

# Detecting Neutrinos at a Muon Collider: Lessons from Cosmic Neutrino Experiments

Michigan State University

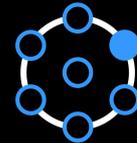


Good neutrinos: Neutrino Physics at a Muon collider

Presented by

Victoria A. Parrish

MICHIGAN STATE  
UNIVERSITY



P-ONE

# Guide

1 Introduction



2  $\nu$  detectors



3 Relevant muC specs



4  $\nu$  detector design



5 Challenges and R&D



6 Outlook

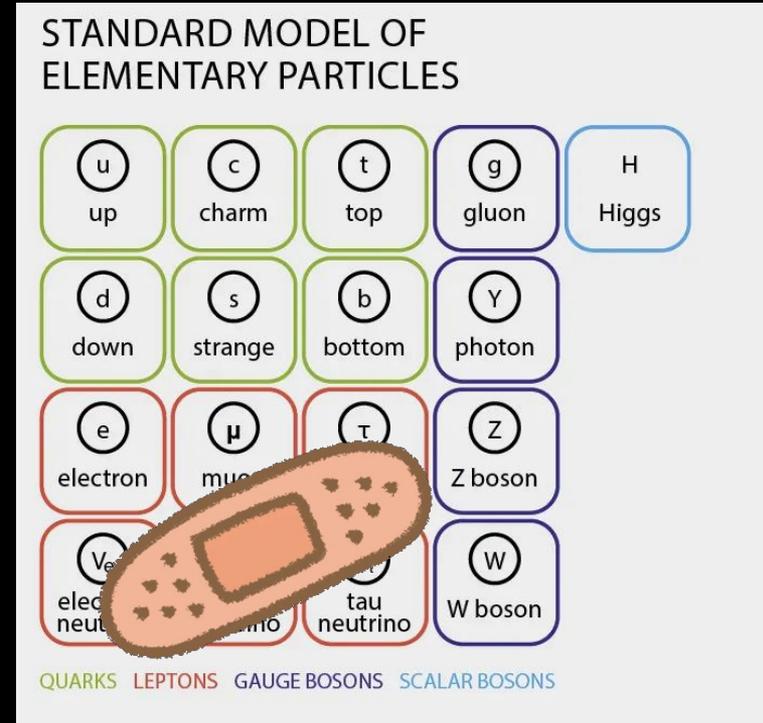


# Introduction

Why pursue neutrino physics at a muon collider?

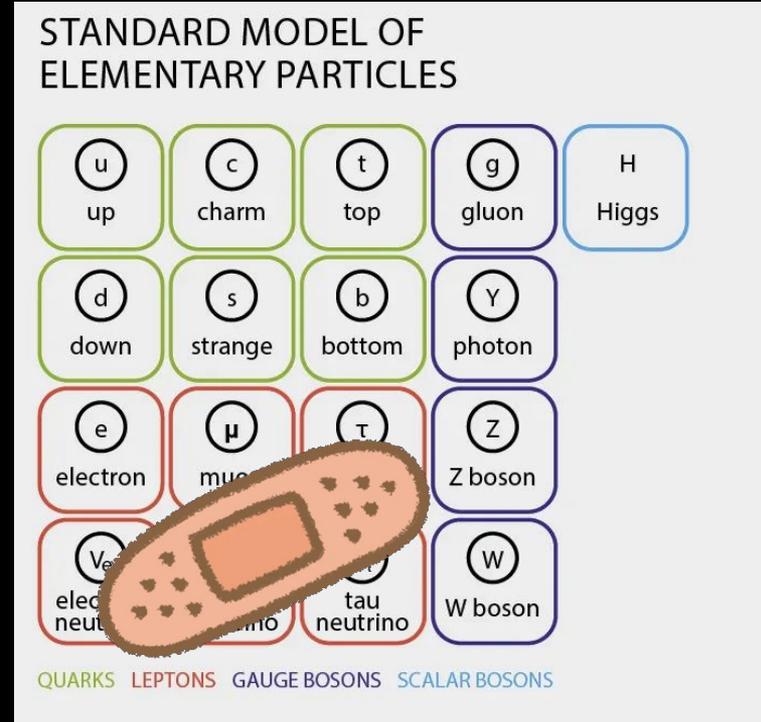
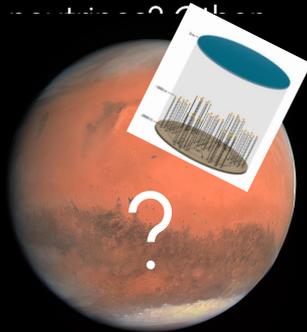
# Neutrino's as the key

- Great theory talks yesterday have motivated many reasons as to why neutrino physics is interesting
- Motivations to understanding neutrino behavior at higher energies
- Can do :
  - BSM/NSI
  - High  $Q^2$  SM precision measurements
- Neutrinos are still the *least* understood particle in the SM
  - Why do they oscillate in flavor?
  - What is the mass ordering hierarchy?
  - Right-handed neutrinos? Sterile neutrinos? Other NSI?
  - Do they break symmetry?
- Understanding them can lead to clarity in SM or BSM physics
- Can't do oscillation measurements at proposed energies



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# Neutrino detectors

A brief overview of the physics precedence set  
by cherenkov detectors

# Cherenkov detectors

# Cherenkov radiation

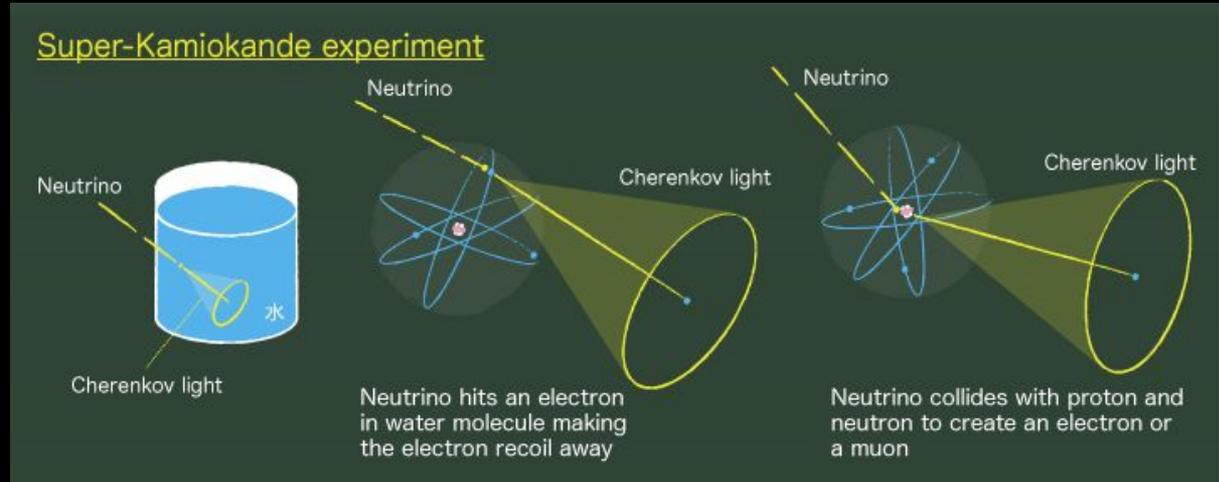
Neutrino interacts with an atom and either NC or CC interactions occur

In water → light emission from resulting interactions from charged current lepton yield cherenkov light

Can determine characteristics like:

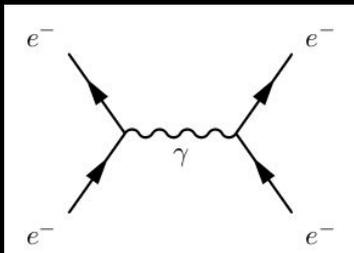
- Energy
- Direction
- Flavor

Can't yet determine shower type (em vs had)

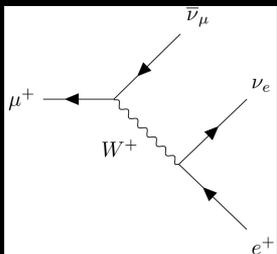


Neutrinos. Photon terrace <https://photonterrace.net/en/photonlab/ohsuka/02/>.

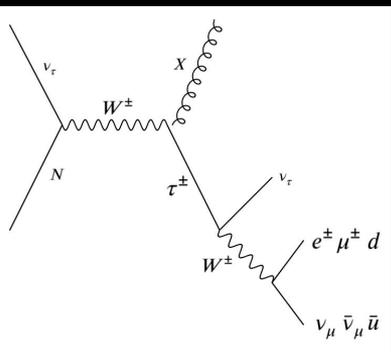
# Process



Electron immediately cascades into Bremsstrahlung radiation



Heavy muon travels for a long time before decaying softly



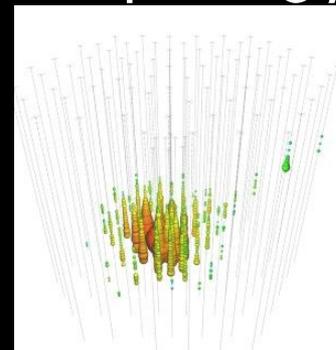
@ tau prod: quark shower  
 @ tau day: either:

1. Hadrons (shower)
2. E (shower)
3. Muon (track) – subdominant (~17% of time)

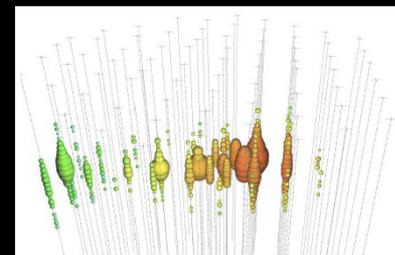
# Topology

IceCube Experiment

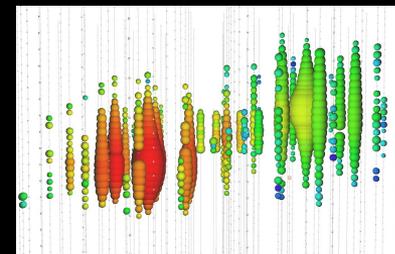
Cascade

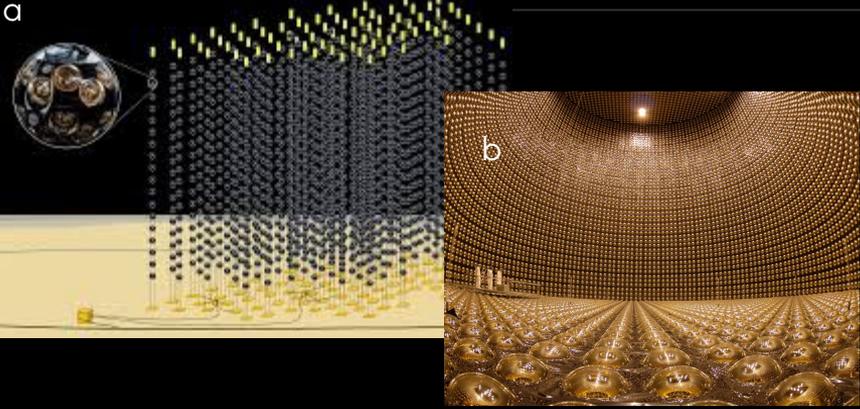


Track



Double cascade ~80% of time seen at >80 TeV scale



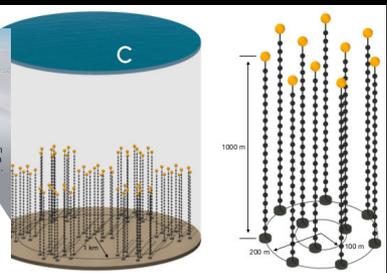
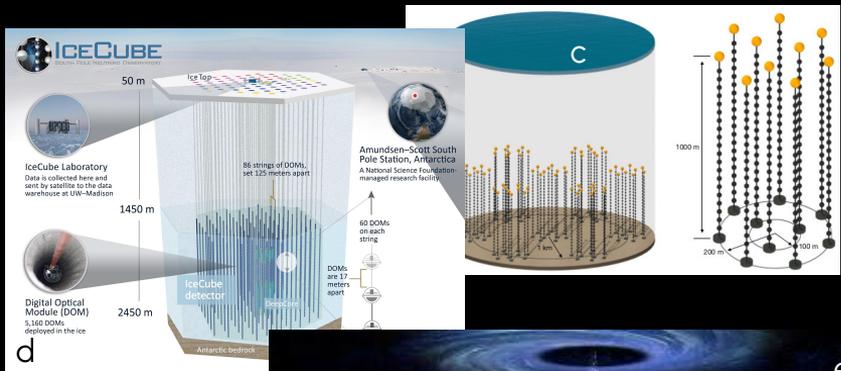


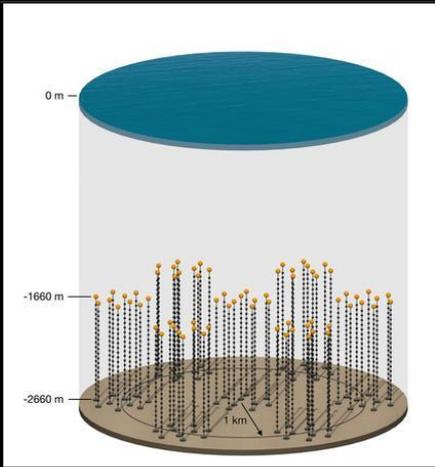
## Cherenkov detection

# Water-based neutrino detectors with large fiducial volumes

Highly sensitive photomultiplier optical modules in an array  
 Two types of these arrays:

1. Neutrino telescope – uses earth as fix target for atmospheric / astrophysical neutrino "beam" productions
  - a. Pros: can access ultra high energy physics regimes for analysis
  - b. Cons: many uncertainties about starting-conditions of event
2. Fixed-beam detector
  - a. Pros: well defined starting conditions for events for more constrained analyses
  - b. Cons: cannot access higher energy regimes
3. Pros: "cheap" to make
4. Cons: inability to distinguish had vs em showers





L. Winter 2024 (for P-ONE Collaboration)

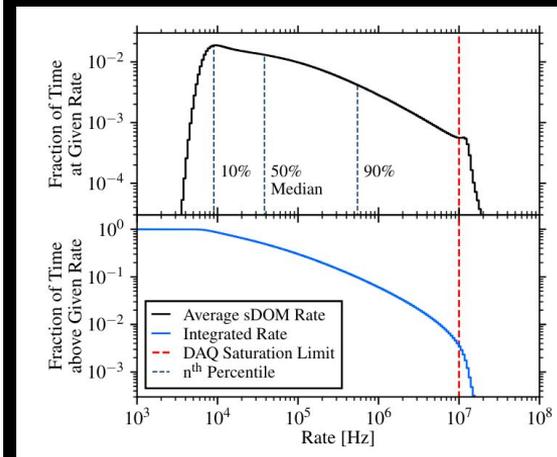
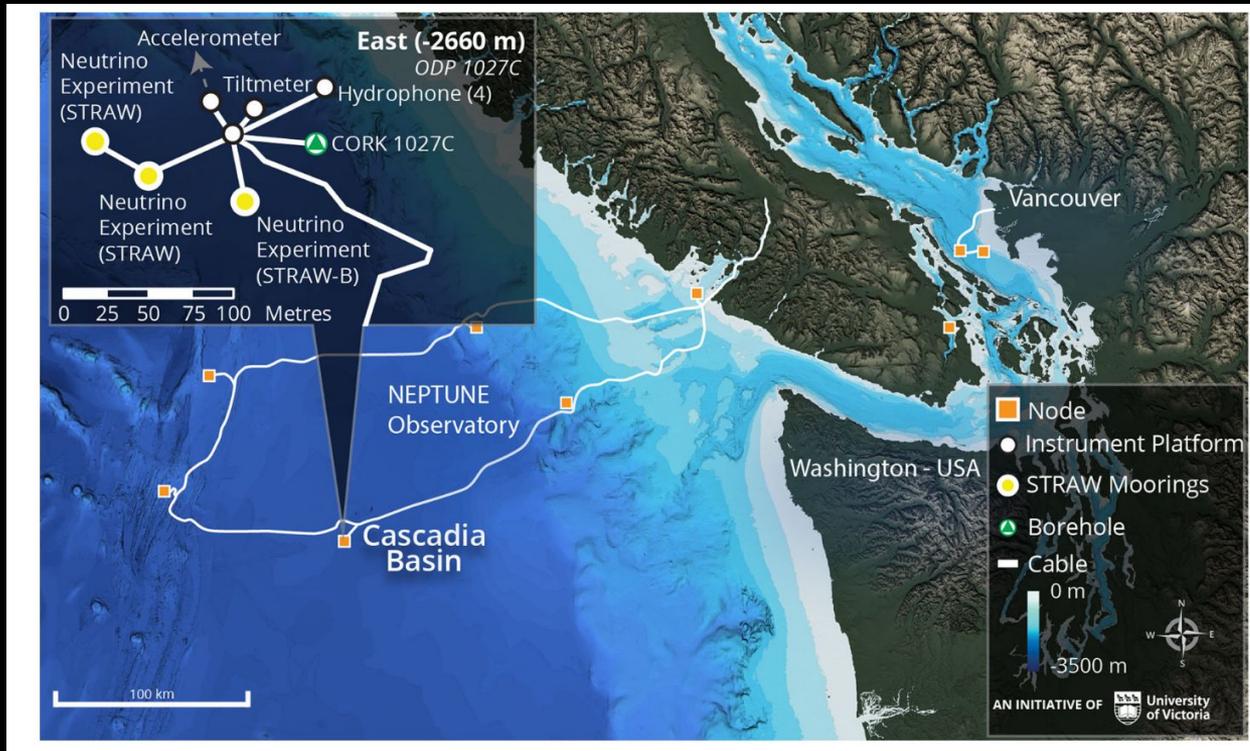


J. Garitz 2025  
(for P-ONE  
Collaboration)

# P-ONE

## The Pacific Ocean Neutrino Experiment

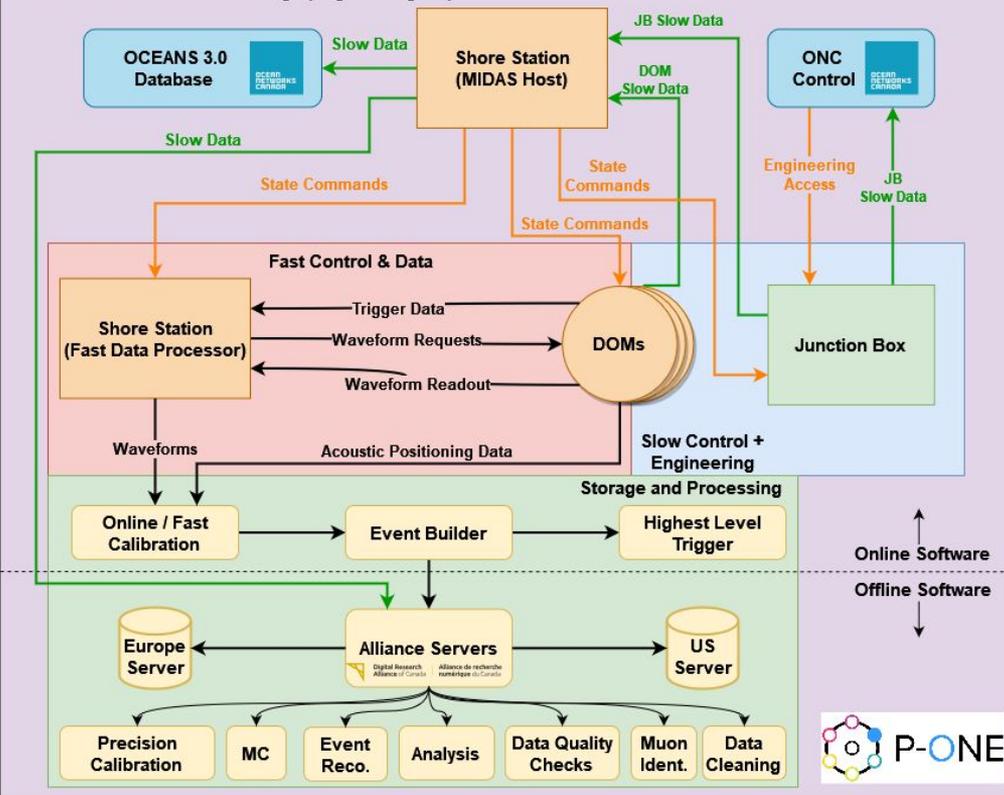
- Unique attributes of P-ONE:
  - Read out *actual* waveforms from DOMs
  - ps timing resolution within PMT hits
  - 10 gigabite / sec bandwidth
  - 1 sec buffer latency on mb
- Well suited for:
  - High rates (10s kHz of noise we already have to account for)
    - Low latency buffers
    - Complex trigger design
    - Streamlined fast DAQ
  - High energy events
    - String and DOM spacing suited for capturing TeV - PeV neutrino events



[arXiv:2108.04961](https://arxiv.org/abs/2108.04961) STRAW pathfinder mission's background rates report. The bottom plot shows the integral fraction of time from a given rate to infinity, showing for which fraction of time a certain rate was exceeded

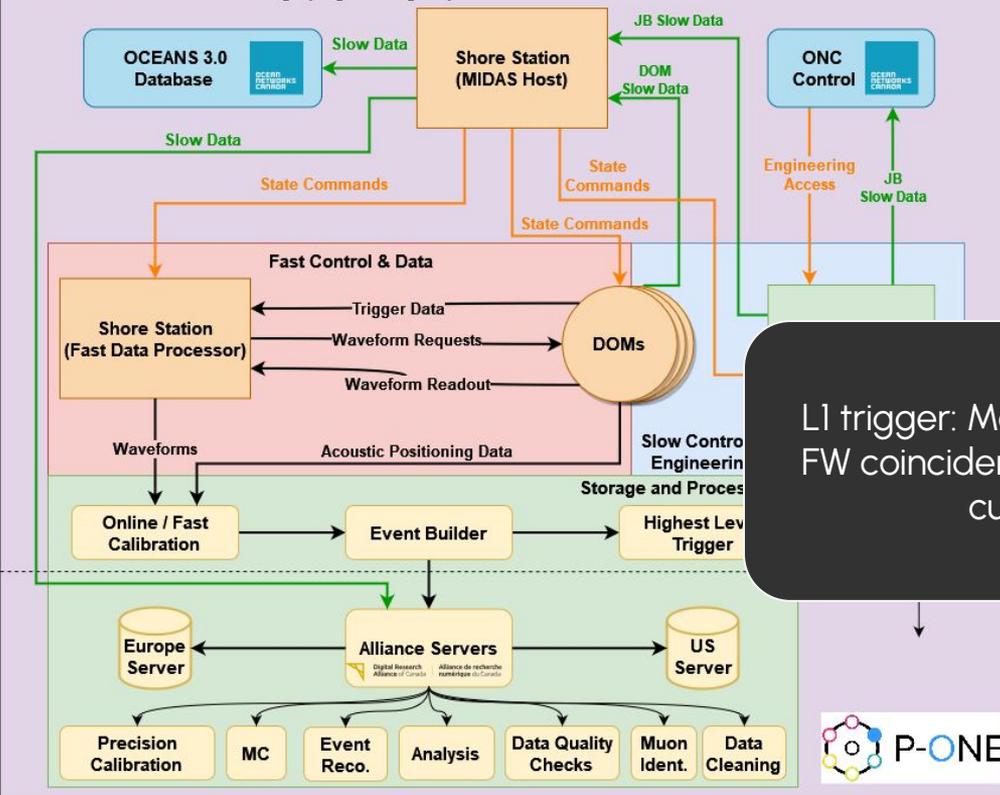
[arXiv:2108.04961](https://arxiv.org/abs/2108.04961) Location for P-ONE on the NEPTUNE experiment hosted by Ocean Networks Canada

### Detector Control and Data Storage (Logical Diagram)

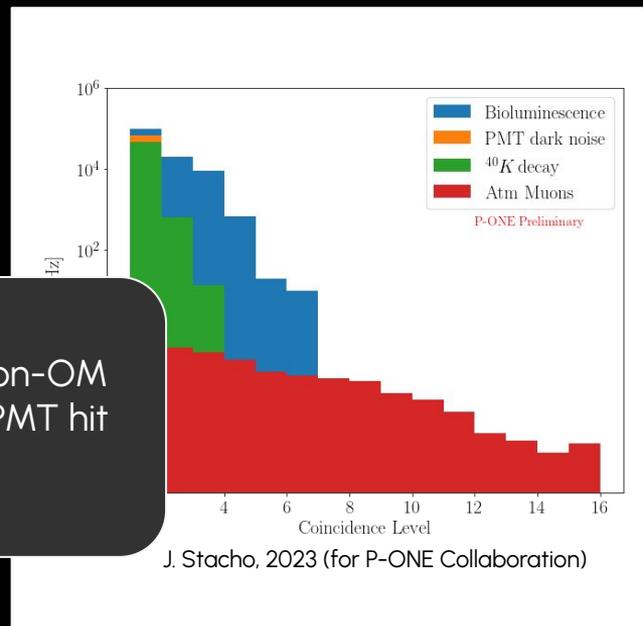


P-ONE Data Control Diagram (C. Spanfellner for P-ONE Collaboration, 2024)

### Detector Control and Data Storage (Logical Diagram)



L1 trigger: Make on-OM FW coincidence PMT hit cut



P-ONE Data Control Diagram (C. Spanfellner for P-ONE Collaboration, 2024)

# The Rate Problem



- Current trigger  $\Rightarrow$  **per-DOM-level hit coincidence**
- May need to categorically change how our L1 on-DOM trigger behaves and what sort of physics could be done on it:
  - **Option 1: Use a Quantum NN on the FPGA of the DOM**
    - Would need to determine this soon if wanted this feature on all DOMs
  - **Option 2: Slap a prescale on the trigger – only take data for x ns before taking again**
    - Avoid “pile up” of events
  - **Option 3: Dedicate a separate “high signal rate” set of strings**
    - Certainly possibly given the narrowness of the beam – the fiducial volume doesn't need to be huge

# The Shower Problem



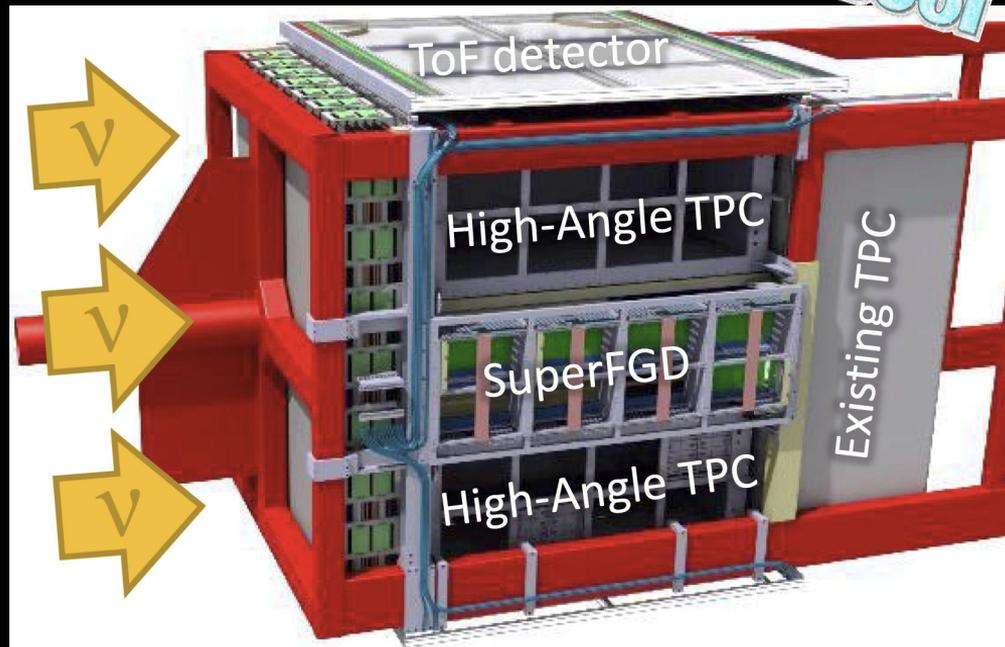
- In order to tell the difference between NC and CC interactions:
  - Require some sort of HCAL + ECAL distinguishing characteristics
- However – progress is being made on resolving shower topologies to determine a **hadronic vs electromagnetic** shower in IceCube
  - P-ONE will have less scatter  $\Rightarrow$  better resolution to try to separate these categories

# Scintillator detectors

omg!  
that's  
so cool

# SuperFGD T2K

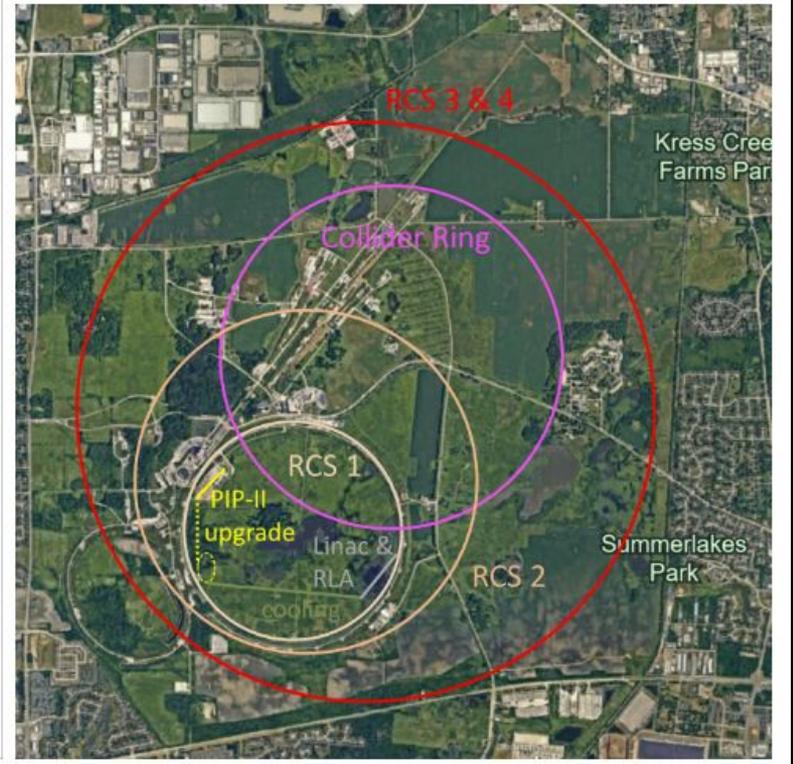
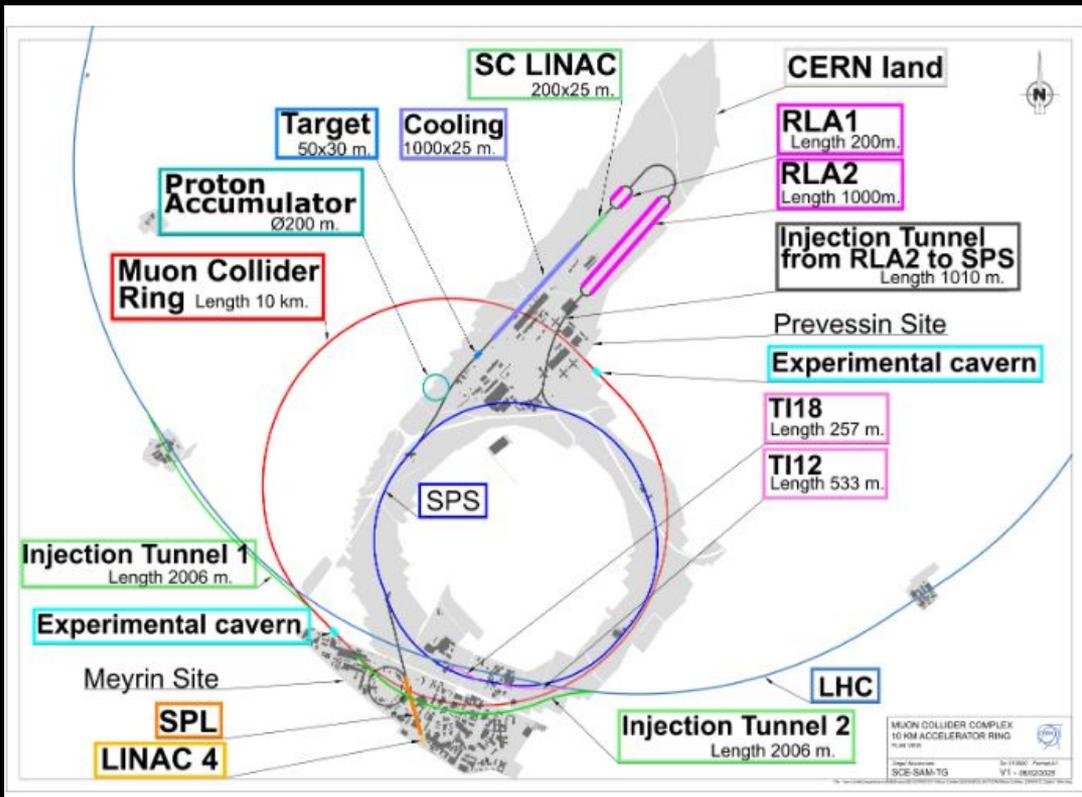
- Near Detector at J-PARC facilities for HyperK
- Designed for very high event rates
- Picosecond timing at channel level
- Materials:
  - Plastic scintillators
  - Wavelength shifting fibers
  - SiMPs
- Purpose (pre-oscillation):
  - Flux
  - Cross section



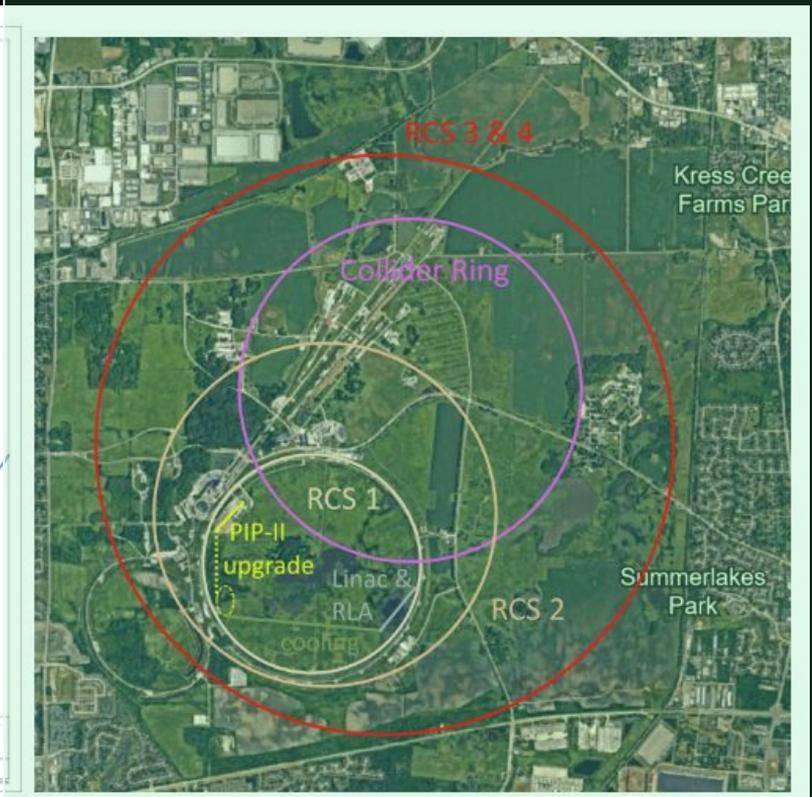
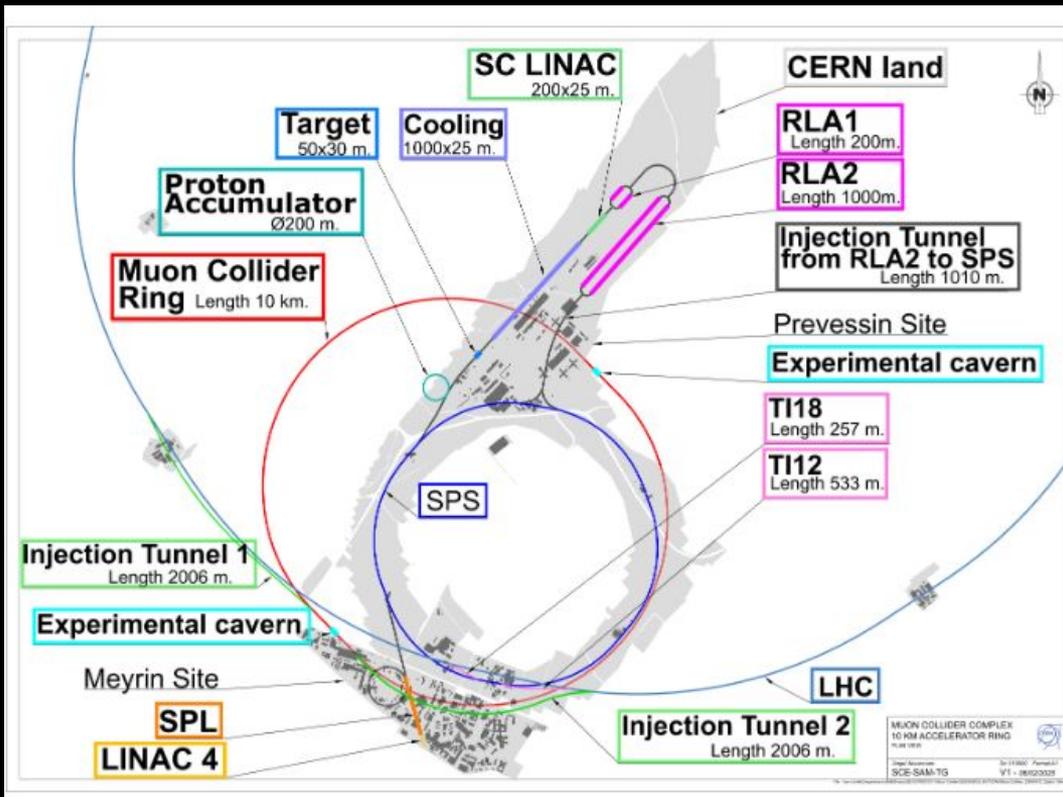
[arXiv:2111.07305](https://arxiv.org/abs/2111.07305)

# Relevant Muon Collider Specs

Production baselines



CERN site (left); Fermilab site (right) ([The Muon Collider, 2025](#))



CERN site (left); Fermilab site (right) ([The Muon Collider, 2025](#))

# Back-of-the-envelope calculations

- Let's assume:
  - 10 TeV muon COM
  - 100 m beam dump line
  - On-axis to P-ONE (for example) @ 3,000 km
  - 1 km diameter muon collider
  - Assuming focused beam (1/gamma)
- Regardless of these varying specs, the rate of neutrinos **will be huge**
  - Since I care about P-ONE:
    - **Rough rate of interaction is ~ 14 Hz\* in water if**
- See Nick's talk for more cases of neutrino beam configurations and rate estimates for different
  - Regardless of case – **Would expect orders of magnitude greater than P-ONE is spec'd to handle for signal rate**

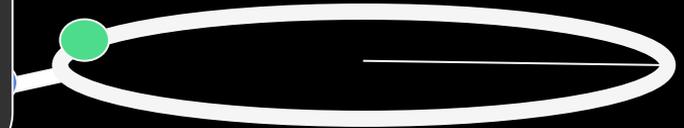


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Since there are many cases of how neutrinos can reach P-ONE, let's just focus on P-ONE

500 m



# $\nu$ detector design

Detector design baselines

# Muon collider neutrino detectors

## Near baseline

Use of existing caverns at Fermilab for

- ND280-like near detector
- Cross section measurements
- Pre-oscillation characterization (flavor tagging)
- Would certainly be able to handle high rates and timing precision required

## Far baseline

P-ONE Detector

- Require a depression angle of  $\sim 14$  degrees from muon collider
- Azimuth along beamline = 293 degrees
- $\sim 3,000$  km from Fermilab site
- Luckily P-ONE is already in its planning phases

# Two Run approach

## Run Type 1

### BSM/NSI/High $Q^2$

- At high energies ( $>$  a few GeV)
- No oscillation seen terrestrially
- Physics that could be done is *everything else*
- Propose that this is the dominate run-type

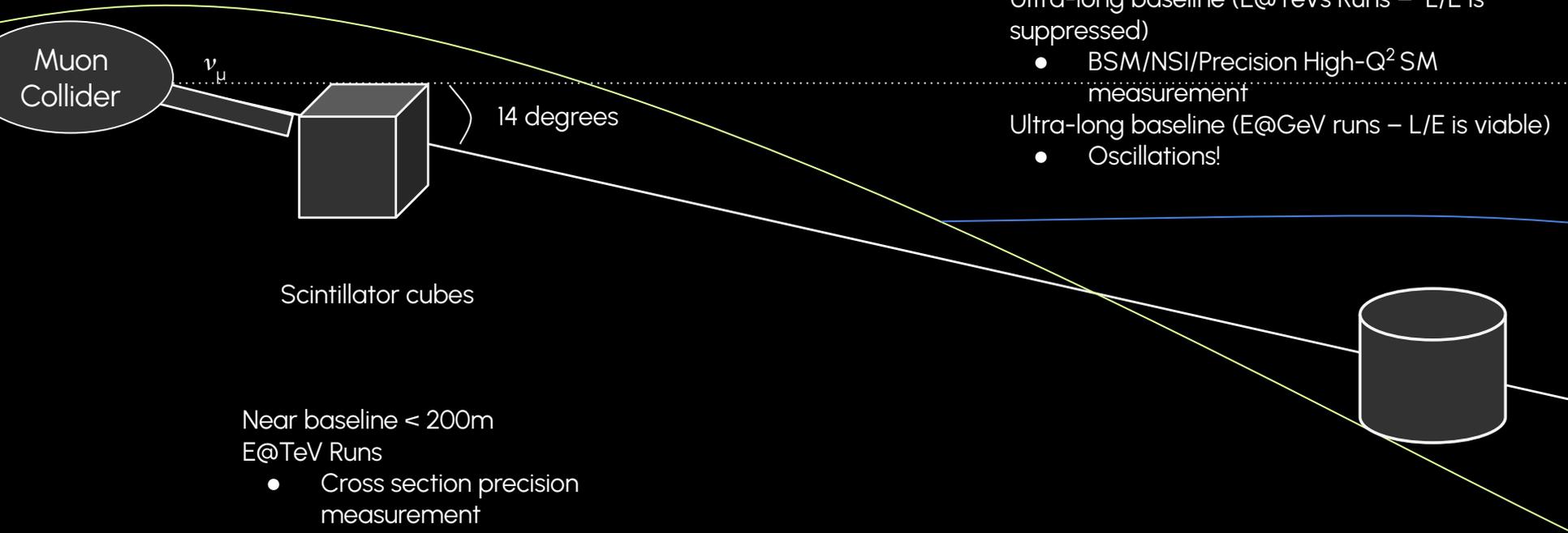
## Run Type 2

### Oscillation Run

- Lower Run conditions to a few GeV (optimize it for whatever sort of oscillation ratio you want to see)
- Dedicate near and far baseline detectors as "oscillation" runs

Near baseline < 200 m

Long baseline 3,000 km



Cherenkov detector

Ultra-long baseline (E@TeV Runs – L/E is suppressed)

- BSM/NSI/Precision High- $Q^2$  SM measurement

Ultra-long baseline (E@GeV runs – L/E is viable)

- Oscillations!

Scintillator cubes

Near baseline < 200m

E@TeV Runs

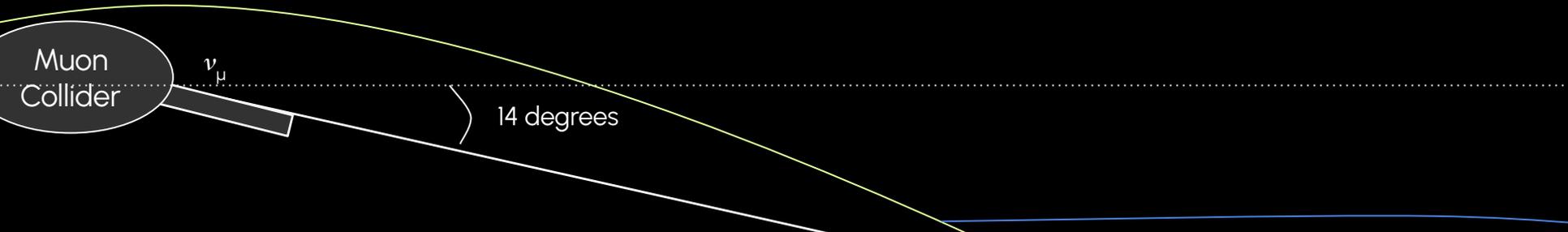
- Cross section precision measurement

E@GeV Runs

- Flavor tagging for pre-oscillation

# Challenges and R&D

Detector construction feasibility



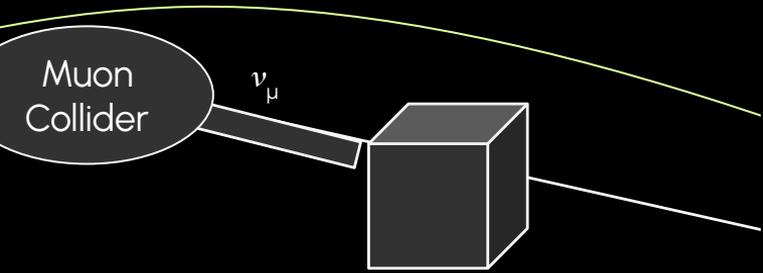
- In order for collinear neutrinos along muon beam dump to reach P-ONE:
  - depressed beam angle of **14.28 degrees\***, dumping muon beam at azimuth of 293 degrees (23 degrees north of due west)
- Current gradient of beam dump for neutrino generation limits is 6 degrees for DUNE
- Would need :
  - 12 more degrees depression
  - Dealing with much higher energy beam
  - TeV run compatibility



Google maps, 2025

\* calculation assuming coordinates are Fermilab and Cascadia Basin

Near baseline < 200 m



Scintillator cubes

- Scintillator cubes
  - Pro: existing infrastructure to support detector assembly on-site
  - Con: cavern will need to be 90 m deep in order to capture events at the beam angle

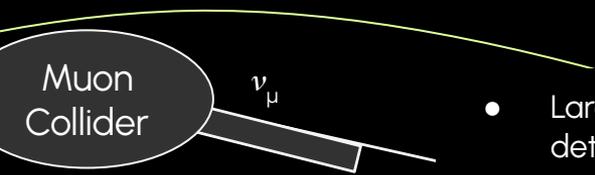
Near baseline < 200m

E@TeV Runs

- Cross section precision measurement

E@GeV Runs

- Flavor tagging for pre-oscillation



- Large fiducial volume cherenkov detector
  - P-ONE currently spec'd for 100s GeV - PeV events
  - For oscillations runs – may need to dedicate a "deep core" of dense strings for lower energy resolution
  - Trigger algorithm overhaul for high signal rate

Long baseline 3,000 km

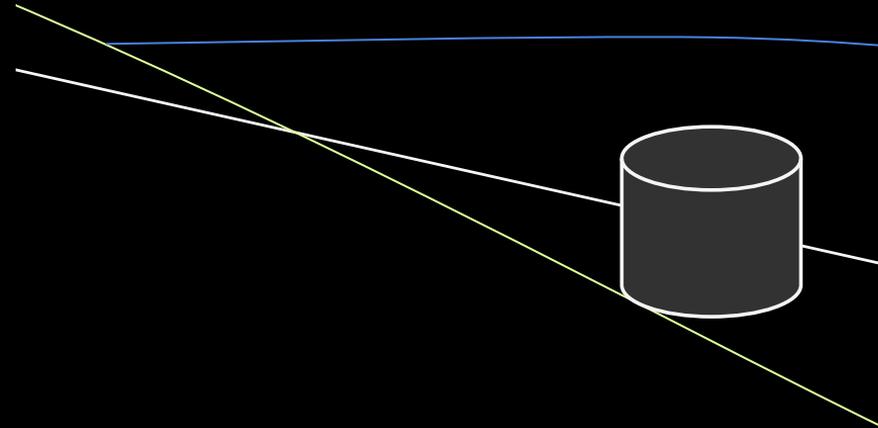
Cherenkov detector

Ultra-long baseline (E@TeV Runs – L/E is suppressed)

- BSM/NSI/Precision High- $Q^2$  SM measurement

Ultra-long baseline (E@GeV runs – L/E is viable)

- Oscillations!



# Outlook

A brief review of key takeaway points

# In all scenarios...

## Cherenkov resolution

- P-ONE might need to undergo an upgrade at some point to implement a lower energy core region to detect these events

## Scintillators

- Scintillators for standard neutrino detectors will need to increase for high energy resolutions
- ND280 already sets such a high bar for precision and rate
- Confident this detector approach could be implemented for very high rates

## Beam curving magnets

- Engineering of Big Magnets is very hard (already a logistical constraint of the muon collider)
- Concern about the ability to curve at depression angle without long beam dump line
- Could compound energy loss down dump line

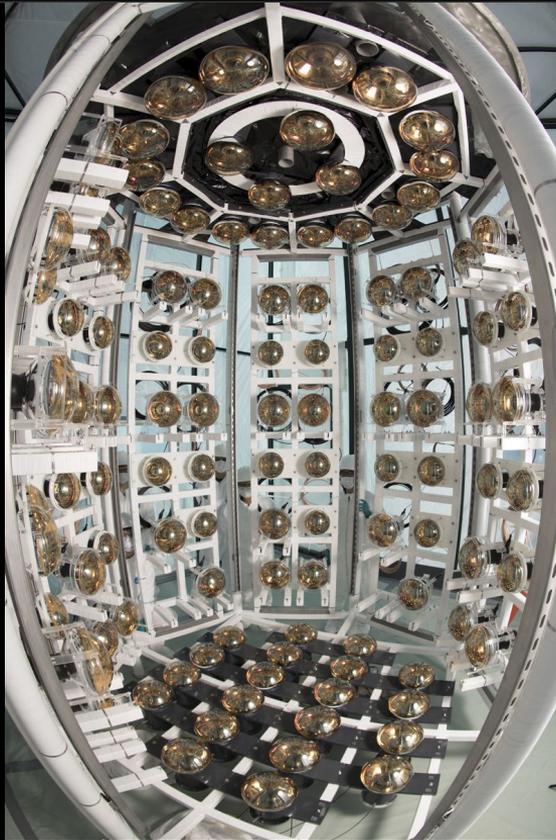
# Neutrino Detector Options

Make *two* run types

- High energy run:
  - Exploits high rate of prod *and* unprobed energy regime of neutrino interactions
  - Precision SM – neutrinos still do not behave how SM predicts them to. Why?
  - BSM/NSI – very possible that these could lead us to *why* neutrinos behave the way they do
  - Near detector would get cross section of beam before P-ONE arrival
  - P-ONE
    - Can already handle:
      - Energy regime
      - Type of measurements of interest
    - Work to do:
      - New trigger design for high signal rate
- Oscillation run:
  - Build off DUNE / HyperK / etc results
    - Do we understand more or less about oscillations? This will inform priority of run type
  - Exploit ultra-long baseline of P-ONE
    - Work to be done: flavor tagging of some sort
  - *Still* probing neutrino oscillations at unprecedented energy regimes because you are at a longer baseline
  - Near detector for flavor tagging

Thank you! Questions?

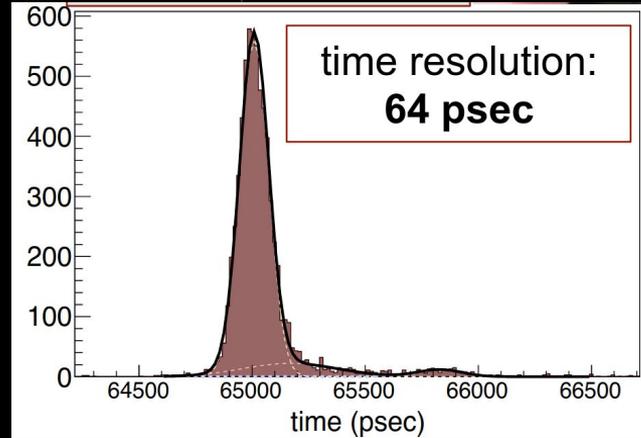
Backup



R. Hanh, 2020

PMT upgrades

# The ANNIE detector



ANNIE Phase II Reconstruction and LAPPDs (E. Drakopoulou, 2018)

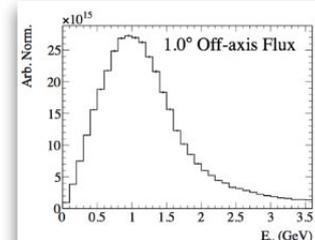
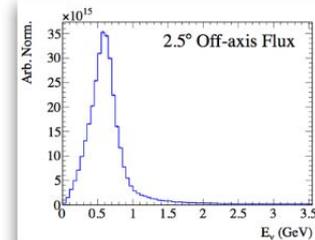
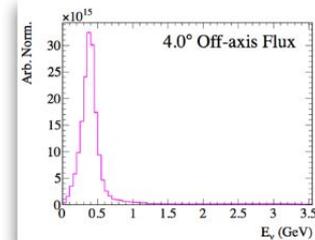
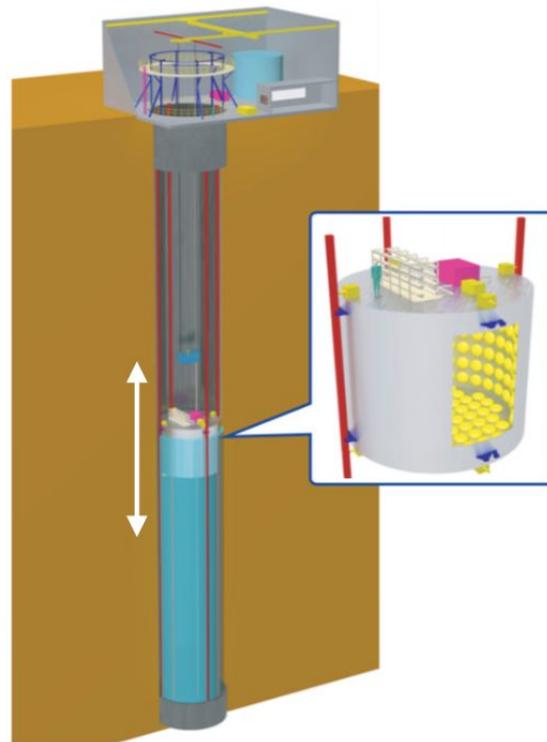
The ANNIE Detector, 202.

Conventional PMT + LAPPDs

Captures majority of light emission + picosecond timing res / mm spatial res

# IWCD

- Intermediary Water Cherenkov Detectors
- Can change position of water column to control off-axis position
- Allows profiling of beam characteristics at different energy ranges
- Useful for beam characteristics and flux measurements



Hyper-K's IWCD near detector, 2019

# References

# References not in-slide

- Slide
  - a. CascadeTrack
  - b. Double cascade
- Slide
  - a. Km3Net array
  - b. SuperK array
  - c. P-ONE array (proposed)
  - d. Trident array
- Slide
  - a. NOvA detector
  - b. ProtoDUNE detector
  - c. MINERvA detector