Calibrating the IceCube's optical array with cosmic ray events

Xinhua Bai, SDSMT

April 9, 2021

This talk summarizes what (some) we did before for AMANDA and IceCube using cosmic ray events measured by SPASE-2 and IceTop. Calibrations and associated systematics a surface array may provide for Gen2 optical array will be outlined for discussion.

Acknowledgement

US NSF EPSCoR RII Track-2, award number: 2019597.

Outline

1. My understanding of the importance of hybrid calibration (brief)
2. Some work we did with SPASE/AMANDA and IceTop/IceCube (forgive me if I missed anything, I am sure I did.)
   2.1 Calibrations
   2.2 Properties of high energy (in-ice) muon and bundle of muons
3. What I think important for Gen-2 (for discussions)

1. My understanding of the importance of hybrid calibration

- Completely lost
- Useful for debugging, fine tune
- Risk in making discovery

- Data ———————— we must live with
- **Instrument calibration** — correct | wrong | correct | wrong
- Simulation ———————— correct | wrong | wrong | correct

Whether the simulation is correct or not is a nontrivial question in Gen2

- Simulation ———————— correct | wrong | wrong | correct
- Reconstruction ———————— correct | wrong | ~correct | wrong
- Physics ———————— correct wrong

Alternative calibrations: moon shadow, modulations, comparison with results from other experiments, etc.

The importance of hybrid calibration: Cosmic rays can be used for both instrument and alternative calibrations, in addition to the calibration by other means

- **Simple comparisons between data and Monte Carlo or between Monte Carlo true and Monte Carlo reconstructed are not enough, which we often use to determine systematics.**

2. Some work we did with SPASE/AMANDA and IceTop/IceCube

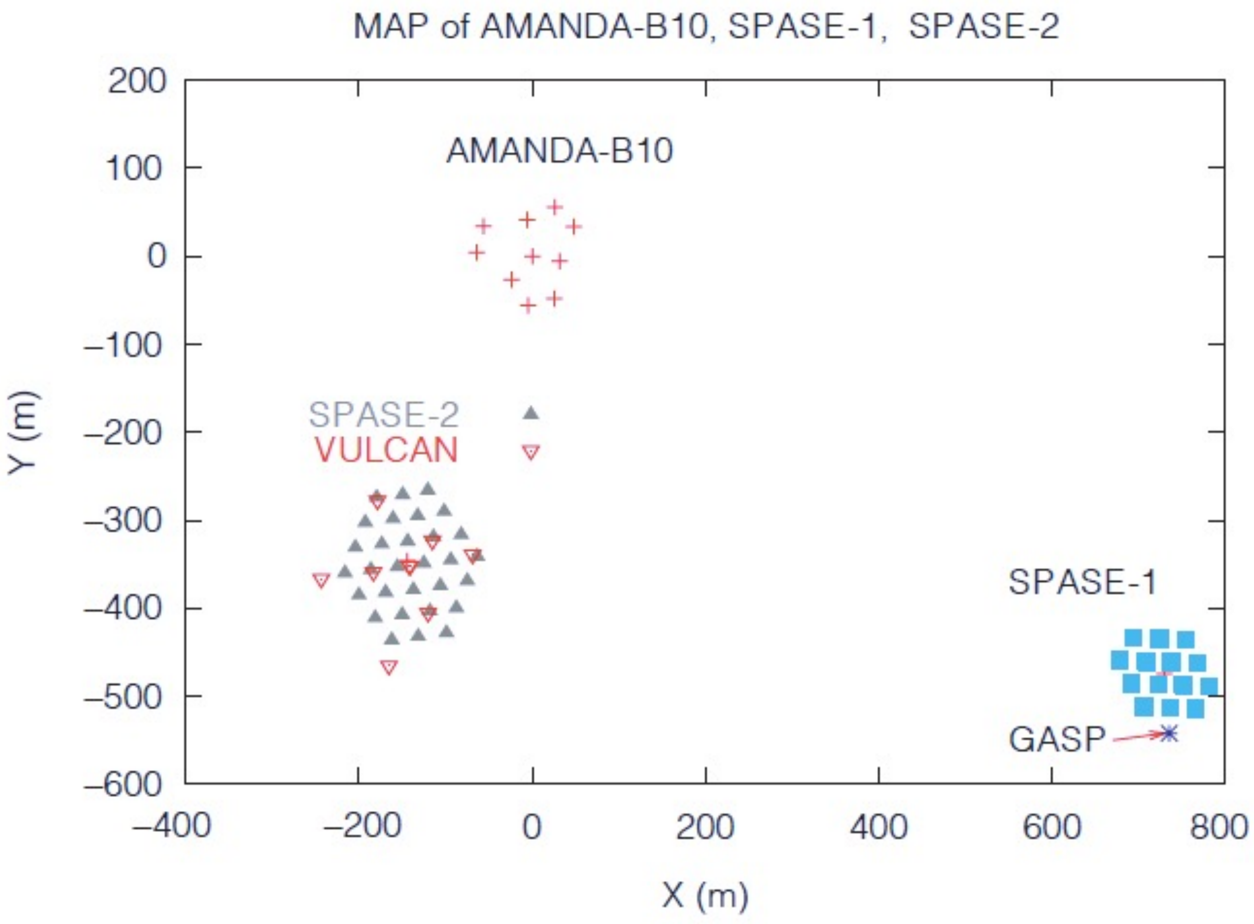
Available online at www.sciencedirect.com
SCIENCE DIRECT
ELSEVIER
Nuclear Instruments and Methods in Physics Research A I (IIII) III–III
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A
www.elsevier.com/locate/nima

Calibration and survey of AMANDA with the SPASE detectors

Proceedings of ICRC 2001: 1 © Copernicus Gesellschaft 2001
ICRC 2001

Calibration and Survey of AMANDA with SPASE

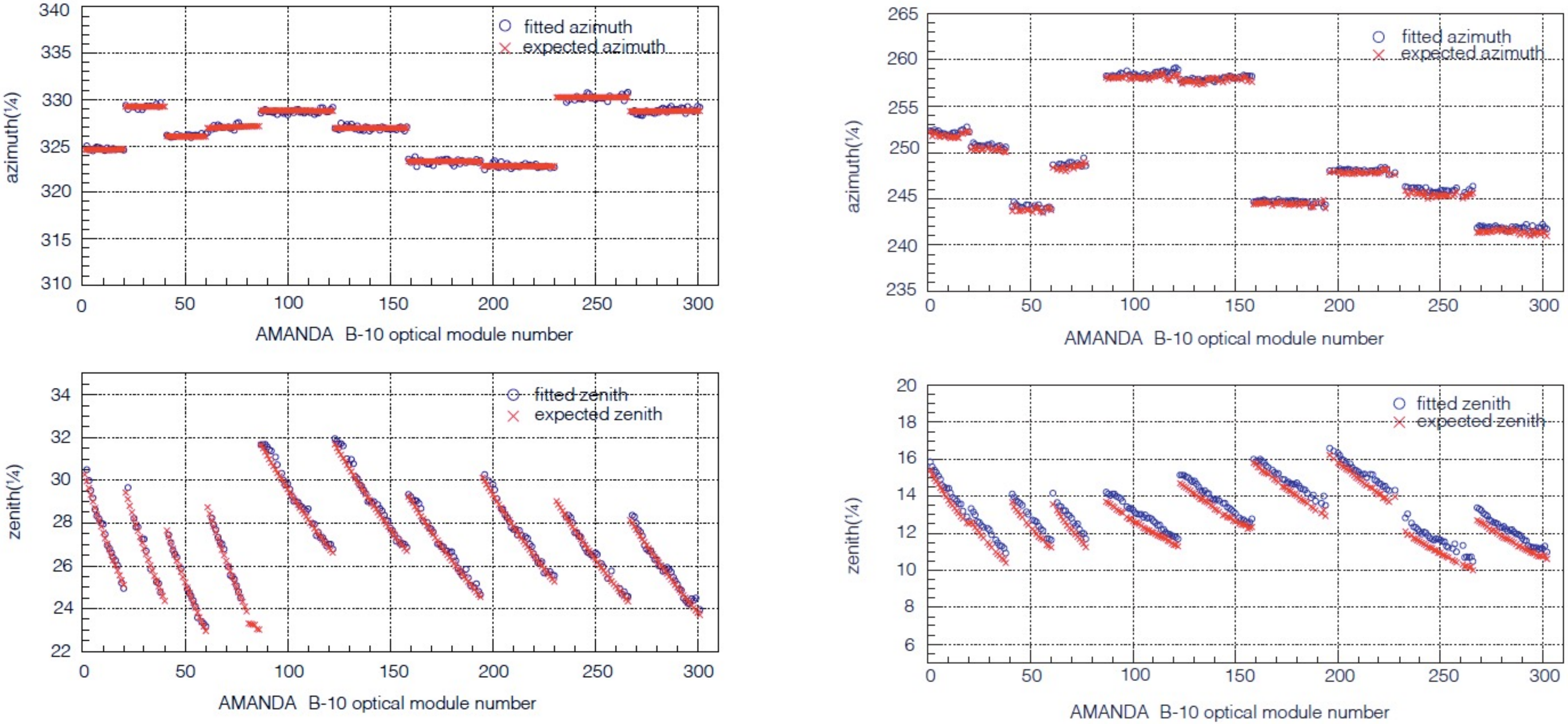
X. Bai[1], R. Engel[1], T.K. Gaisser[1], J.A. Hinton[2], A. Karle[3], M. Kowalski[4], D. Martello[5], T. Miller[6], K. Rawlins[3], K. Rochester[2], G.M. Spiczak[1], Todor Stanev[1], A.A. Watson[2], and the AMANDA Collaboration[7]



Left: Map showing locations of SPASE-1 and SPASE-2 relative to locations of AMANDA-B10 strings at the surface.

A line from the center of B10 to the center of SPASE-2 has a zenith angle of 12 degrees. The corresponding angle to SPASE-1 is 26 degrees.

Muon tomography: Muon survey of AMANDA B10, view from SPASE-1 (left) and SPASE-2 (right).

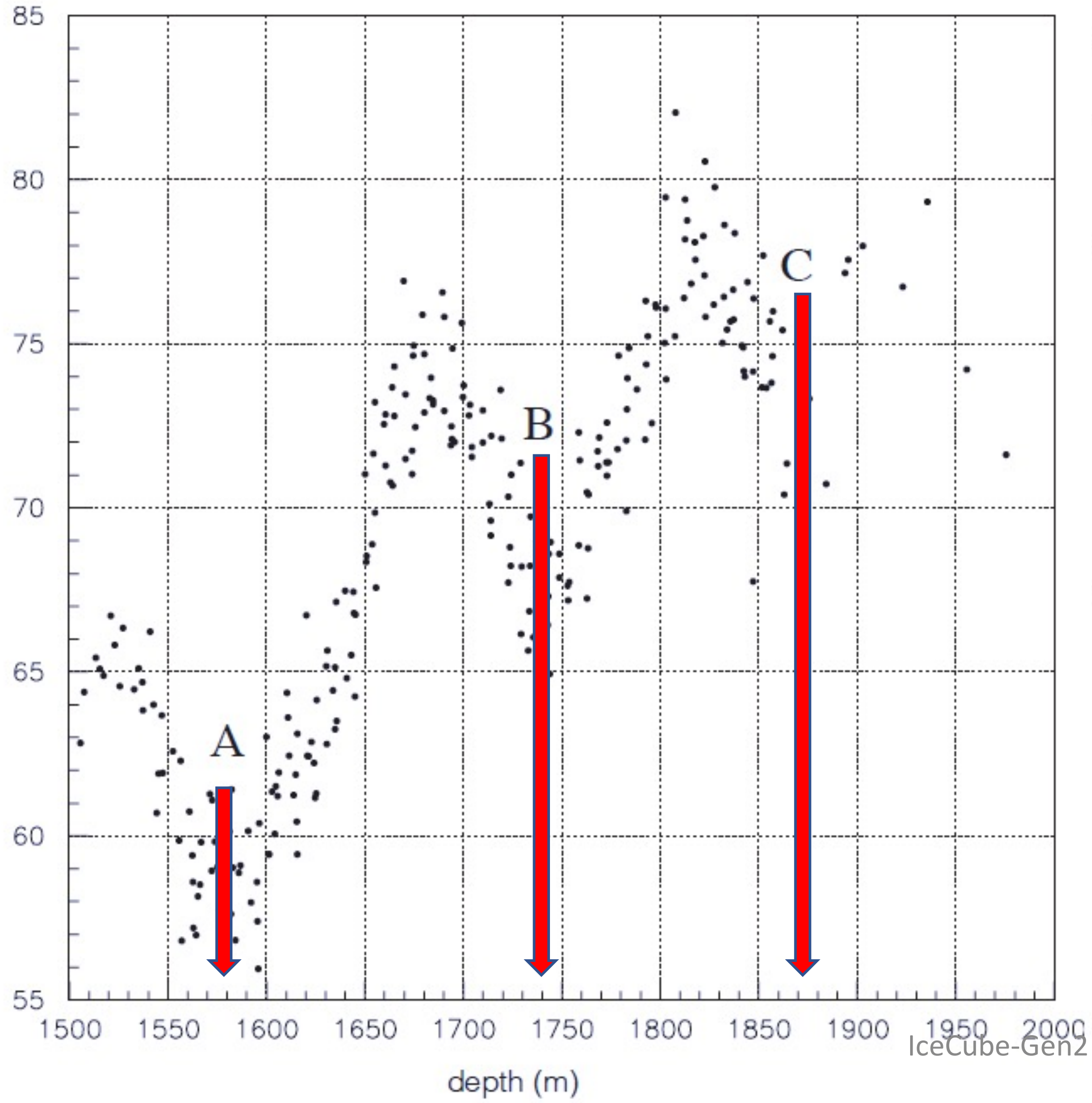


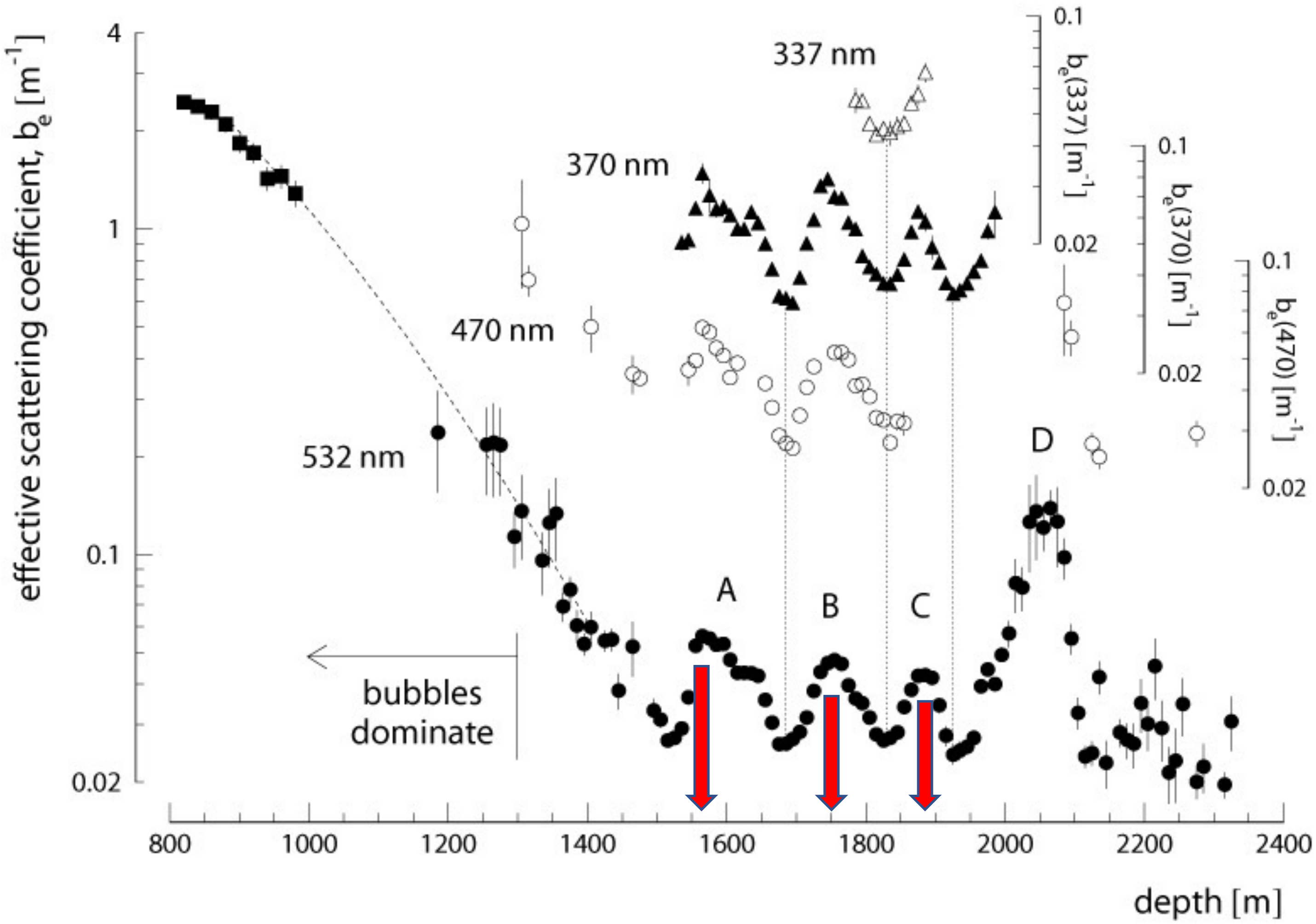
(1) The agreement with the nominal OM locations is within ~0.5° in azimuth (laterally ~3 m). A 0.5° **systematic** offset in zenith – caused by the trigger biases due to the steep zenith angle distribution have not been explicitly removed

(2) The zenith offset has a 2nd order periodic dependence on OM number → a visible bias for events passing above or below the OMs depending on the clarity

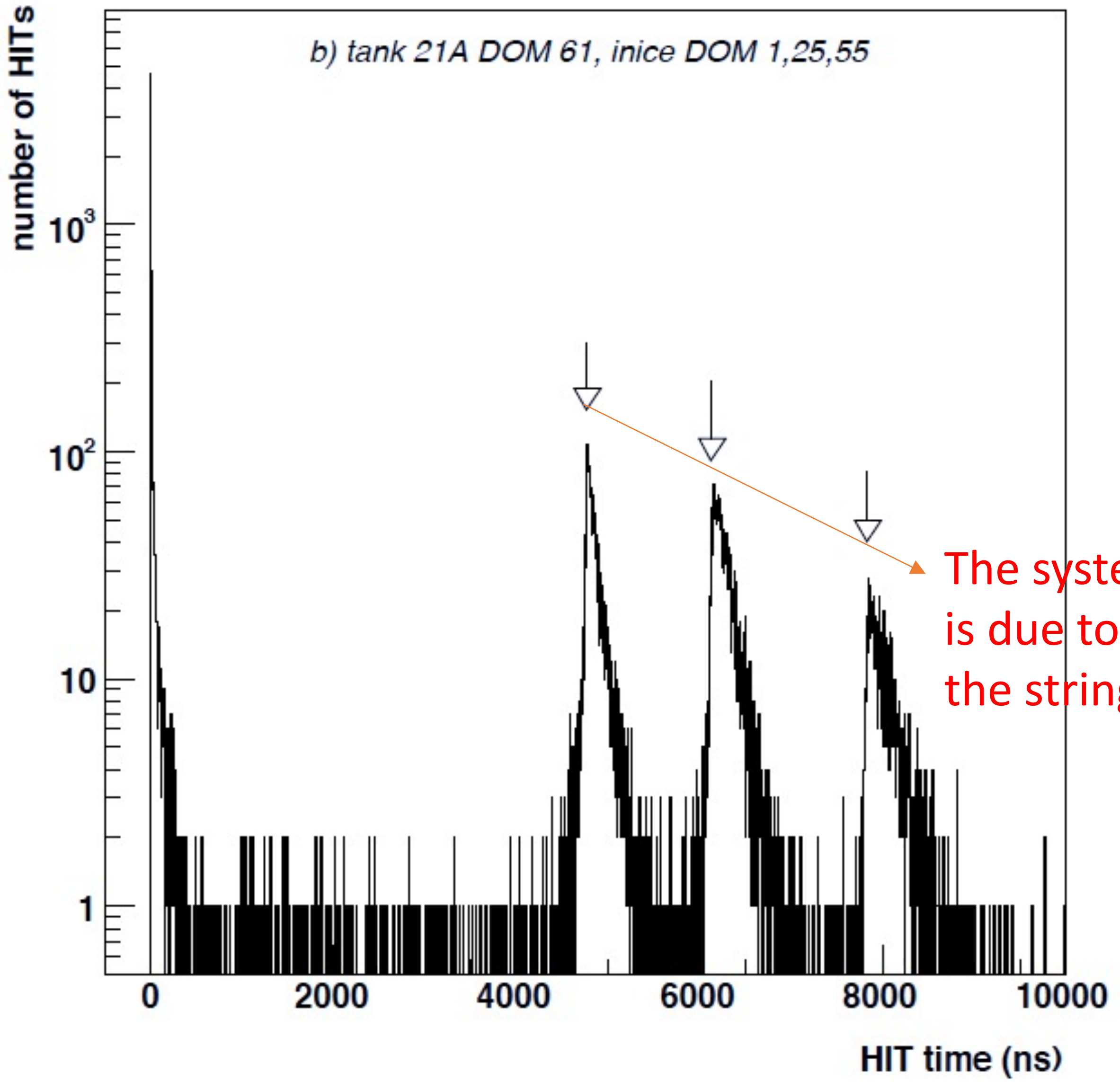
Ice properties: Measure the effective attenuation length of the ice by comparing the response of OMs at different depths to showers as a function of impact parameter. – A very rough method, quite dirty analysis.

The varying ice clarity as a function of depth.





Time synchronization and depth of the DOMs:



arXiv.org > astro-ph > arXiv:astro-ph/0604450v2

Astrophysics

[Submitted on 20 Apr 2006 (v1), last revised 25 Apr 2006 (this version, v2)]

First Year Performance of The IceCube Neutrino Telescope

The IceCube Collaboration

Figure: A distribution of times for events in which at least one of 3 specific DOMs on String-21 (1, 25 and 55) is hit in coincidence with a specific high gain DOM in a surface tank.
-- A very rough method, quite dirty analysis.

The systematic decrease in population of the deeper DOMs is due to muons ranging out between the top and bottom of the string. → A special calibration tool needs more studies.

Time synchronization and depth of the DOMs:

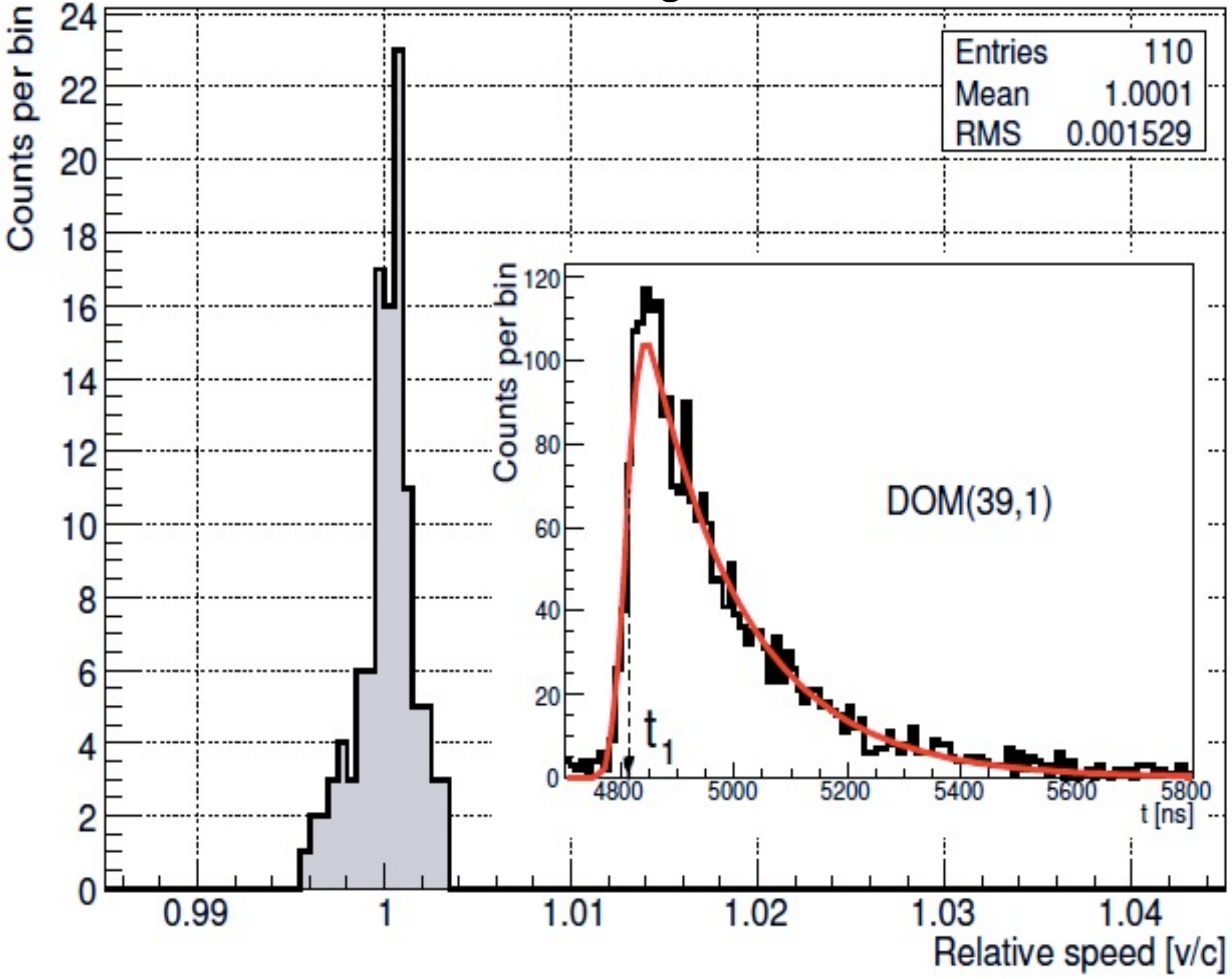
30TH INTERNATIONAL COSMIC RAY CONFERENCE

ICRC'07 Mérida, México

IceTop/IceCube coincidences

XINHUA BAI, THOMAS GAISSER, TODOR STANEV, & TILO WALDENMAIER FOR THE ICECUBE COLLABORATION *

60 DOMs × 2 Strings − 10DOMs = 110 DOMs used

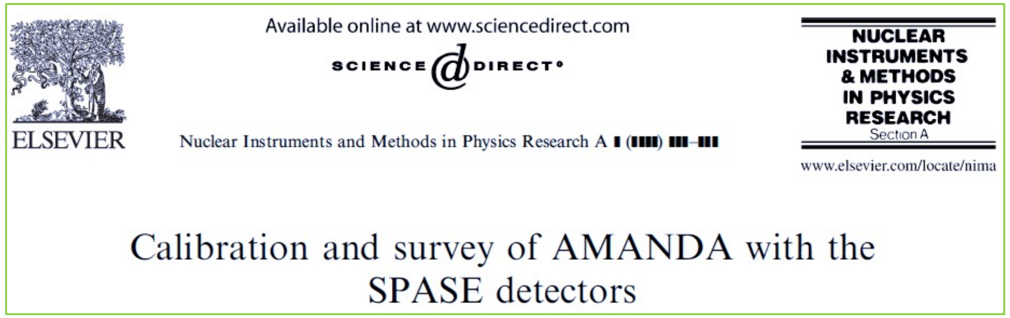


The distribution of muon speed (v) relative to the speed of light (c). The rms of 0.0015 of the distribution of v/c in the Fig. reflects the uncertainties in the system timing, the location of DOMs and the true muon position on the surface.

The rms of 0.0015 corresponds to upper limits on the uncertainty of 12 ns or about 4 m over 2.5 km (4m/2.5km ~ 0.0016).

The cut-in entry shows the time delay on one in-ice DOM → time t_1 to calculate muon speed (v)

Pointing resolution: Distribution of difference between direction assigned by SPASE and that by AMANDA-B10 for coincident events.


Available online at www.sciencedirect.com

SCIENCE DIRECT

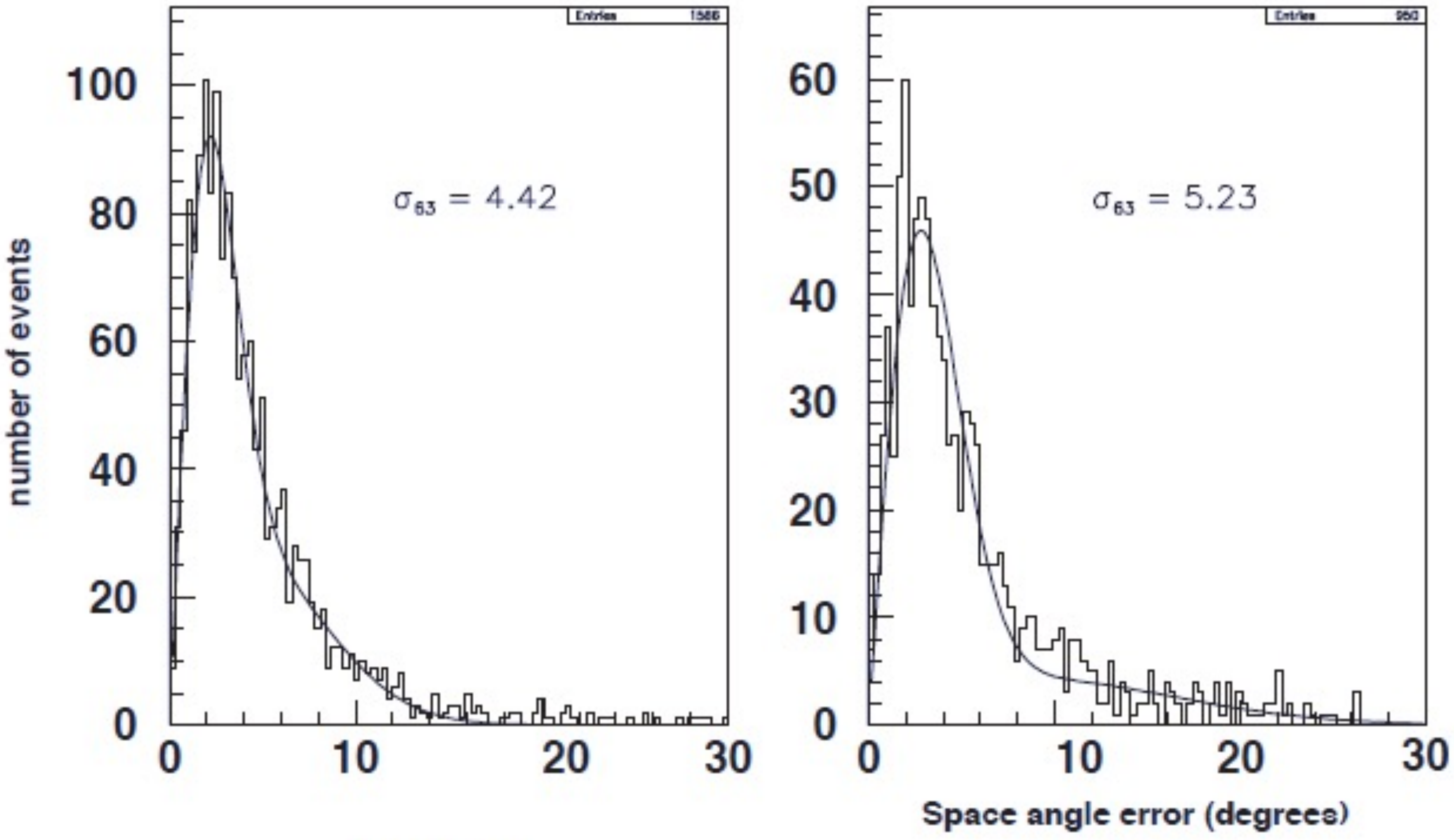
ELSEVIER

Nuclear Instruments and Methods in Physics Research A ▮ (▮▮▮▮) ▮▮▮–▮▮▮

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

www.elsevier.com/locate/nima

Calibration and survey of AMANDA with the SPASE detectors

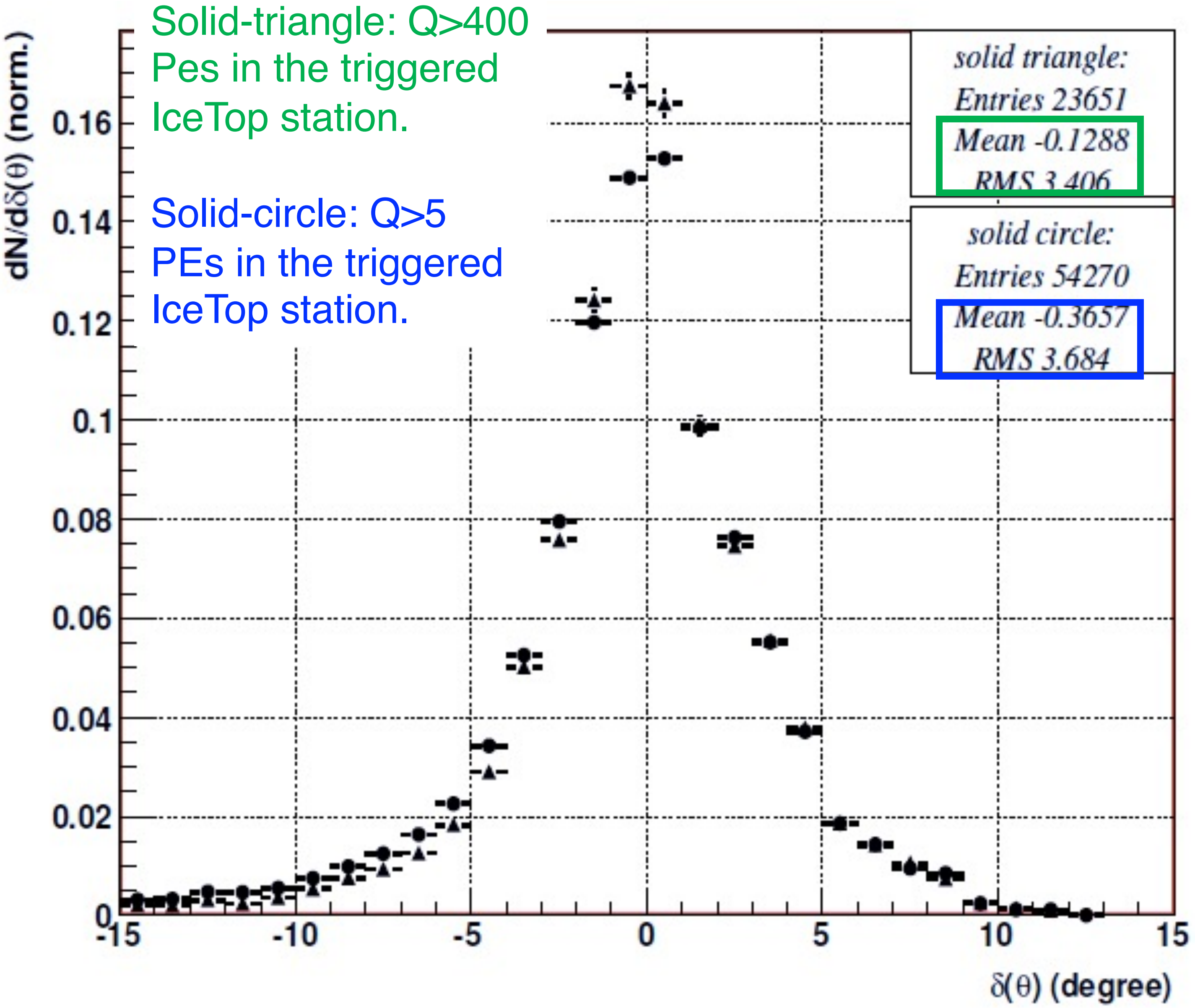


SPASE-1 SPASE-2

- σ_{63}(SPASE) = 1.5 degree
- σ_{63}(B10) = 4.1 degree for events from the direction of SPASE-1
- σ_{63}(B10) = 5.0 from the direction of SPASE-2.

One regret: I don't remember we ever got any useful calibration results for RICE (radio) although we once allowed RICE, SPASE and AMANDA to trigger each other.

Pointing resolution: Figure is the difference between the **zenith angle defined by the line connecting triggered IceTop station and the COG of triggered in-ice DOMs** and **that by the in-ice reconstruction** **-- A very rough method.**



30TH INTERNATIONAL COSMIC RAY CONFERENCE

ICRC'07 Mérida, México

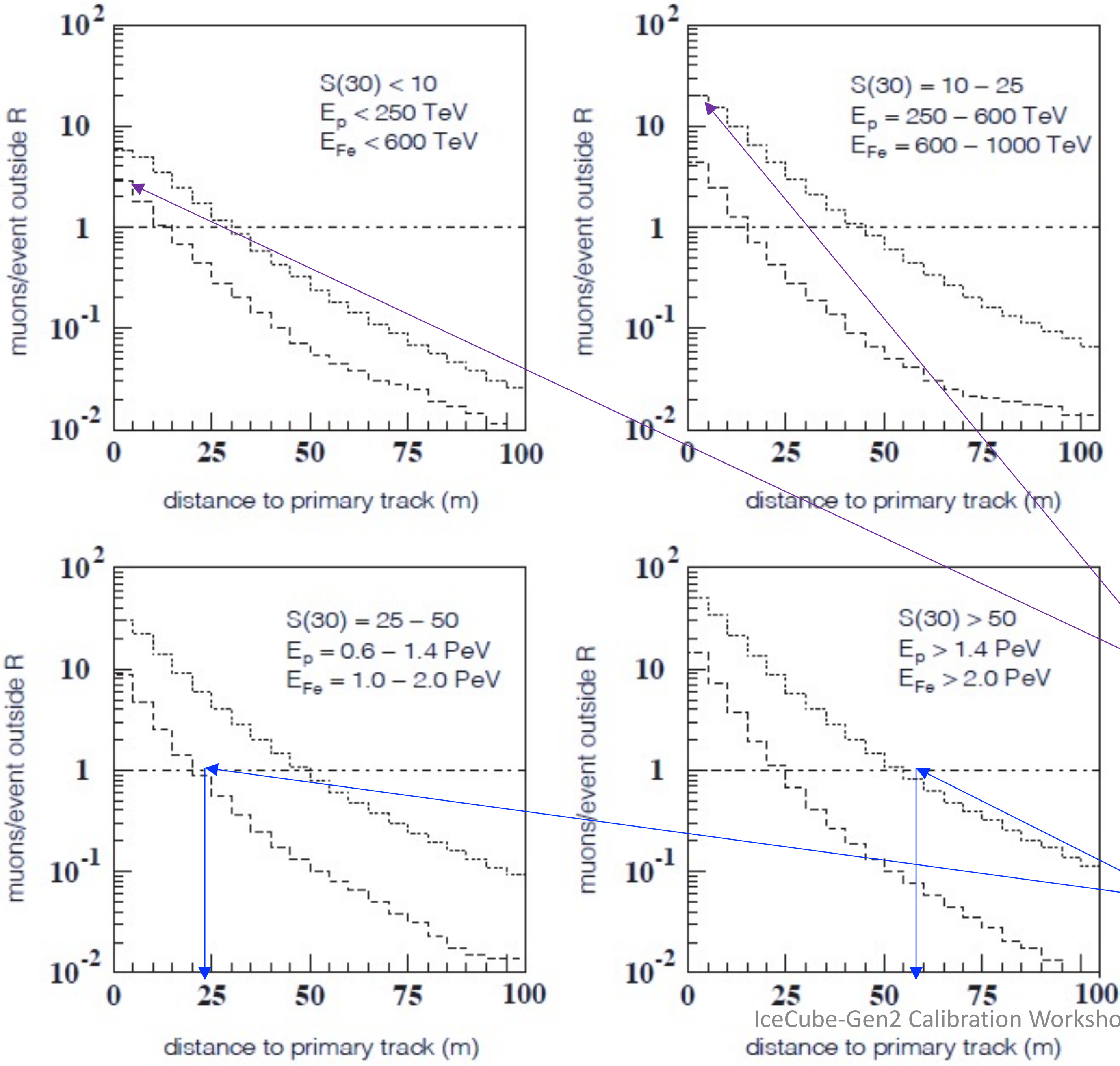
IceTop/IceCube coincidences

XINHUA BAI, THOMAS GAISSER, TODOR STANEV, & TILO WALDENMAIER FOR THE ICECUBE COLLABORATION *

Takeaway:

- **Most of these analyses were rough; Number of events were often limited**
- **Better accuracy should be possibly achieved for similar calibrations in Gen-2.**

Properties of high energy (in-ice) muon and bundle of muons: mean multiplicity and spread



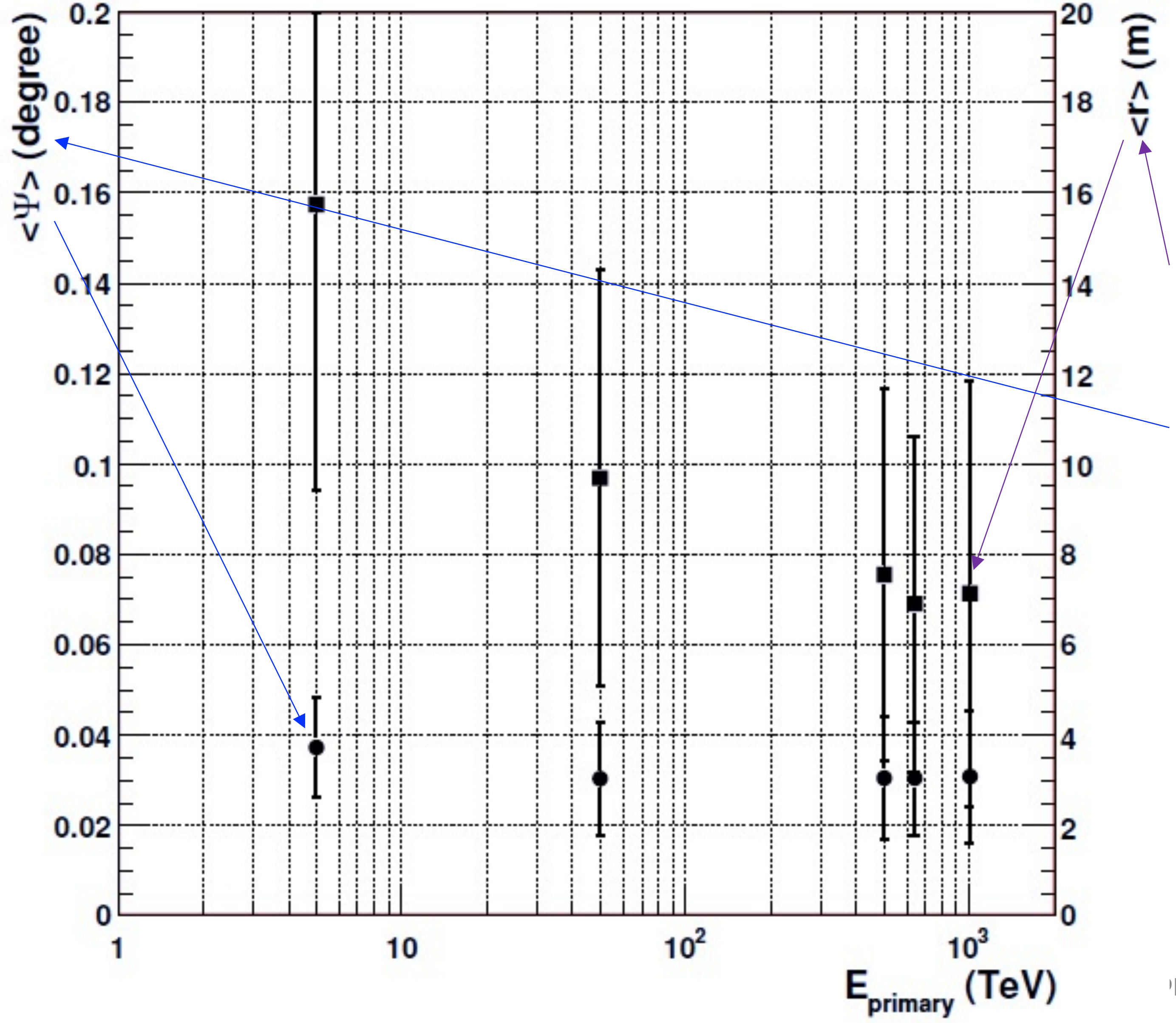
Thank to the better detection techniques, in IceCube and Gen-2, I believe ultimate limits on the accuracy of calibration using CRs largely depend on properties of high energy muons in EASs.

Integral lateral distribution of muons *at the depth of AMANDA* for simulated proton (dashed) and iron (dotted) showers. The plot shows the average number of muons at distances larger than a given radius for the four S(30) intervals described in the text.

The intercept at zero radius is the average muon multiplicity.

Where the histograms meet the horizontal line marks the distance beyond which there is on average less than one muon.

Properties of high energy (in-ice) muon and bundle of muons: mean multiplicity and spread



30TH INTERNATIONAL COSMIC RAY CONFERENCE

ICRC'07 Mérida, México

IceTop/IceCube coincidences

XINHUA BAI, THOMAS GAISSER, TODOR STANEV, & TILO WALDENMAIER FOR THE ICECUBE COLLABORATION *

The mean distance r of muons from air shower core (solid square) as function of primary proton energy.

The average space angle between muons and air shower axis (solid circle)

The error bars represent the rms of average space angle and mean distance r.

Only muons with energy above 460 GeV on the surface are counted. Proton showers were produced at the South-Pole altitude by CORSIKA with QGSJET as the high energy hadronic model.

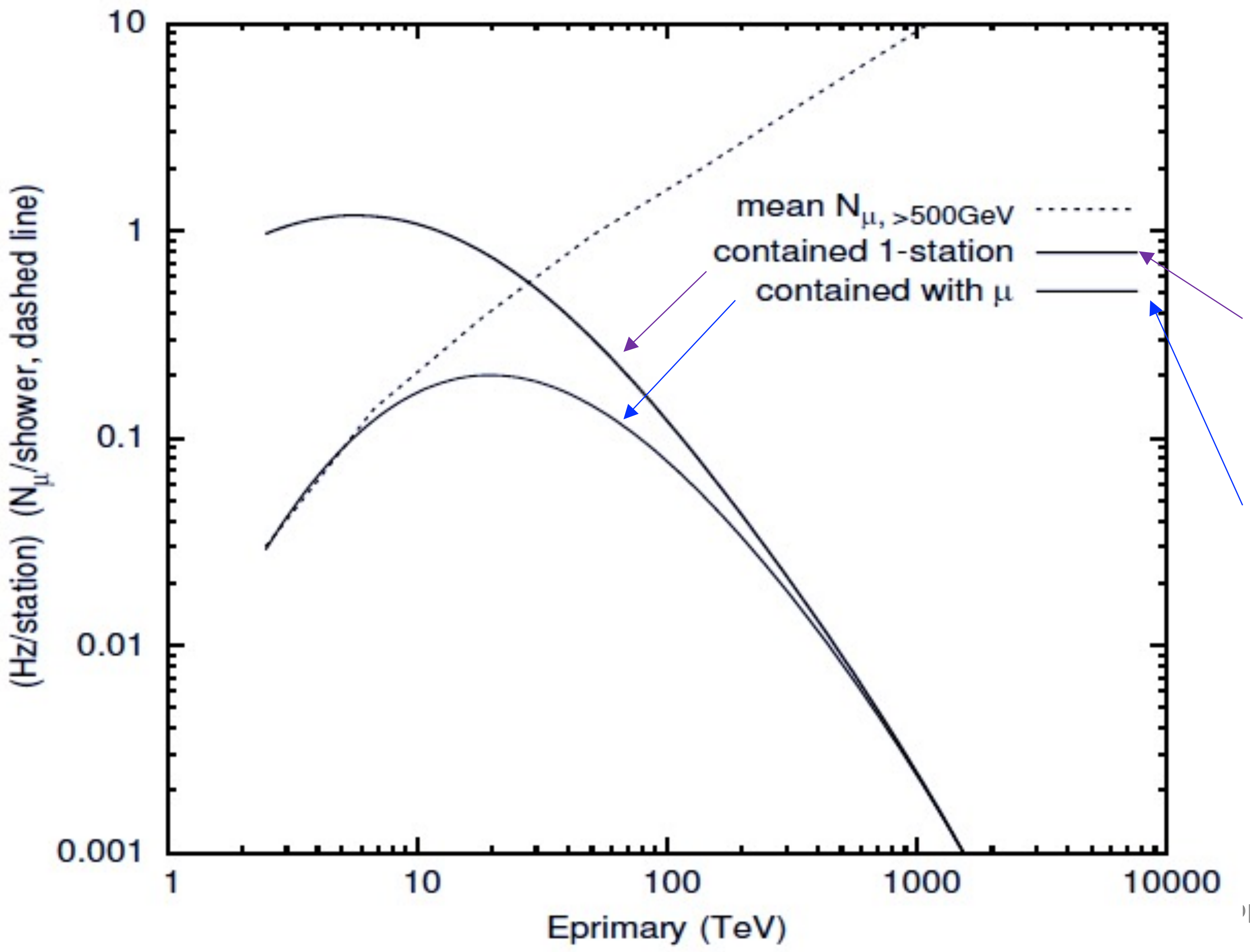
Properties of high energy (in-ice) muon and bundle of muons: small EAS/single station events with HE muon

30TH INTERNATIONAL COSMIC RAY CONFERENCE

ICRC'07 Mérida, México

IceTop/IceCube coincidences

XINHUA BAI, THOMAS GAISSER, TODOR STANEV, & TILO WALDENMAIER FOR THE ICECUBE COLLABORATION *



Response function for **single station events** in IceTop. Only four contained stations were considered.

The dashed line represents the number of muons above 500 GeV at production in a proton shower.

The distribution of primary cosmic-ray proton energies that give single station hits above 30 MeV threshold in each tank.

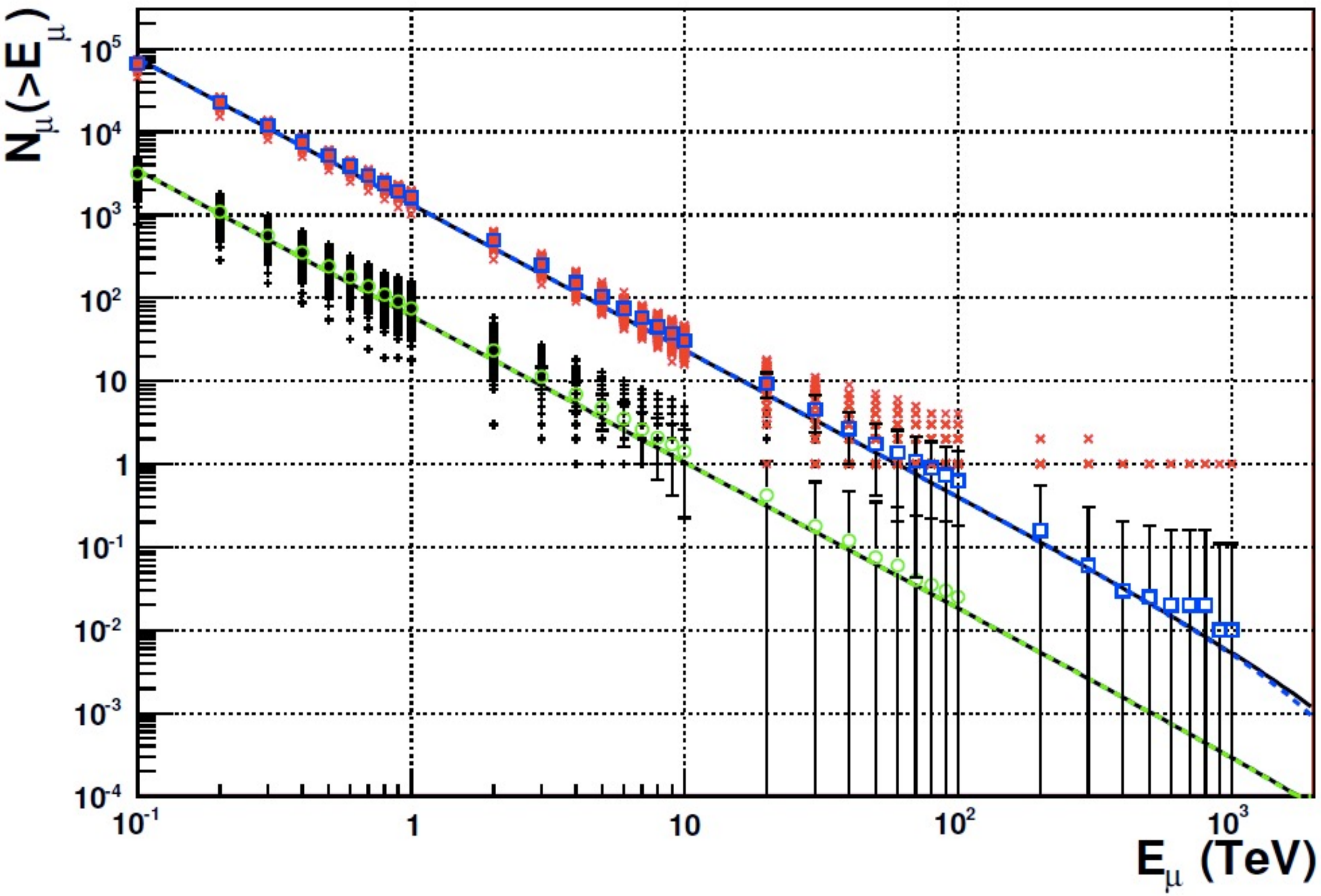
The convolution of the response function with the probability of producing **a muon with E >500 GeV**, corresponding to the distribution of primary energy that gives rise to the single station **coincident** event sample.

Properties of high energy (in-ice) muon and bundle of muons: Number of muons in a bundle, mean and fluctuation

PROCEEDINGS OF THE 31st ICRC, ŁÓDŹ 2009

Muon bundle energy loss in deep underground detector

Xinhua Bai*, Dmitry Chirkin†, Thomas Gaisser*, Todor Stanev* and David Seckel*



Number of muons in the bundles as a function of the muon energy.

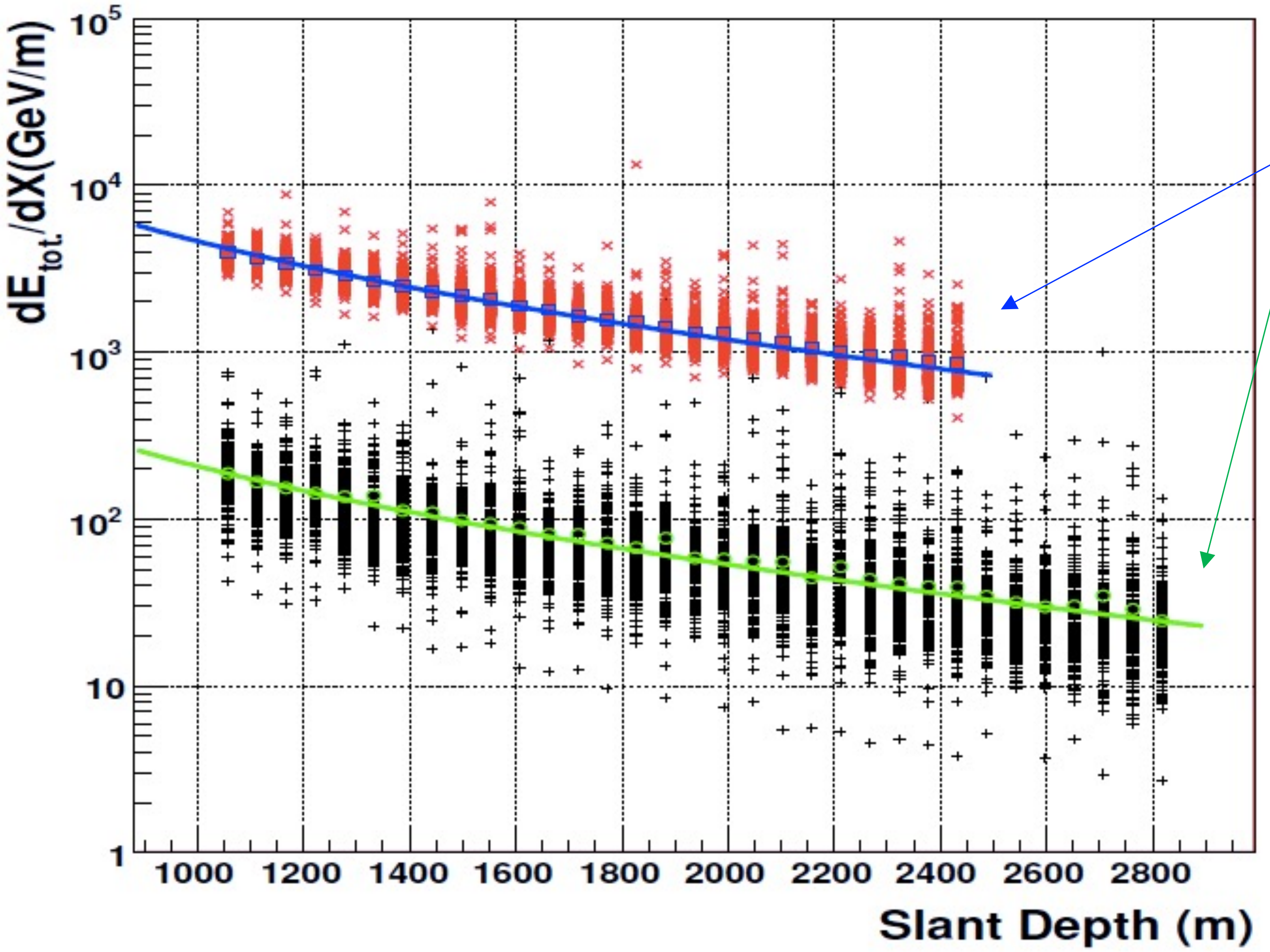
1 EeV iron at 0° zenith (red x).

50 PeV proton at 30° zenith (black +)

The blue open squares and green circles are the averages over all 200 showers at each energy points.

The curves represent Elbert formula.

Properties of high energy (in-ice) muon and bundle of muons: energy loss of high energy muon bundle in deep ice, mean and fluctuation



Muon bundle mean energy loss:

$$\frac{dE_{\mu,B}(X)}{dX} = \omega \cdot b \cdot (p_1 + 1)\frac{1}{V+1}[\frac{1}{p_1+1}(\frac{a}{b})^{-p_1} \cdot V^{-p_1-1} + \frac{1}{p_1}(\frac{a}{b})^{-p_1}V^{-p_1} - \frac{1}{p_1+1}(\frac{a}{b}) \cdot (\frac{E_0}{A})^{-p_1-1} - \frac{1}{p_1}(\frac{E_0}{A})^{-p_1}] \quad (5)$$

Figure: Muon bundle energy loss as function as slant depth.

Red: for vertical 1 EeV iron showers
Black: for 30 degree 50 PeV proton showers.

Open blue squares and green circles are the mean value of the Monte Carlo results for iron and proton showers.

More MC studies have shown that accurate measurement of stochastic energy losses along muon track is very important for

(1) CR mass and energy measurements
(2) Study of prompt muons in >100 PeV CR showers

I think we have a rather reliable understanding of muons in EASs.

What are the ultimate limits on the accuracy of calibration using CRs?

More work is needed to answer this question:

- To improve/fine-tune analysis methods based on the physics properties of EAS, muon and muon bundles
- To use more/recent simulation, reconstruction and data
- To use hybrid/complementary calibration data

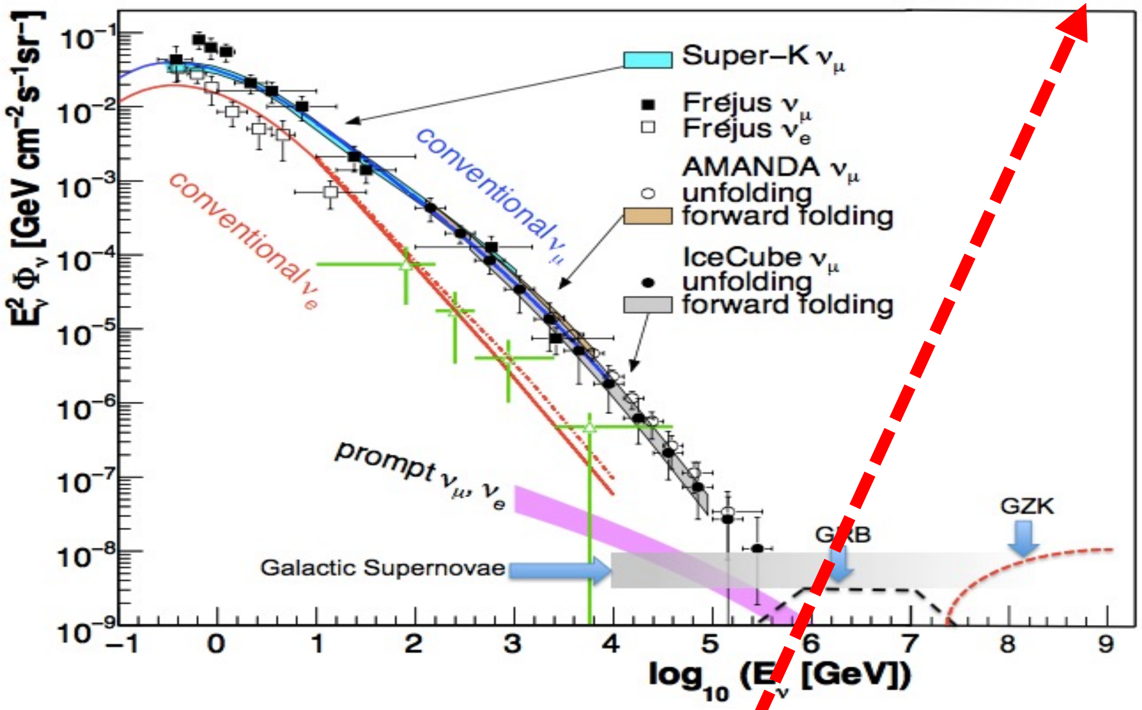
Many of these studies can be done with existing data

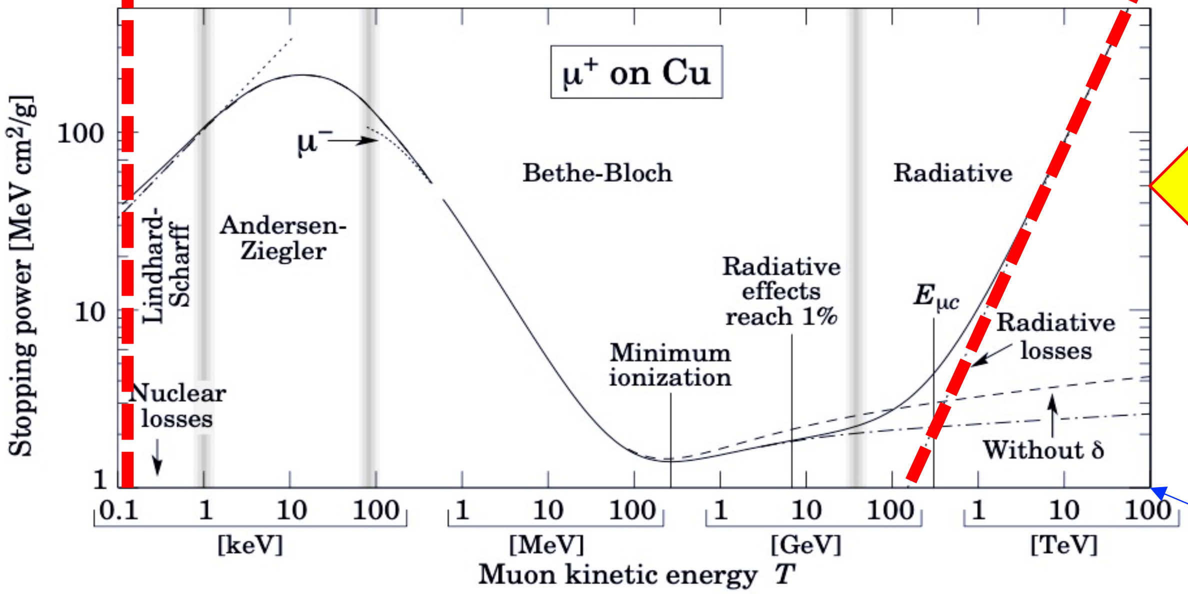
3. Calibrations important for Gen-2, for which CR matters

- Calibration for reliable *absolute energy measurement* at ultra high energies (+1 s)
  - Neutrino astronomy
  - Neutrino physics at unprecedented energies
  - Cosmic ray physics
  - Radio detection
- Calibration for more accurate *energy losses along muon or muon bundle propagation tracks*
  - Comic ray physics
  - Lepton production and atmospheric background for neutrino astronomy at ultra high energies
  - Neutrino flavor identification
- Calibration across *entire Gen-2 detection system* for better reconstruction accuracy:
  - DOM location and array geometry (+1 s)
  - DOM response: Time, charge, and fluctuations (+3 s)
  - Ice property and its impact studied with *true* physics events

How high is the energy/loss which we must care?

>10^7 MeV cm^2/g





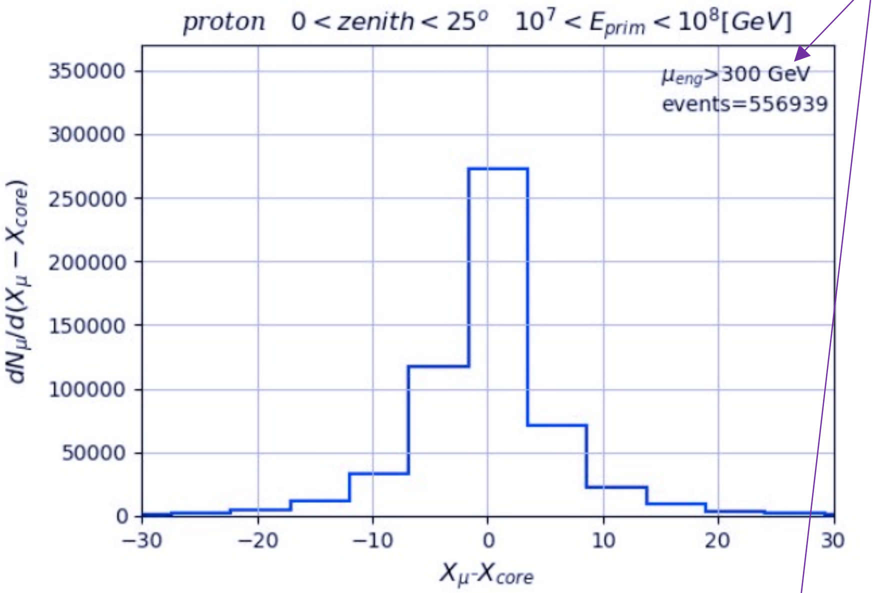
10^5 GeV

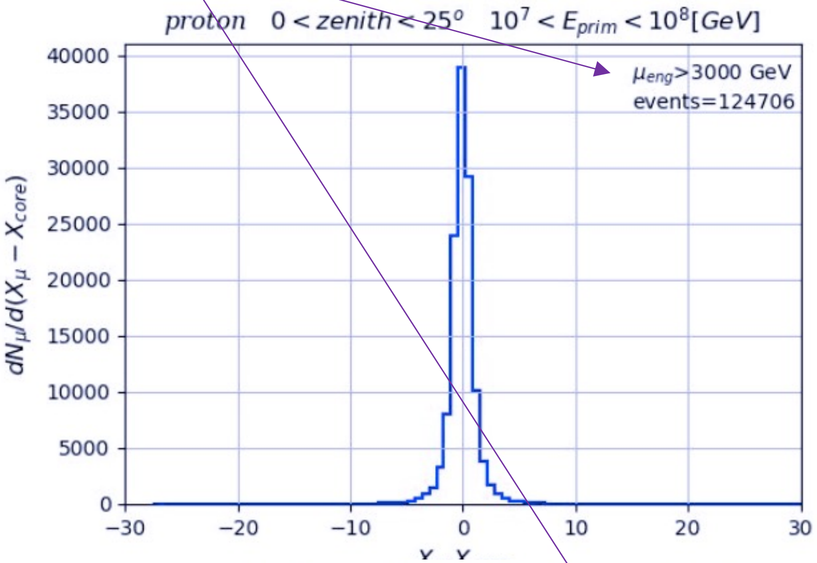
Because I have more confidence in the measurement of CRs and muons than the measurement of astrophysical neutrinos at ultra high energies.

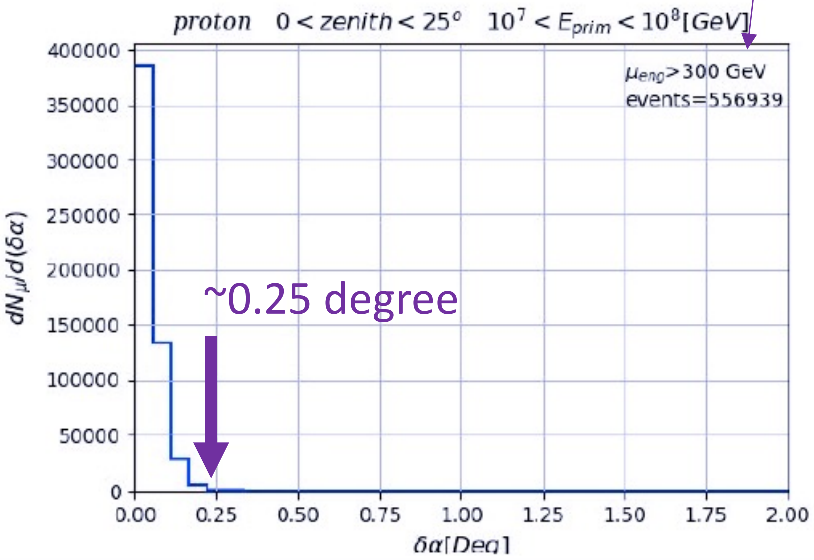
DOM location and array geometry in the entire Gen-2 array

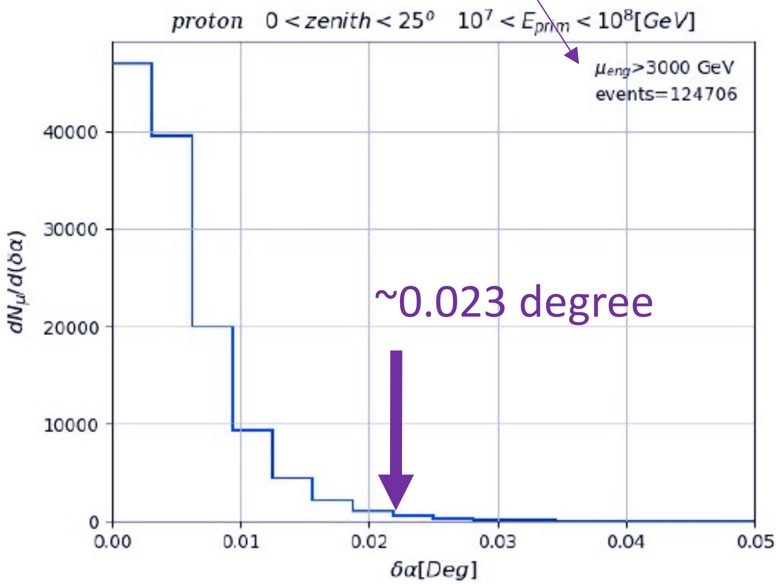
Muon tomography may be more precise by using inclined showers over larger distances. (Thank Diana)

E_muon > 300 GeV E_muon>3000GeV

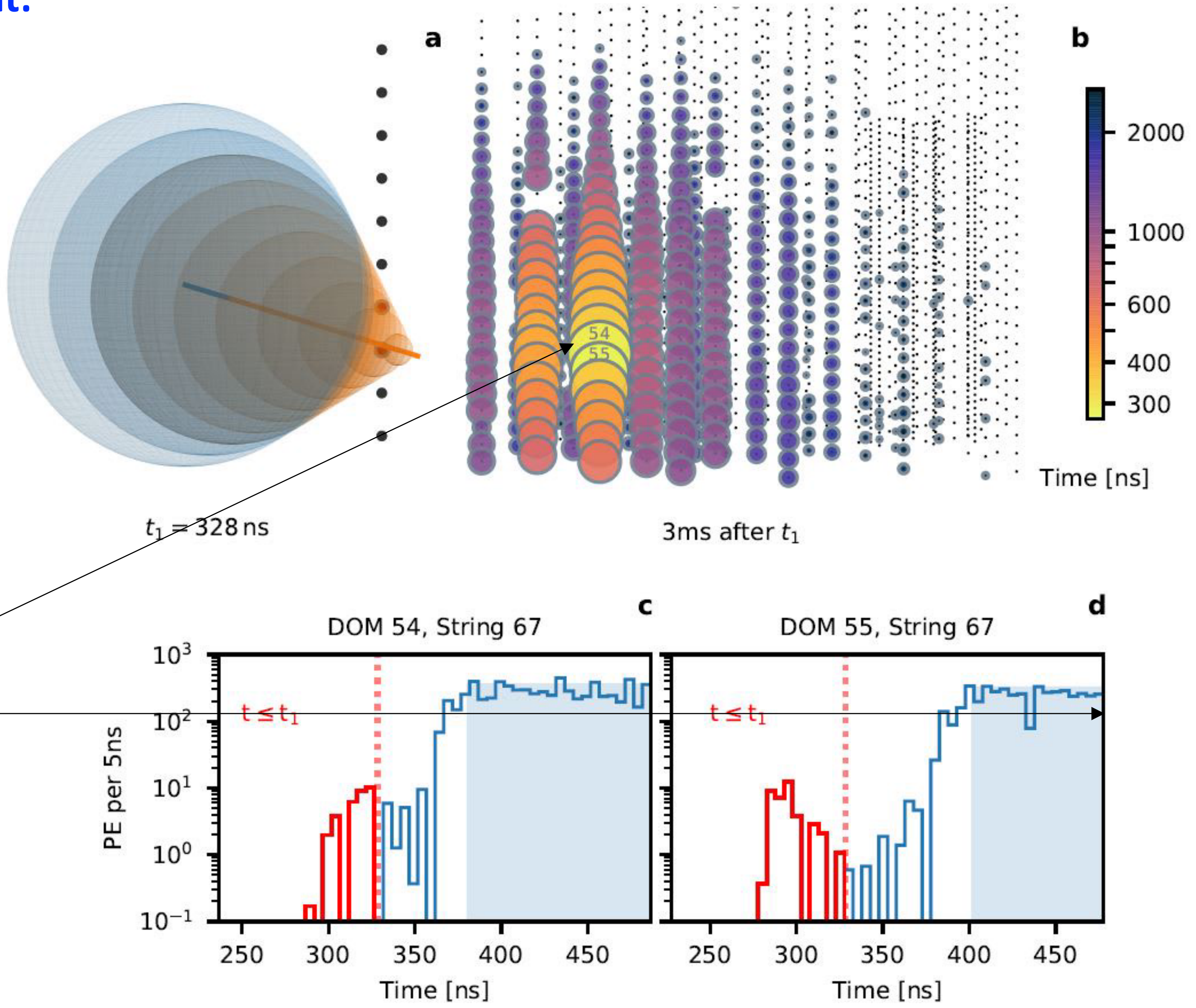








DOM/PMT response to a real event:



>> 100*(500-350)/5= 3,000 PE

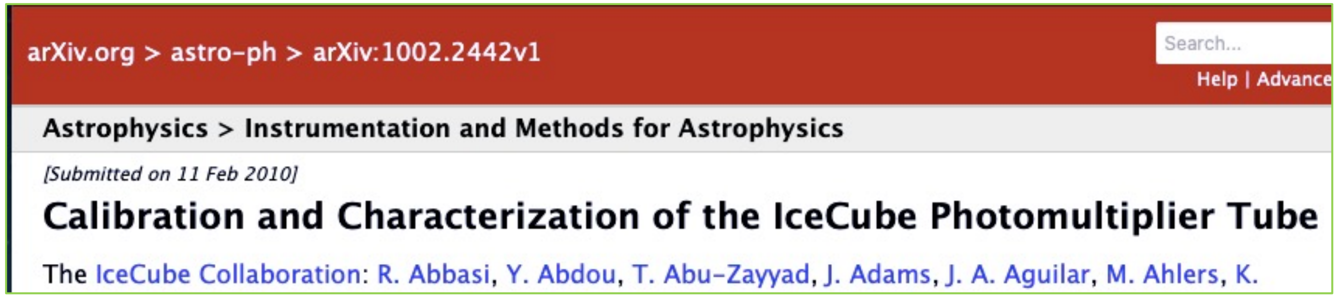
Distributions of the deposited charge over time on the two earliest hit DOMs:

DOM/PMT response: Drop or keep?

The high light level leads to

Left: a substantial afterpulse several hundred ns later

Right: a pre-pulse 30 ns before the main peak


arXiv.org > astro-ph > arXiv:1002.2442v1

Search...

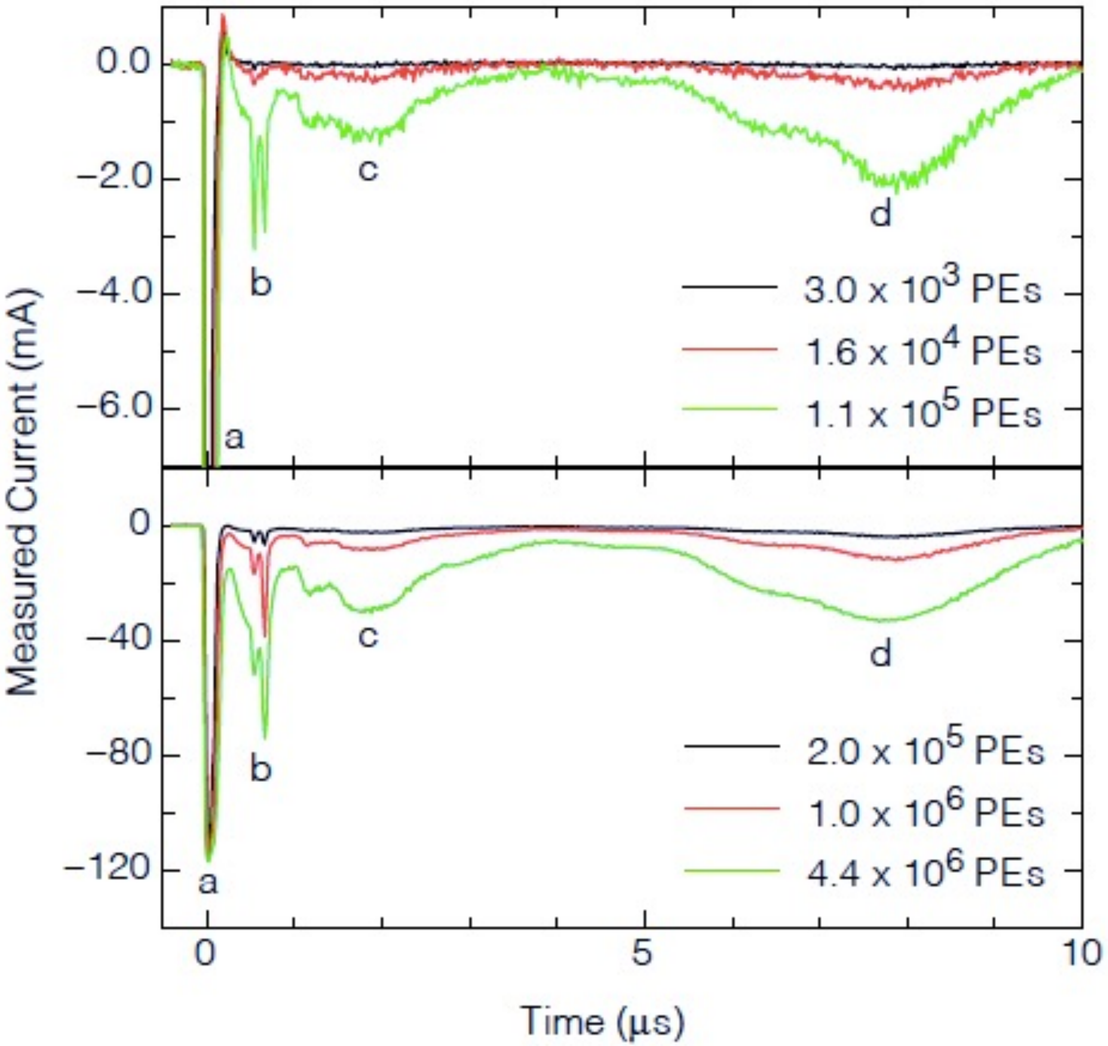
Help | Advance

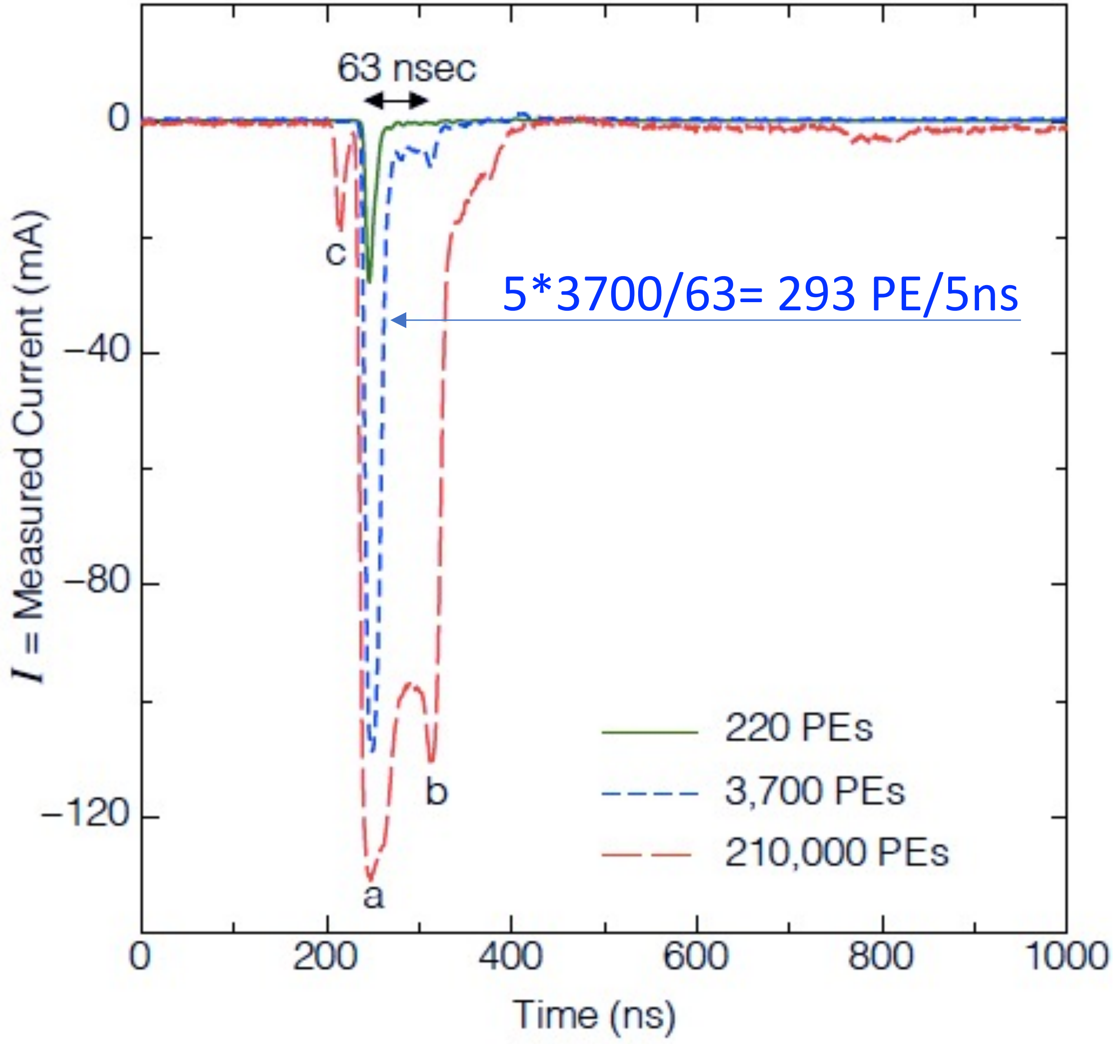
Astrophysics > Instrumentation and Methods for Astrophysics

[Submitted on 11 Feb 2010]

Calibration and Characterization of the IceCube Photomultiplier Tube

The IceCube Collaboration: R. Abbasi, Y. Abdou, T. Abu-Zayyad, J. Adams, J. A. Aguilar, M. Ahlers, K.





ation Wc

Fluctuations and reconstruction for HE events:

A commonly used assumption: The number of detected photons follow a Poisson distribution with mean $\boldsymbol{\lambda} = \boldsymbol{\Lambda}\, E$.
The likelihood $\mathcal{L}$ for an energy E resulting in k detected photons from an event producing photons per unit energy is:

arXiv.org > physics > arXiv:1311.4767

Physics > Instrumentation and Detectors

[Submitted on 19 Nov 2013 (v1), last revised 10 Feb 2014 (this version, v3)]

Energy Reconstruction Methods in the IceCube Neutrino Telescope

IceCube Collaboration: M. G. Aartsen, R. Abbasi, M. Ackermann, J. Adams, J. A. Aguilar, M. Ahlers, D. Altmann,

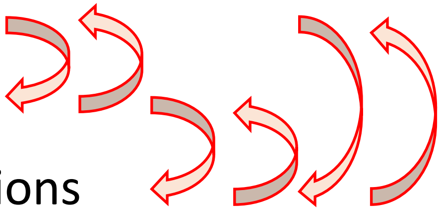
$$
\begin{aligned}
\mathcal{L} &= \frac{\lambda^k}{k!} \cdot e^{-\lambda} \\
\lambda &\rightarrow E\Lambda \\
&= \frac{(E\Lambda)^k}{k!} \cdot e^{-E\Lambda} \\
\ln \mathcal{L} &= k \ln(E\Lambda) - E\Lambda - \ln(k!)
\end{aligned}
$$

Poisson distribution has a $\boldsymbol{\sigma}^2 = \boldsymbol{\lambda}$. Questions:

(1) How precise is the Poisson distribution for high energy events of different types?
(2) For DOMs hit by a lot of photons shall we
   - Drop them, or
   - Keep as many DOMs as possible by decoding the true distribution of photons
(3) Similar argument applies to timing?

One more important thing: New data techniques and their impact on:

- modeling using instrument calibration data
- simulation accuracy using available calibrations
- reconstruction accuracy using available calibrations



These may be entangled more severely with each other in ML

We believe that Gen2 surface array will have a better accuracy in CR measurement than IceTop. A lot of work is still needed to answer this fundamental question:

How much better we can calibrate Gen-2 with CRs?

Thinking what has happened to SPASE/AMANDA and IceTop/IceCube, I believe this is a question we may not be able to answer until Gen-2 is built and analyzed

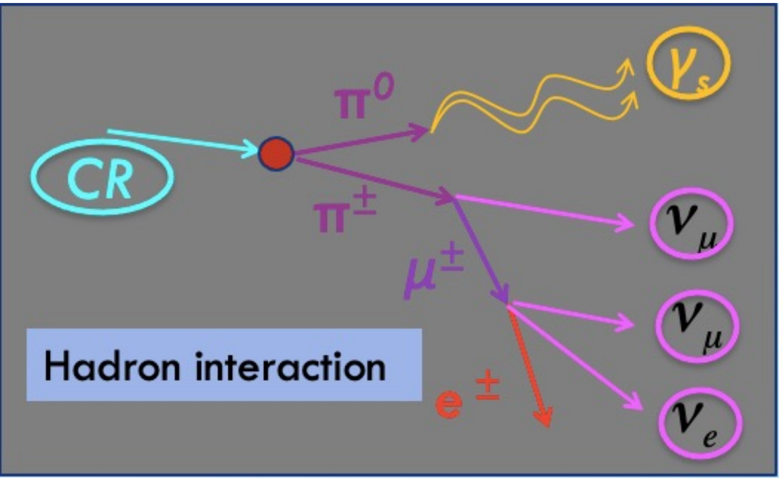
Questions?

Where CR muon may help, quick example in blue

Several quotes from Allan Hallgren & Martin Rongen's summary (2021 Spring Collaboration Meeting):

- Common interesting issue: What is the expected sensitivity for DeepCore HQE DOMs as a function of distance given wavelength dependent ice attenuation
- Current afterpulse simulation based on limited lab knowledge, neglecting high charge characteristics and lacking new effect seen ~100us → limiting promising muon and neutron decay studies
- Follow-up analysis to work by Frederik Jonske, to calibrate the detector geometry (currently assuming perfectly straight strings) using flasher data

Prompt at high energies



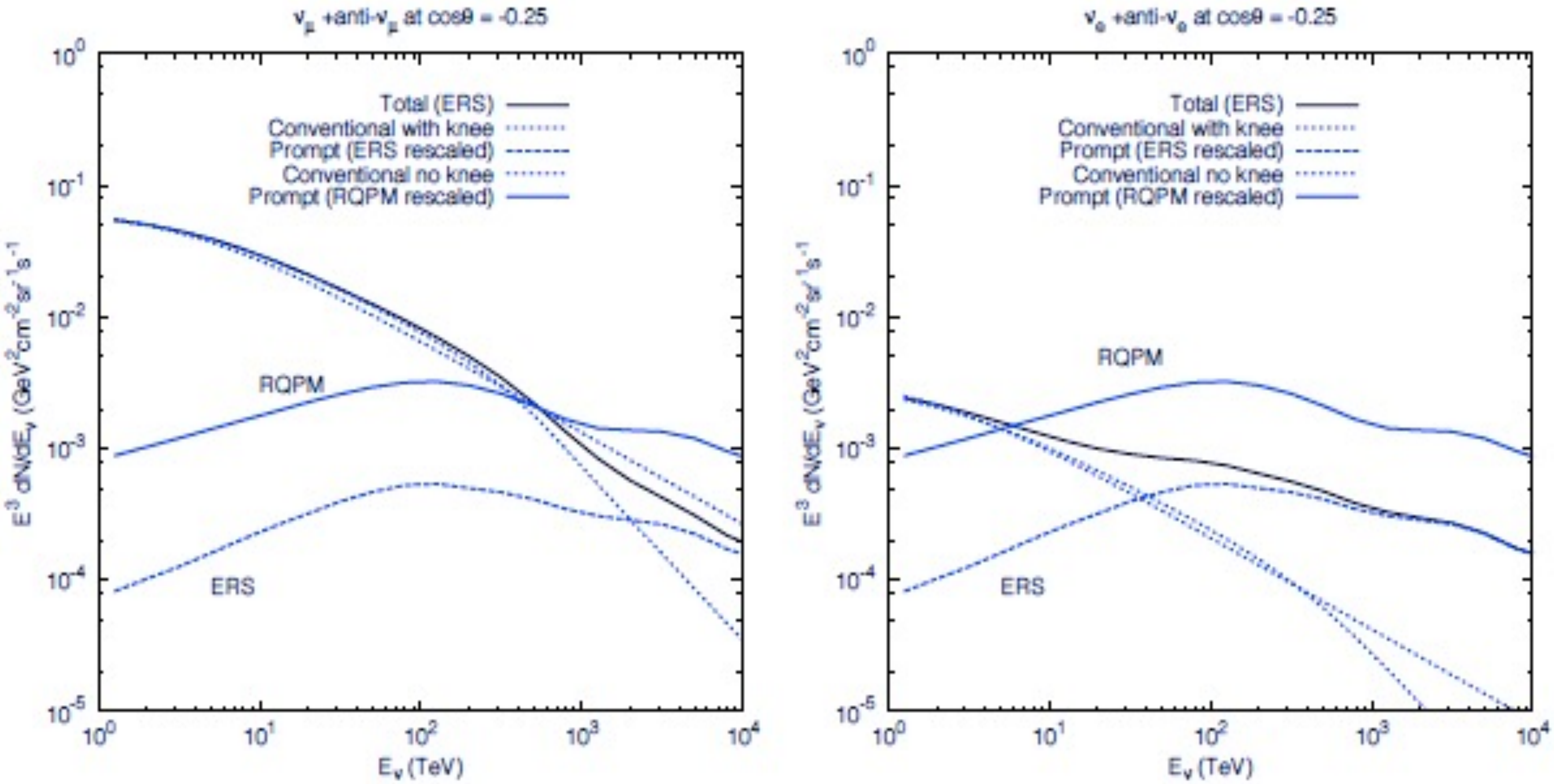


FIG. 4: Neutrino spectra including the prompt contribution. Left: $\nu_\mu + \bar{\nu}_\mu$; Right: $\nu_e + \bar{\nu}_e$.

Thomas K. Gaisser, “Atmospheric leptons the search for a prompt component”, 2013