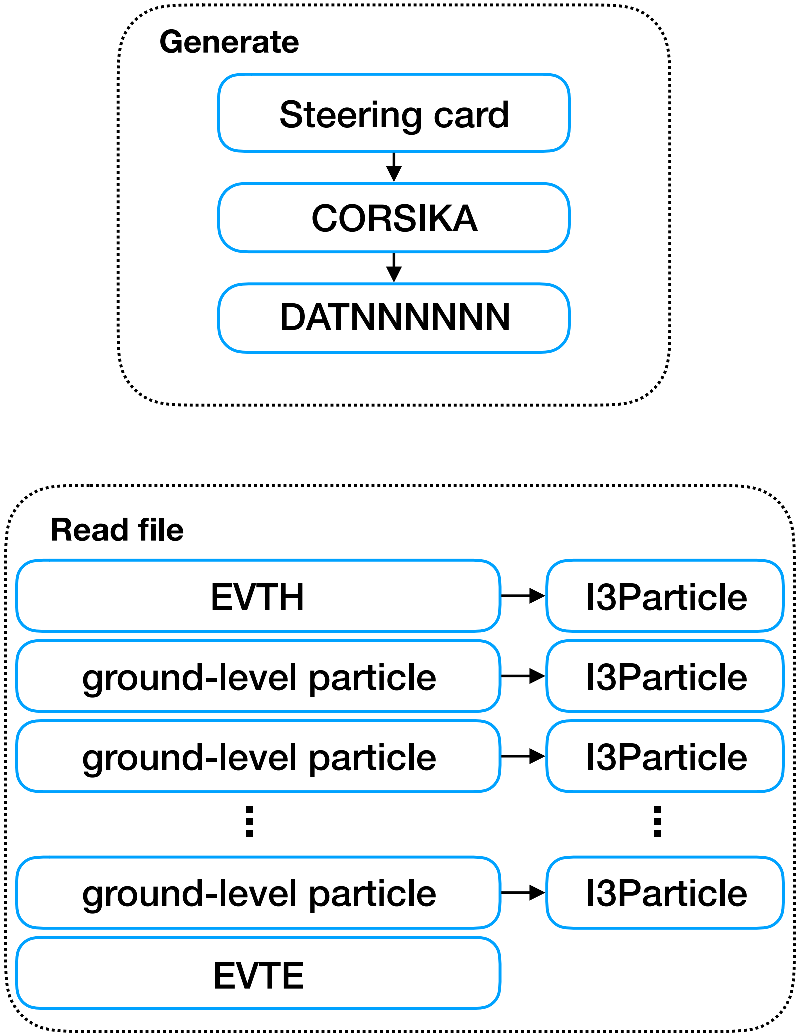
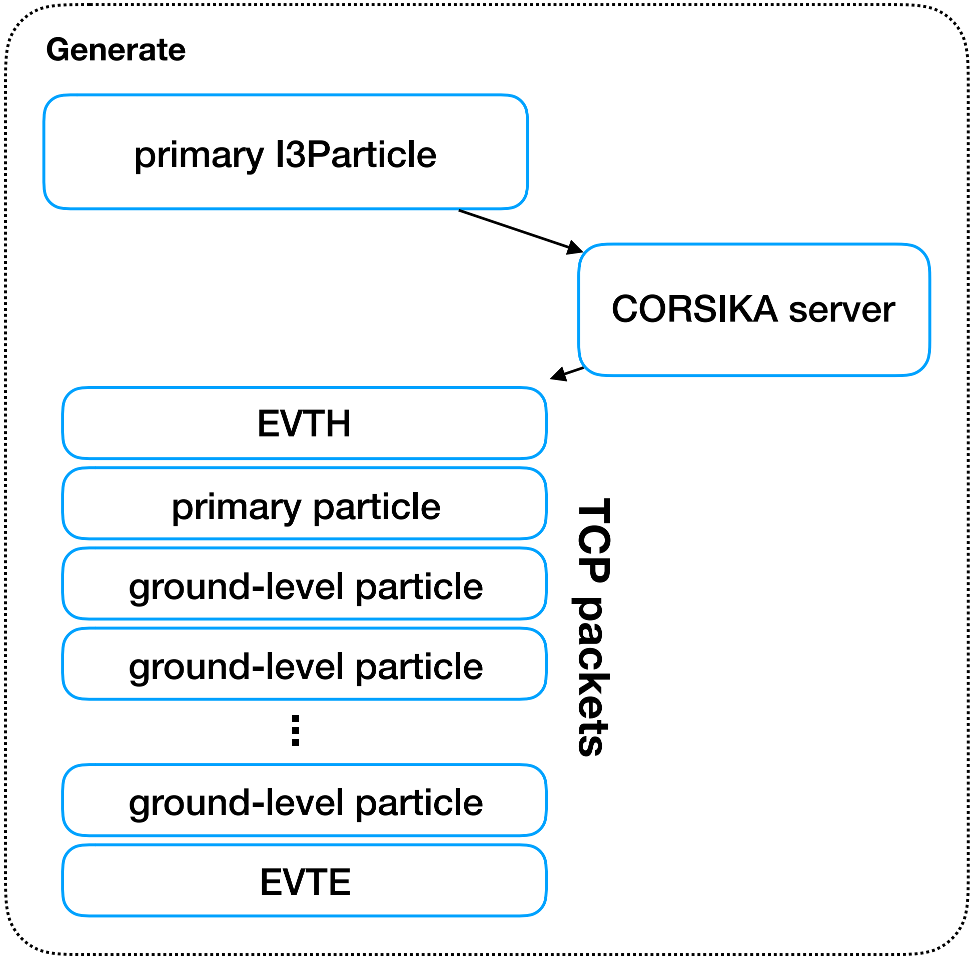


I3CORSIKAService



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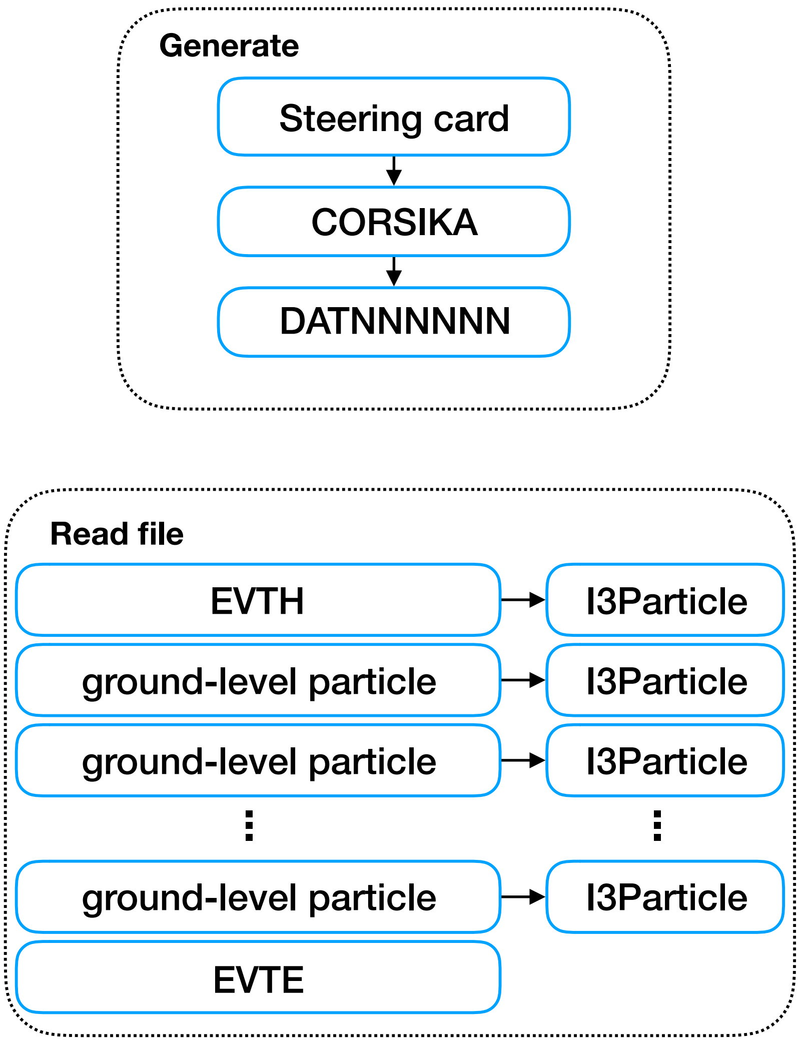
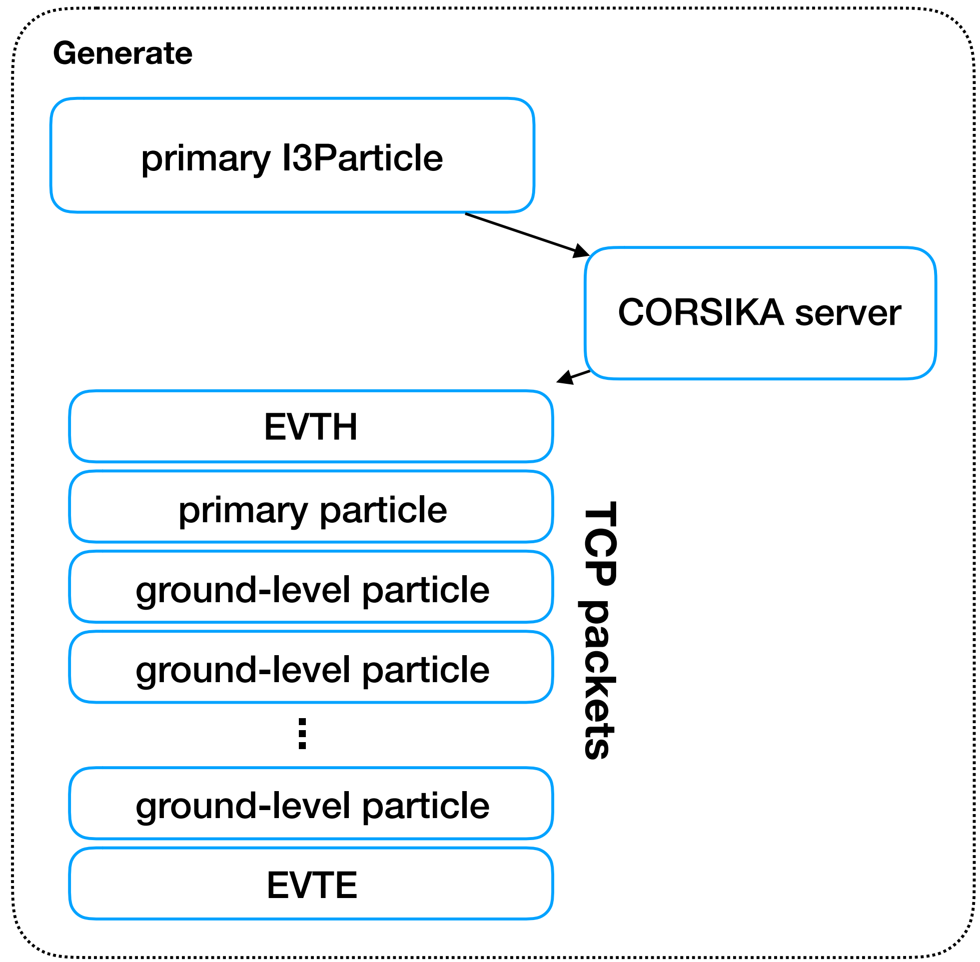
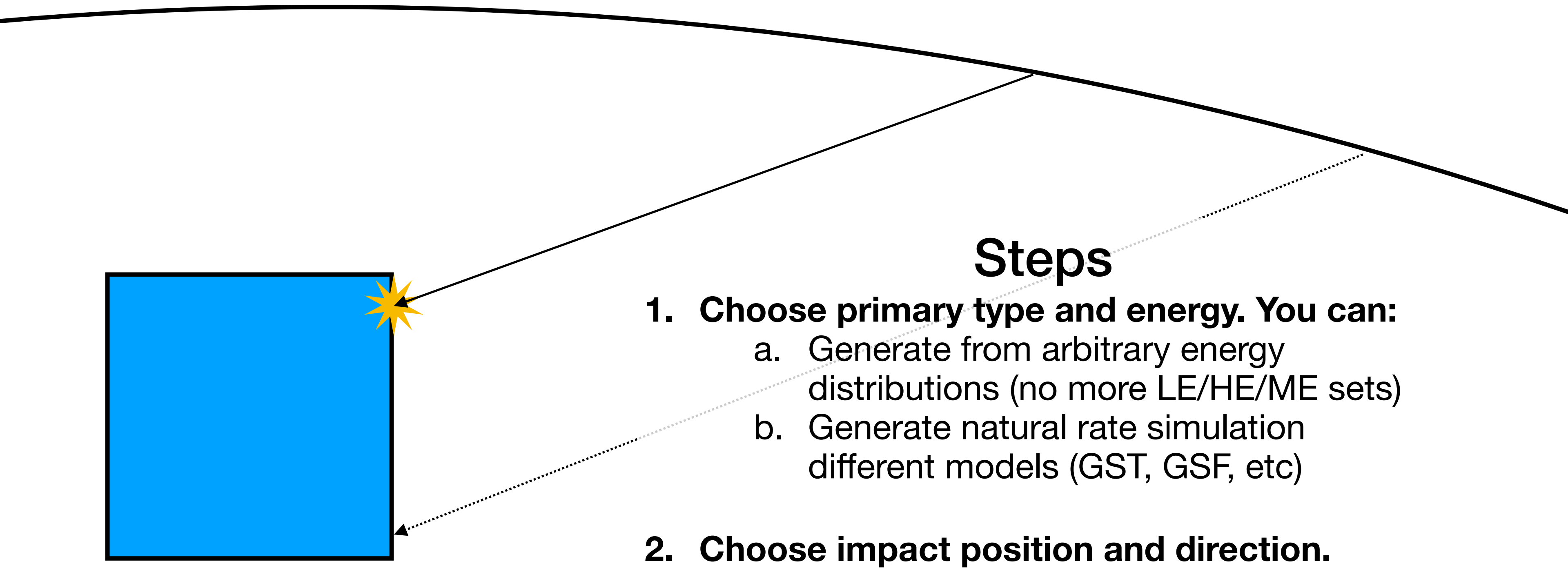




Why is this better?

Controlling shower generation from IceTray



Steps

1. **Choose primary type and energy. You can:**
    a. Generate from arbitrary energy distributions (no more LE/HE/ME sets)
    b. Generate natural rate simulation different models (GST, GSF, etc)

2. **Choose impact position and direction. Based on overburden and trajectory, you can:**
    a. Skip the shower if no muon could reach the impact point
    b. Set muon, hadron, and EM energy thresholds (e.g. does it hit IceTop?)

3. **Choose muon bias factor, e.g. 10^{-4} for main (biased) shower, 1 for coincident showers**

Performance vs stock CORSIKA

	Time per shower (ms on my laptop)			
Energy spectrum	**Stock CORSIKA**	**RemoteControl**	**+skip sub-threshold showers**	**+set energy threshold per shower**
$E^{-2.6}$ 0.6-100 TeV	0.93	0.96	0.60	0.51
E^{-1} 3-30 TeV	3.67	3.66	3.24	2.14
$E^{-2.6}$ 30 TeV-1PeV	17.1	16.9	15.7	9.6
E^{-2} 1 PeV-1 EeV	820	1131	1129	541

CORSIKA 7.64/SIBYLL2.3c, curved atmosphere 12, neutrinos on, 0-90 degrees

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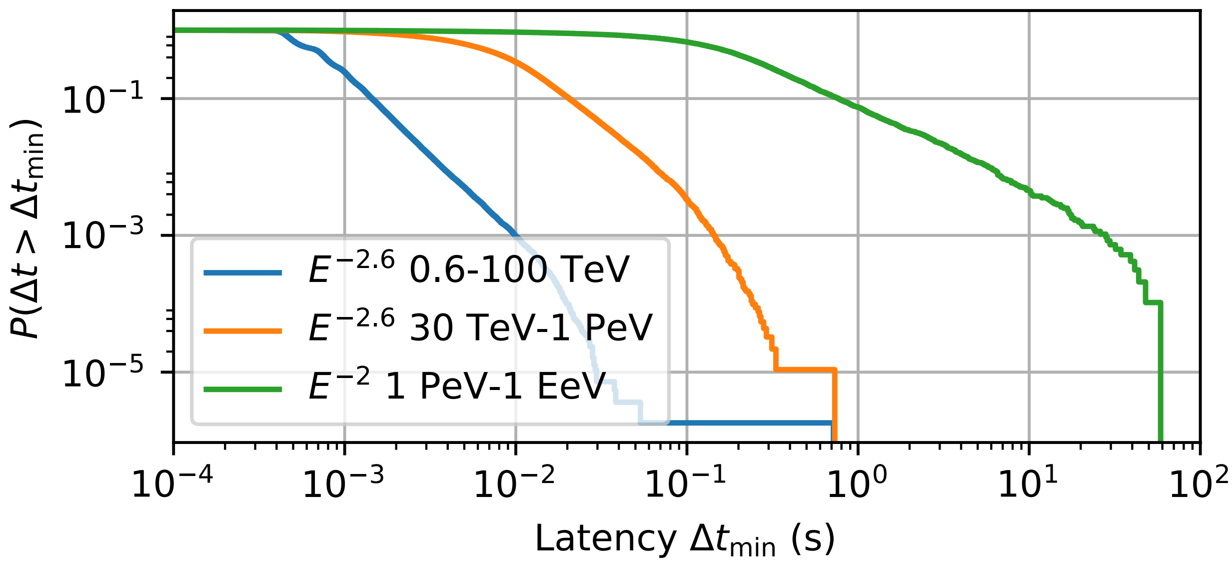
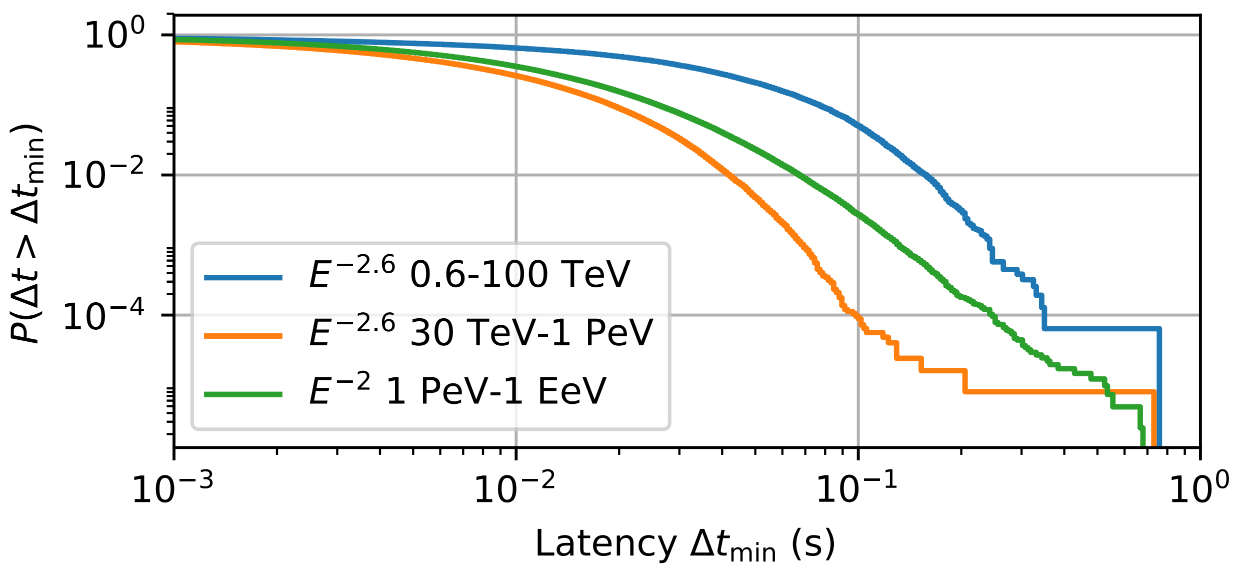
~1.8x speedup

CORSIKA 7.64/SIBYLL2.3c, curved atmosphere 12, neutrinos on, 0-90 degrees

Time per muon vs time per shower



High-energy showers can take a while to finish



Time between muons is similar for different energy ranges