Experimental Lecture
Accelerator Experiment
Detection

D. Jason Koskinen

NBIA PhD School: Neutrinos Underground and in the Heavens
June 23-27, 2014

Niels Bohr Institutet
The Niels Bohr International Academy
Discovery centre for particle physics

Beams

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- Most beams are muon (anti)neutrinos
  - Cern Neutrinos to Gran Sasso (CNGS)
  - Neutrinos at Main Injector (NuMI) at Fermilab
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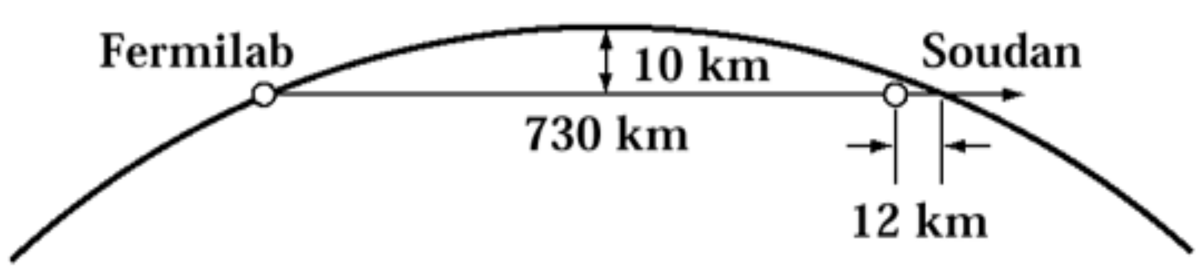
- Detectors have wide divergence in approach

MINOS


Soudan
Duluth
Lake Superior
Lake Michigan
MN
WI
MI
Madison
IA
Fermilab
IL
IN
MO


Fermilab
10 km
Soudan
730 km
12 km

MINOS

- Atmospheric neutrino oscillation experiment optimized for
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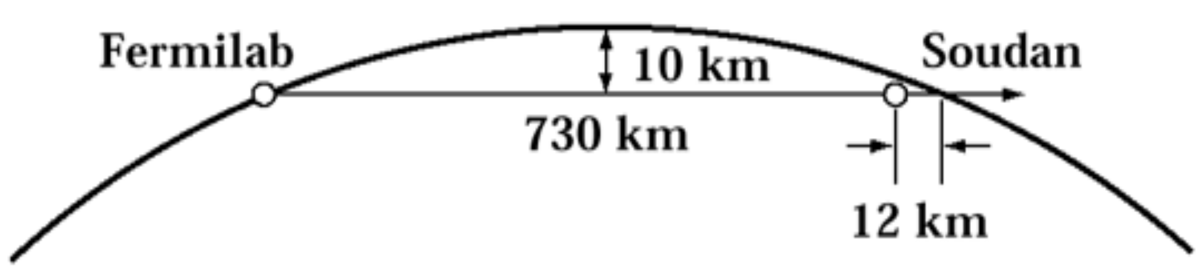
- Two magnetic calorimeter detectors
  - Near detector measures unoscillated
  - Far detector measures oscillated



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  - Provides mass for neutrino interaction
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    - Energy estimator from curvature
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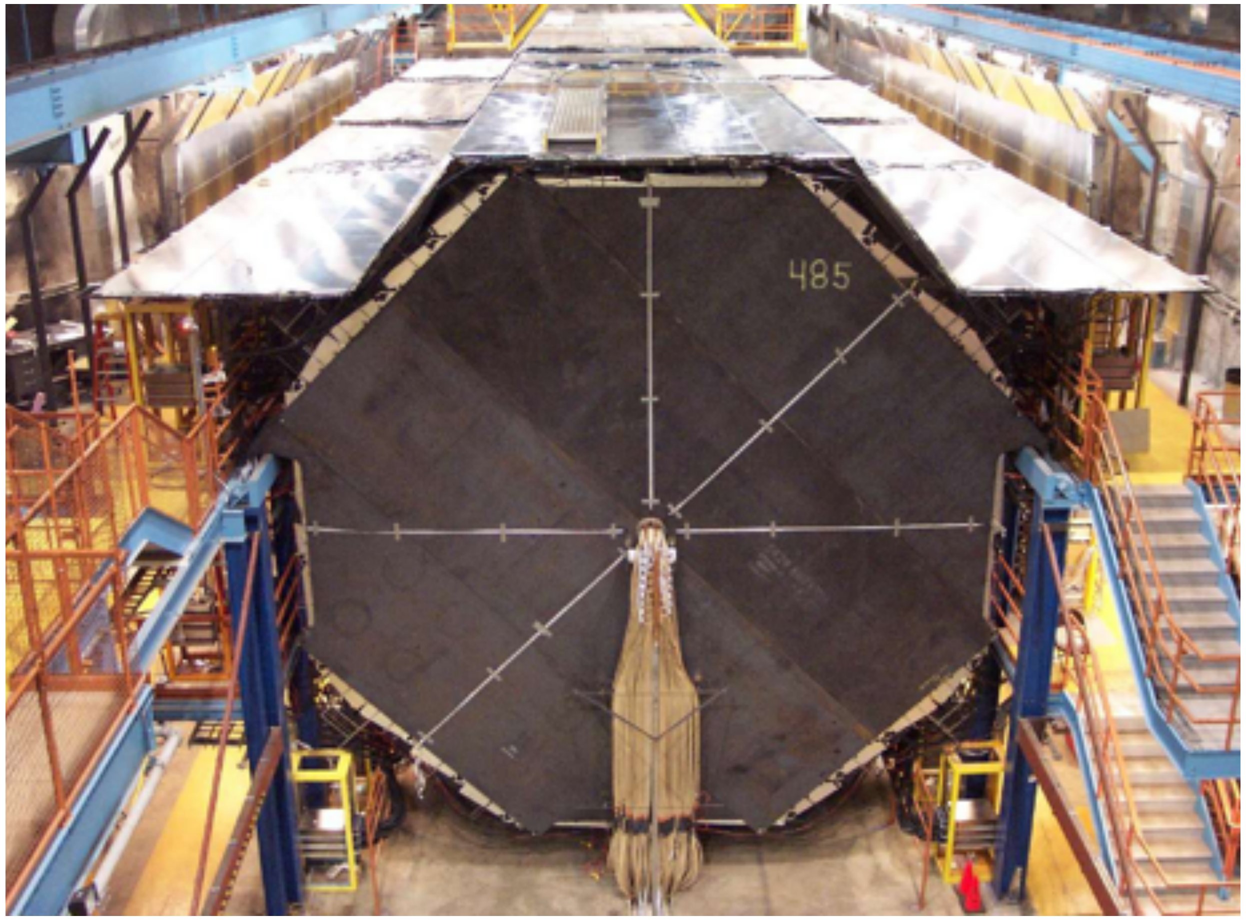
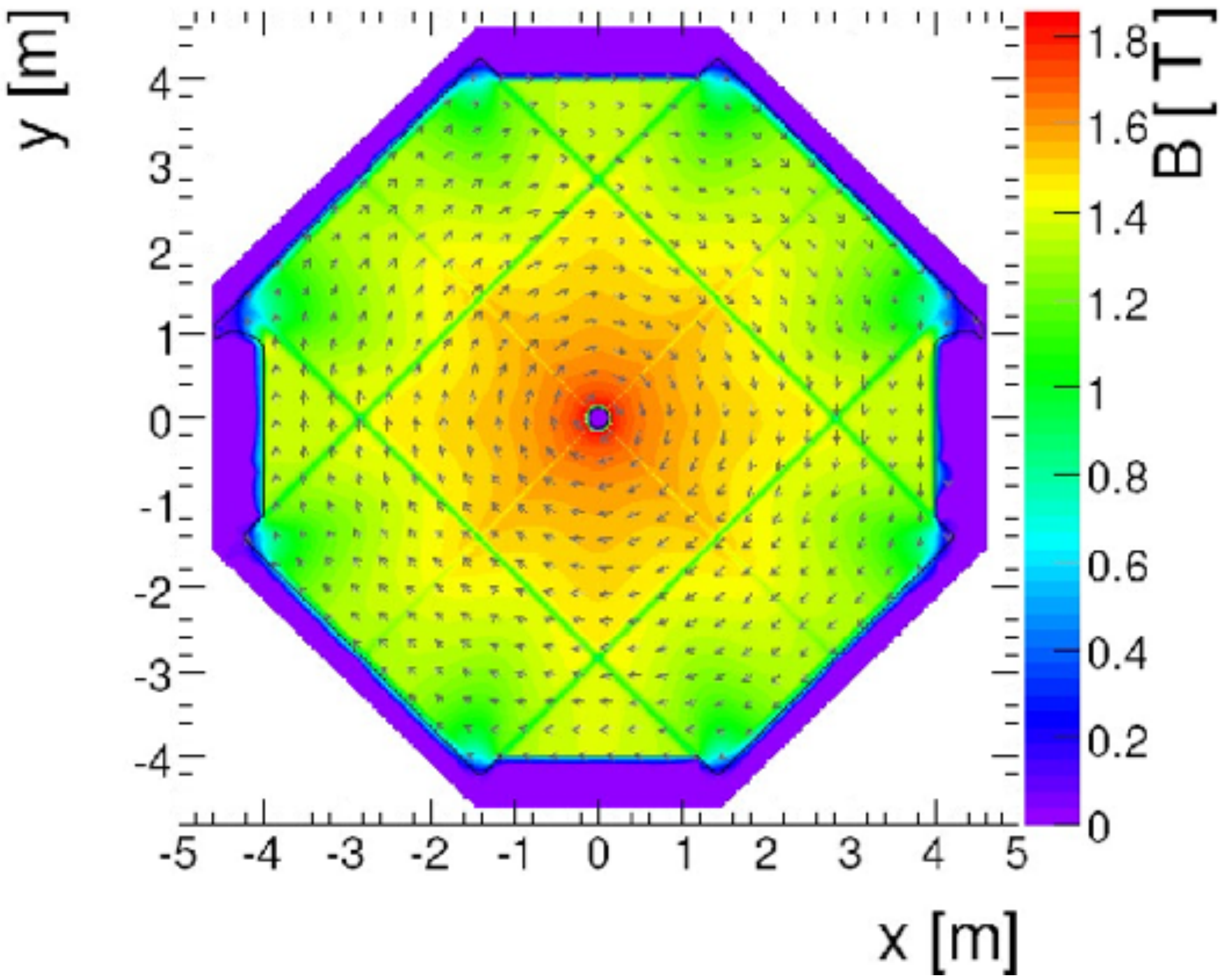
    - Containment by keeping muon in detector
- 1.5 tesla toroidal field

Magnetic Fields

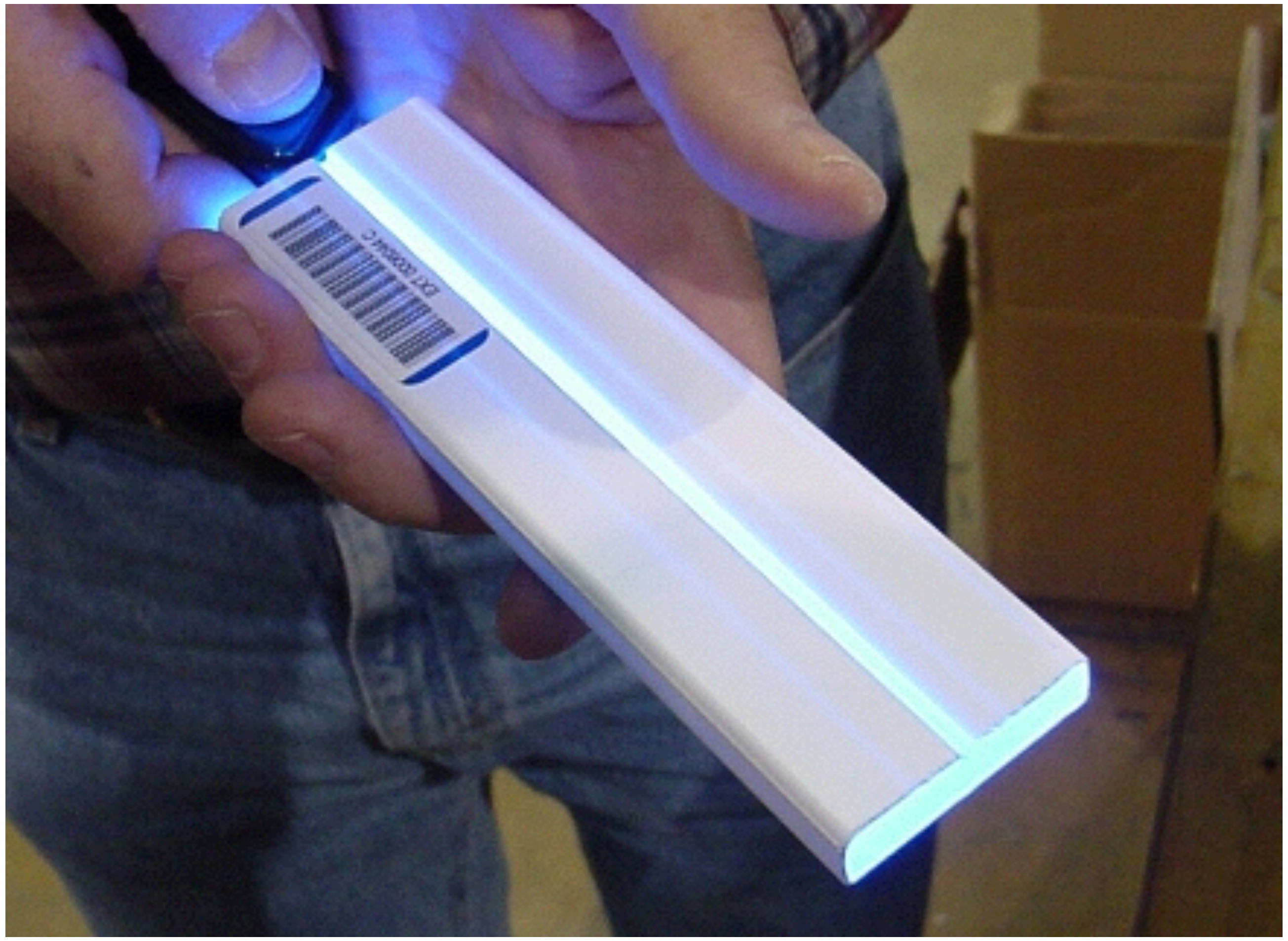
- At GeV+ energies magnetic fields allow muon/anti-muon separation
- Provides energy for muons exiting detector



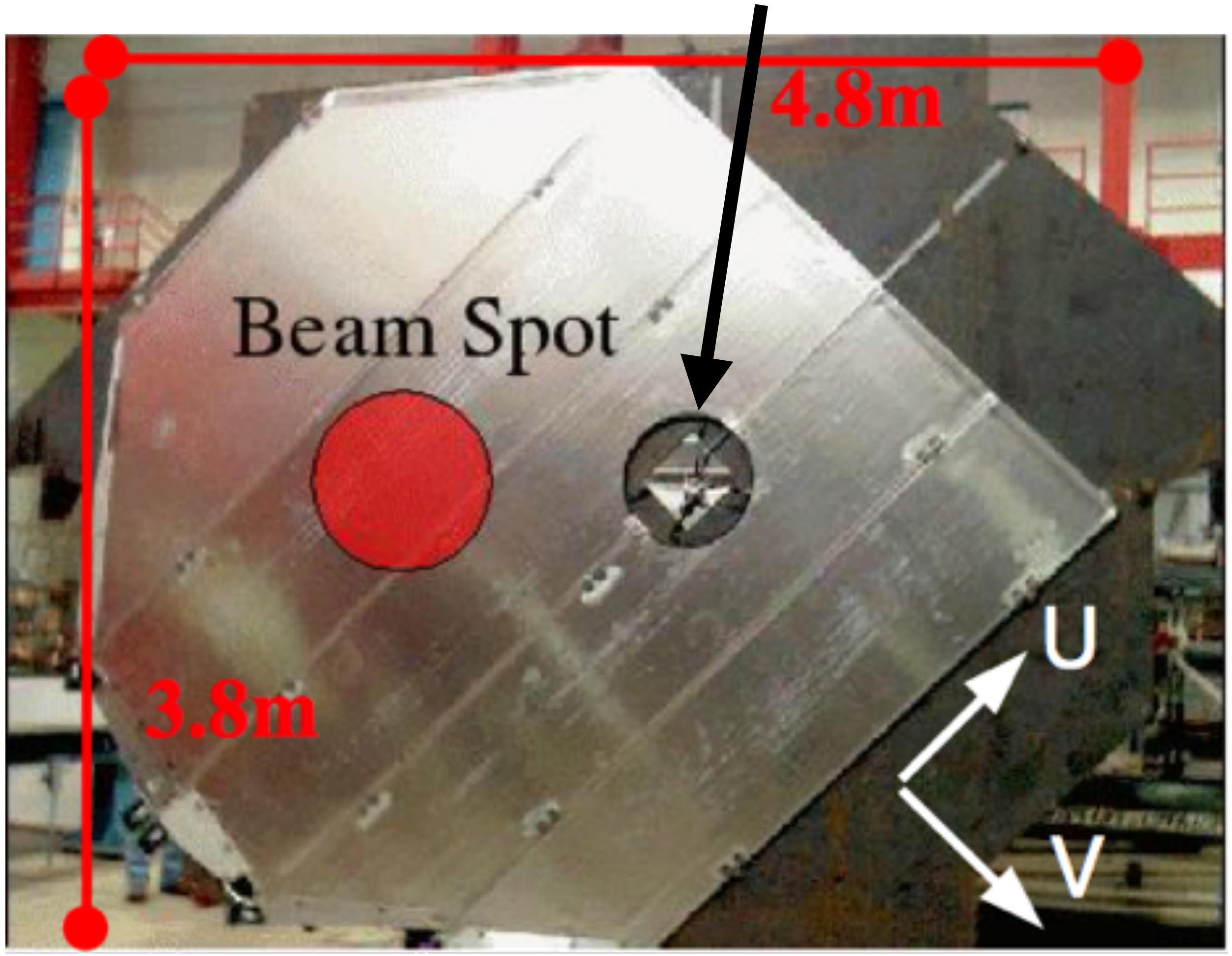


MINOS

- Scintillator strips have orthogonal orientations (U &V)
- Embedded in the strips is a wavelength shifter fiber to transport photons to the PMTs



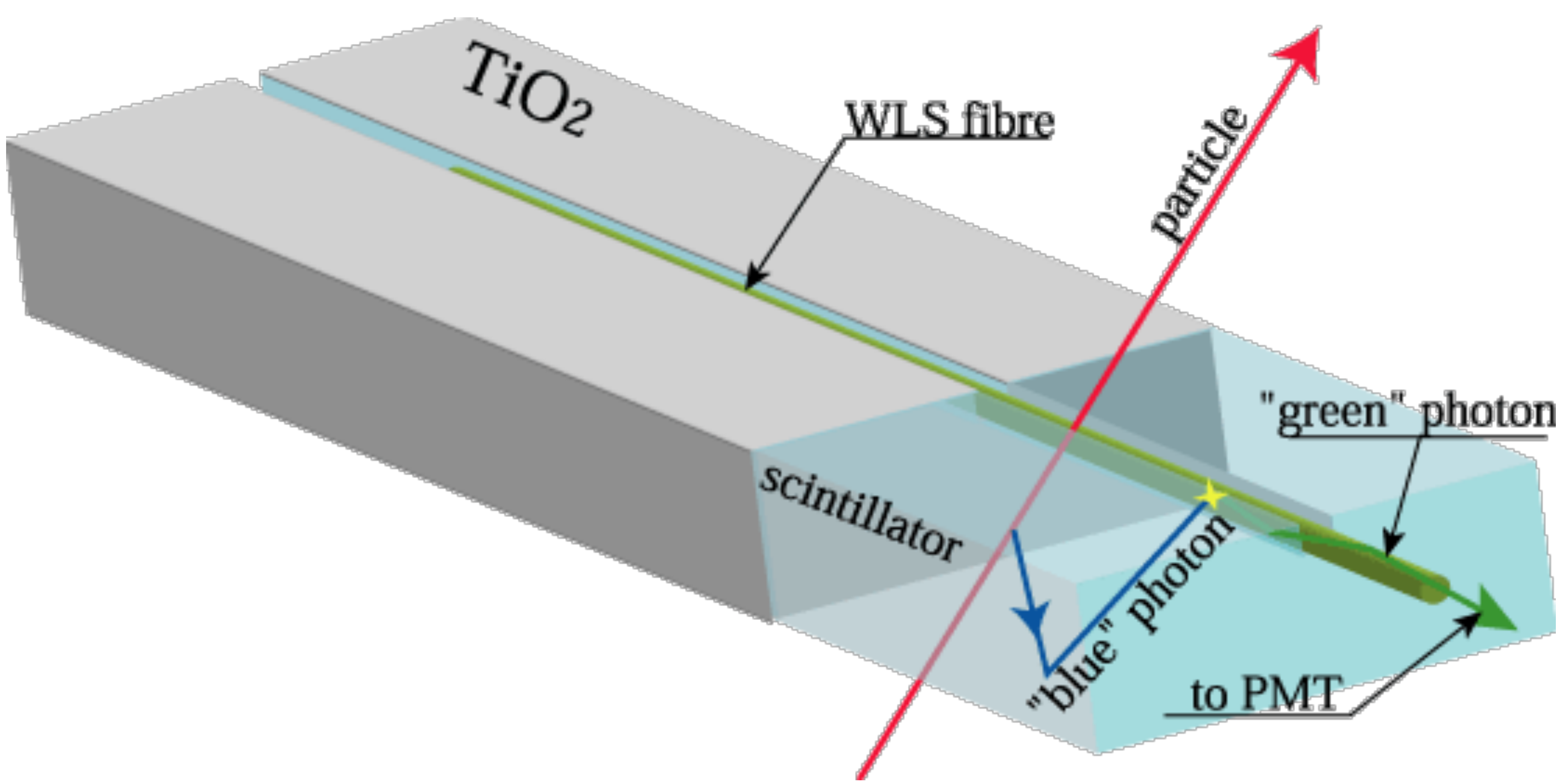
Magnetic Coil Hole



Near Detector
Steel/Scintillator Plane

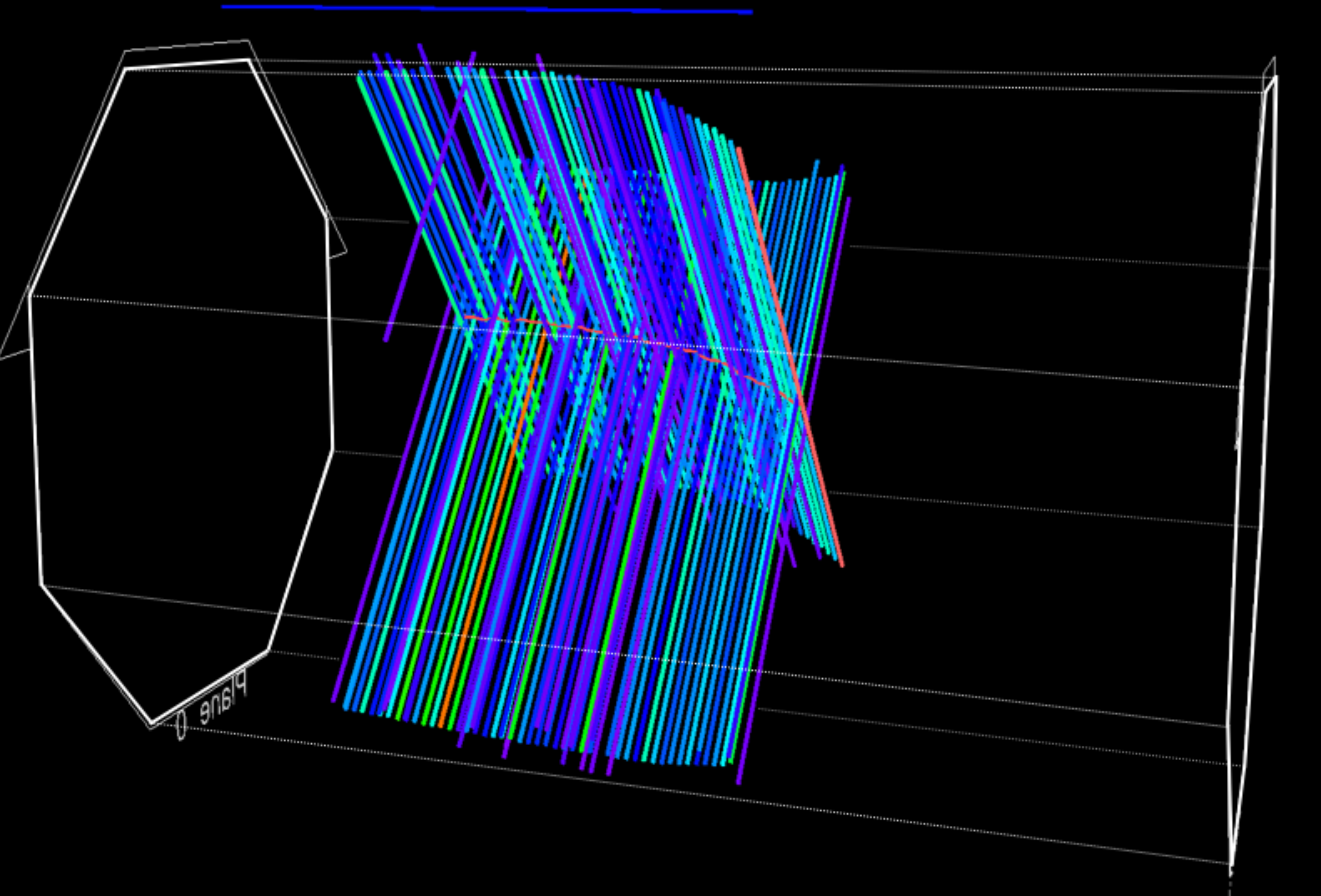
Solid Scintillator

- Wavelength shifting fibers convert blue scintillation light to lower wavelength
  - Reduces attenuation
  - Matches wavelength to PMT response

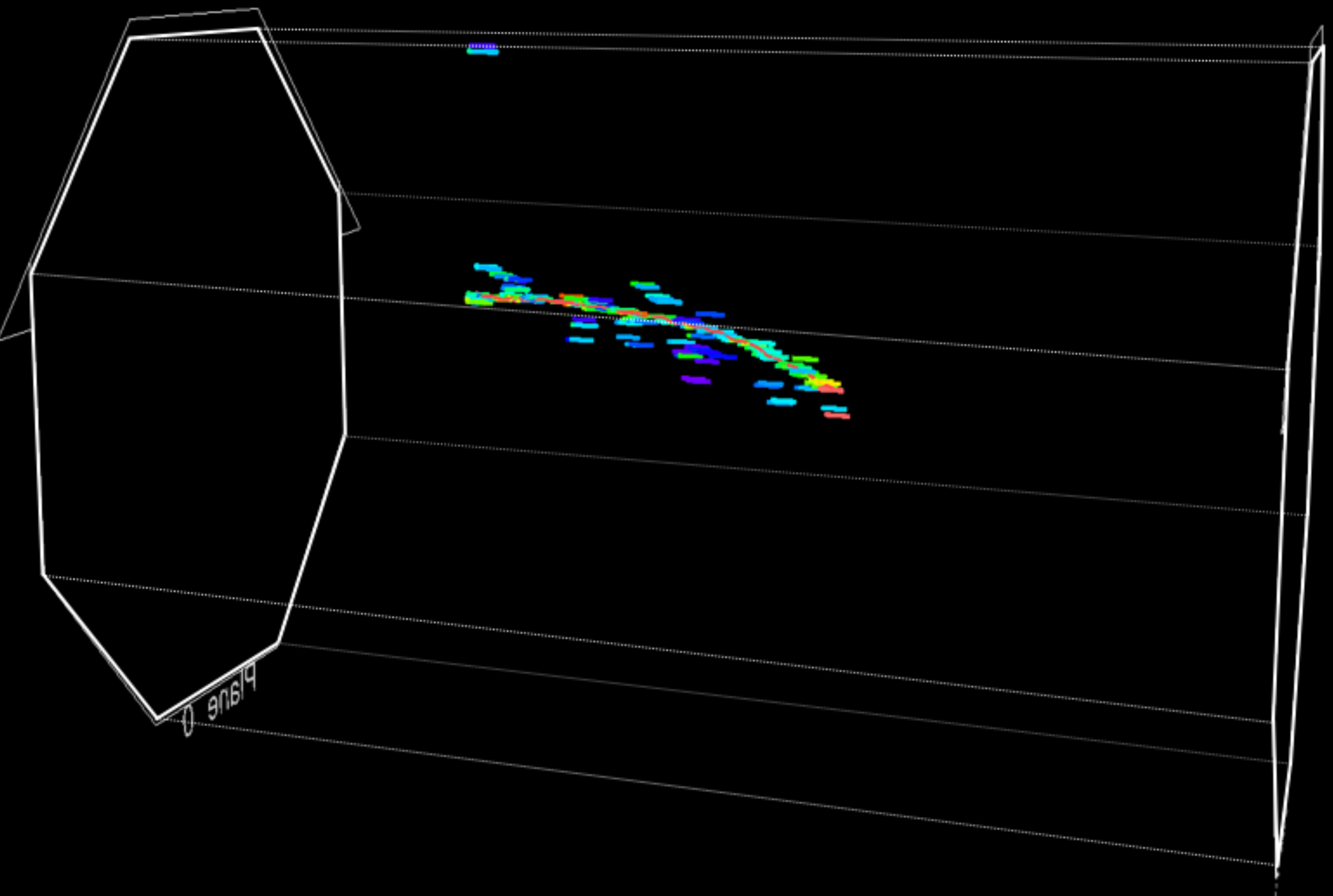


arXiv:0701153

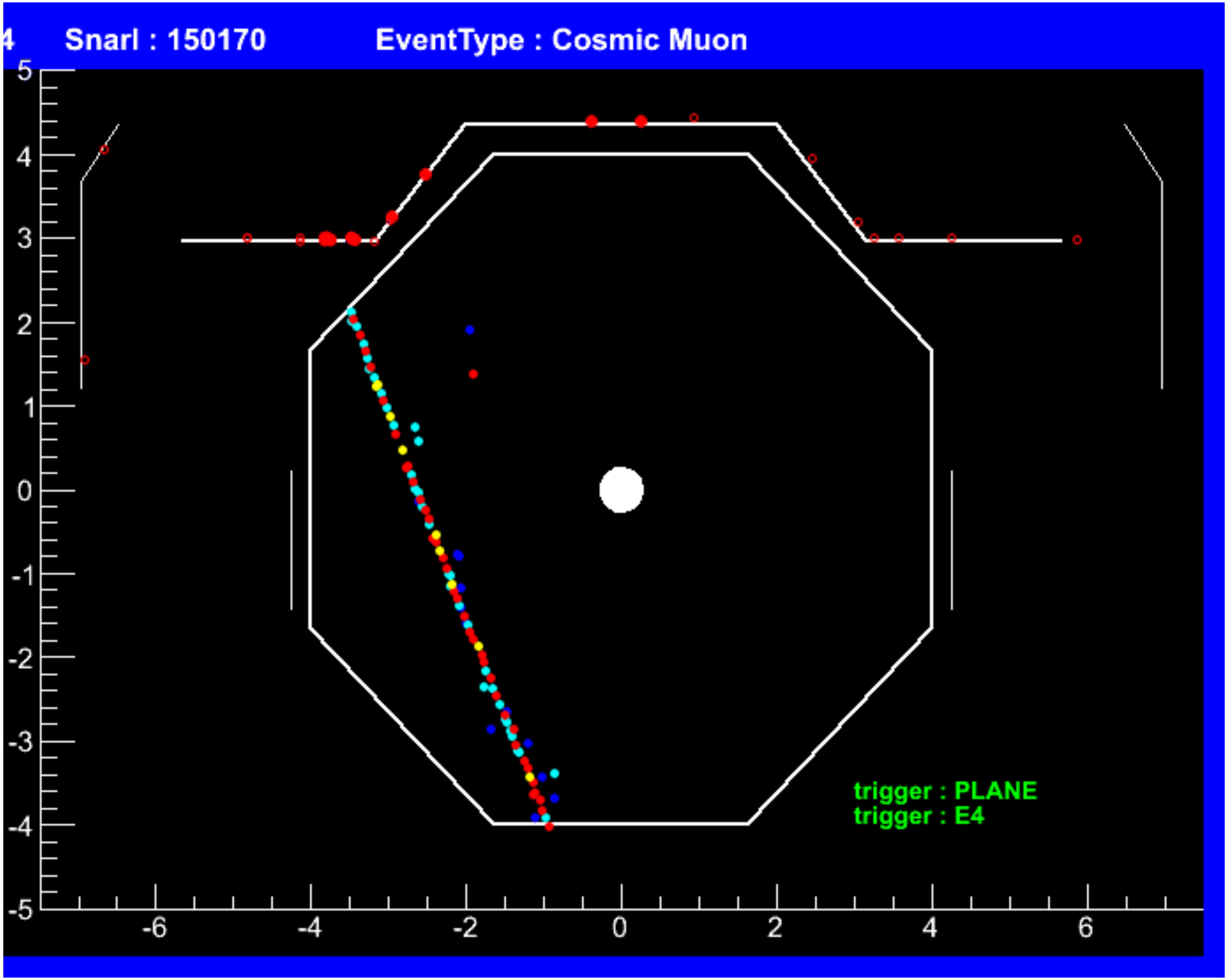
Far Detector Event



Far Detector Event



MINOS Veto Panels



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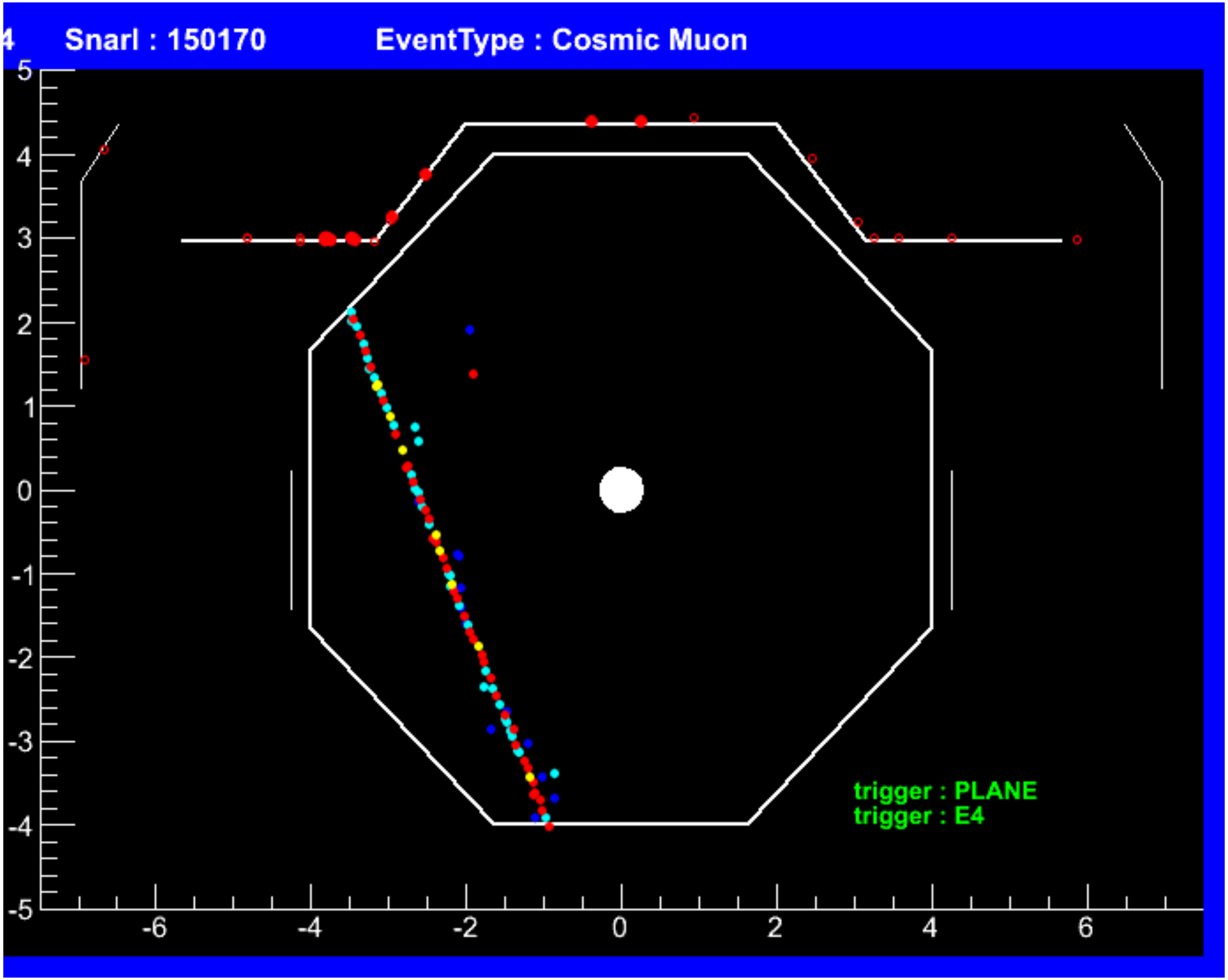

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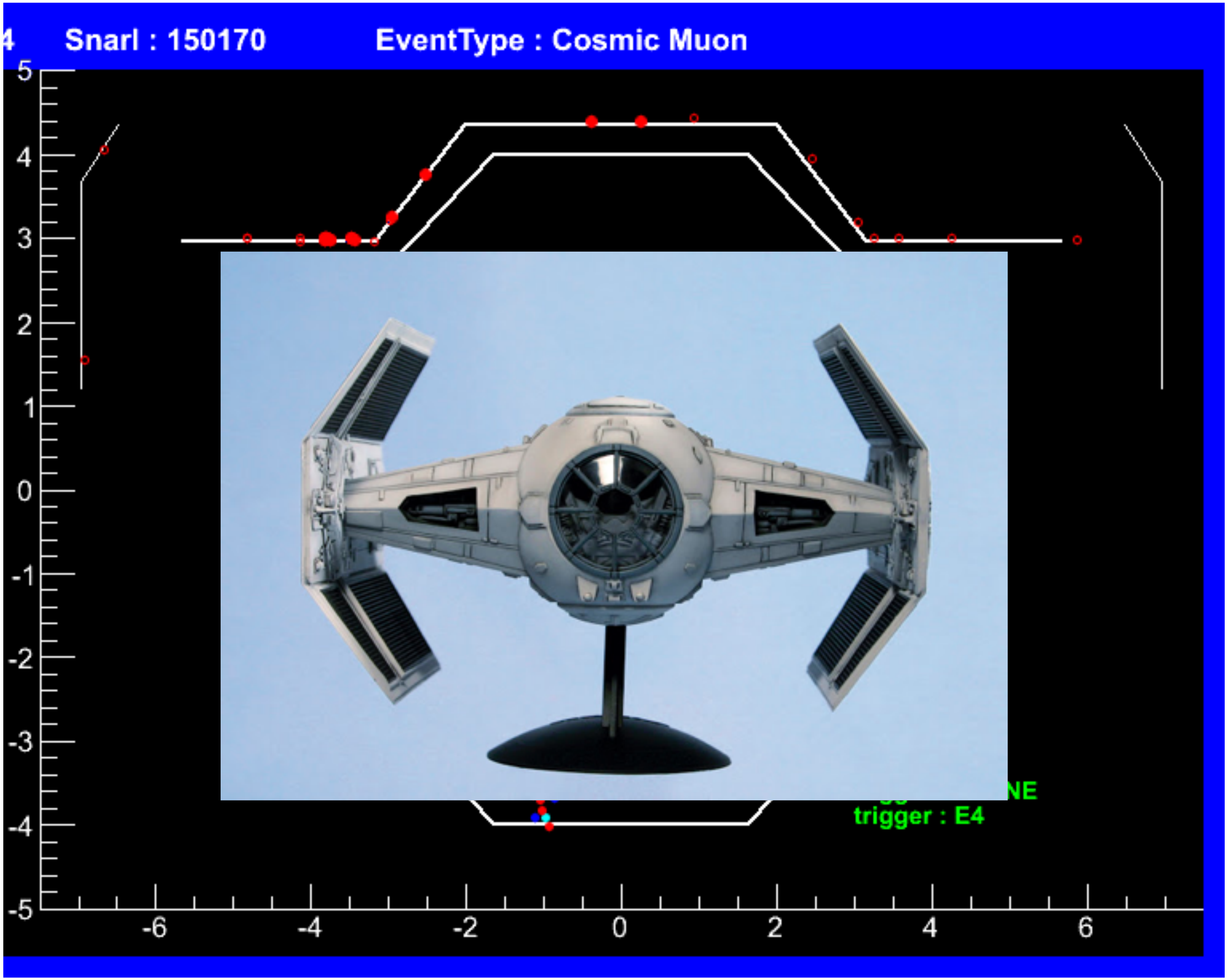

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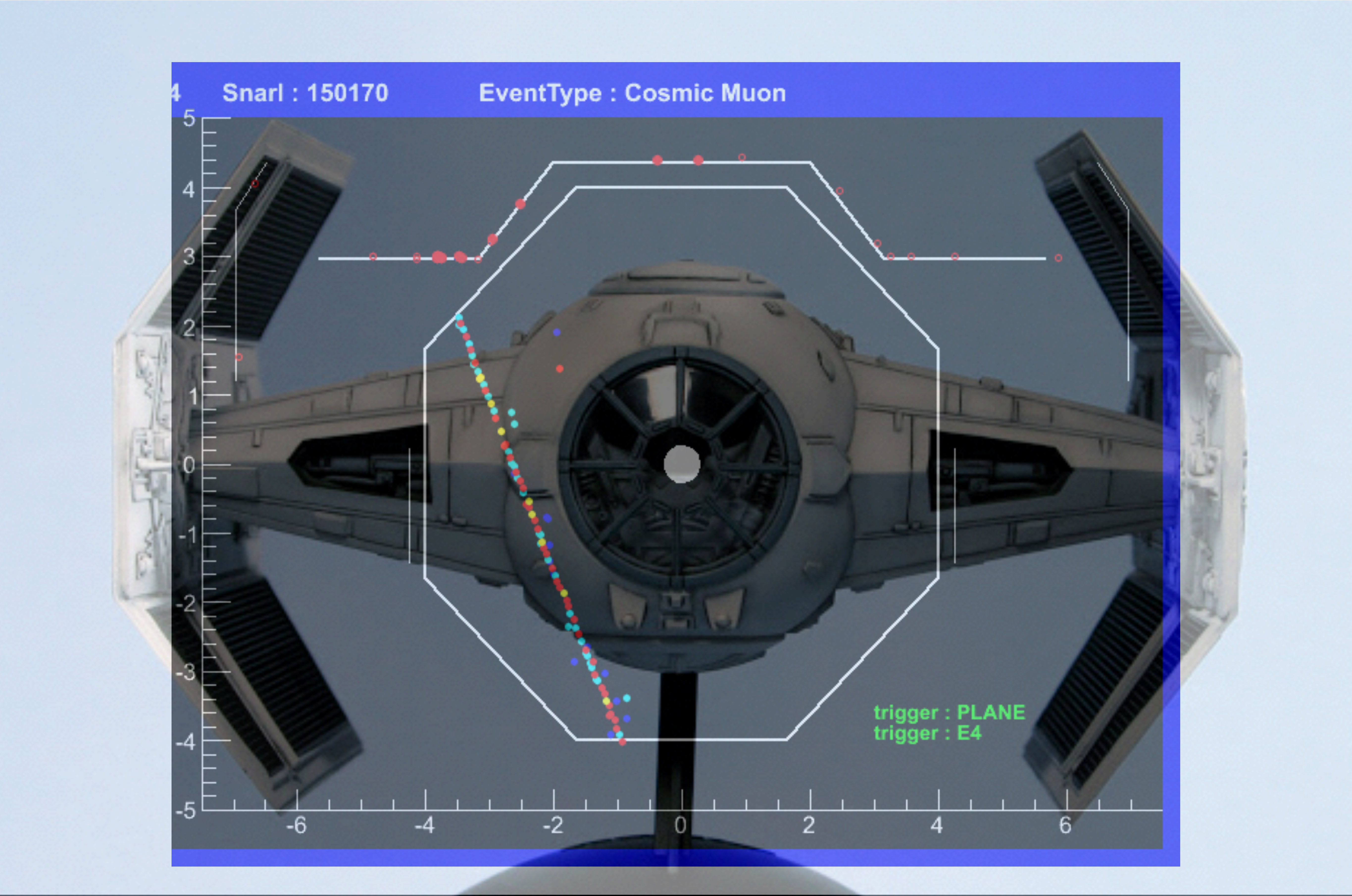

Neutrino Signal

Neutrino Signal

- At the simplest, the goal is to see something ‘appear’ inside the detector
  - Identify interaction within a volume
  - High efficiency identification due to low interaction rate
  - Interaction-specific detector, e.g. identify electron from Charged-Current electron neutrino interaction

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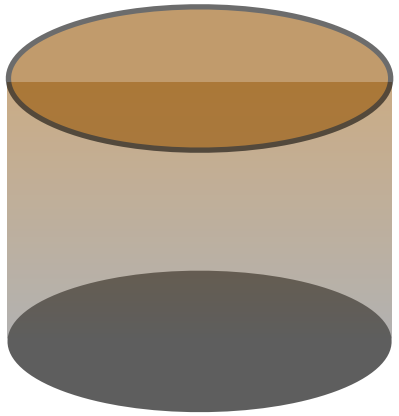
  - Interaction-specific detector, e.g. identify electron from Charged-Current electron neutrino interaction
- Neutrino cross-section is low, so experiments aim for:
  - Large detector mass
  - High neutrino flux
    - Get close to neutrino source
    - Create a powerful source or beam
  - Livetime

Neutrino Background



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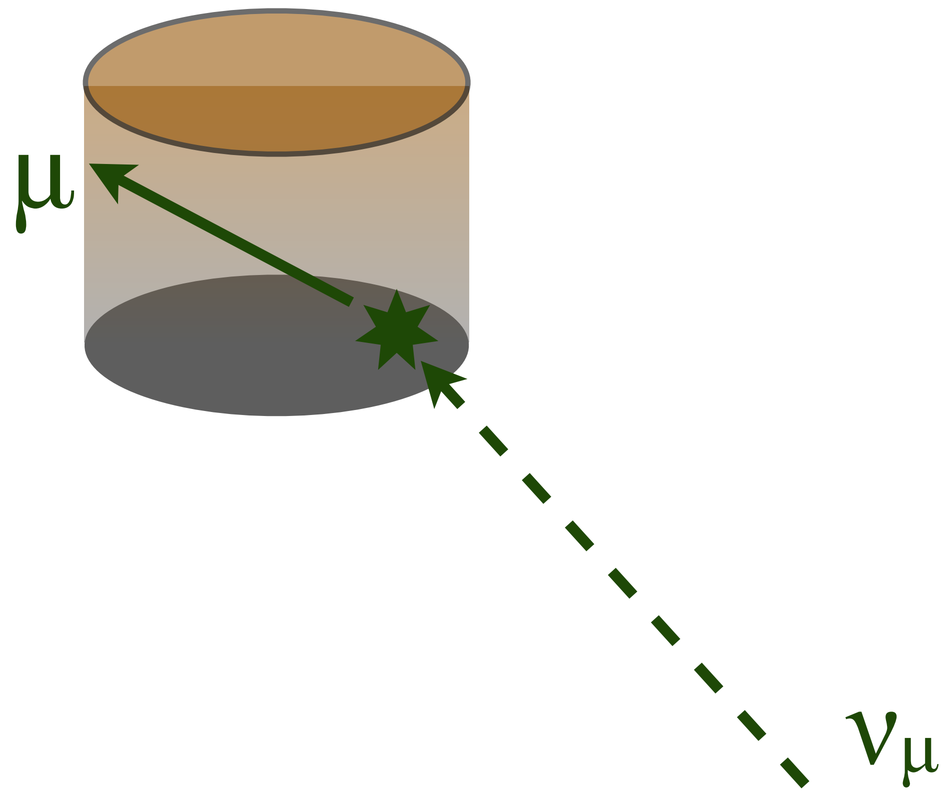

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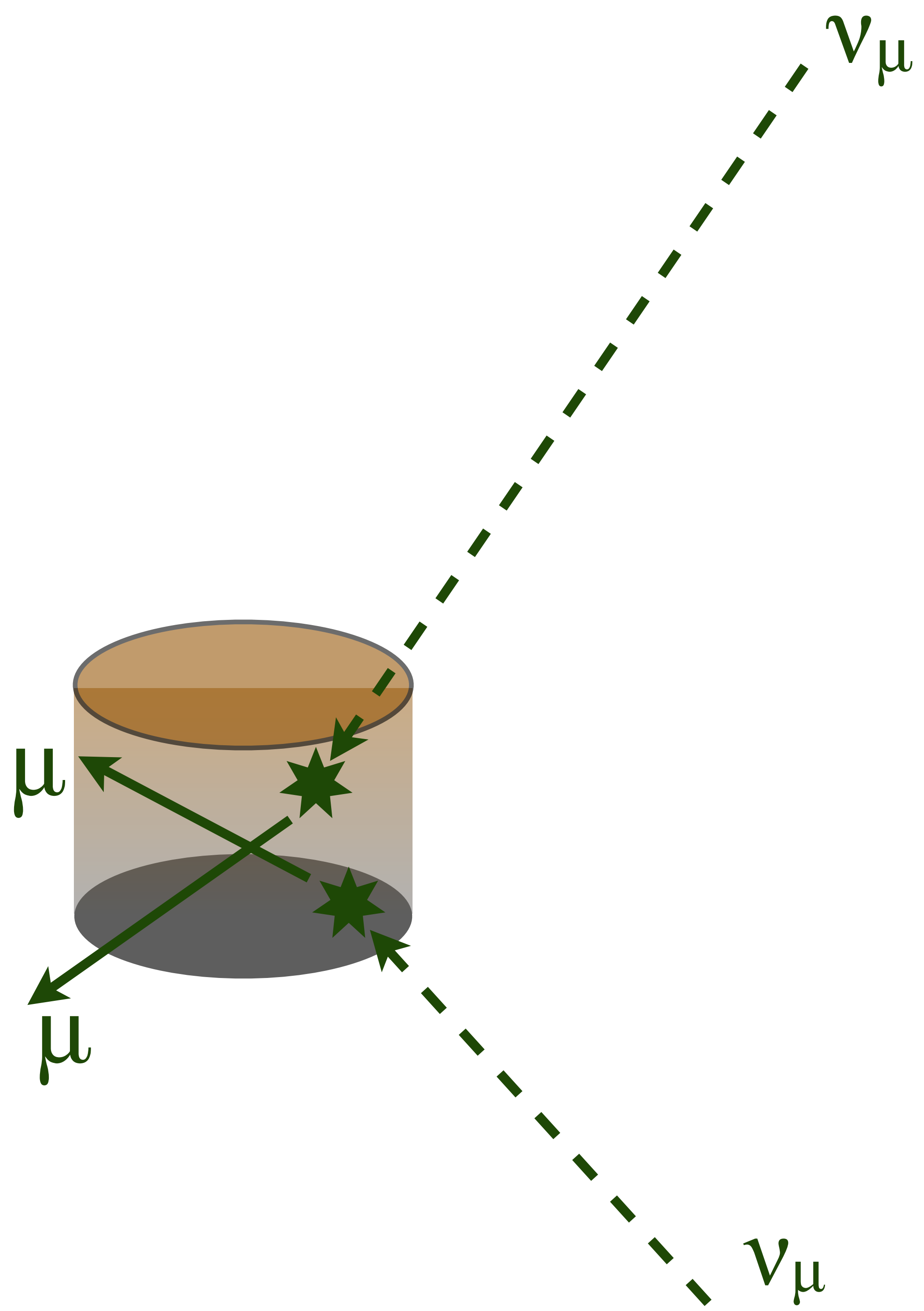

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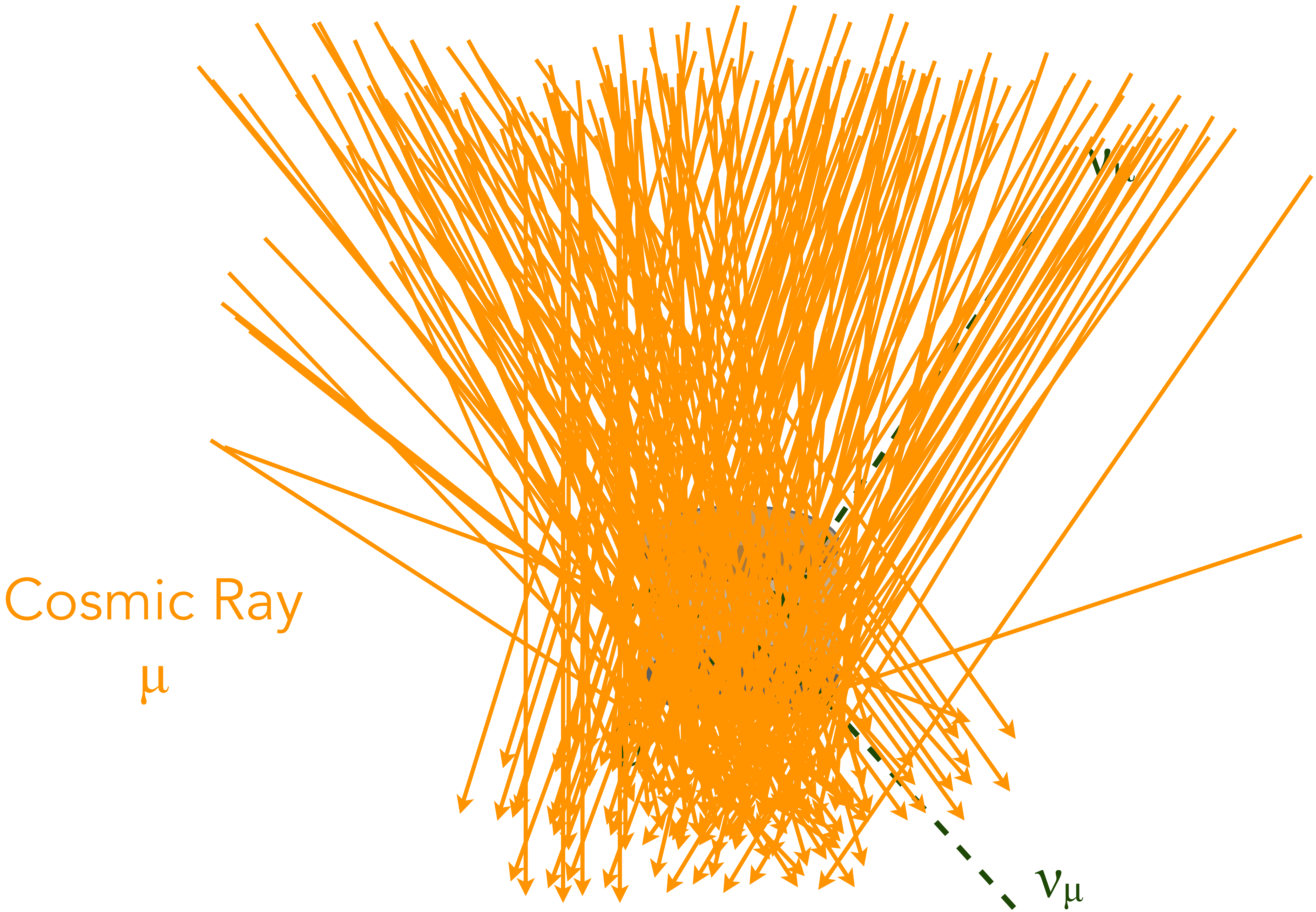
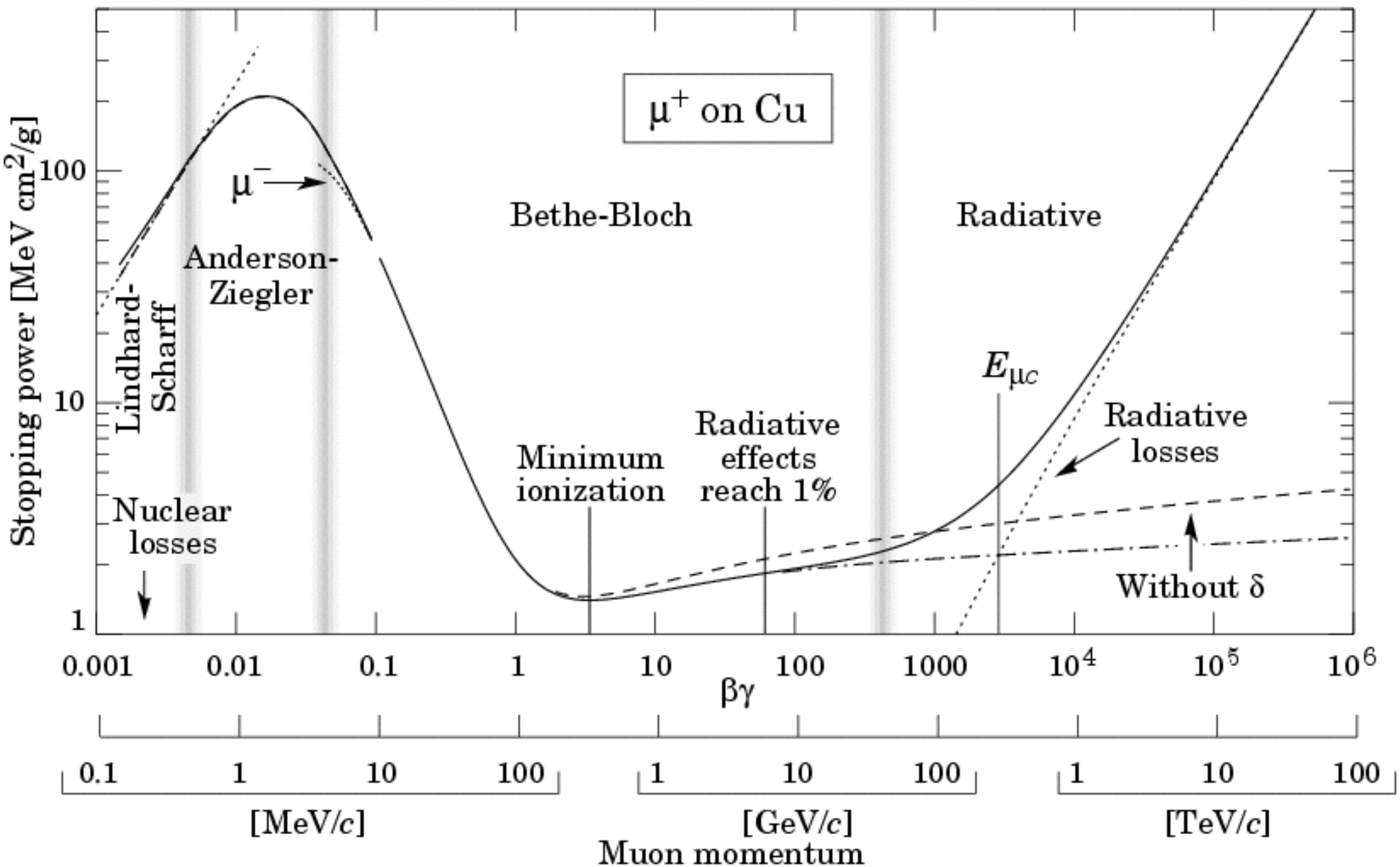


Cosmic Ray Muon Background

- Penetrating muons that interact in the detector
  - Generally much, much more numerous than actual desired neutrinos
  - Muons low energy deposition (~2 MeV cm^2/gram) and therefore a long range
  - Stochastic energy loss produces a non-muon-like signature

Muon Energy Loss in Matter

*Particle Data Group



Muon Stochastic Energy Loss

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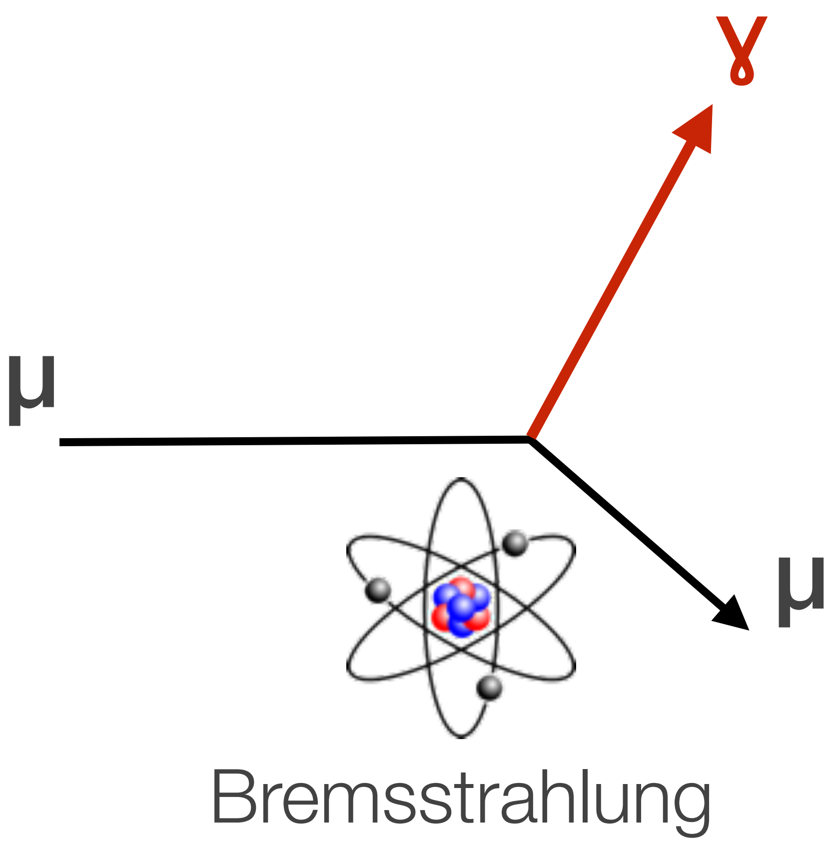

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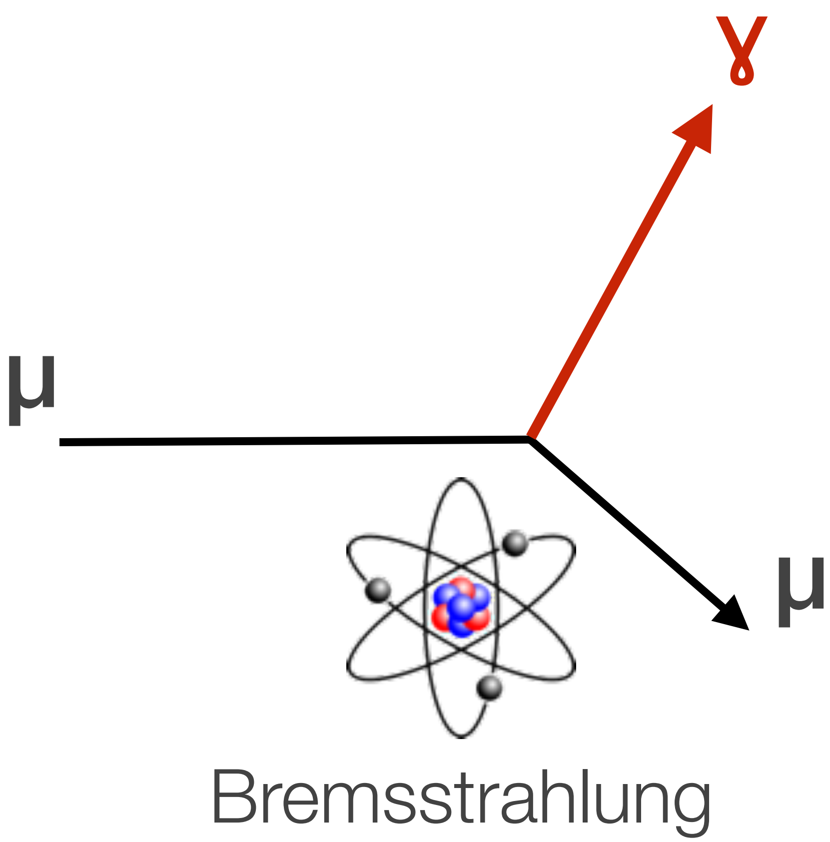

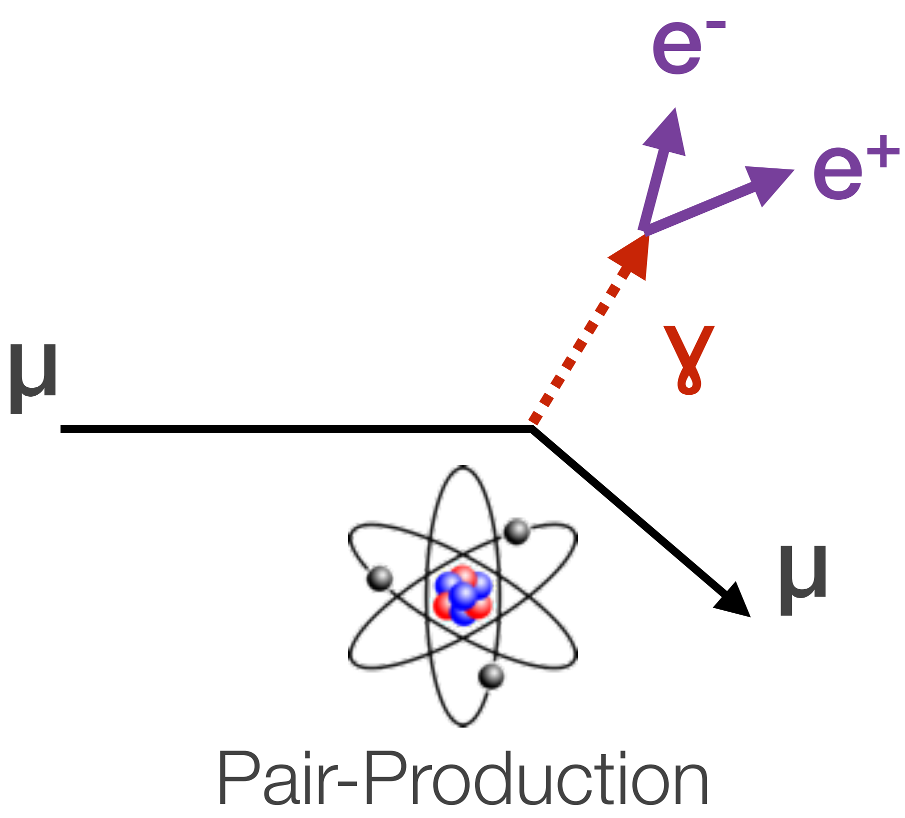

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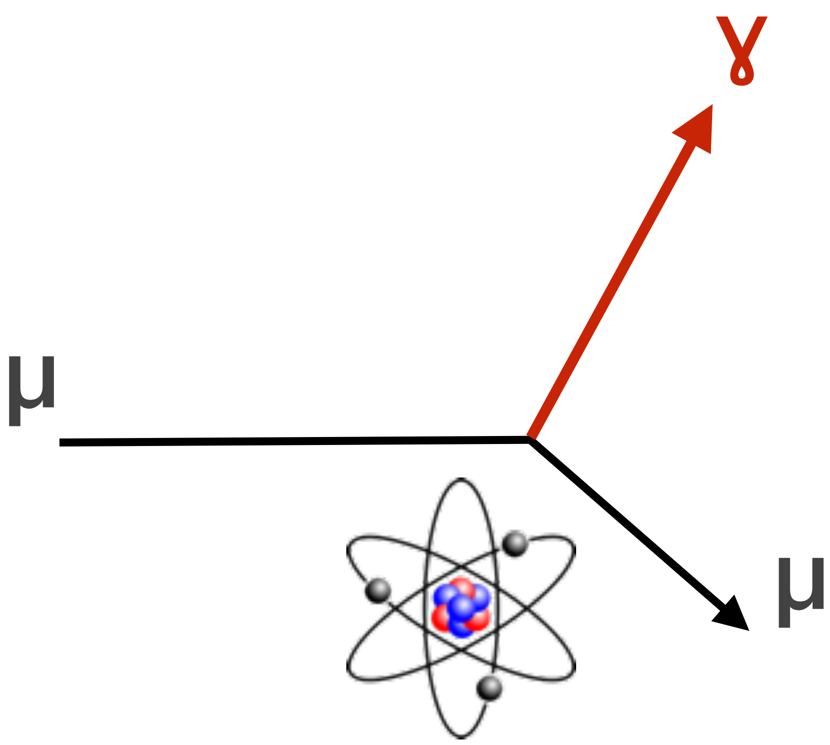
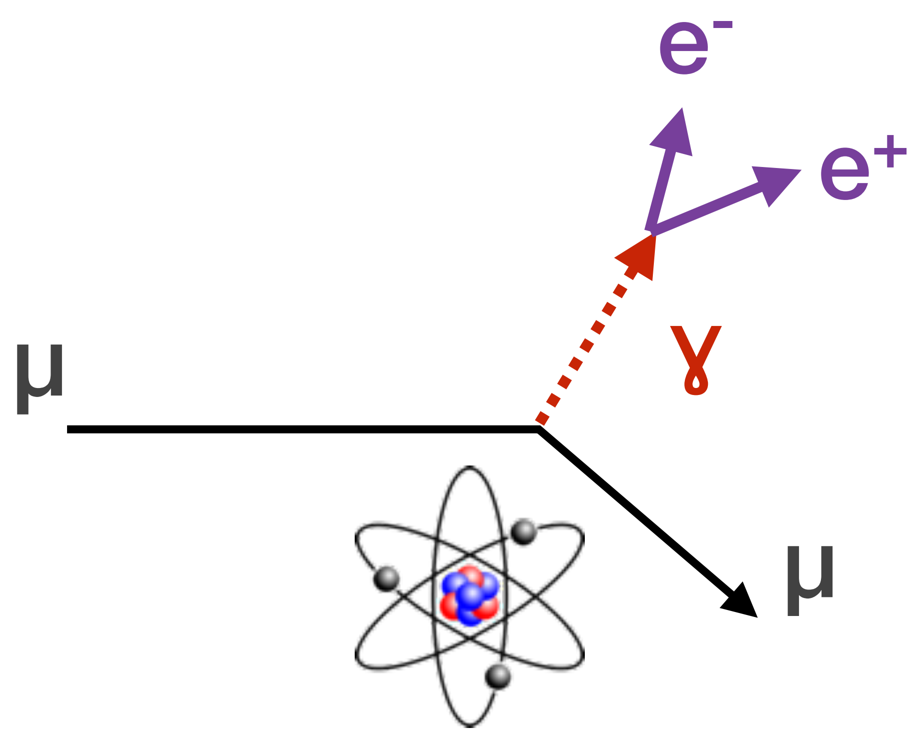
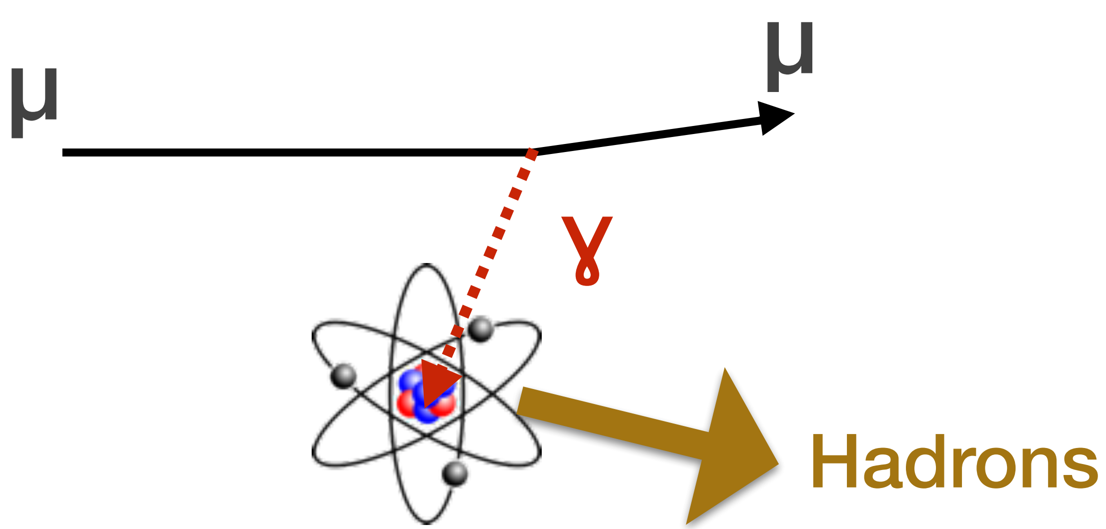


Bremsstrahlung

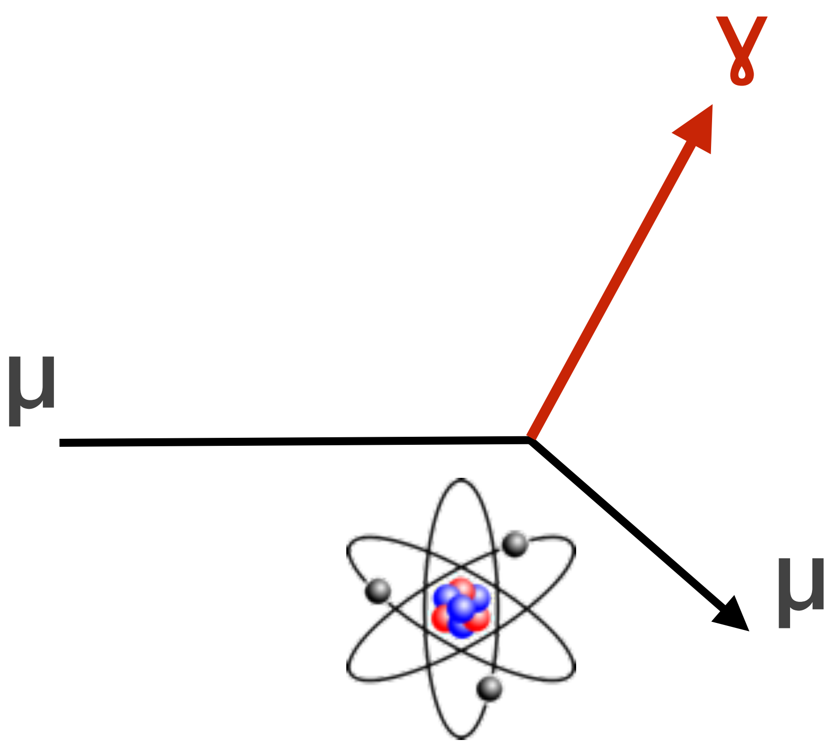


Pair-Production



Photonuclear

Muon Stochastic Energy Loss



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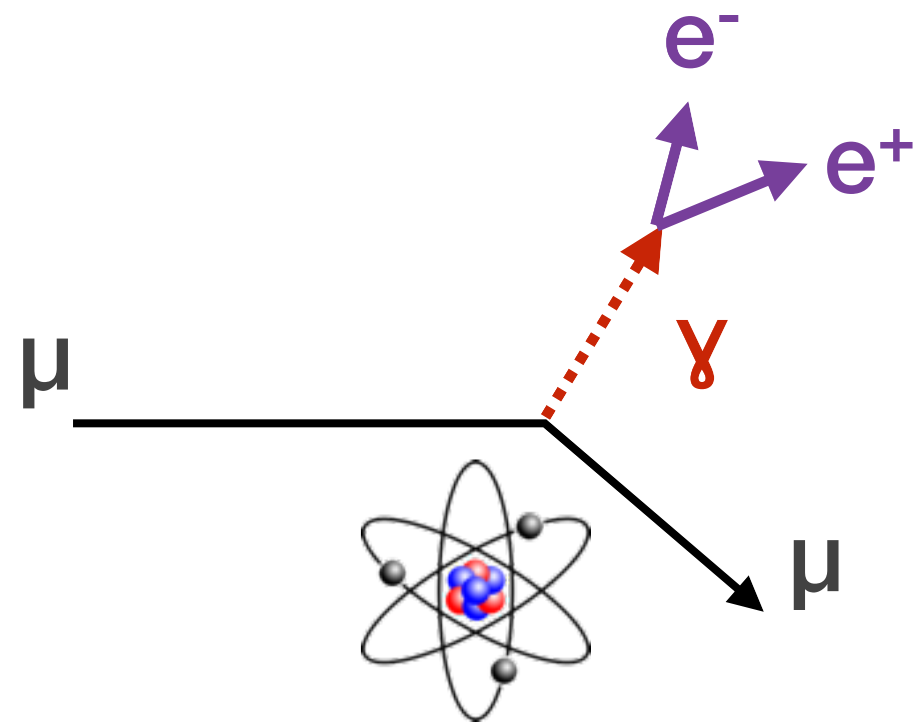

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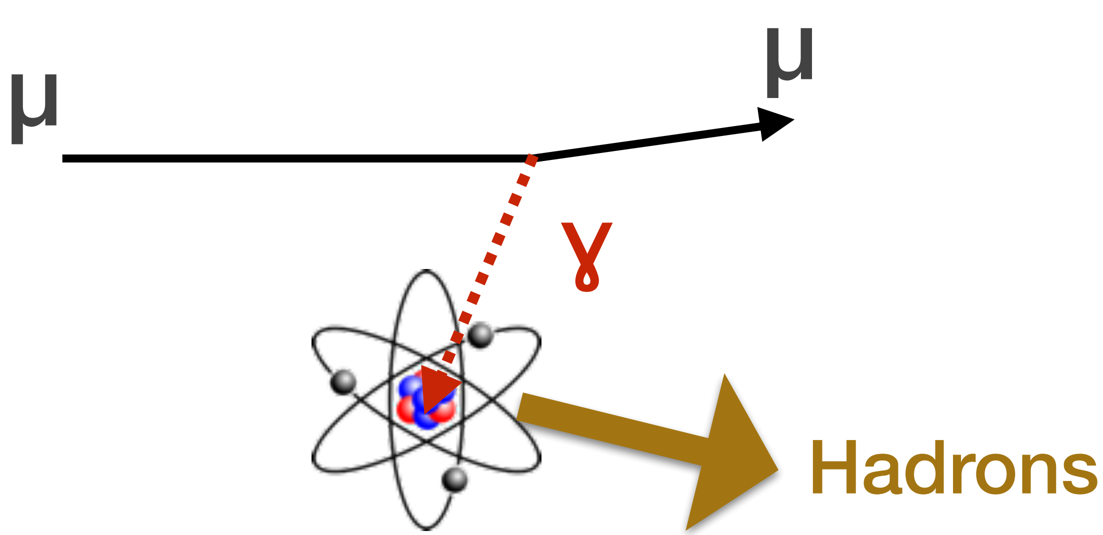

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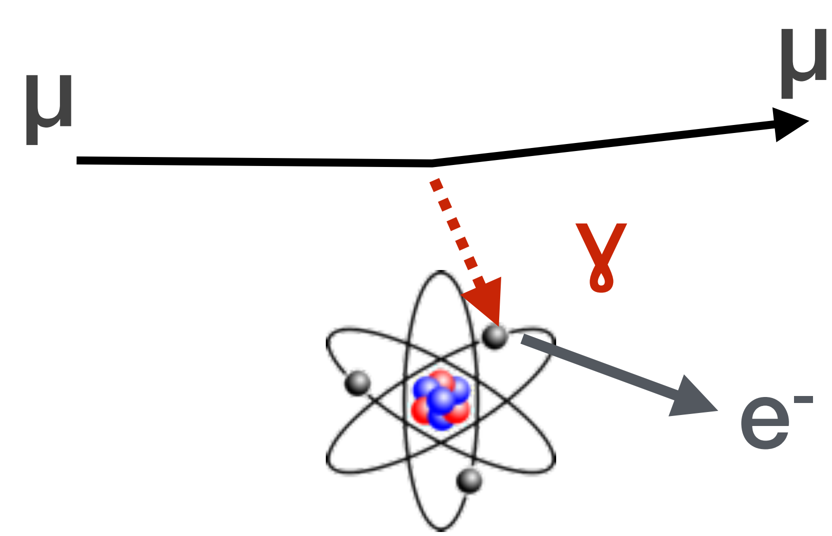
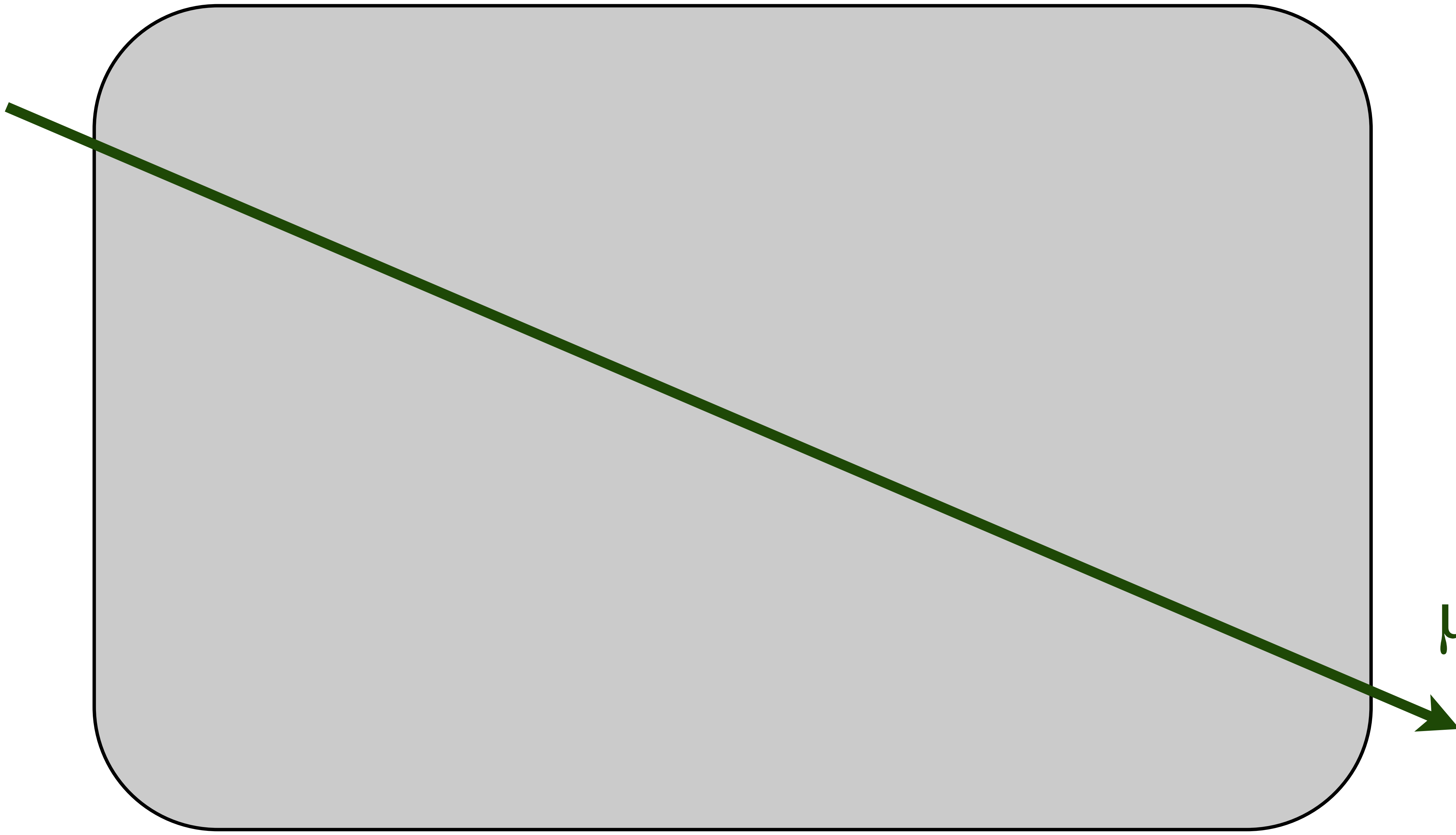


Delta Ray “Knock-on”

Muon Event Cartoon



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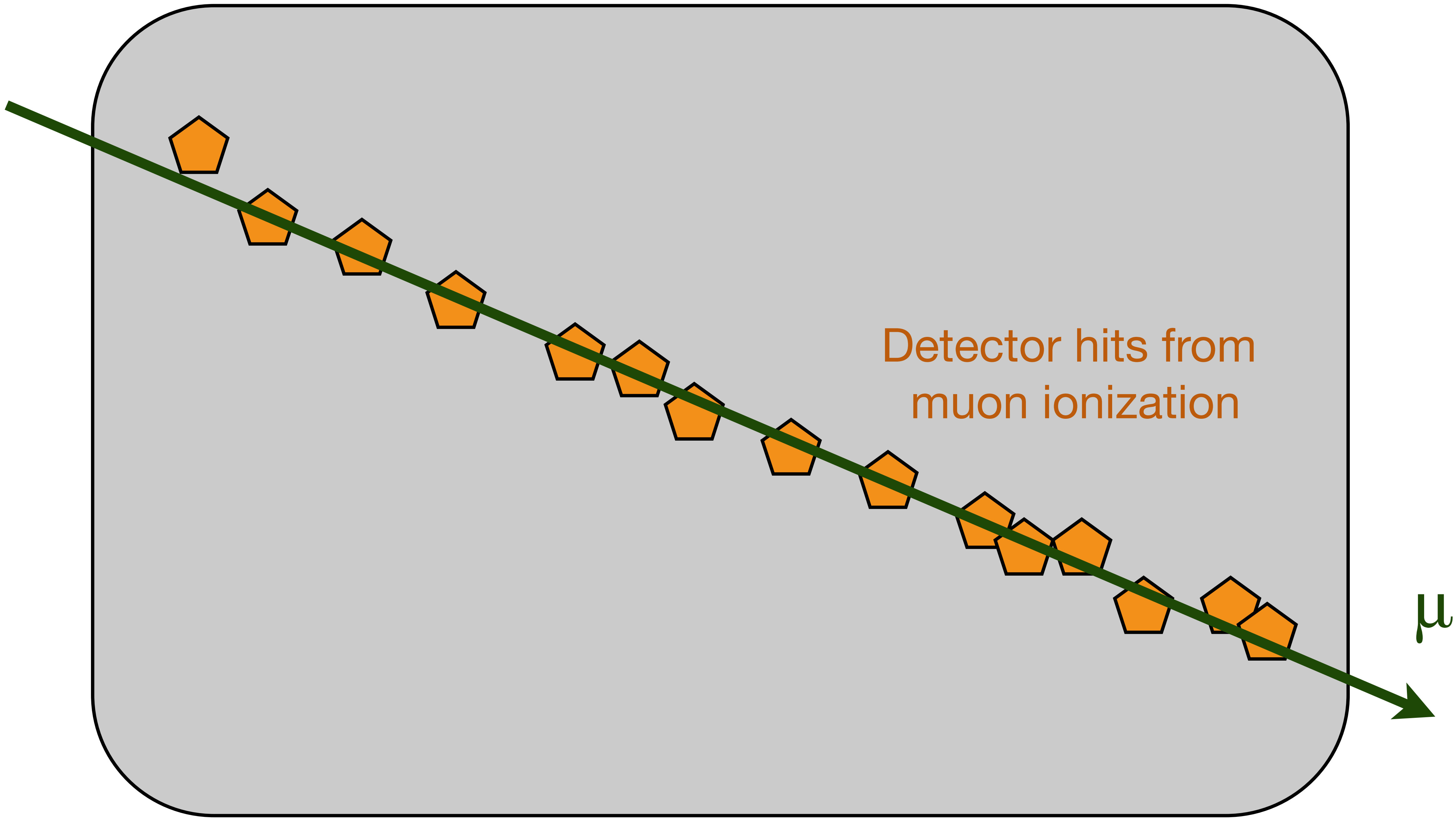
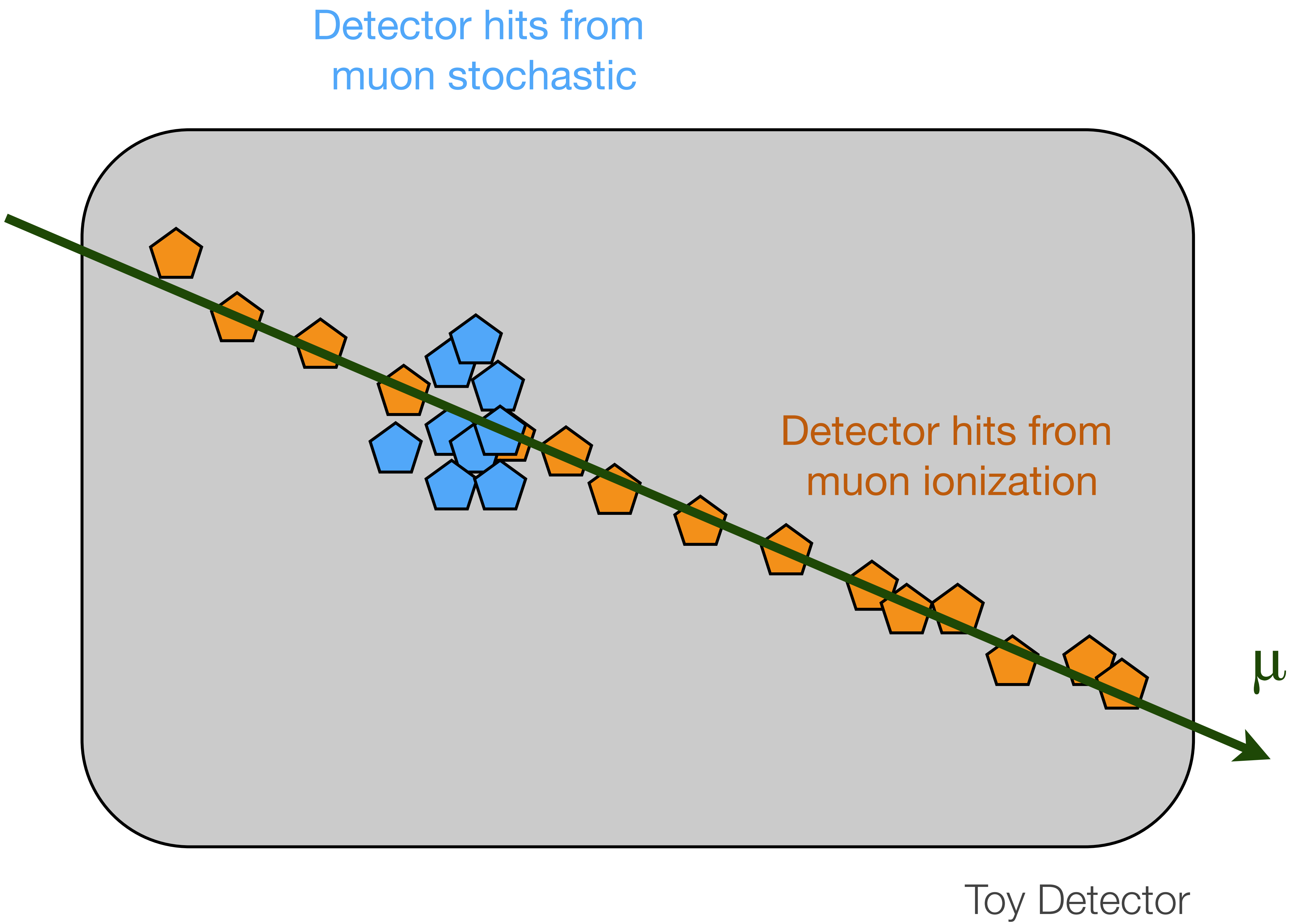


Toy Detector

Muon Event Cartoon



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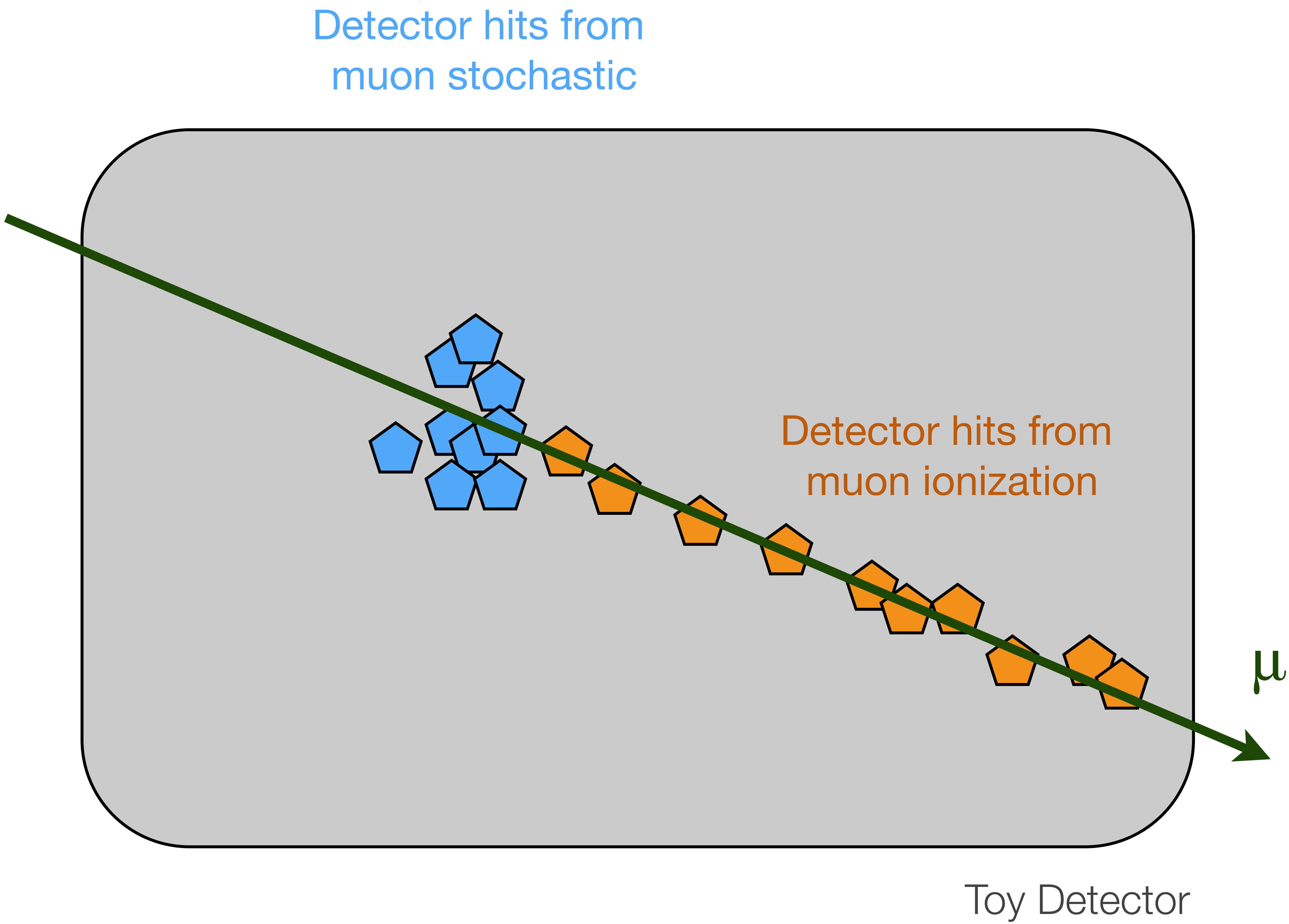
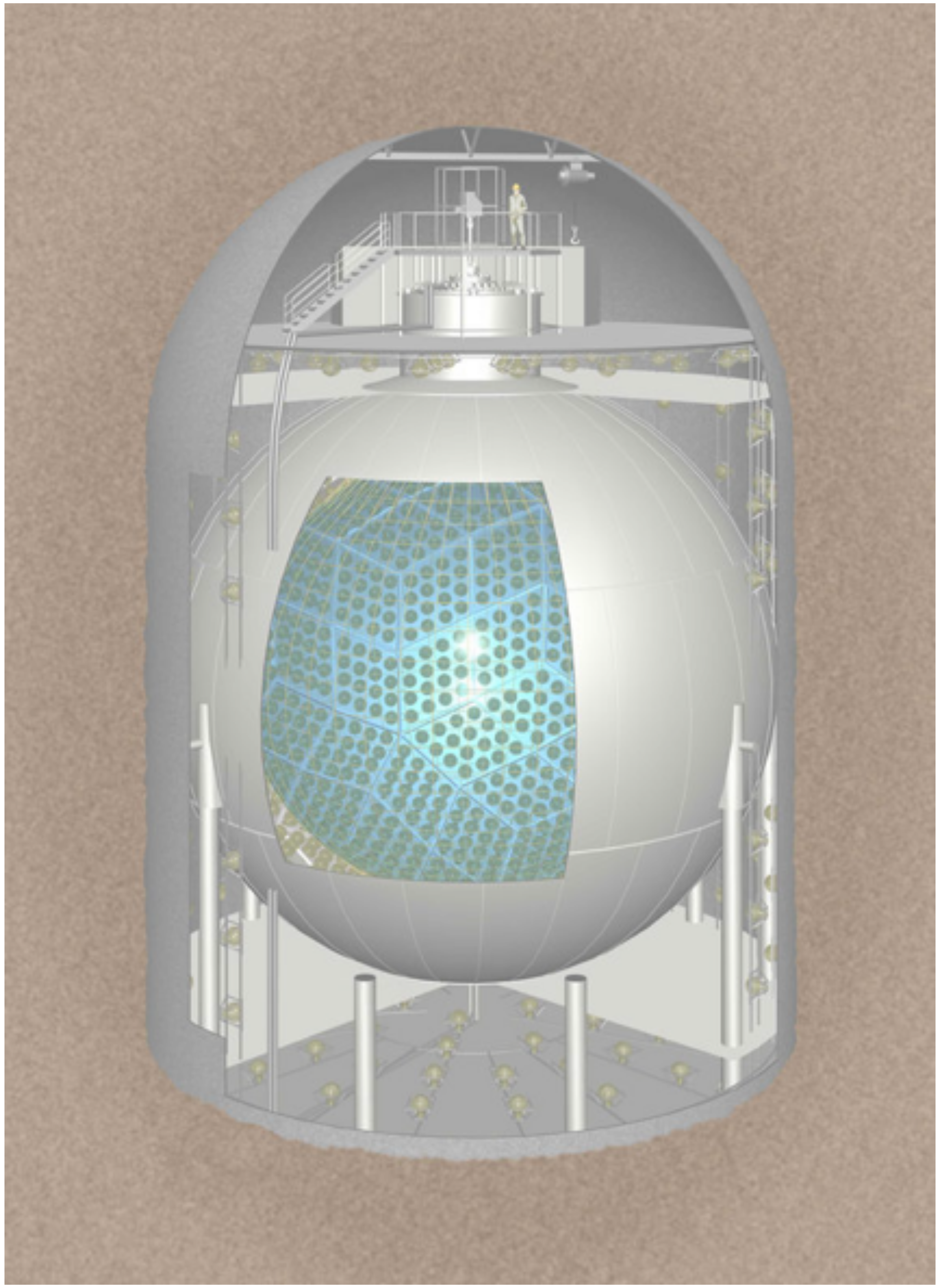


Secondary Muon Effects

KamLAND



Secondary Muon Effects

- Muons can cause radioactive background

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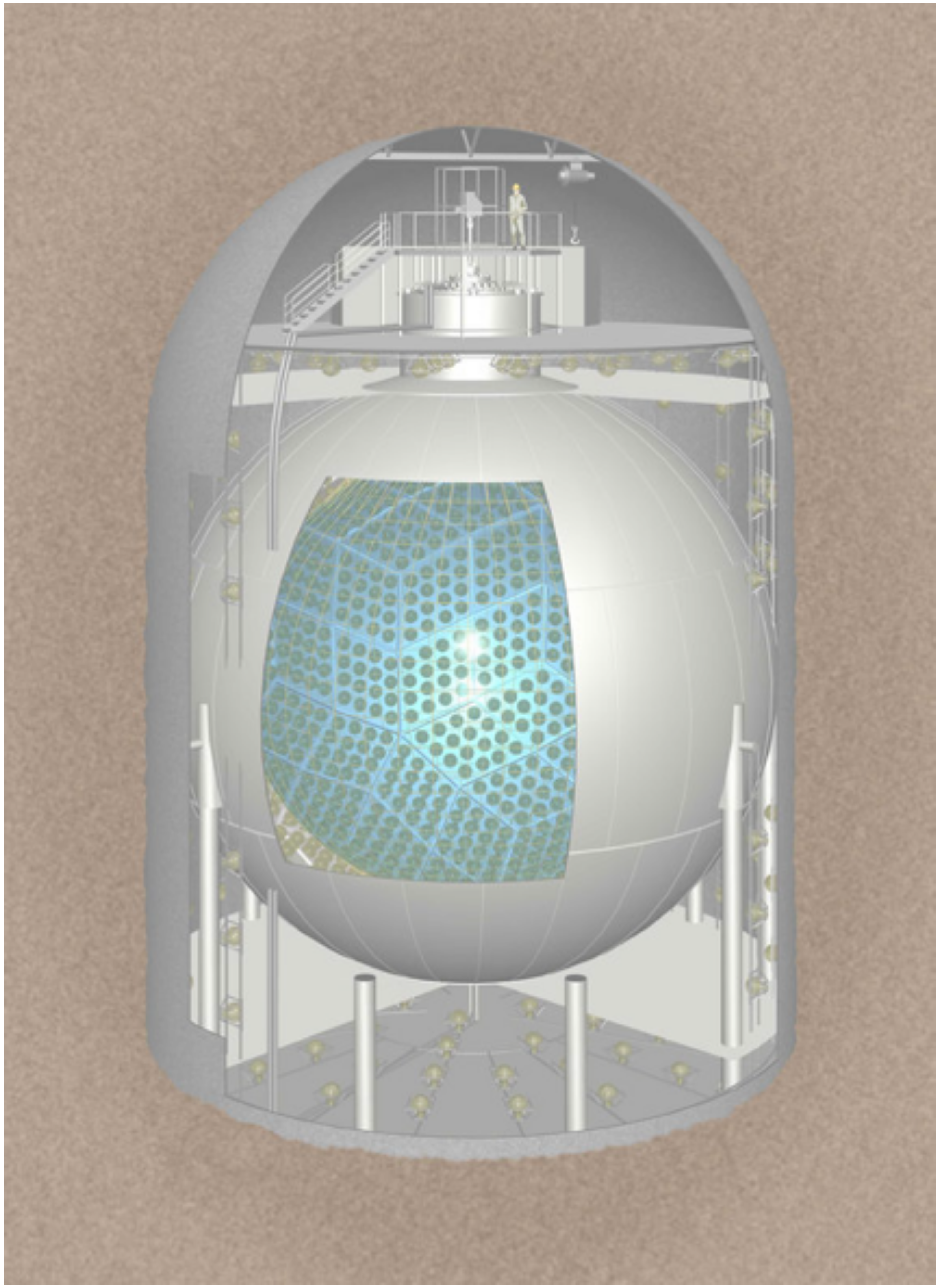

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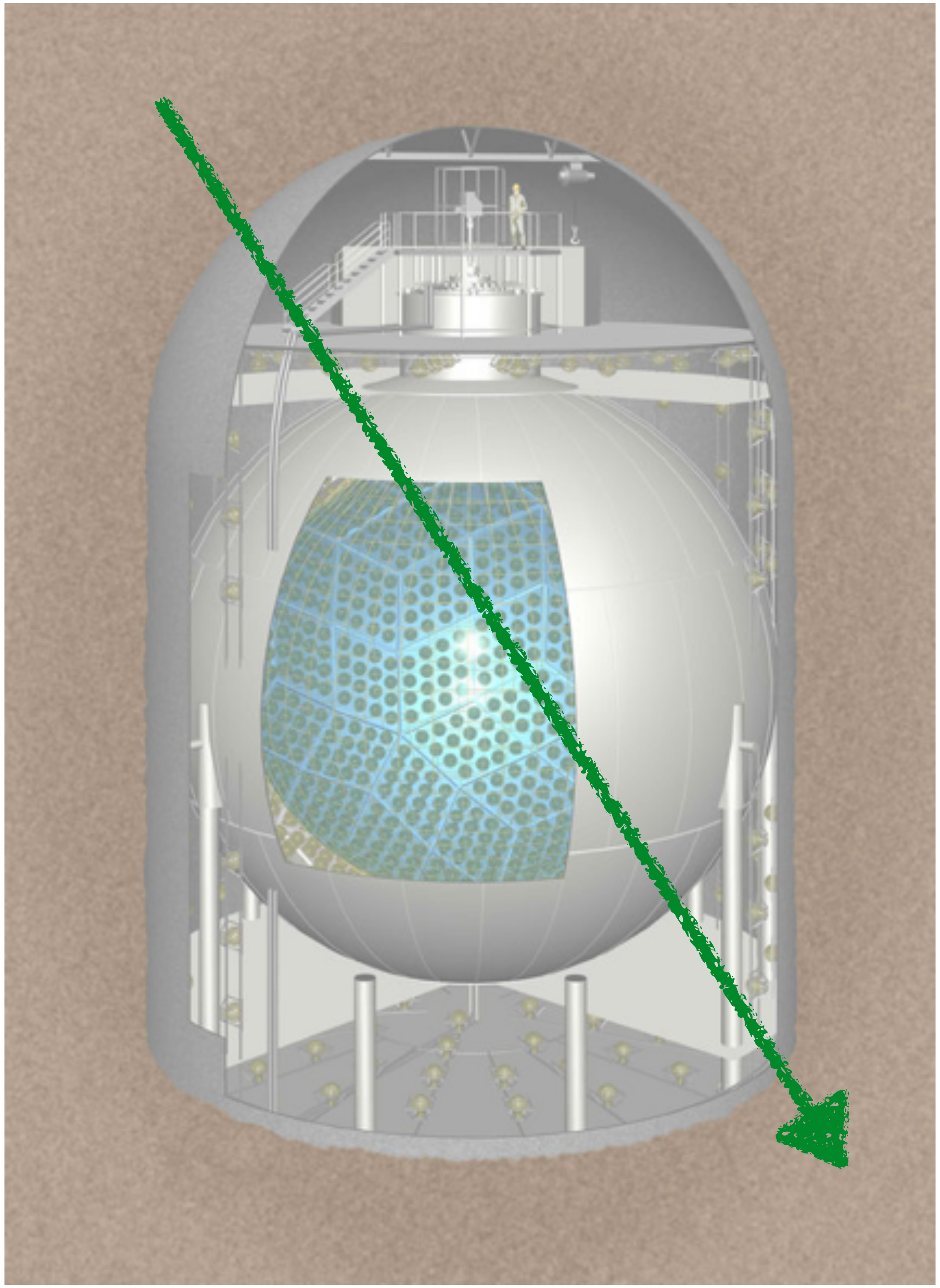

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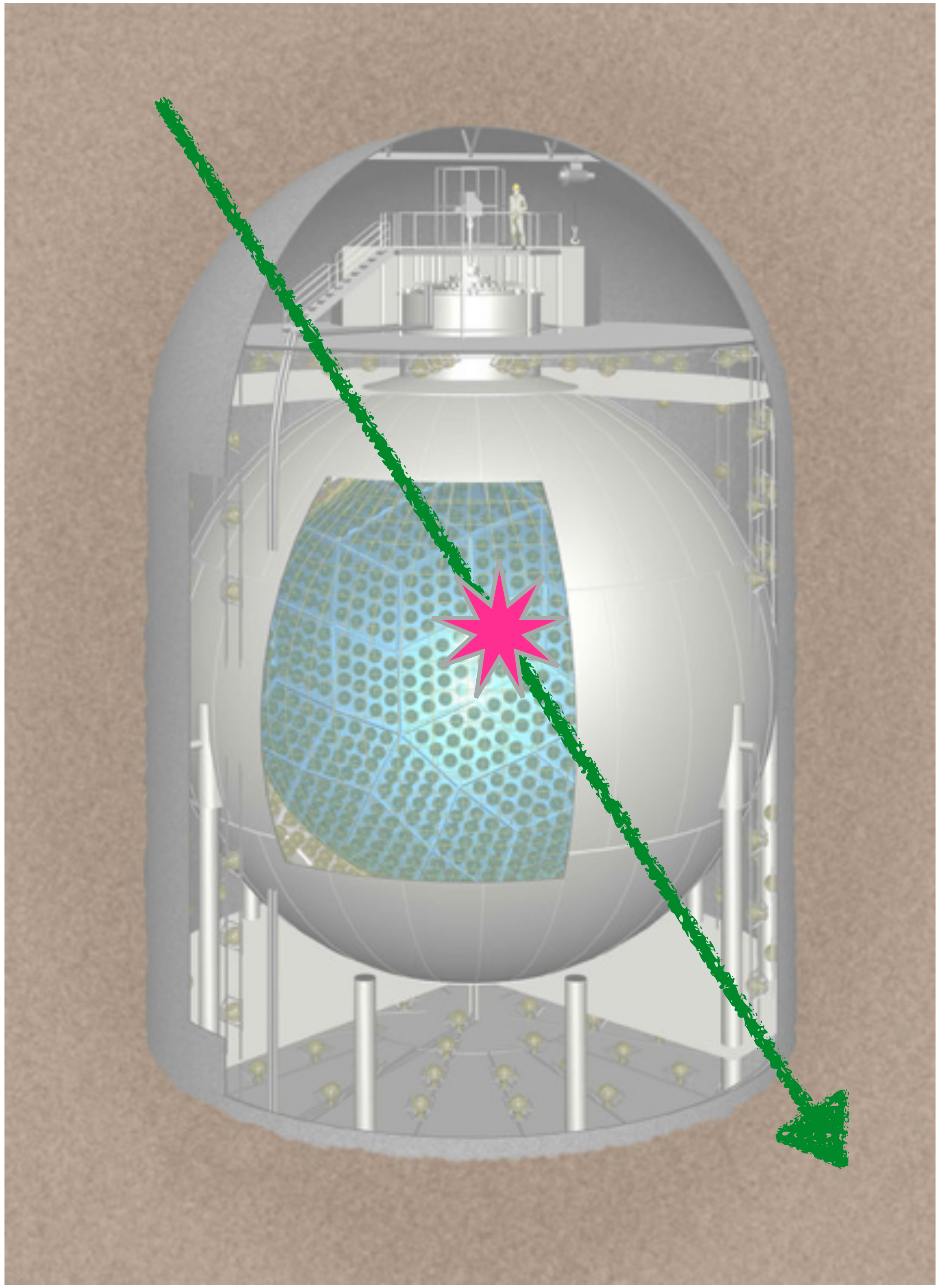

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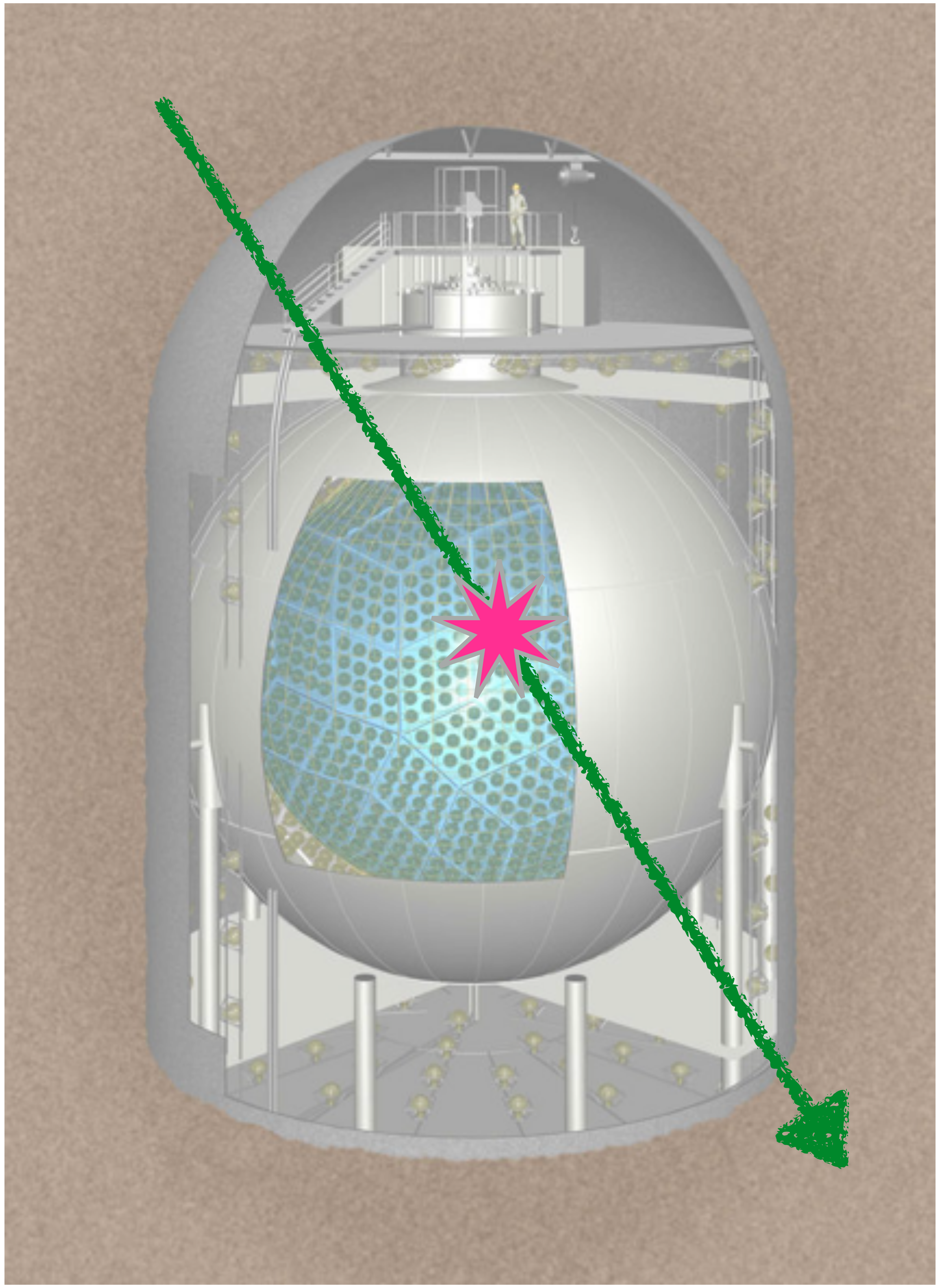
    - **Cosmogenic activated radiation**, i.e. cosmic ray muon creates isotope within the detector which decays long after the muon is gone

KamLAND



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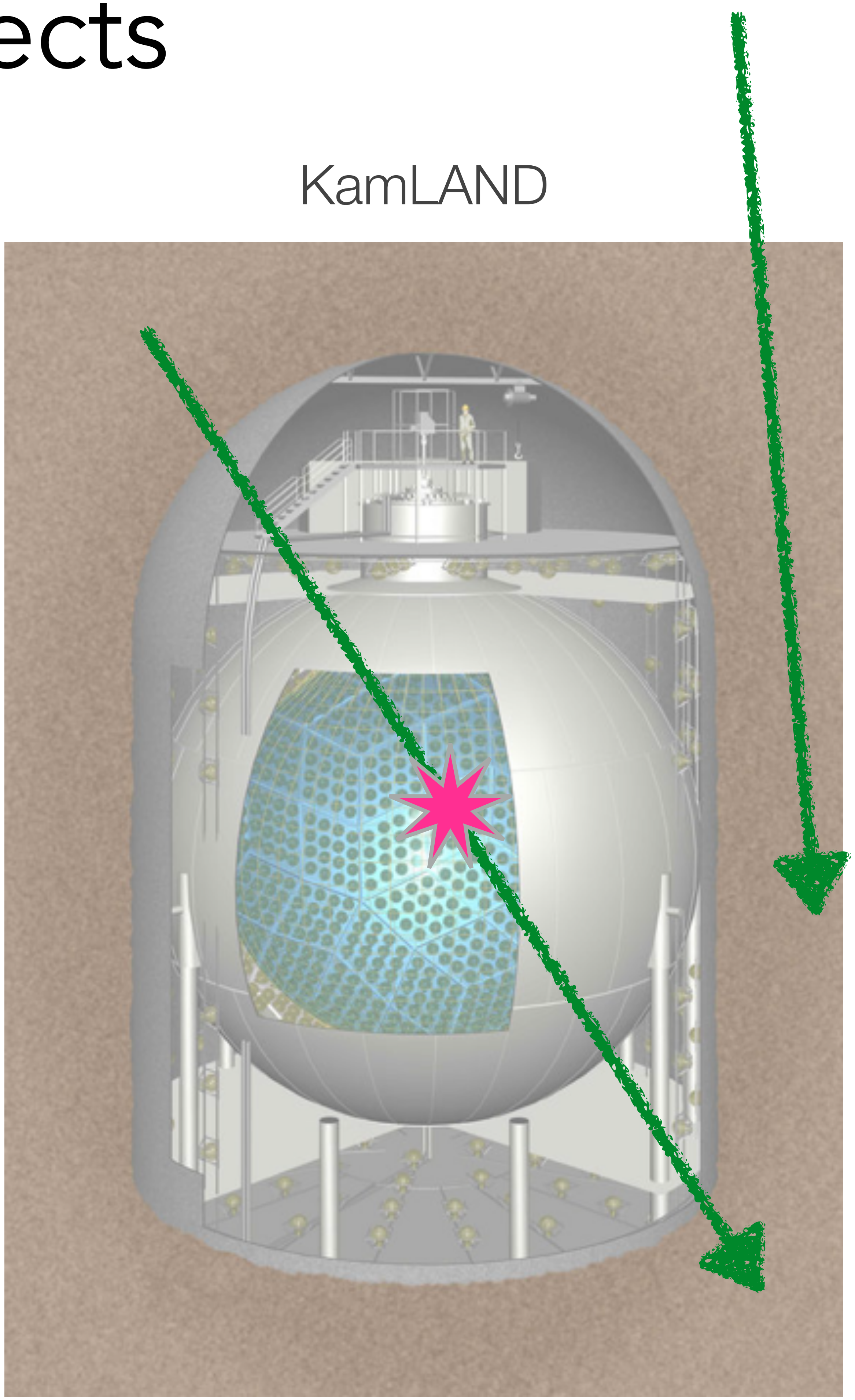

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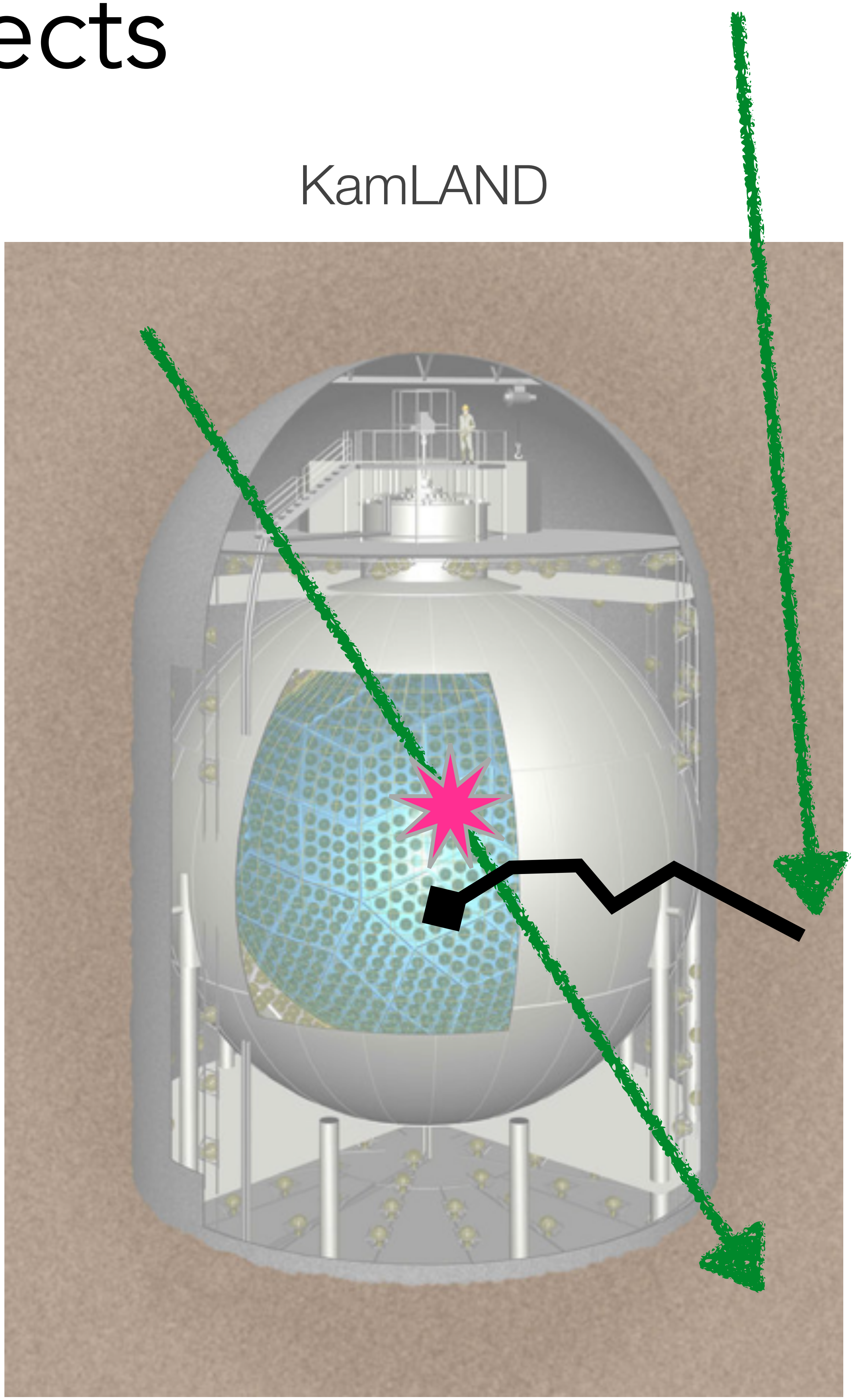

Secondary Muon Effects

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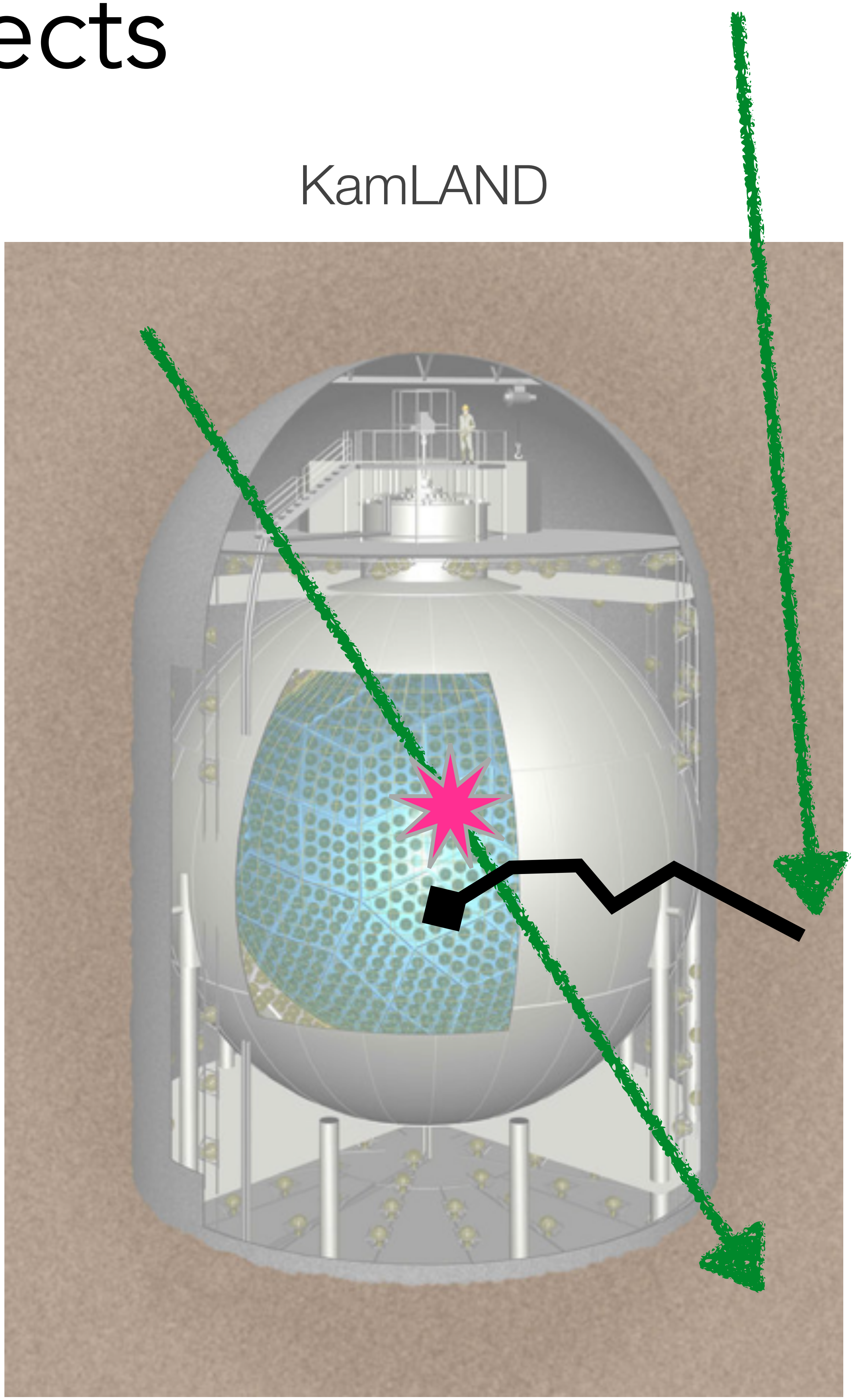
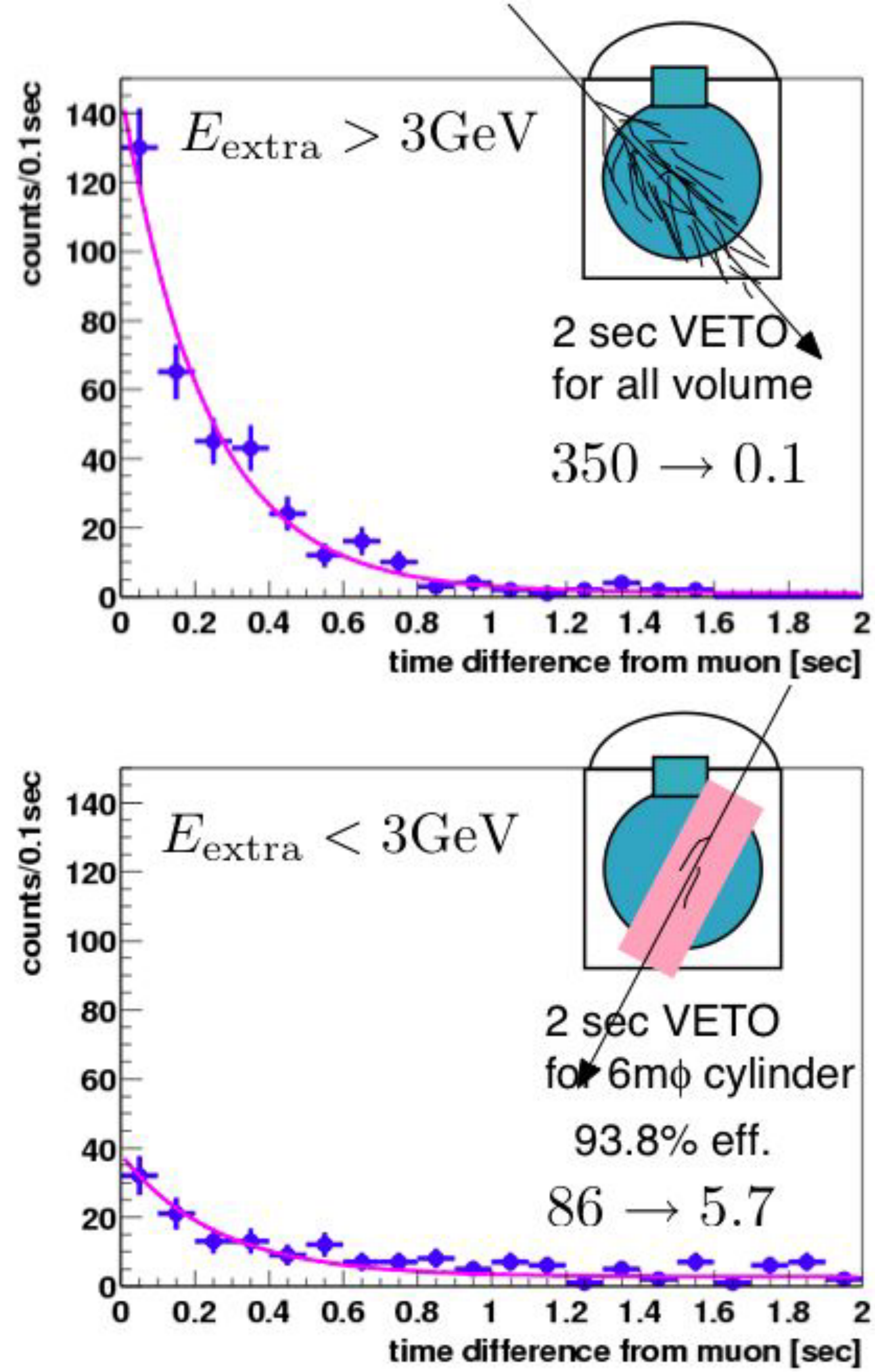
  - **Cosmogenic activated radiation**, i.e. cosmic ray muon creates isotope within the detector which decays long after the muon is gone
  - Muons can dislodge **neutrons** which wander undetected into the detector whereupon they are absorbed or collide

KamLAND



KamLAND

- Use time cut around muon
  - High energy can produce more background in the whole detector
  - Lower energy only requires cuts around the muon path



*P. Decowski, High Energy Physics in the LHC Era 2006

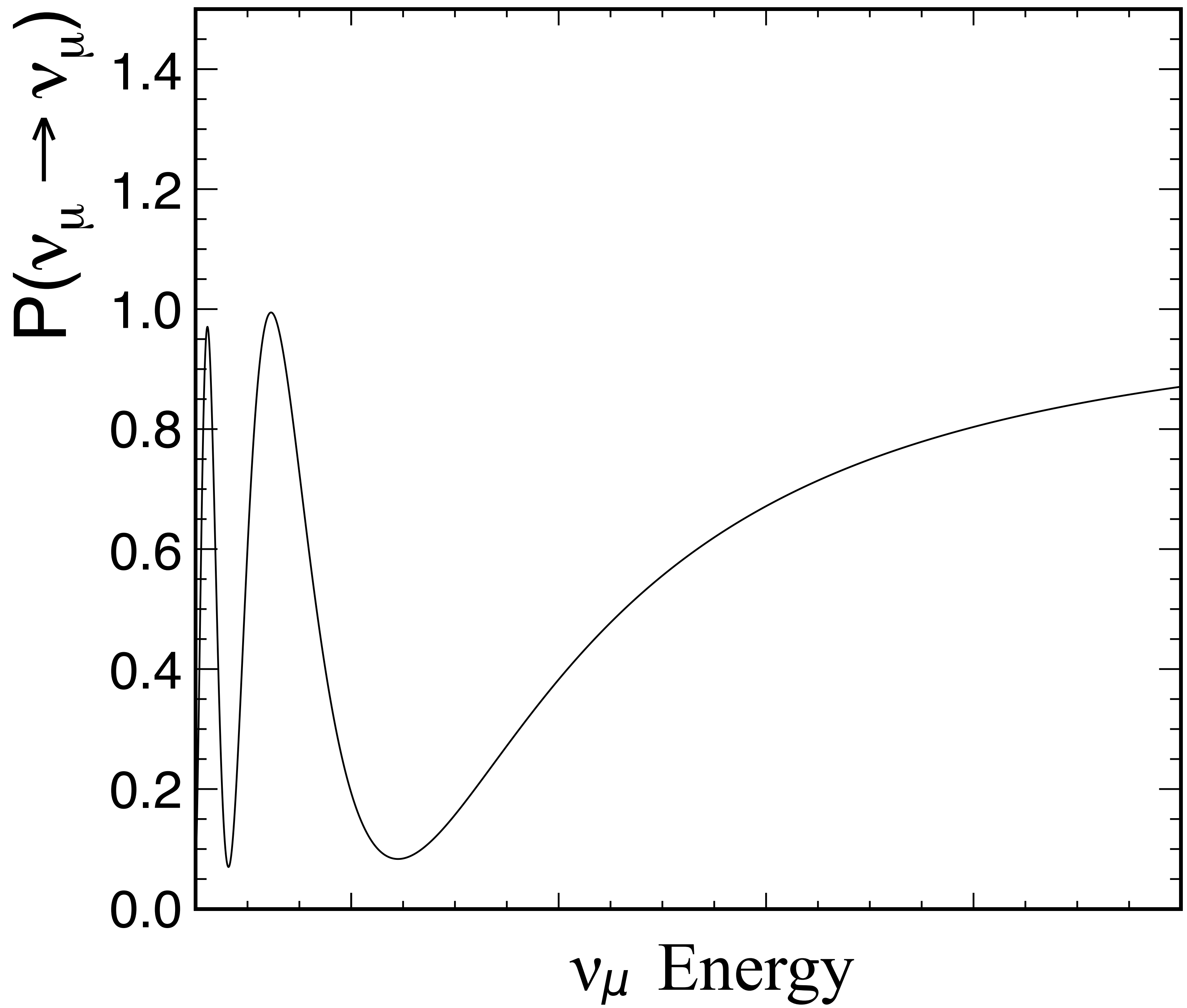
Muon Background

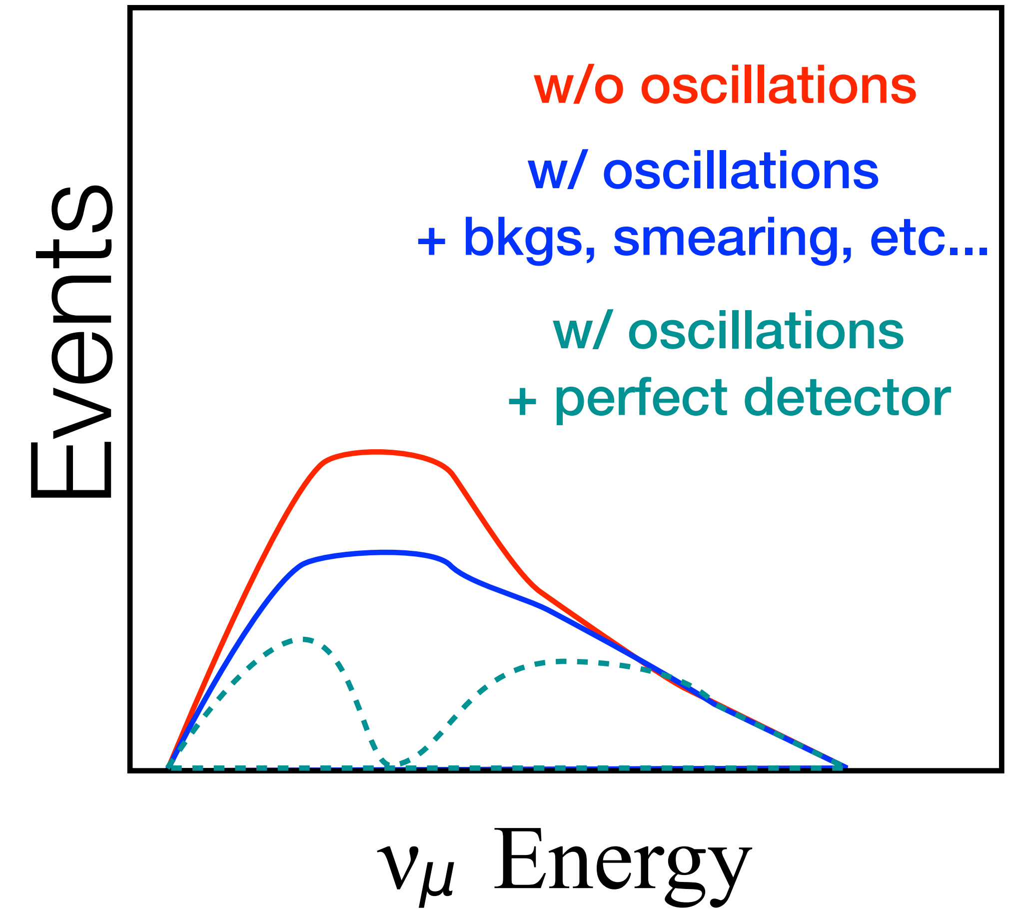
- No matter the detector, atmospheric muons are almost always a background
    - Stochastic processes can confuse event identification algorithms
    - Produce cosmogenic radioactivity which decays long after the muon has departed
    - No detector is 100% sensitive, with enough statistics some muons will 'appear'

Back to Experiments

Generic Oscillations

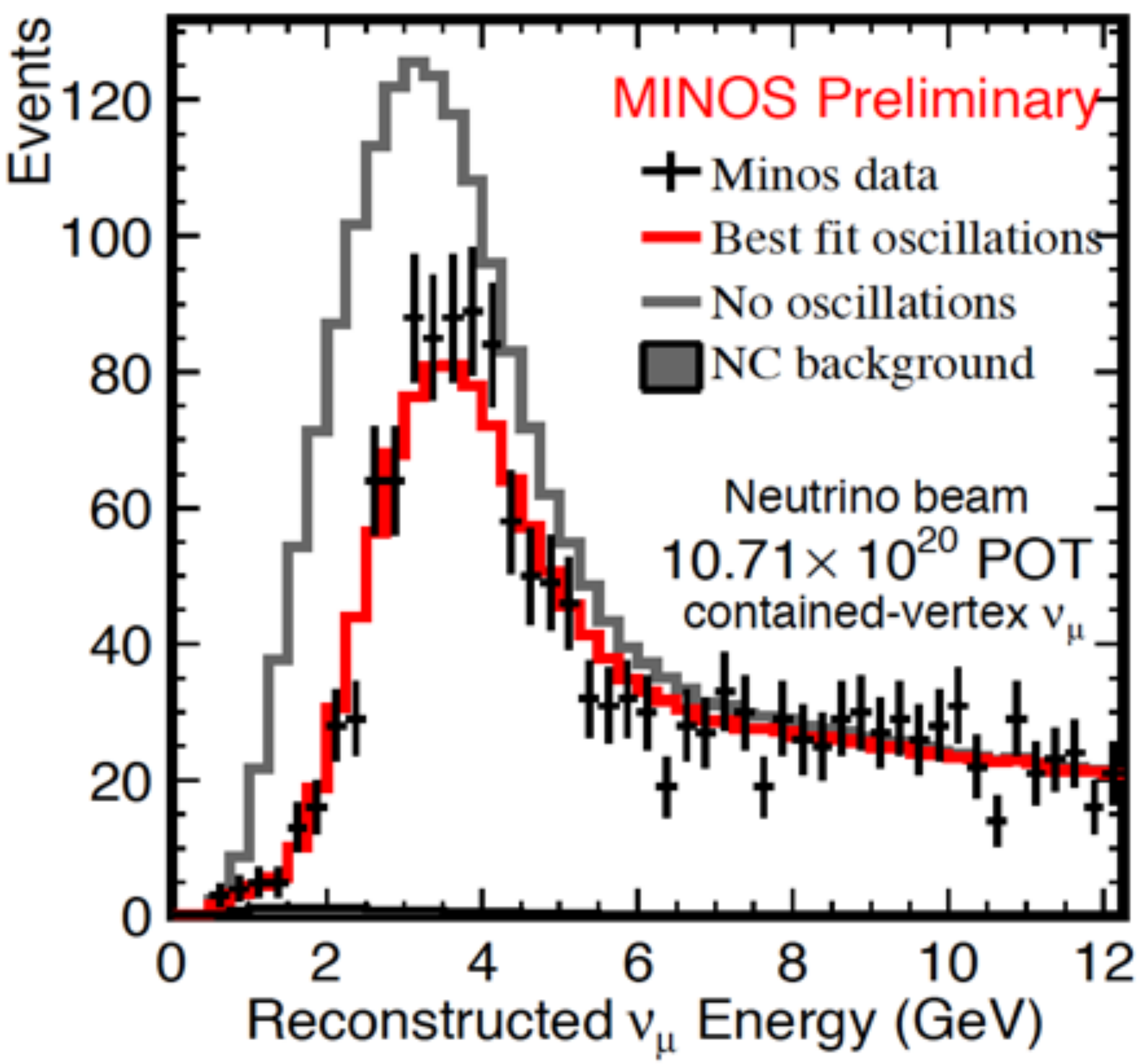
Fixed Baseline L



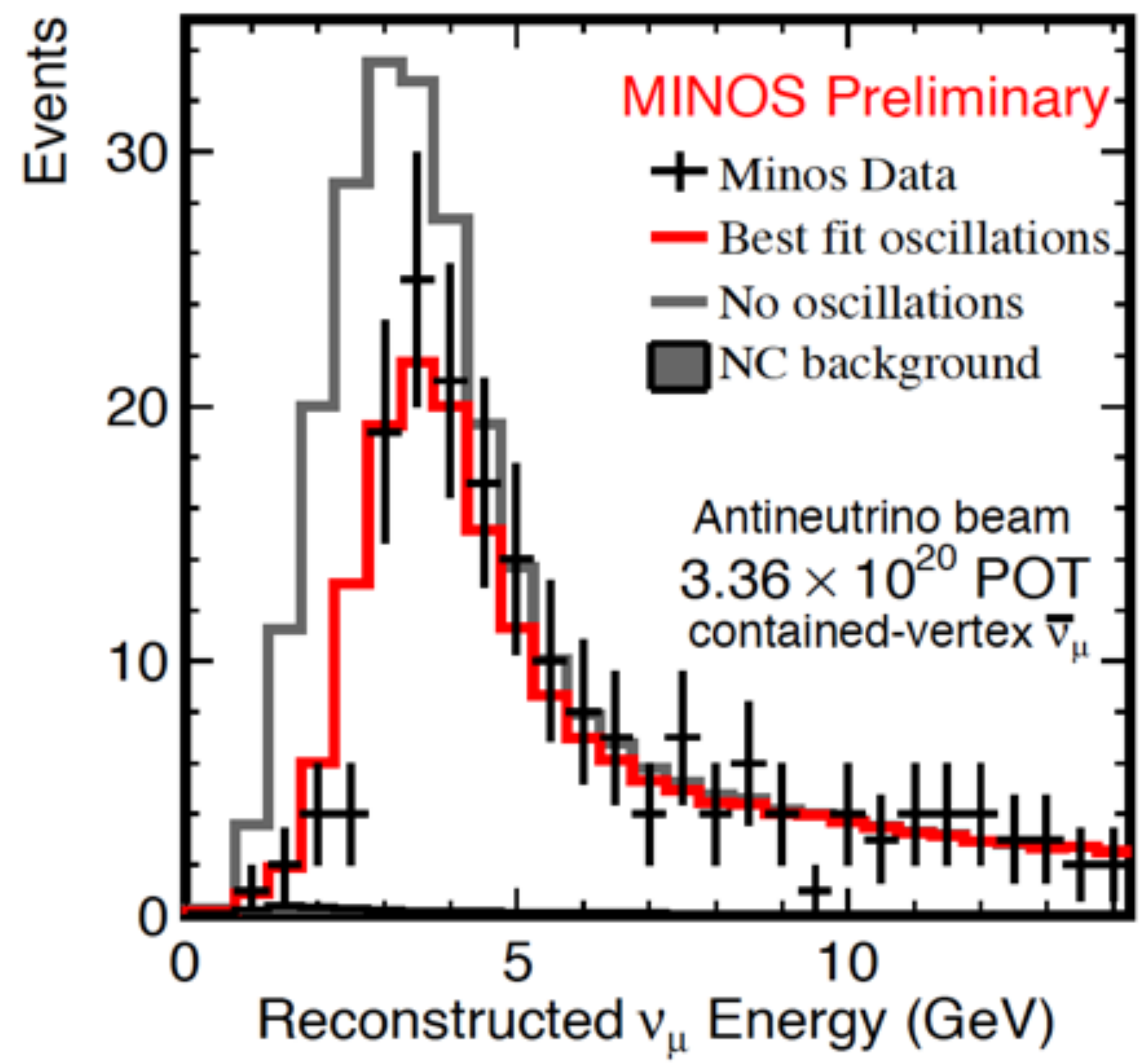


MINOS Far Detector Data

Neutrinos

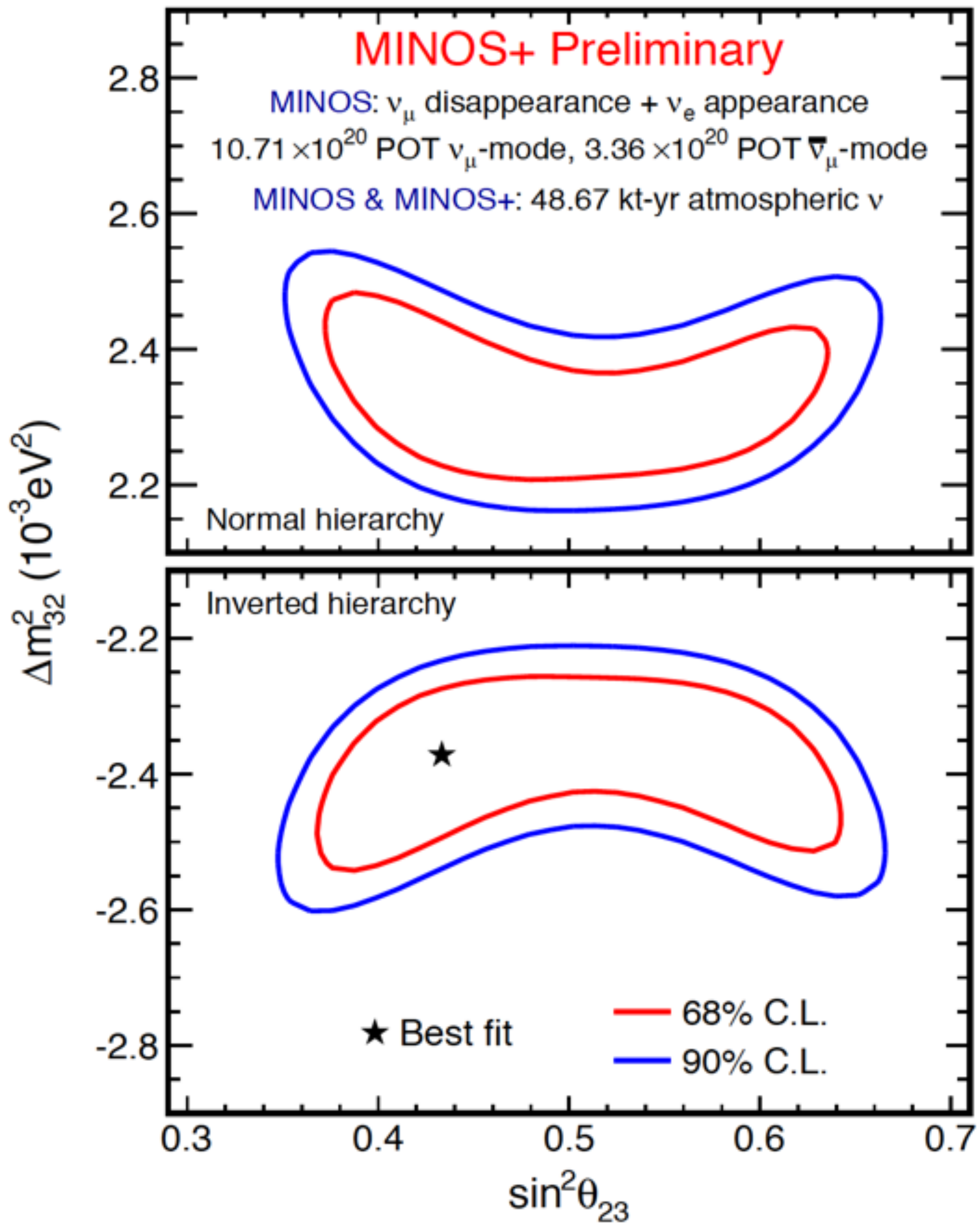


Anti-Neutrinos



*Alex Sousa, *Neutrino 2014*

Oscillation Results



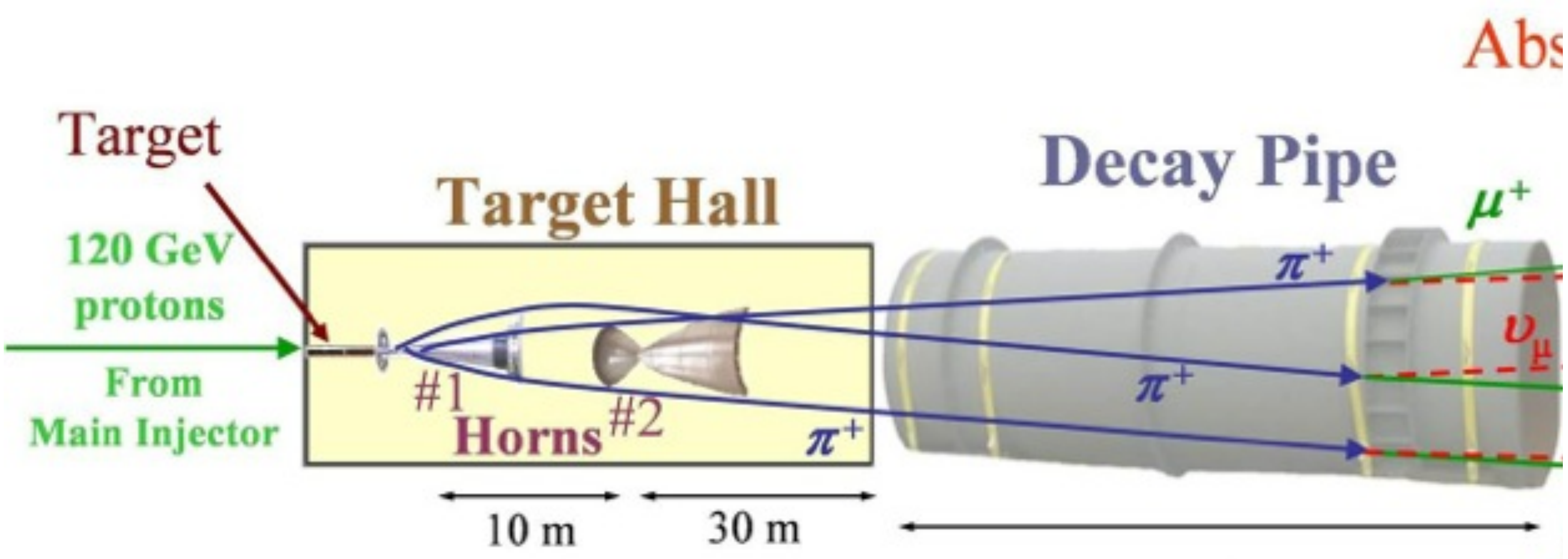
*A. Sousa, *Neutrino 2014*

NOvA

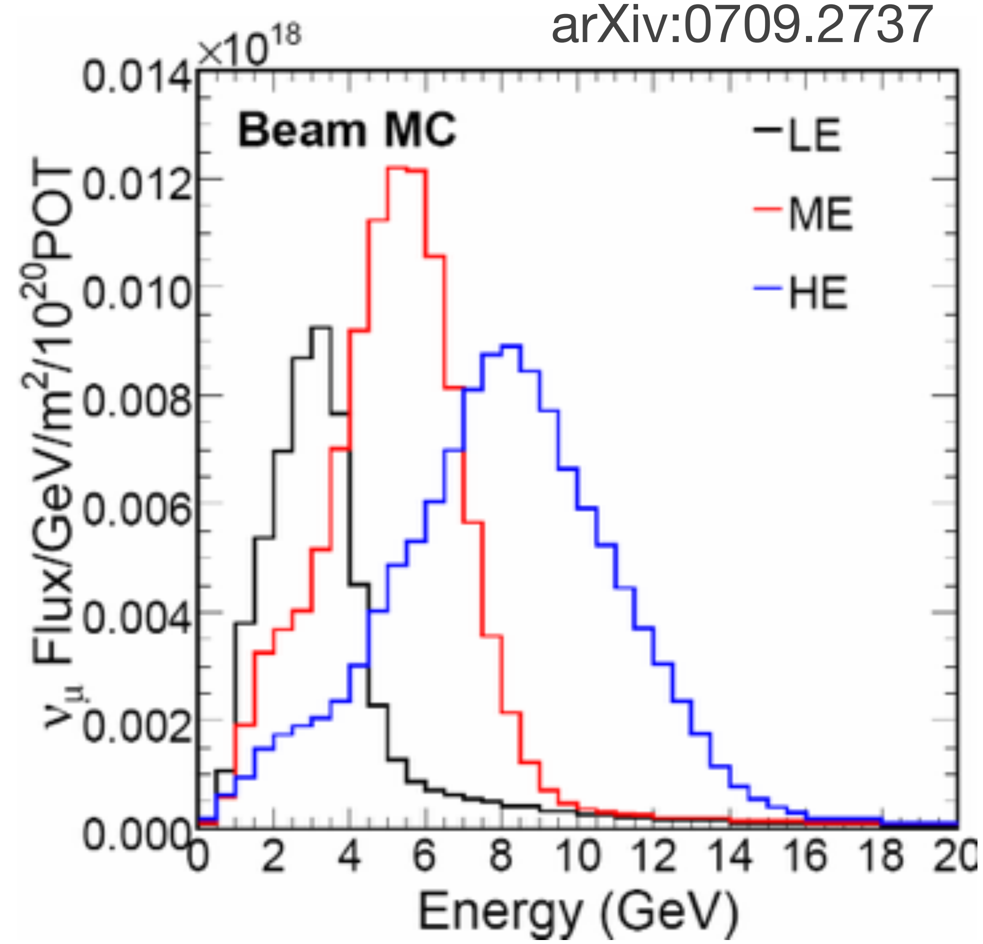
- Off-axis oscillation experiment $\nu_\mu \rightarrow \nu_e$
  - Major physics motivation was measurement of θ_{13}
  - But, has other physics potential
    - Neutrino Mass Hierarchy
    - 3-flavor neutrino mixing
    - Charge-Parity Violation in neutrinos
- NuMI upgraded from 400 kW to 700 kW
- Far Detector is NOT in a mine
  - Uses beam timing, direction, and a big detector

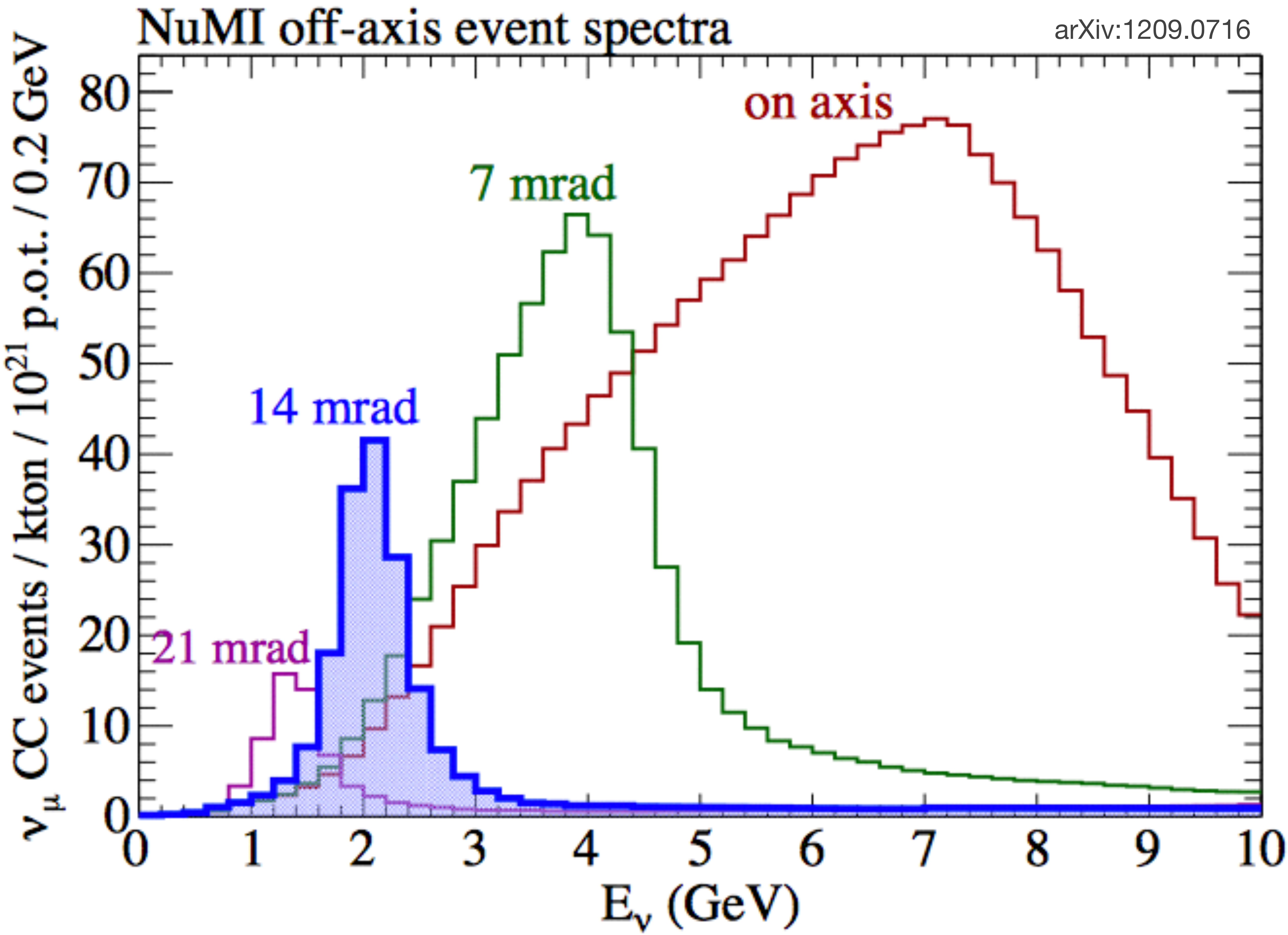
Why Off-Axis?

- On-axis conventional neutrino beams are wide-band, i.e. ‘wide’ distribution in energy producing background neutrinos at unwanted energies
- Intrinsic ν_e contamination in ν_μ beam that is much higher for on-axis directions

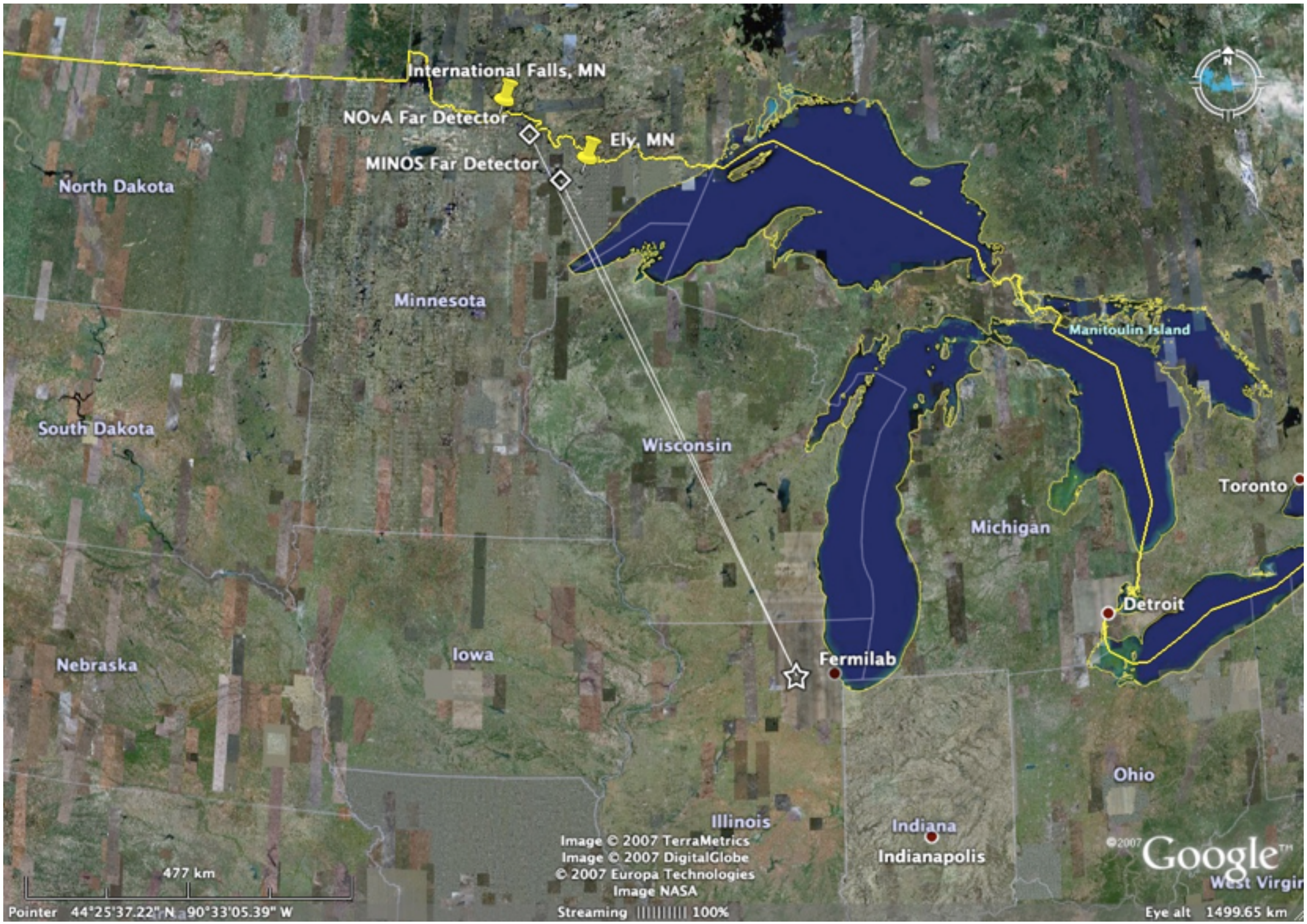


arXiv:0709.2737



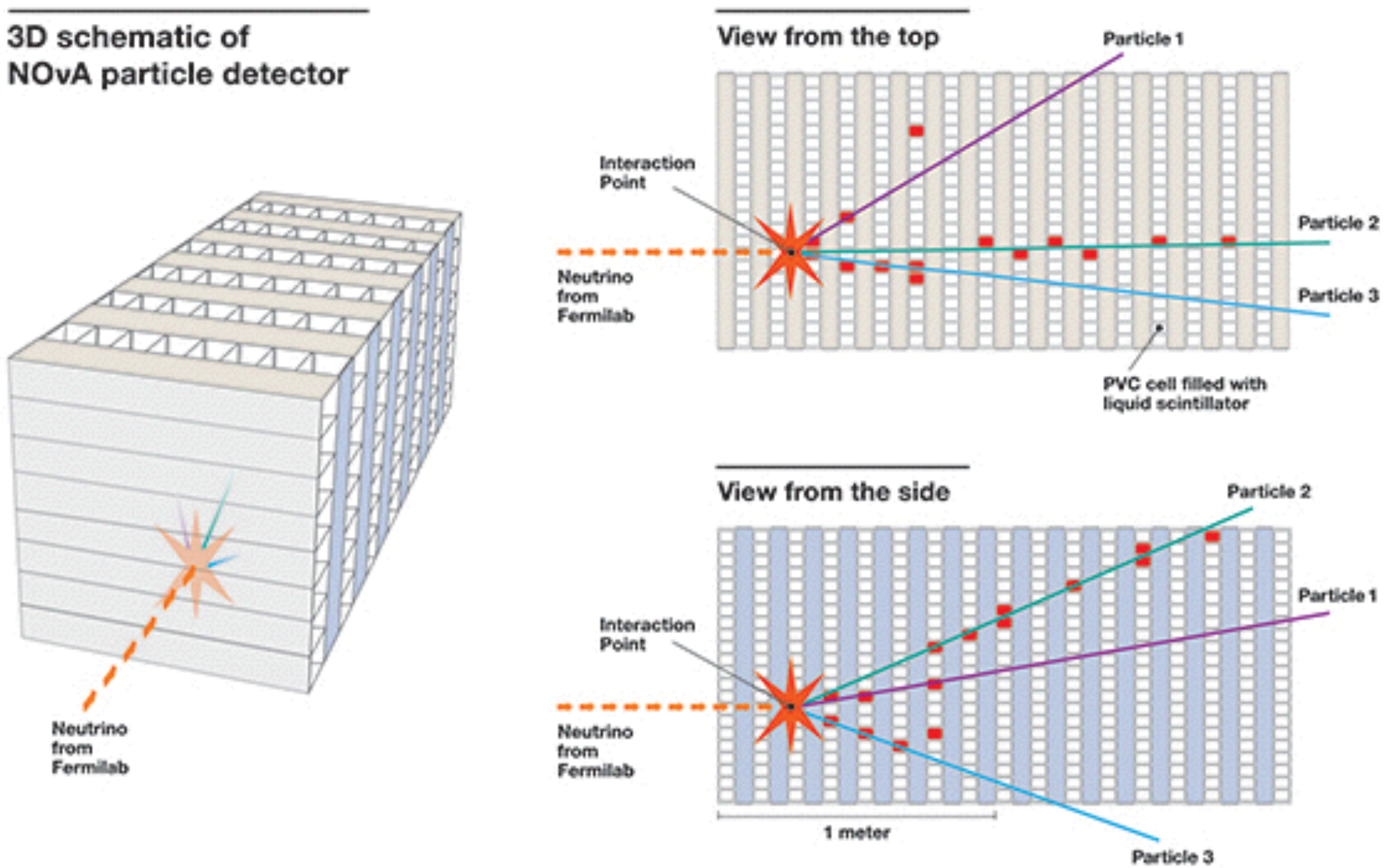

NuMI off-axis event spectra
arXiv:1209.0716
on axis
7 mrad
14 mrad
21 mrad
ν_μ CC events / kton / 10^{21} p.o.t. / 0.2 GeV
0
10
20
30
40
50
60
70
80
0
1
2
3
4
5
6
7
8
9
10
E_ν (GeV)

Off-Axis Baseline



NOvA Detector

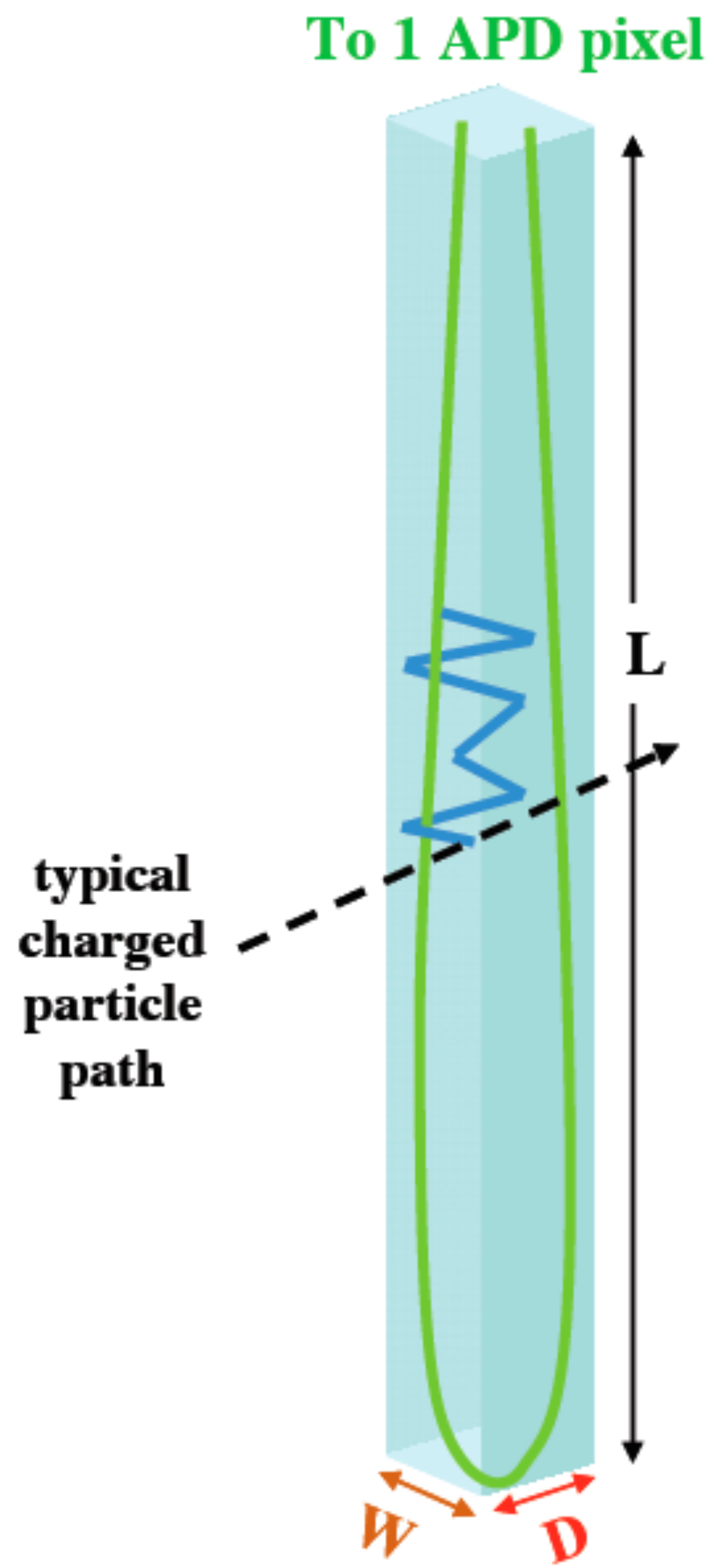
- Uses scintillator to detect (anti)ν_e events
- 14 kiloton volume using a totally active design
- Long (15.7m) plastic cells filled with mineral oil



http://www.fnal.gov/pub/presspass/press_releases/2014/NOvA-20140211-images.html

NOvA Detector Cell

- Wavelength shifting fiber is looped through each cell and readout on an avalanche photodiode (APD)
- Scintillator density is fairly low
  - Bad: Low mass for neutrino interactions
  - Good: Secondary particles travel longer and are easier to identify



NOvA Events

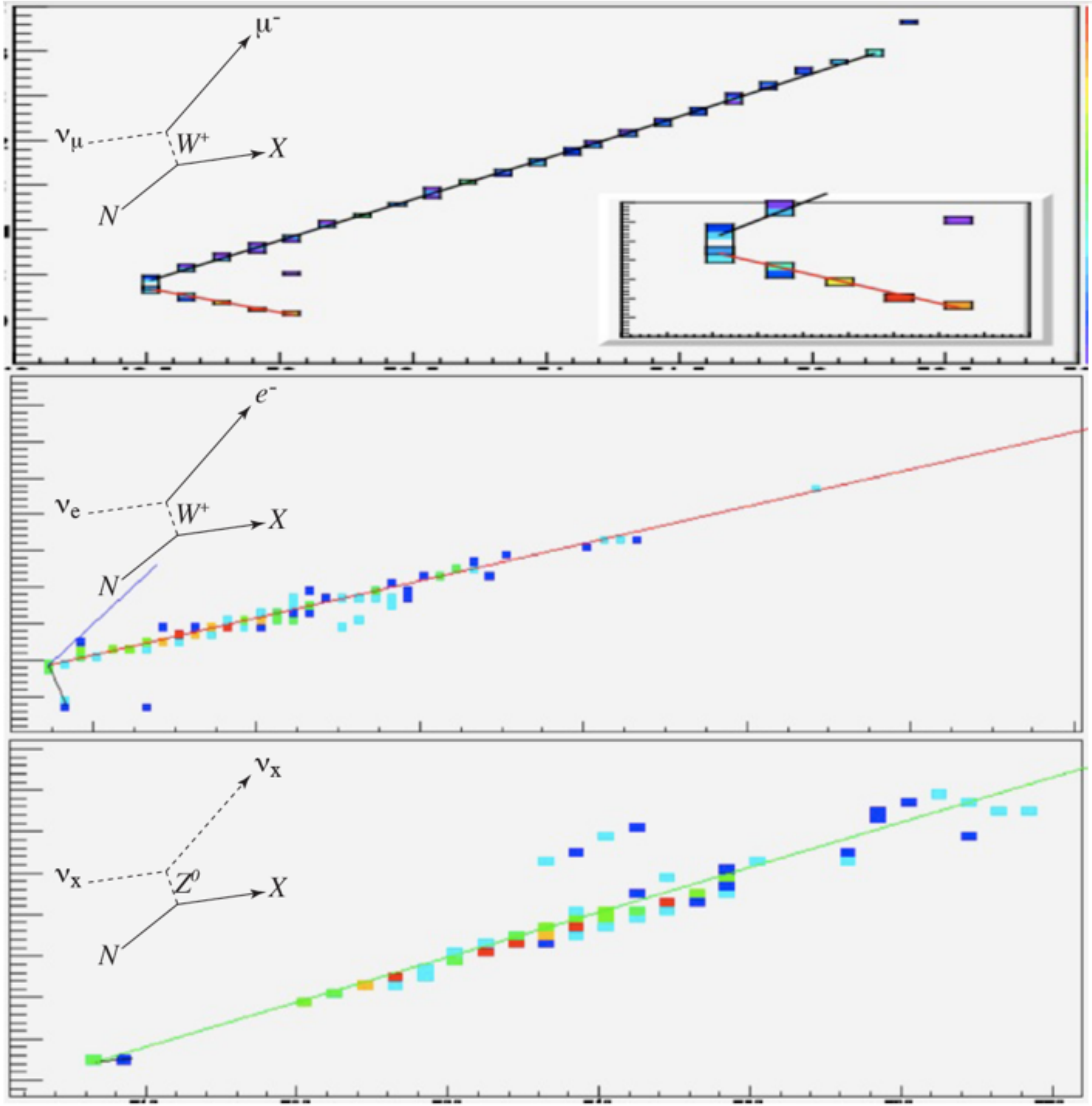


Photo-multiplier Tubes

Photo-multiplier Tubes

- Workhouse of particle and neutrino physics

Photo-multiplier Tubes

- Workhouse of particle and neutrino physics
- Reverse light bulbs - convert light into electricity

Photo-multiplier Tubes

- Workhouse of particle and neutrino physics
- Reverse light bulbs - convert light into electricity
- Around since 1930s

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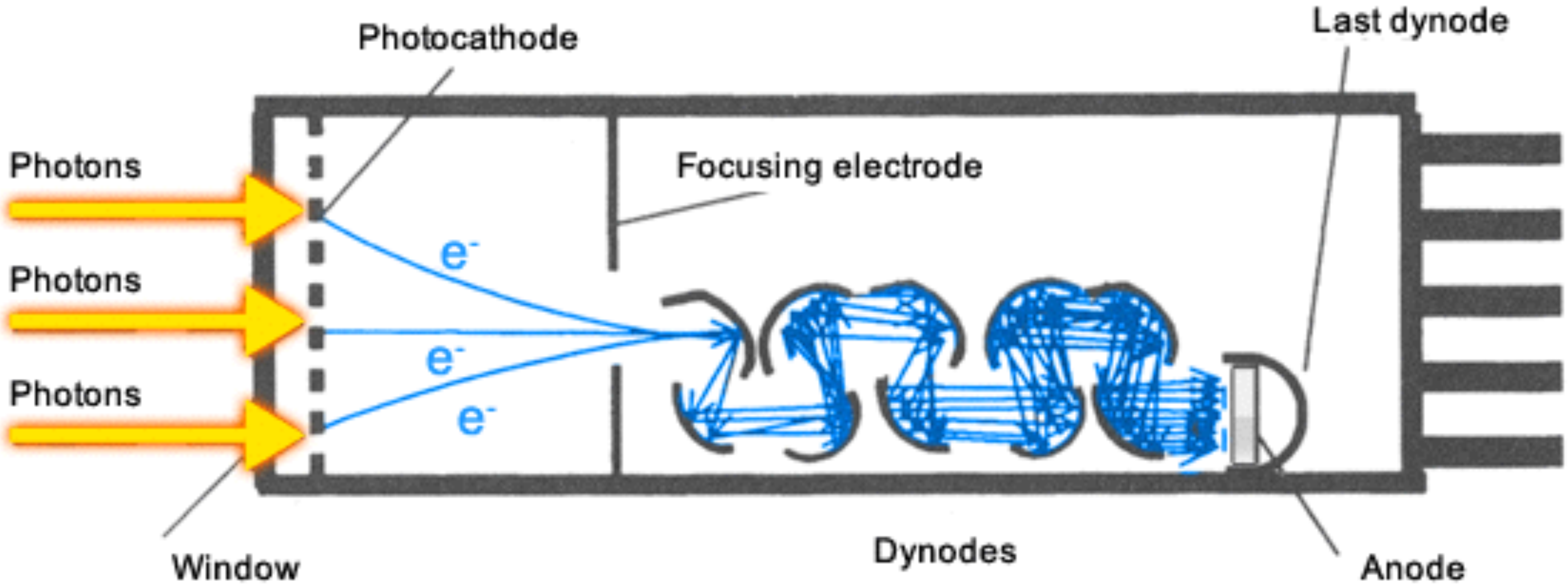
- Reverse light bulbs - convert light into electricity
- Around since 1930s
- Modern PMTs have >20% probability (Quantum Efficiency) of single photon detection

PMT Operation

- Photon strikes photo-cathode, which emits an electron
- Electron is accelerated onto a chain of dynode which create an increased cascade of subsequent electrons



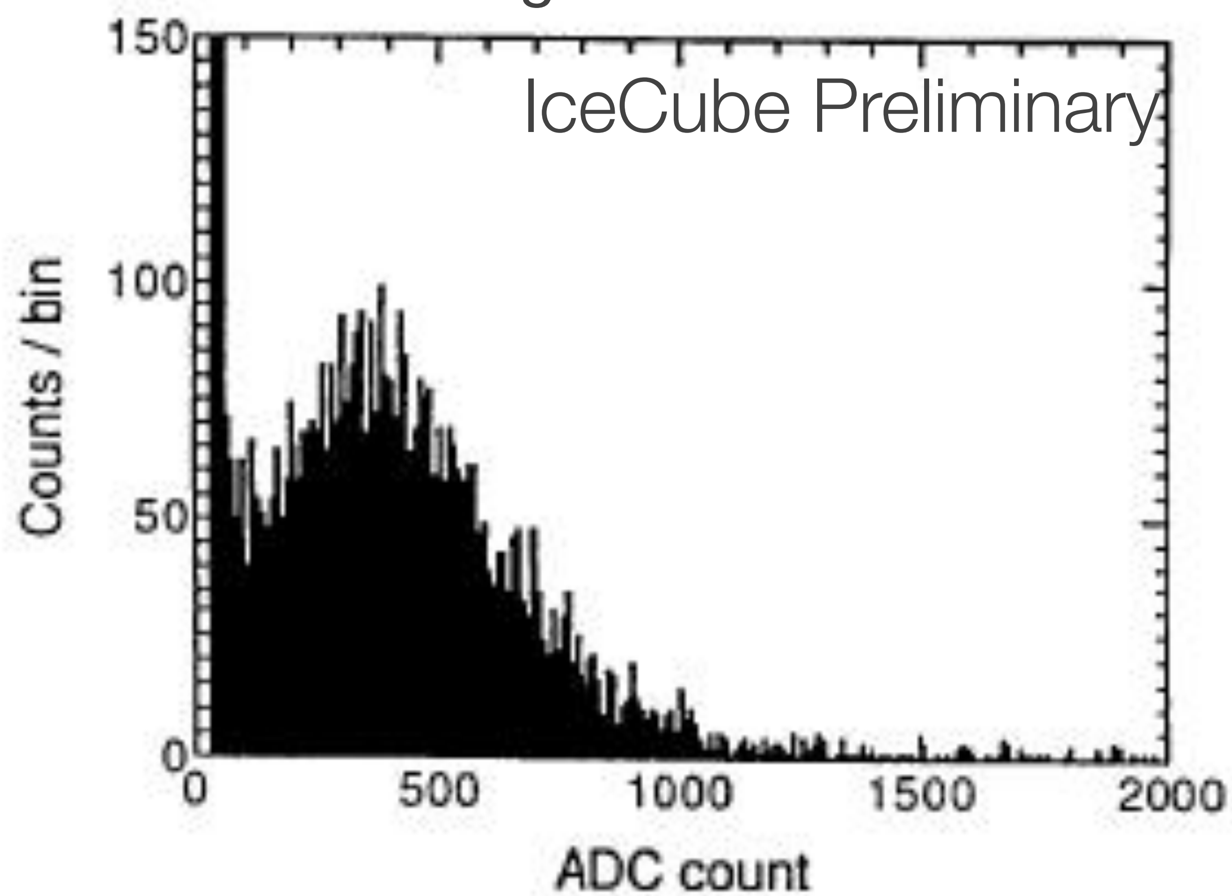
Photomultiplier tubes (PMTs)

*Australian Microscopy & Microanalysis Research Facility

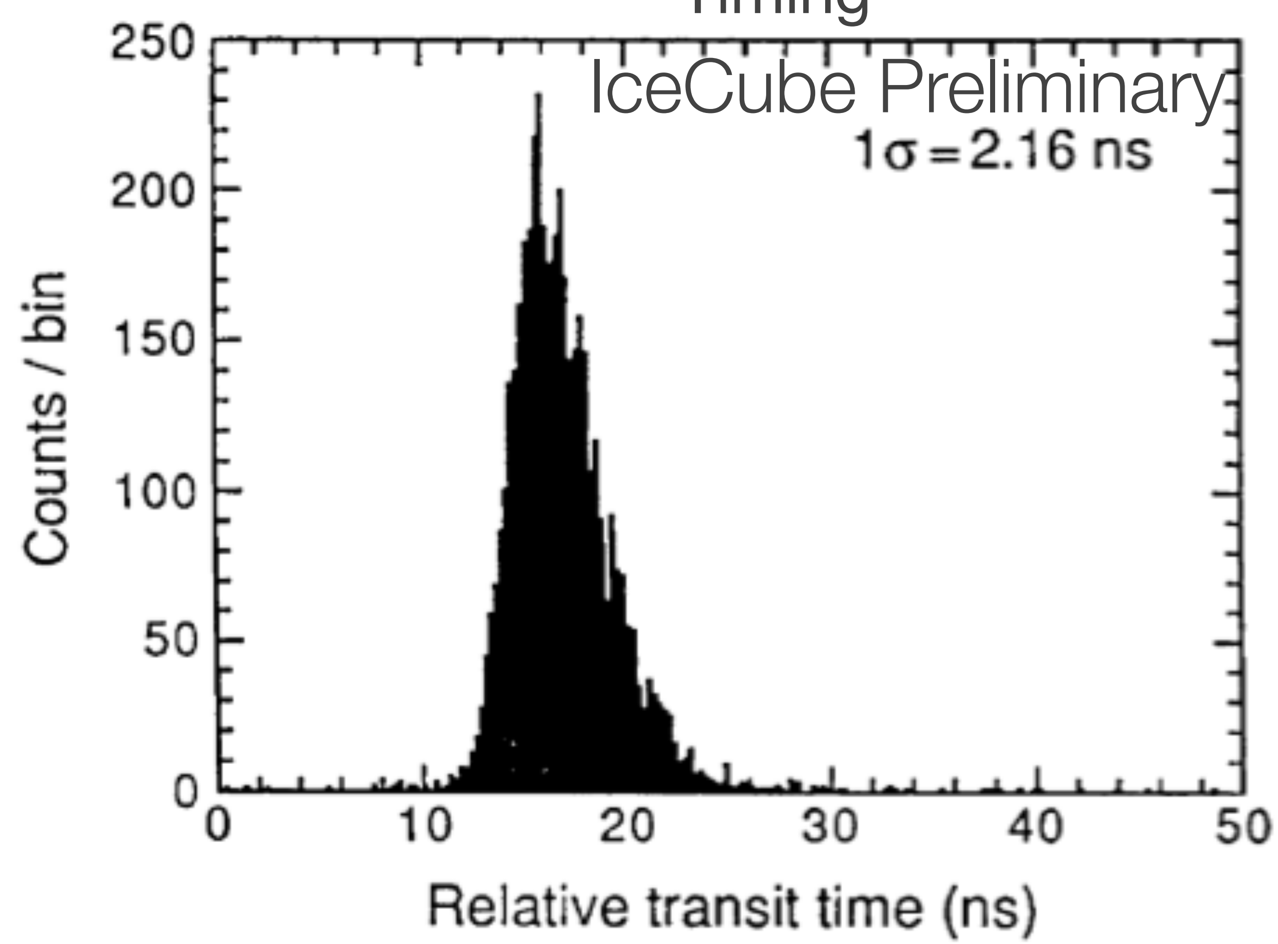
PMT

- Amplification gains are ~10^6-10^7
- Timing is on the order of nanoseconds

Single PE
Charge Distribution



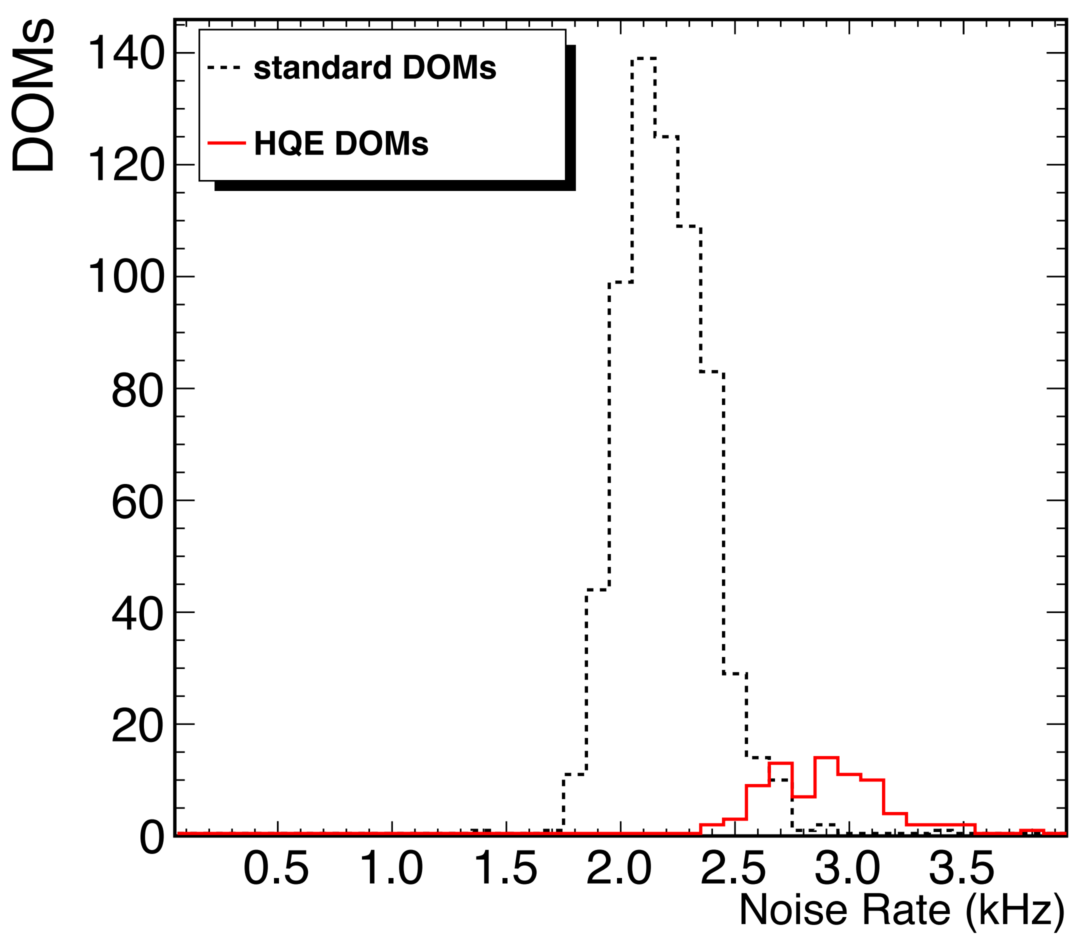
Single PE
Timing

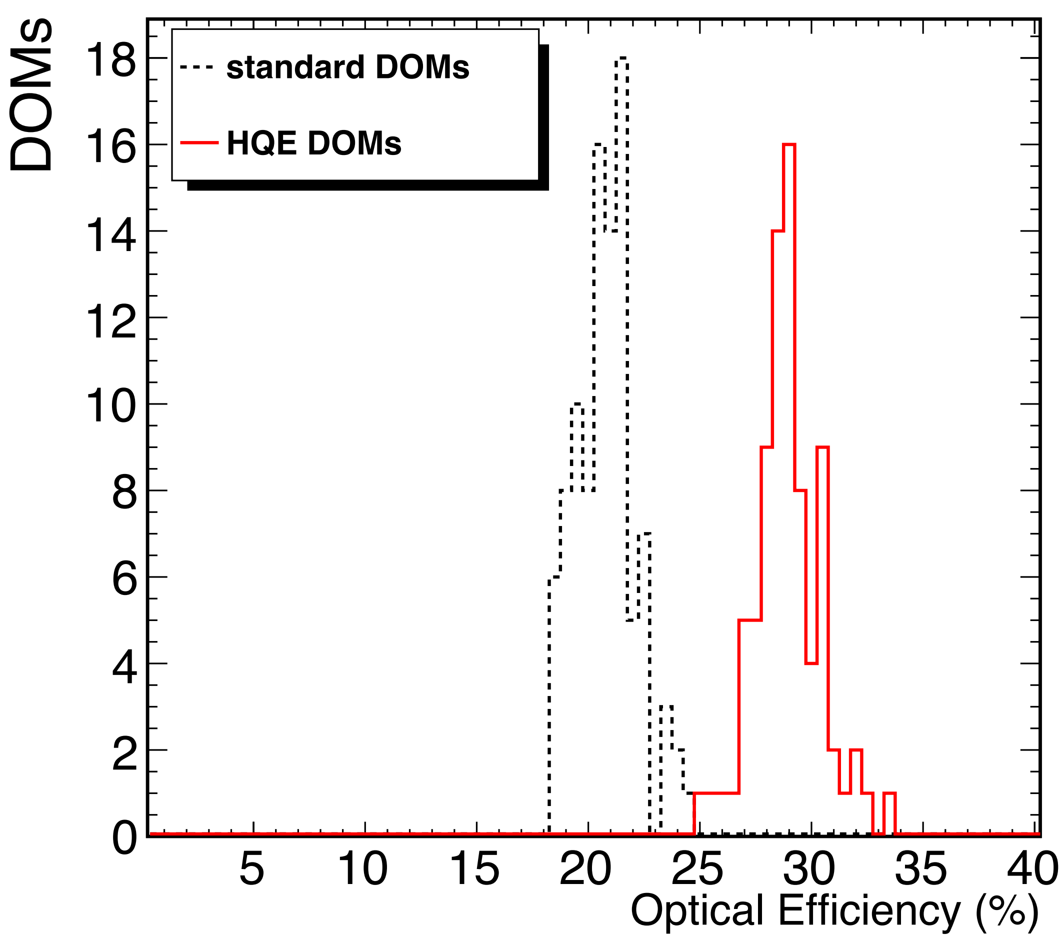


PMT Fluctuation

- There is non-trivial fluctuation from PMT to PMT
  - Charge
  - Quantum efficiency
  - Noise rate

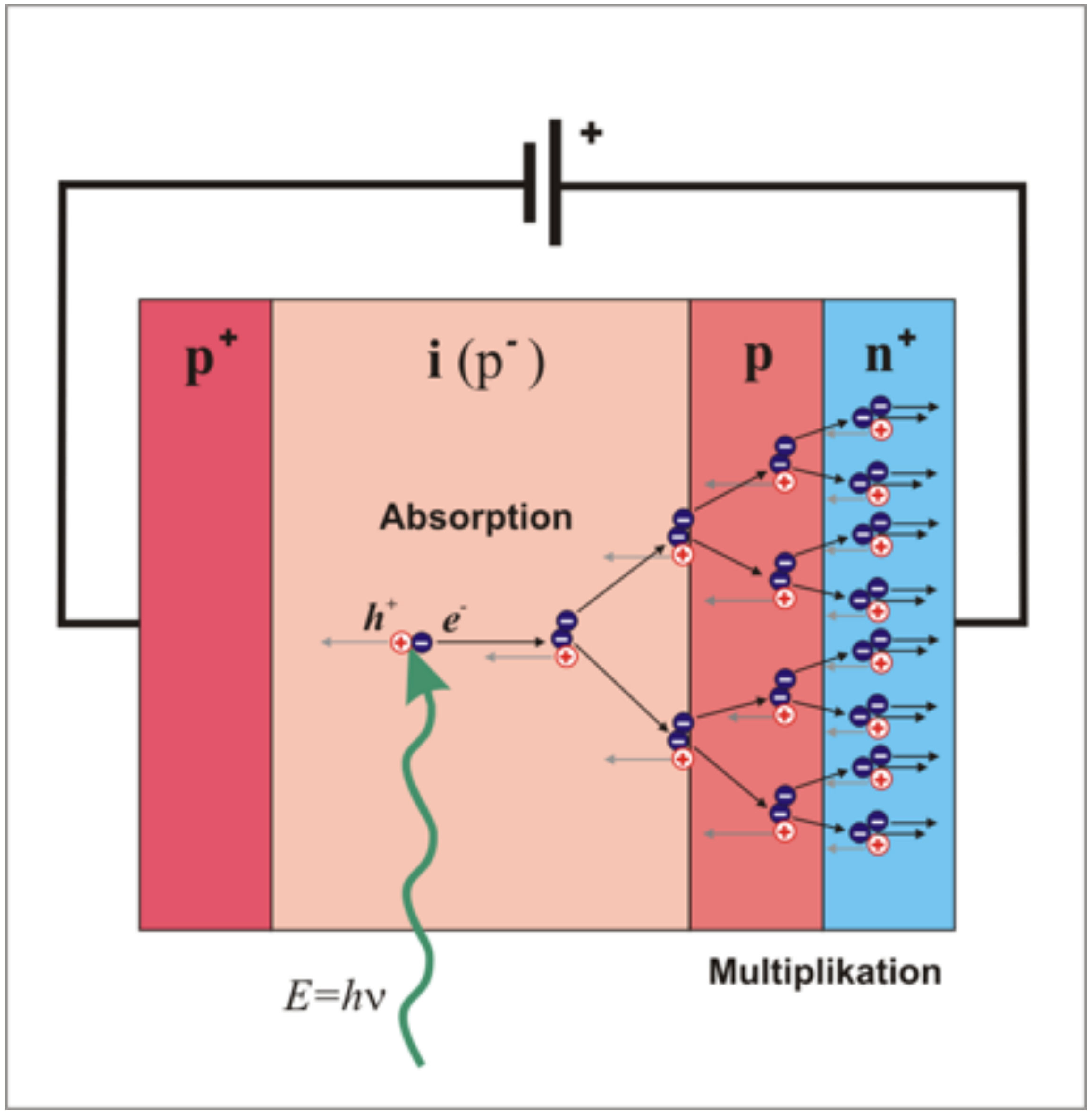
arXiv:1109.6096

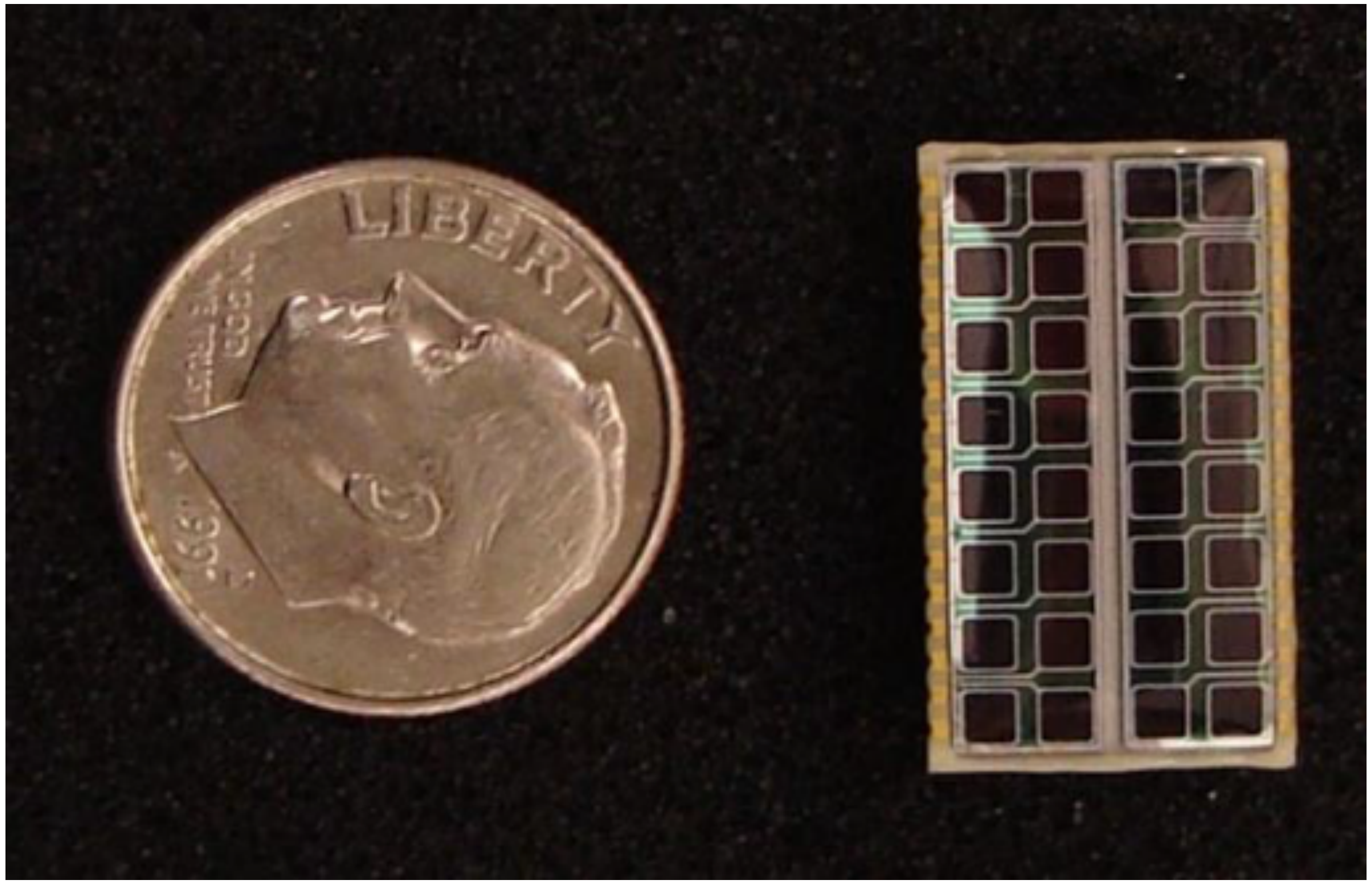




Avalanche Photo-Diode

- Solid State equivalent to PMT

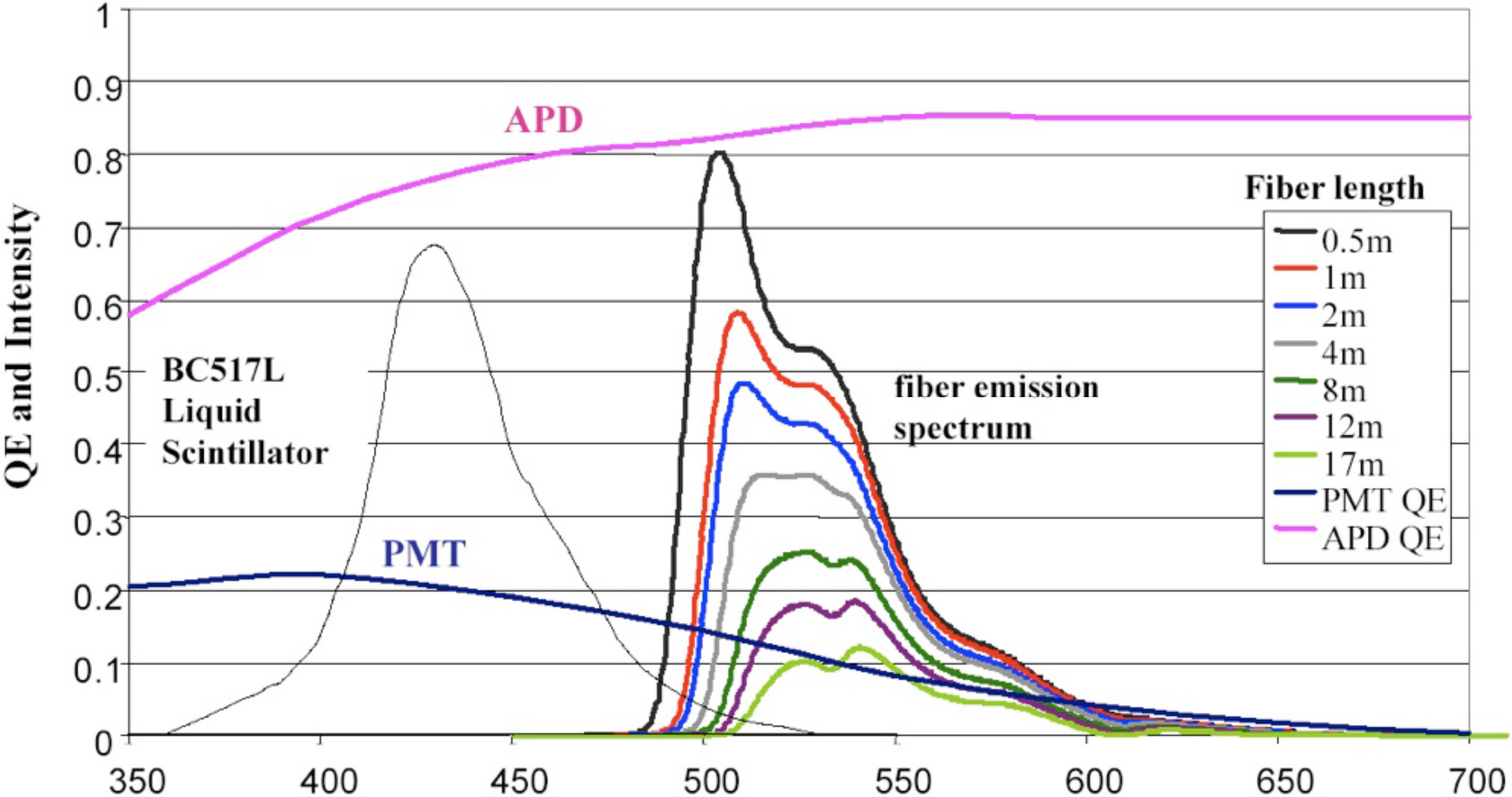




NoVA APD

NOvA APD vs. PMT

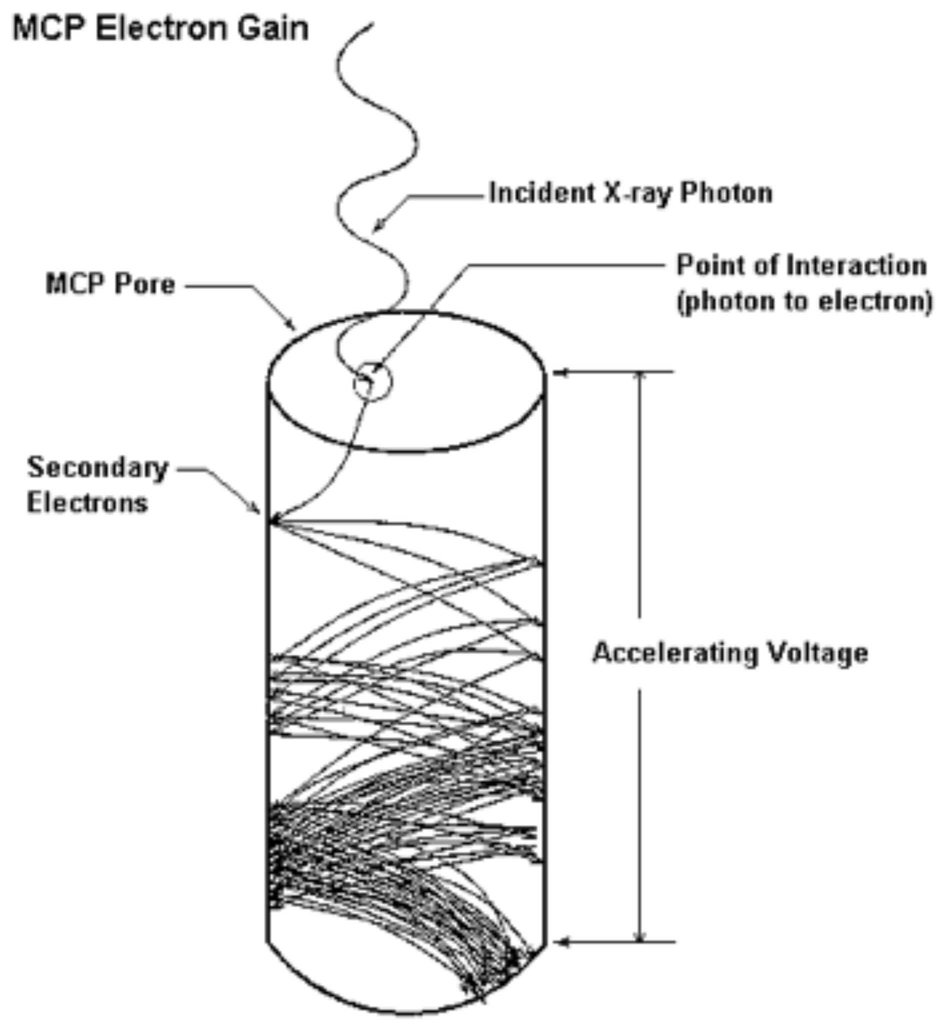
*NOvA Technical Design Report



wavelength

Other Options

- Micro-Channel Plates (MCP)
  - Thousands of mm capillaries that amplify signal
  - Potential for 10-100 picosecond timing
  - Challenges are R&D and manufacturing



- Hybrid PMTs
  - Use APD instead of dynode for PMT
  - Use MPC for electron collection

*M. Sanchez, Aspen Winter Workshop 2013

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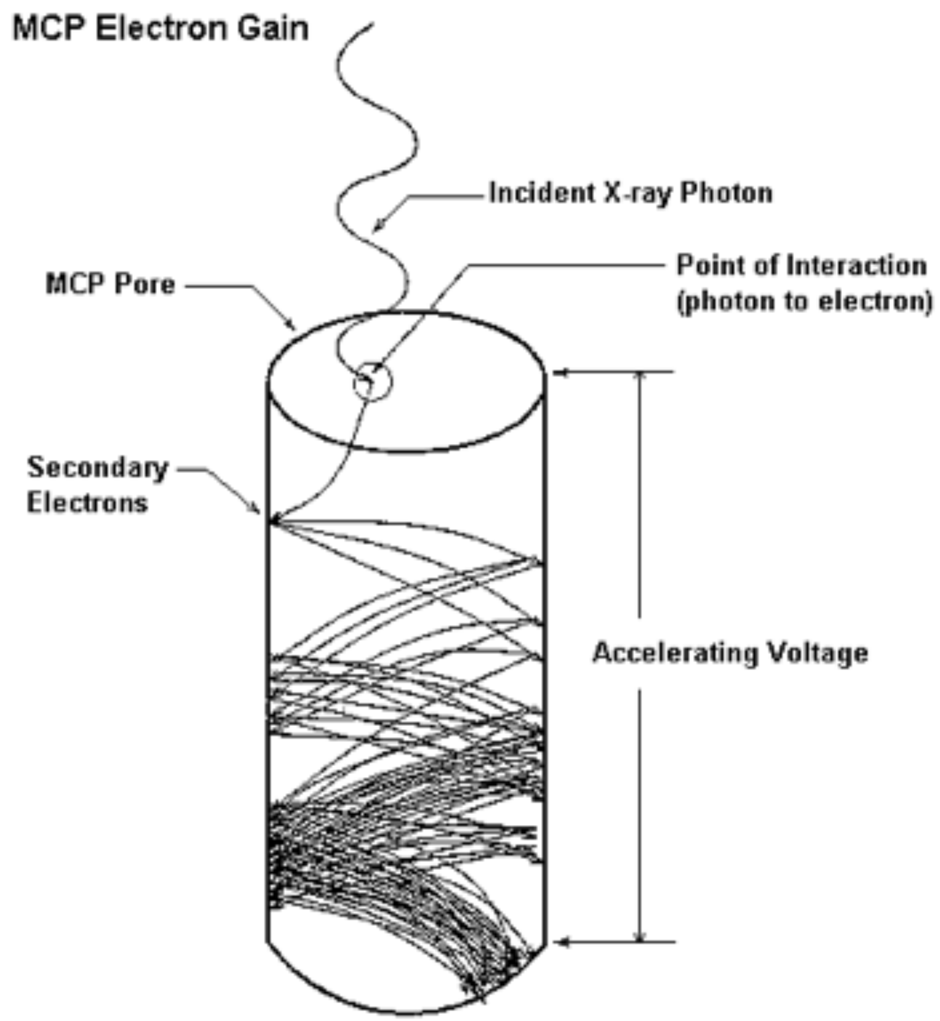
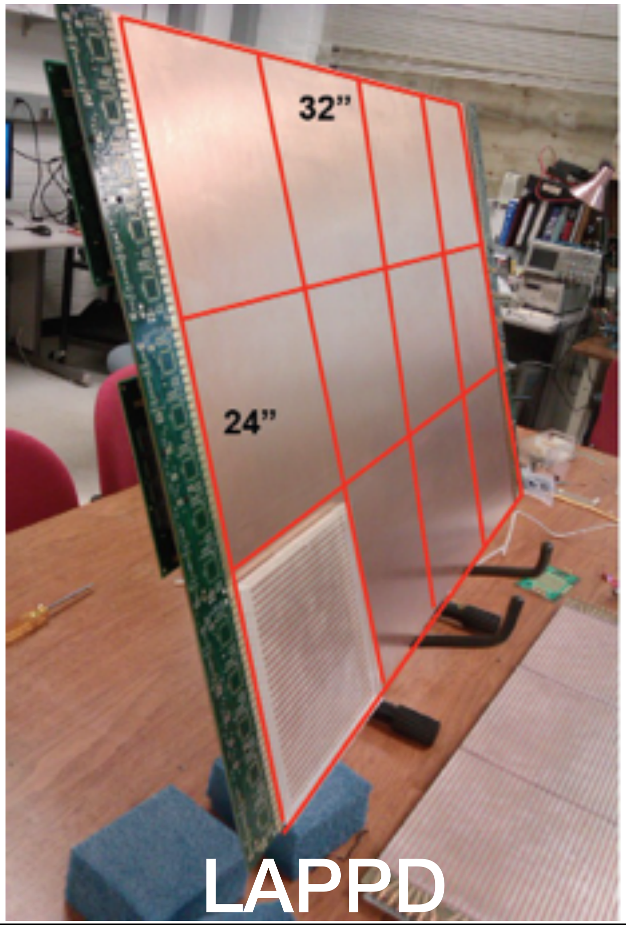
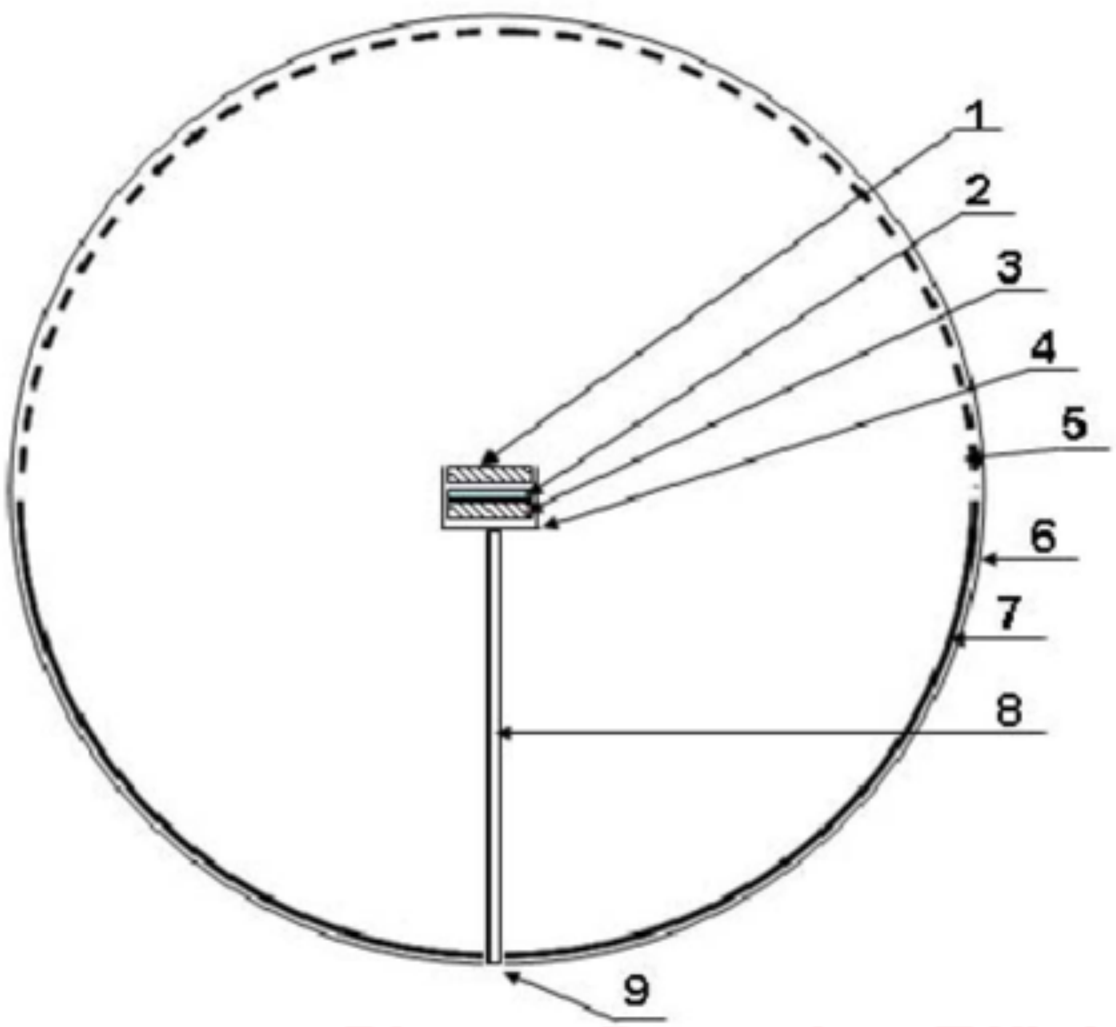




*M. Sanchez, Aspen Winter Workshop 2013

New MCP-PMT Hybrid

1) Using two sets of Microchannel plates (MCPs) to replace the dynode chain
2) Using transmission photocathode (front hemisphere) and reflective photocathode (back hemisphere) } ~ 4π viewing angle!!



1. up MCP
2. anode
3. down MCP
4. insulated trestle table
5. transmission photocathode → 20% * 60% = 12%
6. glass shell
7. reflection photocathode → 70% * 40% * 60% = 17%
8. bracket of the cables
9. glass joint

QE { Transmission cathode: 20%, Reflection cathode: 40% }

➢MCP CE: 60%

PDE

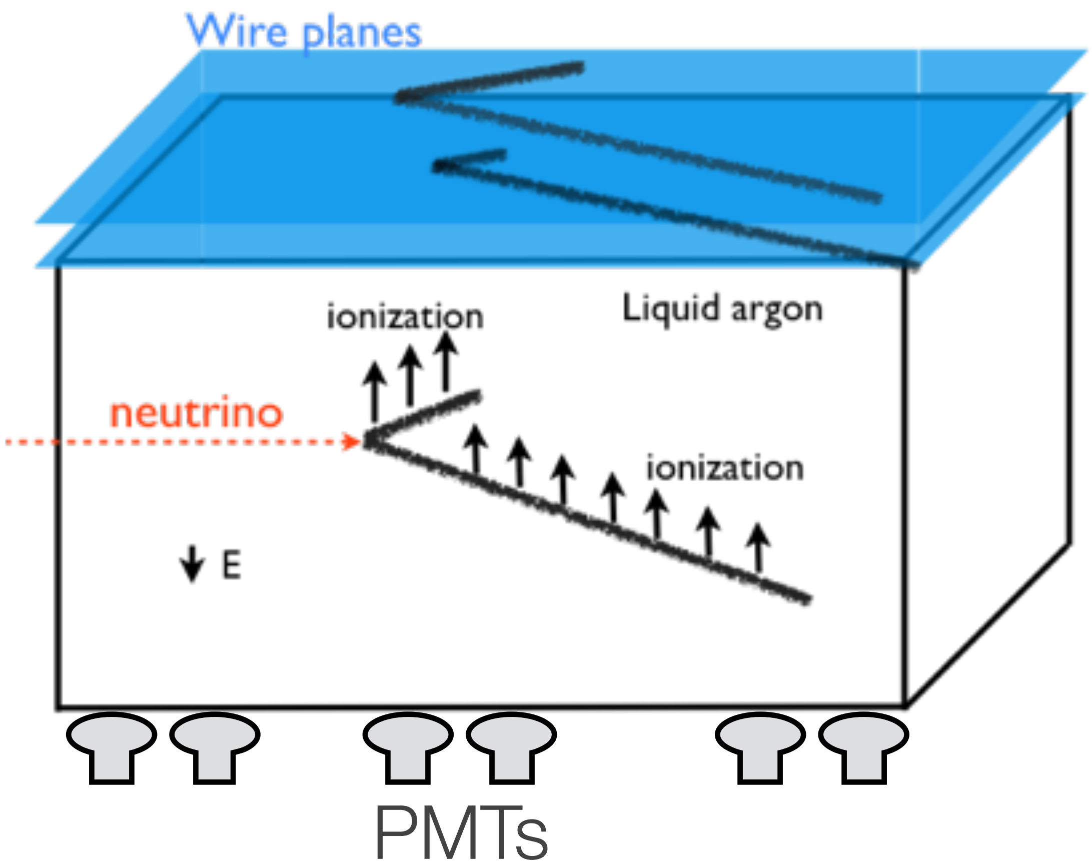
➢Total Photon Detection Efficiency: ~30%

*Sen. Quan, New Developments in Photodection 2011

Photon Collectors Comparison

- PhotoMultiplier Tube (PMT)
  - Known, sturdy, and trusted
  - Excellent timing
  - Expensive
- Avalanche Photo-Diode (APD)
  - 'Cheap' and small
  - High quantum efficiency
  - High noise rate, requires cooling
- In development
  - Micro-channel plates
  - Hybrid PMT style photo-cathode with APD or MCP collector

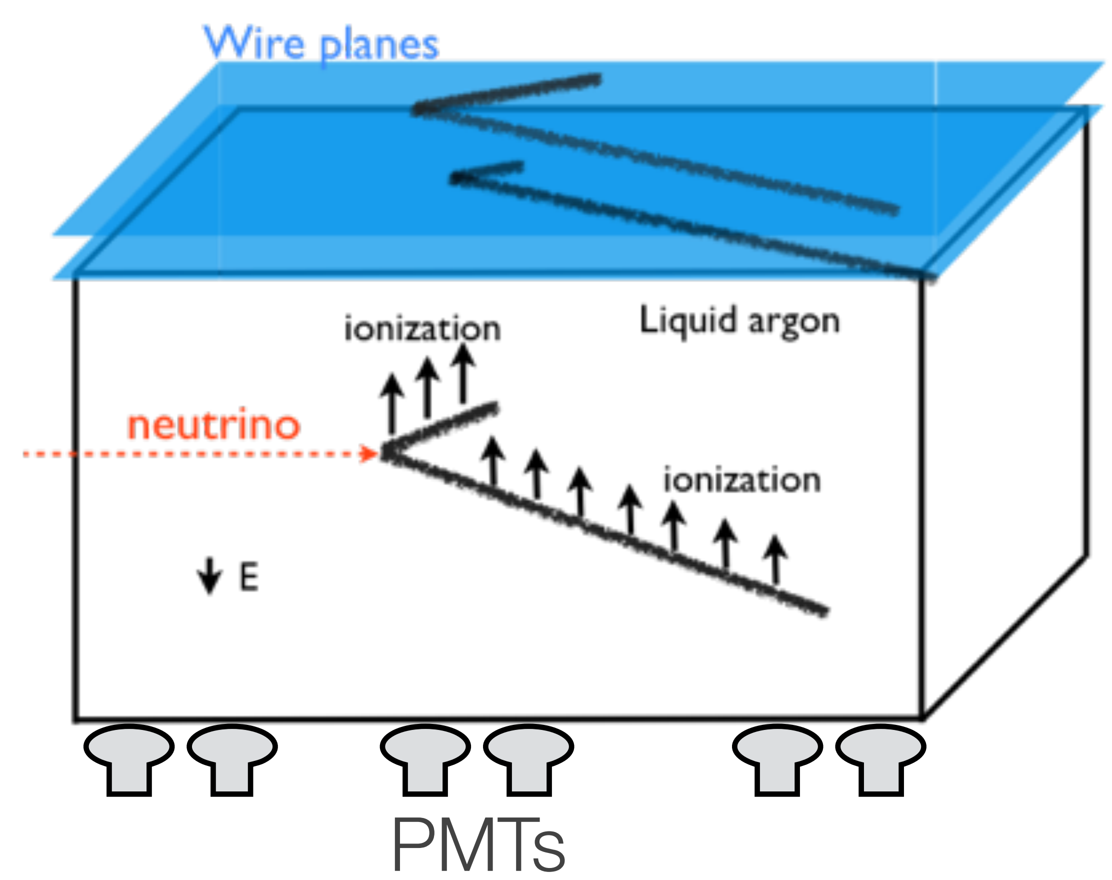
ICARUS



Wire planes
ionization
Liquid argon
neutrino
ionization
E
PMTs

ICARUS

- Liquid Argon (LAr) Time Projection Chamber (TPC)
  - Liquid Argon produces scintillation light
  - Interactions produce ionization (electrons) that 'drift' in a magnetic field
  - Concept is the same for other noble gases too, notably Xenon



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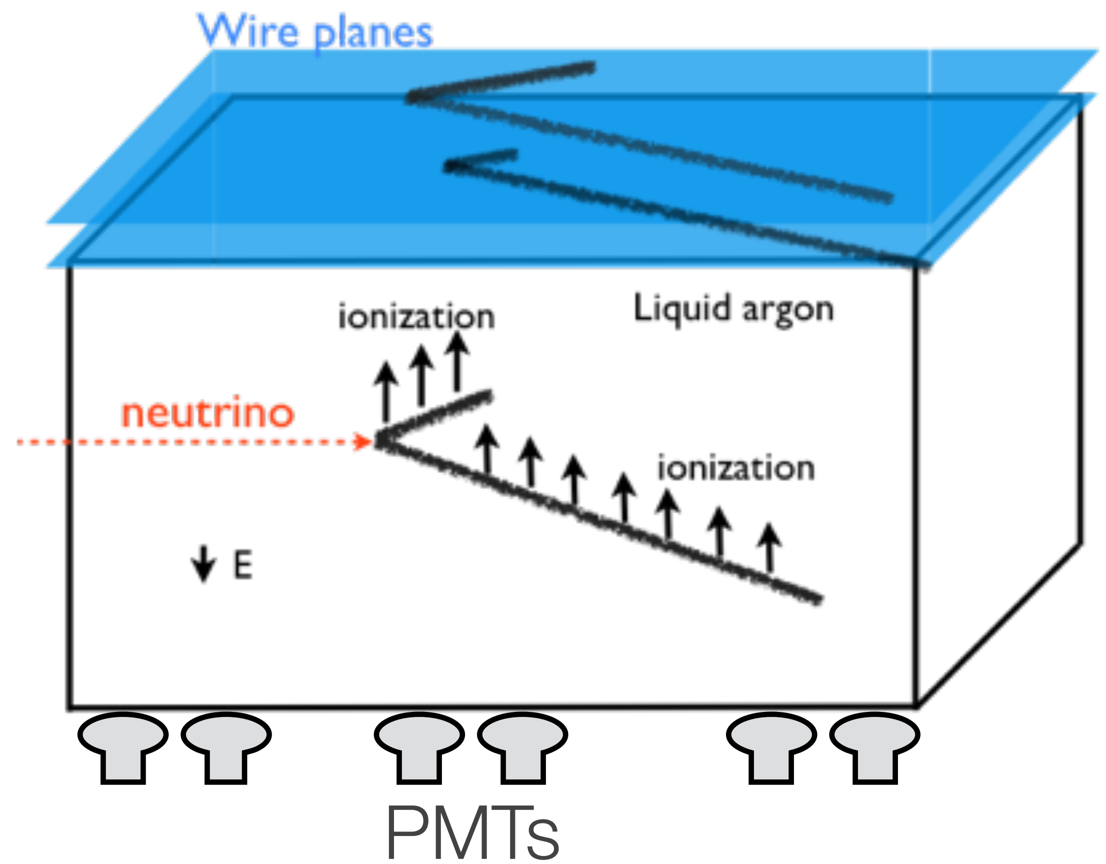

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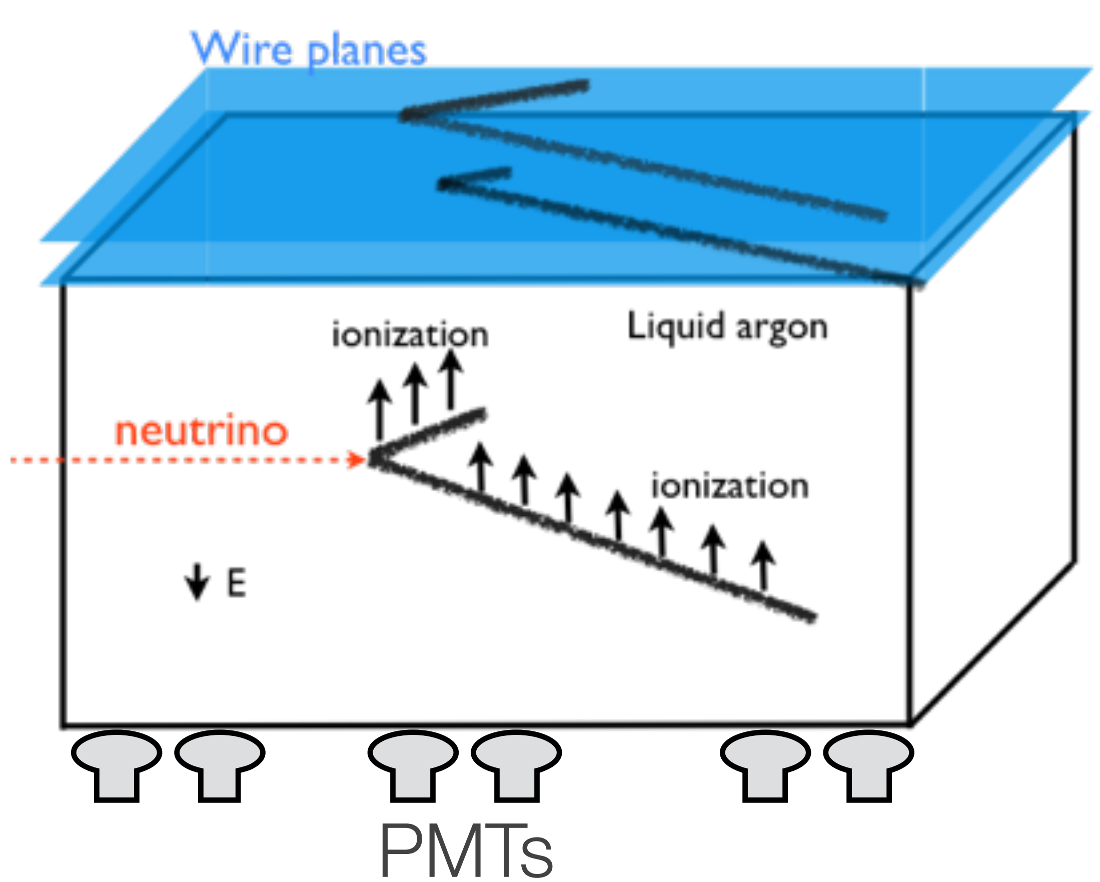
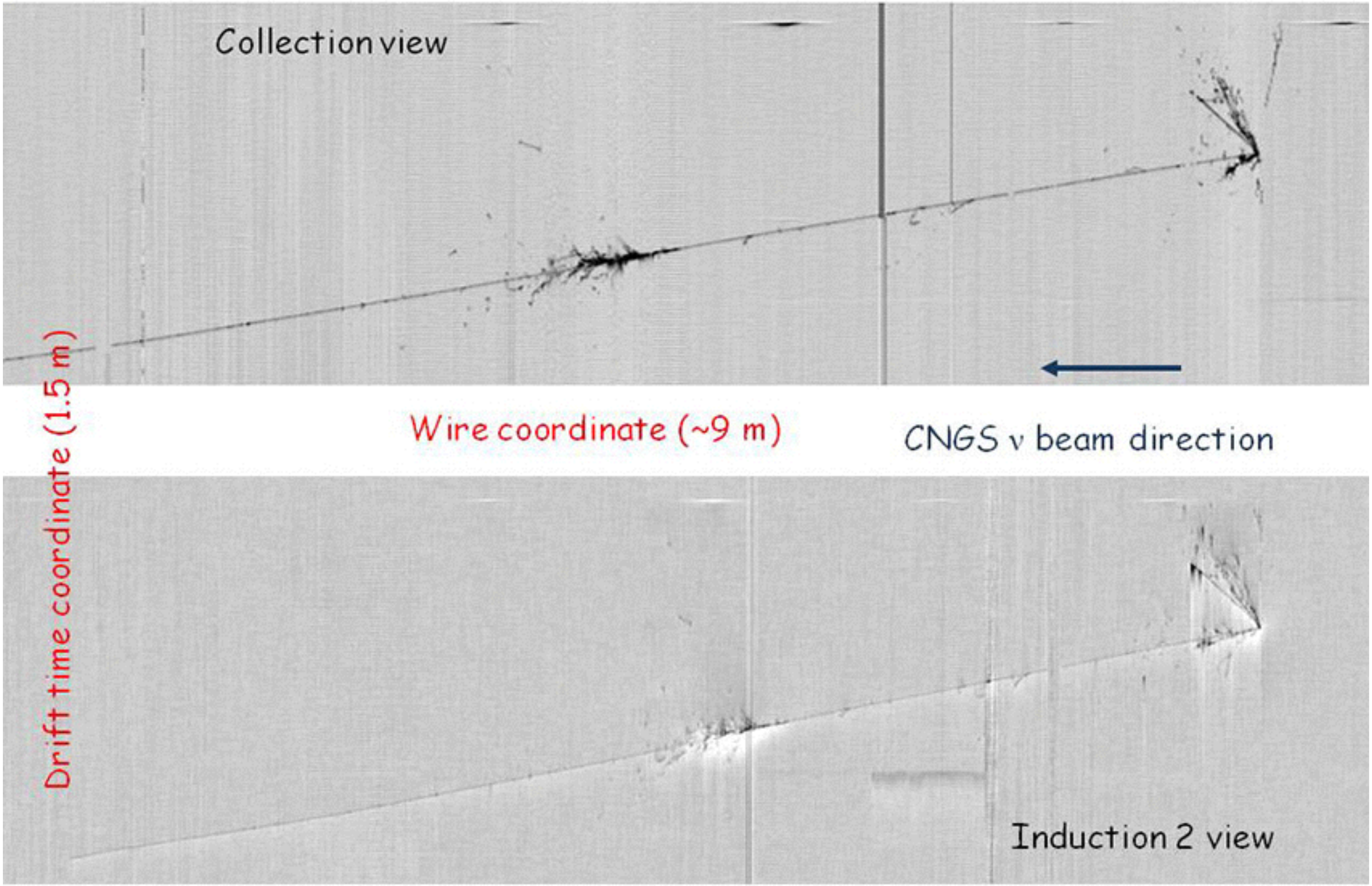
- PMTs trigger the detector to read out the data
- Induction/collection wires at mm spacing collect ionization charge
  - Identify and track individual particles



ICARUS Event

http://icarus.lngs.infn.it/photos/NeutrinoEventsGallery/



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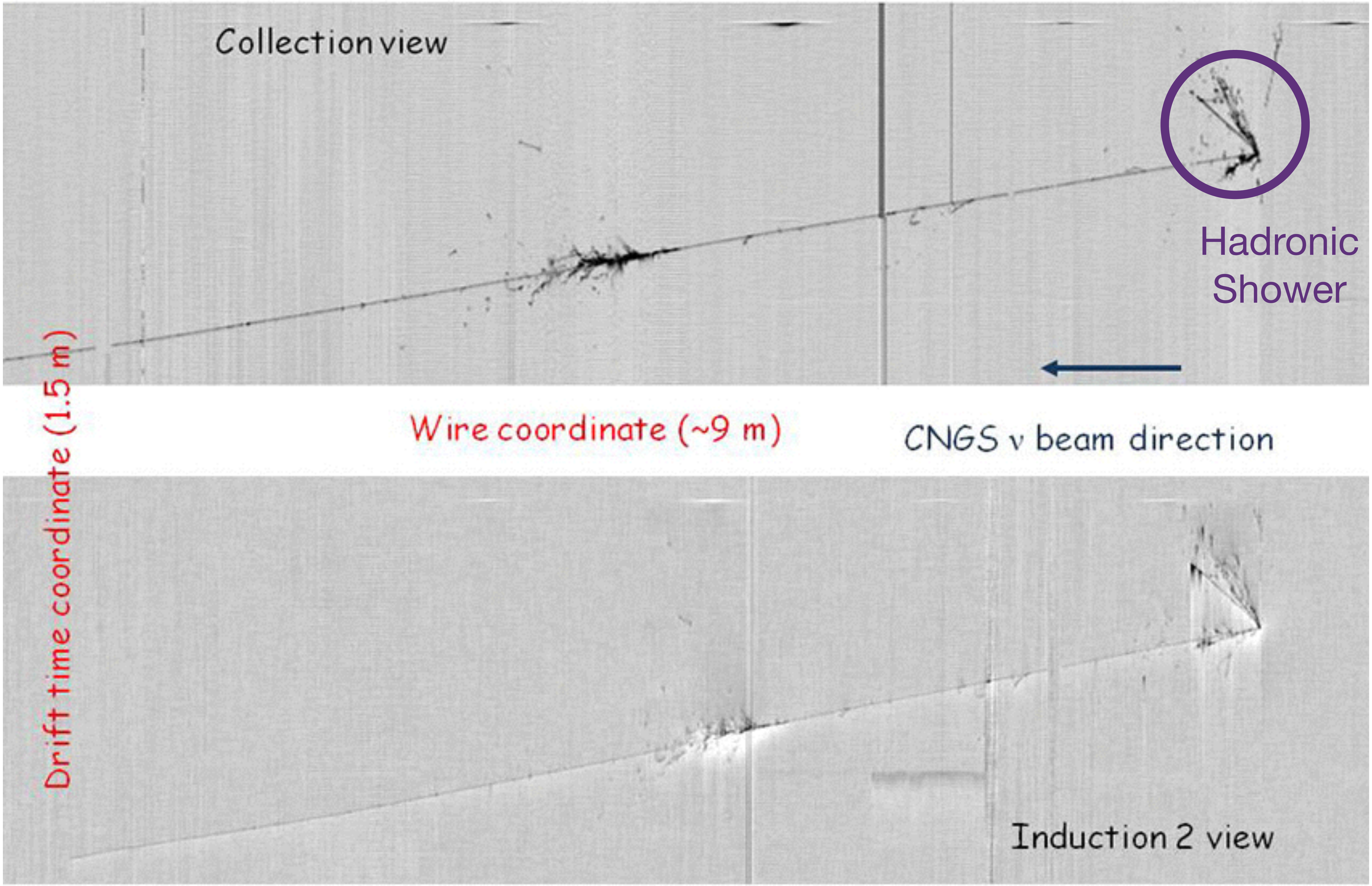

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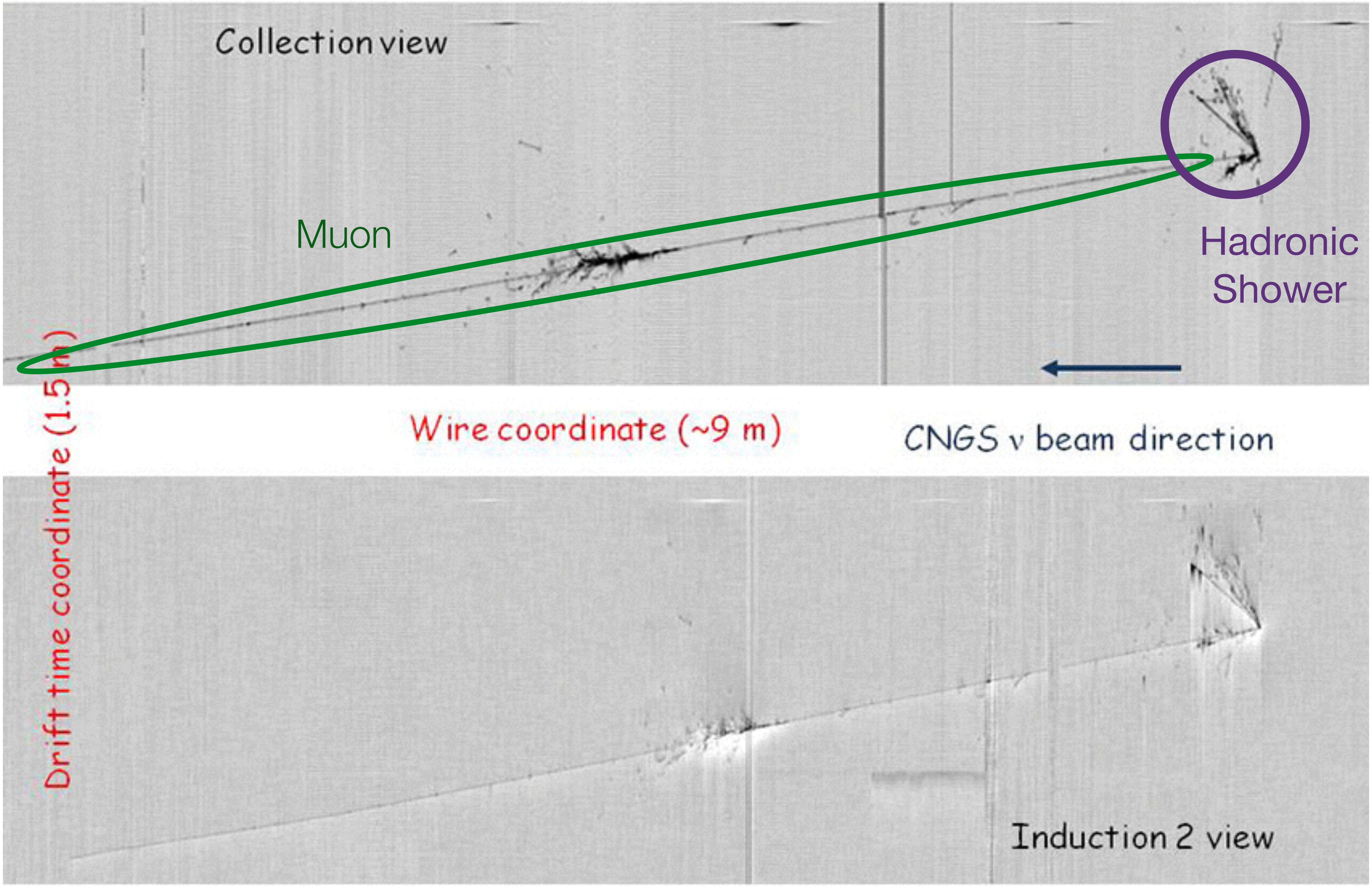

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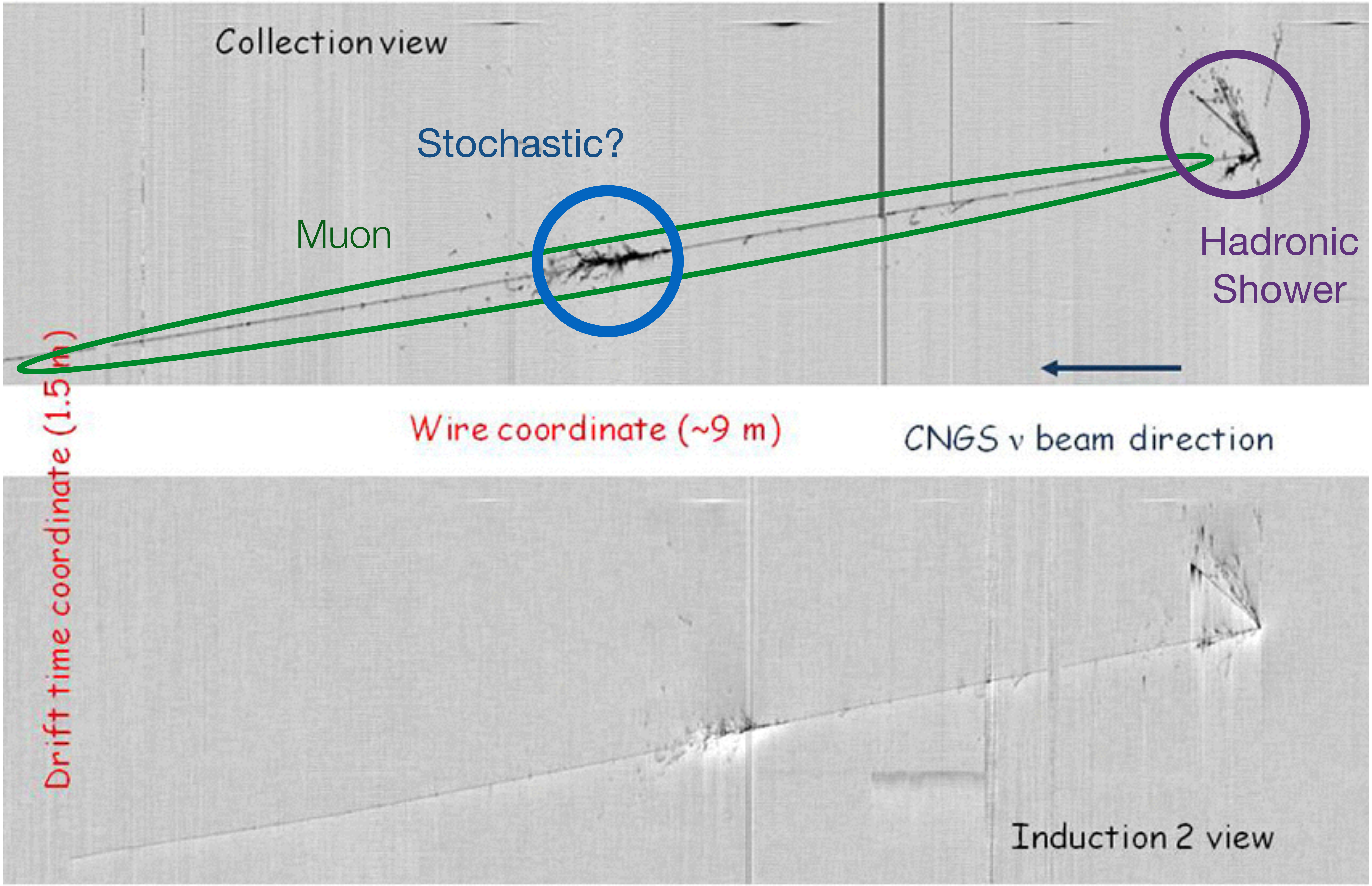

Liquid Noble TPC

- Impurities determine drift length
  - 'Absorb' electrons
  - Ar purity is so high that water will diffuse out of cable sheathing
  - Requires in-situ purification

*T. Yang, Aspen Winter Workshop 2013

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  - Identify and track individual particles

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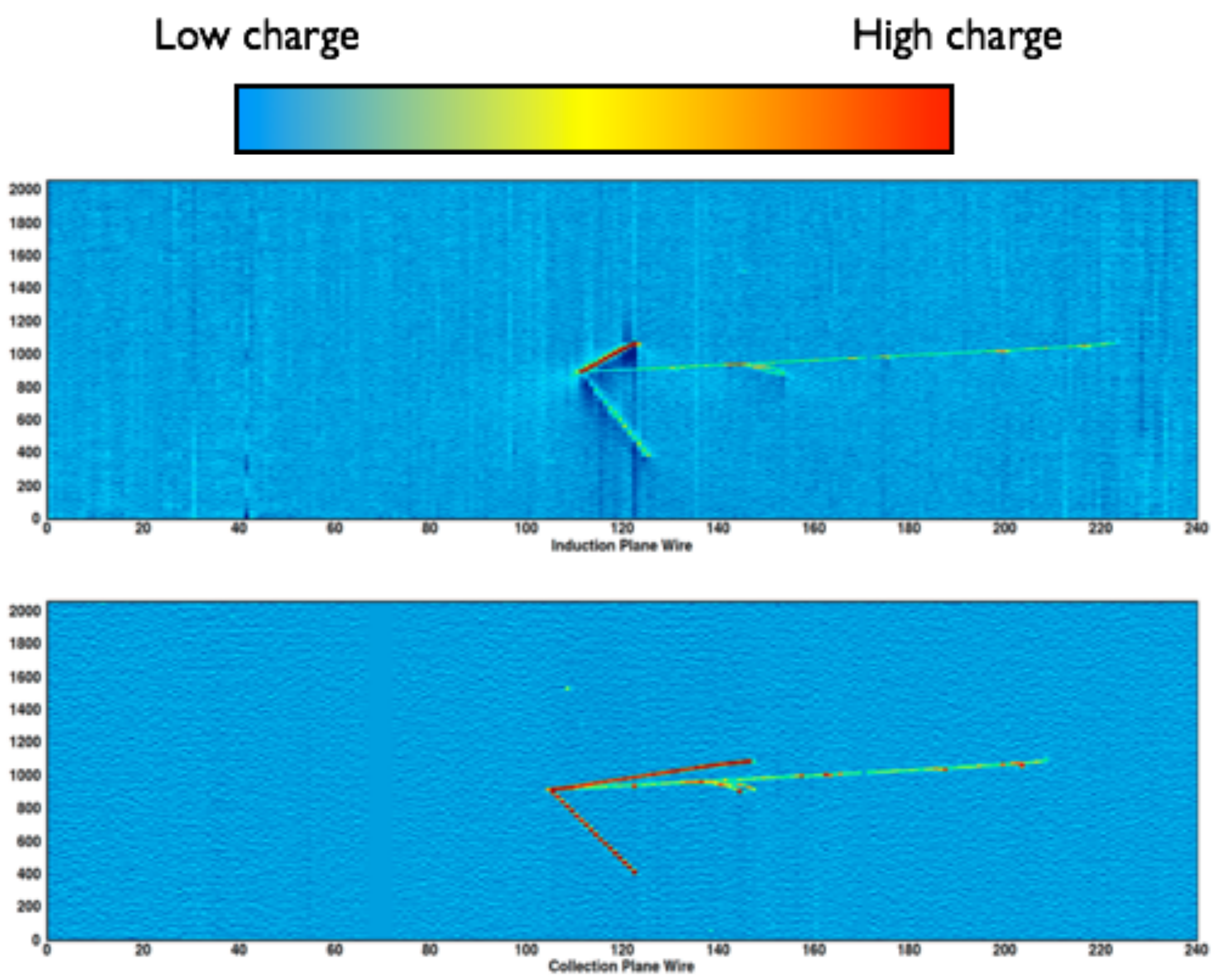

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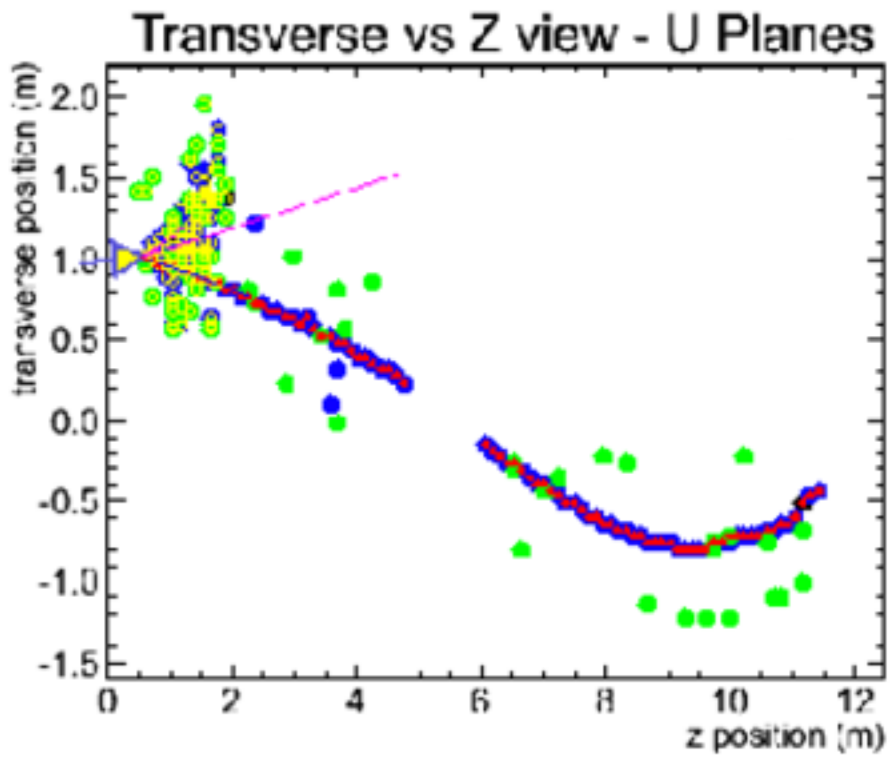
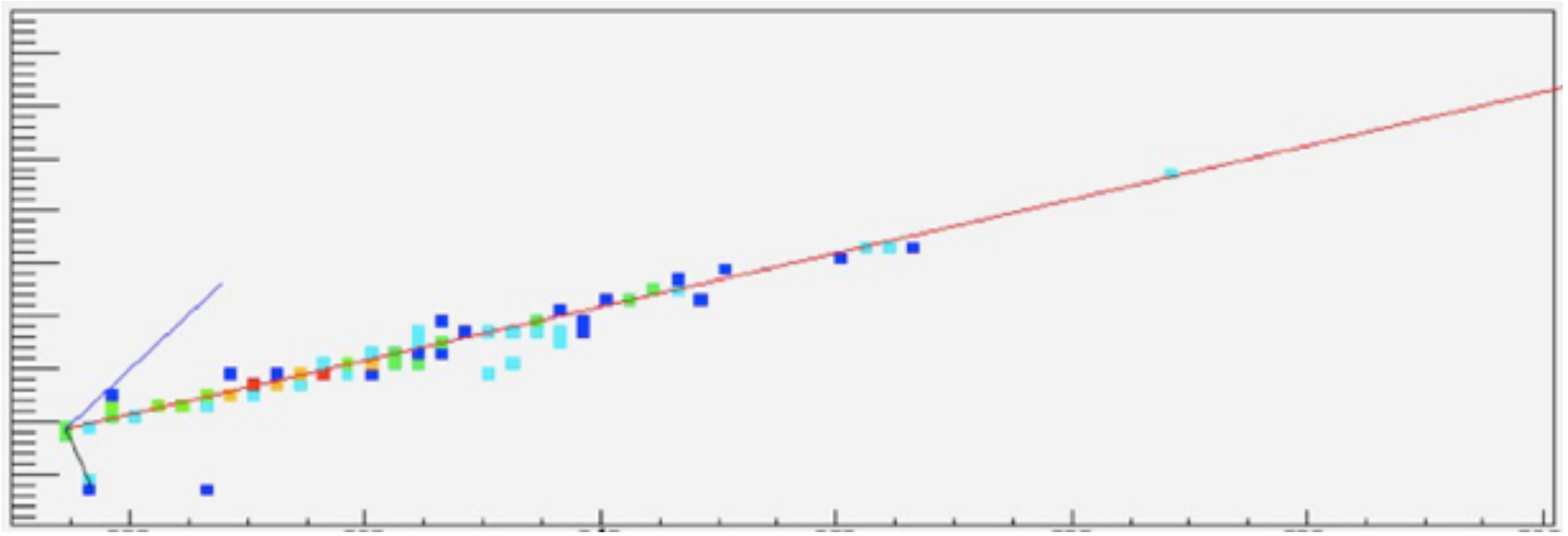
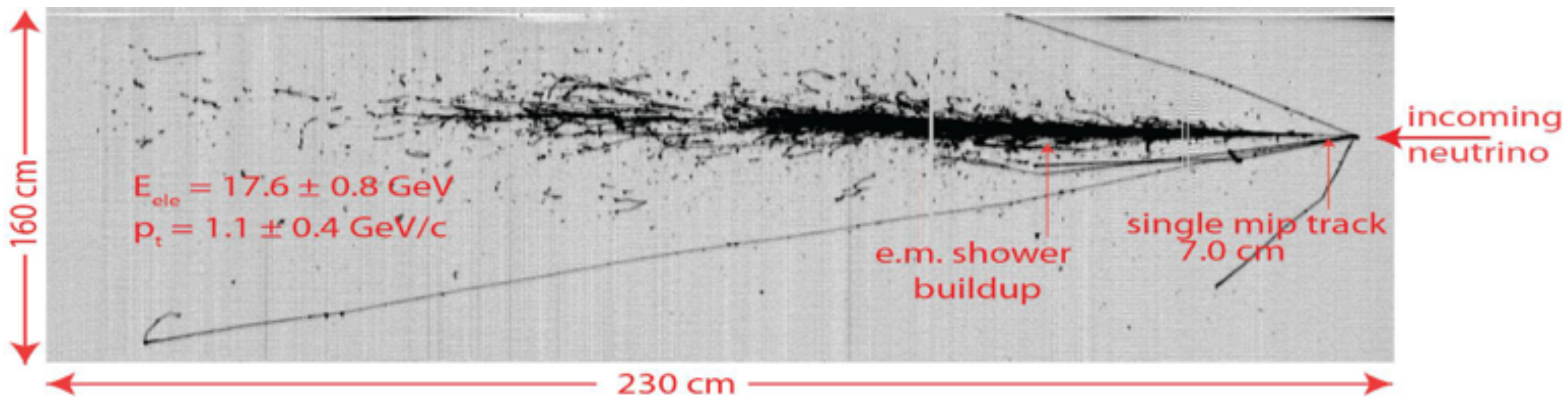
Comparison



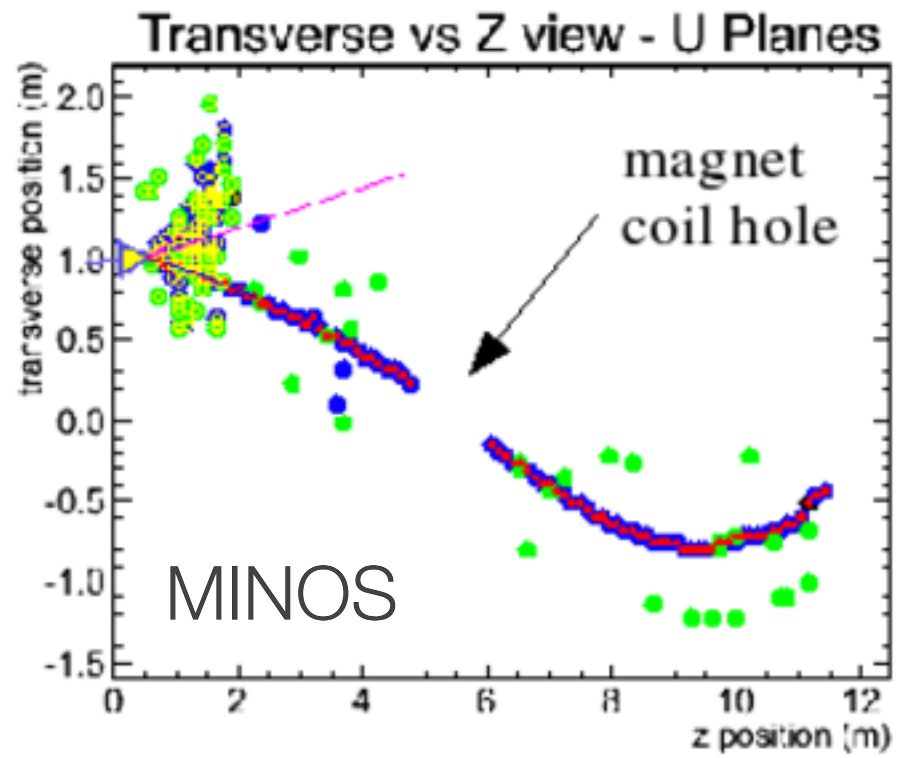
Transverse vs Z view - U Planes
transverse position (m)
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
0
2
4
6
8
10
12
z position (m)





160 cm
230 cm
E_{ele} = 17.6 ± 0.8 GeV
p_t = 1.1 ± 0.4 GeV/c
e.m. shower
buildup
single mip track
7.0 cm
incoming
neutrino

Comparison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2.0
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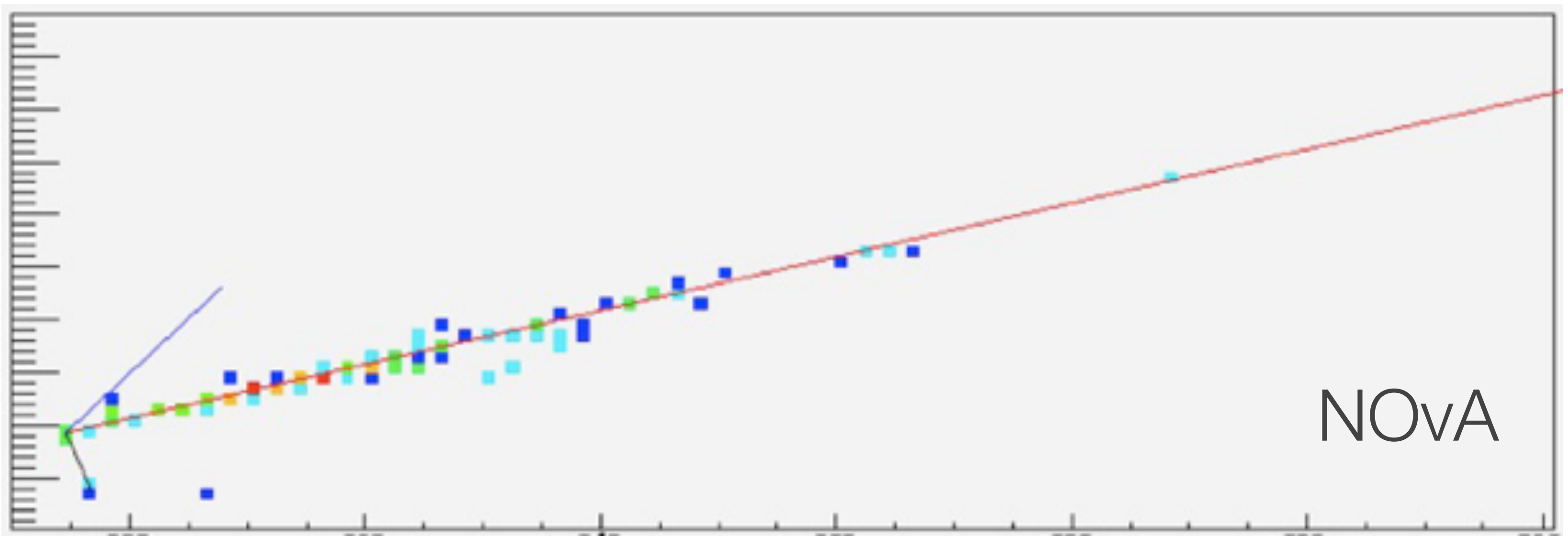
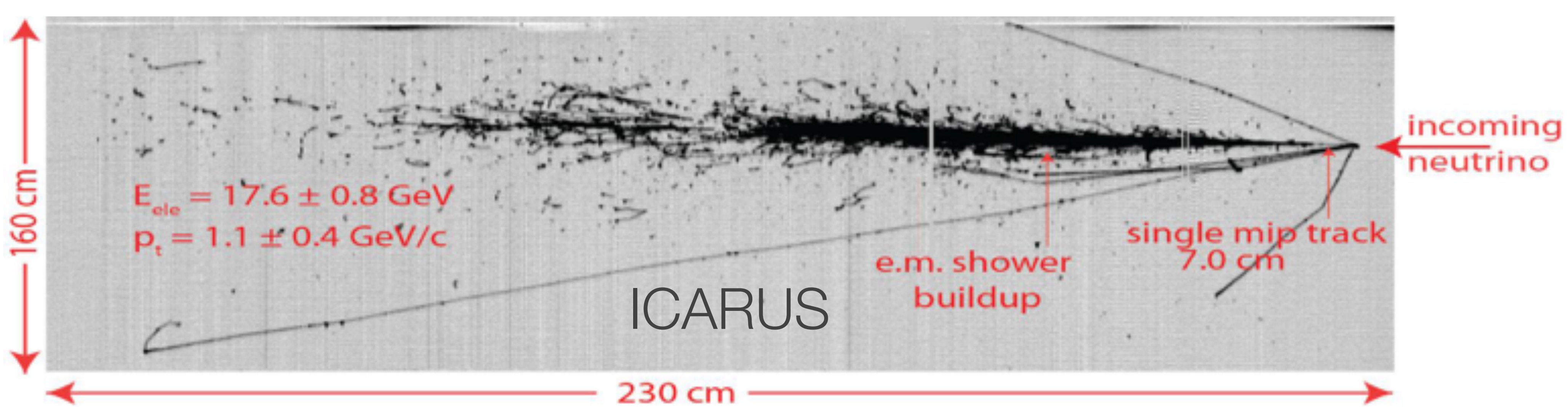
-1.5
0
2
4
6
8
10
12
z position (m)
magnet coil hole
MINOS


NOvA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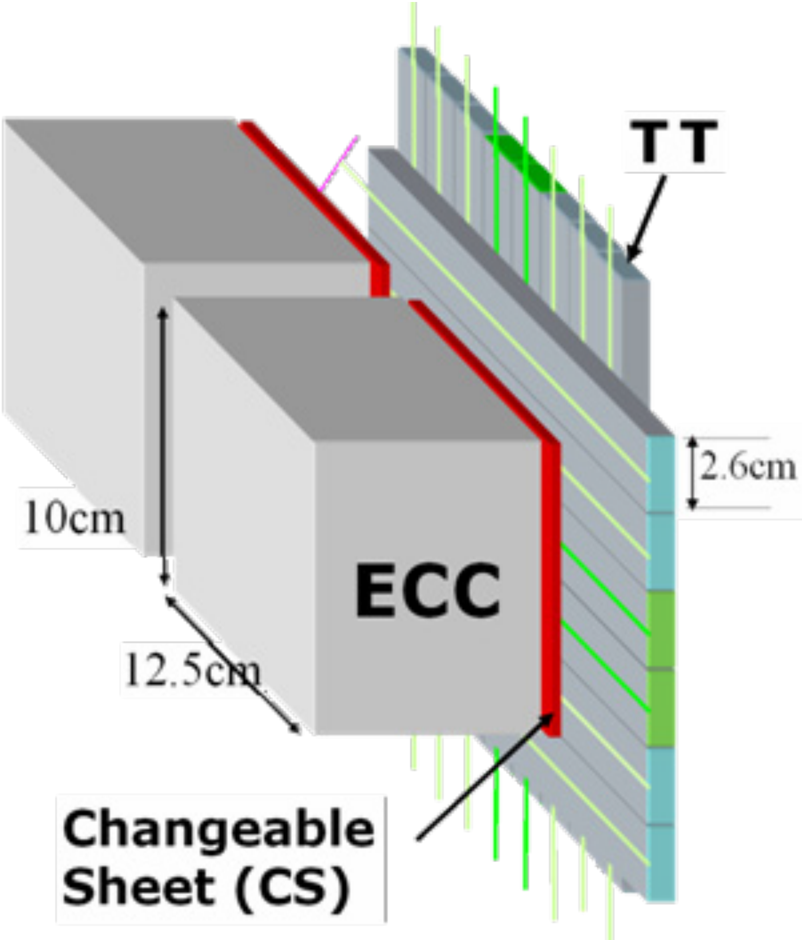
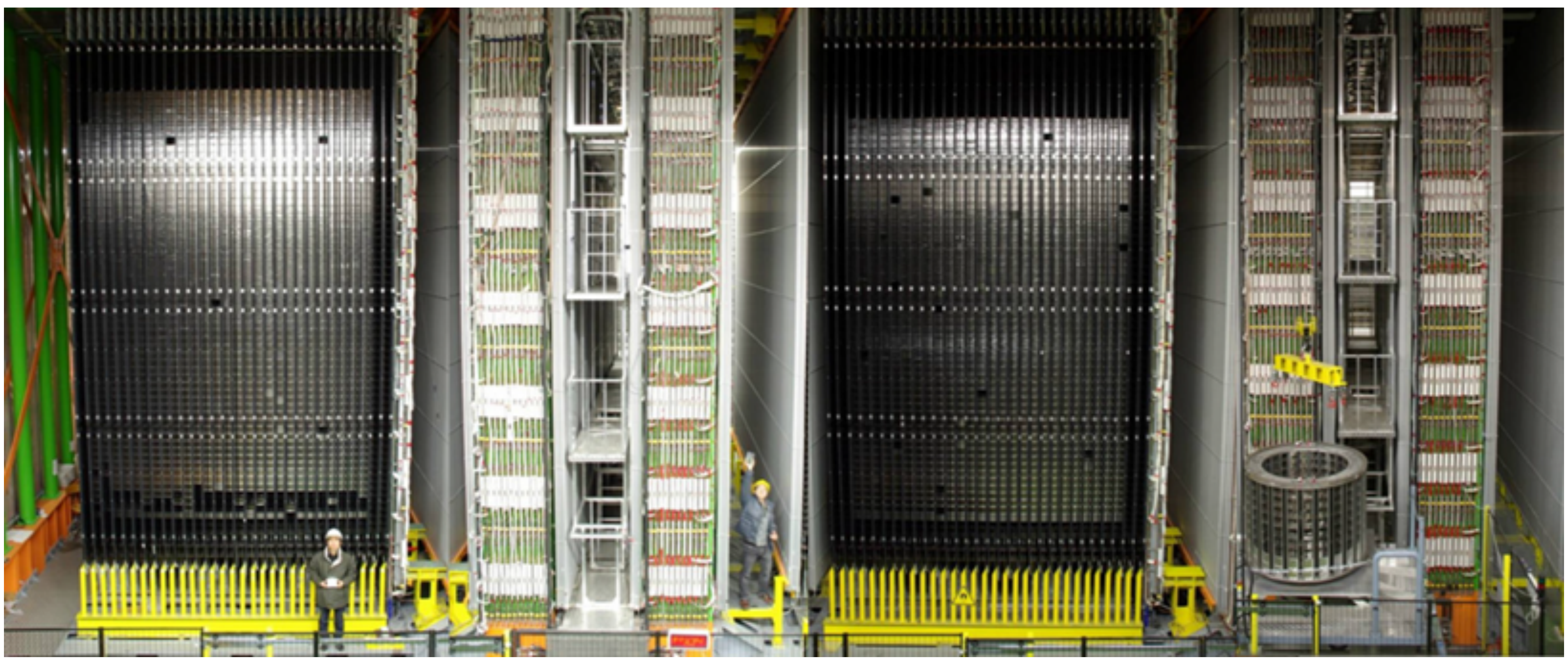
ICARUS
e.m. shower buildup
single mip track 7.0 cm
incoming neutrino
230 cm

OPERA

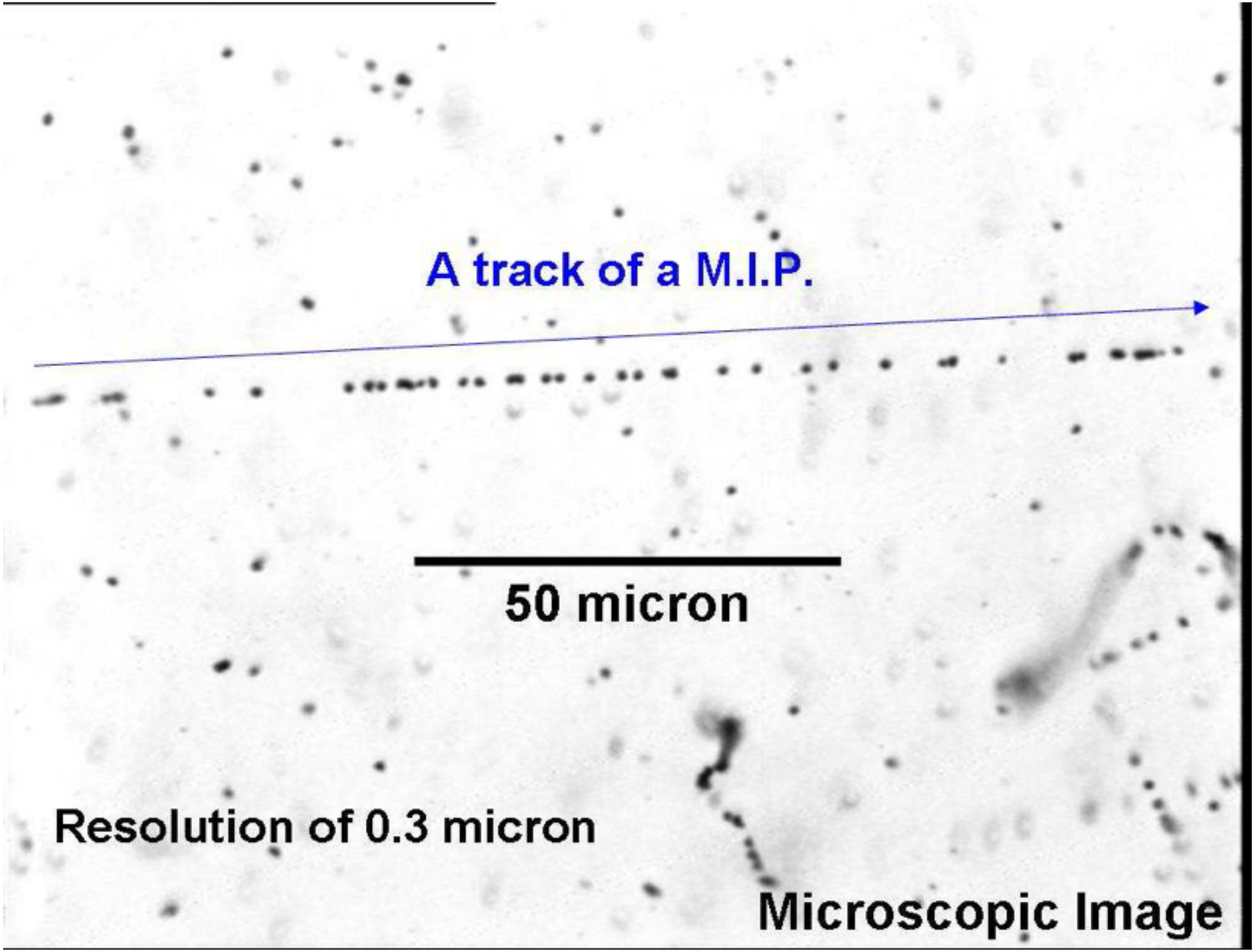
- Emulsion Cloud Chambers
  - Must be chemically developed
  - Robot extracts bricks
- Solid scintillator IDs bricks





arXiv:1308.2553

Emulsion Film



OPERA Events

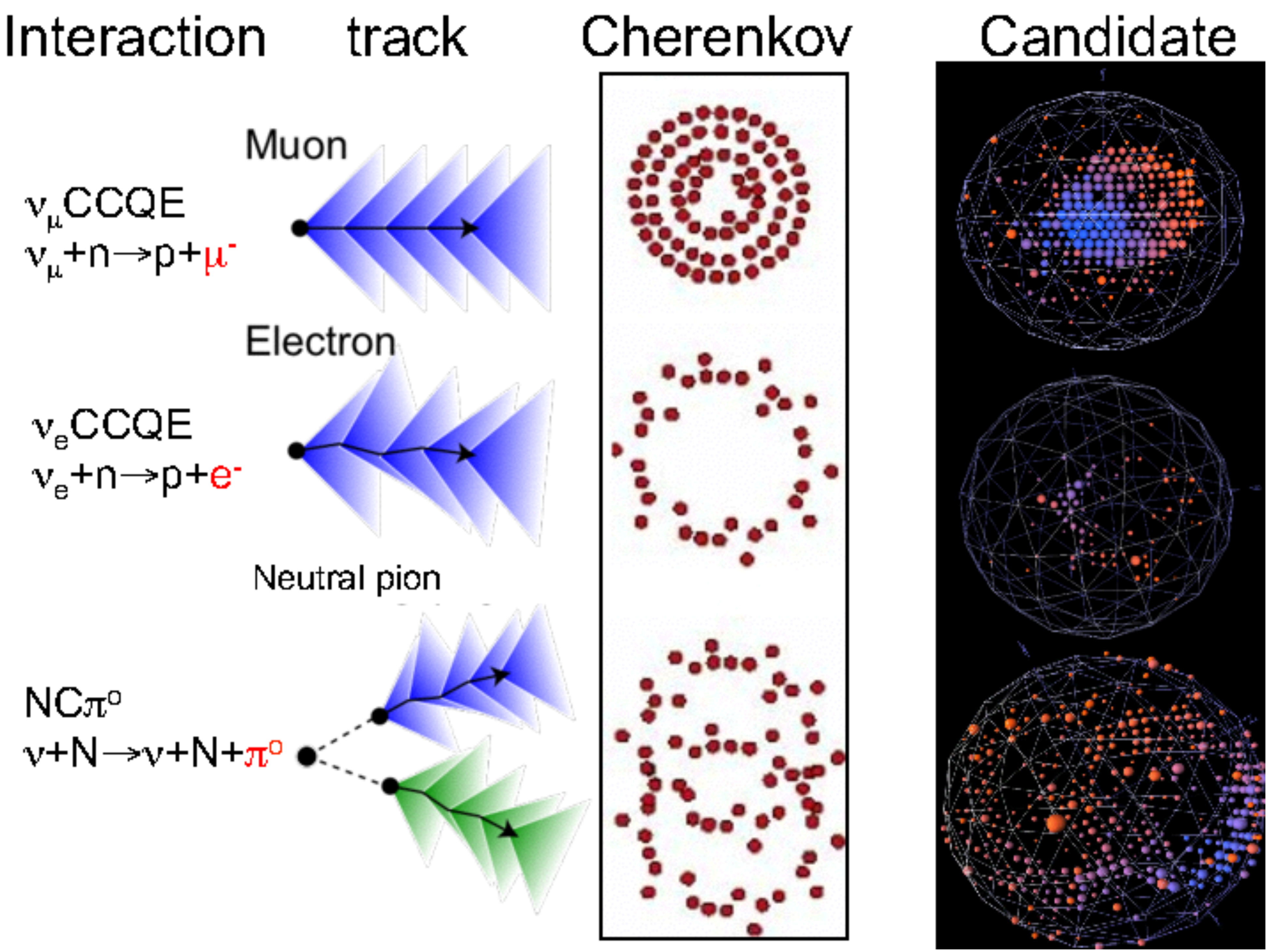
*S. Dusini, Neutrino 2014

Decay channel	Expected signal $\Delta m_{23}^2 = 2.32\ meV^2$	Total background	Observed
$\tau \rightarrow h$	0.4 ± 0.08	0.033 ± 0.006	2
$\tau \rightarrow 3h$	0.57 ± 0.11	0.155 ± 0.03	1
$\tau \rightarrow \mu$	0.52 ± 0.1	0.018 ± 0.007	1
$\tau \rightarrow e$	0.61 ± 0.12	0.027 ± 0.005	0
Total	2.1 ± 0.42	0.23 ± 0.04	4

- 4 observed events
  - 2x tau decays to 1 hadron, tau decay to 3 hadrons, and tau decay to muon
  - 4.2σ confirmation of ν_τ appearance
- Statistics is not high enough to measure oscillation parameters

Short Baseline and Non-Oscillation Beam Experiments

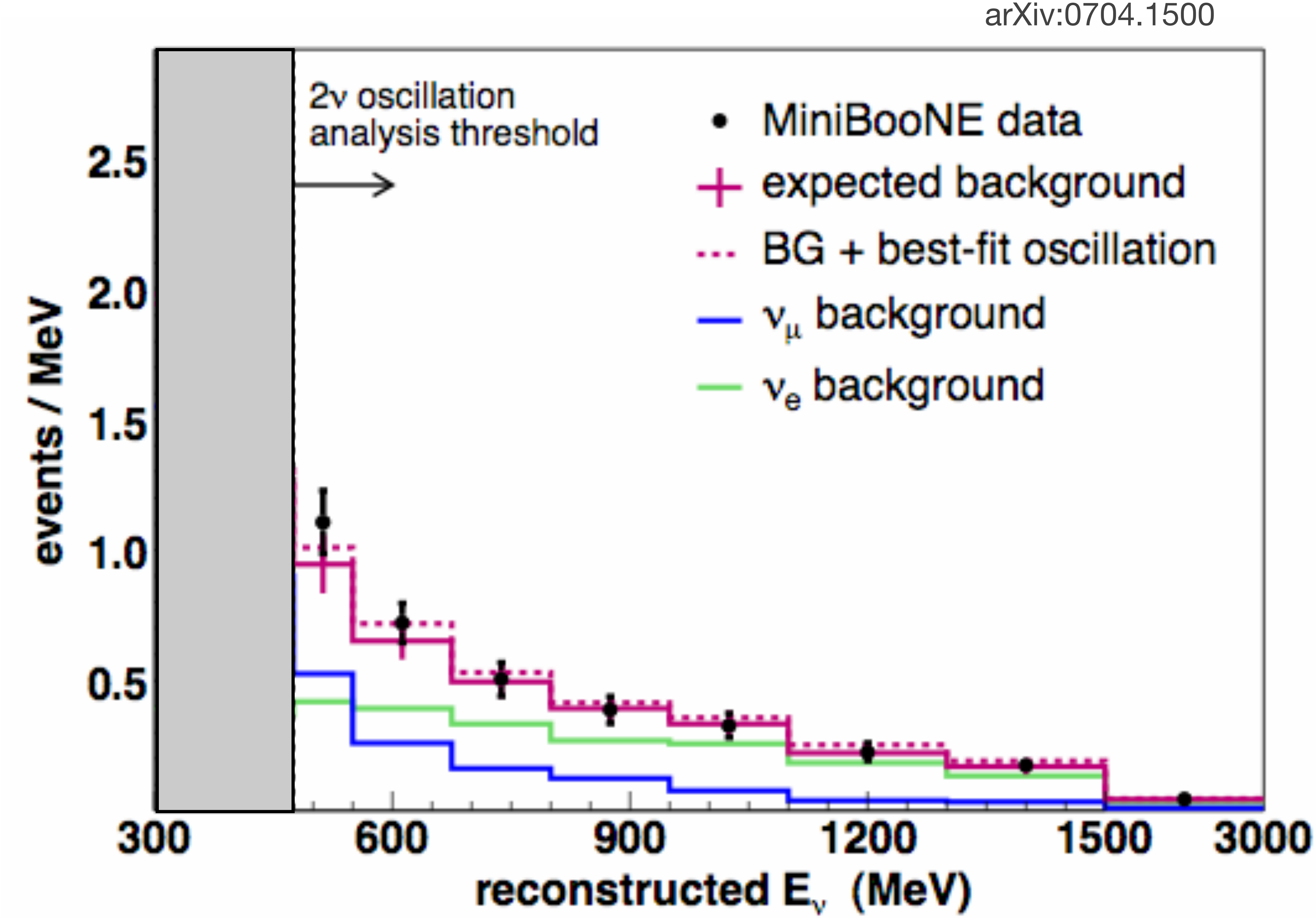
MiniBooNE Cherenkov



*T. Katori, Queen Mary

MiniBooNE First Results

arXiv:0704.1500



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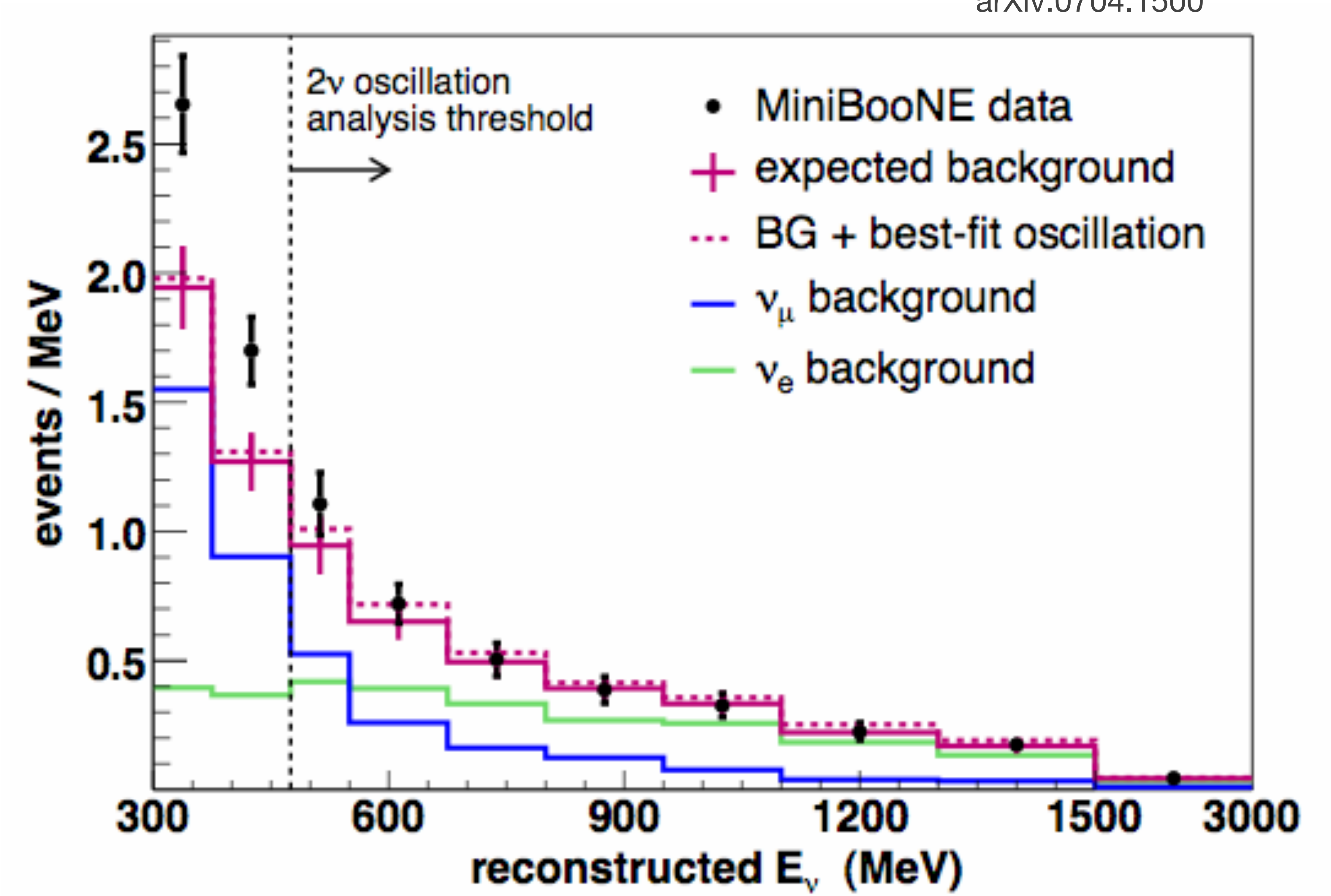
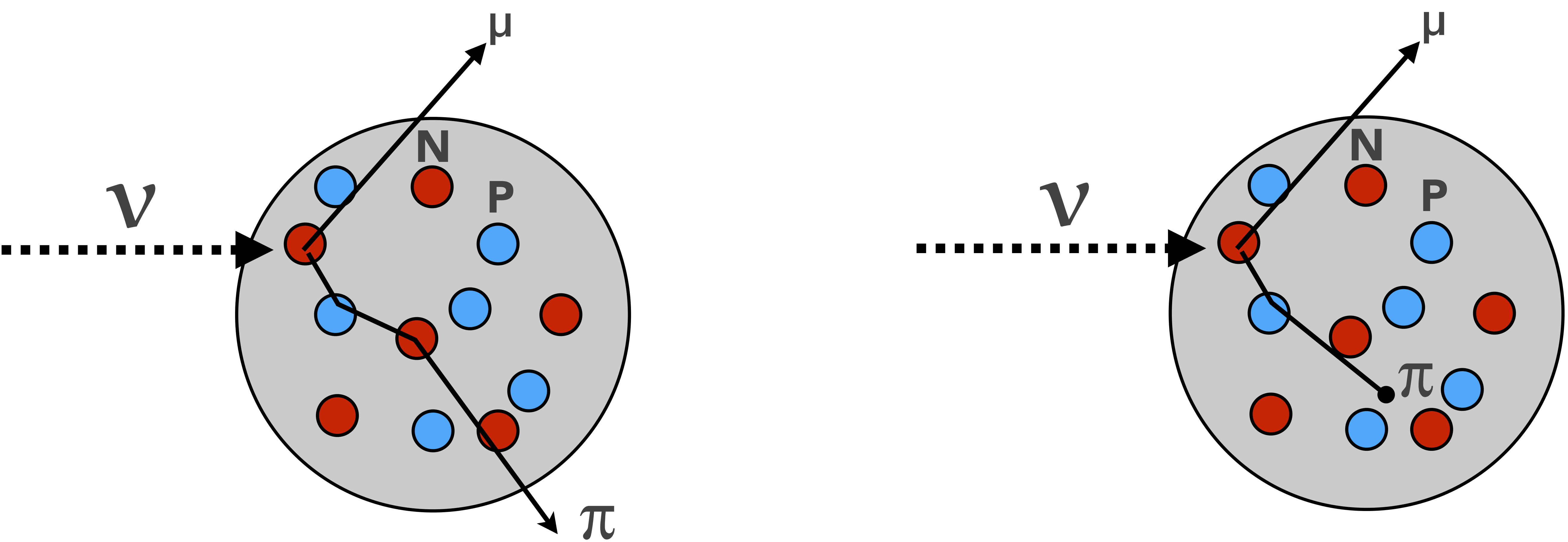
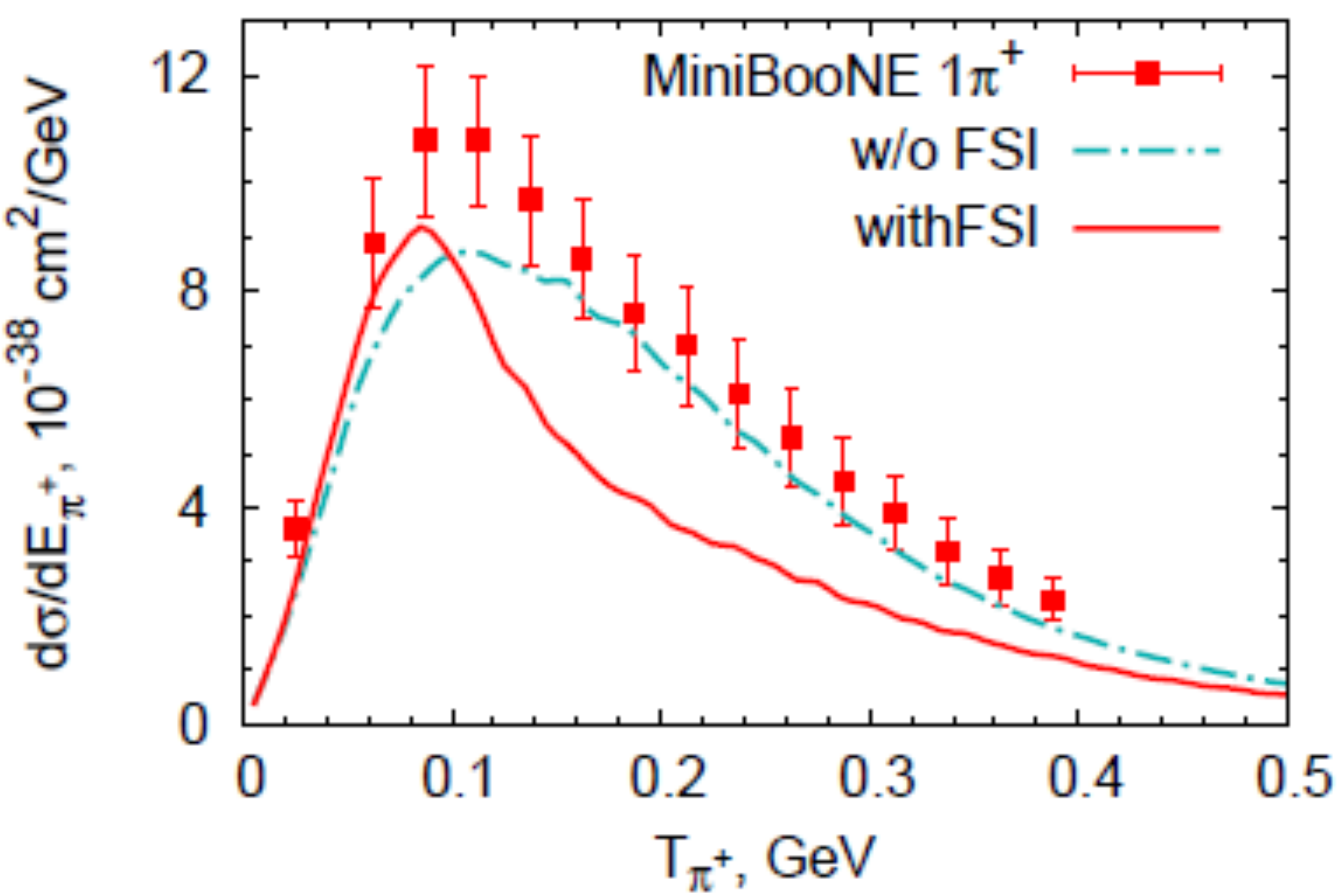


Our Old Friend?



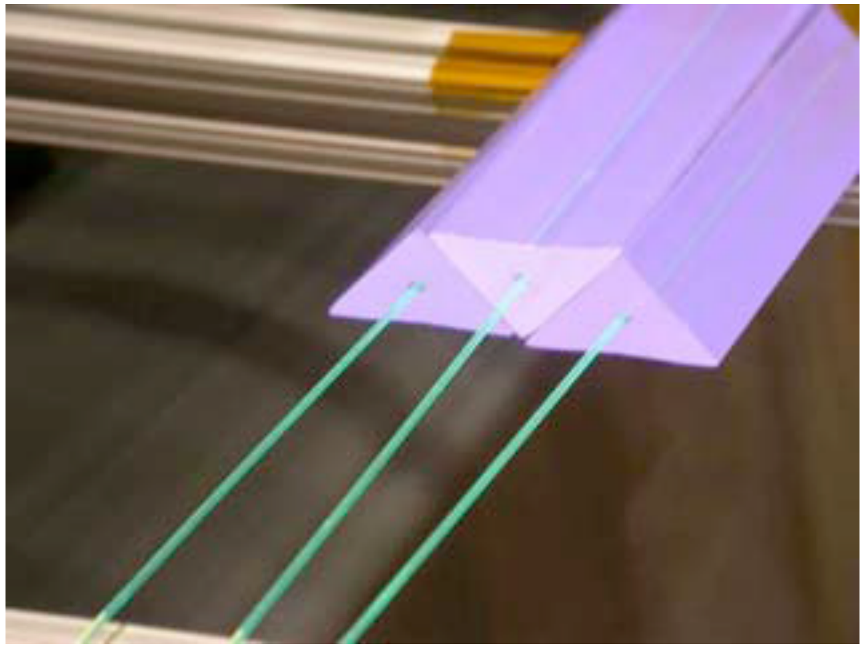
Back to Interactions

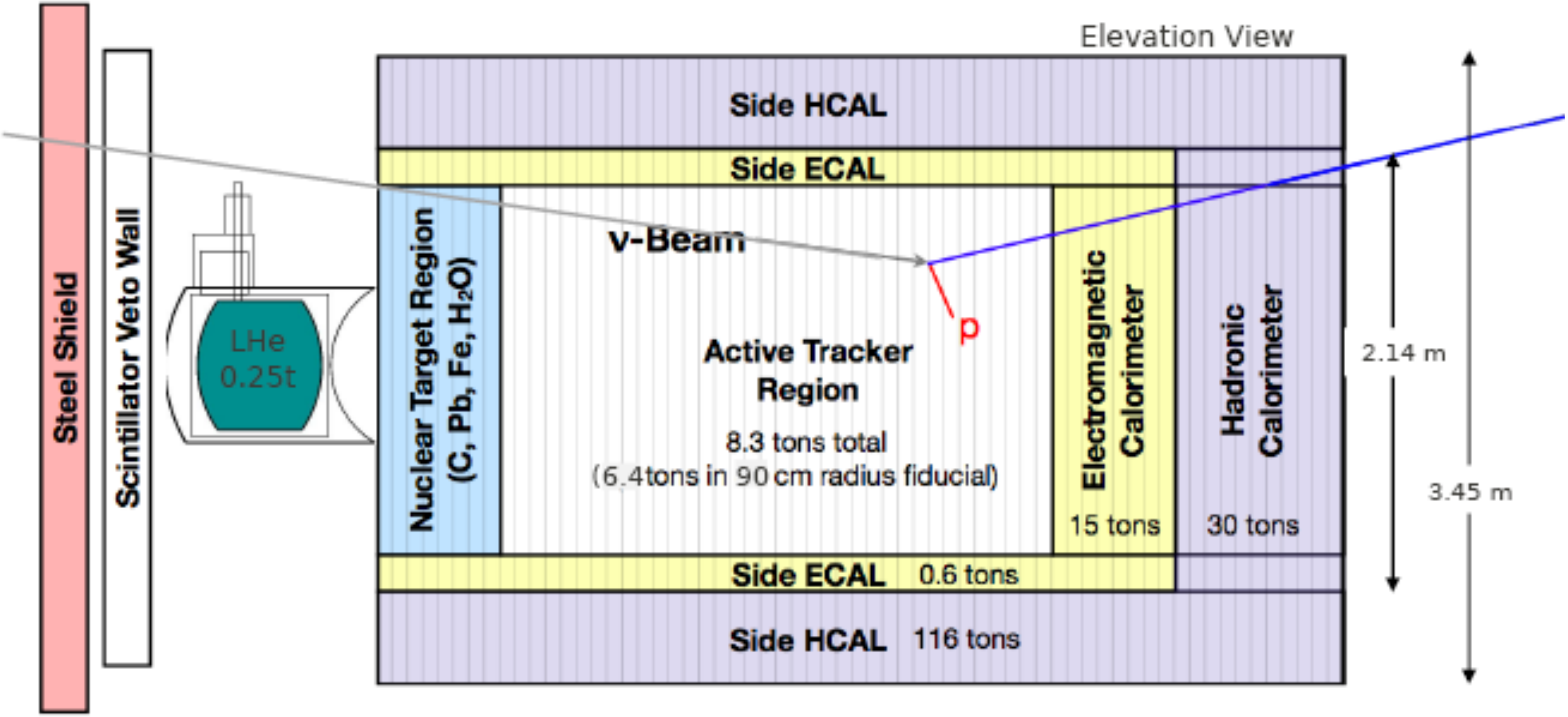
- MiniBooNE final state interactions (FSI)
- Energy determination is determined by detector response which changes as a function of particle
- Could we study this via pion/nucleon scattering?



GiBUU, arXiv:1210.4717

MINERvA



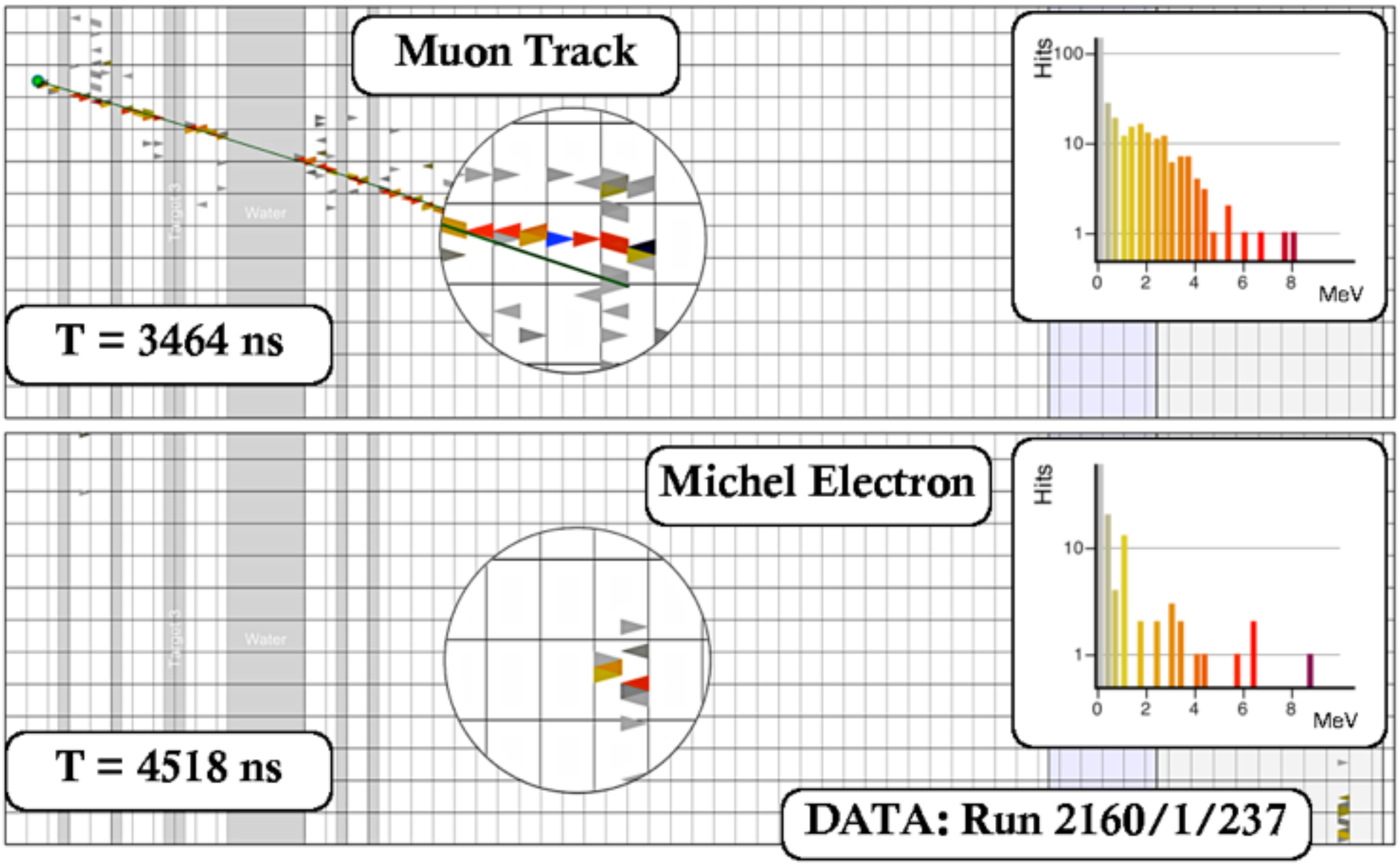


arXiv:1305.5199

Michel Candidate

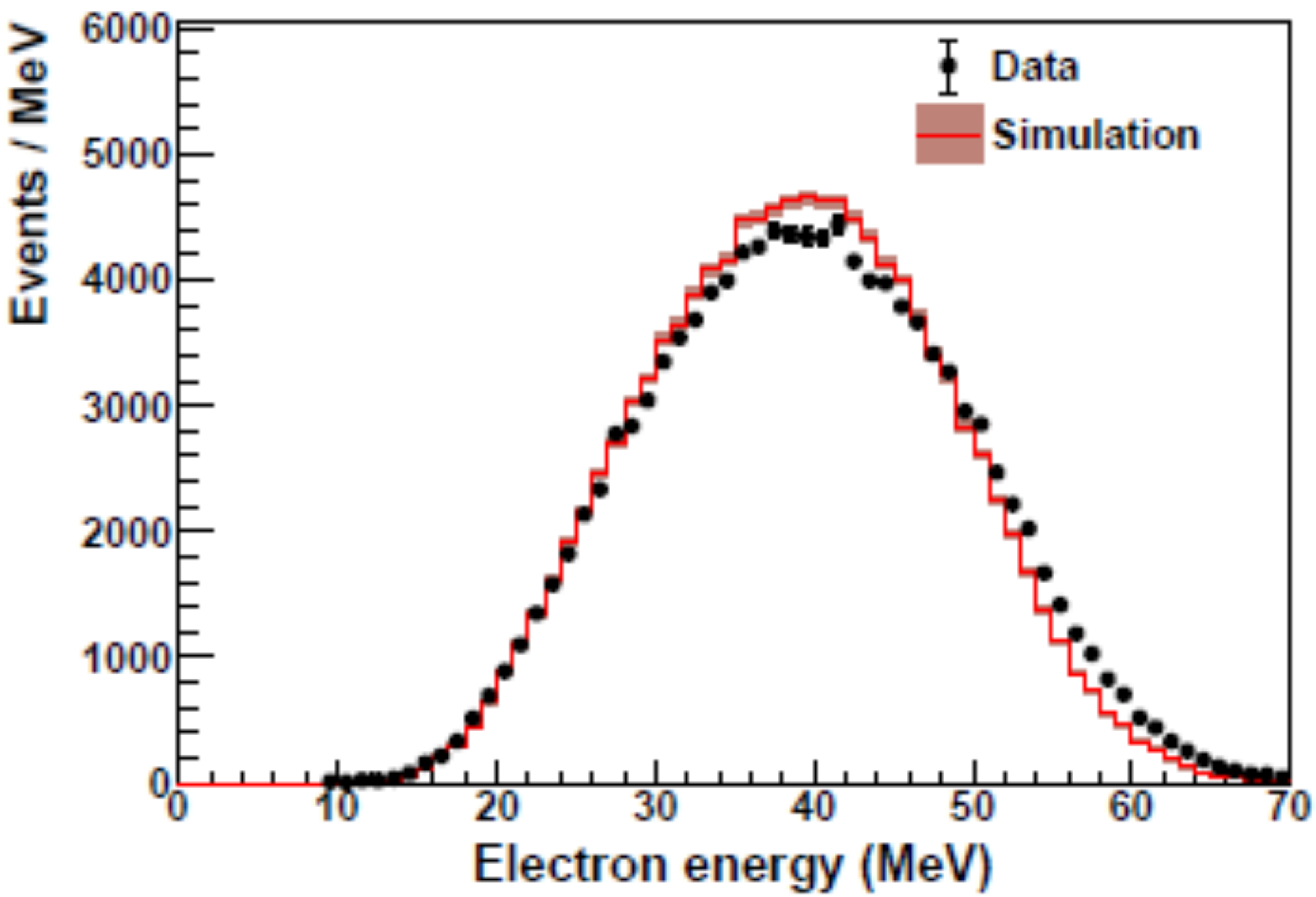
- Calibrate with Michel Electrons coming from muon decay

arXiv:1110.3727



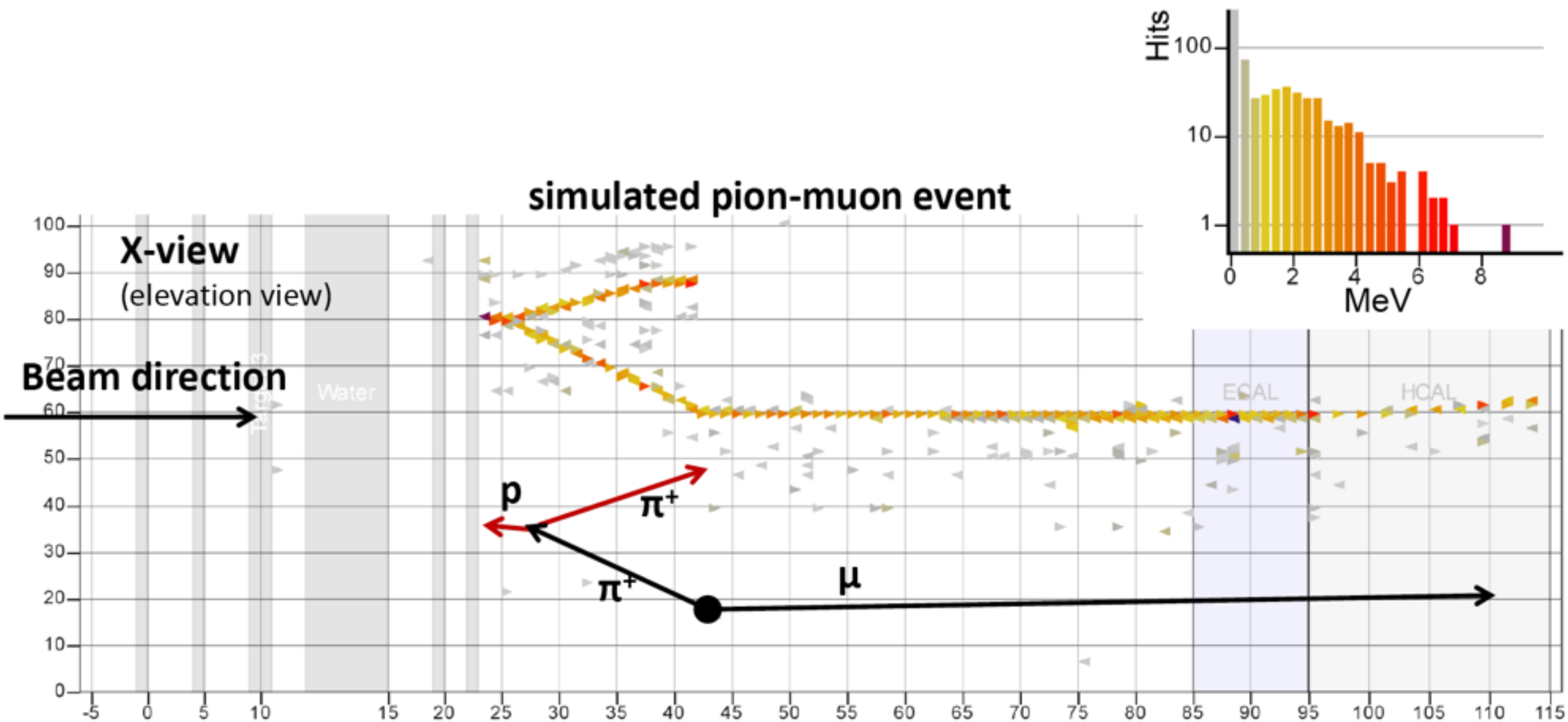
MINERvA Energy Calibration Tool

- Calibrate with Michel Electrons



arXiv:1305.5199

MINERvA Neutrino Event

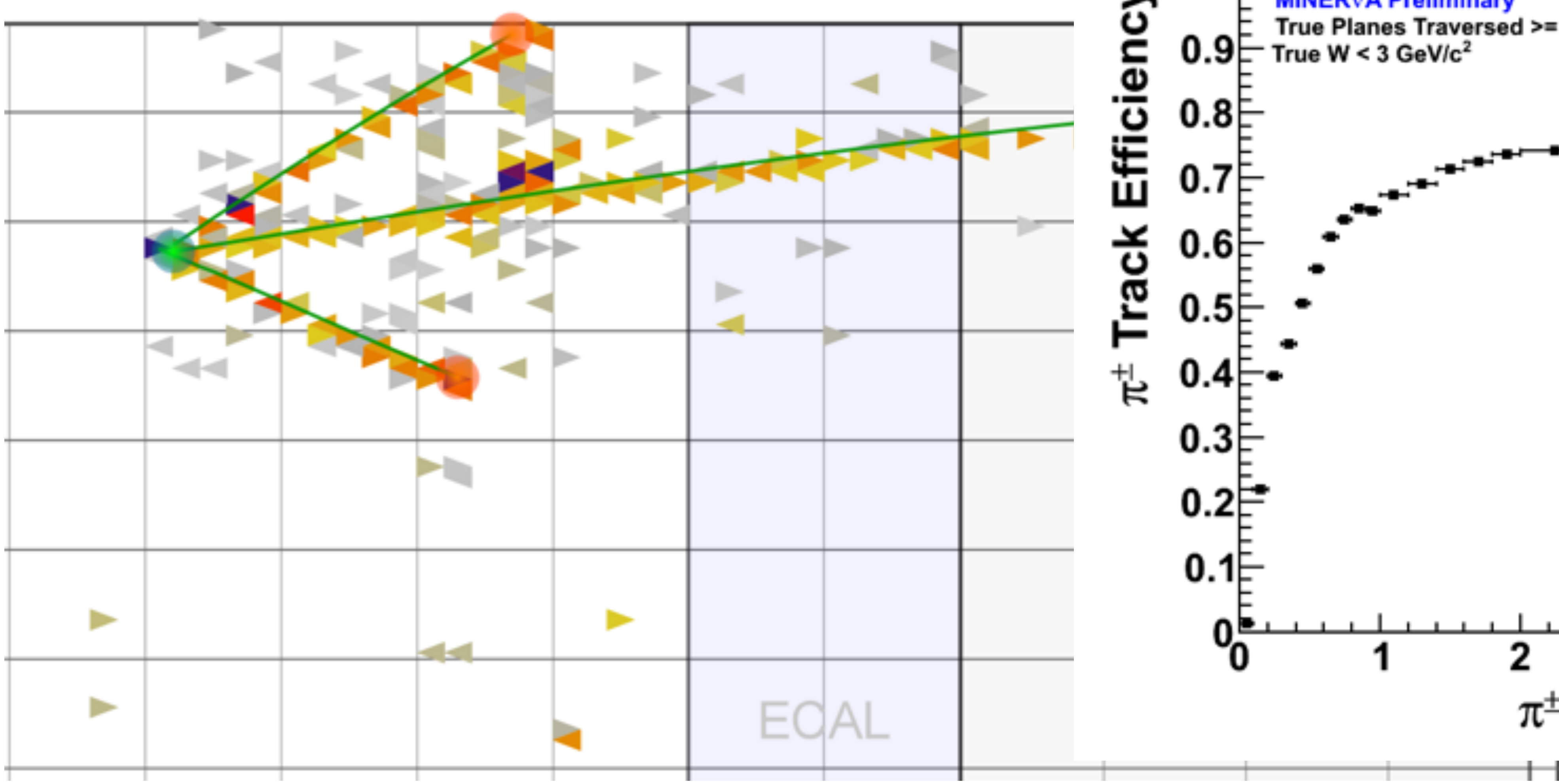


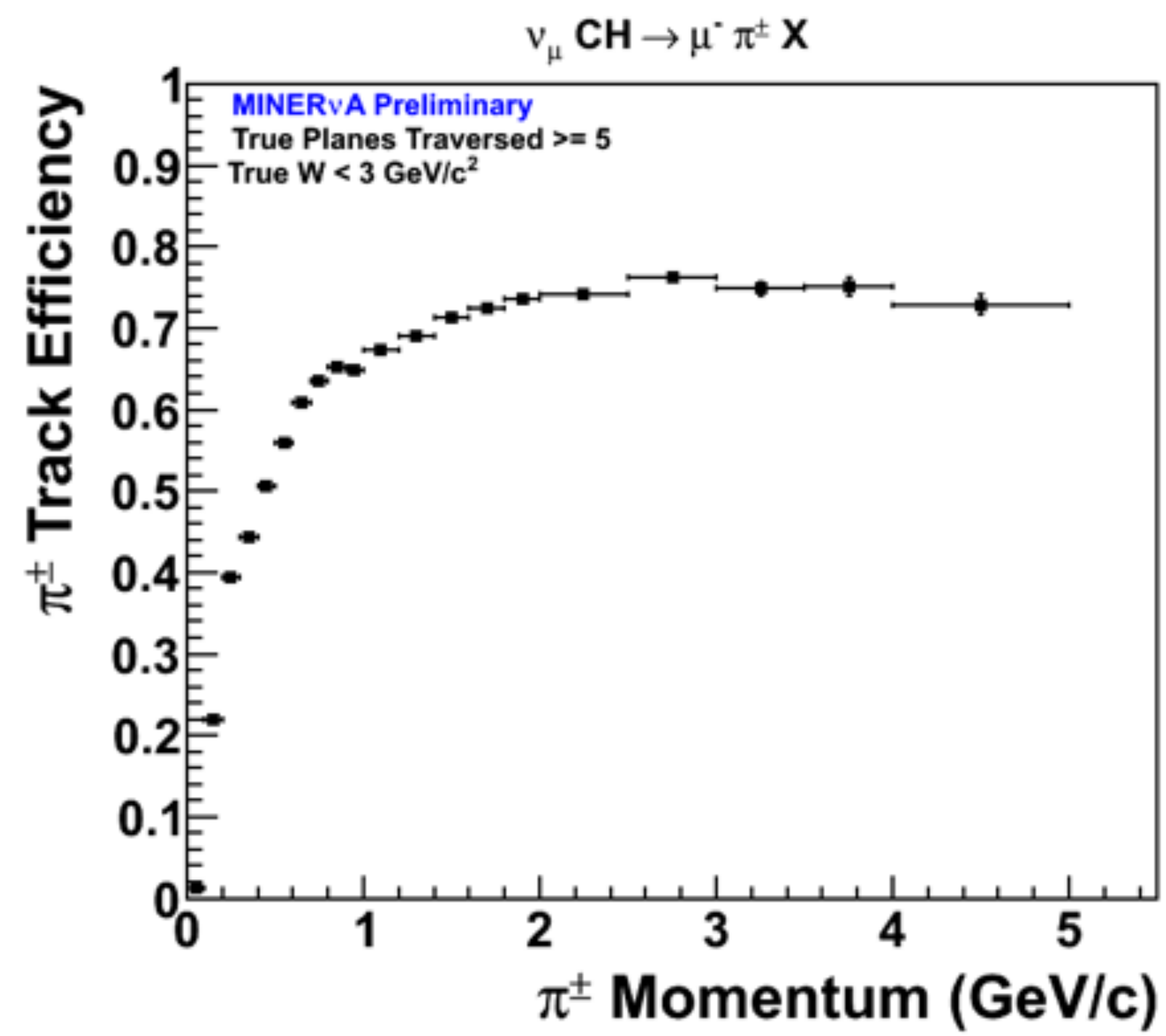
*B. Eberly, U of Pittsburgh

Data Event

- Subtract off muon contribution to interaction vertex energy
- Easy to see muon, but which remaining track is pion vs. proton?

*B. Eberly, U of Pittsburgh





MINERvA Physics

MINERvA Physics

- Study neutrino nucleon Final State Interactions (FSI)
- Measure contributions from the different cross-section processes
  - Resonant
  - Deep Inelastic
  - Quasi-Elastic
- Neutrinos and anti-neutrinos

Wrap-Up

- Muons are common background in neutrino detectors

- Varied detectors for accelerator neutrino beams
  - Magnetized steel and solid scintillator
  - Liquid noble gas Time Projection Chambers
  - Liquid scintillator

- Neutrino interaction physics can be studied using fine-grained detectors in a high flux neutrino beam

Questions?