Efficient simulation of coincident IceTop/IceCube showers with forward muons

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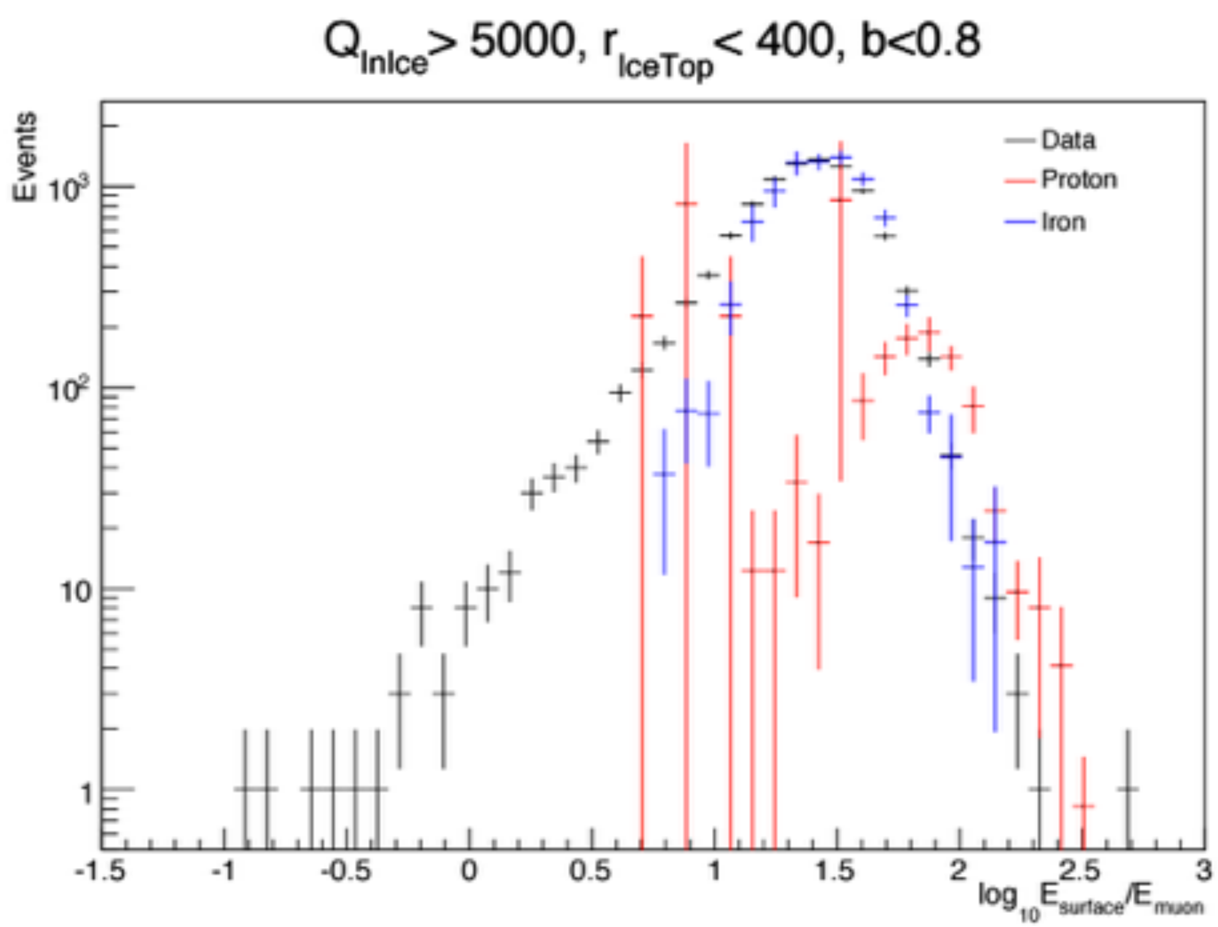
Introduction

- Are events we observe with low ratio of shower to muon energy consistent with current hadronic interaction models?



- Available CORSIKA simulation does not efficiently sample this region of phase space

Kill threshold method

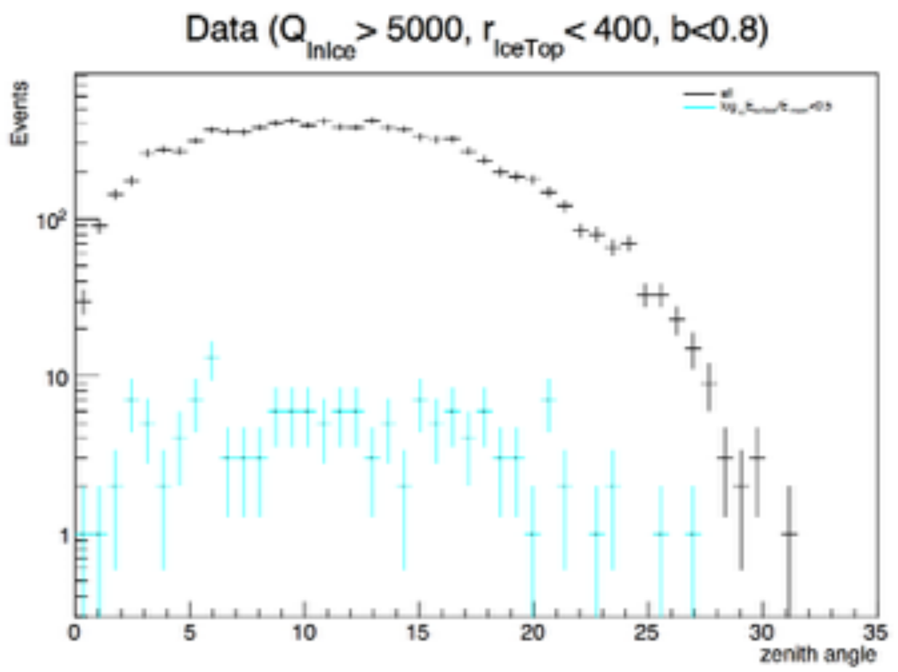
- Method first developed by J. van Santen and K. Jero for the calculation of self-veto probability for neutrinos
- Kill showers once they are no longer capable of producing a muon above a given energy threshold
- "Breadth-first" shower propagation
  - Propagate interesting particles above the energy threshold that are capable of producing muons first
    - Once a muon above threshold is found, continue normal propagation
    - Otherwise kill shower once all particles fall below the threshold
- Don't waste time fully developing showers that don't contain high energy muons

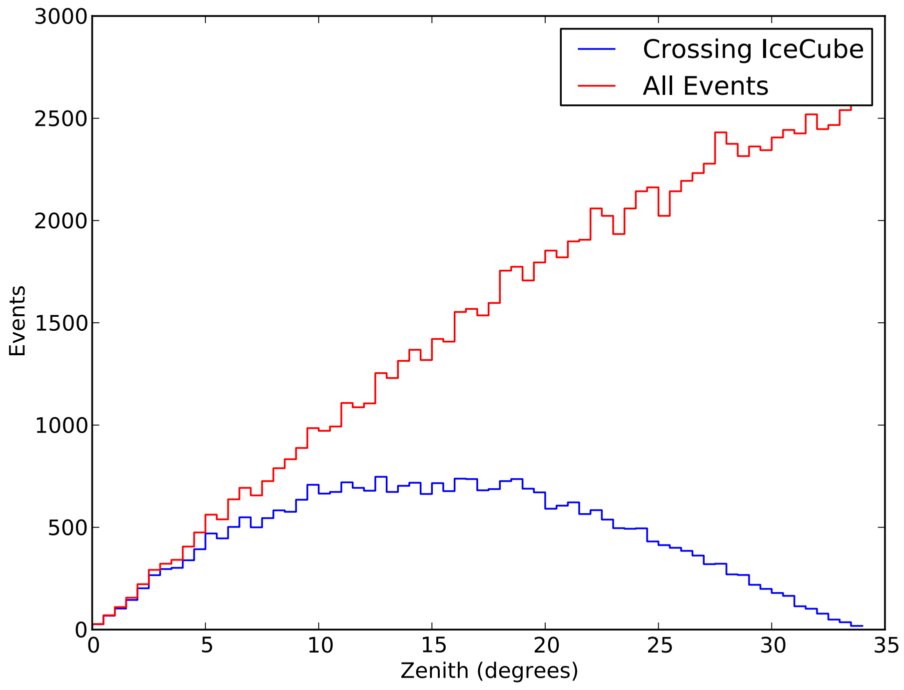
Coincident events

- Zenith angles up to geometric maximum angle of ~35 degrees observed in data sample
- So that shower cores can be distributed uniformly on the surface, by default CORSIKA generates showers with angles sampled according to the projected area of a flat detector

$$\frac{dN}{d\Omega} \propto \cos\theta$$

- However this is very inefficient for coincident events
- Using a simple Monte Carlo, ~2/3 of showers will miss a disk at the top of IceCube



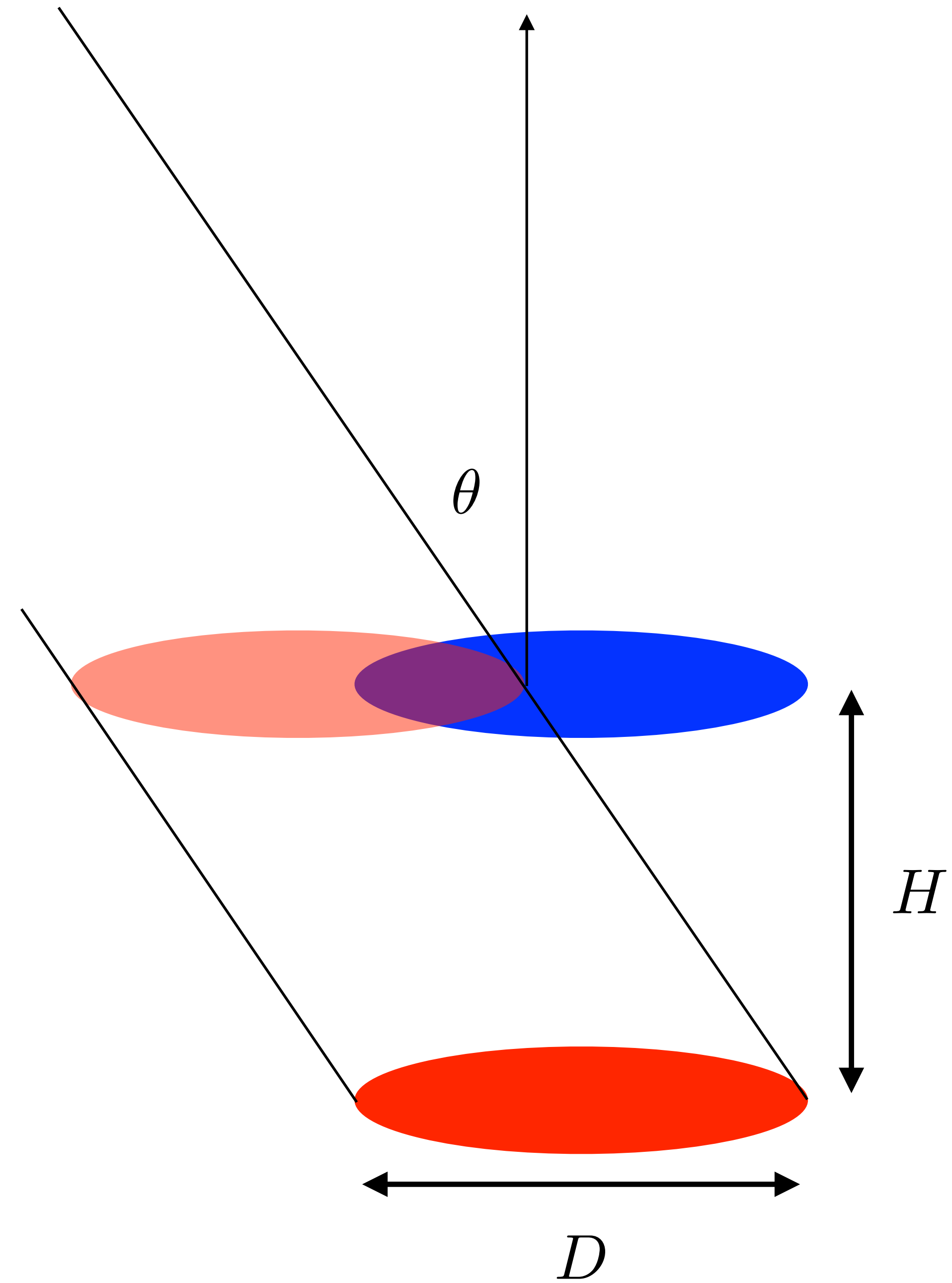


Projected Area Sampling

- Calculate the projected area of the intersection between disks at the surface and at the top of IceCube

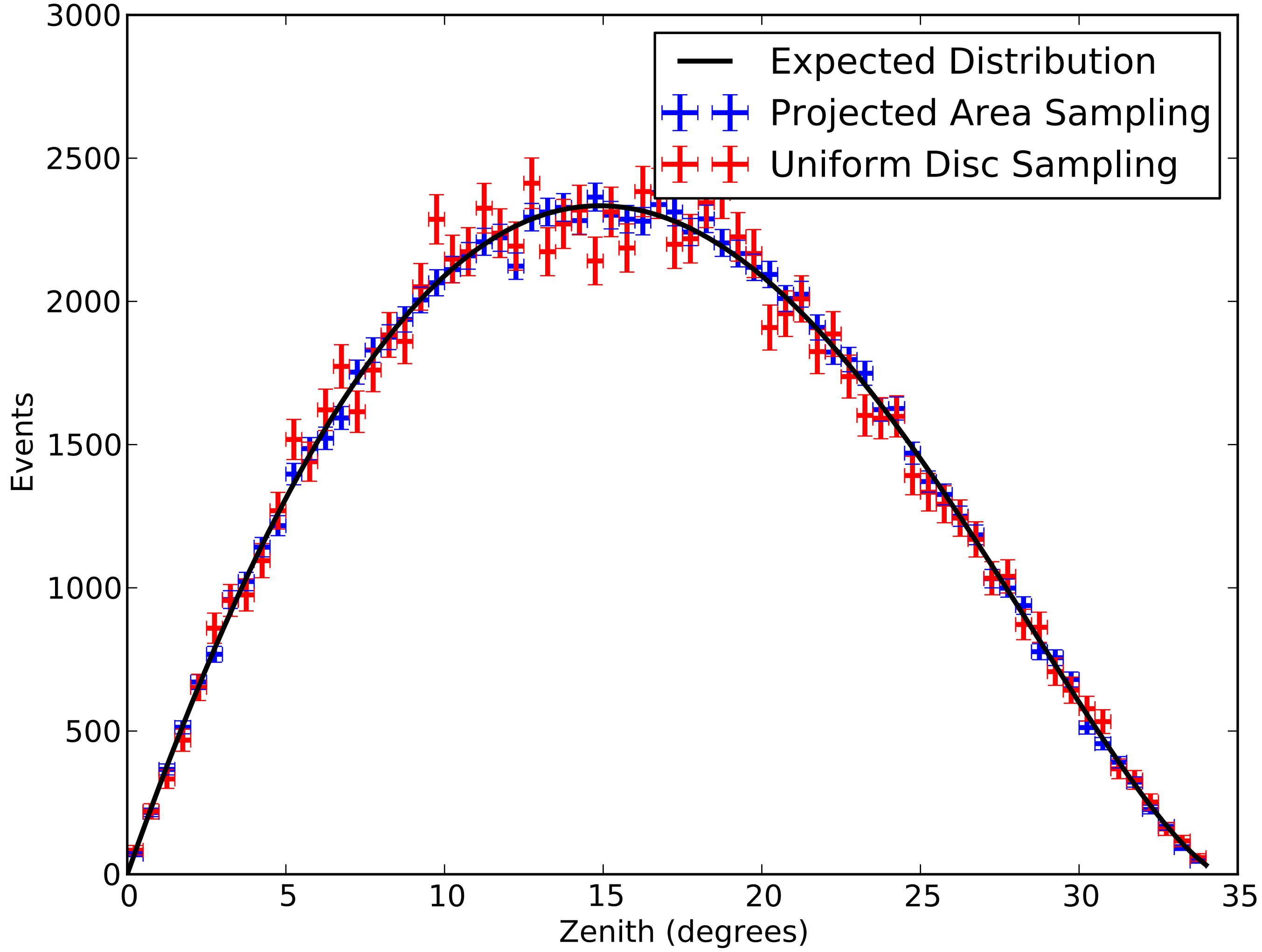
$$\frac{dN}{d\Omega} \propto \frac{1}{2} D^2 \cos\theta \arccos\left(\frac{H}{D}\tan\theta\right) - \frac{1}{2} H D \sin\theta \sqrt{1 - \left(\frac{H}{D}\right)^2 \tan^2\theta}$$

- Modified CORSIKA to sample zenith angles according to this distribution
- Also modified the topsimulator project
  - Use rejection sampling to distribute shower cores on the surface such that they intersect IceCube
  - Handle the EHISTORY option and record production, parent, and grandparent information in the in-ice I3MCTree



Sampling Test

- Analytic formula correctly predicts angular distribution of events crossing disks on the surface and at depth



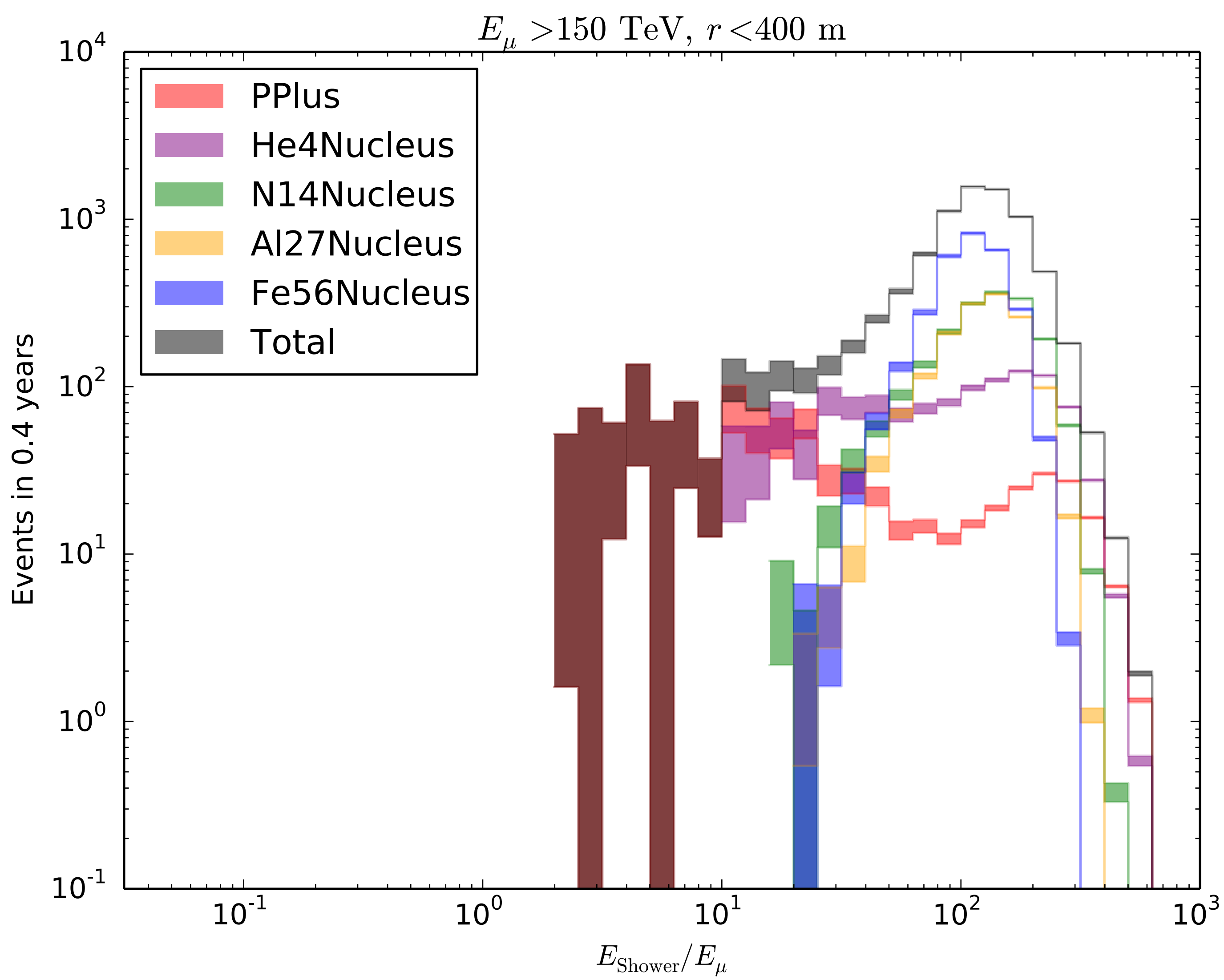
- Uniform disc sampling and projected area sampling give the same results

Simulation

- Scope out the capabilities of the modified CORSIKA with a simplified simulation with no detector response
- Use MC truth variables only:
  - IceTop energy ~ Primary energy - (most energetic muon + neutrino energy)
  - Truncated energy ~ Total bundle energy at detector entrance
- Parameters:
  - Hadronic model: SIBYLL 2.1 (no charm)
  - Energy range: 100 TeV — 100 PeV
  - Zenith range: 0 - 35 degrees
  - H, He, N, Al, Fe primaries weighted to the H3a spectrum
  - Use 150 TeV cut on in-ice muon bundle energy to mimic 5000 PE cut

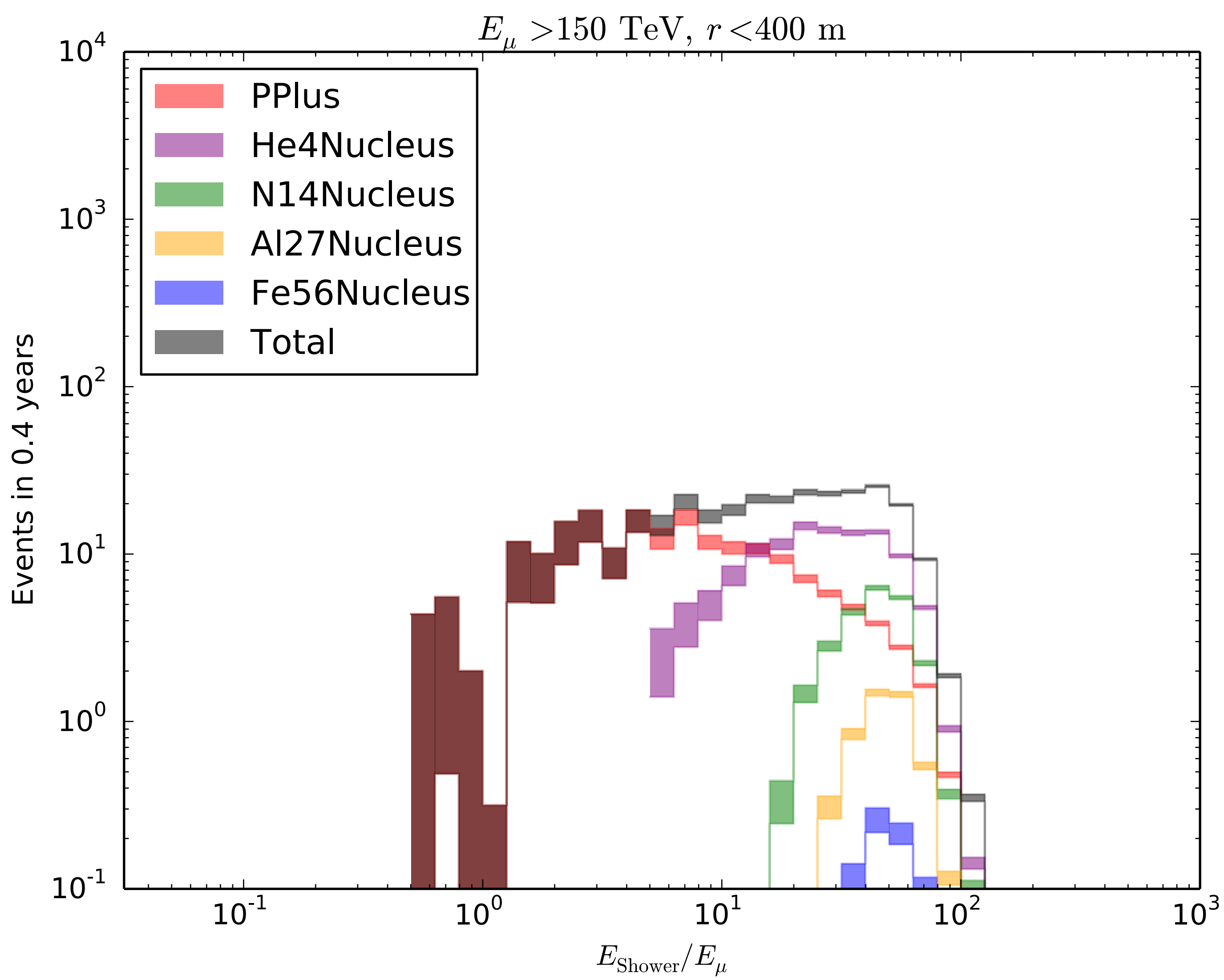
Simulation: no kill threshold

- Simulated 1 million showers per nucleus
- Still can't reach the tail



Simulation: 1% threshold

- Require muon with > 1% of primary energy
- 100 million proton showers generated, 1.7 million survive



Weighting

- How to merge datasets with different kill thresholds?
- Standard Corsika weights:
- $$w = \frac{A_{\text{total}}}{N(E_0)} \Phi_{A,Z}(E_0) \times \text{livetime}$$
- A_{total} = acceptance (integrated area*solid angle) of sampling surface
- $N(E_0)$ = number distribution of simulated events $\int_{E_{\min}}^{E_{\max}} N(E_0) dE_0 = N_{\text{events}}$
- With kill threshold:

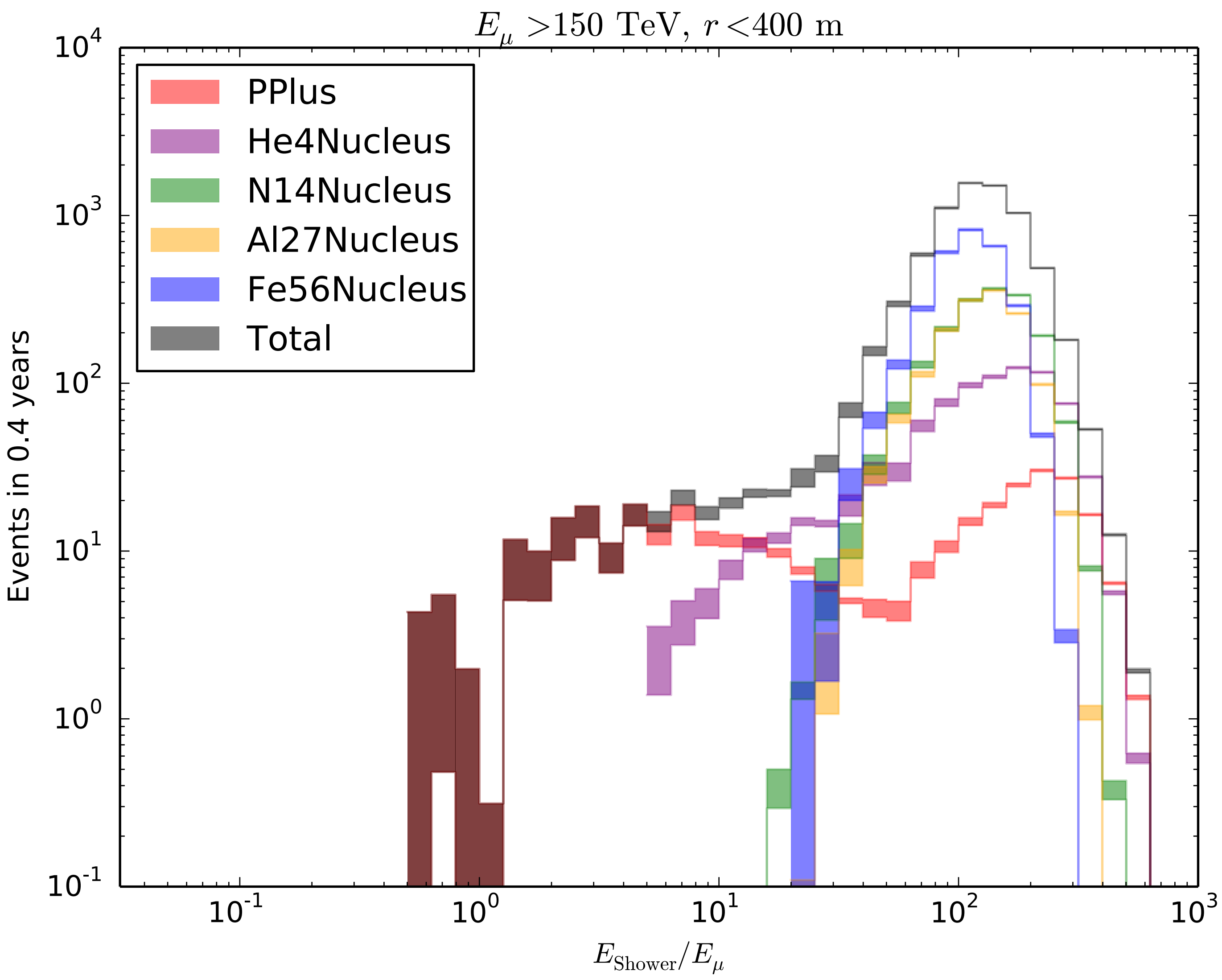
$$N(E_0) = N_{\text{events}} p(E_0) \Theta(E_{\mu,\max} - \text{KCUT})$$

- Combining multiple datasets:

$$N(E_0) = \sum_{j \in \text{datasets}} N_{\text{events},j}\, p_j(E) \Theta(E_{\mu,\max} - \text{KCUT}_j)$$

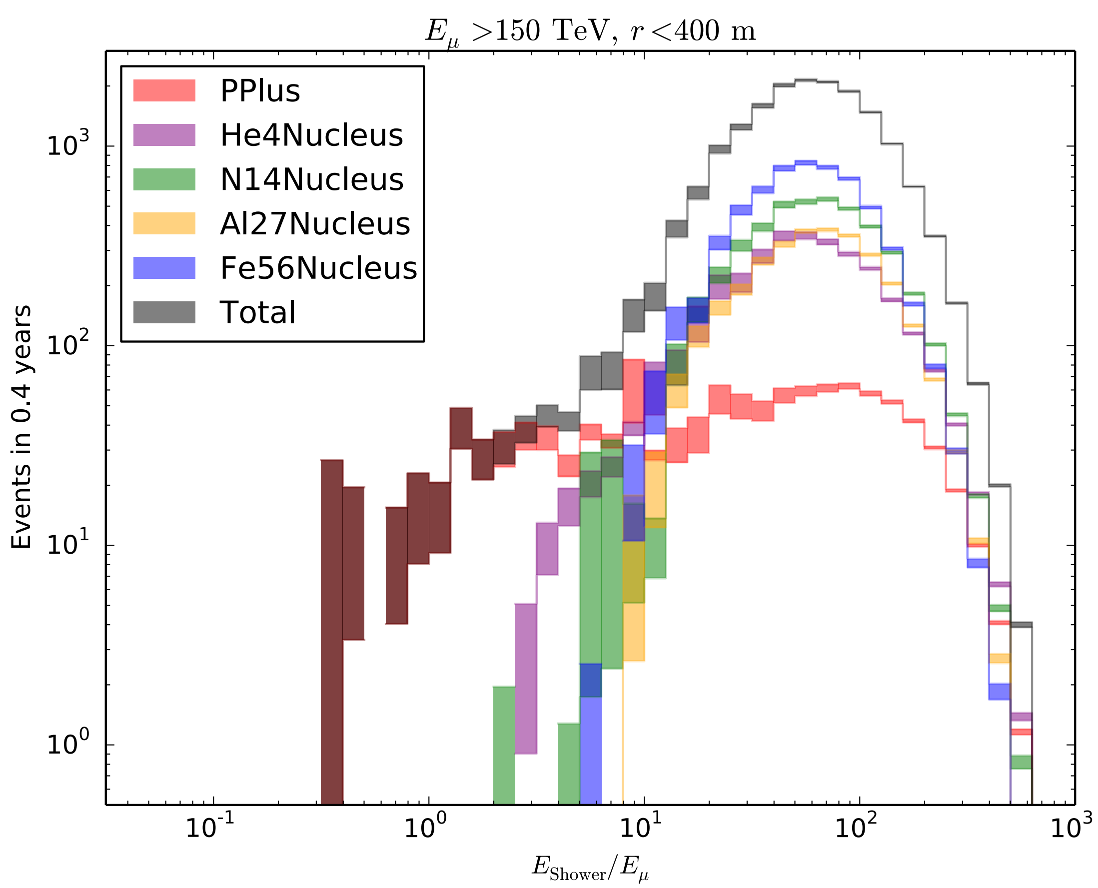
Merging Datasets

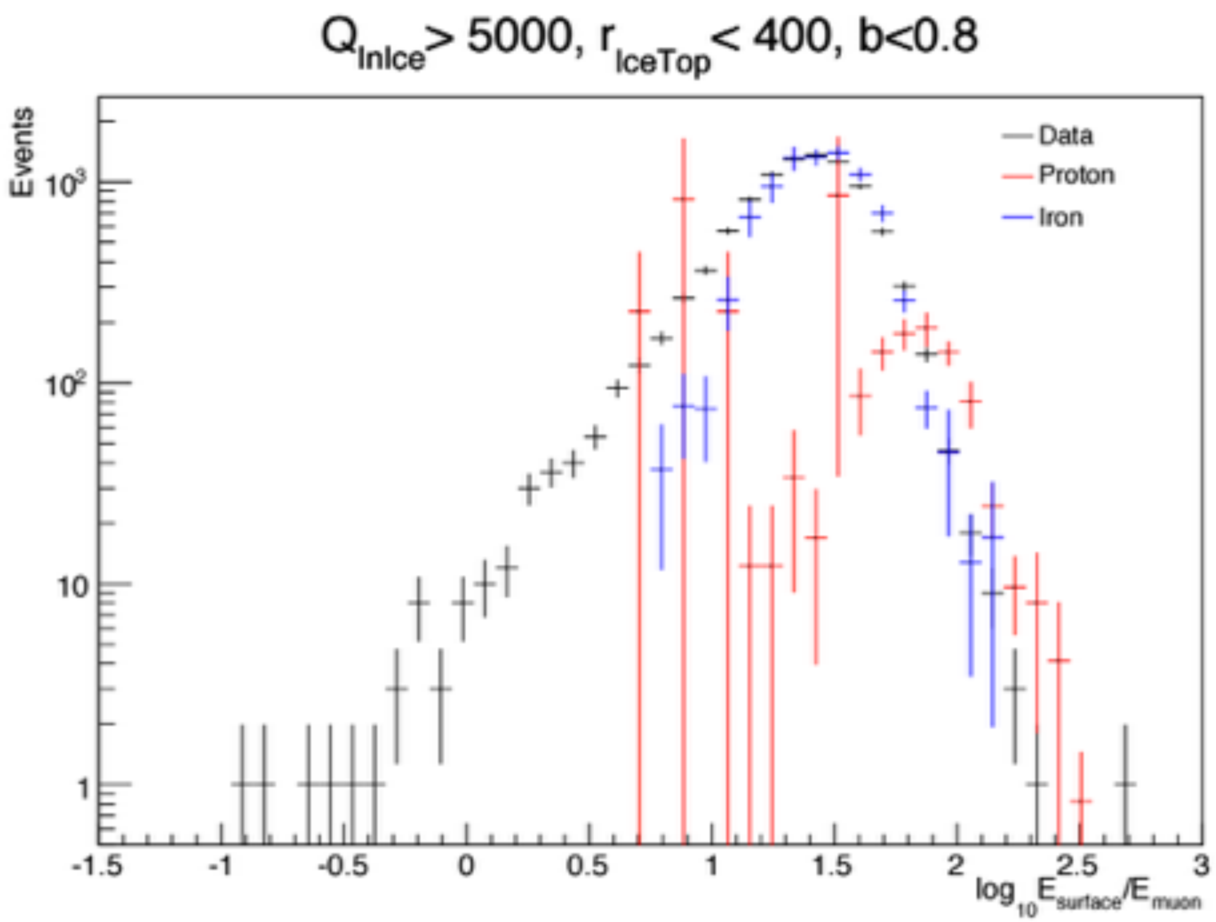
- Can merge datasets to obtain a single prediction across all scales
- Protons dominate tail, iron bundles dominate peak



Comparison to data

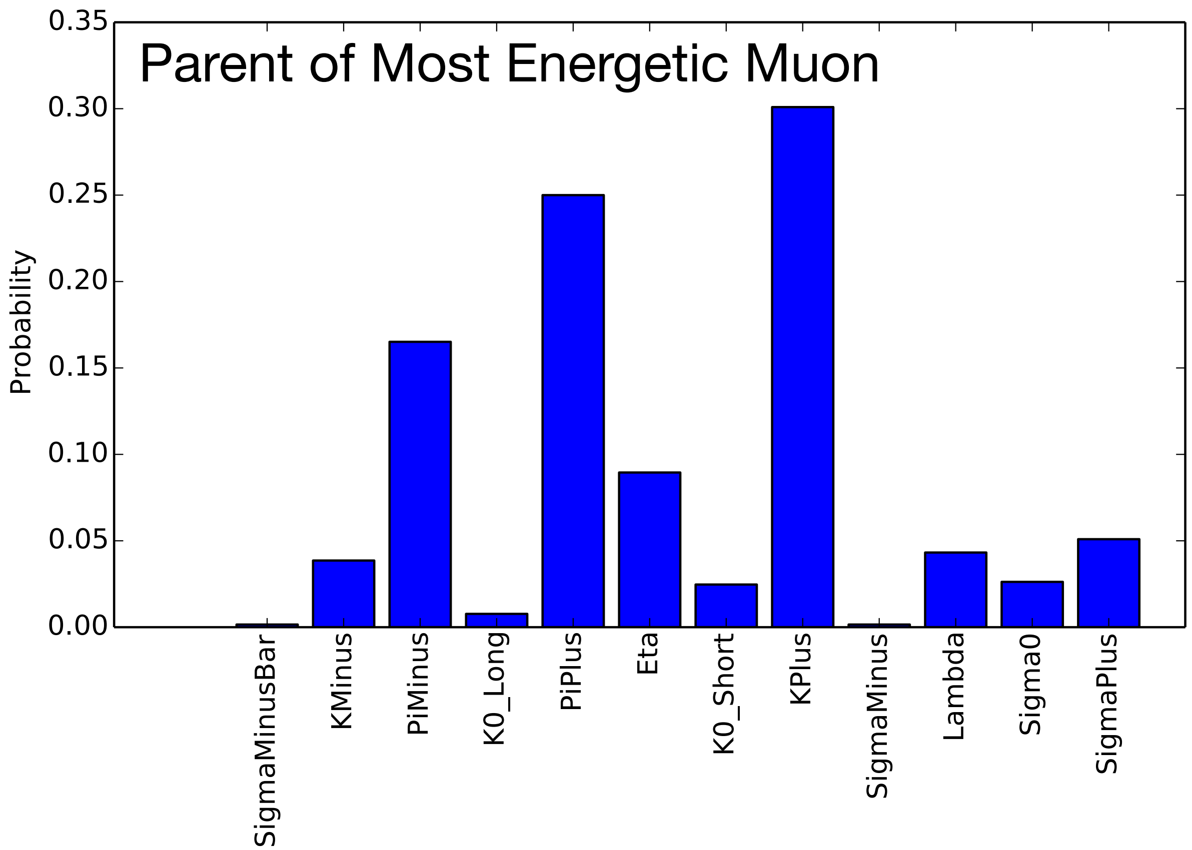
- Crudely jitter in-ice bundle energy by a factor of 2 to mimic Truncated's energy resolution

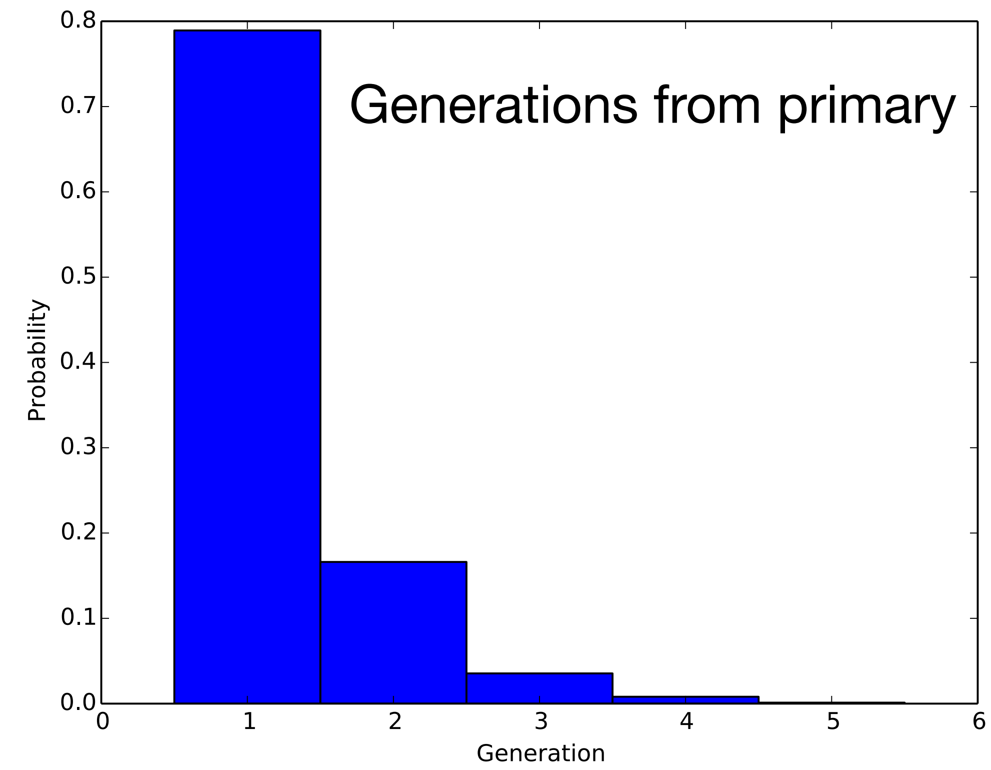


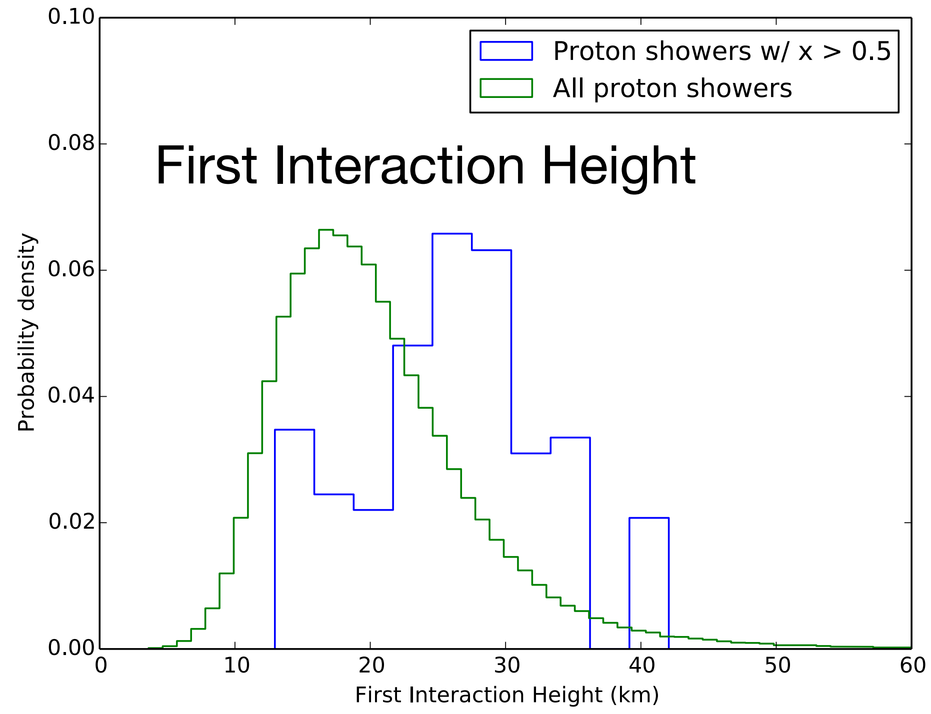


- Detector simulation on the way

Properties of high-x events







- To do: More hadronic models (w/ prompt)

Status and Outlook

- New modifications can greatly increase the efficiency for simulating highly forward muons and IceTop/IceCube coincidences
- Modifications in CORSIKA are preliminary and need to be tested more
- K. Jero and others have independently made very similar developments in CORSIKA
- We will merge our efforts to create an official CORSIKA version useable by everyone
- Large scale simulation production is imminent and would be of general use to many analyses