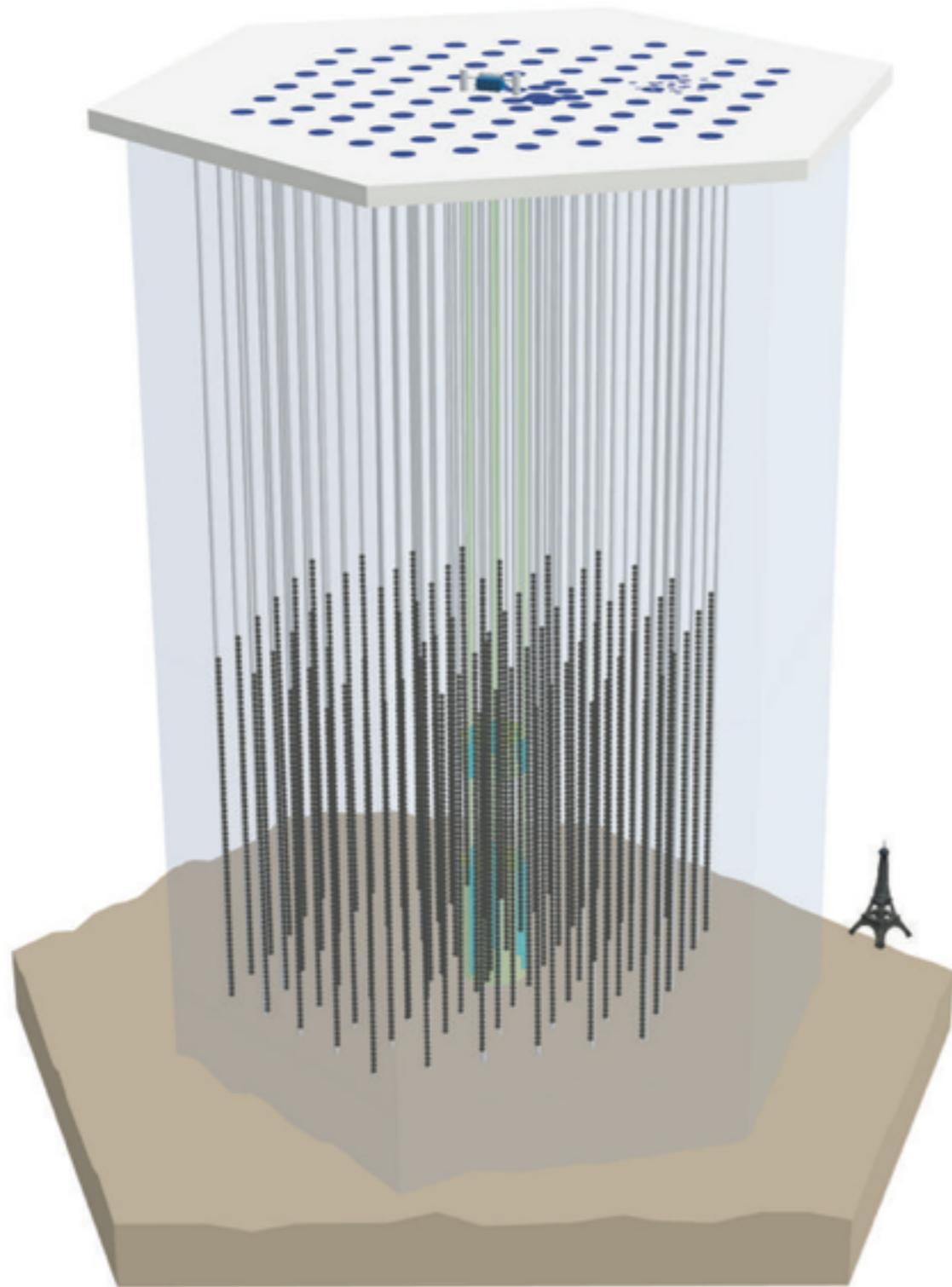


Measuring the flavor ratio of atmospheric neutrinos with IceCube

Jakob van Santen
TAUP 2013, Asilomar



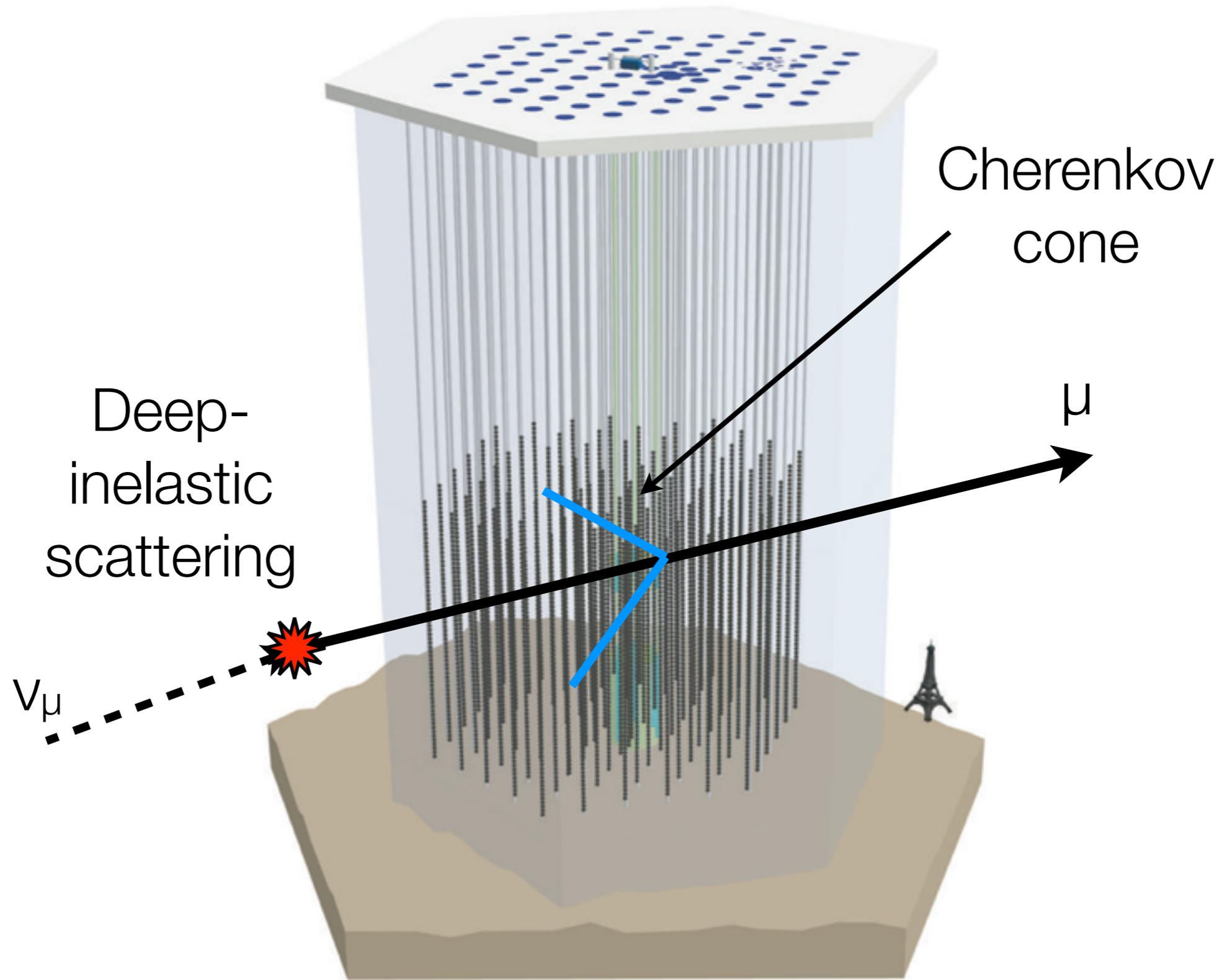
IceCube Neutrino Observatory



Deployed in the deep glacial ice at the South Pole

- ▶ 1 km³ instrumented volume
- ▶ 5160 PMTs
- ▶ 125 m horizontal spacing
- ▶ 17 m vertical spacing
- ▶ Completed in 2010

Detecting neutrinos



Deep-inelastic scattering

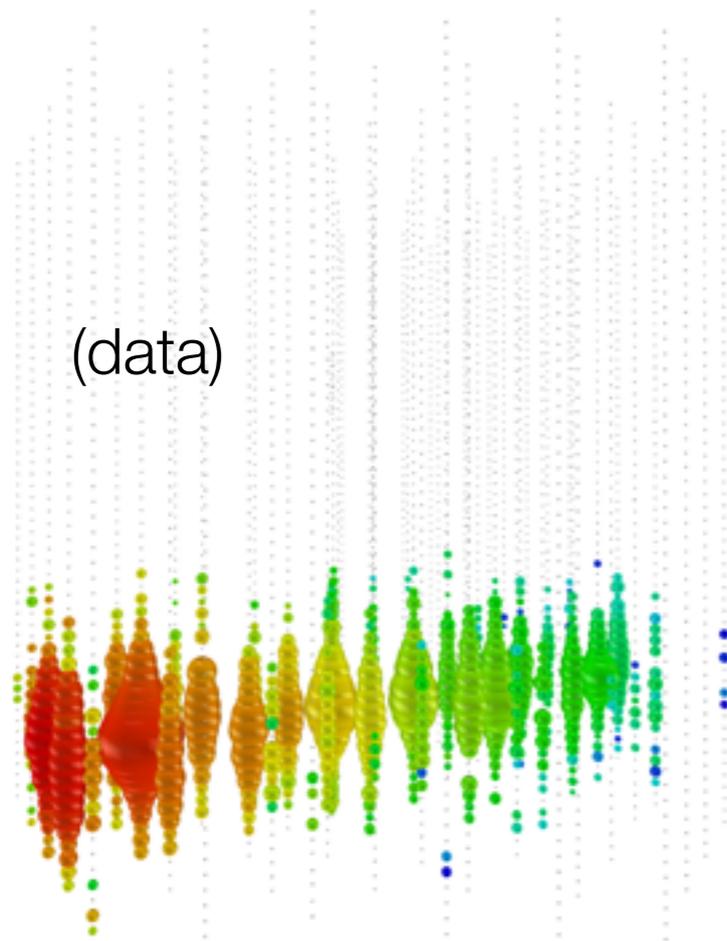
Cherenkov cone

ν_μ

μ

Neutrino event signatures

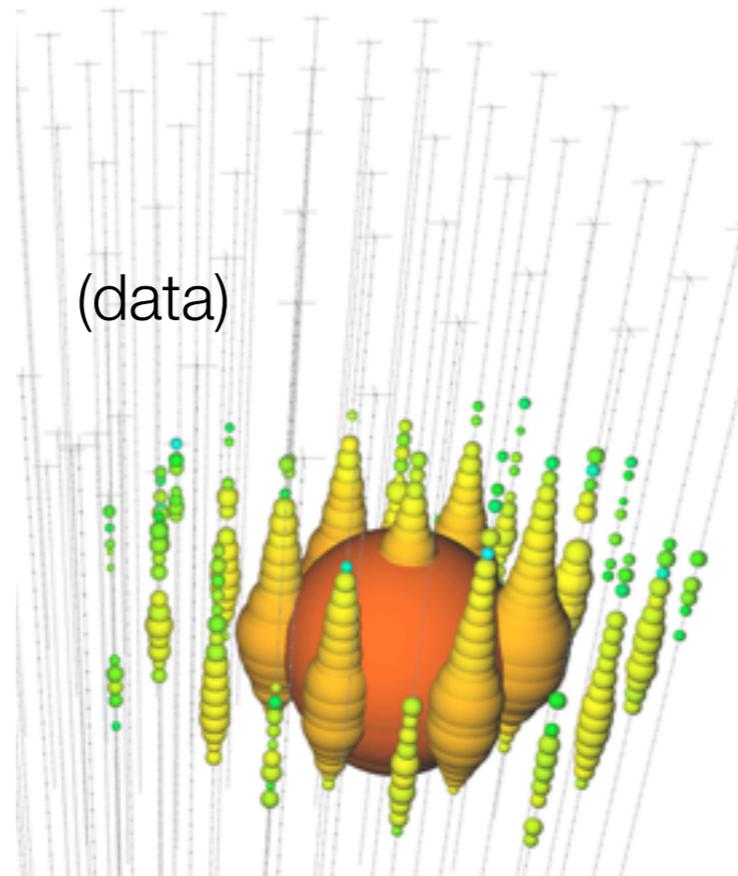
Charged-current ν_μ



Up-going track

Factor of ~ 2 energy resolution
 < 1 degree angular resolution

Neutral-current / ν_e

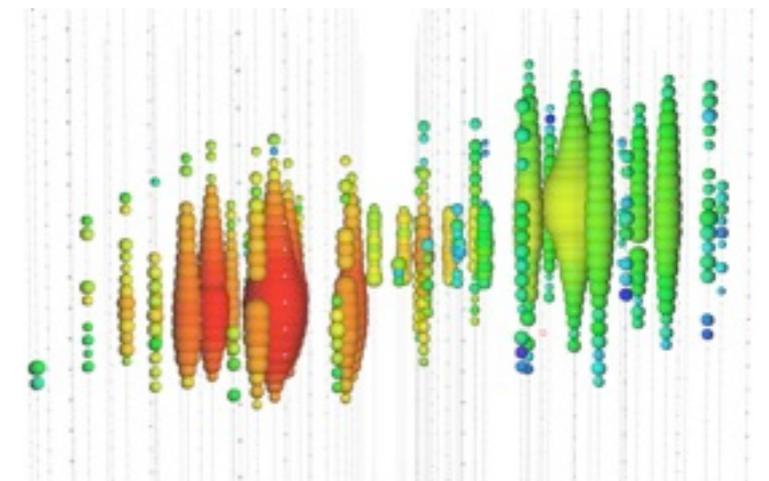


Isolated energy
 deposition (cascade)
 with no track

15% deposited energy resolution
 10 degree angular resolution (above 100 TeV)

Charged-current ν_τ

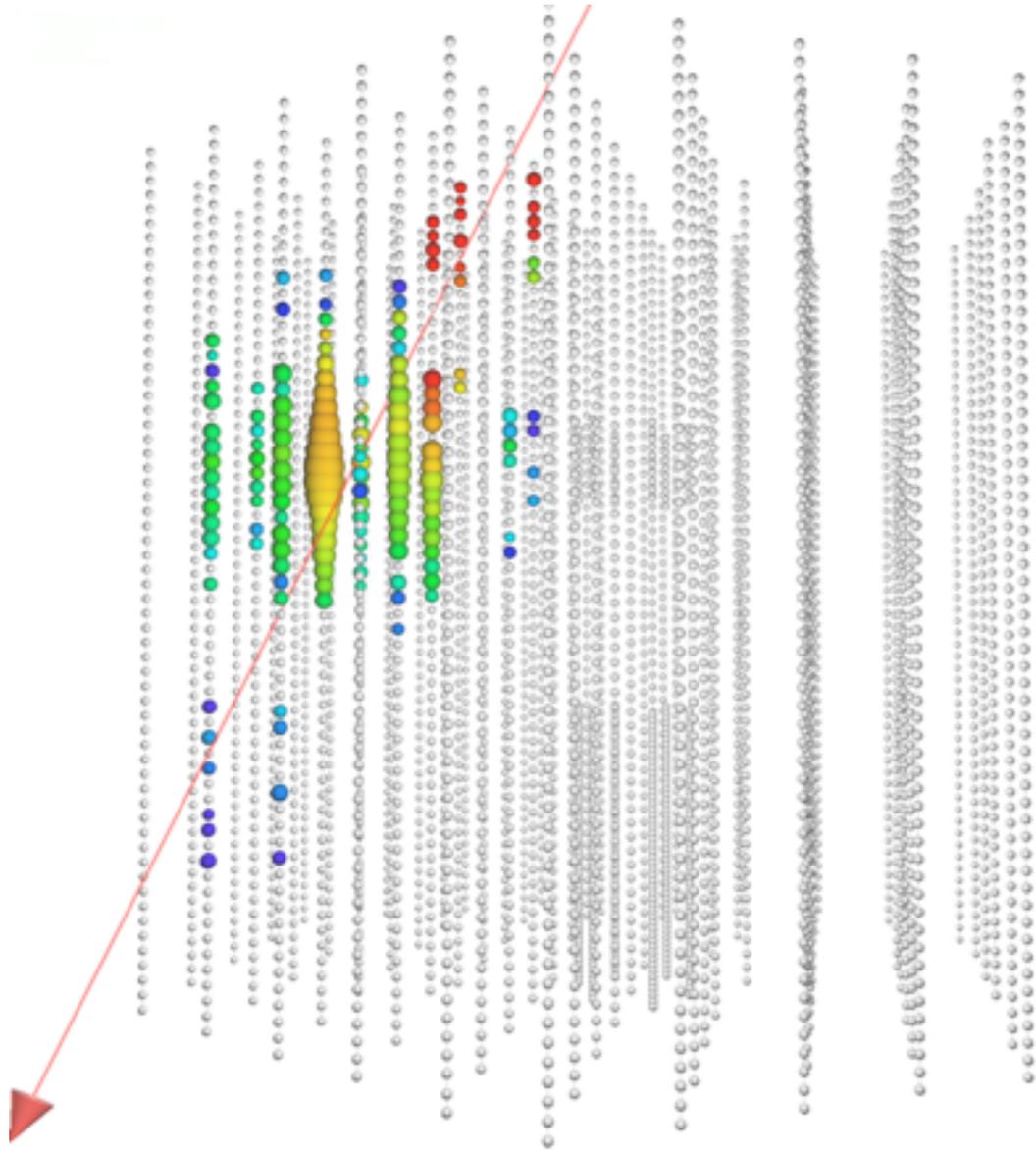
(simulation)



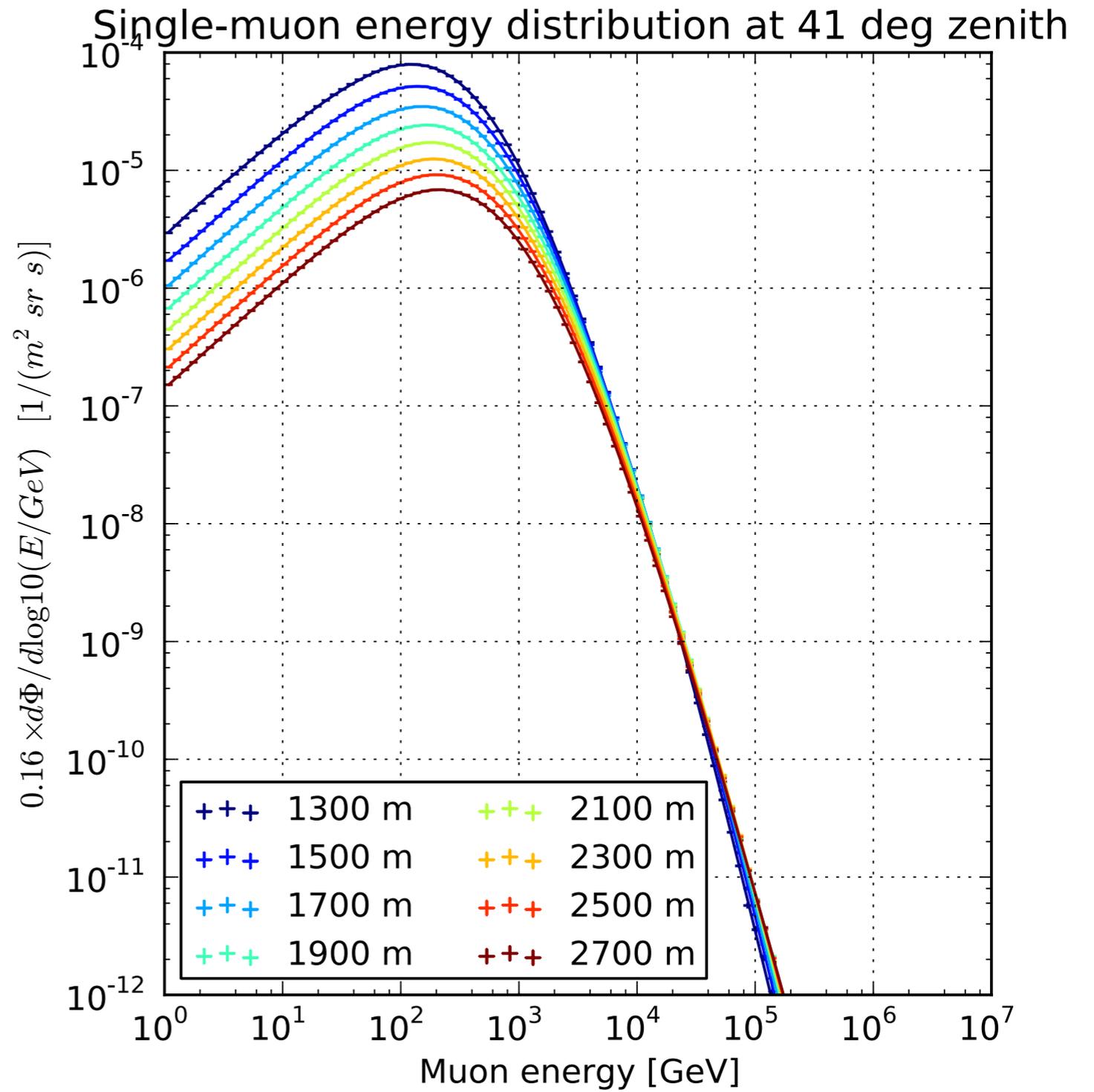
“Double-bang”

(none observed yet)

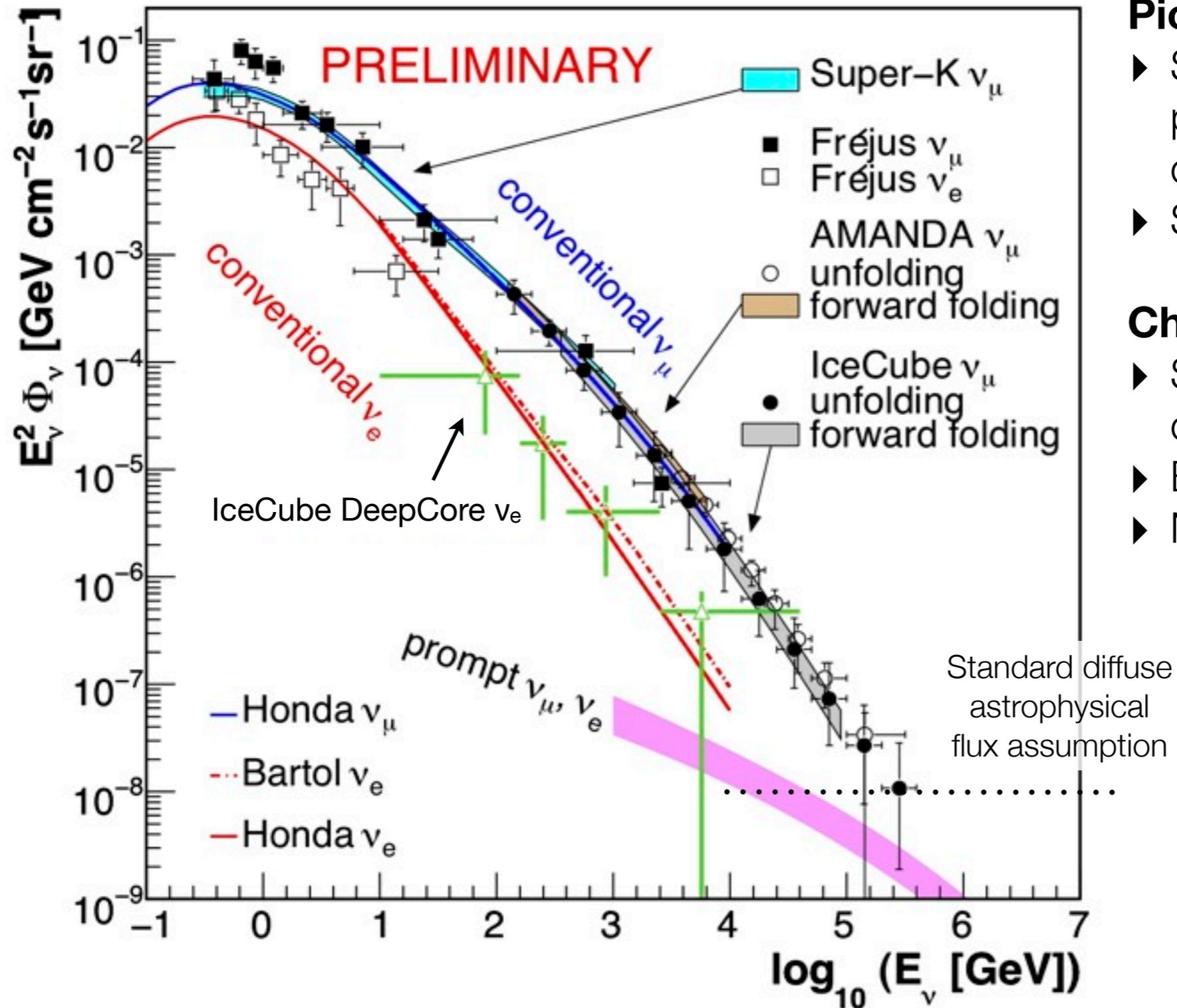
Background: penetrating muons



100 TeV single muon



Atmospheric neutrinos



Pion/kaon component:

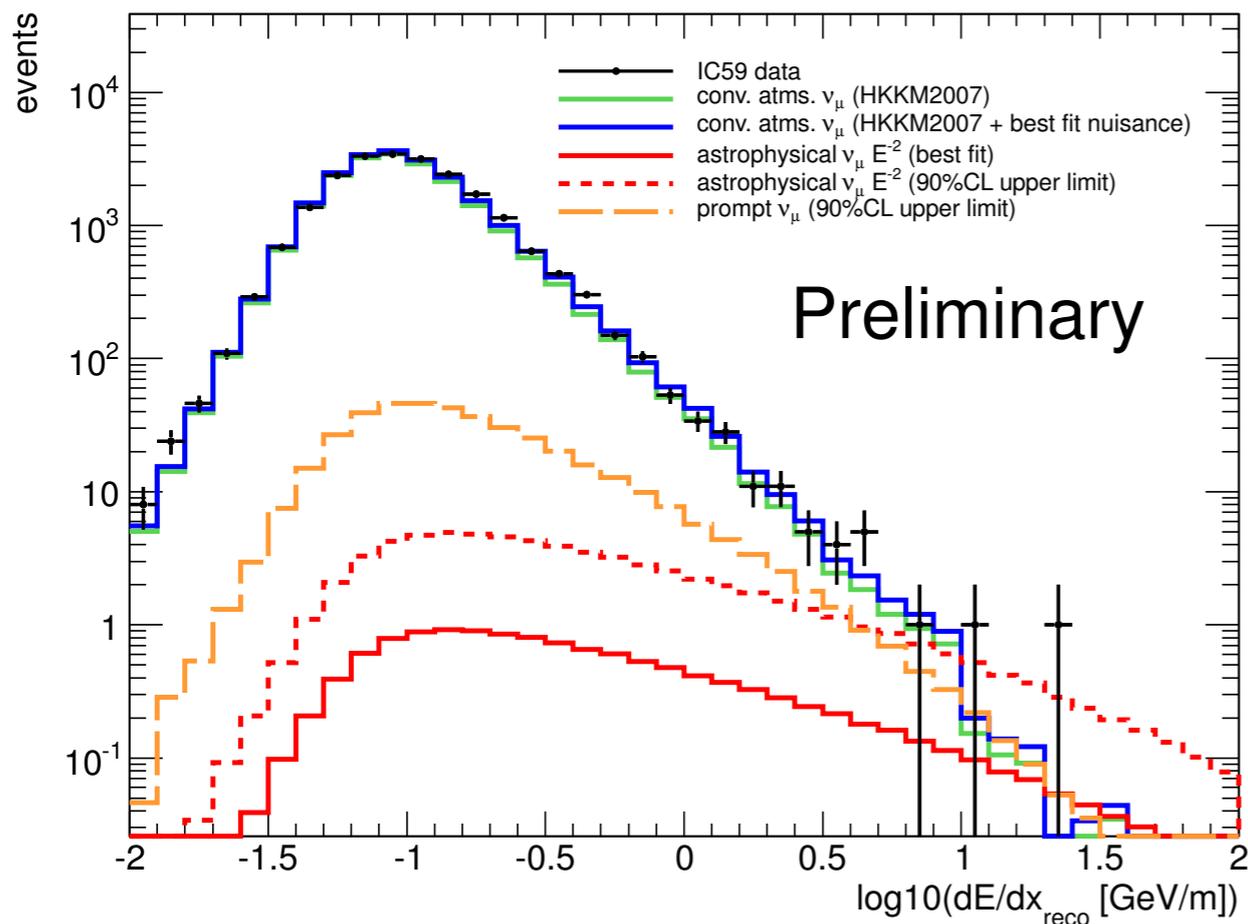
- ▶ Steeply falling spectrum (1 power steeper than primary cosmic rays)
- ▶ Strongly dominated by ν_μ

Charmed meson component:

- ▶ Spectrum should primary cosmic rays
- ▶ Equal parts ν_μ and ν_e
- ▶ Not yet conclusively observed

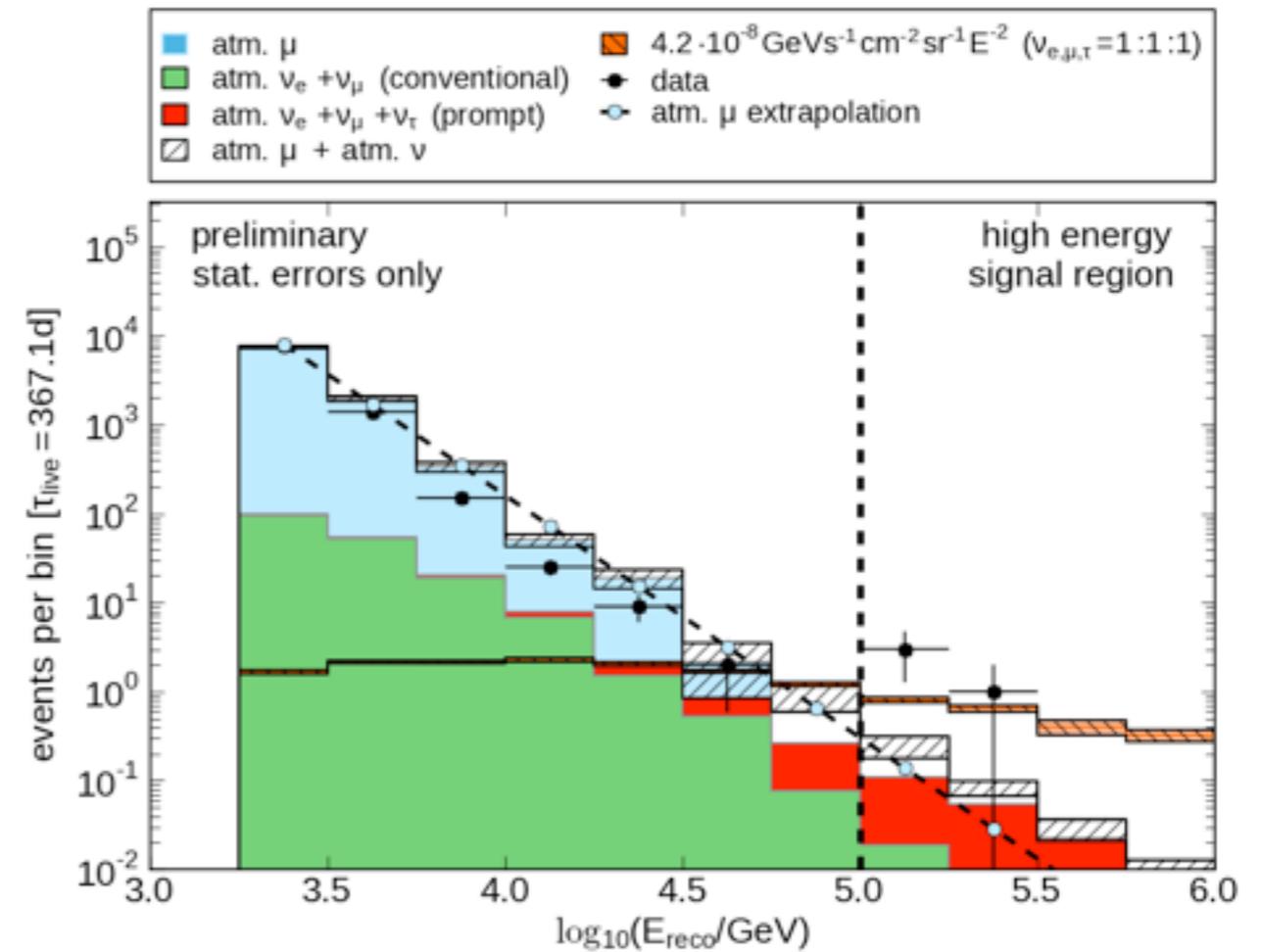
Hints of a high-energy excess

Northern hemisphere ν_μ events in 59-string configuration (2009-2010)



1.8 σ excess over atmospheric expectations

High-energy cascade events in 40-string configuration (2008-2009)

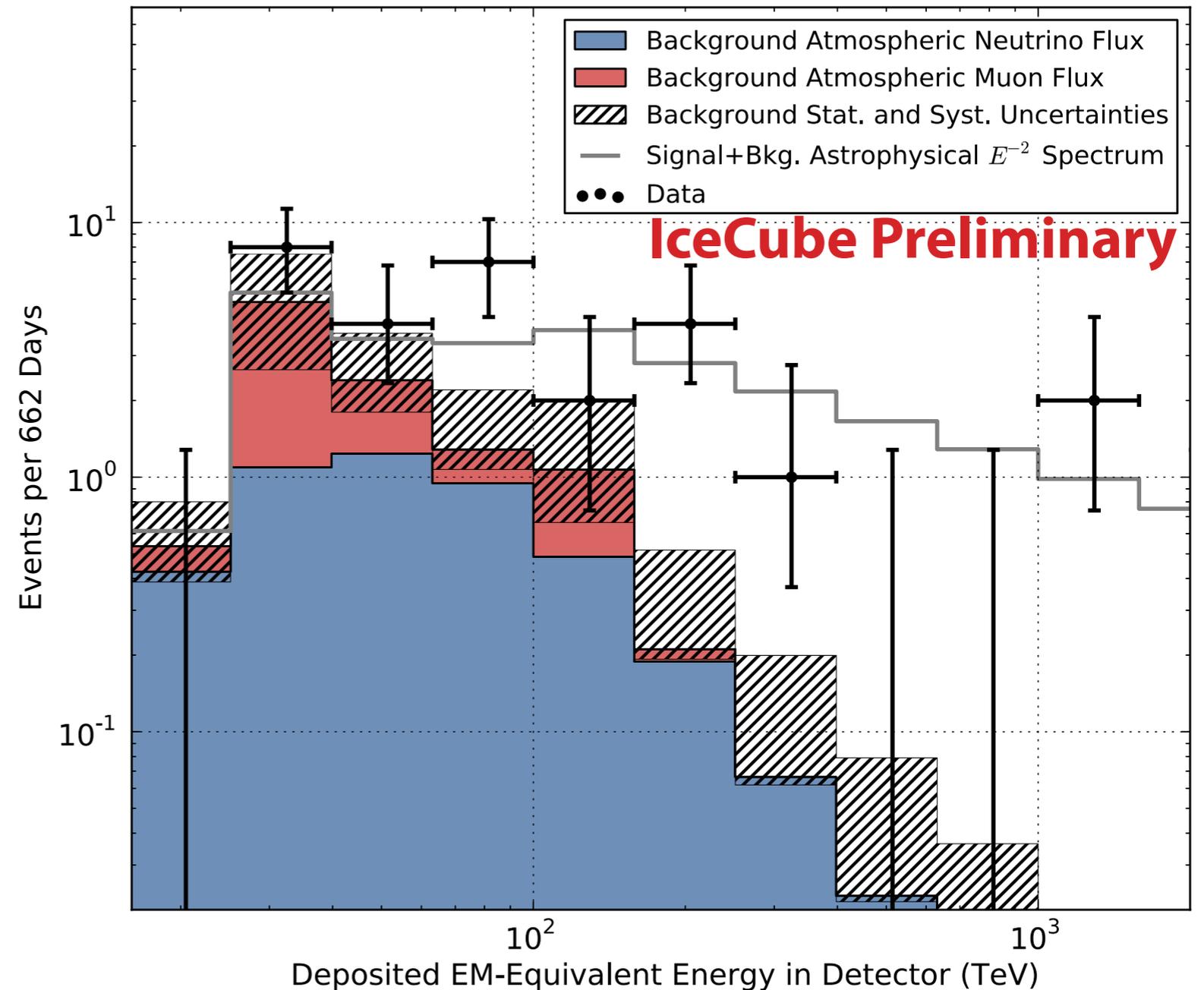


2.4 σ excess over atmospheric expectations

Evidence for a high-energy astrophysical flux

- ▶ 28 events above ~30 TeV observed in two years of data
- ▶ Significant statistical evidence for a high-energy neutrino flux above atmospheric expectations
- ▶ There is a high-energy excess. What more can we learn about it?

High-energy starting neutrino events in nearly-complete and complete detector (2010-2012)



4.1 σ excess over atmospheric expectations
(See talk by C. Kopper later today)

Things you still want to do

Extend to lower energies

to observe transition from atmospheric spectrum to something harder

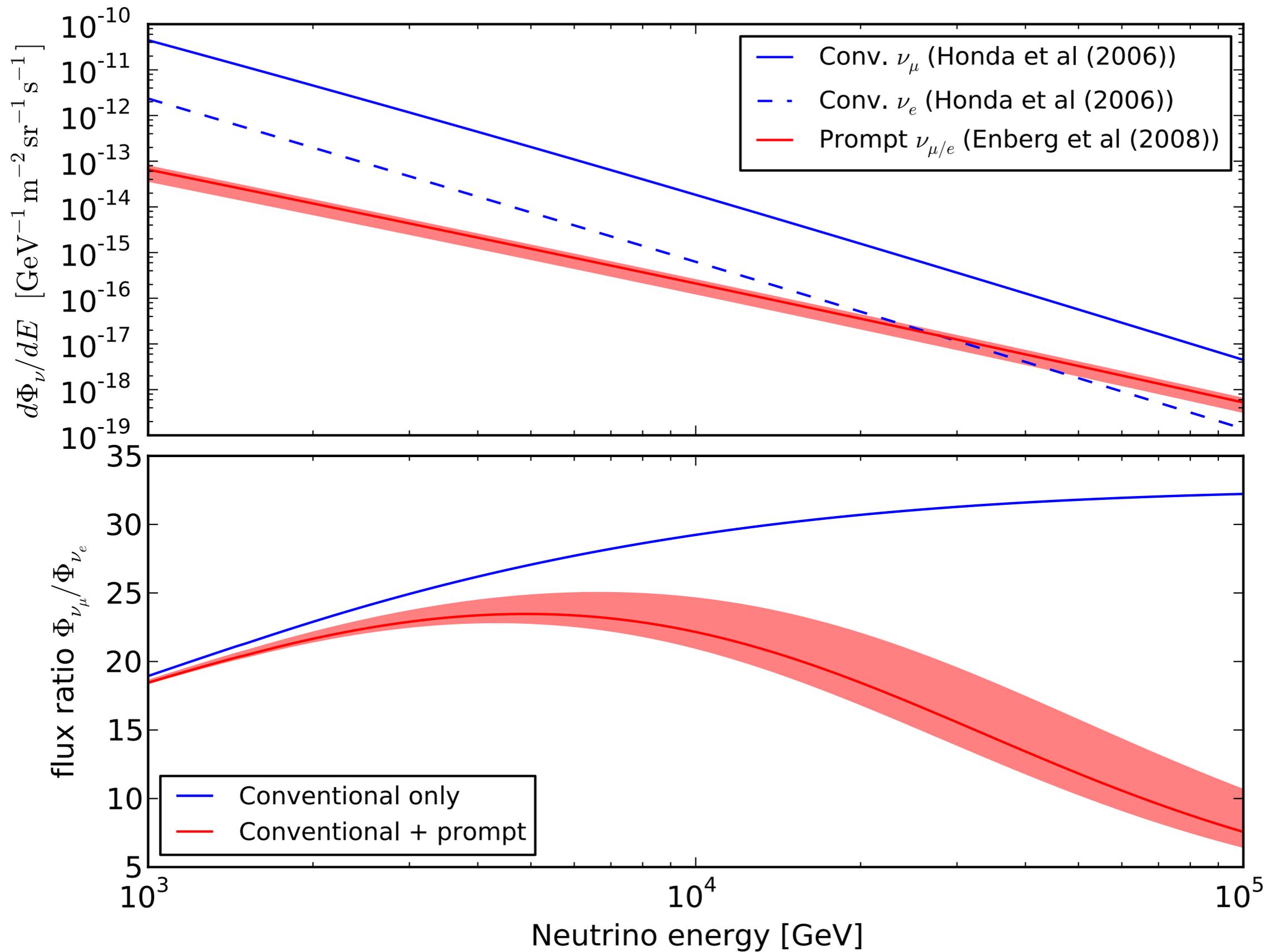
Collect both starting-track and cascade events

to observe the transition from ν_μ -dominance to an equal flavor ratio

Cover both hemispheres

to disentangle atmospheric and extraterrestrial neutrinos

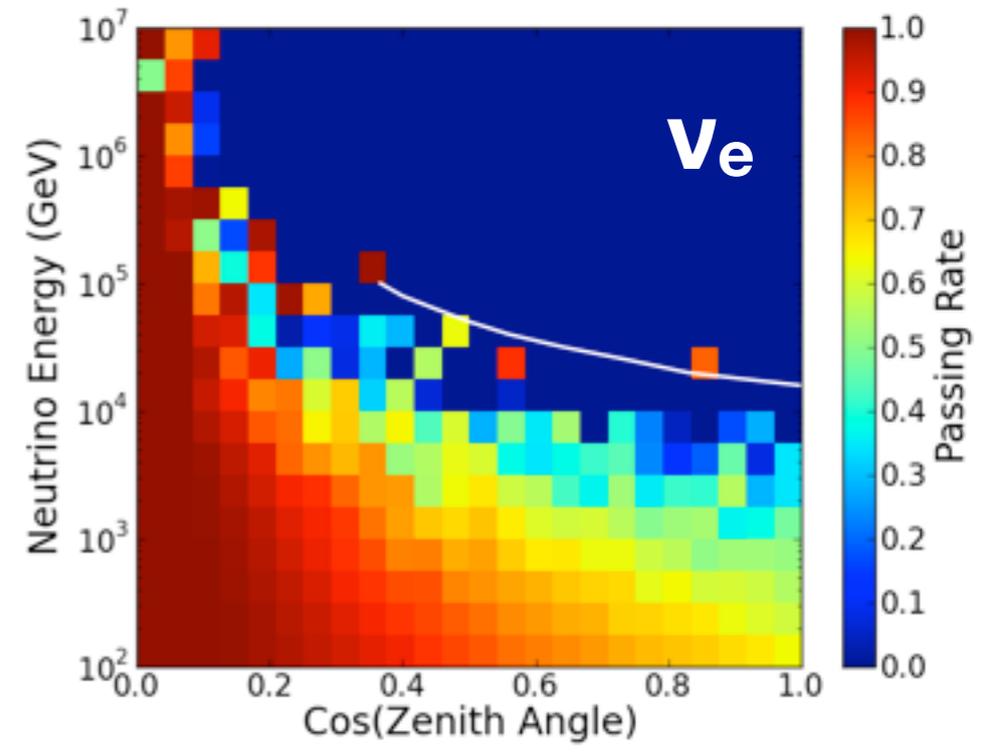
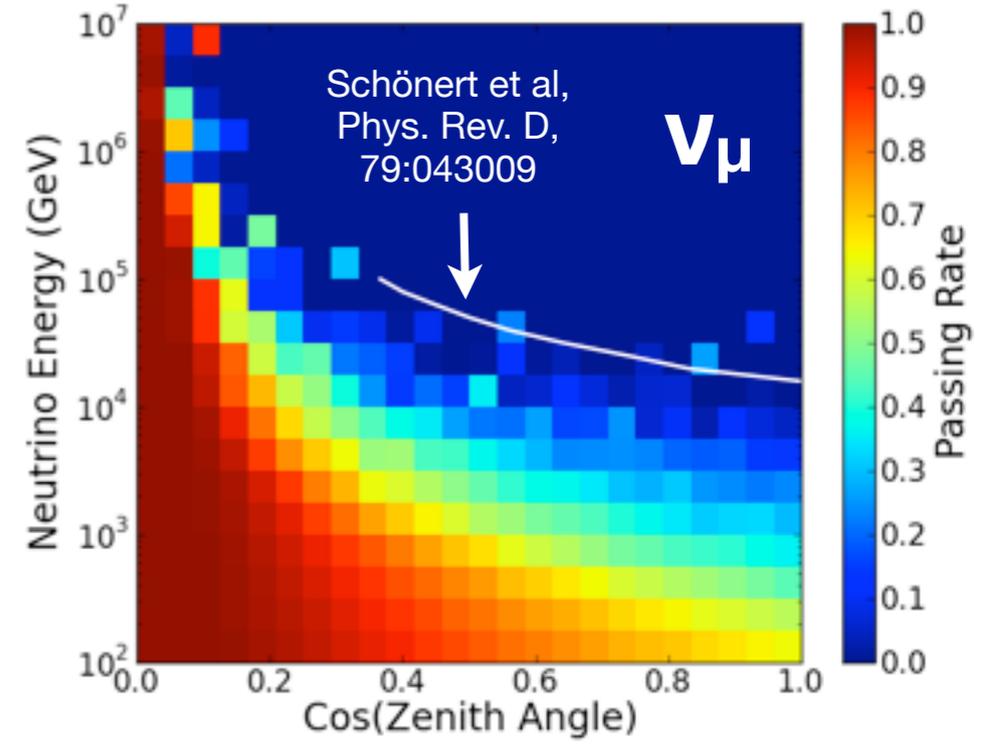
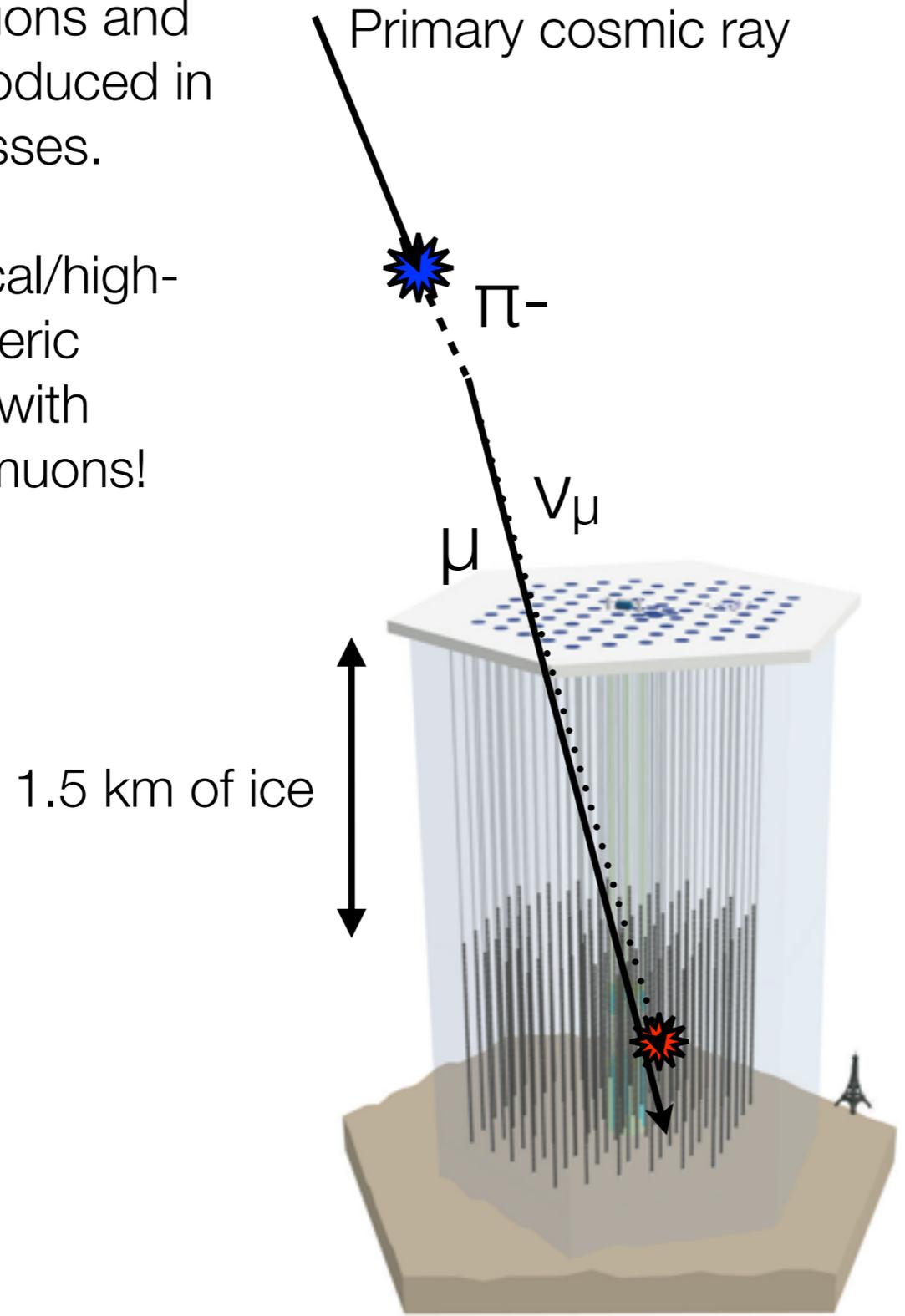
Transition from pion/kaon to charmed meson decay¹⁰



Vetoing down-going atmospheric neutrinos

Atmospheric muons and neutrinos are produced in the same processes.

Sufficiently vertical/high-energy atmospheric neutrinos come with accompanying muons!



Plots courtesy of K. Jero (UW-Madison)

Event selection: starting events

- ▶ Use the outer layer of PMTs (~2400) as an active veto
- ▶ Retain contained neutrino events from both hemispheres
- ▶ Remove penetrating-muon background at high energies (large number of collected photons)

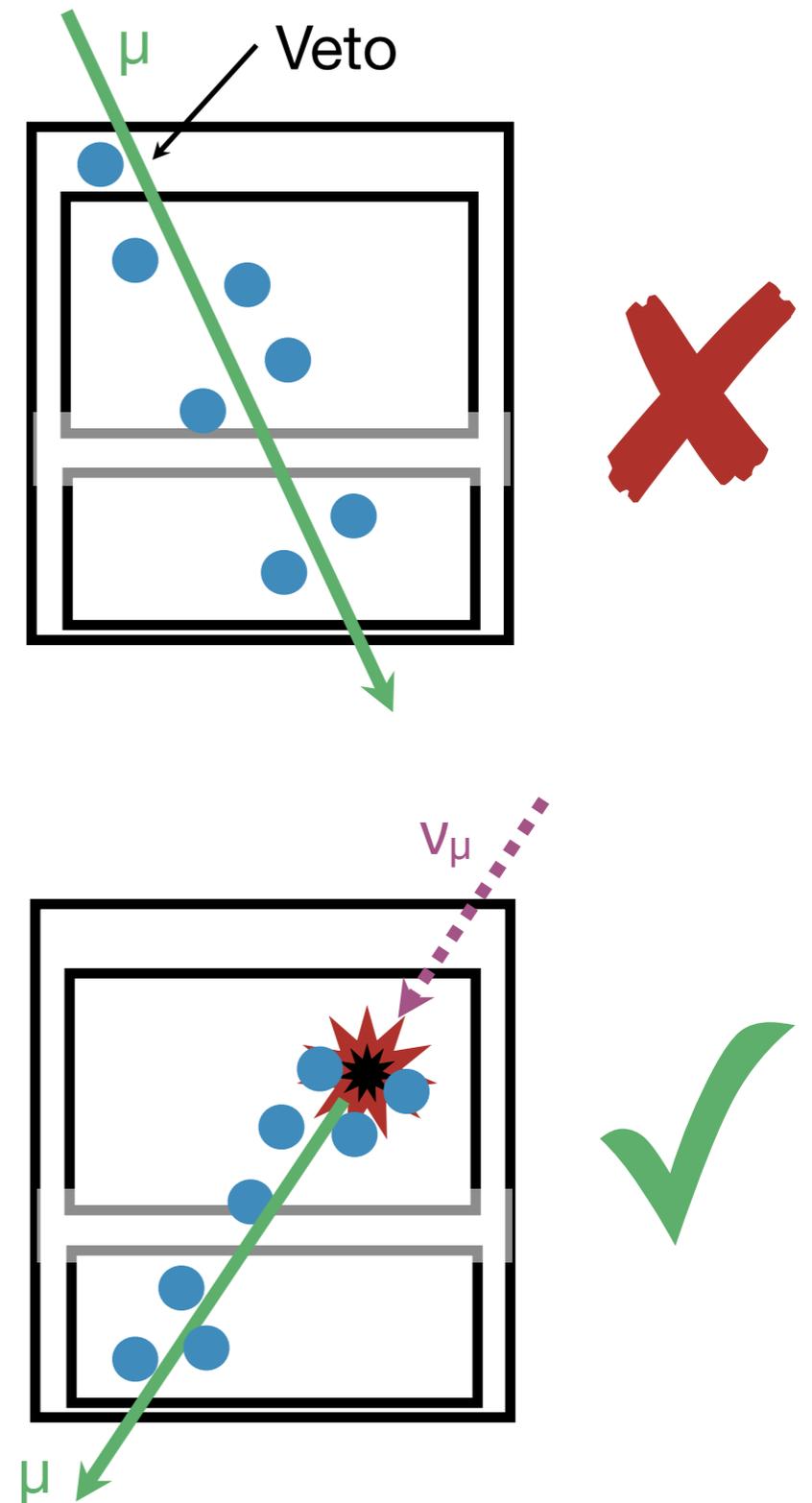
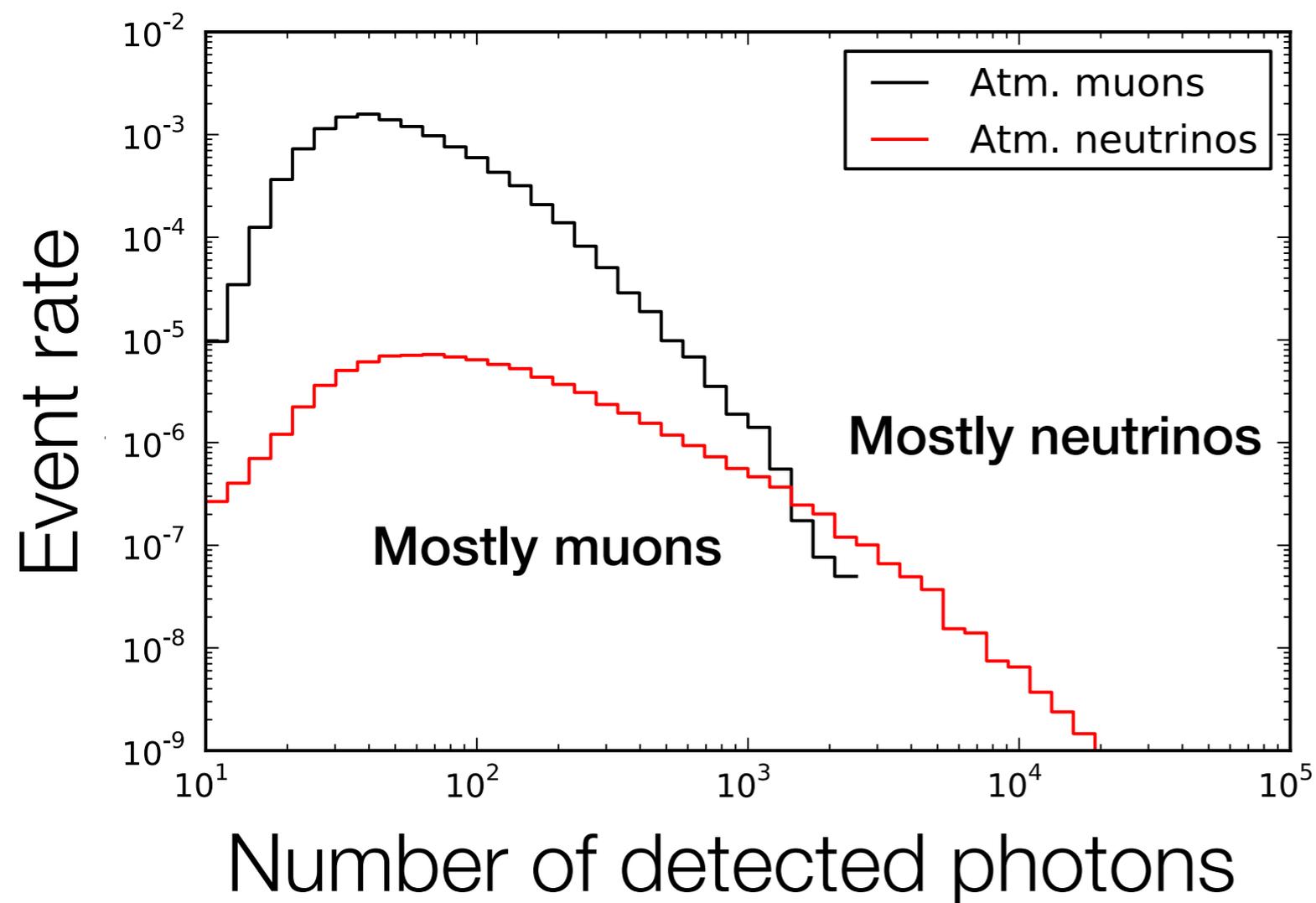
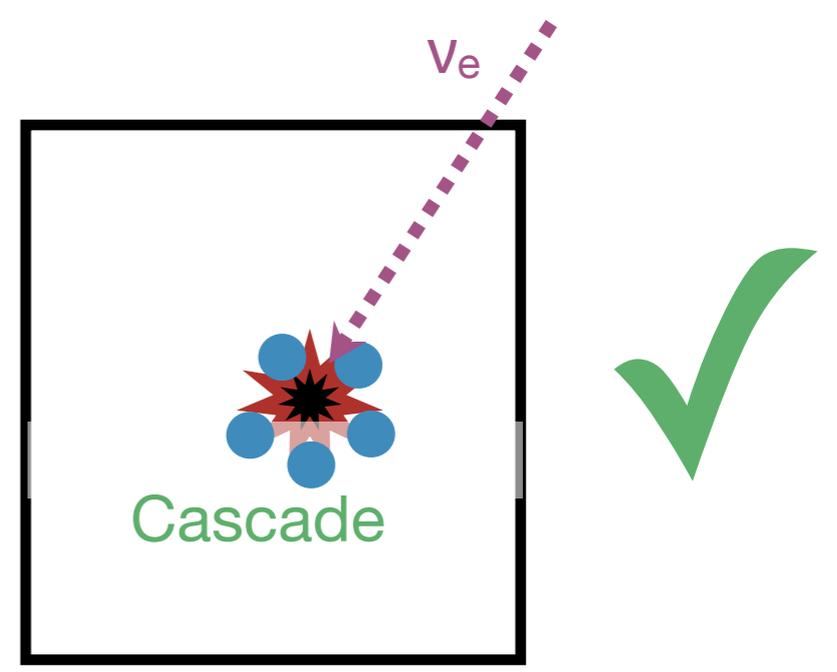
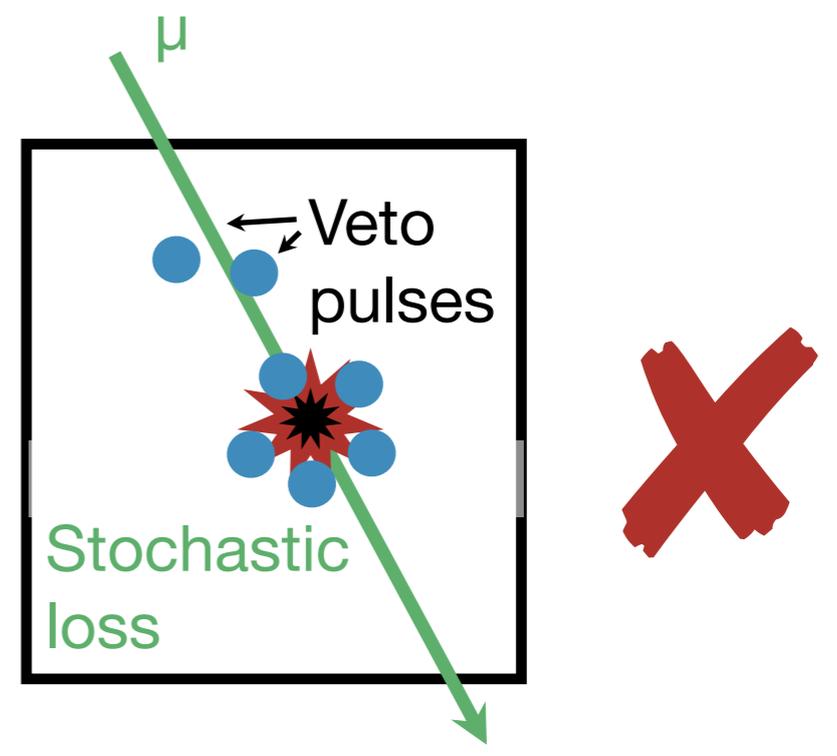
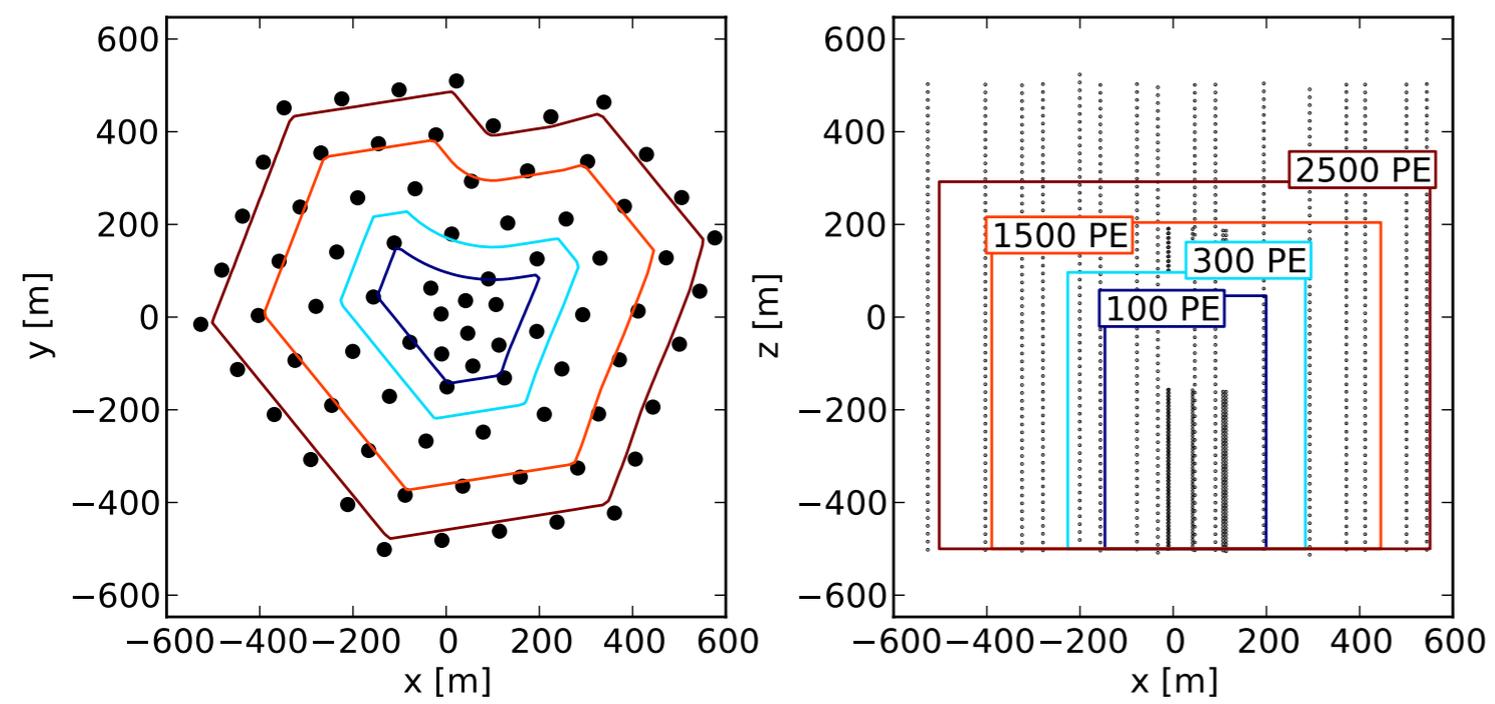


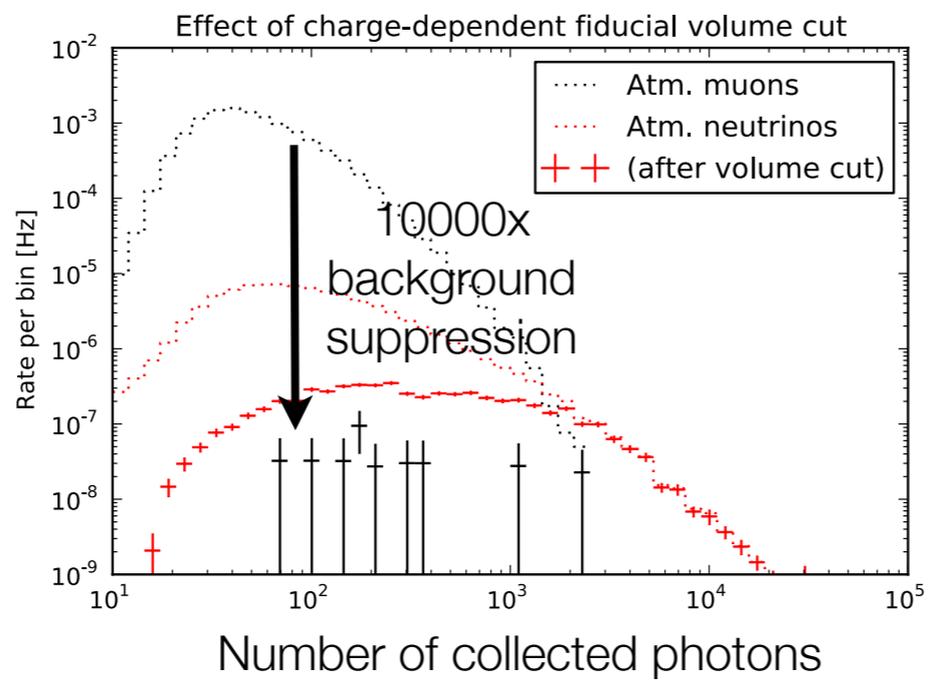
Figure courtesy of C. Kopper (UW-Madison)

Event selection: extending to low energies

- ▶ Search for PMT pulses consistent with a down-going track leading to the event vertex
- ▶ Veto effectiveness scales with number of detected photons and distance from the border of the array



- ▶ Scale fiducial volume with photon count to maintain nearly pure neutrino sample at low energies

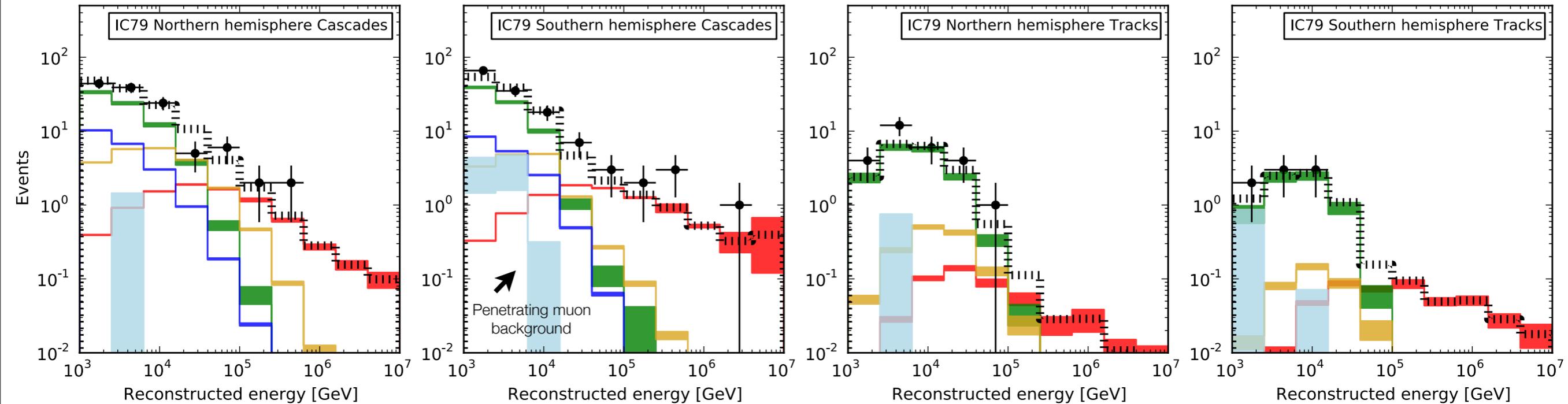


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Analysis principle

Monte Carlo realization

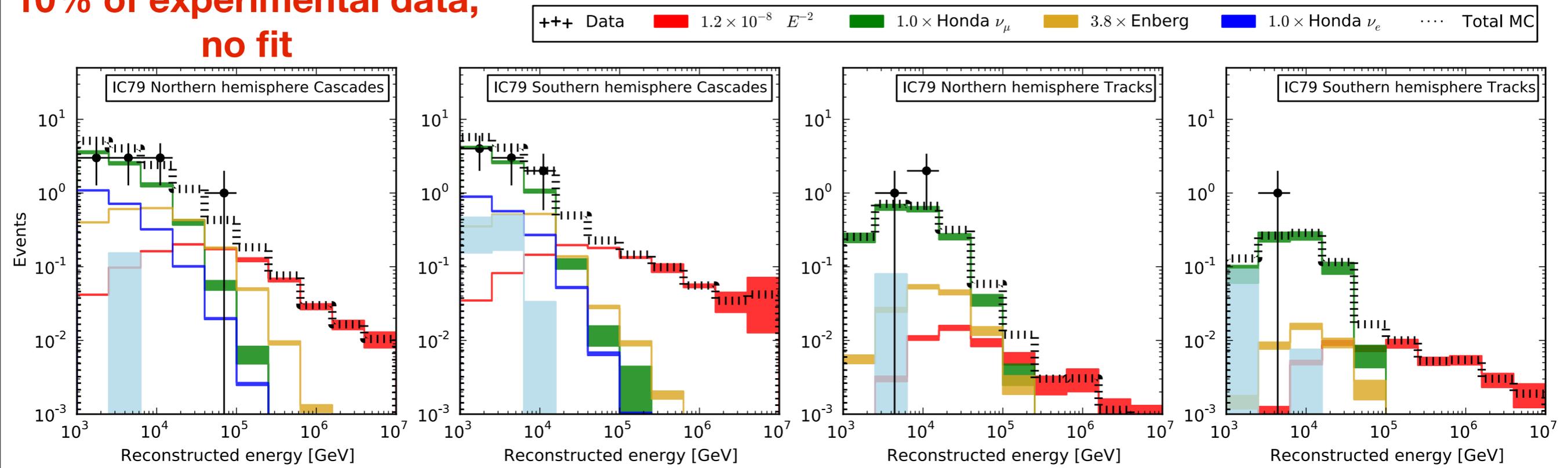
+++ Data $1.2 \times 10^{-8} E^{-2}$ $1.0 \times$ Honda ν_μ $3.8 \times$ Enberg $1.0 \times$ Honda ν_e ... Total MC



- ▶ Observable: distribution of deposited energies
- ▶ Divide sample into tracks/cascades, northern/southern hemisphere
- ▶ < 10 TeV constrains conventional atmospheric contribution
- ▶ 10-50 TeV constrains onset of a component from charmed meson decays
- ▶ Track/cascade split constrains flavor ratio
- ▶ North/south split weakens degeneracy between hard atmospheric component and astrophysical flux

Analysis principle

**10% of experimental data,
no fit**



- ▶ Observable: distribution of deposited energies
- ▶ Divide sample into tracks/cascades, northern/southern hemisphere
- ▶ < 10 TeV constrains conventional atmospheric contribution
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Contained-vertex events in IceCube allow:

Full sky coverage

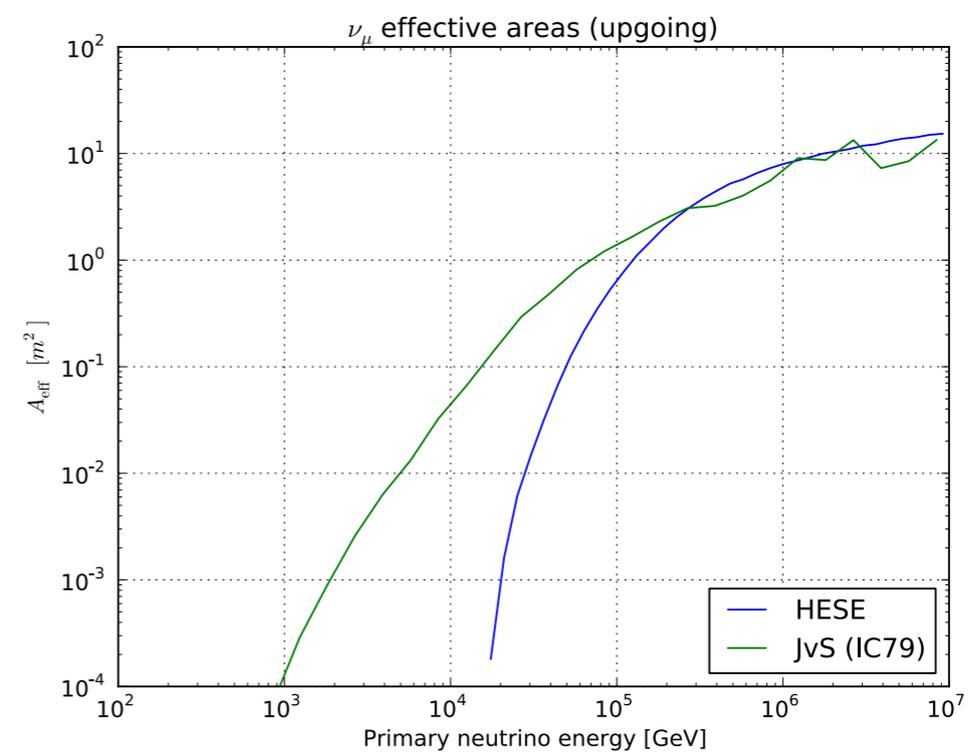
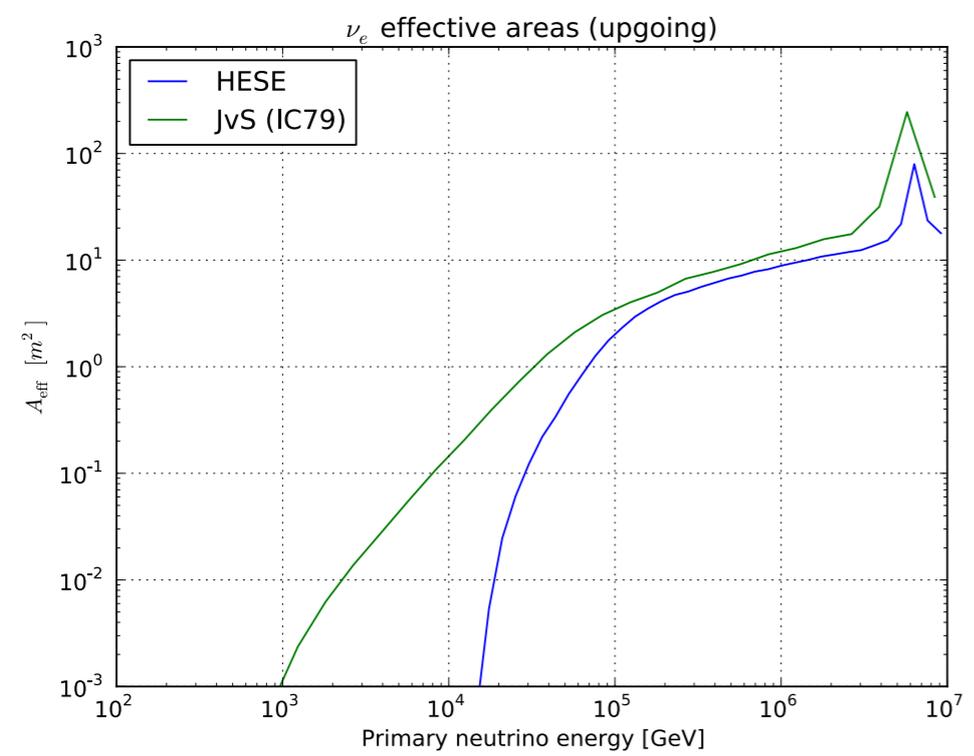
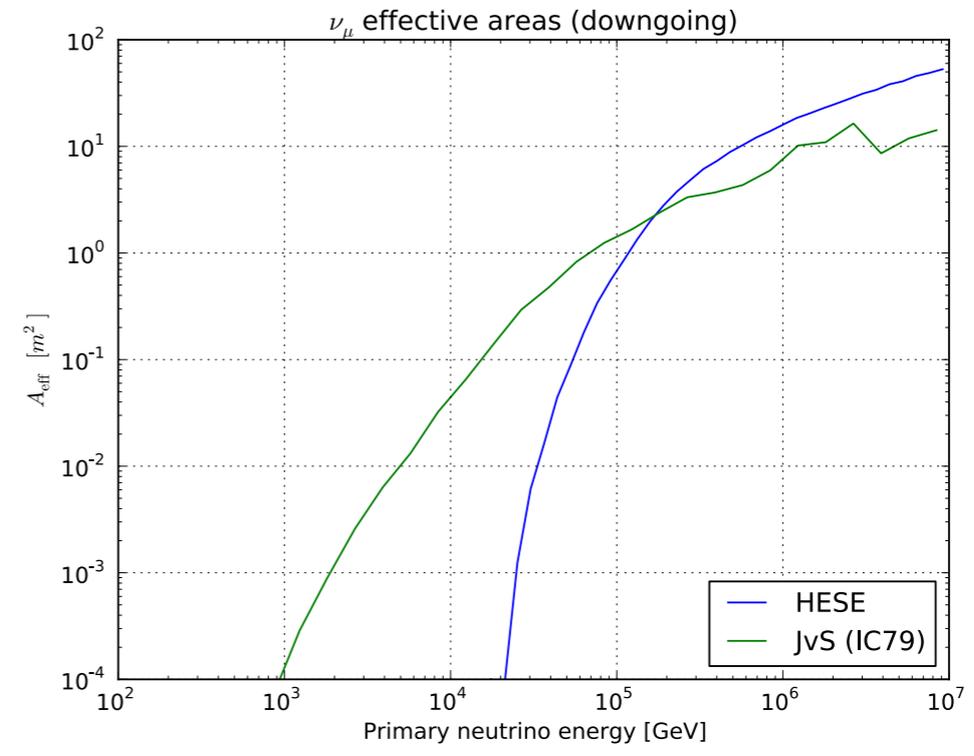
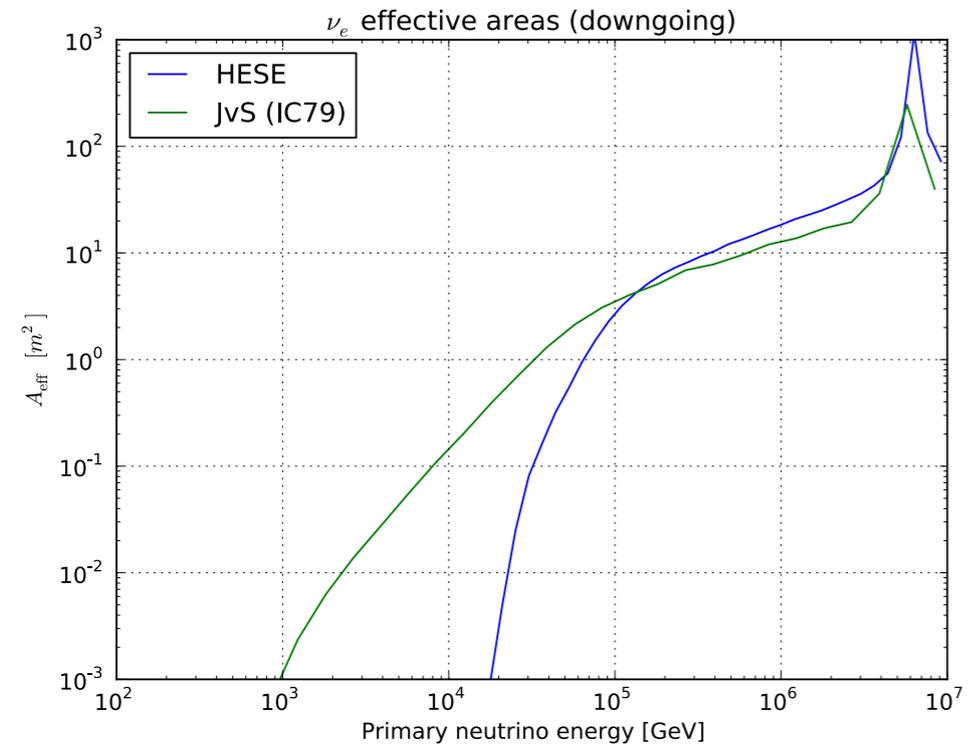
Optimal energy determination

Flavor identification

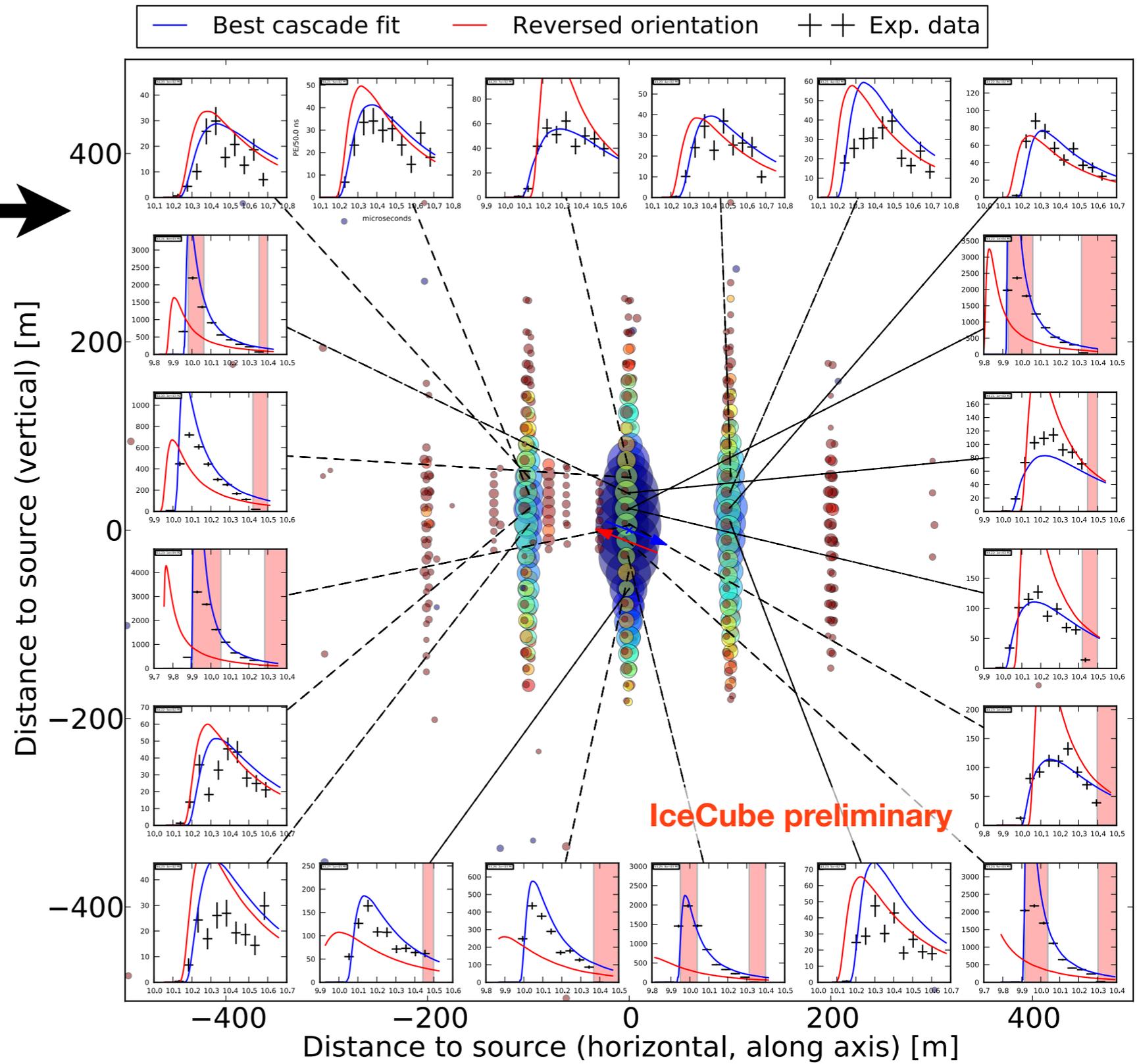
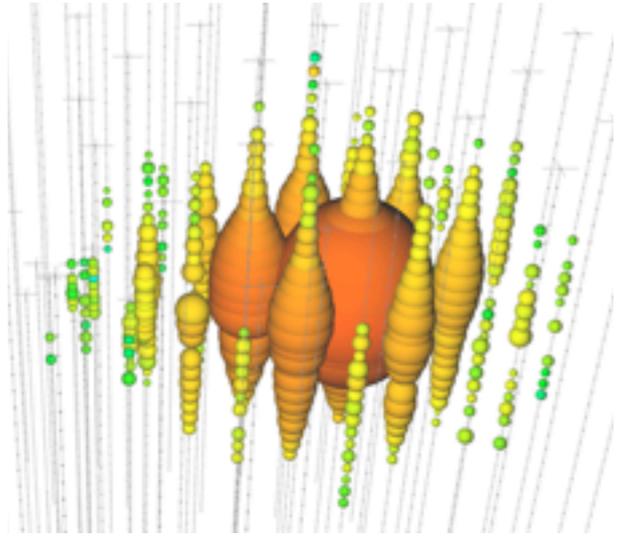
2-year data sample with $O(100)$ events above 10 TeV recently unblinded. Results coming soon!

Backup

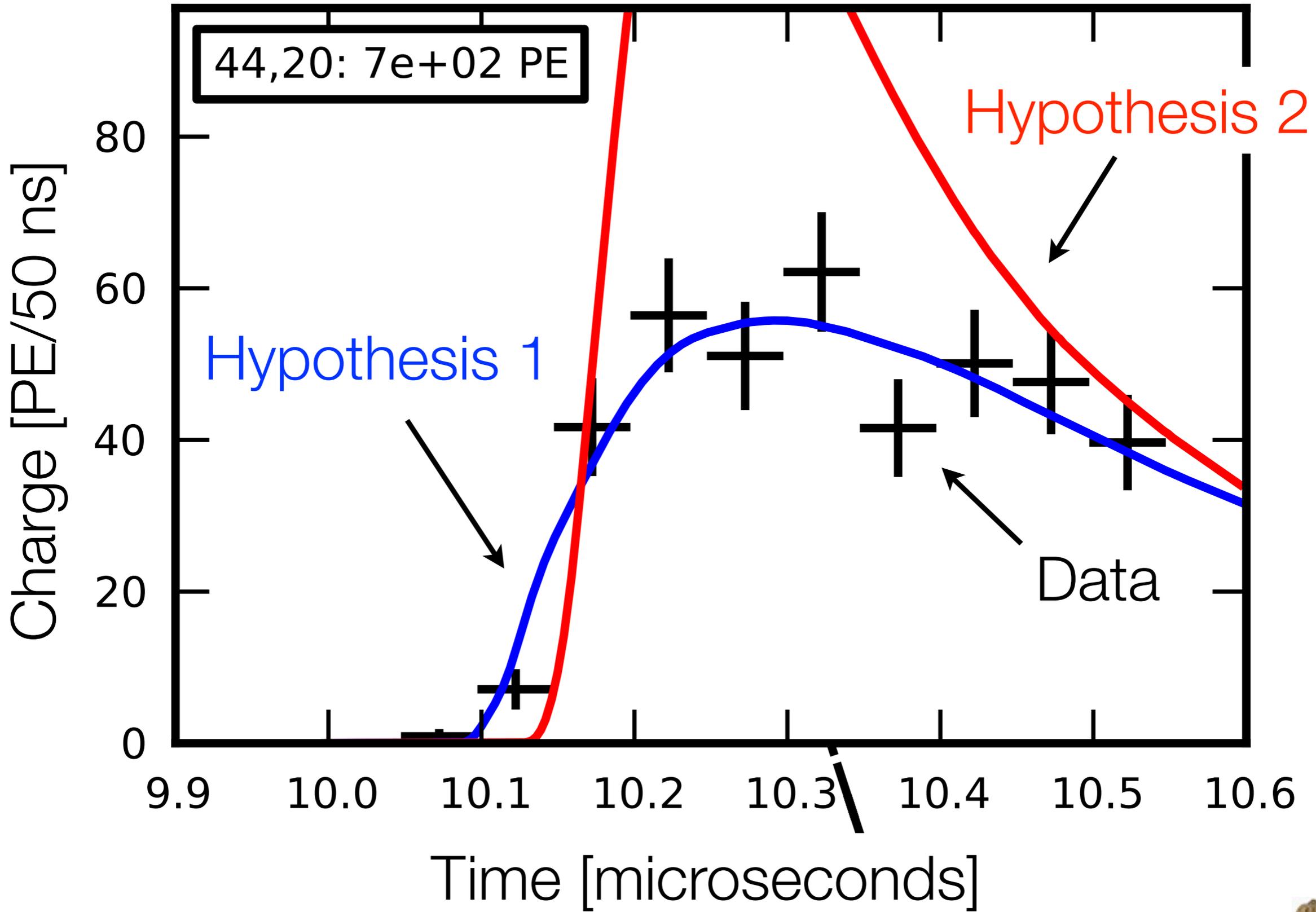
Effective areas



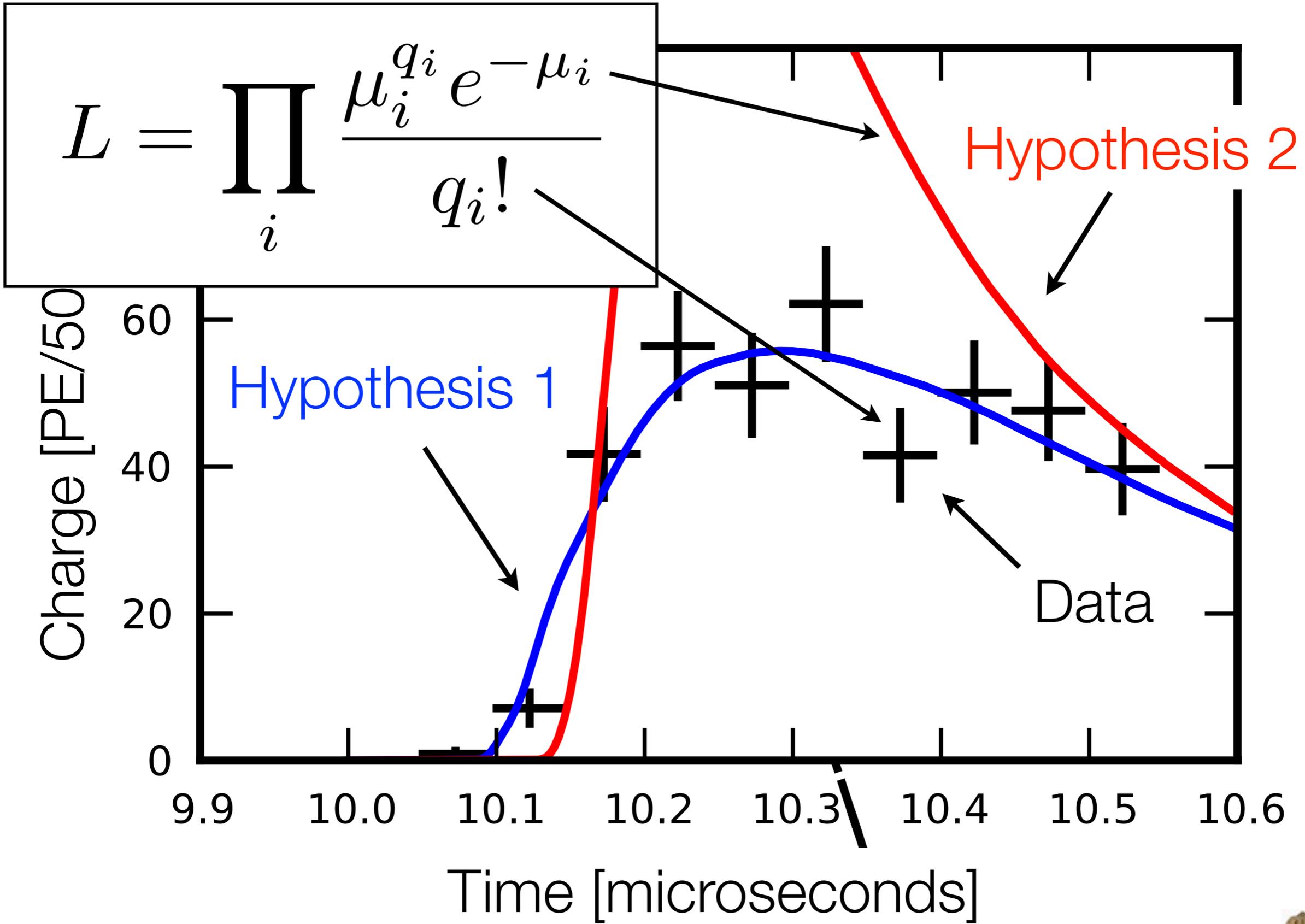
Cascade reconstruction: hypothesis and data



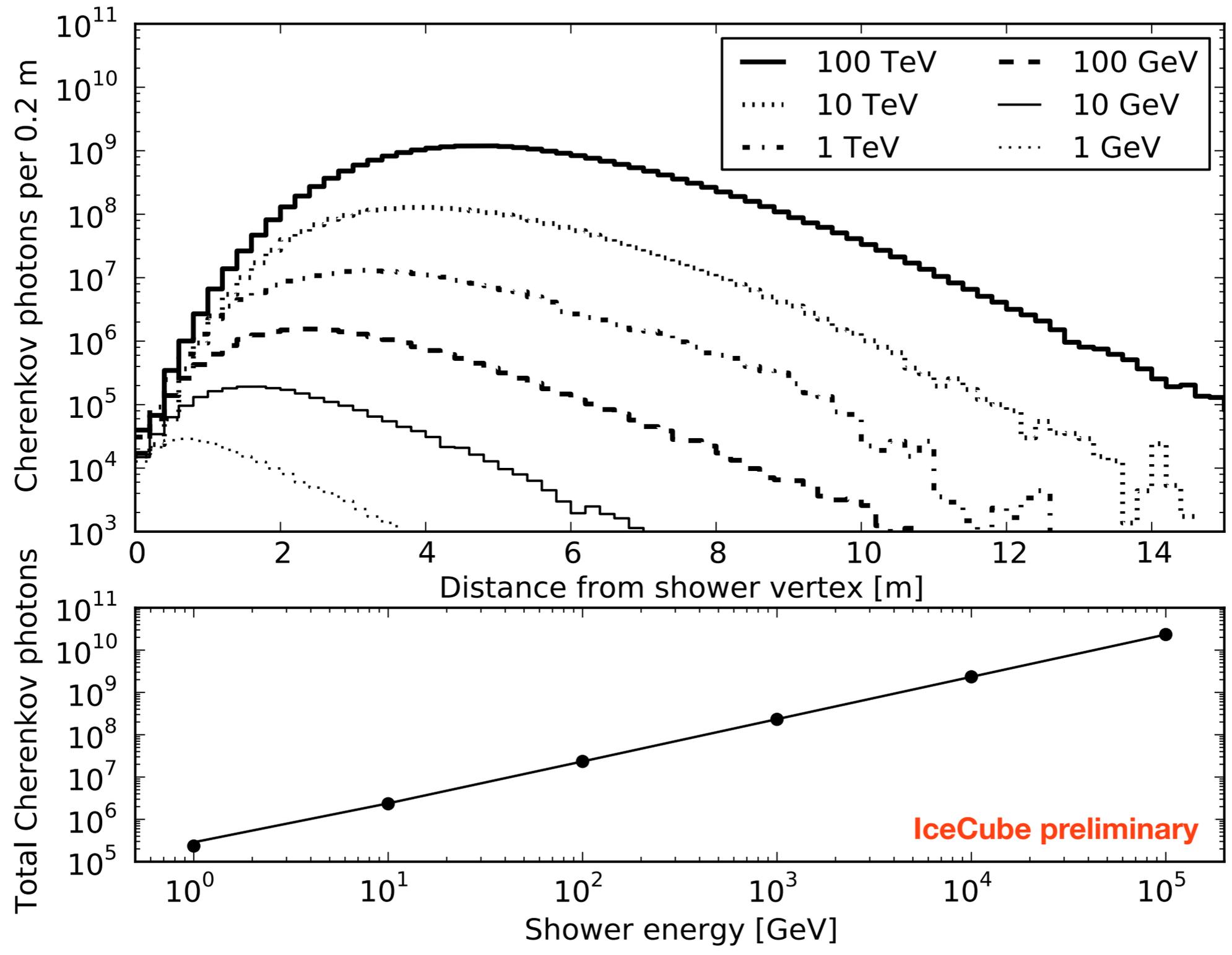
Cascade reconstruction: likelihood fit



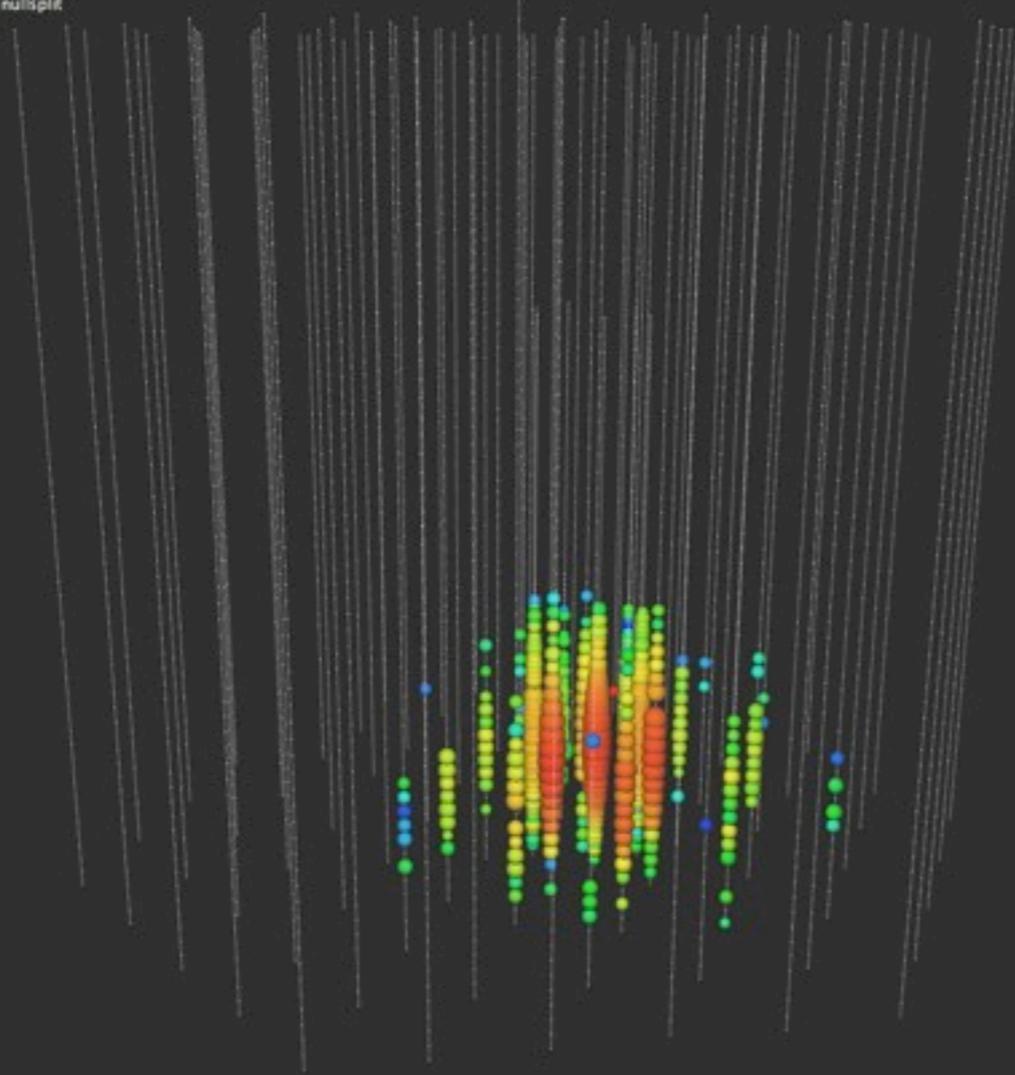
Cascade reconstruction: likelihood fit



Cascade reconstruction: energy

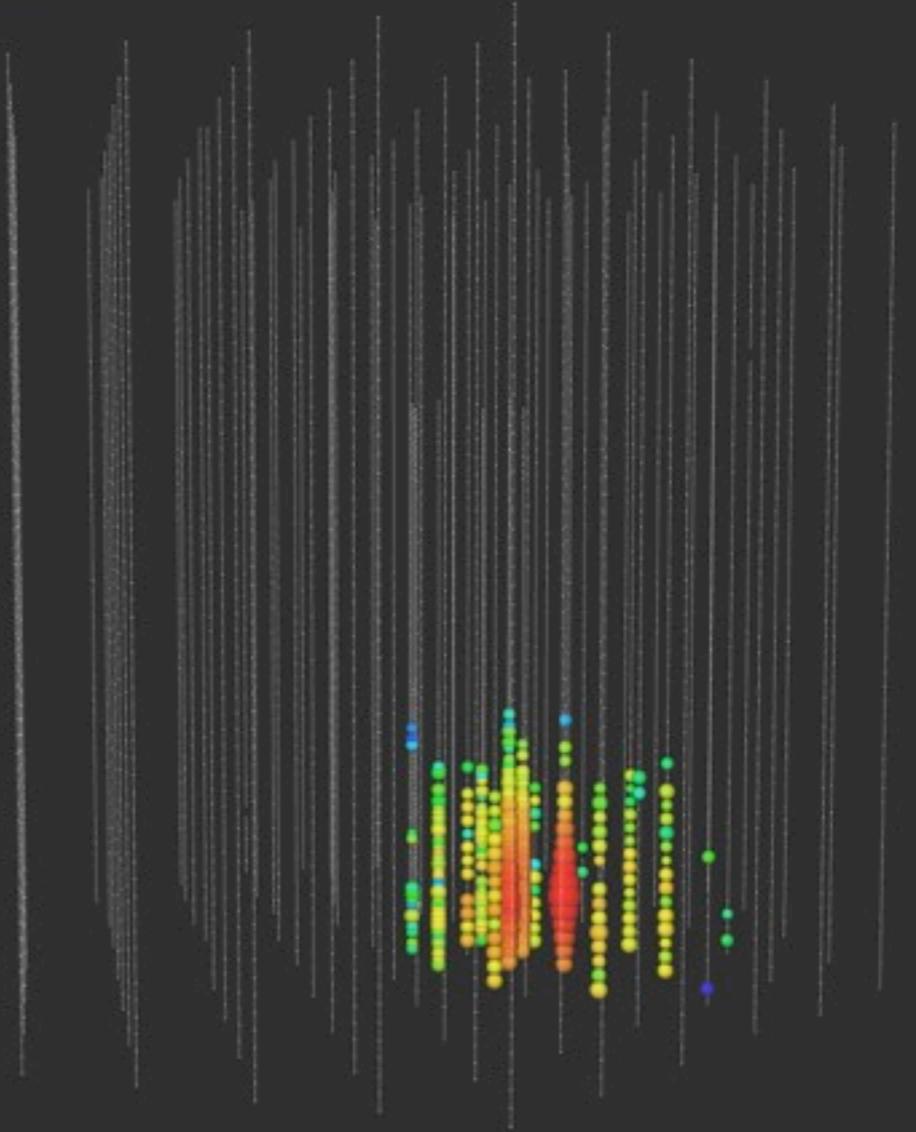


```
[ I3EventHeader ::  
  StartTime: 2010-12-05 00:22:36 UTC  
  EndTime: 2010-12-05 00:22:36 UTC  
  RunID: 117060  
  SubrunID: 0  
  EventID: 36667390  
  SubEventID: 0  
  SubEventStream: nullsplit  
]
```



~ 20 TeV deposited

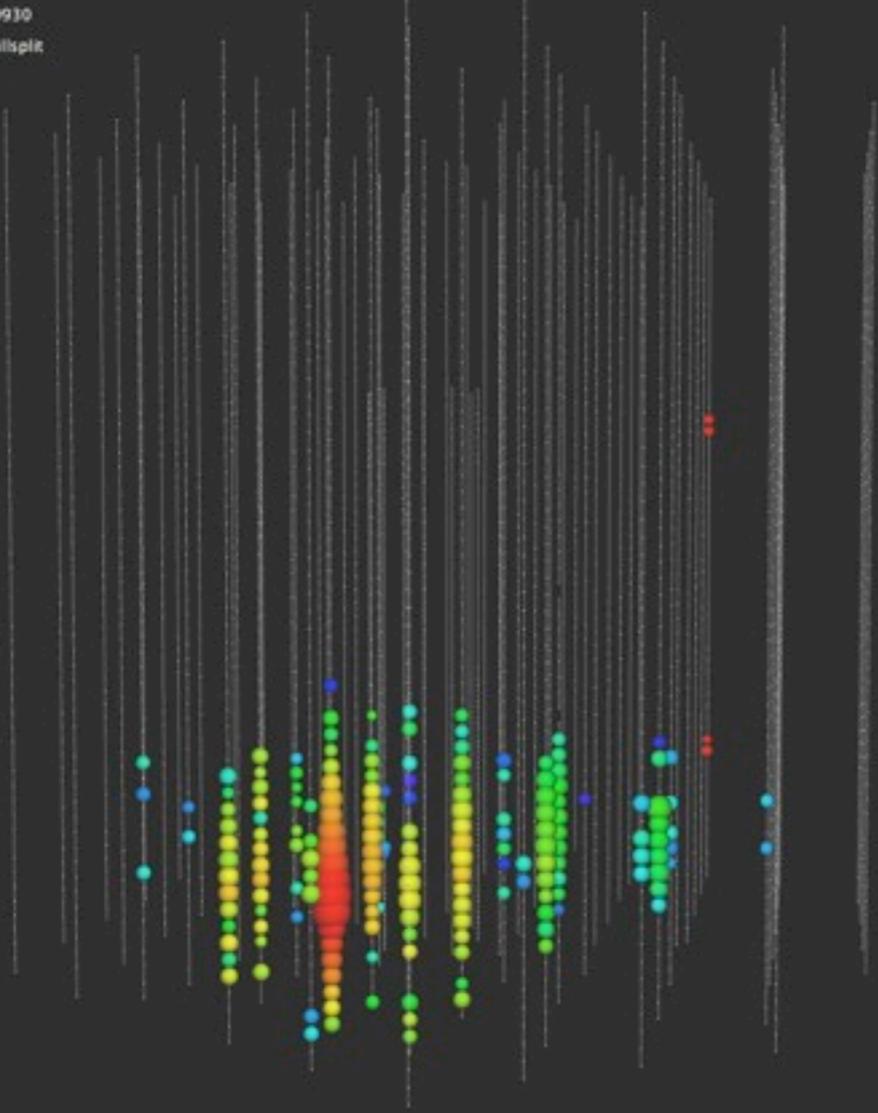
```
[ I3EventHeader ::  
  StartTime: 2011-03-29 00:43:14 UTC  
  EndTime: 2011-03-29 00:43:14 UTC  
  RunID: 117950  
  SubrunID: 0  
  EventID: 9821351  
  SubEventID: 0  
  SubEventStream: nullsplit  
]
```



~ 13 TeV deposited

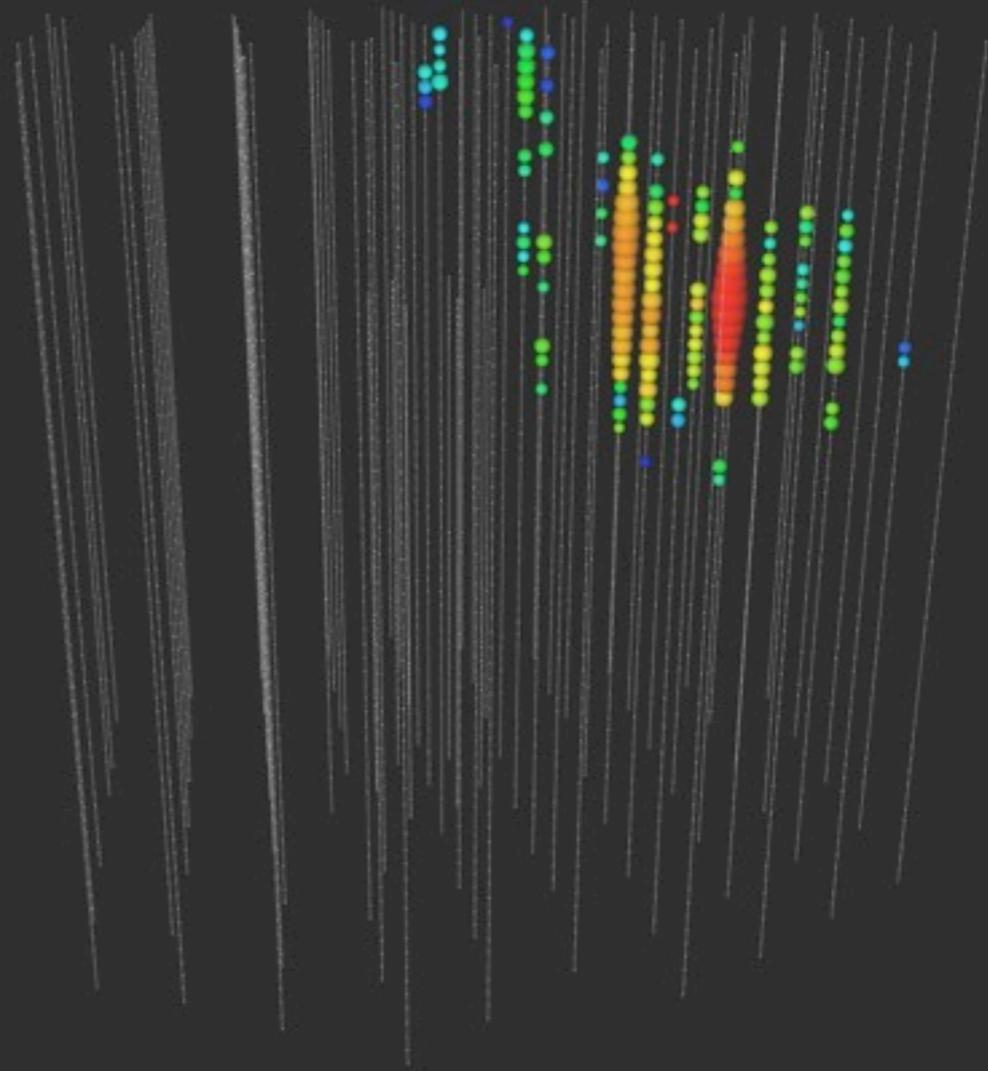
Starting tracks

```
[ I3EventHeader ::  
  StartTime: 2010-12-05 02:48:54 UTC  
  EndTime: 2010-12-05 02:48:54 UTC  
  RunID: 117060  
  SubrunID: 0  
  EventID: 57719930  
  SubEventID: 0  
  SubEventStream: nullsplit  
]
```



~ 18 TeV deposited

```
[ I3EventHeader ::  
  StartTime: 2011-02-24 12:45:45 UTC  
  EndTime: 2011-02-24 12:45:45 UTC  
  RunID: 117810  
  SubrunID: 0  
  EventID: 26050389  
  SubEventID: 0  
  SubEventStream: nullsplit  
]
```



~ 100 TeV deposited

