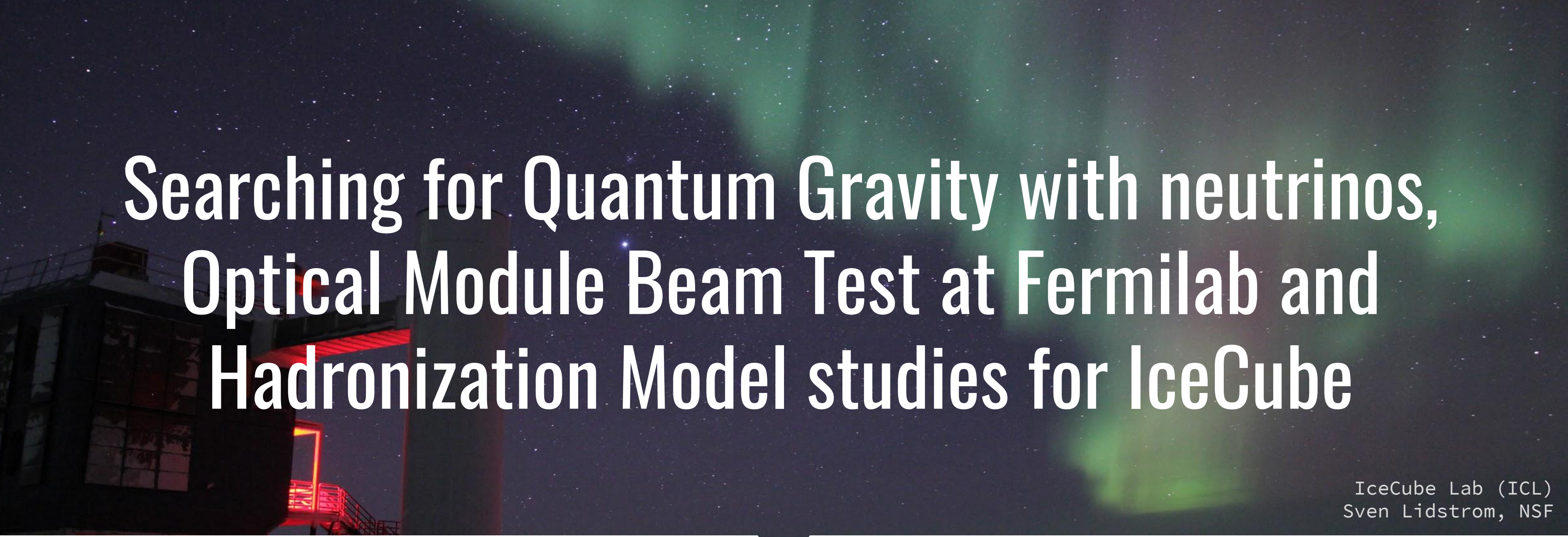

Searching for Quantum Gravity with neutrinos, Optical Module Beam Test at Fermilab and Hadronization Model studies for IceCube

IceCube Lab (ICL)
Sven Lidstrom, NSF

Find us on Facebook!
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Shivesh Mandalia

Queen Mary University of London

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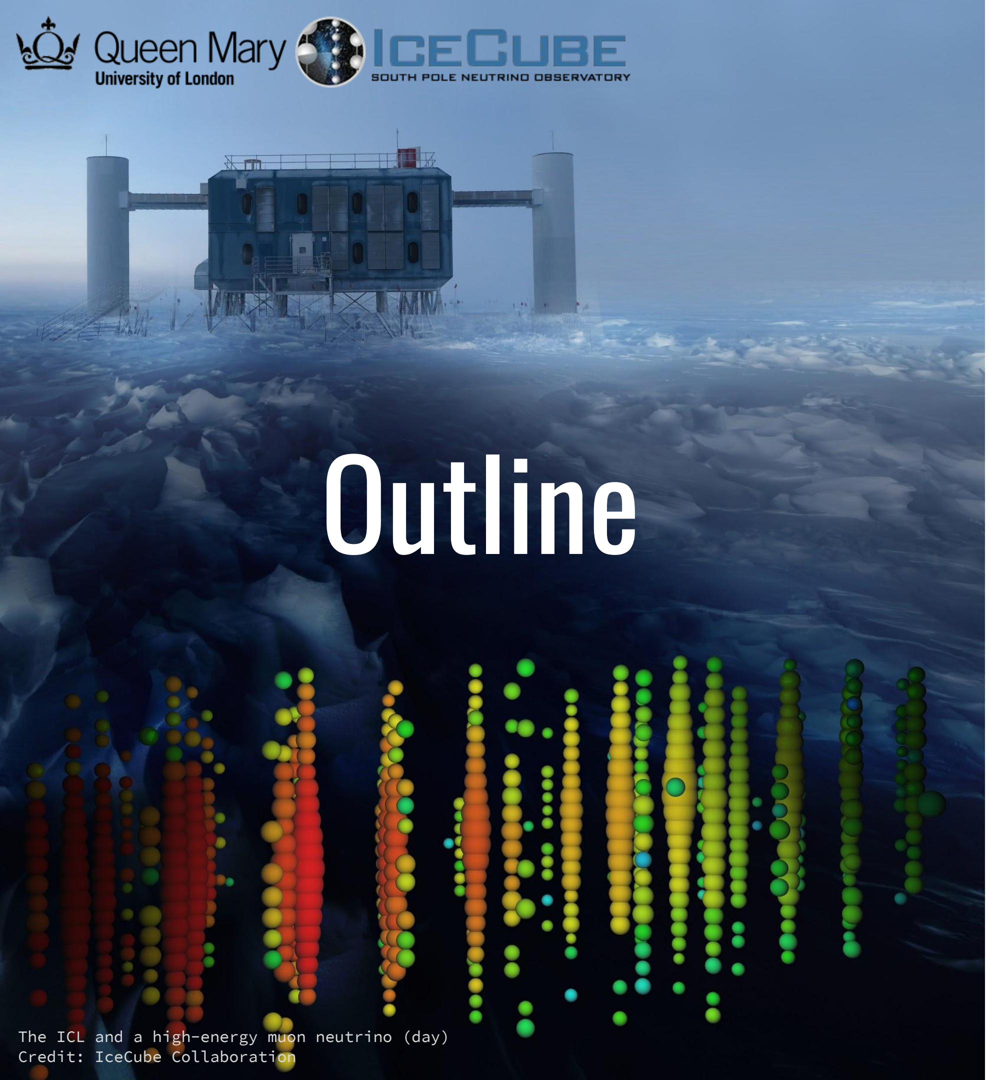
Outline



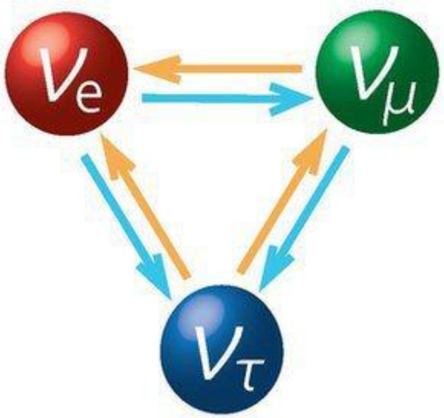
The ICL and a high-energy muon neutrino (day)
Credit: IceCube Collaboration

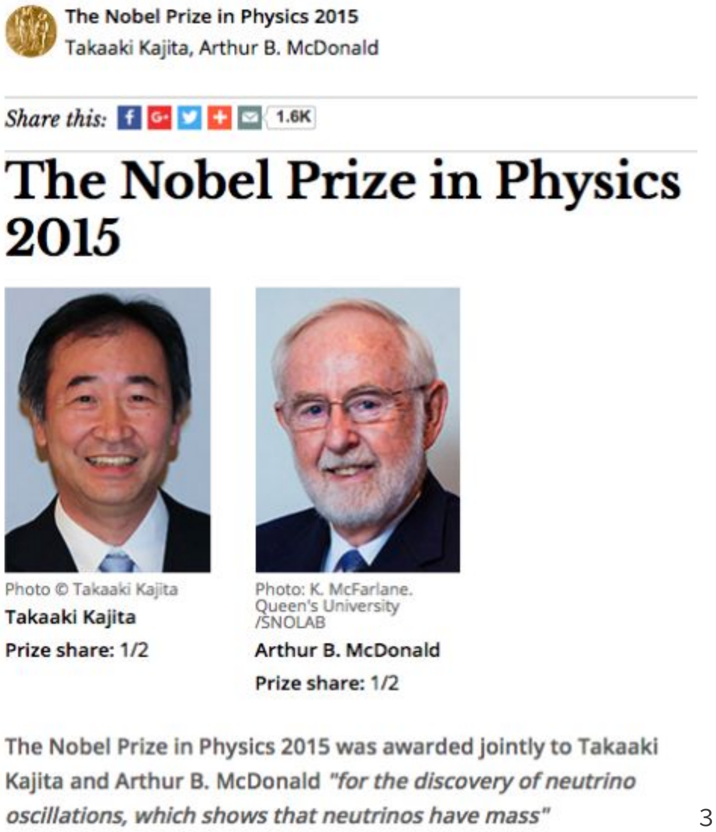
1. Neutrino Standard Model
2. New Physics with Astrophysical Neutrinos
3. IceCube Neutrino Observatory
4. Search for New Physics with the Astrophysical Flavour Ratio
5. IceCube DOM beam test at the FTBF
6. Hadronization modelling in neutrino interactions

Neutrino Standard Model (νSM)

Neutrinos have nonzero mass!

→ Discovered via **neutrino oscillations**




The Nobel Prize in Physics 2015
Takaaki Kajita, Arthur B. McDonald

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The Nobel Prize in Physics 2015

Photo © Takaaki Kajita
Takaaki Kajita
Prize share: 1/2

Photo: K. McFarlane. Queen's University /SNOLAB
Arthur B. McDonald
Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

Neutrino Standard Model (νSM)

Mass state

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$

Flavour state

PMNS mixing matrix

- Relationship between the **flavour** and **mass** states
- 3 x 3 Unitary Matrix
- 6 degrees of freedom

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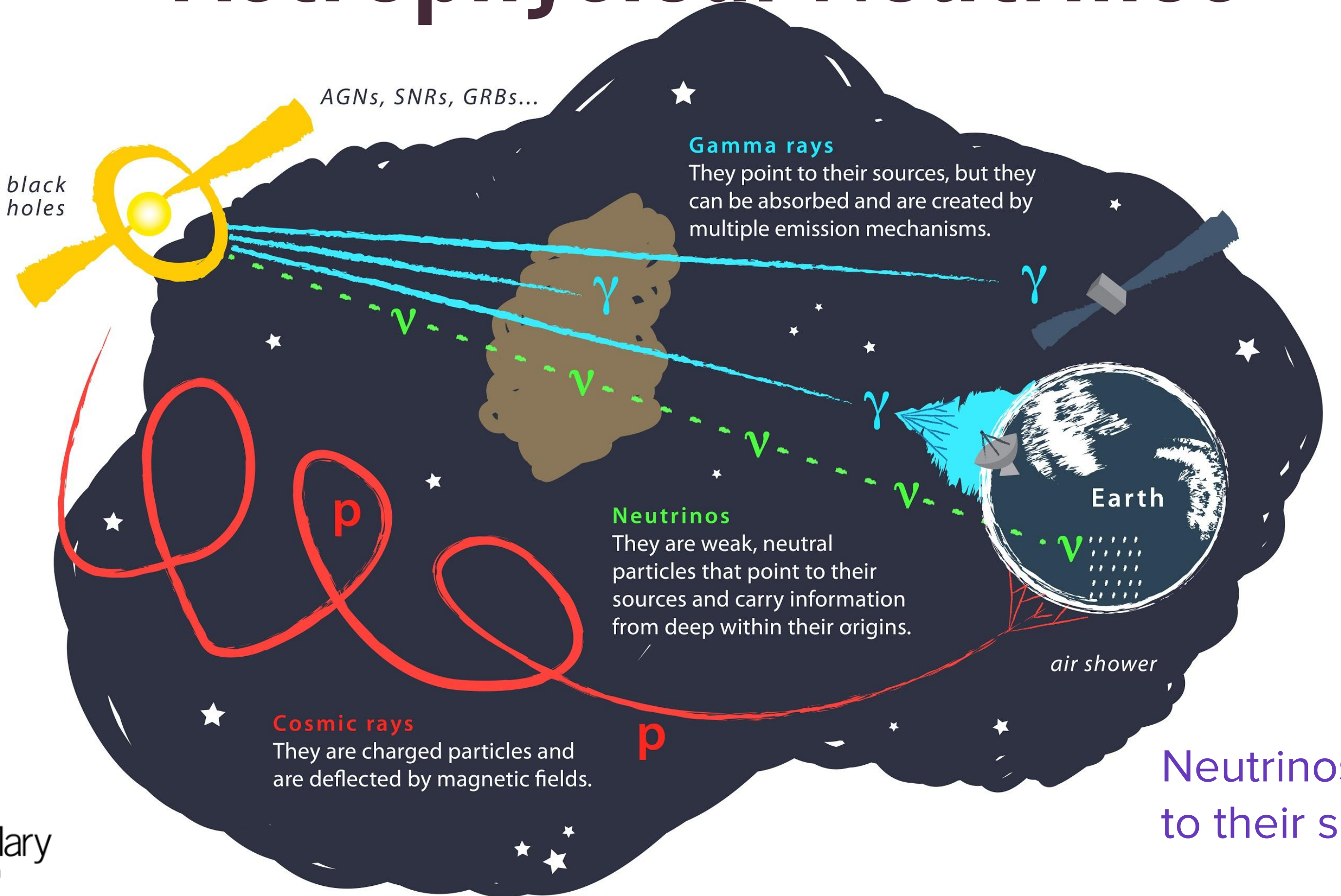
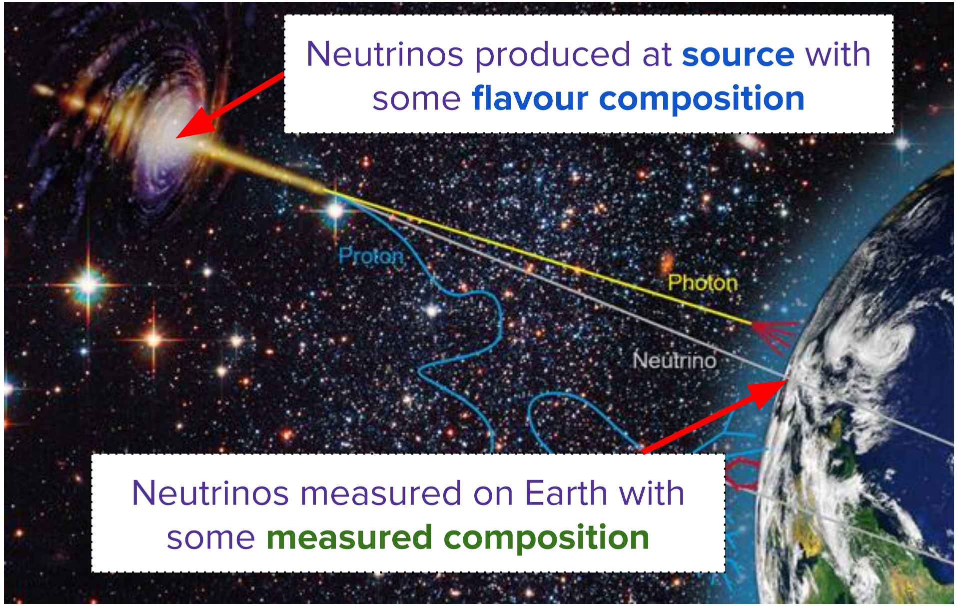
New Physics with Astrophysical Neutrinos

Astrophysical Neutrinos



Neutrinos point back to their source!

Astrophysical Neutrino Flavour



$$P_{\nu_\alpha \rightarrow \nu_\beta} = \sum_i \mid U_{\alpha i} \mid^2 \mid U_{\beta i} \mid^2$$

Example **source** flavour ratio scenarios:

$$(f_e : f_\mu : f_\tau)_\text{S}$$

- ➔ $(1 : 2 : 0)_S$ charged pion-decay
- ➔ $(1 : 0 : 0)_S$ neutron decay dominant
- ➔ $(0 : 1 : 0)_S$ rapid muon energy loss

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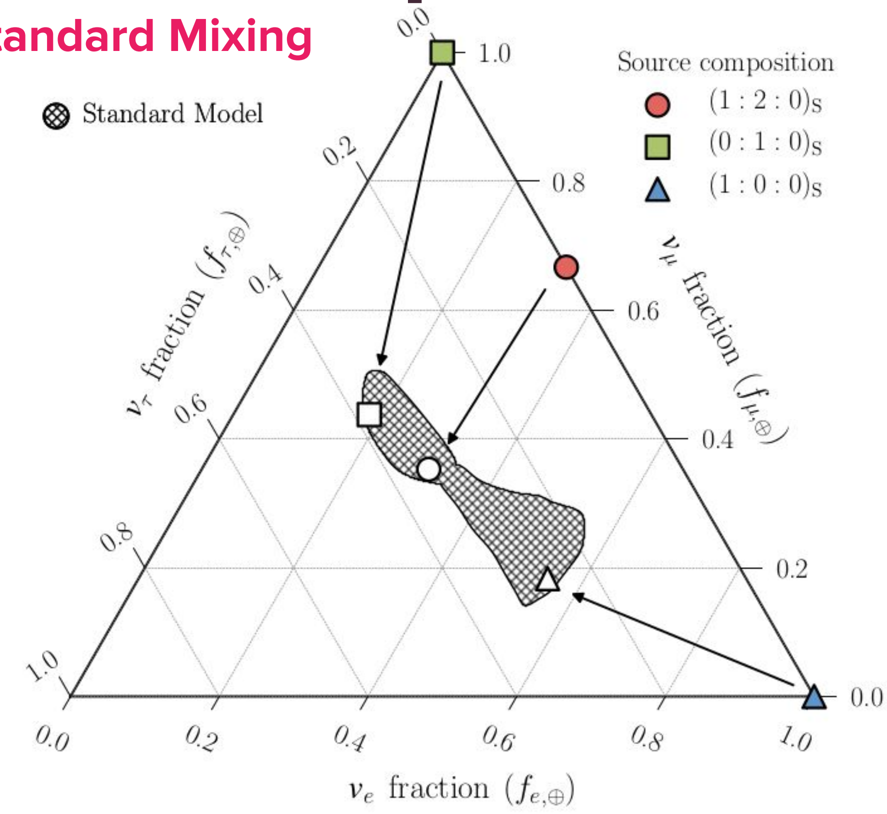
Astrophysical Neutrino Flavour

Standard Mixing



$$P_{\nu_\alpha \to \nu_\beta} = \sum_i | U_{\alpha i} |^2 | U_{\beta i} |^2$$

Example **source** flavour ratio scenarios:

$$(f_e : f_\mu : f_\tau)_S$$

- ➔ $(1:2:0)_S$ charged pion-decay
- ➔ $(1:0:0)_S$ neutron decay dominant
- ➔ $(0:1:0)_S$ rapid muon energy loss

$$(1:2:0)_S \to (0.31:0.35:0.34)_\oplus$$

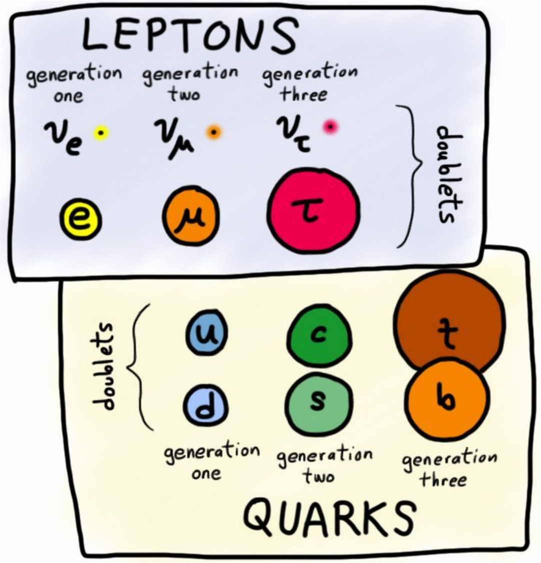
$$(0:1:0)_S \to (0.18:0.44:0.38)_\oplus$$

$$(1:0:0)_S \to (0.55:0.18:0.27)_\oplus$$

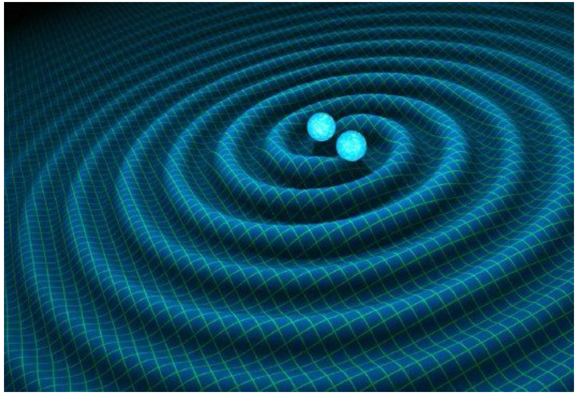
Motivation

Unified theories of the standard model of particle physics and general relativity allow for Lorentz symmetry violation

- ➔ String theory [1]
- ➔ Quantum gravity [2]
- ➔ etc.



+



New Physics Effective Hamiltonian

Introduce new physics in the mixing matrix

$$H_d = \frac{1}{2E} U M^2 U^\dagger + \frac{E^{d-3}}{\Lambda_d} \tilde{U}_d O_d \tilde{U}_d^\dagger = V_d(E) \Delta V_d^\dagger(E)$$

Dimension

Standard Mixing

New Physics Terms

Mixing Matrix with New Physics

➔ **Motivated by Standard Model Extension (SME), which is a general effective field theory framework to look for Lorentz violation**

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New Physics Effective Hamiltonian

Energy

- **Power** of astrophysical ν comes from the energy dependence
- Can provide strong constraints for **higher dimensional** operators

$$\frac{E^{d-3}}{\Lambda_d}\tilde{U}_d O_d \tilde{U}_d^\dagger$$

New Physics Effective Hamiltonian

Energy

- **Power** of astrophysical ν comes from the energy dependence
- Can provide strong constraints for **higher dimensional** operators

$$\frac{E^{d-3}}{\Lambda_d}\tilde{U}_d O_d \tilde{U}_d^\dagger$$

BSM mixing elements

- 3x3 Unitary Matrix
- Fix some elements to obtain **best case limits**
  - Same spirit as LV community

New Physics Effective Hamiltonian

$$\frac{E^{d-3}}{\Lambda_d}\tilde{U}_d O_d \tilde{U}_d^\dagger$$

Energy

- ➔ **Power** of astrophysical ν comes from the energy dependence
- ➔ Can provide strong constraints for **higher dimensional** operators

BSM mixing elements

- ➔ 3x3 Unitary Matrix
- ➔ Fix some elements to obtain **best case limits**
  - ◆ Same spirit as LV community

Scale of New Physics

This is what we are setting limits on!!

- ➔ We will provide limits on the scale of new physics

$$\Lambda_d^{-1}$$

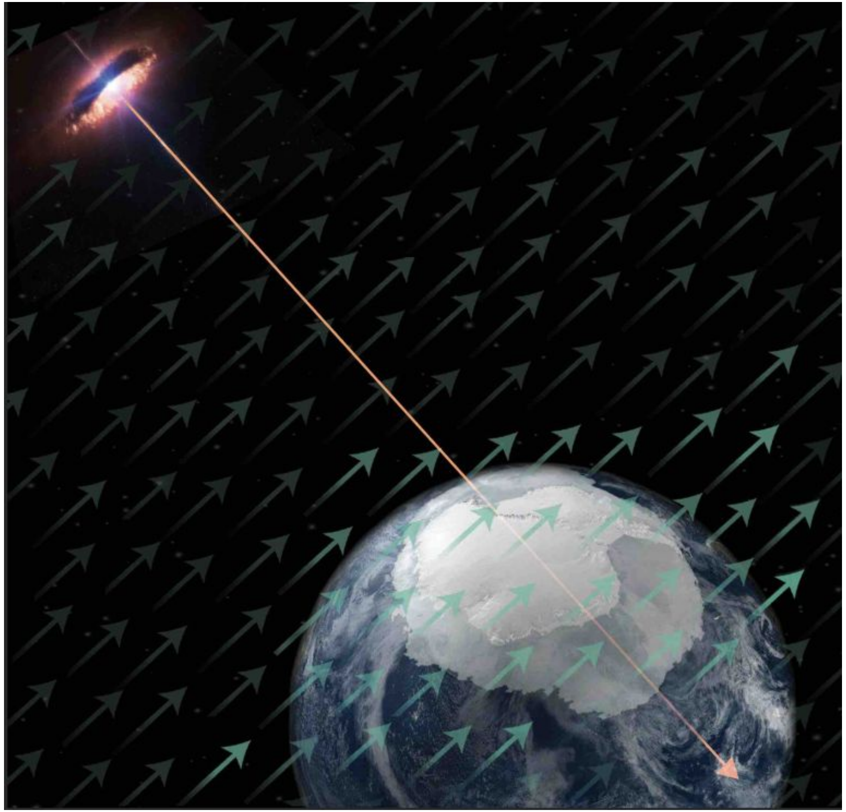
- ➔ For each dimension *d*
  - ◆ $d = 3, 4, 5, 6, 7, 8$

S. Mandalia
2019-10-17

New Physics Interpretation

New operators can be interpreted in different new physics contexts

- → Lorentz and CPT Violation
- → Dark Energy Interaction [1]
- → etc.



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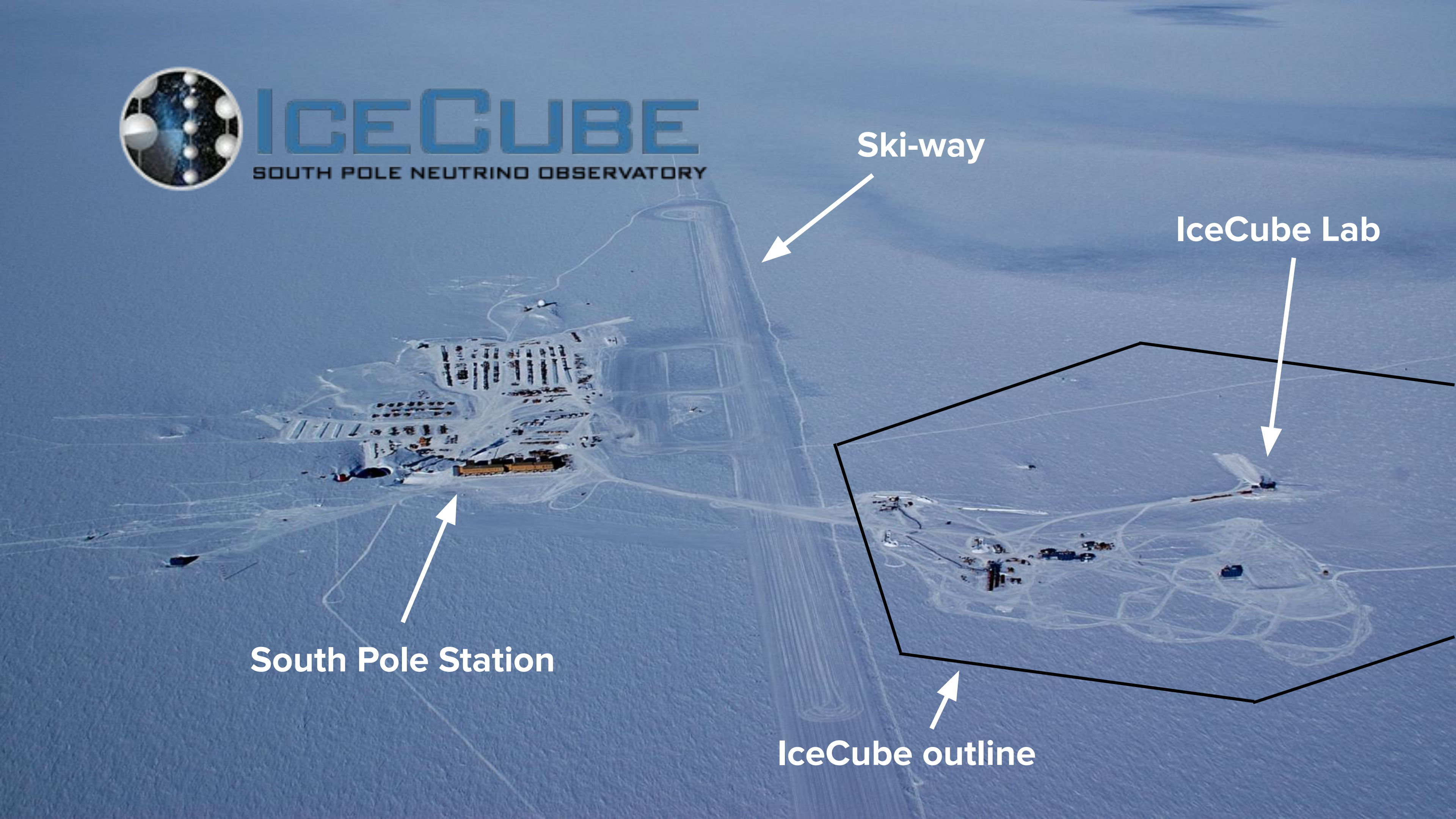
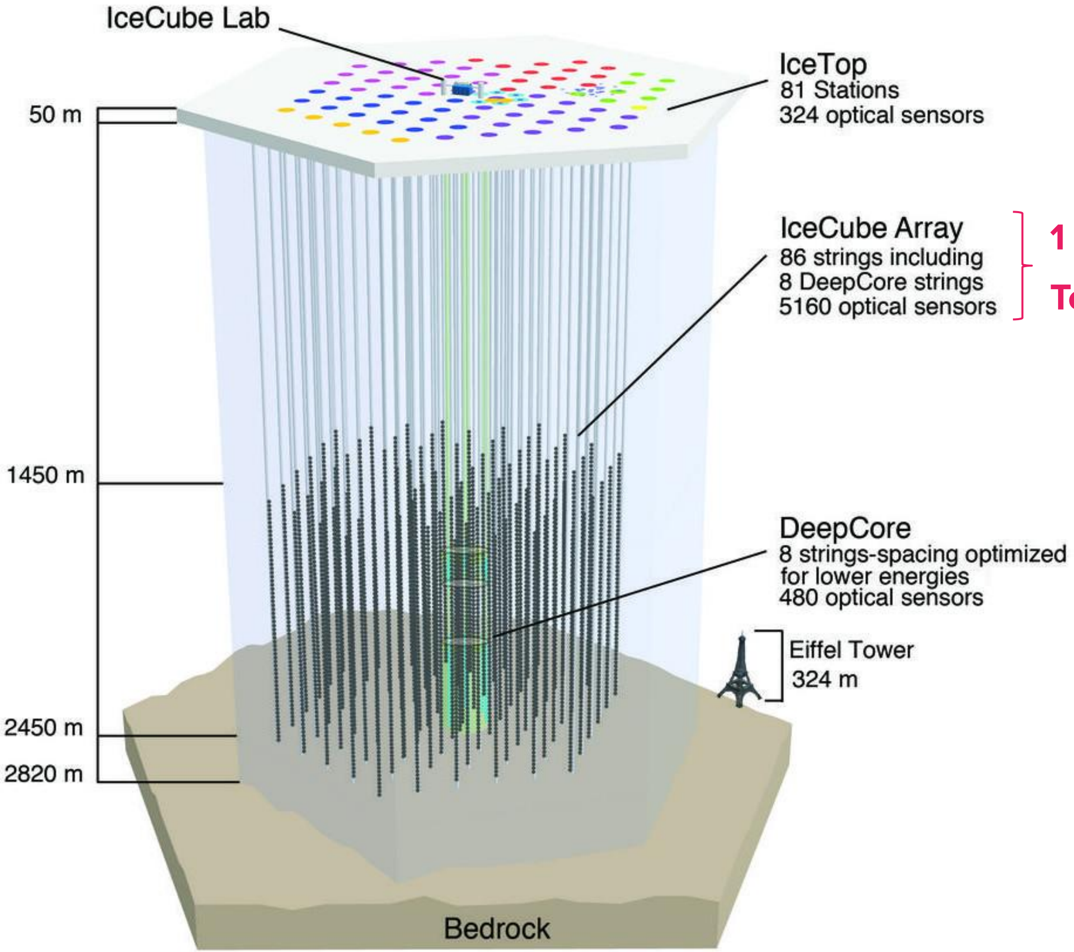

IceCube
SOUTH POLE NEUTRINO OBSERVATORY
Ski-way
IceCube Lab
South Pole Station
IceCube outline



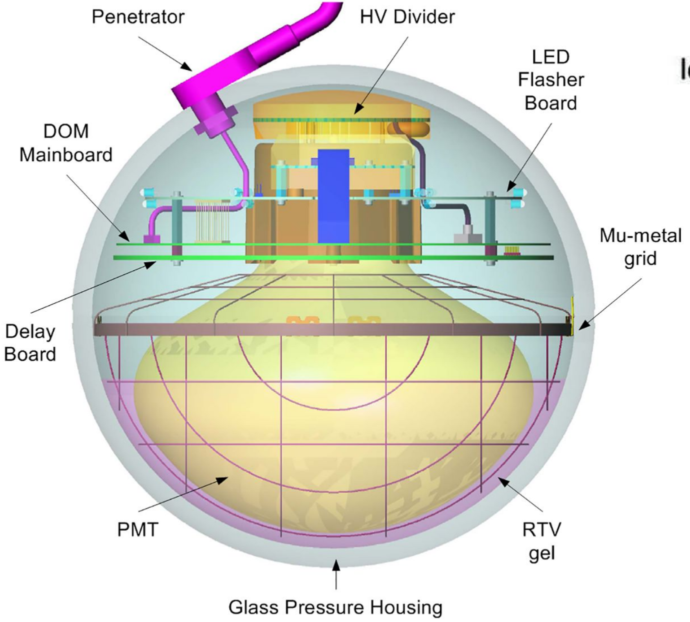
1 Gton

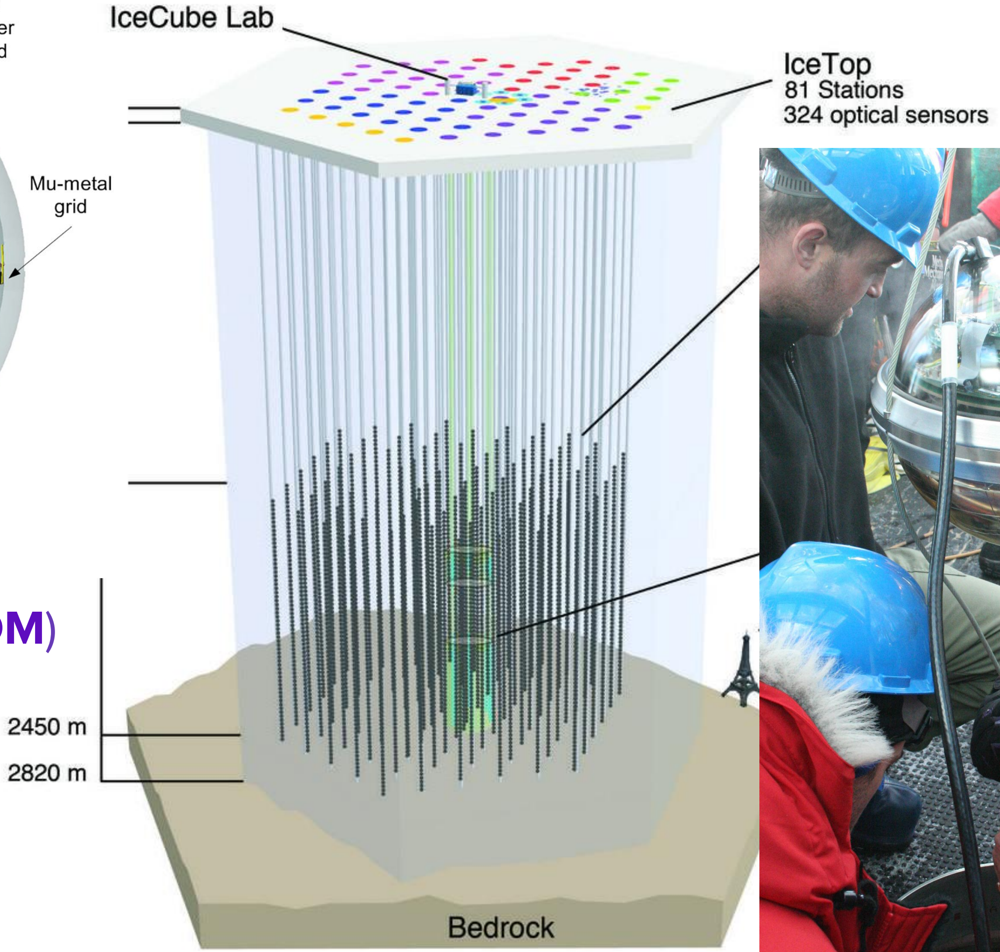
TeV - PeV

10 Mton

GeV - TeV

World's largest Cherenkov neutrino detector!





Digital Optical Module (**DOM**)

World's largest Cherenkov neutrino detector!

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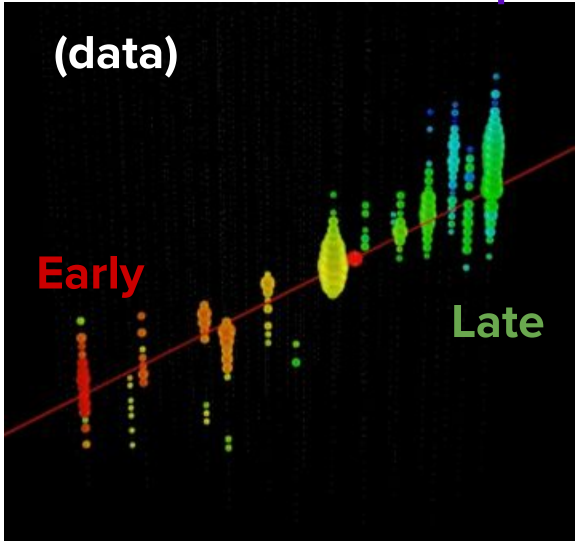
Charged-current ν_μ

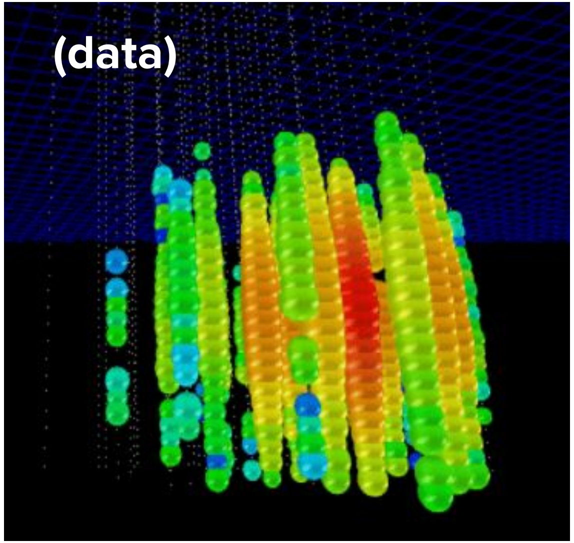


Track

$$\nu_\mu + N \rightarrow \mu + X$$

Angular resolution ~ 0.5°
Energy resolution ~ factor 2

Neutral-current / ν_e

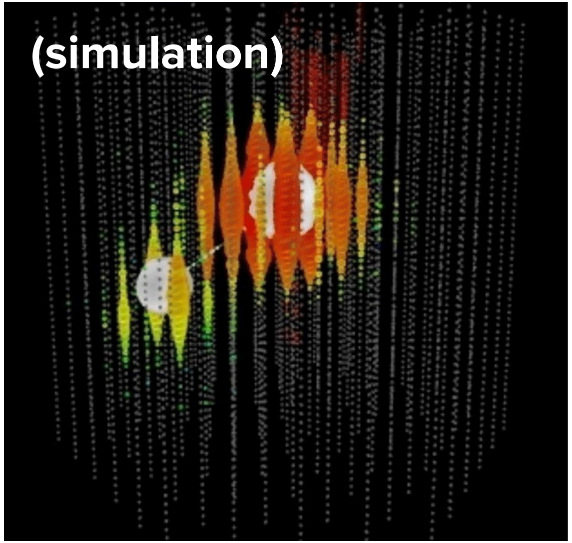


Cascade

$$\nu_e + N \rightarrow e + X$$
$$\nu_x + N \rightarrow \nu_x + X$$

Angular resolution ~ 10°
Energy resolution ~ 15%

Charged-current ν_τ



Double-Cascade

$$\nu_\tau + N \rightarrow \tau + X$$

~ 2 expected in 6 years

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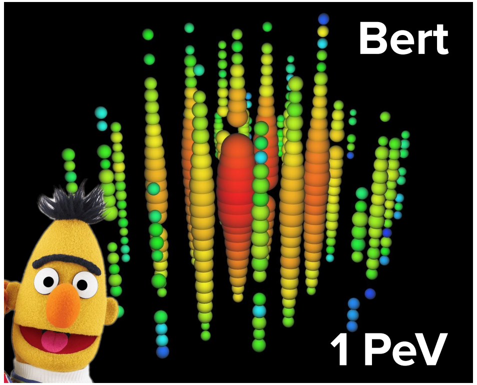
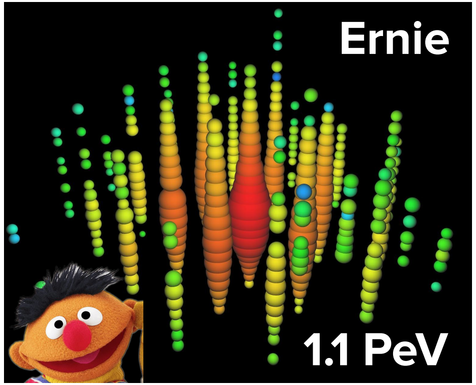
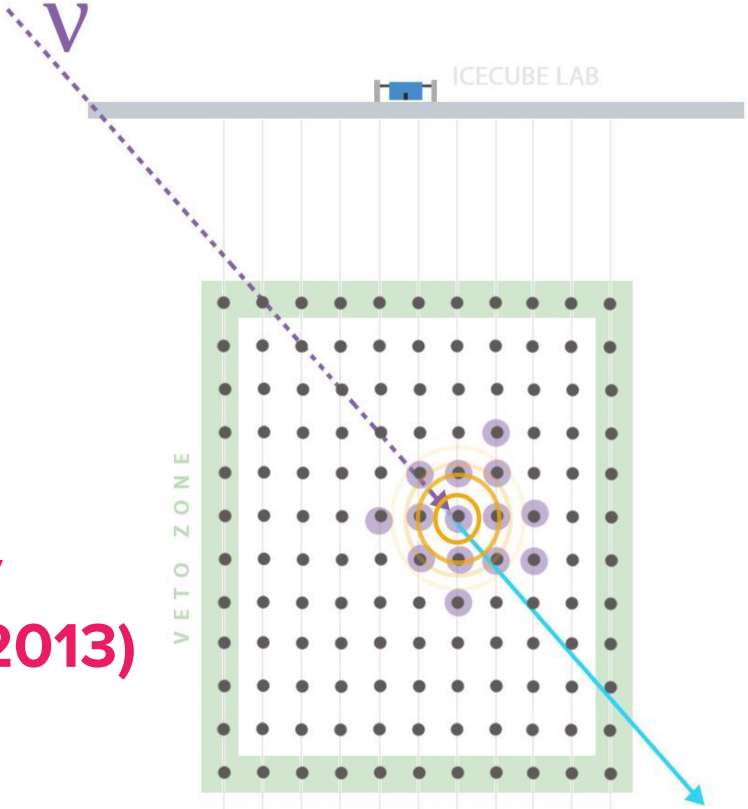
High Energy Starting Events (HESE)







First Evidence for High-Energy Astrophysical Neutrinos! (Science 2013)

IceCube, *Science 342, 1242856 (2013)*

New 7.5 years HESE data!

All energies: 103 events

22 new events in 2016

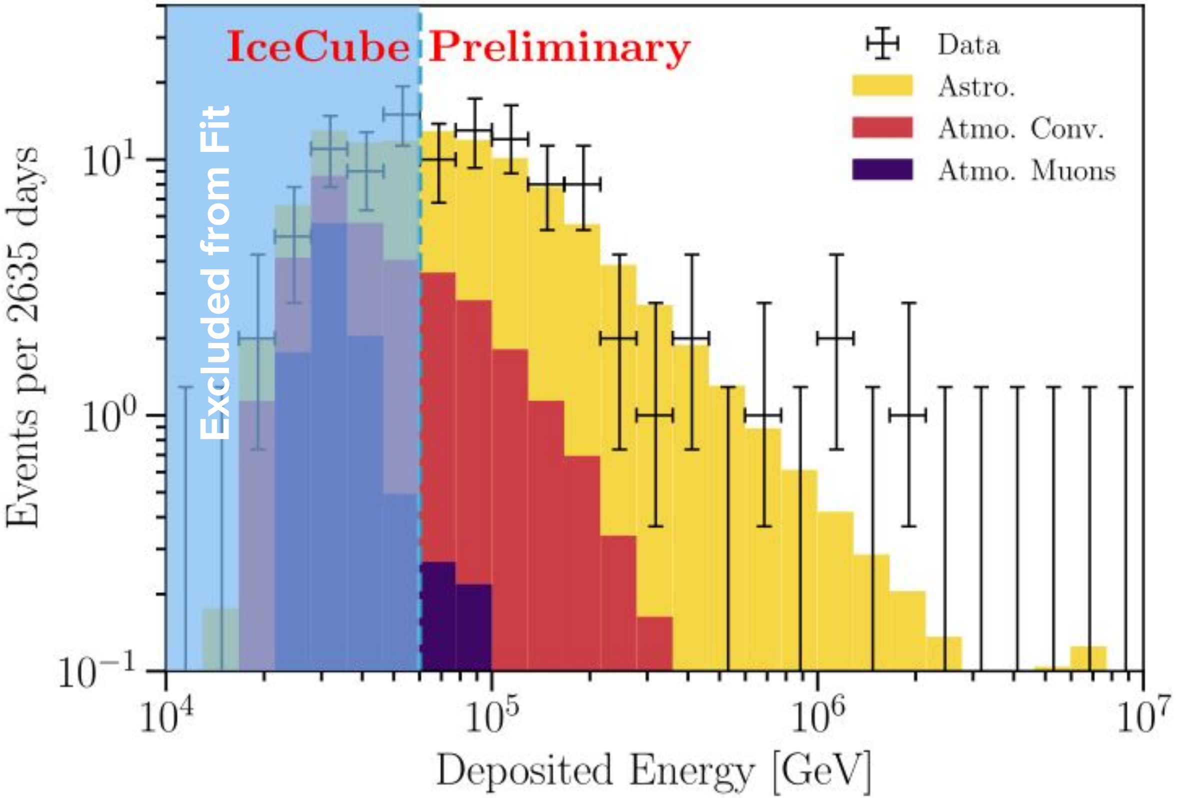
9 new events in 2017

> 60 TeV: 60 events

42 cascades

15 tracks

2 double-cascade



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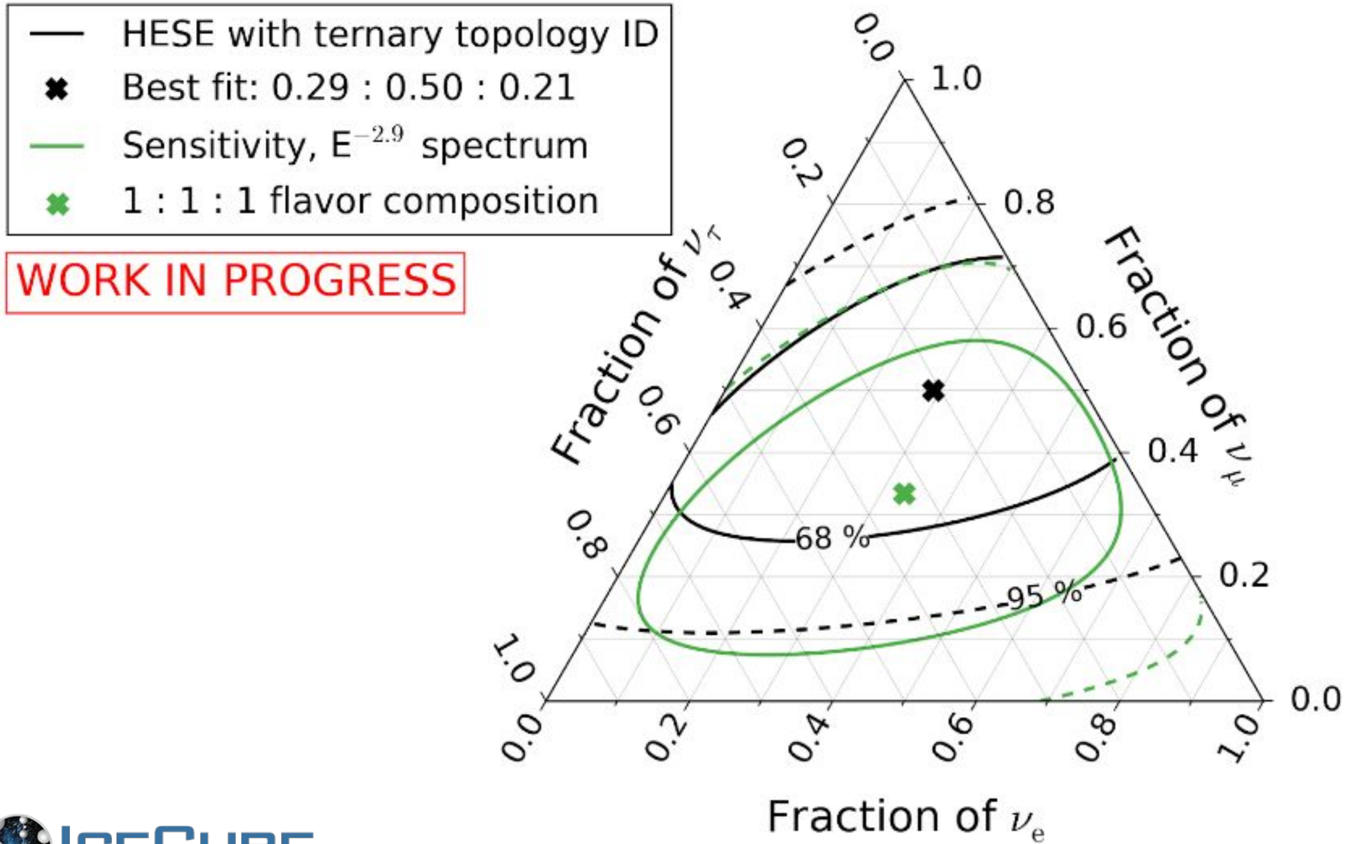
A. Schneider, *ICRC (2019)*, arXiv: 1907.11266

Flavour Ratio Measurement



J. Stachurska, *ICRC (2019)*, arXiv: 1908.05506

Analysis Method

$$H_d = \frac{1}{2E} U M^2 U^\dagger + \frac{E^{d-3}}{\Lambda_d} \tilde{U}_d O_d \tilde{U}_d^\dagger = V_d(E) \Delta V_d^\dagger(E)$$

Dimension

Standard Mixing

NuFIT 3.2 (2018)

$$|U|_{3\sigma} = \begin{pmatrix} 0.799 \to 0.844 & 0.516 \to 0.582 & 0.141 \to 0.156 \\ 0.242 \to 0.494 & 0.467 \to 0.678 & 0.639 \to 0.774 \\ 0.284 \to 0.521 & 0.490 \to 0.695 & 0.615 \to 0.754 \end{pmatrix}$$

Standard model mixings are floated within the NuFIT bounds

$$\begin{matrix} \frac{\Delta m_{21}^2}{10^{-5}\ \mathrm{eV}^2} \\ \frac{\Delta m_{3\ell}^2}{10^{-3}\ \mathrm{eV}^2} \end{matrix} \begin{bmatrix} +2.399 \to +2.593 \\ -2.536 \to -2.395 \end{bmatrix}$$

➔ **+6 nuisance parameters**

Analysis Method

$$H_d = \frac{1}{2E} U M^2 U^\dagger + \frac{E^{d-3}}{\Lambda_d} \tilde{U}_d O_d \tilde{U}_d^\dagger = V_d(E) \Delta V_d^\dagger(E)$$

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$$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2} \quad [+2.399 \to +2.593]$$
$$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2} \quad [-2.536 \to -2.395]$$

➔ **+6 nuisance parameters**

New Physics Texture

New Physics Matrix is fixed to a **maximally oscillating** texture

➔ Set all but **one** of the **New Physics** mixing angles to **0**

$$\tilde{\theta}_{ij,\,d} = \begin{cases} \pi/4 & \in \tilde{\theta}_{13,\,d} \\ 0 & \text{otherwise} \end{cases} \implies \tilde{U}_d = \mathcal{O}_{e\tau} \equiv \begin{pmatrix} \frac{1}{\sqrt{2}} & 0 & \frac{1}{\sqrt{2}} \\ 0 & 1 & 0 \\ -\frac{1}{\sqrt{2}} & 0 & \frac{1}{\sqrt{2}} \end{pmatrix} + \mathbb{0}i$$

$$\tilde{\theta}_{ij,\,d} = \begin{cases} \pi/4 & \in \tilde{\theta}_{23,\,d} \\ 0 & \text{otherwise} \end{cases} \implies \tilde{U}_d = \mathcal{O}_{\mu\tau} \equiv \begin{pmatrix} 1 & 0 & 0 \\ 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 0 & -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix} + \mathbb{0}i$$

➔ **Fit for the New Physics Scale** Λ_d^{-1}

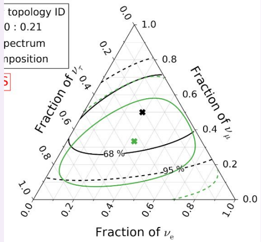
Analysis Method

$$\bar{\phi}^{(d)}_{\beta,\oplus} = \frac{1}{|\Delta E|}\int_{\Delta E}\sum_{\alpha} P^{(d)}_{\nu_\alpha\to\nu_\beta}(E)\,\phi_{\alpha,\mathrm{s}}(E)\,\mathrm{d}E$$

Measured Flavour

$$f^{(d)}_{\beta,\oplus} = \bar{\phi}^{(d)}_{\beta,\oplus}\Big/\sum\nolimits_{\gamma}\bar{\phi}^{(d)}_{\gamma,\oplus}$$

This analysis is an interpretation of this flavour contour



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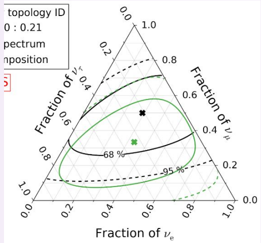

Mixing

➔ Averaged over energy spectrum

$$P^{(d)}_{\nu_\alpha\to\nu_\beta}(E) = \sum\nolimits_i \left|V_{\alpha i,\,d}(E)\right|^2 \left|V_{\beta i,\,d}(E)\right|^2$$

Mixing Matrix with New Physics

BSM introduced in the mixing during propagation

Analysis Method

$$\bar{\phi}^{(d)}_{\beta,\oplus} = \frac{1}{|\Delta E|}\int_{\Delta E}\sum_{\alpha} P^{(d)}_{\nu_\alpha\to\nu_\beta}(E)\,\phi_{\alpha,\mathrm{s}}(E)\,\mathrm{d}E$$

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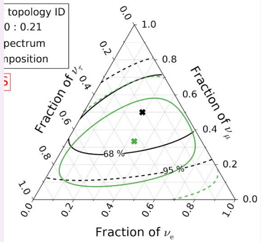

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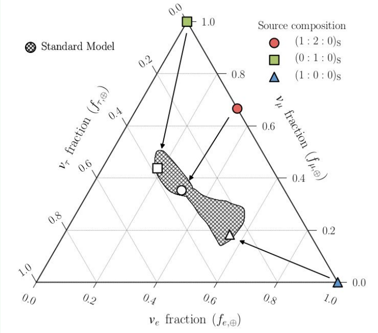
$$P^{(d)}_{\nu_\alpha\to\nu_\beta}(E) = \sum_i \left|V_{\alpha i,\,d}(E)\right|^2 \left|V_{\beta i,\,d}(E)\right|^2$$

Mixing Matrix with New Physics

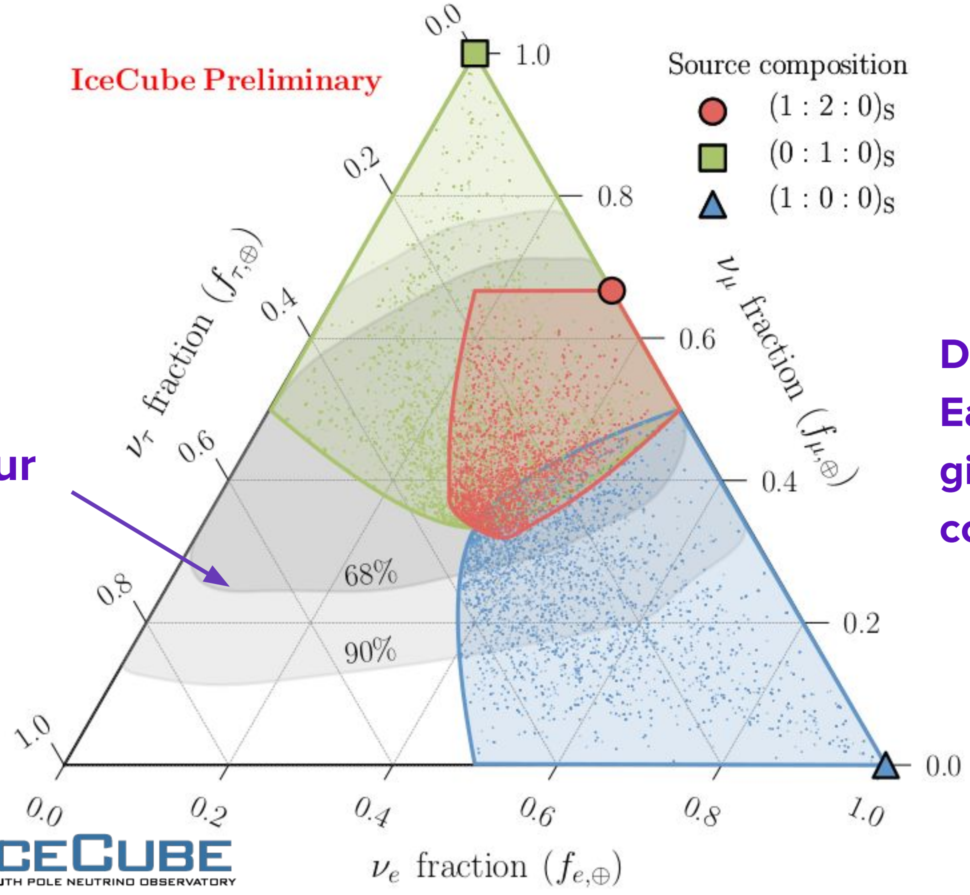
BSM introduced in the mixing during propagation

Source Flux

Fix to a certain model



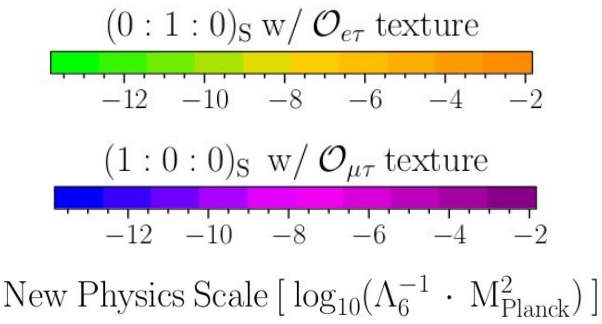
Effect on Flavour Triangle



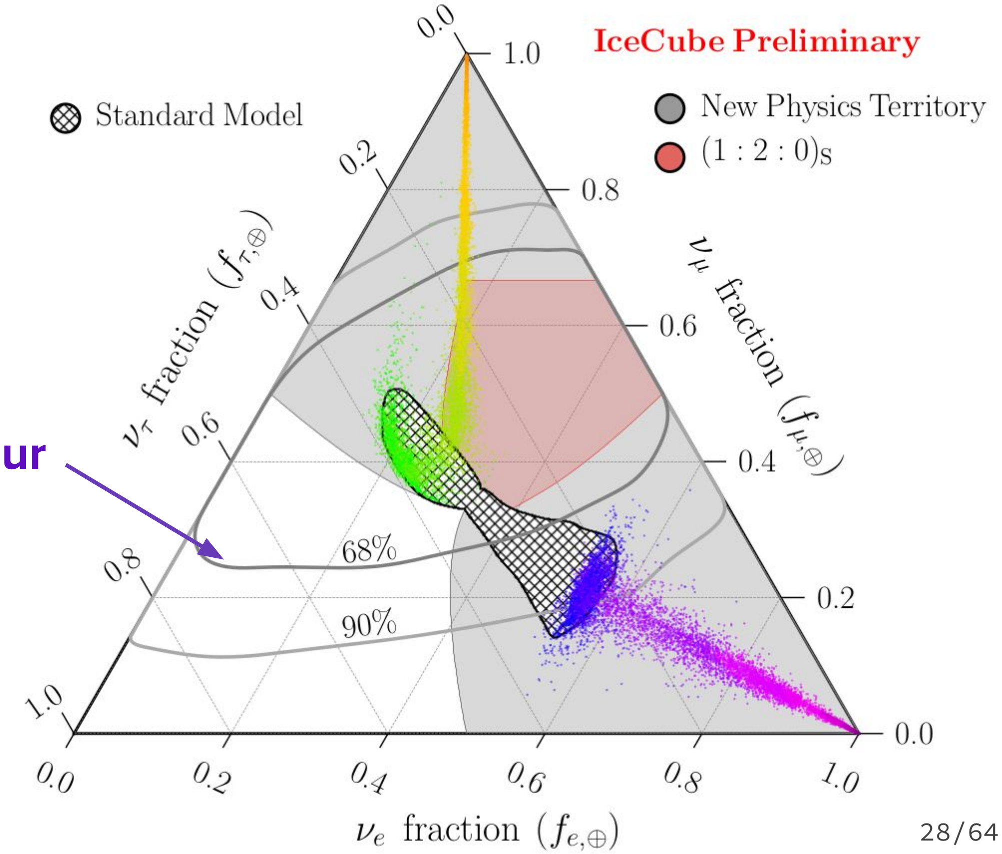
HESE flavour contour

Due to unitarity, the possible Earth flavour ratios for a given initial flavor composition is confined.

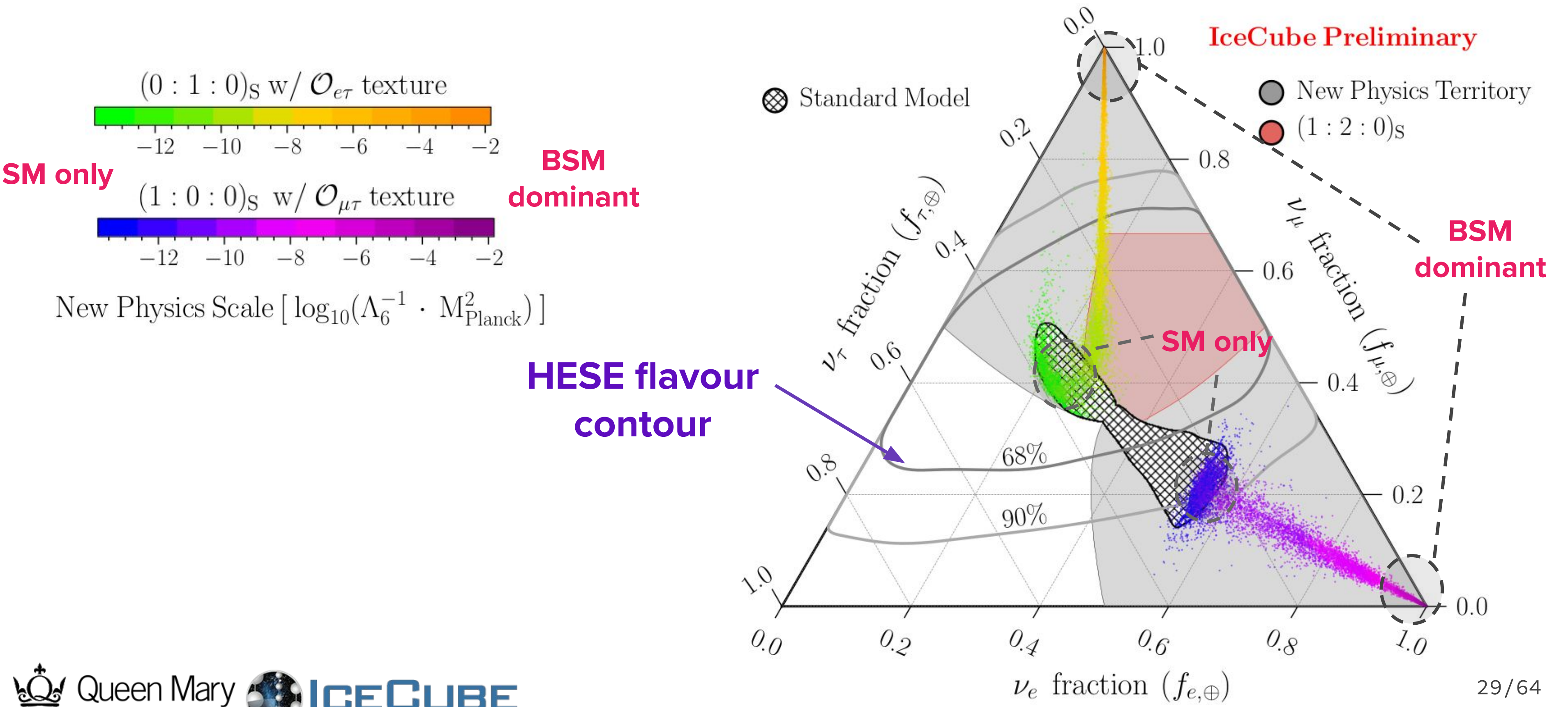
Effect on Flavour Triangle



HESE flavour contour



Effect on Flavour Triangle



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Analysis Specification

Binning

60 TeV < E < 10 PeV **20 bins**
-1 < cos(zenith) < 1 **10 bins**

+ separate binning for double-cascade

J. Stachurska, *ICRC (2019)*, arXiv: 1908.05506

Simulation

- Atmospheric neutrinos from **Honda2006**
  Honda, Morihiro et al., Phys.Rev. D75 (2007) 043006
- Prompt neutrinos from **BERSS**
  Bhattacharya, Enberg, Reno, Sarcevic, Stasto, JHEP 1506 (2015) 110
- Simple power law for astrophysical neutrinos
- DIS cross section from **CSMS** paper
  Cooper-Sarkar, Mertsch, Sarkar, JHEP 1108 (2011) 042
- Analytical oscillation formula

Sytematics

Normalization of flux:

1. conventional (40%)
2. prompt (±2.4 BERS)
3. astrophysical (free)
4. muon background (50%)

+5 nuisance params

Flux components:

1. astrophysical neutrino index (free)

Fit Methods

- **Bayesian Markov Chain Monte Carlo** (main results)
  - Bayes factor hypothesis test

- **11 nuisance parameters in total**
- **+ Λ_d^{-1} parameter of interest**

How do we work in such a high-dim space?

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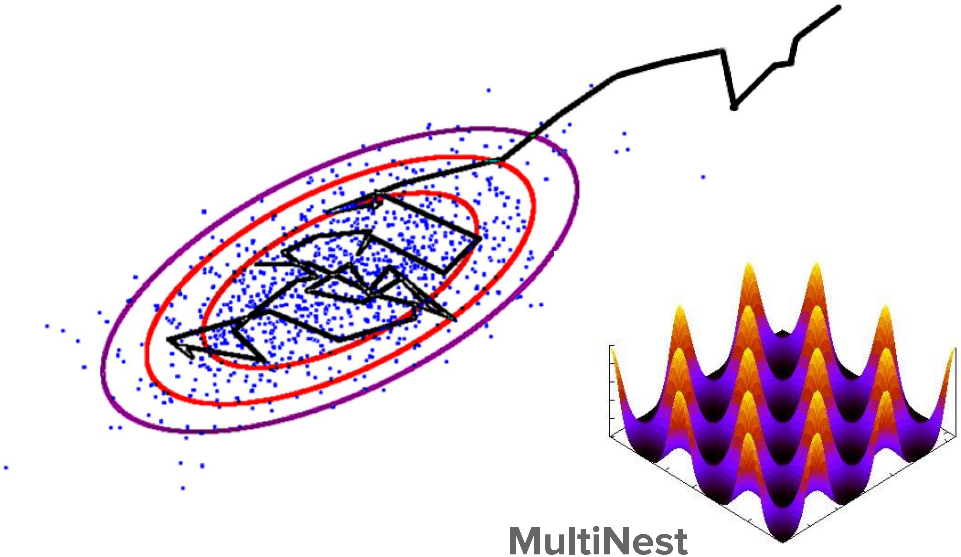
Markov Chain Monte Carlo

Construct a random walk which explores the likelihood space

Random walk is biased such that the distribution approximates the posterior space

Great utility when following a Bayesian statistical treatment



MultiNest

$$P\left(\Theta \mid D\right) = \frac{P(D|\Theta)P(\Theta)}{P(D)}$$

Anarchy Sampling

Need to be careful about which parameters we sample over

➔ **Could introduce artificial biases if not careful**

$$\frac{1}{2E} U M^2 U^\dagger$$

$$U = e^{i\eta} e^{i\phi_1\lambda_3 + i\phi_2\lambda_8} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} e^{i\chi_1\lambda_3 + i\chi_2\lambda_8}$$

We sample in the space defined by the Haar Measure:

$$\mathrm{d}U = \mathrm{d}\left(\sin^2\theta_{12}\right) \wedge \mathrm{d}\left(\cos^4\theta_{13}\right) \wedge \mathrm{d}\left(\sin^2\theta_{23}\right) \wedge \mathrm{d}\delta$$

Volume Elements

Sample uniformly in $s_{12}^2,\ c_{13}^4,\ s_{23}^2,\ \delta$

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A. de Gouvea and H. Murayama, Phys.Lett.B573, 94 (2003), hep-ph/0301050
L. J. Hall, H. Murayama, and N. Weiner, Phys.Rev.Lett.84, 2572(2000),hep-ph/9911341
N. Haba and H. Murayama, Phys.Rev. D63, 053010 (2001), hep-ph/0009174

Constructing a Limit

If no New Physics is found, we can attempt to set a limit

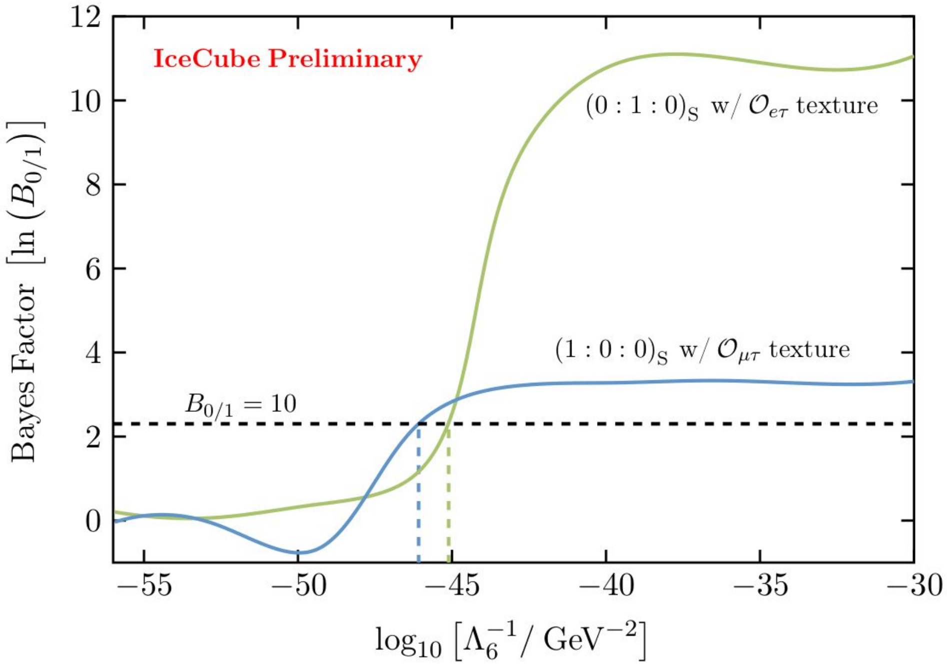
Define Bayes Factor

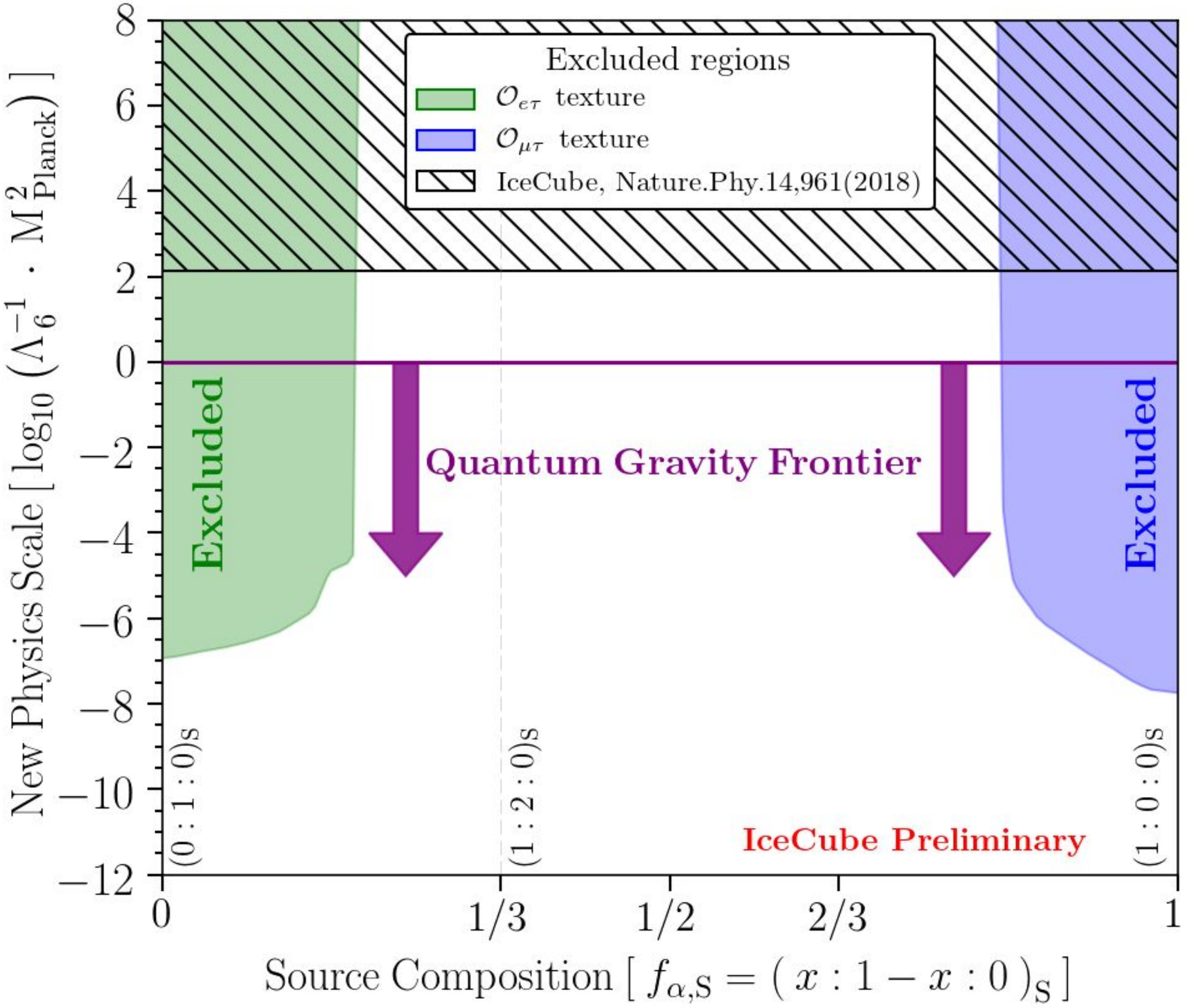
$$B_{0/1}(\mathbf{x}) = \frac{\mathcal{Z}_0(\mathbf{x})}{\mathcal{Z}_1(\mathbf{x})}$$

$$\mathcal{Z}_j(\mathbf{x}) = f(\mathbf{x}|\mathcal{M}_j) = \int f_j(\mathbf{x}|\boldsymbol{\theta}_j)\,\pi_j(\boldsymbol{\theta}_j)\,\mathrm{d}\boldsymbol{\theta}_j$$

We define our threshold as having a "strong strength of evidence" according to Jeffreys' scale

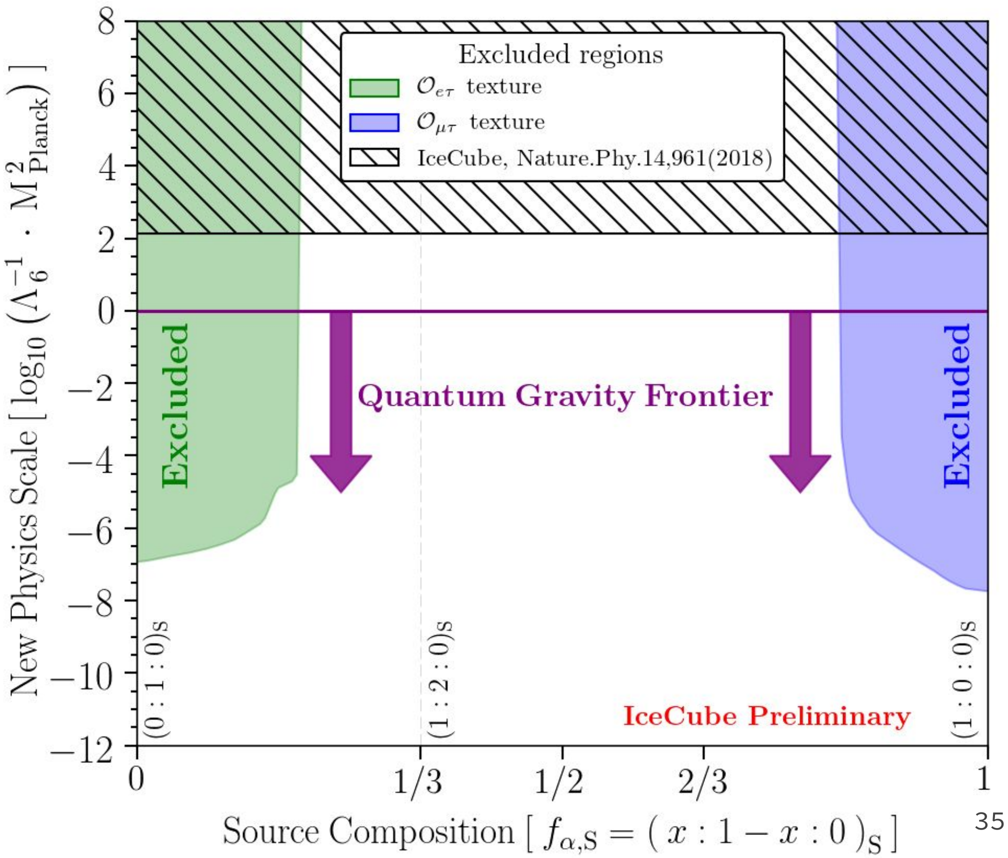
$$B_{0/1} > 10$$




Excluded regions
$\mathcal{O}_{e\tau}$ texture
$\mathcal{O}_{\mu\tau}$ texture
IceCube, Nature.Phy.14,961(2018)
Excluded
Quantum Gravity Frontier
Excluded
IceCube Preliminary
$(0:1:0)_S$
$(1:2:0)_S$
$(1:0:0)_S$
8
6
4
2
0
−2
−4
−6
−8
−10
−12
0
1/3
1/2
2/3
1
New Physics Scale $[\log_{10}(\Lambda_6^{-1} \cdot M^2_{\mathrm{Planck}})]$
Source Composition $[f_{\alpha,S} = (x : 1-x : 0)_S]$

Preliminary Results

- ➔ Limits given per operator dimensionality
- ➔ Limits given for fixed initial flavor composition (x-axis) anda BSM operator texture (in green and blue)
- ➔ **No constraints obtained if the initial flavor composition is pion-based (1:2:0)**
- ➔ **First BSM physics constraints using astrophysical neutrino flavour information**
- ➔ Constraints can be reinterpreted in terms of other BSM physics since they have been expressed as effective operators.

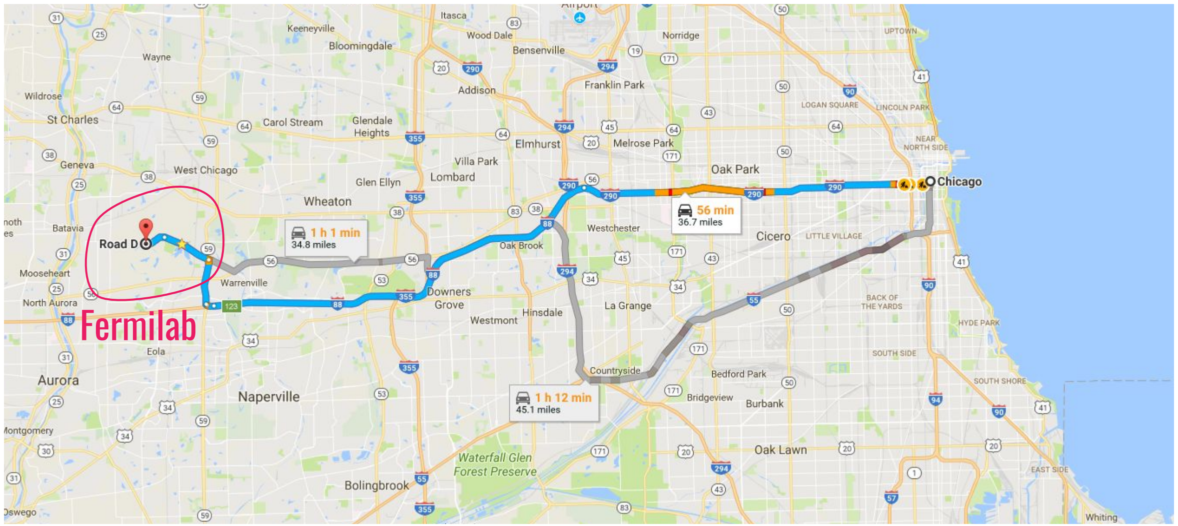


Queen Mary University of London | IceCube South Pole Neutrino Observatory

IceCube DOM beamtest at the FTBF

Sven Lidstrom, NSF

Fermilab



Wilson Hall

- ➔ Discovery of the bottom/top quark
- ➔ Observation of direct CP violation in kaon decays
- ➔ Observation of tau neutrino (DONUT)
- ➔ Headquarters for DUNE

Fermilab

Wilson Hall

➔ Headquarters for DUNE

Fermilab

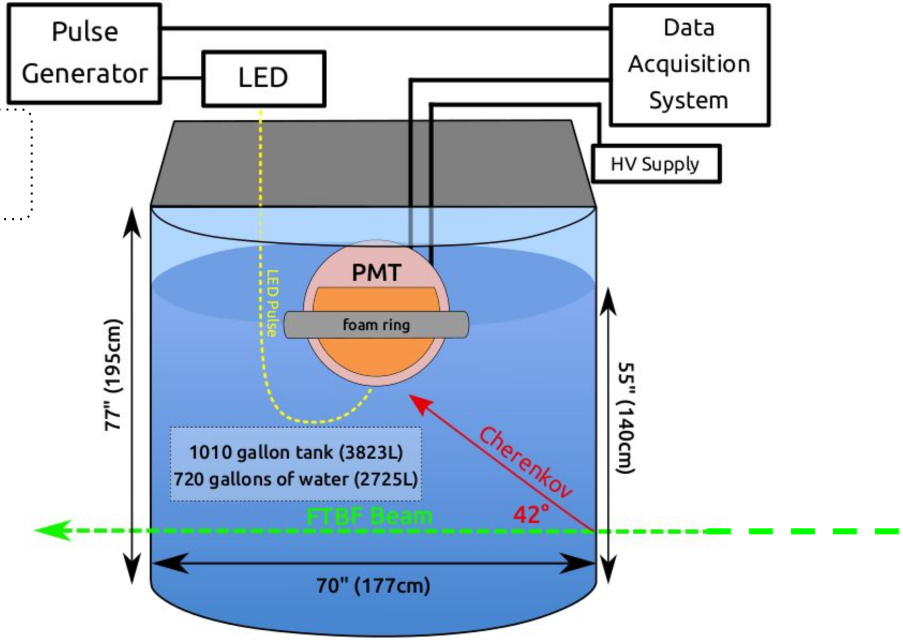
One of the beams at Fermilab is available to users.

From the website: **Fermilab Test Beam Facility (FTBF)**

“The FTBF program provides flexible, equal, and open access to test beams for all detector tests, with relatively low bureaucratic overhead and a guarantee of safety, coordination, and oversight.”

Idea

Tank

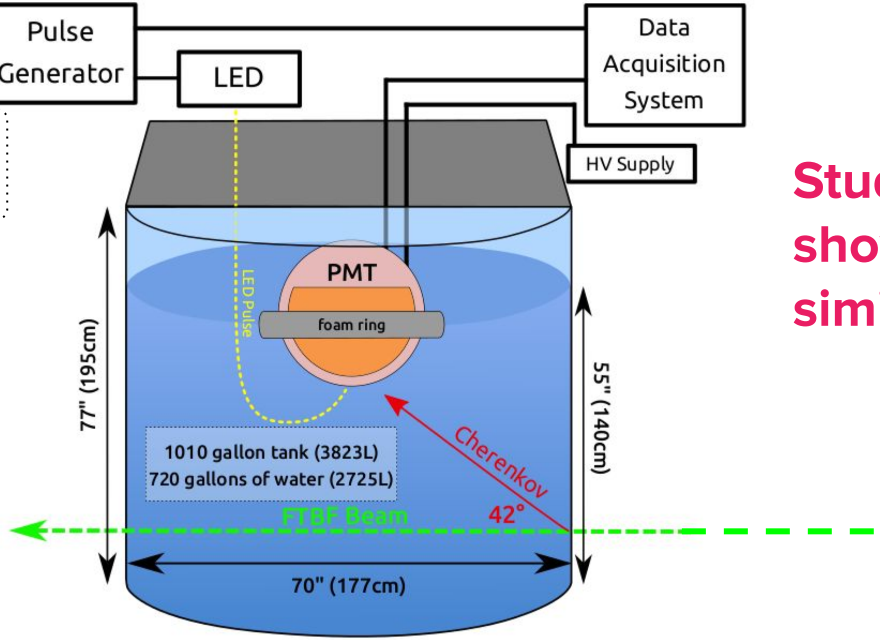


Beam of known particles from
Fermilab Test Beam Facility (FTBF)
http://ftbf.fnal.gov/

- ➔ Black tedlar film coats the inside and outside
- ➔ Filled with distilled water

Idea

Tank



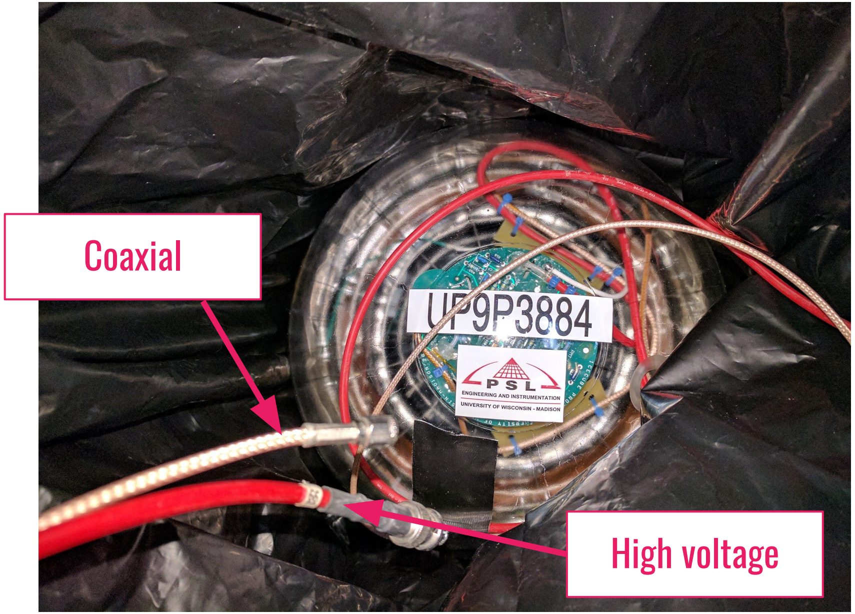
Study PID between MIPs vs EM showers using waveforms of similar charge around a few GeV

Beam of known particles from **Fermilab Test Beam Facility (FTBF)** http://ftbf.fnal.gov/

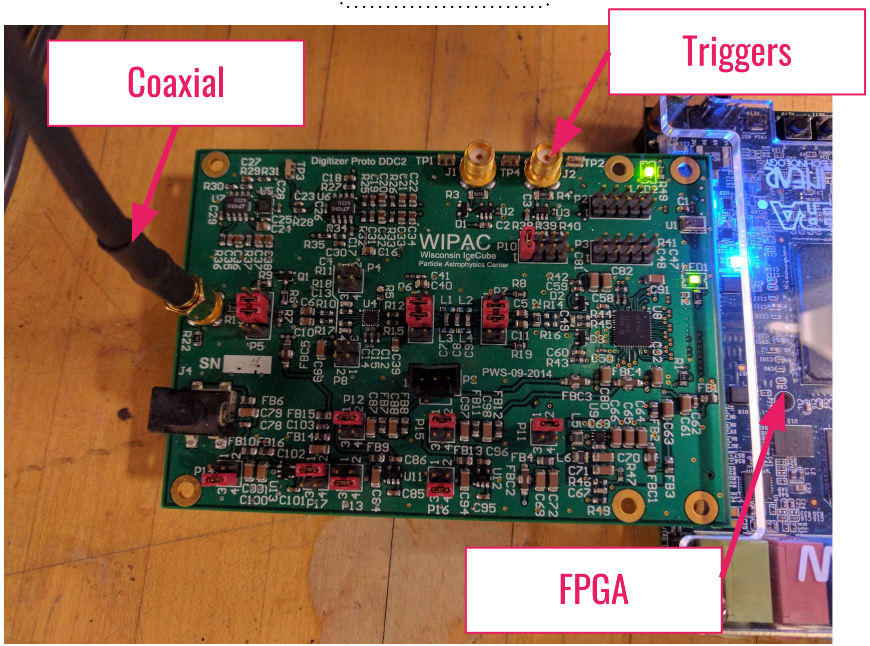
- ➔ Black tedlar film coats the inside and outside
- ➔ Filled with distilled water

Setup

DOM



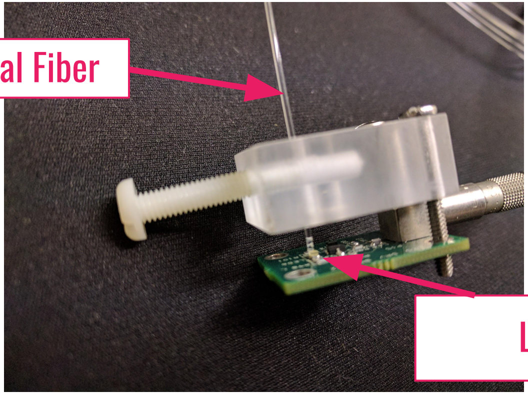
DDC2

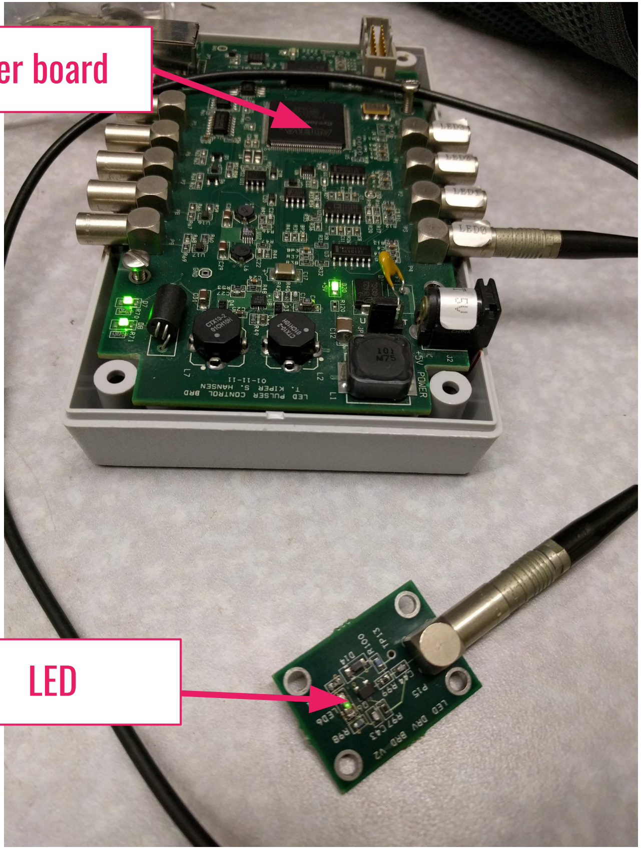


Setup

LED

- Use a well-defined LED pulses to test DOM is operational and produces the expected signal waveform
- FPGA board allows dynamic control of the LED
- We couple the LED light pulse to an optical fiber

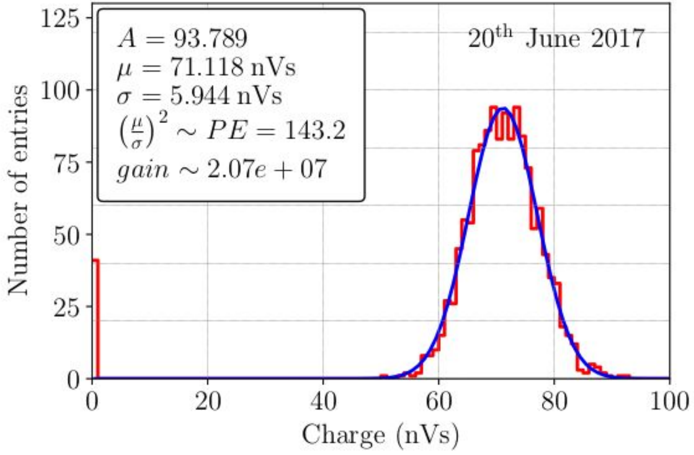


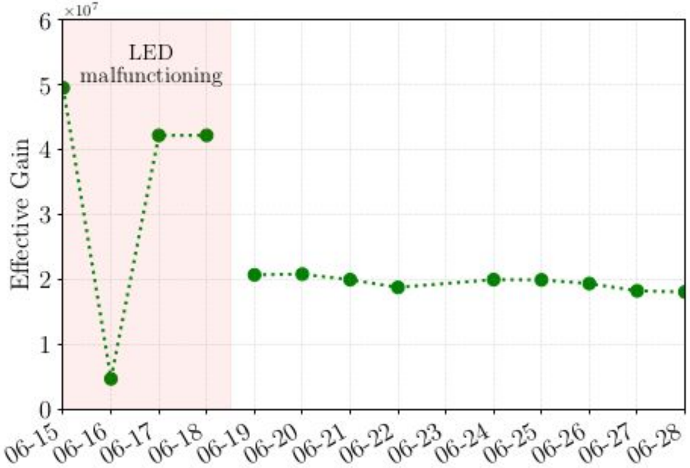


Setup

LED

- We can monitor the **gain** of the PMT by using the LED
  - Fit the charge distribution to a gaussian
  - Using poisson statistics, the number of PE hits and gain can be calculated
- This is useful to test the degradation of the water over the days when we have beam
  - Degradation of distilled water (i.e. changes in the water transparency) will affect the gain we measure on the PMT





Setup

Tank

- Delivered to FTBF
- Wrong colour! We were expecting a black tank
- We coated the inside and outside layers of the tank in a black Tedlar film

Setup

Tank

- ➔ Delivered to FTBF
- ➔ Wrong colour! We were expecting a black tank
- ➔ We coated the inside and outside layers of the tank in a black Tedlar film

Wires get fed through hole in the lid

Setup

Tank

➔ Moved the tank into the MT6.2 enclosure

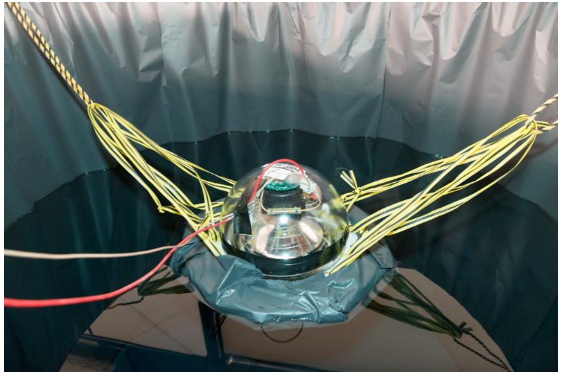
Crane

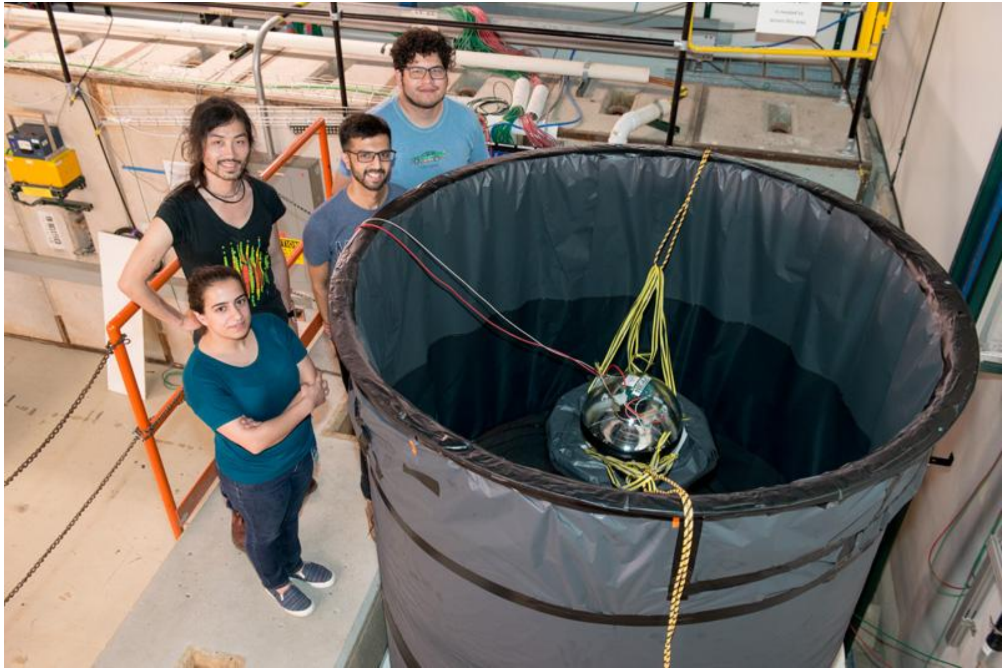
Beam

Setup

Tank

- ➔ Tank was filled with ~ 700 gallons of distilled water
- ➔ DOM was placed at the centre of the tank using ropes





FTBF

Beam details:

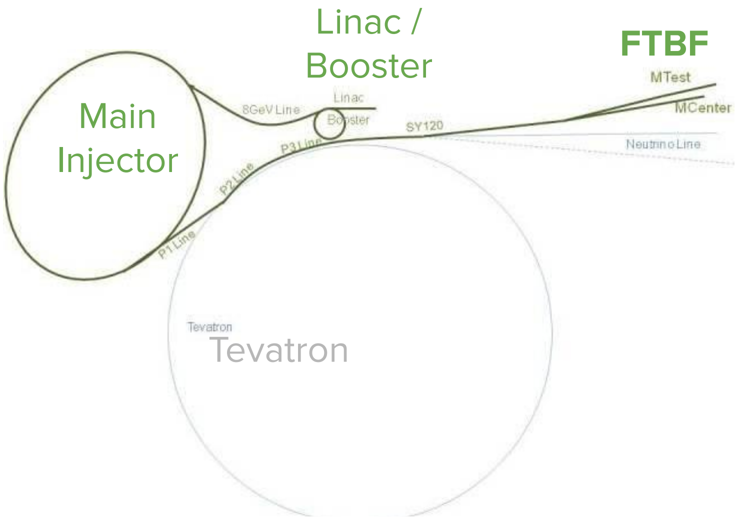
➔ Using the secondary beamline at "MTest"
- ◆ **(120 GeV**: Protons - primary beam from Main Injector)
- ◆ **8 - 60 GeV**: Pions, (some protons possible)
- ◆ **1 - 32 GeV**: Pions, electrons, kaons, or broadband muons

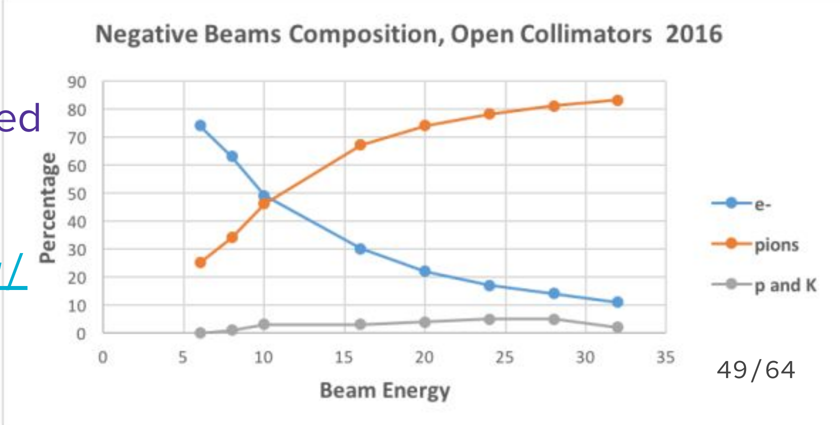
➔ 4 second spill every 60 seconds

➔ Tunable rate (100 Hz - 100,000 Hz), beam available 24/7

➔ At 4GeV pions make up ~30% of the beam
- ◆ This fraction gets smaller as energy is decreased

➔ Full details can be found:
- ◆ http://ftbf.fnal.gov/beam-overview/





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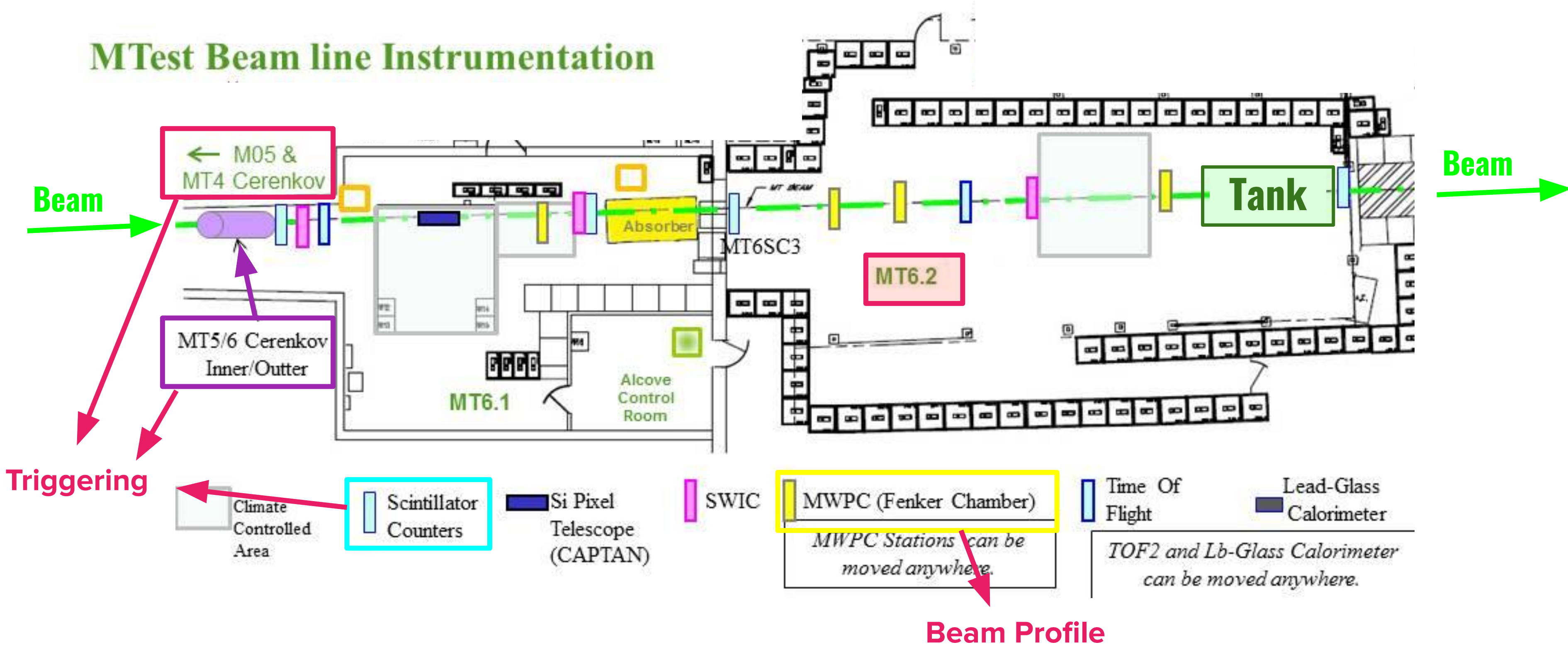
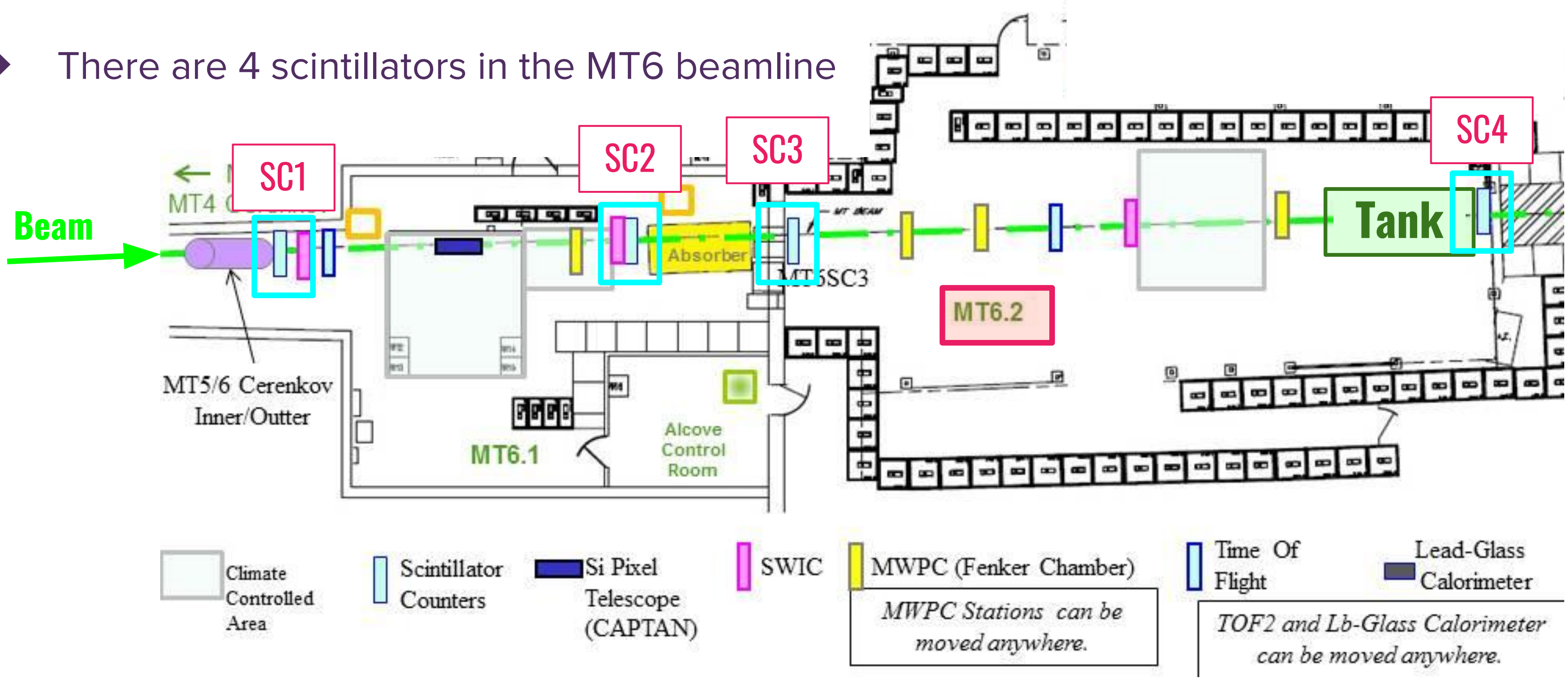
FTBF


MTest Beam line Instrumentation
← M05 &
MT4 Cerenkov
Beam
MT5/6 Cerenkov
Inner/Outter
Triggering
Absorber
MT6SC3
MT6.2
MT6.1
Alcove
Control
Room
Tank
Beam
Climate
Controlled
Area
Scintillator
Counters
Si Pixel
Telescope
(CAPTAN)
SWIC
MWPC (Fenker Chamber)
MWPC Stations can be
moved anywhere.
Time Of
Flight
Lead-Glass
Calorimeter
TOF2 and Lb-Glass Calorimeter
can be moved anywhere.
Beam Profile

Triggering

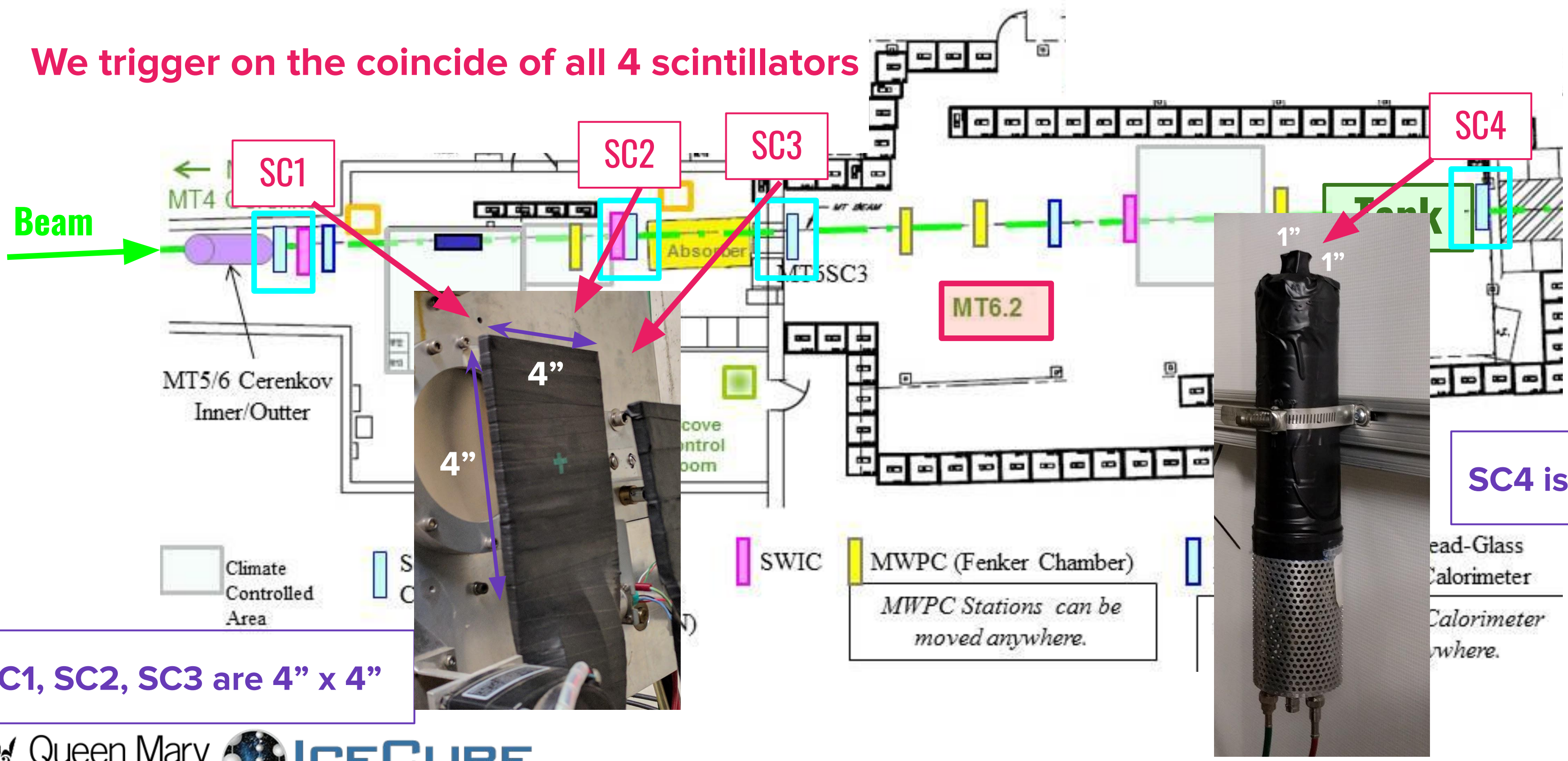
- ➔ There are 4 scintillators in the MT6 beamline



S. Mandalia
2019-10-17

Triggering

➔ **We trigger on the coincide of all 4 scintillators**

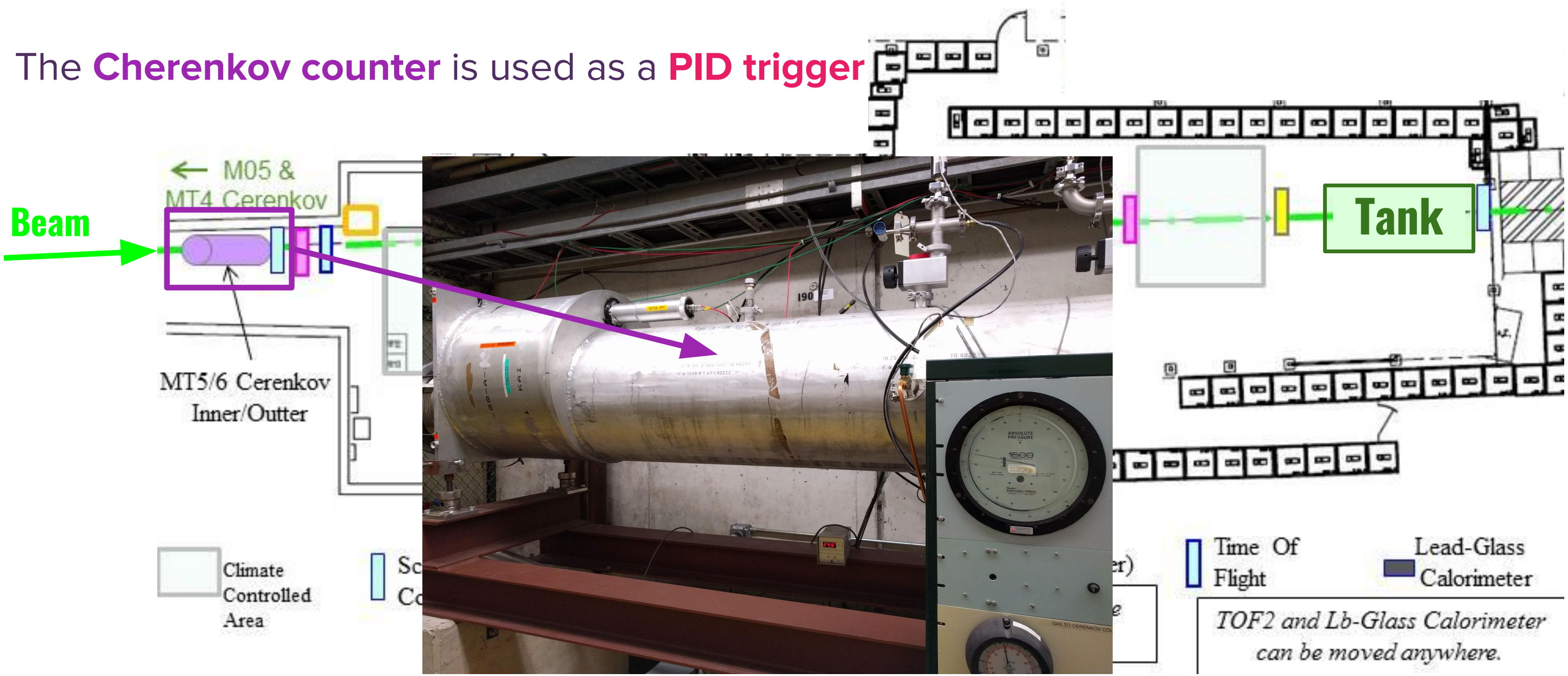


SC4 is 1” x 1”

SC1, SC2, SC3 are 4” x 4”

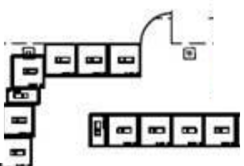
Triggering

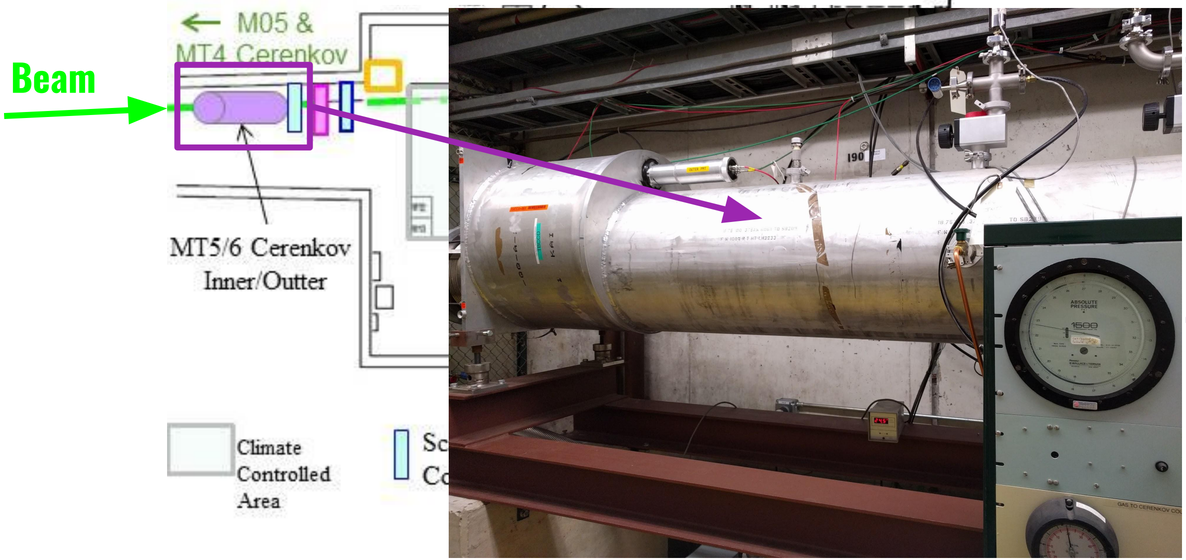
→ The **Cherenkov counter** is used as a **PID trigger**



Triggering

→ The **Cherenkov counter** is used as a **PID trigger**

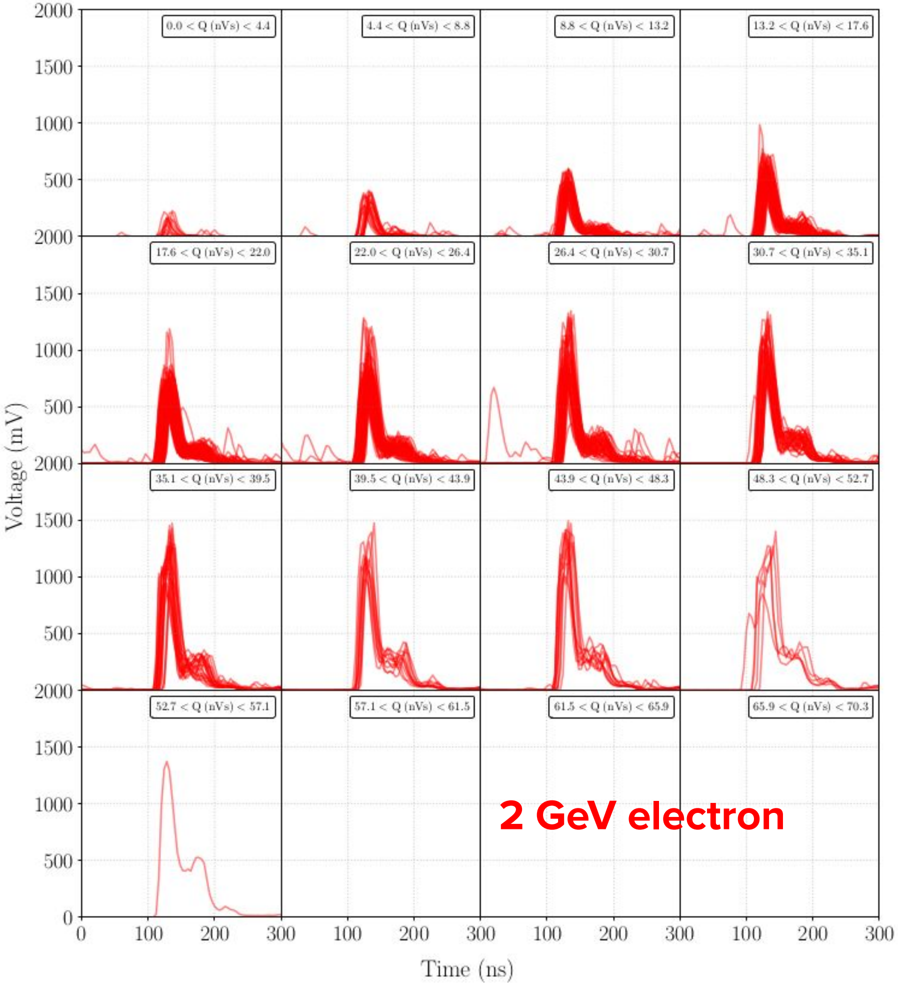


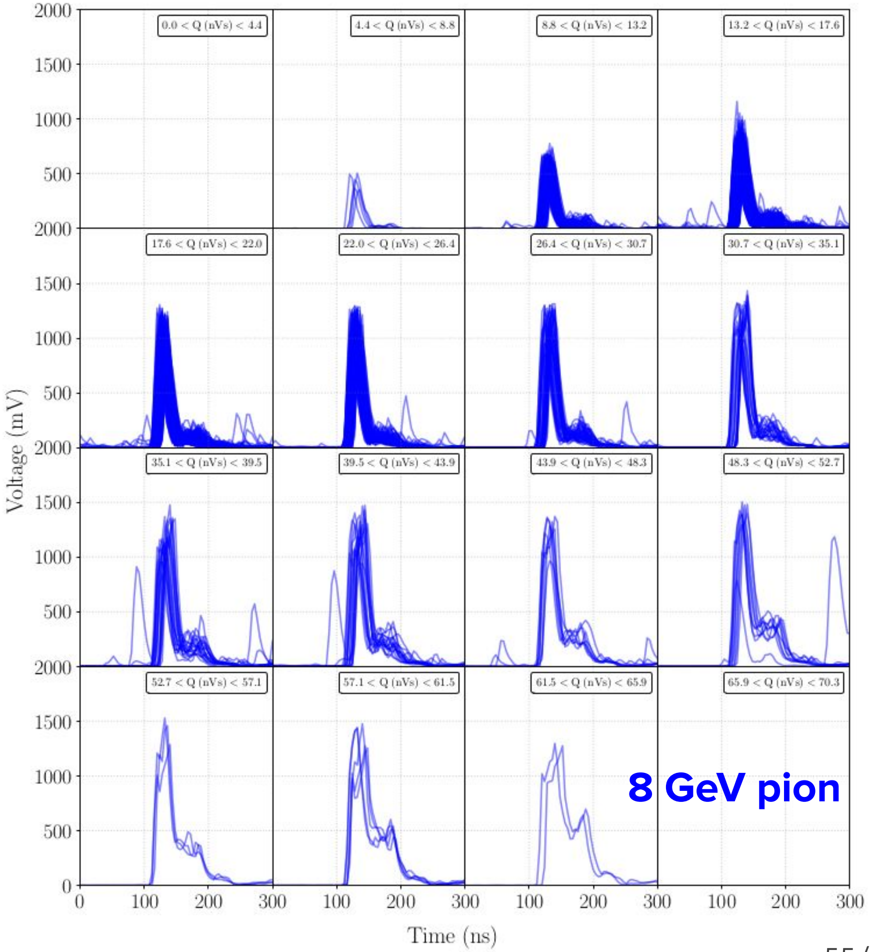


→ We trigger on the Cherenkov counter to select **electrons**

→ We can also do an **anti-coincidence** to trigger on everything **but electrons i.e. MIPs**

→ We use this in (anti-) coincidence with the **4 scintillators** for the final trigger


0.0 < Q (nVs) < 4.4
4.4 < Q (nVs) < 8.8
8.8 < Q (nVs) < 13.2
13.2 < Q (nVs) < 17.6
17.6 < Q (nVs) < 22.0
22.0 < Q (nVs) < 26.4
26.4 < Q (nVs) < 30.7
30.7 < Q (nVs) < 35.1
35.1 < Q (nVs) < 39.5
39.5 < Q (nVs) < 43.9
43.9 < Q (nVs) < 48.3
48.3 < Q (nVs) < 52.7
52.7 < Q (nVs) < 57.1
57.1 < Q (nVs) < 61.5
61.5 < Q (nVs) < 65.9
65.9 < Q (nVs) < 70.3
Voltage (mV)
Time (ns)
2 GeV electron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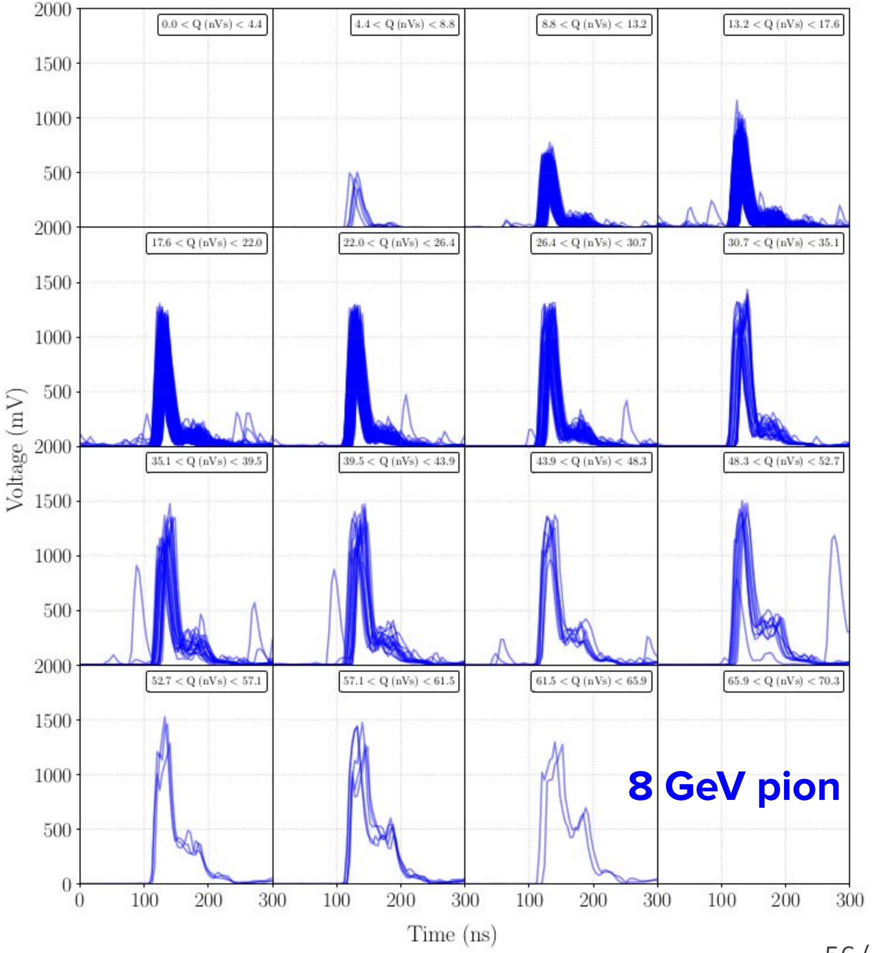
61.5 < Q (nVs) < 65.9
65.9 < Q (nVs) < 70.3
Voltage (mV)
Time (ns)
8 GeV pion

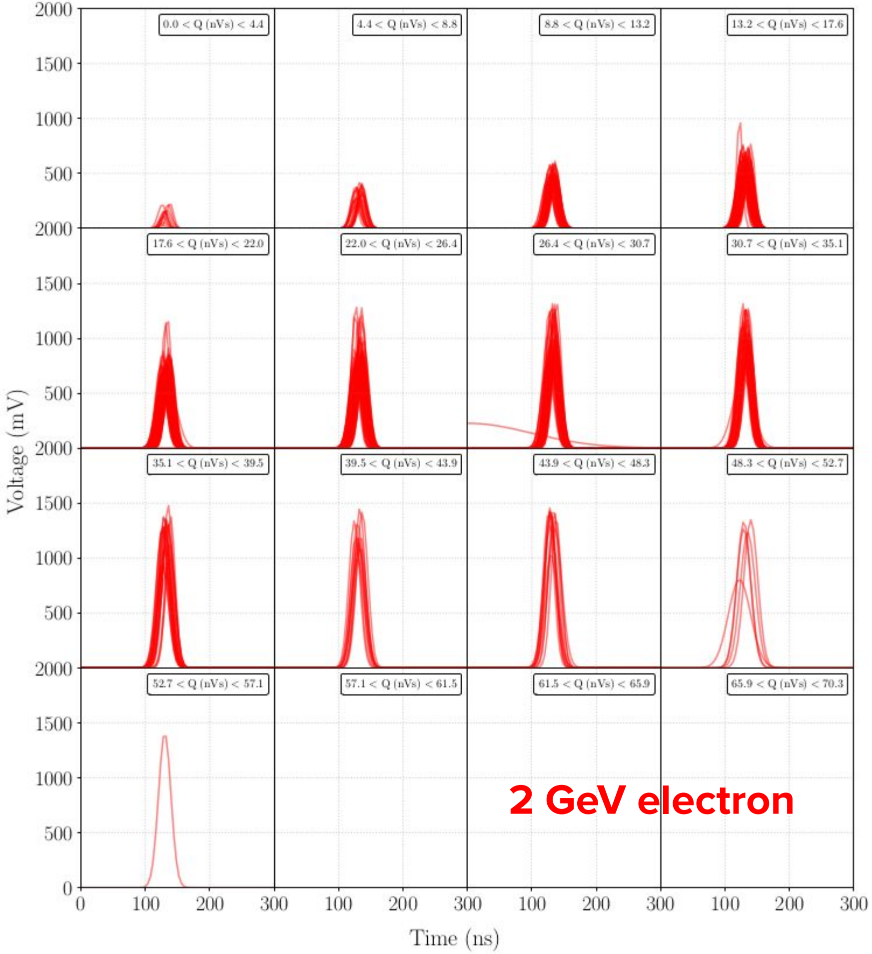
Data

➔ Waveforms observe a **primary** and **secondary** peak

- Secondary peak are due to **late pulses** which are caused by photoelectron backscattering off the dynodes

➔ We isolate the primary pulse by fitting the primary peak with a Gaussian

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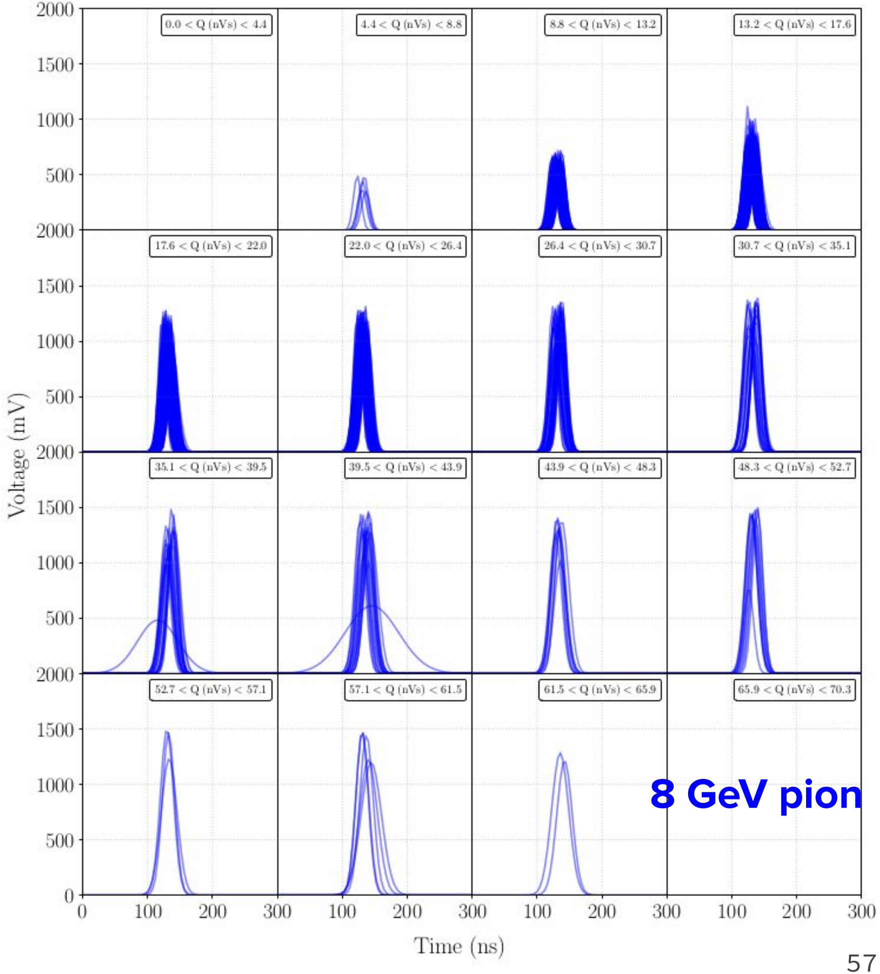
65.9 < Q (nVs) < 70.3
Voltage (mV)
Time (ns)
2 GeV electron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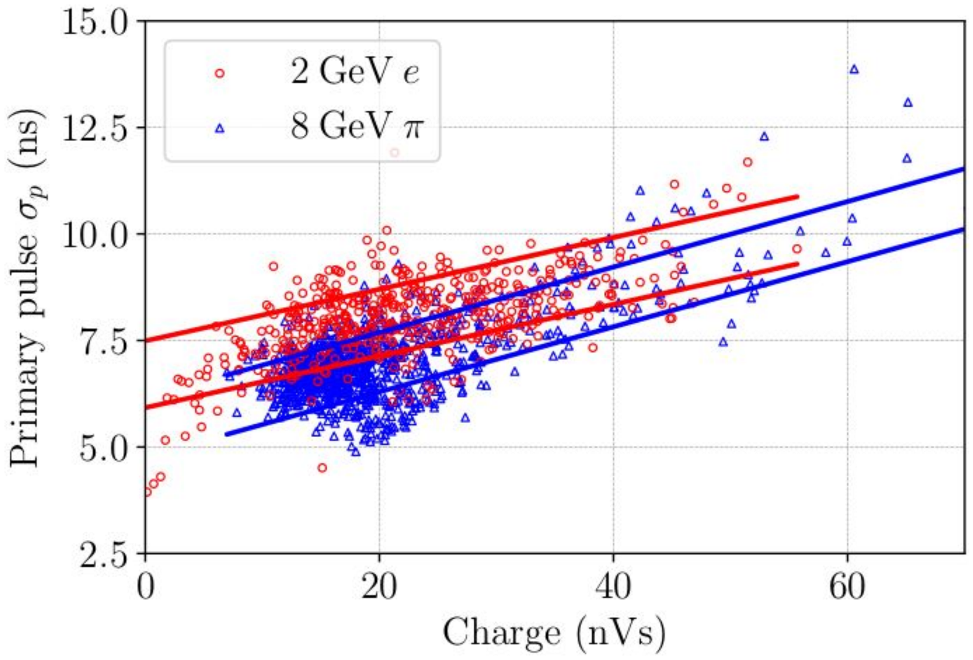
61.5 < Q (nVs) < 65.9
65.9 < Q (nVs) < 70.3
Voltage (mV)
Time (ns)
8 GeV pion

Results

- Comparing waveforms of a **similar charge**
  - Discriminator is simply the **width of the primary pulse**
  - Bands show the one sigma containment region
- At **low charge**, there is a possible discrimination that can be made between 2 GeV electron and 8 GeV pions
- These techniques can be applied to **future neutrino telescopes** focusing on low energy physics, such as the **IceCube-Upgrade**



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Hadronization in neutrino interactions

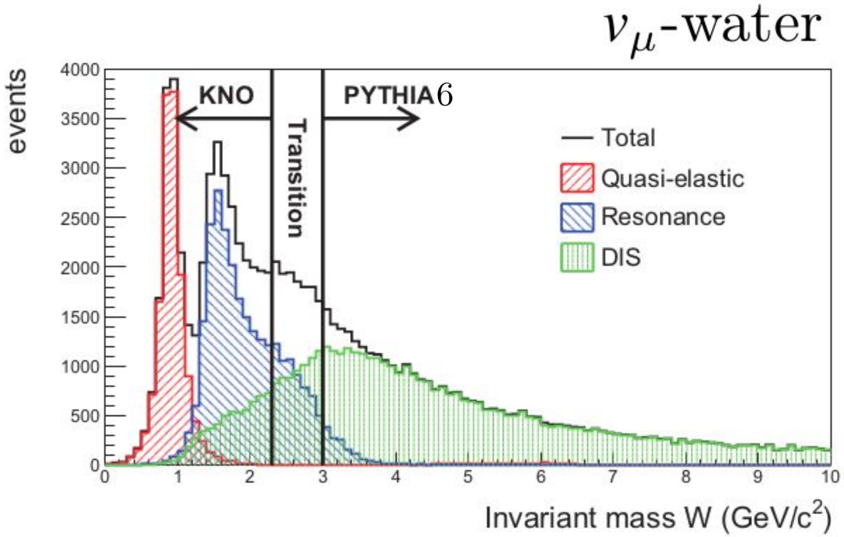
Sven Lidstrom, NSF

Queen Mary University of London ICECUBE SOUTH POLE NEUTRINO OBSERVATORY

Motivation

Hadronization is important at high energies when DIS dominates

- ➔ High-energy atmospheric neutrinos
  - ◆ IceCube (DeepCore) and IceCube-Upgrade
  - ◆ few GeV to ~ 100 GeV oscillation physics
  - ◆ Final state particles from hadronization affects total deposited energy

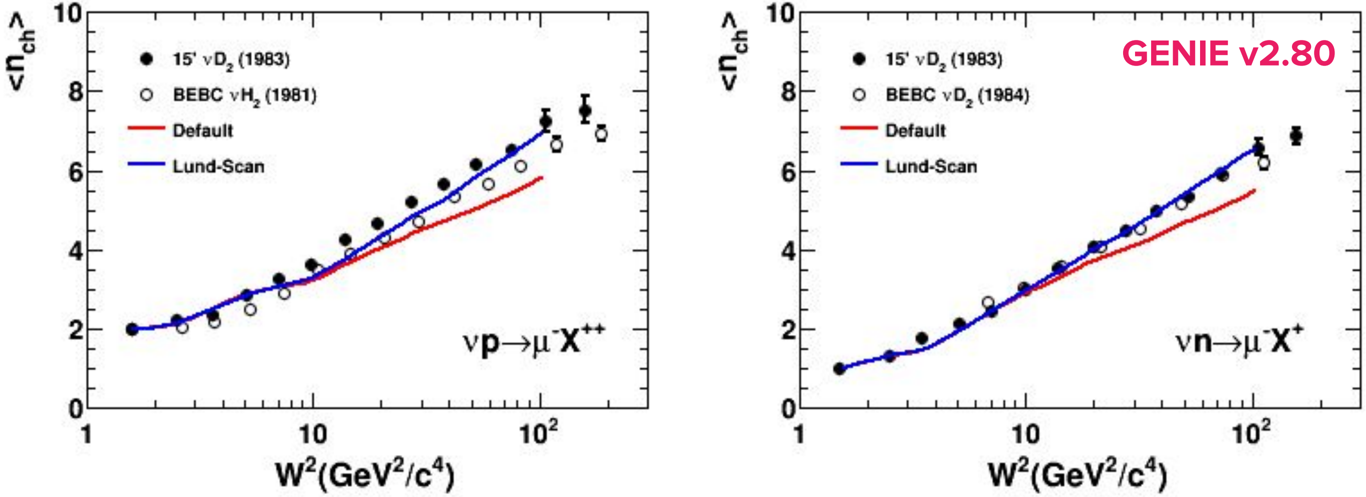


- ➔ ~ TeV energy neutrinos
  - ◆ Hadronization is important if GENIE is extended to the few TeV region (ongoing work)

Pythia 6 Tunings

HERMES (low energy) parameter sets have better agreements with the charged hadron multiplicity data

Parameter	"Lund-scan"
PARJ1	0.02
PARJ2	0.25
PARJ11	0.51
PARJ12	0.57
PARJ21	0.42
PARJ33	0.47
PARJ41	0.68
PARJ42	0.35
PARJ45	0.74
PARL3	(0.44)
PARJ23	(0.01)
PARJ24	(2.0)



	Default Pythia 6	Lund-Scan
PARJ41	0.30	0.68
PARJ42	0.58	0.35

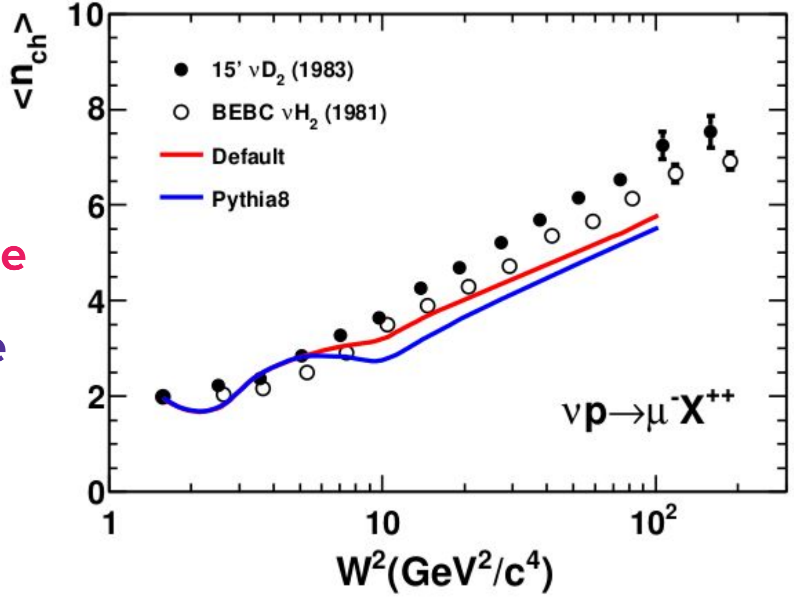
Pythia 8

Pythia 6 is outdated and no longer supported!

- ➔ Upgrade the GENIE to use Pythia 8
  - Directly affects the Hadronization and Decay routines
  - Pythia 8 can be directly interfaced with in C++ so there is no need for ROOT wrapper classes (e.g. TPythia6, TMCParticle)
- ➔ Incorporate different physics aspects of Pythia 8
  - Physics which were absent in Pythia 6 e.g. beam remnant structure
  - Tuning of Pythia 8 parameters to bubble chamber data

Direct Translation to Pythia 8

- Showing averaged charged multiplicity
  - Comparing "Default" Pythia 6 hadronization model with Pythia8
  - Compared also to bubble chamber data
- Will be implemented in next GENIE release
- Both Pythia 6 and Pythia 8 underestimate bubble chamber data
  - Pythia is tuned to high energy LHC experiments
  - We have the technology needed to tune the the hadronization model [1]



Neutrino interferometry for high-precision tests of Lorentz symmetry with IceCube

The IceCube Collaboration*

IceCube, Nature.Phy.14,961(2018)

T. Katori[45*], S. Mandalia[45*], J. Kiryluk[46], M. Lesiak-Bzdak[46], H. Niederhausen[46], Y. Xu[46], G. Kohnen[47],

PYTHIA hadronization process tuning in the GENIE neutrino interaction generator

J. Phys. G42, 115004 (2015)

Teppei Katori and Shivesh Mandalia

Probe Of Sterile Neutrinos Using Astrophysical Neutrino Flavor

arXiv:1909.05341

Carlos A. Argüelles,[1,*] Kareem Farrag,[2,3,†] Teppei Katori,[4,‡]
Rishabh Khandelwal,[5,§] Shivesh Mandalia,[2,¶] and Jordi Salvado[6,**]

Computational Techniques for the Analysis of Small Signals in High-Statistics Neutrino Oscillation Experiments

K. B. M. Mahn[w], S. Mancina[ah], S. Mandalia[af], S. Marka[aq], Z. Marka[aq], R. Maruyama[ap],

arXiv:1803.05390

Thanks for listening!

Test of Lorentz Violation with Astrophysical Neutrino Flavor in IceCube

arXiv:1906.09240

Teppei Katori[1], Carlos A. Argüelles[2], Kareem Farrag[1,3], and Shivesh Mandalia[1]

First look at the PYTHIA8 hadronization program for neutrino interaction generators

JPS Conf. Proc. 12, 010033 (2016)

Teppei KATORI, Pierre LASORAK, Shivesh MANDALIA, and Ryan TERRI

Quest for new physics using astrophysical neutrino flavor in IceCube

arXiv:1908.07602

Corresponding authors: Carlos A. Argüelles[1], Kareem Farrag[†2,3], Teppei Katori[2], Shivesh Mandalia[2]

Queen Mary University of London

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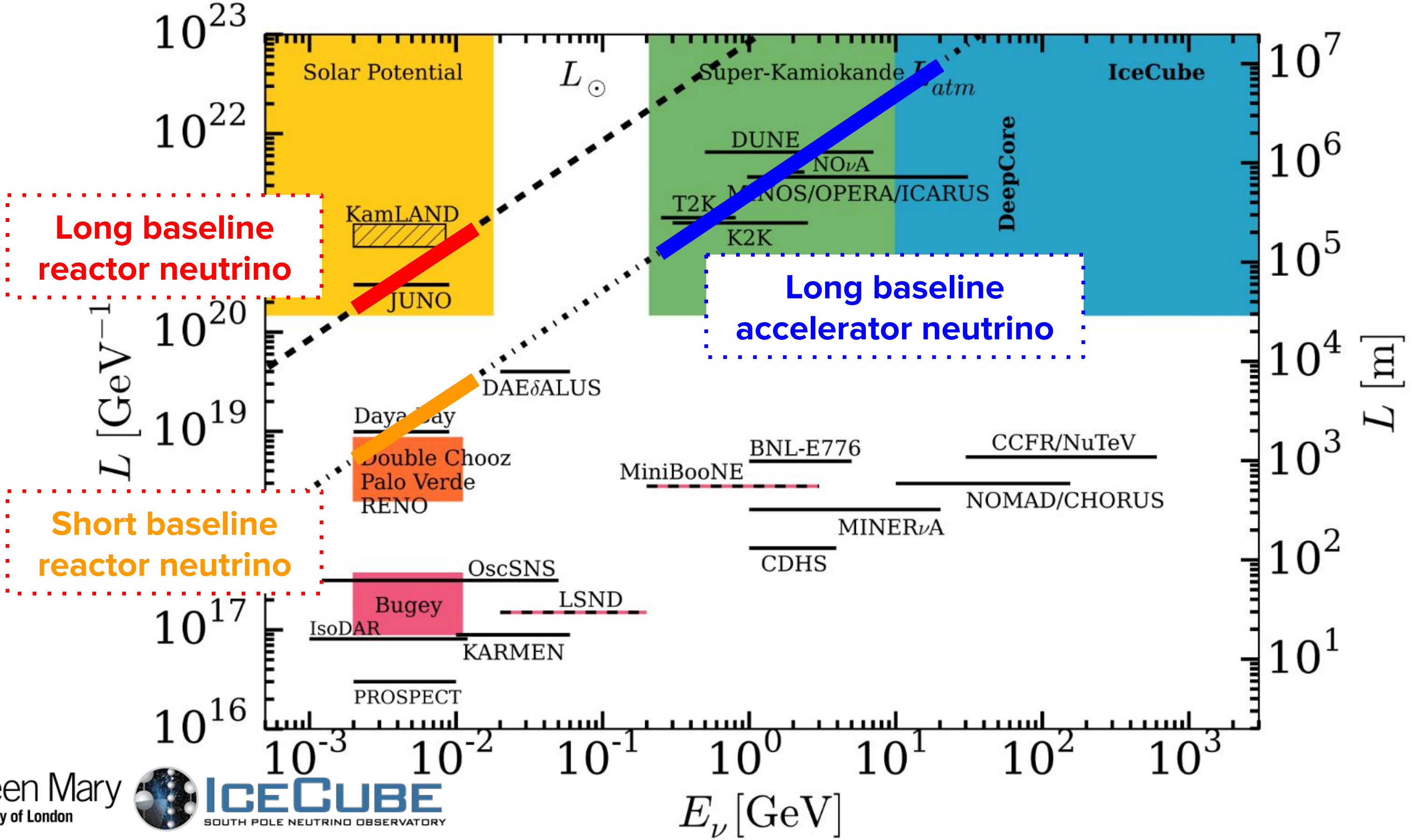
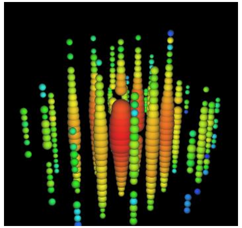
Terrestrial Oscillation Measurement Landscape



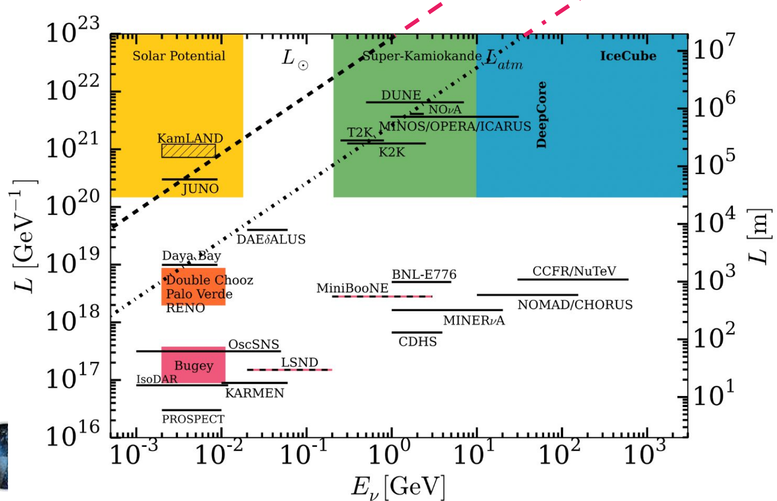
S. Mandalia
2019-10-17

Astrophysical Frontier?

> Mpc (~Andromeda)

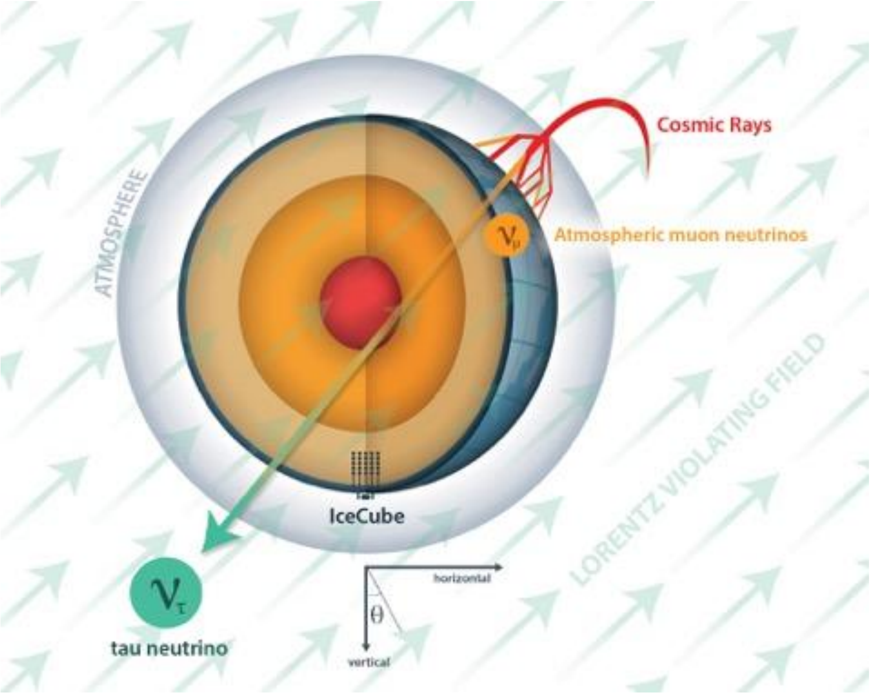


> 100 TeV

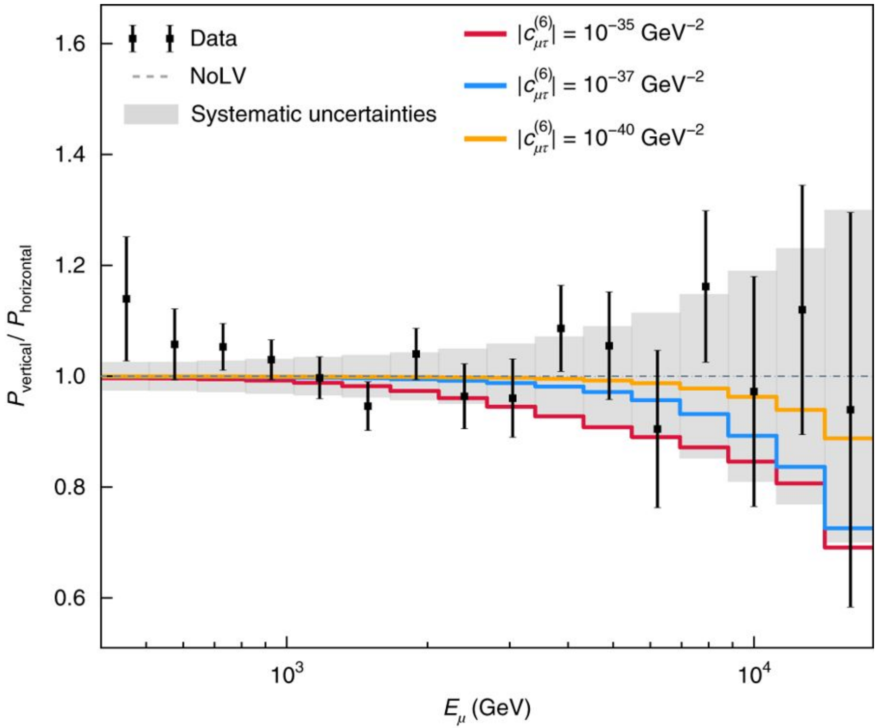


S. Mandalia
2019-10-17

Neutrino interferometry for high-precision tests of Lorentz symmetry



Concept of spectrum distortion



Expected P(vertical)/P(horizontal) for dimension 6 LV operator

Neutrino interferometry for high-precision tests of Lorentz symmetry

Binning

400 GeV < E < 18 TeV ("conventional")
-1 < cos(zenith) < 0 ("up-going")

very similar to 2016 sterile neutrino analysis sample
https://icecube.wisc.edu/science/data/HE_NuMu_diffuse

Simulation

- ➔ Atmospheric neutrinos from **MCEq** https://github.com/afedynitch/MCEq
- ➔ Simple power law for astrophysical neutrinos
- ➔ DIS cross section from **CSS** paper
- ➔ Analytical oscillation formula

Sytematics

6 nuisance params

Normalization of flux:

1. conventional (40%)
2. prompt (free)
3. astrophysical (free)

Flux components:

1. primary cosmic ray index (2%)
2. astrophysical neutrinos index (25%)
3. p/K ratio for conventional flux (10%)

LV Params

$$H \sim \frac{m^2}{2E} + \mathring{a}^{(3)} - E \cdot \mathring{c}^{(4)} + E^2 \cdot \mathring{a}^{(5)} - E^3 \cdot \mathring{c}^{(6)} \cdots \quad (1)$$

$$\mathring{c}^{(6)} = \begin{pmatrix} \mathring{c}^{(6)}_{\mu\mu} & \mathring{c}^{(6)}_{\mu\tau} \\ \mathring{c}^{(6)*}_{\mu\tau} & -\mathring{c}^{(6)}_{\mu\mu} \end{pmatrix} \quad (2)$$

Perform fit for the **3 LV params** for each dimension

Fit Methods

- ➔ Likelihood with Wilk's theorem (our main results)
- ➔ **Bayesian Markov Chain Monte Carlo** http://dan.iel.fm/emcee/current

dalia
10-17

dim.	method	type	sector		limits	ref.
3	CMB polarization	astrophysical	photon		$\sim 10^{-43}$ GeV	[6]
	He-Xe comagnetometer	tabletop	neutron		$\sim 10^{-34}$ GeV	[10]
	torsion pendulum	tabletop	electron		$\sim 10^{-31}$ GeV	[12]
	muon g-2	accelerator	muon		$\sim 10^{-24}$ GeV	[13]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}(\mathring{a}^{(3)}_{\mu\tau})\rvert, \lvert\mathrm{Im}(\mathring{a}^{(3)}_{\mu\tau})\rvert$	$< 2.9 \times 10^{-24}$ GeV (99% C.L.) $< 2.0 \times 10^{-24}$ GeV (90% C.L.)	this work
4	GRB vacuum birefringence	astrophysical	photon		$\sim 10^{-38}$	[7]
	Laser interferometer	LIGO	photon		$\sim 10^{-22}$	[8]
	Sapphire cavity oscillator	tabletop	photon		$\sim 10^{-18}$	[5]
	Ne-Rb-K comagnetometer	tabletop	neutron		$\sim 10^{-29}$	[11]
	trapped Ca^{+} ion	tabletop	electron		$\sim 10^{-19}$	[14]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}(\mathring{c}^{(4)}_{\mu\tau})\rvert, \lvert\mathrm{Im}(\mathring{c}^{(4)}_{\mu\tau})\rvert$	$< 3.9 \times 10^{-28}$ (99% C.L.) $< 2.7 \times 10^{-28}$ (90% C.L.)	this work
5	GRB vacuum birefringence	astrophysical	photon		$\sim 10^{-34}$ GeV^{-1}	[7]
	ultra-high-energy cosmic ray	astrophysical	proton		$\sim 10^{-22}$ to 10^{-18} GeV^{-1}	[9]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}(\mathring{a}^{(5)}_{\mu\tau})\rvert, \lvert\mathrm{Im}(\mathring{a}^{(5)}_{\mu\tau})\rvert$	$< 2.3 \times 10^{-32}$ GeV^{-1} (99% C.L.) $< 1.5 \times 10^{-32}$ GeV^{-1} (90% C.L.)	this work
6	GRB vacuum birefringene	astrophysical	photon		$\sim 10^{-31}$ GeV^{-2}	[7]
	ultra-high-energy cosmic ray	astrophysical	proton		$\sim 10^{-42}$ to 10^{-35} GeV^{-2}	[9]
	gravitational Cherenkov radiation	astrophysical	gravity		$\sim 10^{-31}$ GeV^{-2}	[15]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}(\mathring{c}^{(6)}_{\mu\tau})\rvert, \lvert\mathrm{Im}(\mathring{c}^{(6)}_{\mu\tau})\rvert$	$< 1.5 \times 10^{-36}$ GeV^{-2} (99% C.L.) $< 9.1 \times 10^{-37}$ GeV^{-2} (90% C.L.)	this work
7	GRB vacuum birefringence	astrophysical	photon		$\sim 10^{-28}$ GeV^{-3}	[7]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}(\mathring{a}^{(7)}_{\mu\tau})\rvert, \lvert\mathrm{Im}(\mathring{a}^{(7)}_{\mu\tau})\rvert$	$< 8.3 \times 10^{-41}$ GeV^{-3} (99% C.L.) $< 3.6 \times 10^{-41}$ GeV^{-3} (90% C.L.)	this work
8	gravitational Cherenkov radiation	astrophysical	gravity		$\sim 10^{-46}$ GeV^{-4}	[15]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}(\mathring{c}^{(8)}_{\mu\tau})\rvert, \lvert\mathrm{Im}(\mathring{c}^{(8)}_{\mu\tau})\rvert$	$< 5.2 \times 10^{-45}$ GeV^{-4} (99% C.L.) $< 1.4 \times 10^{-45}$ GeV^{-4} (90% C.L.)	this work

TABLE I: Comparison of attainable best limits of SME coefficients in various fields. IceCube, Nature.Phy.14,961(2018)

Back of the Envelope Sensitivity

Binning = [60 TeV - 10 PeV] 20 bins

$$H_d = \boxed{\frac{1}{2E} U M^2 U^\dagger} + \boxed{\frac{E^{d-3}}{\Lambda_d} \tilde{U}_d O_d \tilde{U}_d^\dagger} = V_d(E) \Delta V_d^\dagger(E)$$

DIM 3

$$\boxed{\frac{1}{E} \cdot 10^{-21}\mathrm{GeV}} \sim \boxed{\frac{1}{\Lambda}}$$

60 TeV ~ 1E4 GeV

$$\Lambda_3^{-1} \sim 10^{-25}\mathrm{GeV}$$

10 PeV = 1E7 GeV

$$\Lambda_3^{-1} \sim 10^{-28}\mathrm{GeV}$$

$$\boxed{10^{-25}\mathrm{GeV} < \Lambda_3^{-1} < 10^{-28}\mathrm{GeV}}$$

DIM 6

$$\boxed{\frac{1}{E} \cdot 10^{-21}\mathrm{GeV}} \sim \boxed{\frac{E^3}{\Lambda}}$$

60 TeV ~ 1E4 GeV

$$\Lambda_6^{-1} \sim 10^{-37}\mathrm{GeV}^{-2}$$

10 PeV = 1E7 GeV

$$\Lambda_6^{-1} \sim 10^{-49}\mathrm{GeV}^{-2}$$

$$\boxed{10^{-37}\mathrm{GeV}^{-2} < \Lambda_6^{-1} < 10^{-49}\mathrm{GeV}^{-2}}$$

Markov Chain Monte Carlo

$$p\left(D\right) = \int p\left(D \mid \Theta, \alpha\right) \cdot p\left(\Theta, \alpha\right)\ d\Theta\ d\alpha$$

The goal is to obtain the posterior distribution marginalised over your nuisance parameters

Joint Posterior

Likelihood

Prior

$$p\left(\Theta, \alpha \mid D\right) = \frac{p\left(D \mid \Theta, \alpha\right) \cdot p\left(\Theta, \alpha\right)}{p\left(D\right)}$$

Marginal Likelihood

$$p\left(\Theta \mid D\right) = \int p\left(\Theta, \alpha \mid D\right) d\alpha$$

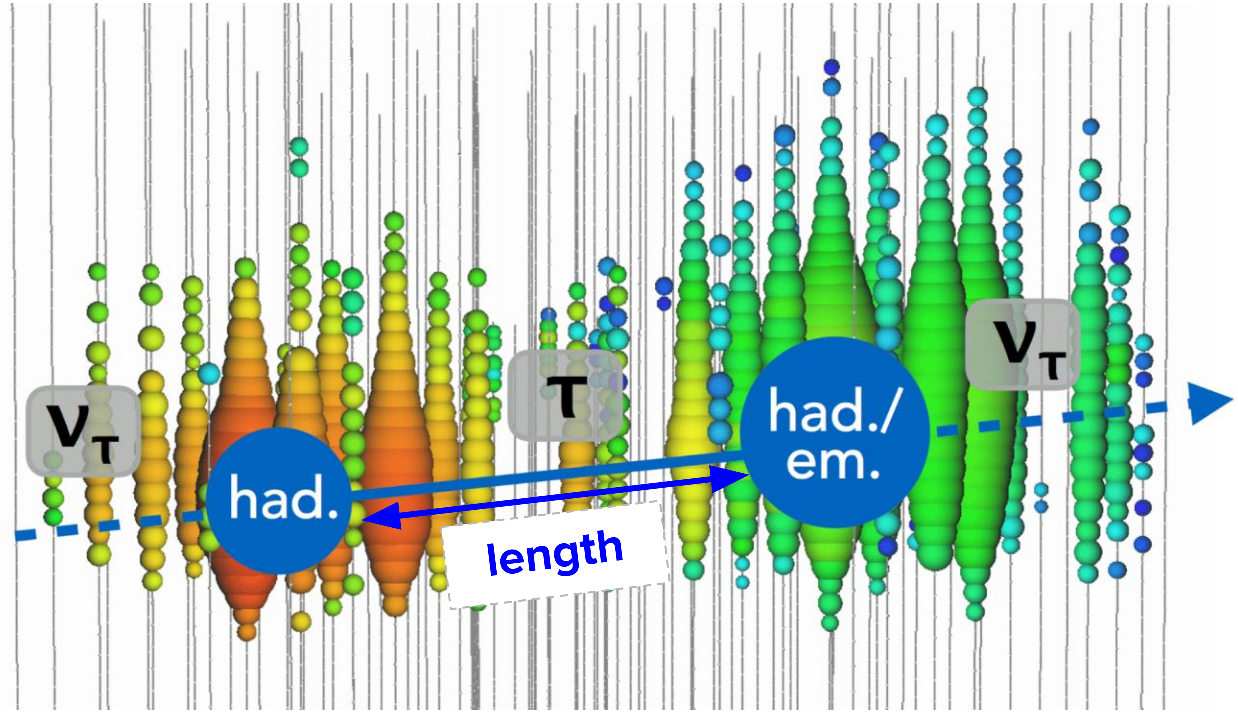
Marginalised Posterior

Problem: In a multidimensional space, the integral over the nuisance parameters is difficult to perform directly

Instead: Use an MCMC to sample over the joint posterior, after which the sampled points can be integrated over in a more straightforward way to obtain the marginalised posterior

Flavour Identification

Updated search for astrophysical tau neutrinos with starting events with double cascades!

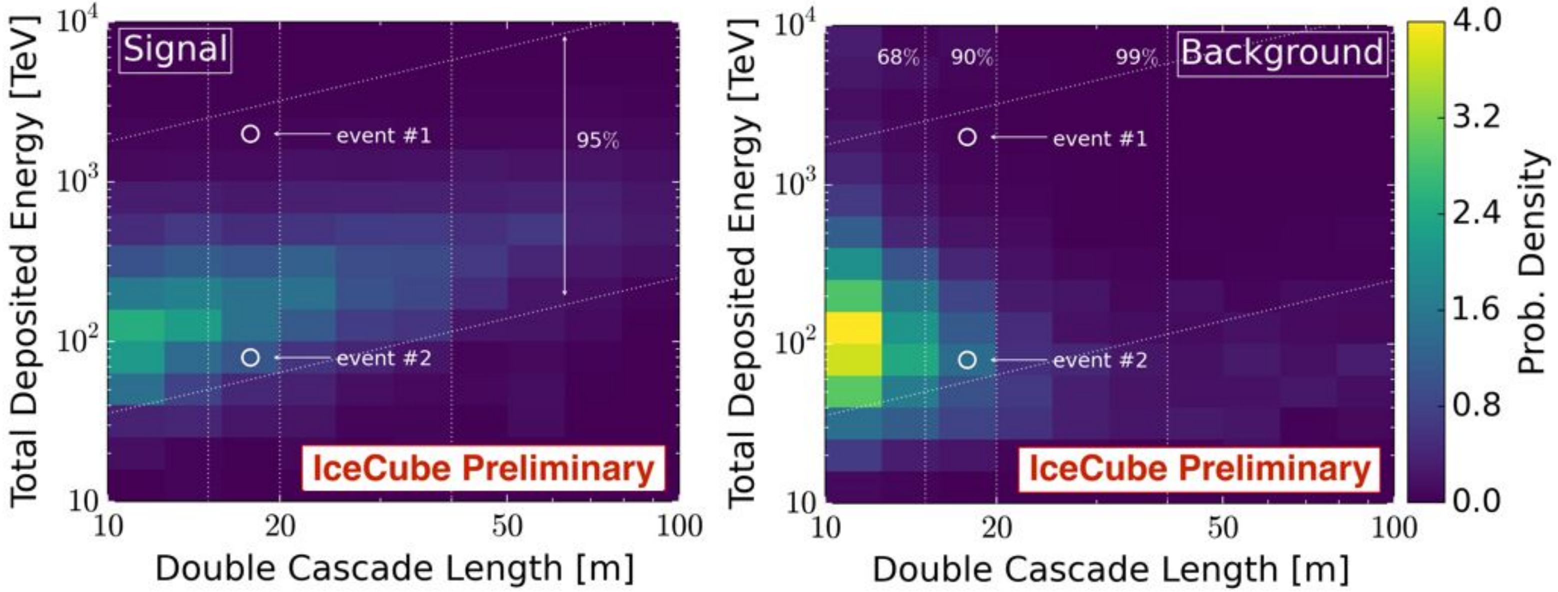


Require:

➔ Both cascades with $E > 1$ TeV
➔ Separation distance > 10 m

J. Stachurska, *ICRC (2019)*, arXiv: 1908.05506

Two Candidate Events



- ➔ **Two double cascade events have been identified!**
- ➔ **Could have arisen from ν_τ or background (astro. or atm.)**
- ➔ **Dedicated studies are on-going**

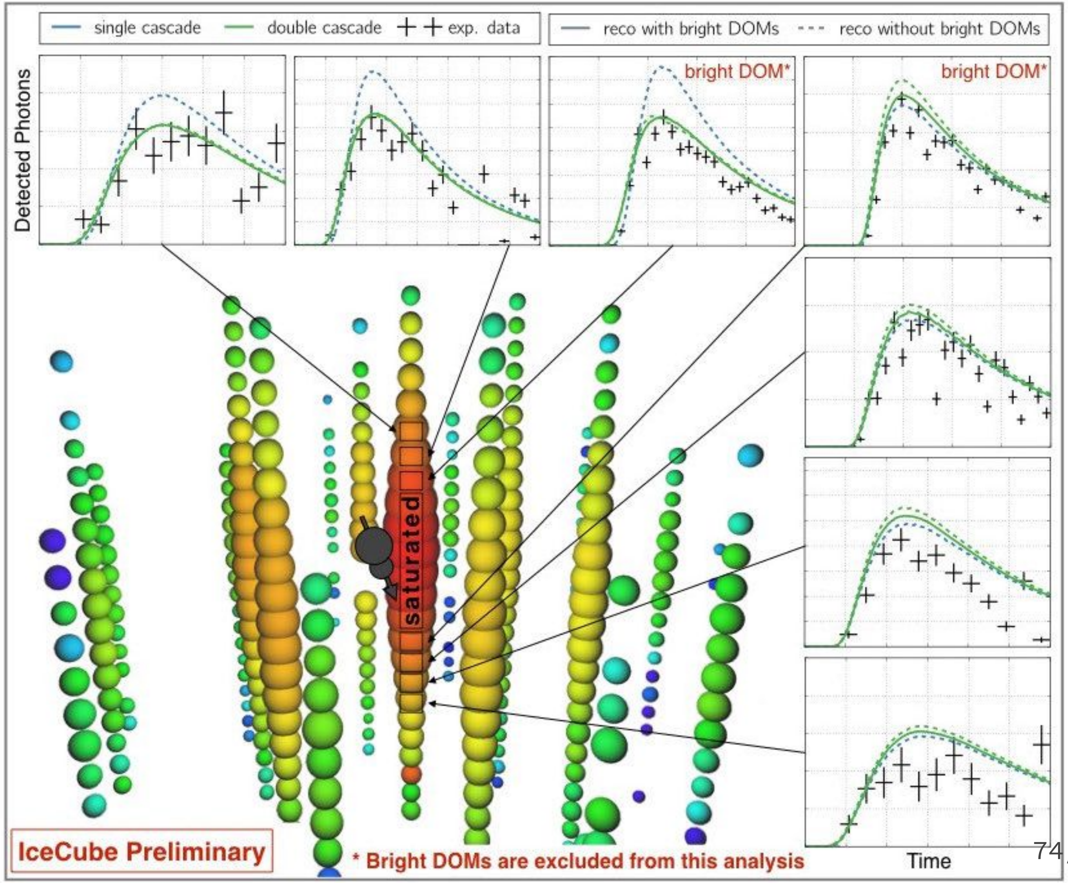
J. Stachurska, *ICRC (2019)*, arXiv: 1908.05506

Two Candidate Events

Candidate Event 1

Some preference for double cascade over single cascade based on DOM-to-DOM charge distributions

Dedicated studies ongoing



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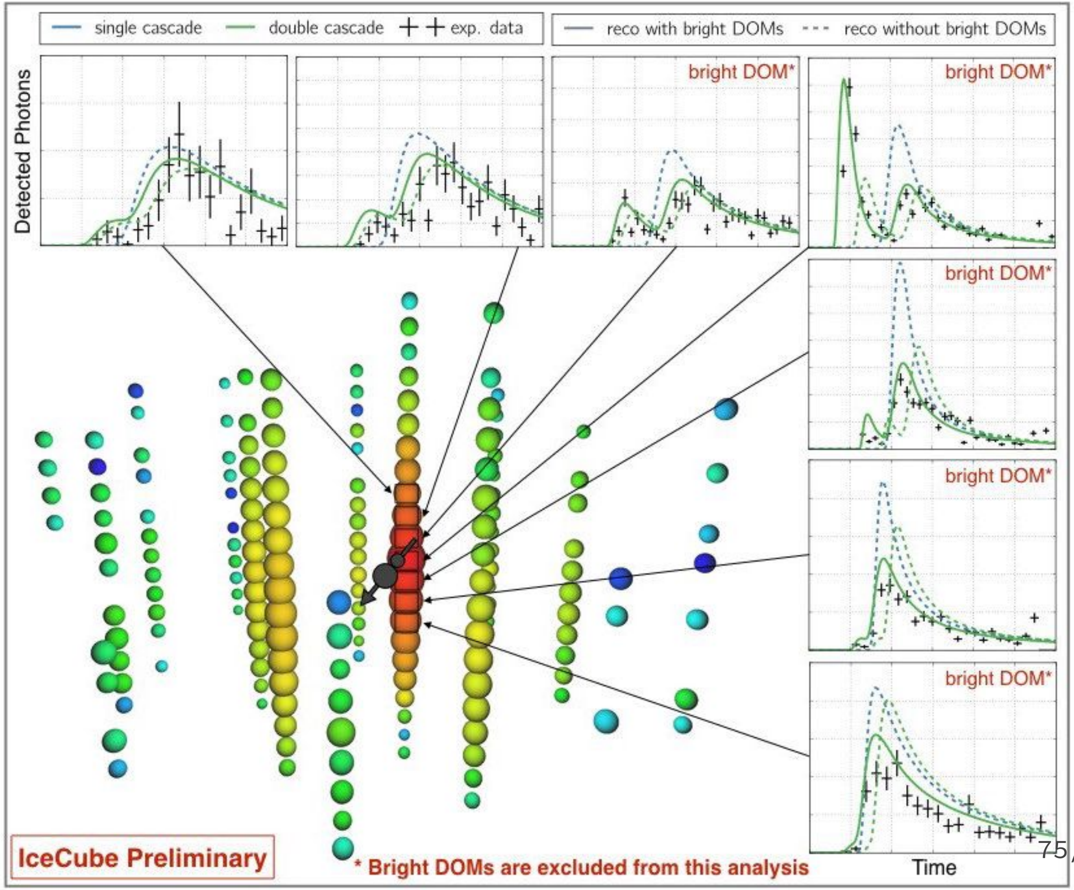
ICECUBE SOUTH POLE NEUTRINO OBSERVATORY

Two Candidate Events

Candidate Event 2

Strong preference for double cascade over single cascade based on DOM-to-DOM charge distributions

Dedicated studies ongoing



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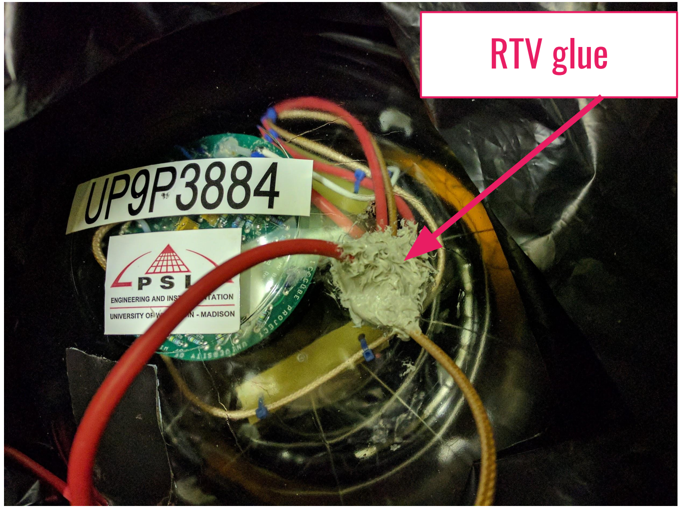
Setup

DOM

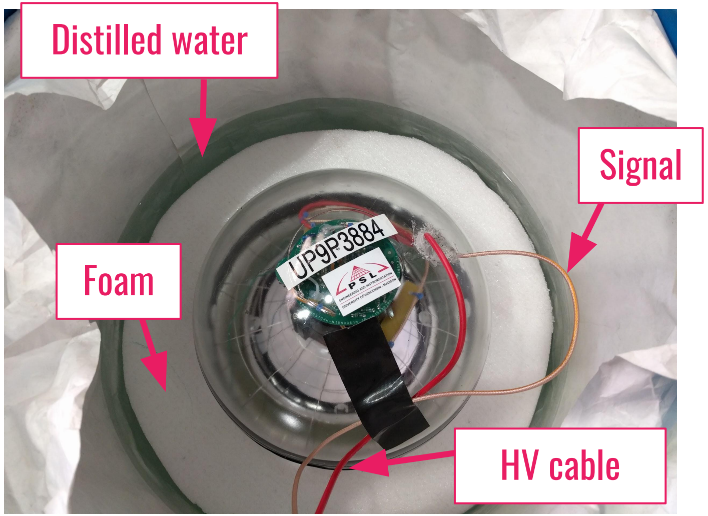
- DOM must be made water-tight
- Penetrator was closed up by using grey RTV glue

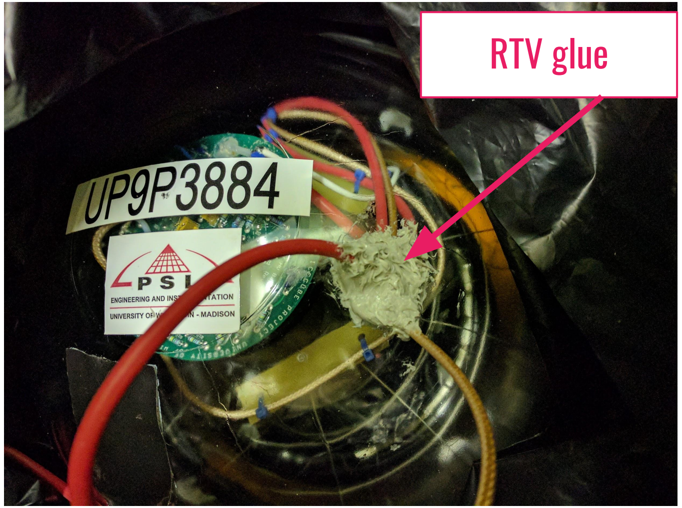


Setup

DOM

- DOM must be made water-tight
- Penetrator was closed up by using grey RTV glue
- Used a 55-gallon drum filled with distilled water as test



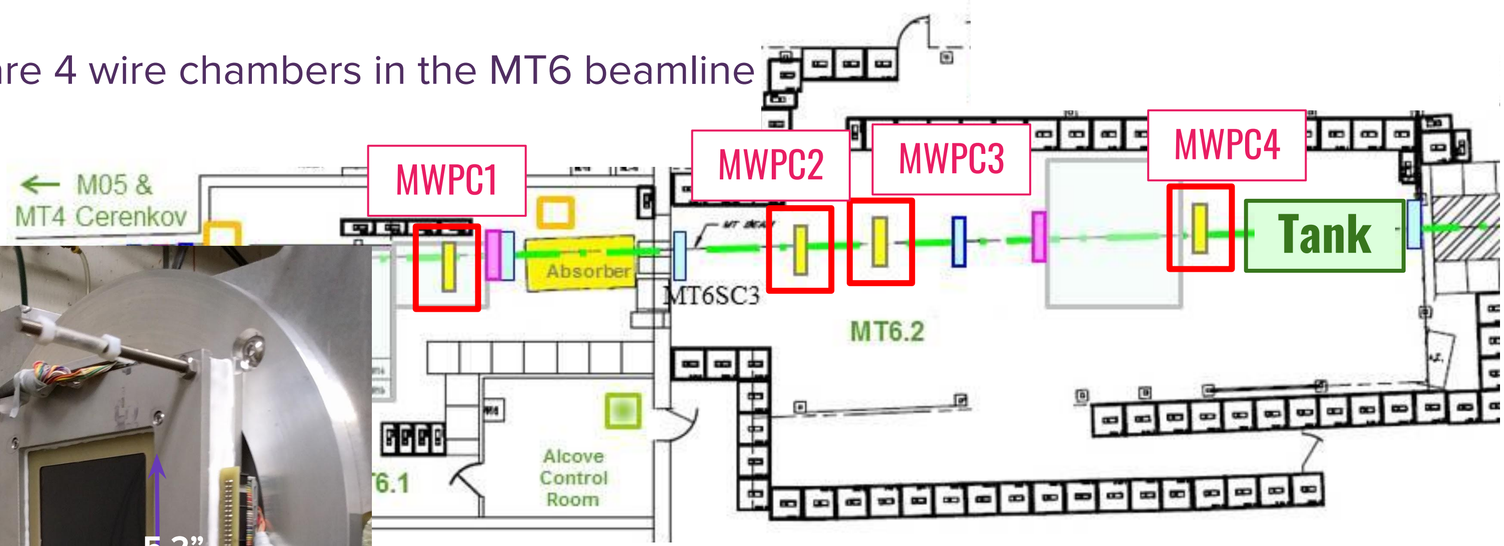


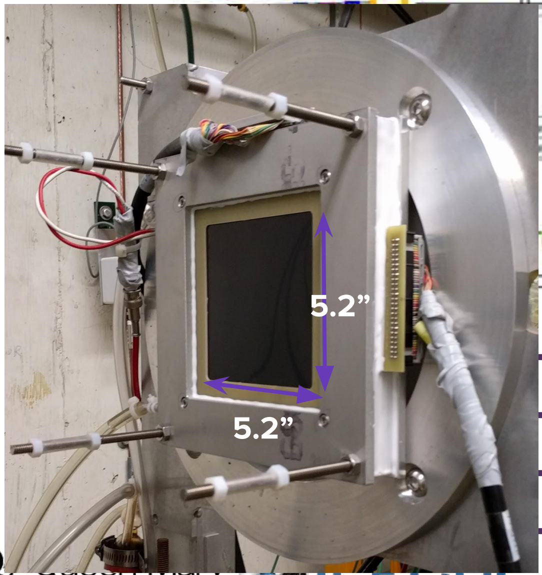
- DOM is very buoyant!
- For stability we made a foam structure which houses the DOM - “floating island”

S. Mandalia
2019-10-17

Beam Profile

→ There are 4 wire chambers in the MT6 beamline





→ Each MWPC has a dimension 5.2” x 5.2”

→ These MWPCs provide **x-y information**

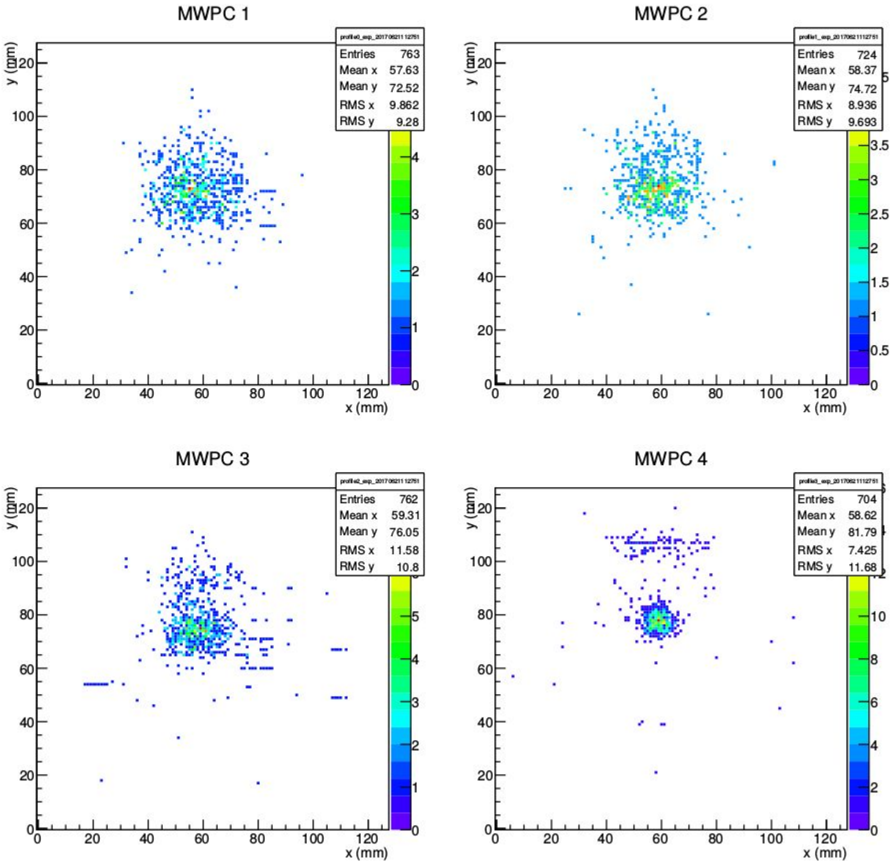
→ We use our trigger on these to **profile the x-y spread** of the beam

→ This is useful to diagnose any problems with the incoming beam

Beam Profile

Example:

➔ 8GeV MIP beam



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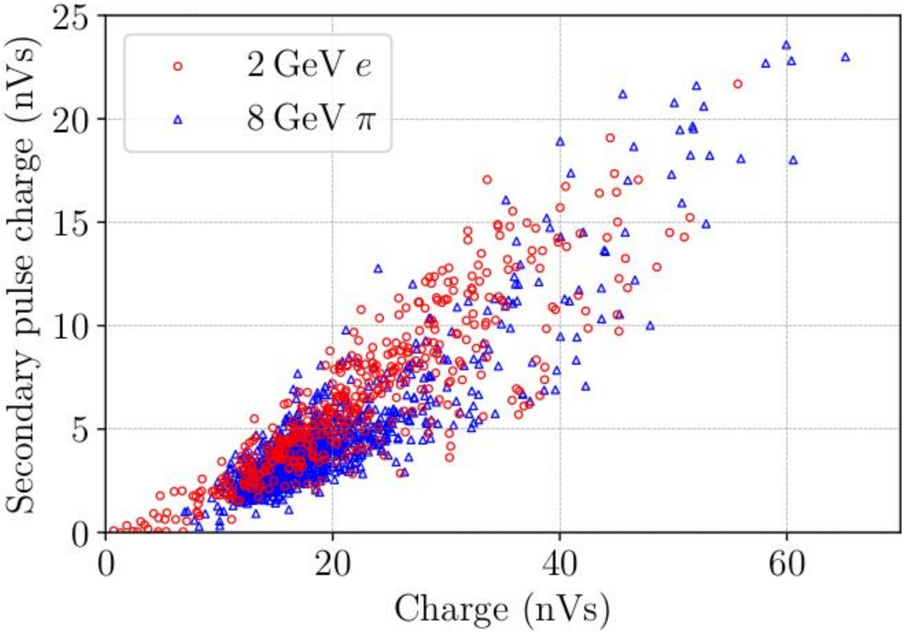

Figure 5.15: Charge of the secondary pulse plotted as a function of the charge of the waveform. In red circles show data points for a 2 GeV electron beam and in blue triangles show data points for an 8 GeV pion beam. For both configurations, it can be seen that the second pulse grows linearly with the total waveform.

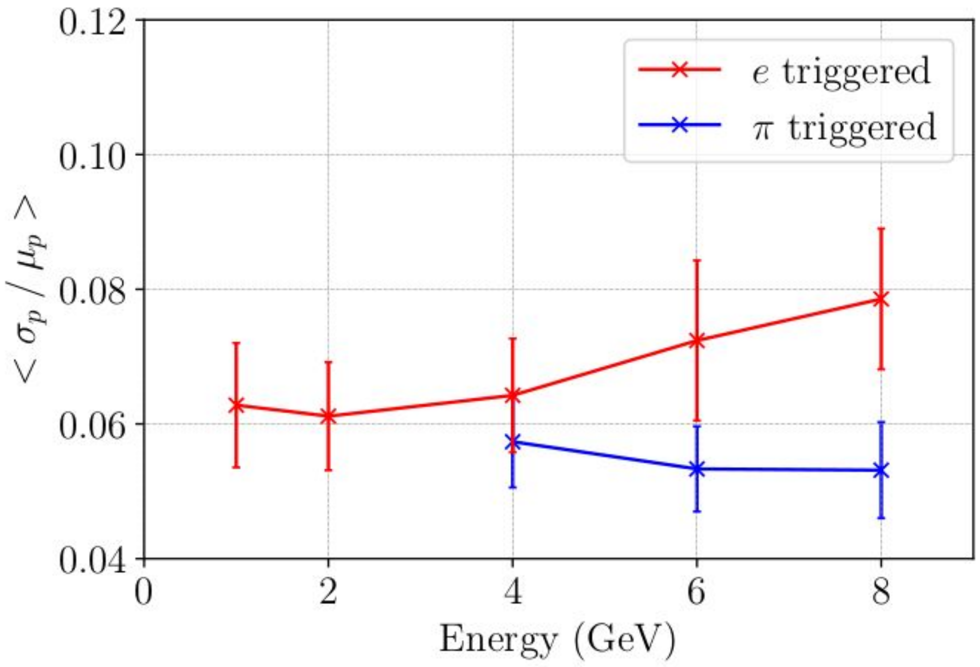

Figure 5.16: Average of the mean normalised primary peak sigma as a function of the beam energy for an electron trigger in red and a pion trigger in blue.

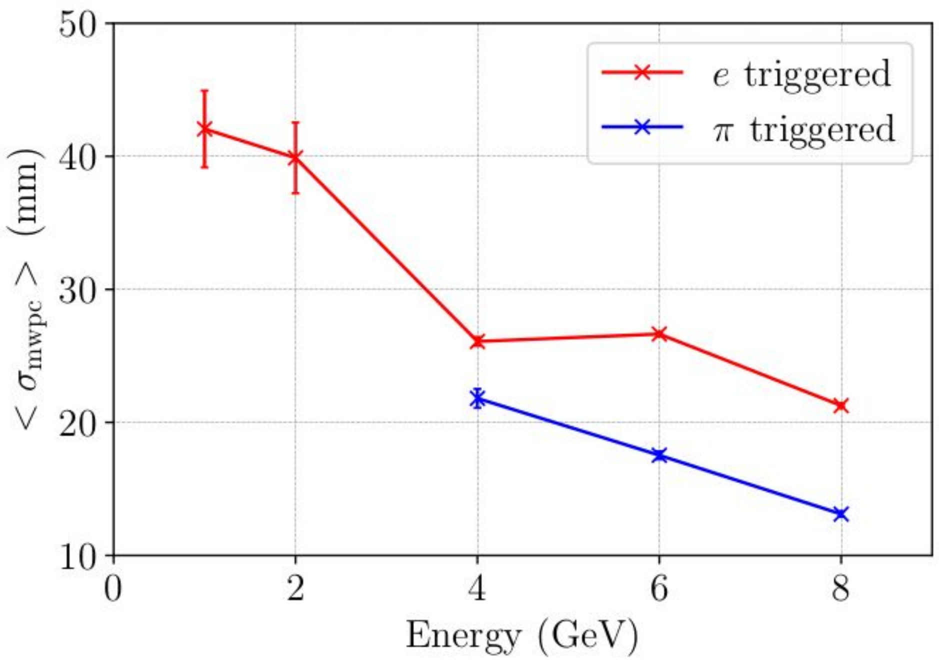

Figure 5.17: Average spread of the beam as a function of the beam energy for an electron trigger in red and a pion trigger in blue. Spread was computed from beam profile data which was taken using 3 multi-wire proportional chambers.

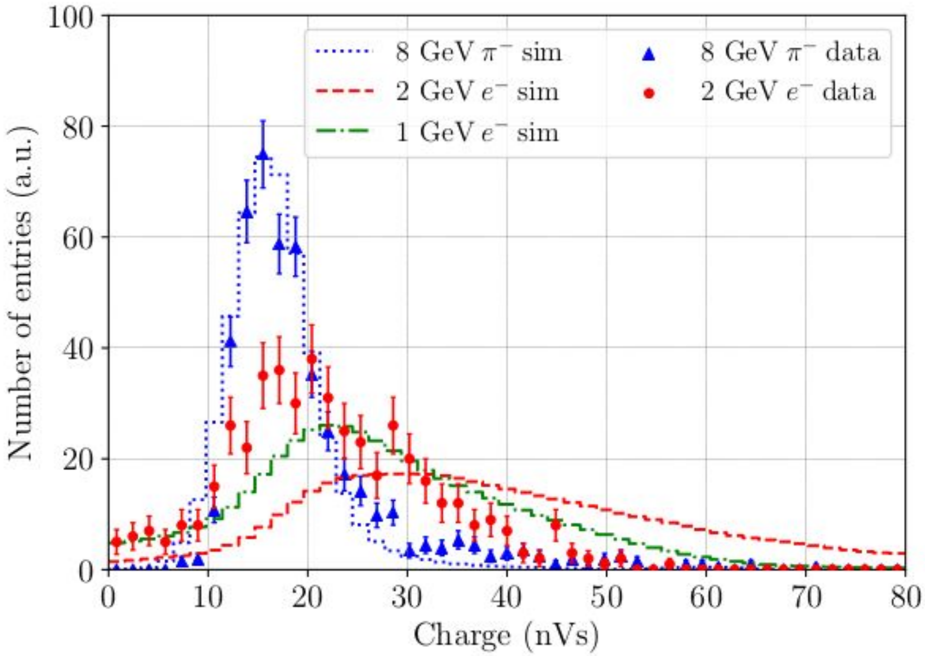

Figure 5.20: Hit distribution of the number of photons hitting the PMT for both electron and pion events. Data points taken from this beam test are compared to Geant4 simulations. The presence of saturation can be seen to have a large affect for very high charge data, such as for the 2 GeV data with electron triggering.

Costas's talk at nuSIS&DIS workshop:
https://indico.cern.ch/event/727283/contributions/3159400/

Driving PYTHIA6 from GENIE

Some amount of monkey business in making **quark + diquark** assignments most certainly due to our own unfamiliarity with PYTHIA. Luckily, overall generation outcomes not sensitive to choices made.

Init state	Hit quark	Leading quark	Remnant system	PYTHIA6 assignment		Weirdness level
ν + p CC	d valence	(d →) u	uu	u	uu	
ν + p CC	d sea	(d →) u	$\bar{d}$ + uud	u	uu	*
ν + p CC	s sea	(s →) u	$\bar{s}$ + uud	u	uu	**
ν + p CC	$\bar{u}$ sea	($\bar{u}$ →) $\bar{d}$	u + uud	u	uu	***
ν + n CC	d valence	(d →) u	ud	u	ud	
ν + n CC	d sea	(d →) u	$\bar{d}$ + udd	u	ud	*
ν + n CC	s sea	(s →) u	$\bar{s}$ + udd	u	ud	**
ν + n CC	$\bar{u}$ sea	($\bar{u}$ →) $\bar{d}$	u + uud	u	ud	***
...	...	...	...	...	...	...
...	...	...	...	...	...	...

Improvements