Neutrino Interferometry at DUNE

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For the DUNE Collaboration

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Top Ten reasons to Study Neutrinos

1. Neutrinos are among the most abundant particles in the universe
2. Neutrinos have been around since the universe was 1 second old
3. Neutrinos are signals from the highest energy accelerators in the universe
4. Neutrinos will teach us about how mass is generated
5. What other fermion could be its own antiparticle?
6. Neutrinos can see inside the nucleus like none else
7. Neutrinos will tell us if we really understand flavor
8. Neutrinos may be the reason that we enjoy such a healthy baryon asymmetry
9. Neutrinos can access physics up to the GUT energy scales
10. Neutrinos broke the standard model and will tell us what is beyond

From 2013 DPF neutrino summary…still true today!

Top Ten reasons to Study Neutrinos

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4. **Neutrinos will teach us about how mass is generated**
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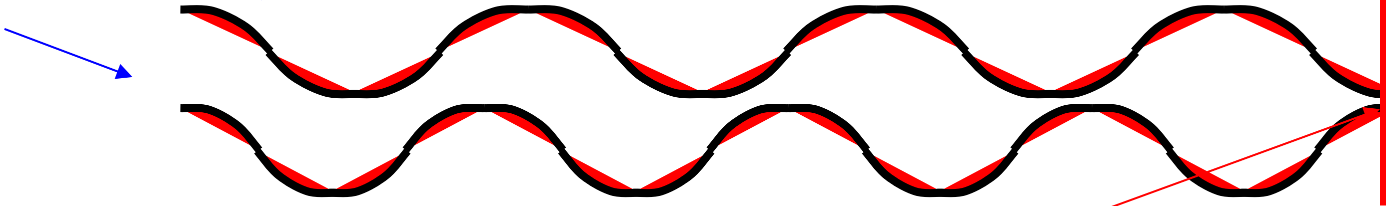
Minimal Oscillation Formalism

- If neutrino mass eigenstates: ν_1, ν_2, ν_3, etc.
- … are not flavor eigenstates: ν_e, ν_μ, ν_τ
- … then one has, e.g.,

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_i \\ \nu_j \end{pmatrix}$$

take only two generations for now!

$$|\nu_\alpha\rangle = \cos{}^{\pi}\!/_{4}\,|\nu_i\rangle + \sin{}^{\pi}\!/_{4}\,|\nu_j\rangle$$

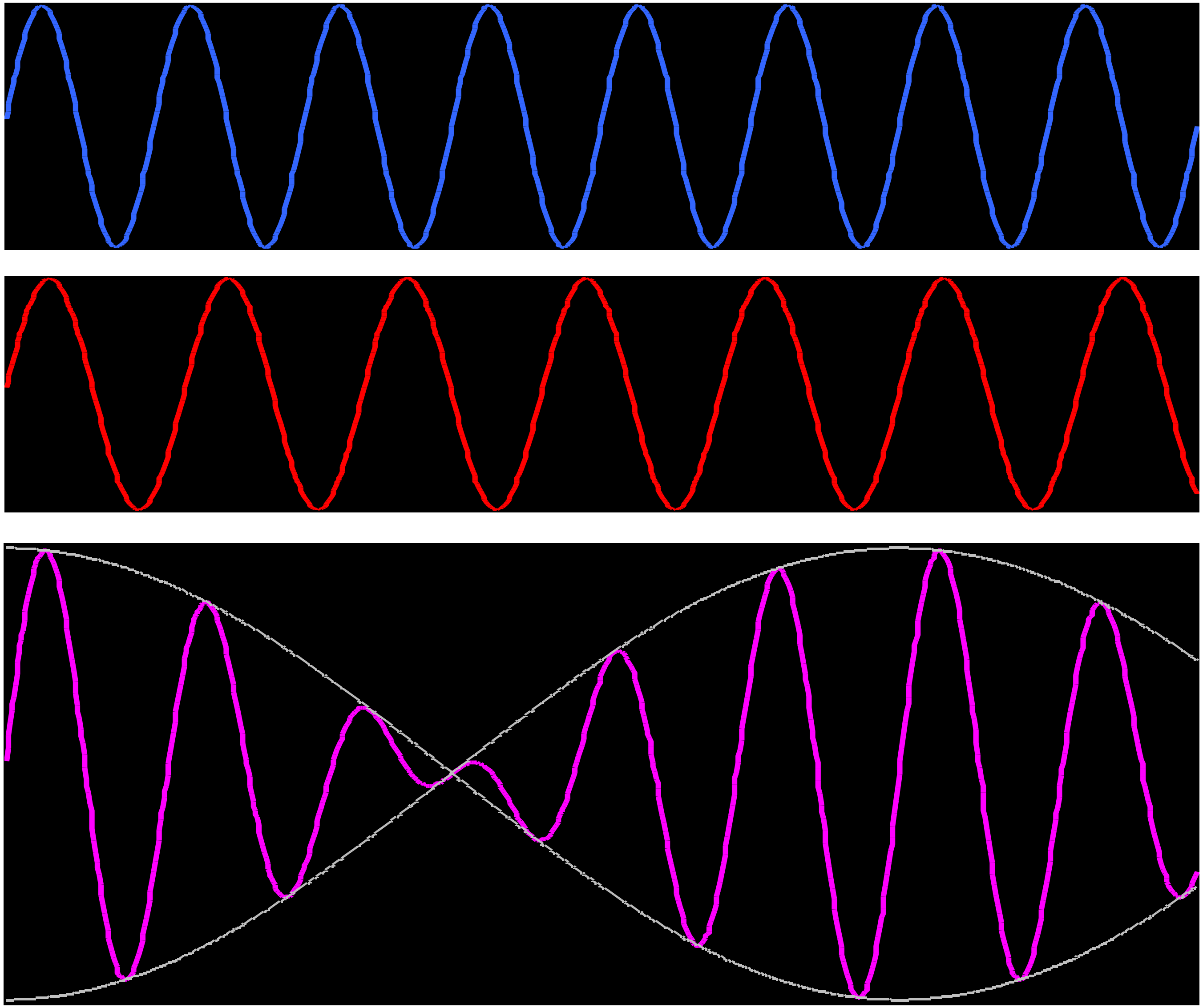


different masses alter time evolution

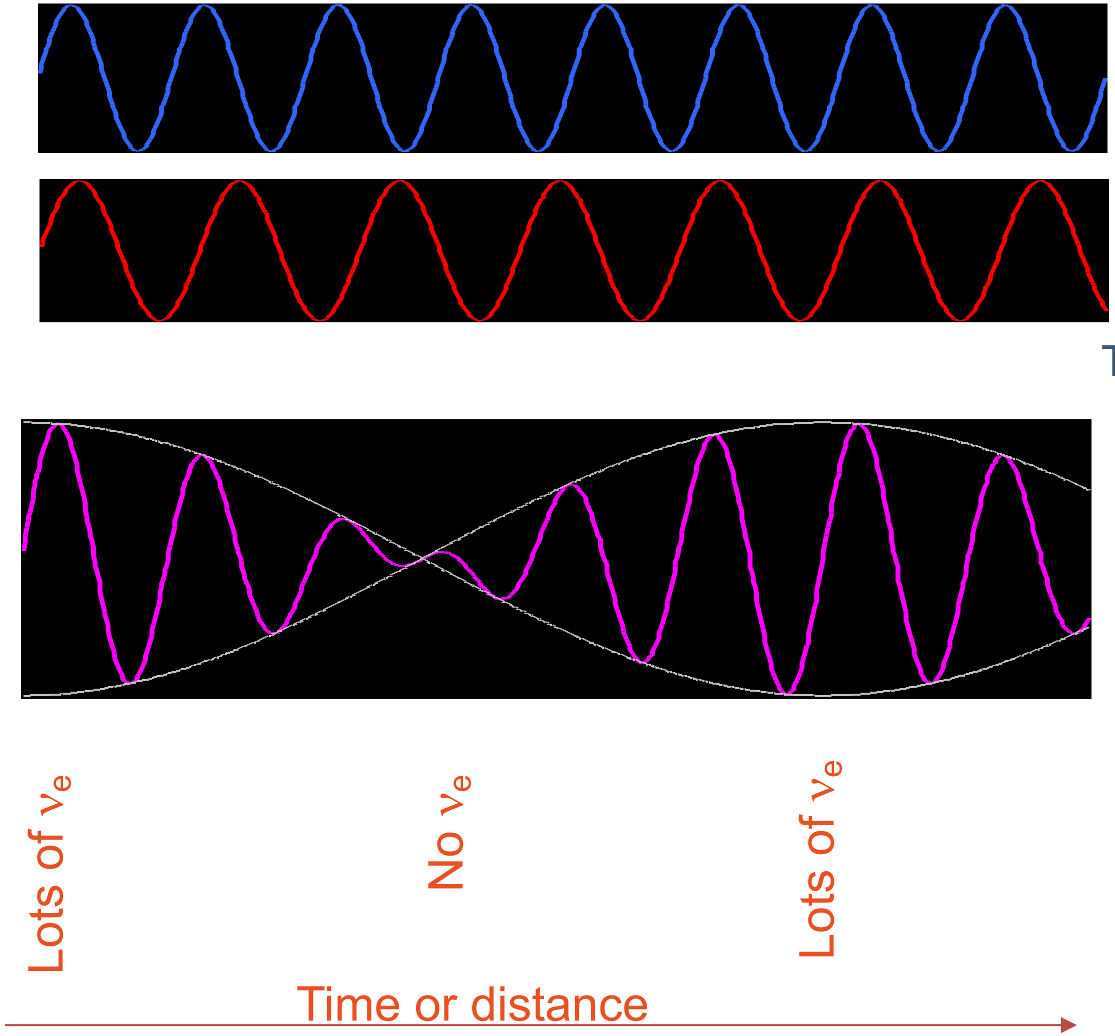
time →

$$|\nu_\beta\rangle = -\sin{}^{\pi}\!/_{4}\,|\nu_i\rangle + \cos{}^{\pi}\!/_{4}\,|\nu_j\rangle$$

Acoustic Analogy (for musicians…)



Neutrino Oscillations



If neutrinos are waves of slightly different frequencies:

Over time, they disappear and reappear

The bigger the frequency difference, the faster the disappearance

Particles are like waves particle mass determines its frequency

Measuring neutrinos oscillating: Measuring mass differences

If one kind of neutrino disappears, another kind must appear

Oscillation Formalism (cont'd)

- So, still for two flavors…

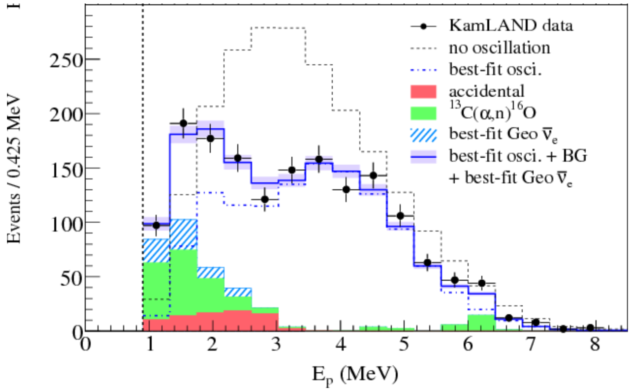
$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2 2\theta \sin^2\left(\frac{(m_2^2 - m_1^2)L}{4E}\right)$$

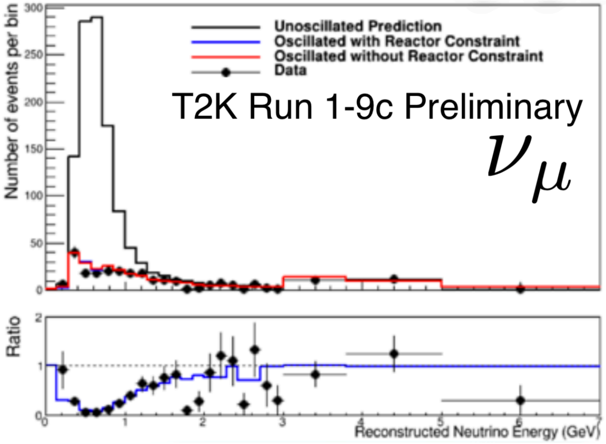
- Oscillations require mass differences
- Oscillation parameters are mass-squared differences, Δm^2, and mixing angles, θ.
- But the signals:
- Reactor ν's: 3MeV neutrinos, 180km
- T2K: 700MeV neutrinos, 295km
- There must be more than two masses, or 2 mass eigenstates

Experimental Details:

L: Baseline

E: Neutrino Energy





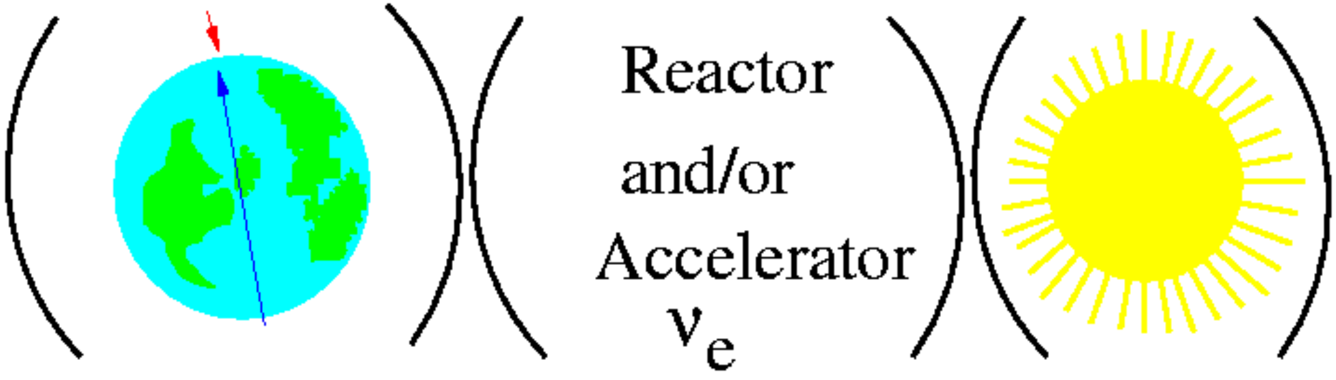
Three Generation Mixing

Lesson learned from studying quarks:
3x3 Unitary matrix is defined by 3 mixing angles and one phase

Call them $\theta_{12}, \theta_{23}, \theta_{13}, \delta$ if $s_{ij} = \sin\theta_{ij}, c_{ij} = \cos\theta_{ij}$, then

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

U=



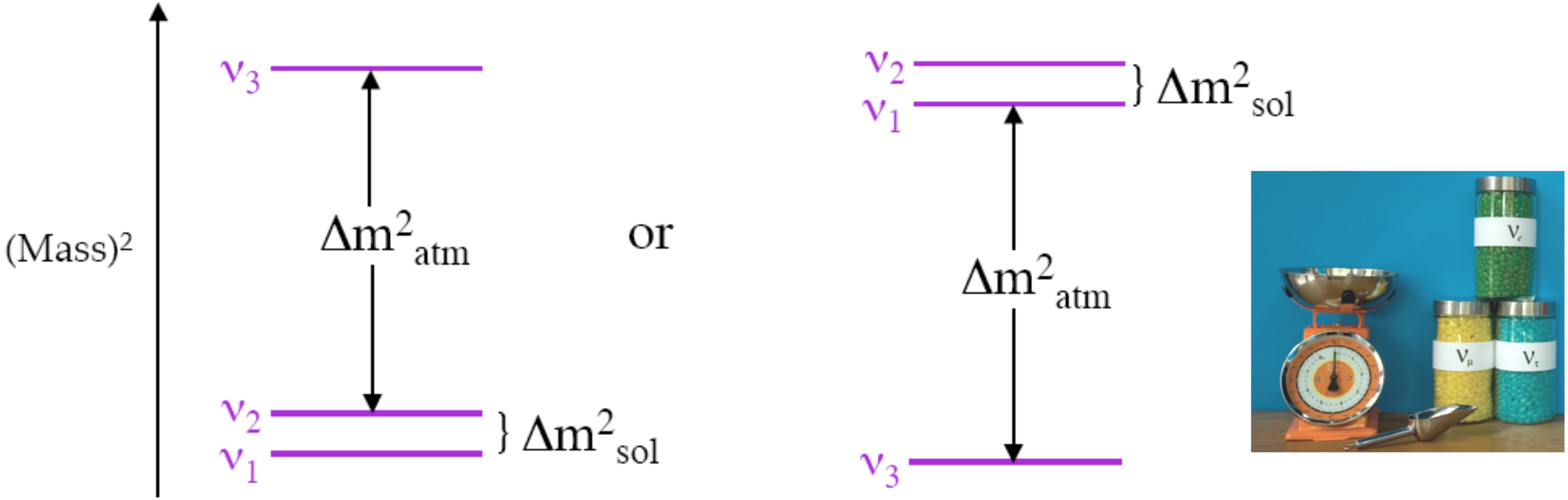
Reactor
and/or
Accelerator
ν_e

- Note the new mixing in the middle, and the phase δ

What don’t we know yet?

- Do Neutrinos and Anti-neutrinos change the same way?
- We know there’s lots of matter in the universe, no antimatter
- We know quark sector CP violation is very small
- Do neutrino mass states have the same mass structure as the charged fundamental particles?

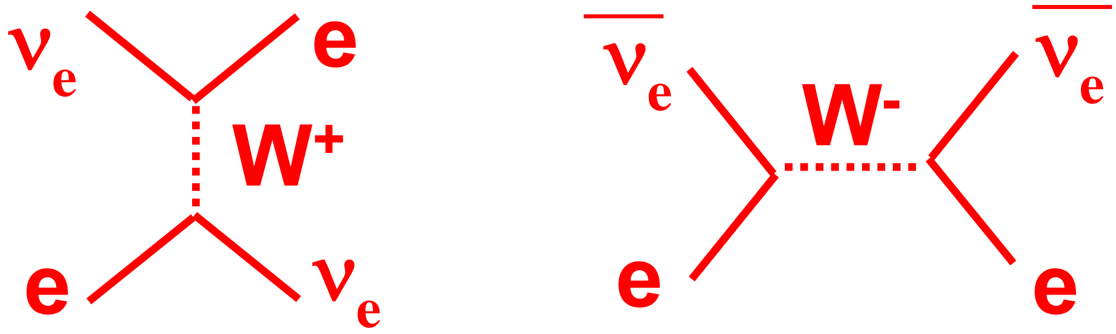
figures courtesy B. Kayser



$\Delta m_{sol}^2 \rightarrow \Delta m_{12}^2 \approx 8\times10^{-5}eV^2$ $\Delta m_{atm}^2 \rightarrow \Delta m_{23}^2 \approx 2.5\times10^{-3}eV^2$

Measuring Mass Ordering

- Electrons in the earth act on ν_e and $\overline{\nu}_e$'s differently from each other, and from ν_μ or ν_τ



Wolfenstein, PRD (1978)

- For 2 generations…

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2 2\theta \sin^2\left(\frac{(m_2^2 - m_1^2)L}{4E}\right)$$

$$x = \frac{2\sqrt{2}G_F n_e E_\upsilon}{\Delta m^2}$$

$$\sin^2 2\Theta_M = \frac{\sin^2 2\Theta}{\sin^2 2\Theta + (\pm x - \cos 2\Theta)^2}$$

$$L_M = L \times \sqrt{\sin^2 2\Theta + (\pm x - \cos 2\Theta)^2}$$

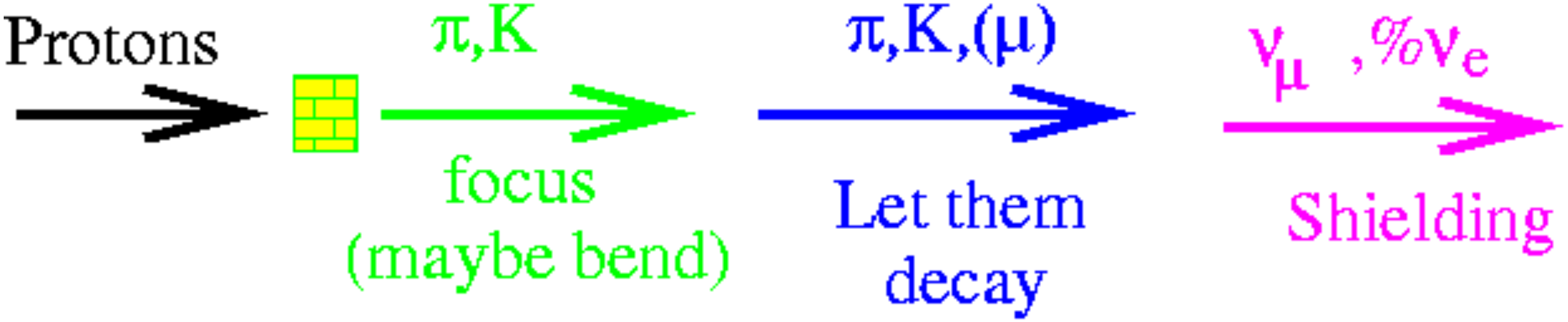
n = e$^-$ density

Bad news: this complicates search for CP violation,

Good news: it means you can measure the mass ordering

Neutrinos from Accelerators

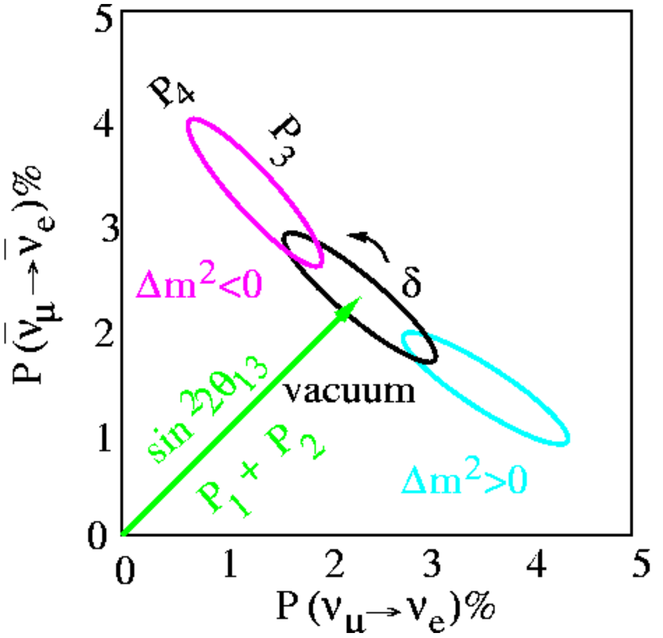
- High energy protons strike block of material
- Unstable particles (π,K) are produced
- Trick: focus the charged particles before they decay to neutrinos
- Next trick: Give the particles time to decay but not too much time, so mostly ν_μ beam



3-generation $\nu_\mu \rightarrow \nu_e$ Probabilities

- $P(\nu_\mu \rightarrow \nu_e) = P_1 + P_2 + P_3 + P_4$

$$
\begin{aligned}
P_1 &= \sin^2\theta_{23}\sin^2 2\theta_{13}\left(\frac{\Delta_{13}}{B_\pm}\right)^2\sin^2\frac{B_\pm L}{2}\\
P_2 &= \cos^2\theta_{23}\sin^2 2\theta_{12}\left(\frac{\Delta_{12}}{A}\right)^2\sin^2\frac{AL}{2}\\
P_3 &= J\cos\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\cos\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2}\\
P_4 &= \mp J\sin\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\sin\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2}
\end{aligned}
$$



Minakata & Nunokawa JHEP 2001

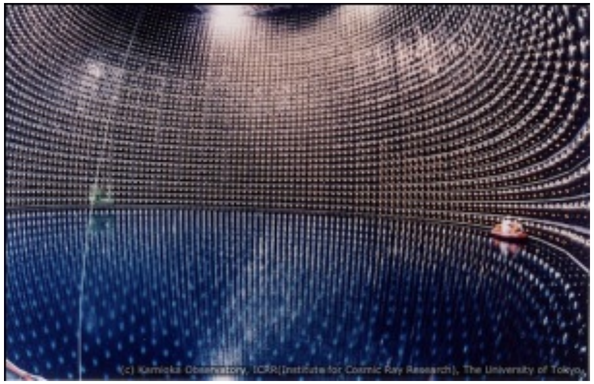
- Much more complicated than 2-generation mixing
- Interference between atmospheric and solar terms is where CP violation arises
- Size of that interference is function of all angles, including θ_{13}
- Measurement at one L and E is not enough!

Fast Forward 20 years:

- Two accelerator experiments probing “atmospheric anomaly”
- Near and Massive Far Detectors: 14-50kton
- Very intense beams of protons: 400-700kW

- NOvA
  - 810km, mostly under WI
  - 2GeV neutrinos
  - Liquid Scintillator Detector (sees charged particles)

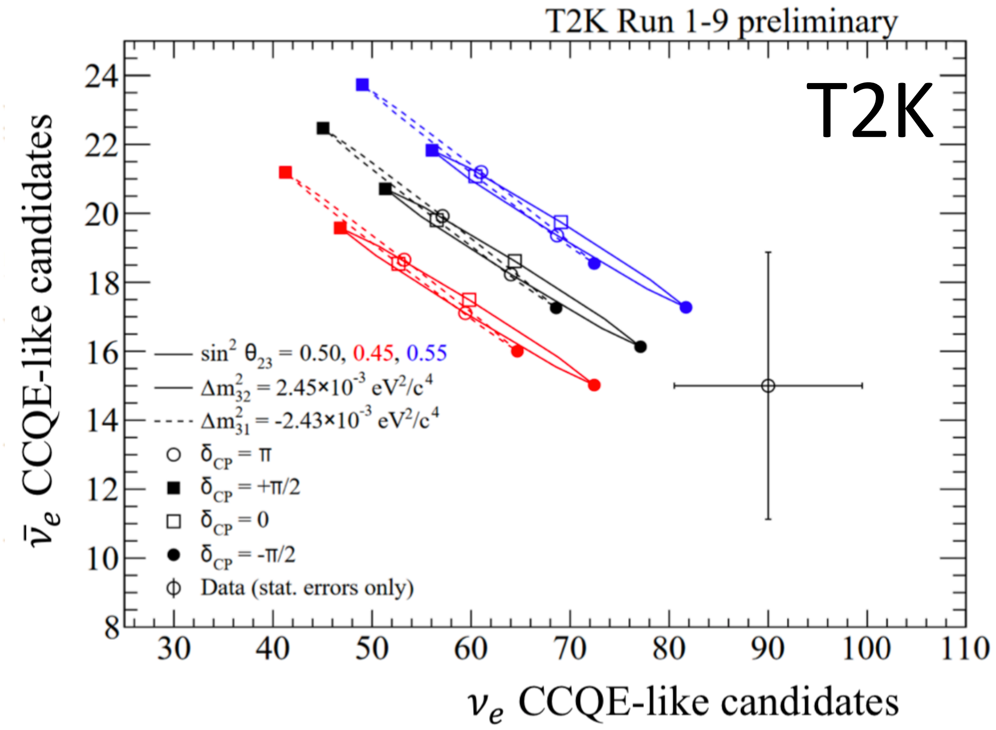
- T2K
  - 295km E to W under Japan
  - 700MeV neutrinos
  - Water Cerenkov detector (sees e and μ)



(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Tokyo

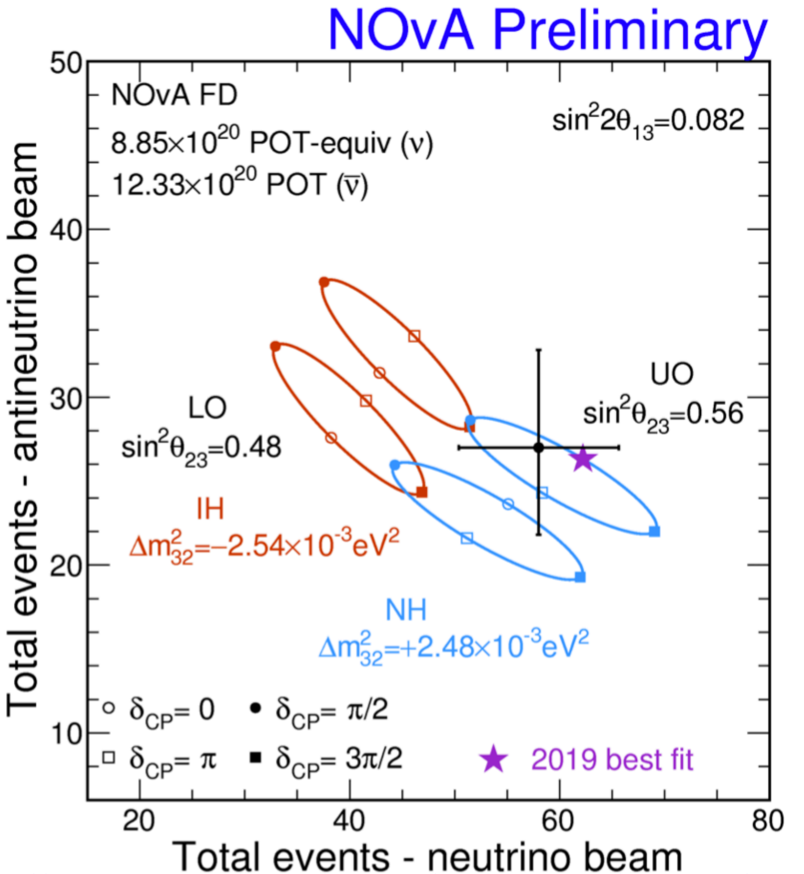
Appearance of ν_e in a ν_μ beam

- Both experiments have run in neutrino and antineutrino beams



https://indico.cern.ch/event/773605/contributions/3498113/attachments/1897012/3130048/NuFACT2019_T2K_plenary_FBench.pdf

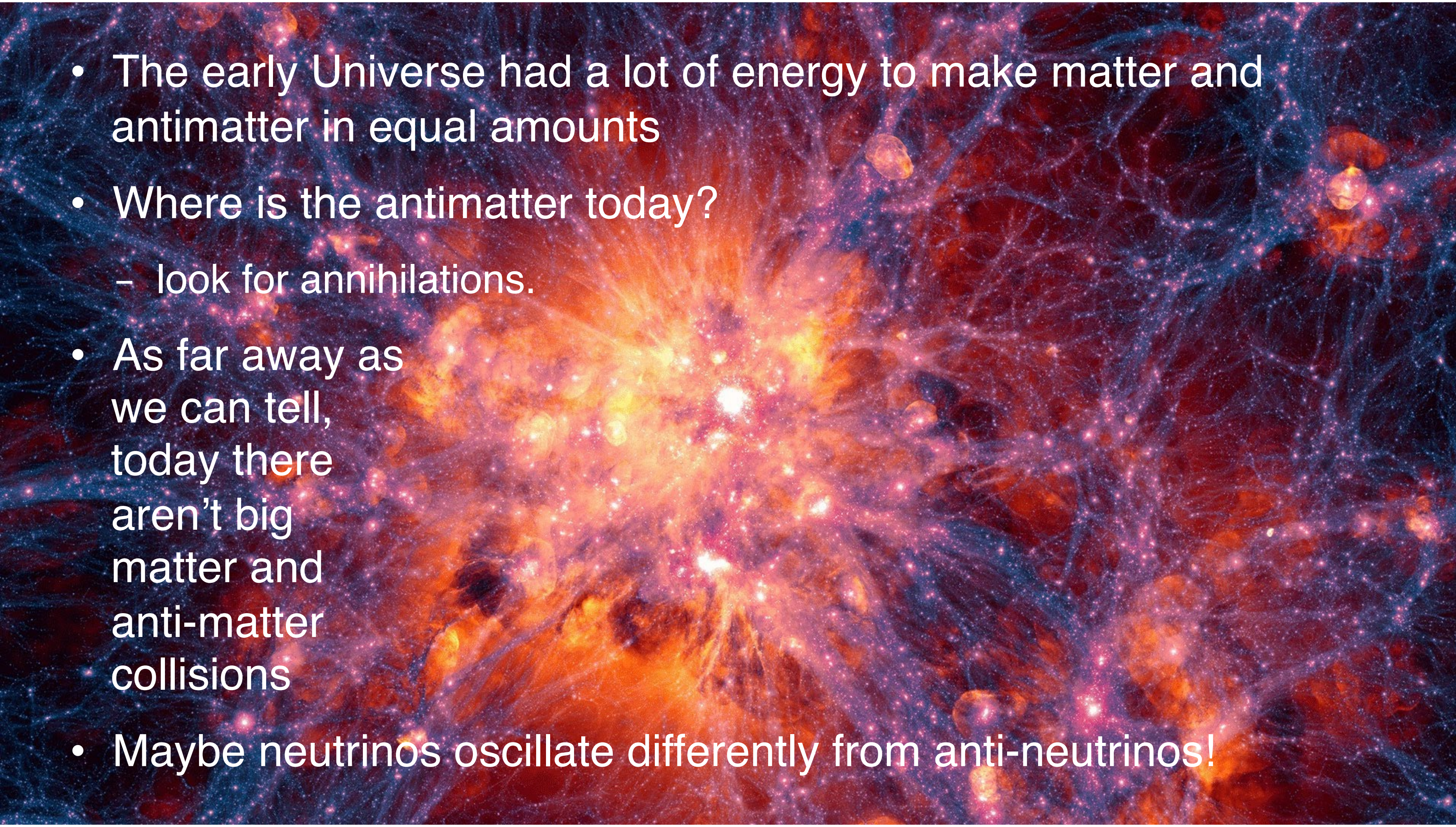
F. Bench, NuFact 2019



https://indico.cern.ch/event/773605/contributions/3498114/attachments/1897026/3130086/ESmith_NOvA_NuFACT2019_8-26-2019.pdf

E. Smith, NuFact 2019

Why is CP-violation so important?

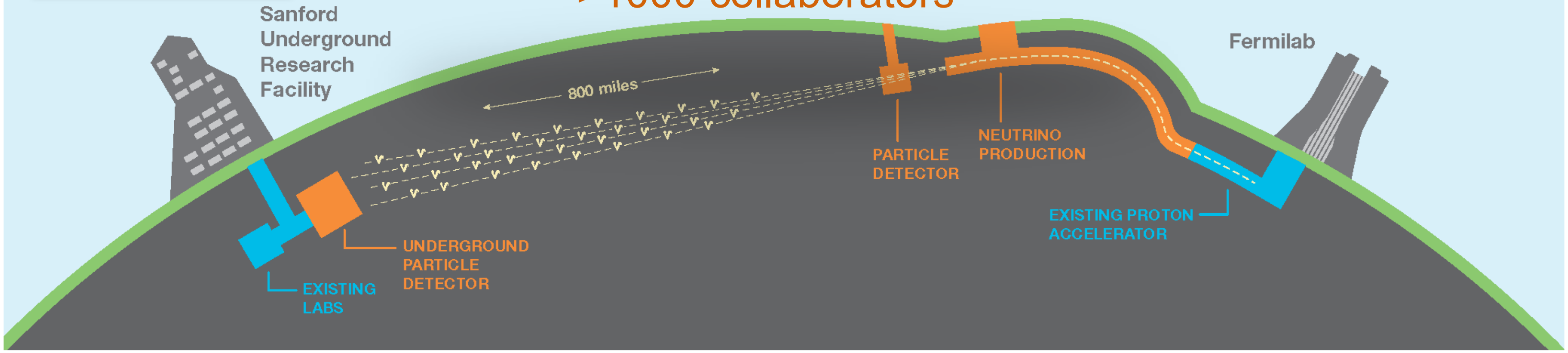


- The early Universe had a lot of energy to make matter and antimatter in equal amounts
- Where is the antimatter today?
  - look for annihilations.
- As far away as we can tell, today there aren’t big matter and anti-matter collisions
- Maybe neutrinos oscillate differently from anti-neutrinos!

DUNE

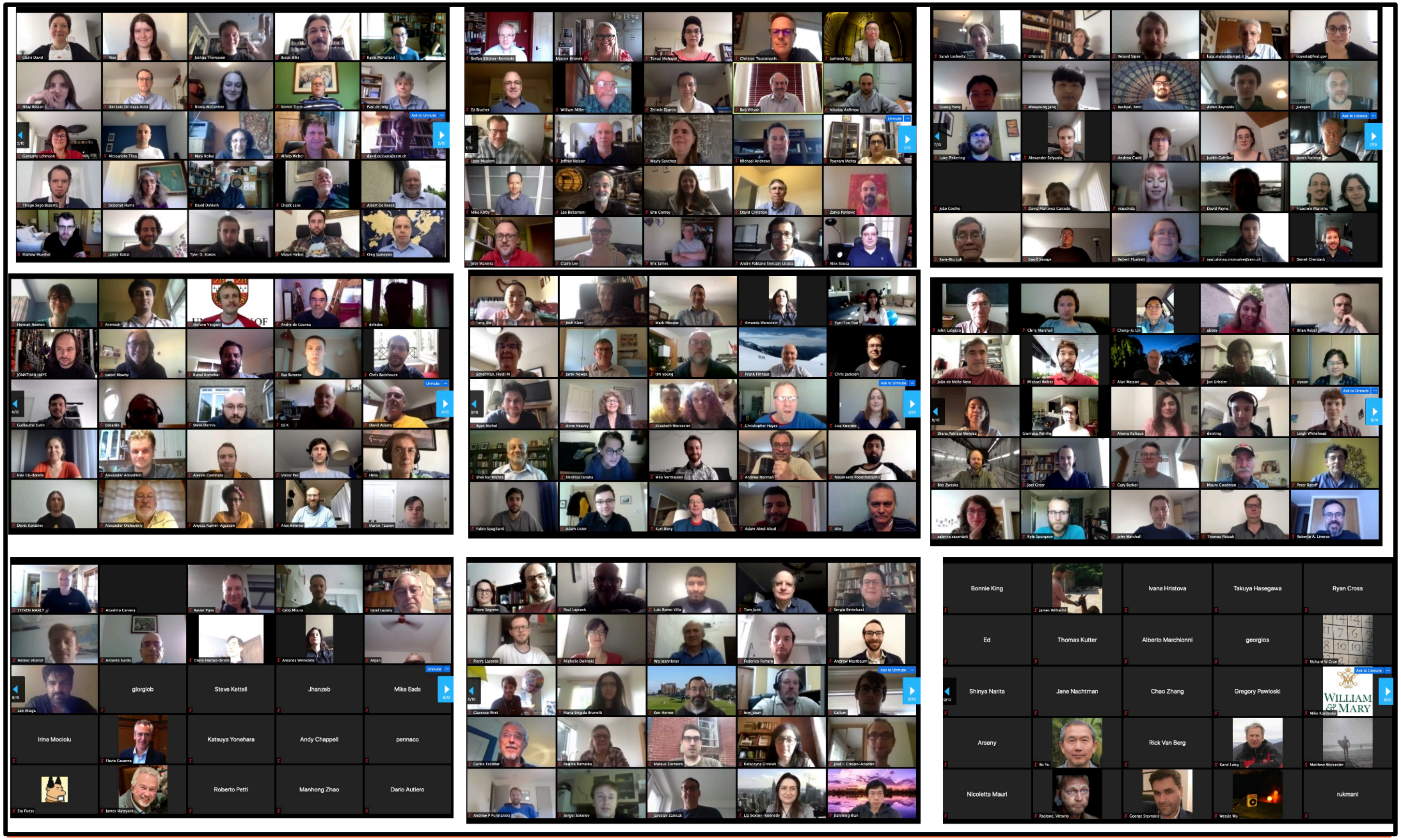
Measure ν_e appearance and ν_μ disappearance in a wideband neutrino beam at 1300 km to measure mass ordering, CP violation, and neutrino mixing parameters in a single experiment. Large detector, deep underground allows sensitivity to rare processes and low-energy physics.

>1000 collaborators



May 2020 Collaboration Photo

~250 participants!



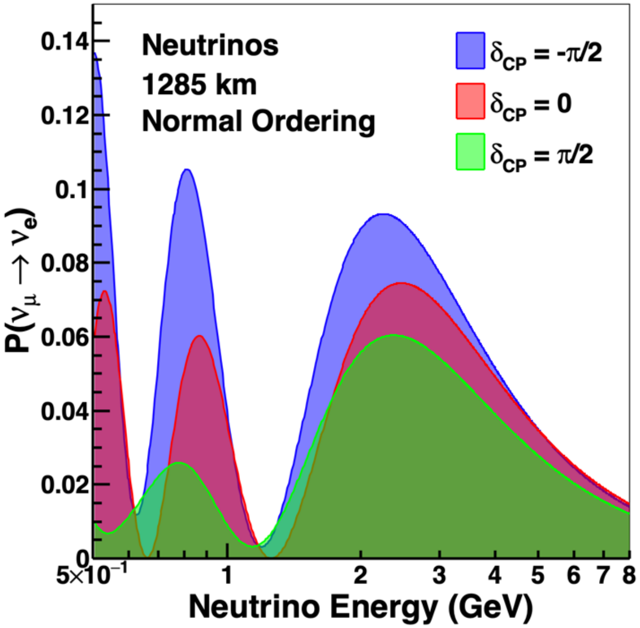
ν_e Appearance at DUNE

$$\begin{aligned}P(\nu_\mu \to \nu_e) \;\simeq\;& \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2\\ &+\sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}+\delta_{\mathrm{CP}})\\ &+\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2,\end{aligned}$$

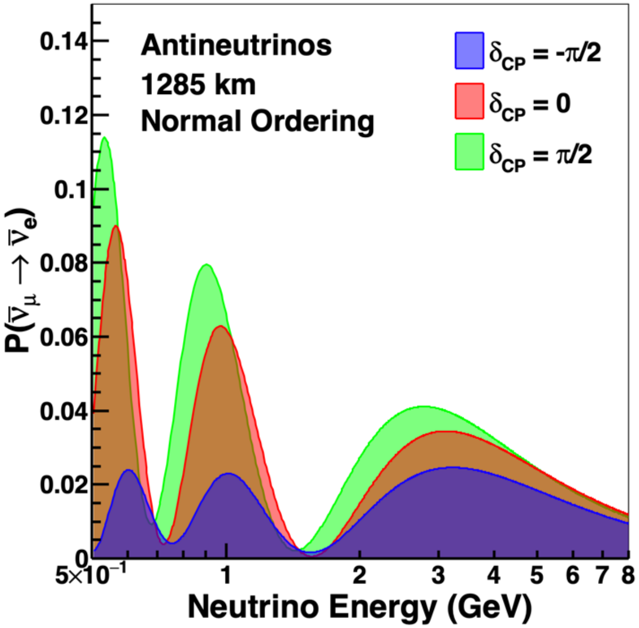
$$a = G_F N_e / \sqrt{2}$$

$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E}$$

Neutrinos

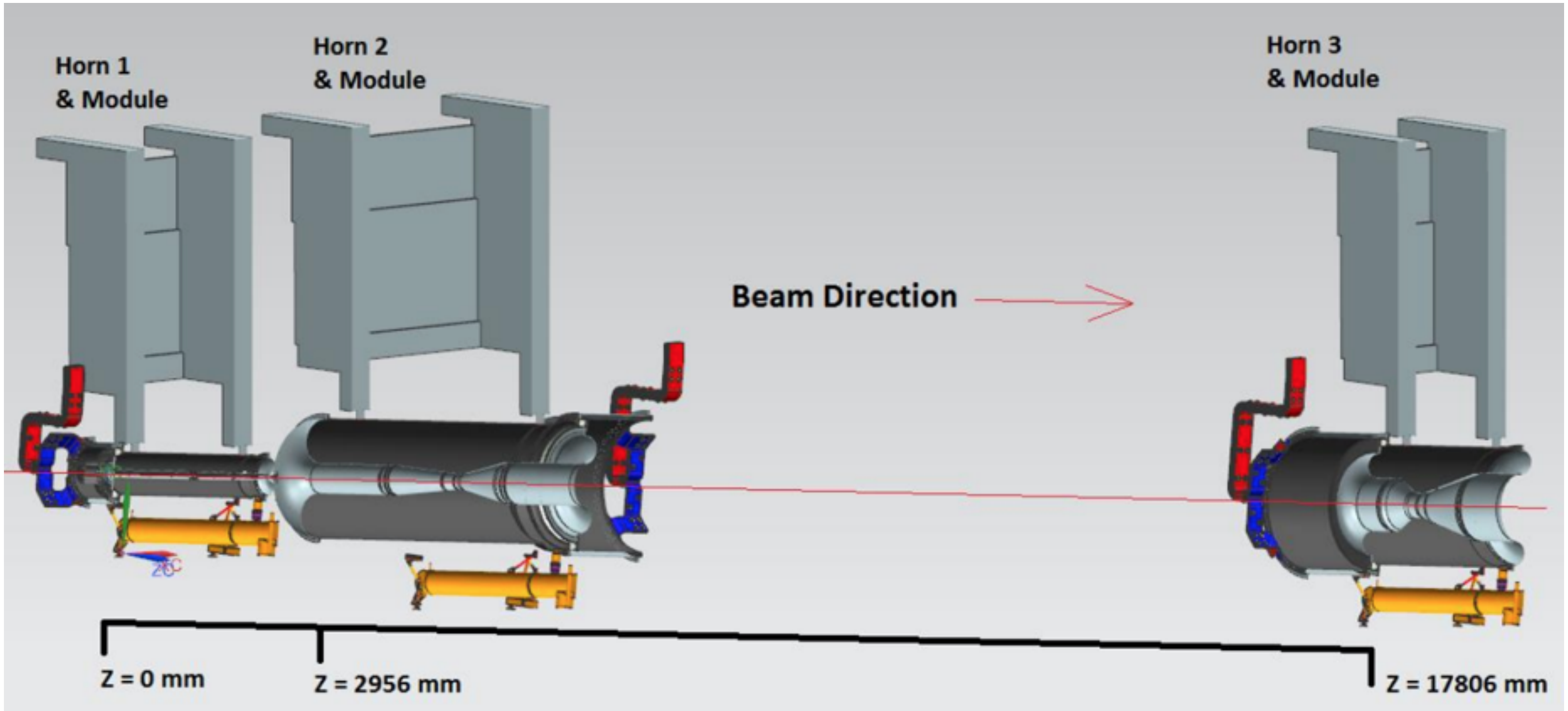


Antineutrinos



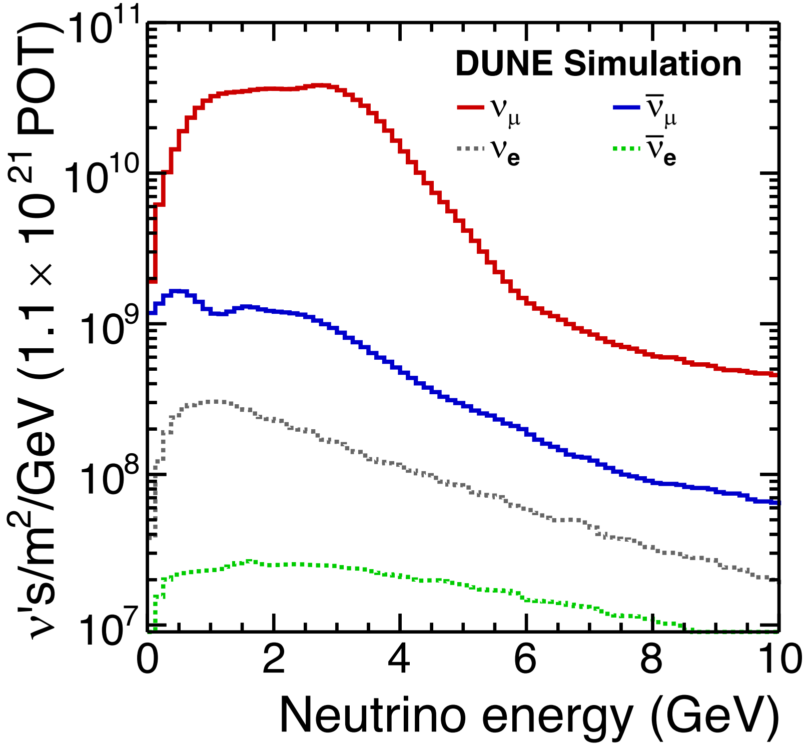
LBNF Neutrino Beam

- 120-GeV protons from FNAL accelerator complex
  - 1.2 MW beam power, upgradeable to 2.4 MW
- Neutrino beam line designed using genetic algorithm to optimize CP violation sensitivity

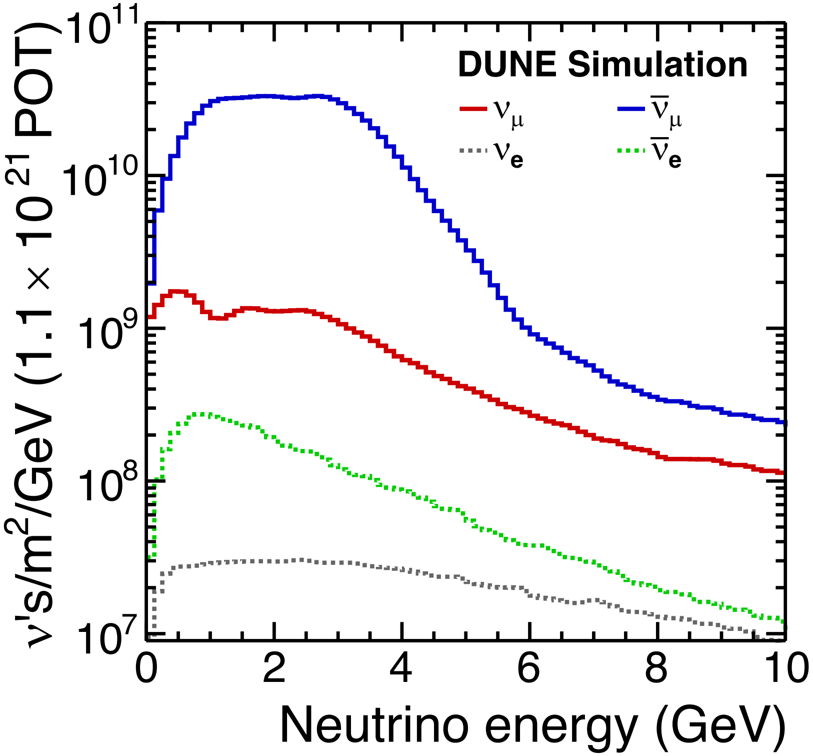


Neutrino Flux

Neutrino Mode:



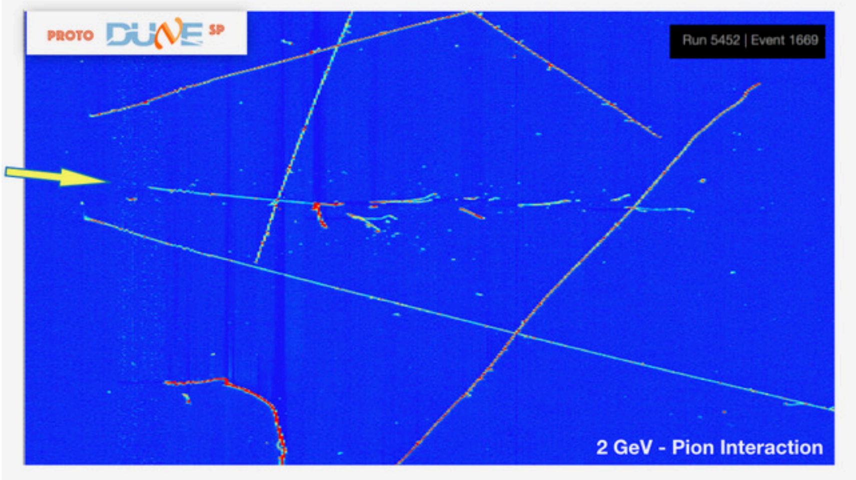
Antineutrino Mode:

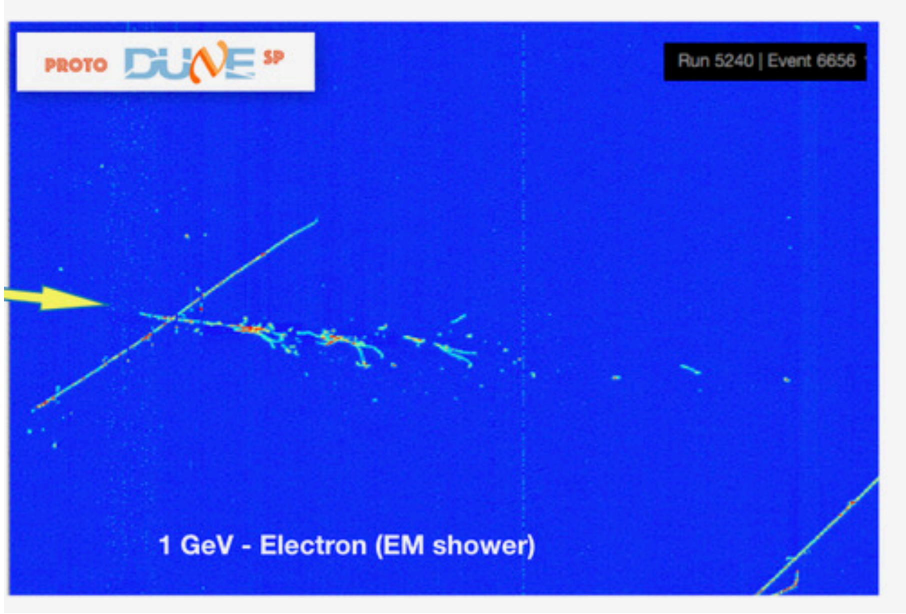


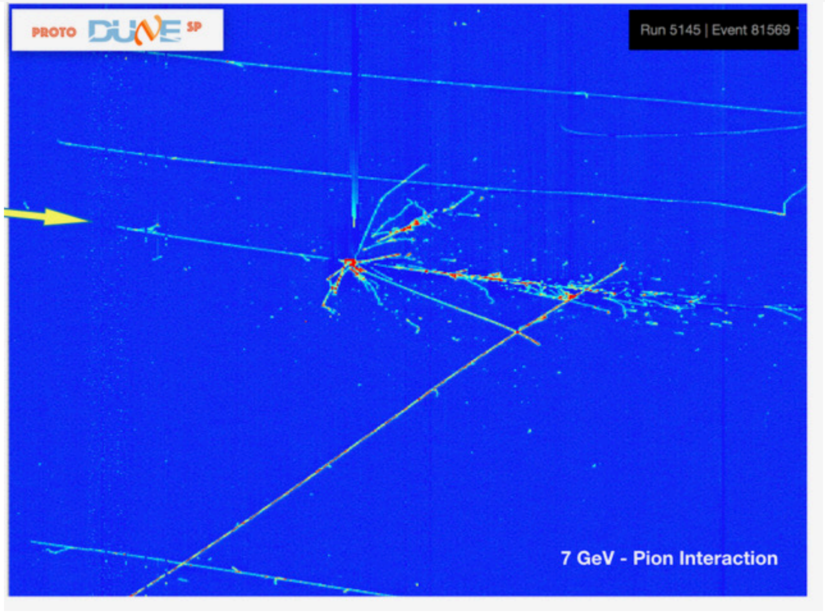
POT: Protons on Target

Building enormous detectors

- Liquid Argon Detection Technique: electronic bubble chamber
- Have built 1kton-scale detectors now, tested scalable design in test beam at CERN







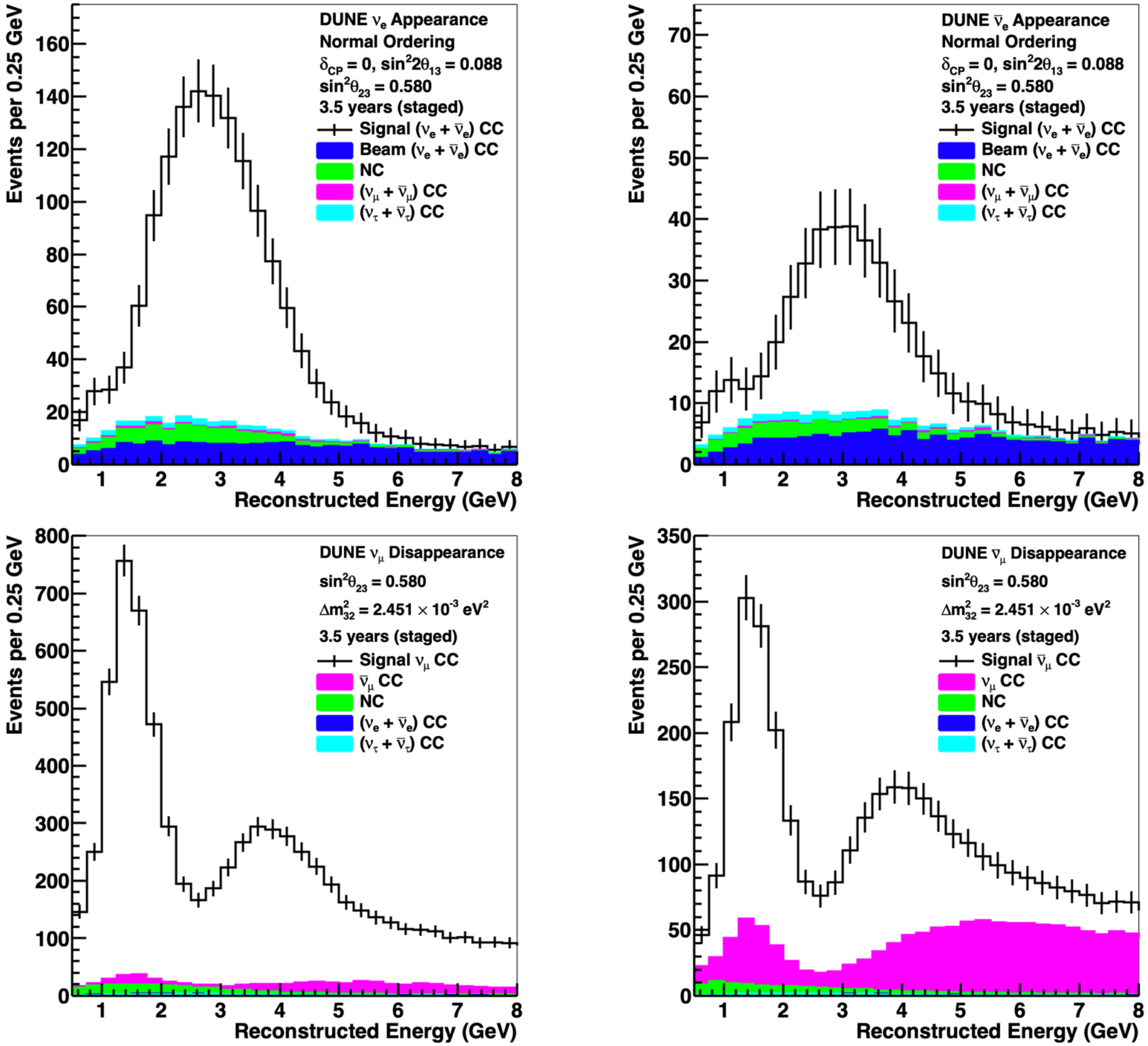
Far Detector Spectra

Neutrino Mode

Antineutrino Mode

Appearance

Disappearance



Order 1000 appearance events in 7 years

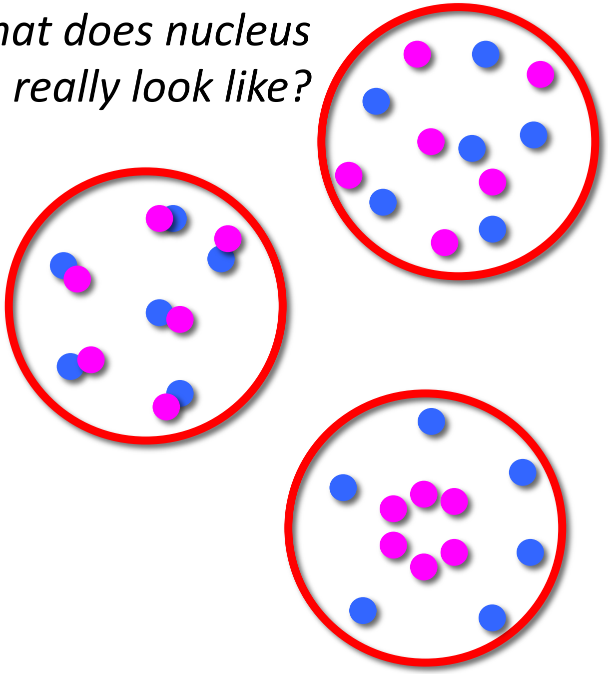
Order 10,000 disappearance events in 7 years

Broad spectrum combined with high event rates allows real test of framework!

Is a beam and a far detector enough?

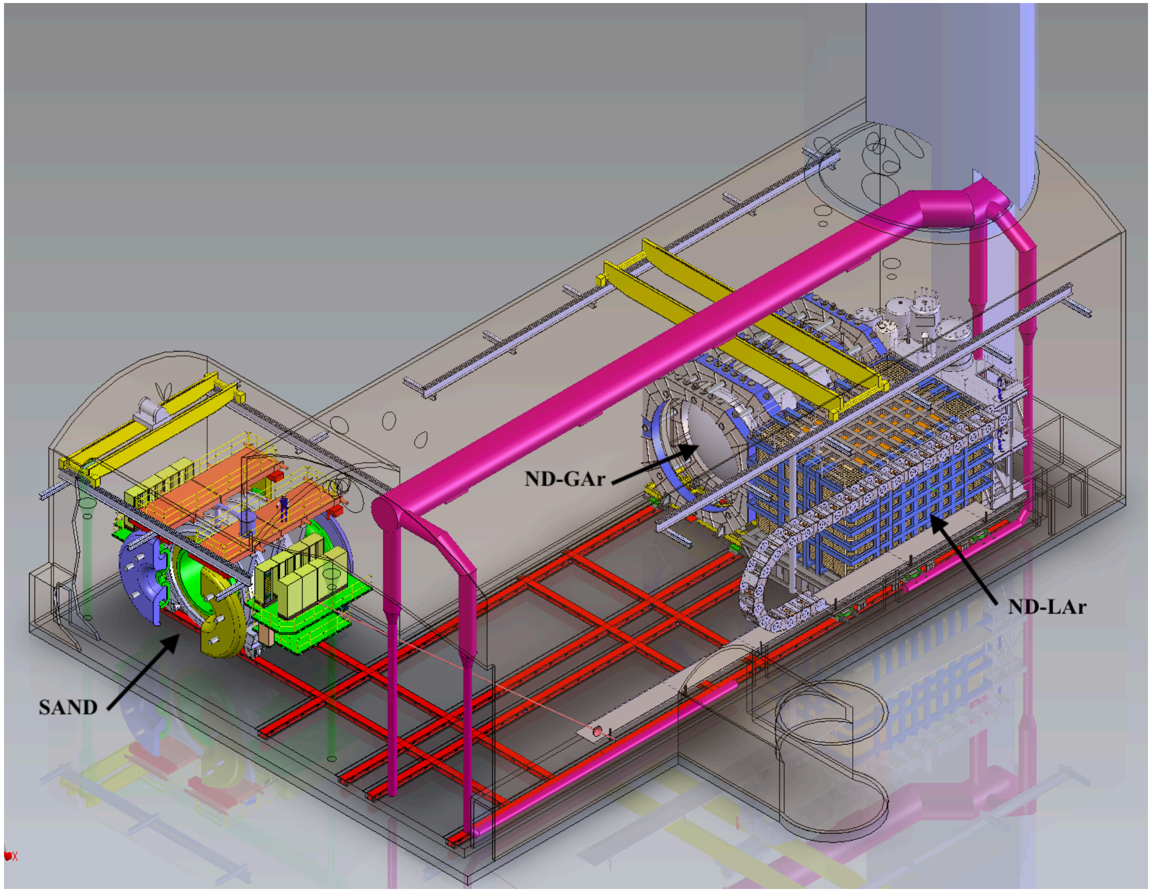
- NO! Measuring visible energy ν_μ and ν_e spectra in a far detector and comparing them to predictions relies on many ingredients:
  - Accurate flux predictions
  - Accurate detector simulations informed by test beam measurements (next talk)
  - Accurate predictions of how the ν energy gets translated into visible energy
- This last ingredient calls for two things:
  - a Near Detector which measures the beam before oscillations
  - A model of how neutrinos interact in nuclei to produce particles that can be seen in Liquid Argon
- This last ingredient has been focus of a lot of work lately…
  - Flood of new measurements from several experiments…

What does nucleus really look like?



DUNE Near Detector

- Located 574 m from ν beam target
- Will see millions of events



- **Three Components+rails, four jobs:**
- **ND-LAr:** Modular, pixelized liquid argon TPC
  - Primary target
  - Most like Far Detector
- **ND-GAr:** High pressure gaseous argon TPC plus ECAL and magnet
  - μ momentum
  - Lower threshold
- **PRISM:** ND-LAr & ND-GAr move off-axis to observe varied beam spectra

SAND: Scintillator Tracker surrounded by ECAL and magnet

  - On-axis beam monitor

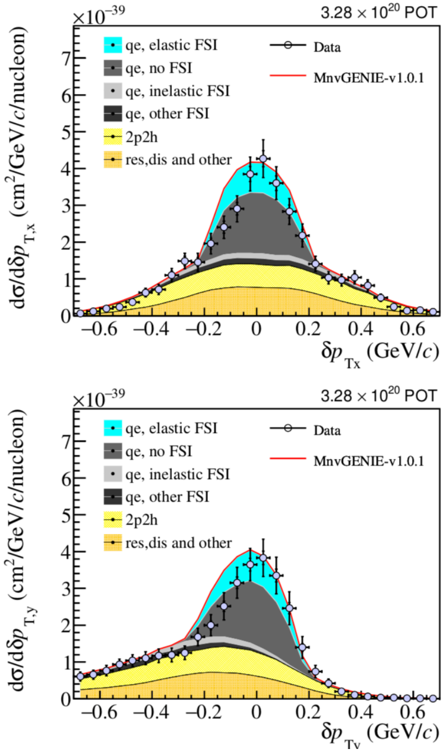
What have we learned?

- The models we have been using up until now need help!
- Early models assume that nucleus is made of non-interacting partons, total cross section is just the sum of the parts
- This is not true: the nucleus plays an important role!
  - Modifies the initial state nucleons
  - Modifies the particles kinematics and identity on their way over the nucleons
  - There are correlations between nucleons that affect final visible energy
- Evidence for this has been pouring in, theories have been improved, new models incorporated
- But we have only just begun…will need to translate these to predictions on argon…

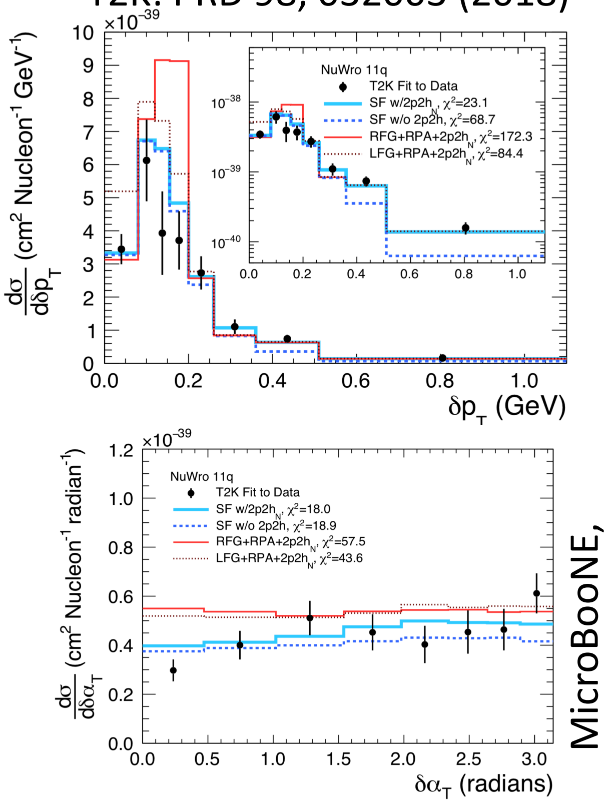
Recent Results showing effect of Nucleus

- New observables combining hadronic and leptonic information to give new handles on nuclear effects

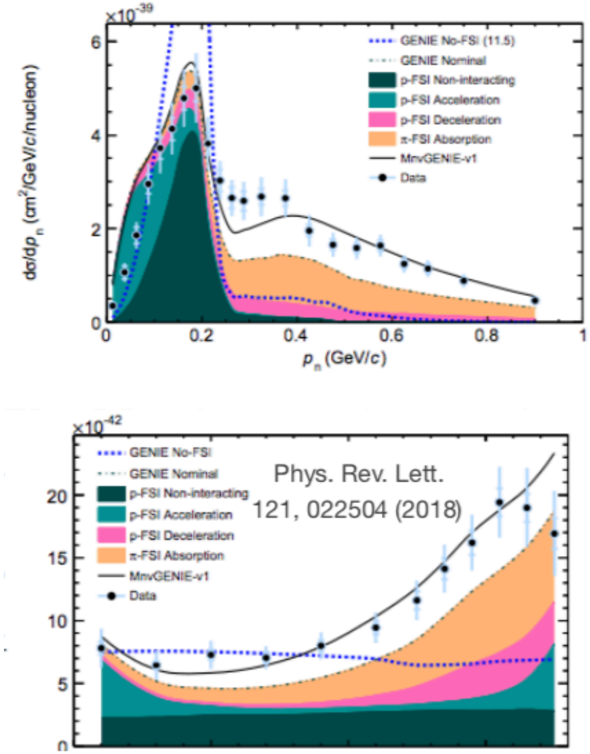
MINERvA, PRD.101.092001 (2020)



T2K: PRD 98, 032003 (2018)

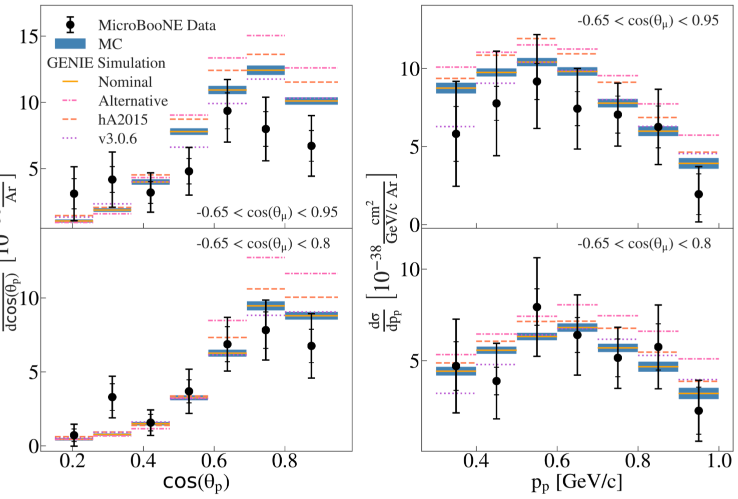


MINERvA



Phys. Rev. Lett. 121, 022504 (2018)

MicroBooNE, arXiv:2006.00108



DUNE Timeline & Plans

- Far site construction underway
- Near site preparation underway
- protoDUNEs (large scale FD prototypes at CERN Neutrino Platform) taking data now
- Far detector physics data expected in late 2020s
- Neutrino beam expected to be available on similar timescale
- Details of timeline will be finalized when project is baselined (expected this year)

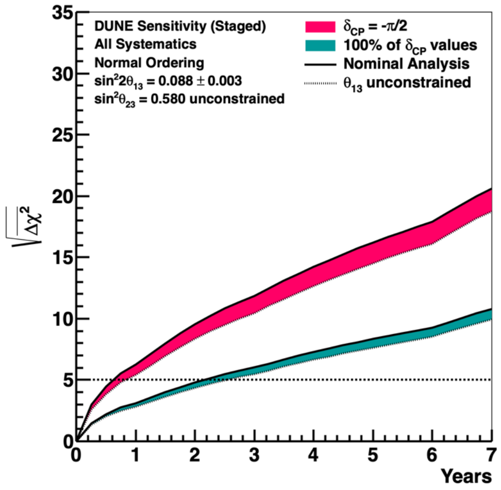
DUNE In Canada

- There are now three DUNE Collaborators with faculty positions in Canada:
  - Nikolina Ilic, IPP Fellow, University of Toronto (and the next speaker!)
    - Focus: DAQ and Beyond the Standard Model Physics
    - Postdoc: Jacopo Pinzino now, soon Nico Giangiacomi
  - Claire David at York University
    - Focus: Calibrations and Large Scale Computing, and Machine Learning
    - Postdoc: TBD
  - Both Claire and Nikolina are bringing the tools of ATLAS to DUNE
  - Yours Truly, York University
    - Focus: Near Detector prototype commissioning, measurements and Neutrino Interactions
    - Student Rowan Zaki
    - Postdoc: TBD
- There is plenty of room, please join us!
- Lots of exciting opportunities in Detector Technology, new unique Physics measurements, and International Collaboration!

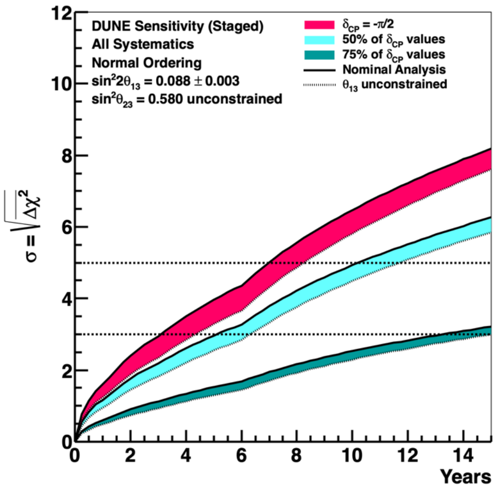
Summary

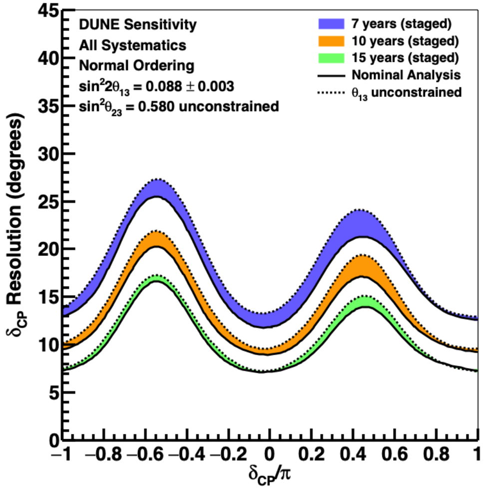
- The fact that Neutrinos have mass gives us many new windows beyond the standard Model
- DUNE's primary physics goals include determination of the mass ordering of neutrinos, and precise measurement of all parameters governing long-baseline oscillation in a single experiment: θ_{23}, θ_{13}, Δm^2_{32}, δ_{CP}
- We will also be ready for new surprises!

Mass Ordering Sensitivity



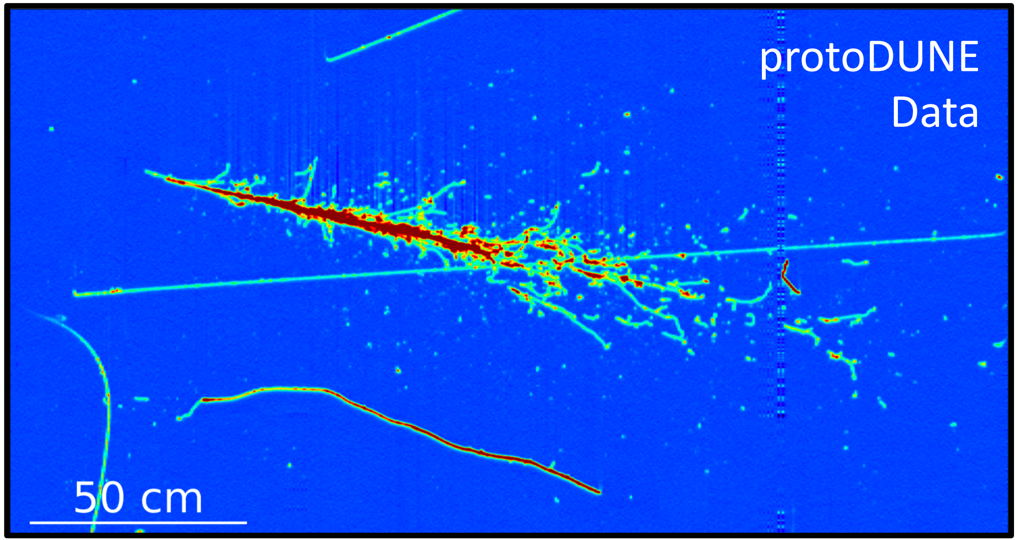
CP Violation Sensitivity





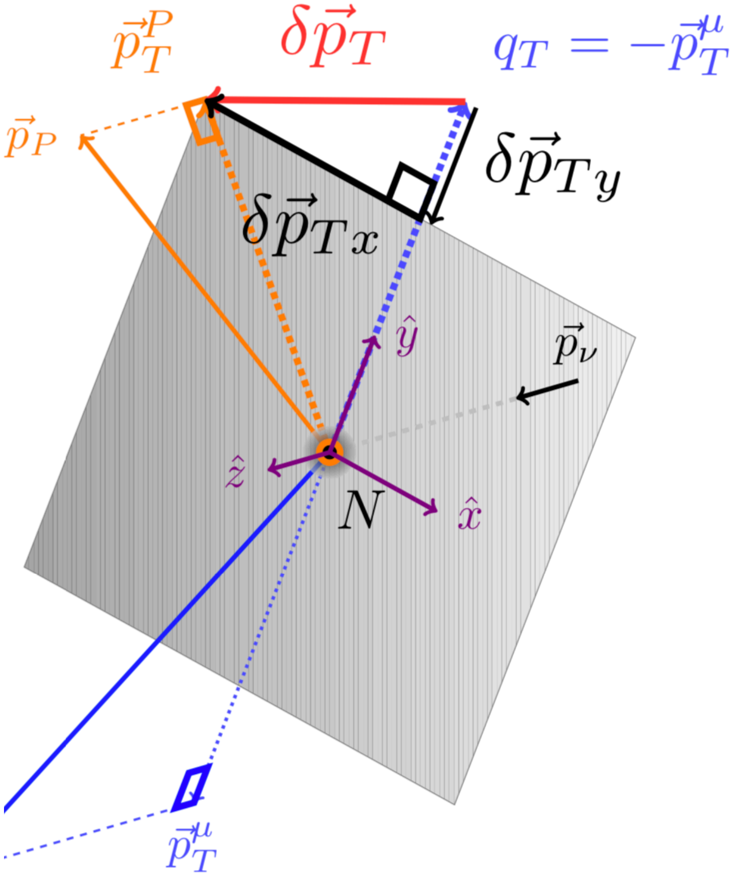
More DUNE Information

- DUNE Technical Design Report
  - Volume 1, Introduction to DUNE, arXiv:2002.02967
  - Volume 2, DUNE Physics, arXiv:2002.03005
  - Volume 3, Far Detector Technical Coordination, arXiv:2002.03008
  - Volume 4, Far Detector Single-phase Technology, arXiv:2002.03010
- Paper on long-baseline analysis to be submitted to EPJC
- Paper on CVN event classification to be submitted to PRD

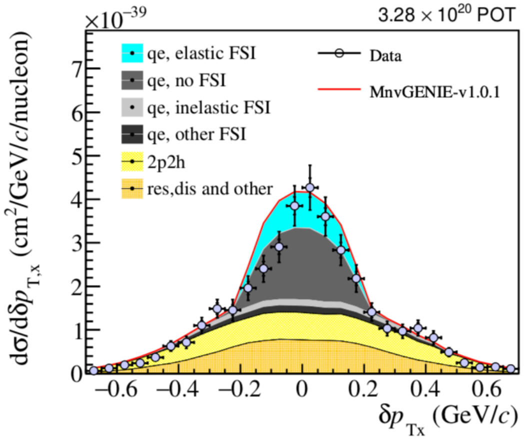


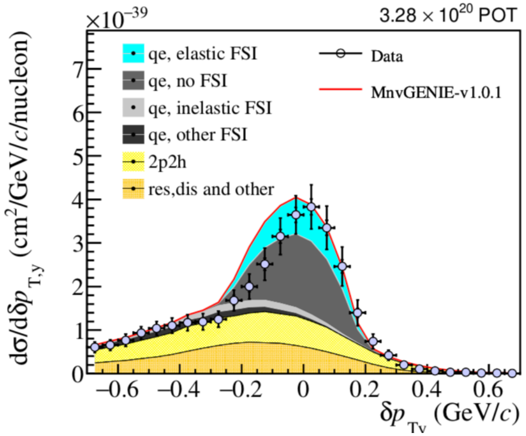
Transverse Variables to see inside nucleus

- If you can measure the momentum and angle of both the proton and muon in an event with no mesons in the final state, there are lots of new lampposts to look under:

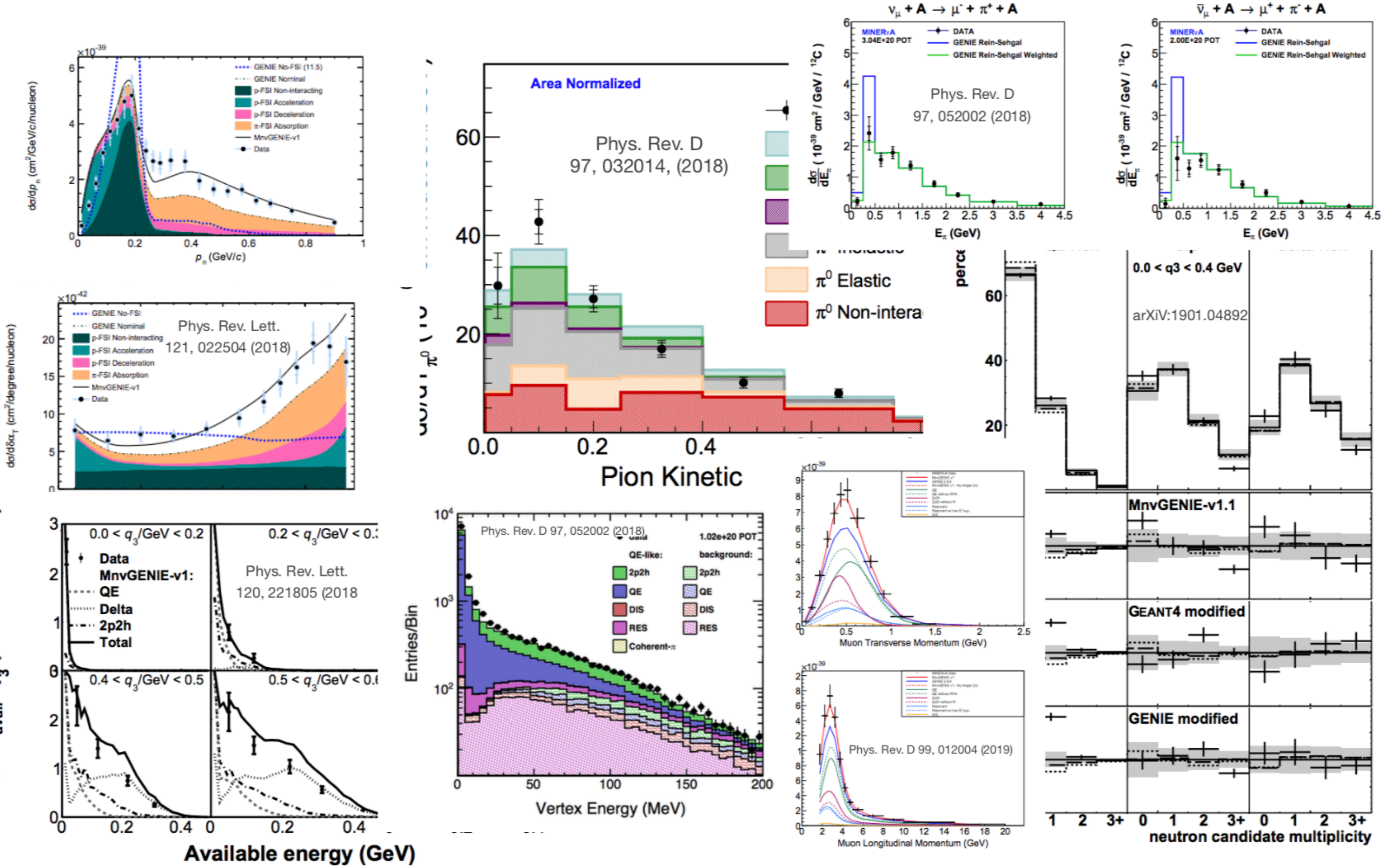


PhysRevD.101.092001





Recent MINERvA results



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- Important to have lots of statistics, fine grained detector, dedicated team trying to look at neutrino interactions in a new way…From L. Fields, Fermilab User’s Meeting 2019