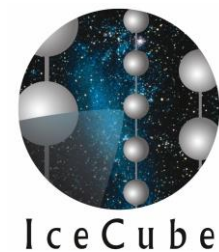# MULTI-FLAVOUR **PEV** NEUTRINO SEARCH
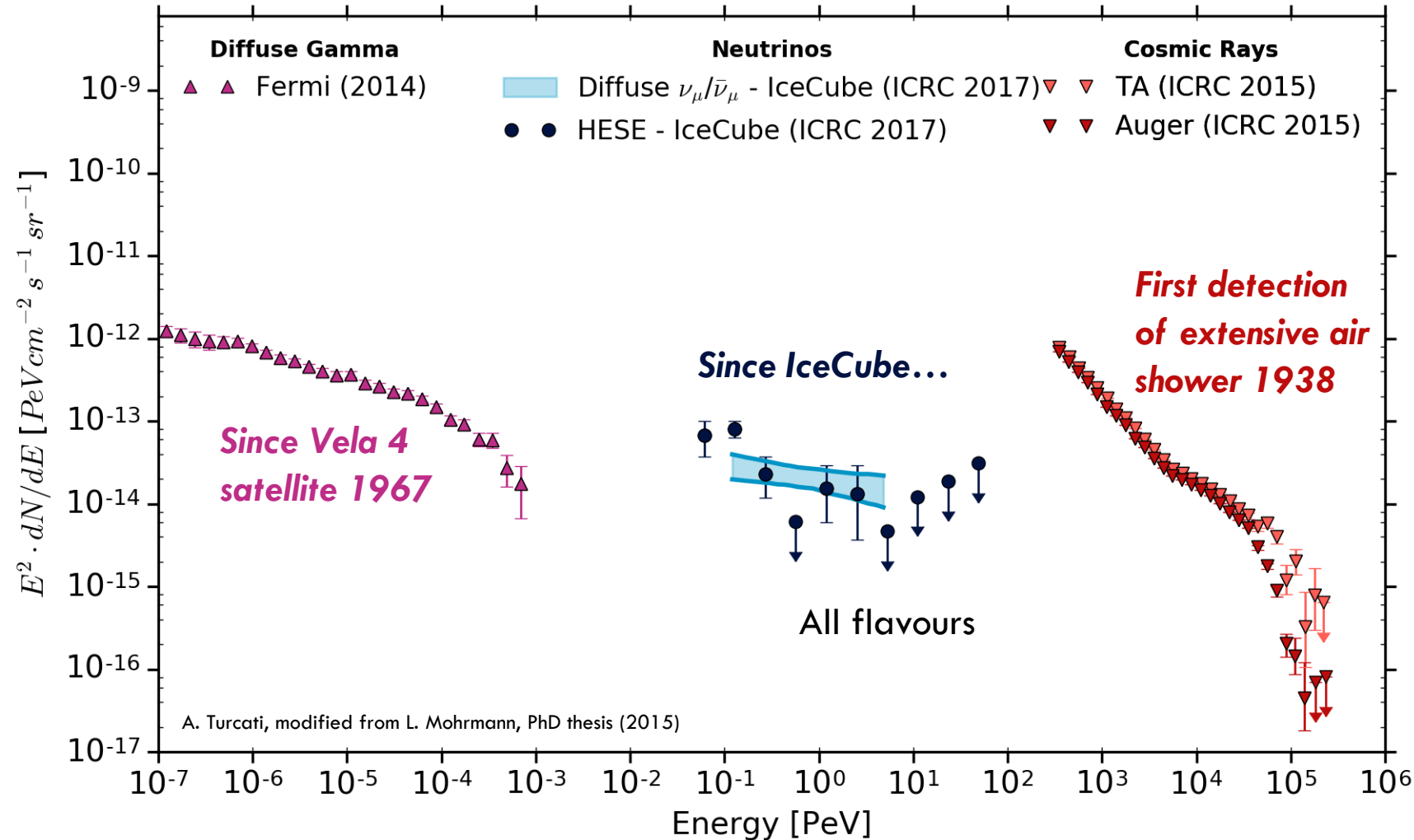
LU LU for the **IceCube** Collaboration, **Chiba** University, Japan

RICH PHYSICS HIDDEN AT PEV REGION

Diffuse Gamma
▲ ▲ Fermi (2014)

Neutrinos
▬ Diffuse $\nu_\mu/\bar{\nu}_\mu$ - IceCube (ICRC 2017)
● ● HESE - IceCube (ICRC 2017)

Cosmic Rays
▽ ▽ TA (ICRC 2015)
▽ ▽ Auger (ICRC 2015)

Since Vela 4 satellite 1967

Since IceCube...

All flavours

First detection of extensive air shower 1938

A. Turcati, modified from L. Mohrmann, PhD thesis (2015)

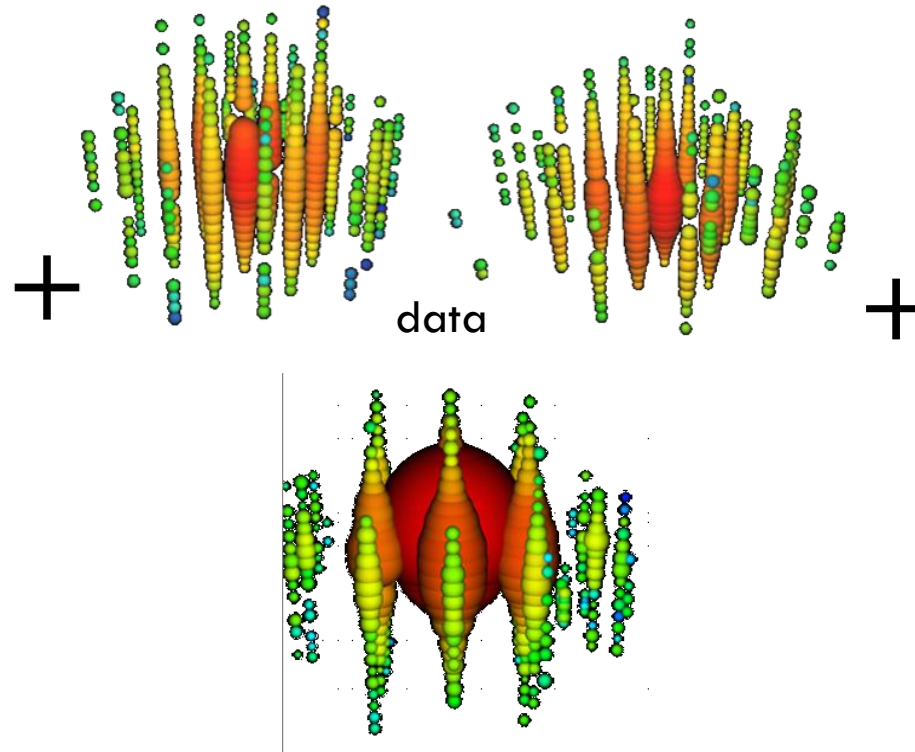$E^2 \cdot dN/dE \, [PeV cm^{-2} \, s^{-1} \, sr^{-1}]$

Energy [PeV]

Cut-off?
Connection to UHECR?
Cosmogenic neutrinos?
Glashow resonance?!
Nue bar ratio?
Next generation radio array…

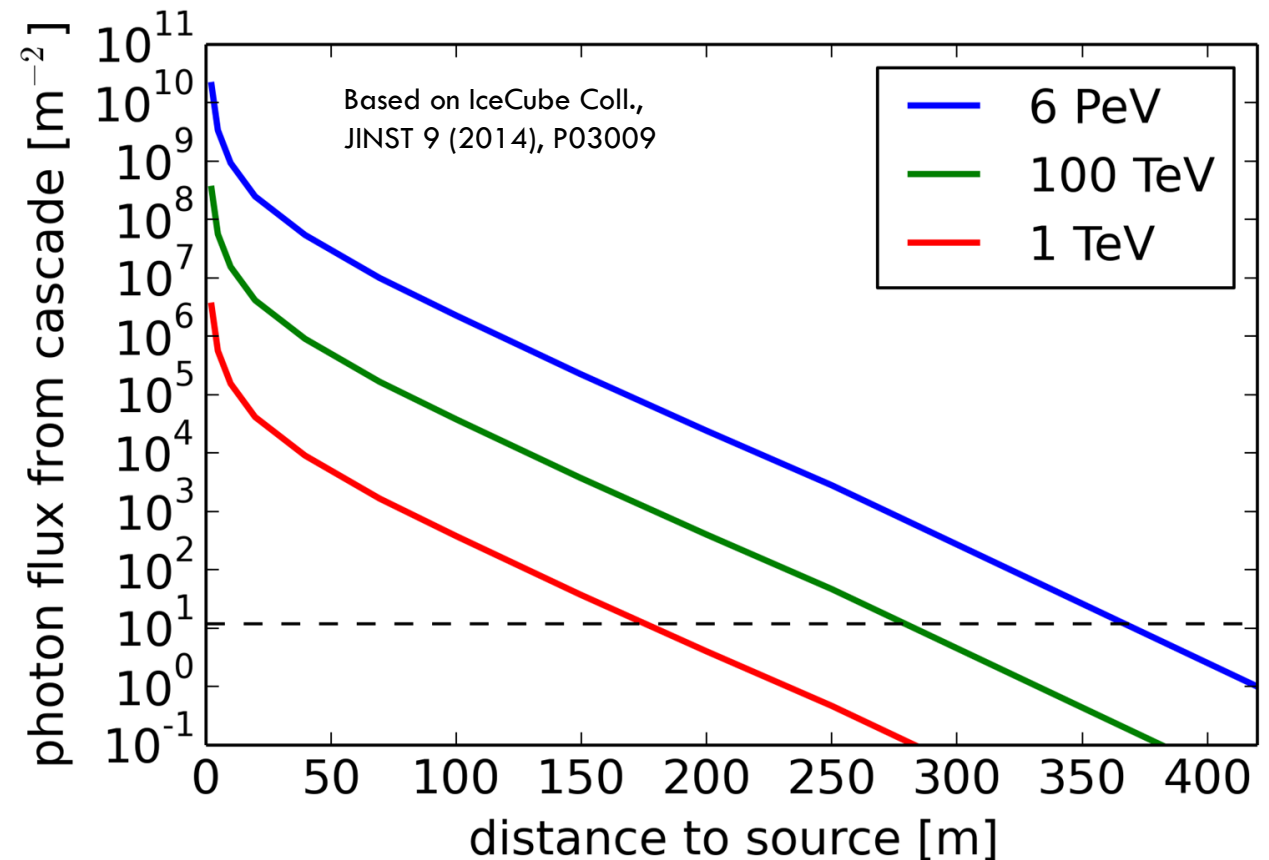# 4 PUBLISHED EVENTS WITH ENERGY > PEV
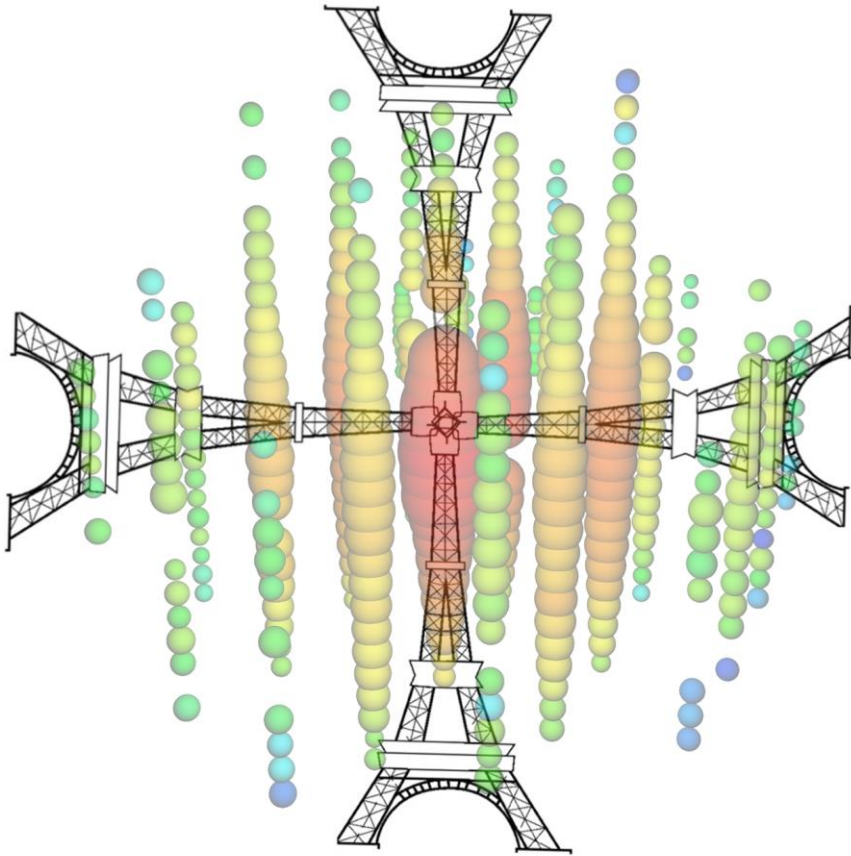
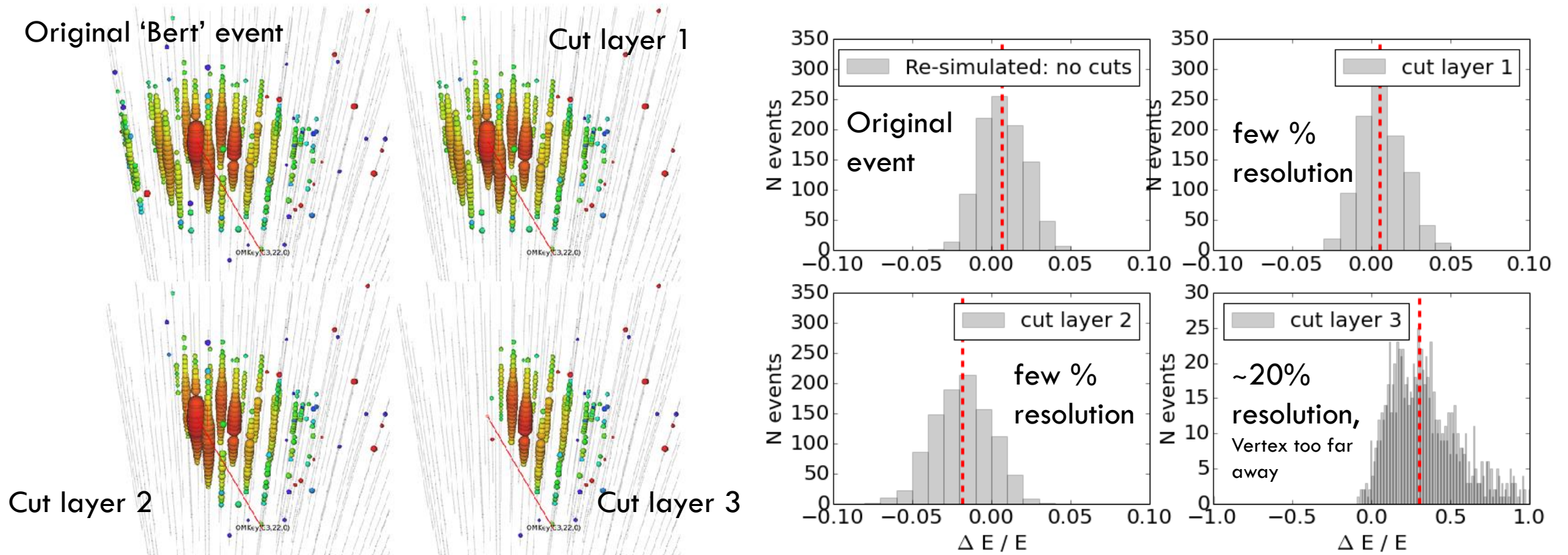**Through-going track**

Contained cascades

data

2.6 PeV deposited energy*

+

+
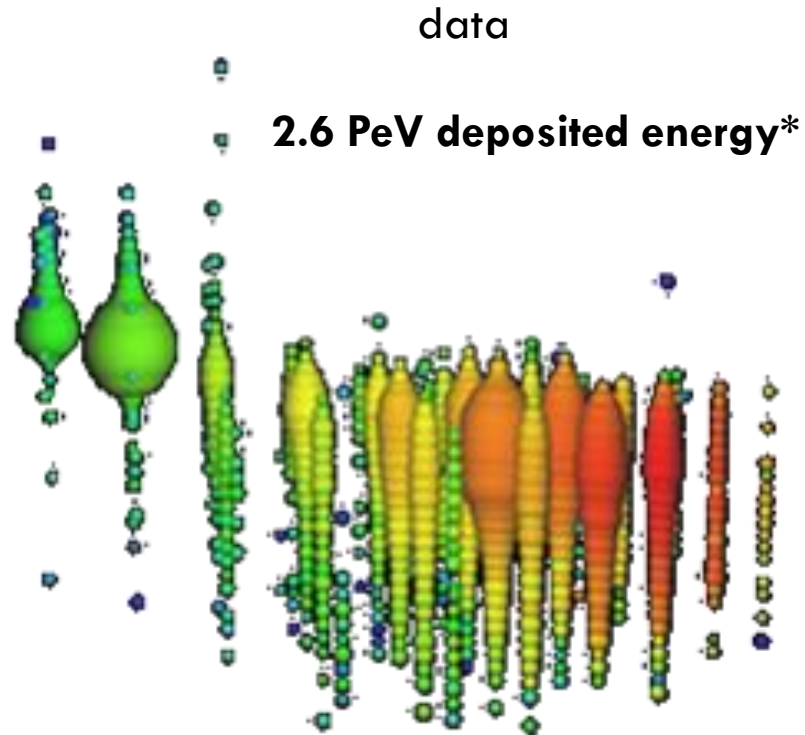
data

Where else to search for PeV events ?

PEV EVENTS ARE HUGE → VERTEXES OF CONTAINED CASCADES ARE RESTRICTED DUE TO SHOWER SIZE

Based on IceCube Coll., JINST 9 (2014), P03009

CAN WE RECONSTRUCT PARTIALLY-CONTAINED CASCADES? – DATA DRIVEN TEST

Original 'Bert' event

Cut layer 1

Cut layer 2

Cut layer 3

Original event

few % resolution

few % resolution

~20% resolution, Vertex too far away

Observed consistent bias in data and MC

A NEW EVENT SELECTION:
PEV ENERGY PARTIALLY-CONTAINED EVENTS

**Partially-contained cascades**

Contained cascades
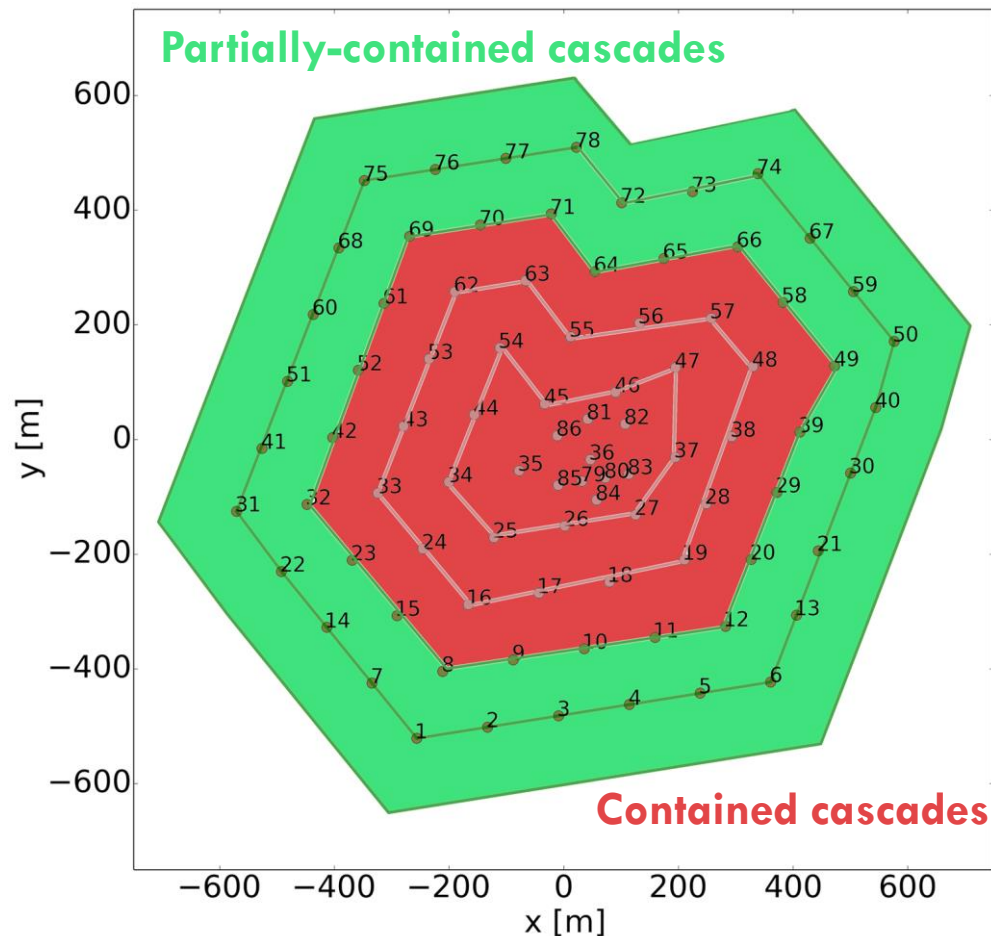
- To ensure **no overlap** with existing datasets:
  - Apply anti containment cuts
  - Apply anti through-going track cuts
- Optimised for selecting 6.3 PeV **Glashow resonance**
- Combine all three channels for cut-off fitting

L. Mohrmann

Interaction:
  NuEBar -> Hadrons
Primary
  Type : NuEBar
  Energy: 8.15e+06GeV
Muon
  Type : MuPlus
  Energy: 8.33e+01GeV
Cascade
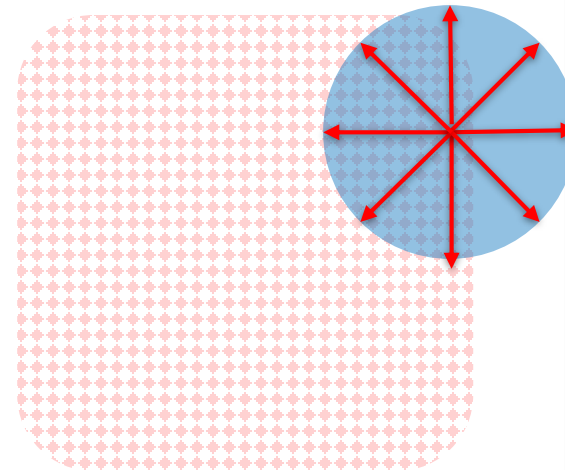 Type : Hadrons
  Energy: 8.15e+06GeV
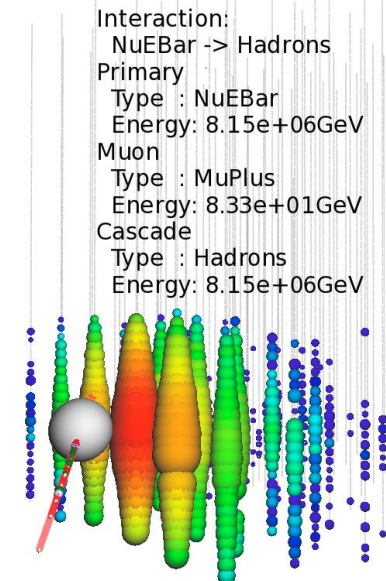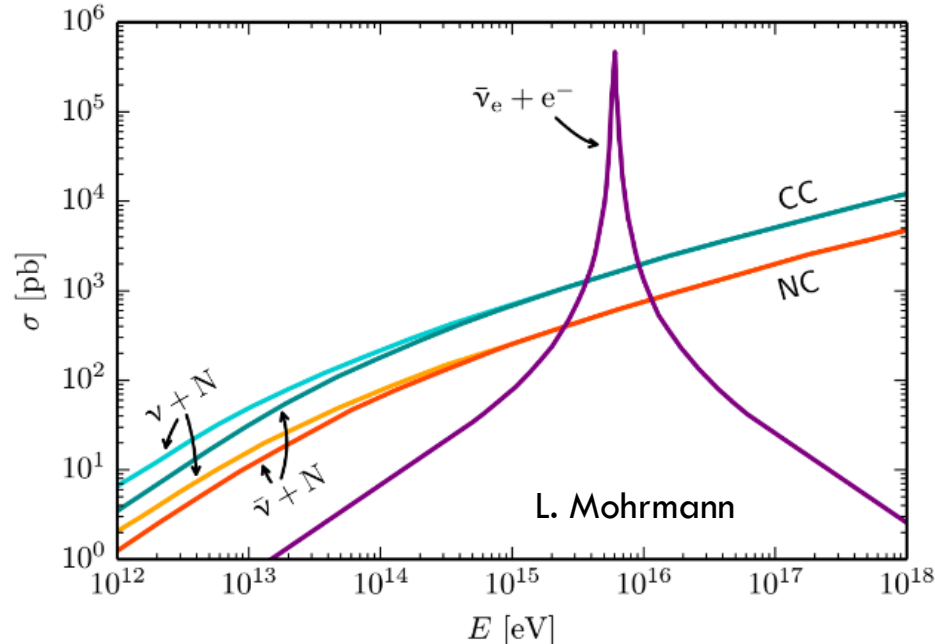
THE ATMOSPHERIC MUON BACKGROUND (1/3)

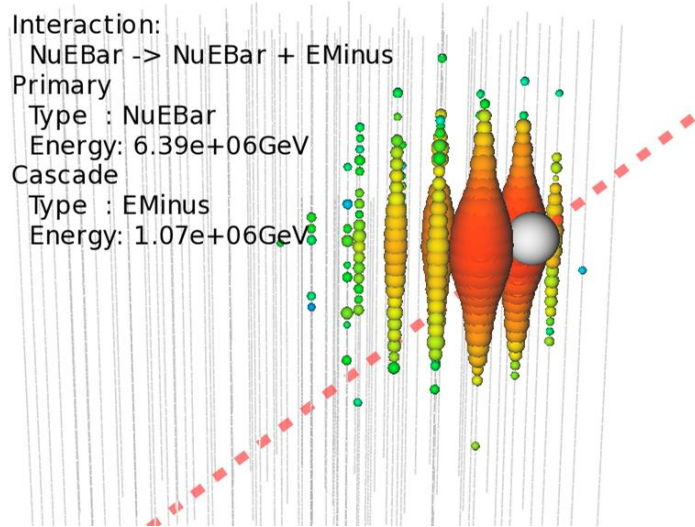Muons entering from the top are relatively easy to identify

Muon track background
(easily rejected)
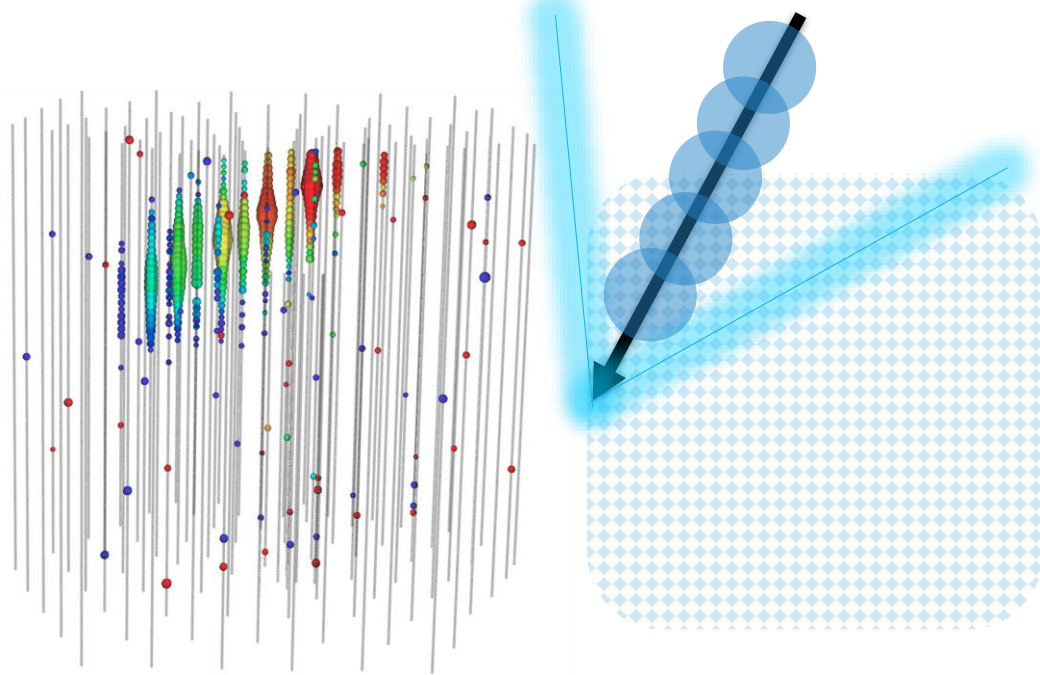
PeV neutrino cascade signal（MC）

Interaction:
 NuEBar -> NuEBar + EMinus
Primary
 Type : NuEBar
 Energy: 6.39e+06GeV
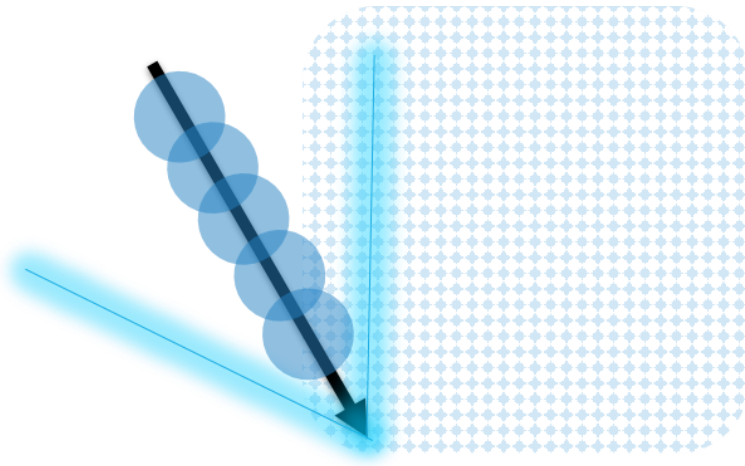Cascade
 Type : EMinus
 Energy: 1.07e+06GeV

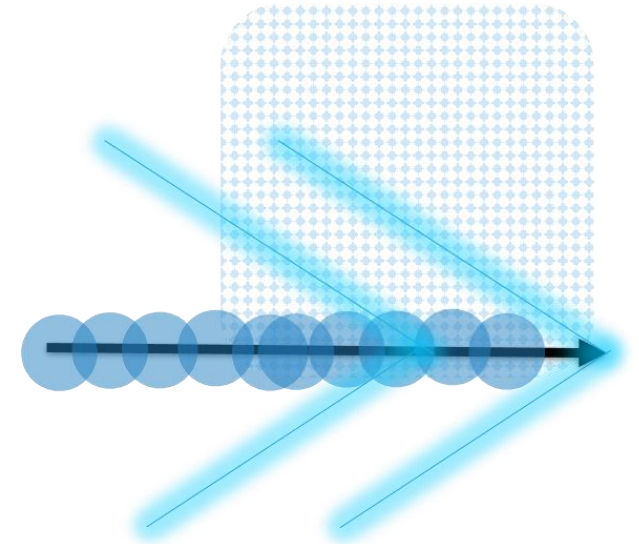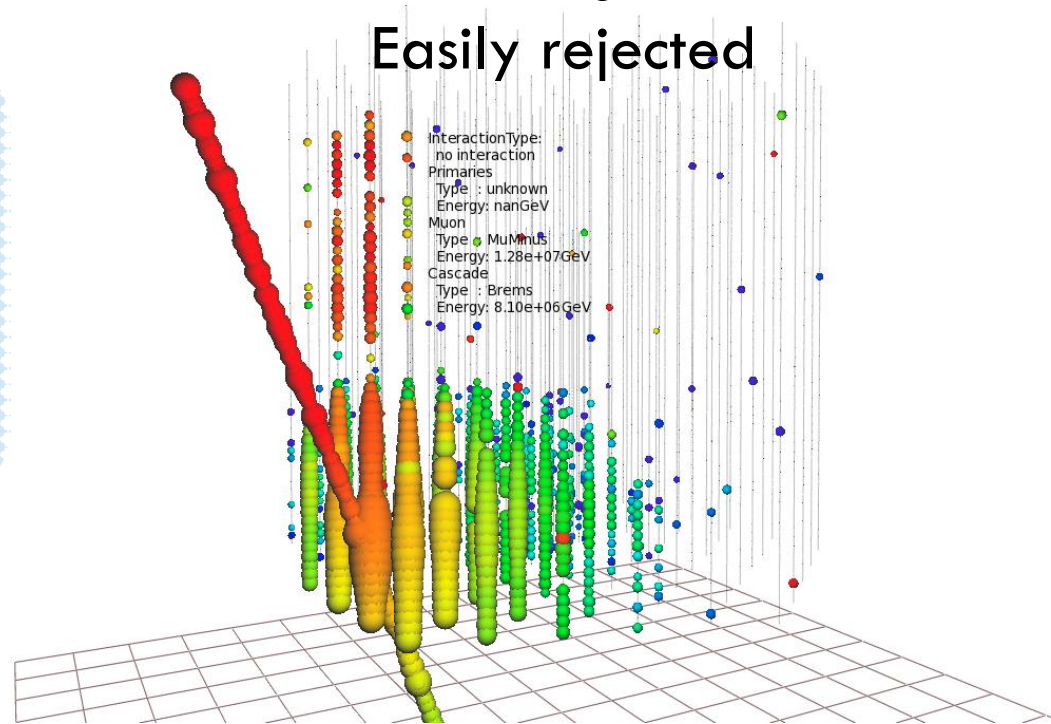The shape of the deposited signal is more spherical

THE ATMOSPHERIC MUON BACKGROUND (2/3)

Muons entering from the bottom: vertical and horizontal

Muon background
Easily rejected

InteractionType:
no interaction
Primaries
    Type : unknown
    Energy: nanGeV
Muon
    Type : MuMinus
    Energy: 1.28e+07GeV
Cascade
    Type : Brems
    Energy: 8.10e+06GeV

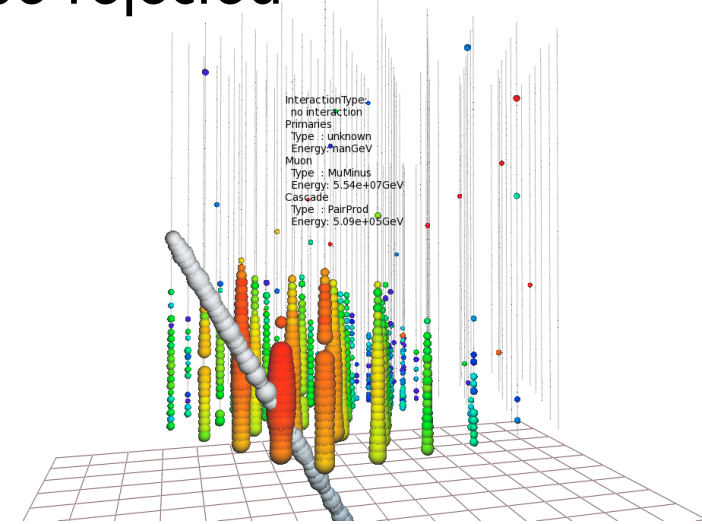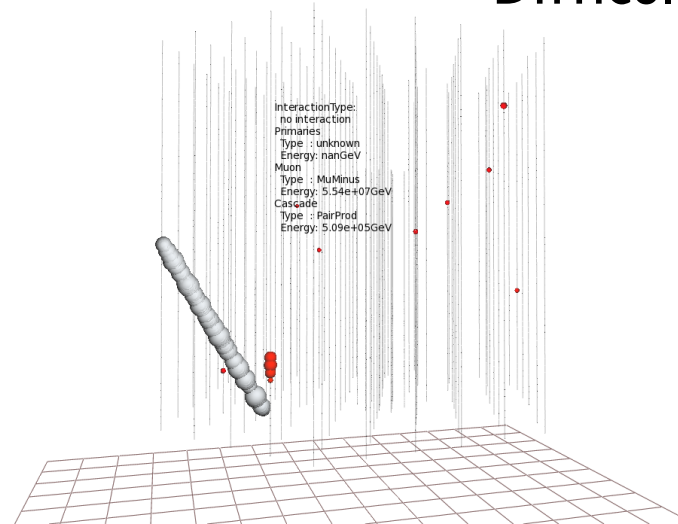Track feature before the
bright cascade

Through-going track

Can also reject these classes of background with light deposit patterns

THE ATMOSPHERIC MUON BACKGROUND (3/3)

Muons entering from the bottom: between vertical and horizontal

Difficult just by looking at the shape of the event

Muon background

Difficult to be rejected
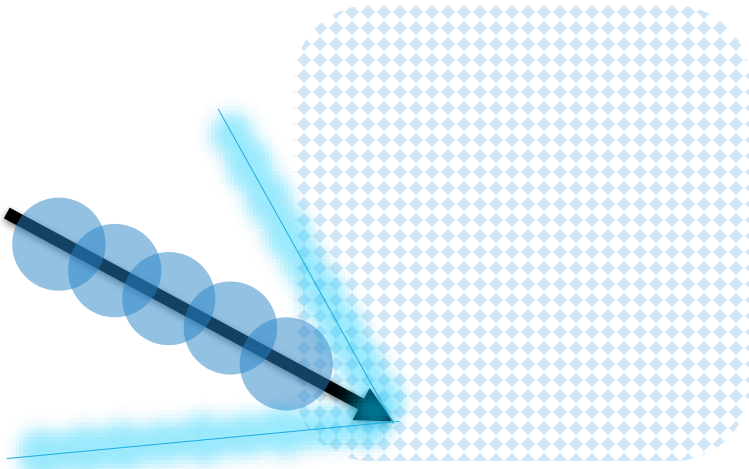
Studying timing sequence of how light travels reveals this is a muon track

Machine-learning approach used 11 features including geometry, timing, signal rise etc.

SIGNAL VS BACKGROUND

Use BDT score for classification
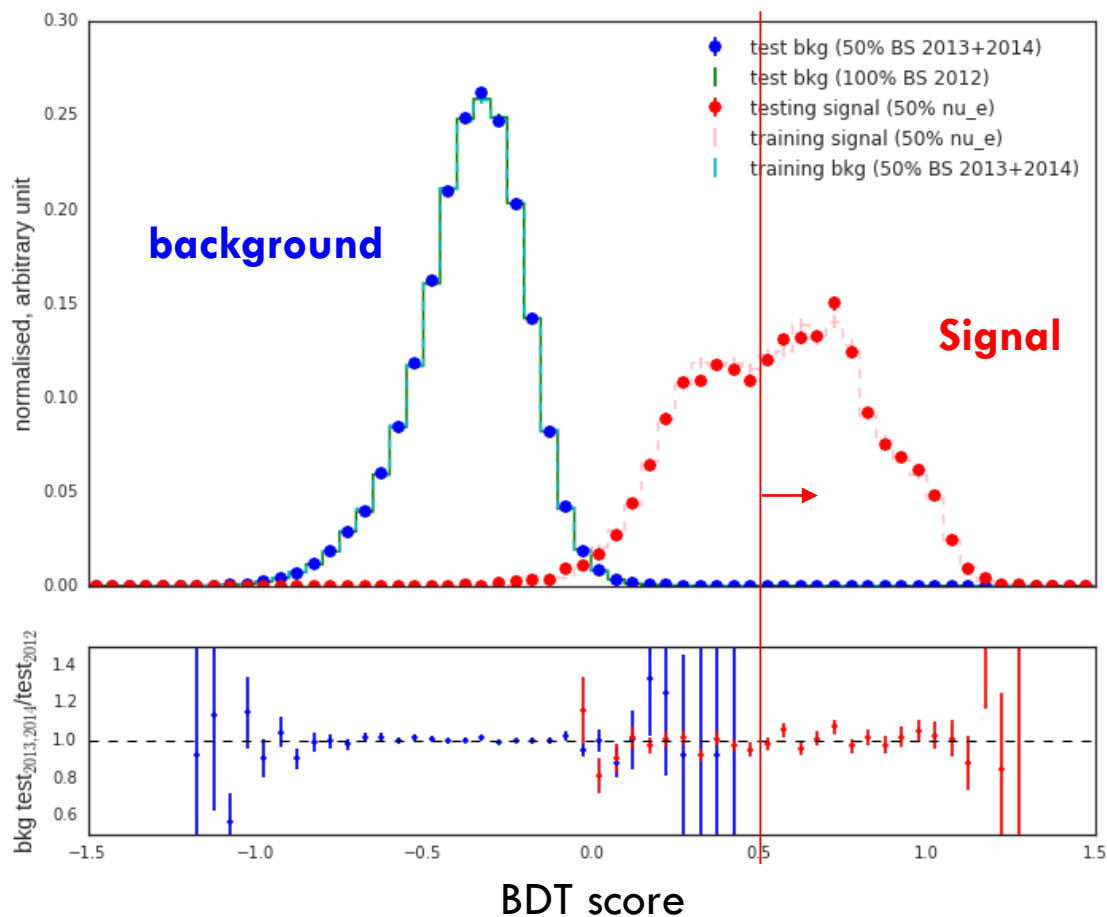
Background rejection after each cut

For all the PeV nue triggered events, the contained cascade analysis collects ~20%; the partially-contained channel is sensitive to ~40% and the remaining unselected 40% are at dust-layer (bad optical property) or far away from outer strings.

~X2 SENSITIVITY FOR GLASHOW RESONANCE
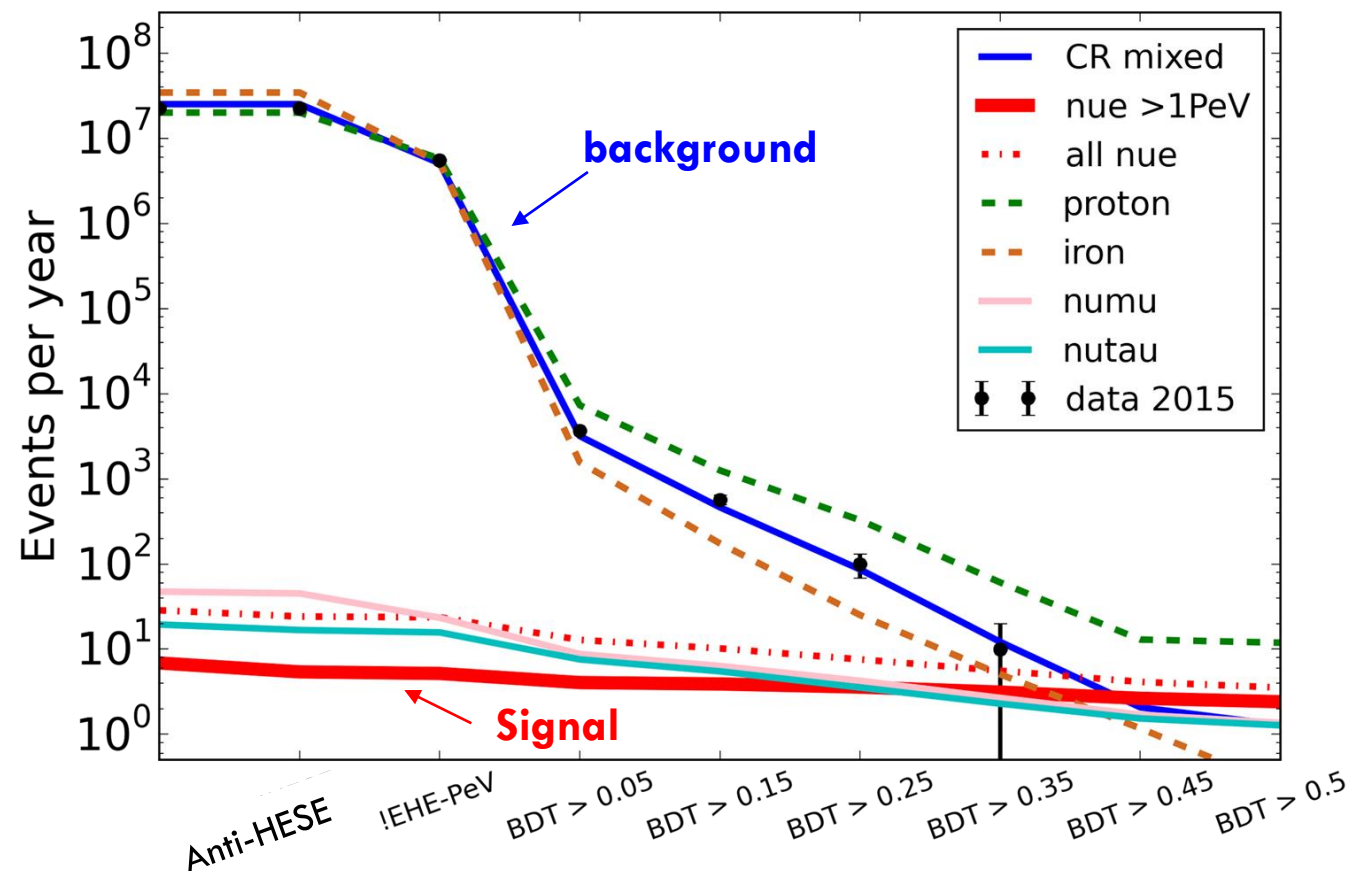

Contained cascades
Partially-contained
Through-going track

Legend:
- HESE ν_e
- PEPE ν_e
- EHE-PeV ν_e

IceCube Preliminary

Effective Area [m^2] vs $\log_{10}(E^\nu/\text{GeV})$

PEPE/HESE

data

data

data

4.6 years (2012-2016) of data, only 1 event of energy far beyond PeV (next slide)

11
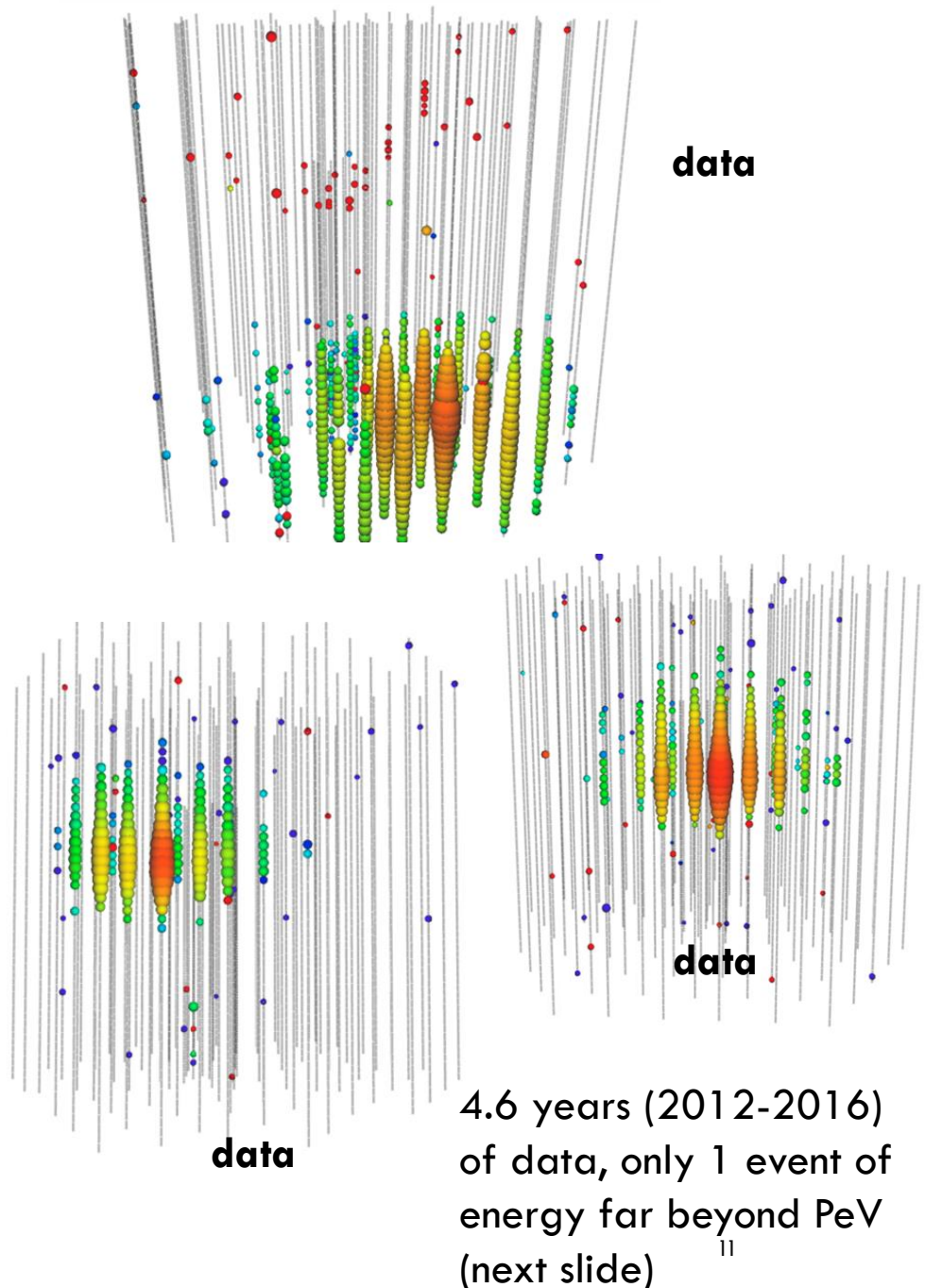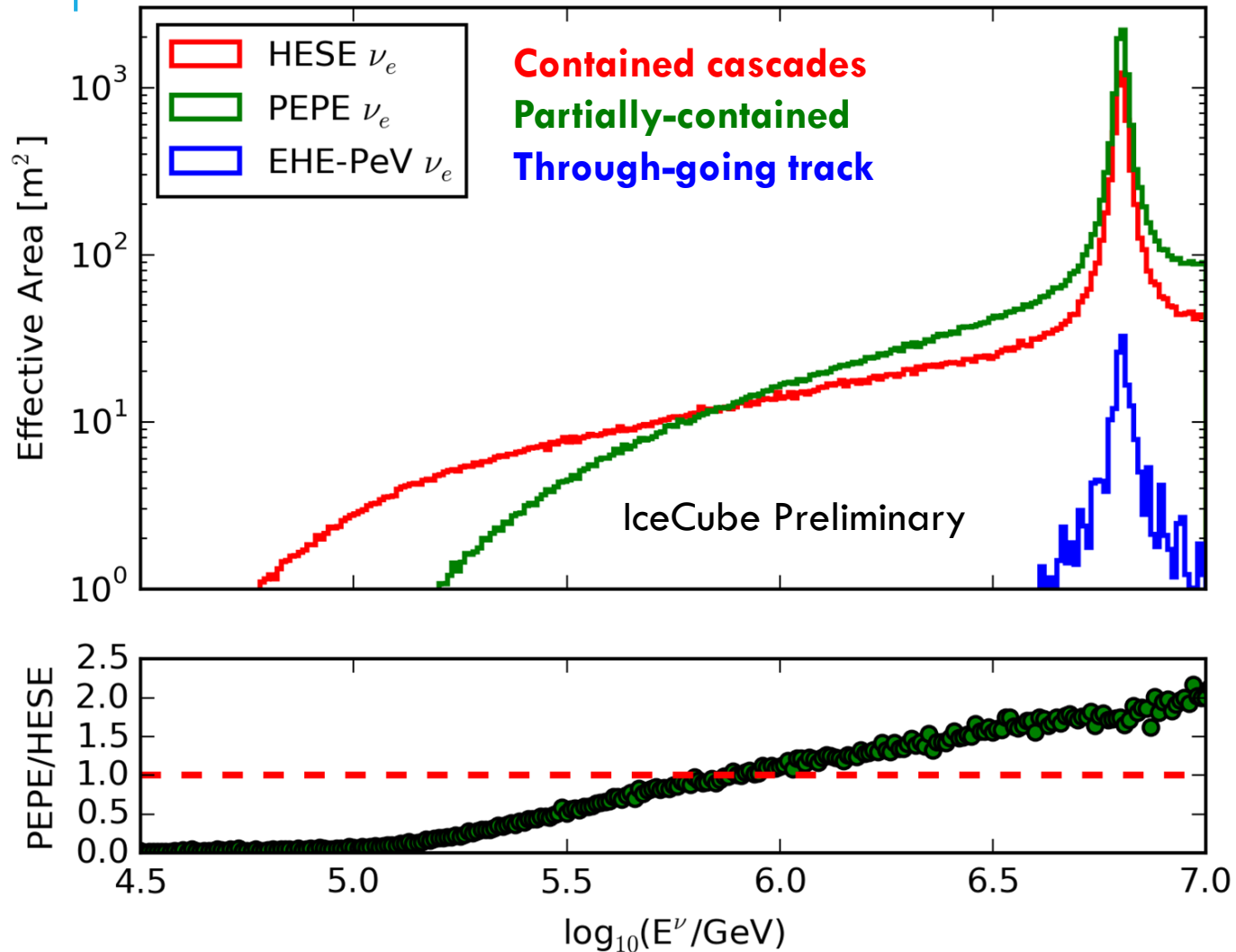
HIGHEST-ENERGY NEUTRINO CANDIDATE

State-of-art reco: details in the next talk by Tianlu Yuan
Median: 6.02 PeV

Distance on xy plane from the centre

IceCube preliminary

Brighter than all published PeV events

In progress: muon background systematics

data
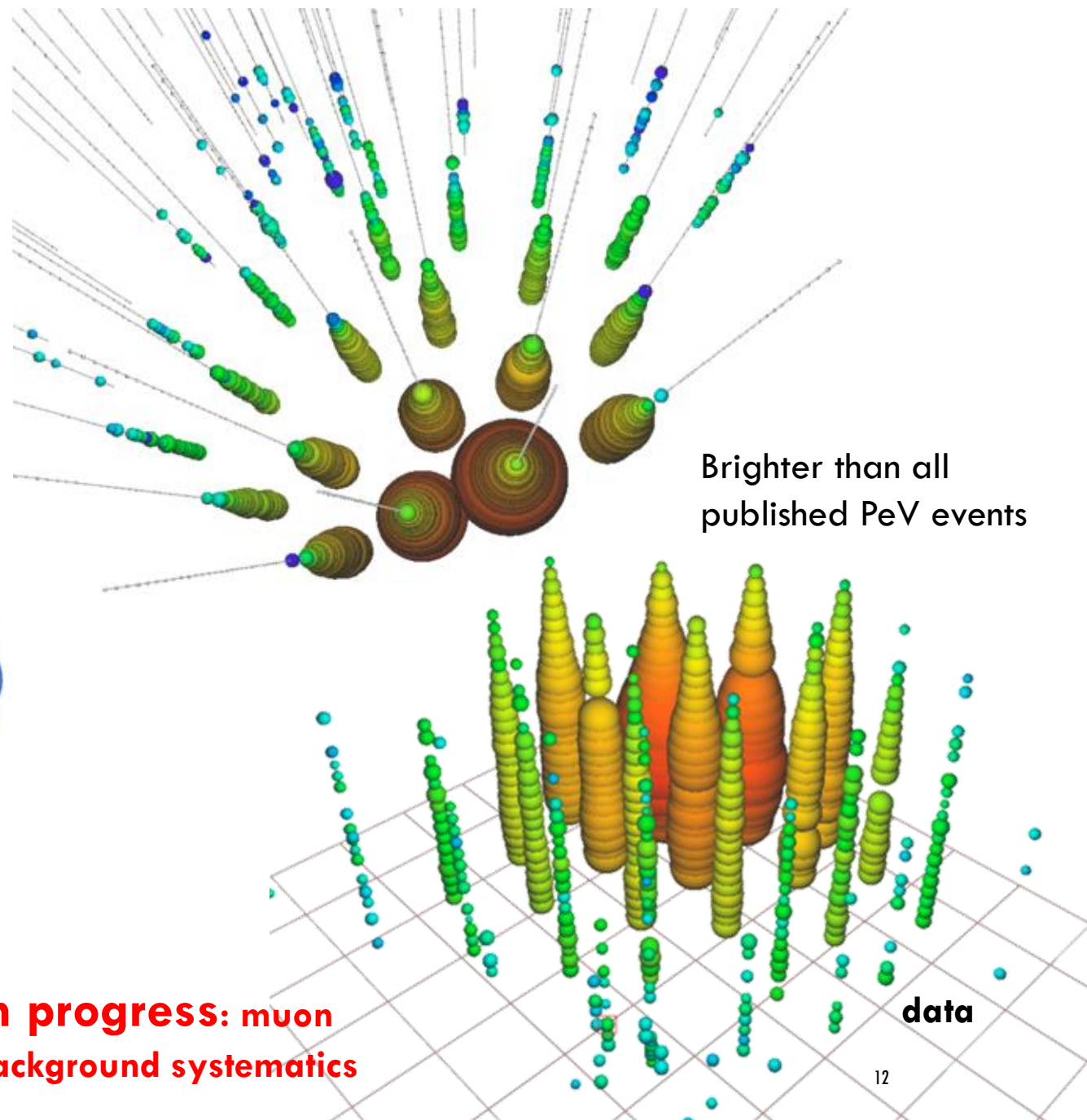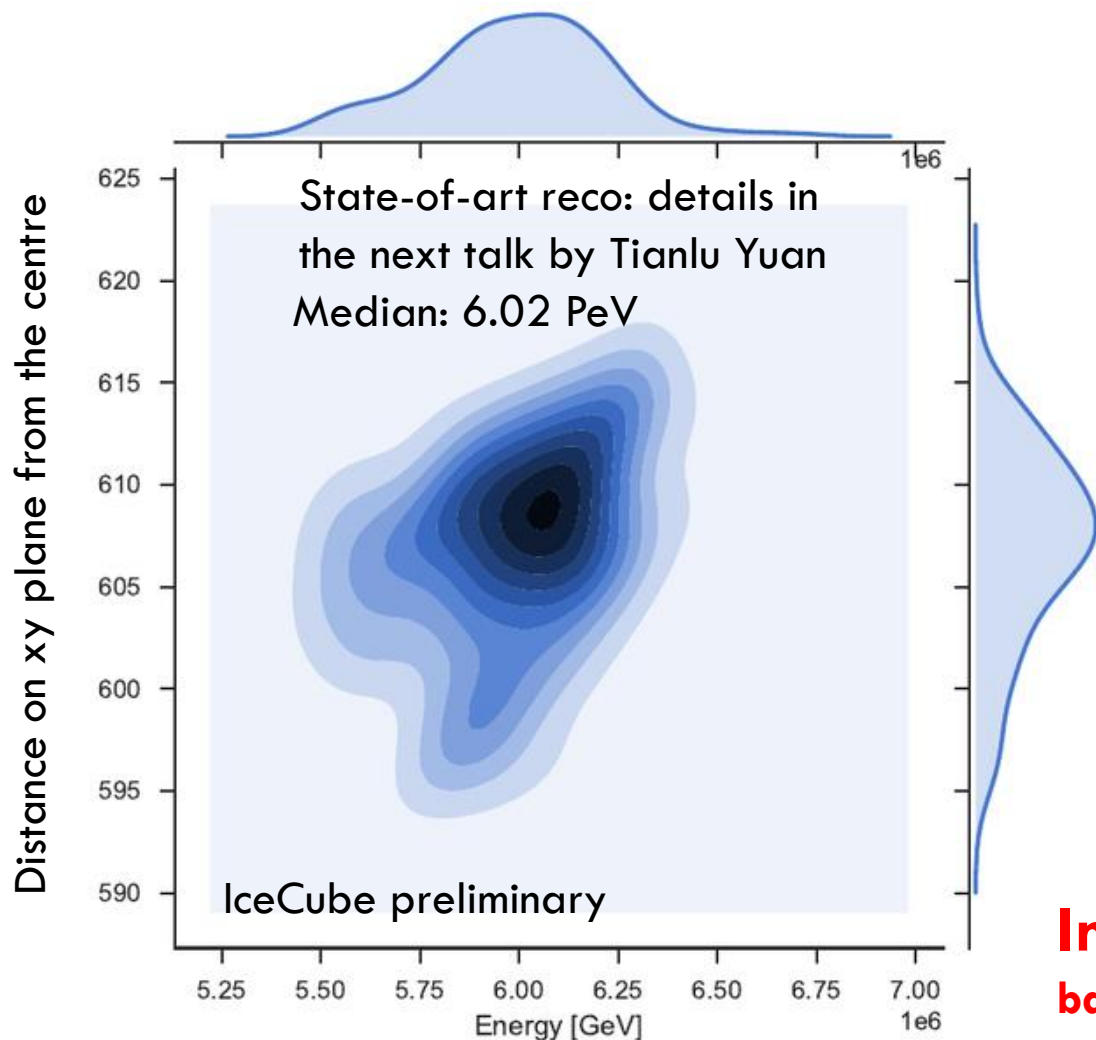
At the highest energies $E_{proxy} > 400$ TeV

CONSISTENT WITH DIFFUSE ν_μ NEUTRINO SPECTRUM

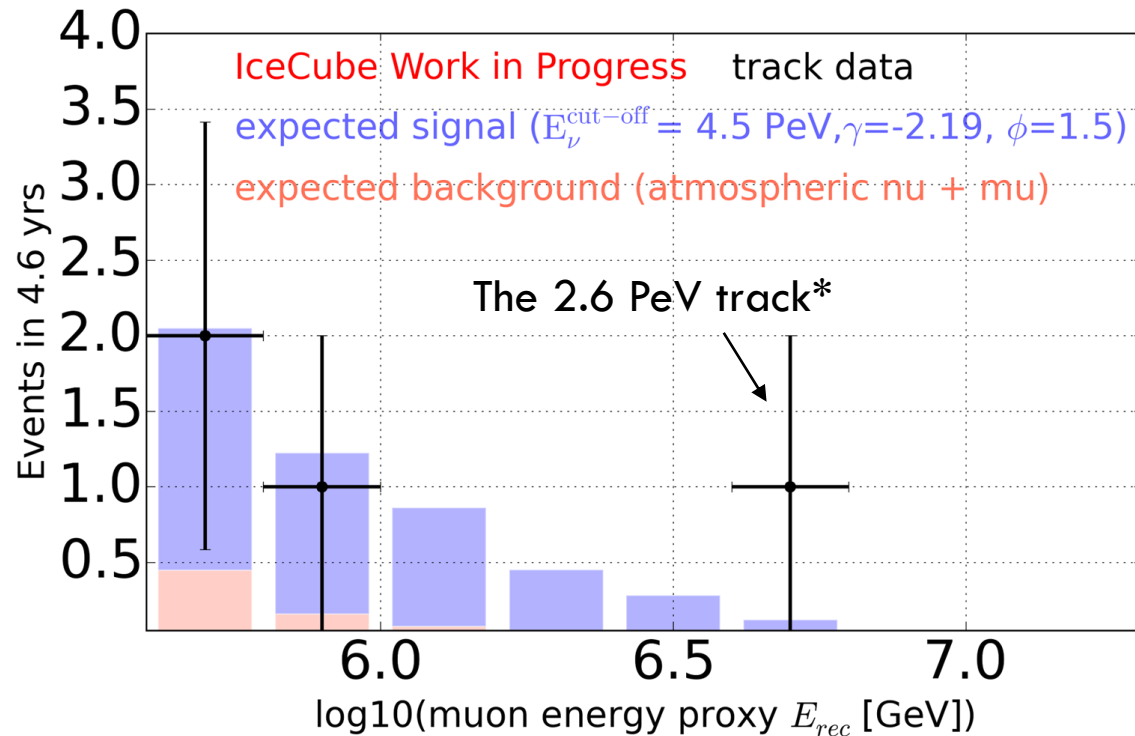C. Haack, PoS(ICRC 2017)981 $\Phi = 10^{-18} \times 1.5 \times (\frac{E}{100\text{TeV}})^{-2.19} e^{-E/4.5\text{PeV}} \text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}$

Below are **stacked histograms**

Track sample in this analysis

Cascade sample in this analysis
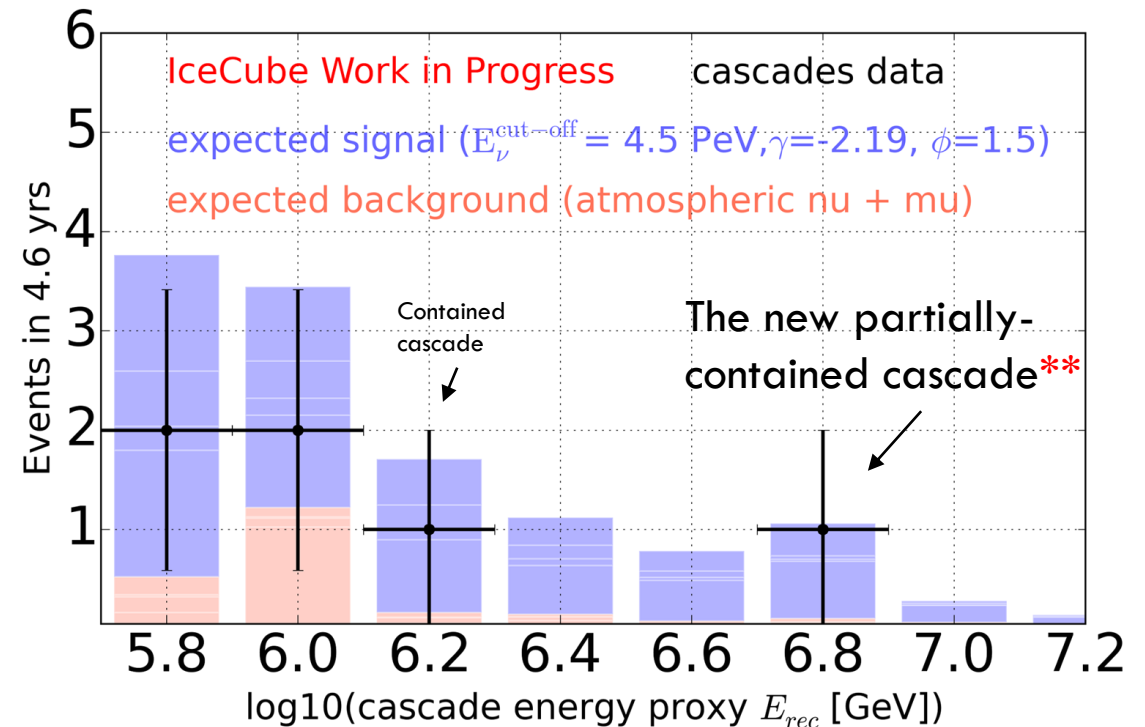
*2.6 PeV is deposited energy not the energy proxy shown for estimating muon energy.

** systematic errors of muon background under study 2011 data will be added later (year of Ernie & Bert)

THE CUT-OFF IS NOT SIGNIFICANT DUE TO LIMITED STATISTICS FOR >400 TEV EVENTS

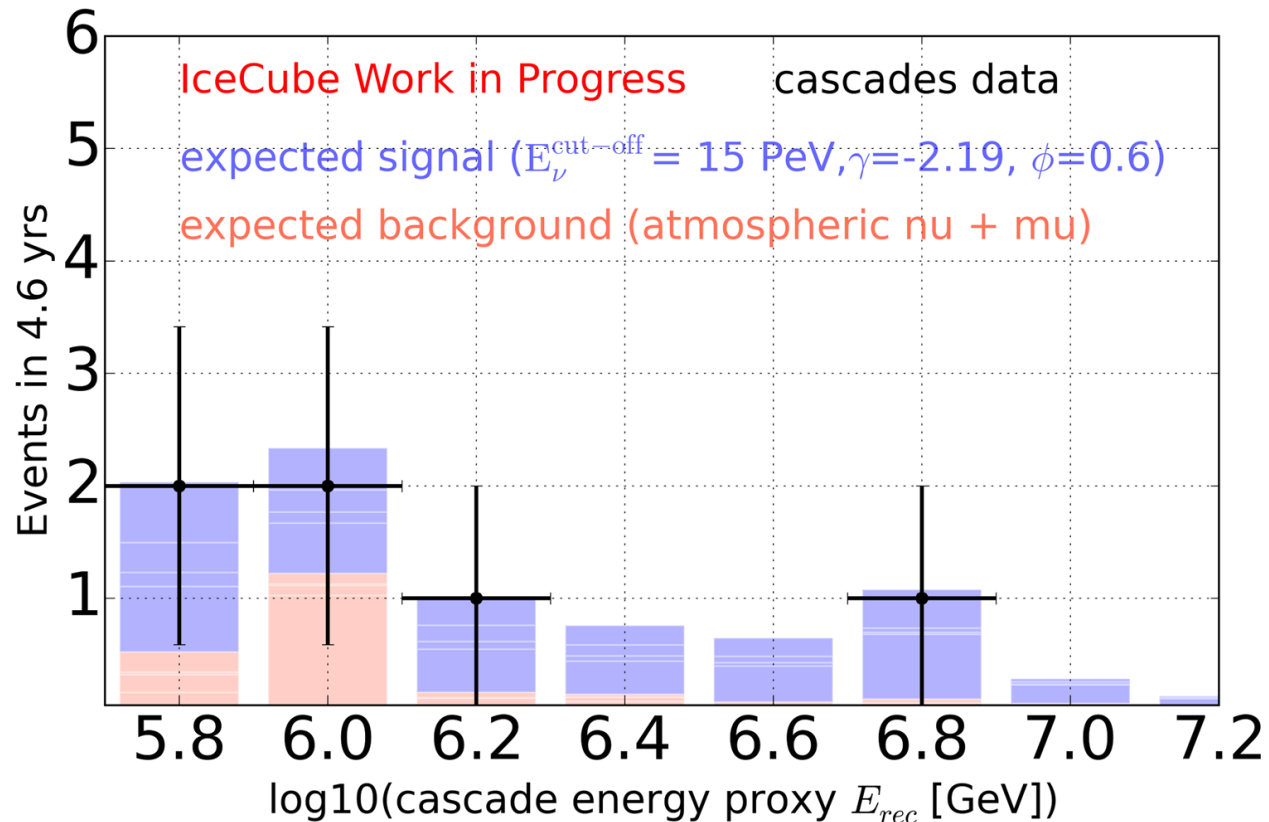For example below shows comparing cascade data to when assuming cut-off energy at 15 PeV

IceCube Work in Progress — cascades data

expected signal ($E_\nu^{\text{cut-off}}$ = 15 PeV, γ=-2.19, ϕ=0.6)

expected background (atmospheric nu + mu)

Events in 4.6 yrs

log10(cascade energy proxy E_{rec} [GeV])

In total 10 events are with energy proxy > 400 TeV
2 from contained cascades
4 from up-going track
4 from partially contained cascades

One more year of data will be added

Fit for cut-off combining track and cascade samples is planed.

We Need Gen2 to resolve >PeV flux!

CONCLUSIONS

- A **new** event selection which has **no overlap** with existing event selections were developed to search for **PeV** partially-contained **cascades**.

- The sensitivity to the **Glashow** resonance is **~2** compared to the contained cascades.

- **One event was found with energy far beyond PeV**. It is partially-contained cascade and brighter than all published PeV events. Preliminary study shows it is ~ 6 PeV. **We are still investigating the probability for this event to be due to muon background**. This event is however is unlikely to be originated from cosmogenic origin.

- In total 10 events were found with energy proxy > 400 TeV from 4.6 years of data taking. **They are consistent with best-fit from 8 years up-going diffuse numu with a cut-off.** More studies are under way to combine track and cascade channels for constraining the cut-off.
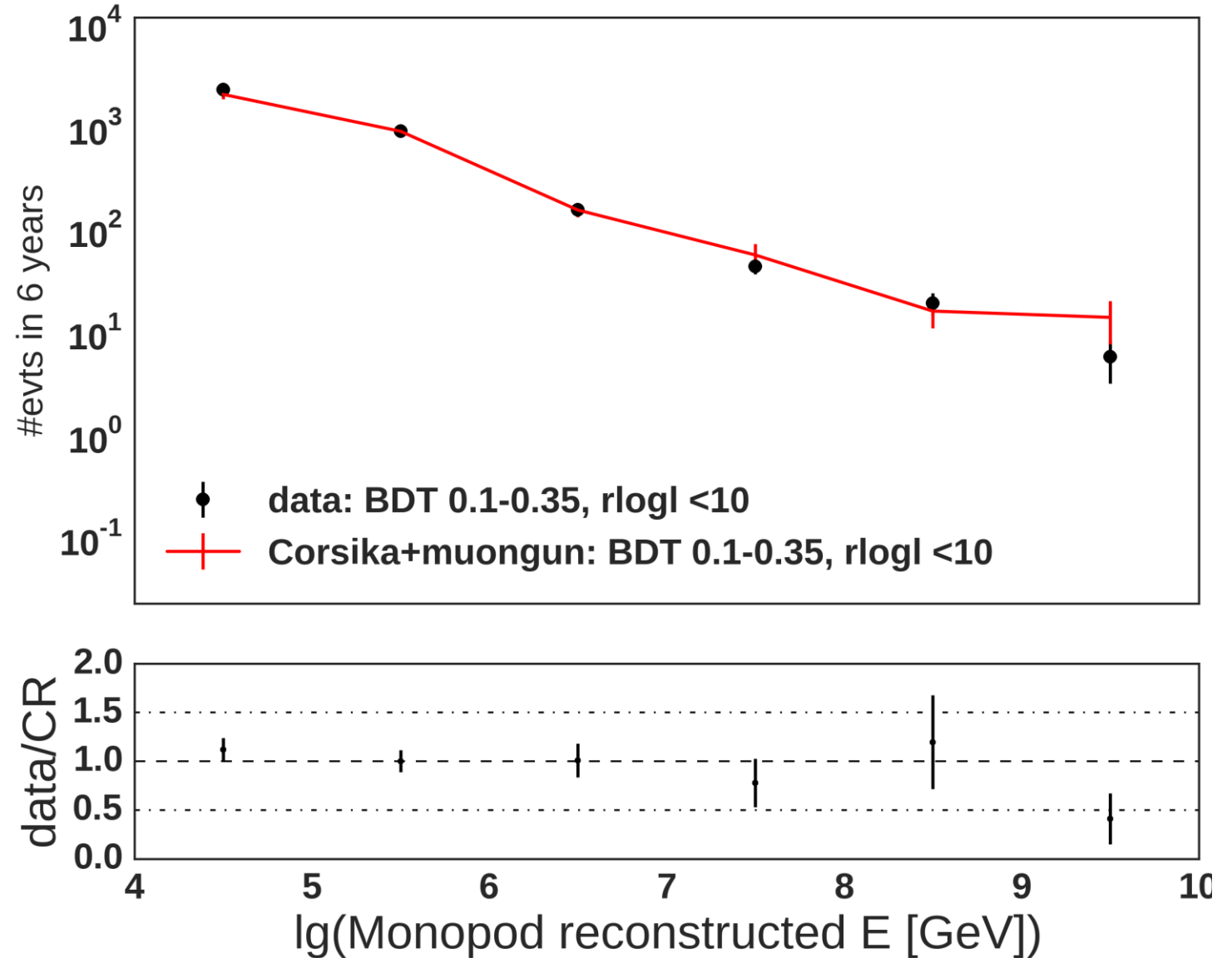
Holographic IceCube

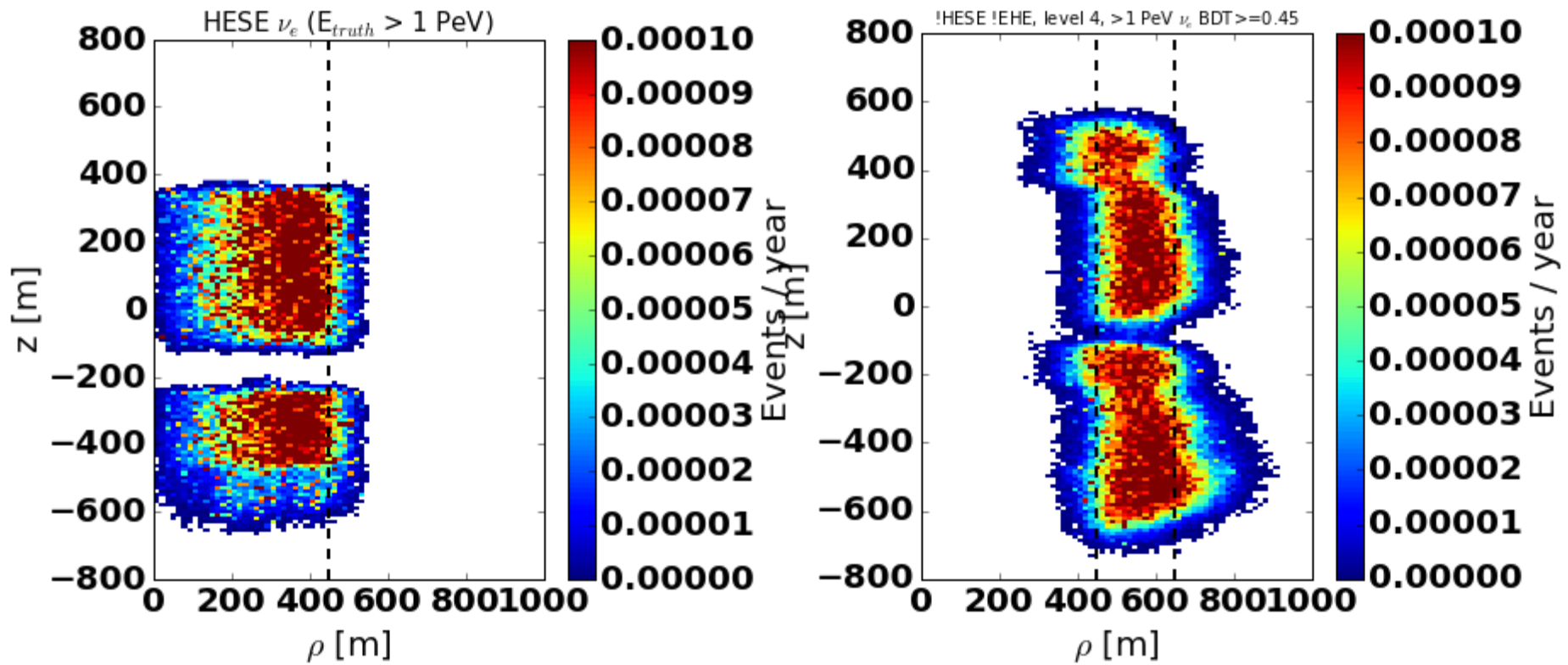# Visualise IceCube PeV events with Augmented Reality
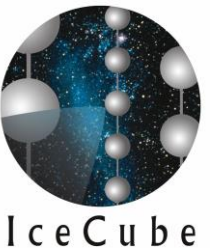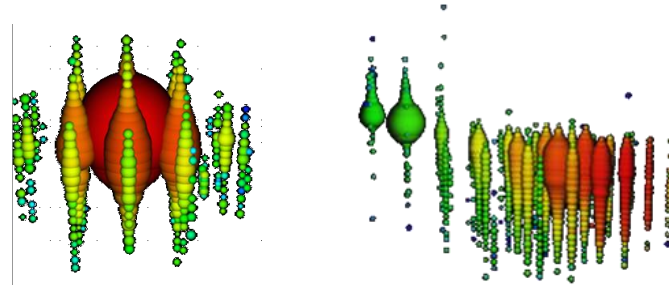
lu.lu@icecube.wisc.edu

backup

- We are able to measure the muon background energy spectrum by selecting a sub-sample at close-to-signal region.
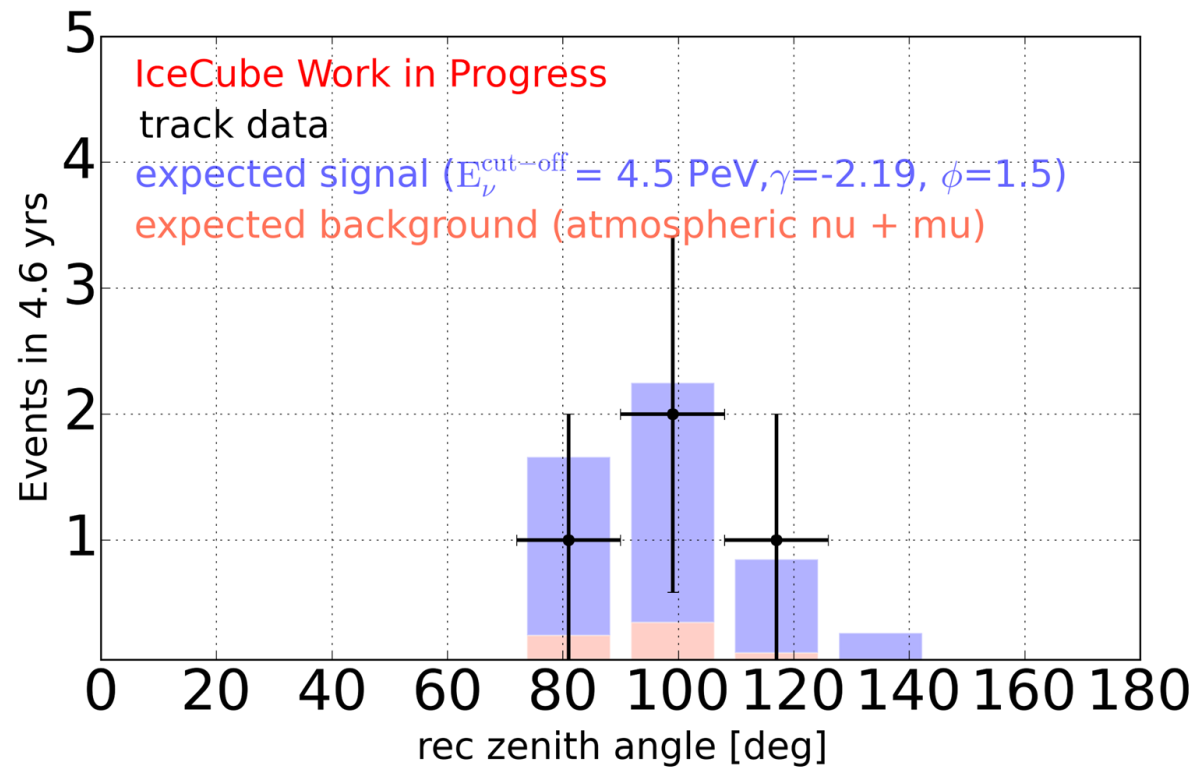
- Good data-MC agreement was observed

WHY HESE PEV EVENTS ARE ALL ABOVE Z=0

At the highest energies $E_{proxy} > 400$ TeV

ZENITH ANGLE DISTRIBUTION OF TRACKS

C. Haack, PoS(ICRC 2017)981

$$\Phi = 10^{-18} \times 1.5 \times (\frac{E}{100TeV})^{-2.19} e^{-E/4.5PeV} GeV^{-1} cm^{-2} s^{-1}$$

IceCube Work in Progress
track data
expected signal ($E_\nu^{cut-off} = 4.5$ PeV, γ=-2.19, ϕ=1.5)
expected background (atmospheric nu + mu)

Events in 4.6 yrs

rec zenith angle [deg]

The analysis only looked into 4.6 years of data (2012-2016)
Two of the PeV contained cascades in 2011 **will be added**

In total 10 events are with energy proxy > 400 TeV
2 from contained cascades
4 from up-going track
4 from partially contained cascades

it should be noted that the energy proxy used in the forward fitting are not from the best reconstruction tools which rely on extensive calculations on GPU clusters.

THE 6 PEV EVENT WAS ALSO FOUND IN THE GZK NEUTRINO SEARCH INDEPENDENTLY

The background-only hypothesis - **rejected** by p-value of 0.024% (3.5σ).

The p-value of favoring GZK against E^{-2} -like: **2.47%**. The compatibility of E_ν^{-2} type against GZK-like is **78.8 %,** concluding that the observation is consistent with the existence of astrophysical flux but inconsistent with GZK flux.

GZK model tests

Model	Event rate per livetime	p-value
Ahlers 10 EeV Best	6.96	1.8%
Ahlers 3 EeV Best	5.75	4.6%
Ahlers 1 EeV Best	3.73	19.2%
Kotera SFR	4.80	13.3 %
Aloisio SFR	6.31	4.1 %

THE CUT-OFF IS NOT SIGNIFICANT DUE TO LIMITED STATISTICS FOR >400 TEV EVENTS

The Glashow energy bin provides probe for constraining cut-off energy, however, the flux is low and we only have one data point...
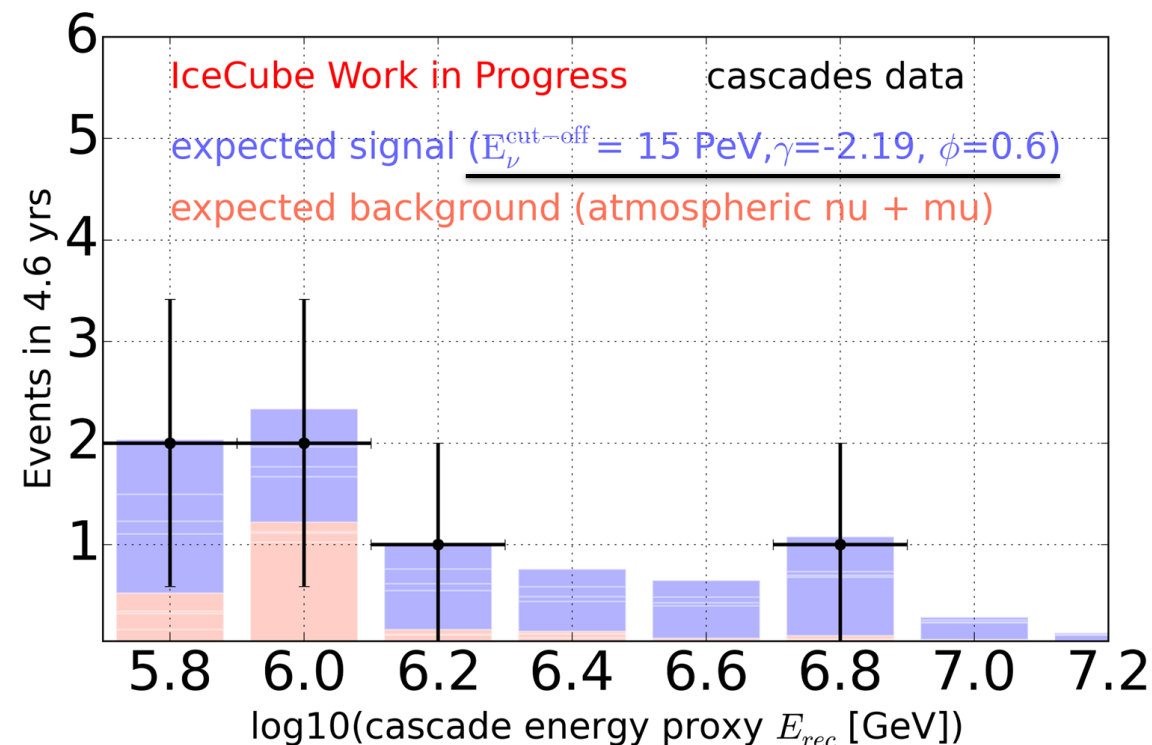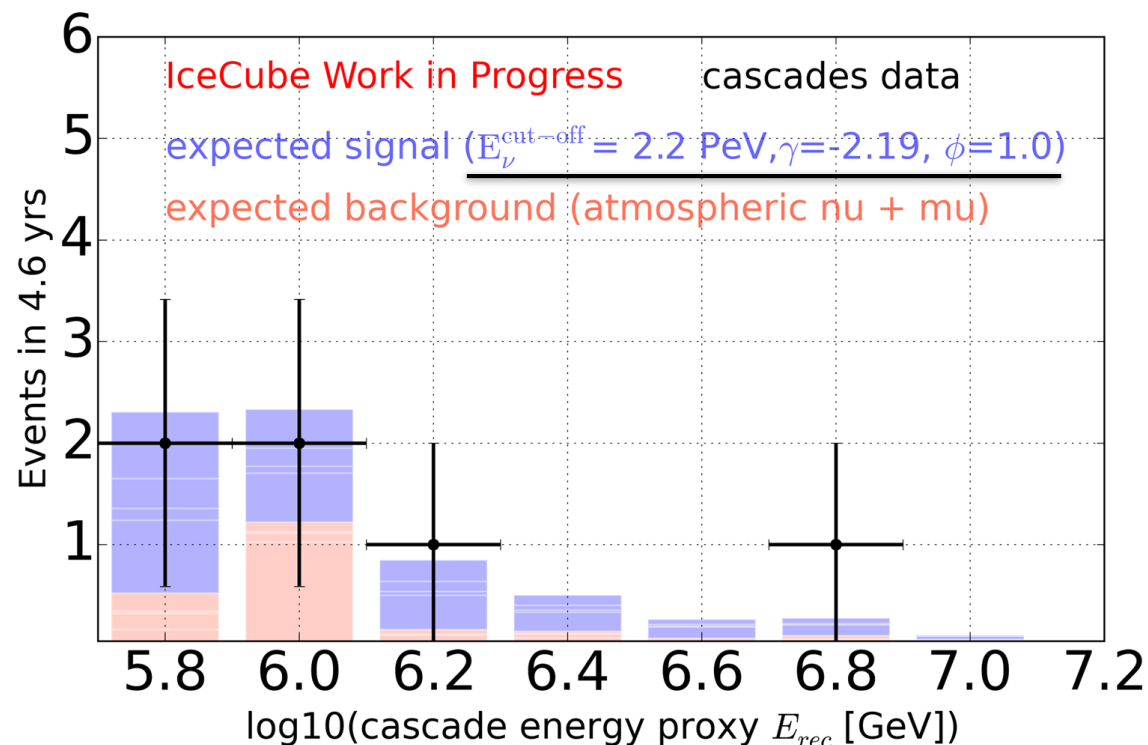
work in progress to combine all channels **and to include systematic errors**

one more year of data will be added