Oscillation physics with accelerators

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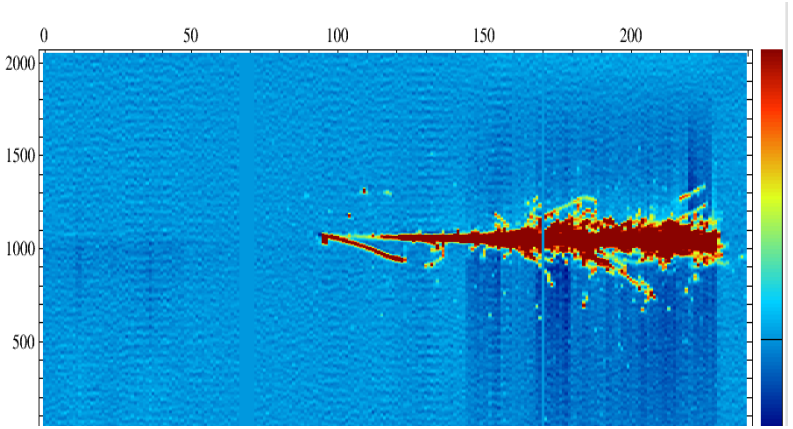
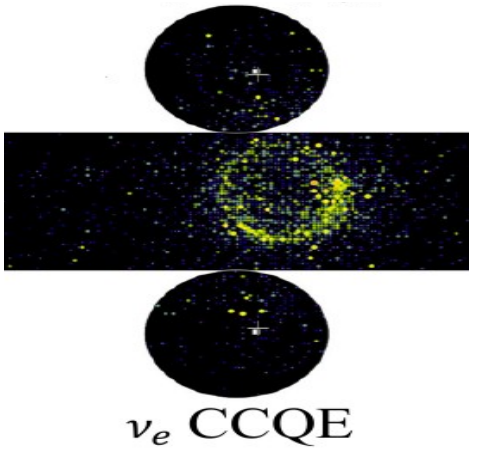
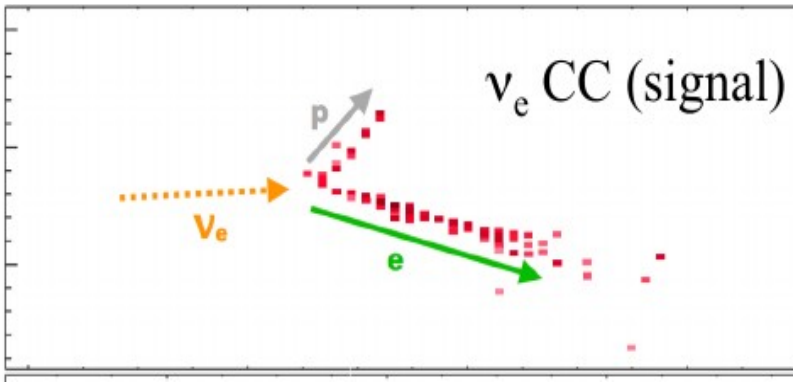
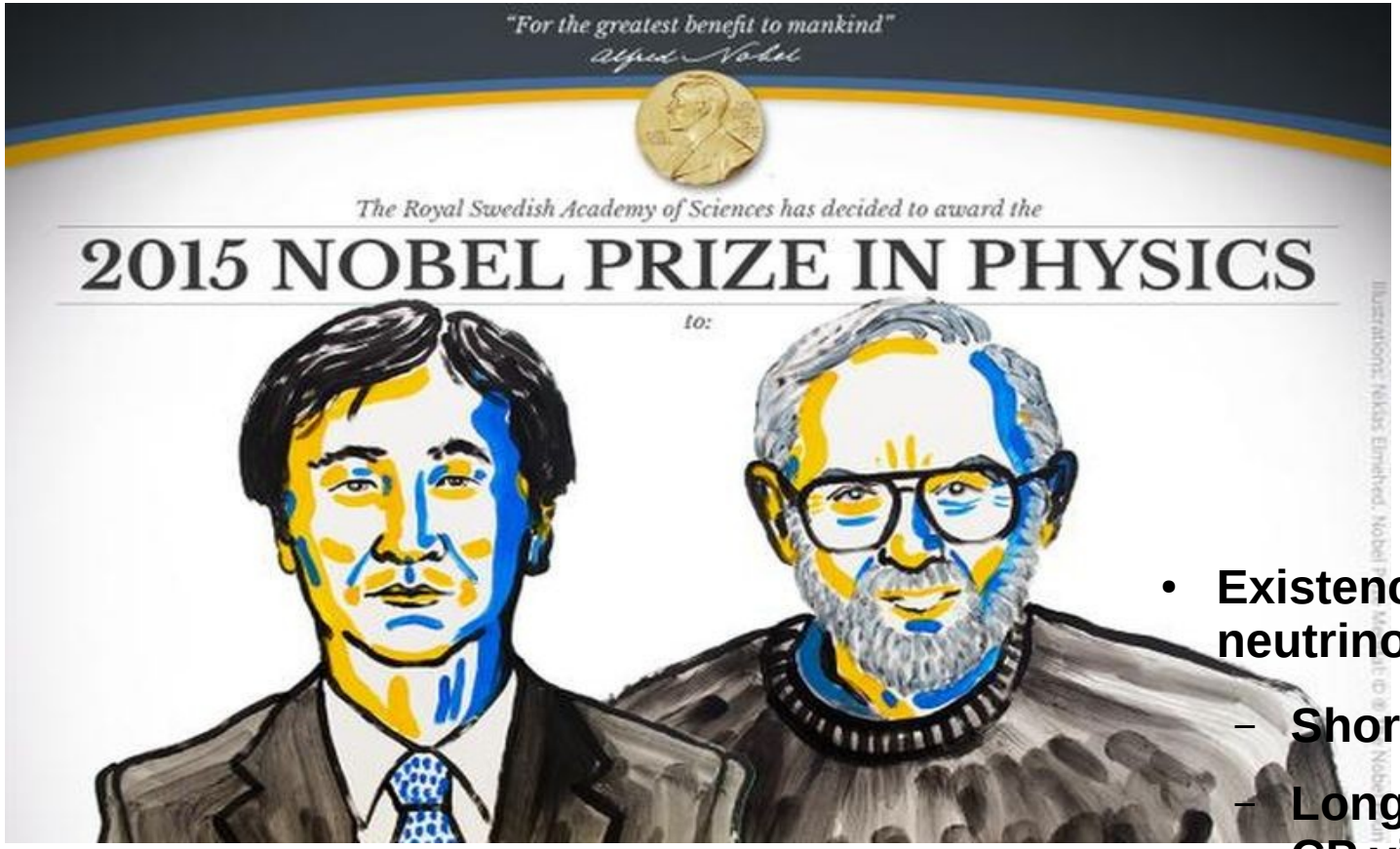






Exciting Times for Neutrino Oscillations!



- **Existence of oscillations in neutrino physics:**
  - **Short baseline anomalies.**
  - **Long baseline looking for CP violation & Mass Hierarchy**
- **How do we get there?**
- **How can we maximize our chances of getting the physics?**

Apologies, for slide outdated by a couple of days.

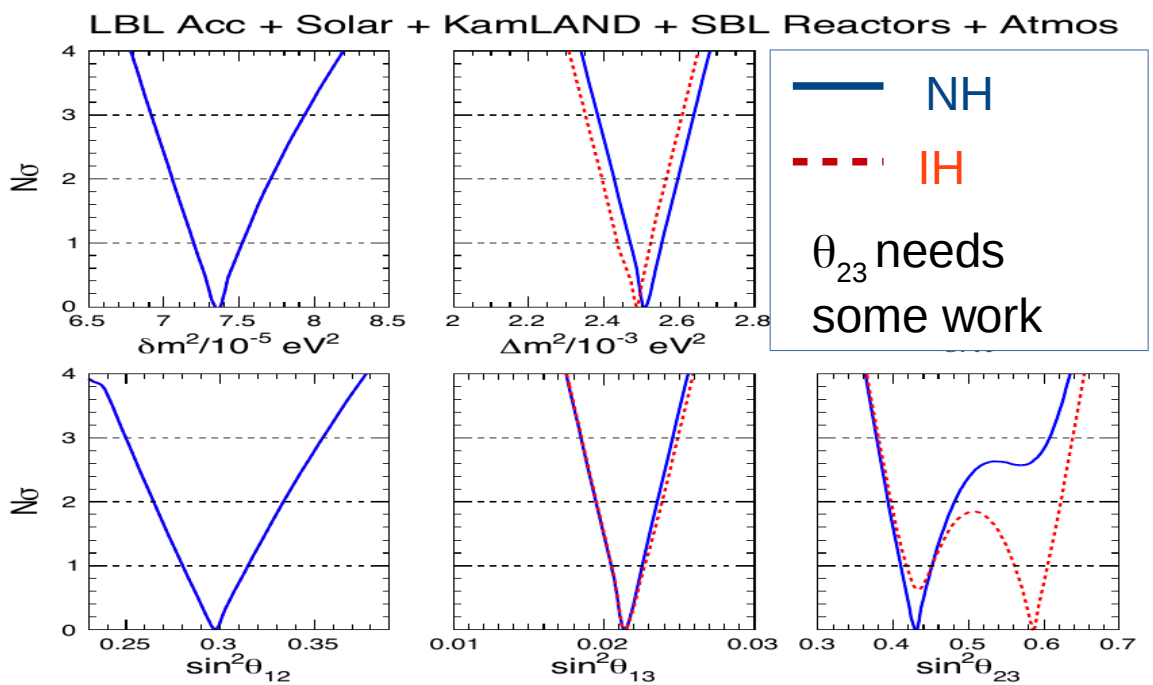
Neutrino Oscillations

23 13 12

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric Reactor/Interference Solar

$\mu \Rightarrow \tau$ $\mu \Leftrightarrow e$ $e \Leftrightarrow \mu$



We understand the parameters of neutrino oscillations pretty well.

We have measured the mass splitting and mixing angles (more or less).

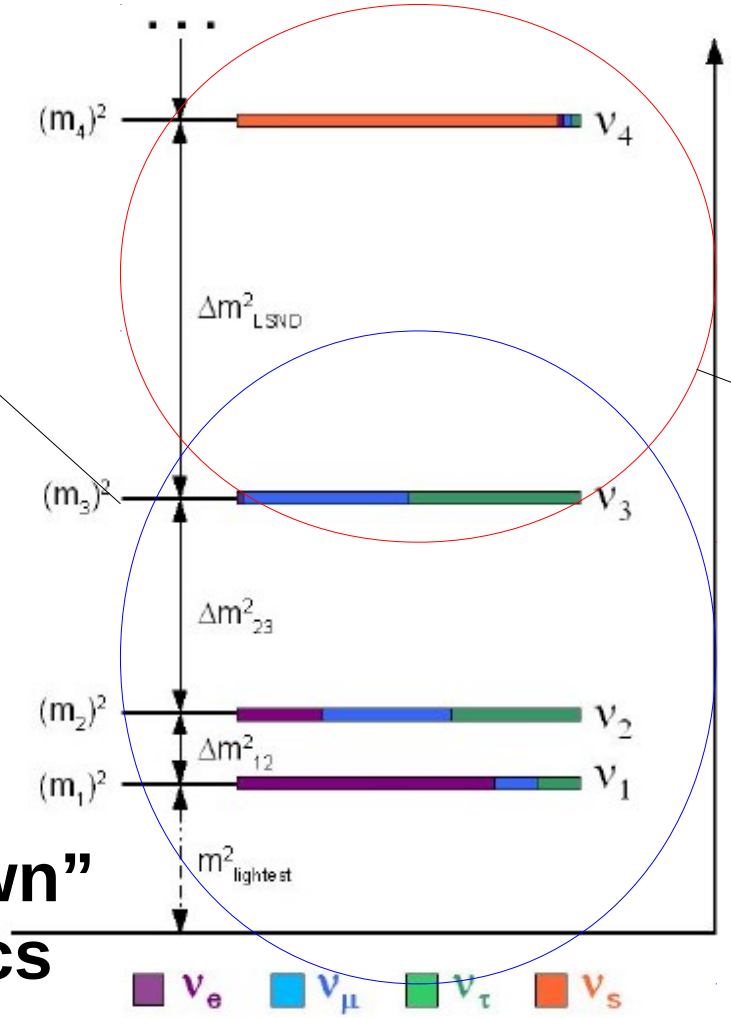
The mixing pattern is a bit strange compared to quarks (large mixings).

A.Marrone@ Neutrino16

Our Current State of Knowledge

The neutrino model

- Our picture of Neutrinos in the standard model is almost complete.
- "Large" mixing angle θ_{13} opens the way to measuring CP violation



"Unknown" physics

- Short baseline measurements hint at oscillations **incompatible with 3 neutrino model**.
- Tantalizing anomalies that could be interpreted as a new neutrino state – **the sterile neutrino.**
- At tension with results from MINOS+, DayaBay and IceCube.

"Known" physics

Big Questions in ν-physics (a subset)

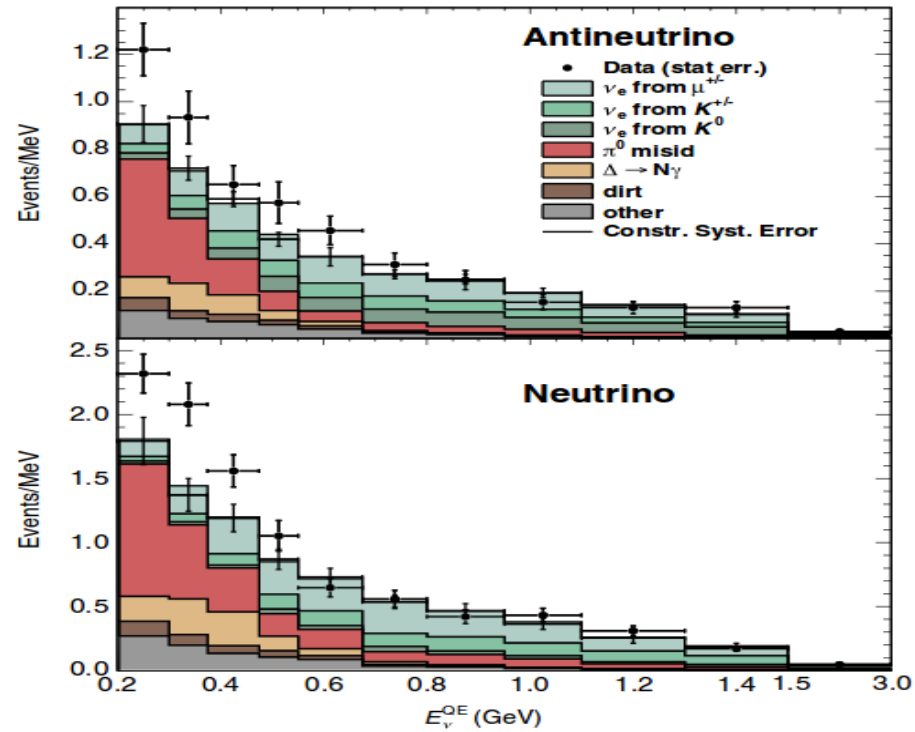
- Focusing on those we can answer with accelerator neutrinos:
  - Are there more neutrino states?
  - Is θ_{23} maximal?
  - What is the neutrino mass-ordering?
  - Is there CP-violation in the neutrino sector?
- Optional:
  - Is there Unitarity in the neutrino system?
  - Non-standard interactions?

Existence of Sterile Neutrinos

Experiment	Type	Channel	Significance
LSND	DAR	$\bar{\nu}_\mu \to \bar{\nu}_e$ CC	3.8σ
MiniBooNE	SBL accelerator	$\nu_\mu \to \nu_e$ CC	3.4σ
MiniBooNE	SBL accelerator	$\bar{\nu}_\mu \to \bar{\nu}_e$ CC	2.8σ
GALLEX/SAGE	Source - e capture	ν_e disappearance	2.8σ
Reactors	Beta-decay	$\bar{\nu}_e$ disappearance	3.0σ

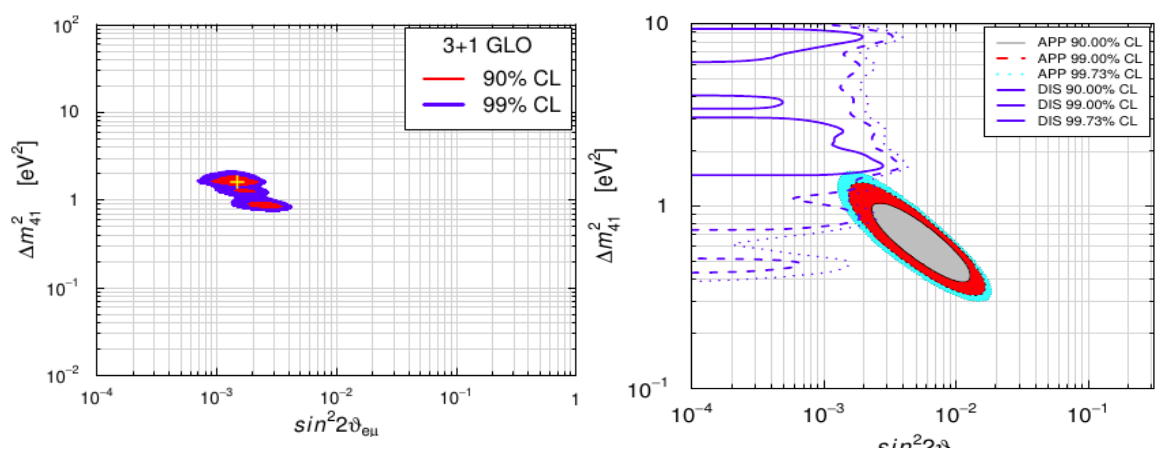
K. N. Abazajian et al. "Light Sterile Neutrinos: A Whitepaper", arXiv:1204.5379 [hep-ph], (2012)

Phys. Rev. Lett. 110, 161801 (2013)



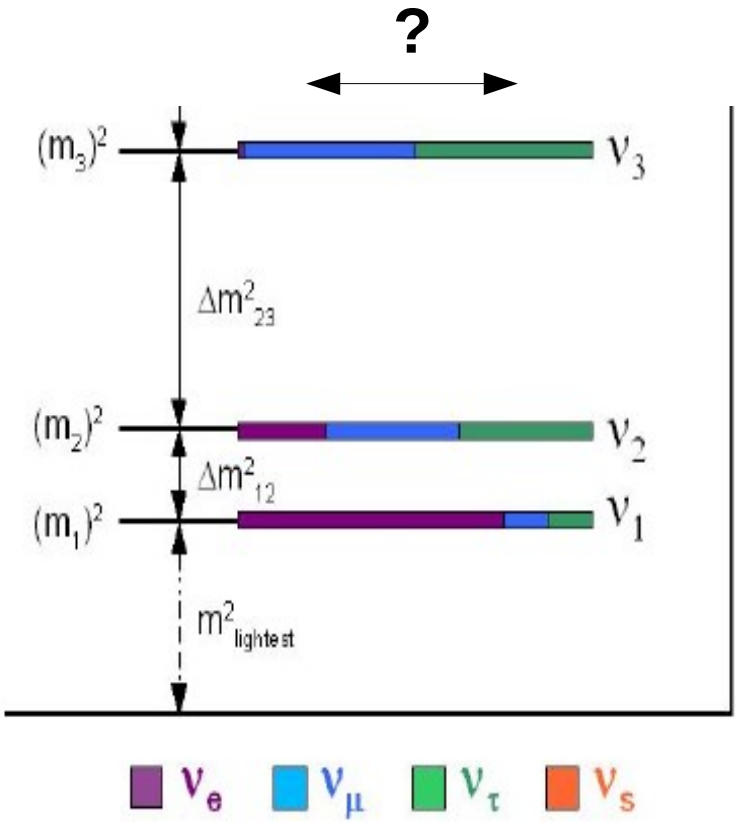
- Very different experimental techniques are hinting at short baseline oscillations.
- If confirmed, we would be seeing new particles! Physics beyond the standard model.
- Tension with other experiments, e.g. long-baseline disappearance.
- Either way we need to understand: yes or no.

Update of [Gariazzo, CG, Laveder, Li, Zavanin, JPG 43 (2016) 033001]

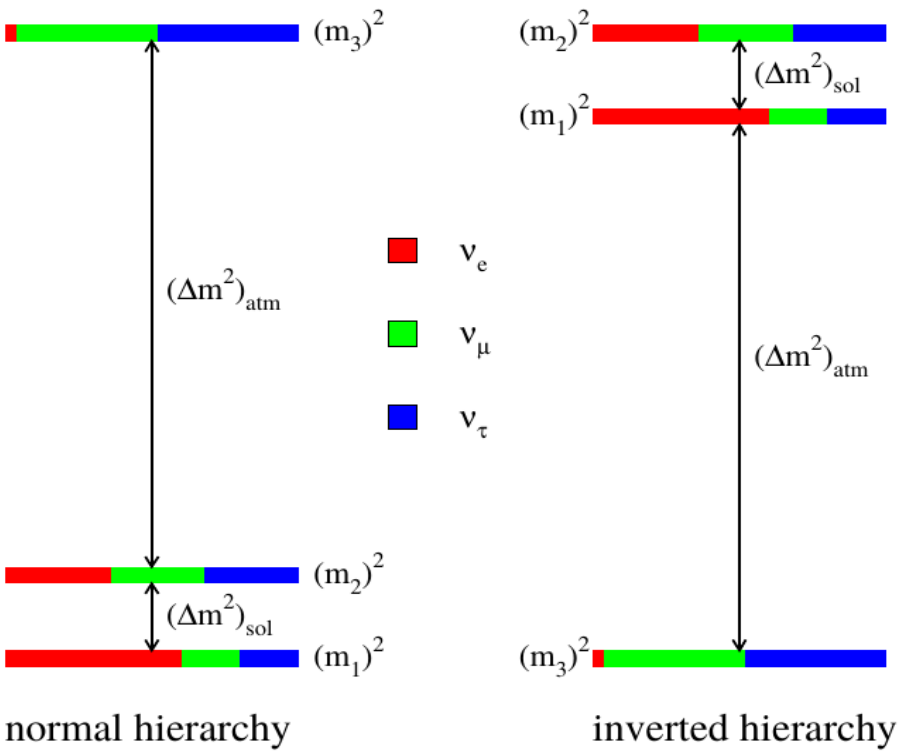


Is θ_{23} maximal?

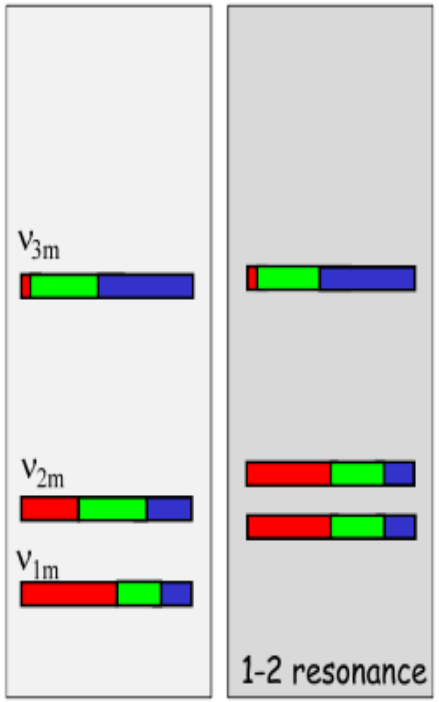
- Is mixing in the atmospheric sector maximal or a bit less?
- If so, is ν_3 more ν_μ or ν_τ? (in which octant?)
- If not maximal, this will affect our measurements of δ_{CP} and mass ordering.
- Measure e.g. through ν_μ disappearance.



Neutrino Mass Ordering



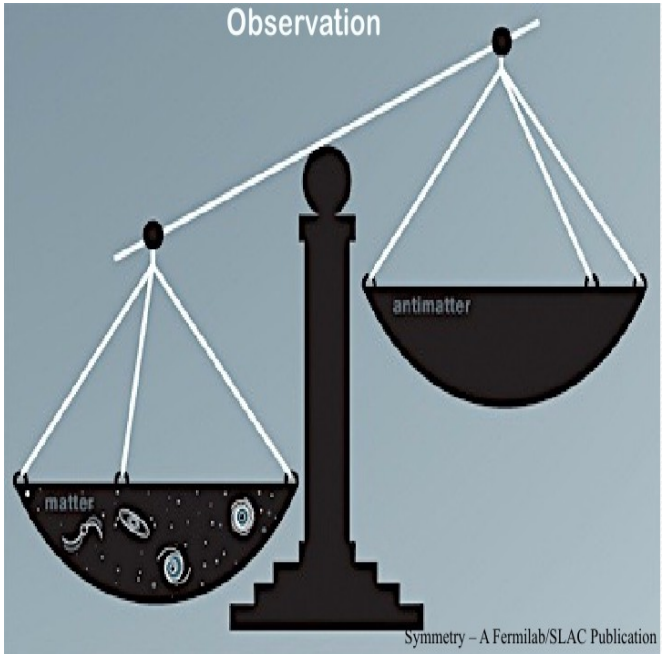
- We know the sign of Δm^2_{12} from matter effects in the Sun.
- Not in the case of Δm^2_{23} yet. Can be "normal" or "inverted".
- Measurement through $\nu_\mu \rightarrow \nu_e$ using matter effects.



A. Smirnov

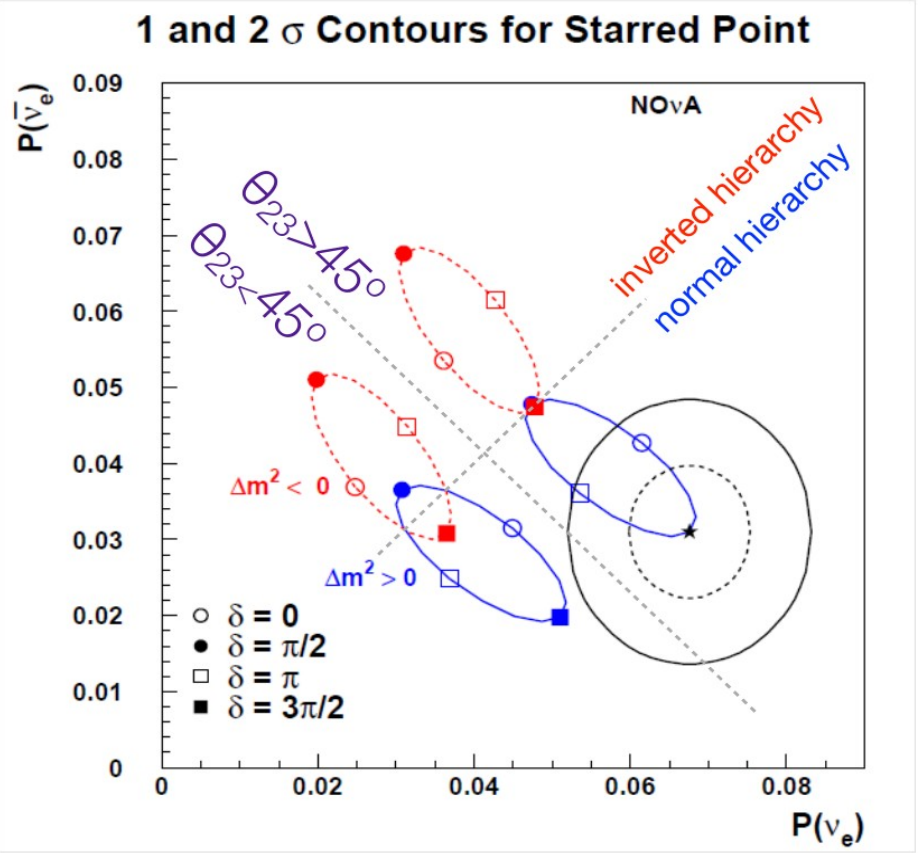
CP-violation

- Measurement through difference between $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- θ_{13} must be non-zero to have chance of measurement (fortunately it is).
- If δ ends up at a value with small asymmetry will be very difficult to measure.



CP-violation vs MH vs θ_{23}

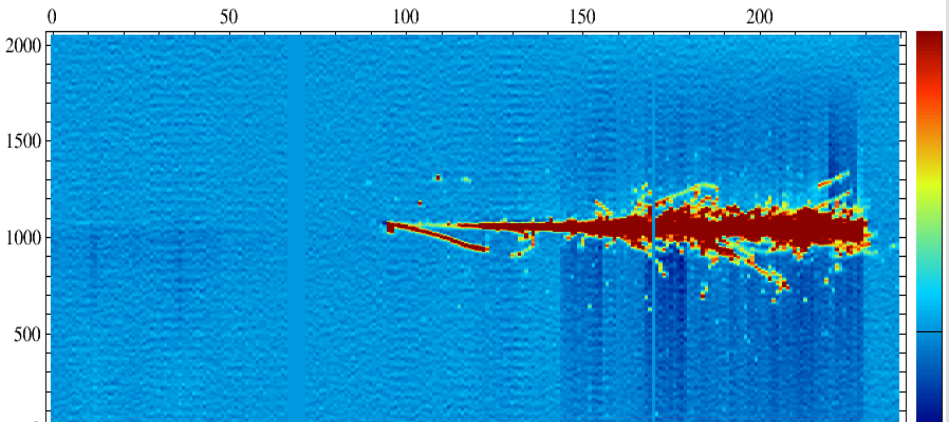
- There is interplay between these three measurements.
- There are different strategies to avoid it.
- Can set up experiment to not be sensitive to one or more effects, or control all of them.
- Multiple measurements will be helpful.

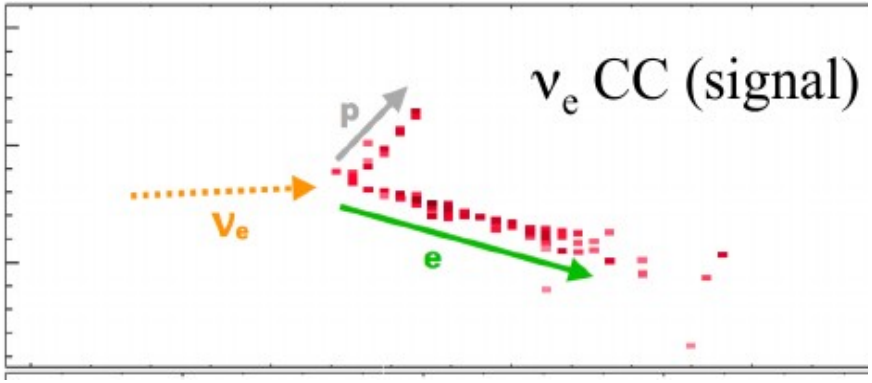


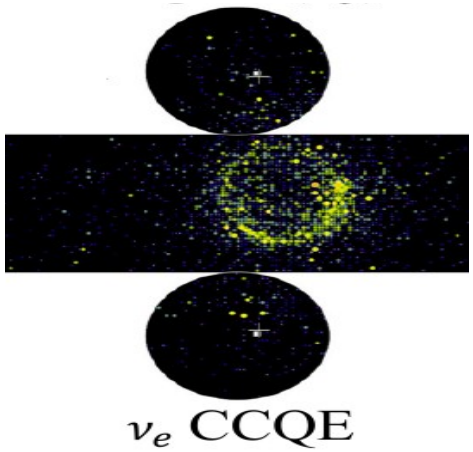
M. Messier

Electron Neutrino Appearance

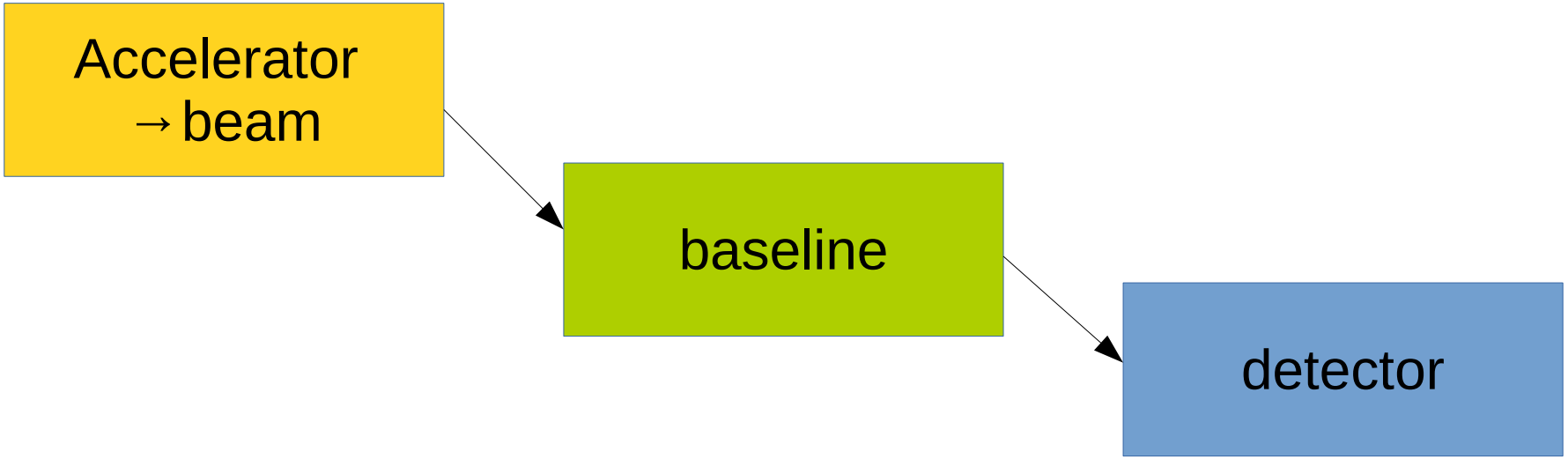
- Electron neutrino appearance amplitude happens to depend on θ_{13},θ_{23}, δ_{CP} and matter effects. Meaning, we will be seeing a lot of it throughout this talk.
- This also means, that experiments will run into similar types of backgrounds. Most likely photons, e.g. coming from π^0 decays.
- Hence I may mention battling backgrounds for this particular channel.







What makes up an accelerator oscillation experiment?

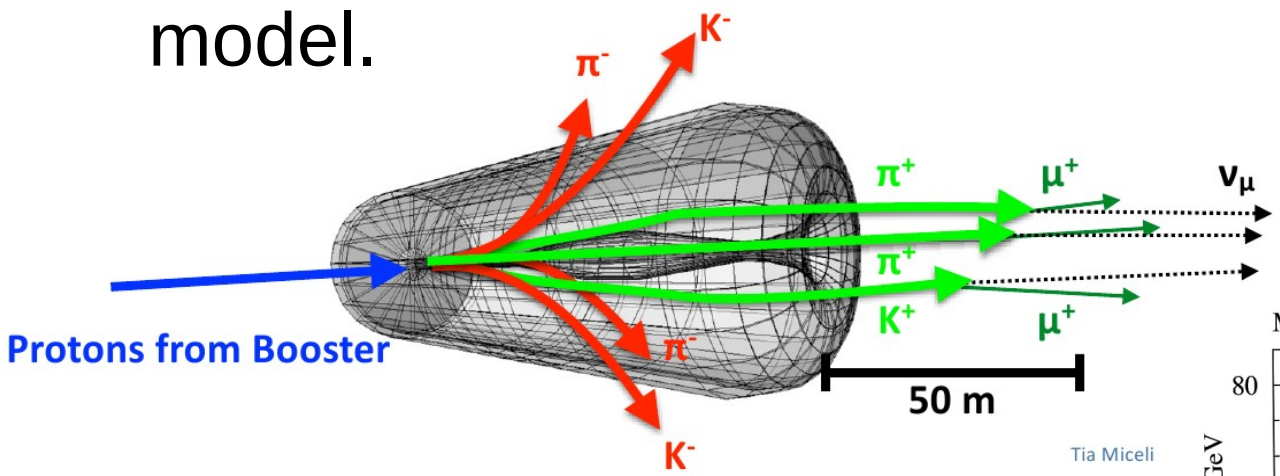


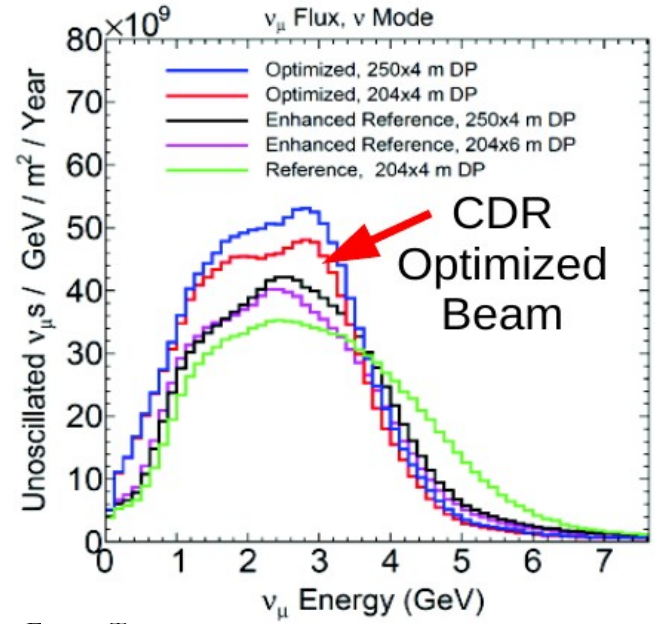
- To perform precision measurements we would ideally like to control L/E, energy, backgrounds, flux, and have lots of events both appearance/disappearance, and a wide energy range to see a couple of maxima (and a pony).

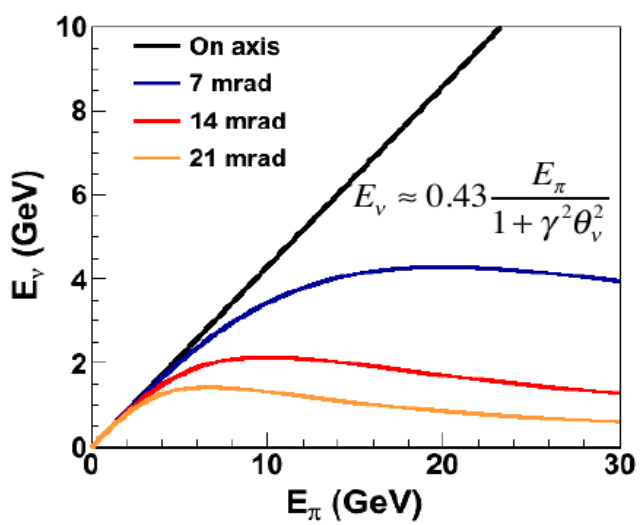
Neutrino Beams

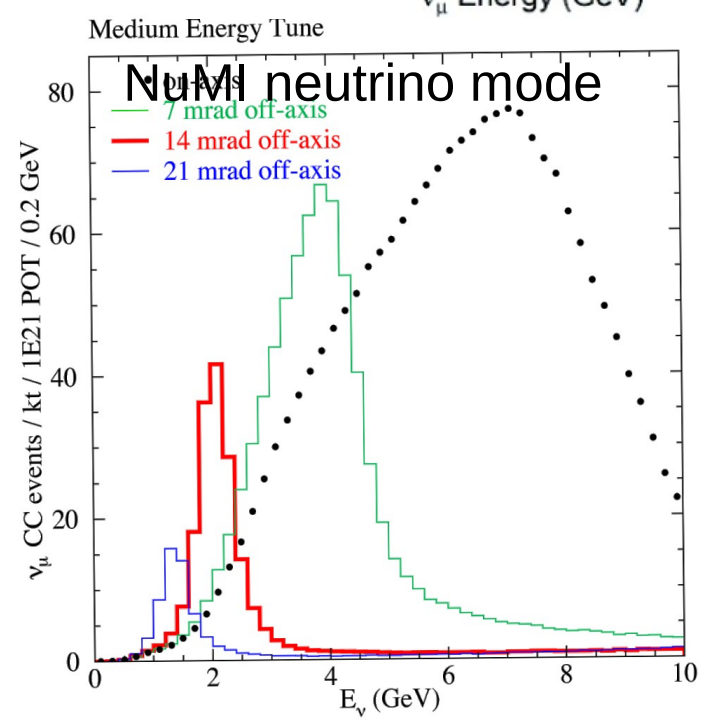
DUNE horn design optimised using genetic algorithms

- Broadband vs narrowband?
- Flux not easy to model.





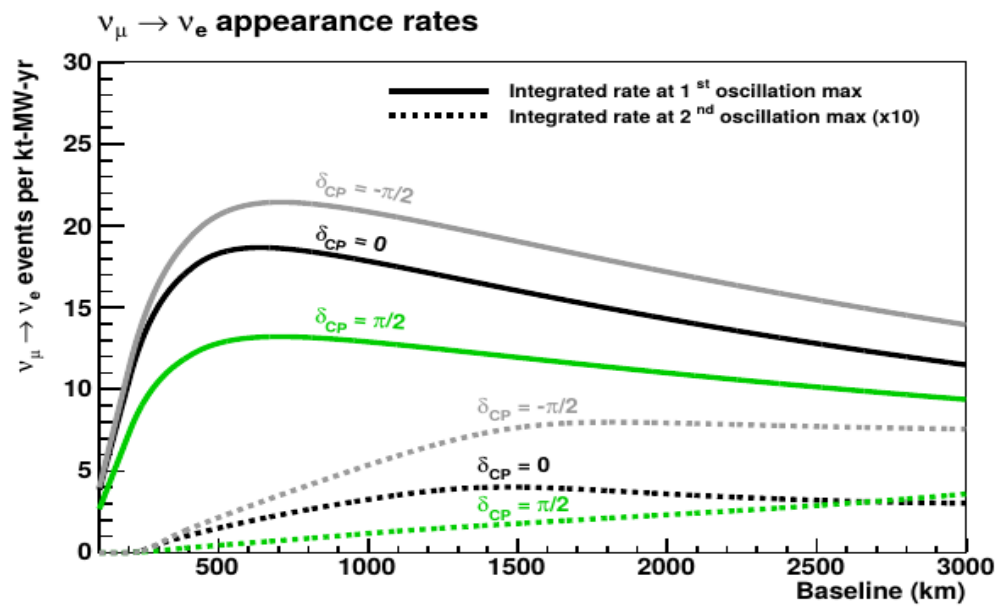


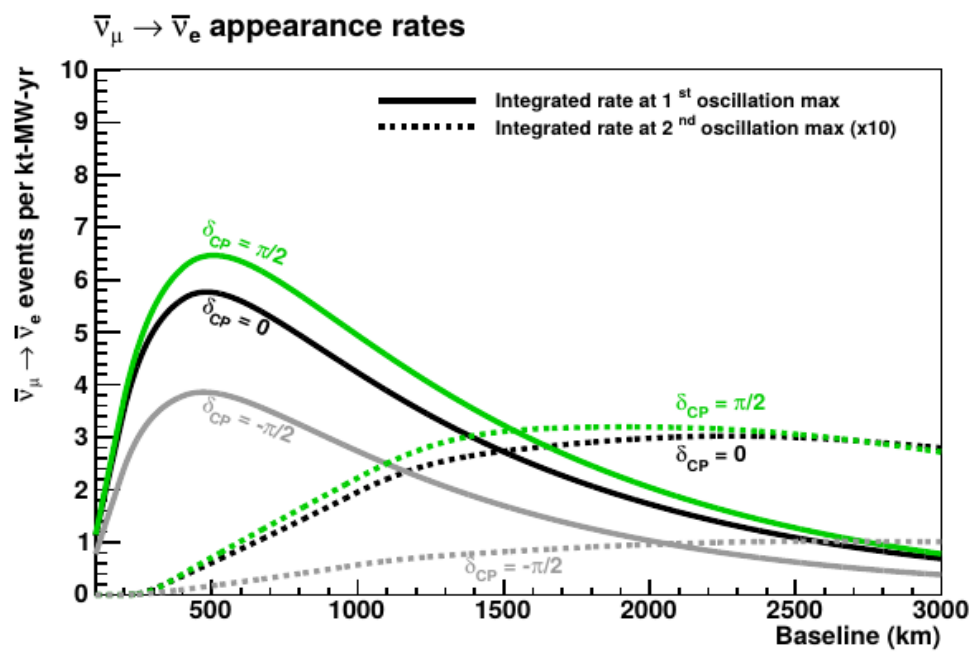


Also other ideas, Cyclotrons, DAR

Baseline

- The baseline, or rather the L/E, selects the physics you can to do:
  - Short baselines → larger Δm^2 (mostly sterile neutrino searches)
  - Long Baselines – matter effects come into play at some point, CP violation can be visible.
- Good idea to try to maximize oscillation probability.
- Optimize baseline, energy and detector for best physics sensitivity. Make sure you have enough events.

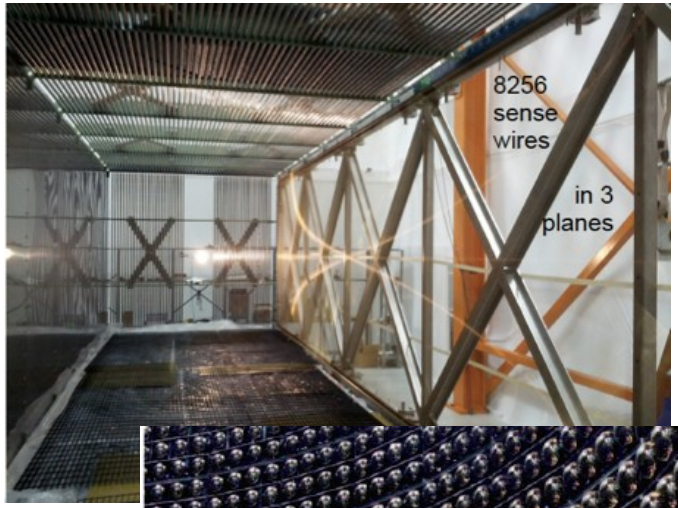


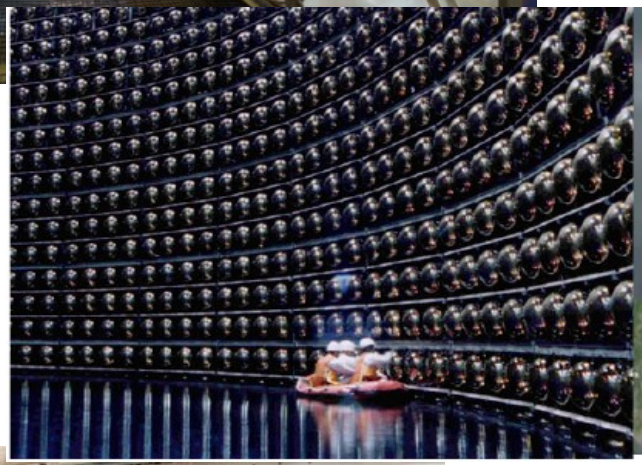


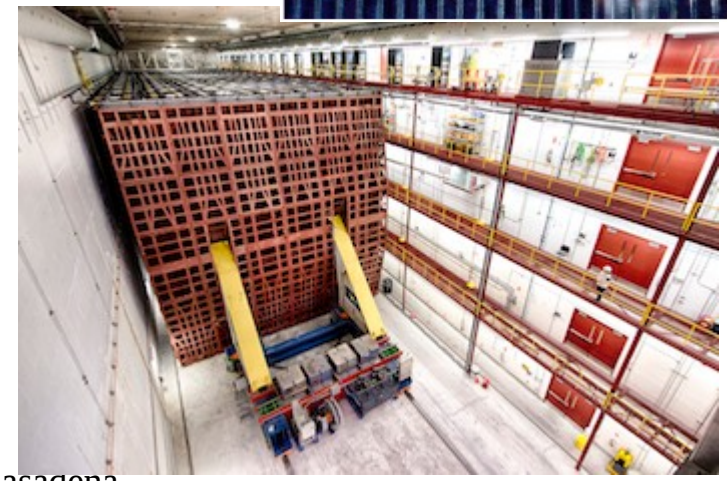
Arxiv:1311.0212

Detectors

- Different approaches/philosophies.
- Water Cherenkov/Liquid Argon/Scintillator main technologies on the market.
- Each has strengths, e.g. optimal energy – you can tailor your neutrinos to them.
- Need to have near detectors – better control of Flux and Systematics, a near detector helps (more on that in next talk by H. Tanaka)



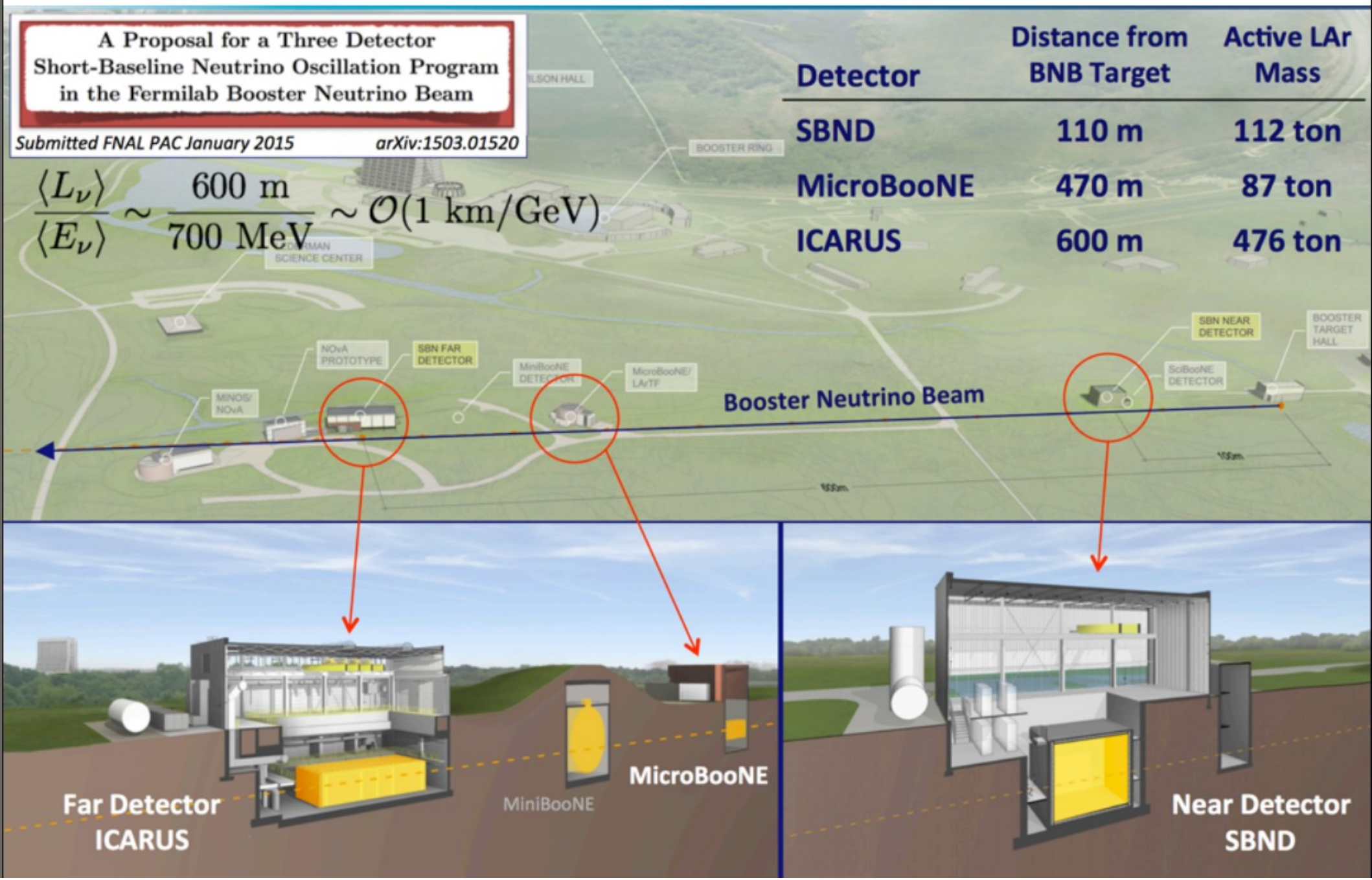




Let's talk about measurements

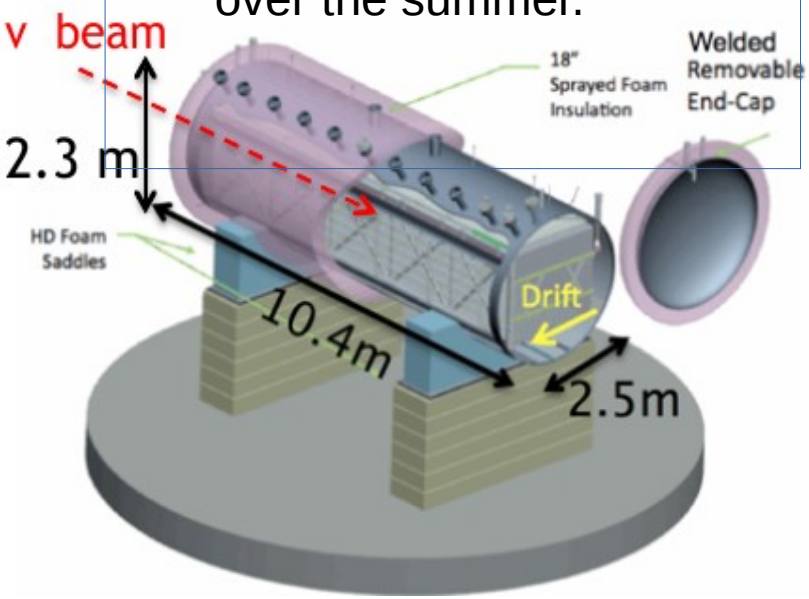
- I will go with baseline length and then time. Along that I will try to mention technology/R&D developments where applicable.
  - Short Baselines,
  - Current results from Long Baseline measurements
  - Future prospects of Long Baseline measurements.
- A good source of information: the ICFA roadmap document http://icfa.fnal.gov/wp-content/uploads/2016-05-07-nuPanel-roadmap-Final.pdf (you can provide feedback until Oct 15th)

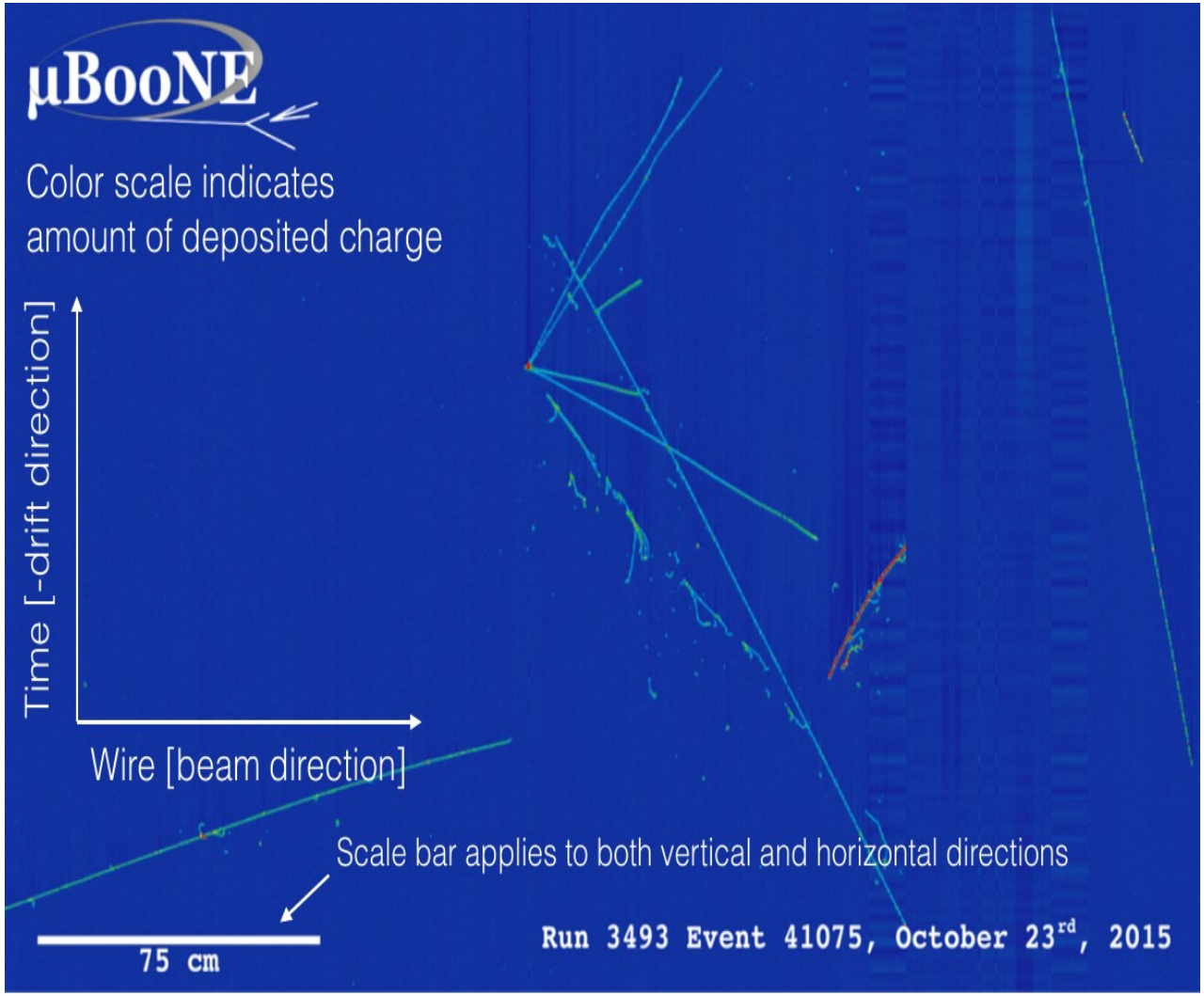
SBN Program at Fermilab



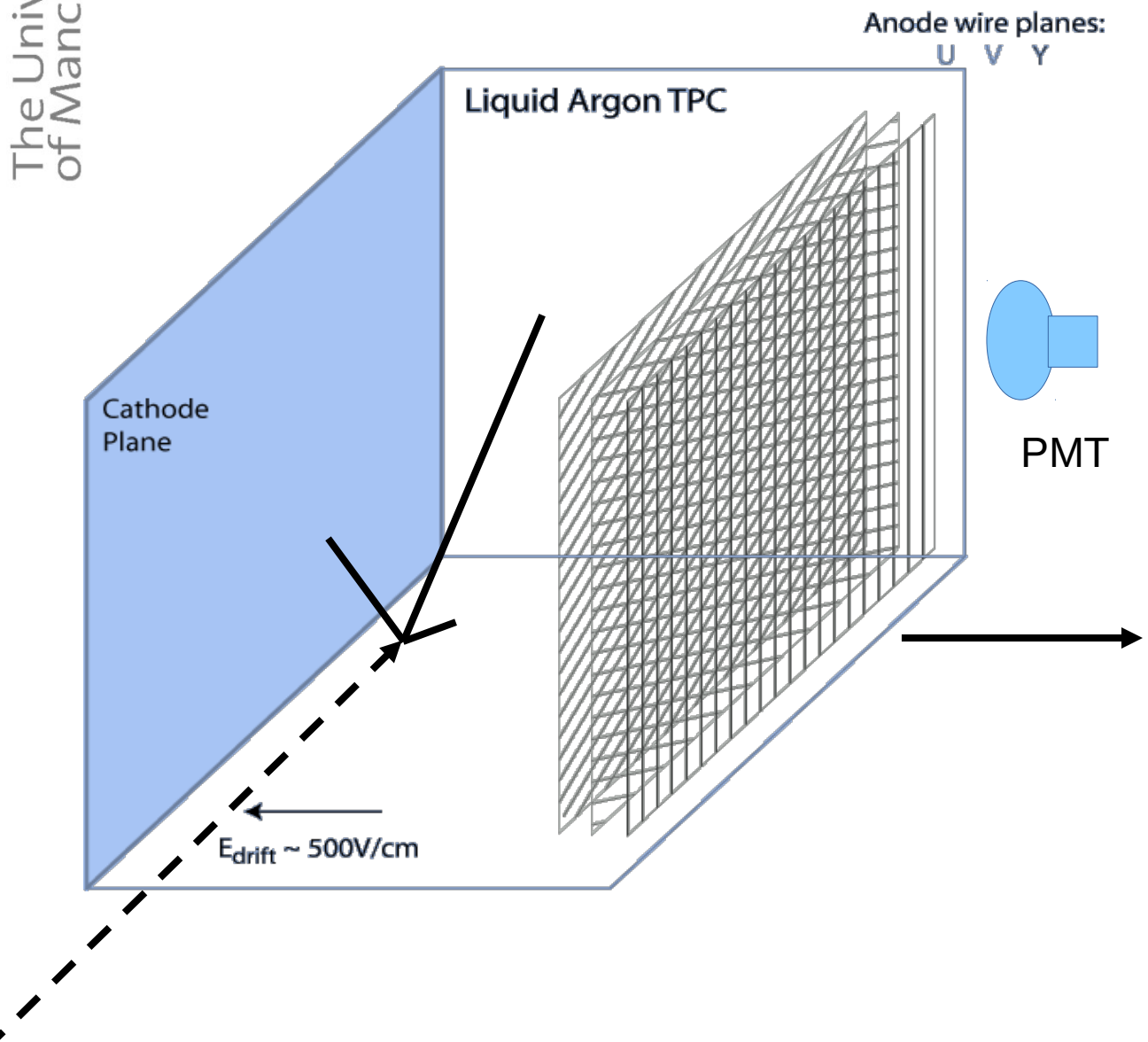
MicroBooNE

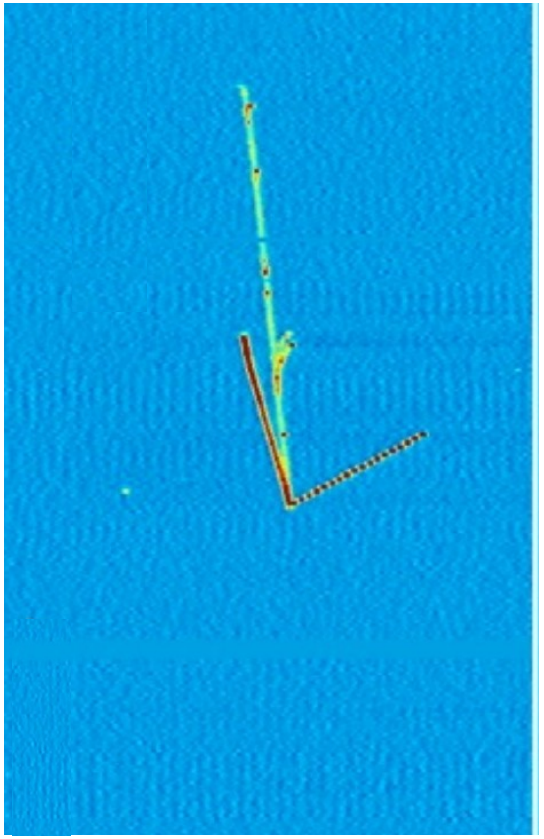
- Already Running in the Booster Neutrino Beam line.
- Just in front of MiniBooNE.
- 87 tons of Active liquid argon.
- Acquired its first year's worth of data.
- Several upgrades installed over the summer.





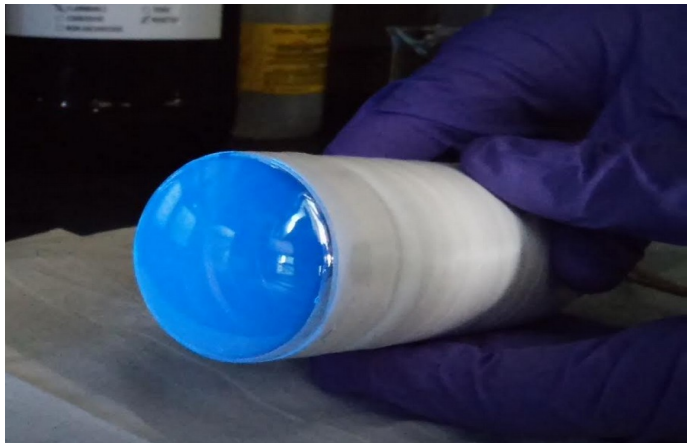
LArTPC Operation

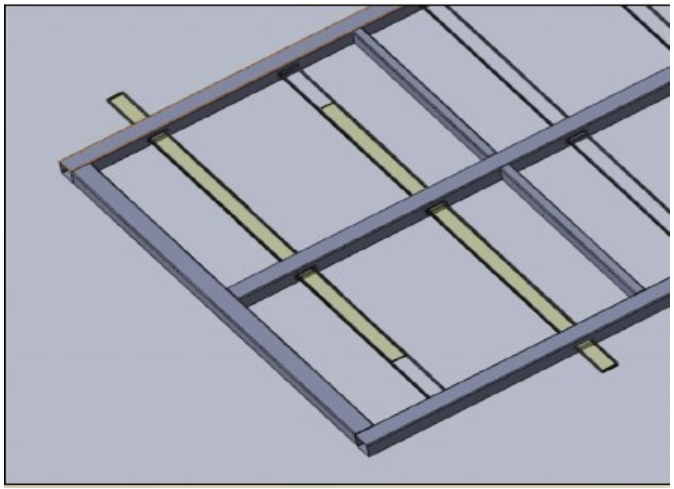




Scintillation Light

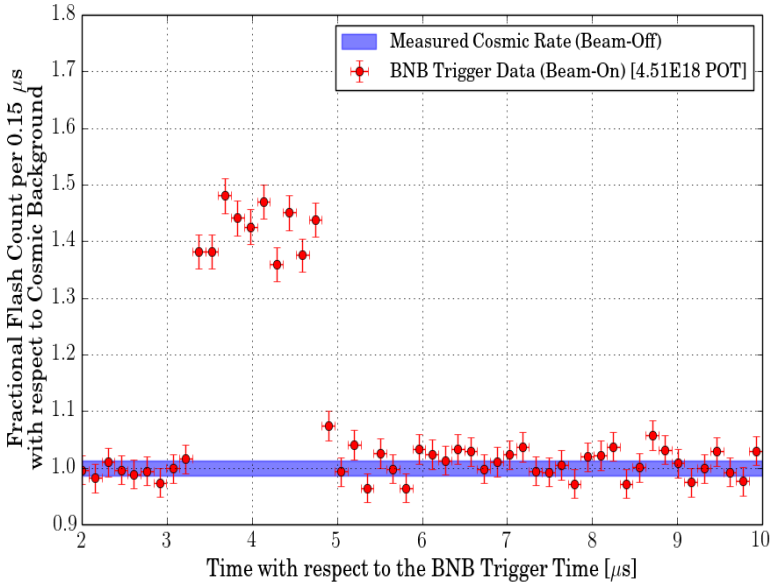
- Liquid argon is a prolific scintillator.
- The light is always there, complementary to the charge.
- Light is emitted at VUV wavelengths, need to downshift.
- Also need to maximize coverage without blowing up number of electronics channels.
- This is where rapid R&D in LArTPCs is happening.

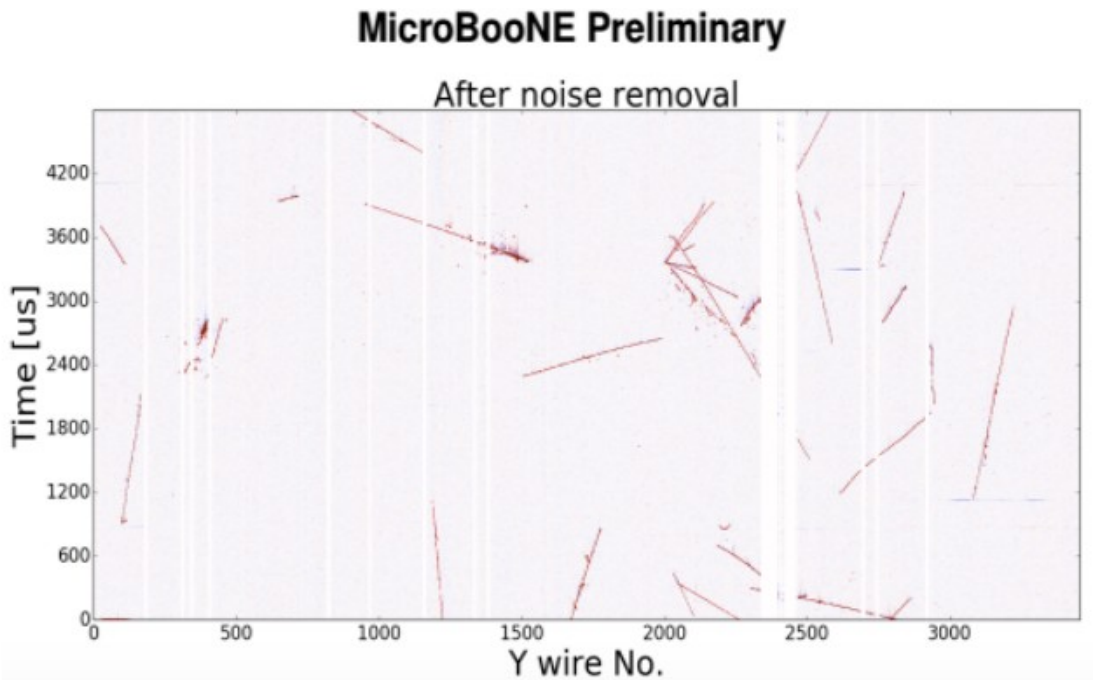


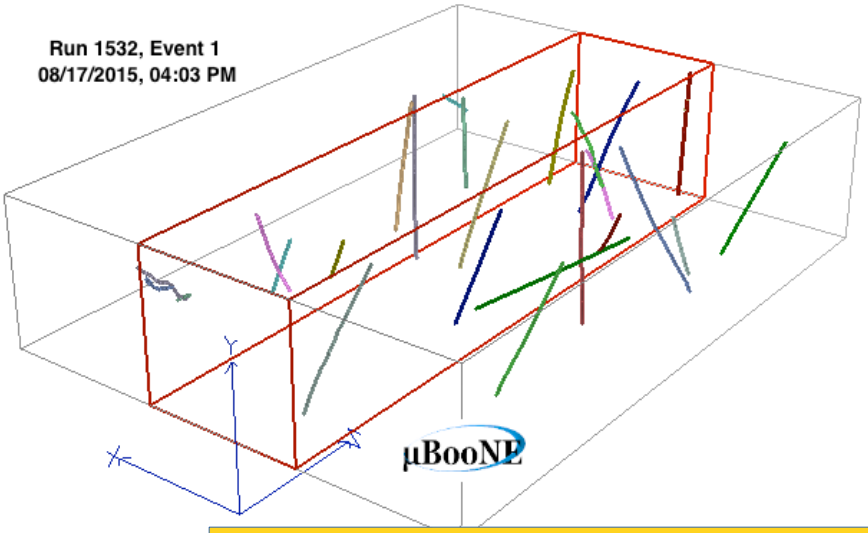


MicroBooNE

- Big step in understanding the operation of LArTPCs on the surface.
- Experience with cold electronics, HV, UV laser and many other aspects of operation.



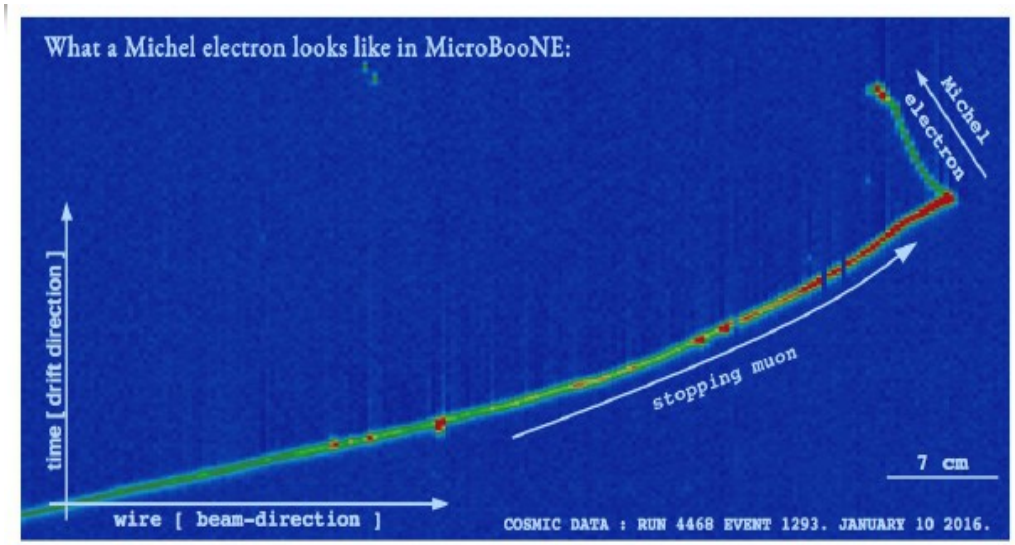


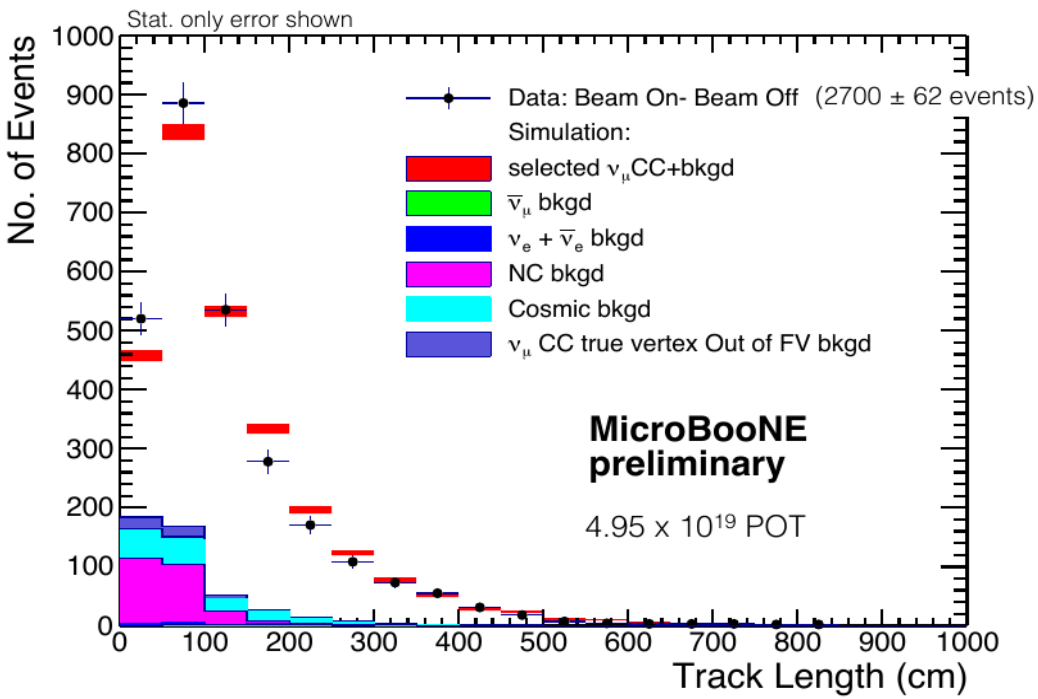


Talks, by Xin Qian and Sarah Lockwitz tomorrow

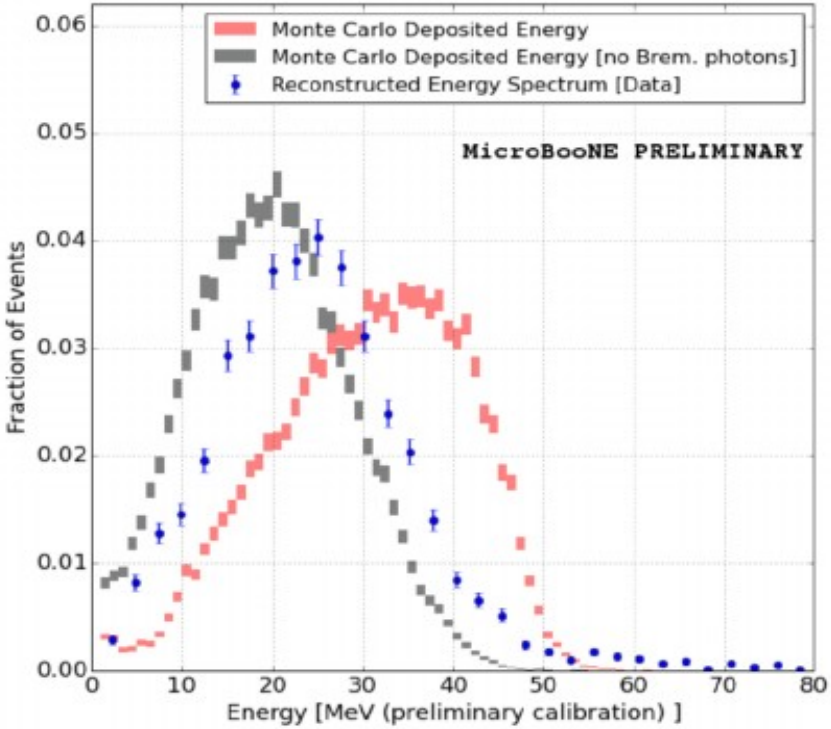
MicroBooNE

- Providing first physics results.
- Beam muon-neutrinos and Michel electrons.





Simulation scaled to same number of events as data



SBN Buildings Construction @Fermilab

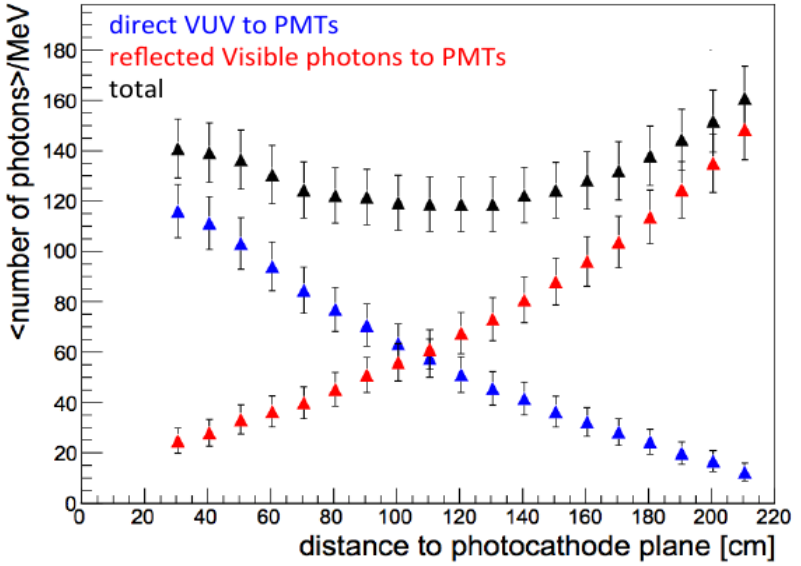
SBND location

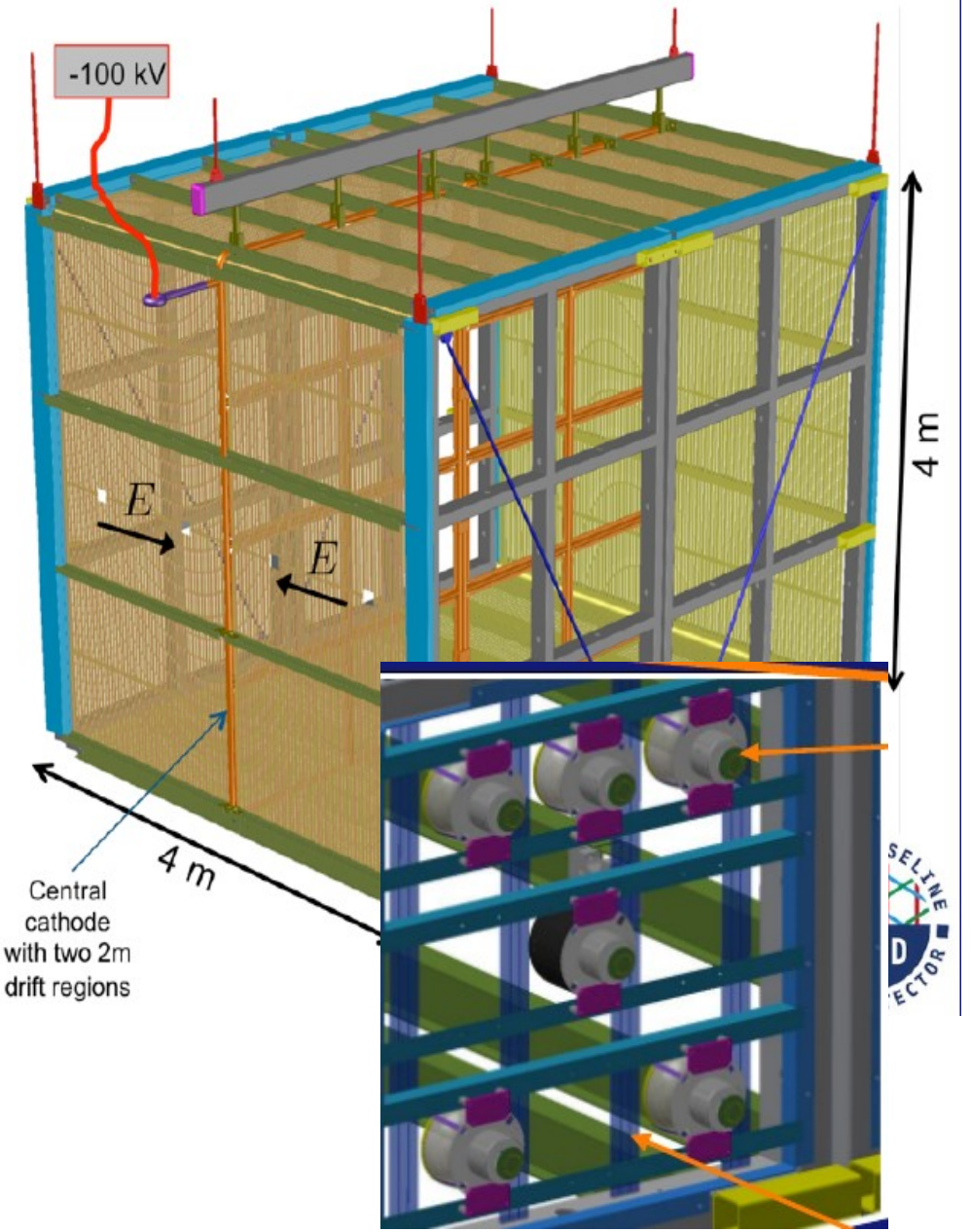
ICARUS location

Inside of the ICARUS TPC

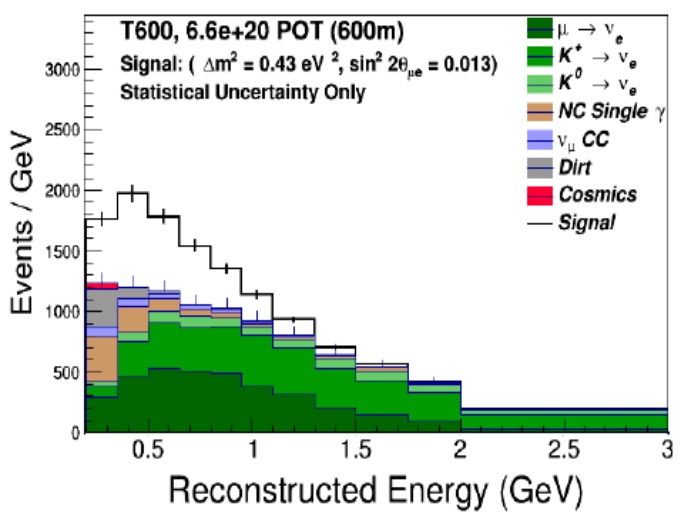
SBND

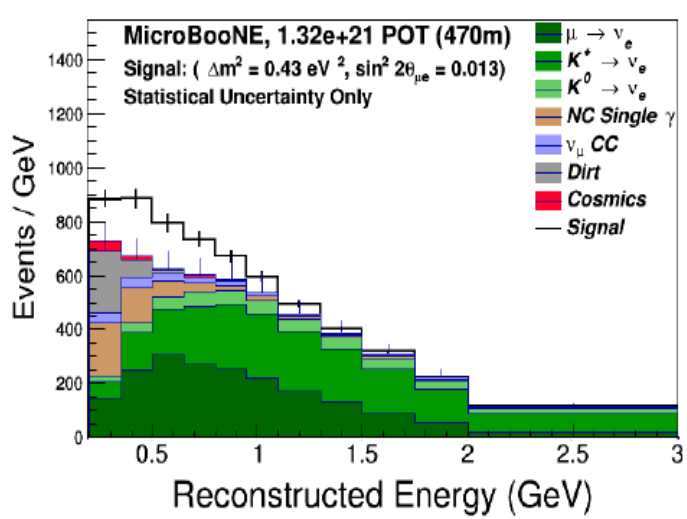
- SBND will see on the order of a million neutrino events/year.
- R&D activity to develop the light collection system.
- The LDS in SBND will have a very high light yield that could enhance the performance of the TPC.

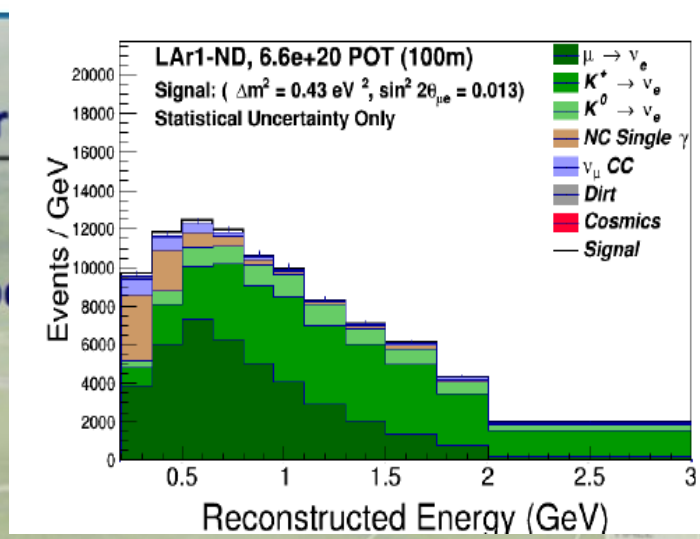


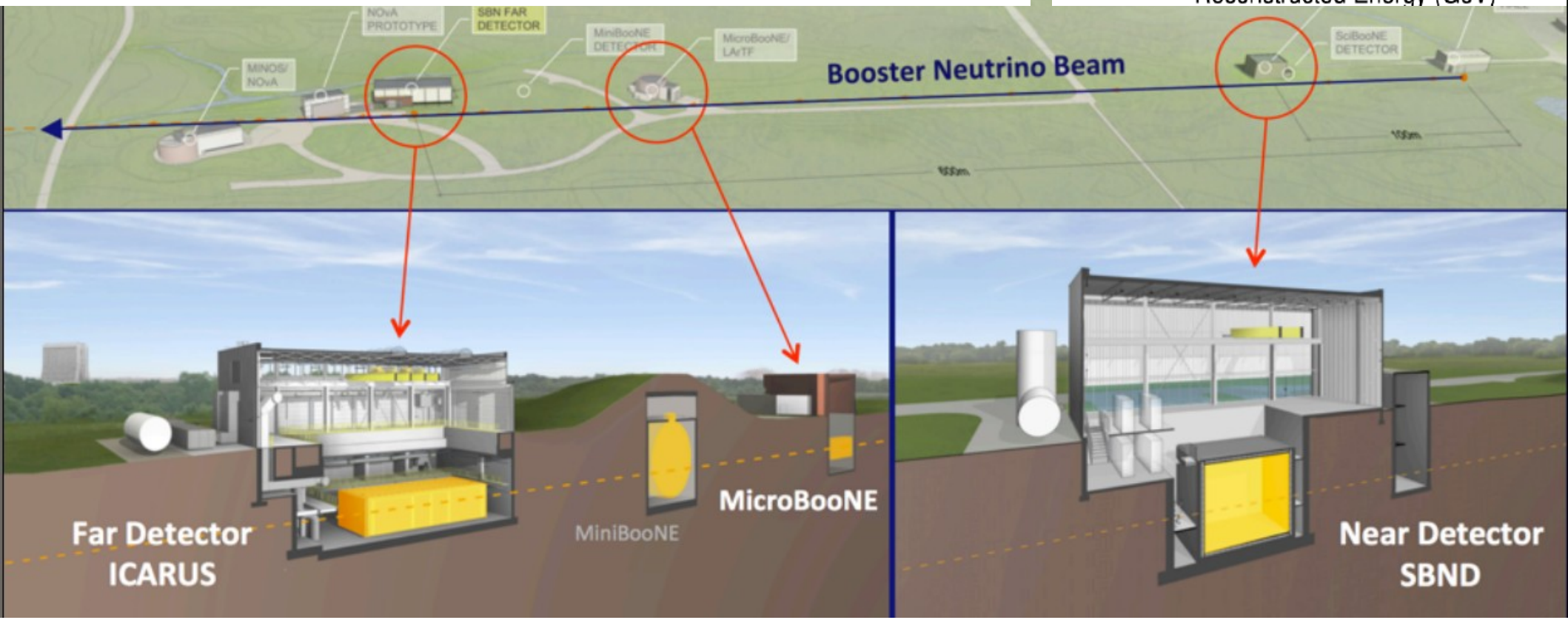


SBN Program at Fermilab









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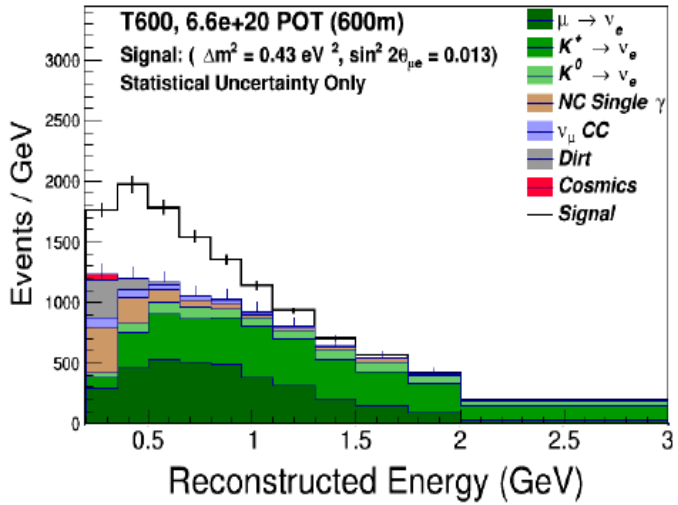
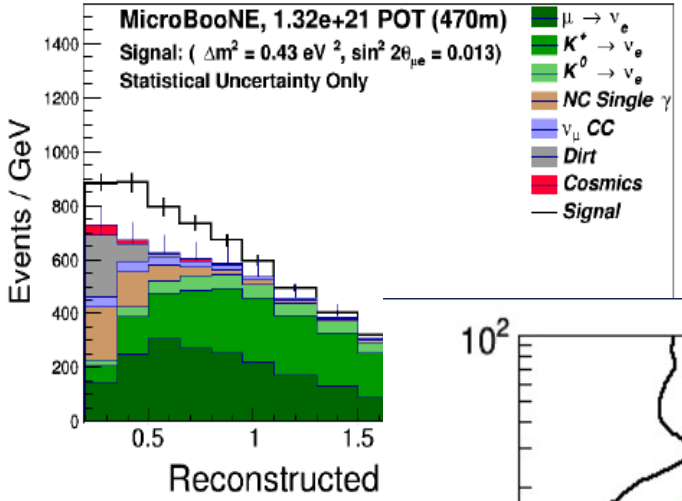
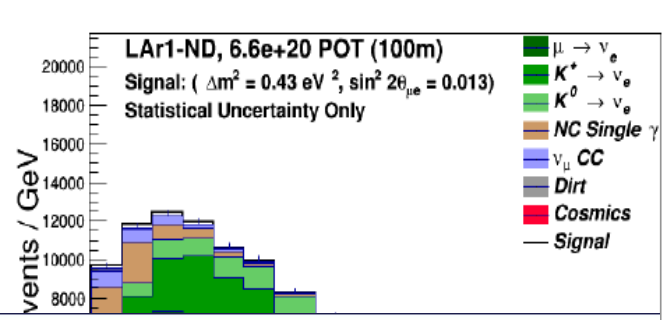
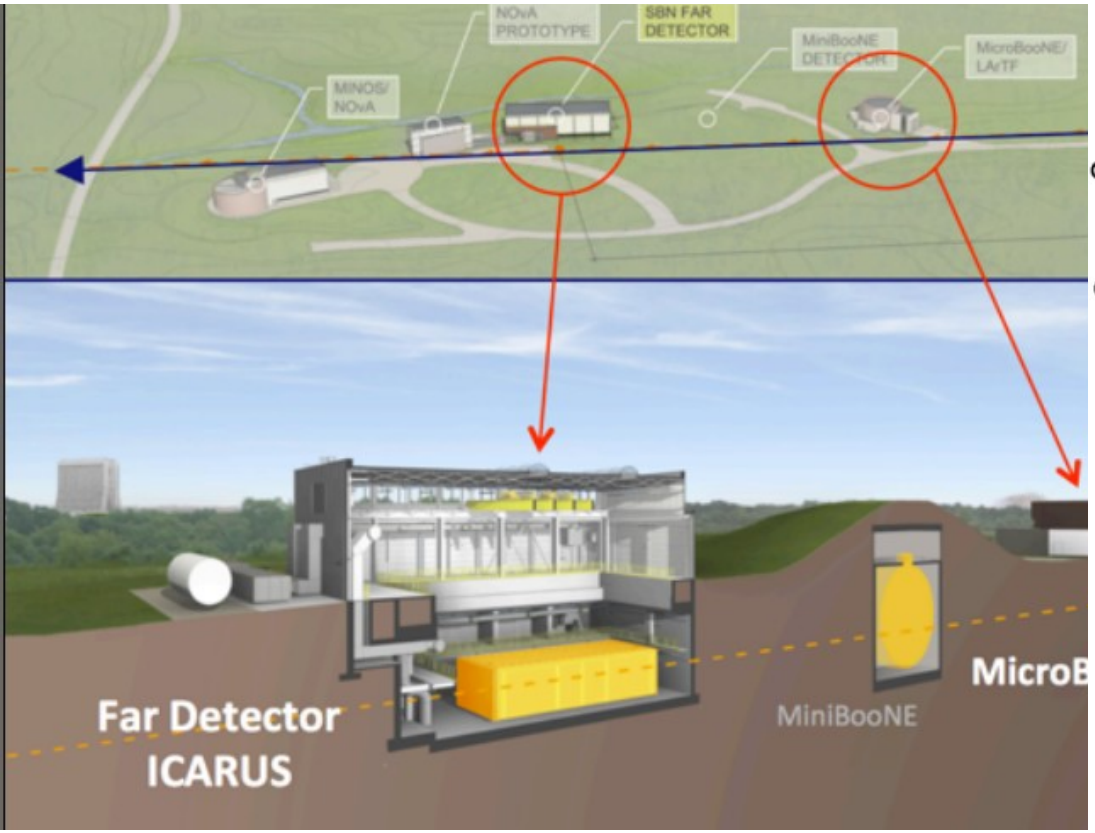
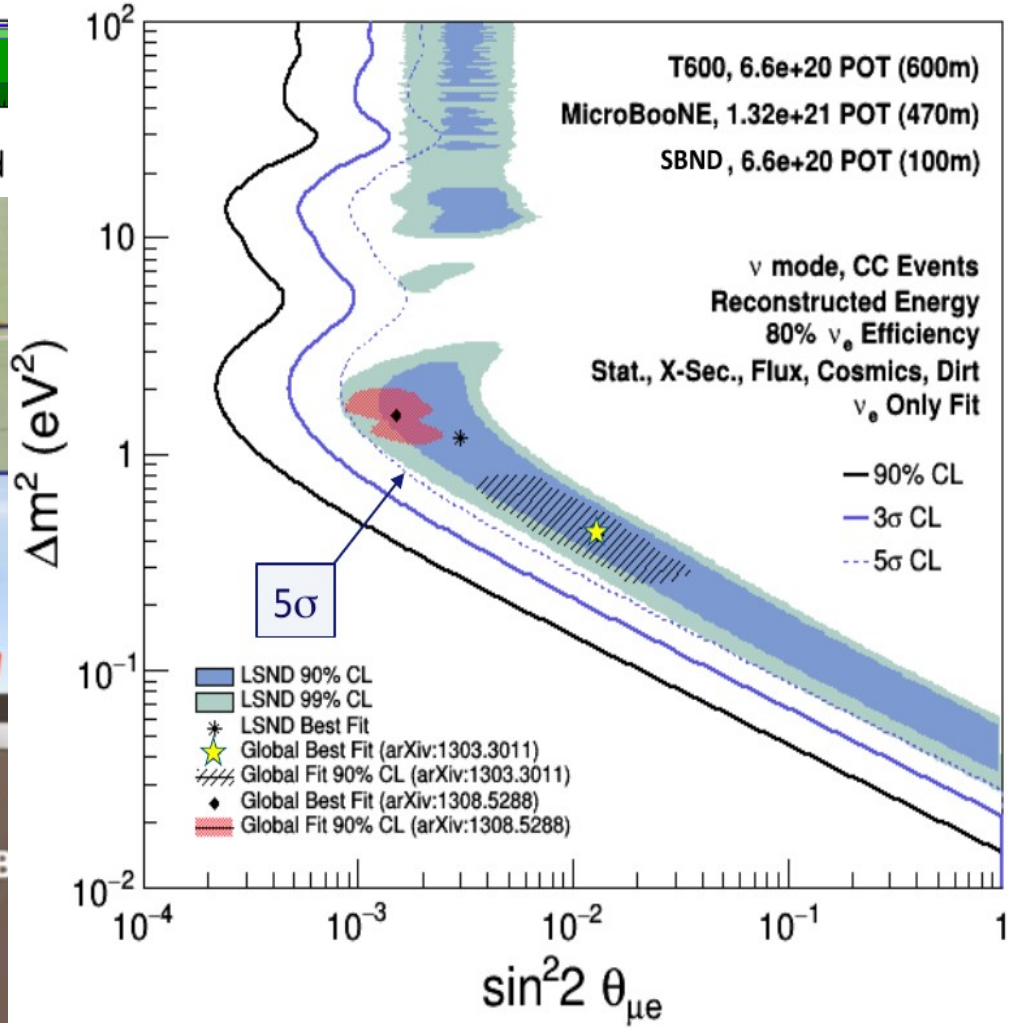








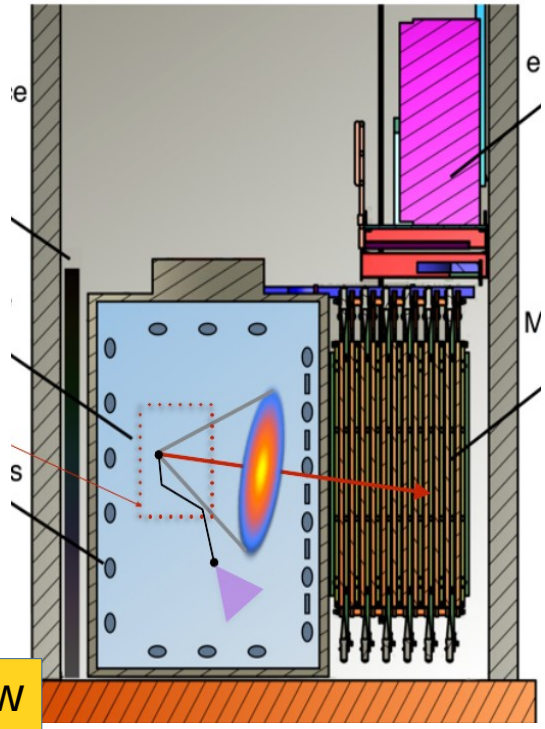


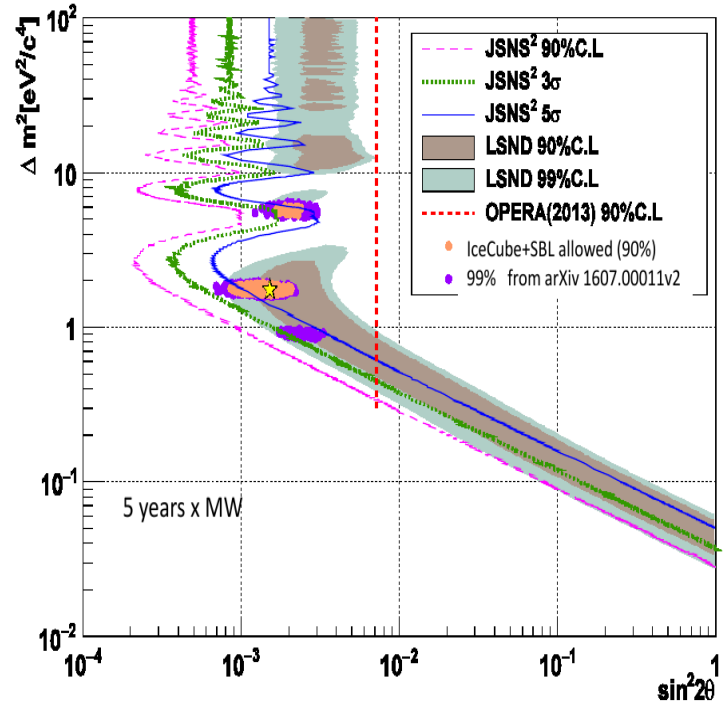
Other Short Baseline Experiments

ANNIE is studying the behaviour of neutrons in neutrino interactions.

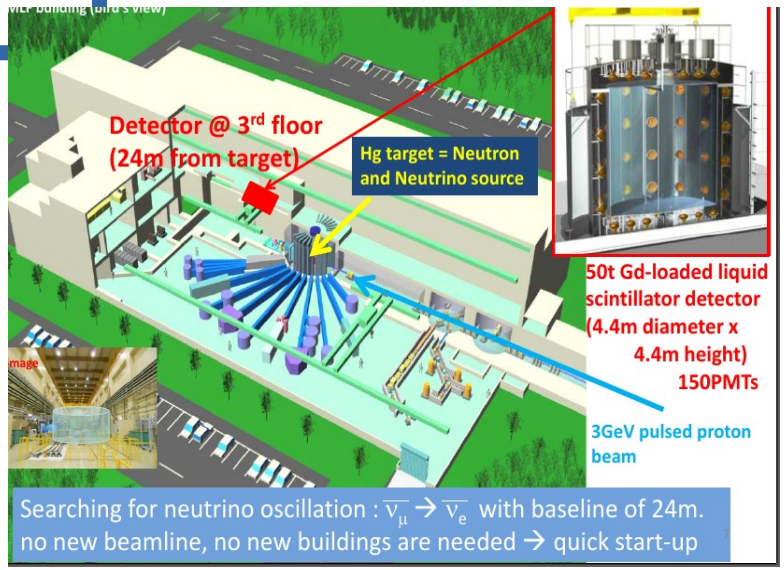
In parallel testing performance of LAPPDs in Gd-doped water.

LAPPD talk by J.Eisch tomorrow





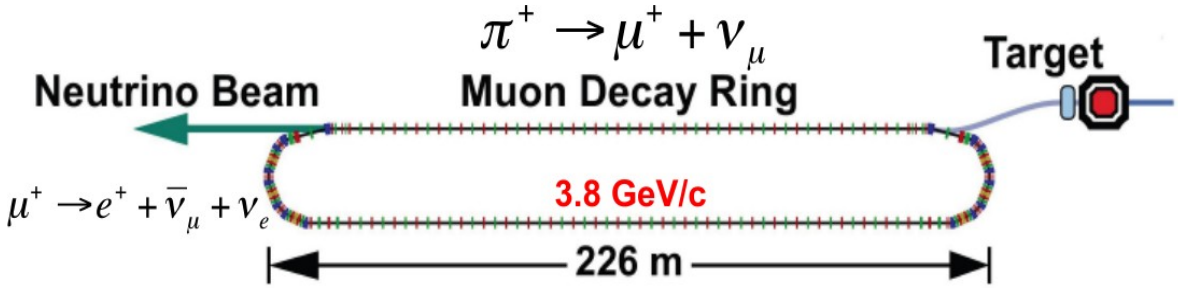
- JSNS^2 expects to take to take data in 2018-2019. (Recently received funding for first 2 modules.)
- Direct test of LSND!

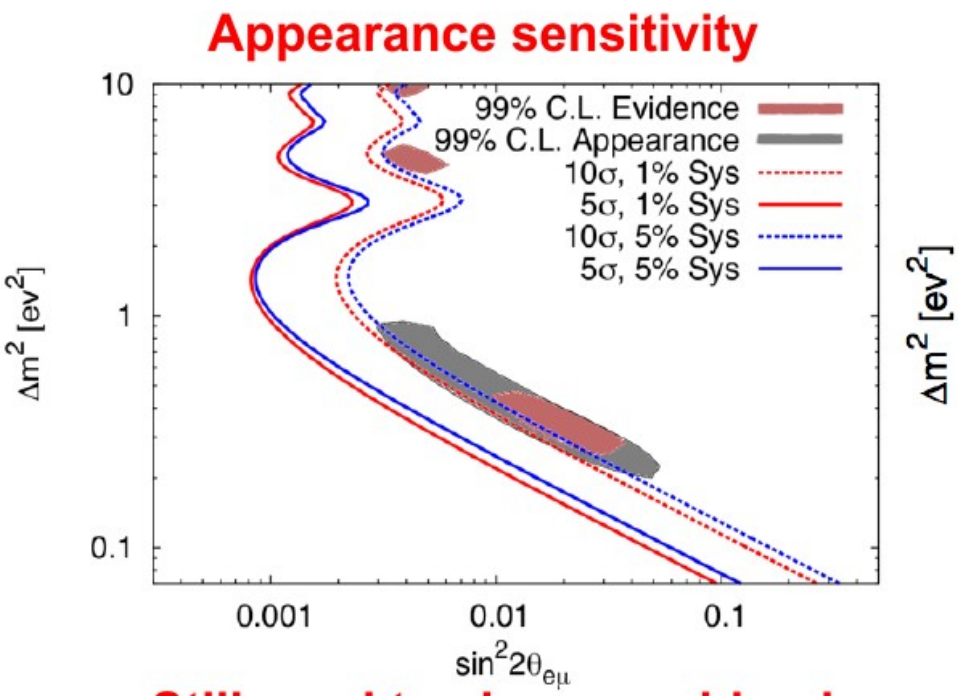


Maruyama@ICHEP

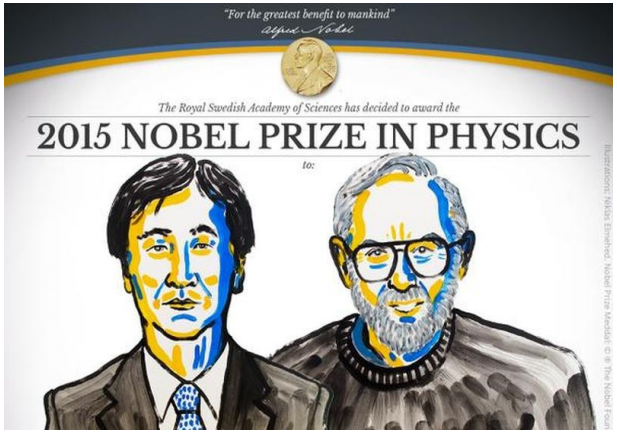
Future Options

- NuSTORM provides a ver well defined beam.
- A good way to search for sterile neutrino while developing the technology for a future Neutrino Factory.
- Currently in talks with CERN.
- Possible decision frame around 2020, after SBN experiments conclude.



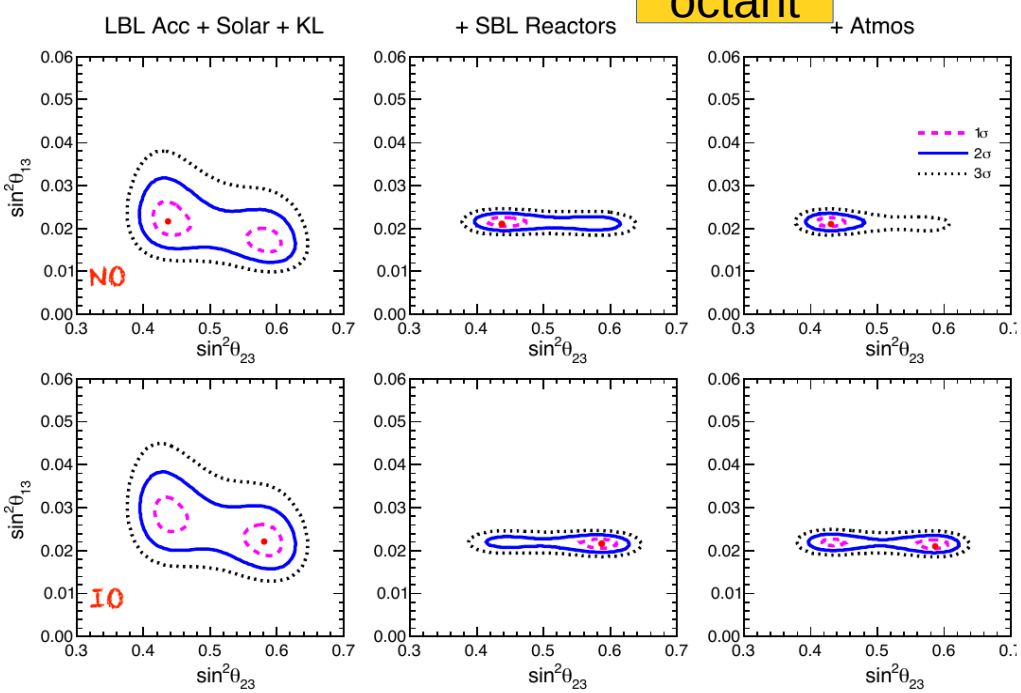


Switching Gears to LBL



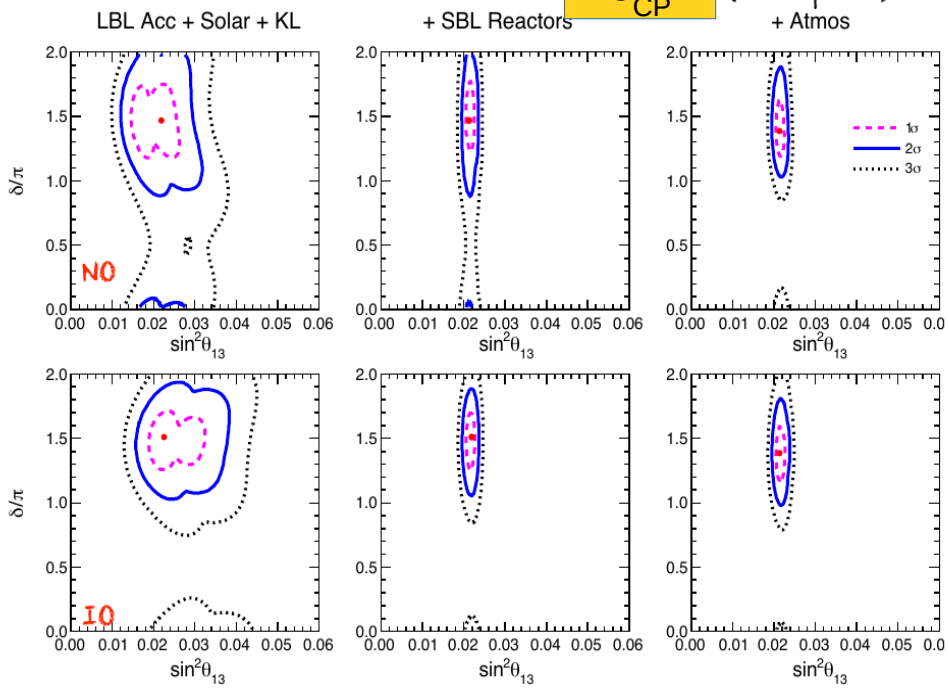
- 2015 is so last year.
- 2016 also not too shabby.
- We've had a very exciting summer in neutrino physics:

octant



Atmospheric data do not spoil this trend but introduce some differences in the relative likelihood of the two octants in NO and IO. Octant degeneracy may show up in terms of "bumps" or "double bands" when marginalized away →

δ_{CP} (SK+DeepCore)

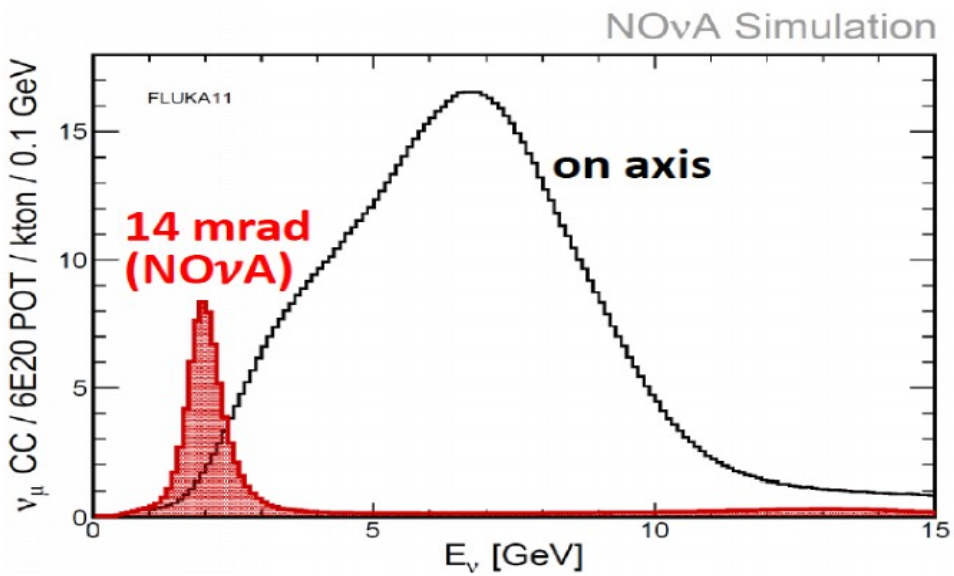


Results in the (δ,θ_{13}) plane corroborated by atmospheric data

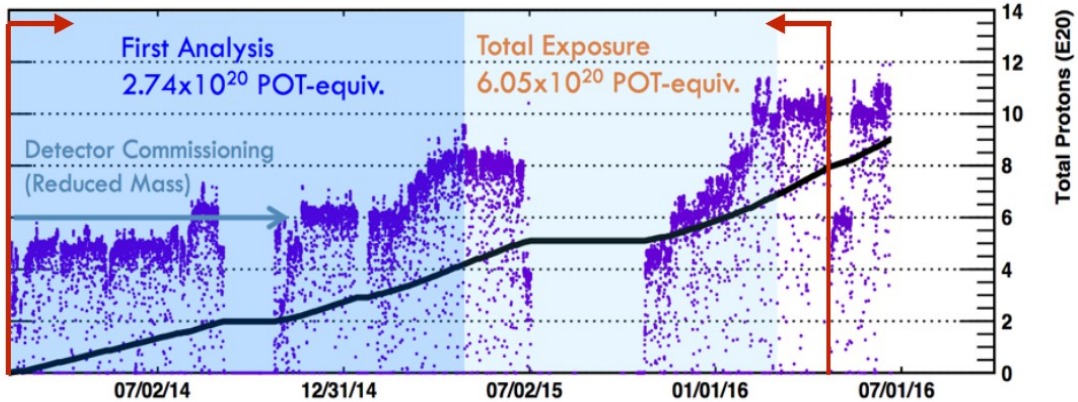
A.Marrone@ Neutrino16

NOvA

- 810 km baseline.
- Functionally identical near and far detectors.
- Off-axis beam with energy centered around 2GeV.

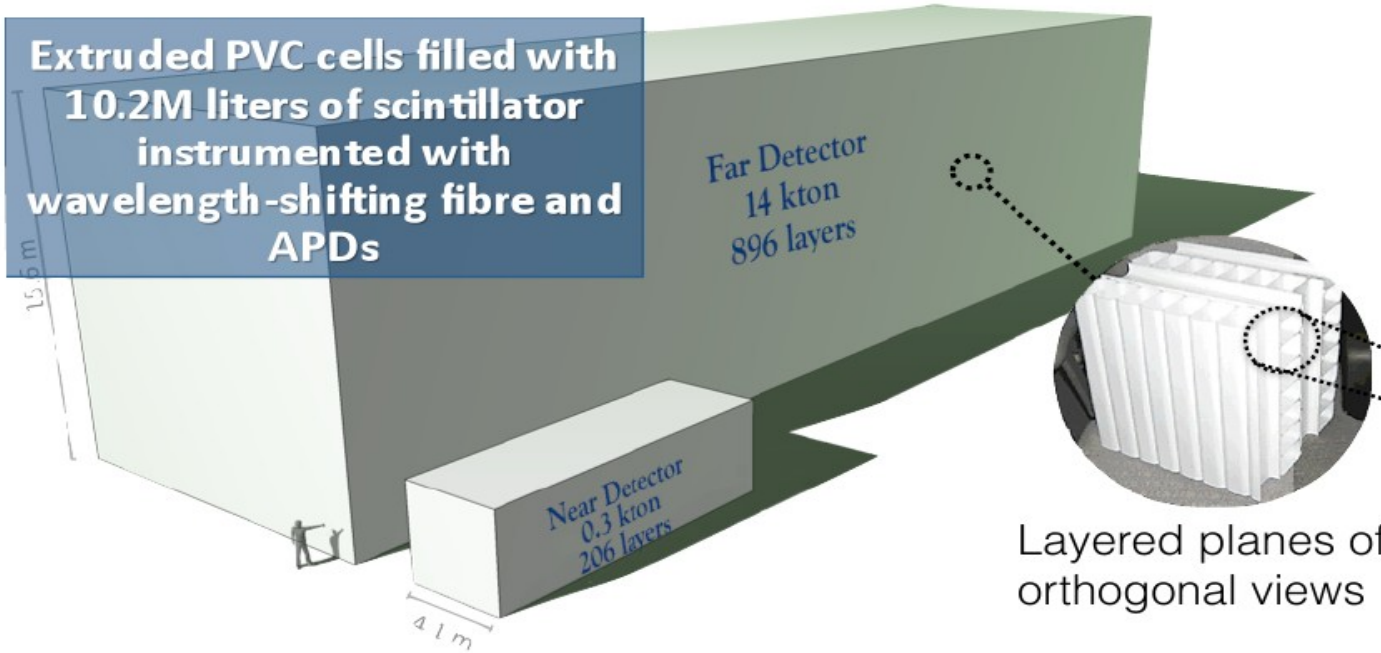


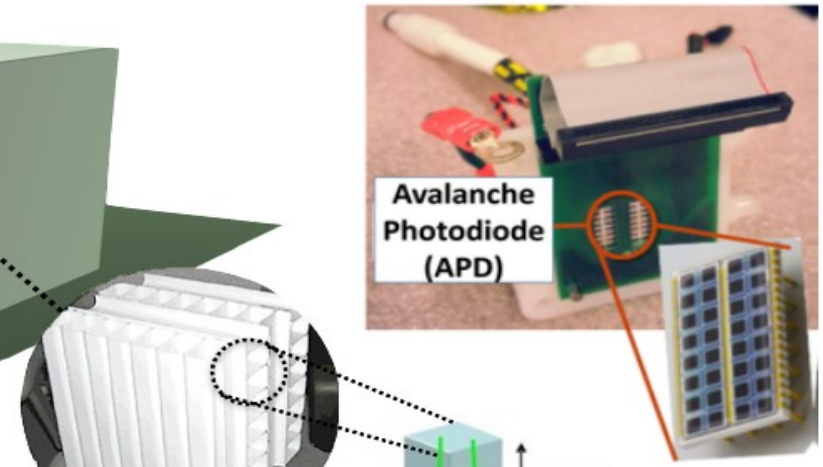
700 kW design reached on Jun 13th



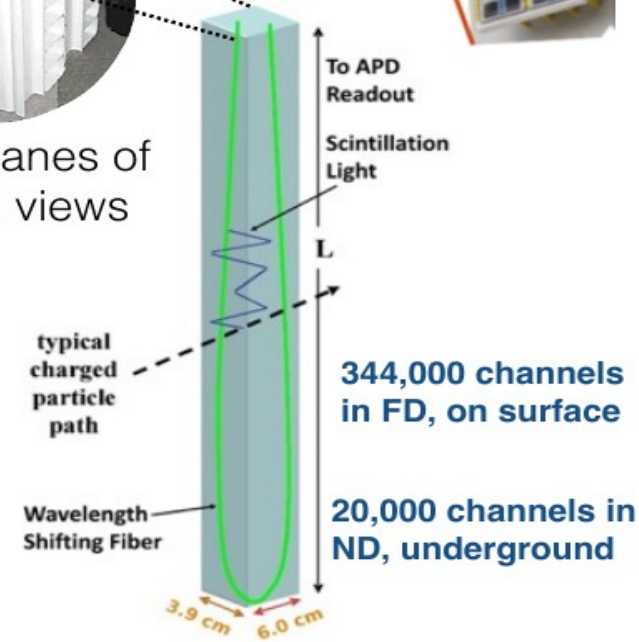
NOvA Principle of operation

Functionally-identical PVC-cell Near and Far Detectors filled with 10.2M liters of scintillator





Layered planes of orthogonal views



344,000 channels in FD, on surface

20,000 channels in ND, underground

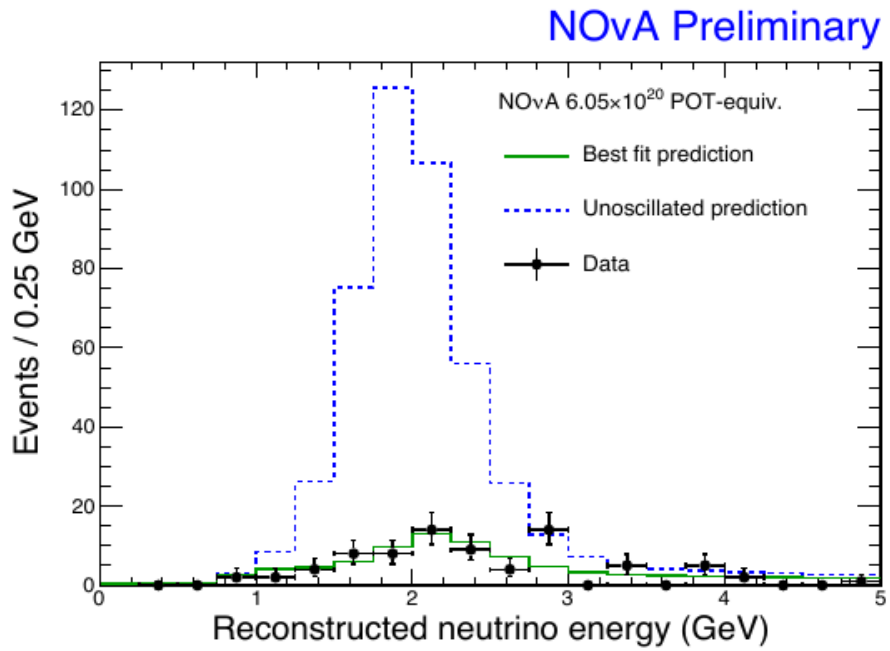
Low-Z materials, 65% active

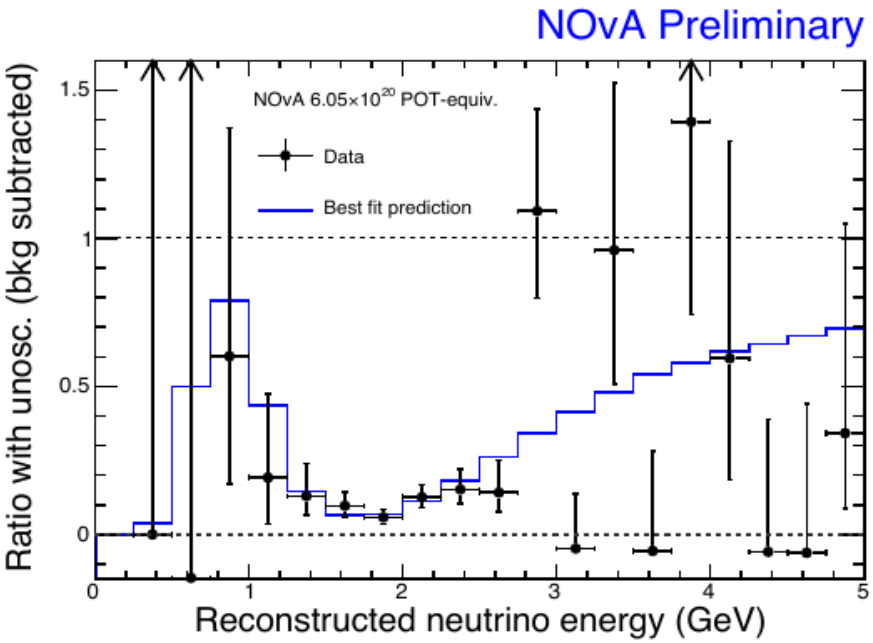
DAQ runs with zero deadtime

Triggers on beam, SNEWS, exotics, cosmic ray calibration samples

Taken from K. Matera @ICHEP

NOvA ν_μ Disappearance

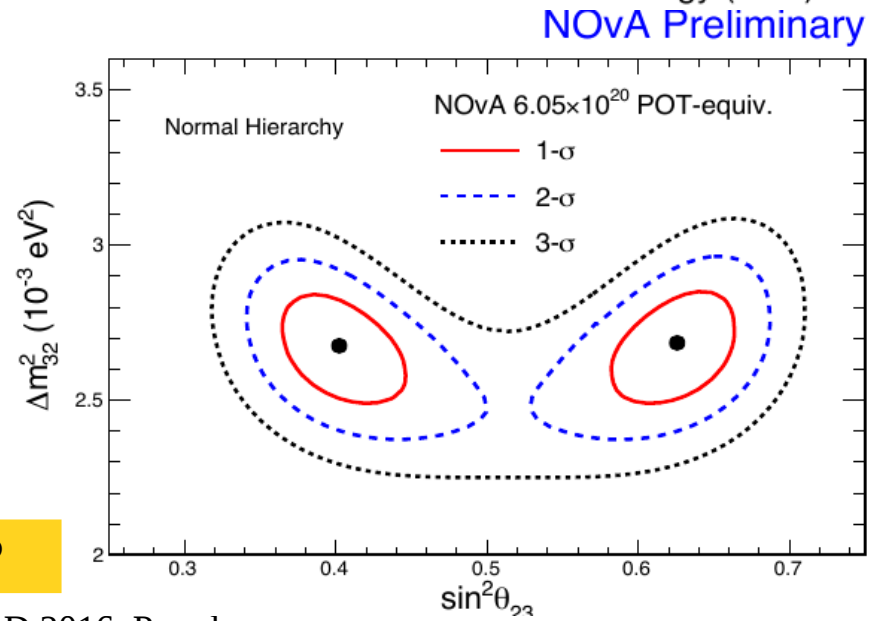




$$\Delta m^2_{32} = (2.67 \pm 0.12) \times 10^{-3}\mathrm{eV}^2$$

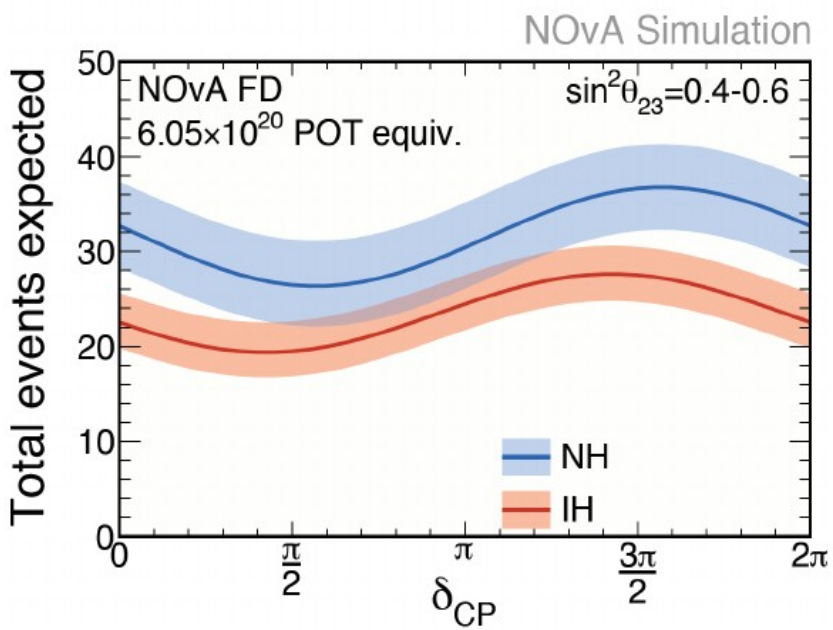
$$\sin^2(\theta_{23}) = 0.40^{+0.03}_{-0.02}(0.63^{+0.02}_{-0.03})$$

- Maximal mixing excluded at 2.5 sigma



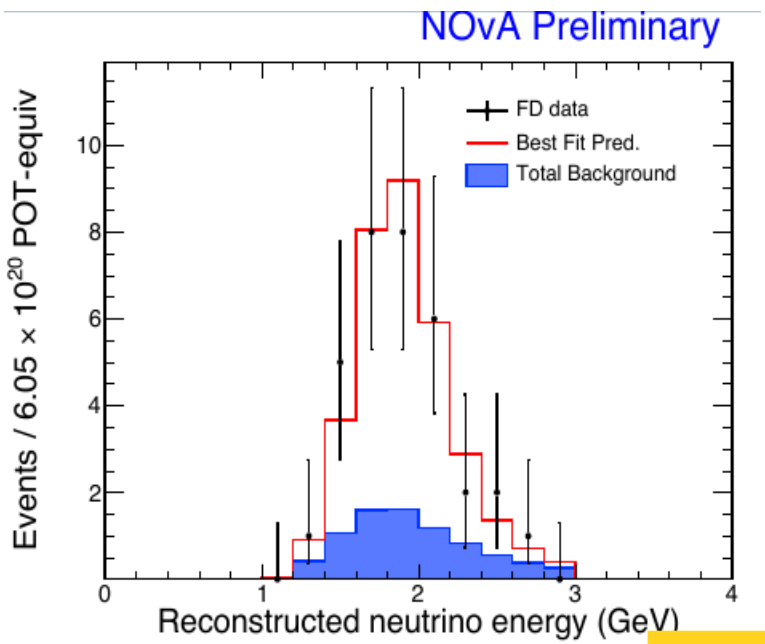
K. Matera @ICHEP

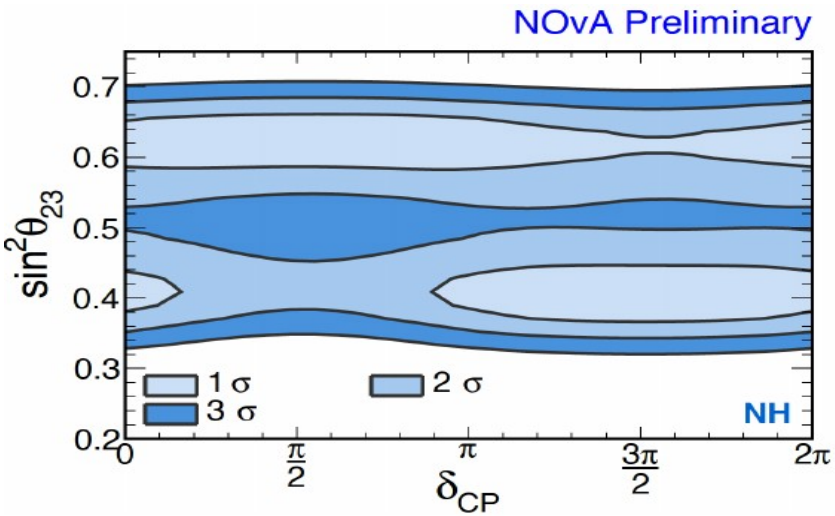
NOvA ν_e Appearance

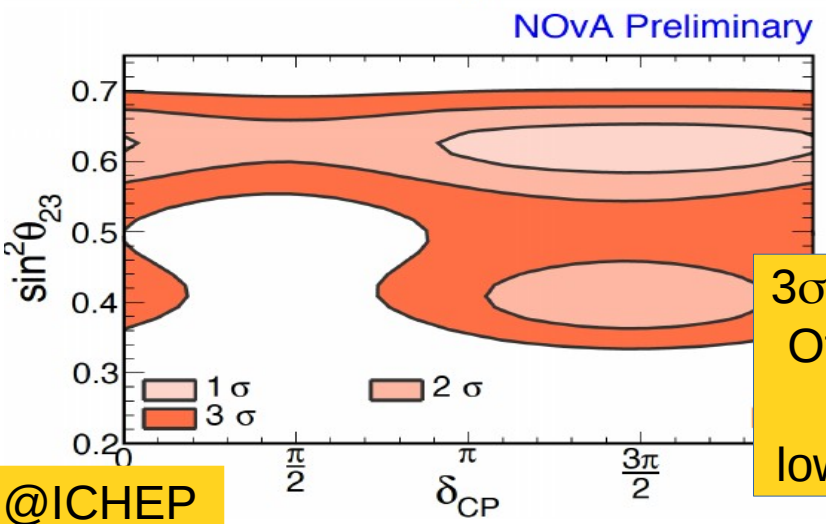


Observe 33 events for 8.2 expected backgrounds.

For maximal mixing expect 36(19) - NH(IH)



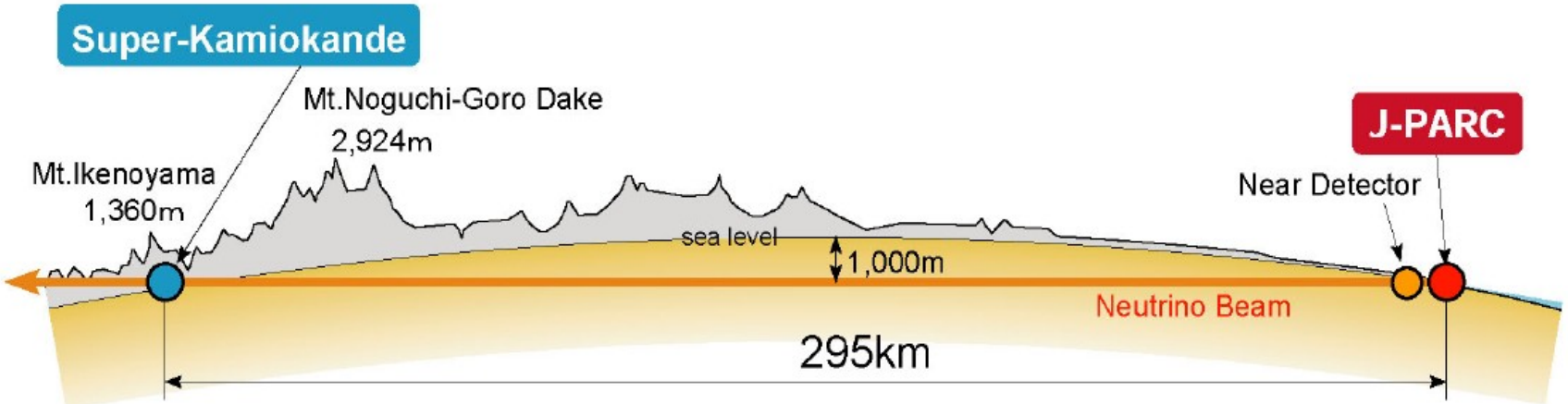




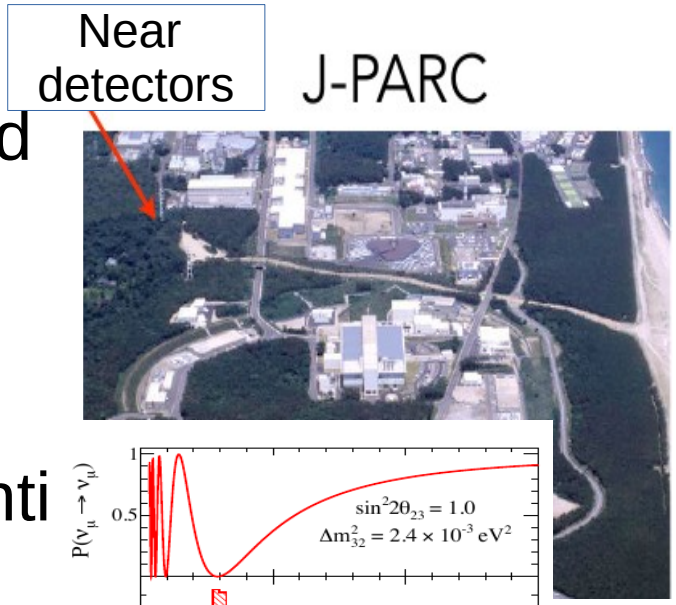
3σ exclusion Of δ_{CP}~π/2 in IH, lower octant

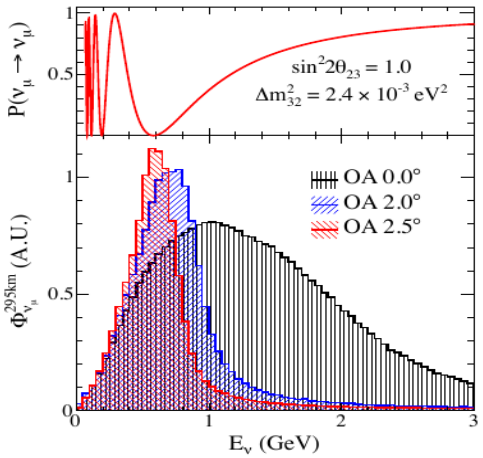
J. Bian @ICHEP

T2K

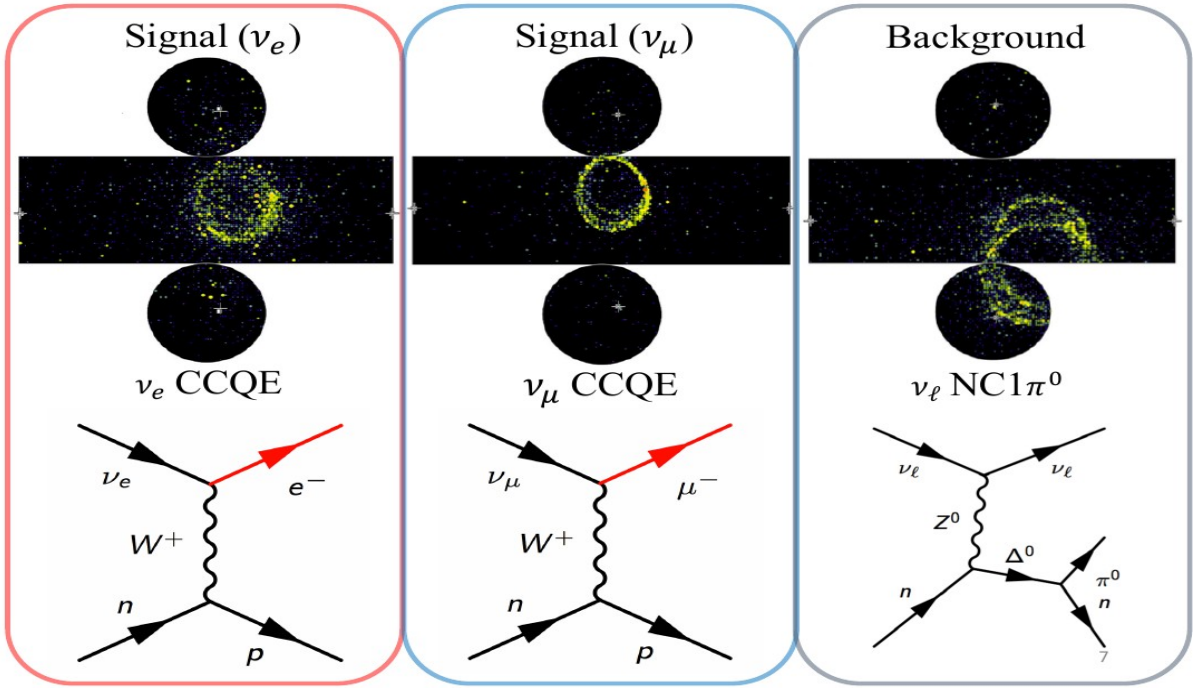


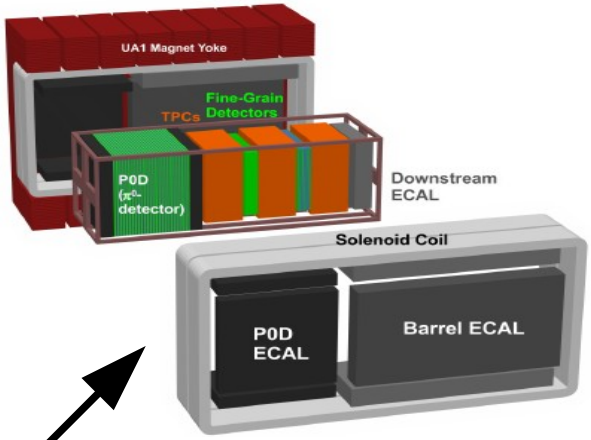
- Off-axis beam energy centered around 600 MeV.
- Studying ν_μ disappearance and ν_e appearance (and for anti neutrinos.)



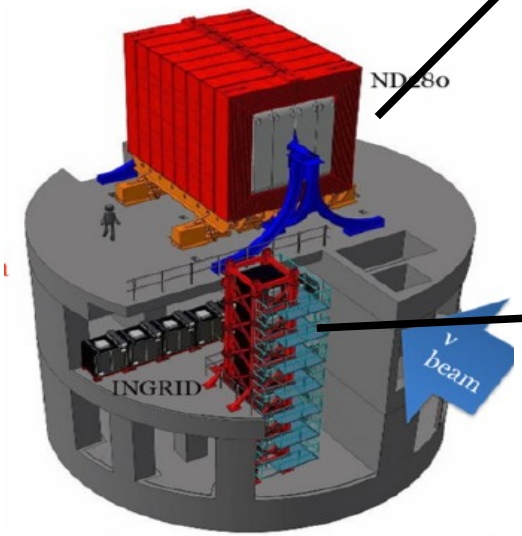


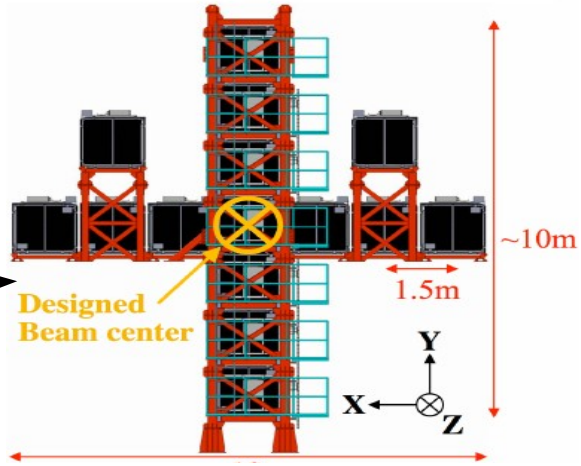
T2K detectors





- Complex of on-axis and off-axis near detectors to understand the flux.

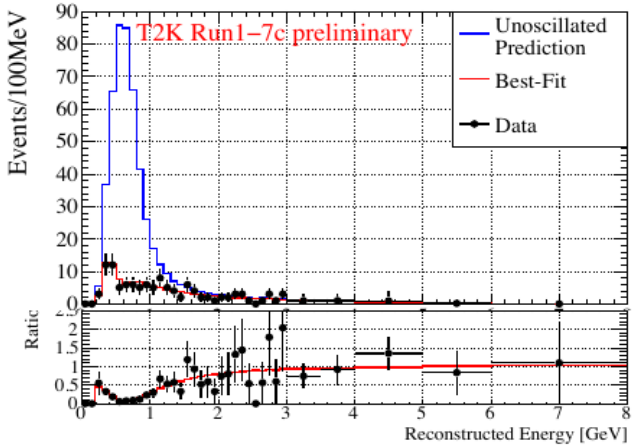




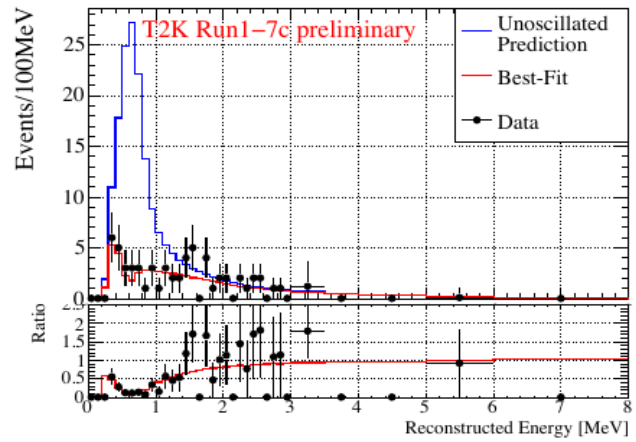
T2K ν_μ + $\bar{\nu}_\mu$ disappearance

- ν_μ: 135 events observed (135.8 events expected)
- $\bar{\nu}_\mu$ 66 events observed (64.2 events expected)
- Joint fit of $\sin^2\theta_{23}$ consistent with maximal mixing.

ν_μ

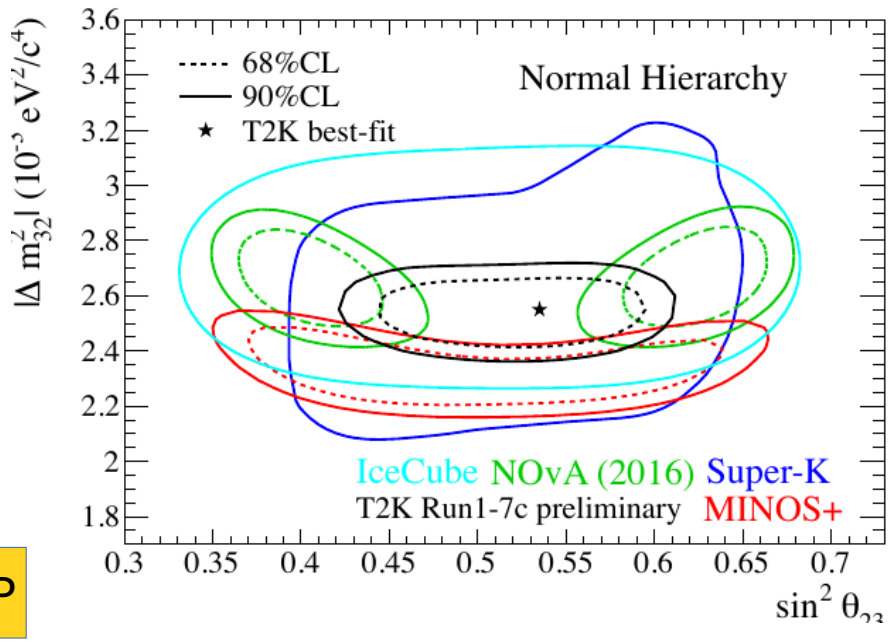


$\bar{\nu}_\mu$



Test of CPT

- Consistent with maximal mixing

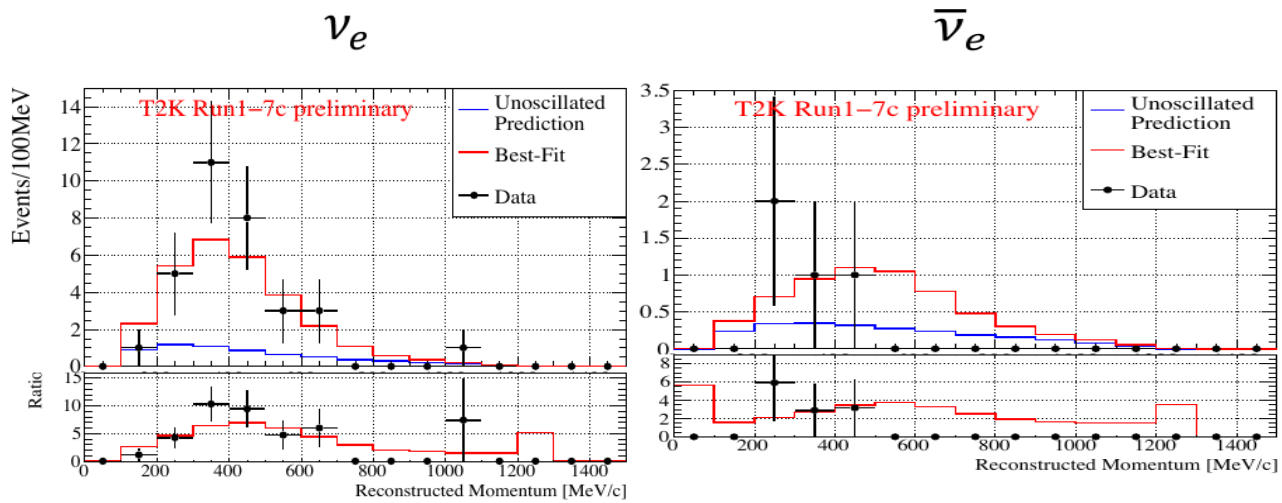


Daya Bay:
$|\Delta m^2_{ee}| = (2.45 \pm 0.08)\times 10^{-3} eV^2$
90% CL (NH)

K.Iwamoto@ICHEP

T2K $\nu_e + \bar{\nu}_e$ appearance

- T2K observed 32 neutrinos and 4 anti-neutrinos.
- This is a larger asymmetry than expected in best case scenario: (29/6 @ NH, $\delta_{CP} = 3\pi/2$)
- **A 90% exclusion of $\delta_{CP} = 0$ or π**

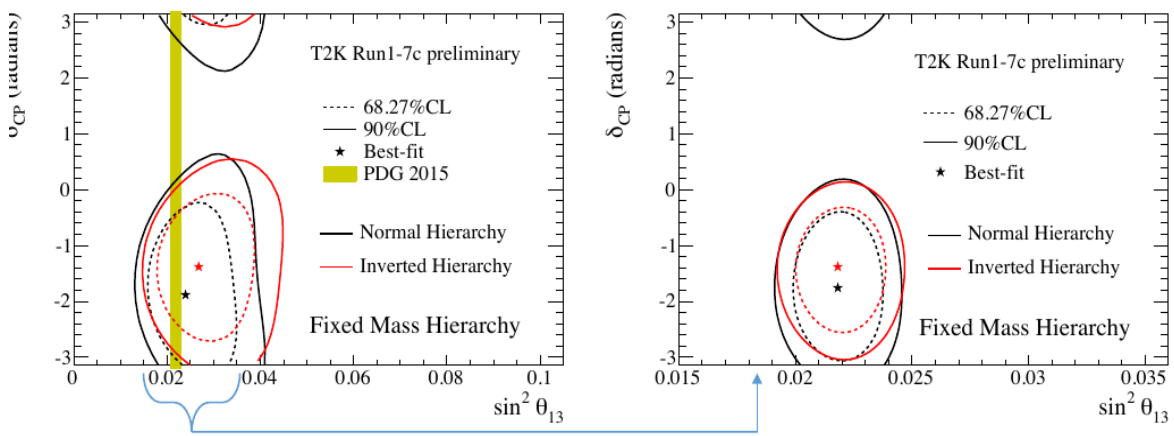


32 events observed

4 events observed

T2K-Only

T2K Result with Reactor Constraint ($sin^2\, 2\theta_{13} = 0.085 \pm 0.005$)

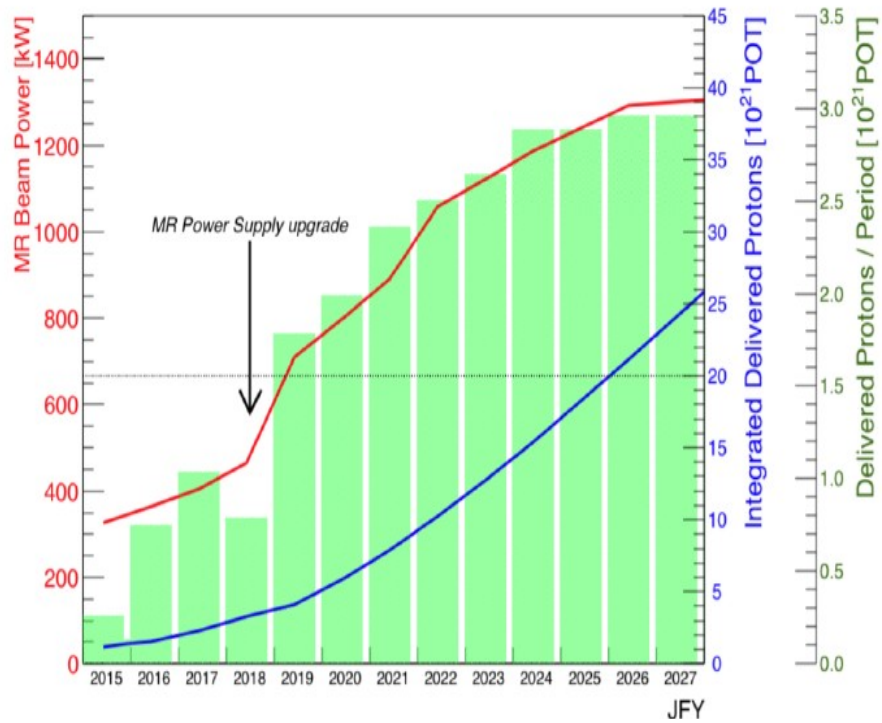


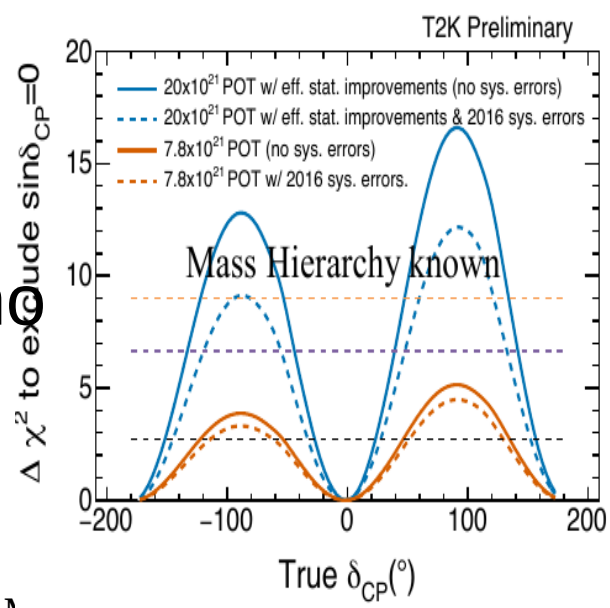
- T2K-only result consistent with the reactor measurement
- Favors the $\delta_{cp} \sim -\frac{\pi}{2}$ region

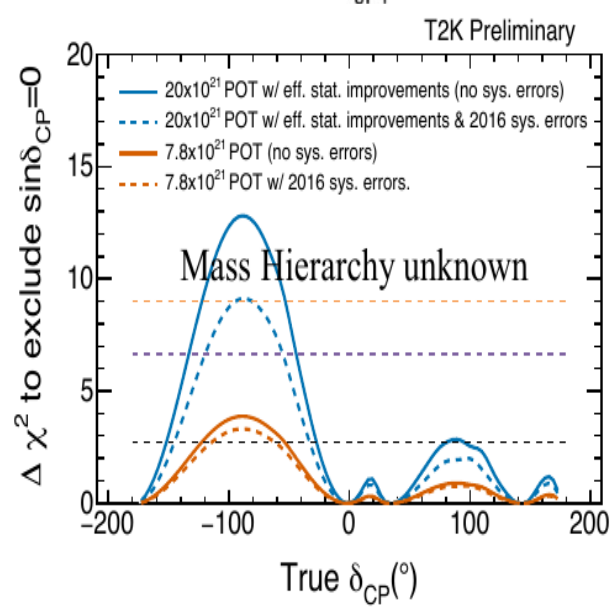
K.Iwamoto@ICHEP

T2K going forward

- Received stage one approval to 20e21 POT (~2026) – T2K-II (3σ sensitivity to δ_{CP})
- Ongoing development of HPTPC near detector.
- NuPrism and TITUS (intermediate near detectors)
- Super-K will be GD-doped soon – neutrino/anti-neutrino differentiation.





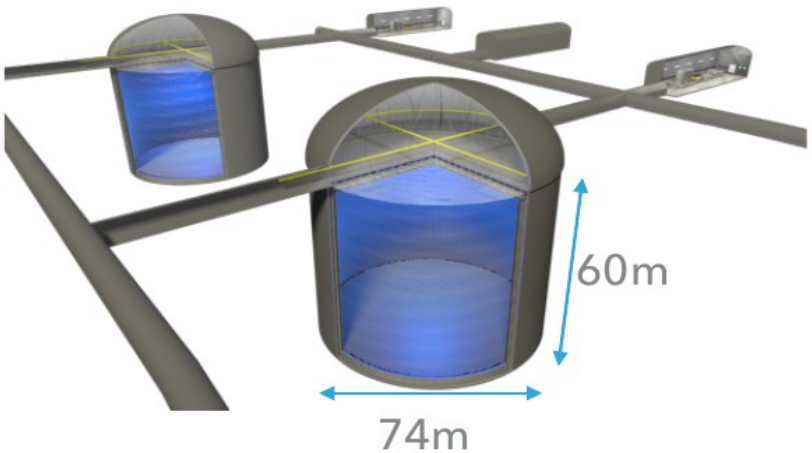


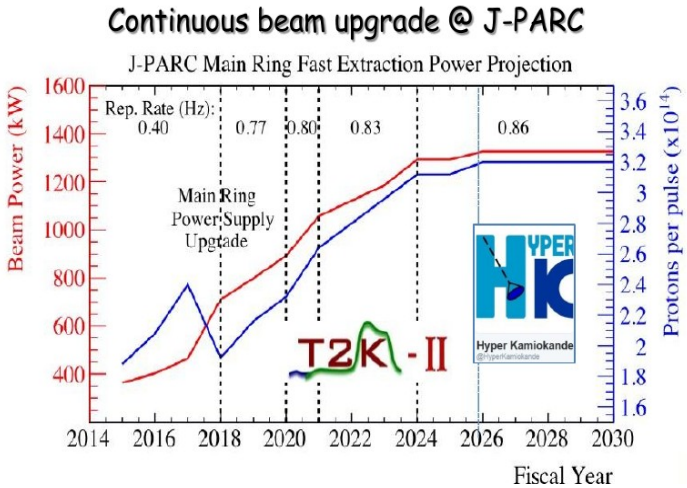
Back to the Future

- To get to levels of a 5 sigma CP violation measurement we will need next generation experiments. They will need:
  - Higher intensity beams: allow longer baselines + more neutrinos
  - More detector mass
  - Better energy resolution
- Two big projects going on: HyperKamiokande in Japan and DUNE in the US.

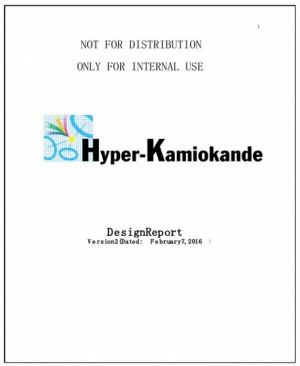
Hyper Kamiokande

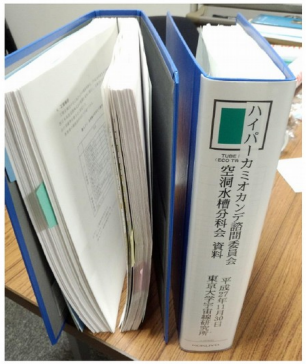
- J-Parc Beam upgrade to 1.3 MW
- Hyper-K Tank:
  60 m tall x 74 m diameter
  40,000 50cm φ PMTs →
  40% photo-coverage
- 260 kton mass (total fiducial volume is ~10x larger than Super-K)





Design Report

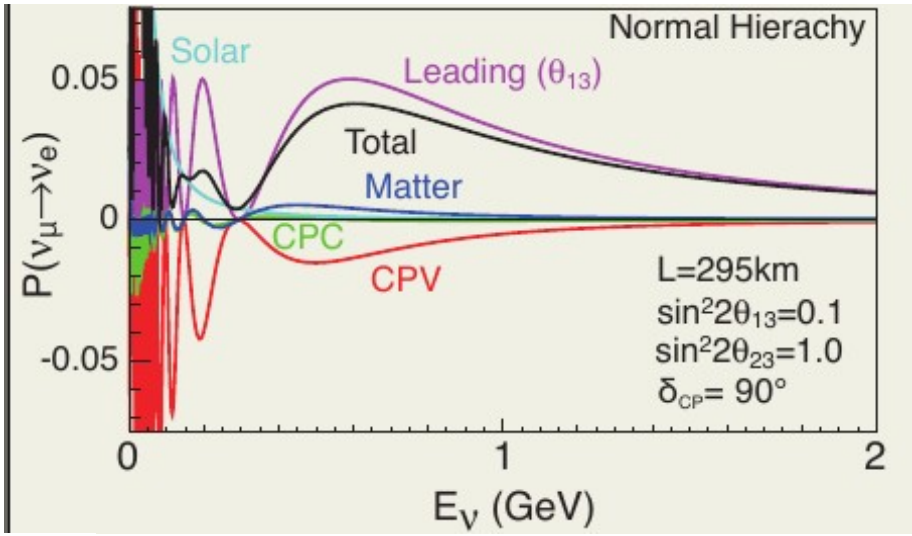


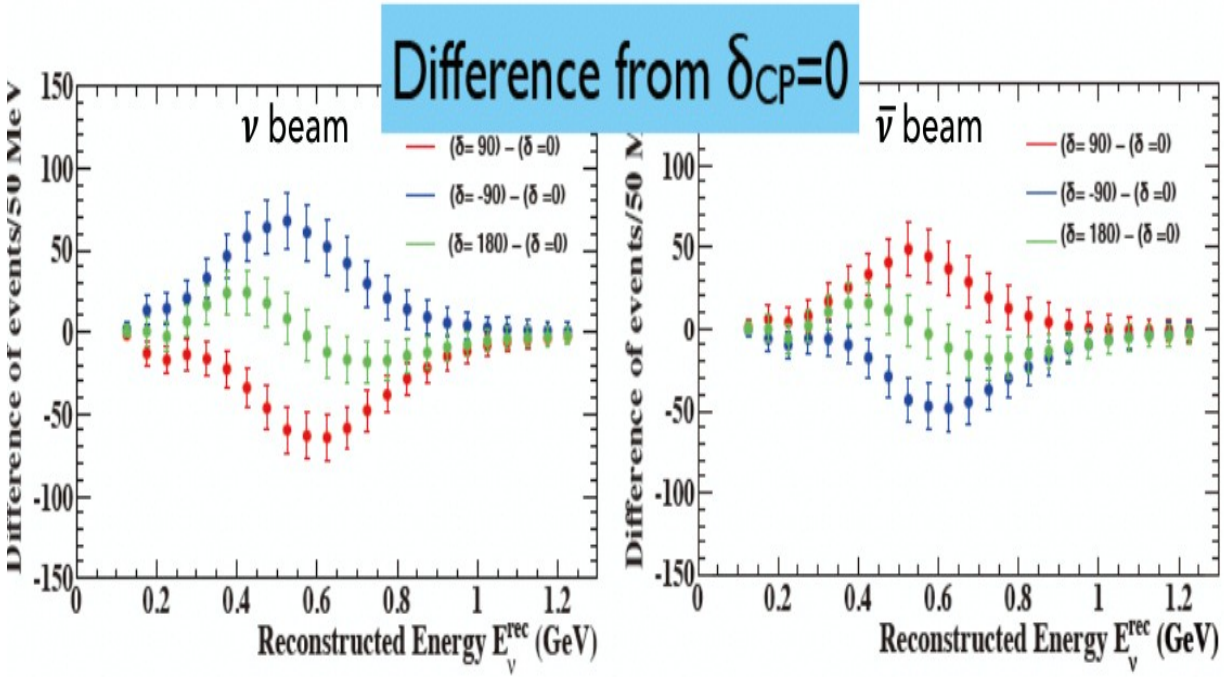


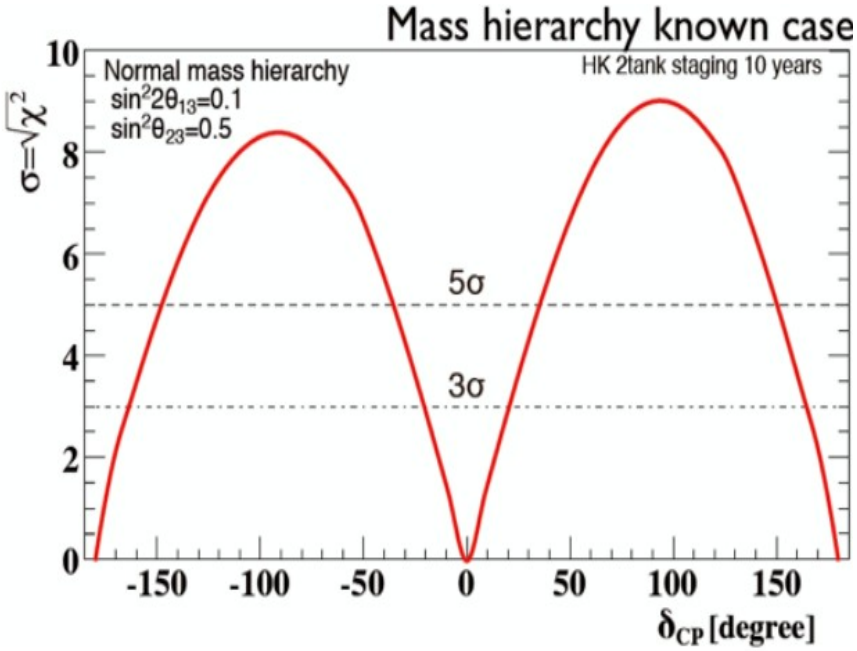
Submitted to the Hyper-K Advisory Committee.

Hyper K Physics

- CP violation up to >5σ
- Mass hierarchy from atmospheric neutrinos (at 295 km CPV effects dominate).



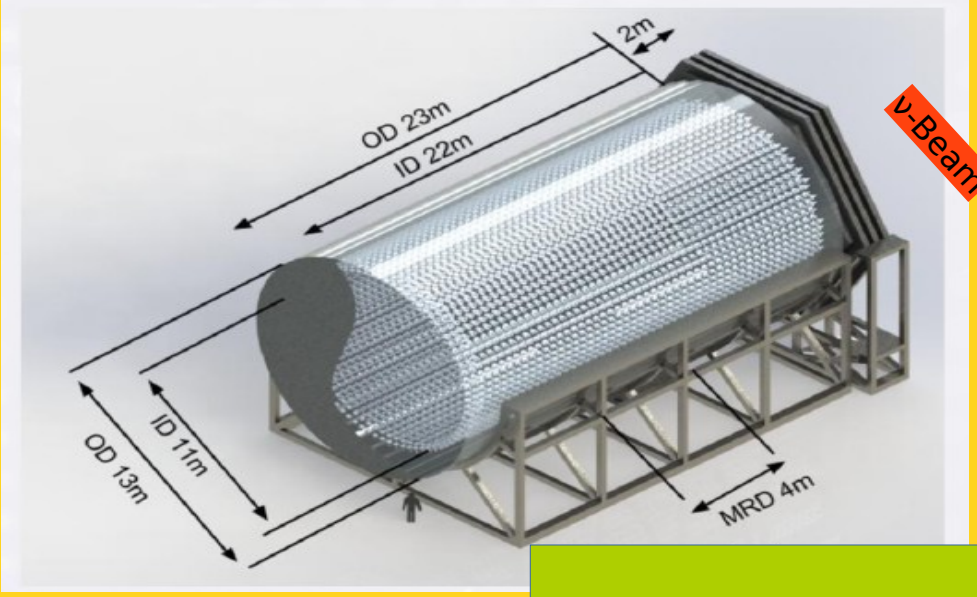




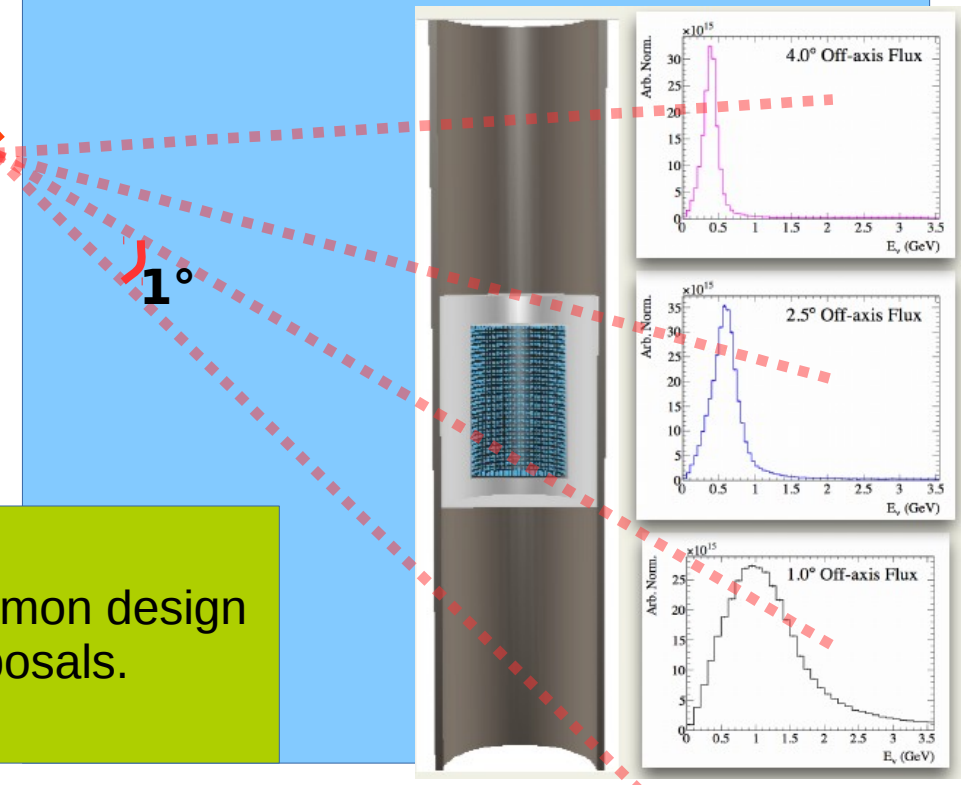
HK (and T2K) near detectors

- A number of near detector ideas proposed for T2K-II & HK:

TITUS: 2.5° off-axis, @1.8 km.
Gd-loading for neutron detection.
Magnetized muon range detector.
1.27 kton FV



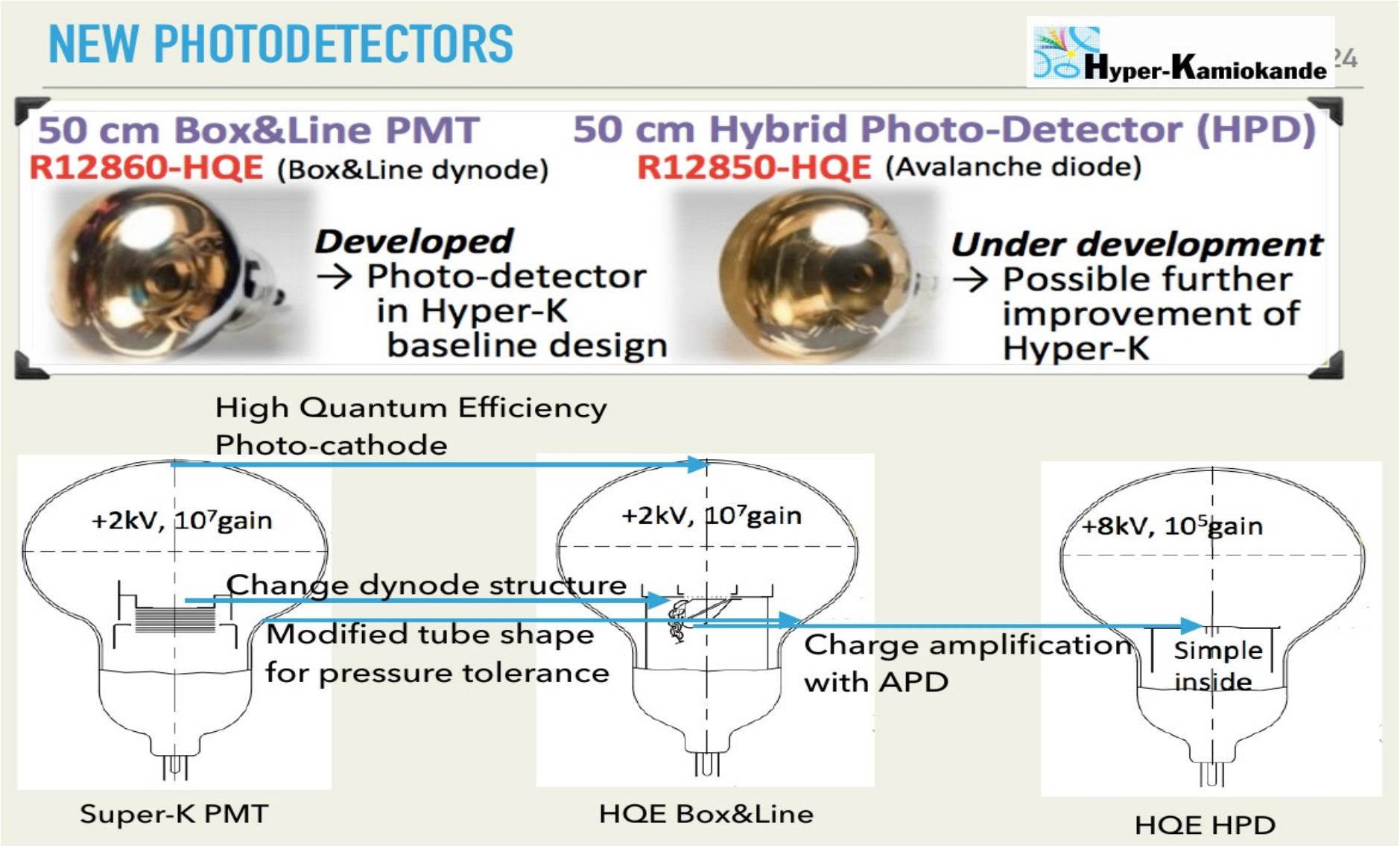
NuPRISM:
Spans angles from 1° to 4°
Different, well defined energies at different angles (0.4 -1 GeV)
Linear combinations can reconstruct far detector spectrum



Searching for a common design of the two proposals.

Hyper-K PMT R&D

- HK is developing larger PMTs:

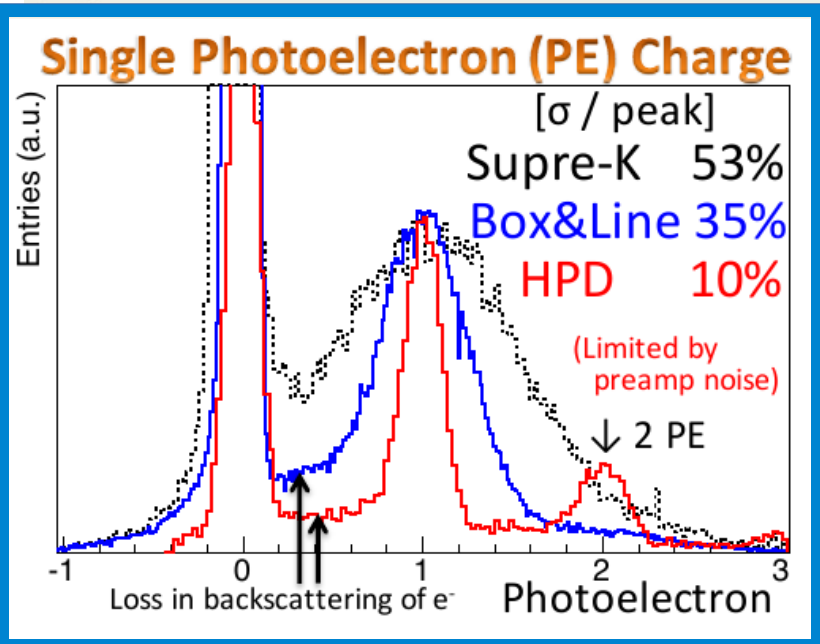


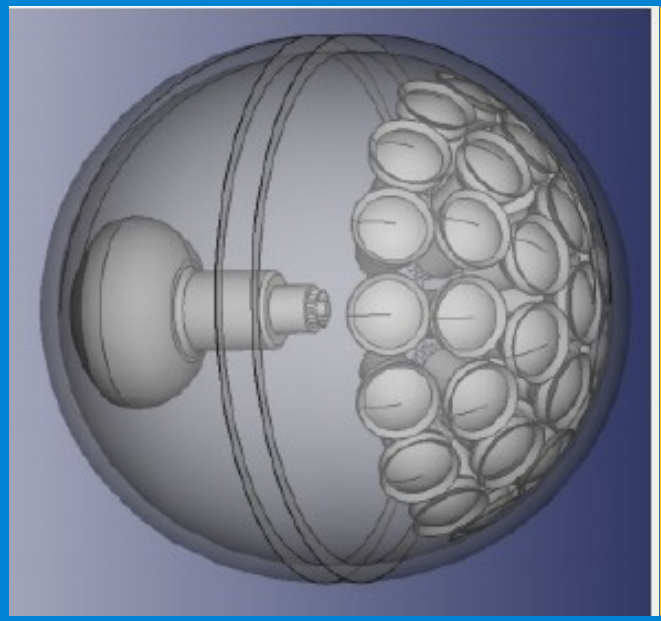
M. Hartz@NuFact16

Talk by T.Feusels tomorrow

Hyper-K PMT R&D

- R&D effort on developing larger PMTs:



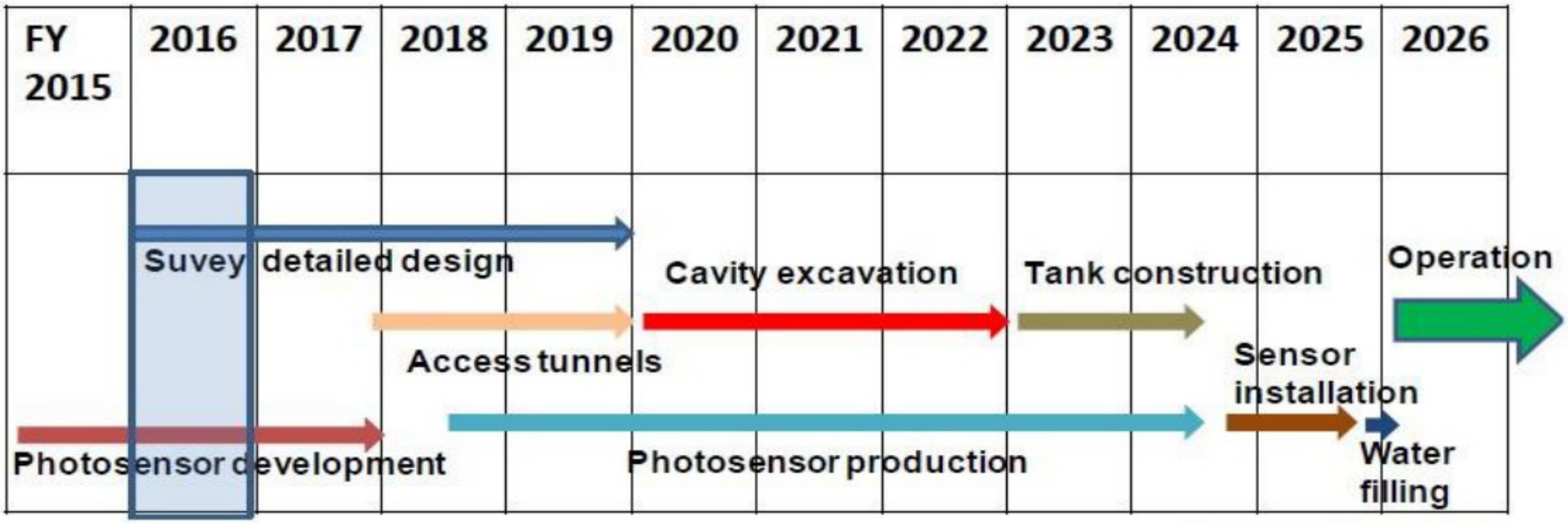


Studying the possibility of Using multiple PMT Assemblies (DOMs) A'la the mediterranean Neutrino experiments.

M. Hartz@NuFact16

Hyper-K timeline

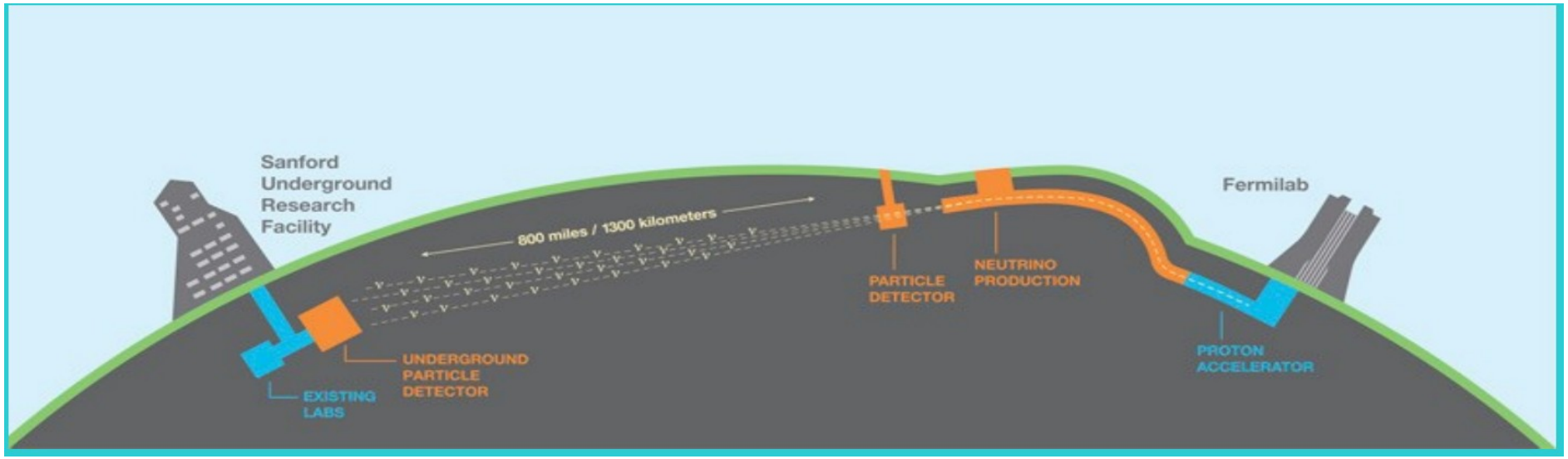
Possible construction schedule



- Assuming HK proposal approved before the end of 2017
- Access tunnels/cavity excavation and PMT production dominate the timeline

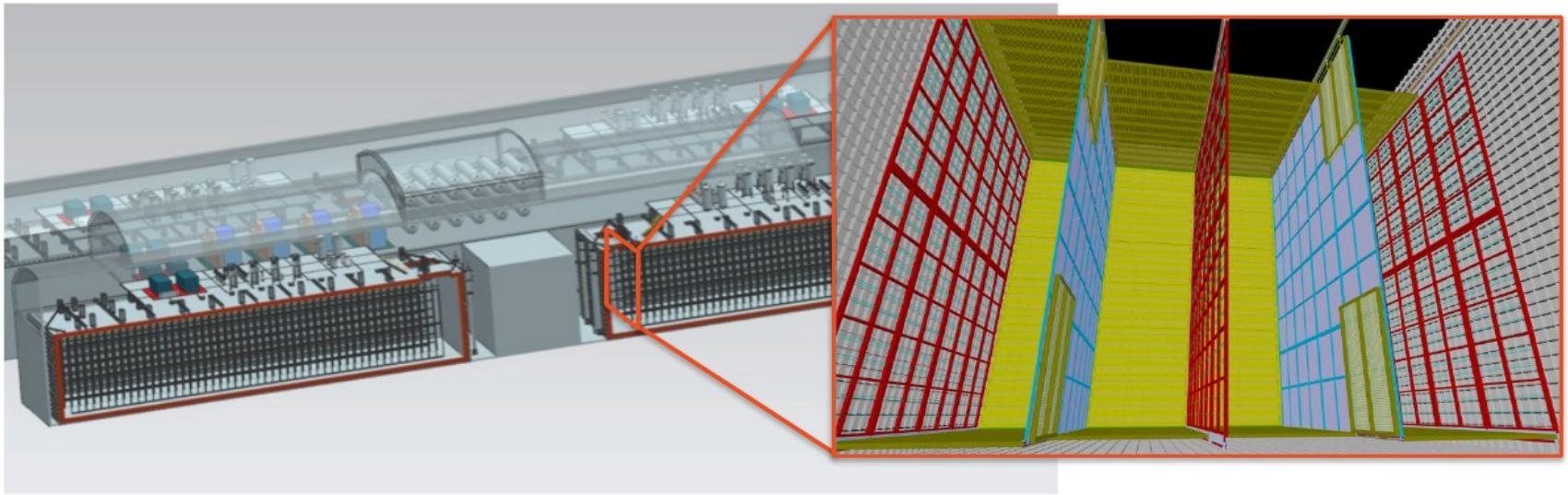
Obayashi@NuFact16

DUNE



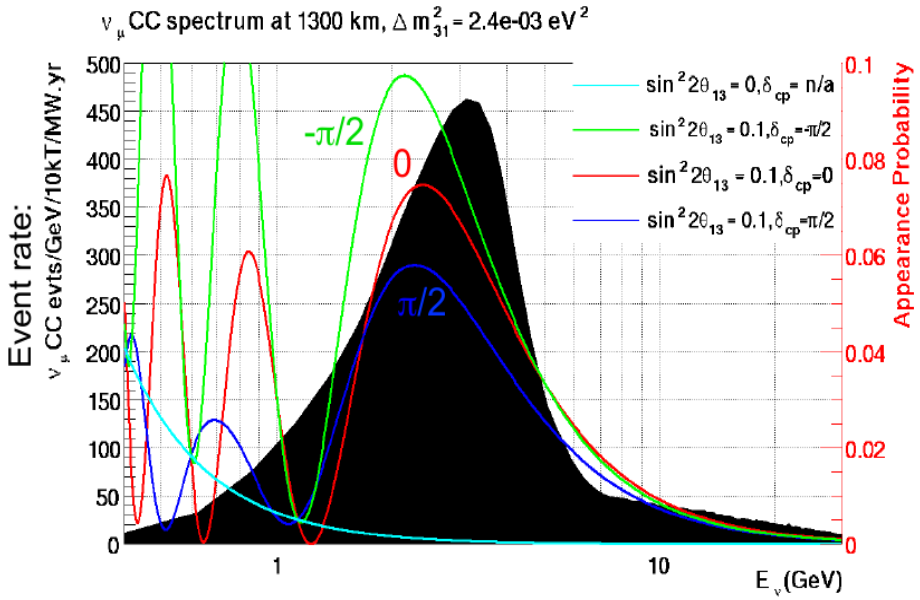
- Broadband beam from Fermilab to SURF.
- Baseline 1300 km, beam on in 2026 (final design 2.3 MW).
- Four 10 kTon liquid argon modules

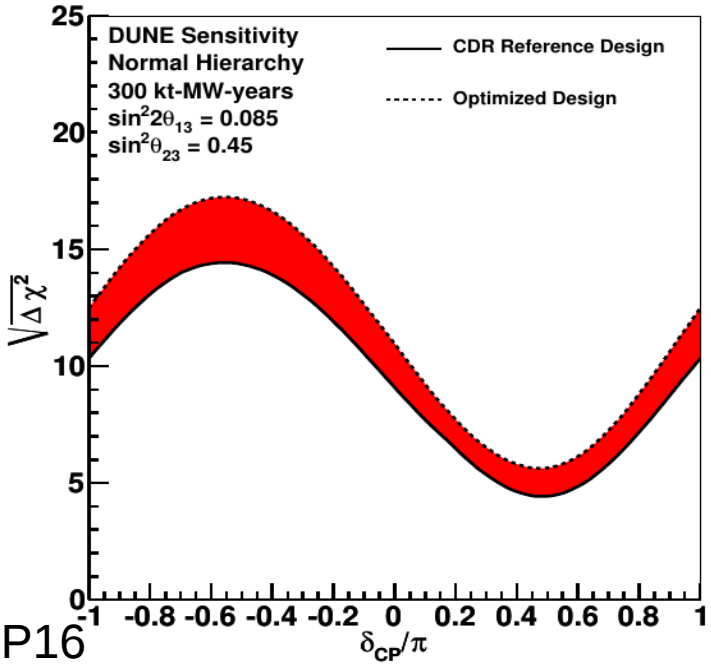
Two detector designs for first two modules: single and double phase.

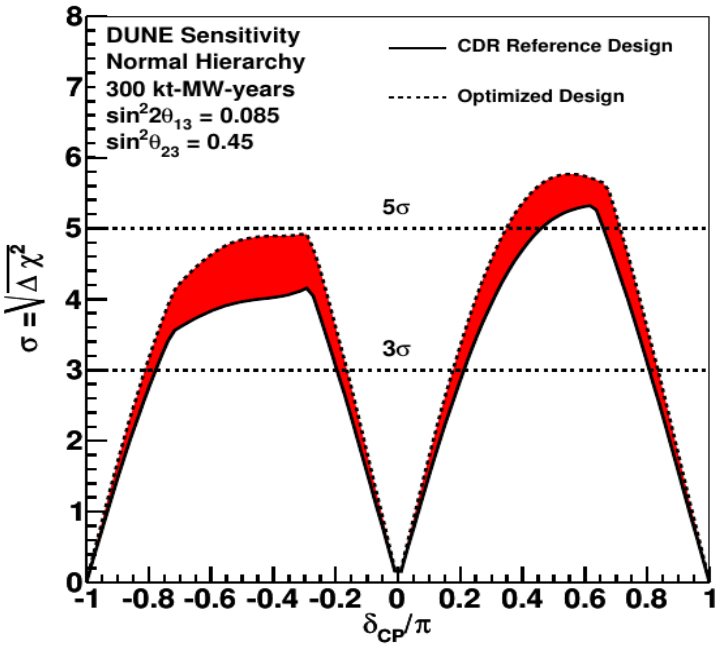


DUNE physics reach

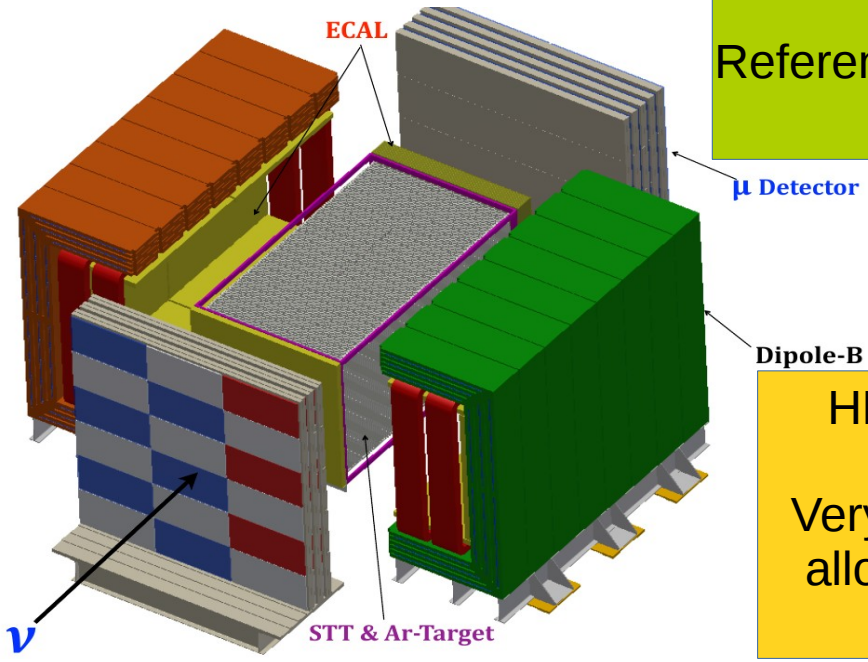
- Broadband beam and long baseline allow disentangling mass hierarchy and CPV.
- 5σ resolution on Mass Hierarchy for all values of δ_{CP}



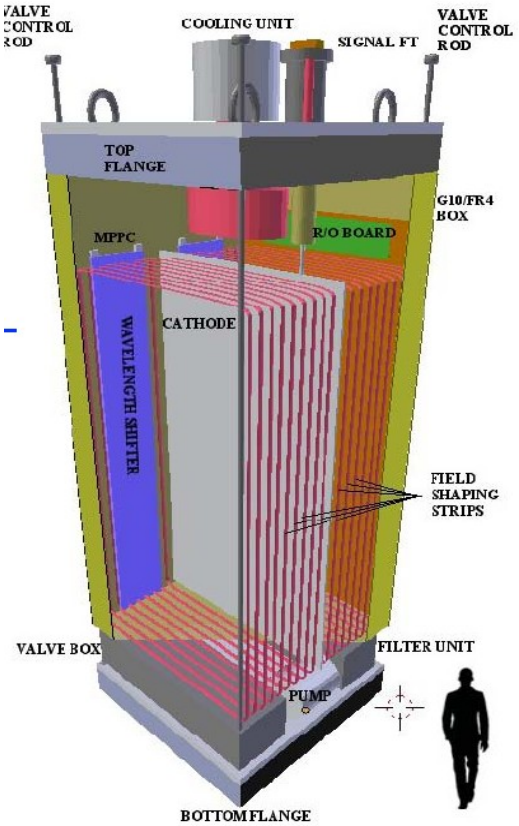




DUNE Near Detector Design



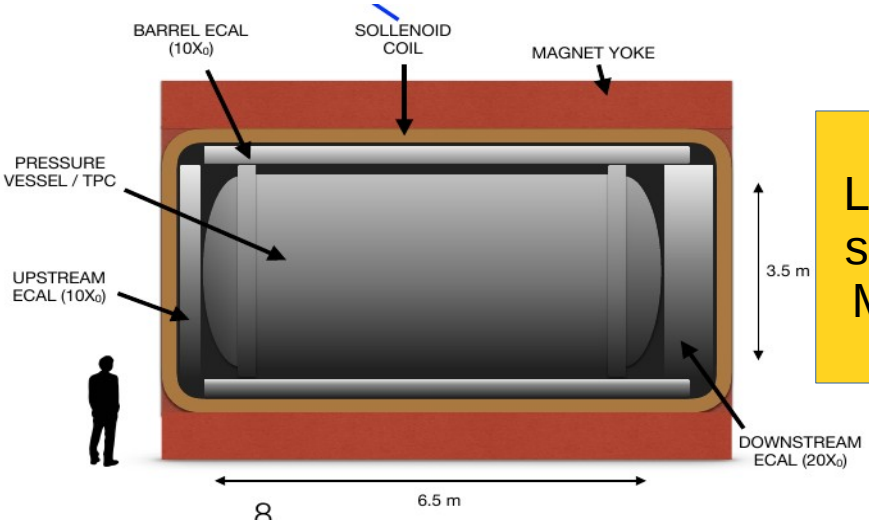
Reference design.



HPTPC Similar to T2K/HK Idea.
Very good resolution, allows resolving low energy traks.

NOMAD inspired detector

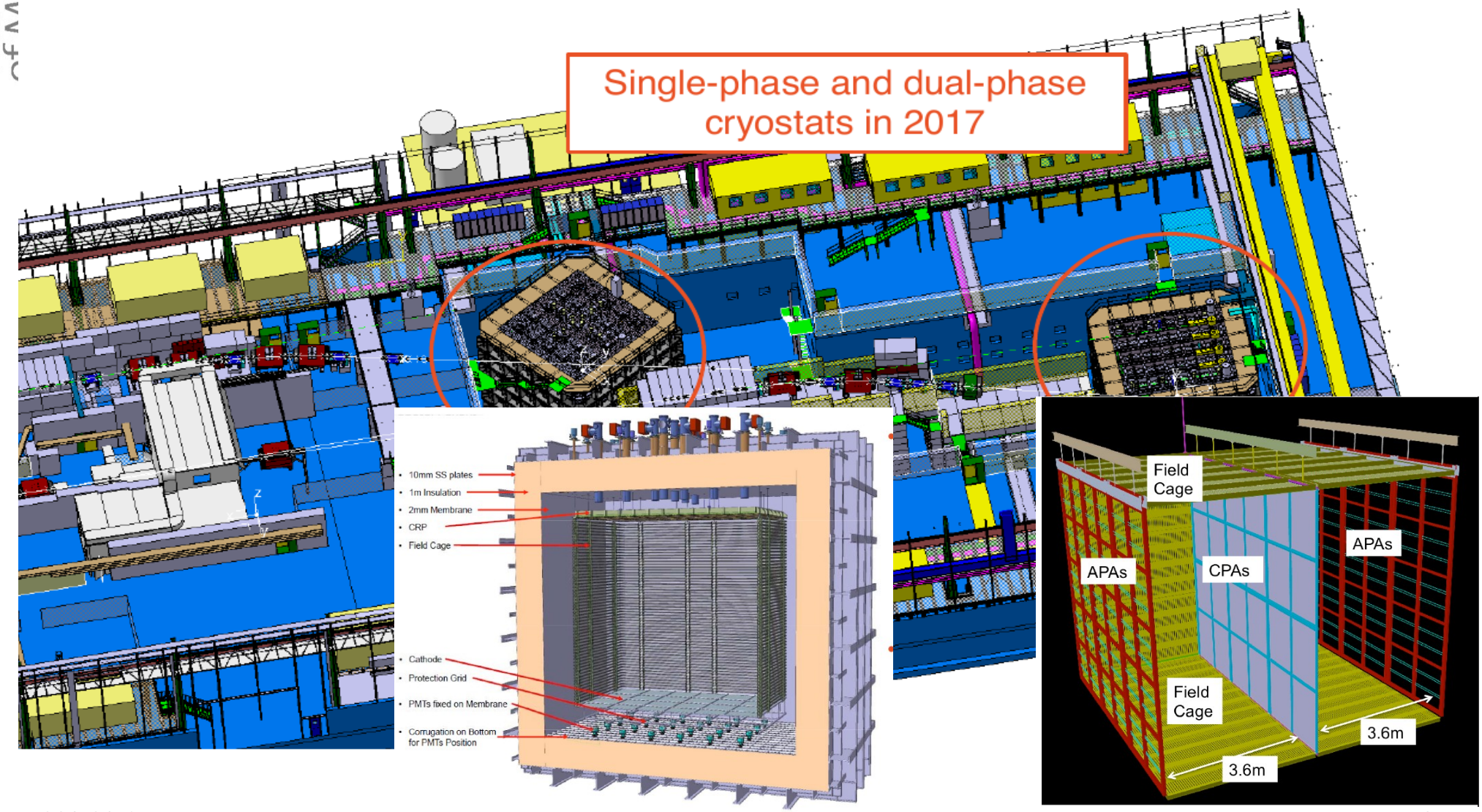
- Magnetized straw-tube based tracking system
- Pb-scintillator sampling ECAL
- RPC-based muon tracker
- Multiple Targets (incl. Argon)



Liquid argon detector, similar to ArgonCube . Modular construction.

DUNE/LAr technology R&D

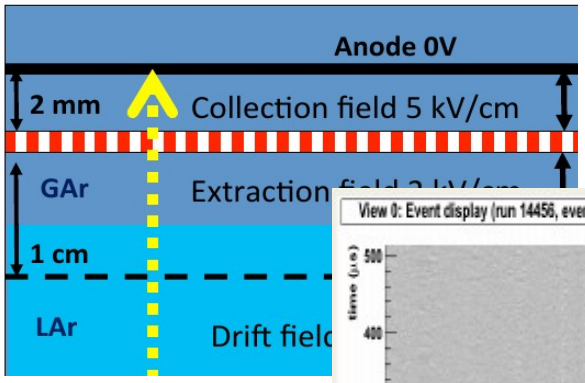
- A very large effort currently ongoing to install the two protoDUNE detectors in the CERN

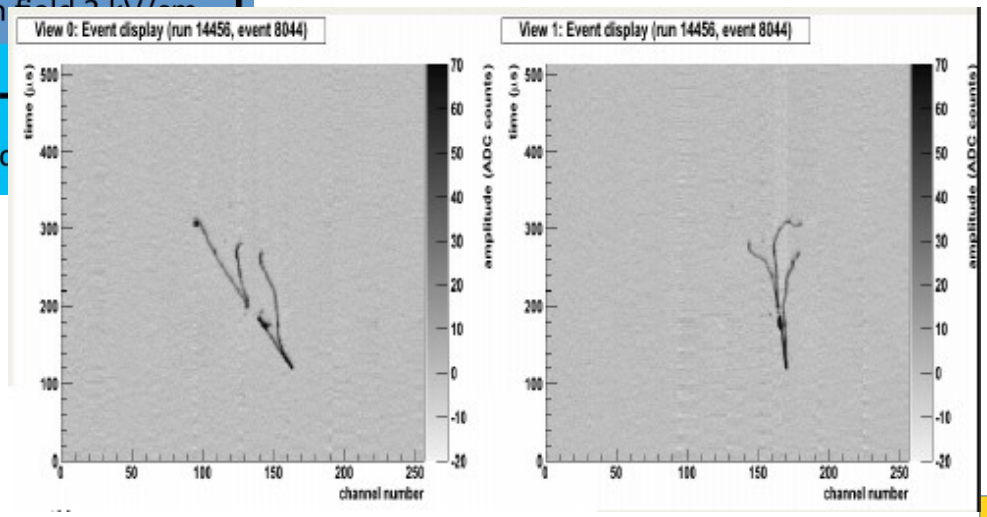


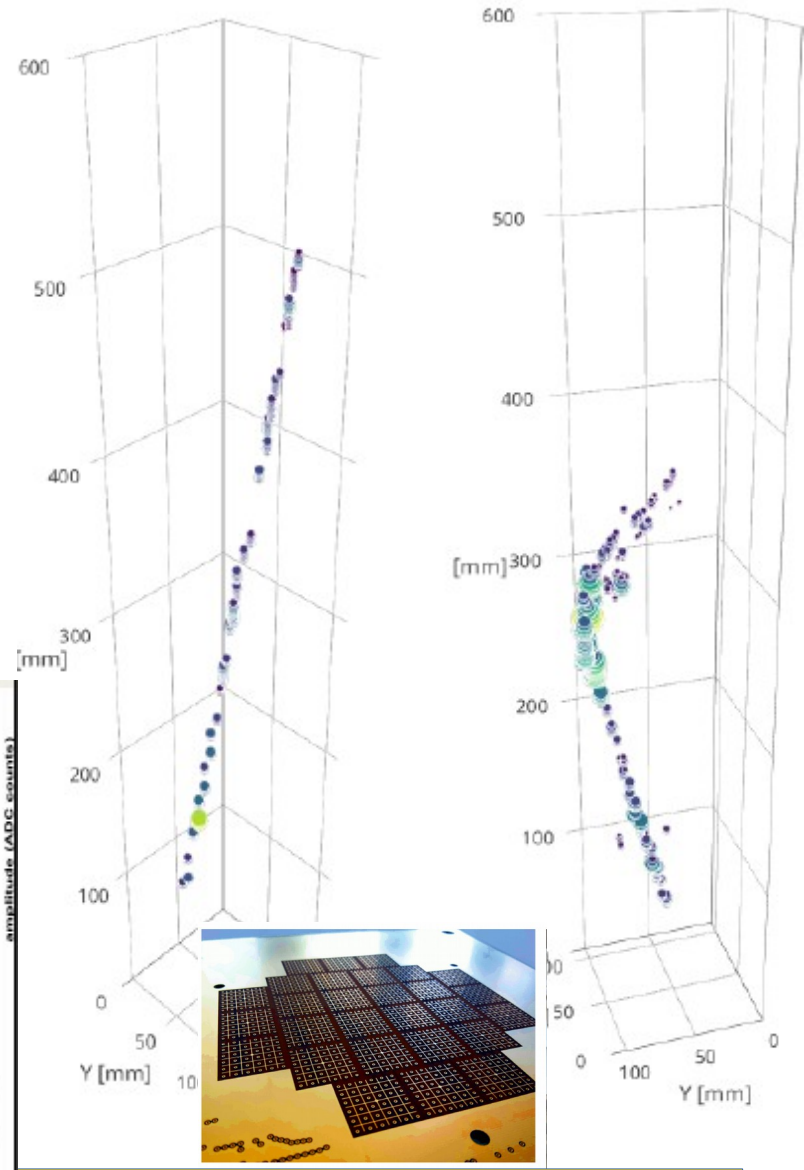
DP Charge readout and SP R&D

Preliminary
Courtesy of LHEP-Bern

- The double phase design uses LEMs (Large Electron Multipliers) to read out the amplified charge.
- Excellent signal to noise.





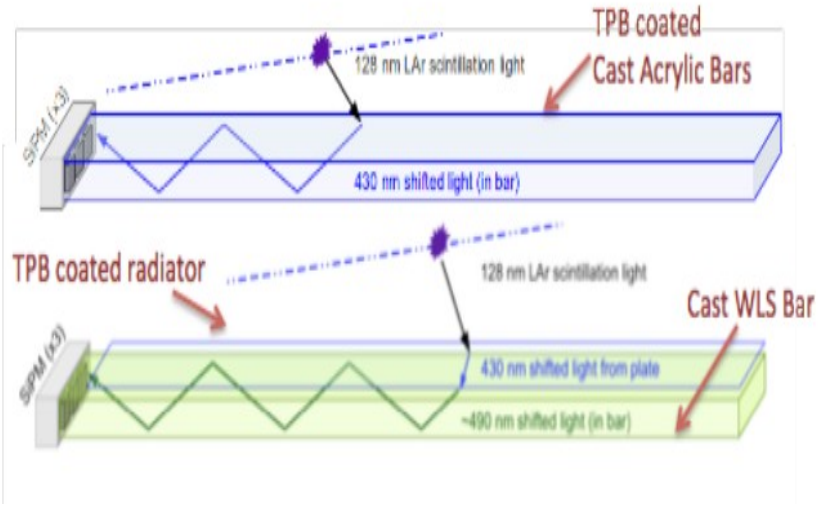


Talk by J.Asaadi tomorrow

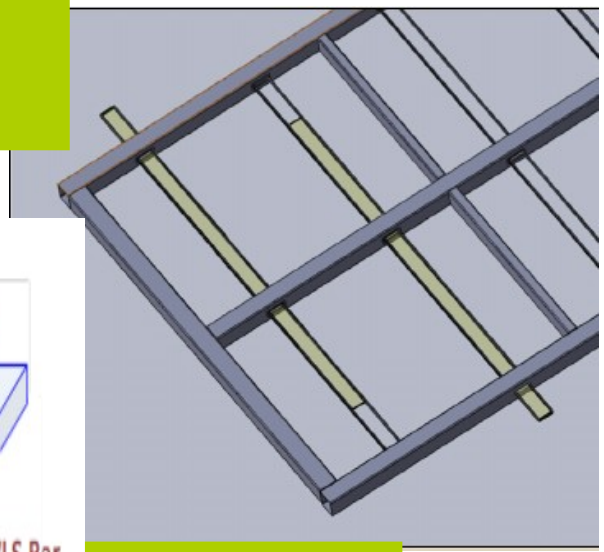
Light Collection R&D in LAr

- Goal is to get as much light with as few channels as possible and taking up as little space as you can.

WLS coated light guide bars (multiple designs under consideration)

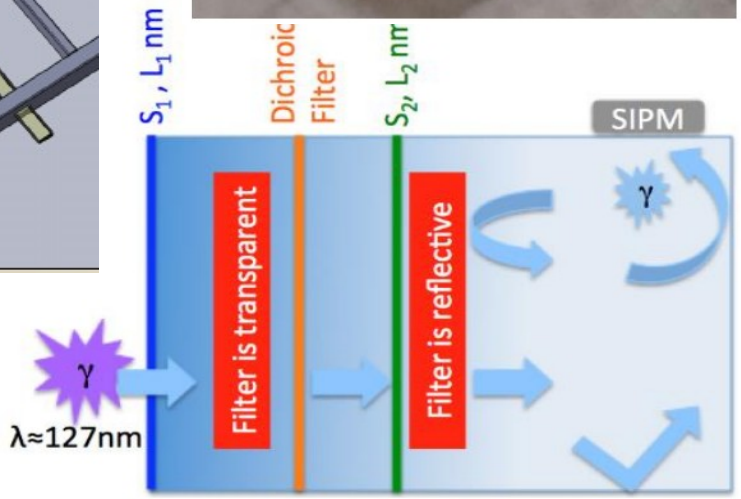


Talks, by J. Moon and B. Howard tomorrow



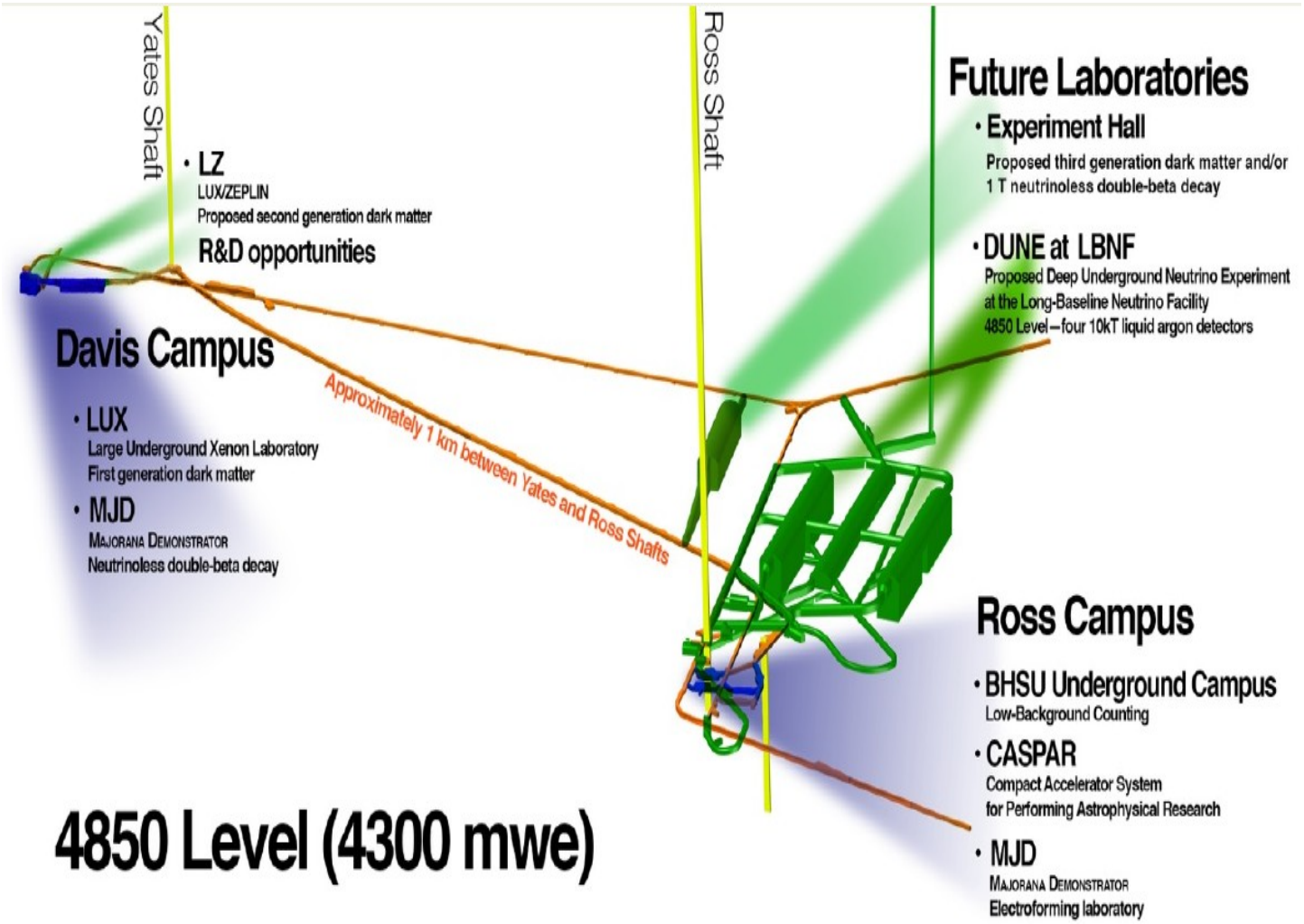
Fit into APA frames

ARAPUCA



Talk by A.A. Machado tomorrow

DUNE timeline



2017: Far Site Construction Begins

2018: protoDUNEs at CERN

2021: Far Detector Installation Begins

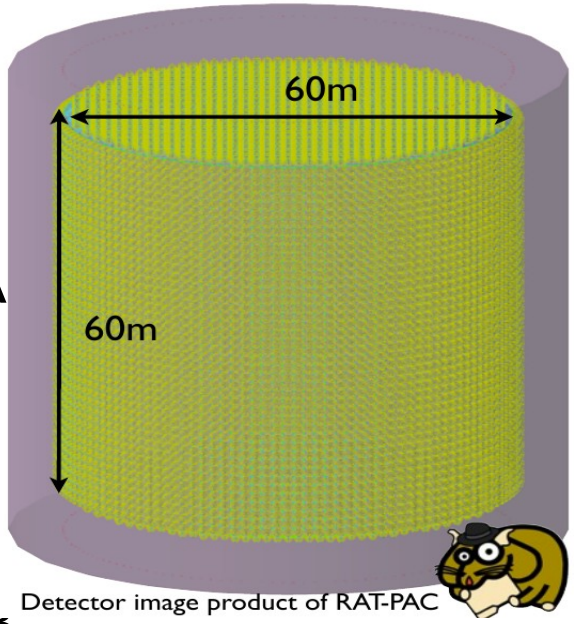
2024: Physics Data Begins (20 kt)

2026: Neutrino Beam Available

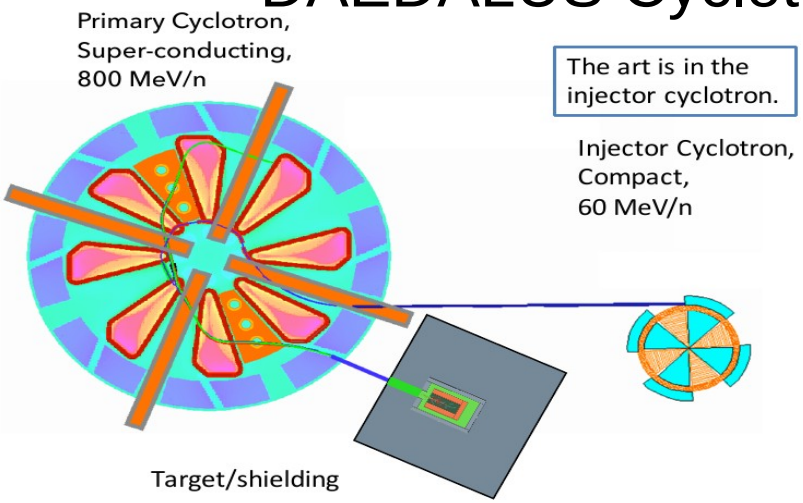
E. Worcester@ICHEP16

Other ideas (some far off in the future)

ASDC,
e.g. THEIA

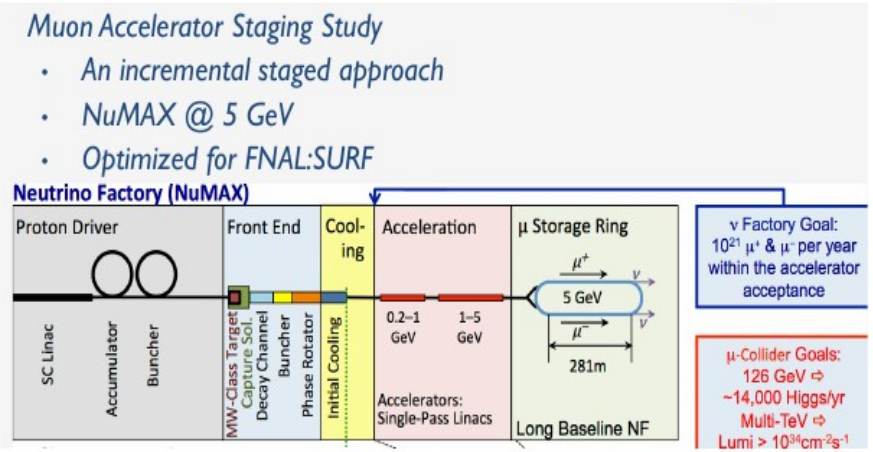


DAEDALUS Cyclotron



ESSνSB

Neutrino Factory



MANCHESTER 1824

The University of Manchester

Summary

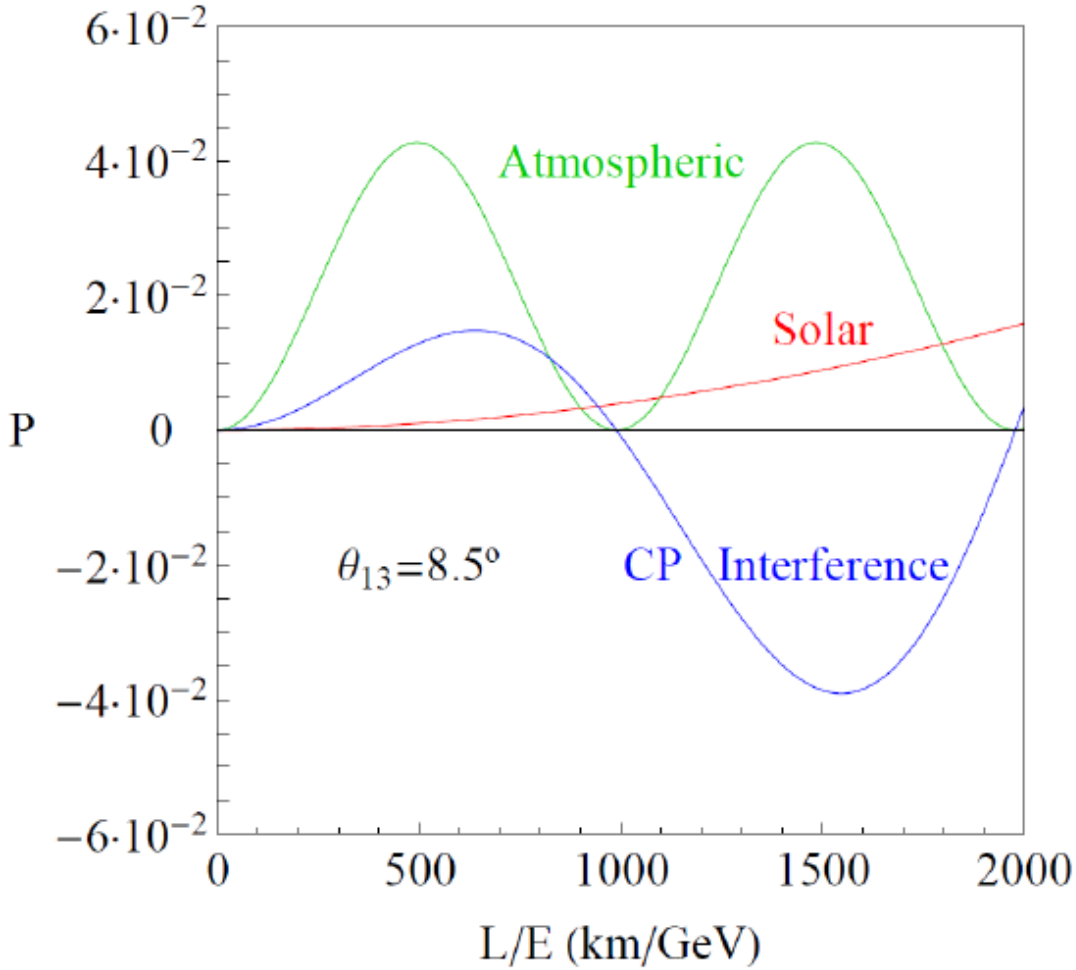
- Accelerator neutrino beams enable precision measurements of neutrino oscillation parameters.
- A very eventful summer: great results from MINOS+, T2K and NOvA.
- Hope even more will come soon.
- SBN accelerator program in operation and construction – first results in not too long.

MANCHESTER 1824

The University of Manchester

Thank you for your attention

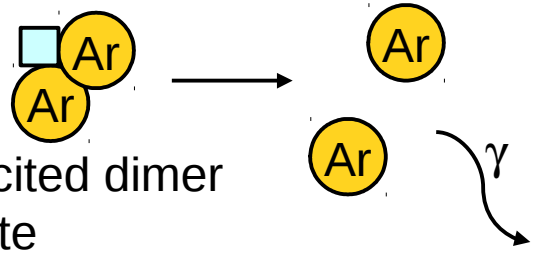
Optimization of facilities for large θ_{13}



Signal systematics and not stats become the bottleneck for large θ_{13}, explore second peak? P. Coloma and EFM 1110.4583

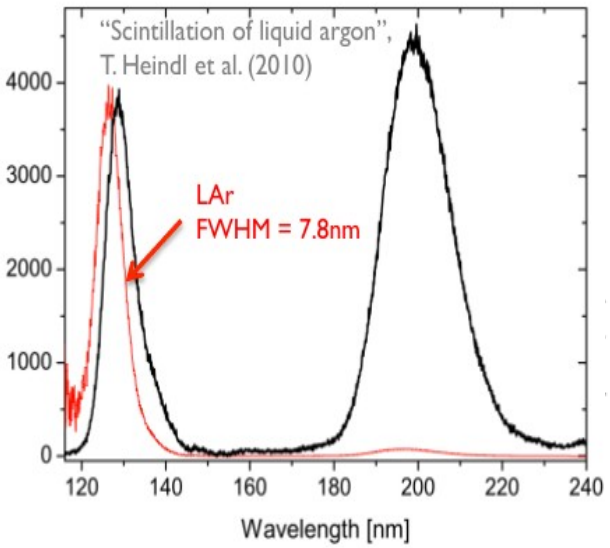
Scintillation Light in Argon

Emission:



Excited dimer state

Photons are all ~128 nm – VUV

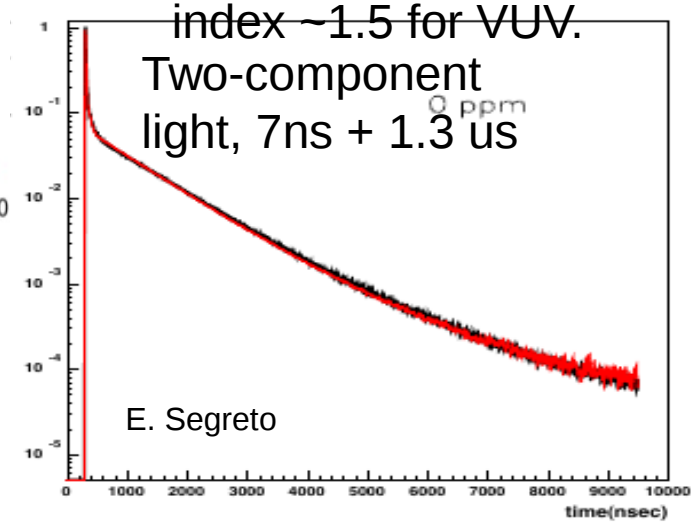


Transport:

Liquid argon is mostly transparent to its scintillation.

At longer distances Rayleigh scattering ~55cm f(λ) and absorption, e.g. on nitrogen ~30 m @2ppm N_2 begins to play a role. Note high refractive index ~1.5 for VUV.

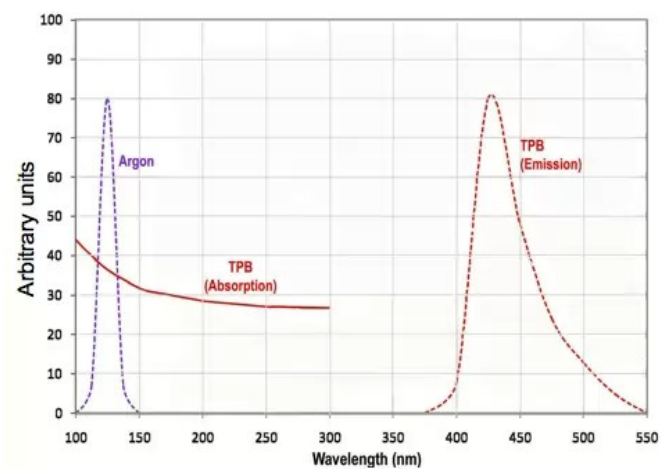
Two-component light, 7ns + 1.3 us



Detection:

Liquid argon is almost the only thing transparent to its scintillation.

Detection is challenging – most often need to use Wavelength shifting compounds, like TPB.



Matter effects

$$P(\nu_e \to \nu_\mu) = P(\nu_\mu \to \nu_e) = \sin^2 2\theta_M \sin^2(\Delta m_M^2 L/4E)$$

Passage through matter changes the effective Δm^2 and mixing angles:

$$\Delta m_M^2 = \Delta m^2 \sqrt{\sin^2 2\theta + (\cos 2\theta - x_\nu)^2}$$

$$\sin^2 2\theta_M = \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - x_\nu)^2}$$

Effects are Energy and density dependent.

$$x_\nu \equiv \frac{2\sqrt{2} G_F N_e E}{\Delta m^2}$$

Sign inverted For anti-nu

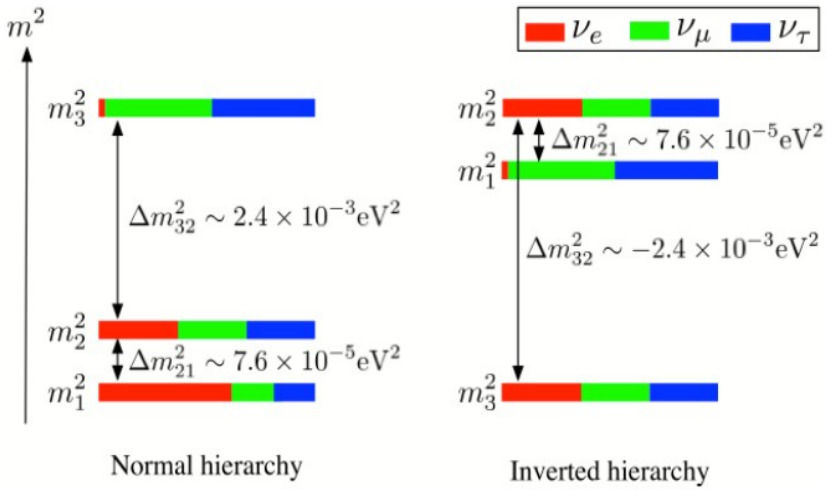
Example: 1000km baseline, through the mantle, $\Delta m_{31}^2 \sim 2.4 \times 10^{-3} eV^2$

$$|x_\nu| \simeq E/12\,\mathrm{GeV}$$

After B. Kayser

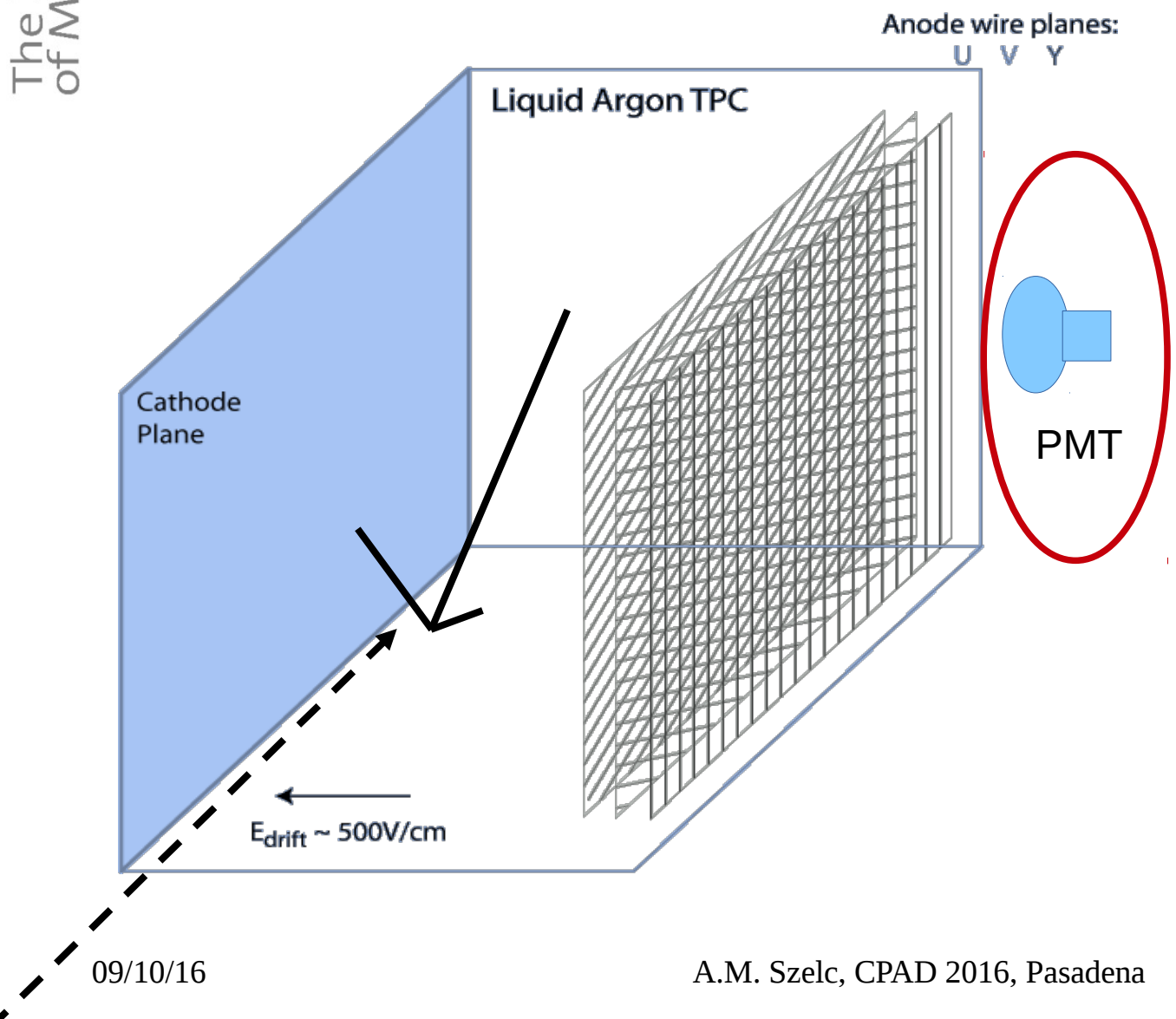
T2K oscillation parameter dependence

- $\sin^2 2\theta_{13}$ and $\sin^2 \theta_{23}$
  - Leading terms
  - "Octant" dependence; whether $\theta_{23} > 45^o$, $\theta_{23} < 45^o$, or $\theta_{23} = 45^o$
- δ_{cp}: **±27% effect at T2K for $\theta_{23} = 45^o$**
  - $\delta_{cp} \sim -\frac{\pi}{2}$: enhances $P(\nu_\mu \to \nu_e)$, suppresses $P(\bar{\nu}_\mu \to \bar{\nu}_e)$
  - $\delta_{cp} \sim +\frac{\pi}{2}$: suppresses $P(\nu_\mu \to \nu_e)$, enhances $P(\bar{\nu}_\mu \to \bar{\nu}_e)$
- **Mass hierarchy**: **±10% effect at T2K**
  - Normal: enhances $P(\nu_\mu \to \nu_e)$, suppresses $P(\bar{\nu}_\mu \to \bar{\nu}_e)$
  - Inverted: suppresses $P(\nu_\mu \to \nu_e)$, enhances $P(\bar{\nu}_\mu \to \bar{\nu}_e)$



Iwamoto@ICHEP

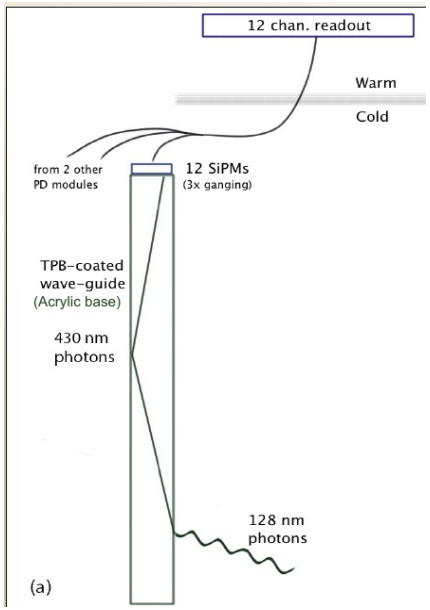
LArTPC detectors (2)

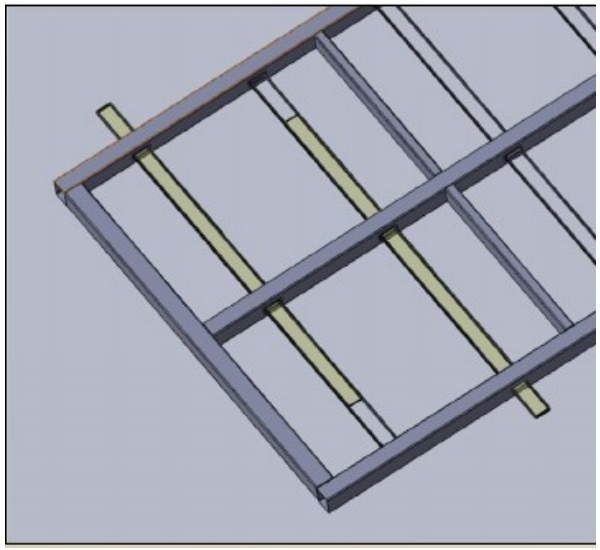


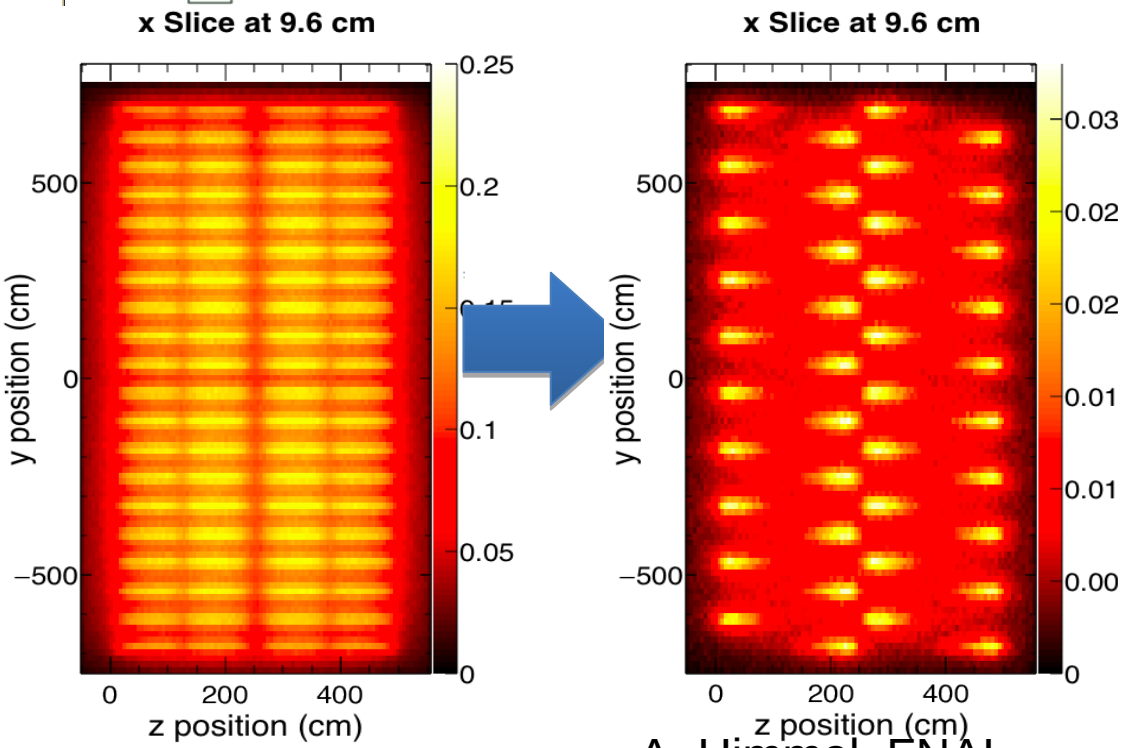
- LArTPCs seem to do a good job using ionization charge.
- We can also use scintillation light for a variety of applications.
-

SiPMs + coated bars

- WLS coated bars coupled to SiPMs (current DUNE baseline design).
- SiPM timing not as good as PMTs (Industry is working on this).
- Photon travel time in bar adds to this.
- Work ongoing to minimize attenuation in bars.
- Tested in 35ton – prototype and test-stands.

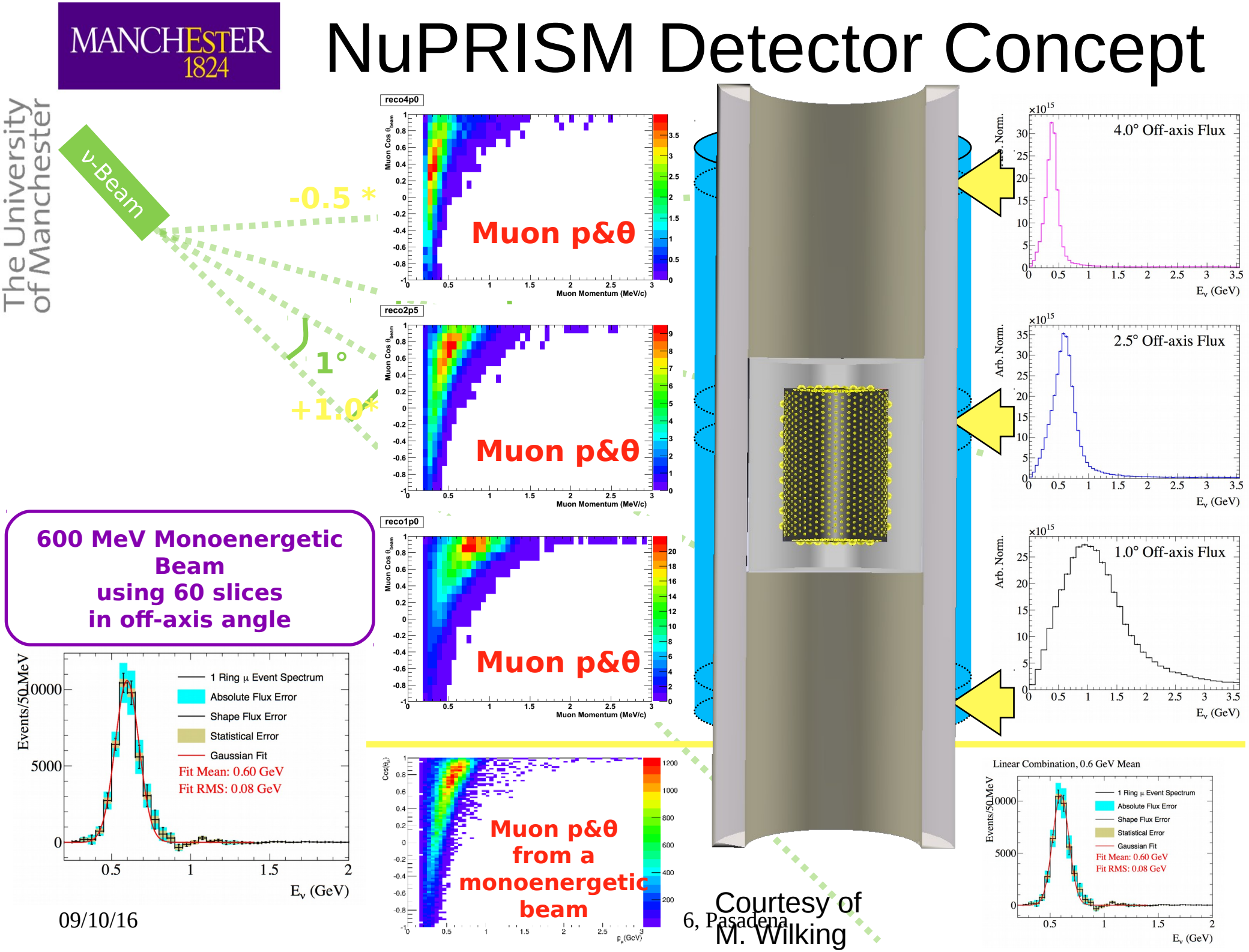






A. Himmel, FNAL

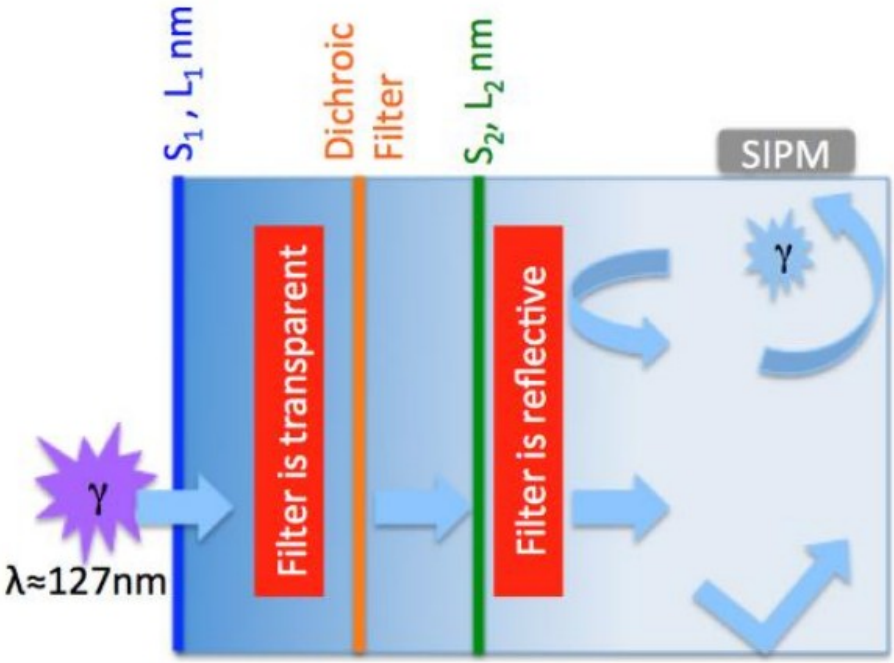
NuPRISM Detector Concept

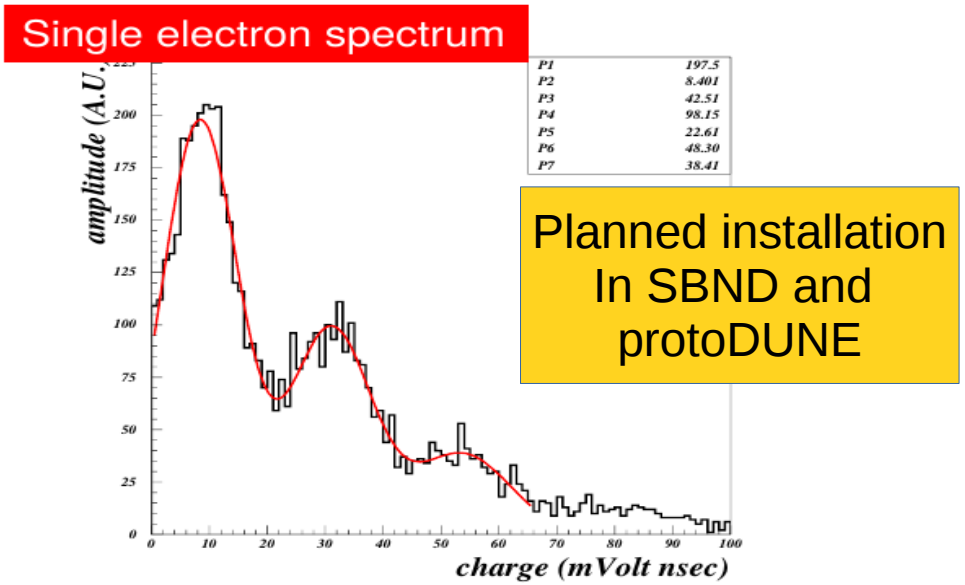


Courtesy of M. Wilking

The ARAPUCA light trap

- A way to enlarge the active surface without increasing number of channels.
- Use dichroic filters + 2 WLS





E. Segreto & A. Bergamini-Machado