# Simulating penetrating atmospheric leptons in IceCube

## Early experiments with adaptive sampling

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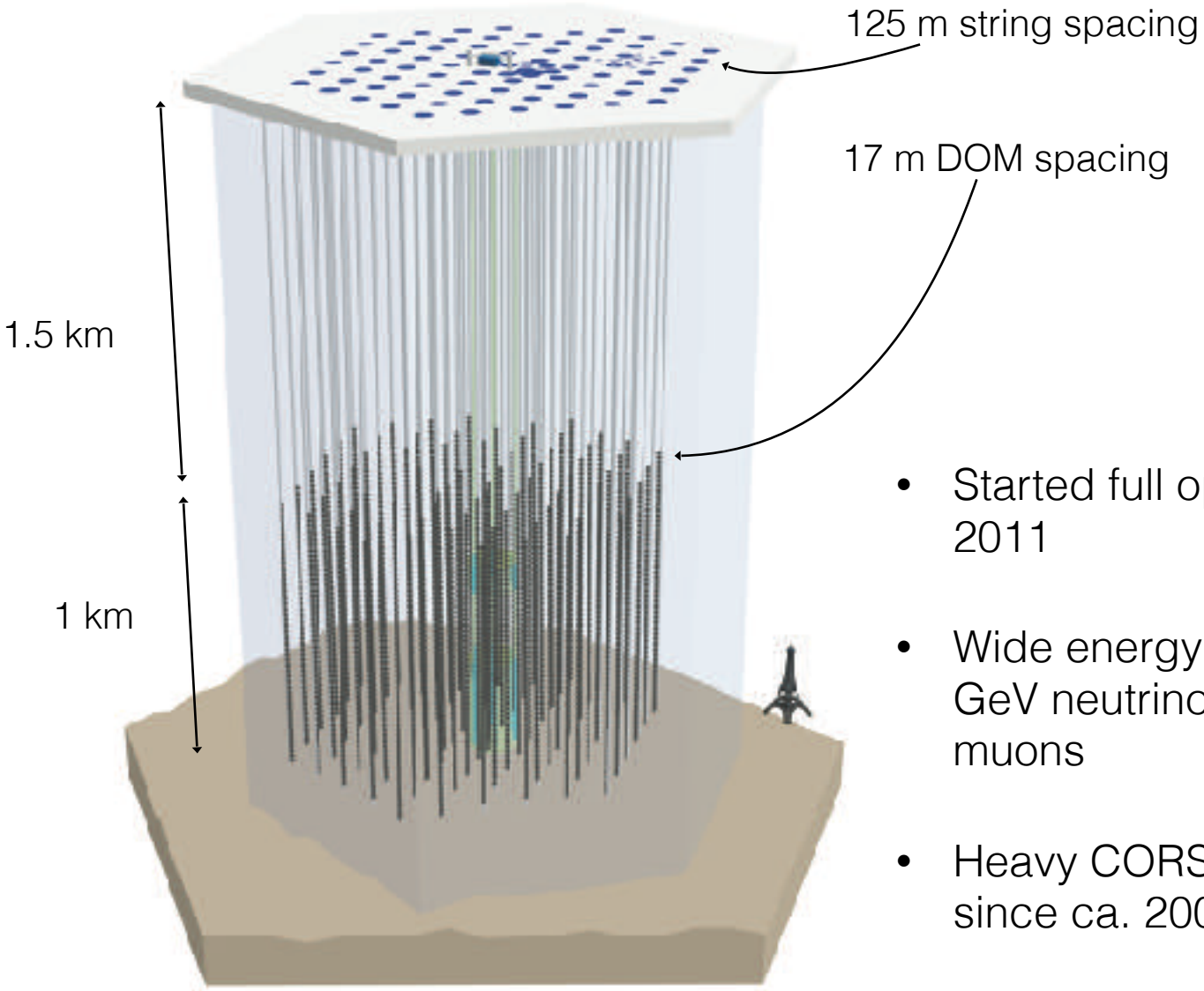
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

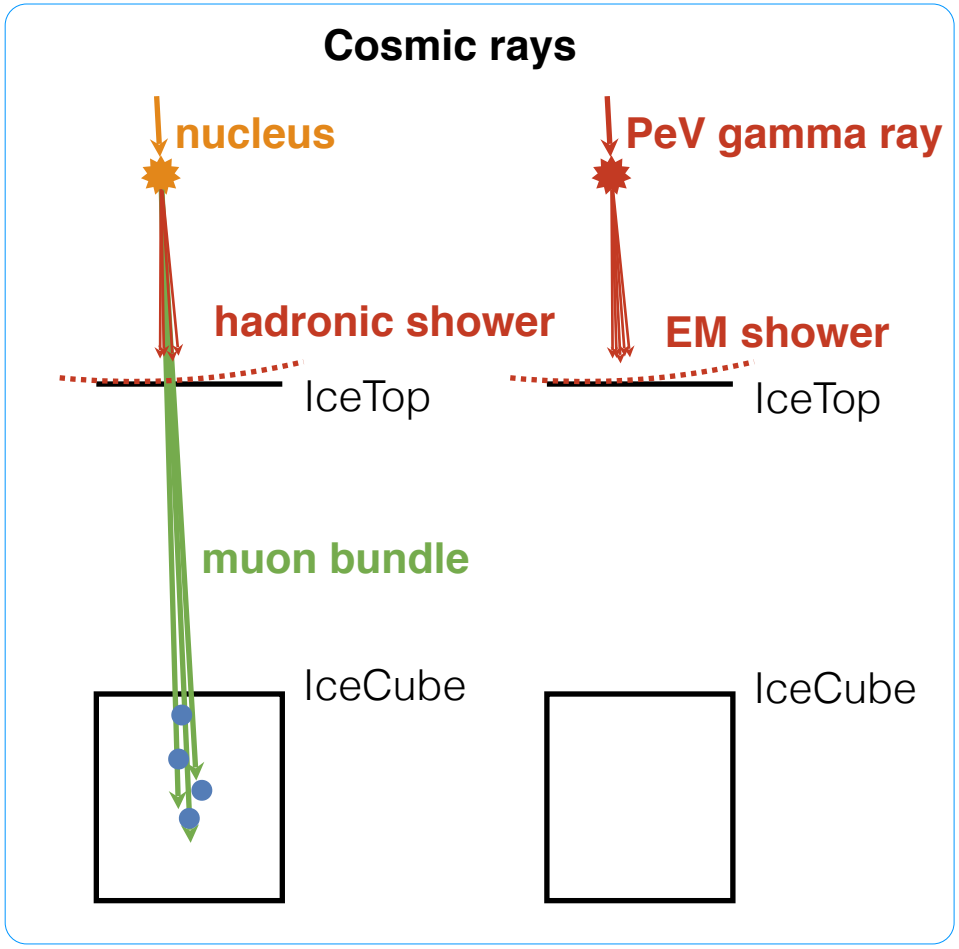
# IceCube

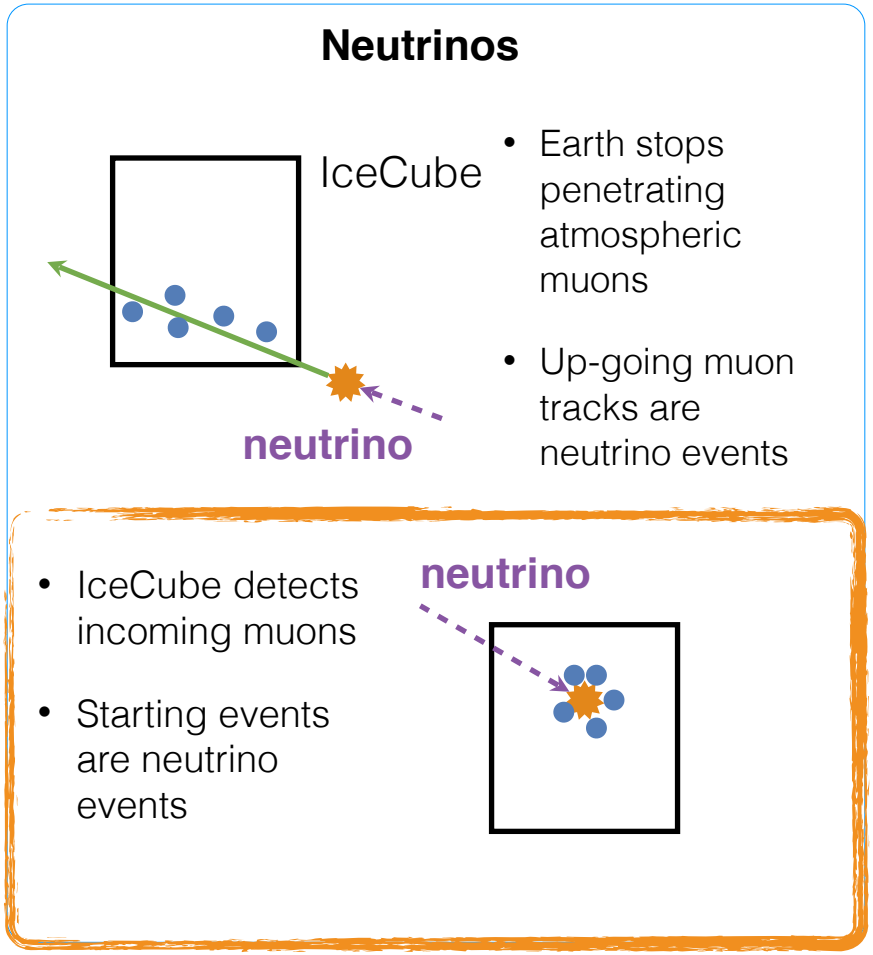
## an optical Cherenkov detector in the deep Antarctic ice




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

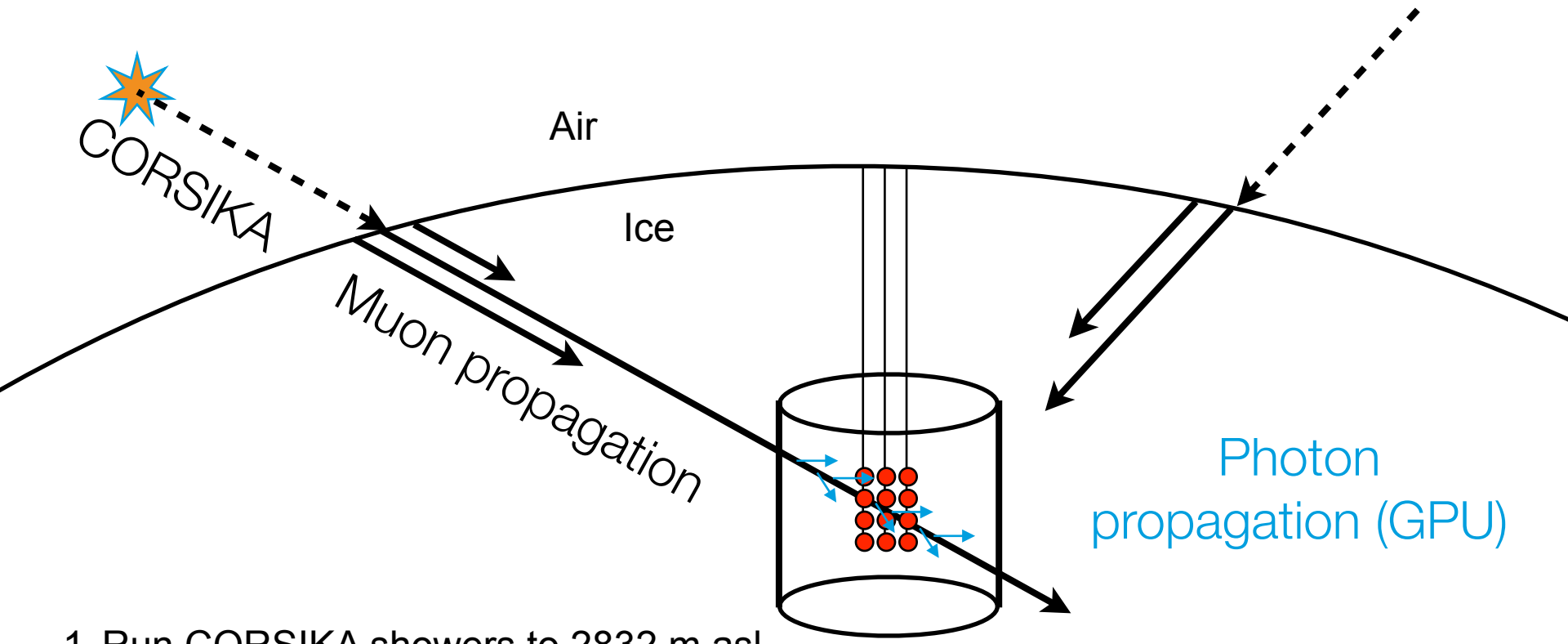
# CR, gamma, and neutrino detection




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

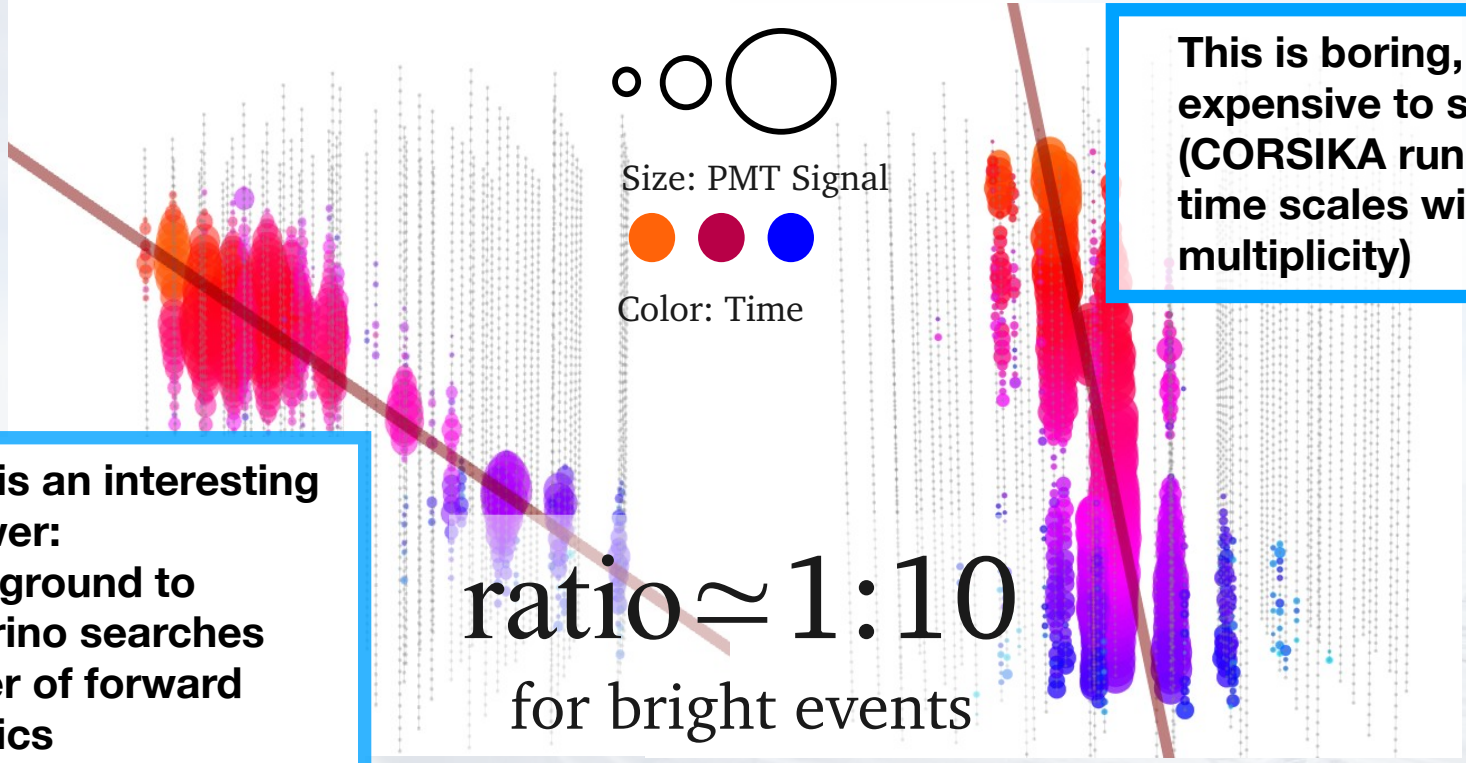
# CORSIKA in IceCube




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




**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

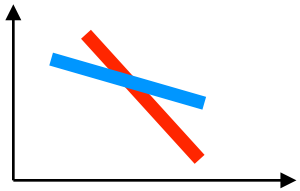
Energy Spectrum follows **Nuclei**



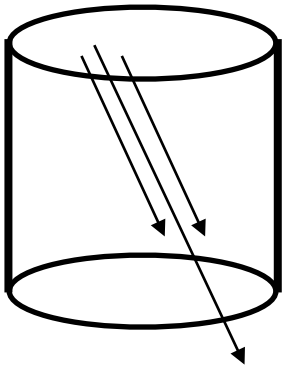
**Patrick Berghaus, 2012**

# Simulating interesting showers

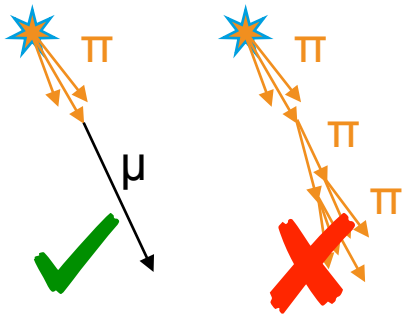
- Carefully tune injected energy spectrum & mass composition to avoid simulating excessively high-multiplicity showers. **Only accounts for average shower behavior.**



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



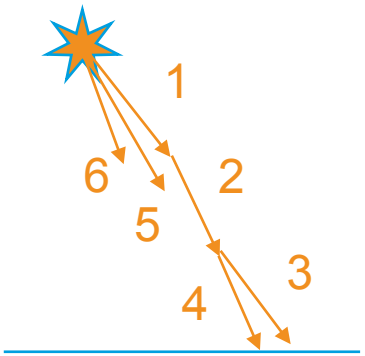
- Apply a known bias by aborting boring showers as quickly as possible. **Used to require mucking about in CORSIKA internals (ICECUBE1 option from v7.50); now significantly easier with D. Baack's dynamic stack.**



# Cor++: CORSIKA plug-ins in C++

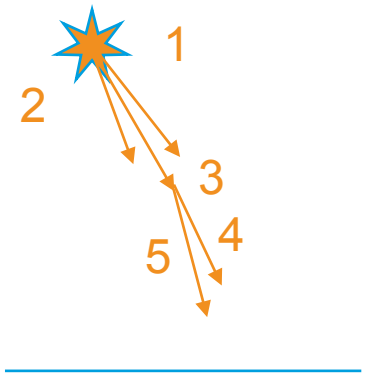
**Standard CORSIKA**

- Secondaries of each interaction to FIFO storage
- Depth-first propagation
- Minimizes in-memory size of shower




**DYNSTACK CORSIKA (since v7.57, June 2017)**

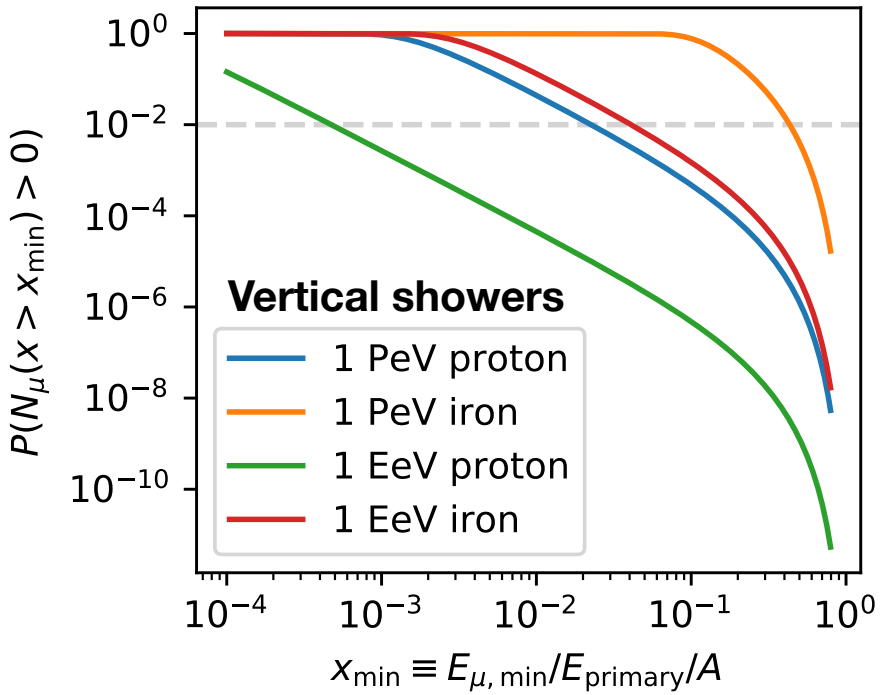
- Secondaries to custom storage
- Can change propagation order, drop particles, stop the entire shower, gather statistics, etc.
- Similar to Geant4 actions

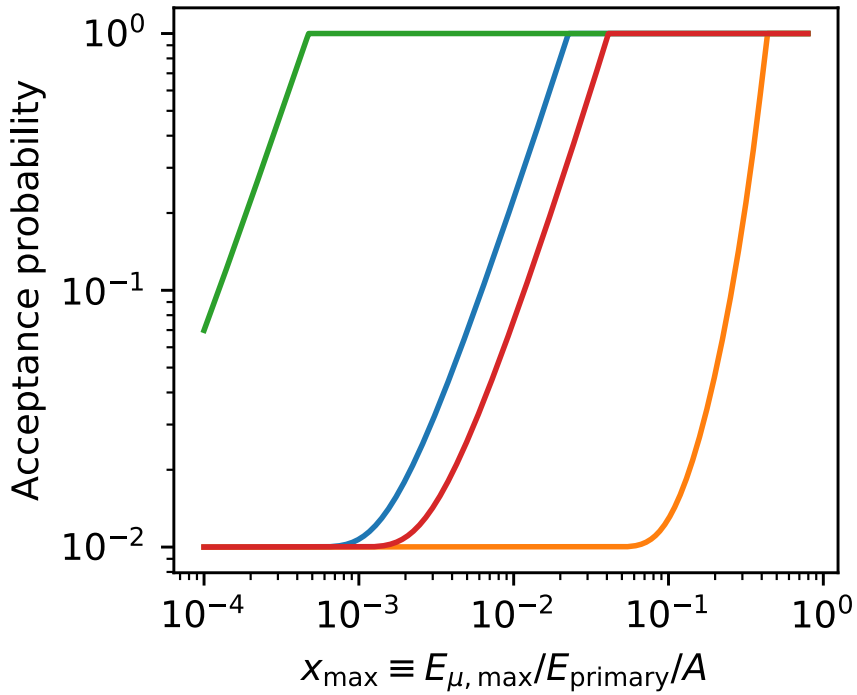



https://github.com/tudo-astroparticlephysics/Cor-PlusPlus

# Biasing scheme for single-like showers

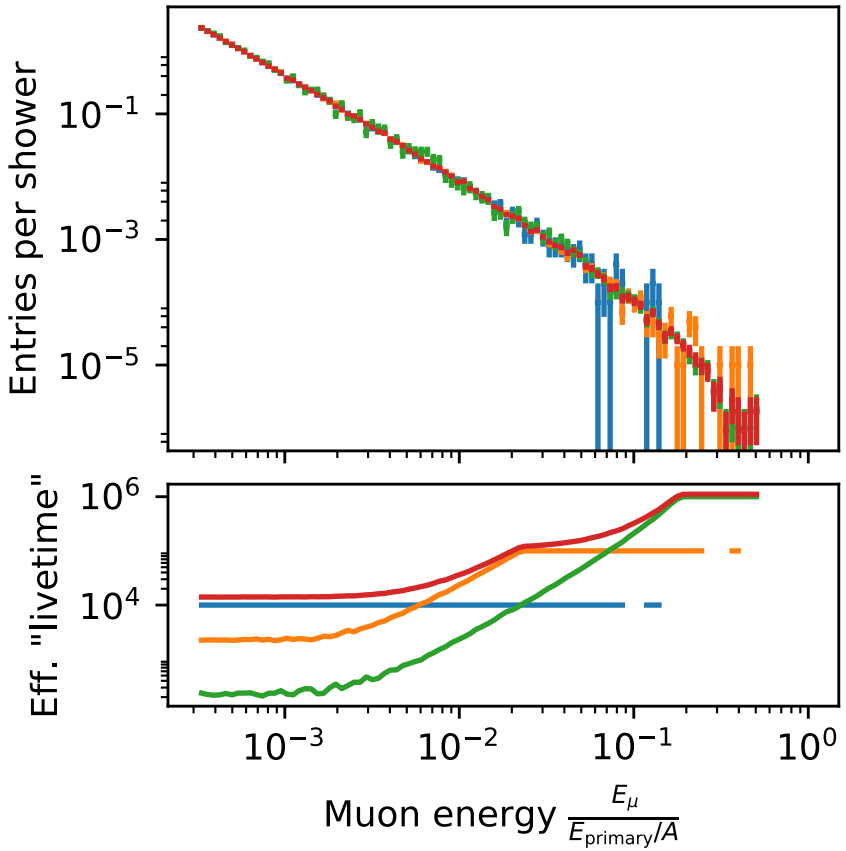
- **User specifies a target fraction of showers to accept ("bias factor," e.g. 0.01)**
- **Plugin uses the Elbert formula to pick a muon energy threshold for each shower**

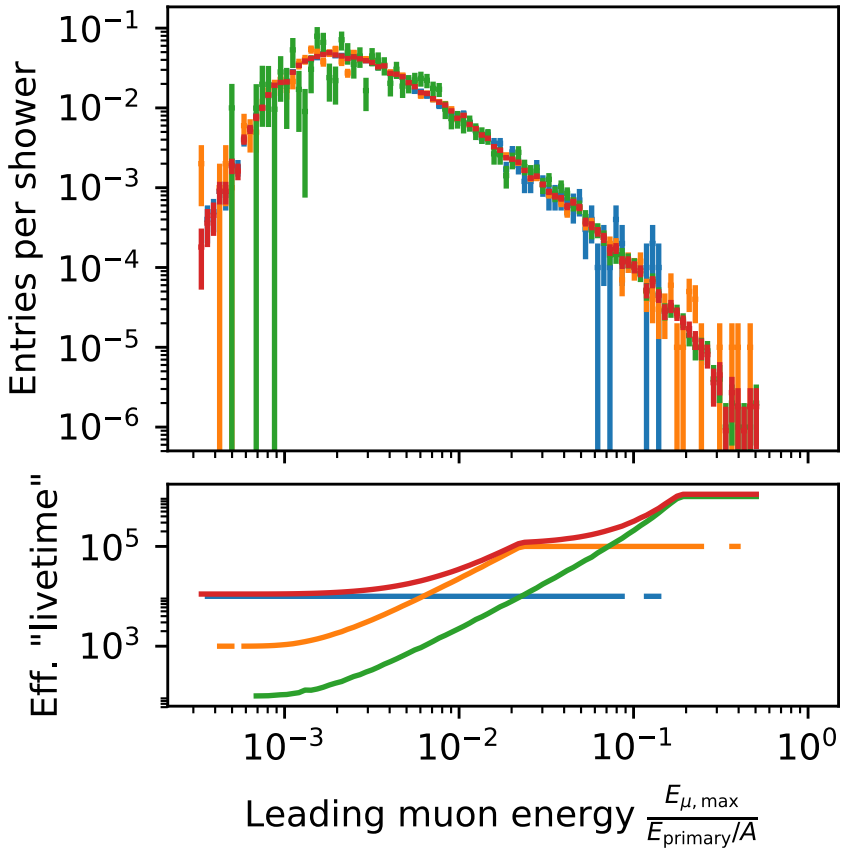


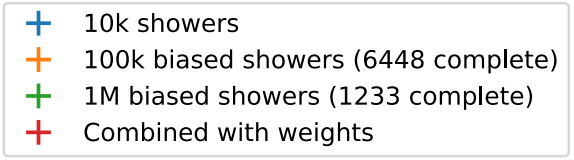




- Shower is killed with a probability **(always < 1!)** based on the highest-energy muon in the shower
- Kill probability increases monotonically with energy, so shower can be killed before the first muon is produced.

# 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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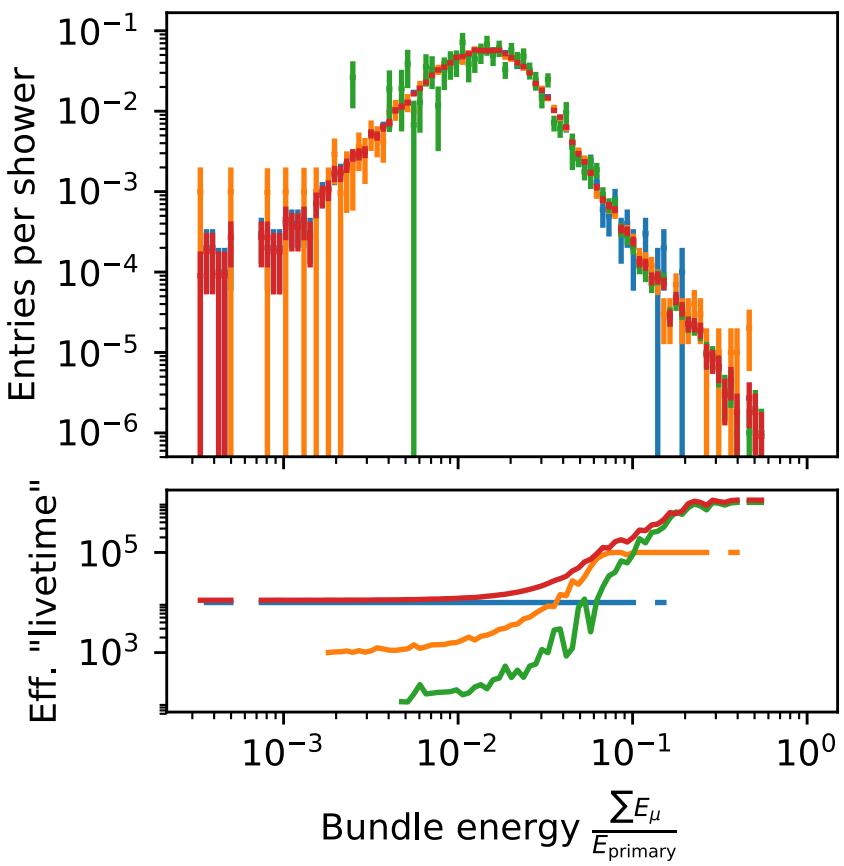


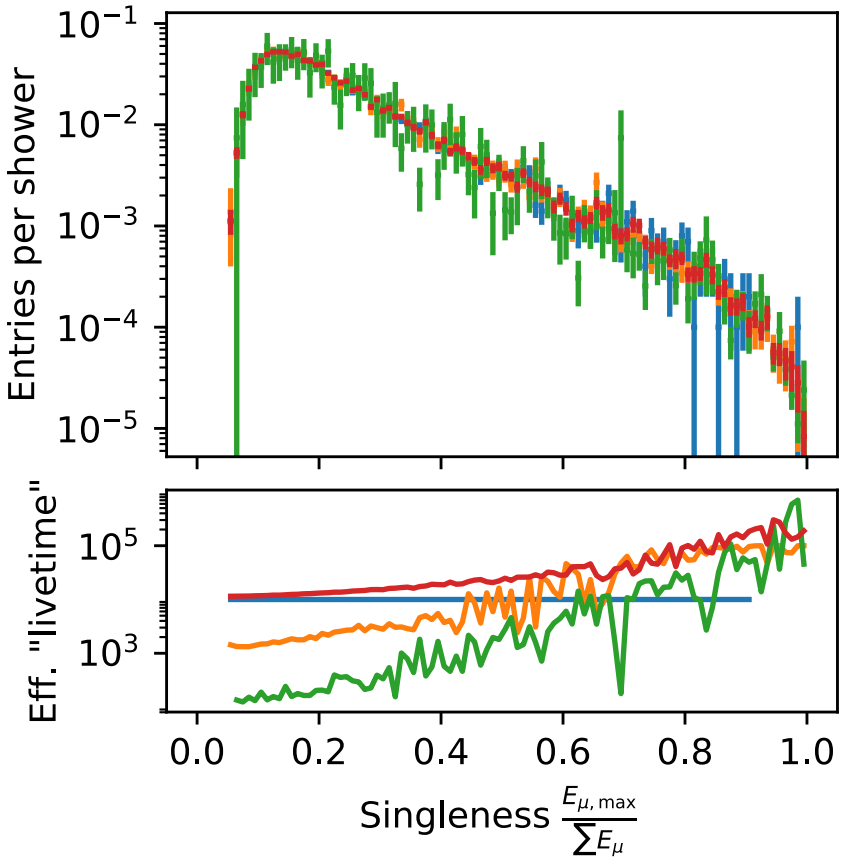


- 10k showers
- 100k biased showers (6448 complete)
- 1M biased showers (1233 complete)
- Combined with weights

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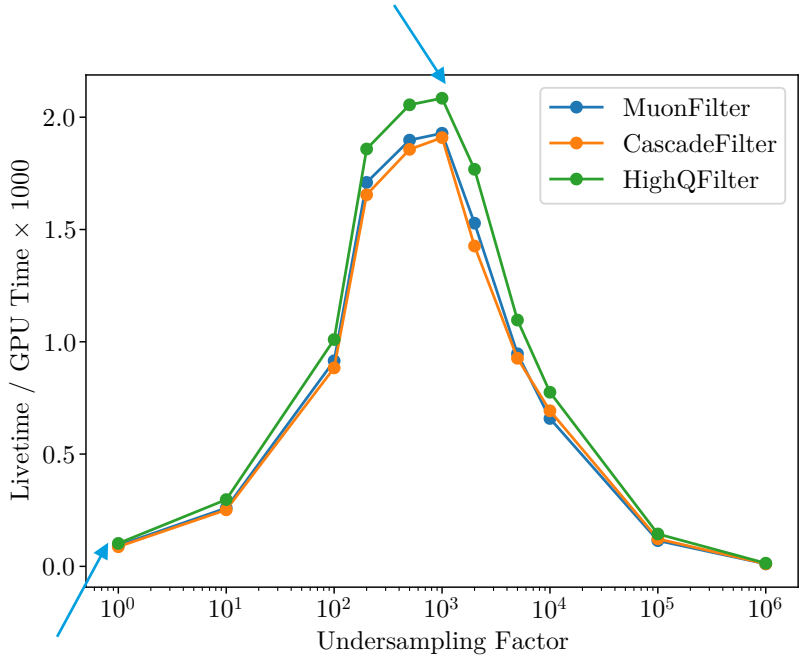
# Figure of merit: effective livetime/walltime

- Weight: simulated cosmic ray fluence / expected flux (1/s) * undersampling weight
- Effective livetime: sum(w)/sum(w^2)
- ~similar to integrated luminosity
- Currently optimal biasing speeds up computation by a factor ~10

Optimized sampling




Natural-rate sampling

K. Meagher @ CHEP 2023

# Next steps

- Generalize!
- Replace 1D bias with an ML model
- Learn arbitrary target distributions
  (i.e. different event selections)
- Investigate bias book-keeping in
  higher dimensions