Tracking/Calorimeter Neutrino Detectors

- The concept
- The process
- The detectors
- The signals
- The analysis

Many thanks to
Mark Messier (IU) and Tom Carroll (UW)

https://forms.gle/gUYf7JzRpZUziyV38

Throughout the lectures I've given specific references to papers where appropriate. The material here leans heavily on these three texts:

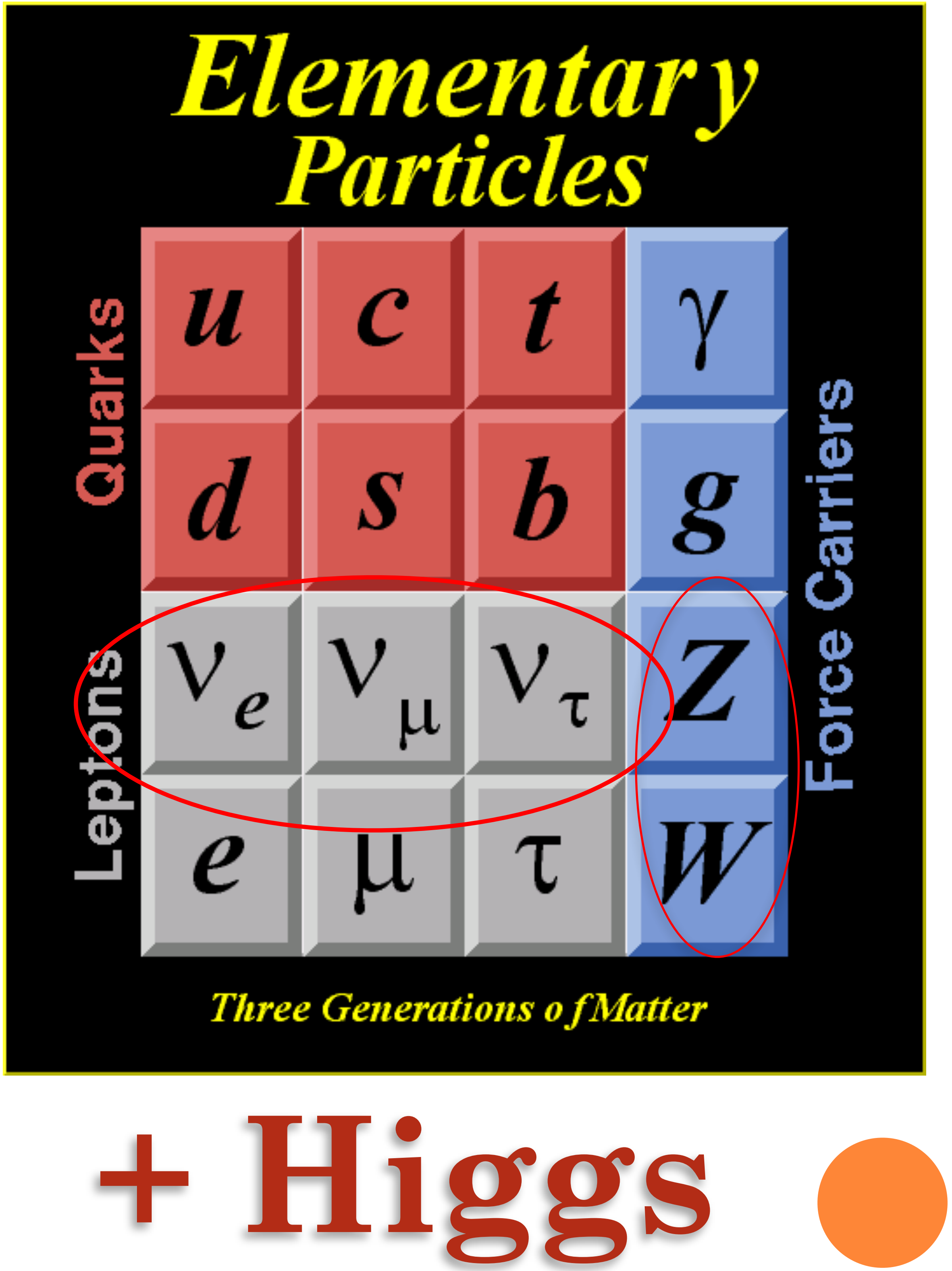
- W.R. Leo, Techniques for Nuclear and Particle Physics Experiments, A How-to-Approach.
- Richard Fernow, Introduction to experimental particle physics.
- Christopher Tully, Elementary Particle Physics in a Nutshell.
- Passage of particles through matter, Particle Data Group.

The Concept

- The overarching design of a detector is dictated by the physics ……………

The Standard Model

- The SM is the most exquisitely tested theory known to man
  - 3 generations of quarks and leptons and 3 forces mediated by Gauge Bosons
  - Each family separated by ΔQ=1
- Recently discovered Higgs particle leaves no doubt over its correctness
  - Gives mass to the Gauge Bosons
- One (gaping) hole has appeared in the SM :
  - neutrinos must be massless but they are not



Parity Violation

- The weak interaction only "sees" left handed fermions, and ignores right handed ones.

Parity Violation

- The weak interaction is parity violating. Yang and Lee predicted it, CS Wu 1957 proved it
- Life imitates science

- Only the men were "seen" by the Nobel committee
- Like the left-handed particles are only seen by the weak interaction

The Concept

- The overarching design of a detector is dictated by the physics ……………
- neutrino detectors have to have very many protons and neutrons in them, to encourage a weak interaction (WI)
- interaction rate = # neutrinos x WI cross section x #nucleons
- WI cross section is about 10^{-38} cm^2 at GeV energies
- Detectors have to contain kilo-tons of mass = $6x10^{32}$ nucleons/kilo-ton to allow enough interactions to be measured
- Therefore…..detectors are mostly monolithic unlike LHC detectors for reasons of cost

Facts of life for the neutrino experimenter...

Numerical example for typical accelerator-based experiment

$$N_{\rm obs} = \left[\int \mathcal{F}(E_\nu)\sigma(E_\nu,...)\epsilon(E_\nu,...)dE_\nu d...\right]\frac{M}{A\, m_N}T$$

N_{obs}	:	number of neutrino events recorded
$\mathcal{F}$	:	Flux of neutrinos ($\#/\mathrm{cm}^2/\mathrm{s}$)
σ	:	neutrino cross section per nucleon $\simeq 0.7\frac{E_\nu}{[\mathrm{GeV}]}\times 10^{-38}\mathrm{cm}^2$
ϵ	:	detection efficiency
M	:	total detector mass
A	:	effective atomic number of detector
m_N	:	nucleon mass
T	:	exposure time

typical "super-beam" flux at 1000 km

typical accelerator up time in one year

$$N_{\rm obs} = \left[\frac{1}{\mathrm{cm}^2\mathrm{s}}\right]\left[0.7\times 10^{-38}\frac{E_\nu}{\mathrm{GeV}}\mathrm{cm}^2\right][\epsilon]\,[1\ \mathrm{GeV}]\left[\frac{M}{20\cdot 1.67\times 10^{-27}\ \mathrm{kg}}\right]\left[2\times 10^7\ \mathrm{s}\right]$$

$$N_{\rm obs} = 4\times 10^{-6}\frac{E_\nu}{[\mathrm{GeV}]}\epsilon\frac{M}{\mathrm{kg}}$$

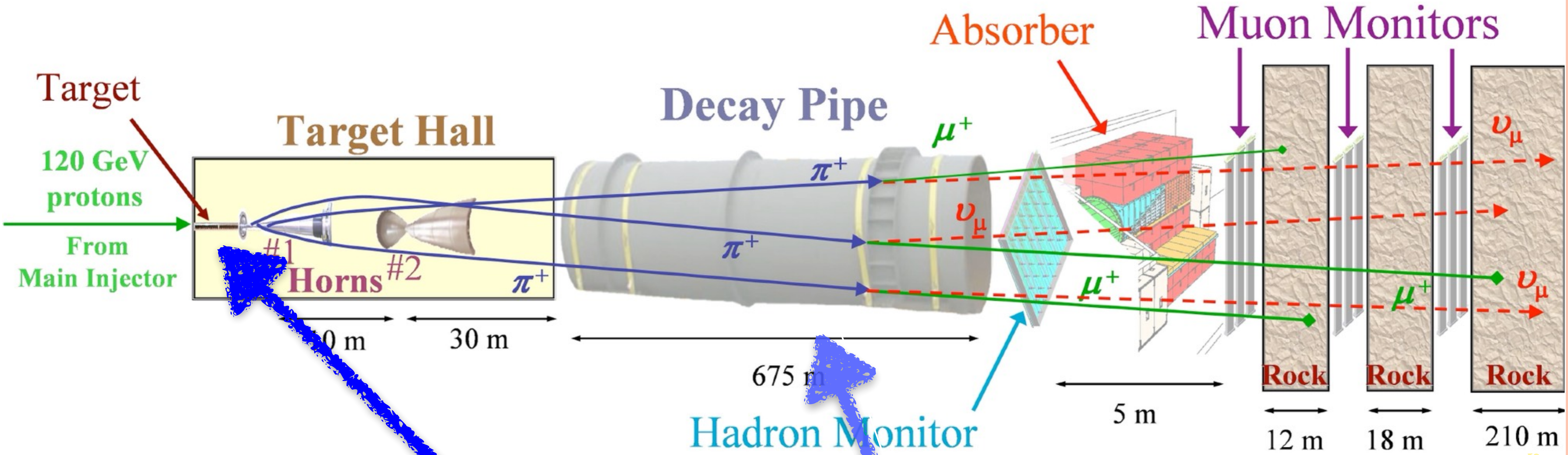
need detector masses of 10^6 kg = 1 kton to get in the game

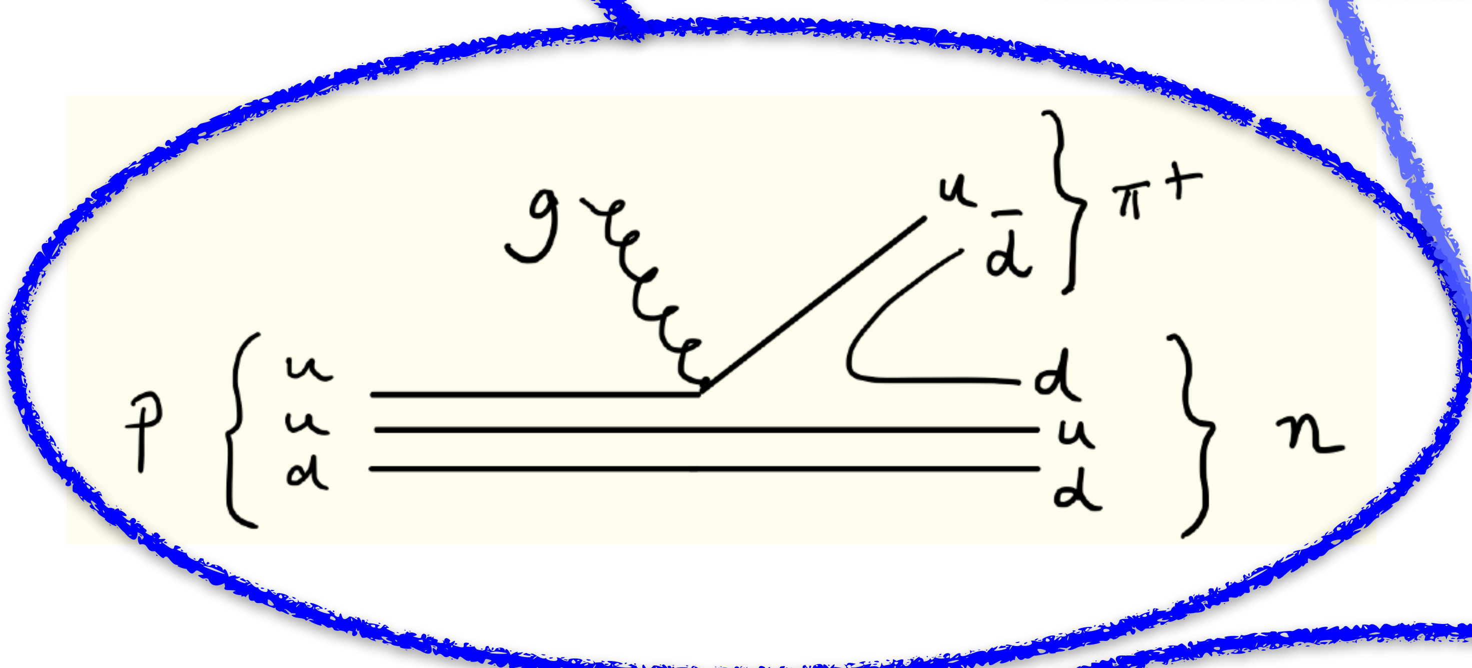
work at high energies if you can

push this as high as you can

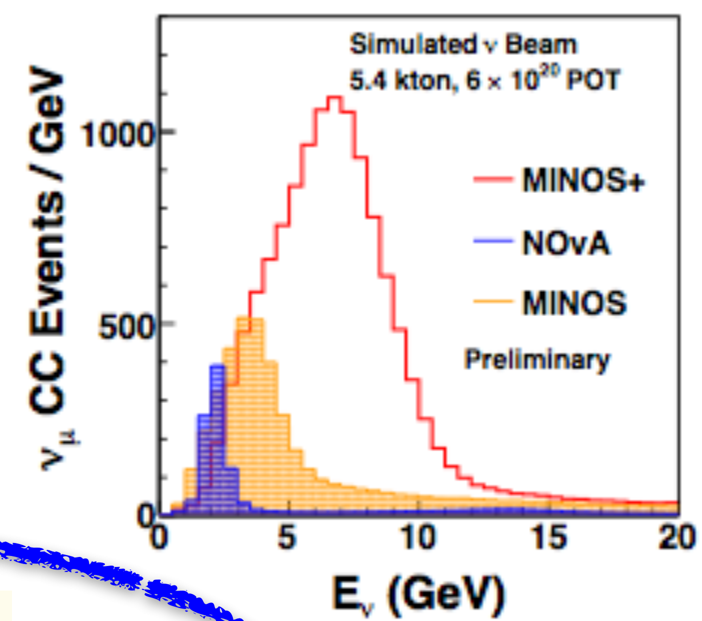
Challenge to the experimentalist: maximize efficiency and detector mass while minimizing cost

The NuMI beam at Fermilab: best in the world





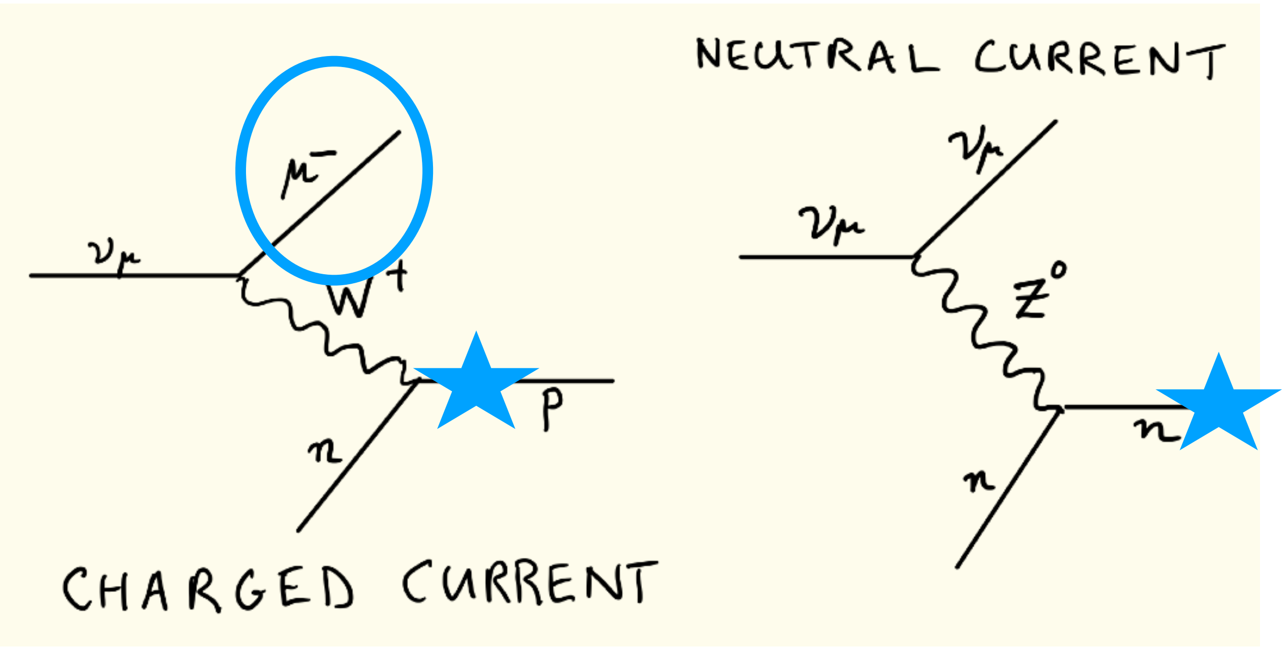
$$\pi^+ \longrightarrow \mu^+ \nu_\mu$$



A neutrino interacts

- The result is a charged lepton (CC) and some hadronic energy ★ (CC or NC)

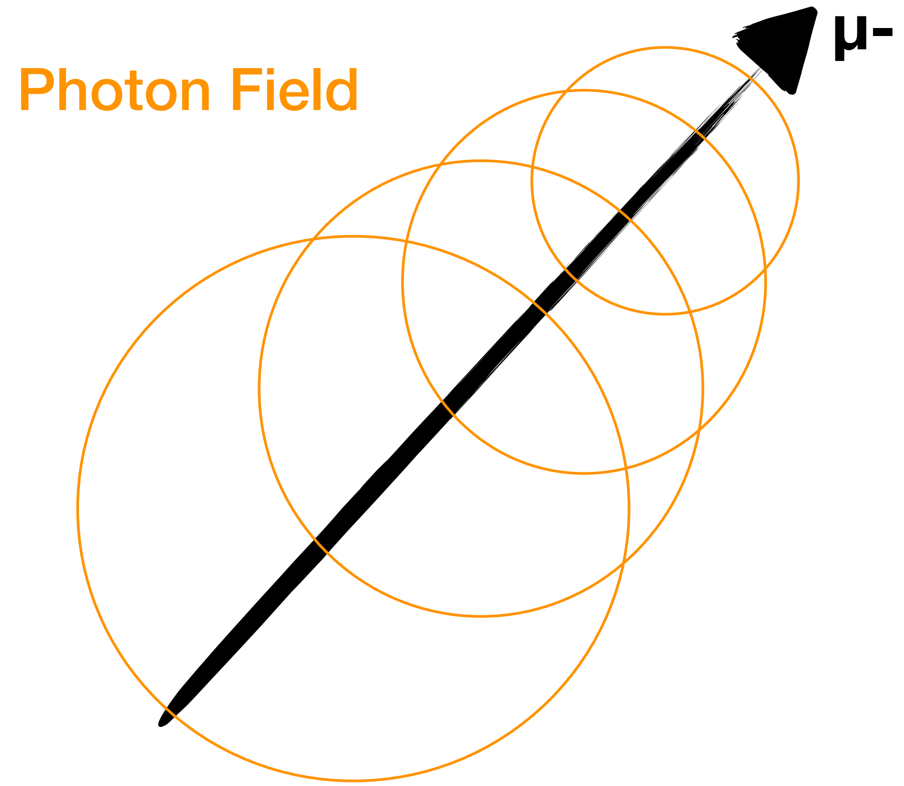
- Muon neutrinos are the easiest to detect.. higher energy owing to pion parent mass and penetrating nature of their charged lepton's path



Lets follow the muon….

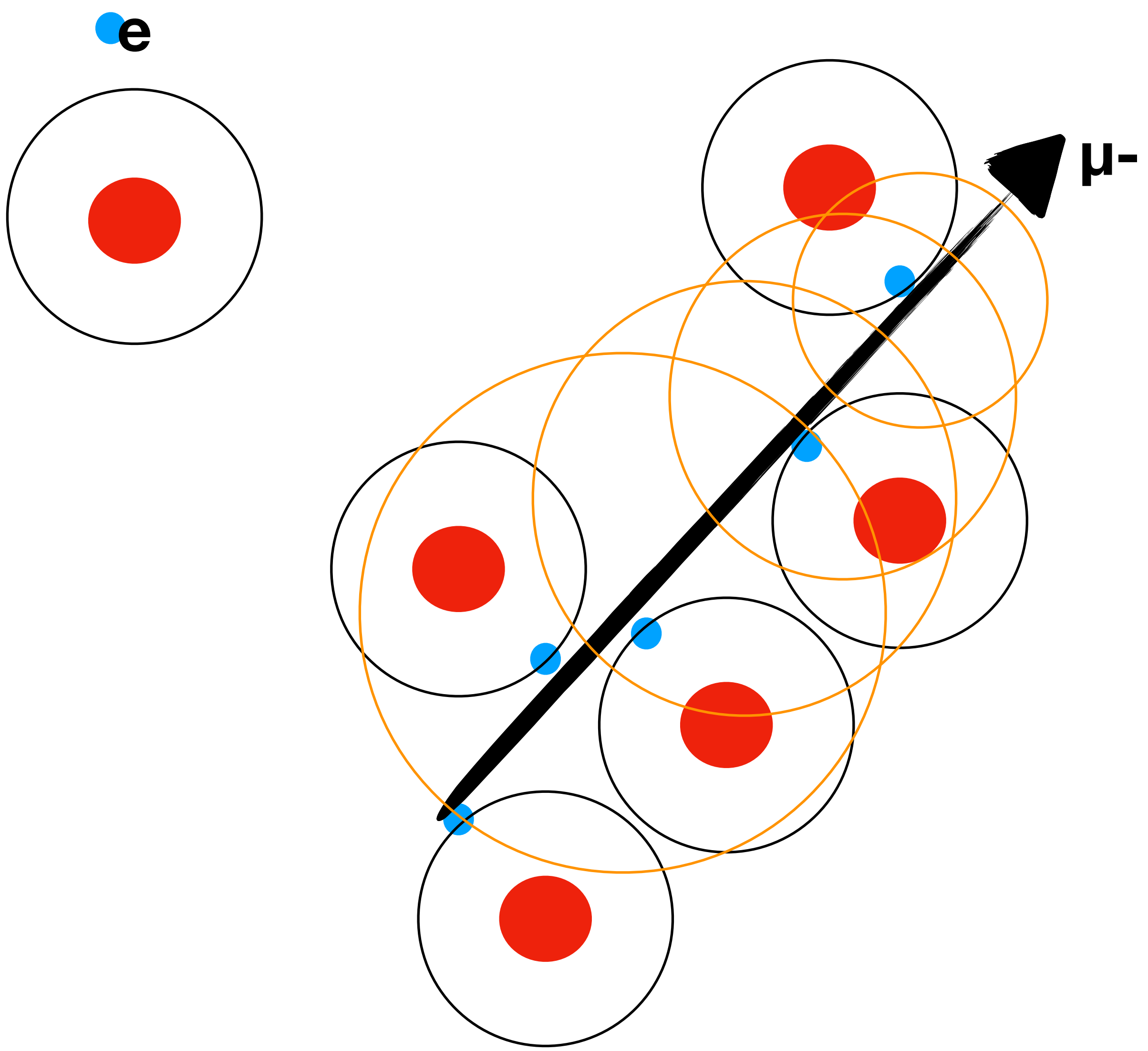
charged particle in a vacuum

- Take a charged particle (in this case a muon)



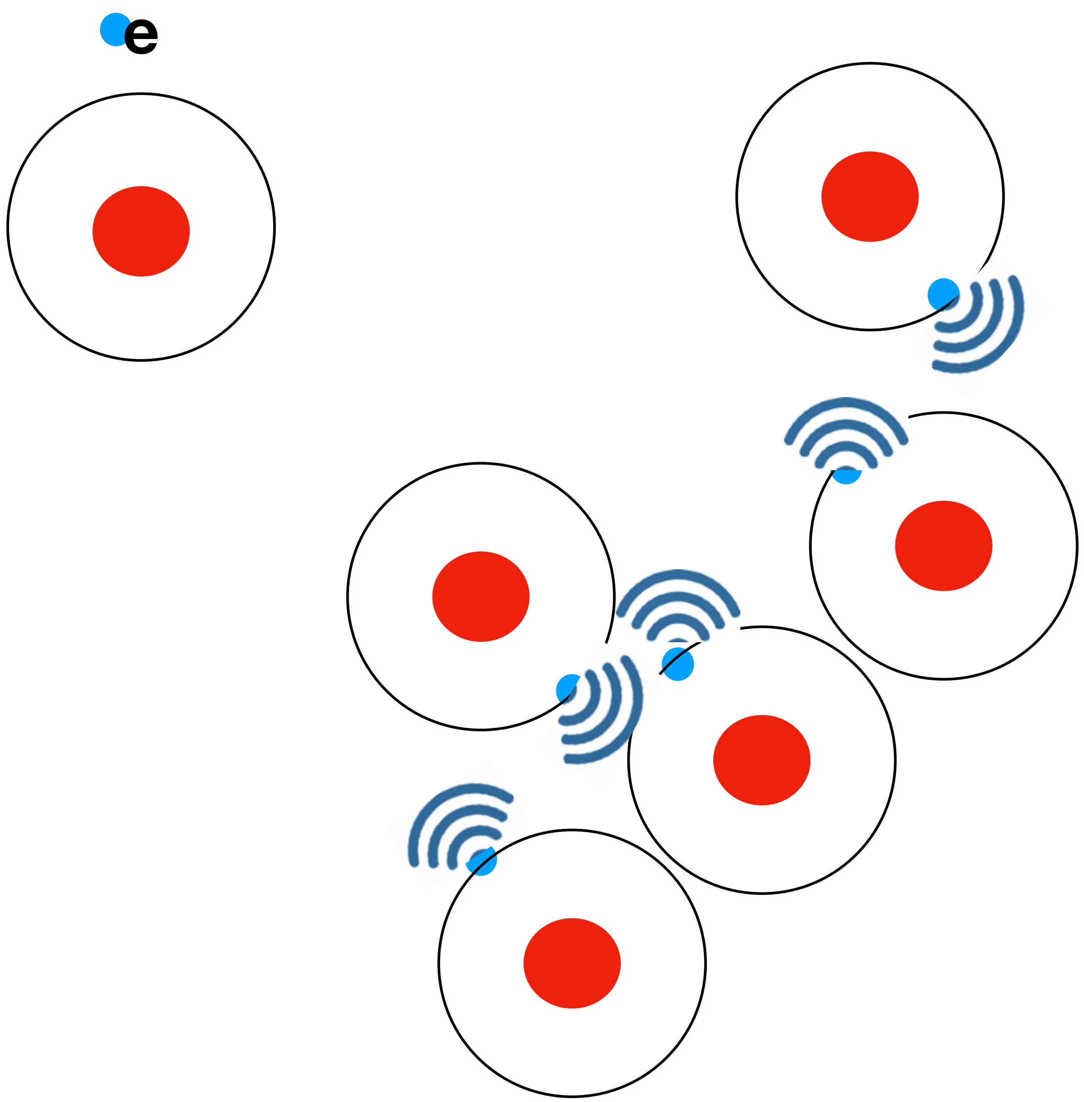
Charged particle in material

- Take a charged particle (in this case a muon)
- **Add a medium (with molecules containing atoms)**



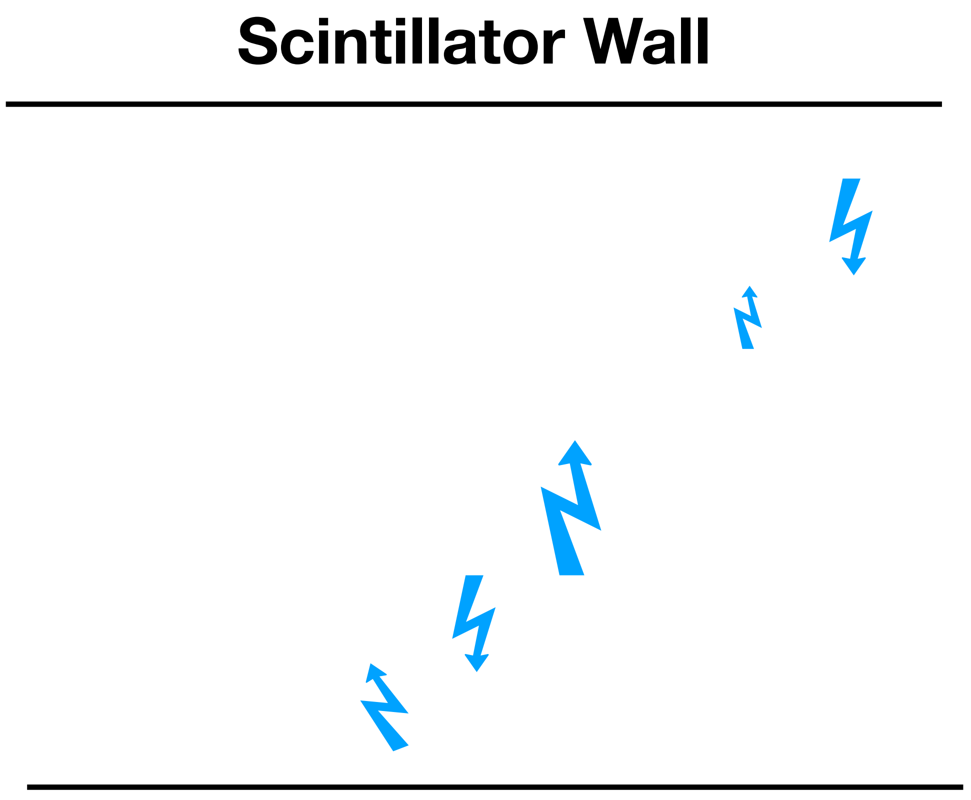
charged particle in scintillator

- Take a charged particle (in this case a muon)
- Add a medium (with molecules containing atoms)
- **Photon field excites valence electrons**



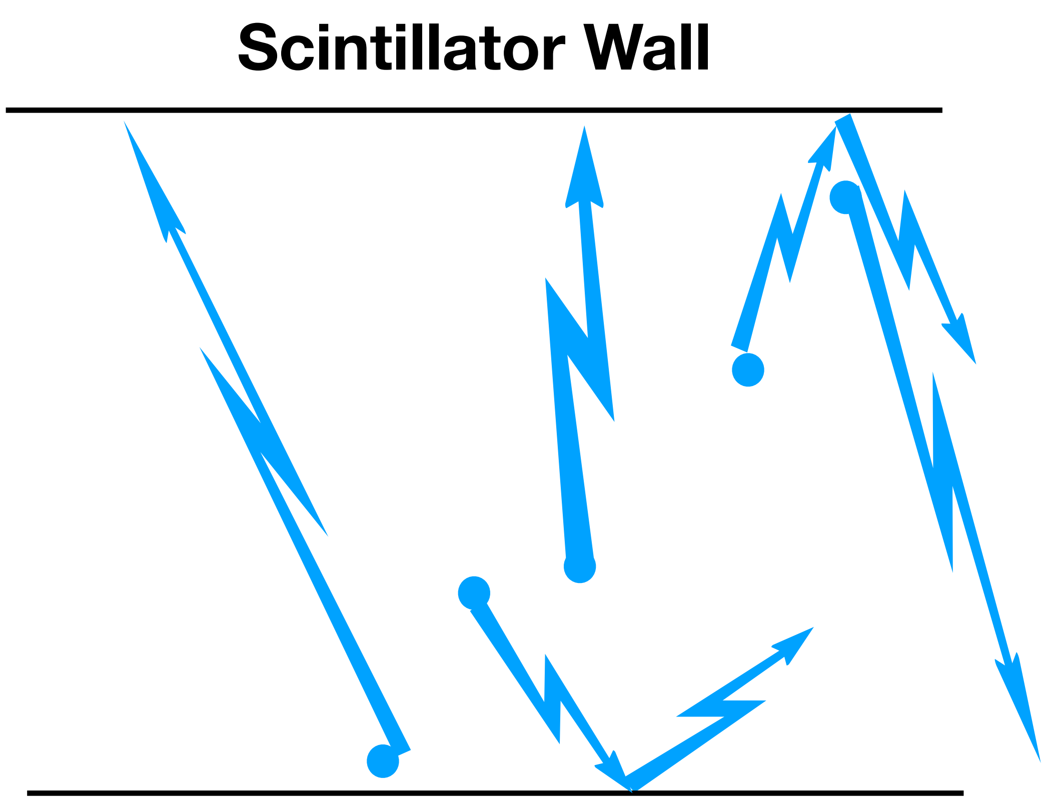
after the muon has gone

- Take a charged particle (in this case a muon)
- Add a medium (with molecules containing atoms)
- Photon field excites valence electrons
- **When they drop back, they give out photons which travel through the scintillator**



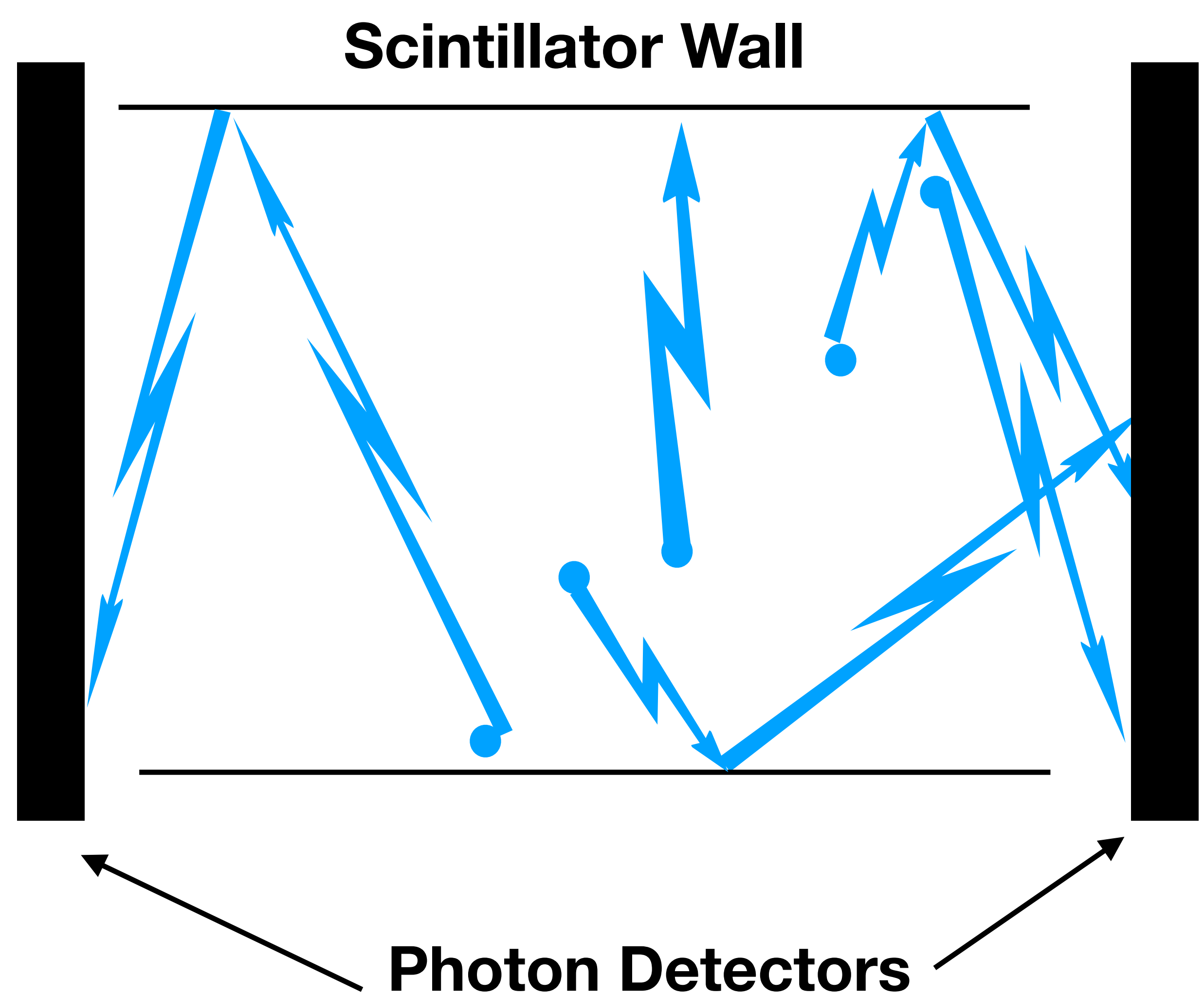
information left is photons

- Take a charged particle (in this case a muon)
- Add a medium (with molecules containing atoms)
- Photon field excites valence electrons
- When they drop back, they give out photons which travel through the scintillator
- **Photons travel to walls and bounce around**



Measure energy loss of muon: calorimeter

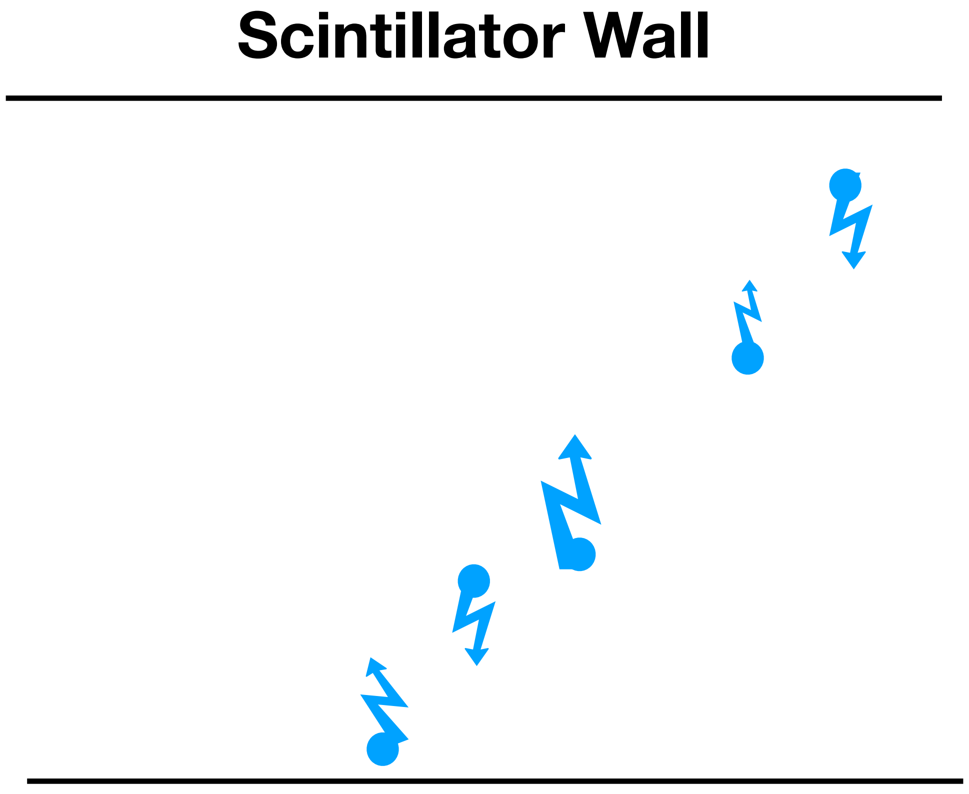
- Take a charged particle (in this case a muon)
- Add a medium (with molecules containing atoms)
- Photon field excites valence electrons
- When they drop back, they give out photons which travel through the scintillator
- **Count the photons at the ends**



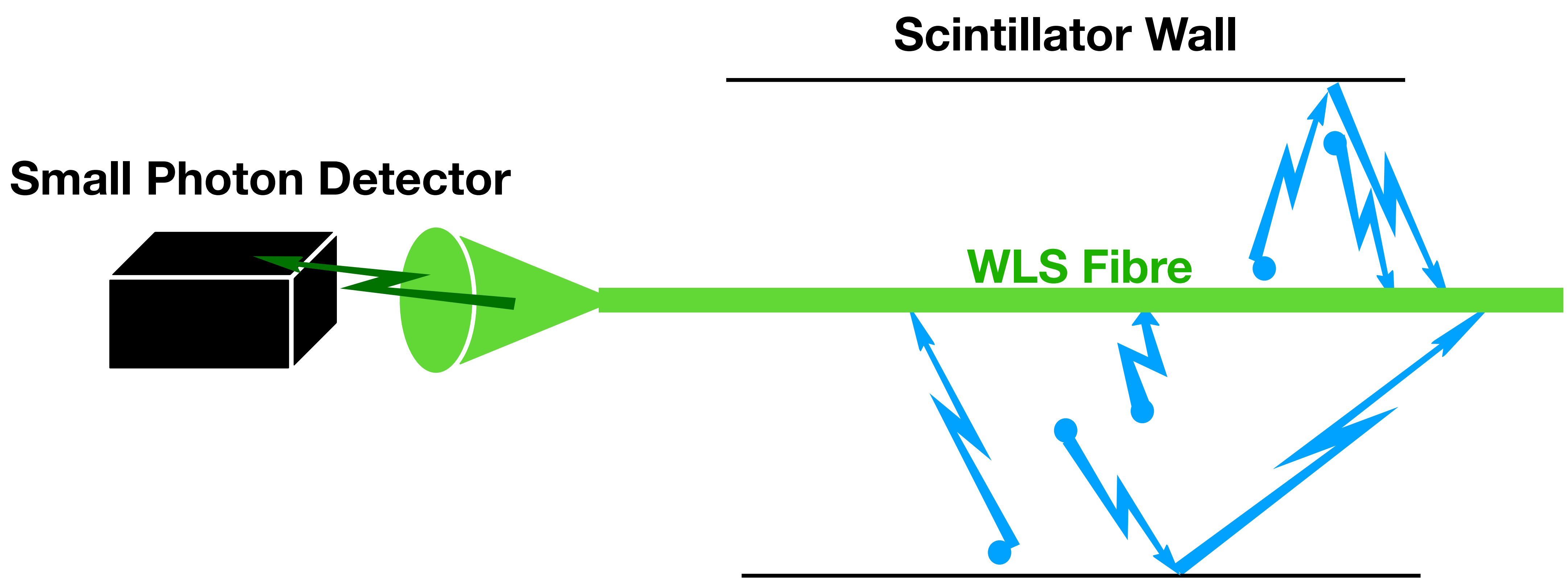
Number of photons is proportional to energy deposited

MINOS AND NOVA

- Take a charged particle (in this case a muon)
- Add a medium (with molecules containing atoms)



MINOS and NOVA



Wave Length Shifting (WLS) Fibre: Absorbs blue light and emits lower energy green
Collects light so easily steerable to a photon detector
Changes wavelength to better suit a given photon detector

MINOS

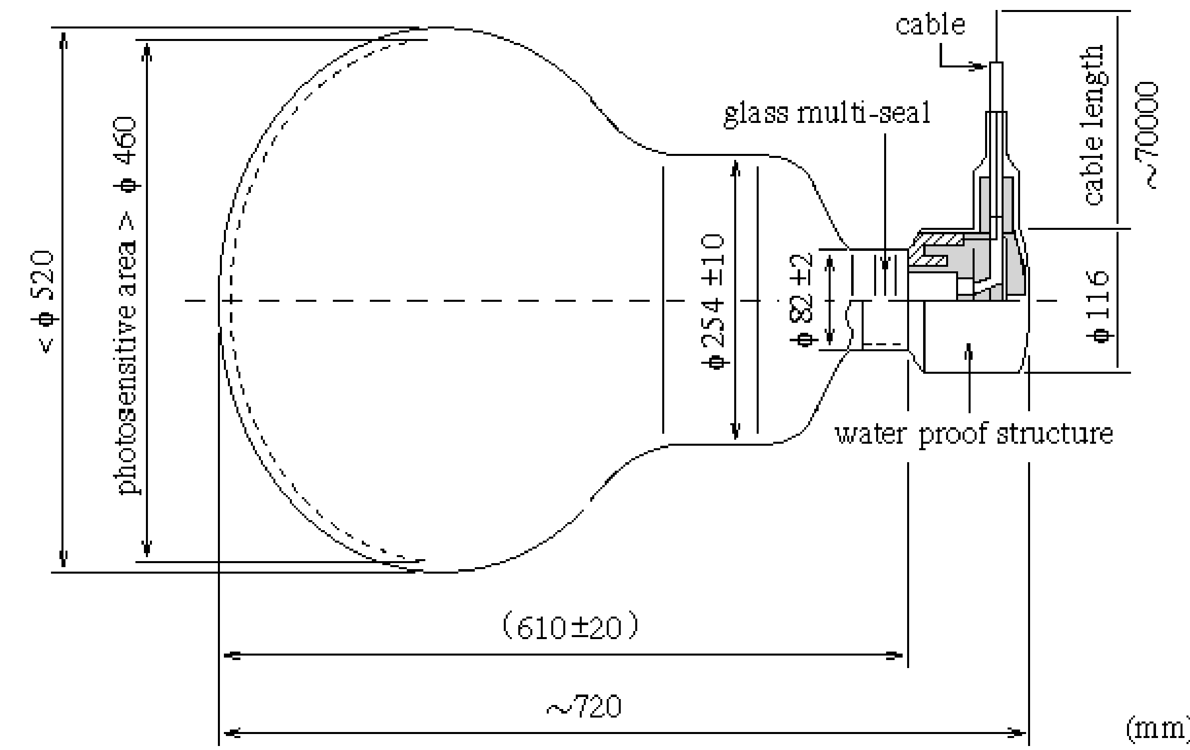
WLS Fibre

Hamamatsu M16
Multi-channel Photomultiplier

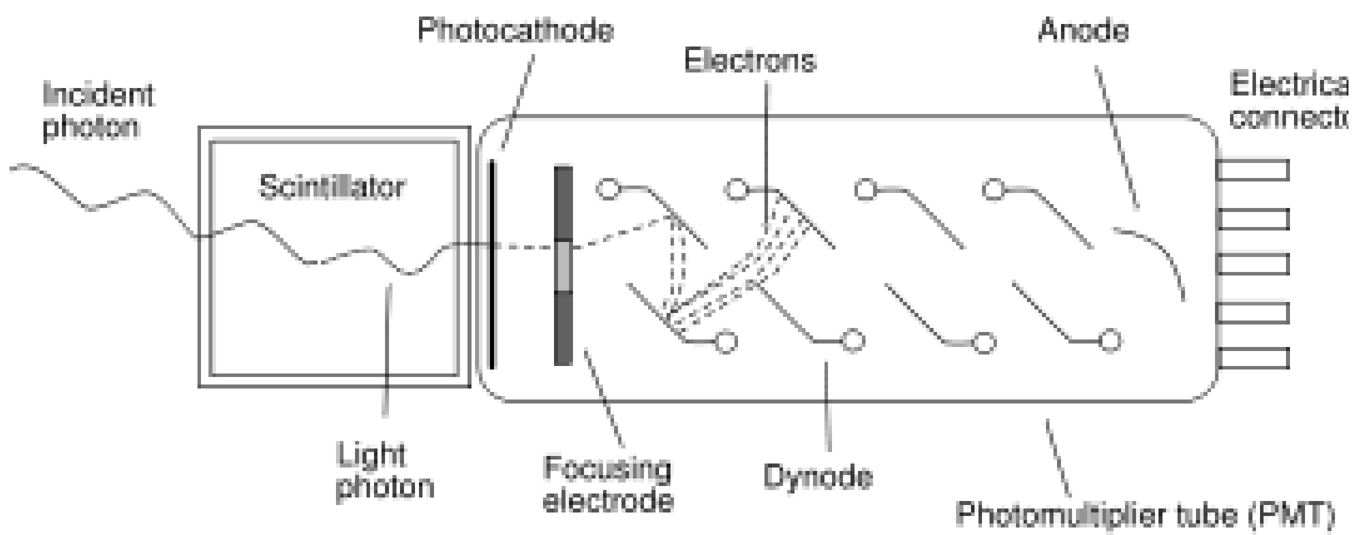
Photomultiplier tubes

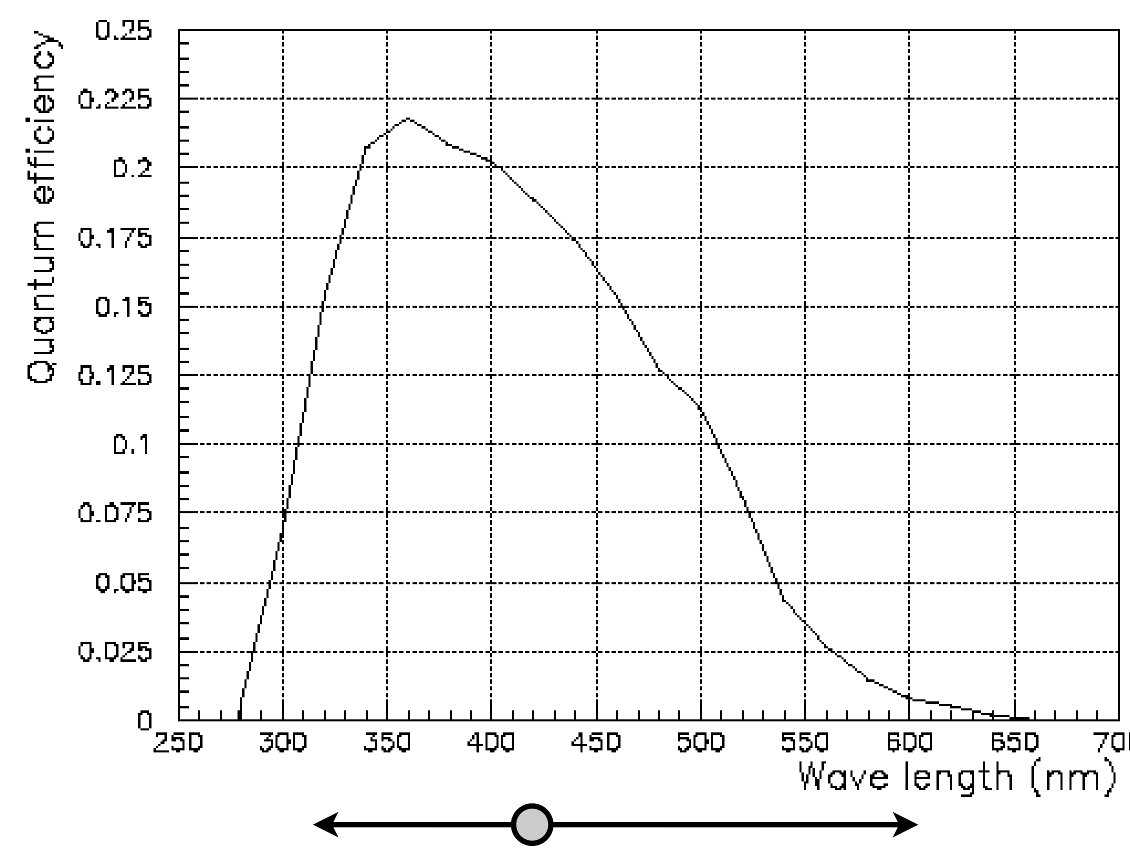
Photon incident on the ***photocathode*** produces a ***photo-electron*** via the photoelectric effect. Probability to produce a photoelectron is called the ***quantum efficiency*** of the PMT.

Output signal is seen as a current delivered to the ***anode***. Typical ***gains*** are 10^6 yielding pC-scale currents



100 ns transit time, 2.2 ns time resolution





wavelength of plastic scintillator photons

A series of plates called ***dynodes*** are held at high voltage by the *base* such that electrons are accelerated from one dynode to the next. At each stage the number of electrons increases. Probability to get first electron from the photocathode to the first dynode is called the ***collection efficiency***.

Photomultiplier tubes

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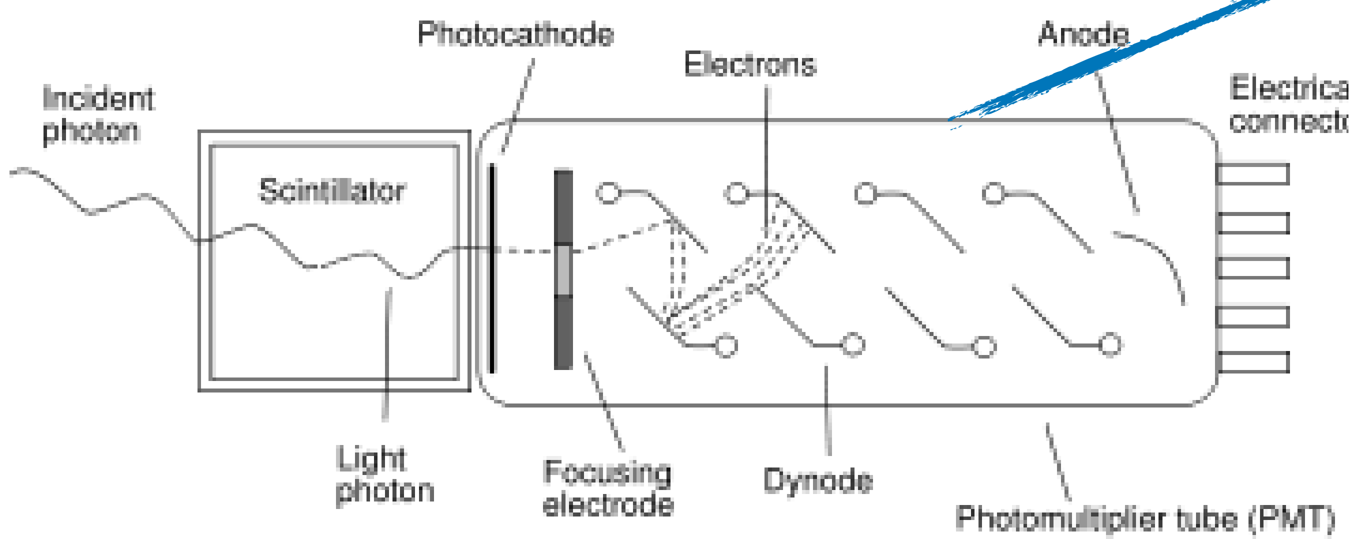

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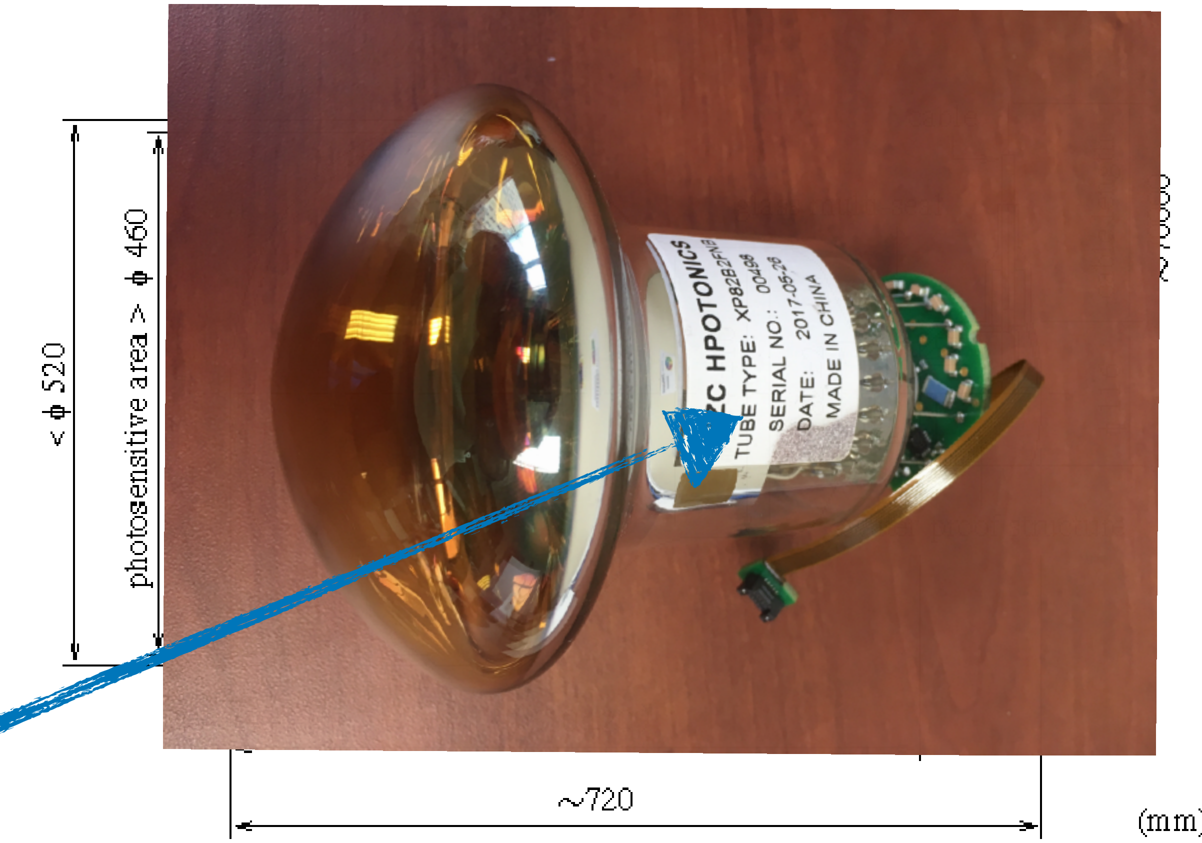
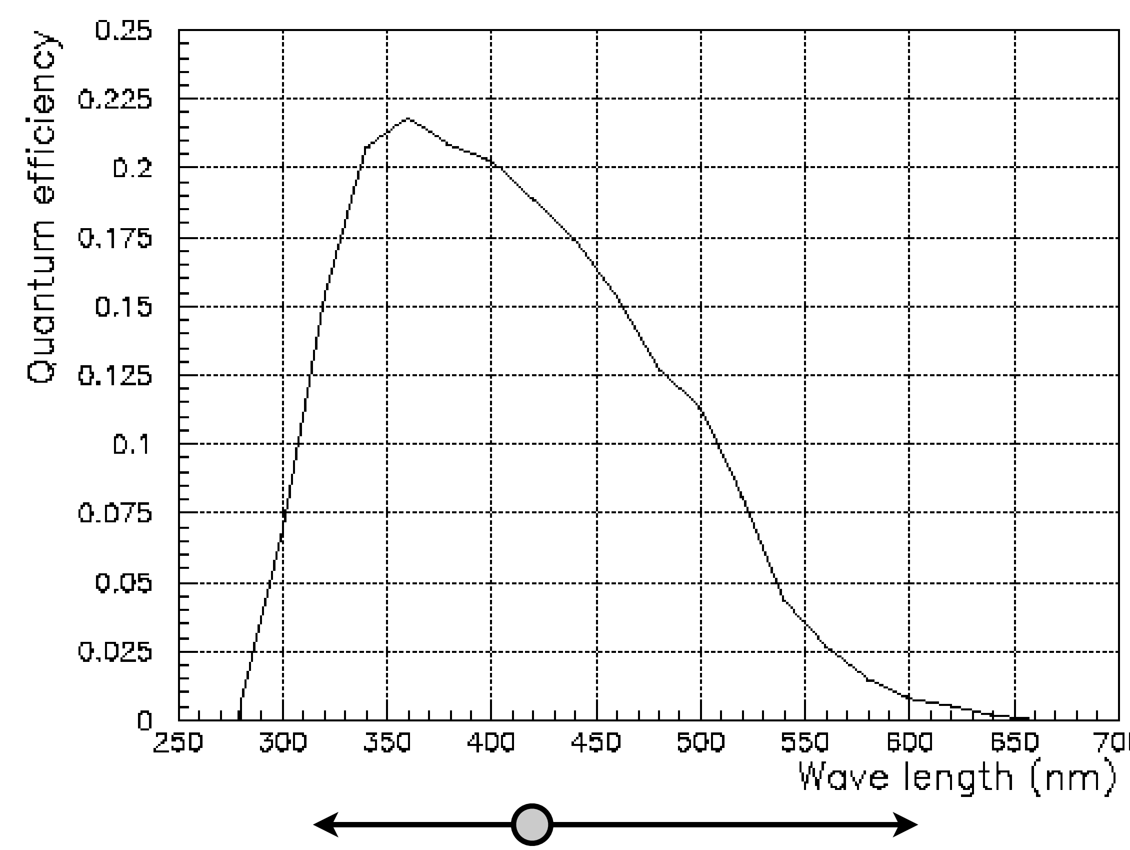


100 ns transit time, 2.2 ns time resolution



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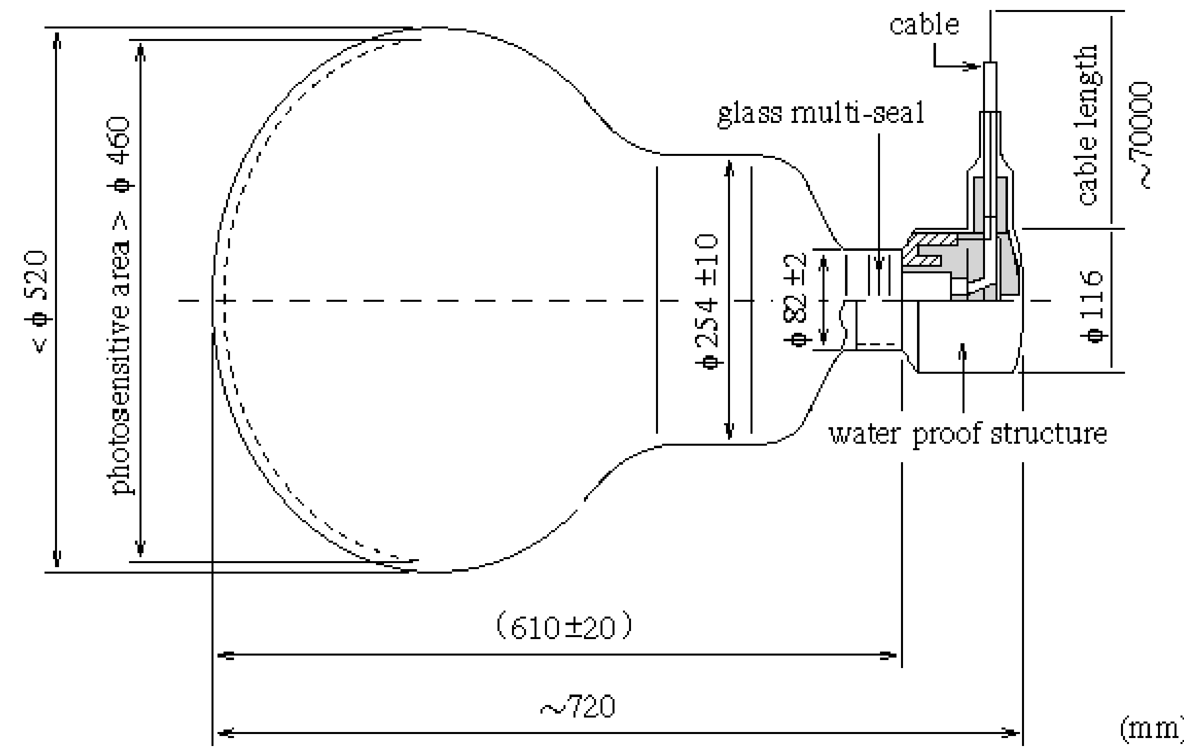

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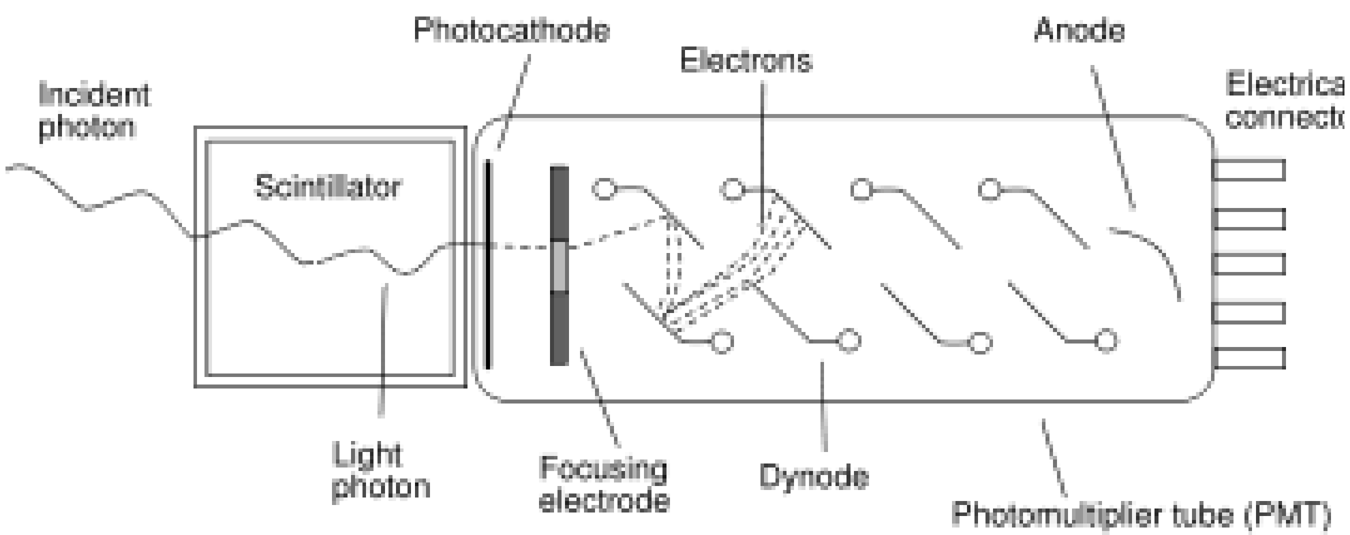

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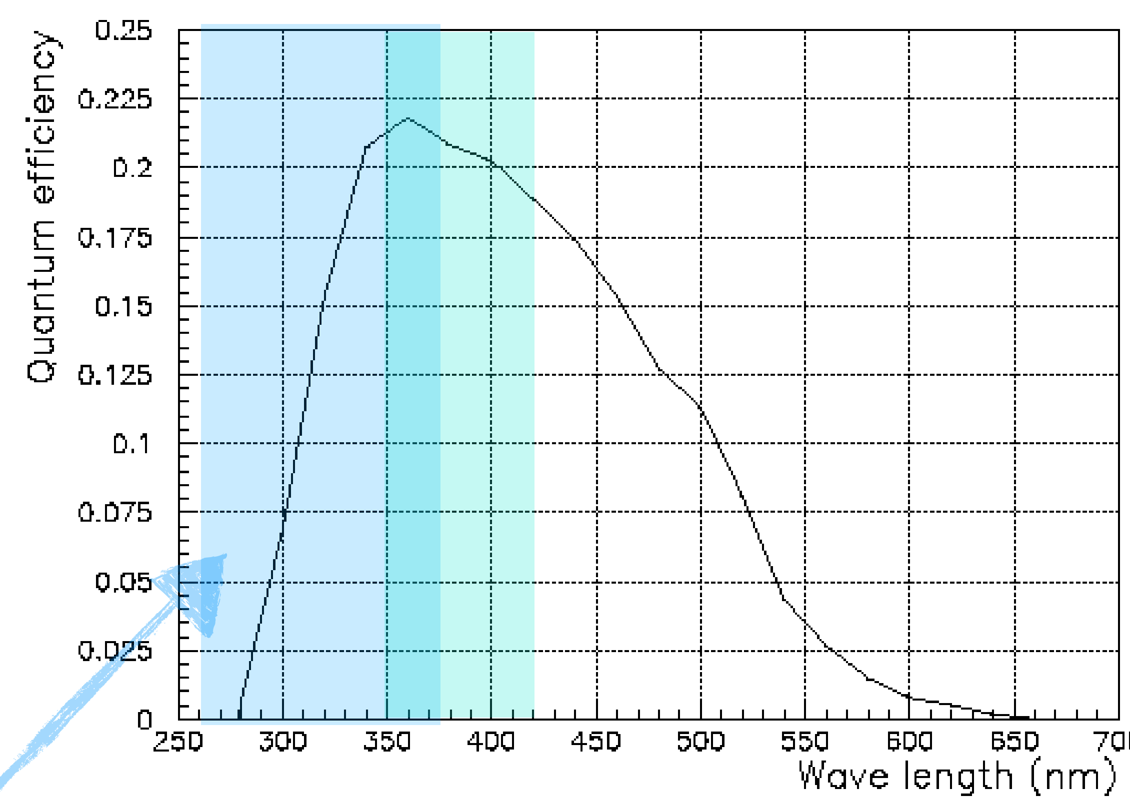

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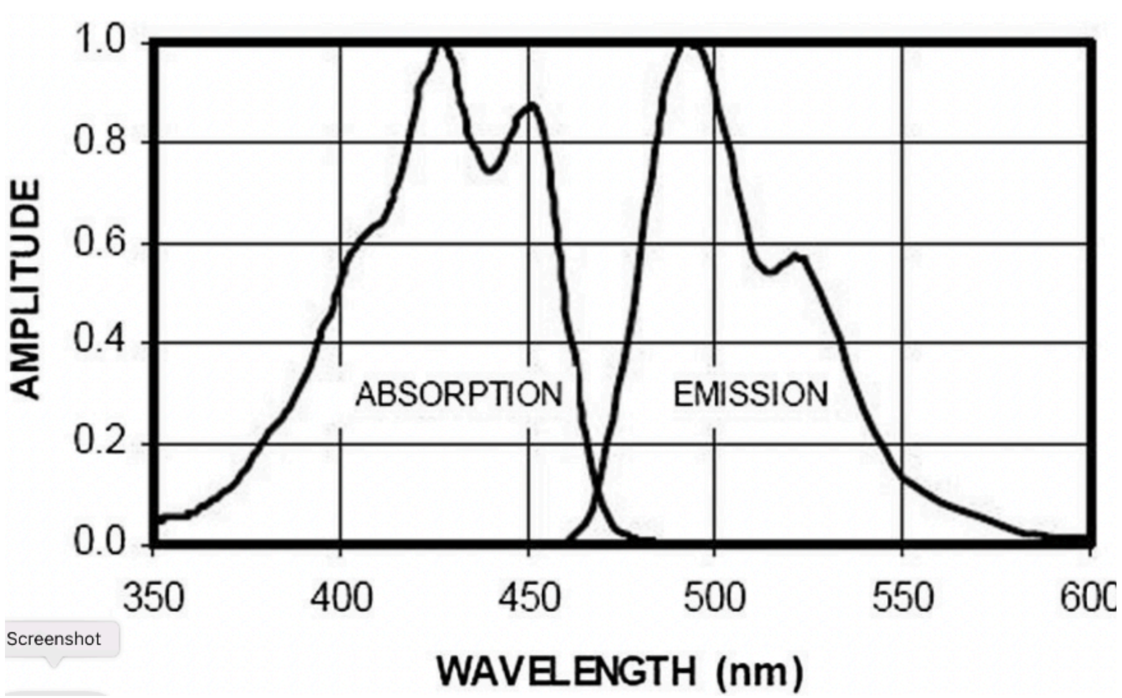
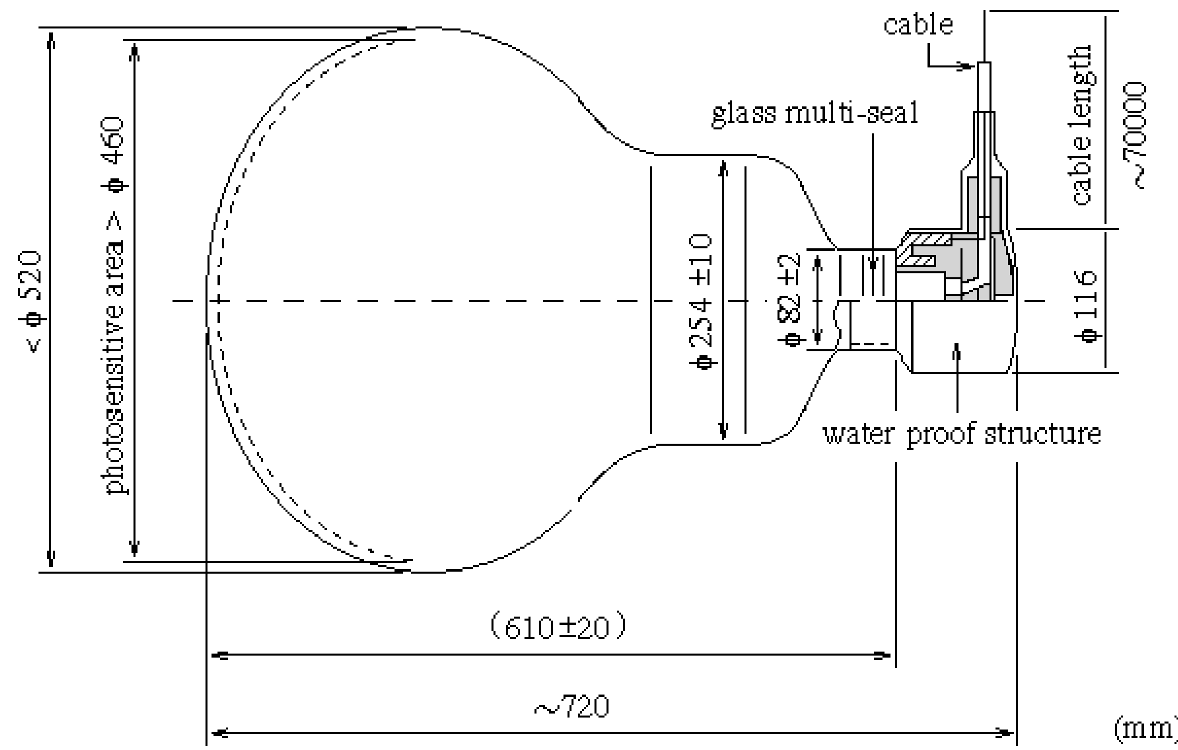
scintillator absorbs here

wavelength of plastic scintillator photons

Wavelength matters





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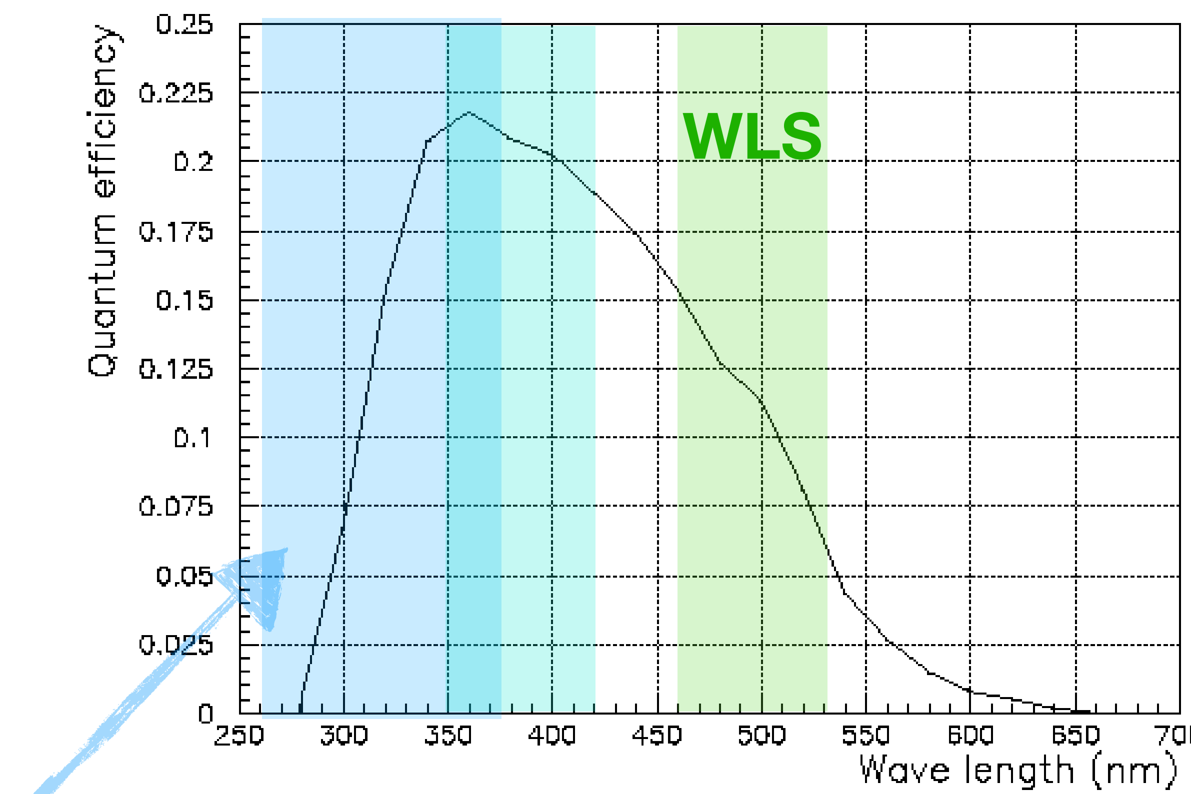

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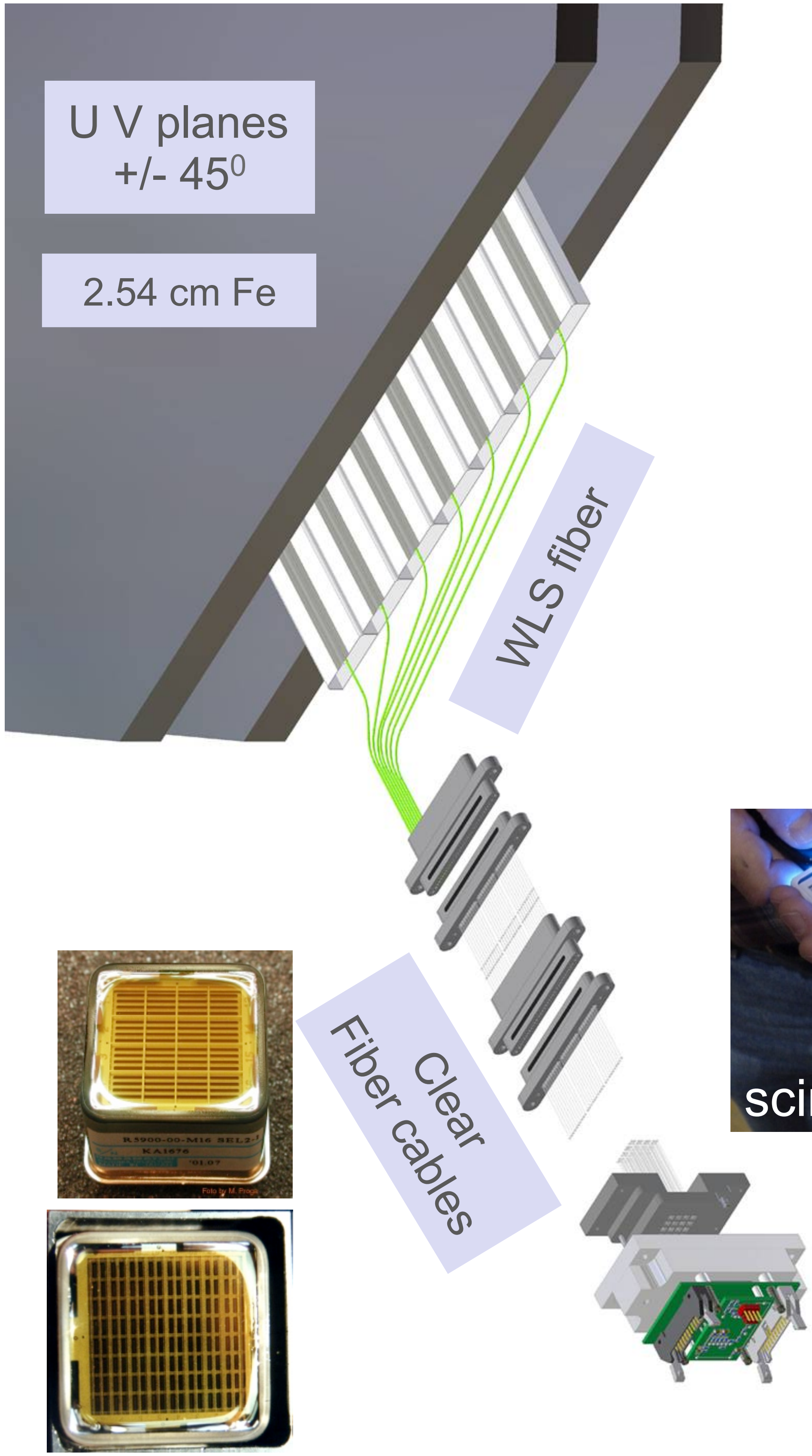
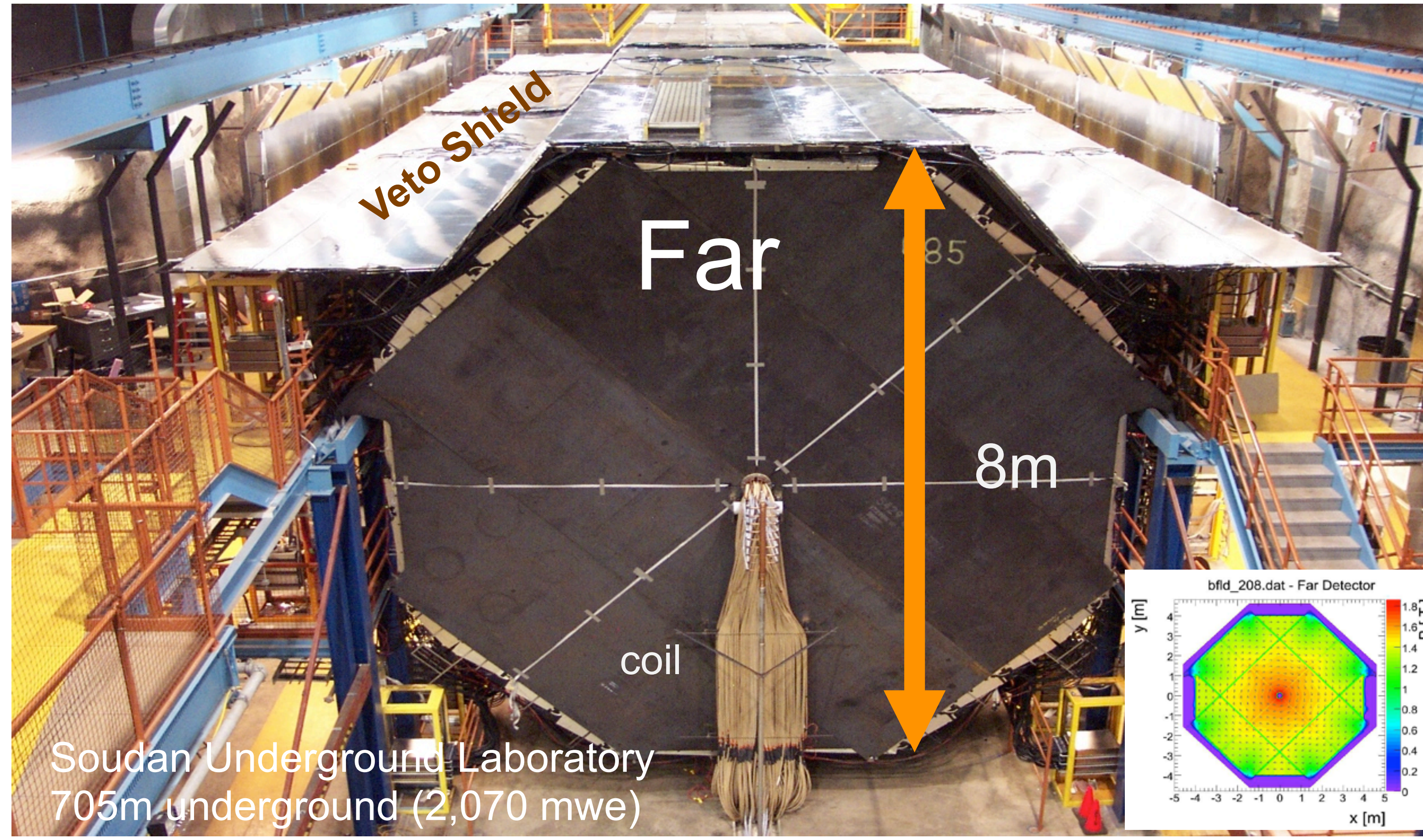
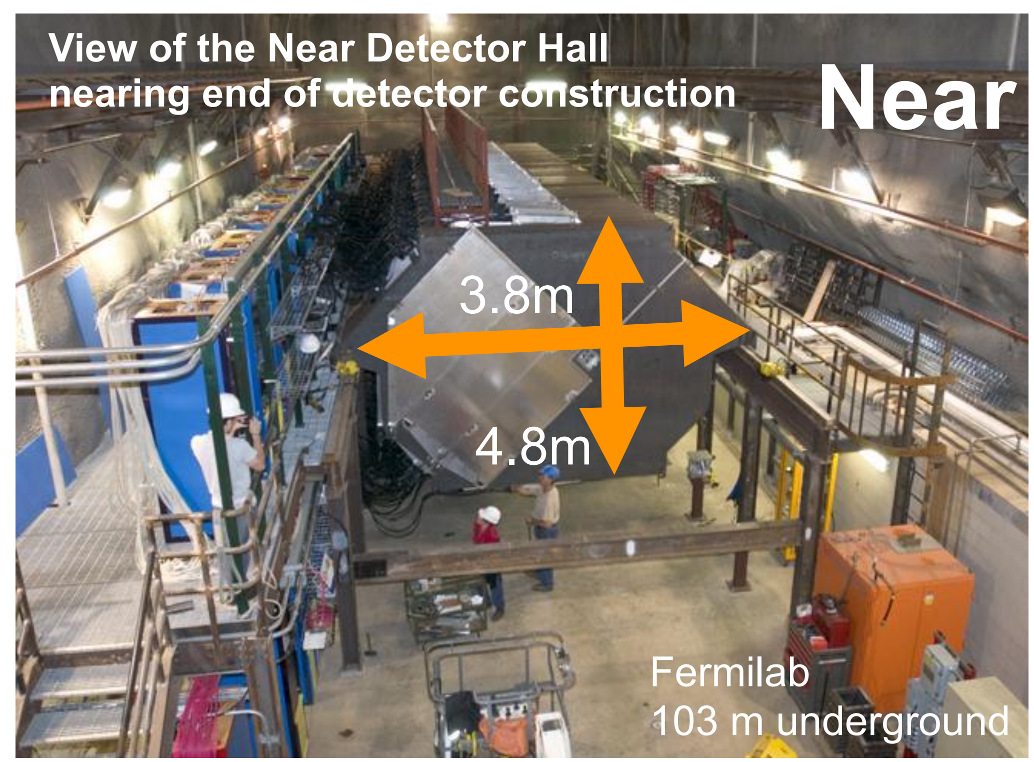
wavelength of plastic scintillator photons

MINOS

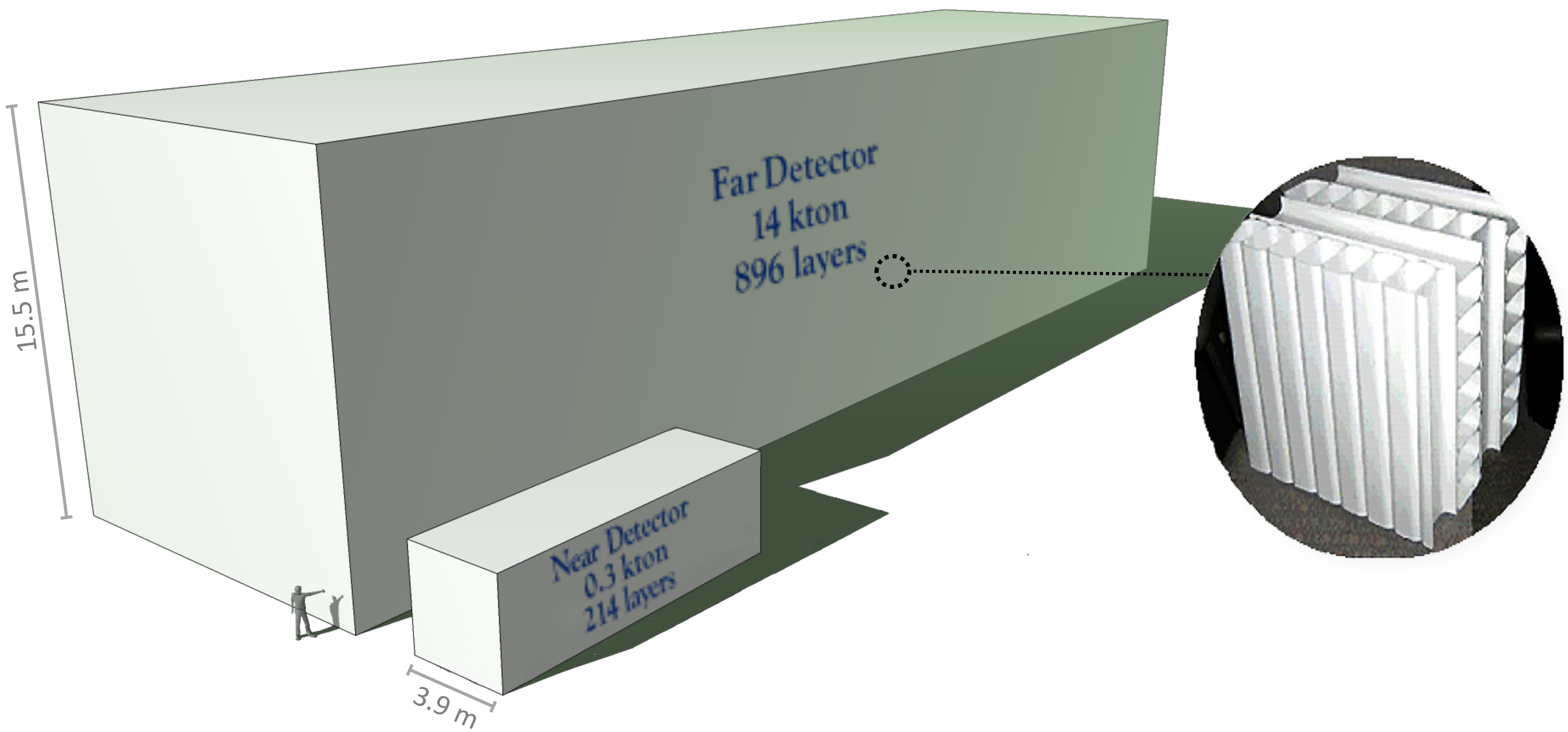

U V planes
+/- 45⁰
2.54 cm Fe
WLS fiber
Clear
Fiber cables

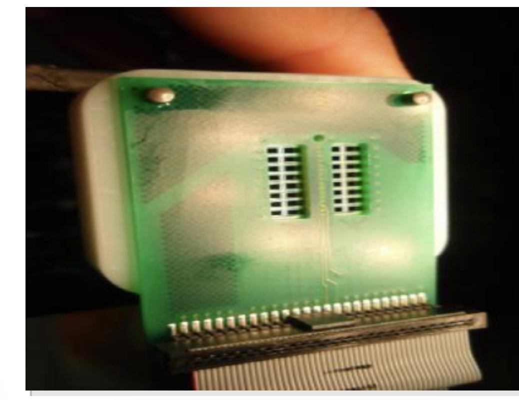

scintillator

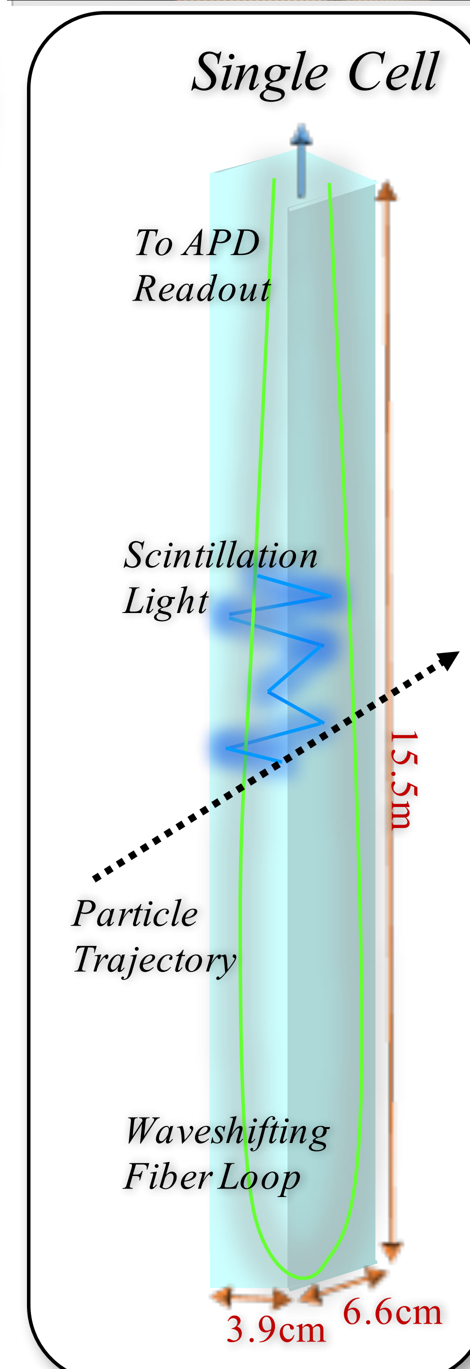

Veto Shield
Far
8m
coil
Soudan Underground Laboratory
705m underground (2,070 mwe)
bfld_208.dat - Far Detector
y [m]
x [m]
B [T]


View of the Near Detector Hall
nearing end of detector construction
Near
3.8m
4.8m
Fermilab
103 m underground

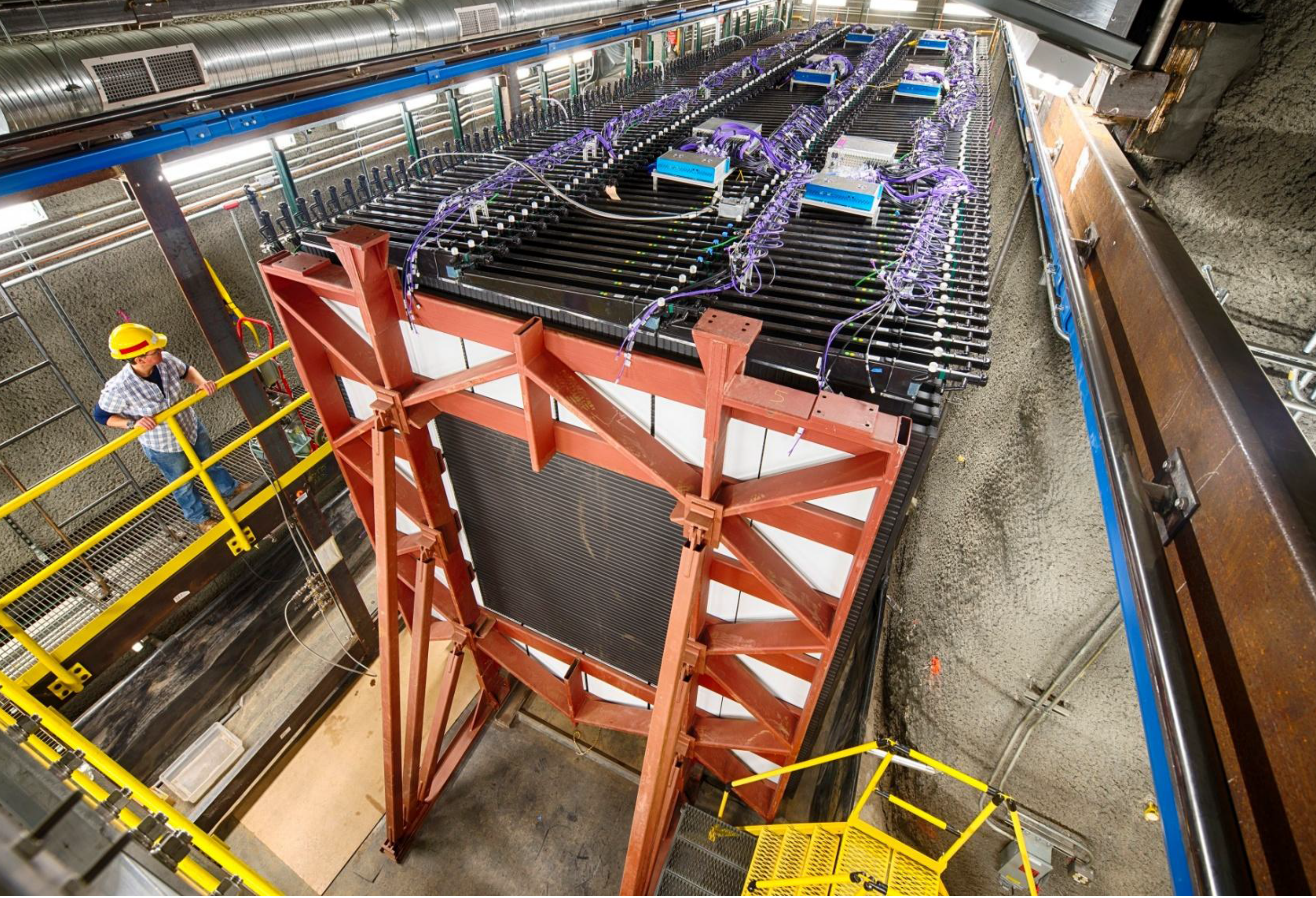
NOvA Detectors





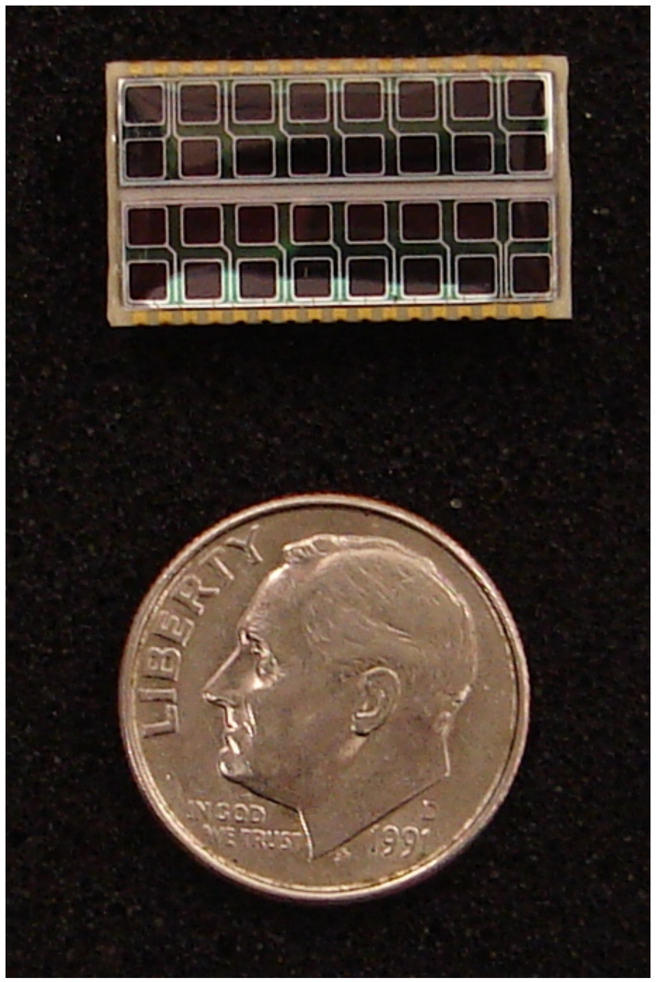


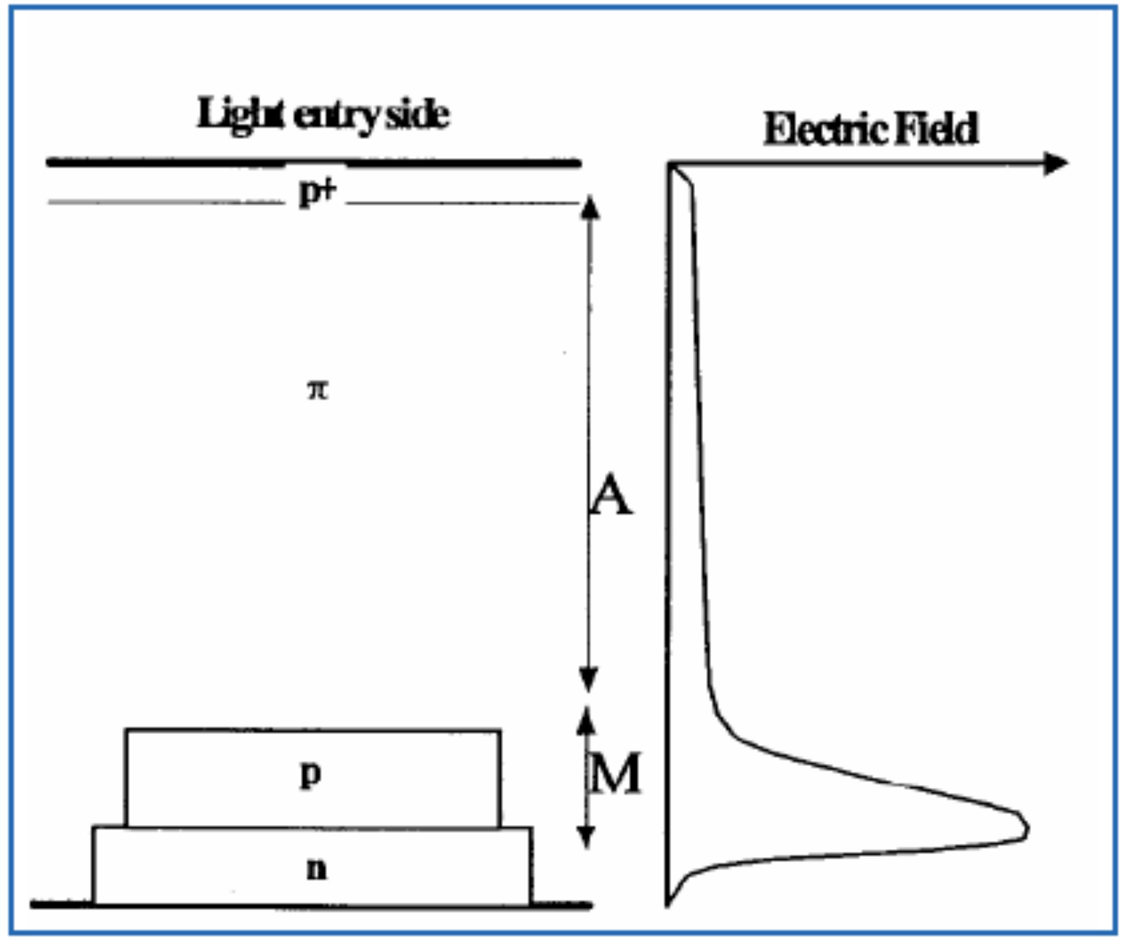
- Two functionally identical detectors (to measure before and after oscillations *not part of this talk)
- Extruded plastic cells alternating vertical and horizontal orientation filled with **liquid** scintillator
- Charged particles passing through cells produce light which is collected by a wavelength shifting fibre and read out with an **Avalanche Photo-Diodes**



NOVA

Avalanche photo diodes (APD)





Absorption region

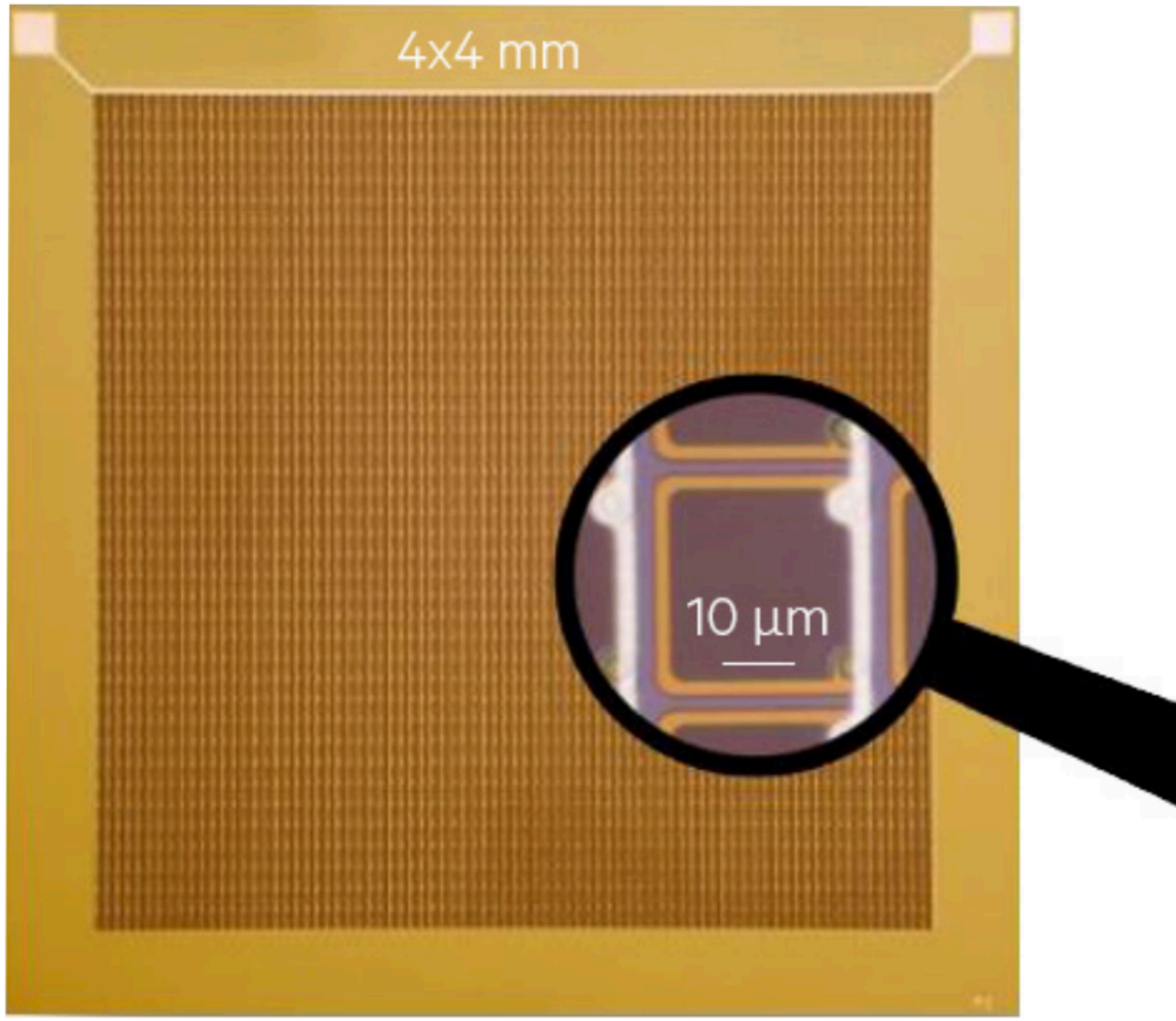
Multiplication region

High (80%) quantum efficiency even into UV
Large dark currents - must be cooled to -10°C to get noise down to ~10 pe equivalent
Low gains, x100

Silicon Photomultipliers - SiPMs (MCCP??)

- Large array of small APDs pixels.
- Each APD pixel is operated slightly above the breakdown voltage (Geiger mode)
- When light is incident on a pixel it initiates an avalanche within the pixel, multiplying with a gain of $\sim 10^6$ up to a maximal current set by either an active of passive quenching circuit.
- The output is proportional to the number of activated pixels which gives a count of the number of photoelectrons.

Figure 1



https://www.first-sensor.com/cms/upload/appnotes/AN_SiPM_Introduction_E.pdf

Silicon Photomultipliers - SiPMs

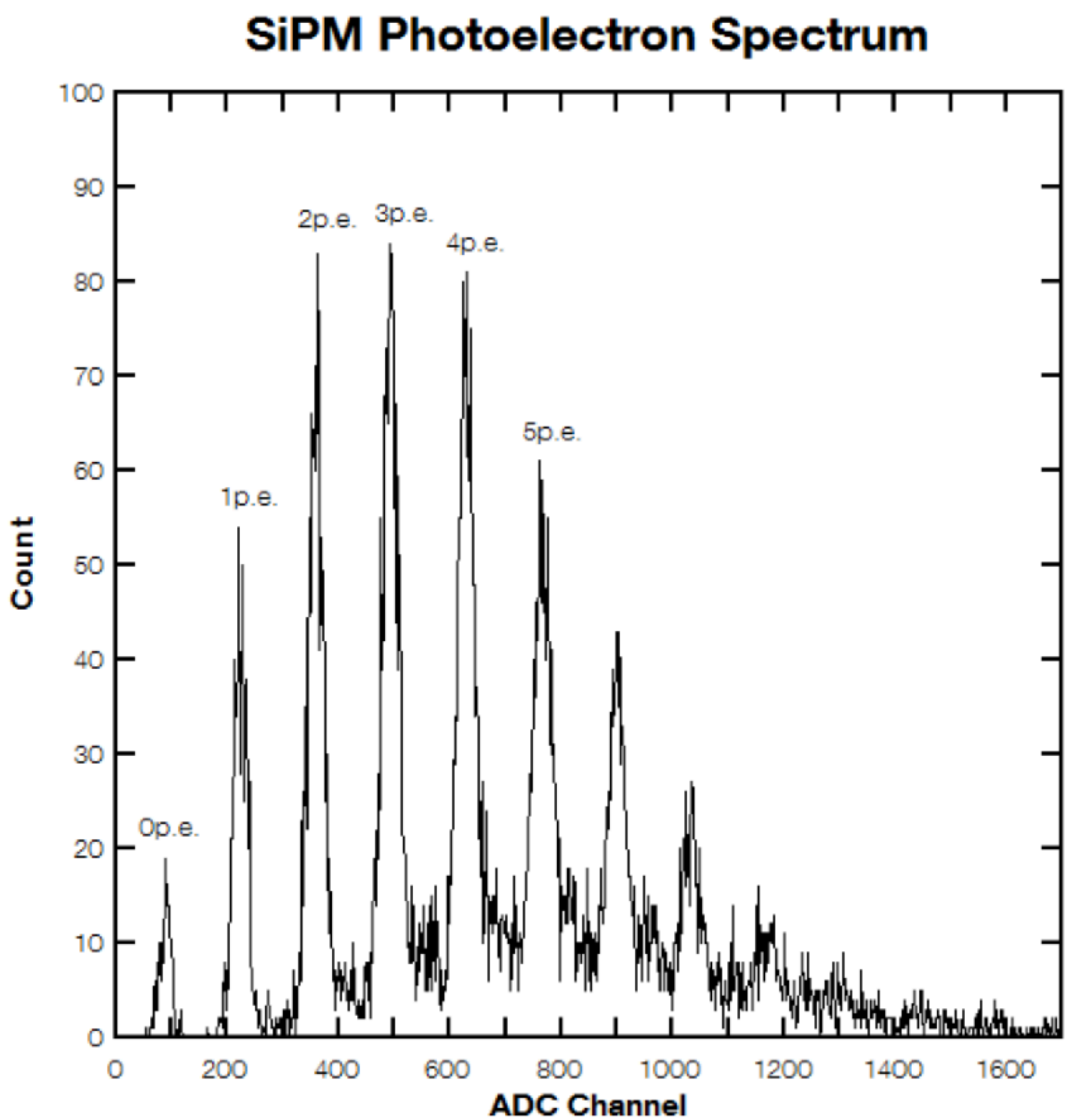


Figure 7, Photoelectron spectrum of the SiPM, achieved using brief, low-level light pulses, such as those from Fig. 6.

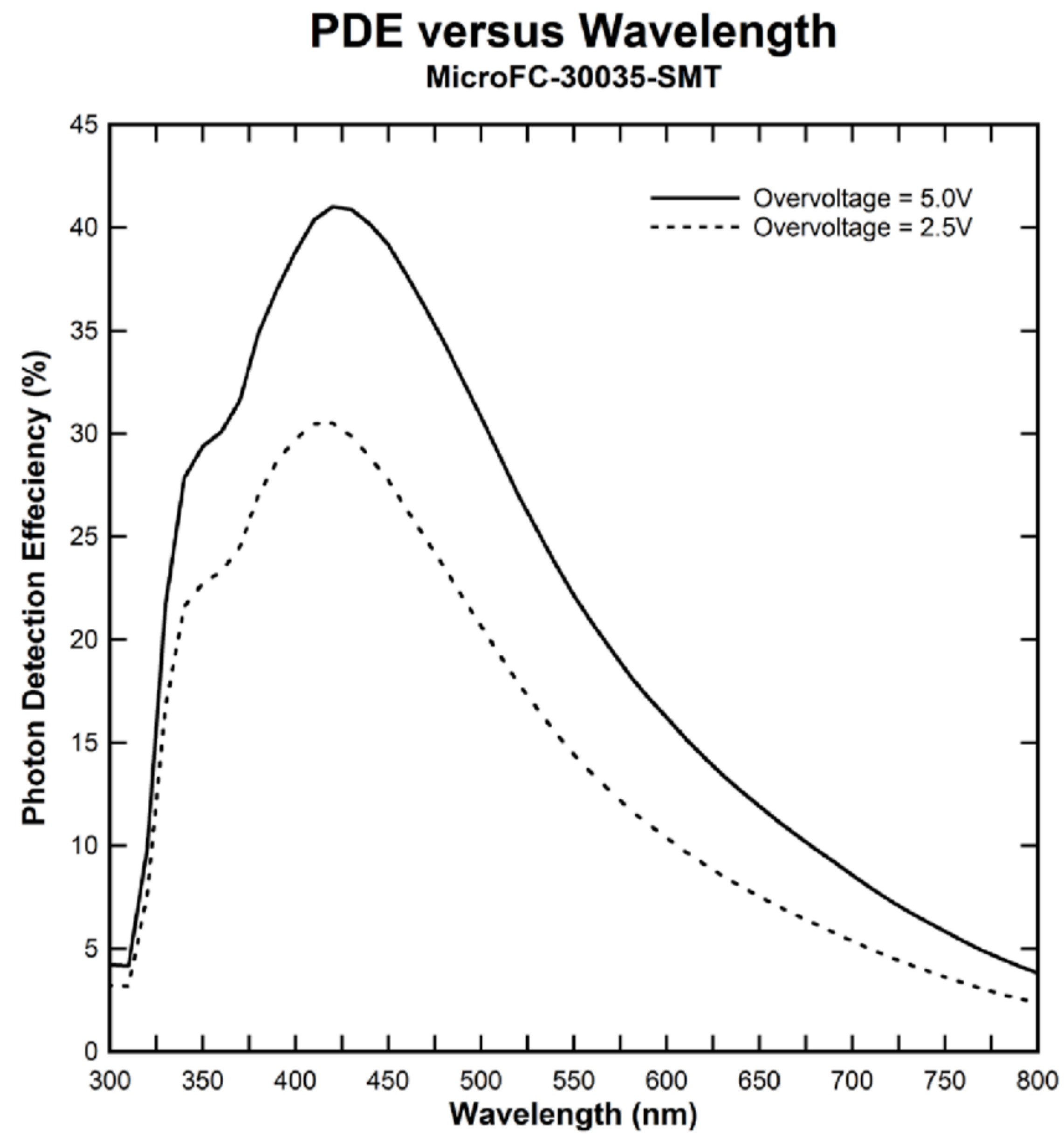
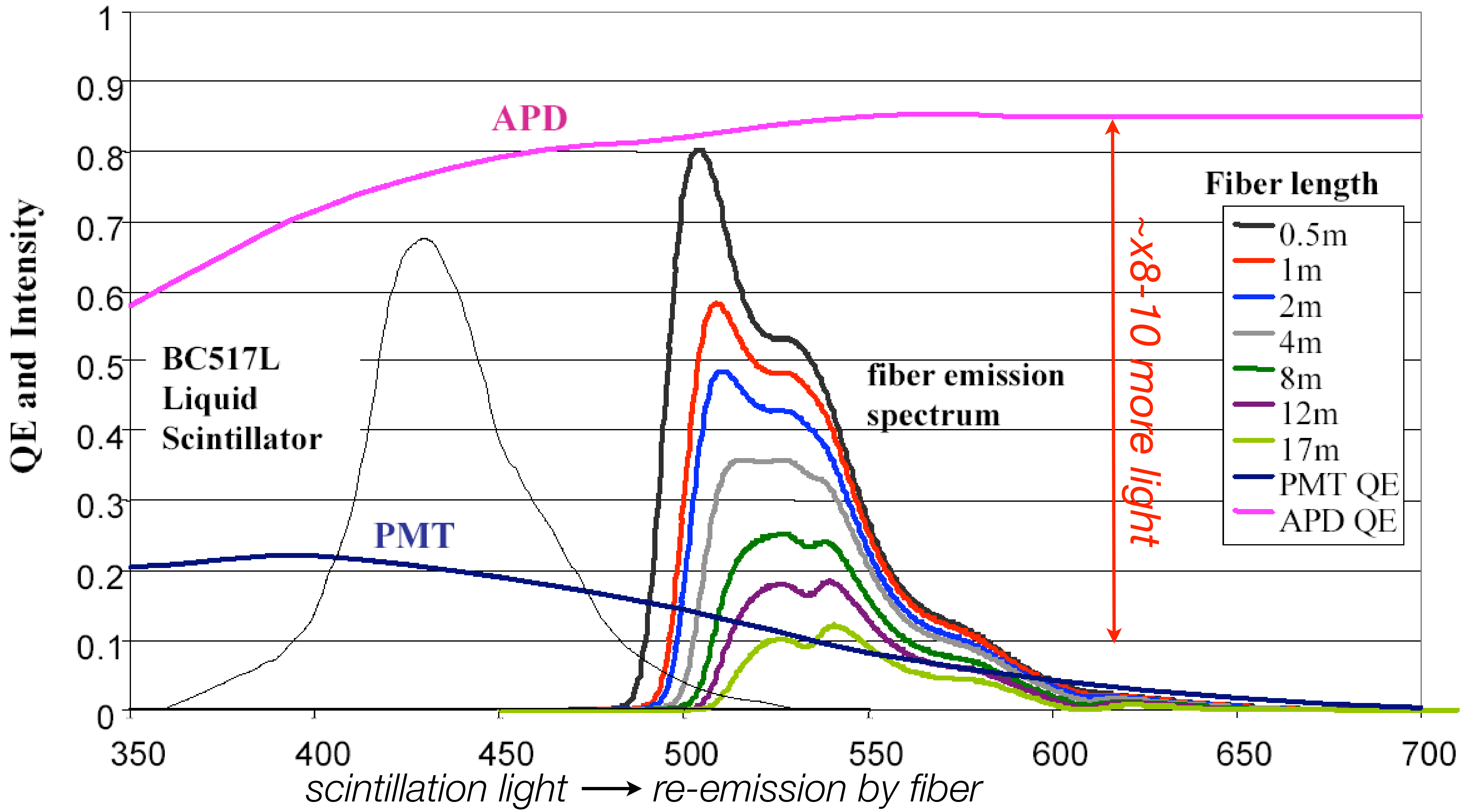


Figure 16, PDE as a function of wavelength for different overvoltages.

https://www.sensl.com/downloads/ds/TN%20-%20Intro%20to%20SPM%20Tech.pdf

NOvA Fiber and Photodetector

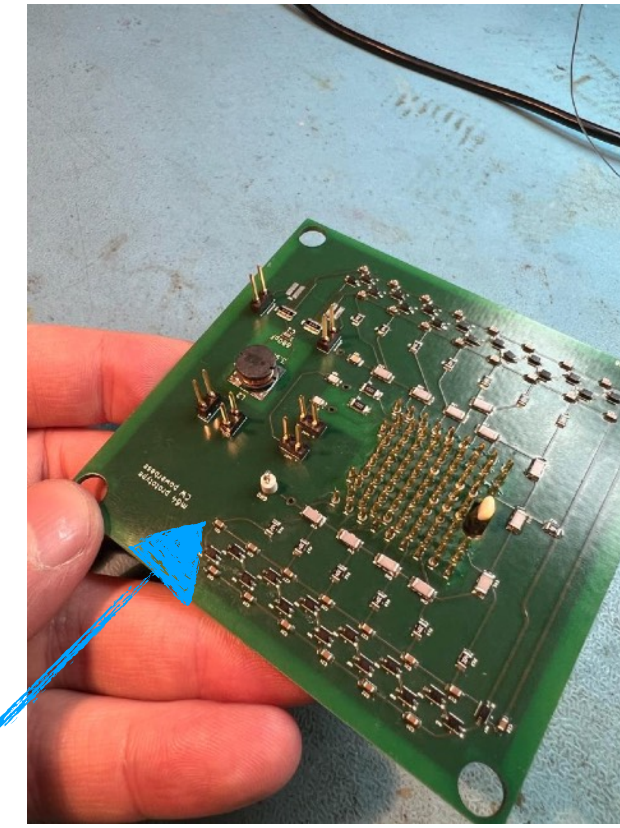


The high QE of APD's, especially at long wavelength, is crucial to NOvA performance

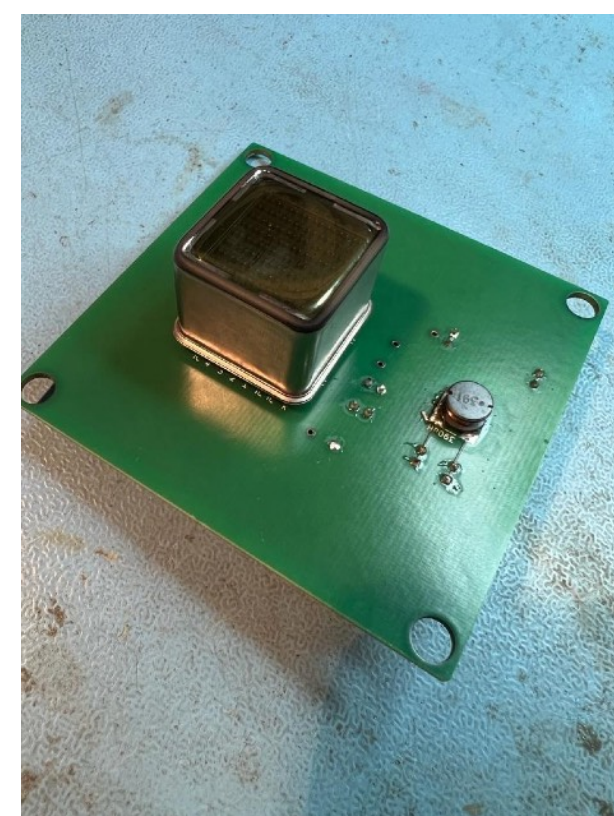
The Analysis

- Once the photo detectors register the light, **electronics** are needed to turn analog signal into bytes
- This is a whole talk by itself, involving electronic components
    - ADC = Analoge to Digital converter
    - ToT = Time over threshold
    - Discriminators, thresholds, noise levels, dead time ….
    - Electronics boards, Cockroft Walton HV circuits

saves money and space on cables and costly HV units



3.3V in, 800V out



The Analysis

- Once the photo detectors register the light, **electronics** are needed to turn analog signal into bytes
- After you have bytes, you have to arrange what they mean to see patterns
- Look at total charge for dE/dx and position of each strip

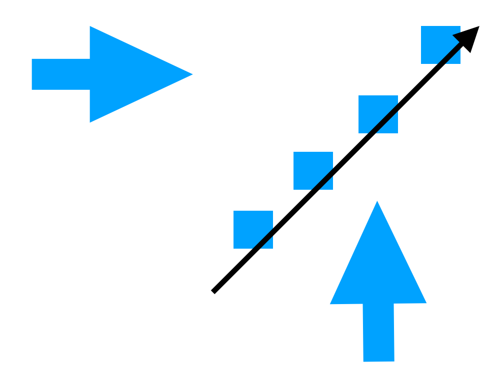
00F3B142 →

F3 : CODE OF PHYSICAL POSITION

B1 : CODE OF TIME OF HIT

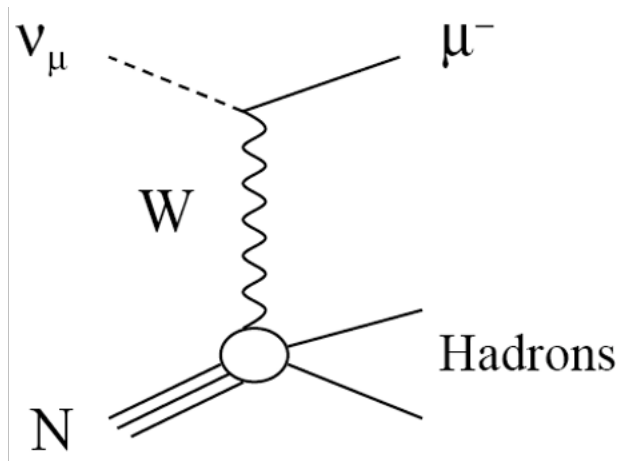
42 : CODE OF TOTAL LIGHT OF HIT

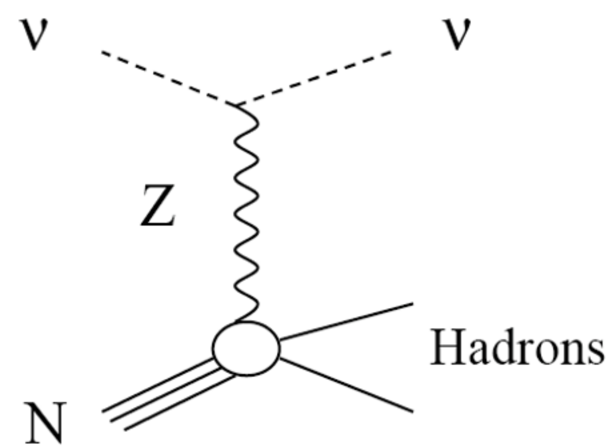
DECODE

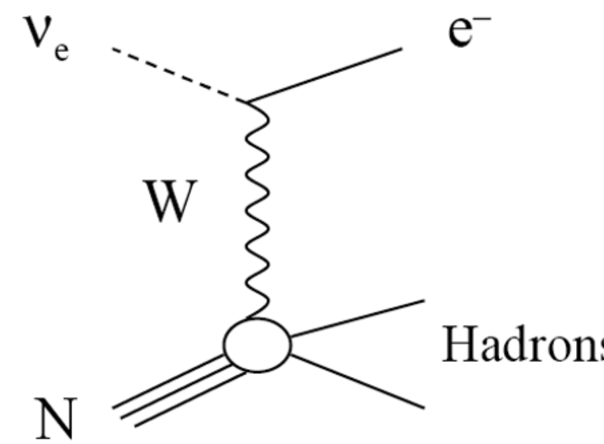


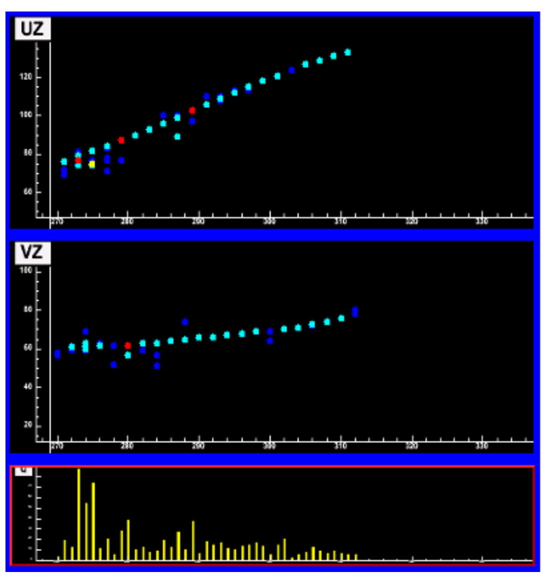
FIND BEST LINE

MINOS events



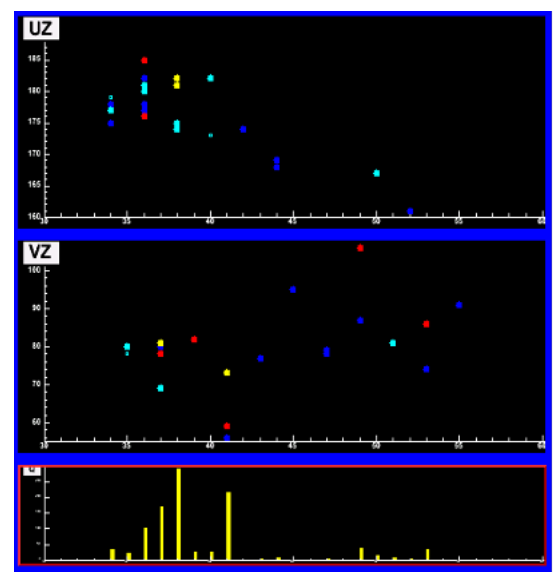






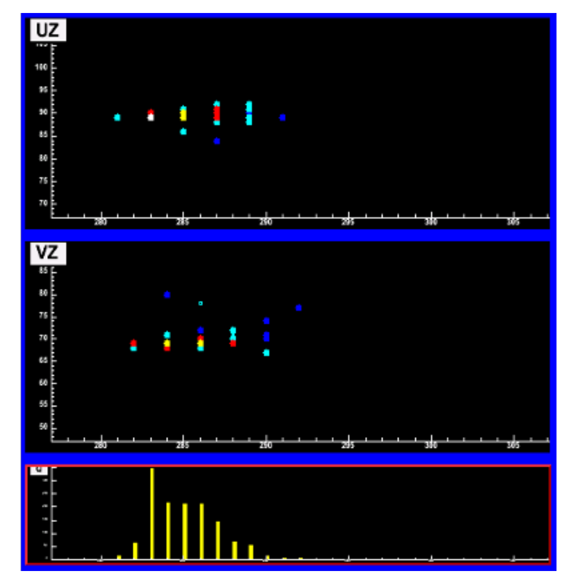
60 planes

long μ track+ hadronic activity at vertex



10 planes

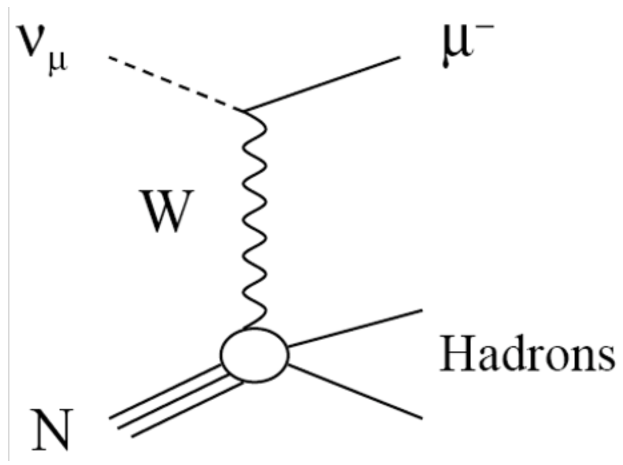
short event, often diffuse

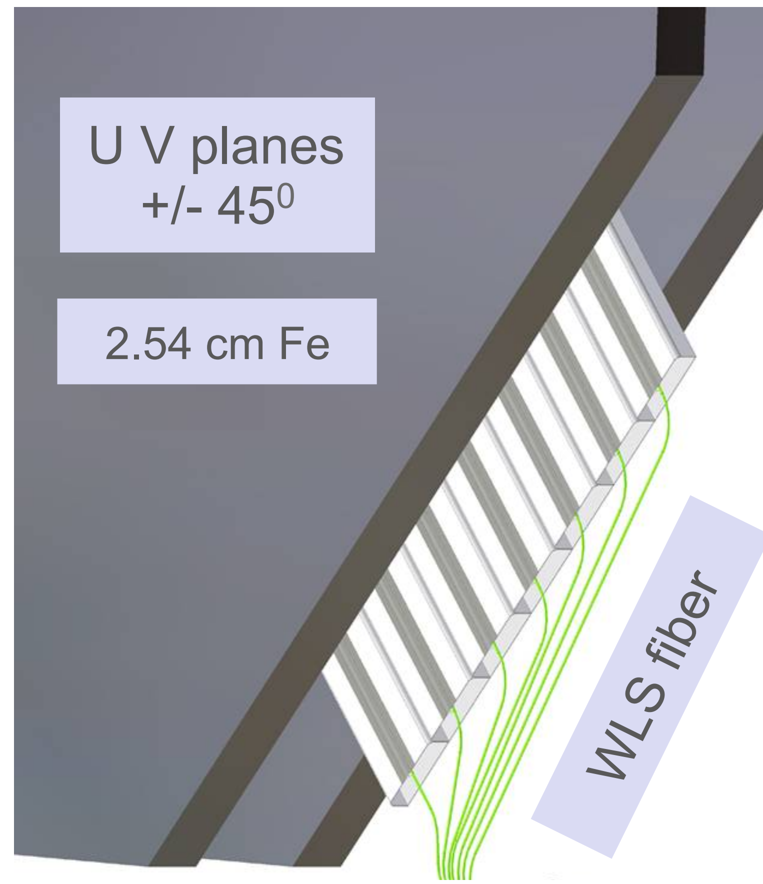


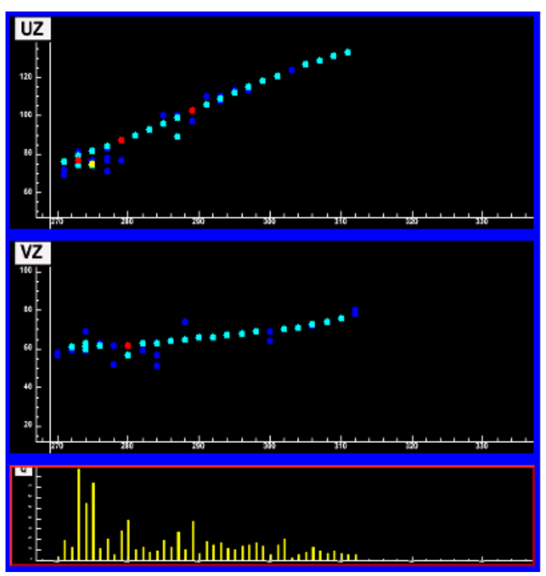
10 planes

short, with typical EM shower profile

MINOS events







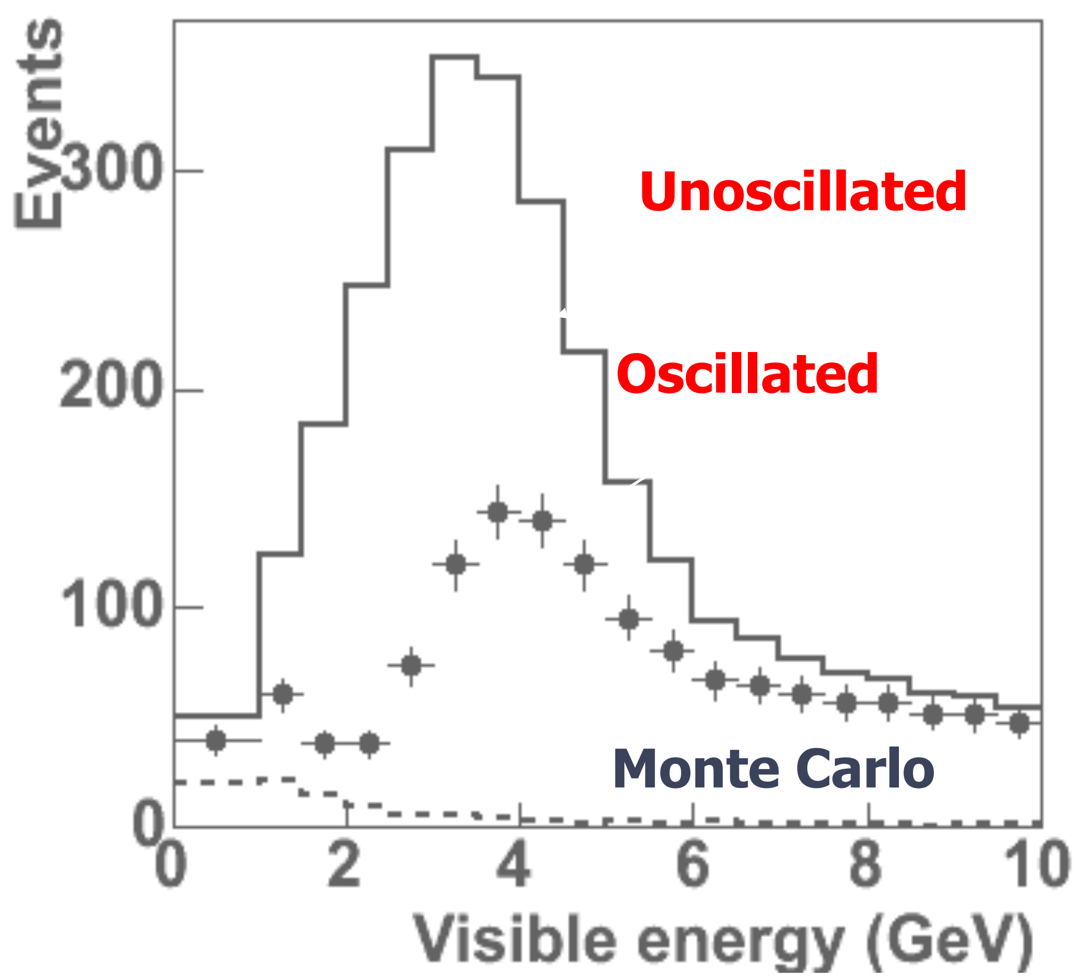
long μ track+ hadronic activity at vertex

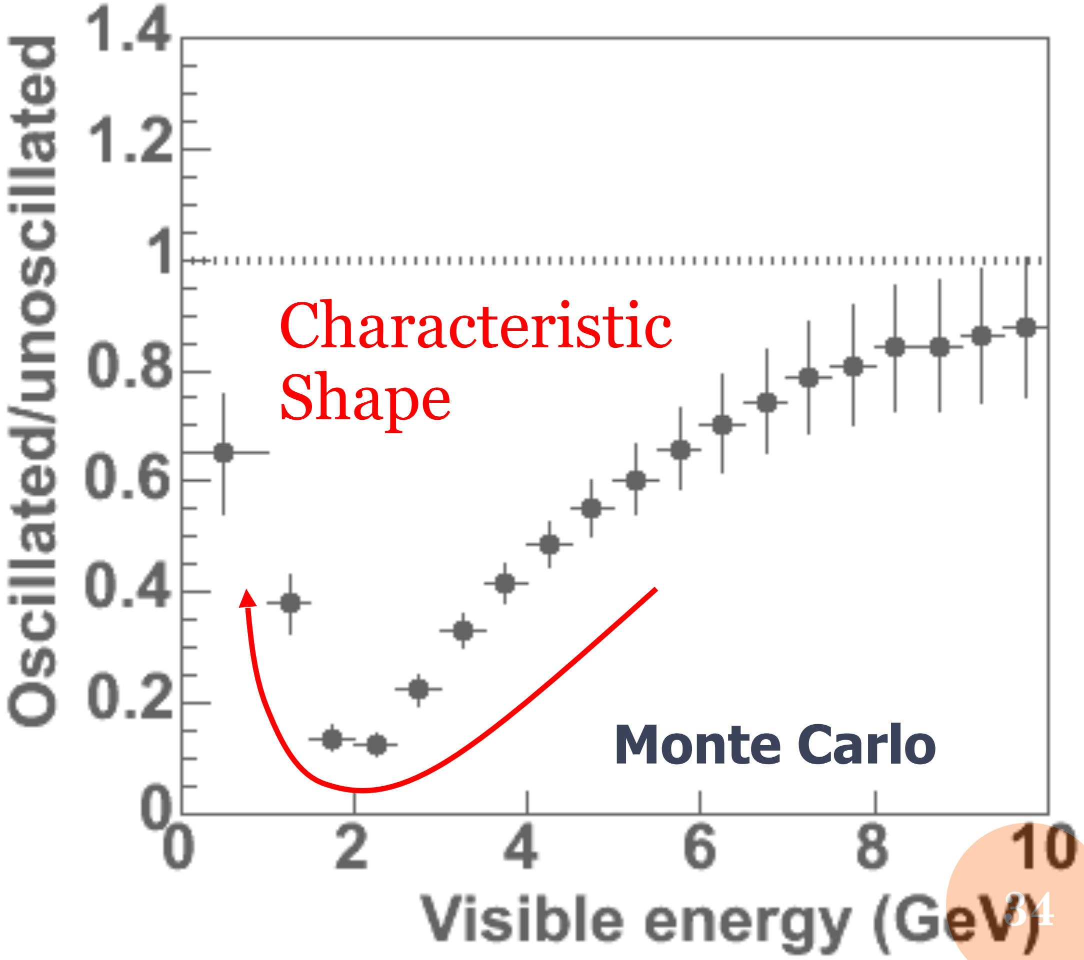
- Steel plates are there to provide nucleons for the neutrino to interact with
- Muons are the only particles that will go through many planes

DISAPPEARANCE : 2 DETECTOR GOLD STANDARD

- Predict un-oscillated spectrum at the further detector using the nearer detector and knowledge of kinematics using 2-flavour approximation

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2(1.267 \Delta m^2 L / E)$$





ν_μ disappearance

- Predict un-oscillated spectrum at the further detector using the nearer detector and knowledge of kinematics using 2- flavour approximation

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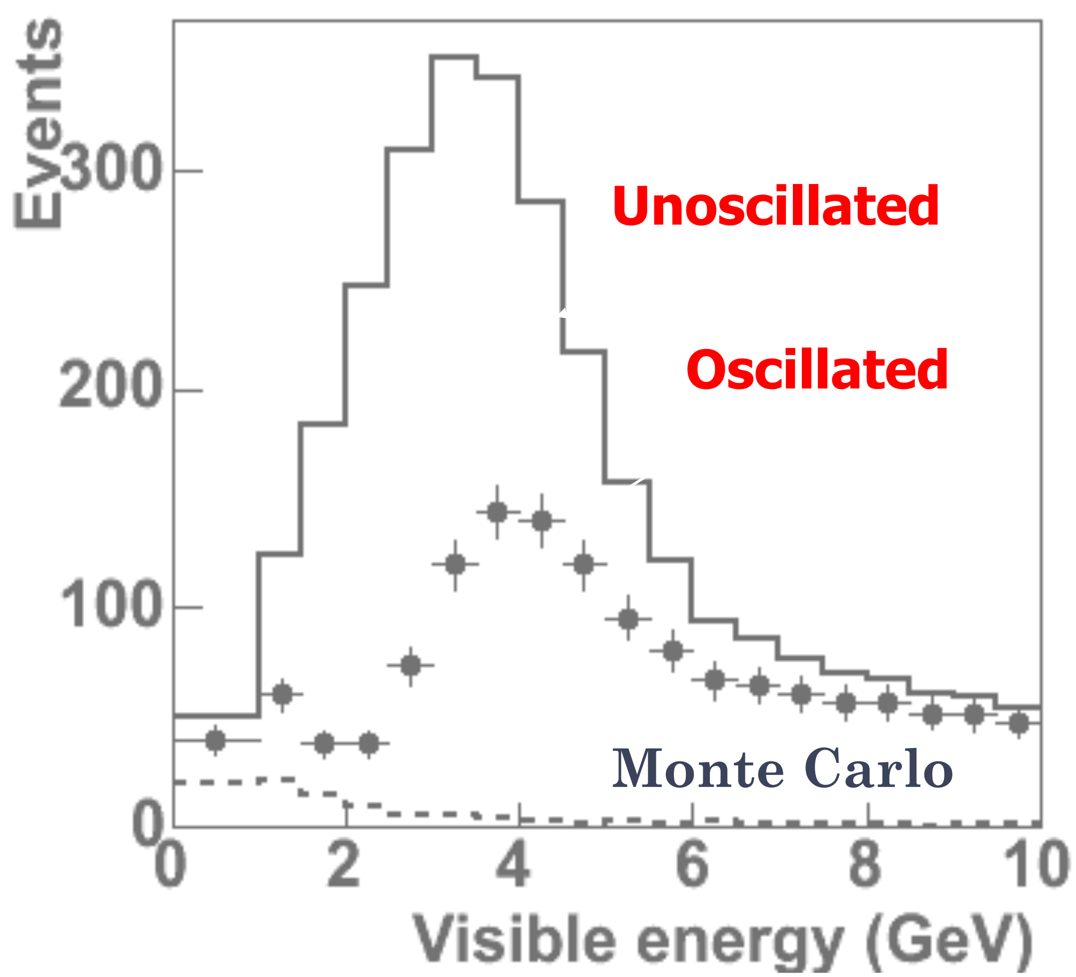

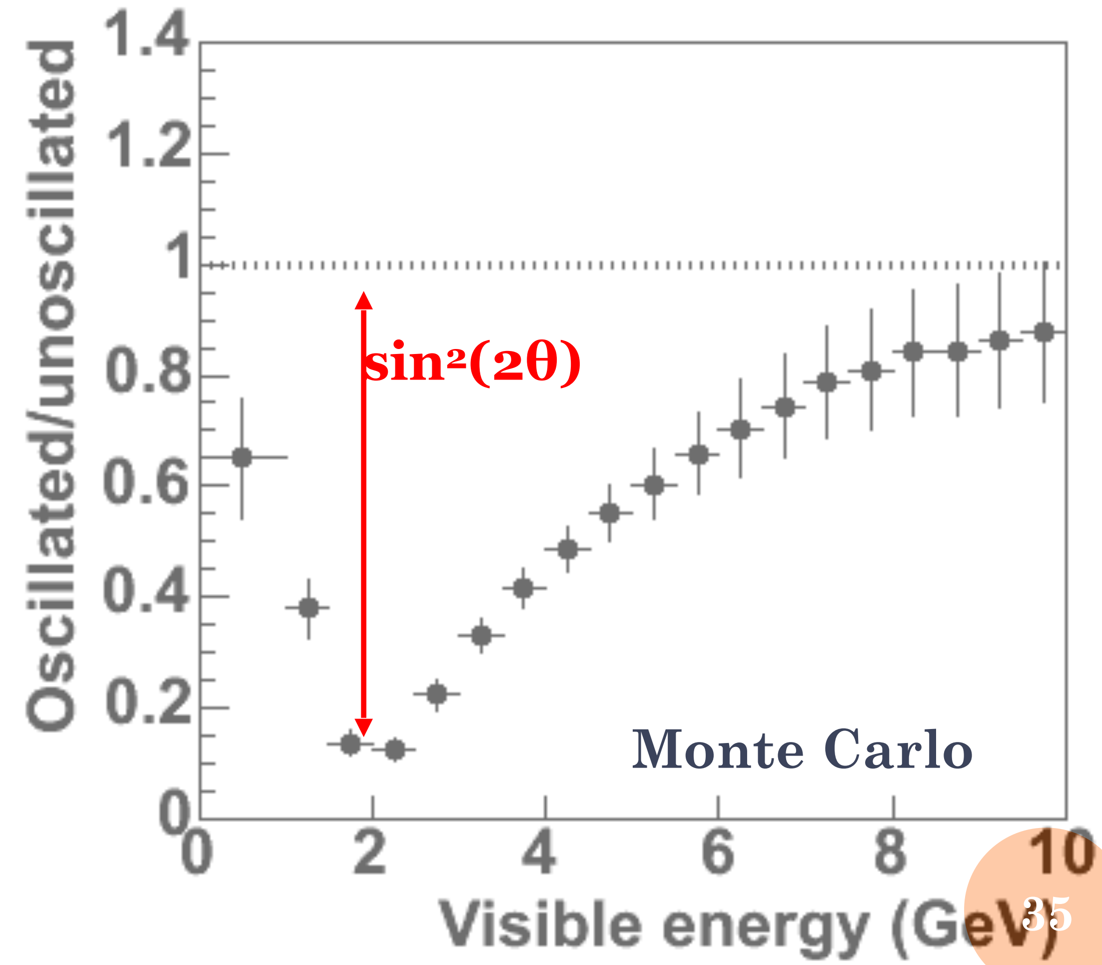

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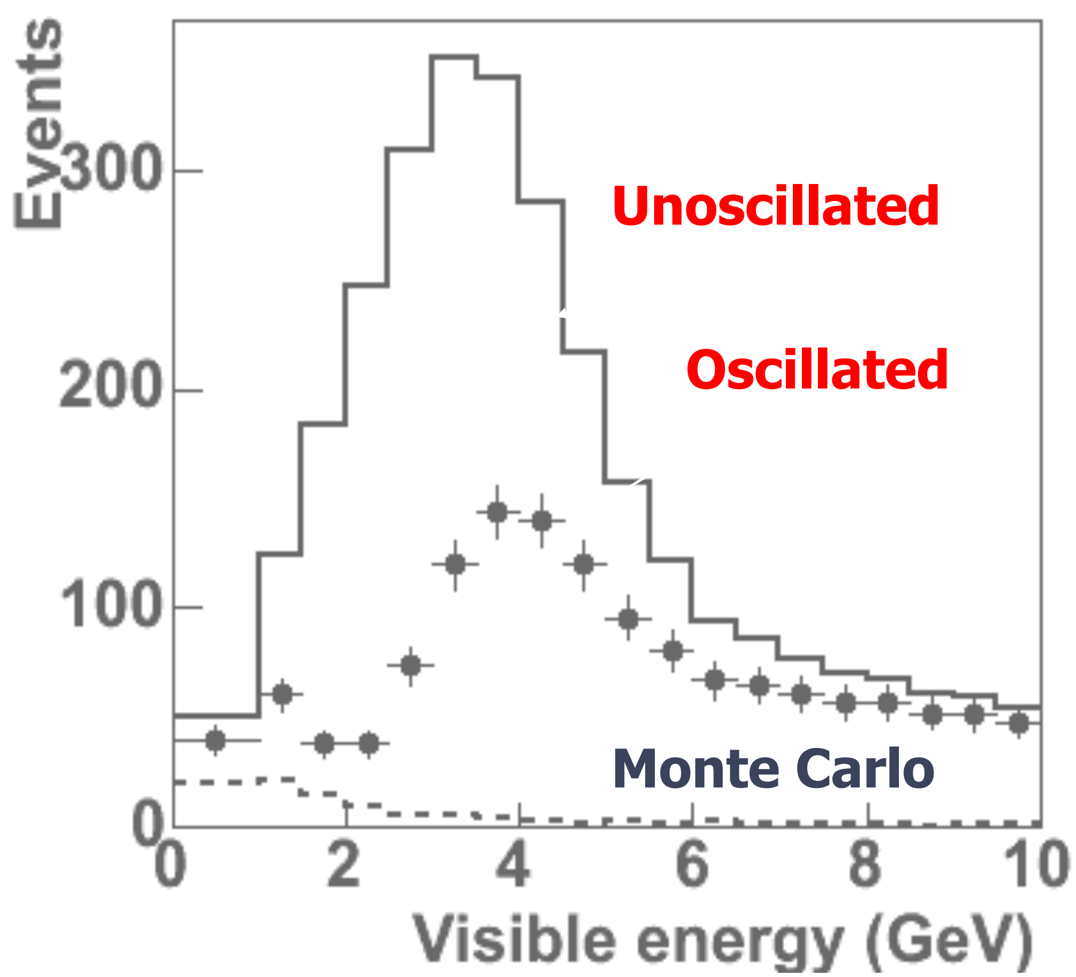
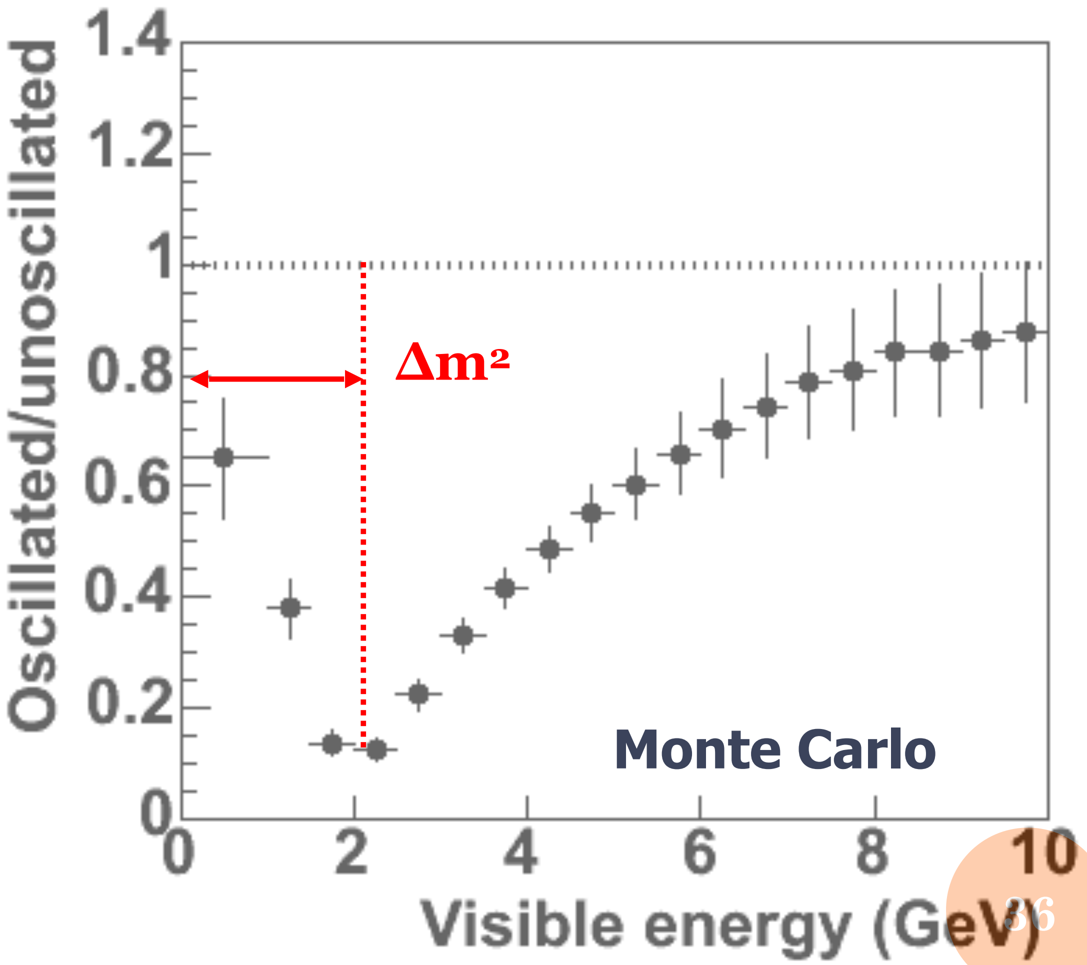
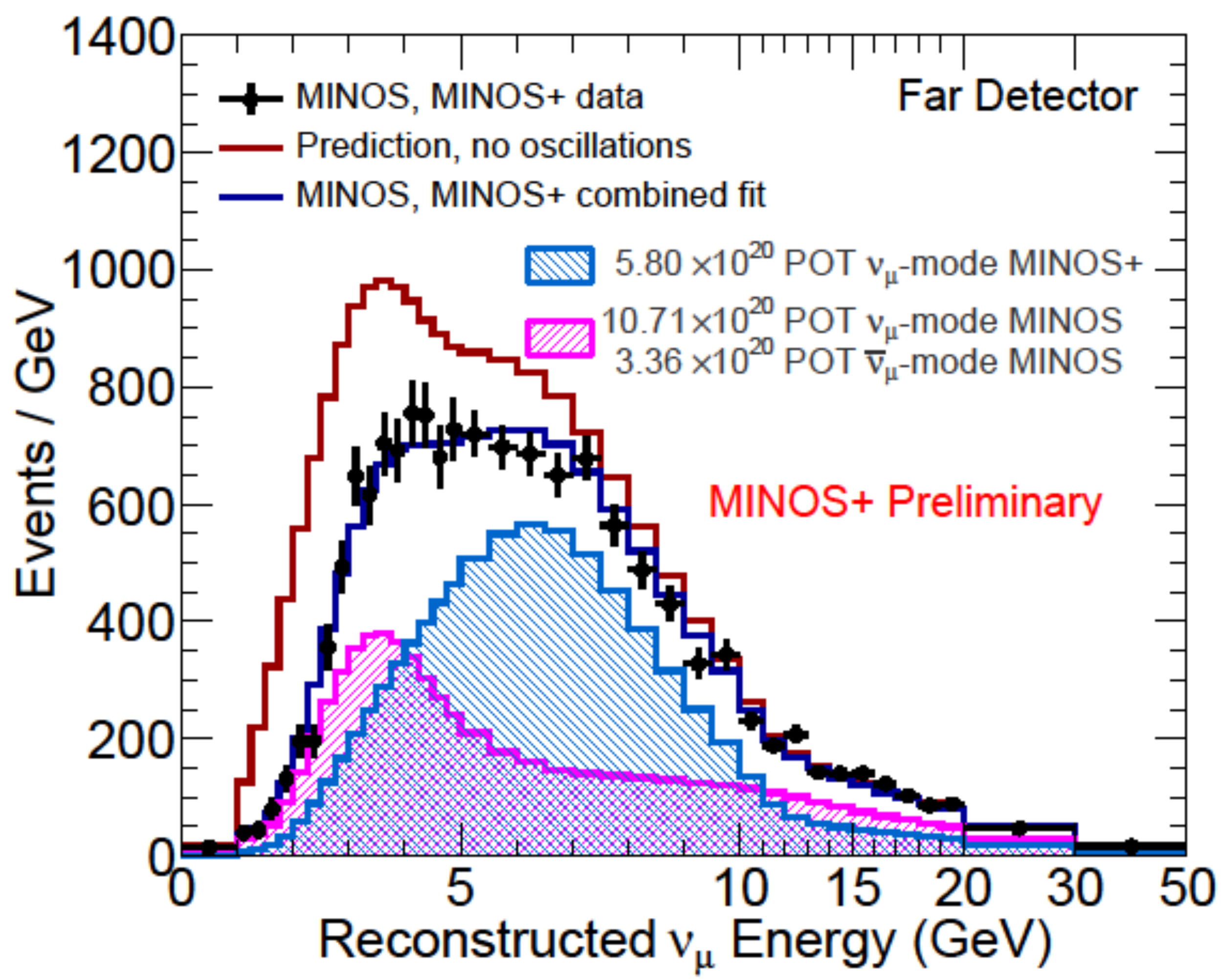
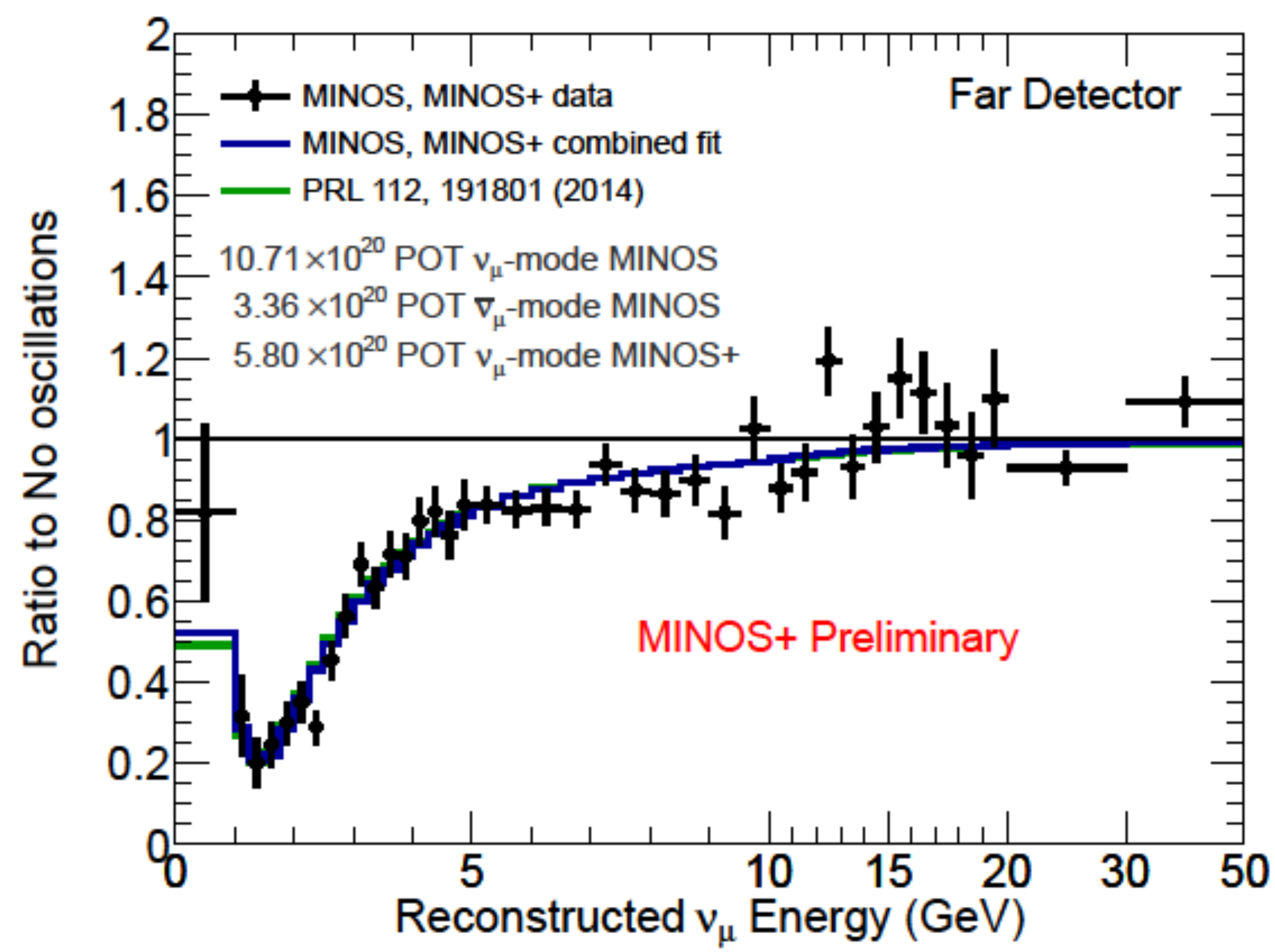


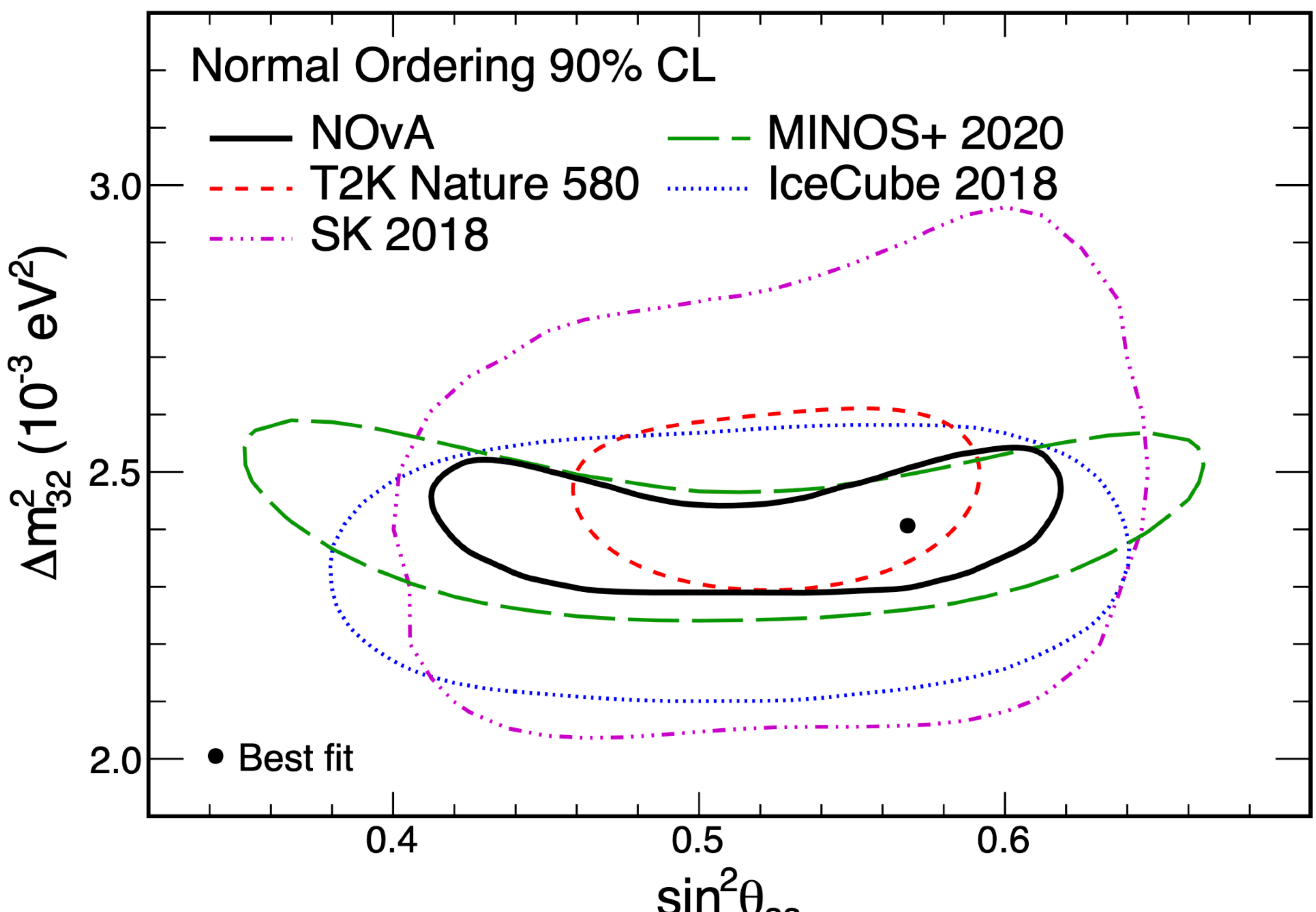


Three Flavour Oscillations

- MINOS was designed to measure the atmospheric scale oscillation parameters Δm^2_{32} and $\sin^2 2\theta_{23}$
  - Look for disappearance of CC ν_μ interactions in the FD relative to ND.
  - Continue the search with MINOS+







Normal Ordering 90% CL
NOvA
T2K Nature 580
SK 2018
MINOS+ 2020
IceCube 2018
Best fit
3.0
2.5
2.0
0.4
0.5
0.6
Δm^2_{32} (10^{-3} eV^2)
$\sin^2\theta_{23}$

MINOS was designed based on Kamiokande results of 1995/6 Region was at about $\Delta m^2 = 10^{-2}\ eV^2$

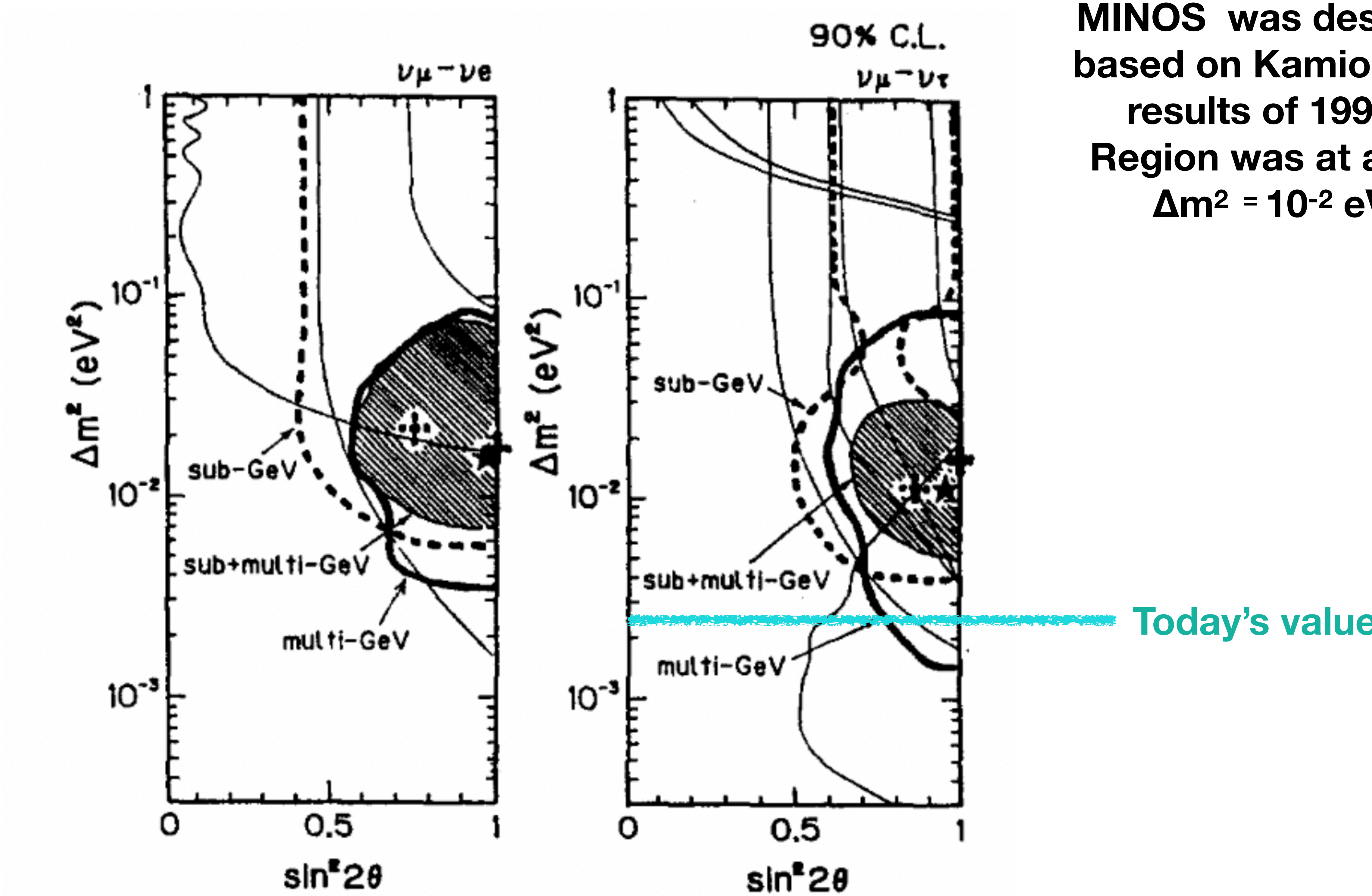
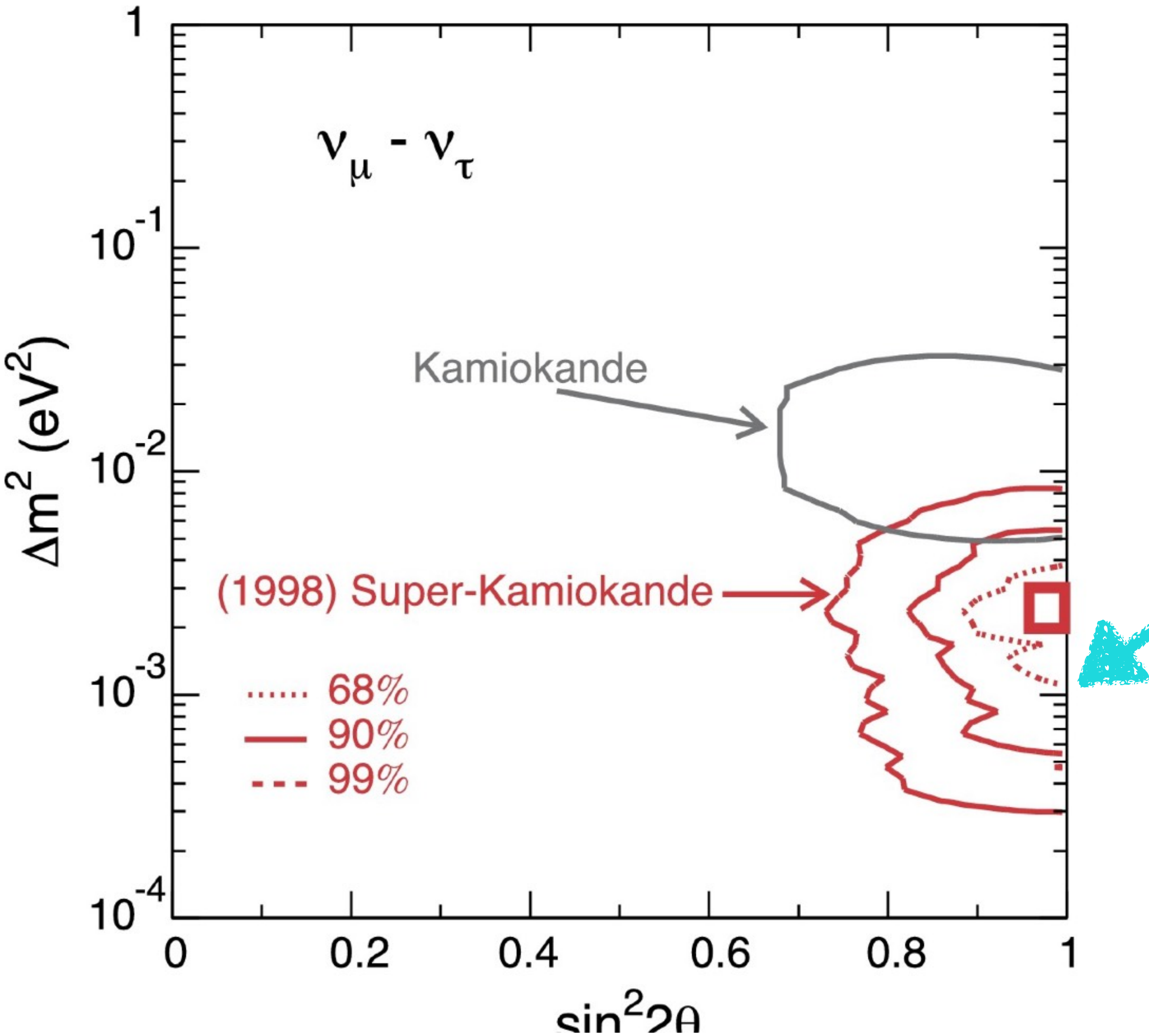


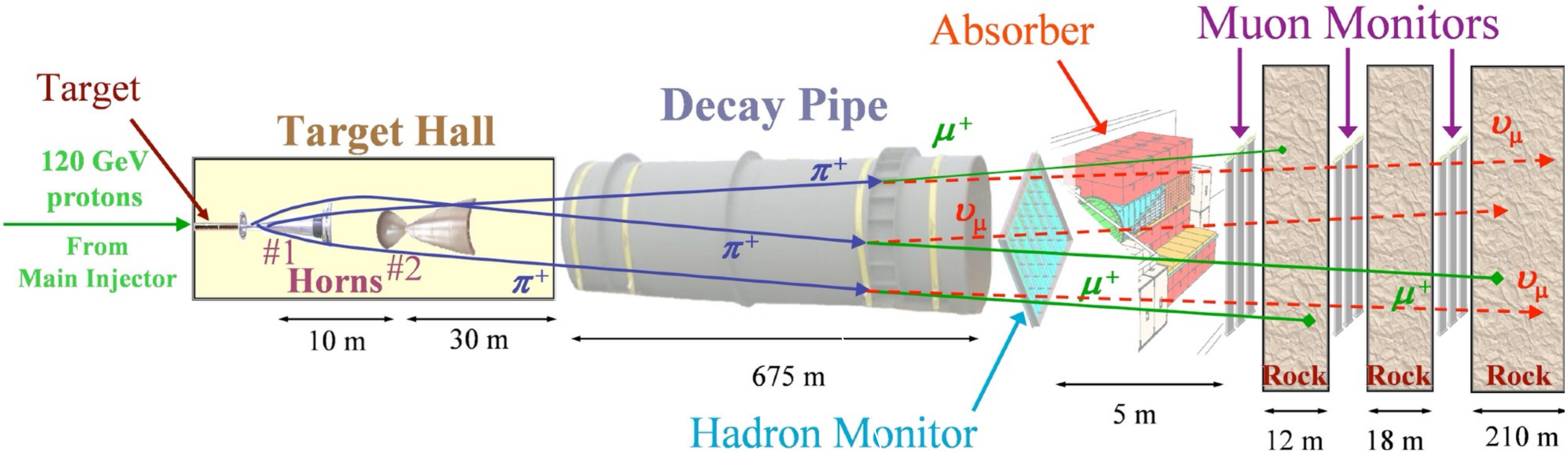
Figure 10. Allowed regions from sub-GeV, multi-GeV and combined data analysis are shown for $\nu_\mu \leftrightarrow \nu_e$ and $\nu_\mu \leftrightarrow \nu_\tau$ oscillation modes.



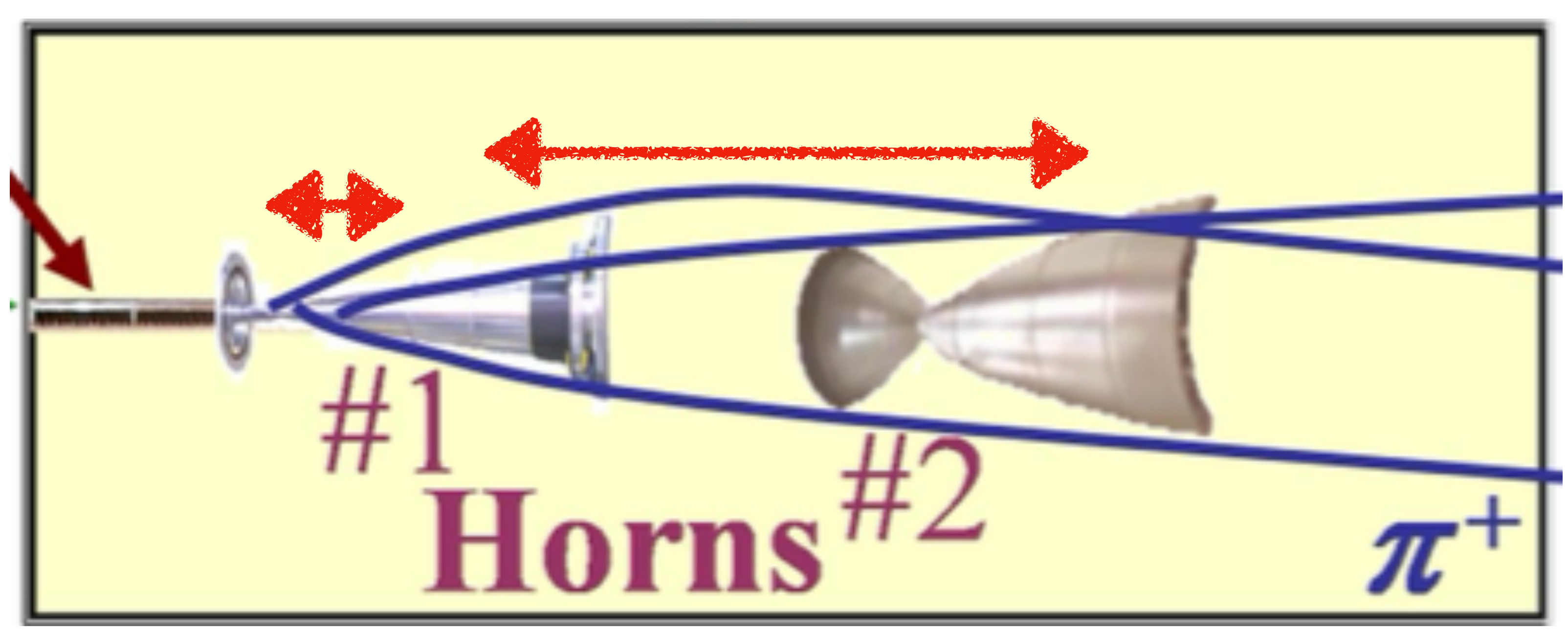
In about 2000, DOE commissioned another review of MINOS due to the new SuperK results

$\Delta m^2 < 10^{-3}$ eV^2 would mean oscillation peak at <0.5GeV, impossible to see!

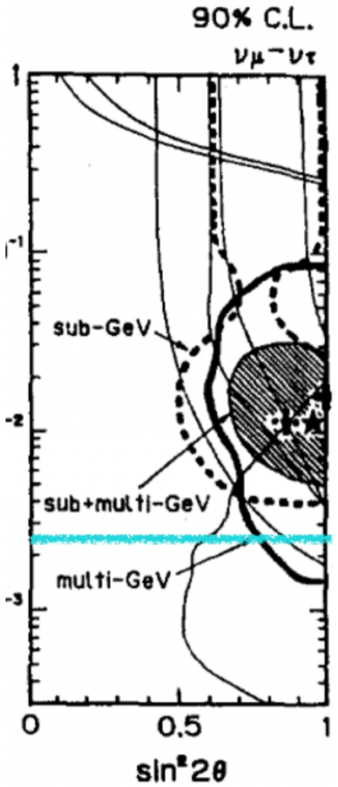
Luckily, The NuMI beam had the ability to change the distance between the two horns, and so was able to reduce the neutrino beam peak to 3 GeV!!
VERY LUCKY!

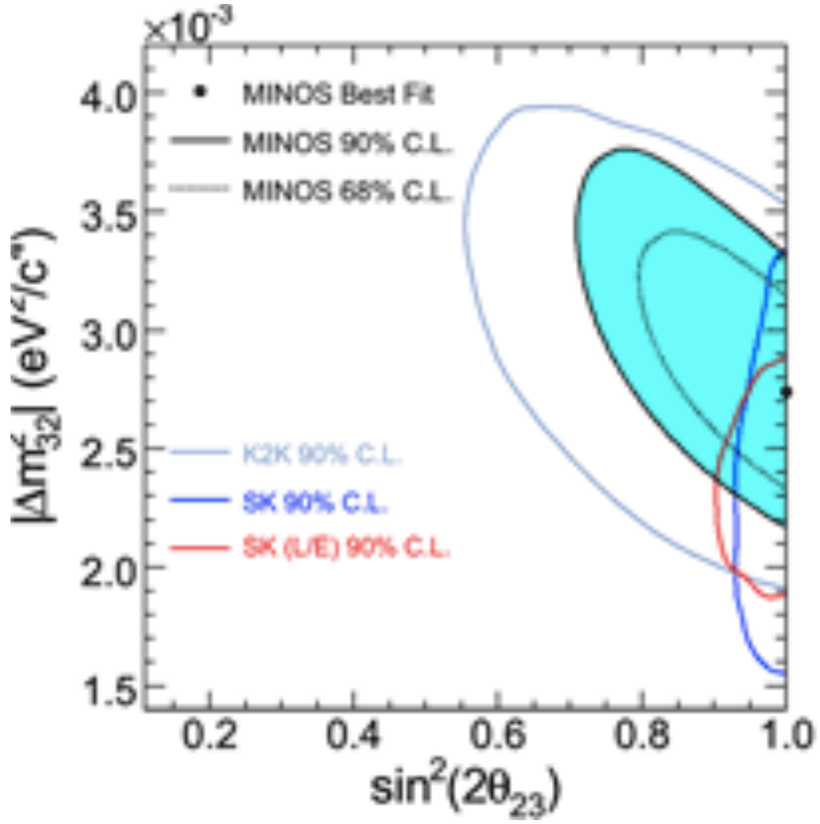


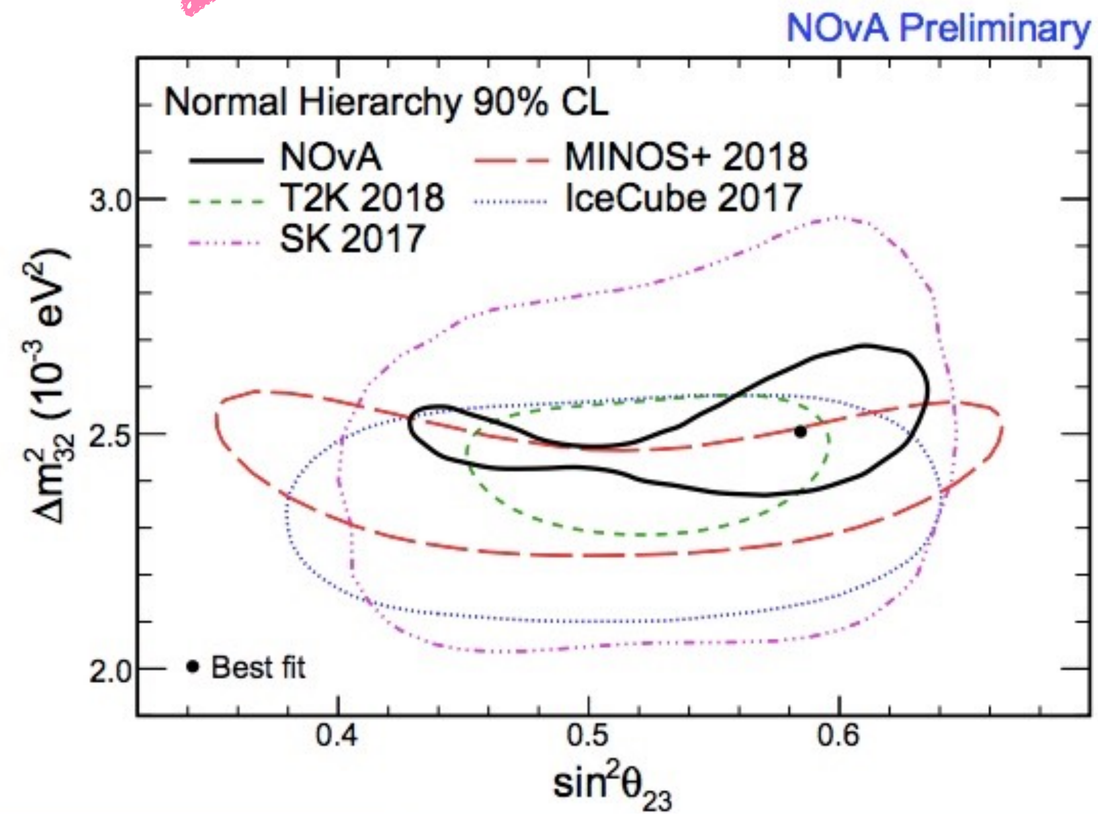
Change position of horns..
change energy of focussed pions..
change energy of neutrinos!



2018

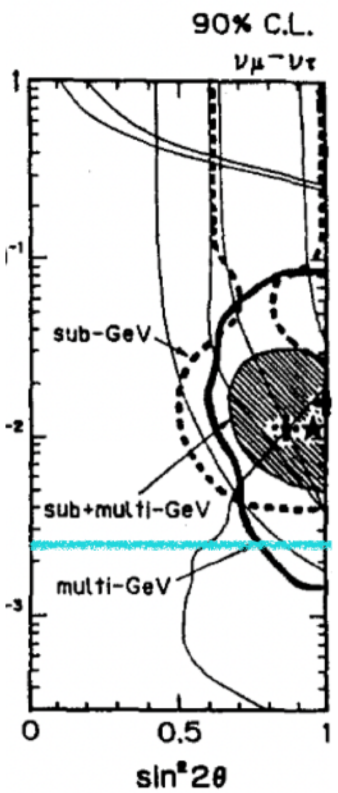


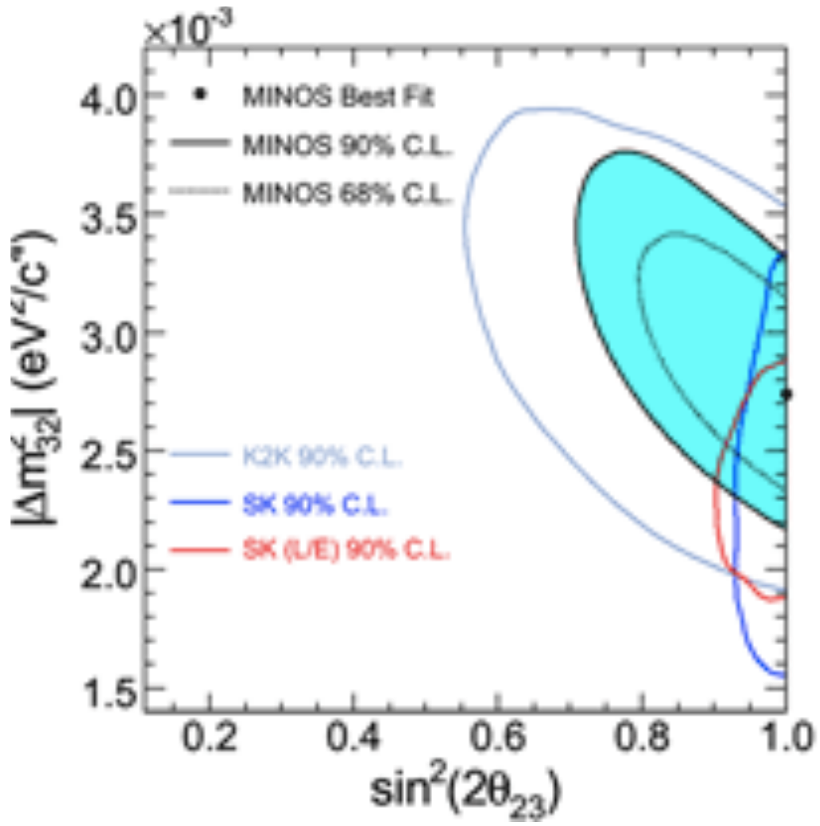


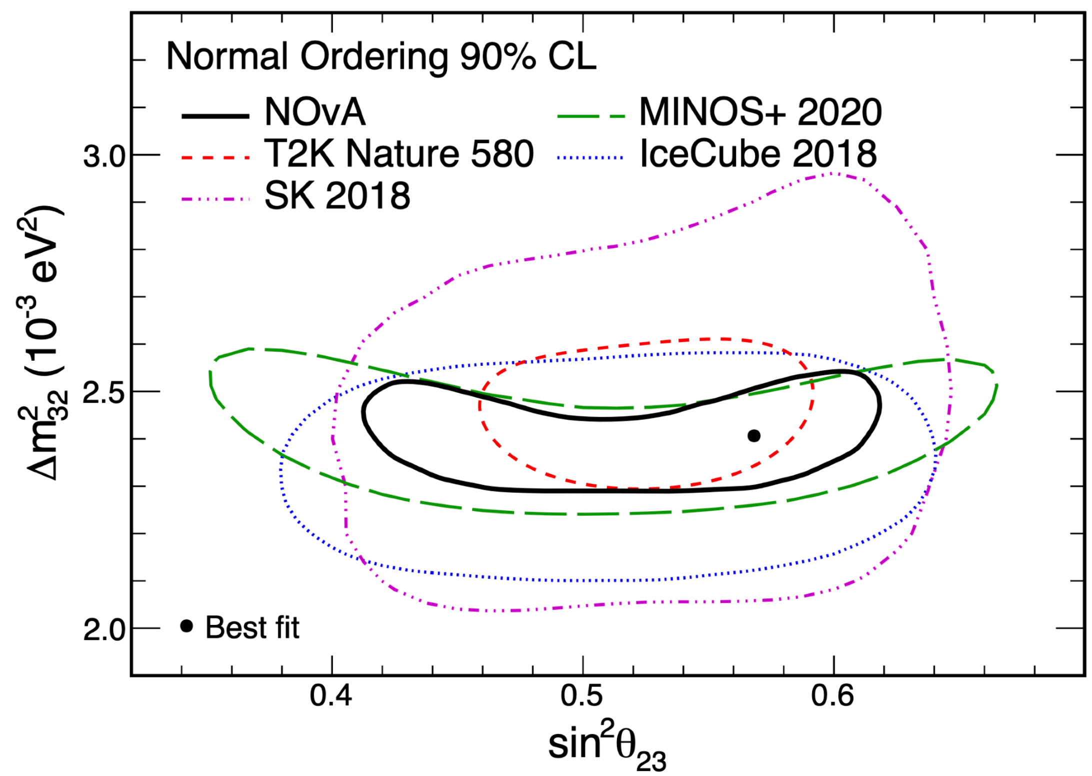


- This plot has taken more almost 30 years to achieve (1994-now)

2020



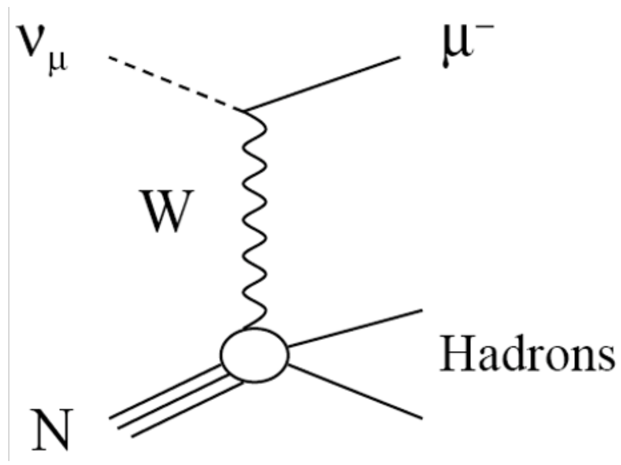


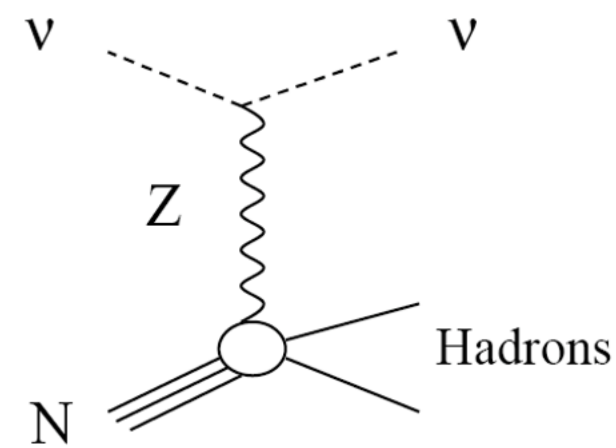


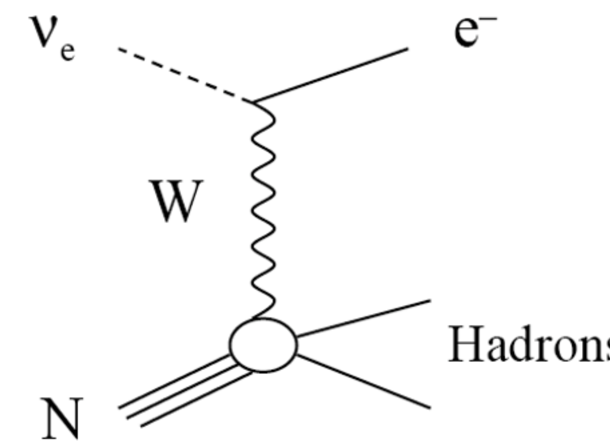
- This plot has taken more almost 30 years to achieve (1994-now)
  - And it is still changing…a lot!
- What if $\sin^2\theta_{23}$ is maximal?
  - Is this evidence of a new symmetry? A Big Thing?
  - Are there any theoretical insights that would tell us what to do next?

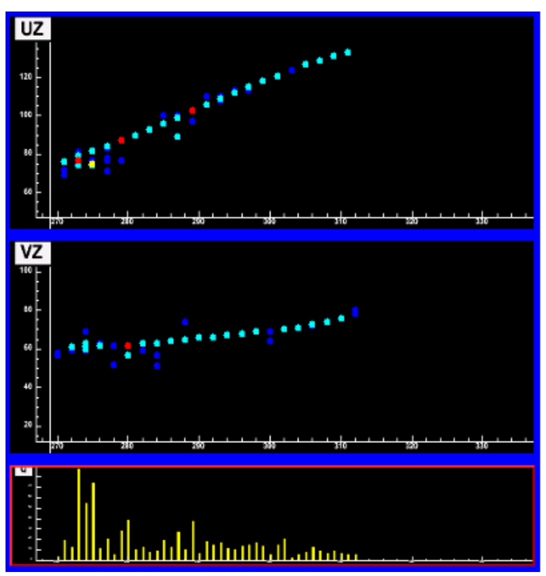
Another tale

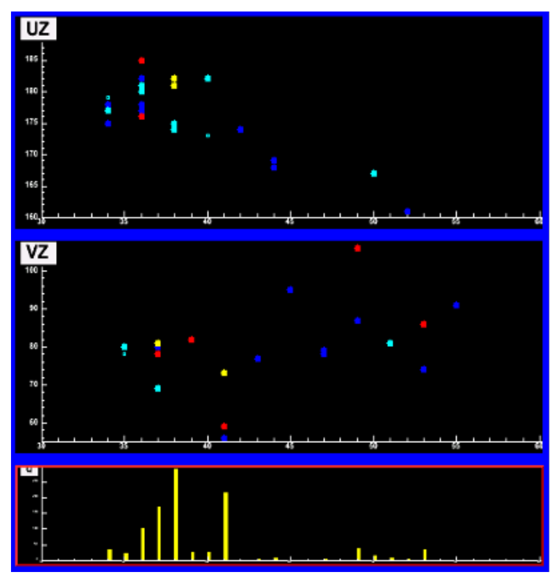
MINOS events

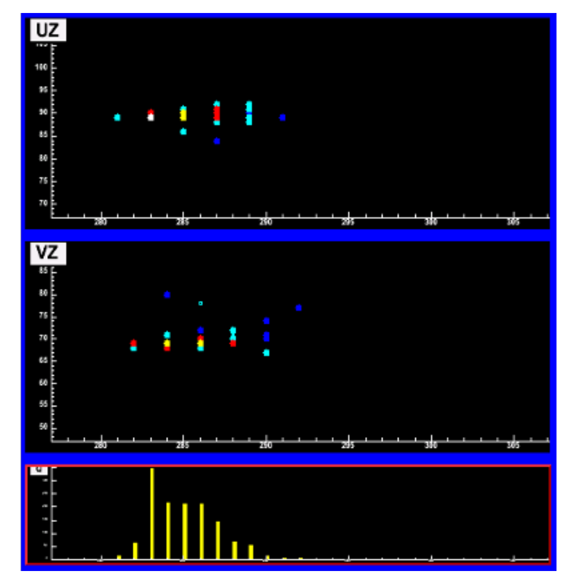












60 planes

10 planes

10 planes

long μ track+ hadronic activity at vertex

short event, often diffuse

short, with typical EM shower profile

Another Story

- MINOS was designed to measure muon neutrino disappearance
- As soon as that was measured, the search focussed on sub-dominant electron neutrino appearance
- This channel was not in the proposal but provided first hints!

August, 2011
890 citations!

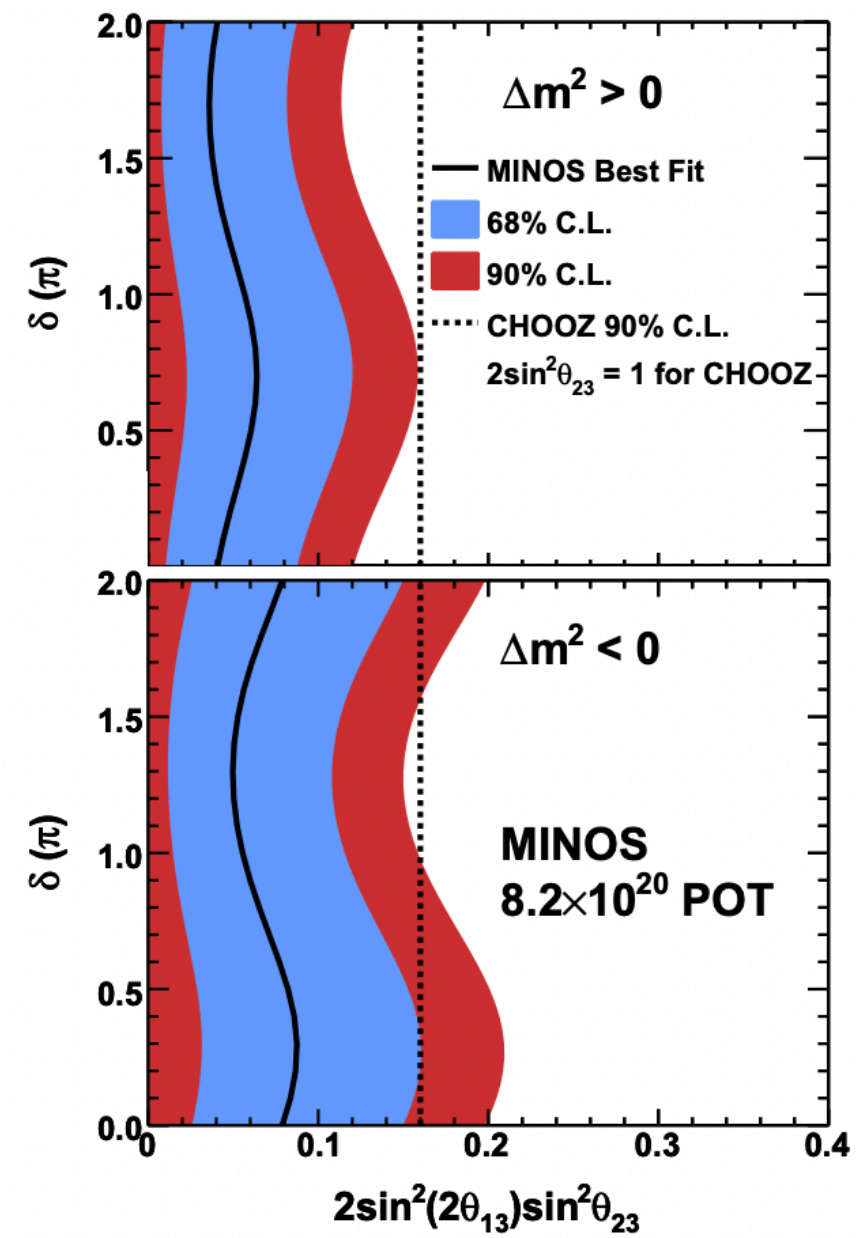


FIG. 3: Allowed ranges and best fits for $2\sin^2(\theta_{23})\sin^2(2\theta_{13})$ as a function of δ. The upper (lower) panel assumes the normal (inverted) neutrino mass hierarchy. The vertical dashed line indicates the CHOOZ 90% C.L. upper limit assuming $\theta_{23} = \frac{\pi}{4}$ and $\Delta m^2_{32} = 2.32\times10^{-3}$ eV^2 [10].

Another Story

- MINOS was designed to measure muon neutrino disappearance
- two years more data provided evidence, still only 90% C.L

April 22, 2013
278 citations

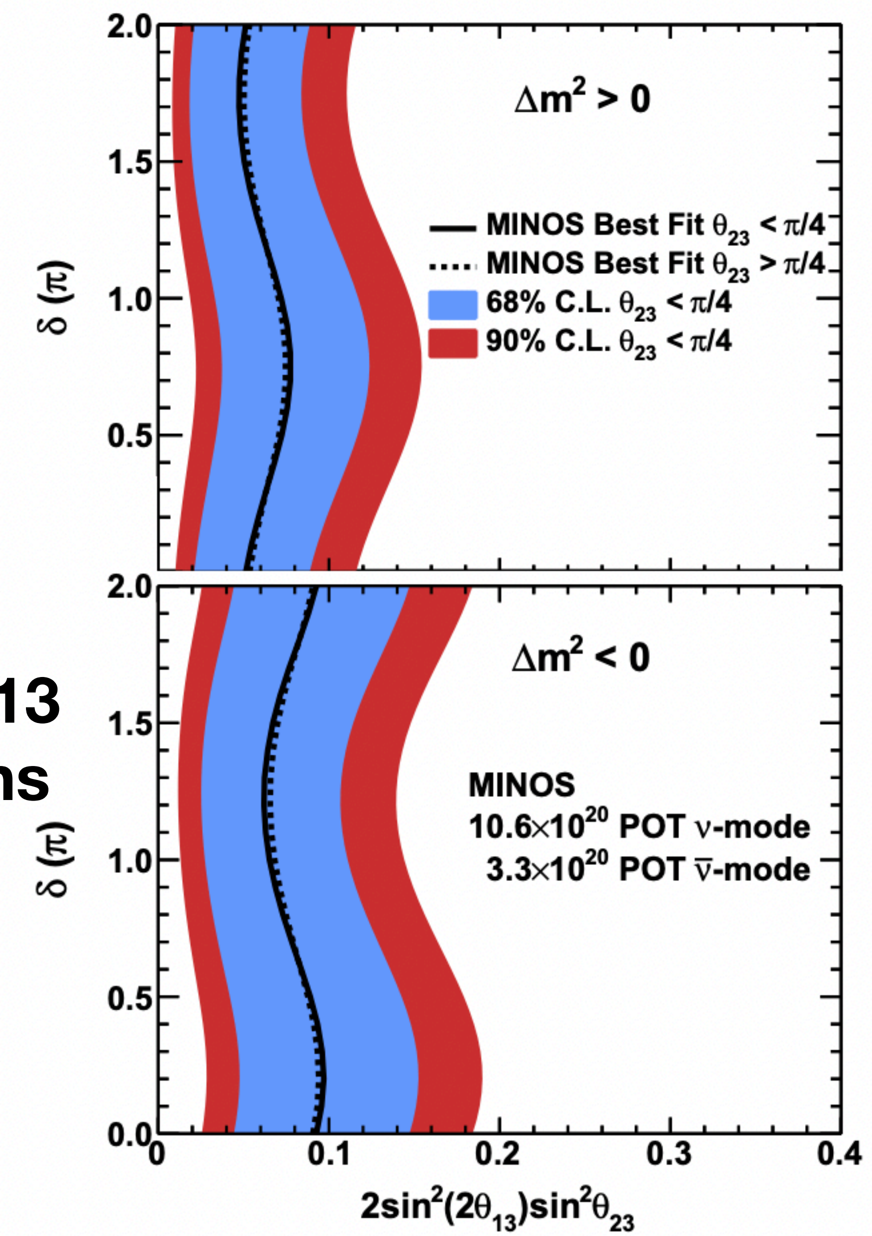
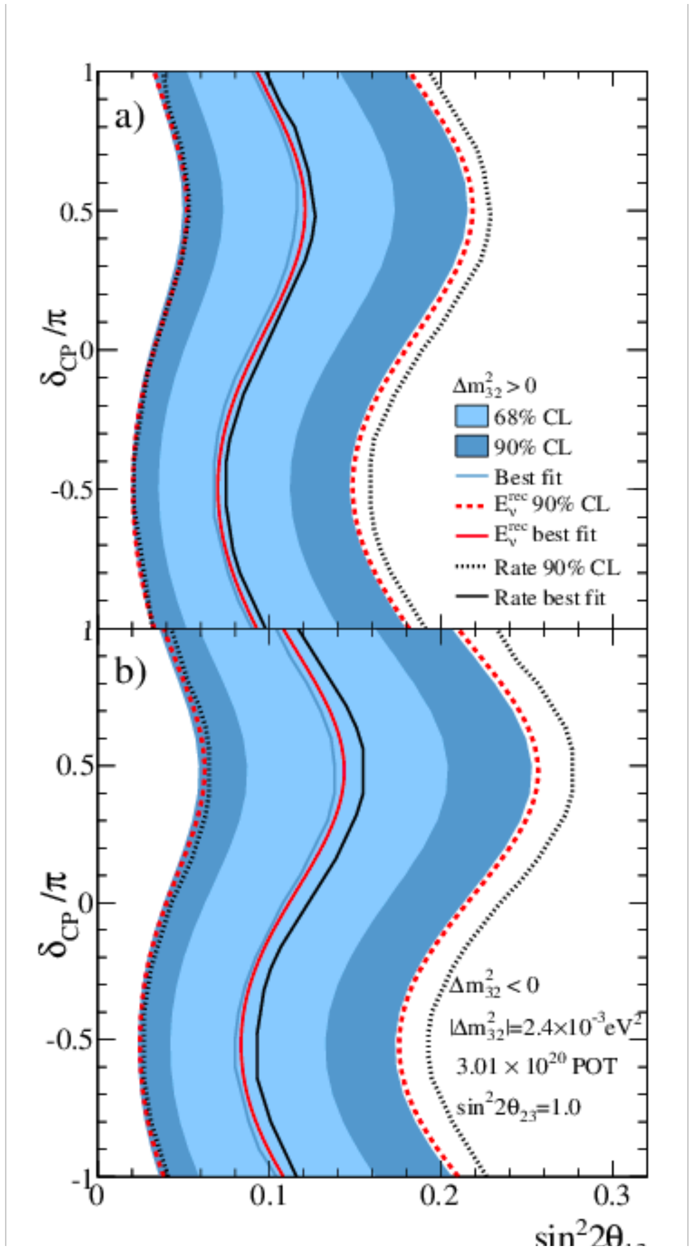


FIG. 3: The 68% and 90% confidence intervals of allowed values for $2\sin^2(2\theta_{13})\sin^2(\theta_{23})$ as a function of δ for the two mass hierarchies.

Another Story

- T2K was designed to look for electron neutrino appearance
- Very close race at the start… 10 days earlier!
- 90% C.L. evidence

April 3, 2013
268 citations



Another Story

- T2K was designed to measure electron neutrino appearance
- off-axis beam centered on oscillation maximum
- When you design an experiment, better to optimise for what you are looking for!

November 19th 2013
663 citations

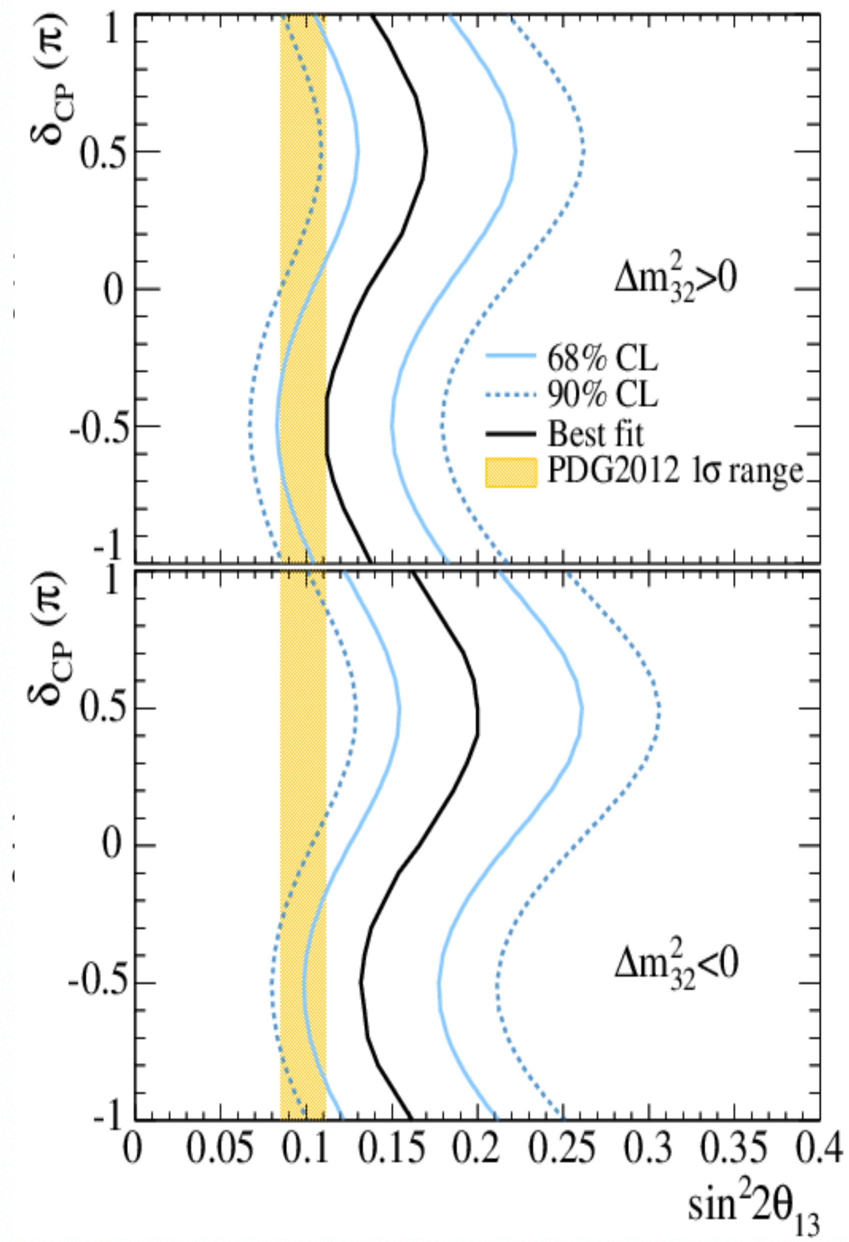


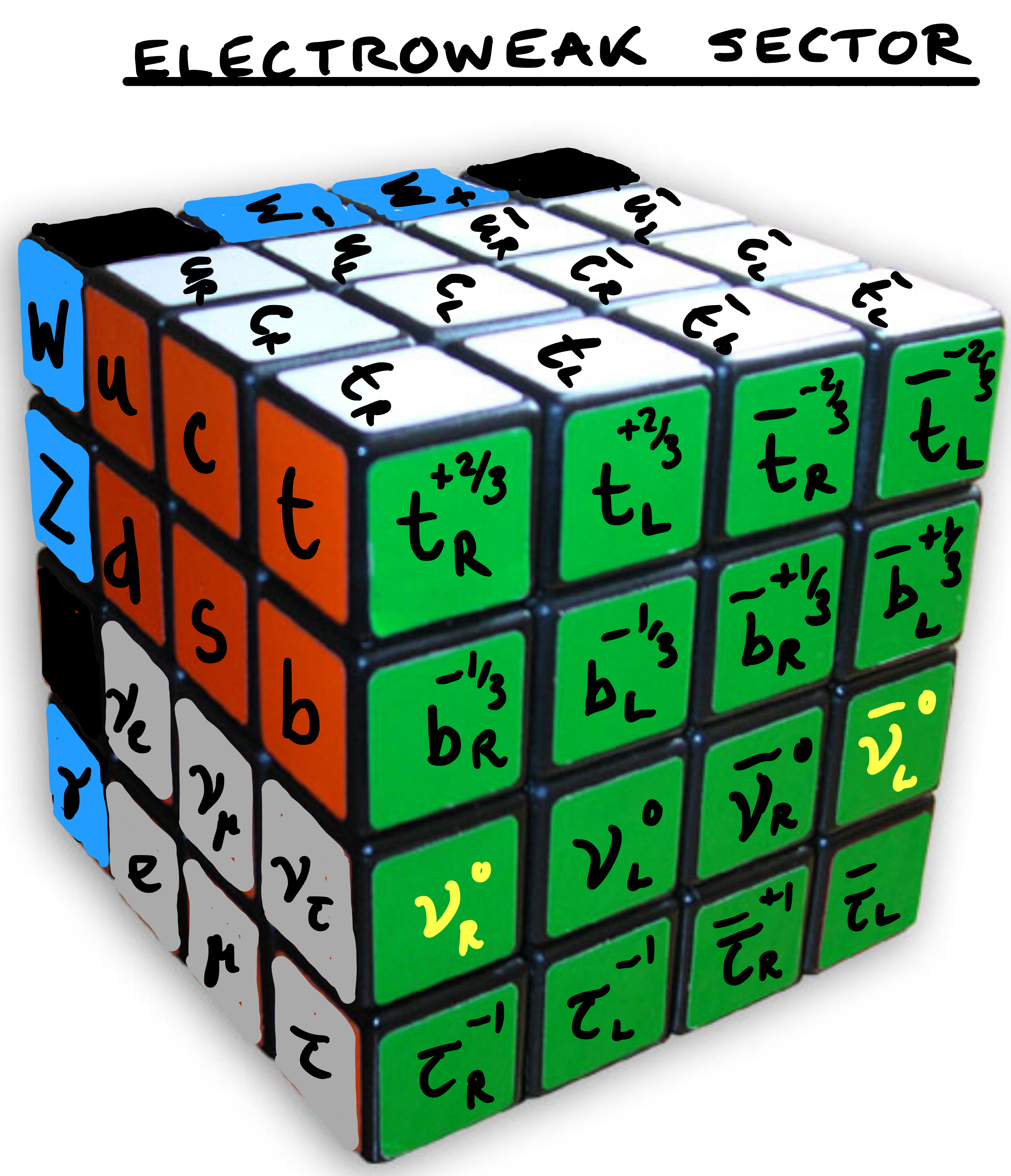
FIG. 3: The 68% and 90% confidence intervals of allowed values for $2\sin^2(2\theta_{13})\sin^2(\theta_{23})$ as a function of δ for the two mass hierarchies.

Wind up

- The overarching design of a detector is dictated by the physics ....
    - **This is always true**
- Neutrino detectors have to be large and therefore monolithic to be affordable
- Tracking/calorimeter designs measure energy via dE/dx and direction : an additional magnetic field helps to measure high energy muons via their curvature
- detecting the light created by the charged particles is of paramount importance
- Innovations from the physicists produce better results than the proposals imagine, over time

Lets look at the weak interaction

- Rubik's Cube is more complicated!
  - charged leptons can interact with photons
  - neutrinos are different
    - photons don't interact with them
- Neutrinos are the only neutral fermions and that makes them special 
  -



LETS LOOK AT THE WEAK INTERACTION

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