Precision neutrino oscillation physics with DUNE

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Tata Institute of Fundamental Research
ASET colloquium
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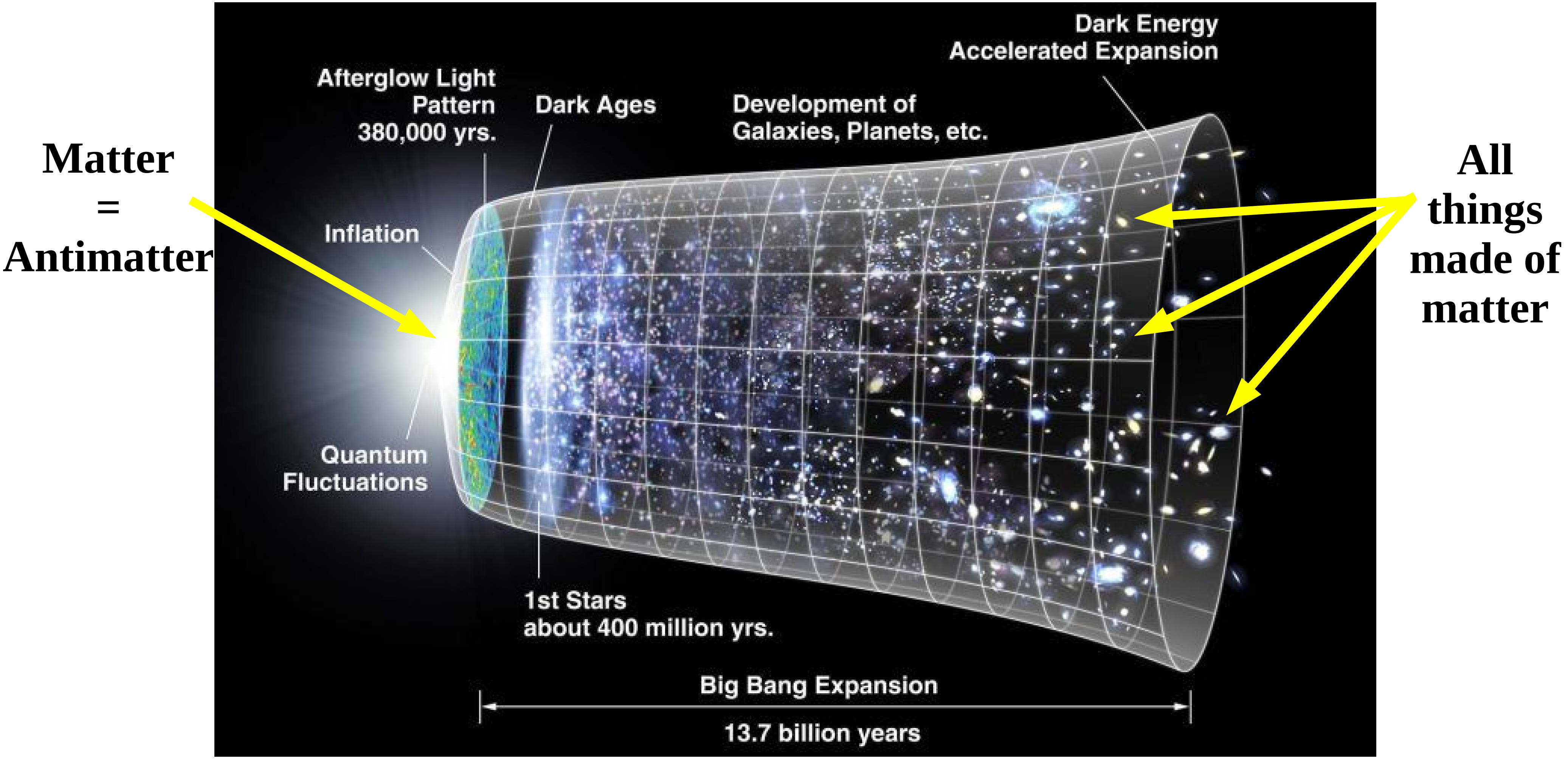
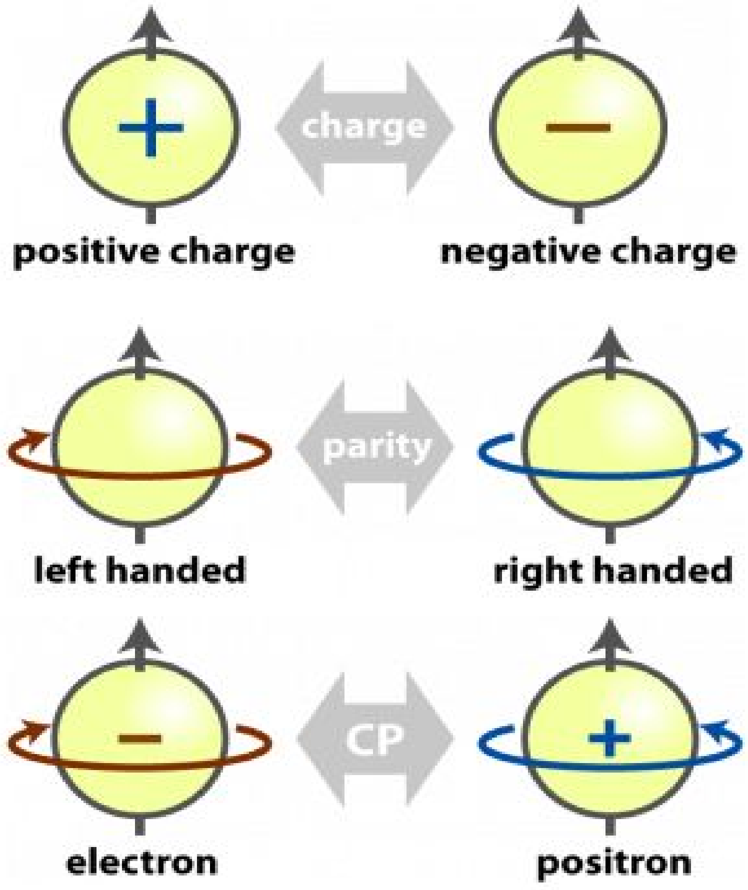
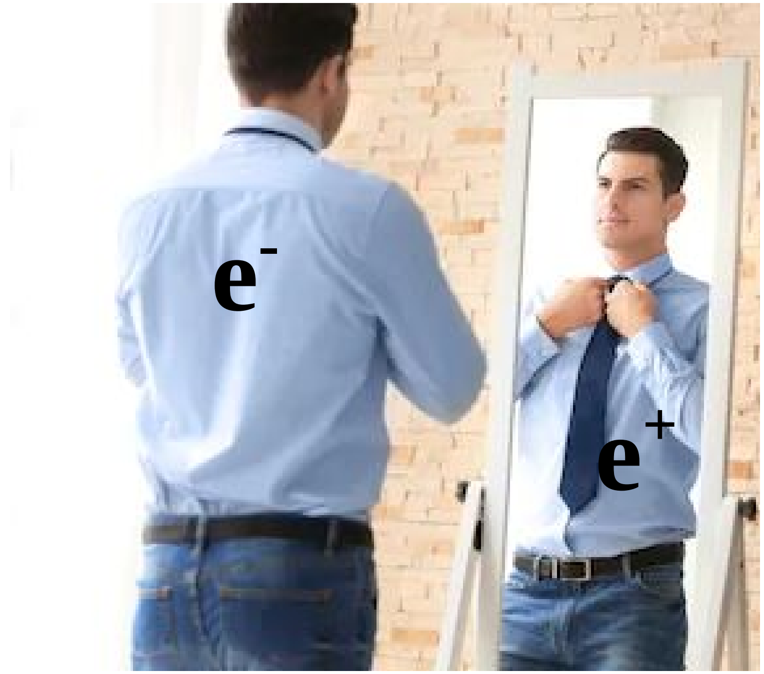
Big picture question:
What happened to the antimatter?



CP symmetry must be violated for matter-antimatter asymmetry



- Charge-parity "CP" symmetry = physics invariant for particle ↔ antiparticle + mirror image transformation



Where is the CP violation to explain the imbalanced universe?

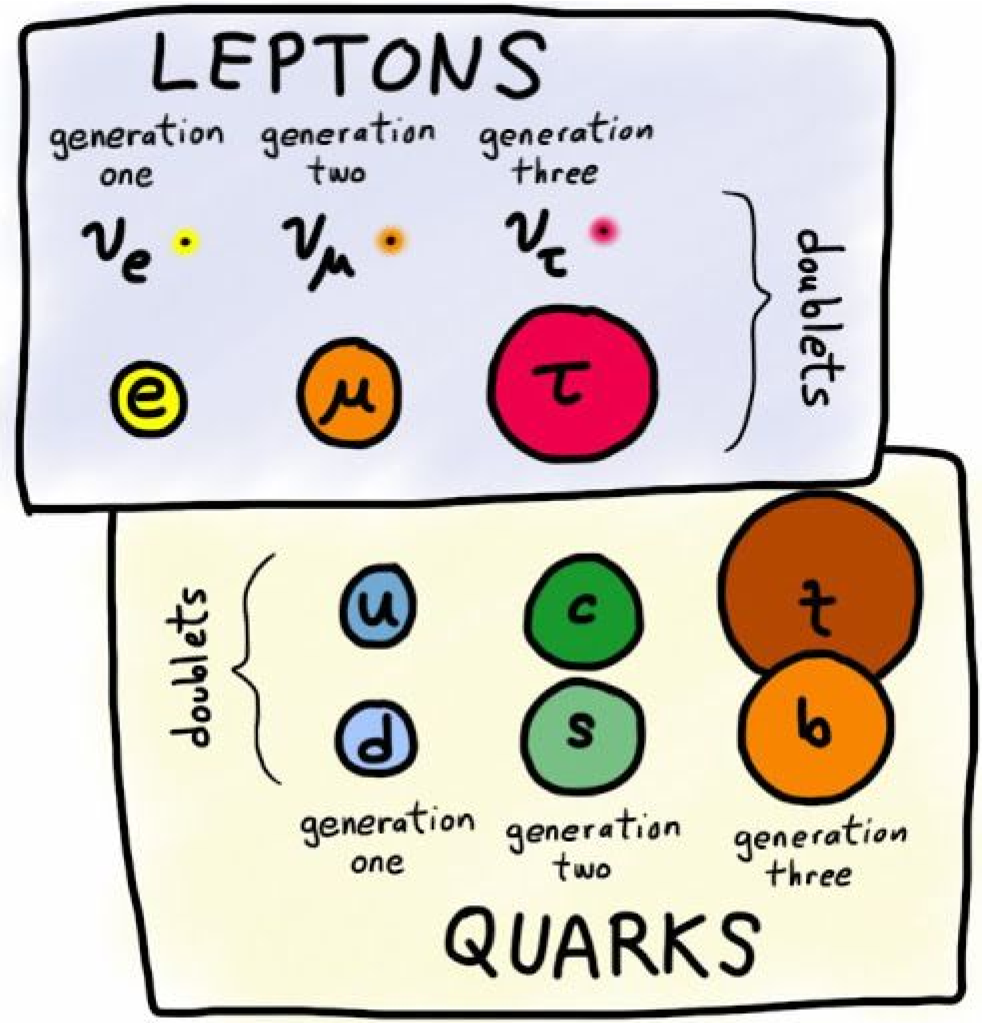
- CP violation has been observed in the quark sector, but it is far too small to explain the asymmetry
- If neutrinos violate CP, they could be responsible for the asymmetry
- If neutrinos do not violate CP, it is a strong indication of some new physics where the CP violation is hiding

Outline

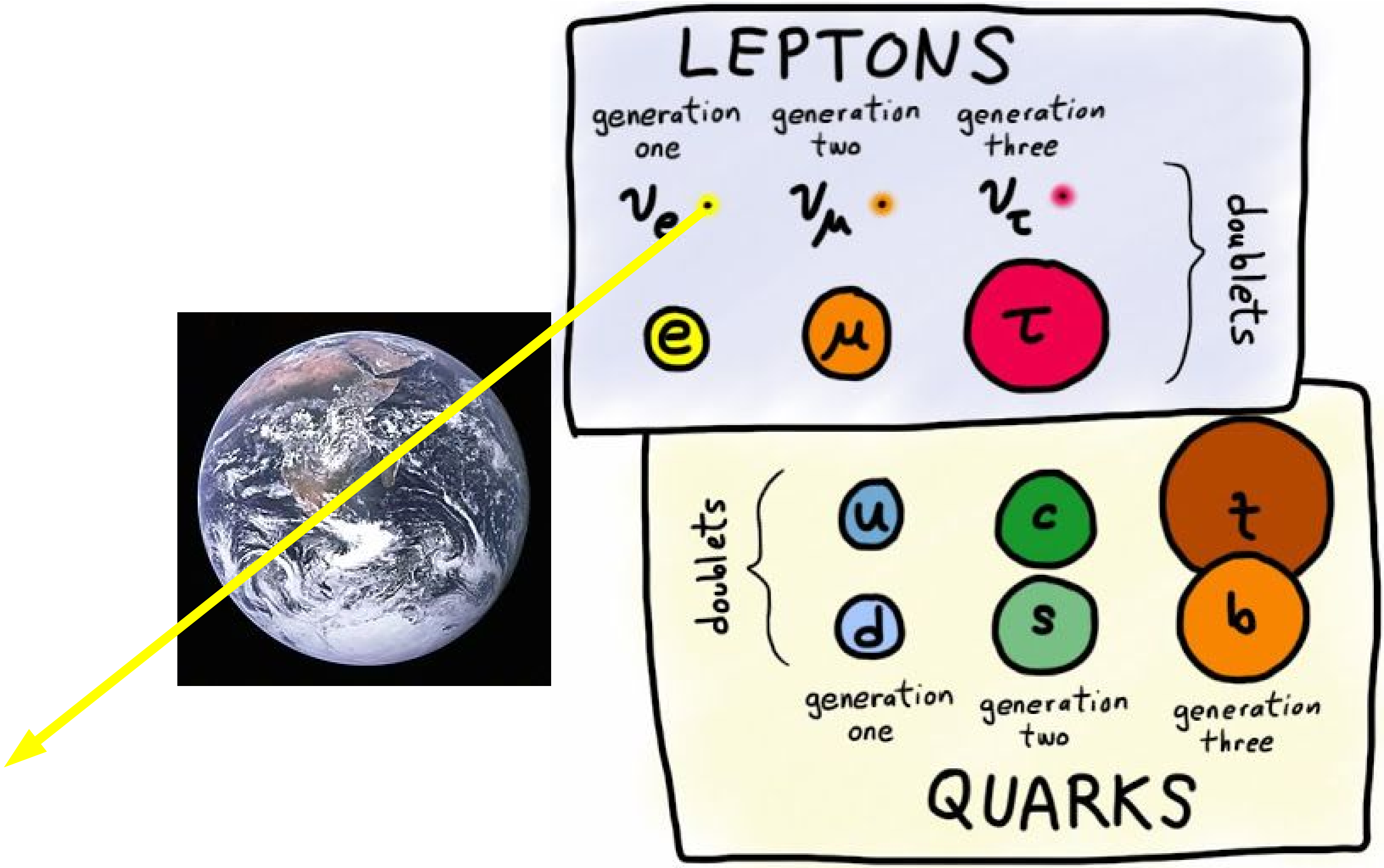
- Neutrinos & neutrino oscillations
  - What we know and how we know it
  - The missing pieces, including CP violation
  - How we measure neutrino oscillations and why it's hard
- The Deep Underground Neutrino Experiment (DUNE)
  - Precision neutrino oscillation physics

Neutrinos are neutral, weakly-interacting leptons

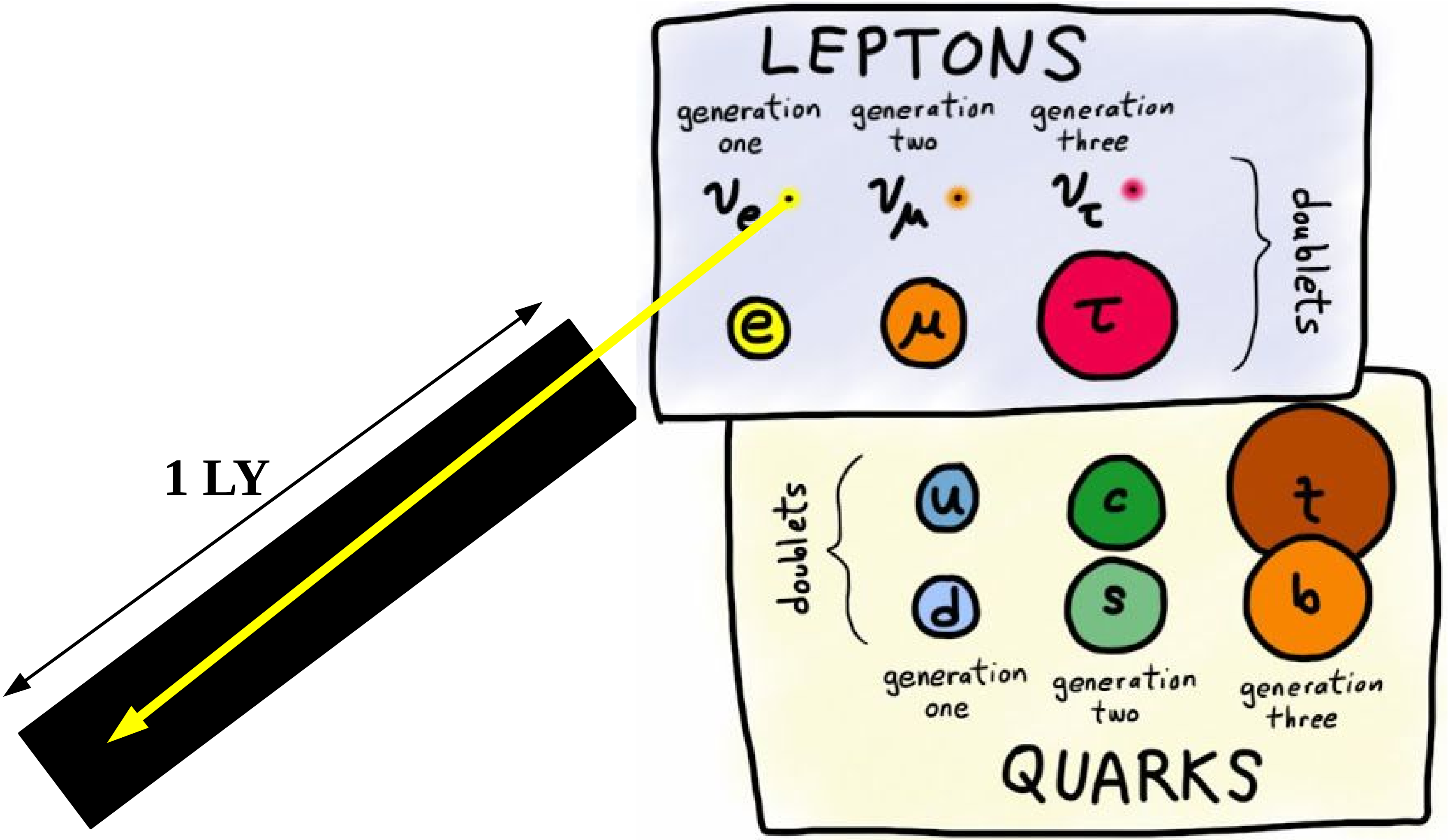
- Neutrinos have no electric charge
  - No strong or electromagnetic forces – only weak interactions
  - Very difficult to study neutrinos – they do not interact with detectors
- Neutrinos have (almost) no mass



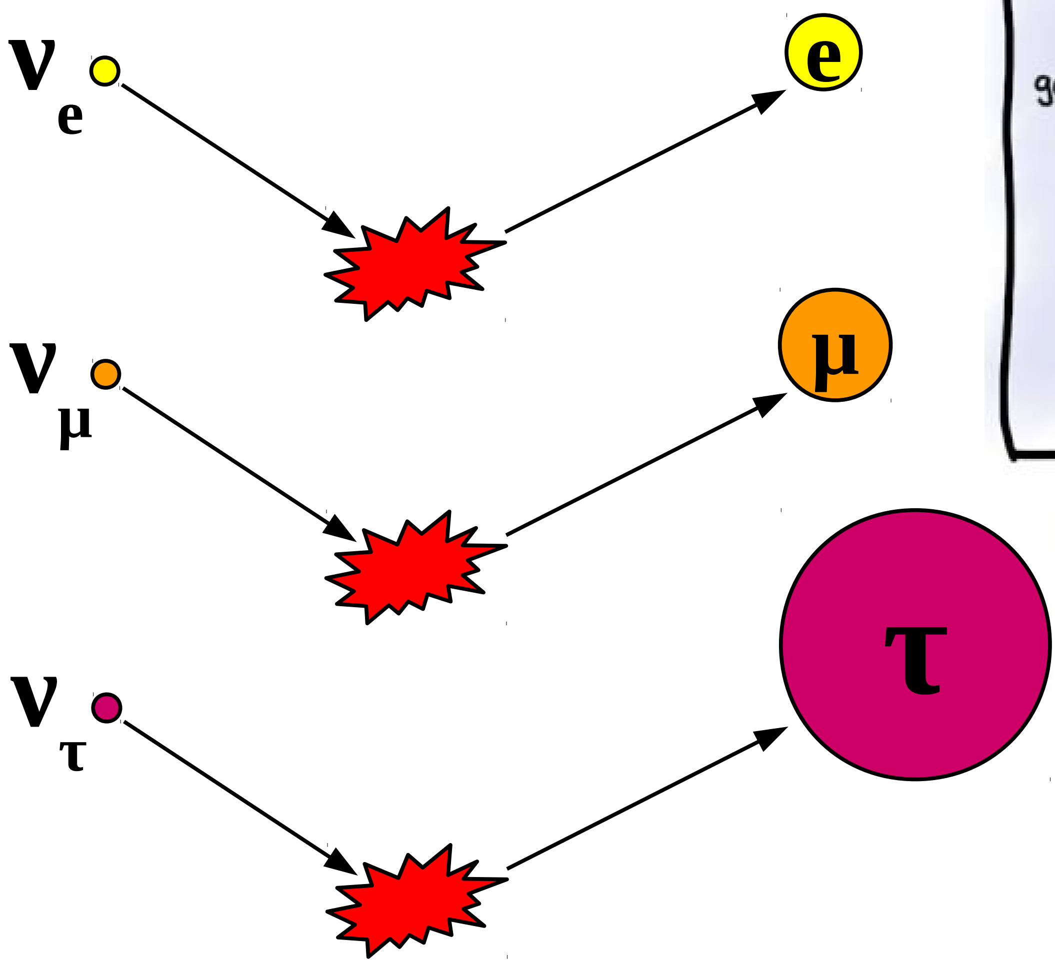
Neutrinos interactions are *weak*

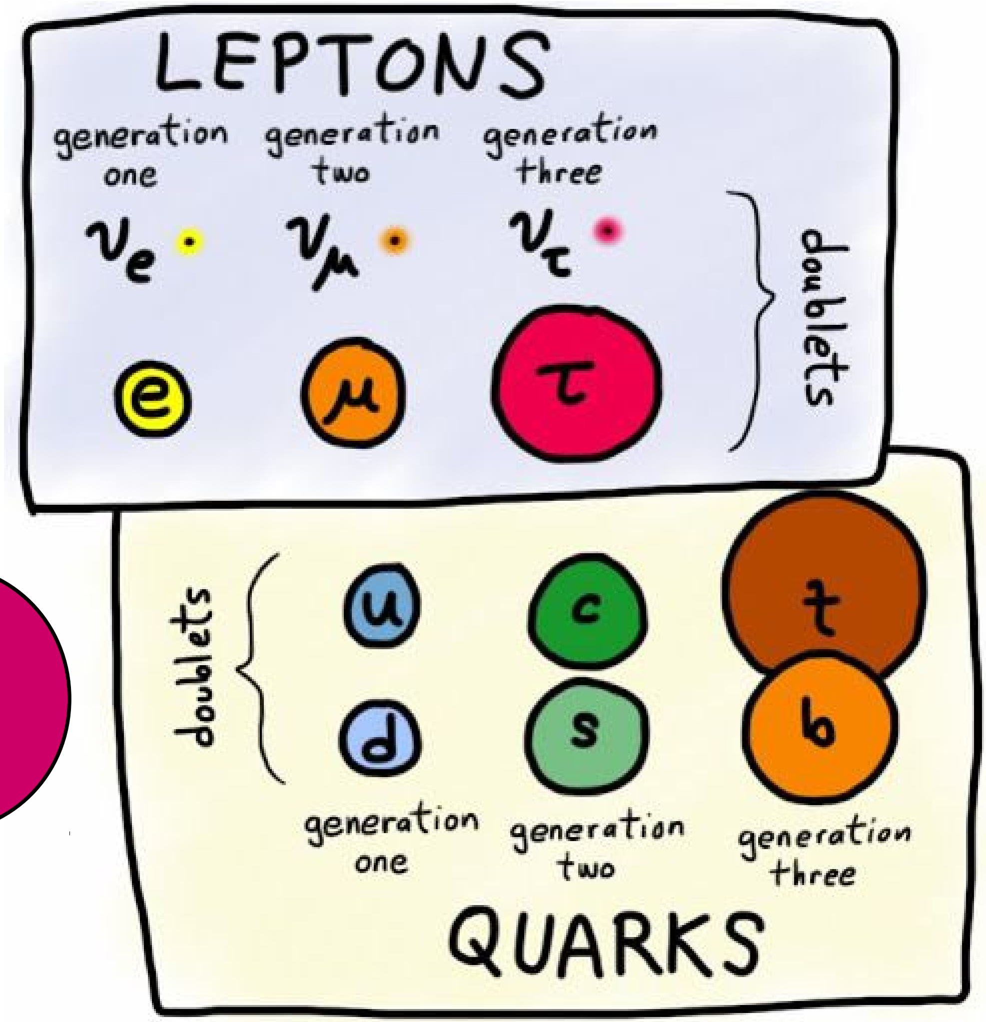


Neutrinos interactions are *weak*

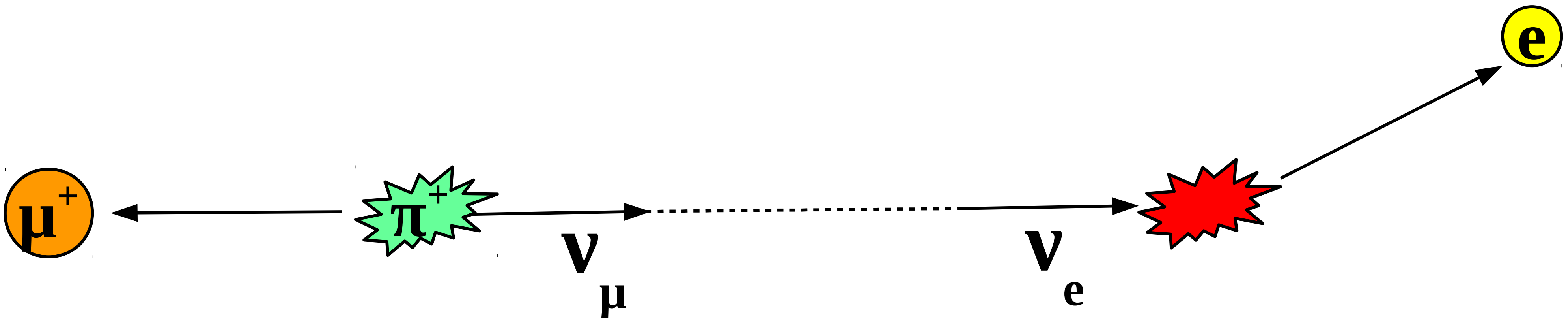


Neutrinos come in three flavors, corresponding to charged leptons

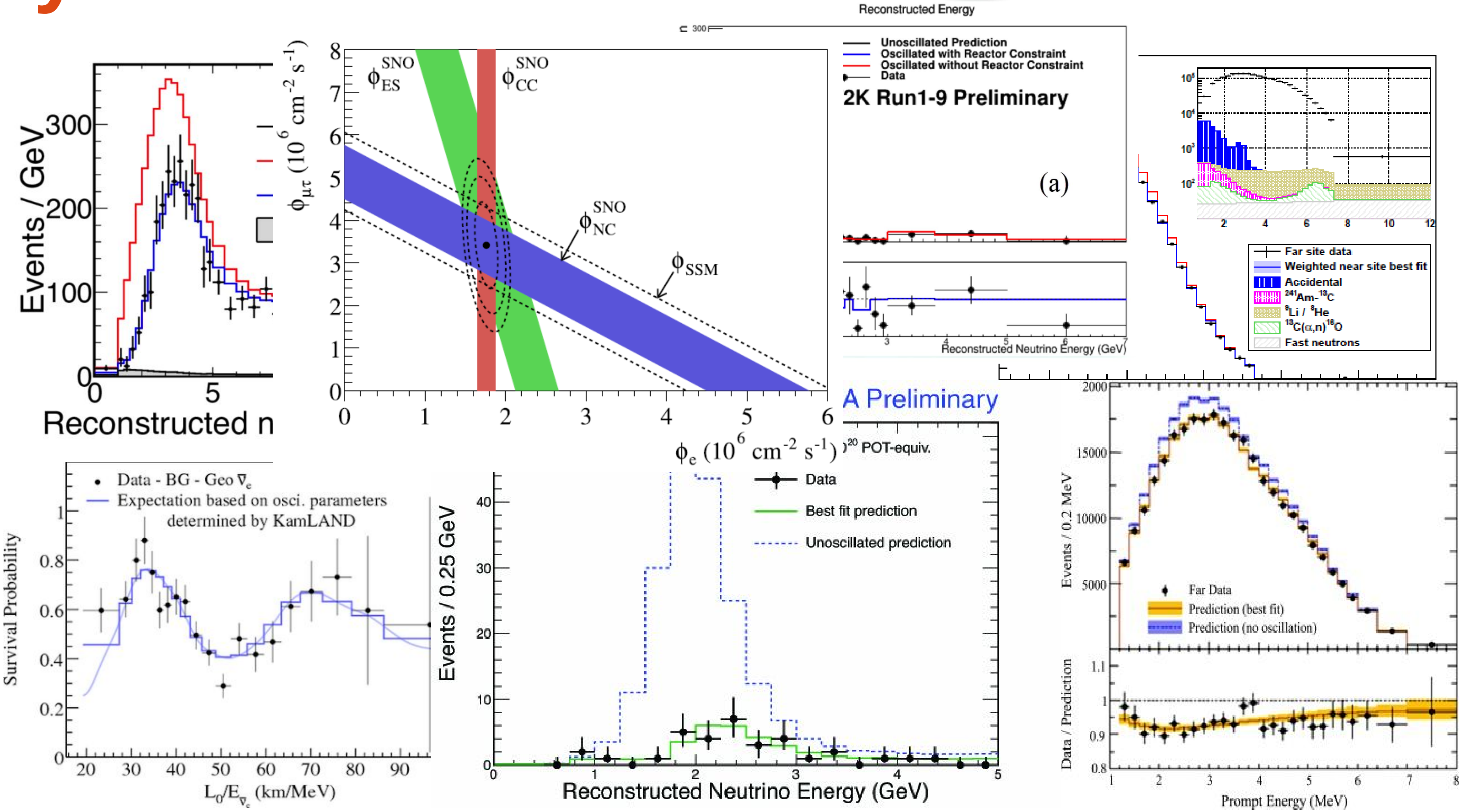




Neutrino "oscillation"



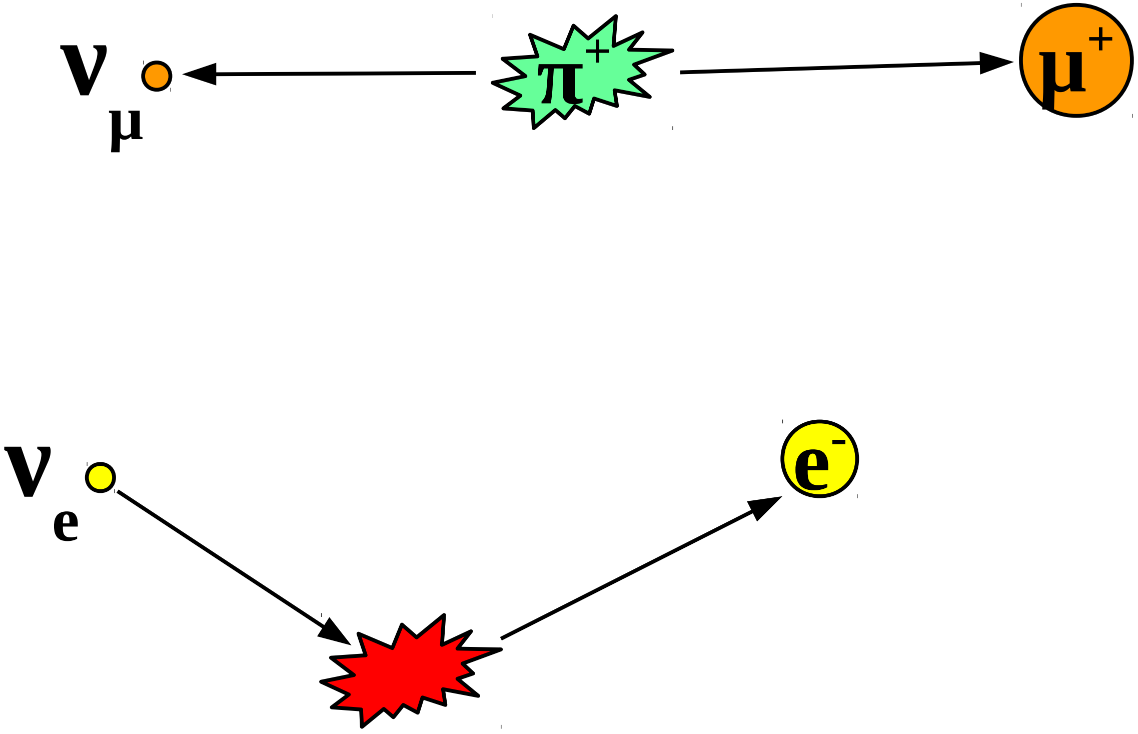
Many experiments over the past 20 years have measured ν oscillations



Neutrinos are born (and die) in states of definite flavor

Flavor eigenstates

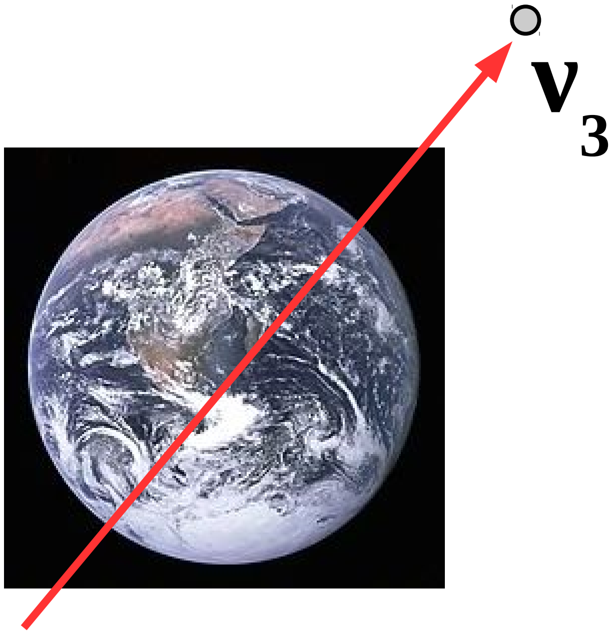
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$



Neutrinos live in states of definite mass

Flavor eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$



Mass eigenstates

$$\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

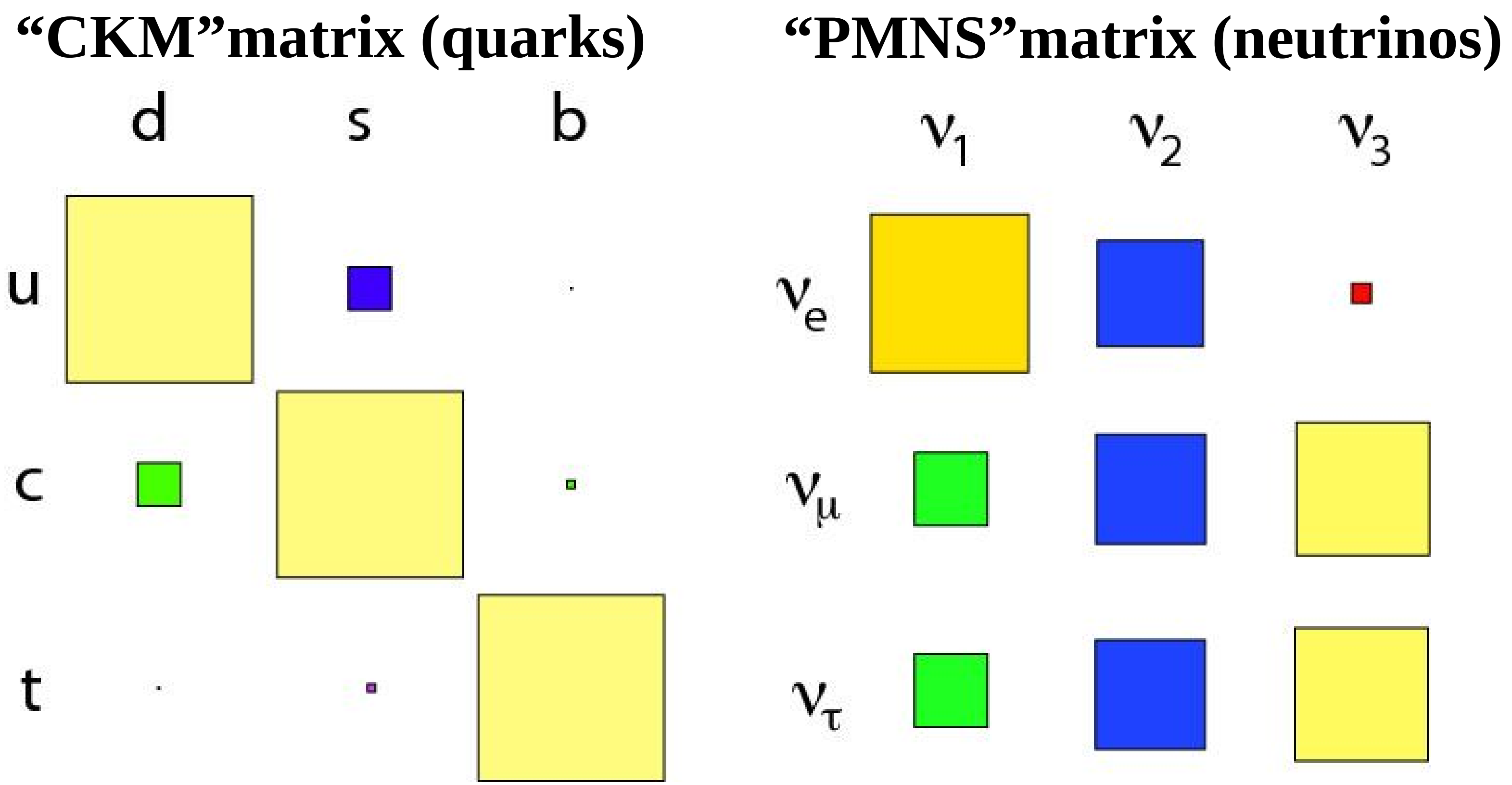
Neutrino oscillation requires mixing and mass differences

Flavor eigenstates Mass eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}_{U_{\mathrm{PMNS}}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

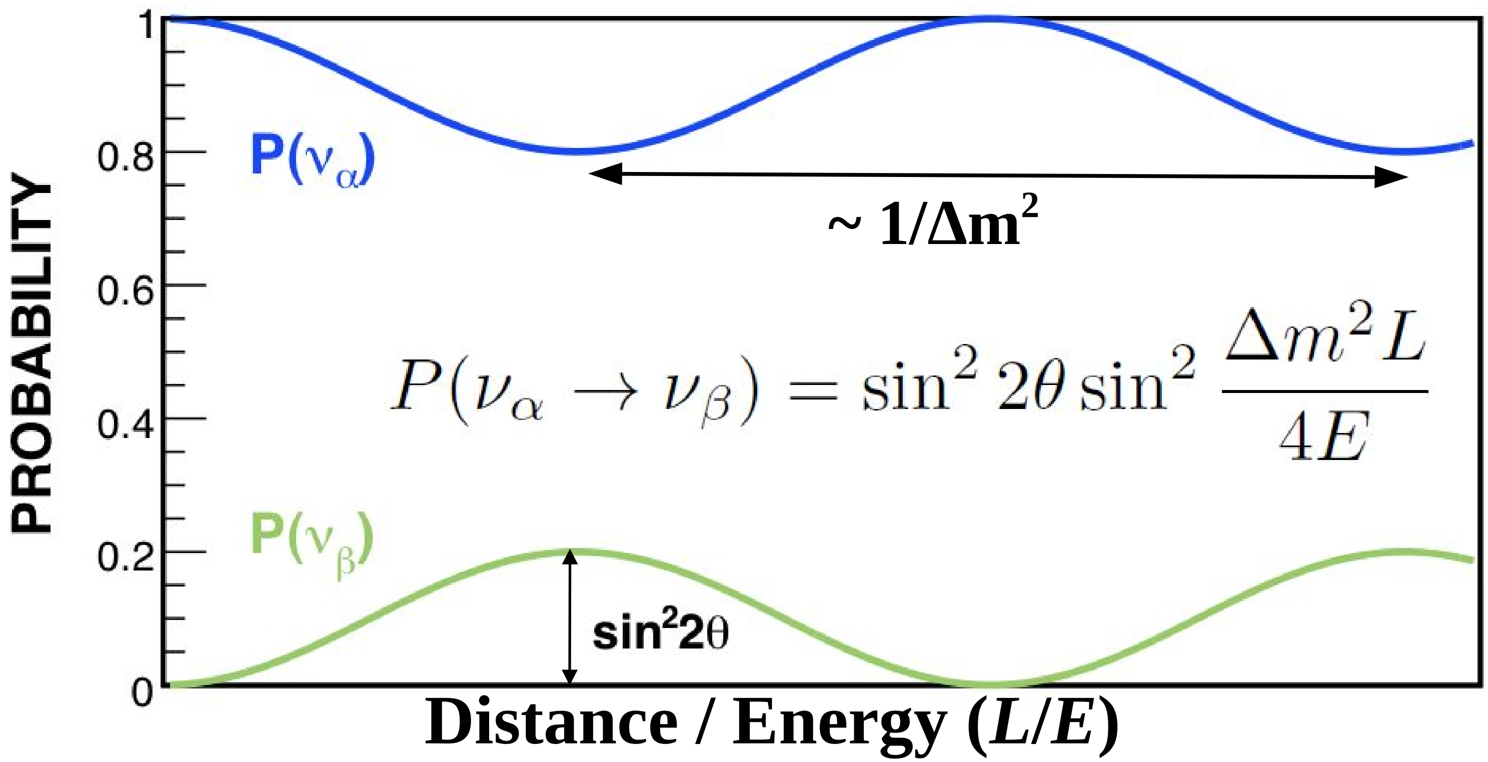
- Observation of neutrino oscillations implies that
  - U_{PMNS} is not diagonal
  - The masses of ν_1, ν_2, ν_3 are not equal

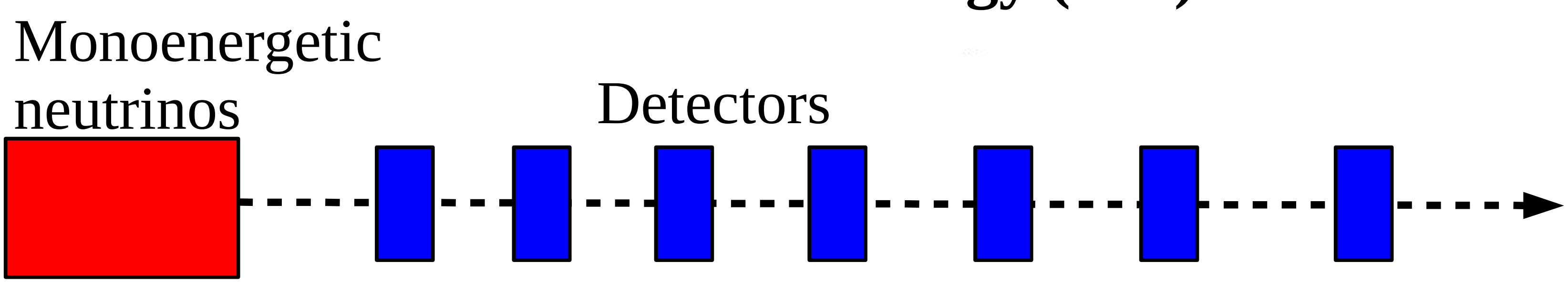
Quarks mix, but neutrinos mix more



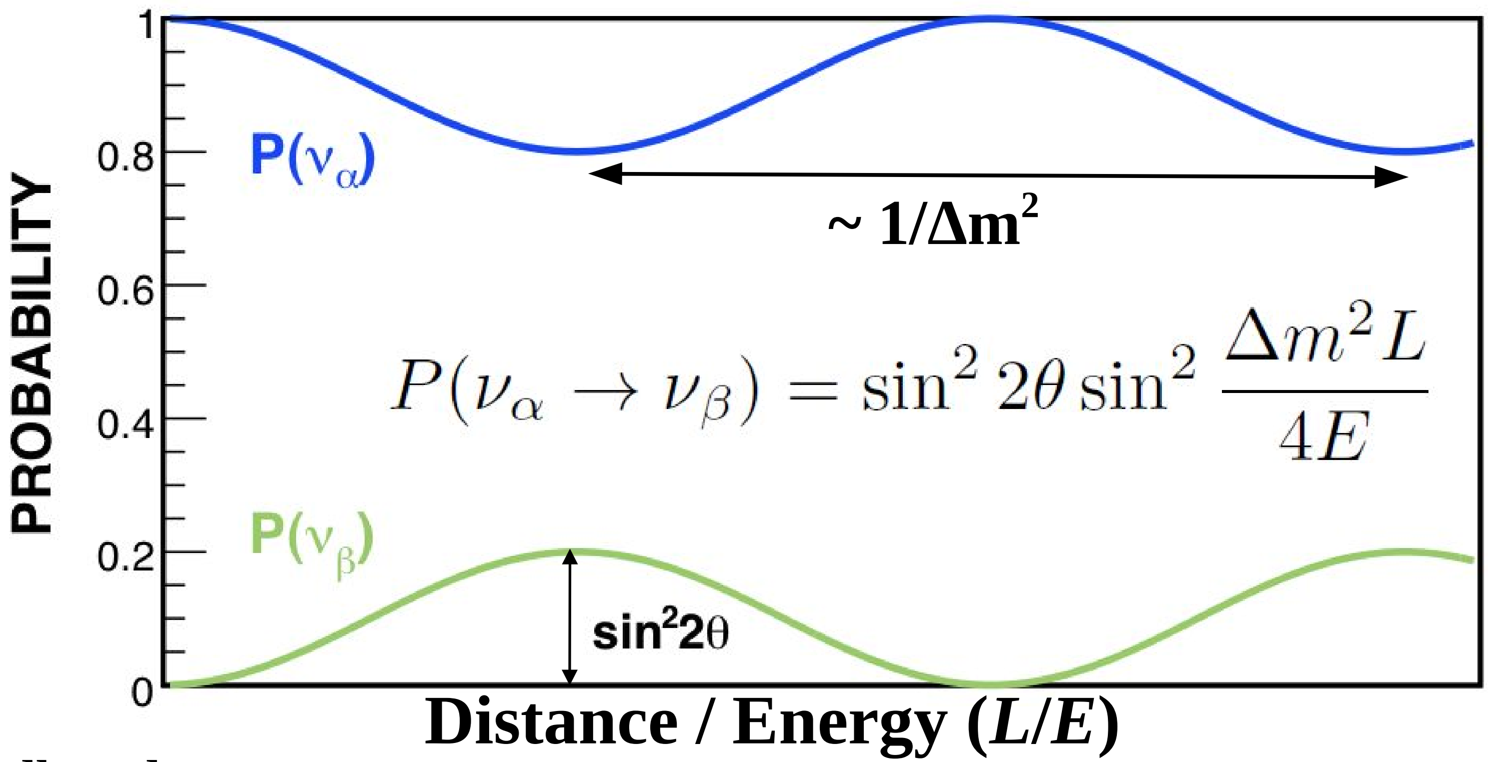
- Mixing is not unique to neutrinos – quarks mix too!
- We have measured these matrices, and we find that neutrinos mix a lot more than quarks

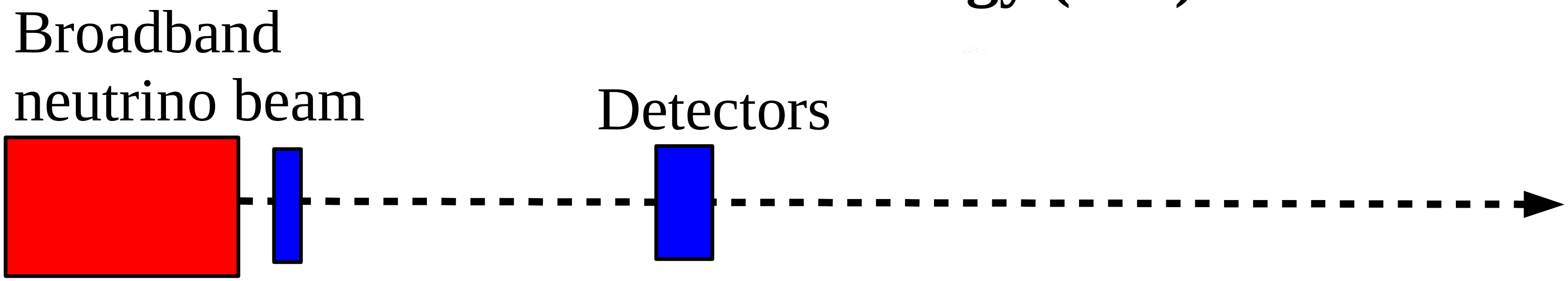
Measuring neutrino oscillations: probability vs. L/E





Measuring neutrino oscillations: probability vs. L/E





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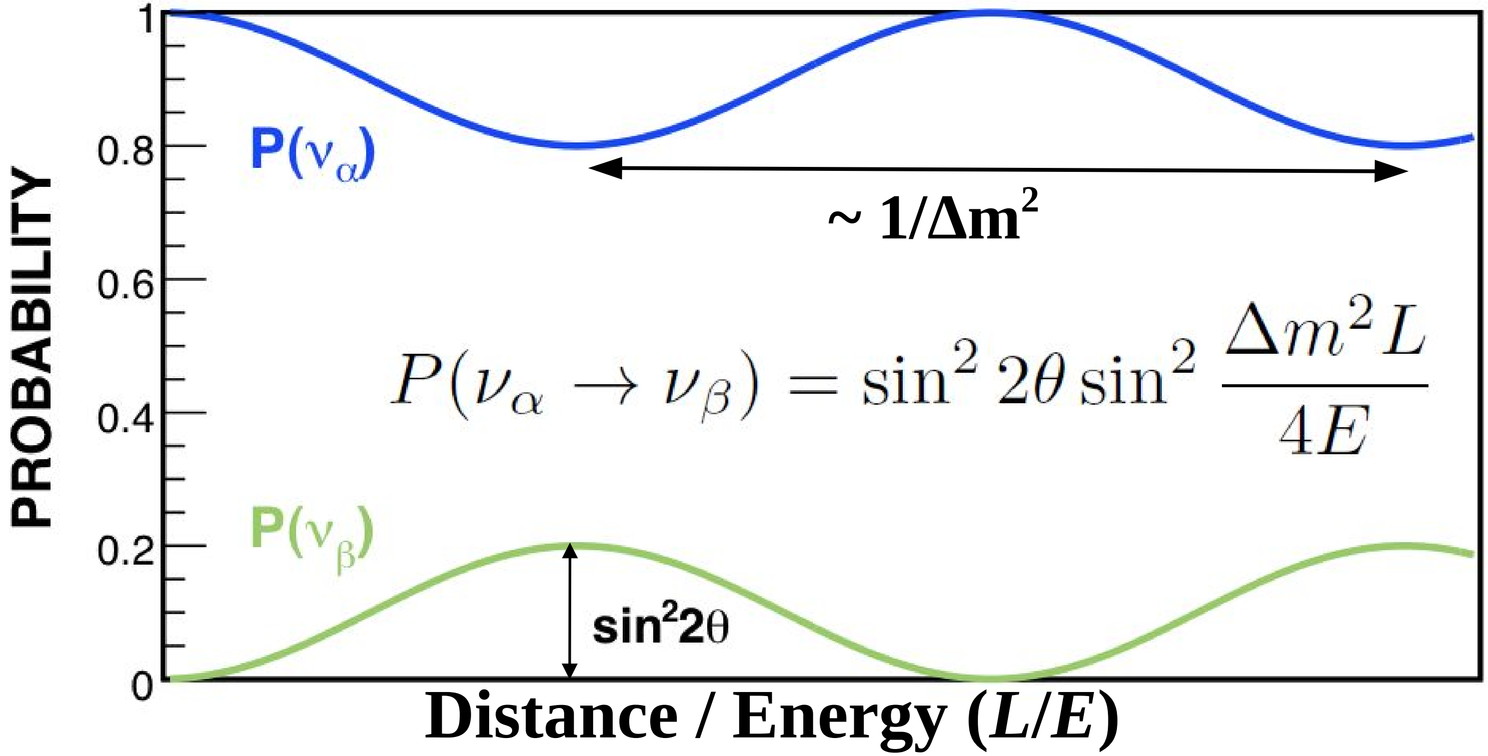
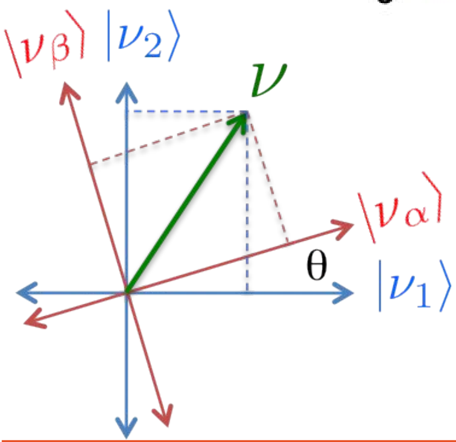
Mixing matrix can be written in terms of these "angles"



$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E}$$



$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

flavor states mass states

The PMNS matrix can be parameterized in terms of angles

Flavor eigenstates ... Mass eigenstates

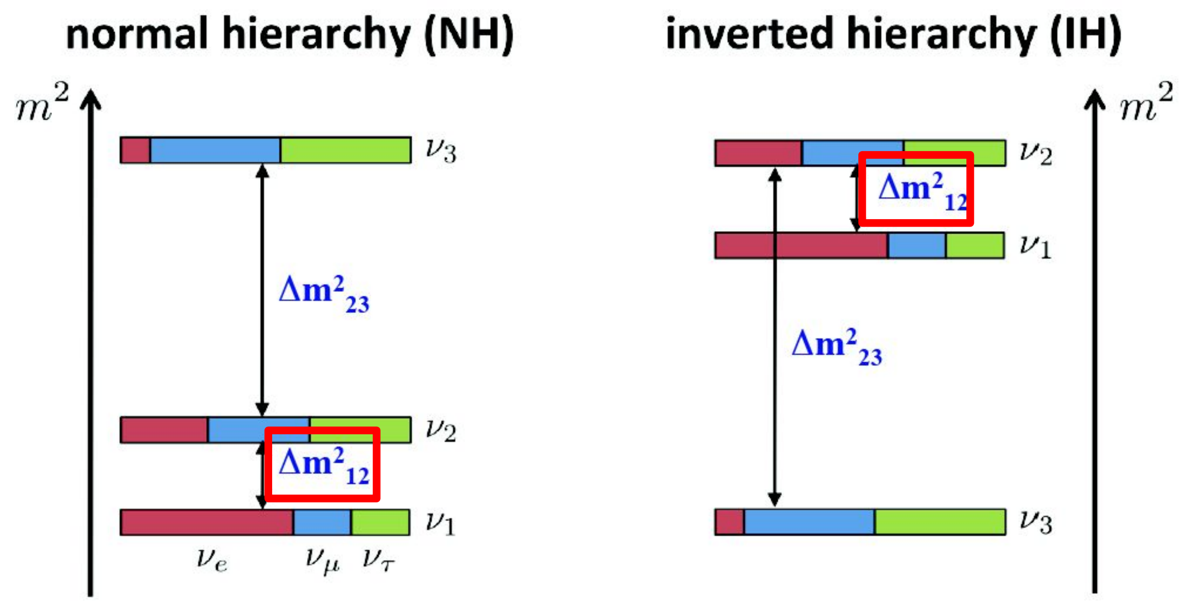
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}_{U_{\mathrm{PMNS}}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

"atmospheric" ... $c_{ij} = \cos\theta_{ij}$ ... "solar"

$$U_{\mathrm{PMNS}} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\mathrm{I}} \underbrace{\begin{pmatrix} c_{13} & 0 & e^{-i\delta_{\mathrm{CP}}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{\mathrm{CP}}} s_{13} & 0 & c_{13} \end{pmatrix}}_{\mathrm{II}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\mathrm{III}}$$

What we know

Parameter is measured by:
Solar/reactor

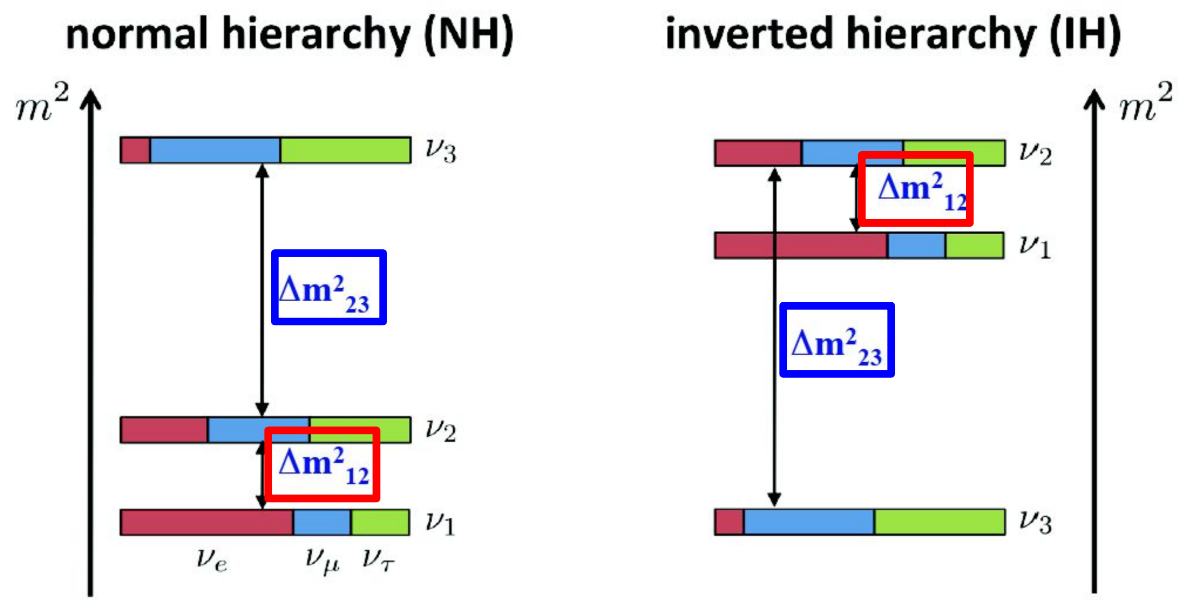


"atmospheric" $c_{ij} = \cos\theta_{ij}$ "solar"

$$U_{\rm PMNS} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\rm I} \underbrace{\begin{pmatrix} c_{13} & 0 & e^{-i\delta_{\rm CP}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{\rm CP}} s_{13} & 0 & c_{13} \end{pmatrix}}_{\rm II} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\rm III}$$

What we know

Parameter is measured by:
Solar/reactor
Atmospheric/accelerator



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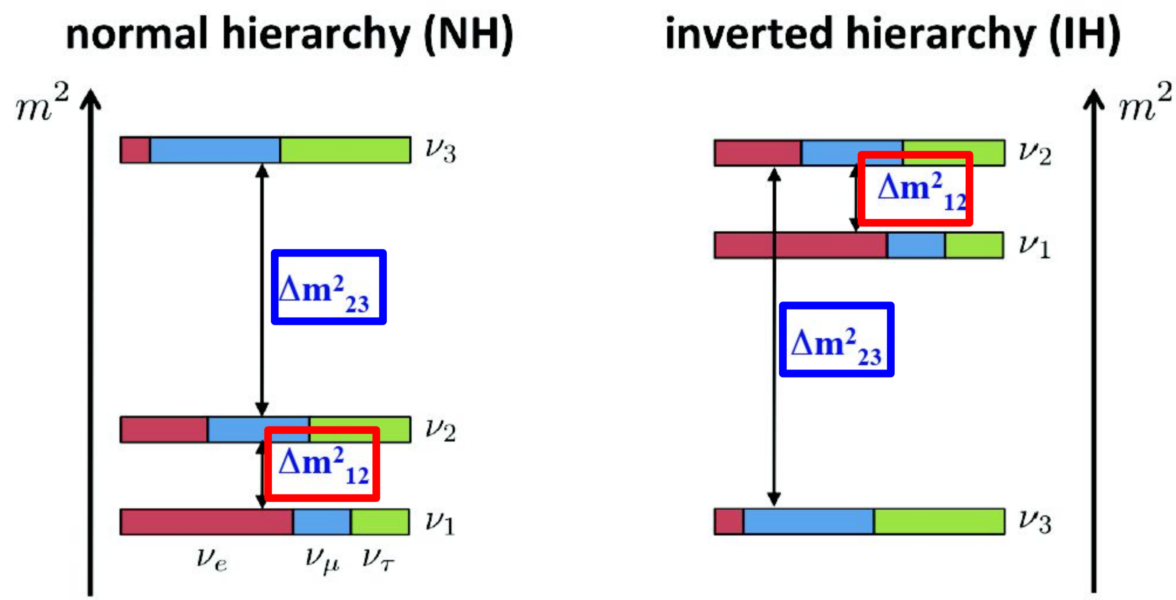
$$U_{\text{PMNS}} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{I}} \underbrace{\begin{pmatrix} c_{13} & 0 & e^{-i\delta_{\text{CP}}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{\text{CP}}} s_{13} & 0 & c_{13} \end{pmatrix}}_{\text{II}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{III}}$$

What we know

Parameter is measured by:
Solar/reactor
Atmospheric/accelerator
Reactor/accelerator



"atmospheric" $c_{ij} = \cos\theta_{ij}$ "solar"

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Unknown: Do neutrinos violate CP symmetry? Is $\delta_{CP} = 0$?

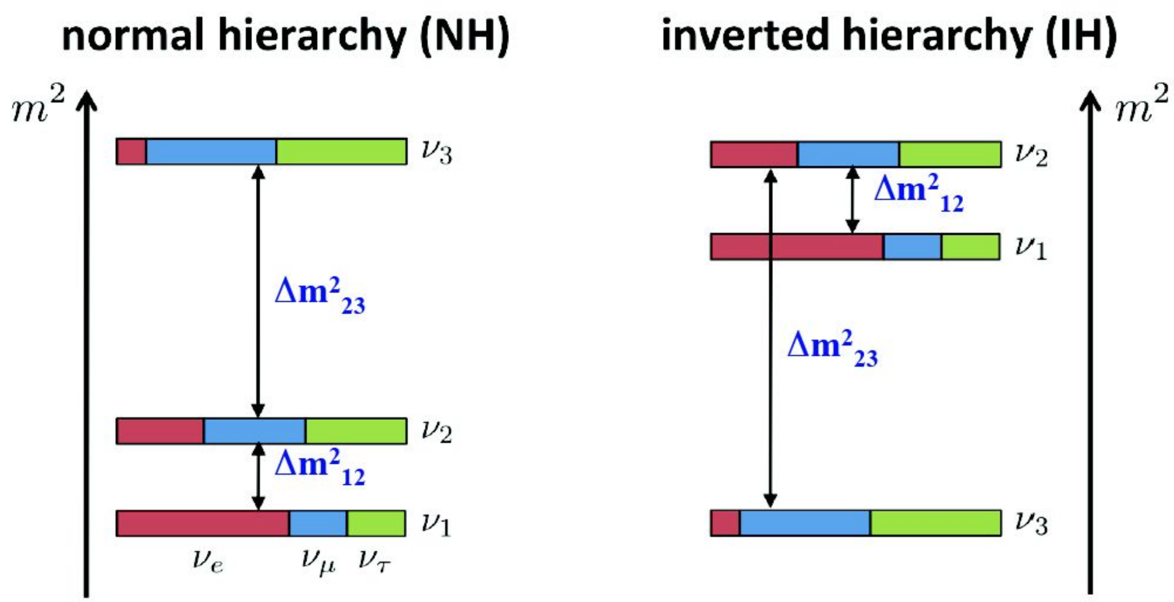
- CP violation is a crucial ingredient in generating the matter-antimatter asymmetry observed in the universe
- If neutrinos violate CP, they could be responsible for the matter-antimatter asymmetry
- If not, that means there is probably some new physics responsible for the matter-antimatter asymmetry

"atmospheric" $c_{ij} = \cos\theta_{ij}$ "solar"

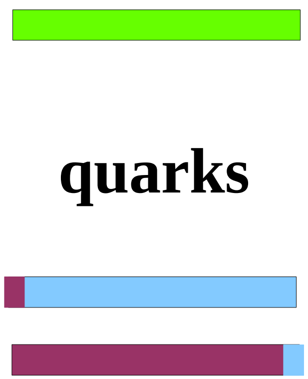
$$U_{\mathrm{PMNS}} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\mathrm{I}} \underbrace{\begin{pmatrix} c_{13} & 0 & e^{-i\delta_{\mathrm{CP}}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{\mathrm{CP}}} s_{13} & 0 & c_{13} \end{pmatrix}}_{\mathrm{II}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\mathrm{III}}$$

Unknown: What is the mass ordering? Is ν_3 heaviest or lightest?

- We know there is one very small mass difference and one (relatively) large one



- We don't know whether ν_3 is the lightest (normal ordering) or the heaviest (inverted ordering)
- Data in the last two years show a weak preference for the normal ordering



$P(\nu_\mu \rightarrow \nu_e)$ is sensitive to CP violation

$P(\nu_\mu \rightarrow \nu_e) \simeq$

what we can measure

$\cos(\Delta_{31} + \delta_{CP})$

what we want

Mass difference $\Delta_{ij} = \Delta m_{ij}^2 L / 4E_\nu$

- The oscillation probability for $\nu_\mu \rightarrow \nu_e$ depends on δ_{CP}

...And a lot of other stuff

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

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

Mass difference $\Delta_{ij} = \Delta m_{ij}^2 L/4E_\nu$

H. Nunokawa, S. J. Parke, and J. W. Valle, Prog.Part.Nucl.Phys., vol. 60 (2008)

- The oscillation probability for $\nu_\mu \to \nu_e$ depends on δ_{CP} – and all the other parameters!
- Measuring δ_{CP} requires precise knowledge of everything else

Mass ordering = sign of Δ31

$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2$$
$$+\sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{\Delta_{31}-aL}\Delta_{31}\frac{\sin(aL)}{aL}\Delta_{21}\cos(\Delta_{31}+\delta_{CP})$$
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Matter density $a = G_F N_e/\sqrt{2}$

Mass difference $\Delta_{ij} = \Delta m_{ij}^2 L/4E_\nu$

- Mass ordering and CP-violating phase are degenerate for baseline up to ~1200 km → want very long baseline
- Matter matters: ν_e feel an additional potential due to electrons in the earth

Matter and δ flip sign for $\bar{\nu}_\mu$

$$P(\bar{\nu}_\mu \to \bar{\nu}_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}+aL)}{(\Delta_{31}+aL)^2}\Delta_{31}^2$$
$$+\sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}+aL)}{\Delta_{31}+aL}\Delta_{31}\frac{\sin(aL)}{aL}\Delta_{21}\cos(\Delta_{31}-\delta_{CP})$$
$$+\cos^2\theta_{23}\sin^2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2$$

H. Nunokawa, S. J. Parke, and J. W. Valle, Prog.Part.Nucl.Phys., vol. 60 (2008)

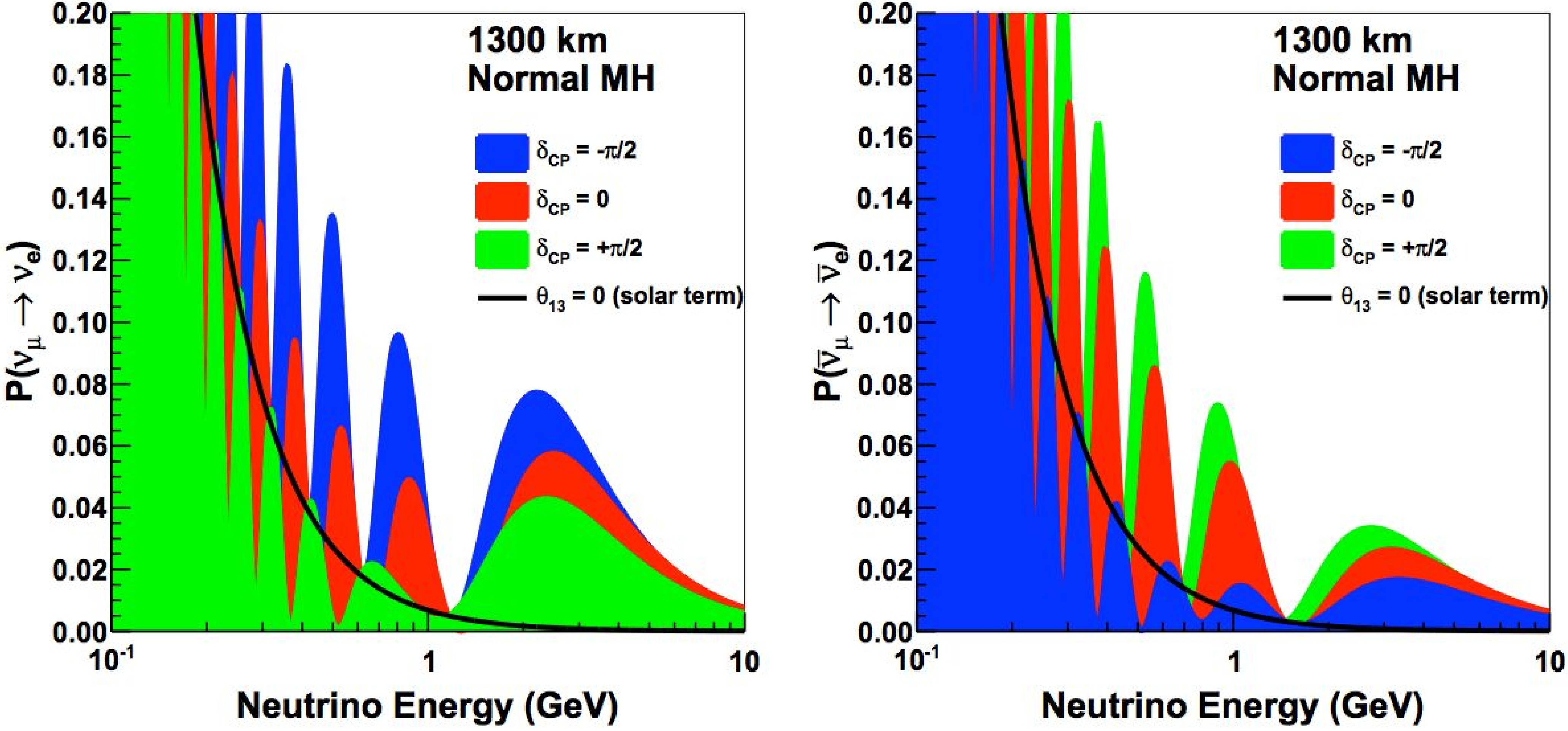
Matter density $a = G_F N_e/\sqrt{2}$

Mass difference $\Delta_{ij} = \Delta m_{ij}^2 L/4E_\nu$

- Matter terms and CP-violating term flip sign for antineutrino oscillations
- Incredibly valuable to be able to measure both $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$

Non-zero δ_{CP} changes oscillation probabilities for ν and $\bar{\nu}$

Neutrino | **Antineutrino**



Experimental requirements to measure δ_{CP}

Intense, broadband neutrino beam

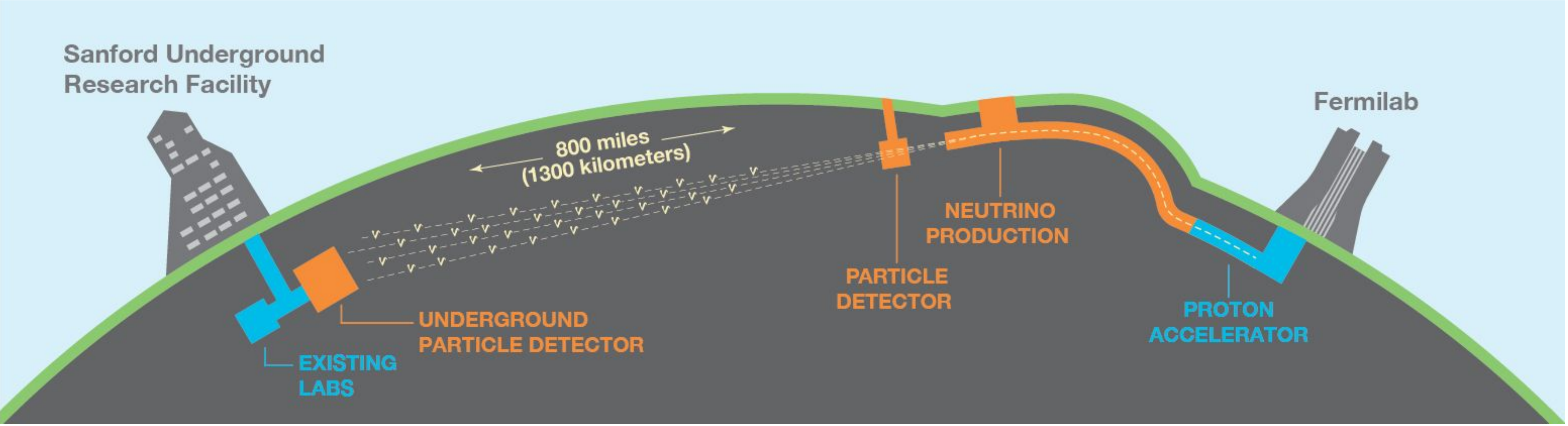
Switchable between ν_μ and $\bar{\nu}_\mu$

Huge detector at L > 1200km

Separate μ from e

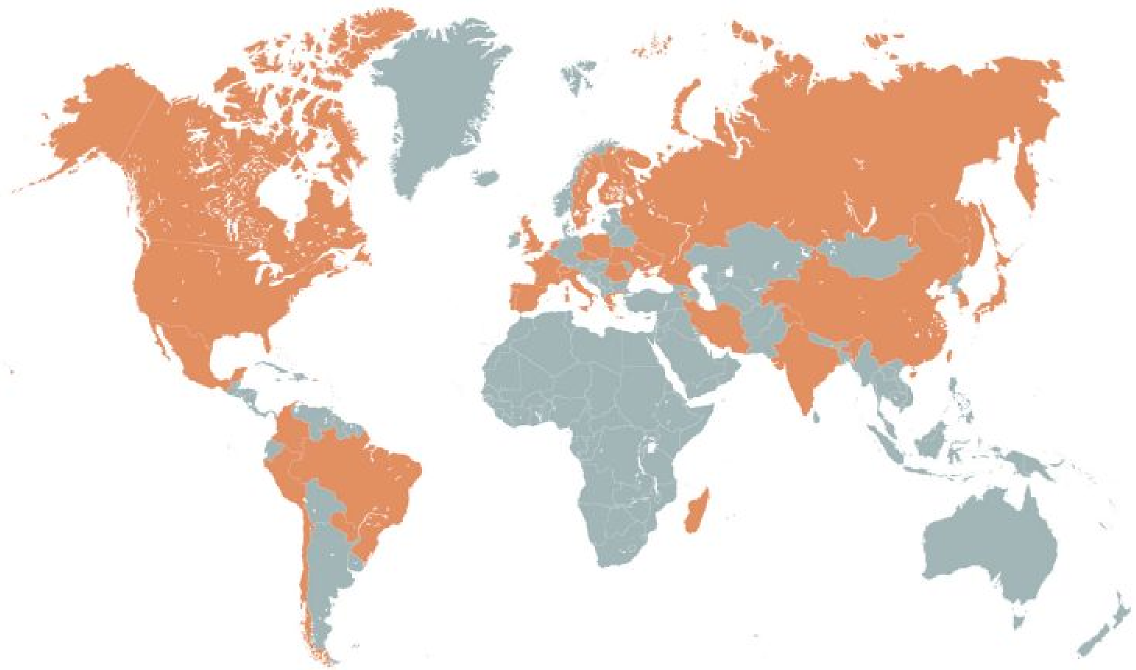
Precise measurement of neutrino energy

DEEP UNDERGROUND NEUTRINO EXPERIMENT



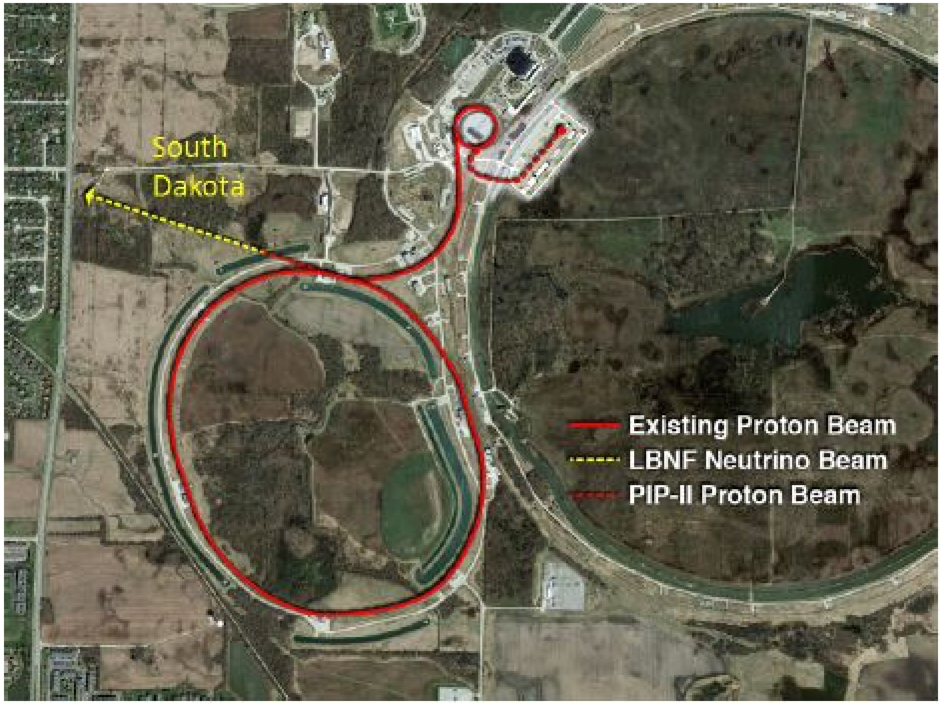
- Intense neutrino source from upgraded Fermilab accelerator, switchable between neutrino and antineutrino beams
- 70,000 ton far detector in Lead, South Dakota, 1300 km from source
- Highly capable near detector facility at Fermilab, 500 m from source
- Currently digging holes, fully operational in 2026

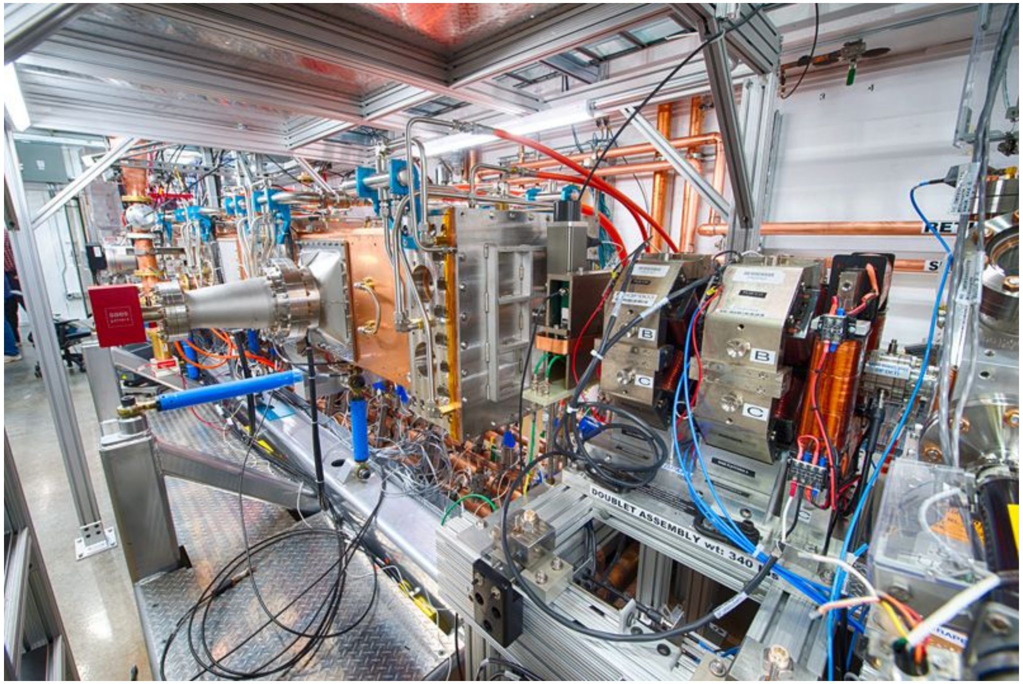
The DUNE international collaboration



- 1132 collaborators from 188 institutions in 31 countries (+CERN)

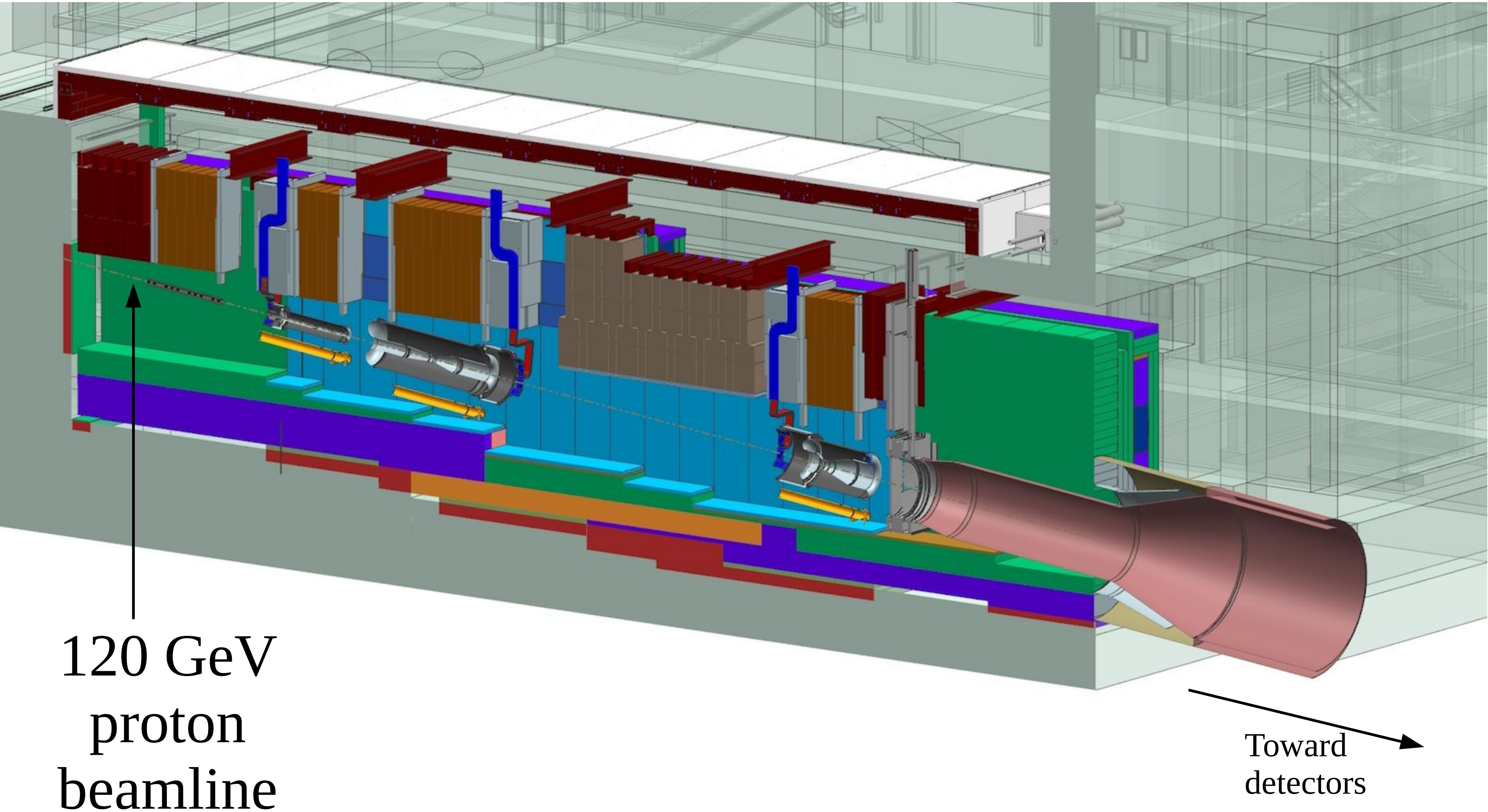
Making neutrinos starts with an upgraded accelerator



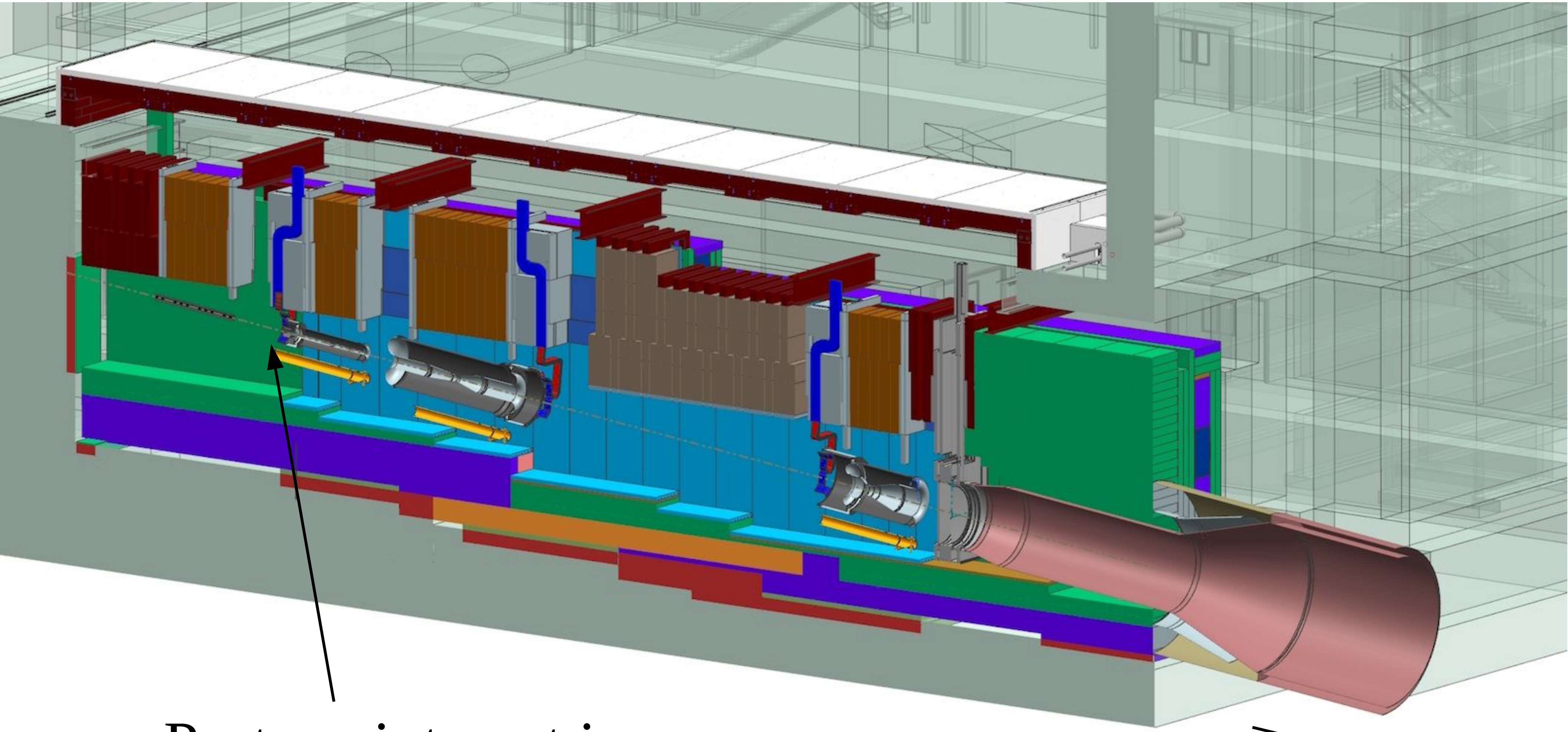


- Upgraded Fermilab accelerator to produce proton beam with intensity up to 2.4 MW
- New magnets being designed and built in India at BARC, IUAC, RRCAT, and VECC

Making neutrinos



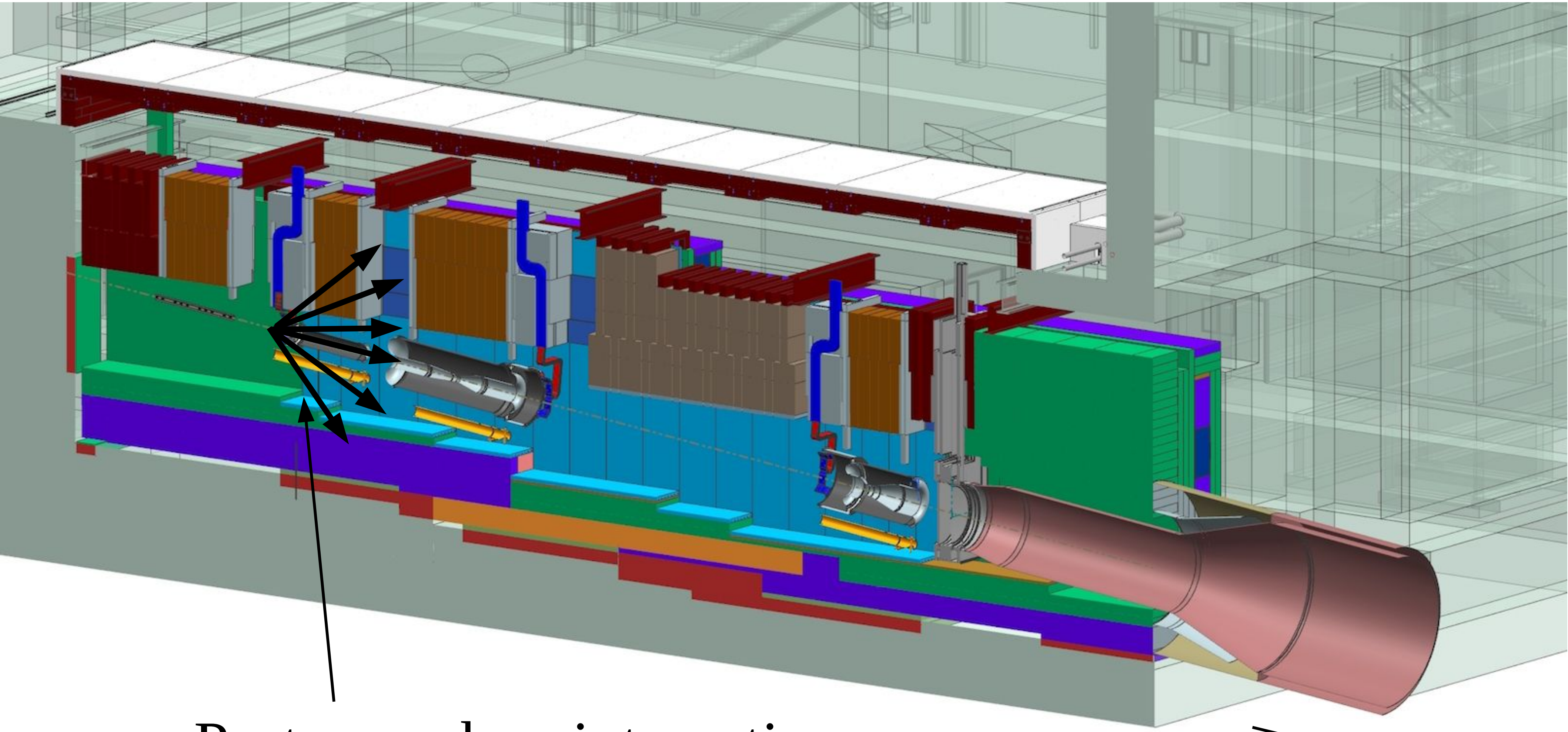
Making neutrinos



Protons interact in a graphite target

Toward detectors

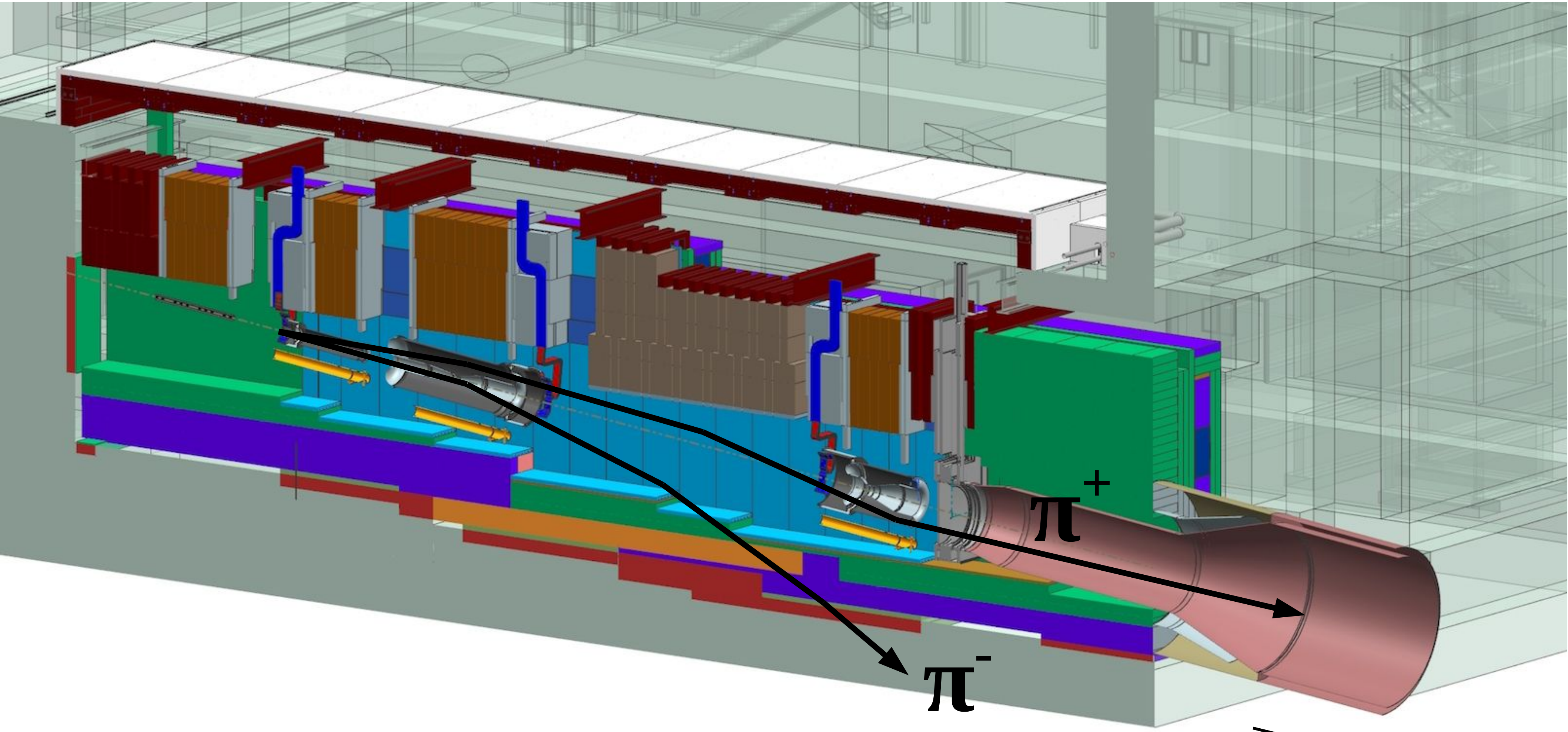
Making neutrinos



Proton-carbon interactions produce charged pions & kaons

Toward detectors

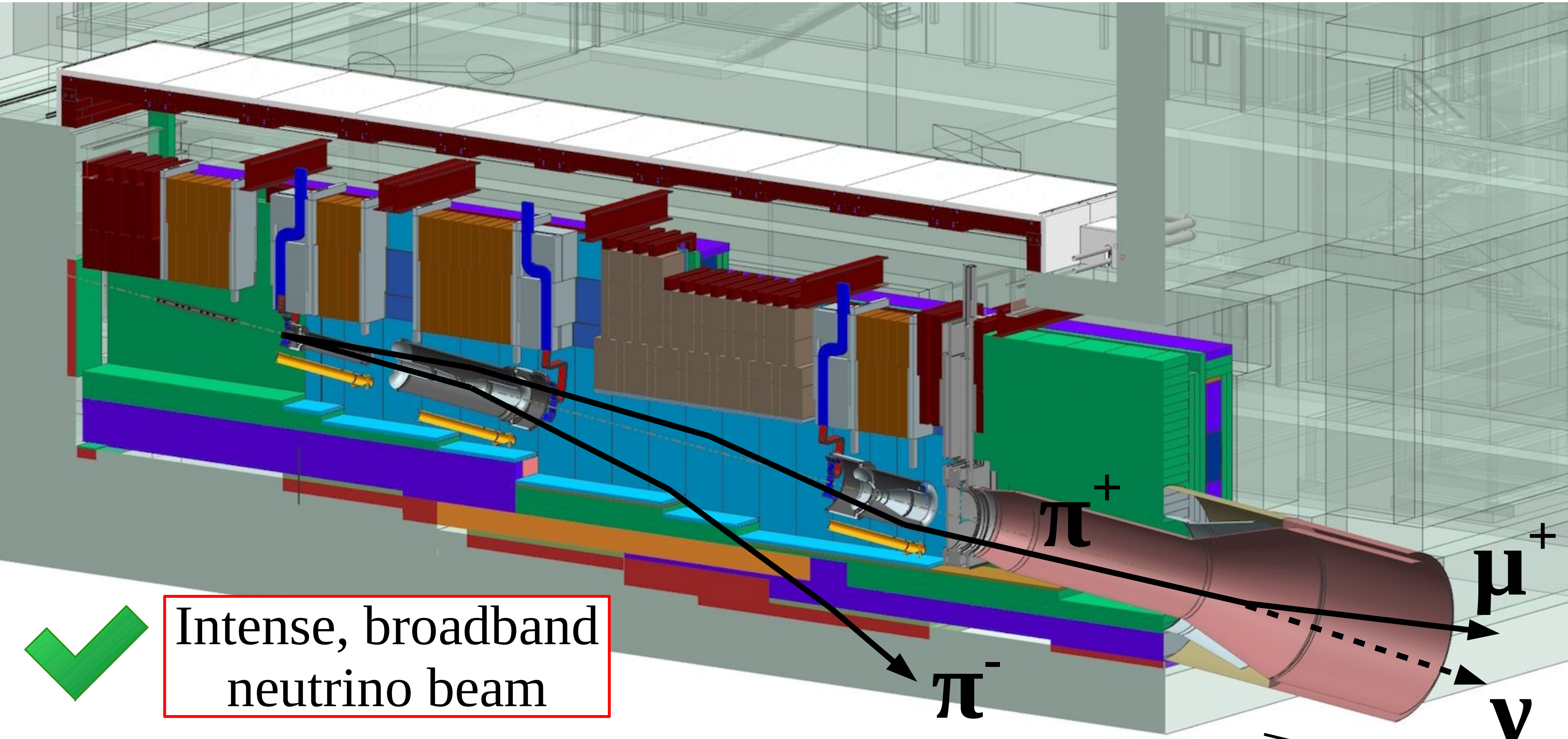
Making neutrinos



Magnetic horns focus one sign into a decay pipe, and defocus the other

Toward detectors

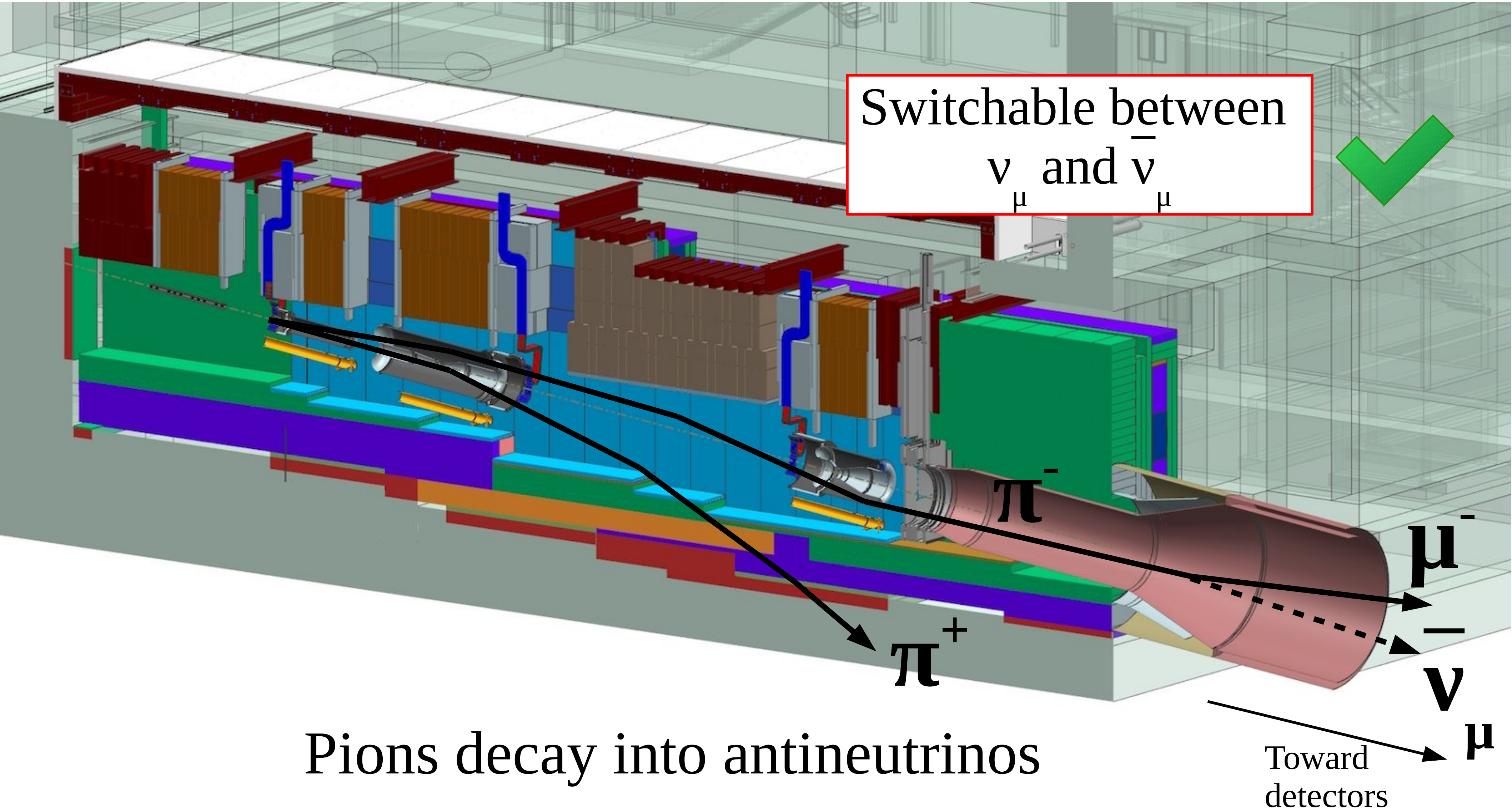
Making neutrinos



Intense, broadband neutrino beam

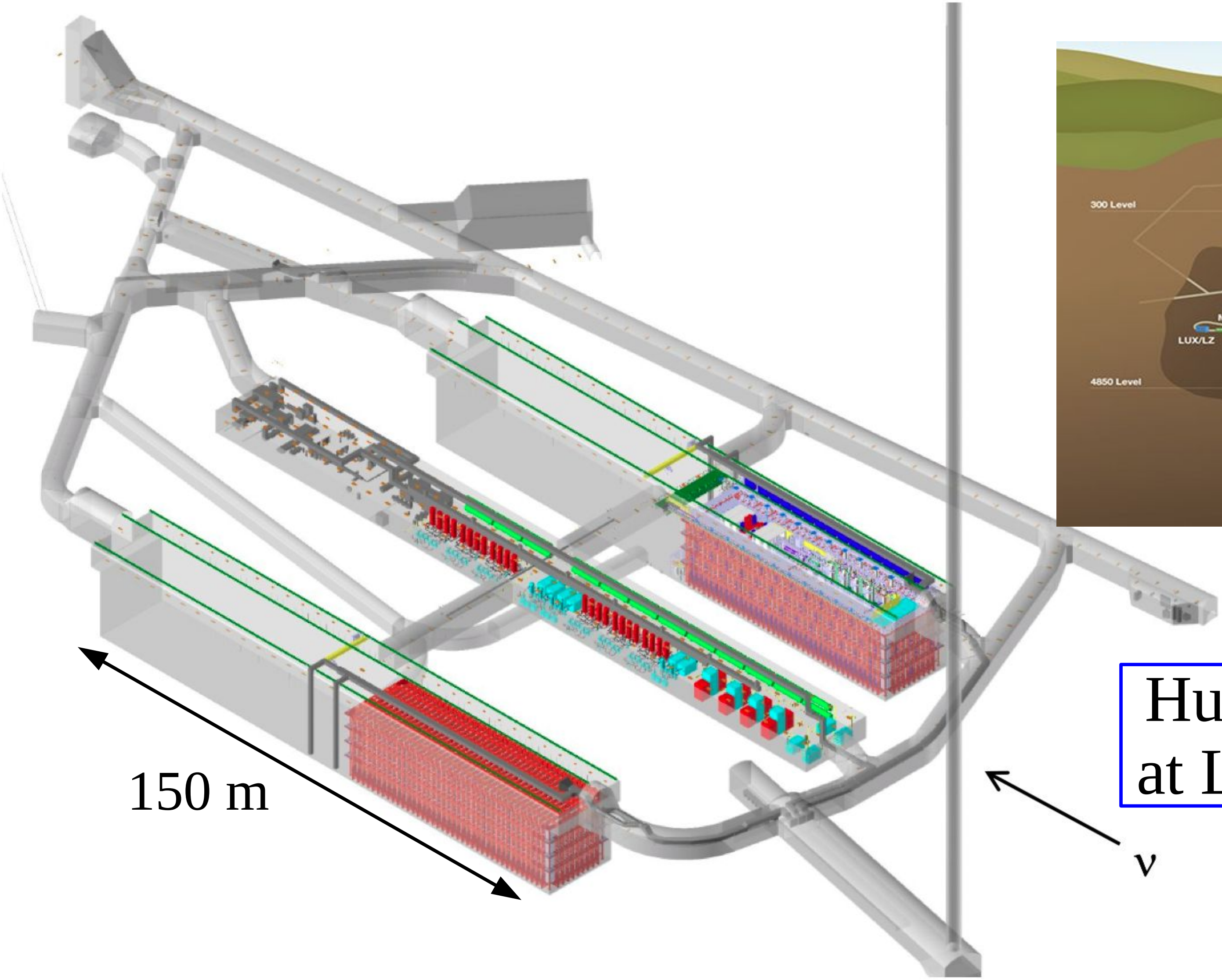
Pions decay into neutrinos

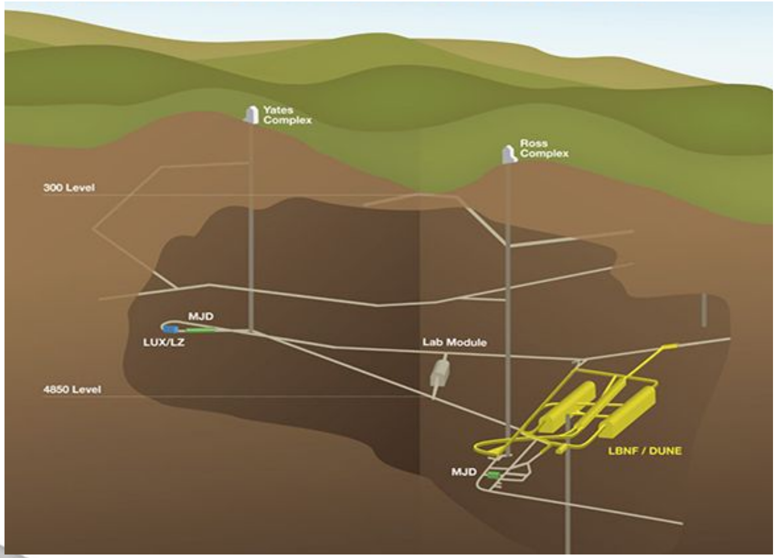
Making antineutrinos



Pions decay into antineutrinos

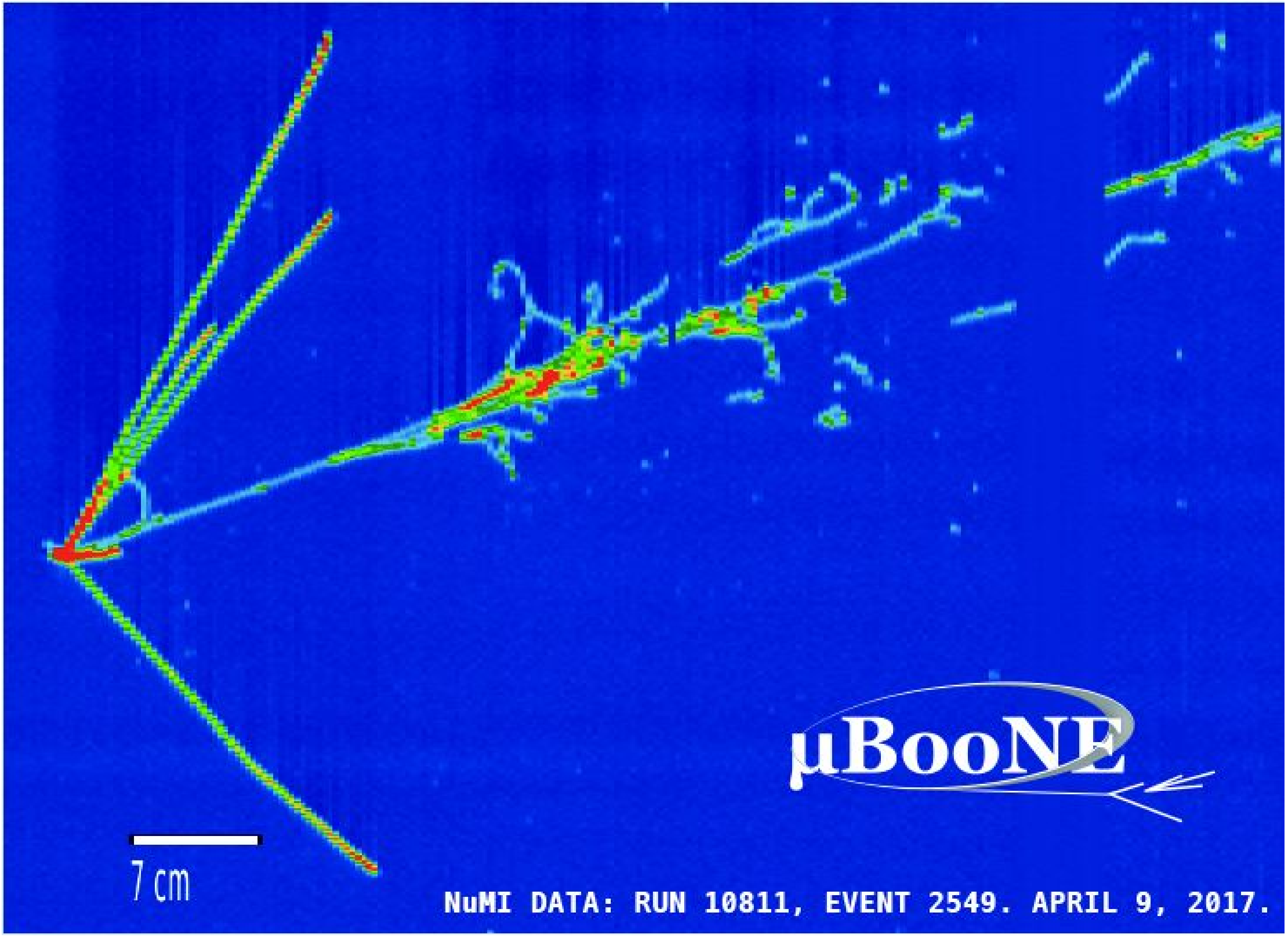
Underground far detectors: 70,000 tons at L = 1300 km



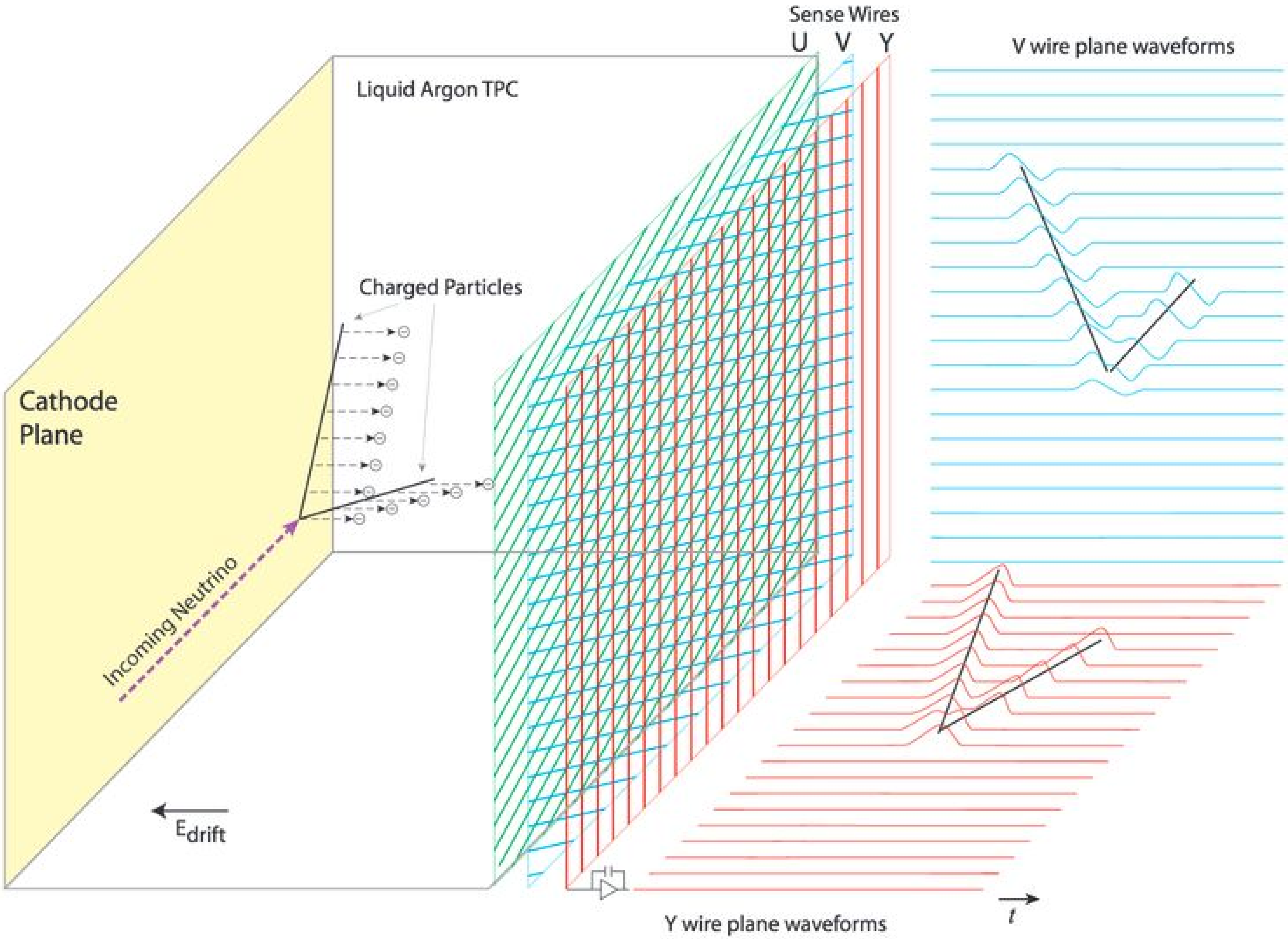


Huge detector at L > 1200km

The Far Detector: 70 kiloton Liquid Ar Time Projection Chamber

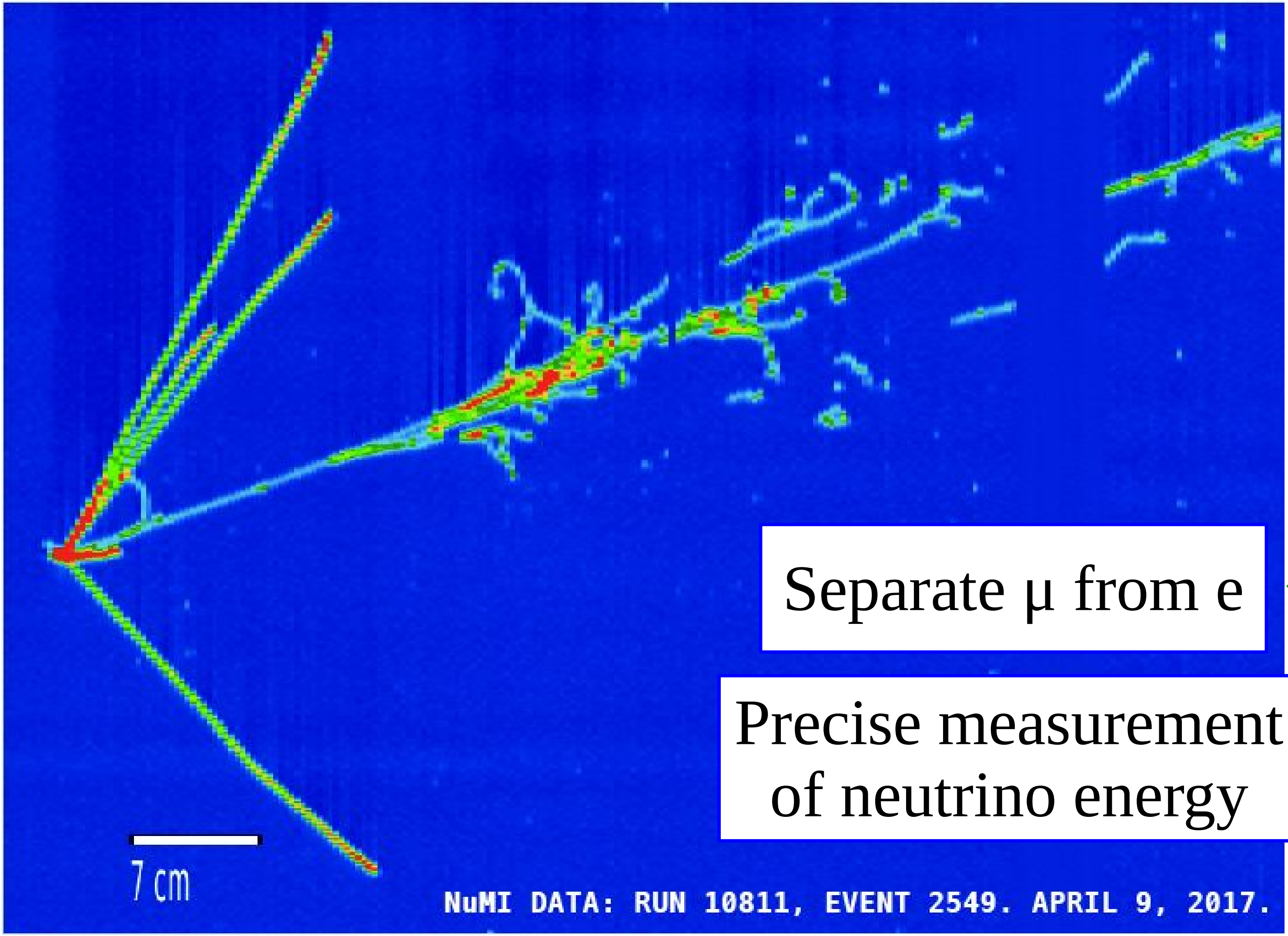


LAr TPC technology



MicroBooNE JINST 12.10 (2017)

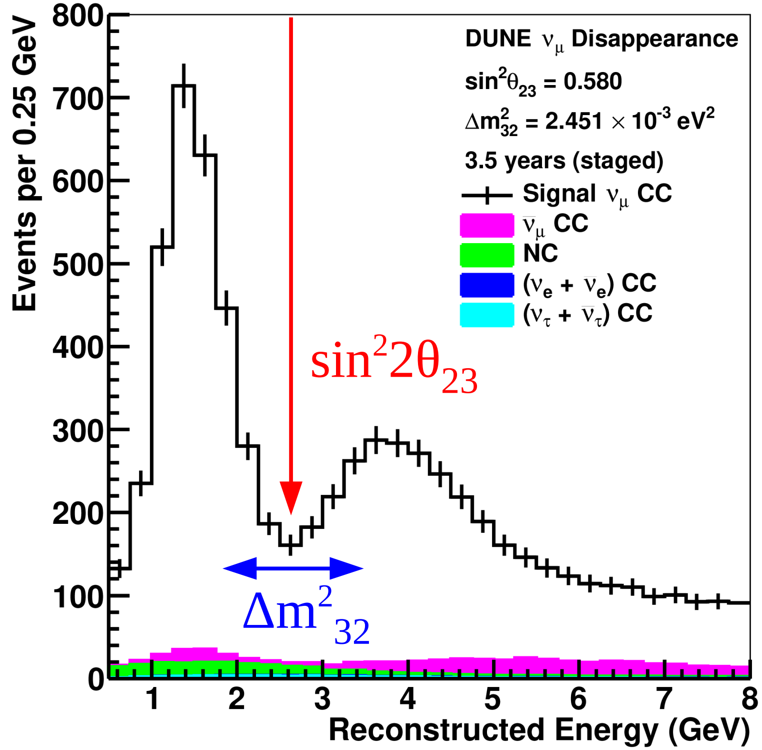
LAr TPC can identify μ & e, measure energy of ν interaction products

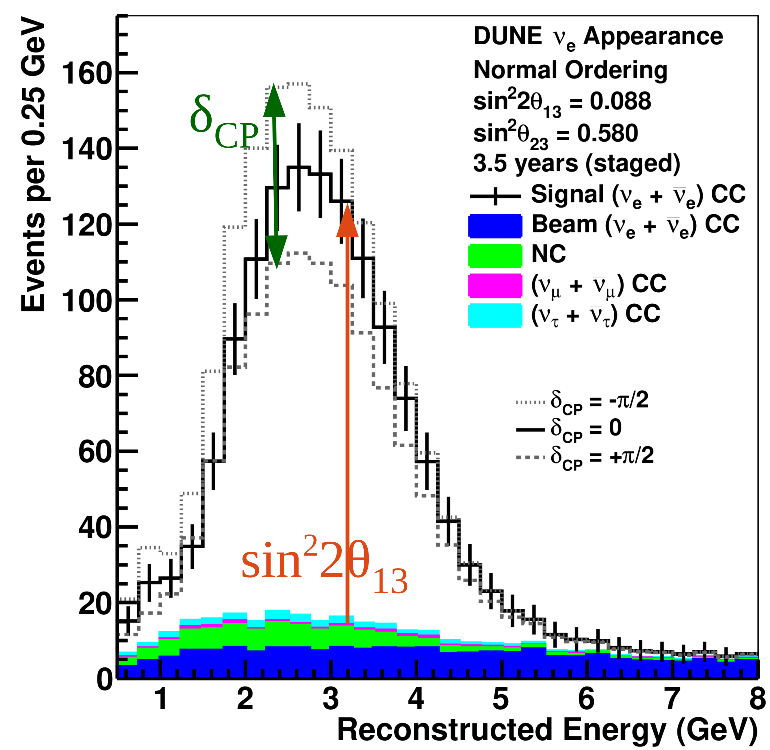


- Separate μ from e ✓
- Precise measurement of neutrino energy ✓

DUNE can measure $\nu_\mu \rightarrow \nu_e$ with ~3% statistical uncertainty

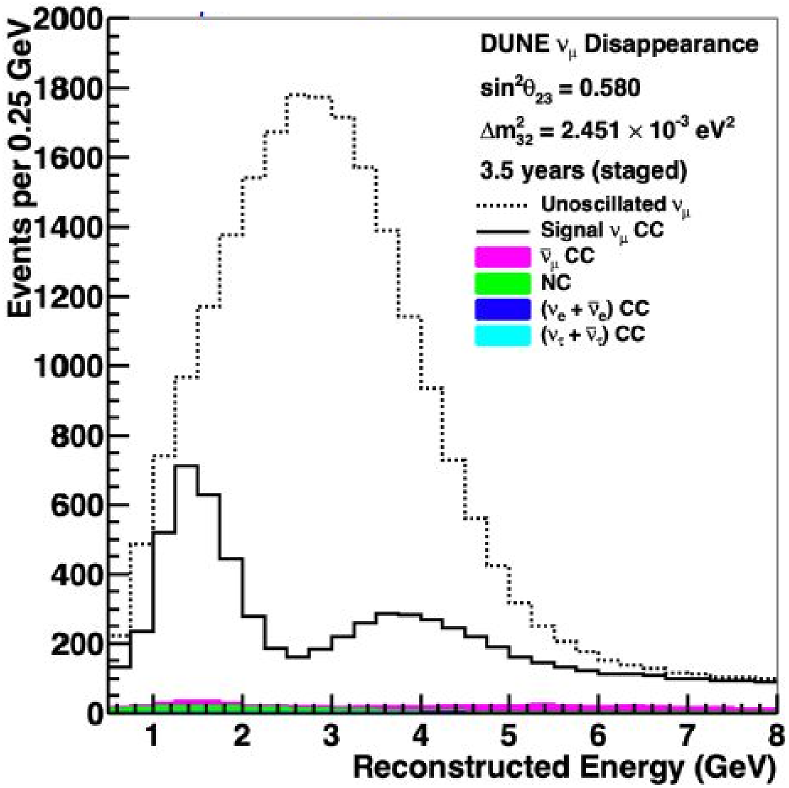
- δ_{CP} sensitivity is due to $\nu_e/\bar{\nu}_e$ samples
- ν_μ "disappearance" sample for precision measurements of other oscillation parameters





Systematics must be constrained at the level of ~3%

- Oscillations occur as a function of true neutrino energy
- But detector measures event rate = flux x cross section, as a function of visible energy
- Uncertainties in neutrino-argon cross sections, and the relationship between neutrino energy and visible energy are crucial
- Measure it with the near detector



DUNE requires a highly capable near detector system

Intense, broadband neutrino beam

Switchable between ν_μ and $\bar{\nu}_\mu$

Huge detector at L > 1200km

Separate μ from e

Precise measurement of neutrino energy

Measure initial ν flux

Measure ν interactions

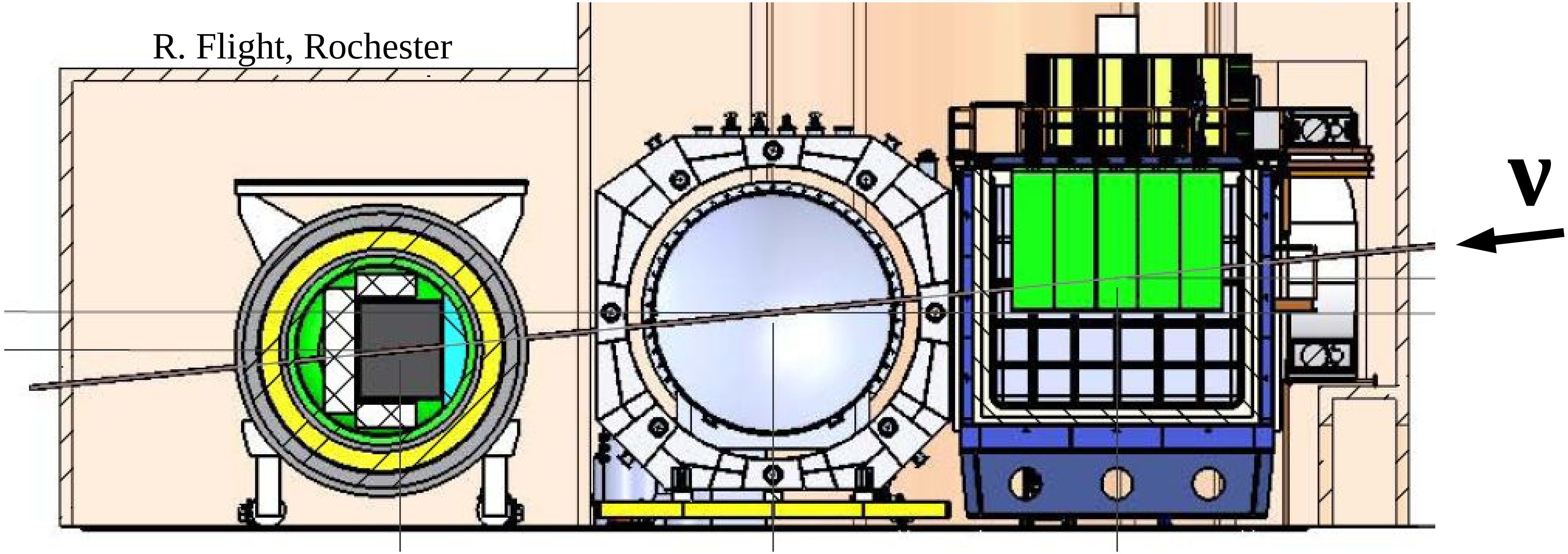
$E_\nu \leftrightarrow E_{reco}$

Monitor the neutrino beam

Near Detector discussion meeting this week

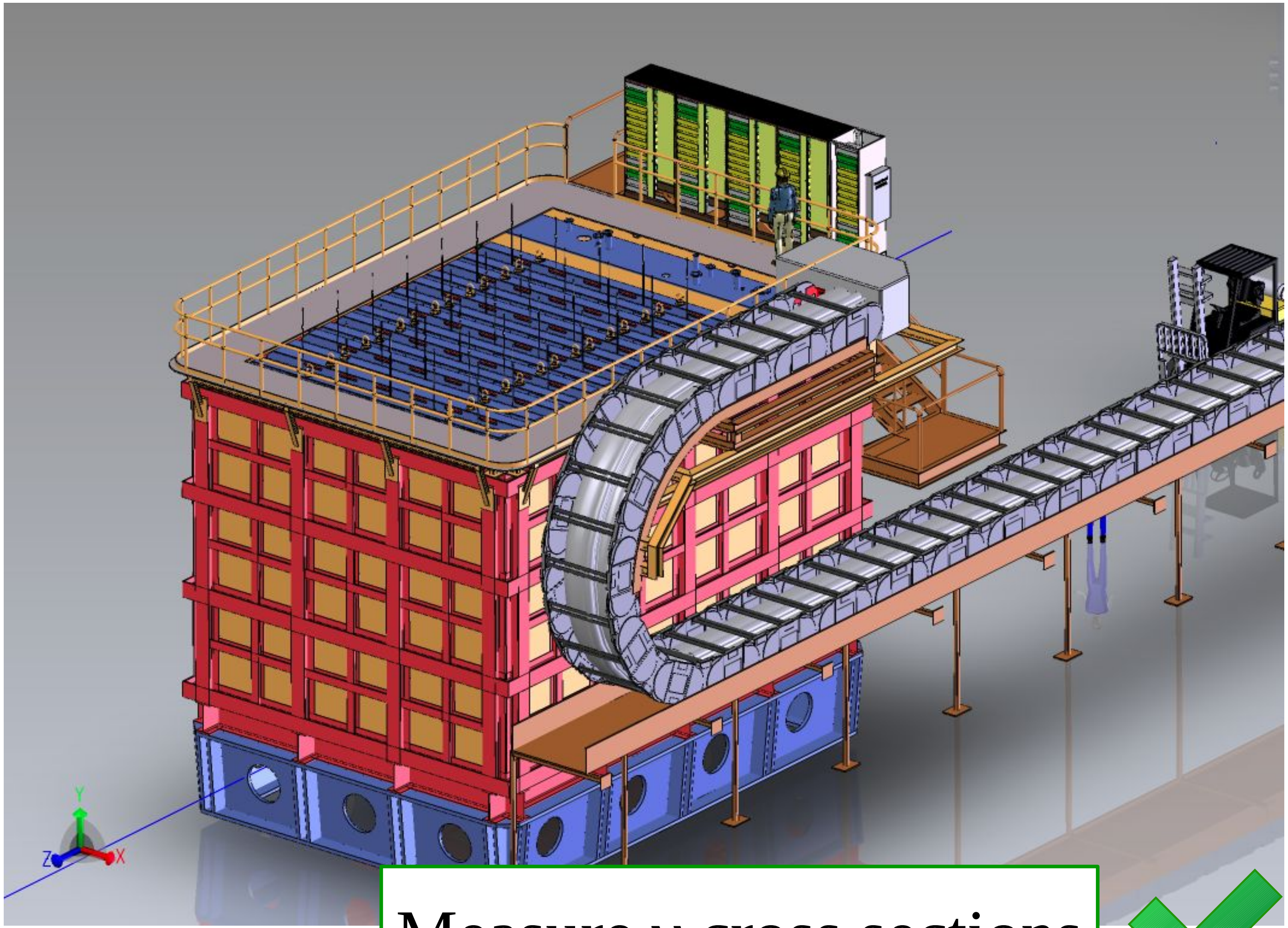
- Three-day meeting to discuss DUNE near detector will conclude tomorrow
- Interesting discussions on many aspects of the ND program, with particular focus on collaboration with TIFR and Indian institutions

The DUNE Near Detector: precision systematic constraints



- LAr TPC functionally similar to far detector
- Magnetized, high-pressure gaseous Ar TPC with high-performance calorimeter
- Magnetized plastic scintillator tracker & on-axis beam monitor

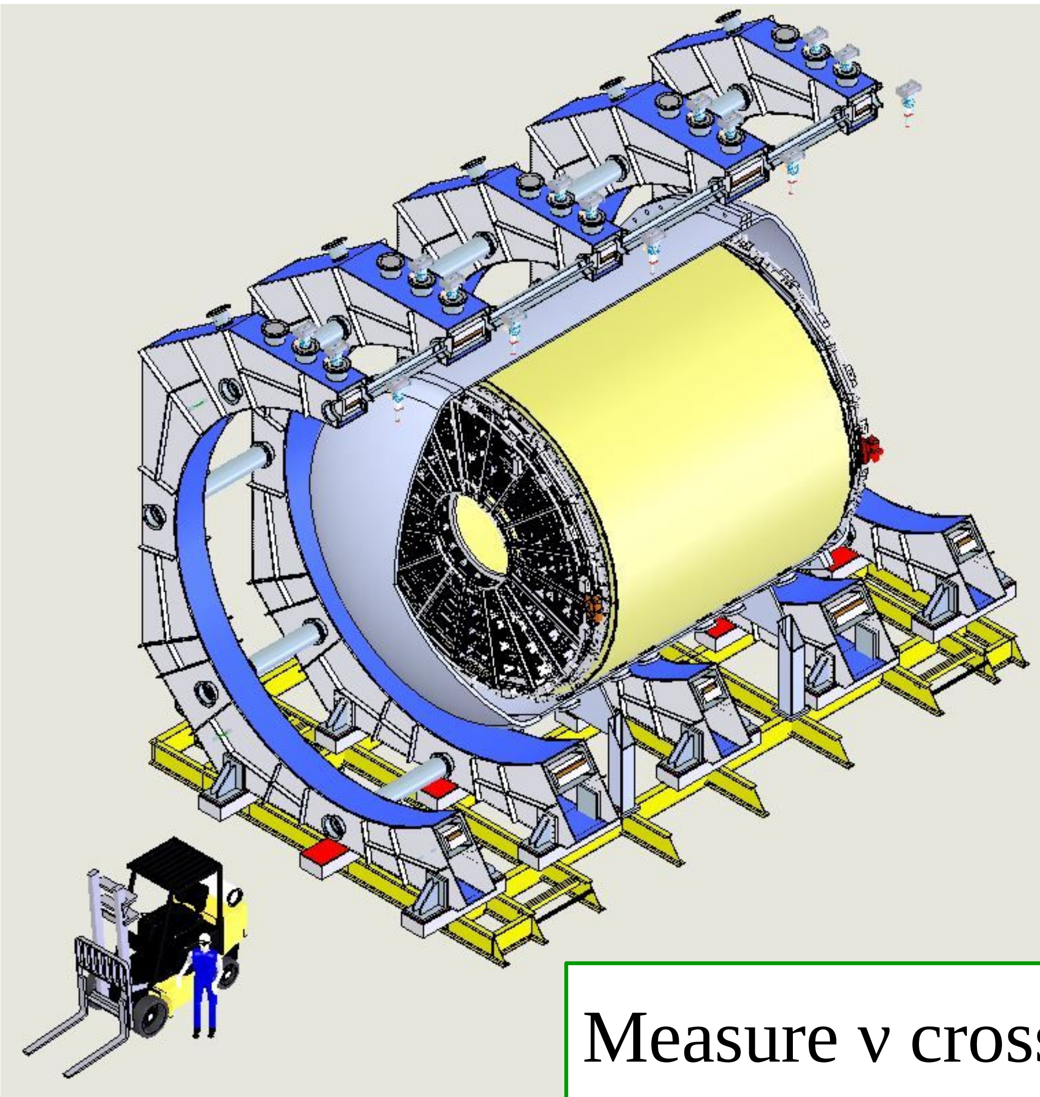
ArgonCube: pixelated LAr TPC to measure ν-Ar interactions



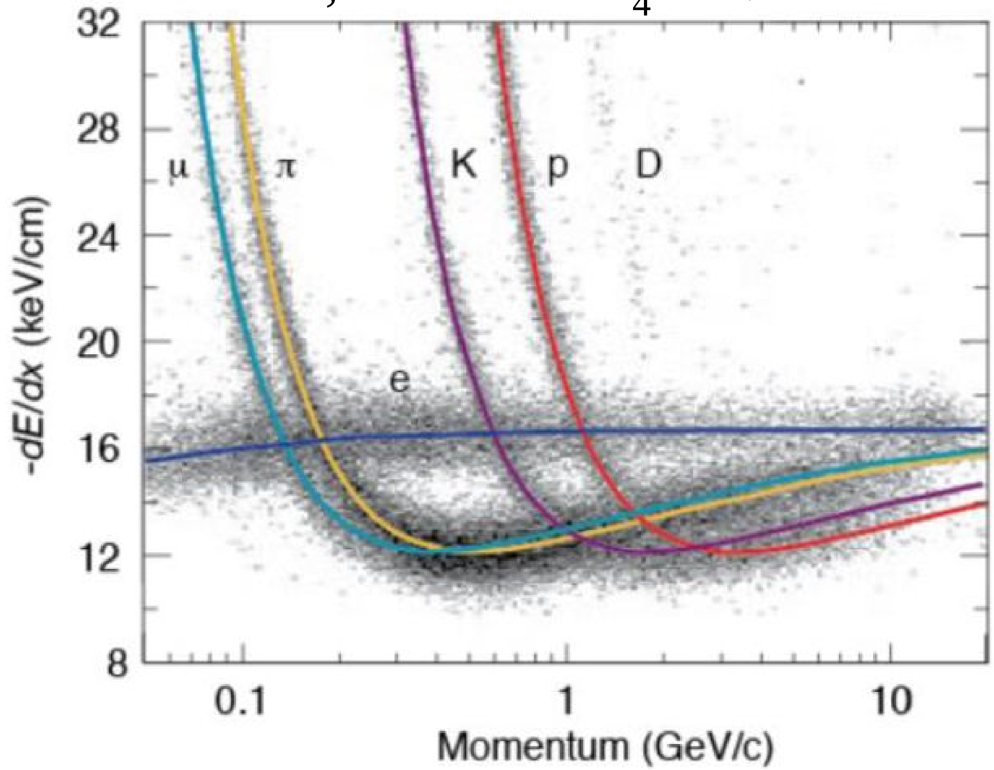
Measure ν cross sections

- >50M neutrino interactions per year – will be the largest sample ever collected
- Study cross sections in very similar detector to FD

High-pressure gaseous argon TPC: ν-Ar interactions in exquisite detail



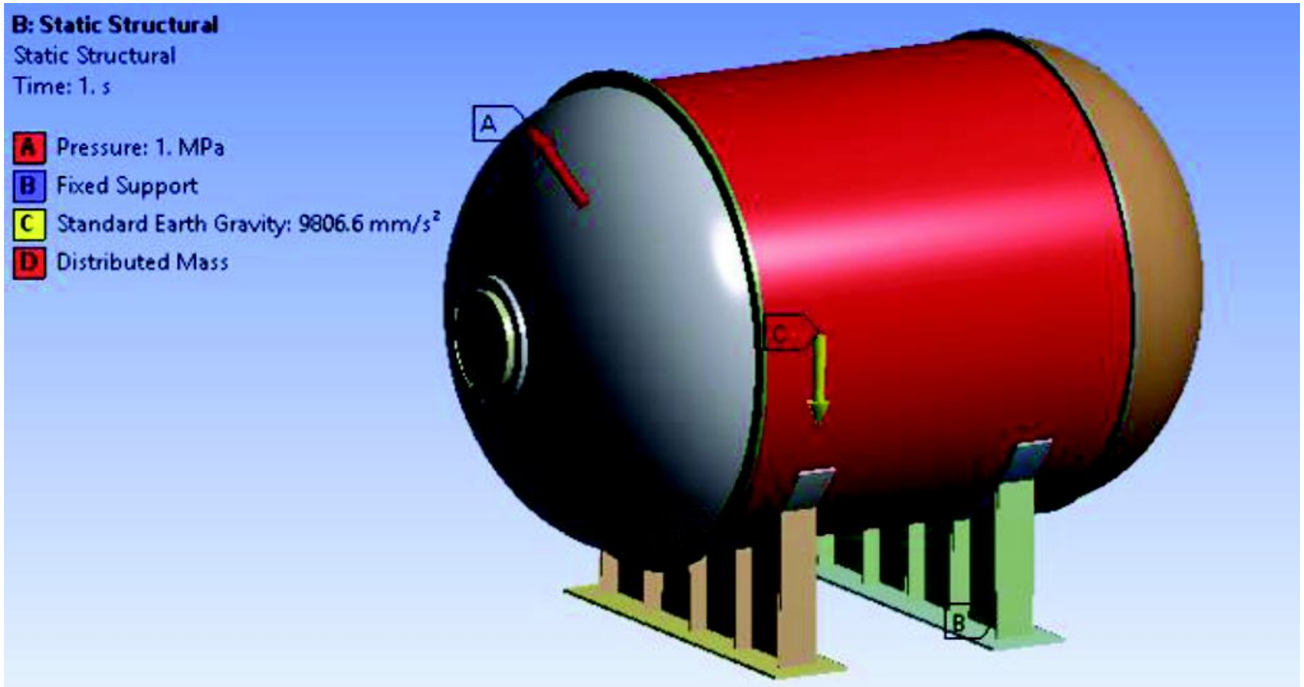
PEP-4, 80/20 Ar-CH_4 at 8.5 atm



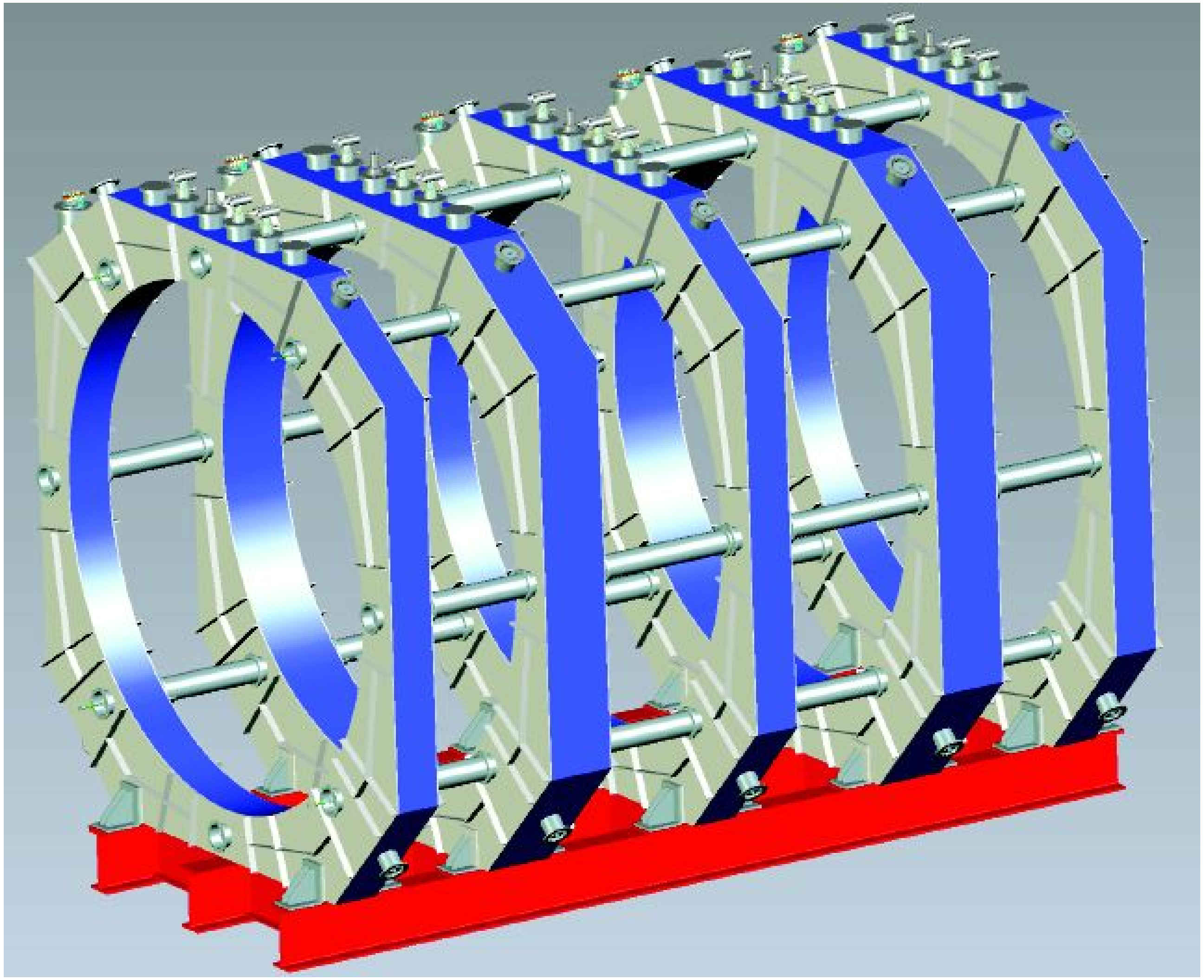
Measure ν cross sections

Pressure vessel for HPgTPC design from BARC

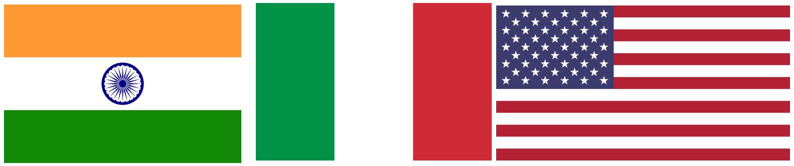
- Vessel must be very large to accommodate 5m TPC radius, and very thin so that photons do not shower
- Leads to complicated engineering requirements, currently under design at BARC



Magnet system for gaseous TPC

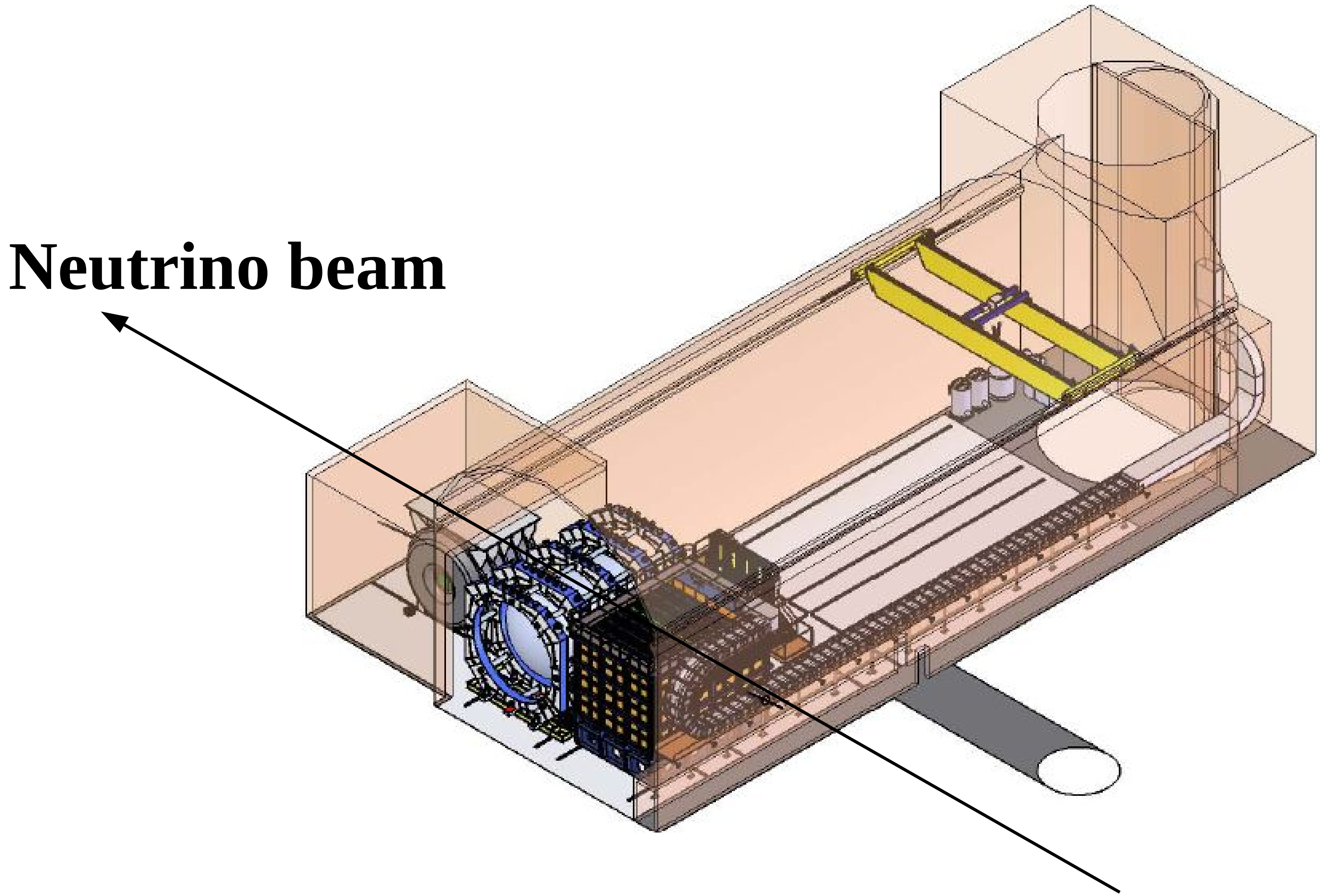


- Reference is 5-coil superconducting Helmholtz design, but optimization is still ongoing
- Potential for collaboration between India, Italy, and United States

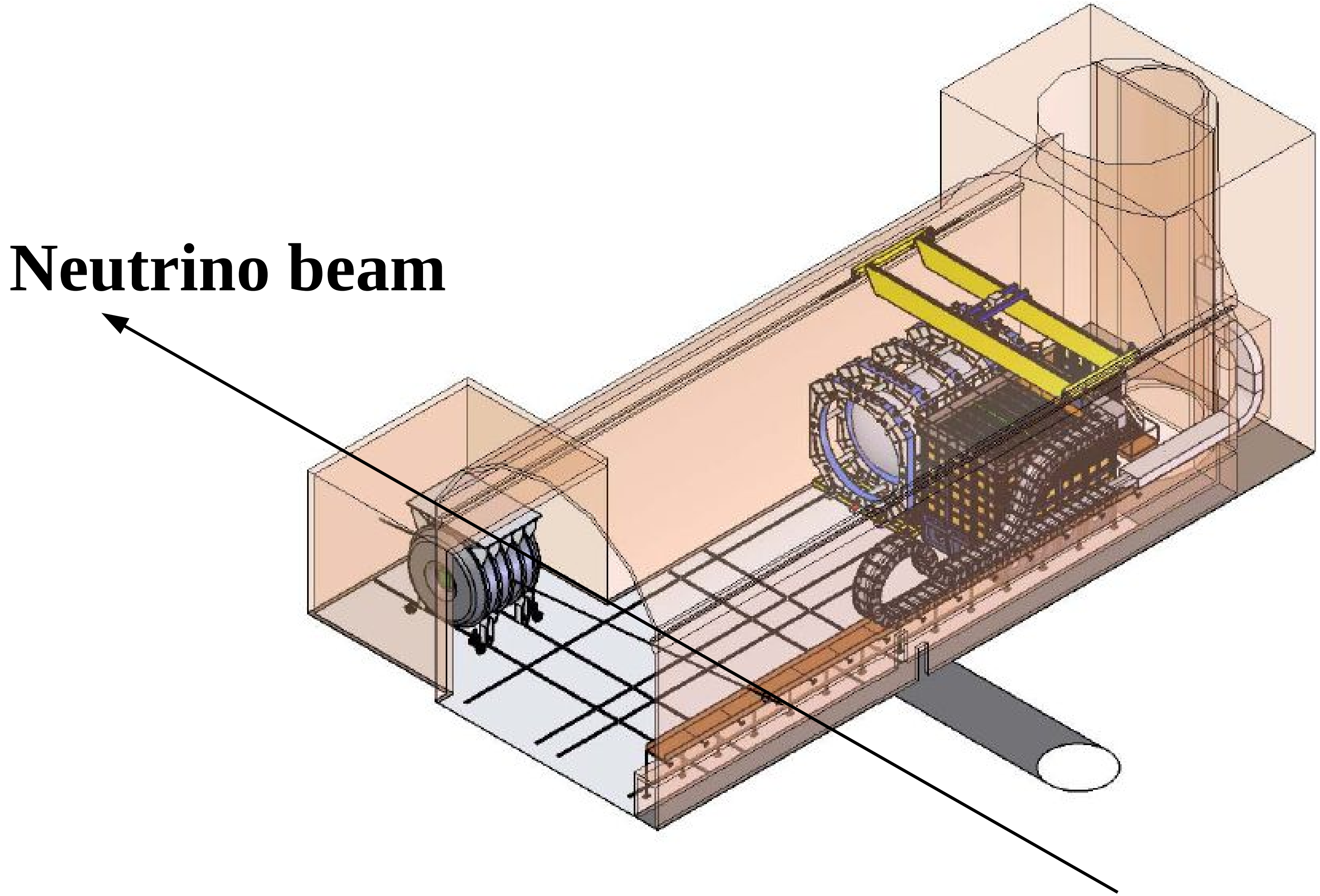


BERKELEY LAB
LAWRENCE BERKELEY NATIONAL LABORATORY

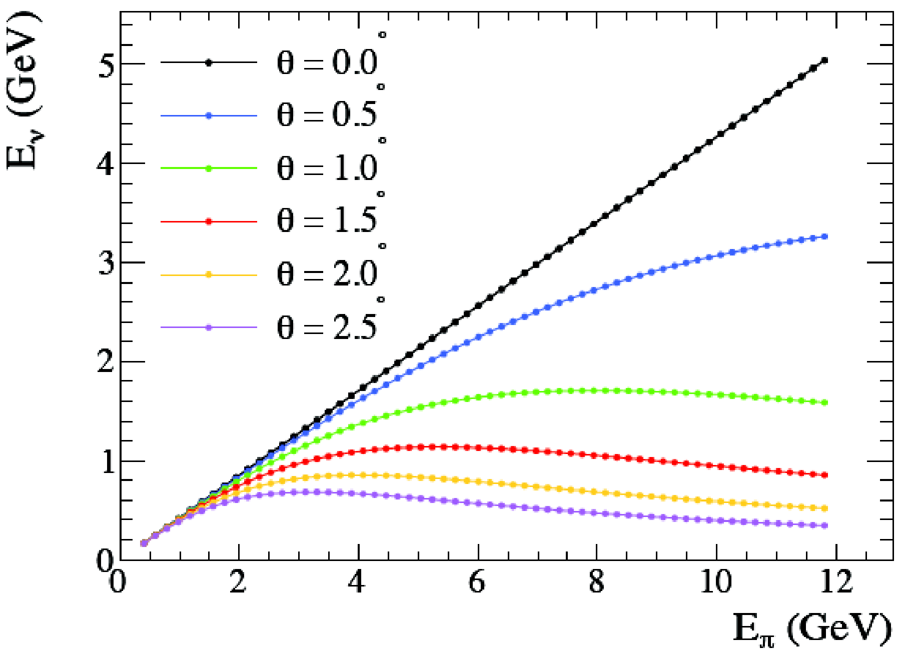
ND in the underground facility

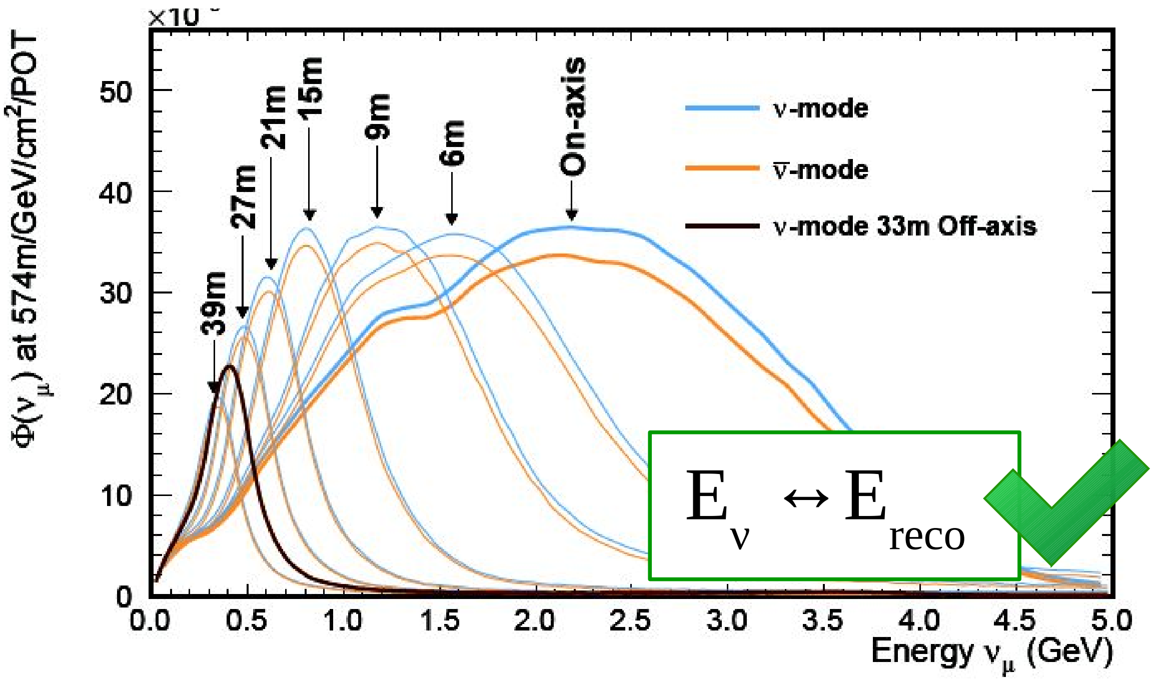


The near detector will move up to 33m off-axis



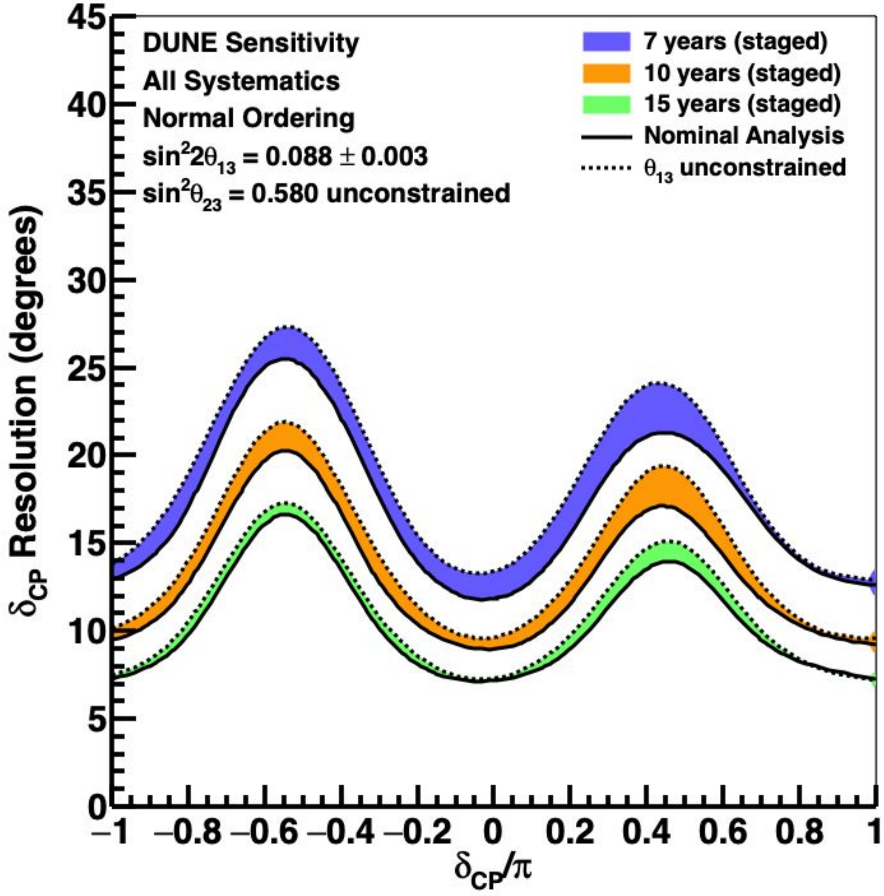
Directly probing E_ν-dependence with a movable ND





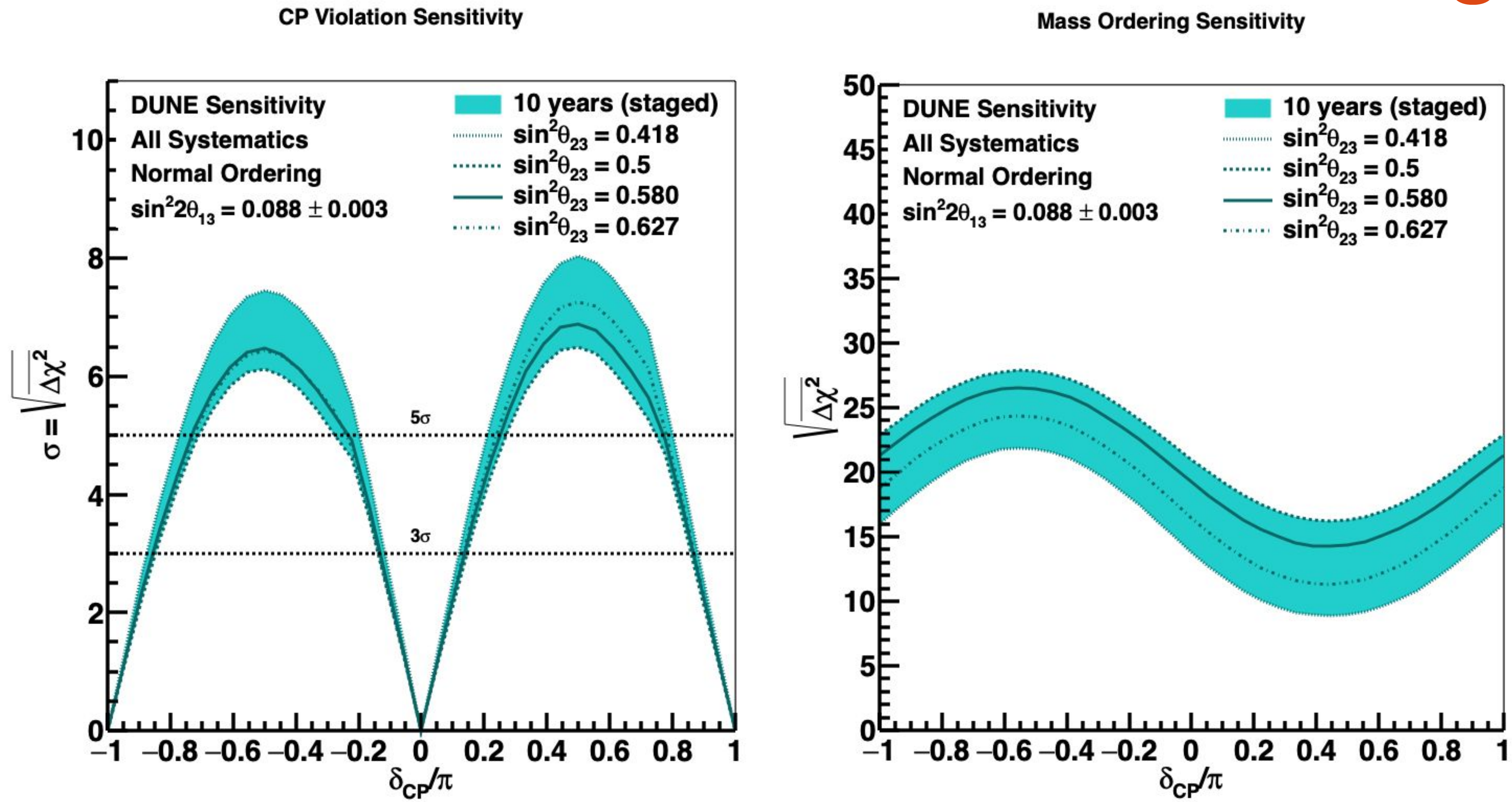
- Due to the pion decay kinematics, the neutrino flux is peaked at lower energies if you look off-axis
- The ND will slide 33m off-axis to access many different flux spectra, directly measuring effects that depend on E_ν

Estimated sensitivity to δ_{CP}



- DUNE's resolution is 13-25 degrees after 7 years, depending on the true value
- After 15 years, the resolution is ~8 degrees at CP-conserving values, and ~16 degrees at maximally-violating values

CP violation and mass ordering



- >5σ discovery potential for $\delta_{CP} \neq 0$ for >50% of true values
- Definitive mass ordering determination regardless of true values of parameters

Lots of physics, too little time

- DUNE is sensitive to nucleon decay, and competitive with existing limits in many channels
- Supernova neutrinos, if we get lucky
- Numerous other physics searches beyond the Standard Model, including:
  - Sterile neutrinos
  - Light dark matter
  - Neutrino tridents
  - Non-standard interactions

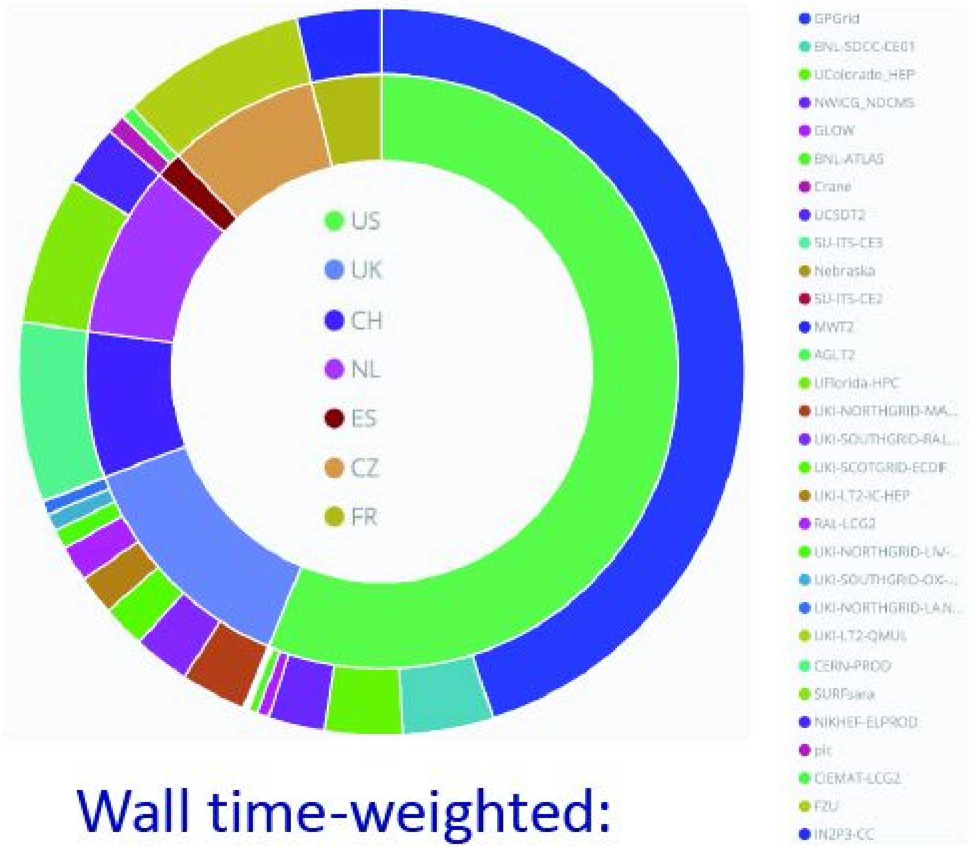
Conclusions

- DUNE brings neutrino physics to the precision era:
  - Measurement of δ_{CP}, and discovery of CP violation in neutrino sector if it is sufficiently large
  - Determination of the neutrino mass ordering
  - Precise measurements of oscillation parameters
- Measurement is very challenging: requires intense beam; huge, highly-capable far detector; precision near detector
- DUNE is designed to overcome these challenges

Thank you!

Backups

Computing: a worldwide effort

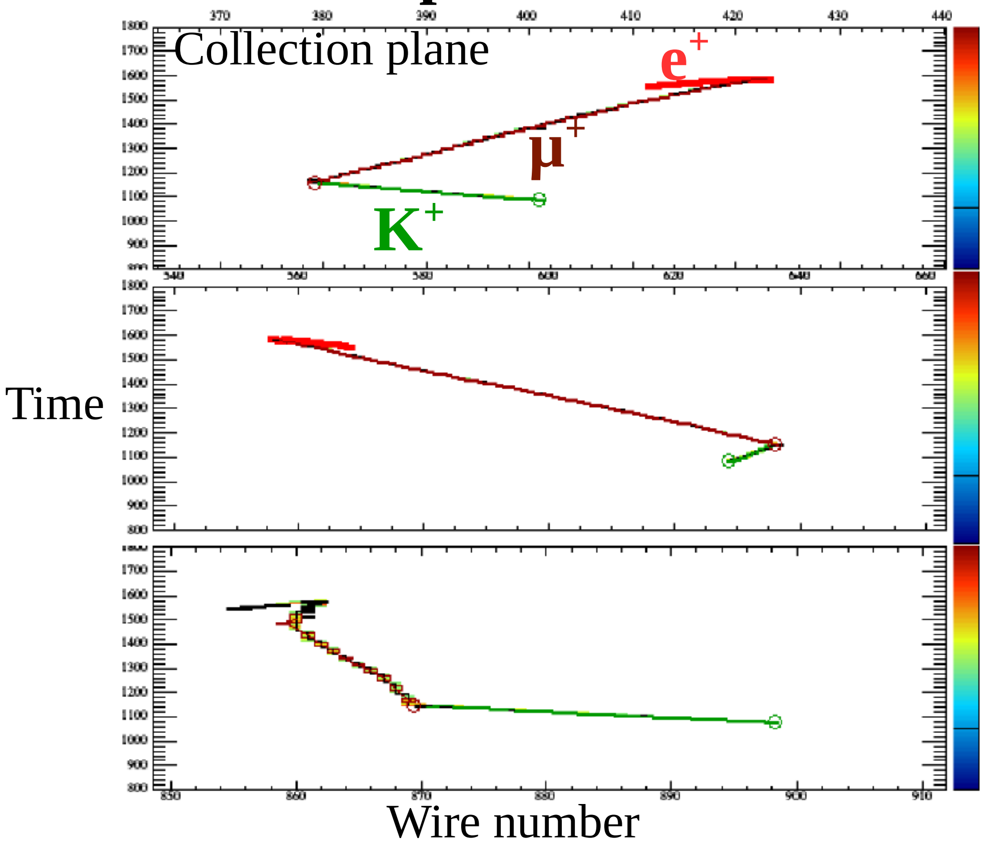


Wall time-weighted:
56% US

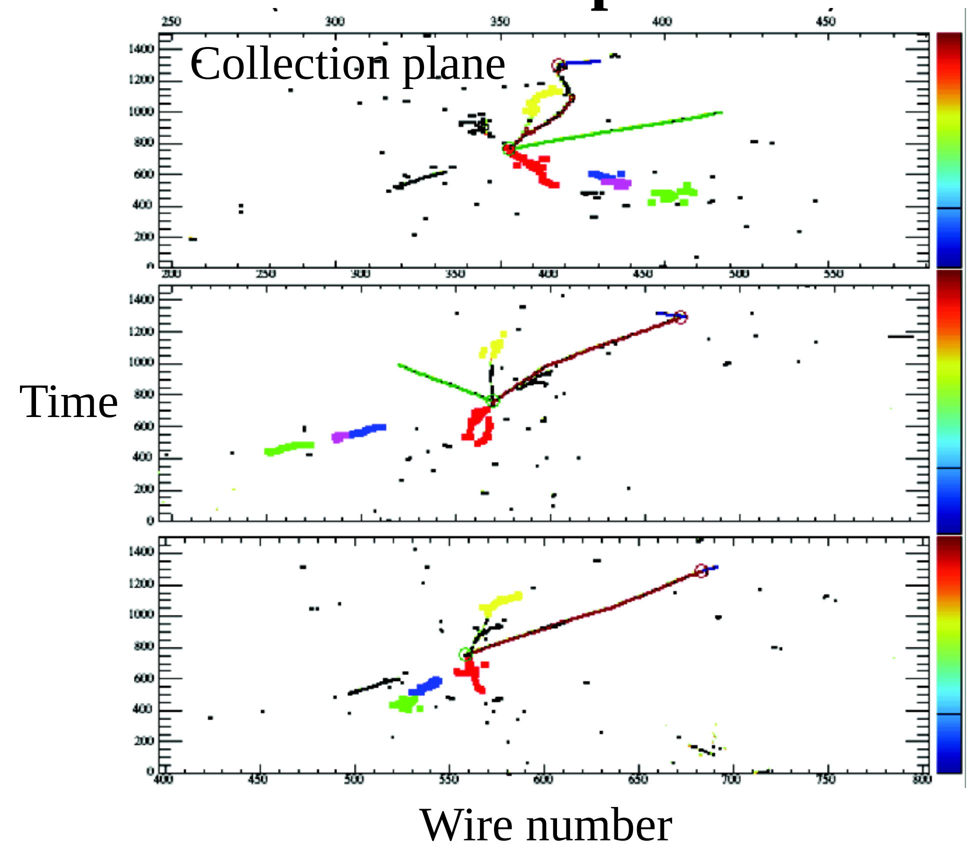
- DUNE computing is distributed all over the world
- About 50% of DUNE's overall computing is done in the United States
- Discussions are underway about using the computing cluster at TIFR for DUNE

Nucleon decay & $n\bar{n}$ oscillations

$p \rightarrow K^{+}\nu$

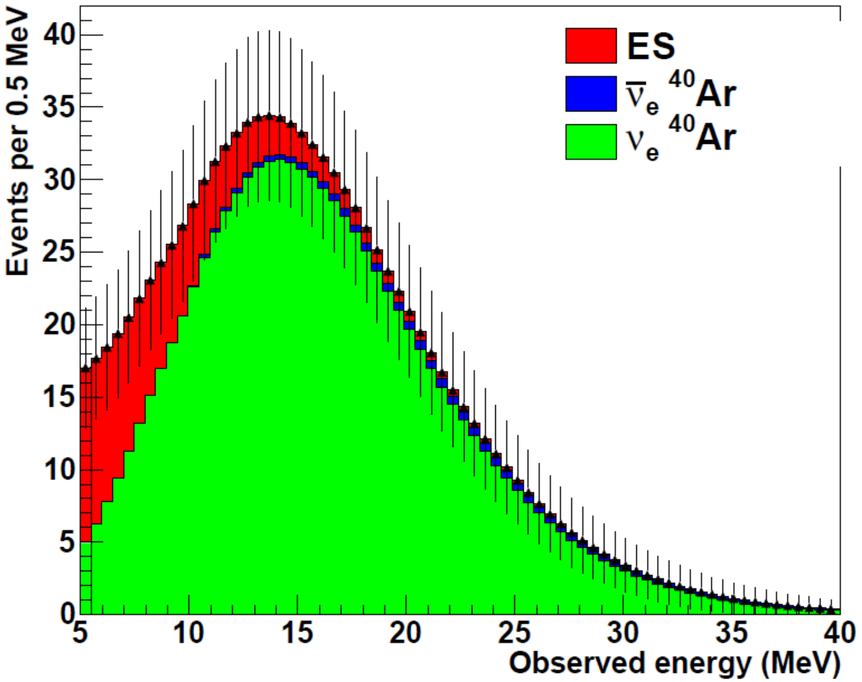


$n\bar{n} \rightarrow$ pions

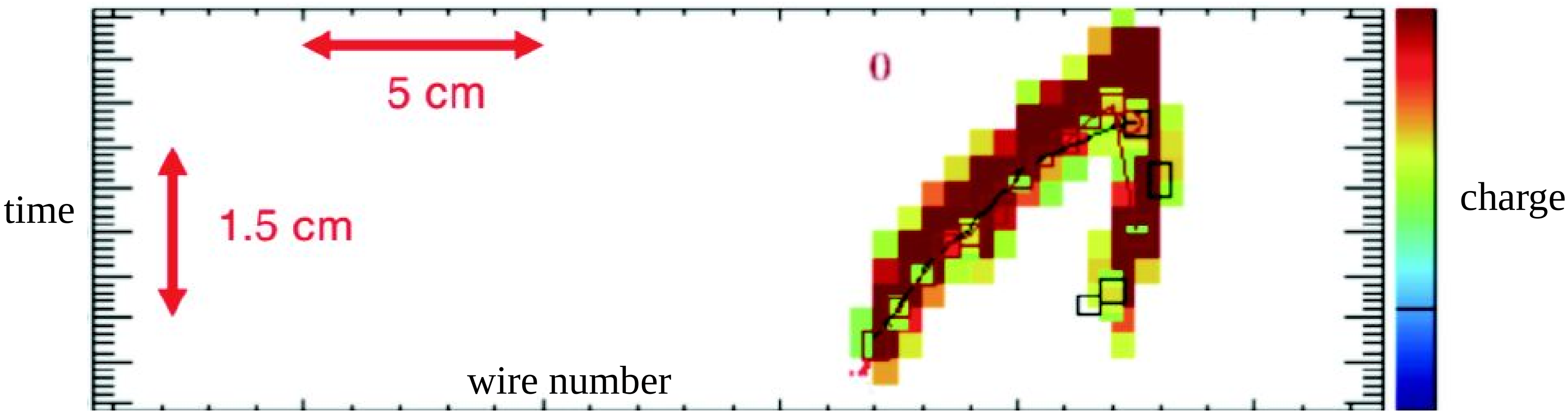


- Updated analyses with full simulation & reconstruction will be presented in upcoming TDR

Supernova burst neutrinos

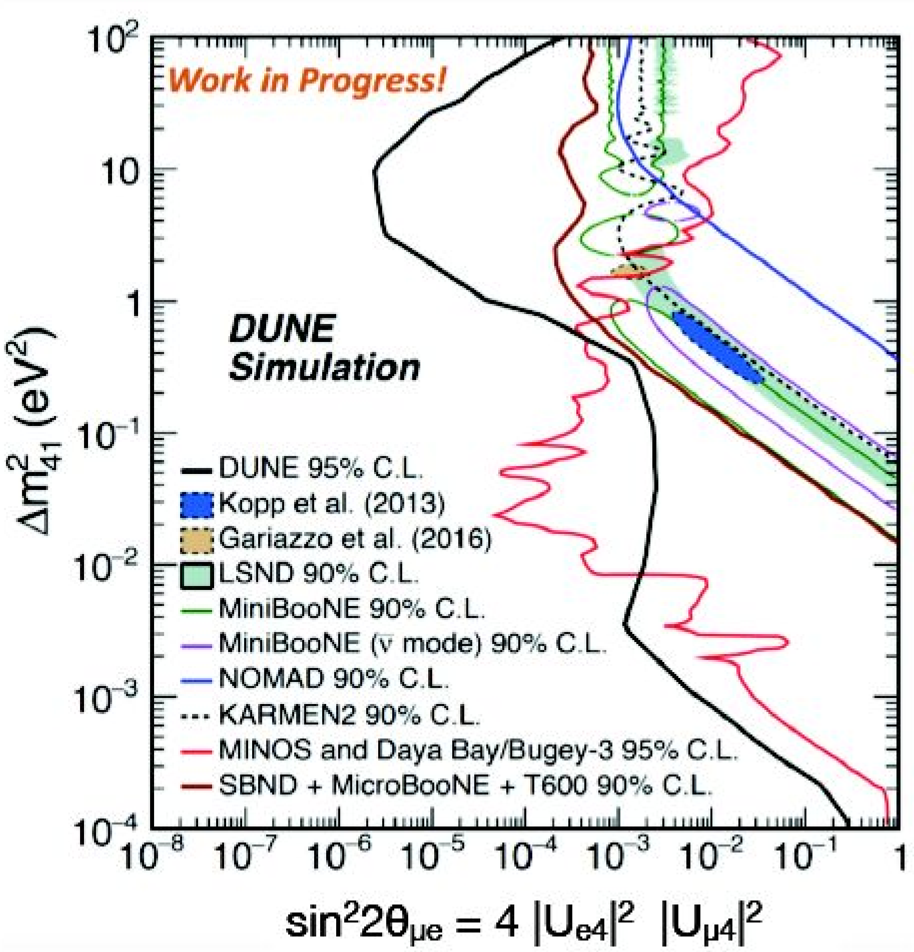


- DUNE will see 100s to 1000s of neutrinos from a supernova burst
- Primary channel in LAr is $\nu_e\,{}^{40}Ar \rightarrow e^-\,{}^{40}K^*$



BSM searches

- Sterile neutrinos
- Light dark matter
- Boosted dark matter
- Non-standard interactions
- Neutrino tridents
- Large extra dimensions
- Likely much more!



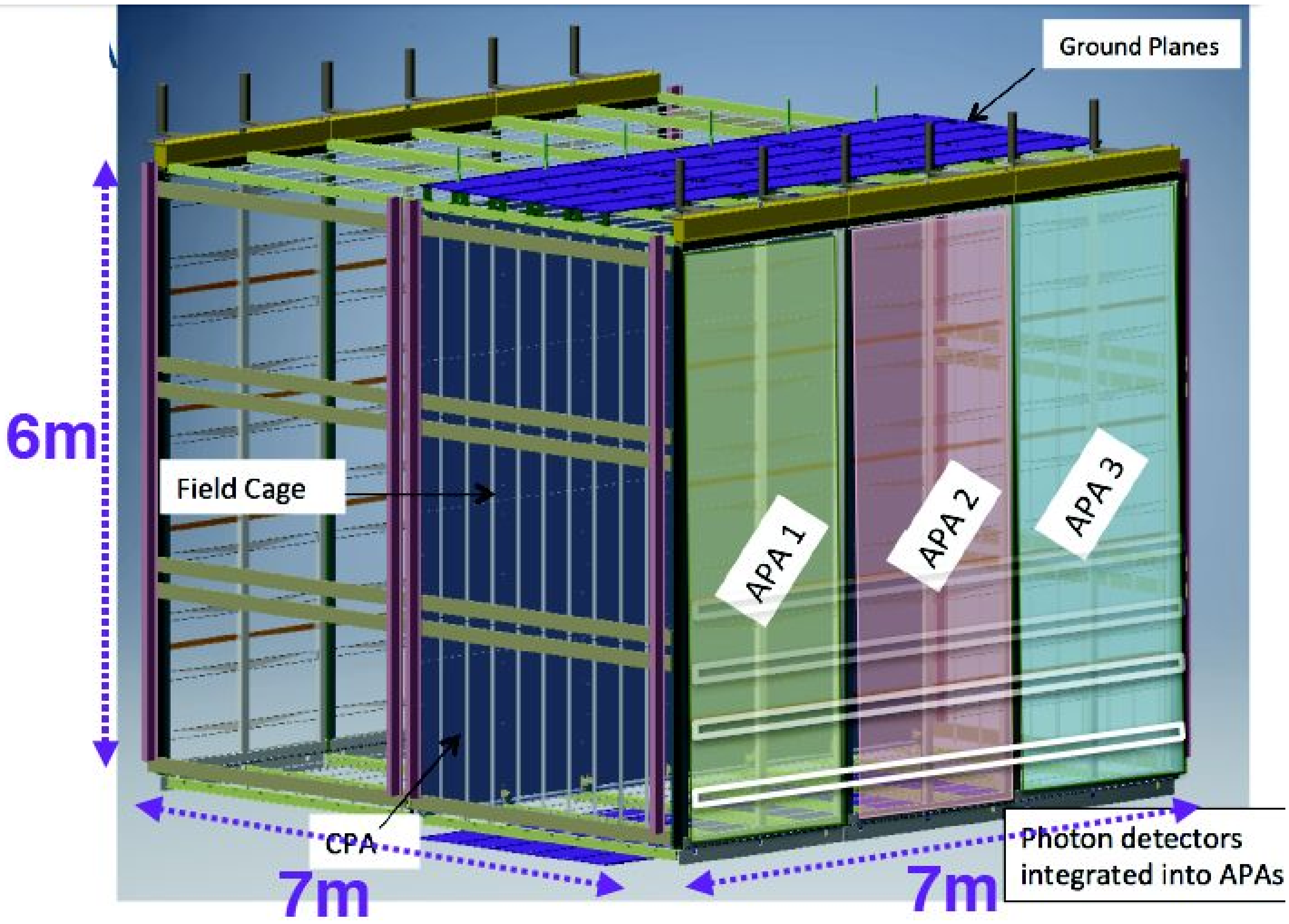
Sakharov conditions for dynamical baryon asymmetry

- Baryon number violation
- C- and CP-symmetry violation
  - C-symmetry would balance the interactions that produce more baryons with interactions that produce more antibaryons
  - CP-symmetry would ensure equal numbers of left-handed baryons and right-handed antibaryons, and vice versa
- Interactions out of thermal equilibrium
  - Otherwise CPT symmetry would balance processes increasing and decreasing the baryon asymmetry

ProtoDUNE: prototyping the DUNE far detector design

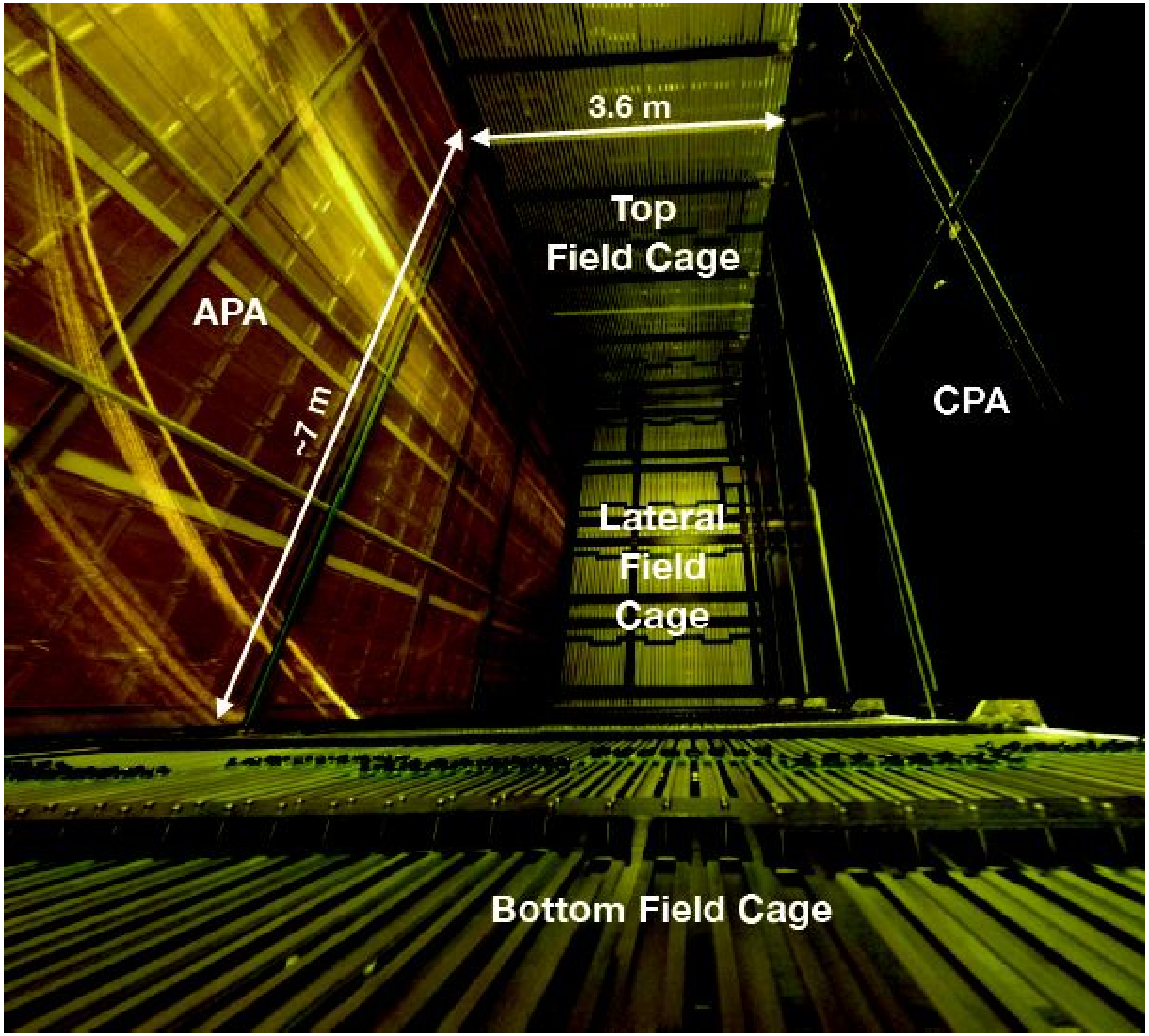
- Two prototype detectors located at CERN neutrino platform
- Single phase and dual phase
- Test detector engineering, and also hadron beam physics program

ProtoDUNE-SP



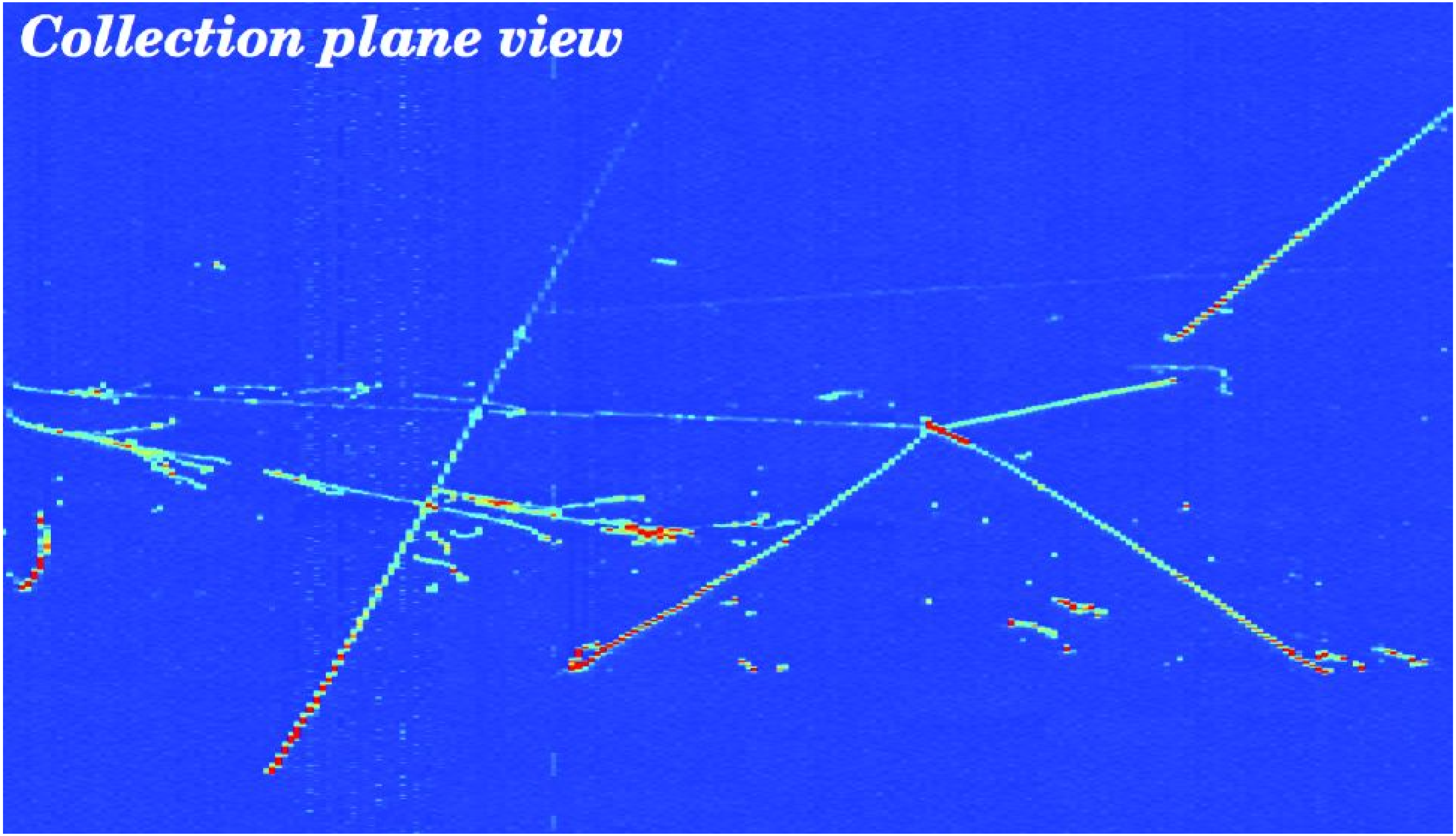
- Full scale prototype – same voltage, drift distance as DUNE SP
- Test of design, installation, operation, stability
- Measure hadron response in LAr

ProtoDUNE-SP



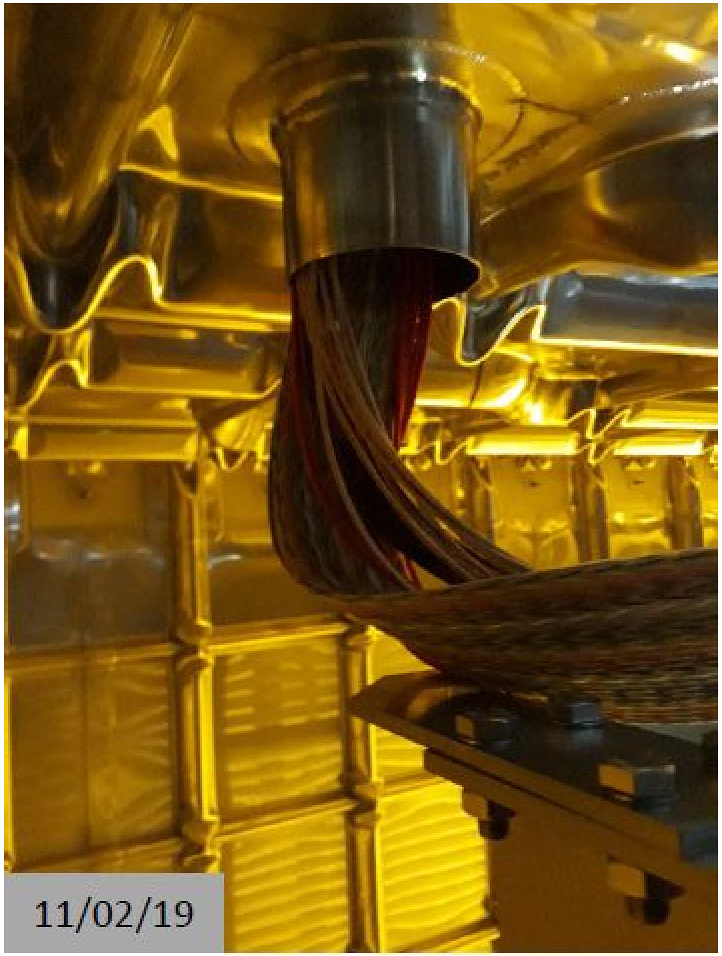
- Beam physics run Sep 21 – Nov 11
- Pions, protons, electrons, kaons from 0.3-7 GeV, total ~4M triggers
- Achieved stable running at 180kV, ~8ms electron lifetime, ~600 ENC noise → S/N ~ 38

ProtoDUNE-SP event display



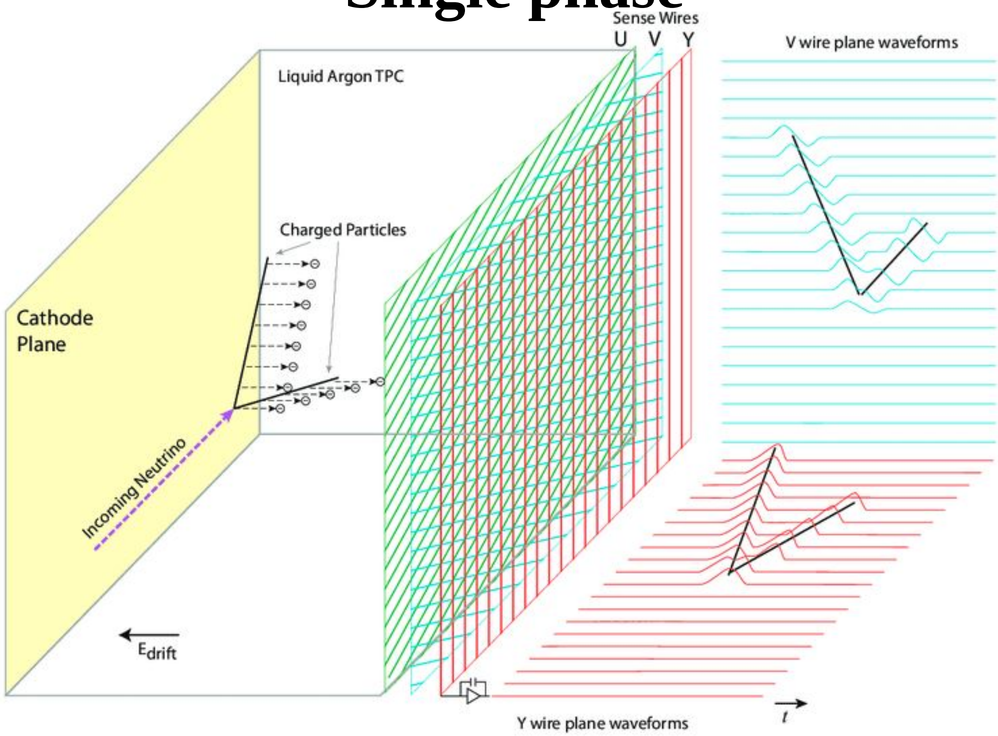
ProtoDUNE-DP

- Complete dual-phase detector assembled in cryostat since March 2019
- Purging, cooling, filling this summer
- End of filling will be ~August

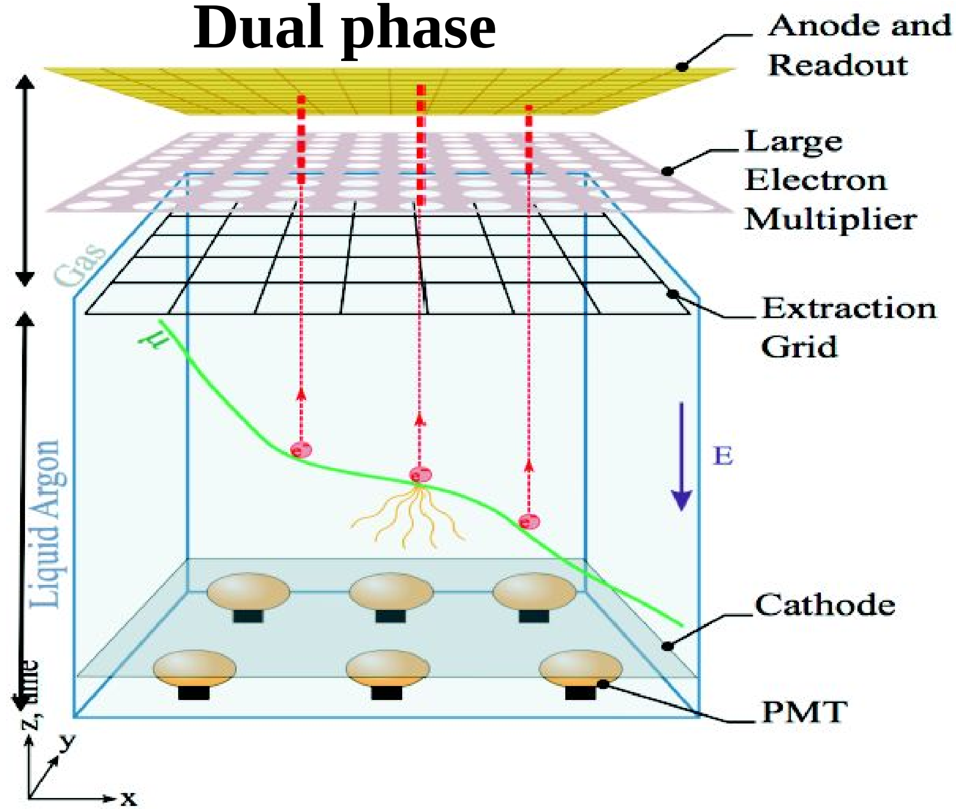


Two detector technologies

Single phase

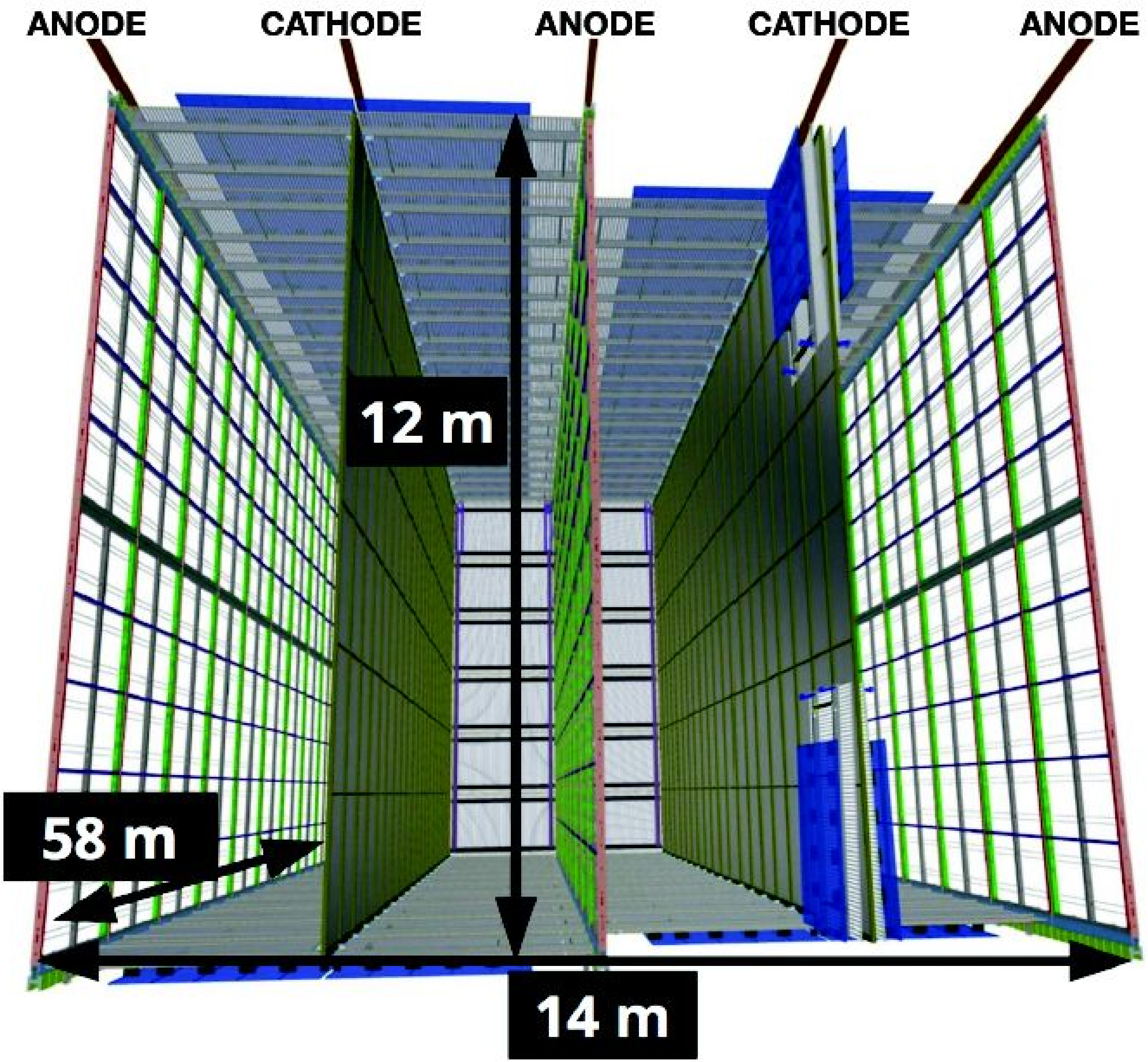


Dual phase



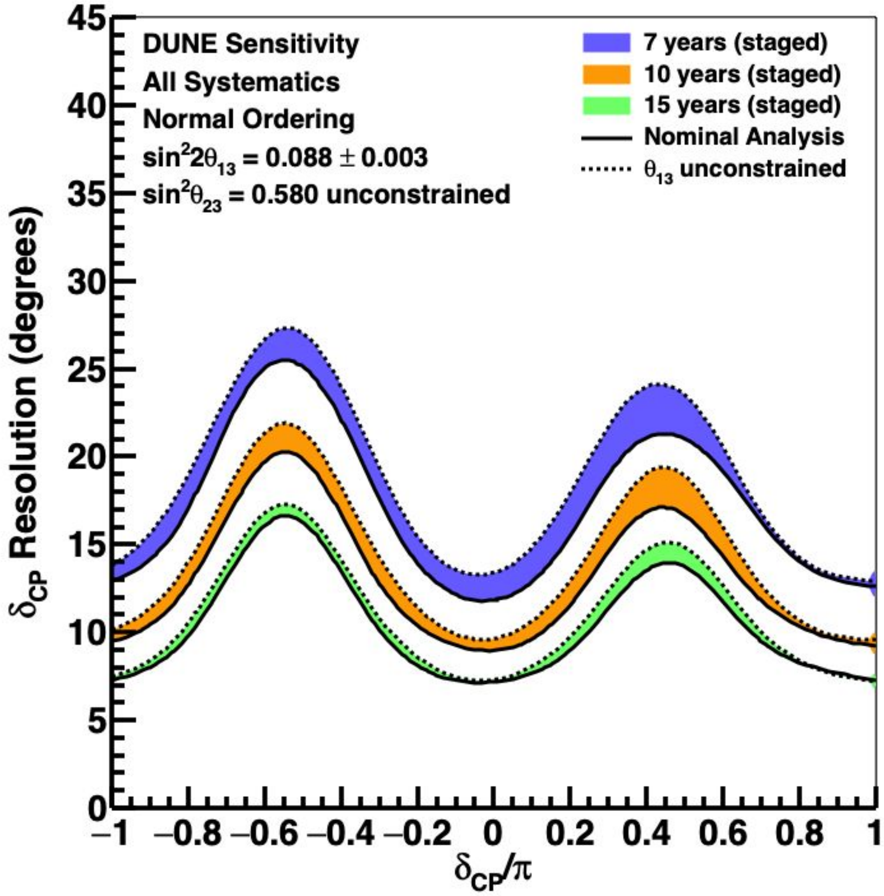
- Single phase: all liquid, charge read out by two induction wire planes and one collection plane
- Dual phase: Charge drifts vertically, amplified and read out in gas phase for larger signal/noise

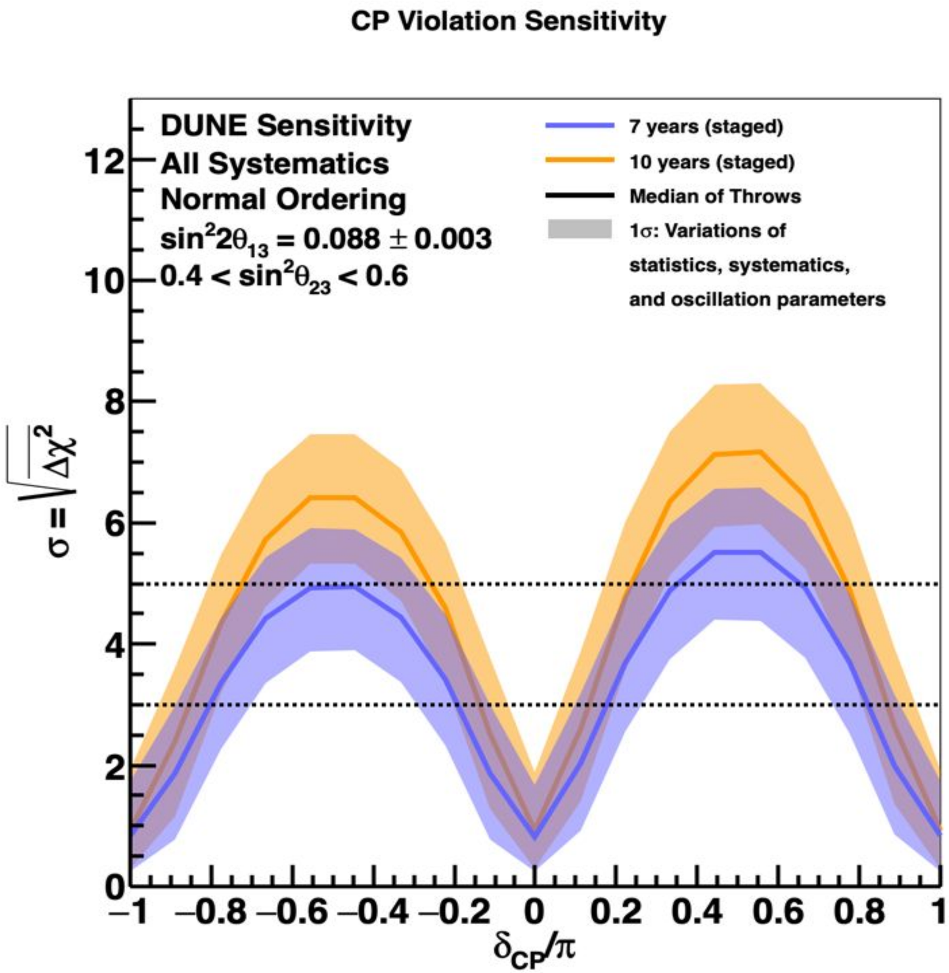
Profile of 17 kiloton module



- 2 cathode planes → 4 drift regions each ~3.6m
- 500 V/cm field = 180 kV potential

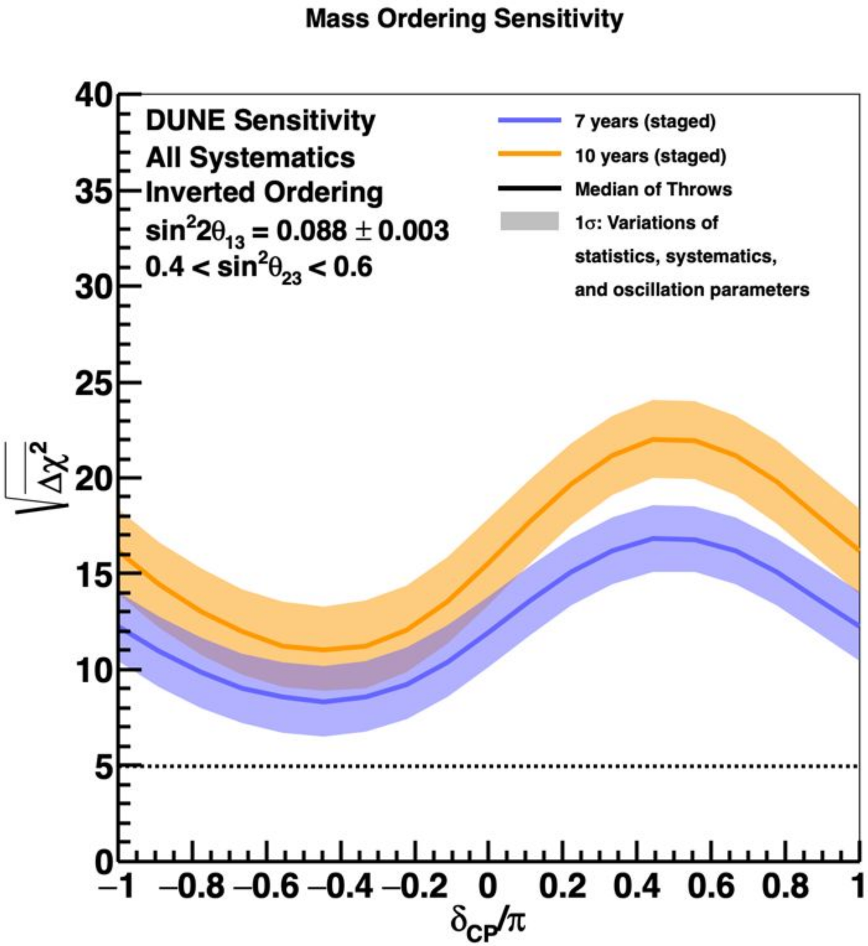
CP sensitivity

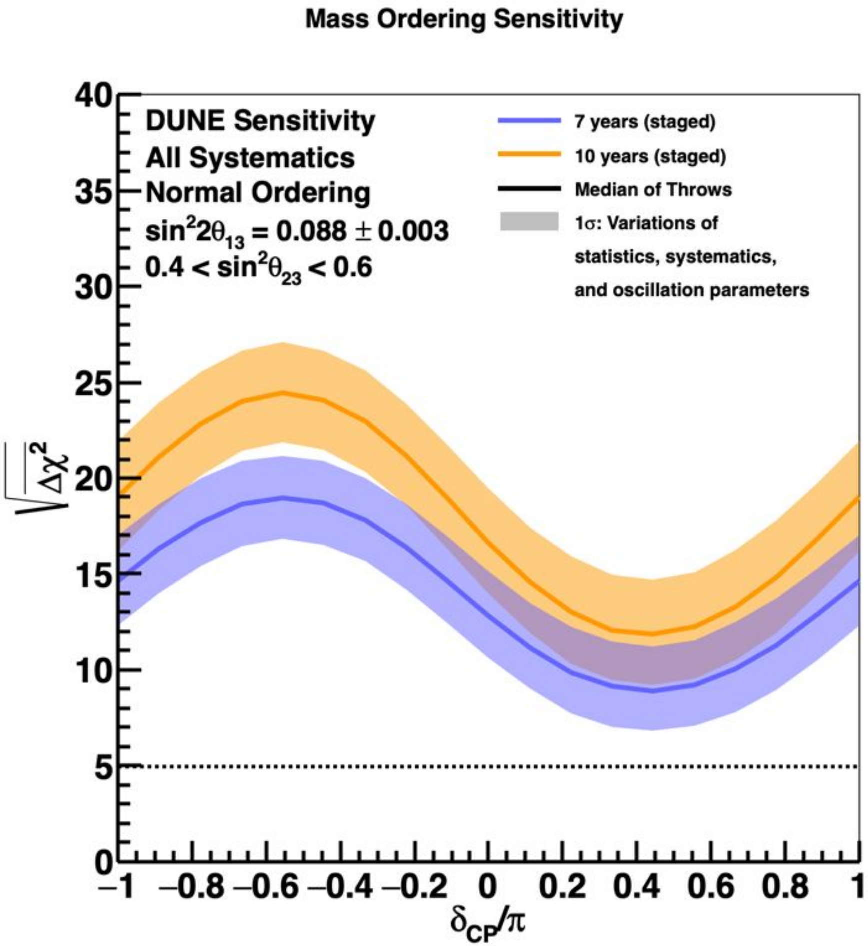




- blah blah blah

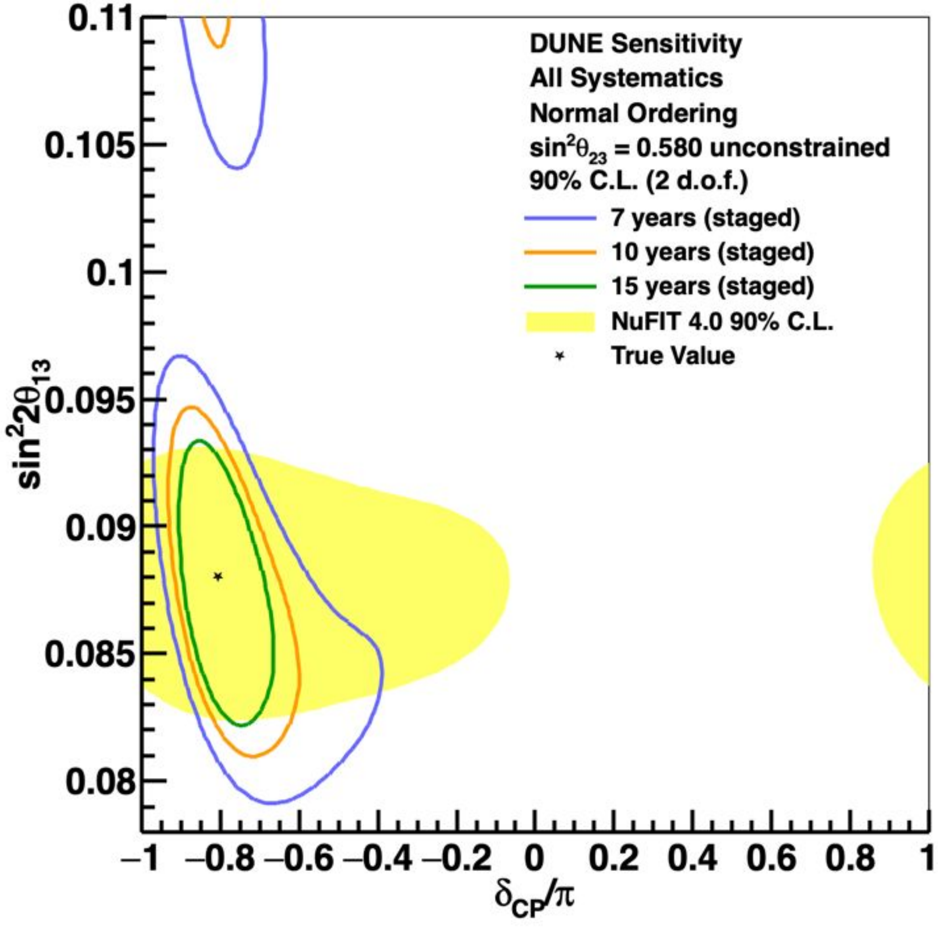
MH sensitivity

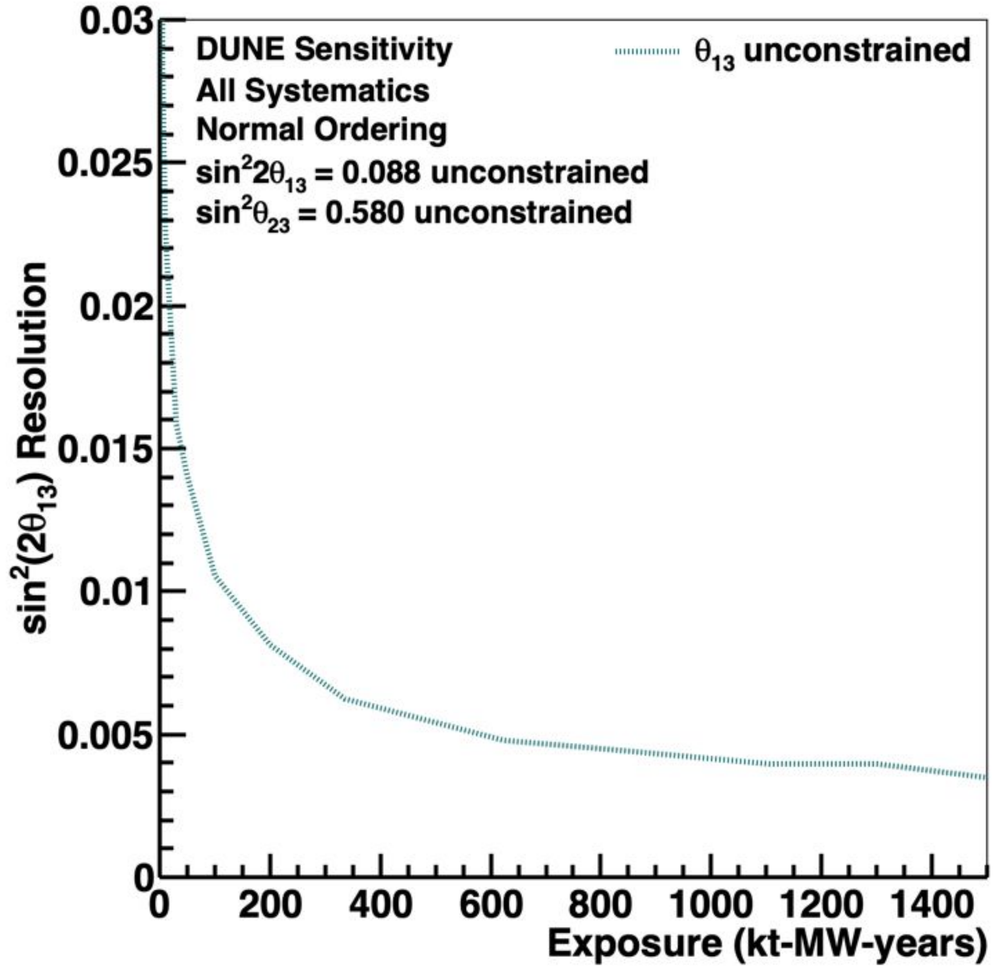




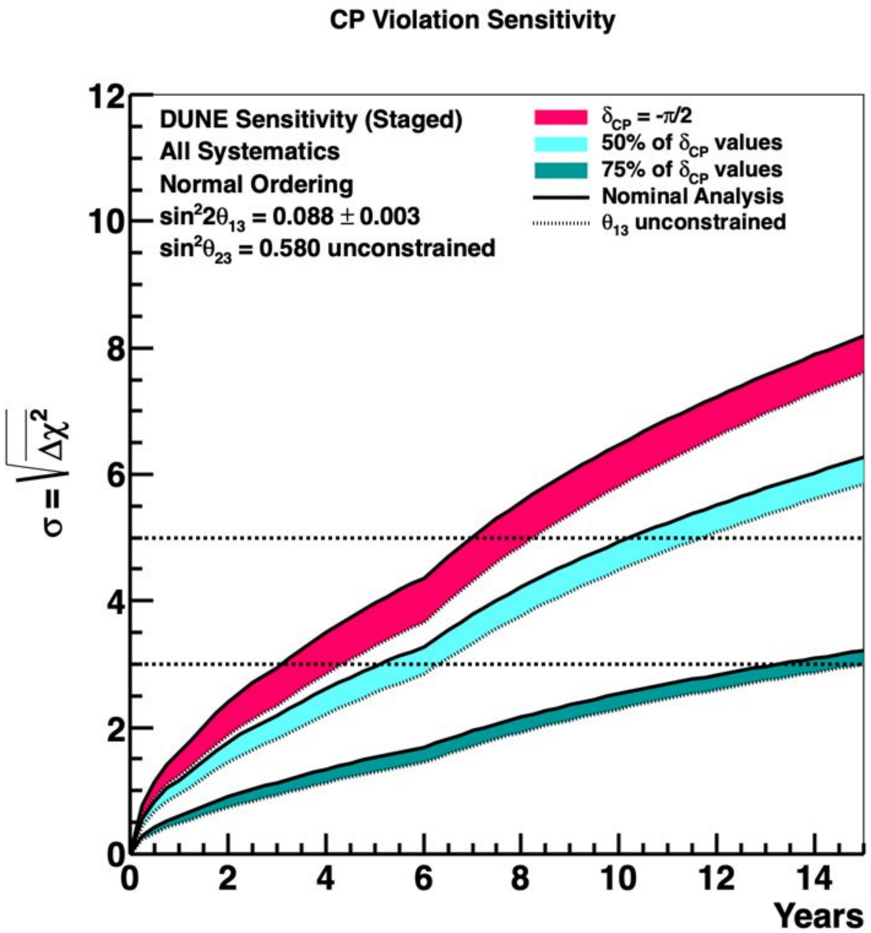
- blah blah blah

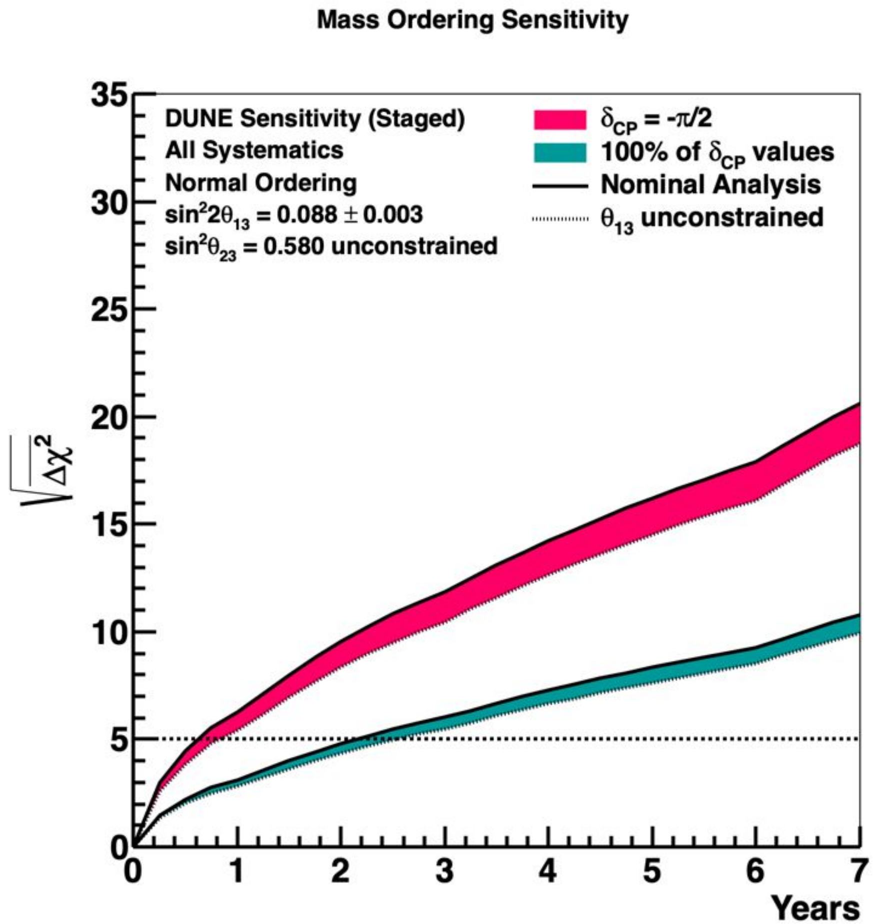
DUNE will reach reactor precision of θ_{13} with full data set





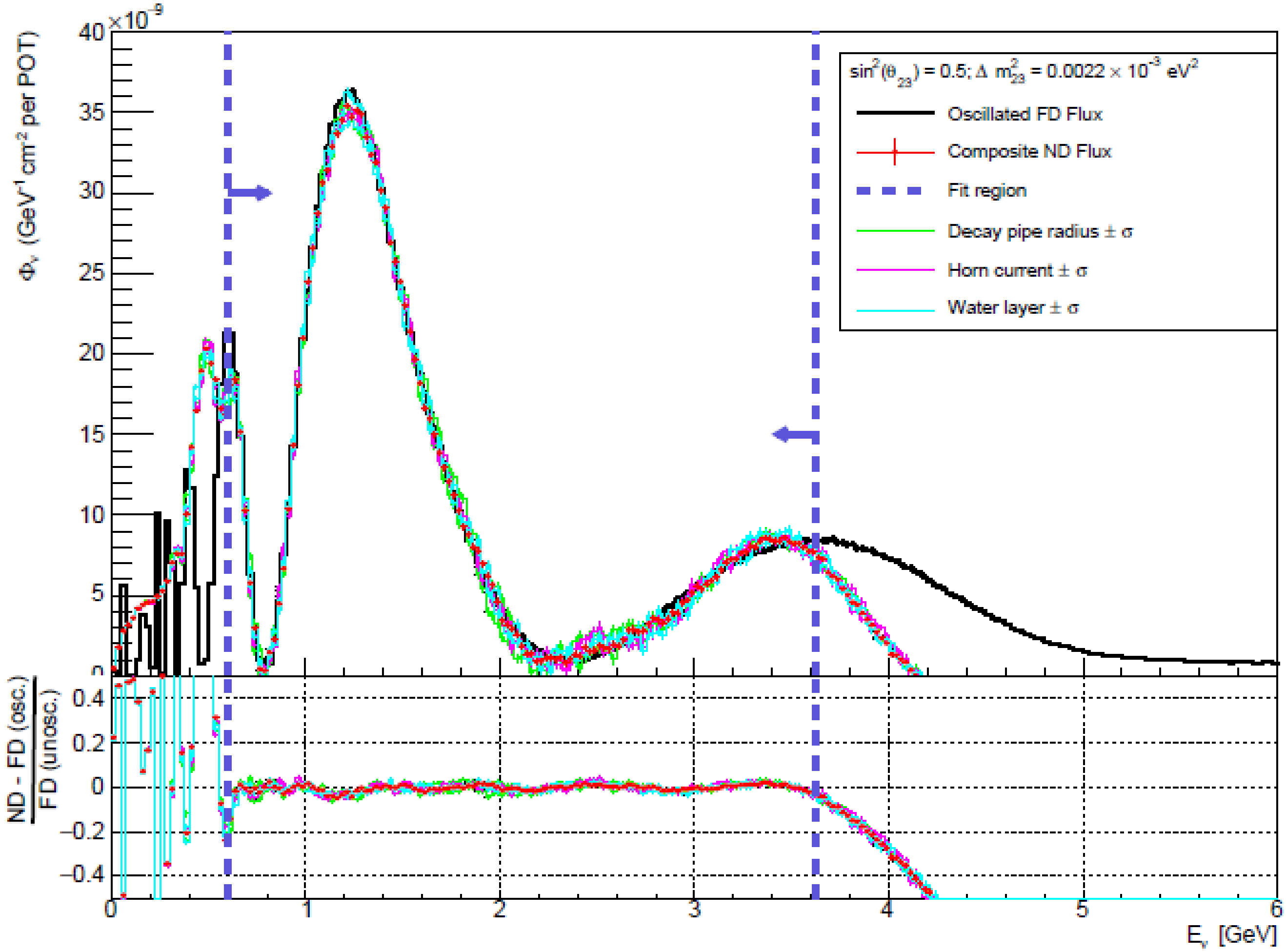
Mass ordering in ~2 years



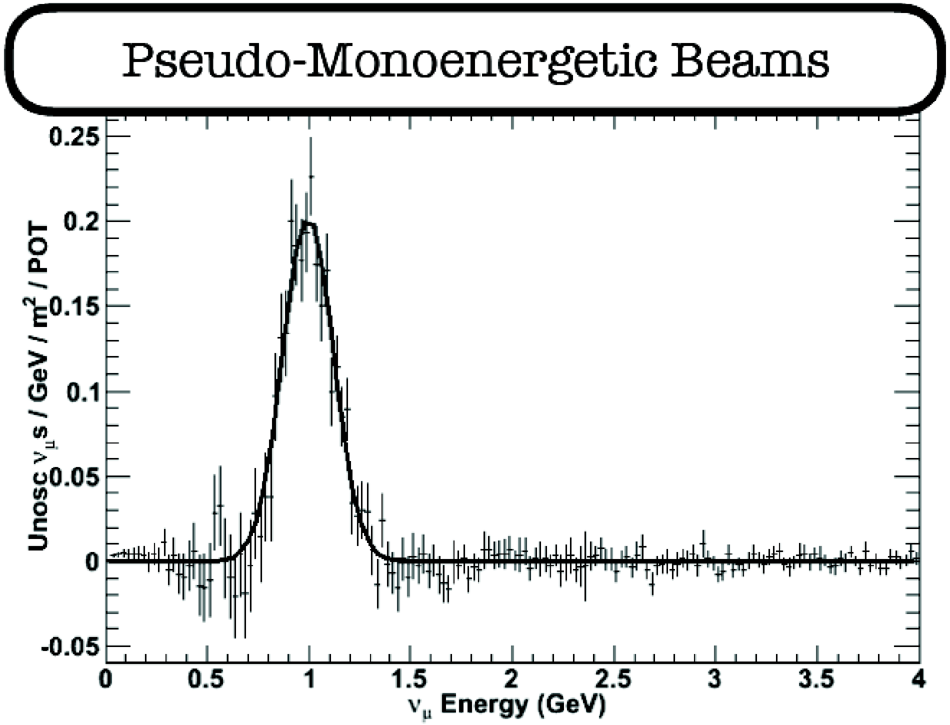


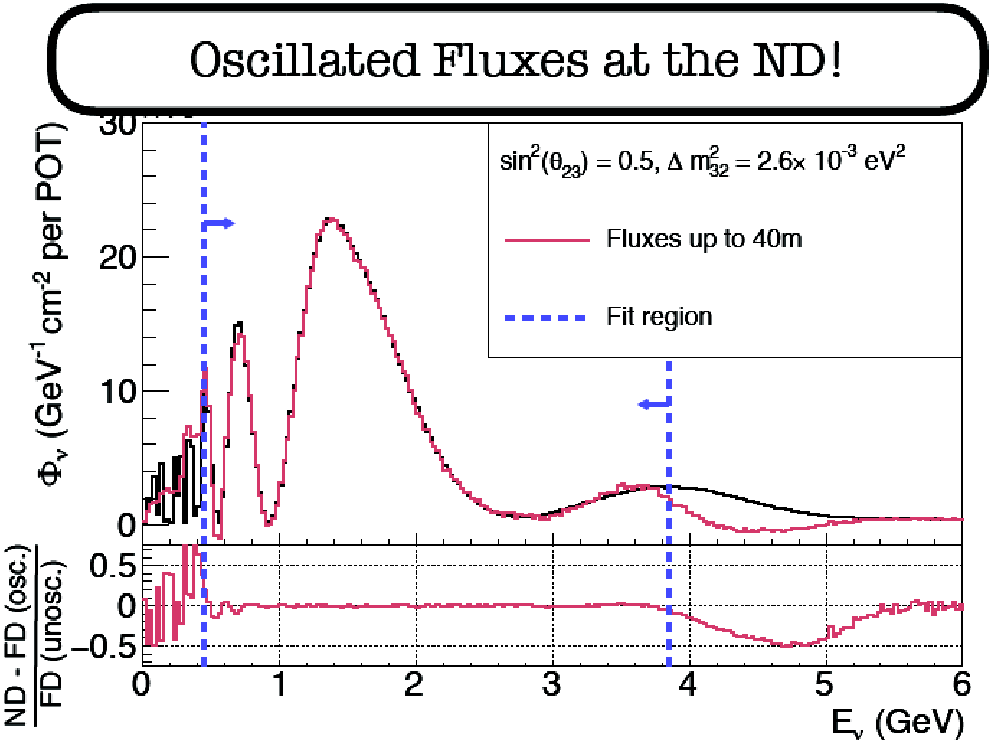
- DUNE will make world-leading measurements throughout its program

FD oscillated flux matching with off-axis ND spectra



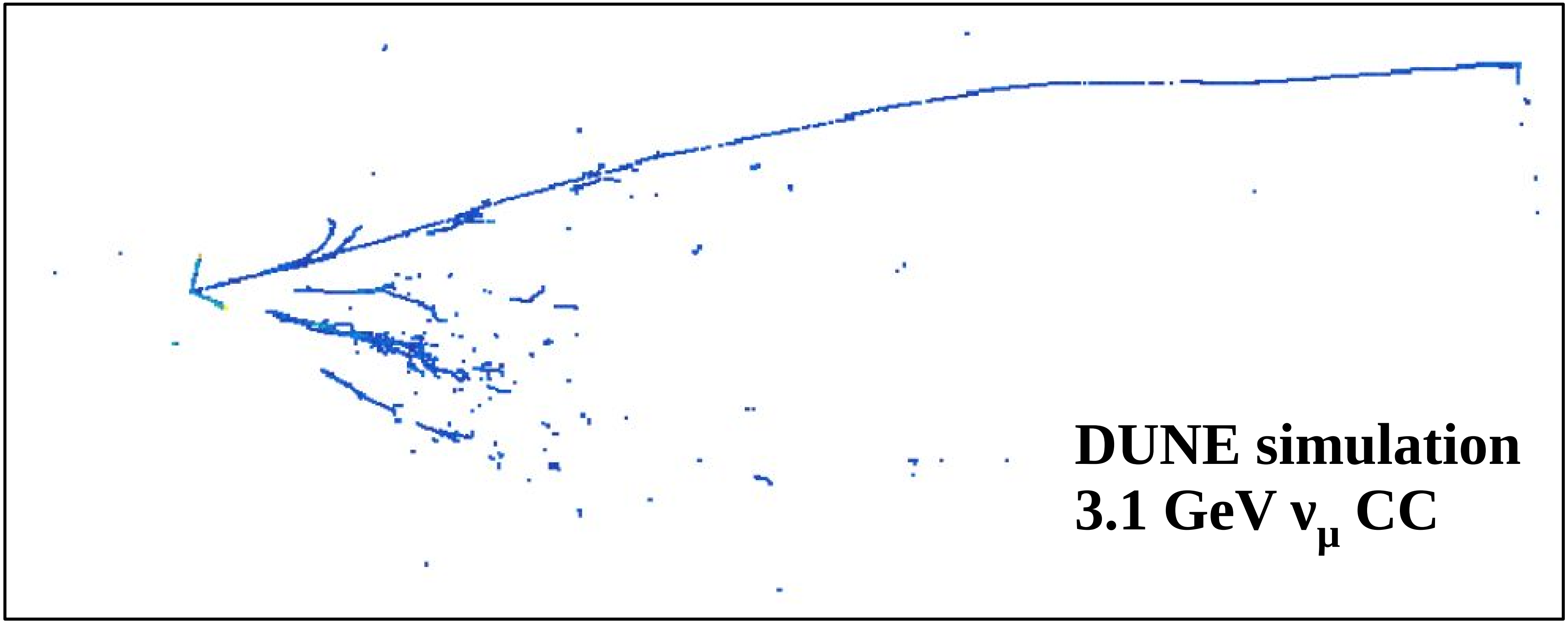
Reproduce FD flux with linear combinations of ND samples





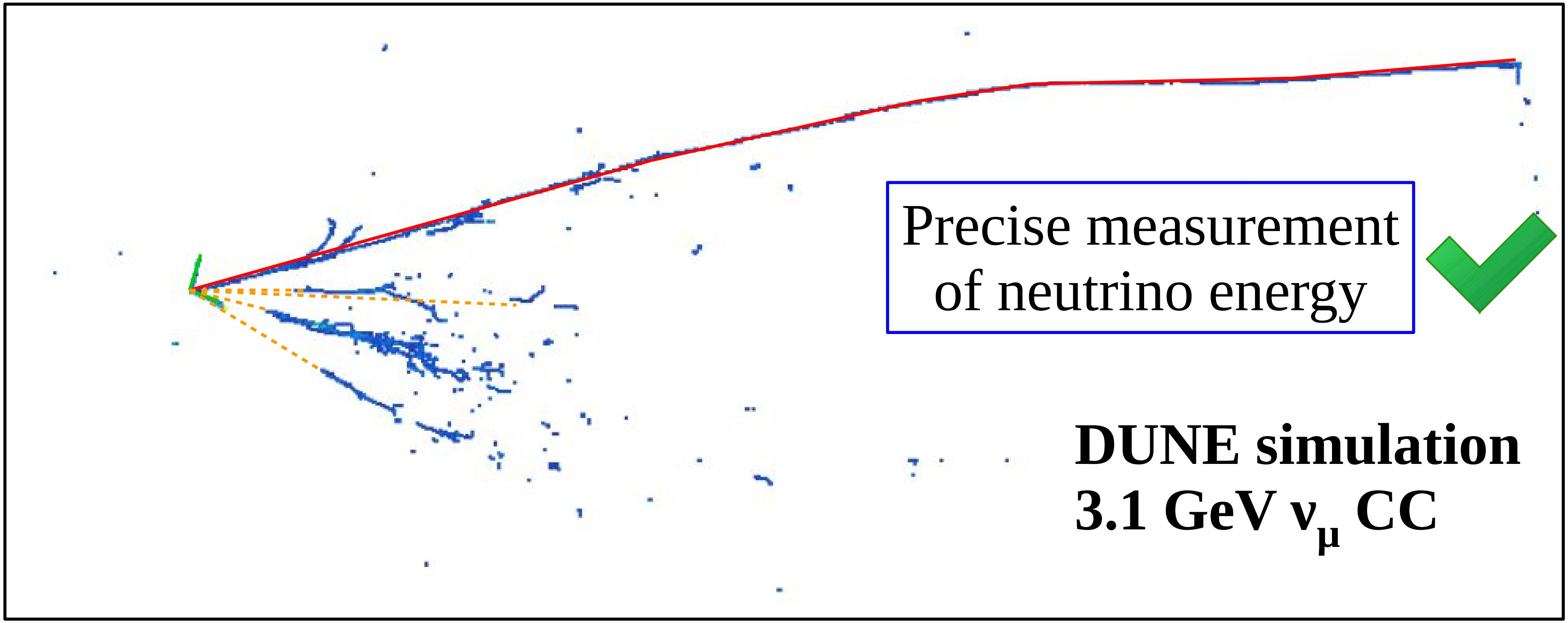
- By taking linear combinations of spectra at different off-axis angles, we can create pseudo-monoenergetic beams
- Or we can create a replica oscillated FD flux for some set of oscillation parameters

Measuring neutrino energy



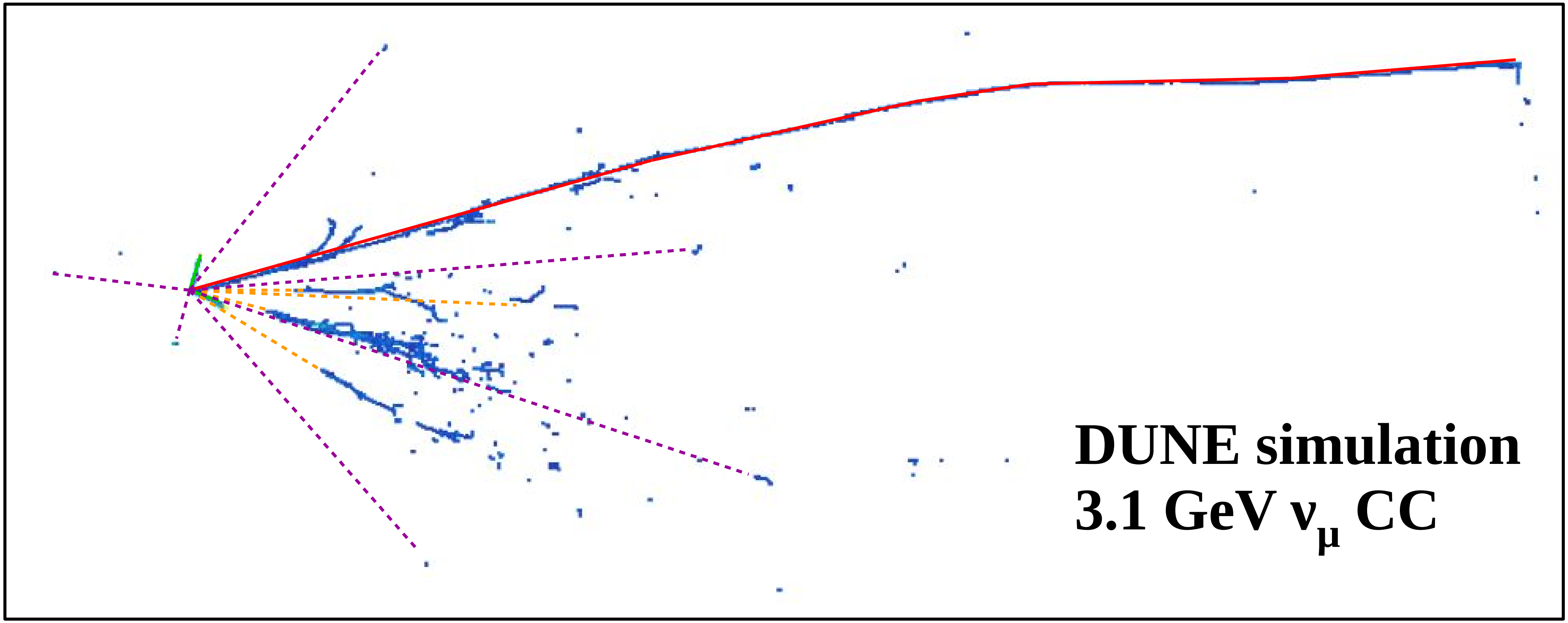
- LAr TPC can "see" ionization energy deposited by charged particles, and measure this energy
- $E_\nu = E_\mu + E_{\pi^\pm} + E_{\pi^0} + E_p + E_n + \ldots$

Measuring neutrino energy



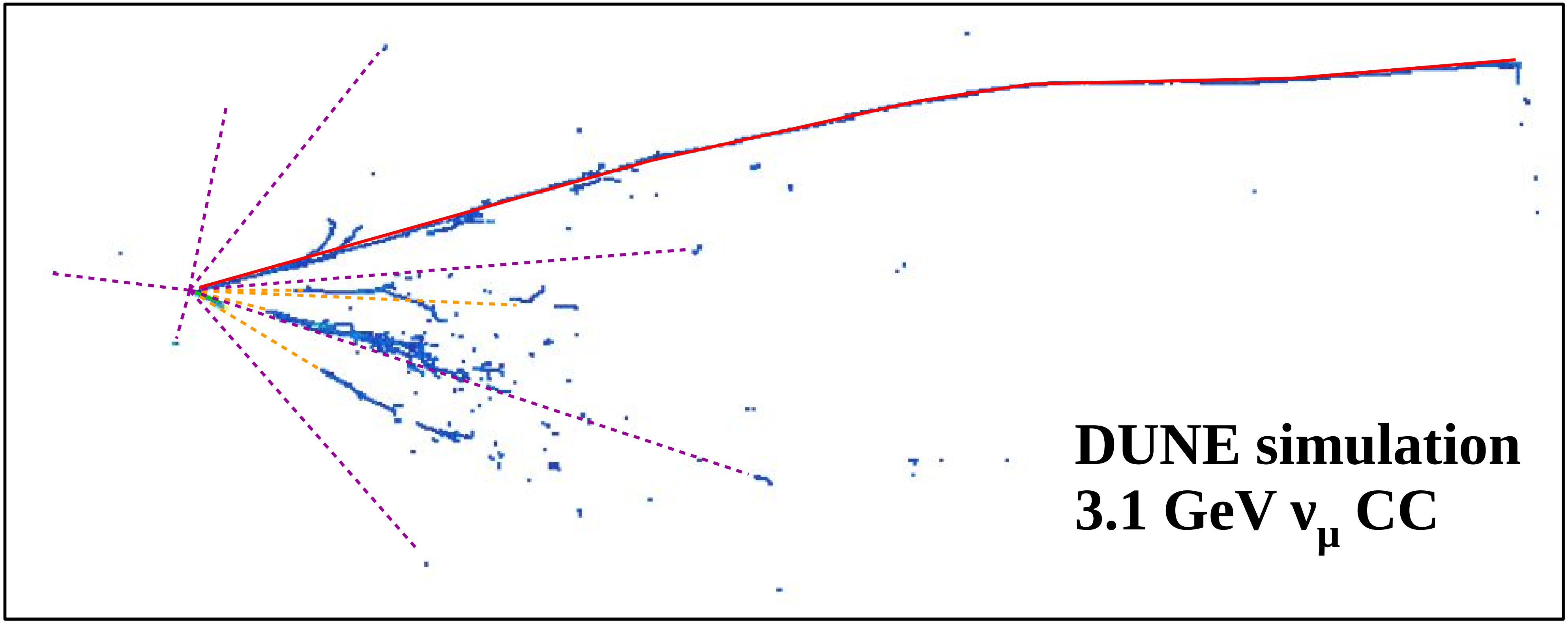
- Leptons, pions, and protons are all seen by DUNE, and can be reconstructed, albeit with somewhat different response functions
- $E_\nu = E_\mu + E_{\pi^\pm} + E_{\pi^0} + E_p + E_n + \ldots$

Measuring neutrino energy



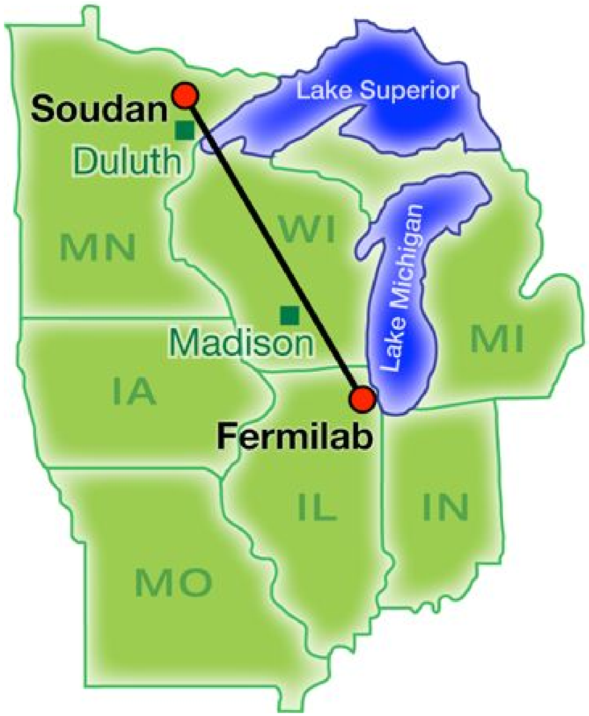
- Neutrons show up as small blips in the detector, and their energy is mostly lost, i.e. “missing energy”
- $E_\nu = E_\mu + E_{\pi^\pm} + E_{\pi^0} + E_p + E_n + \ldots$

Measuring neutrino energy



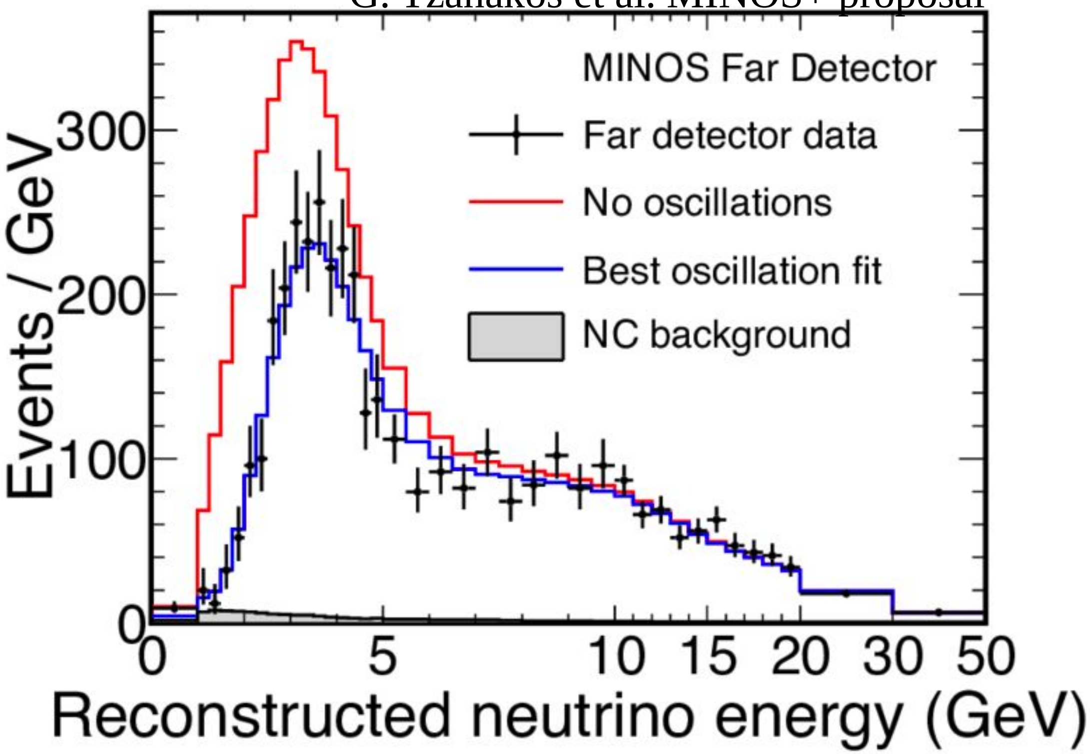
- If you change the composition of the final state, i.e. if there are more neutrons and fewer protons, then the reconstructed energy will be impacted
- $E_\nu = E_\mu + E_{\pi^\pm} + E_{\pi^0} + E_p + E_n + \ldots$

ν_μs disappear in the USA, too



W.C. Louis Physics 4, 54

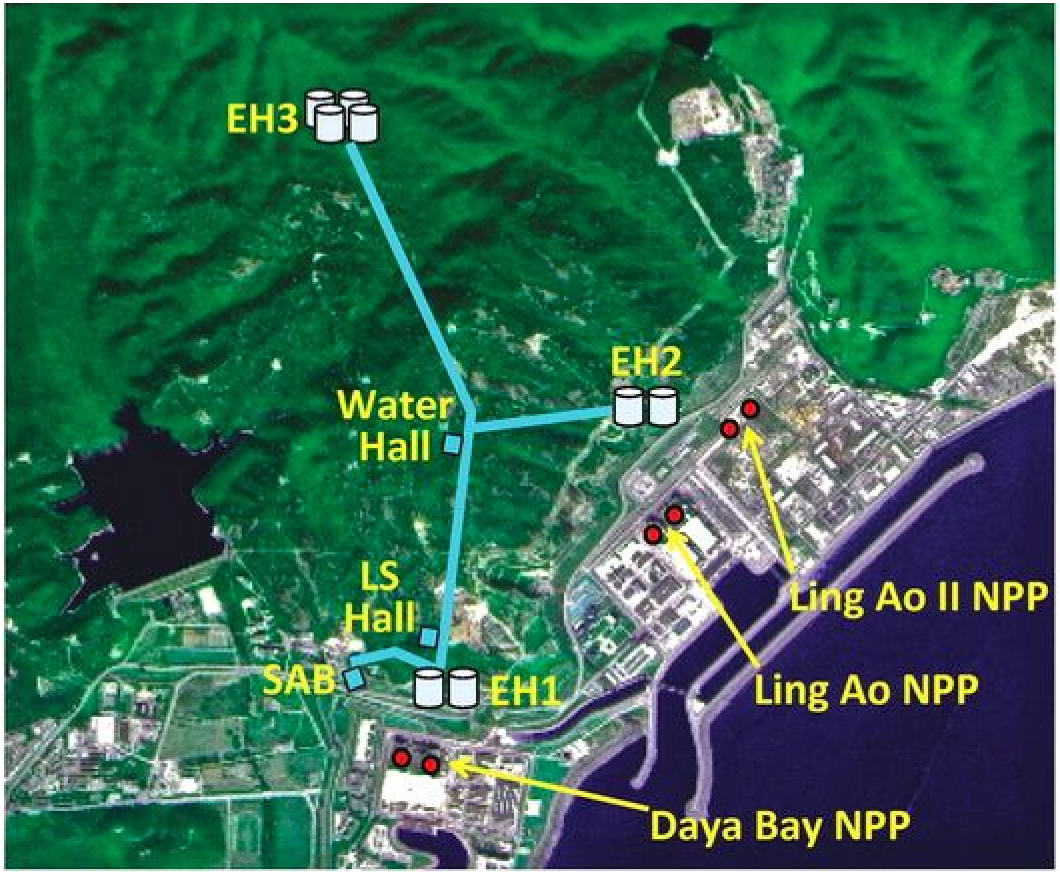
G. Tzanakos et al. MINOS+ proposal



- Muon neutrino beam produced at Fermilab and measured in northern Minnesota
- A deficit is observed due to $\nu_\mu \rightarrow \nu_\tau$ oscillations

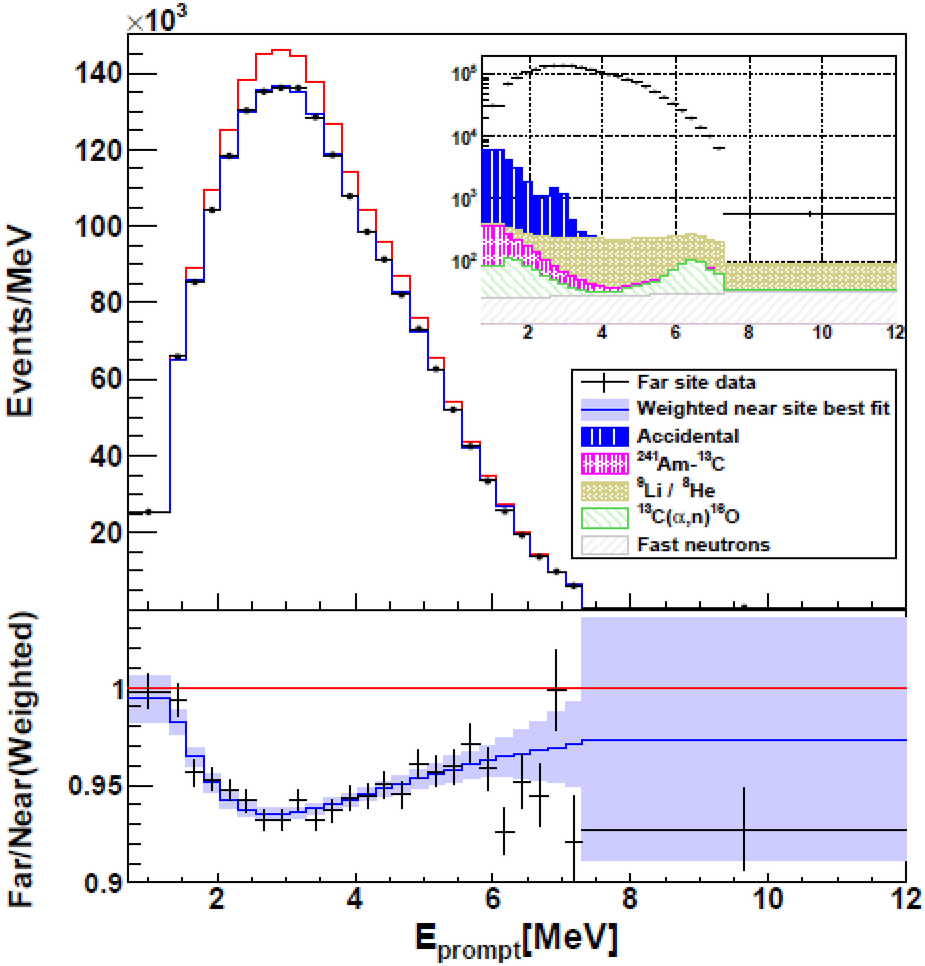
$\bar{\nu}_e$ disappearance at Daya Bay

- Nuclear reactors provide excellent source of “free” electron antineutrinos from beta decays
- Daya Bay measures neutrinos from six reactor cores, with four detectors at a distance of 2 km
- Four near detectors measure the initial neutrino spectrum very near the cores

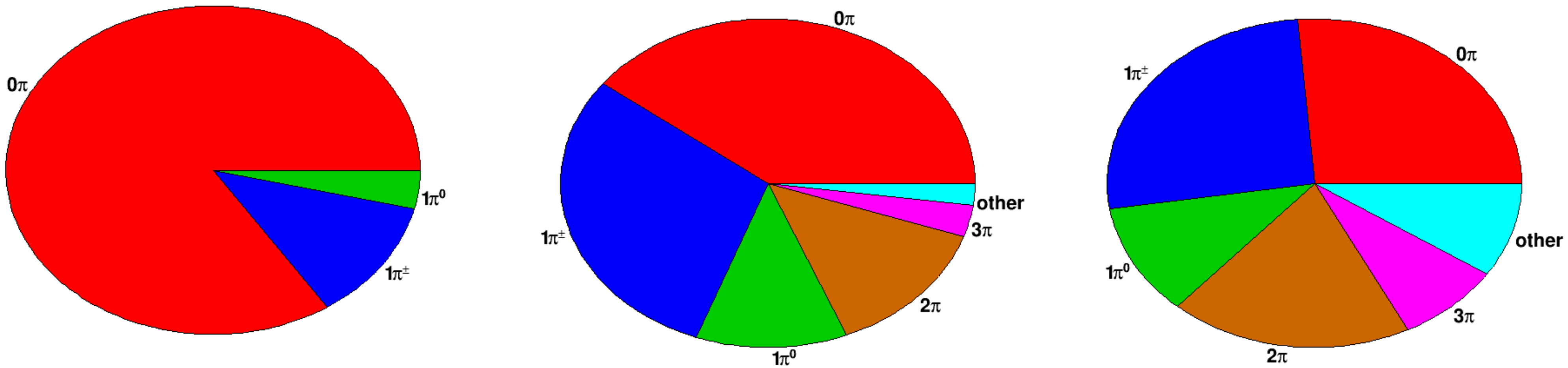


Far detectors see fewer $\bar{\nu}_e$s

- Daya Bay is only sensitive to electron neutrinos
- Observe fewer at the far detectors than is expected based on near detector rate
- $\bar{\nu}_e$s oscillate to other flavors



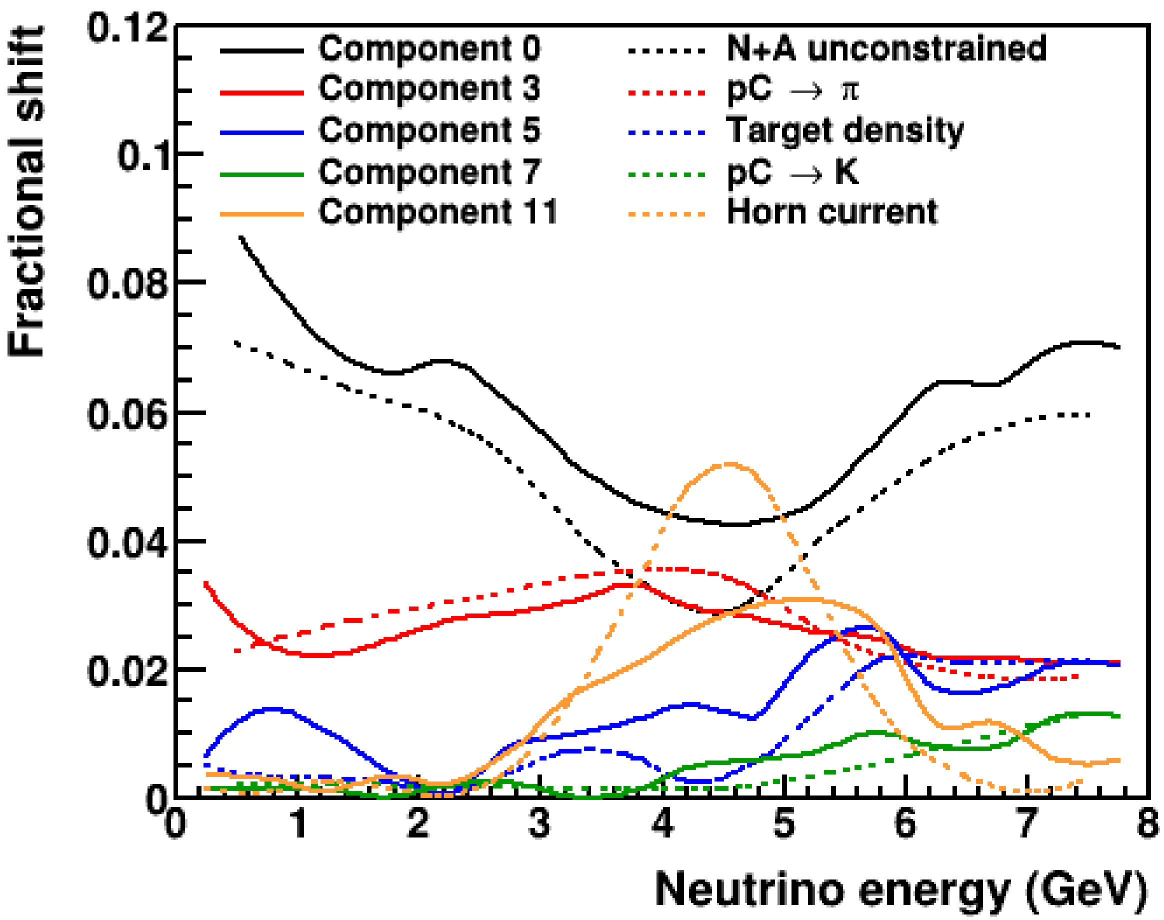
Event mixture in DUNE oscillation sample is very different from T2K



$0.4 < E_\nu < 0.8$ GeV $2.3 < E_\nu < 2.7$ GeV $4.0 < E_\nu < 4.5$ GeV

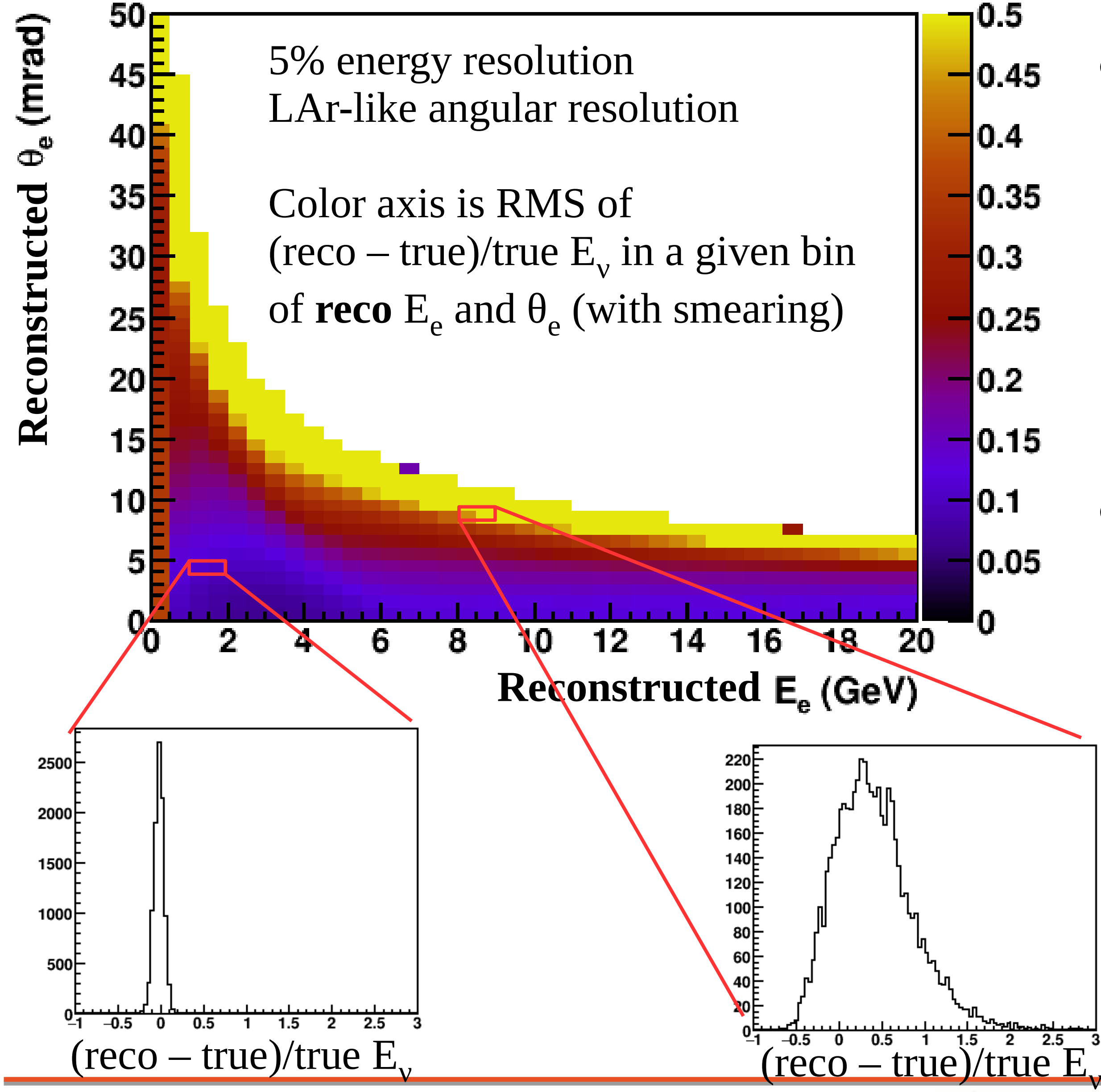
- GENIE "DefaultPlusValenciaMEC" on Ar
- DUNE oscillation peak region is roughly 40% 0π, 40% 1π, 20% 2+π
  - Compared to T2K ~85% 0π
- Huge amount of theory work has dramatically improved our modeling of CC0π – we need this same commitment to 1π, 2π, SIS/DIS, etc. for DUNE

Flux uncertainty principal component analysis



- The largest HP & focusing uncertainties show up as principal components of the full flux covariance
- The largest 30 components are treated as nuisance parameters in DUNE TDR sensitivity analysis

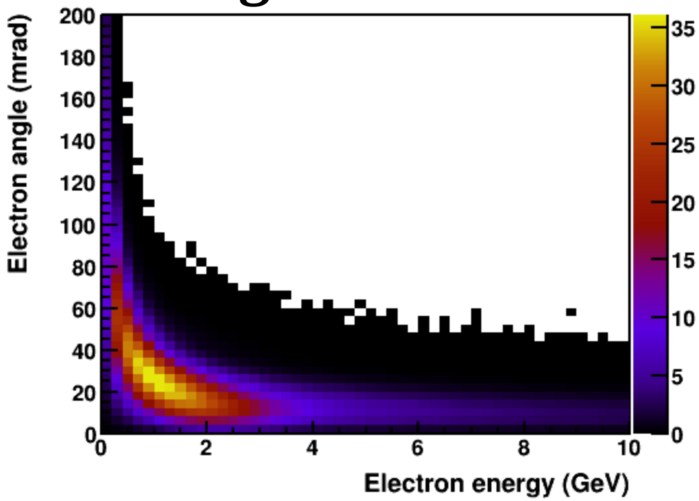
E_ν resolution vs. (E_e, θ_e)



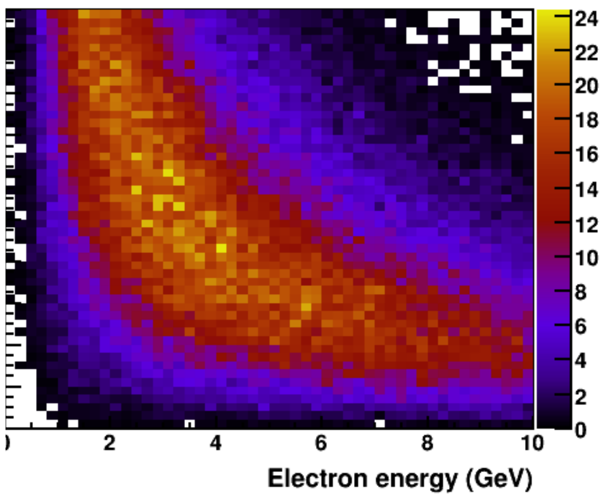
- Energy resolution is quite good in a region of (E,θ), basically where $E\theta^2$ is very small
- Effectively, select a subsample of good, and unbiased energy resolution and measure shape from it
- Requires very high statistics

ν+e scattering signal and backgrounds in E,θ

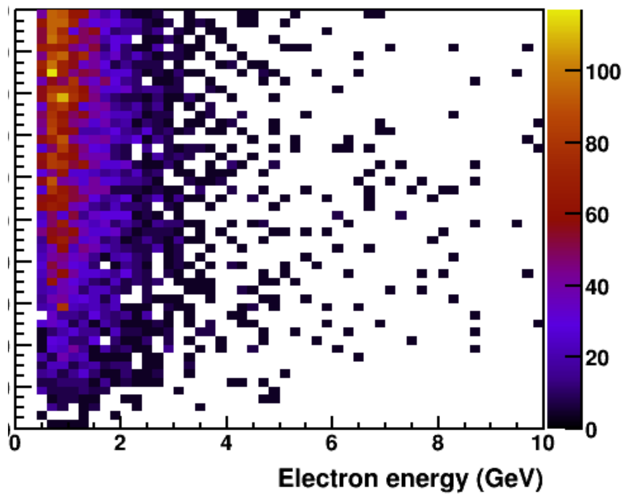
Signal ν+e



ν_e CC

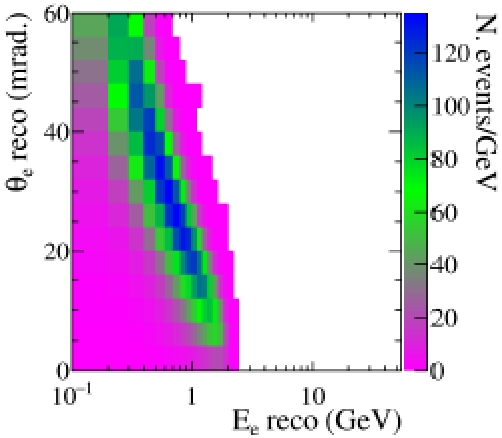


NC π^0

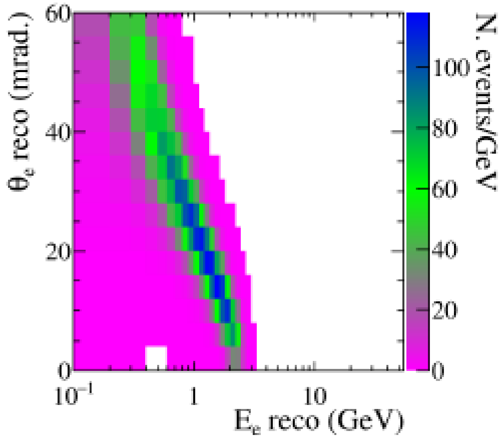


- Signal is subject to kinematic constraint $E_e\theta_e^2 < 2m_e$
- Dominant background is ν_e CC at very low Q^2
- But background shape in E, θ is very different from signal, and realistic uncertainties on background shape still do not produce signal-like distribution

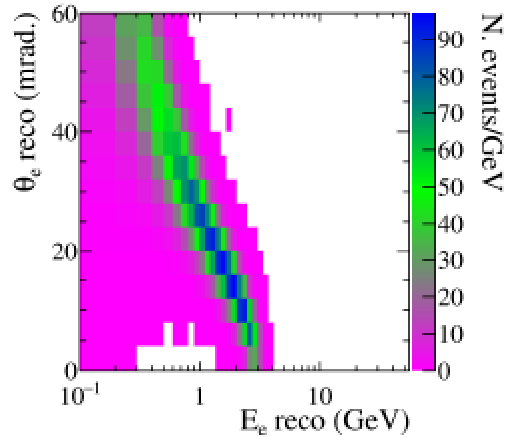
2D templates for ν+e signal



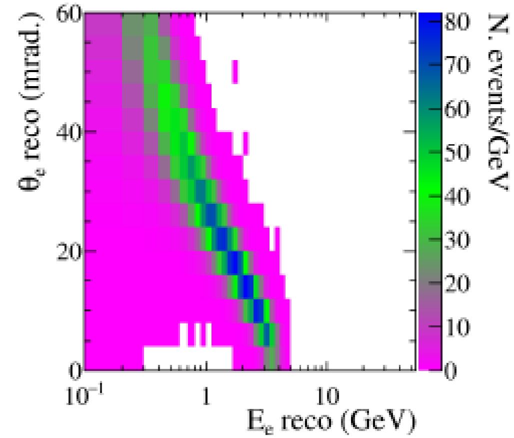
E_1 (0–2 GeV)



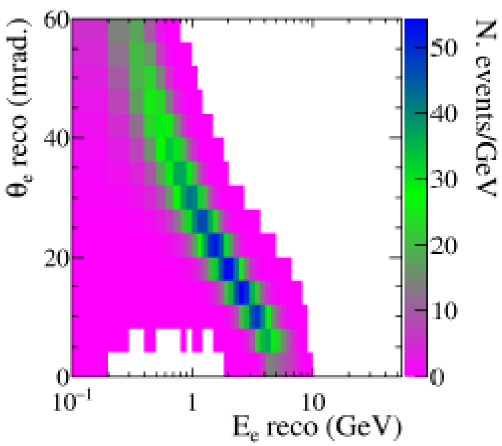
E_2 (2–2.625 GeV)



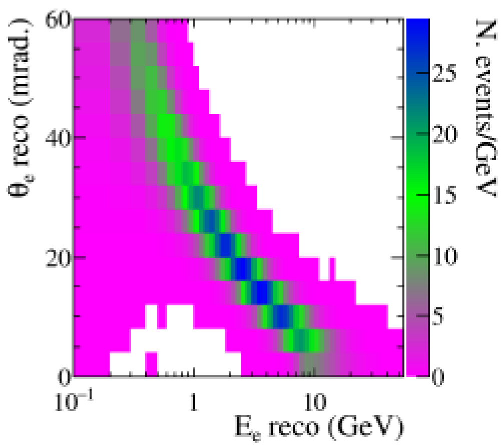
E_3 (2.625–3.25 GeV)



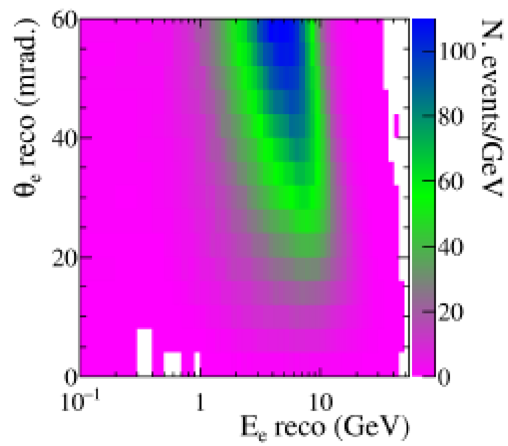
E_4 (3.25–4.25 GeV)



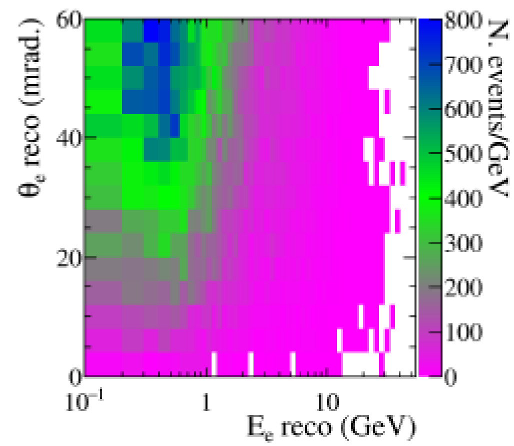
E_5 (4.25–8 GeV)



E_6 (>8 GeV)



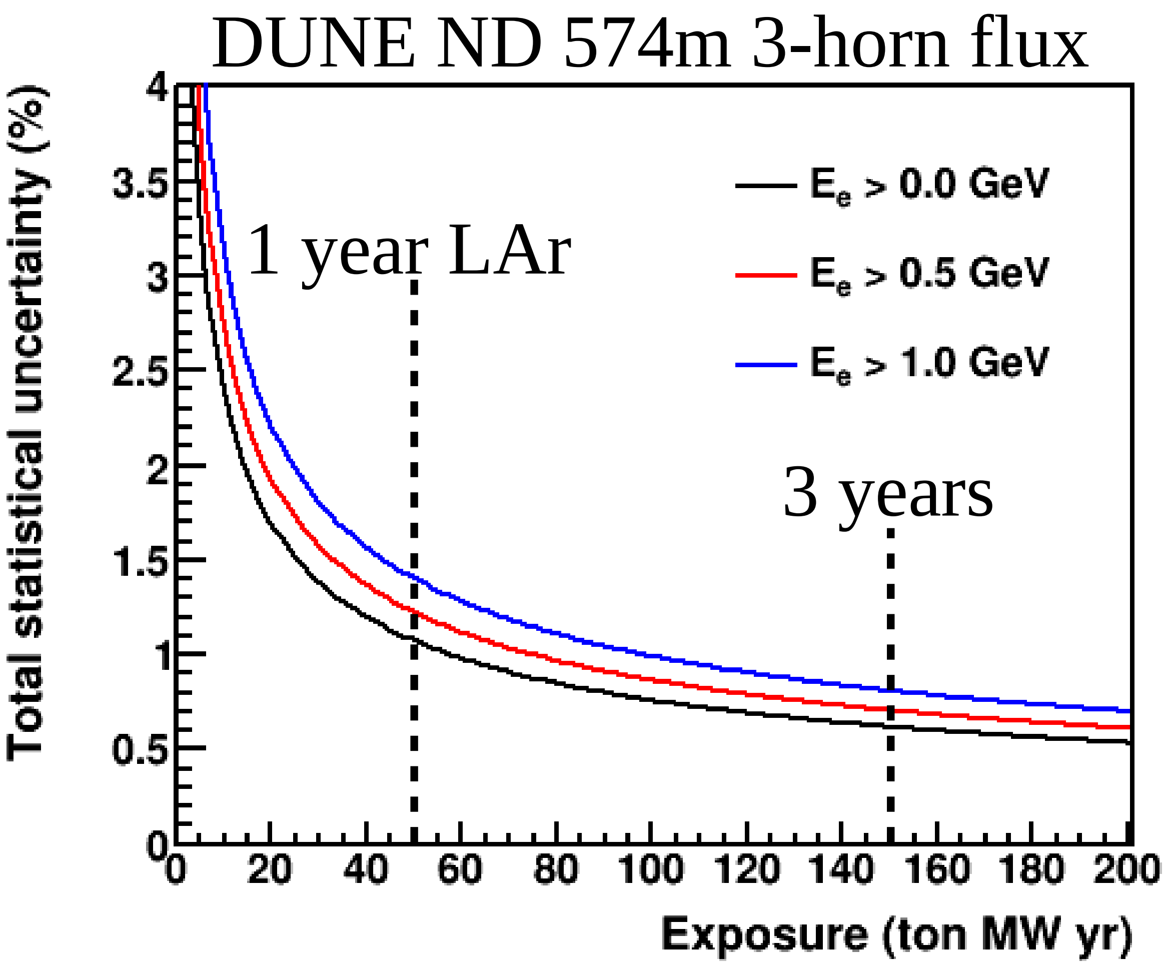
ν_e



γ

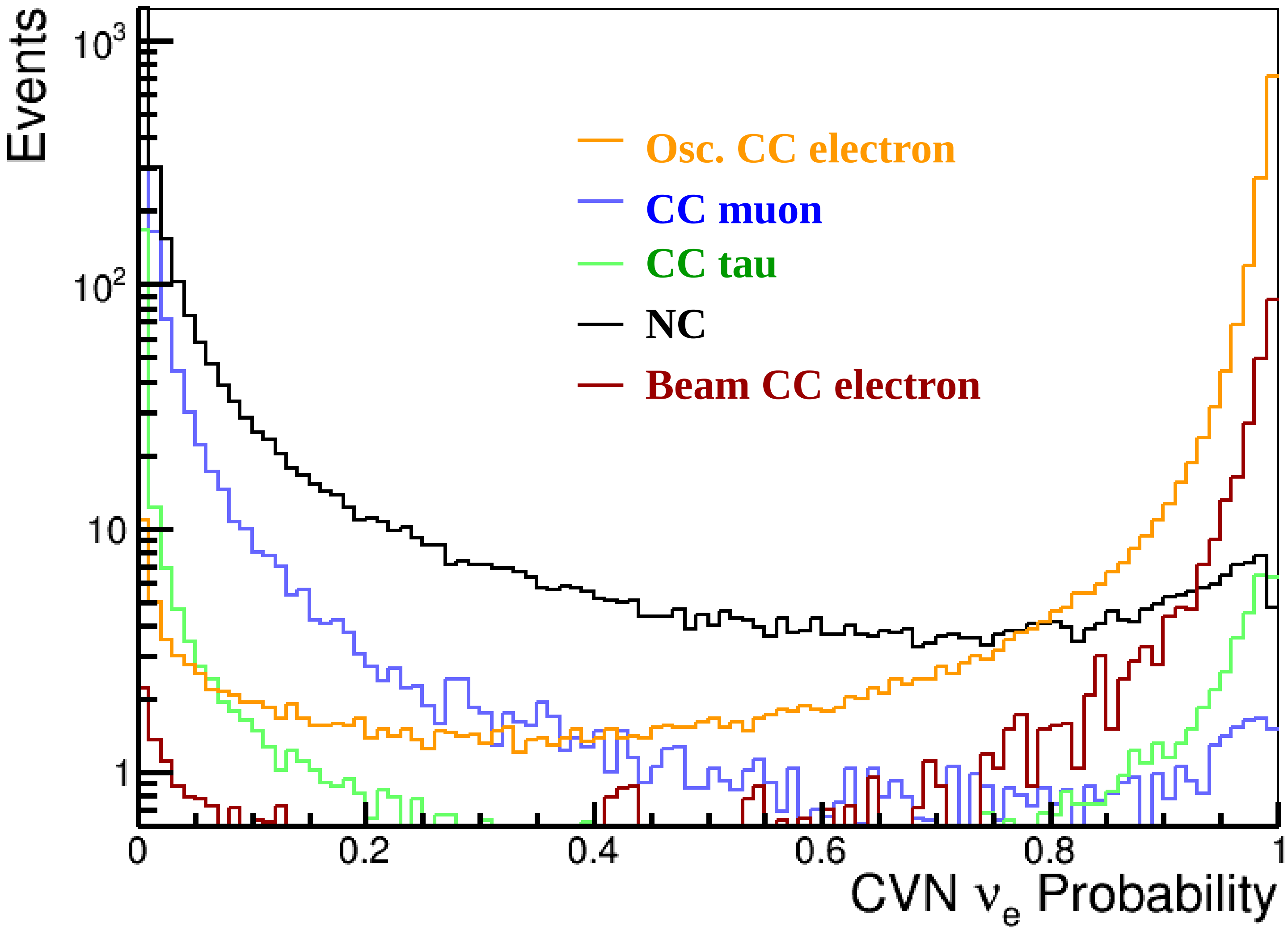
- Each template is a bin of neutrino energy, and adds events in (E,θ)

DUNE ND ν+e statistics



- DUNE LAr ND at ~50t F.V. will have ~15k events in 3 years, even with very conservative thresholds
- >100x more statistics than MINERvA LE analysis

Far detector event selection: FHC ν_e CVN probability



- FHC event probabilities from CVN
- Cut at 0.85 for this analysis
- Selects oscillated and intrinsic electrons

Neutrino oscillation probability

$$P(\nu_\alpha \rightarrow \nu_\beta) = \frac{\Phi_{\nu_\beta}(E_\nu, L)}{\Phi_{\nu_\alpha}(E_\nu, 0)}$$

- The goal of any neutrino oscillation experiment:
  - Measure the flux of neutrinos of flavor β at a distance *L*
  - Compare it to the flux of neutrinos of flavor α at the source
  - As a function of neutrino energy
  - Disappearance (α = β) and appearance (α ≠ β)

We measure neutrino interactions, not fluxes directly

$$N(E_\nu) = \Phi(E_\nu) \times \sigma(E_\nu) \times \epsilon(E_\nu)$$

- Observed interaction rate, *N*, depends on fluxes, but also cross sections (σ), and detector acceptance (ε)
- Cross sections, in particular, are highly uncertain

Energy reconstruction is challenging

$$N(E_{reco}) = \int \Phi(E_\nu) \times \sigma(E_\nu) \times \epsilon(E_\nu) \times \mathbf{D}(E_\nu \rightarrow E_{reco}) dE_\nu$$

- And the observed rate is measured as a function of *reconstructed* energy, which is connected to neutrino energy E_ν by some smearing matrix **D**
- This matrix dependent on your particular detector, but also depends strongly on neutrino interactions

Uncertainties are reduced with near detector measurements

$$\frac{N^{far}(E_{reco}) = \int \Phi(E_\nu, L) \times \sigma(E_\nu) \times \epsilon(E_\nu) \times \mathbf{D}(E_\nu \to E_{reco}) dE_\nu}{N^{near}(E_{reco}) = \int \Phi(E_\nu, 0) \times \sigma(E_\nu) \times \epsilon(E_\nu) \times \mathbf{D}(E_\nu \to E_{reco}) dE_\nu}$$

- Near detector in the same flux, with the same nuclear target, and a similar detector technology, will constrain many uncertain parameters

But there is no magical "cancellation"

$$\frac{N_{\nu_\beta}^{far}(E_{reco}) = \int \Phi_{\nu_\beta}(E_\nu, L) \times \sigma_{\nu_\beta}(E_\nu) \times \epsilon_{\nu_\beta}^{far}(E_\nu) \times \mathbf{D}_{\nu_\beta}^{far}(E_\nu \rightarrow E_{reco}) dE_\nu}{N_{\nu_\alpha}^{near}(E_{reco}) = \int \Phi_{\nu_\alpha}(E_\nu, 0) \times \sigma_{\nu_\alpha}(E_\nu) \times \epsilon_{\nu_\alpha}^{near}(E_\nu) \times \mathbf{D}_{\nu_\alpha}^{near}(E_\nu \rightarrow E_{reco}) dE_\nu}$$

- There are many differences between the observed interaction rates at the near and far detectors, which lead to systematic uncertainties:
  - Fluxes are different primarily due to oscillations
  - Cross sections are strongly energy-dependent, potentially different nucleus, or different neutrino flavor
  - Even if ND and FD are "functionally identical," acceptance and energy reconstruction will be somewhat different due to the sizes

But there is no magical "cancellation"

?

$$\frac{N^{far}_{\nu_\beta}(E_{reco}) = \int \Phi_{\nu_\beta}(E_\nu, L) \times \sigma_{\nu_\beta}(E_\nu) \times \epsilon^{far}_{\nu_\beta}(E_\nu) \times \mathbf{D}^{far}_{\nu_\beta}(E_\nu \rightarrow E_{reco}) dE_\nu}{N^{near}_{\nu_\alpha}(E_{reco}) = \int \Phi_{\nu_\alpha}(E_\nu, 0) \times \sigma_{\nu_\alpha}(E_\nu) \times \epsilon^{near}_{\nu_\alpha}(E_\nu) \times \mathbf{D}^{near}_{\nu_\alpha}(E_\nu \rightarrow E_{reco}) dE_\nu}$$

- All of these terms depend on E_ν, so this product cannot be factorized
- Even if the ND and FD were literally identical, the flux differences mean that nothing actually cancels
- Independent knowledge of flux and cross sections is very helpful

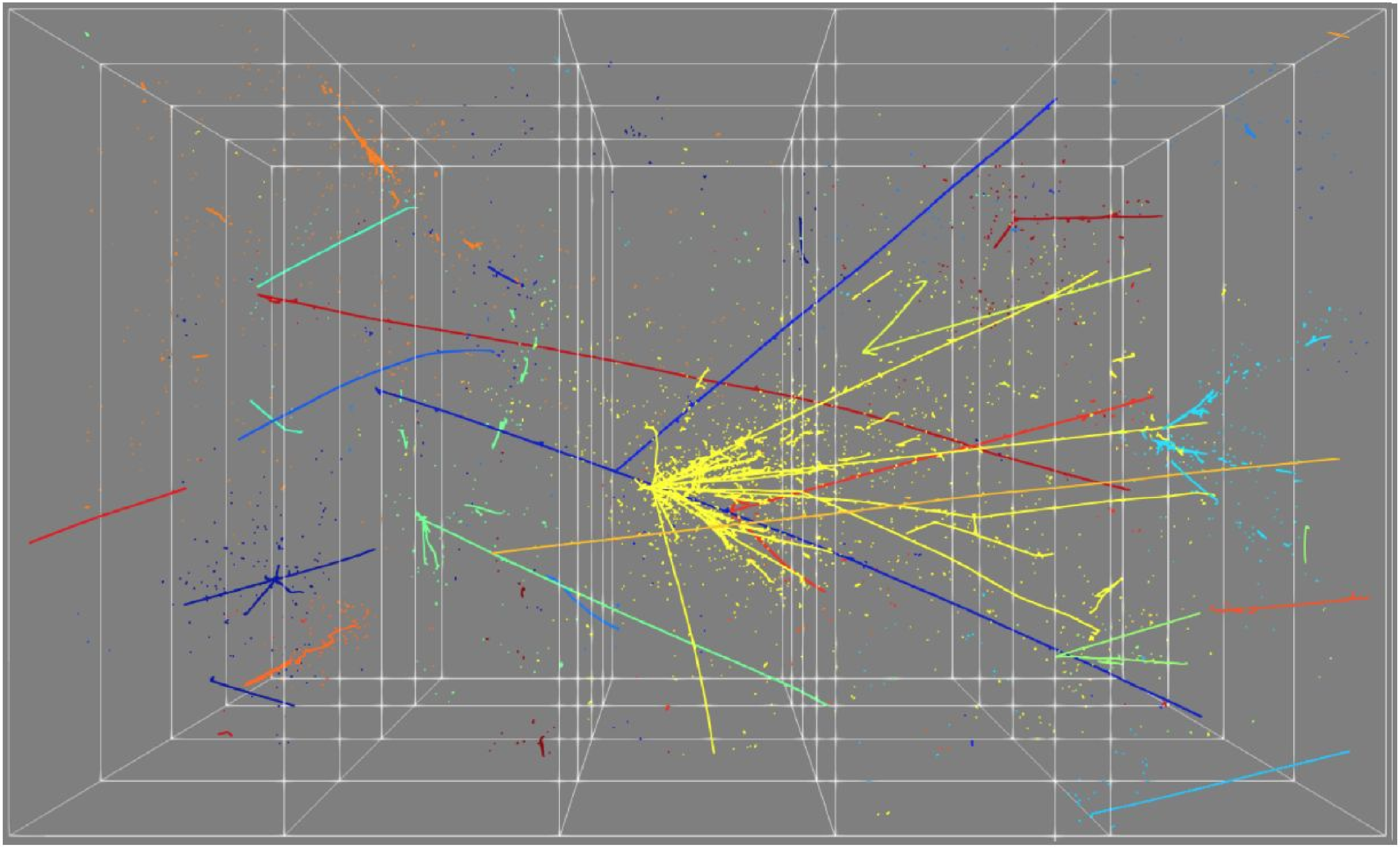
But there is no magical "cancellation"

no

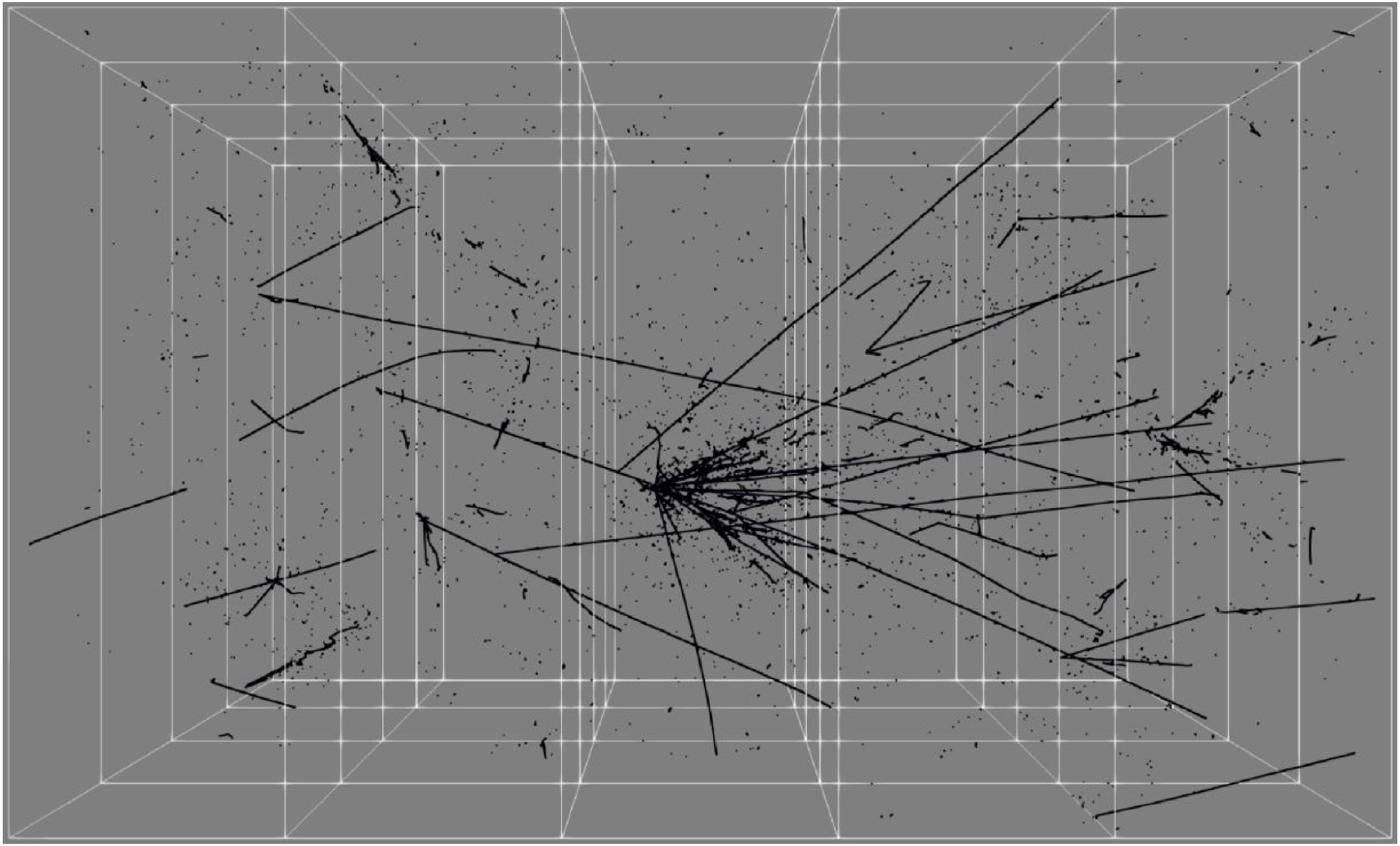
$$\frac{N^{far}_{\nu_\beta}(E_{reco}) = \int \Phi_{\nu_\beta}(E_\nu, L) \times \sigma_{\nu_\beta}(E_\nu) \times \epsilon^{far}_{\nu_\beta}(E_\nu) \times \mathbf{D}^{far}_{\nu_\beta}(E_\nu \to E_{reco}) dE_\nu}{N^{near}_{\nu_\alpha}(E_{reco}) = \int \Phi_{\nu_\alpha}(E_\nu, 0) \times \sigma_{\nu_\alpha}(E_\nu) \times \epsilon^{near}_{\nu_\alpha}(E_\nu) \times \mathbf{D}^{near}_{\nu_\alpha}(E_\nu \to E_{reco}) dE_\nu}$$

- All of these terms depend on E_ν, so this product cannot be factorized
- Even if the ND and FD were literally identical, the flux differences mean that nothing actually cancels
- Independent knowledge of flux and cross sections is very helpful

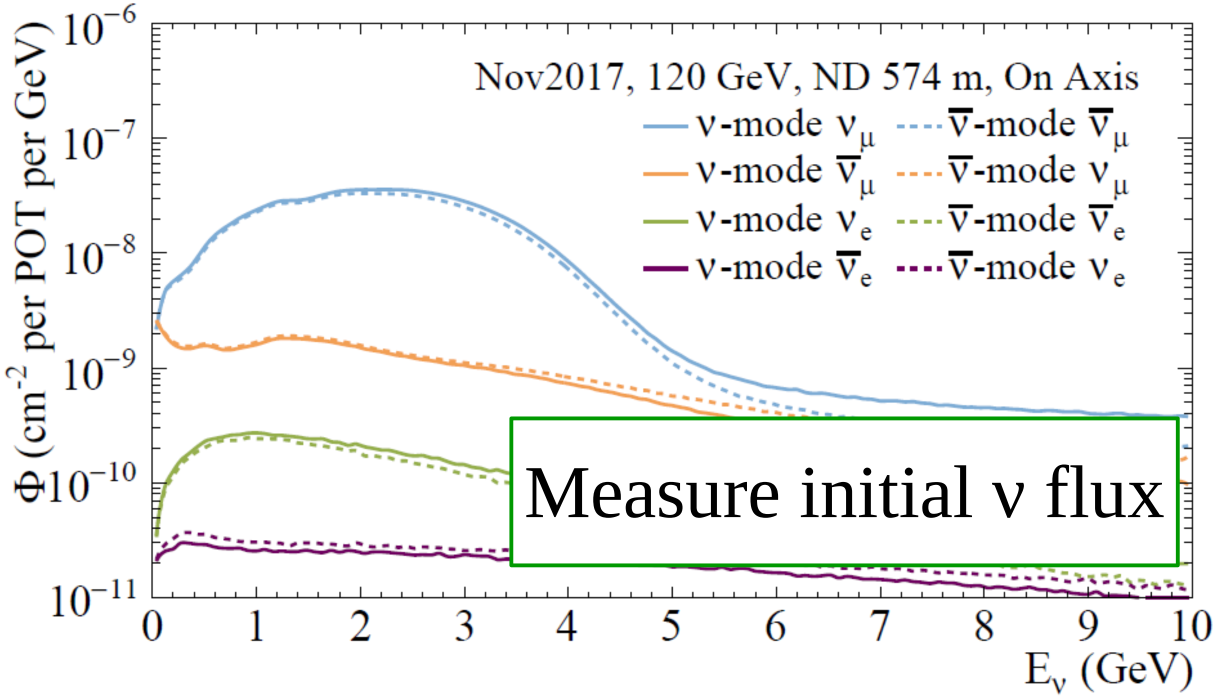
One beam spill at 1MW in LAr ND...

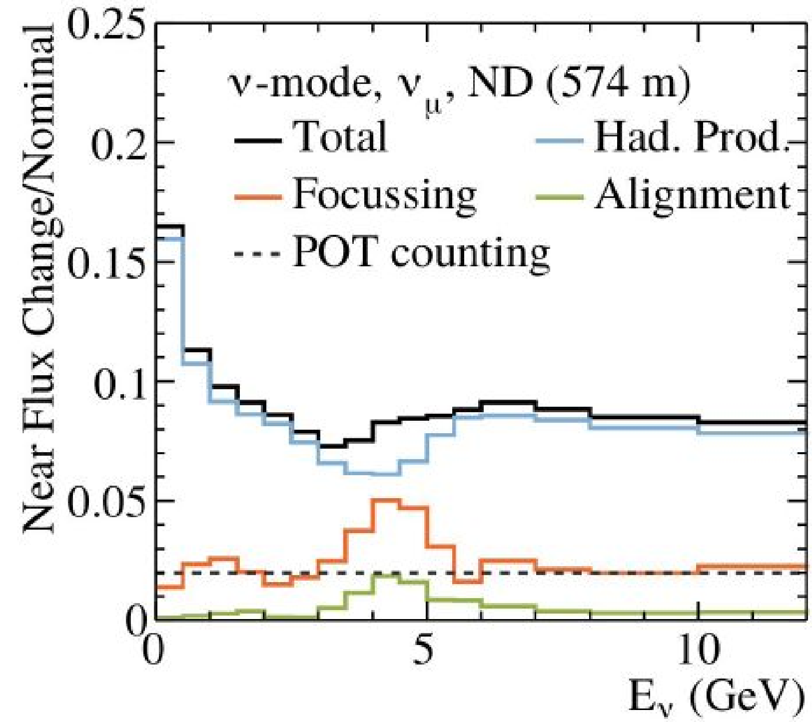


...without timing resolution



DUNE near detector must constrain the initial neutrino flux

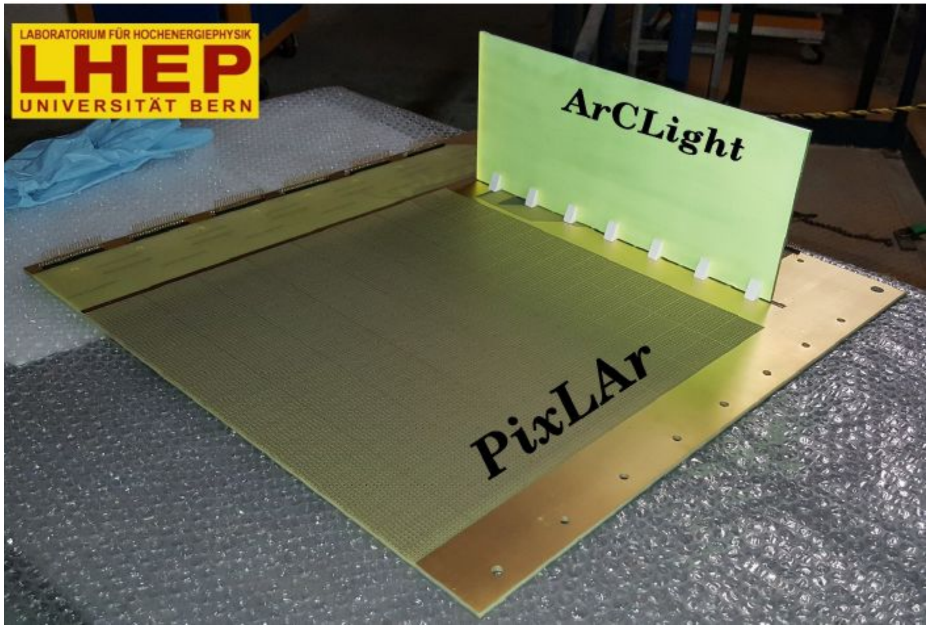




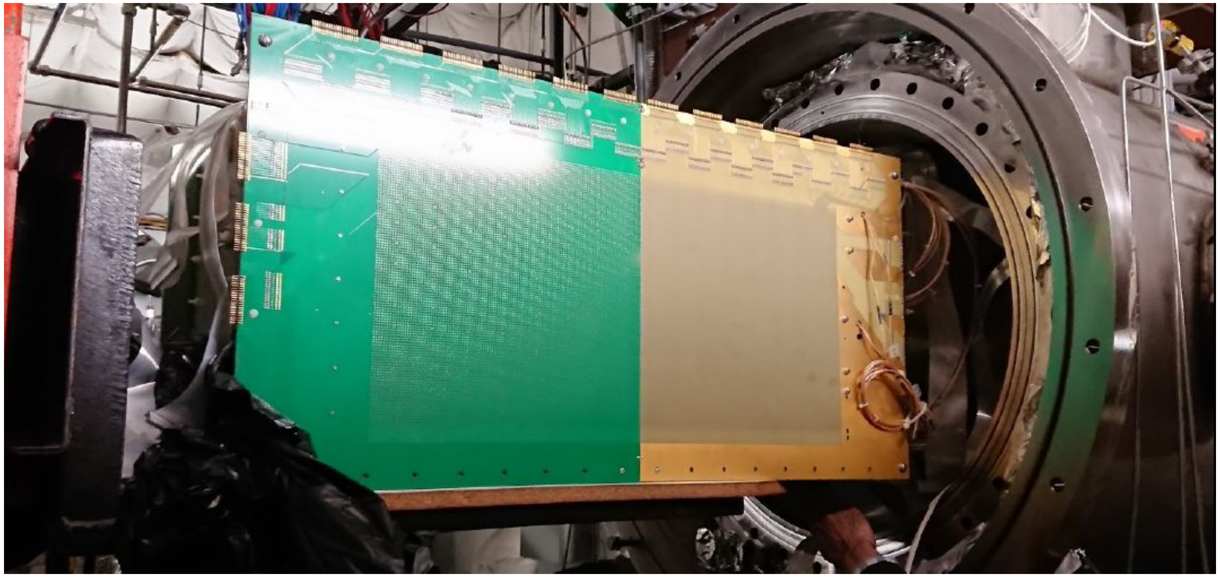
- Neutrino flux is known at the 10% level due to uncertainties in meson production in proton-carbon interactions, and modeling of the beam focusing
- This is not good enough – need few % constraint from ND

ArgonCube concept

- Full three-dimensional readout with pads
  - Pad coordinates give two dimensions + third from drift time
  - Removes reconstruction ambiguities present in projective readout
  - Greatly reduces event overlap
- Modular, optically segmented
  - Each 1x1m module has its own photon detector, covering the walls orthogonal to pixel planes
  - Few ns timing resolution
  - Can separate optical signals from different neutrino interactions



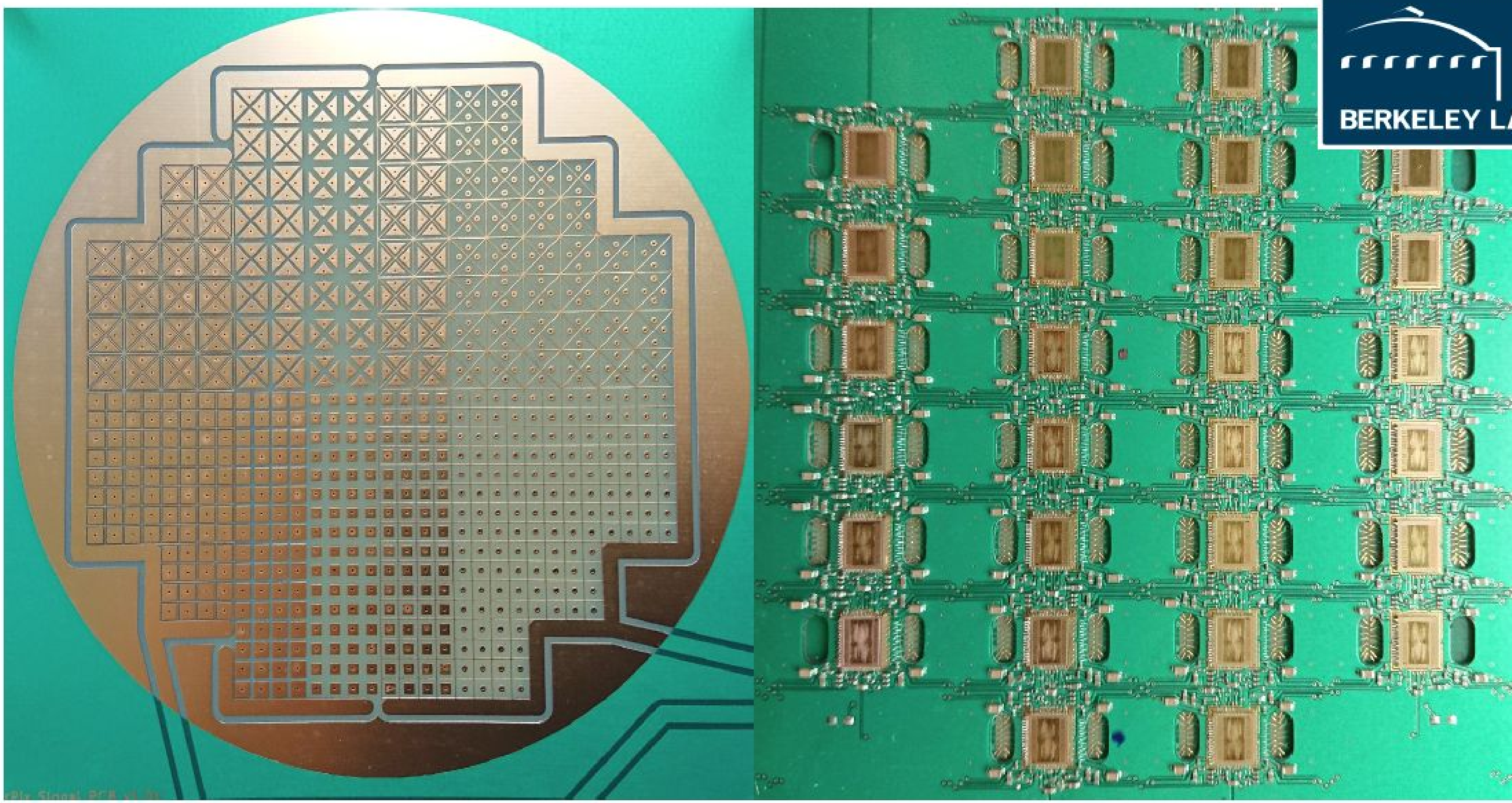
PixLAr tests at Fermilab



- Pixel plane in LArIAT experiment at Fermilab in hadron test beam
- Demonstrates pixel concept for liquid TPC
- But electronics do not support single-channel readout → analog multiplexing

LArPix: dedicated pixel electronics for LAr TPCs

See parallel talk Friday afternoon by Dan Dwyer



- Low-power, single-channel readout developed at LBNL, tested at LBNL and Bern

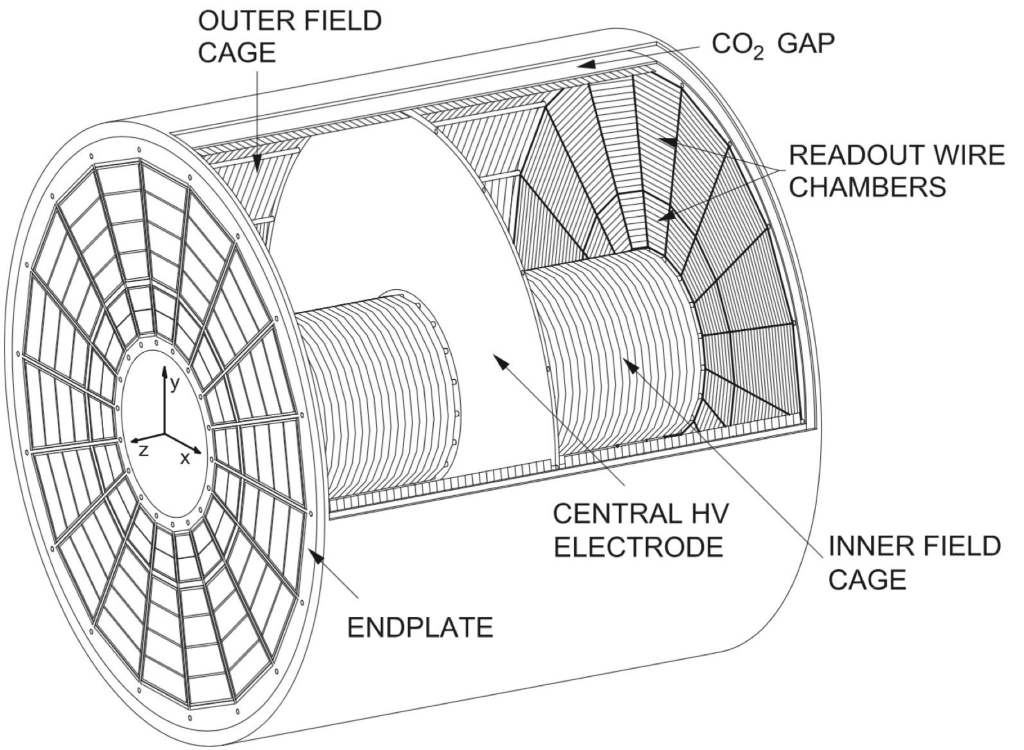
ArgonCube 2x2

- 2x2 module prototype, each 70x70x140cm^3
- Plan to run with cosmic rays in 2019 at Bern
- Move to Fermilab and run in NuMI in 2020 as part of protoDUNE-ND

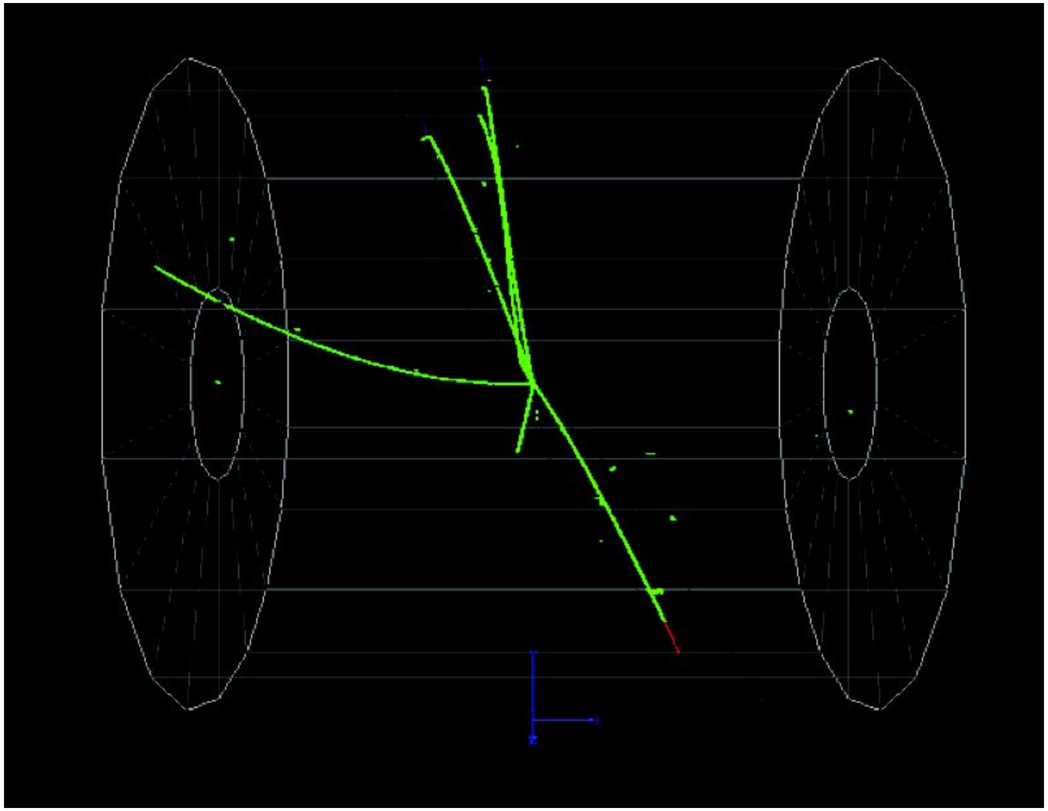
ArgonCube

High-pressure gas TPC

- 10bar 90-10 Ar-CH_4 mixture
- Repurpose ALICE readout chambers (available in 2019), filling central hole with new chamber
- New front-end electronics



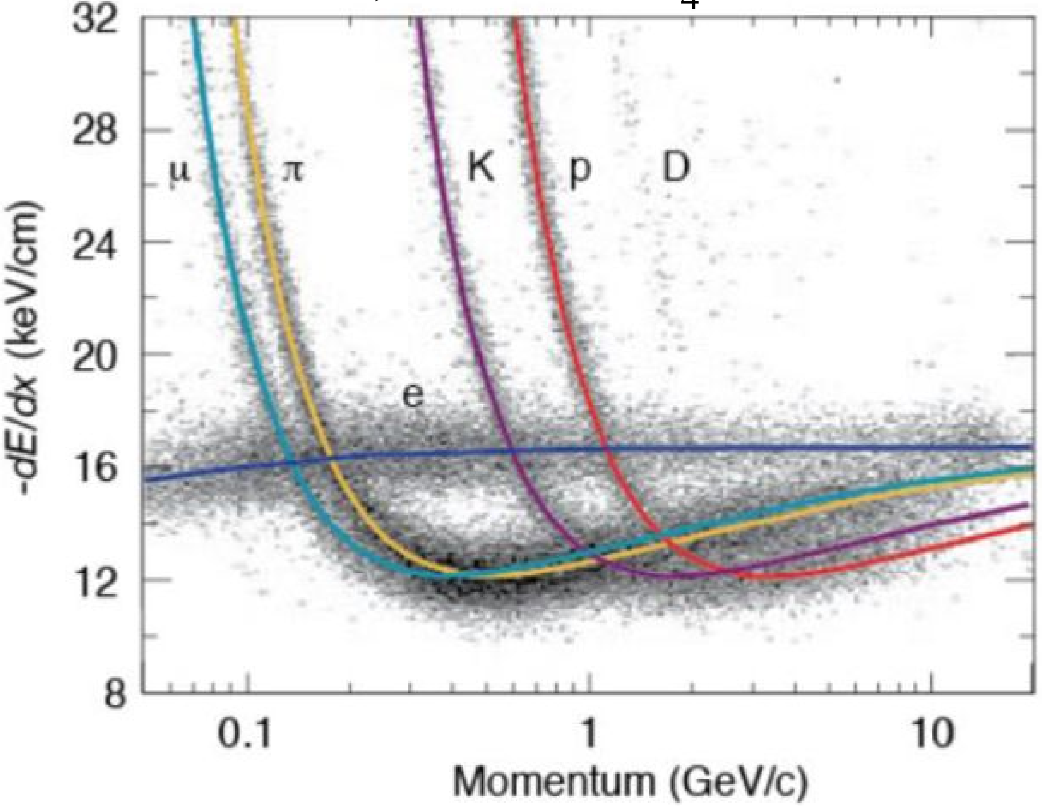
New software: GArSoft



Expected performance of gas TPC based on ALICE & PEP-4 experience

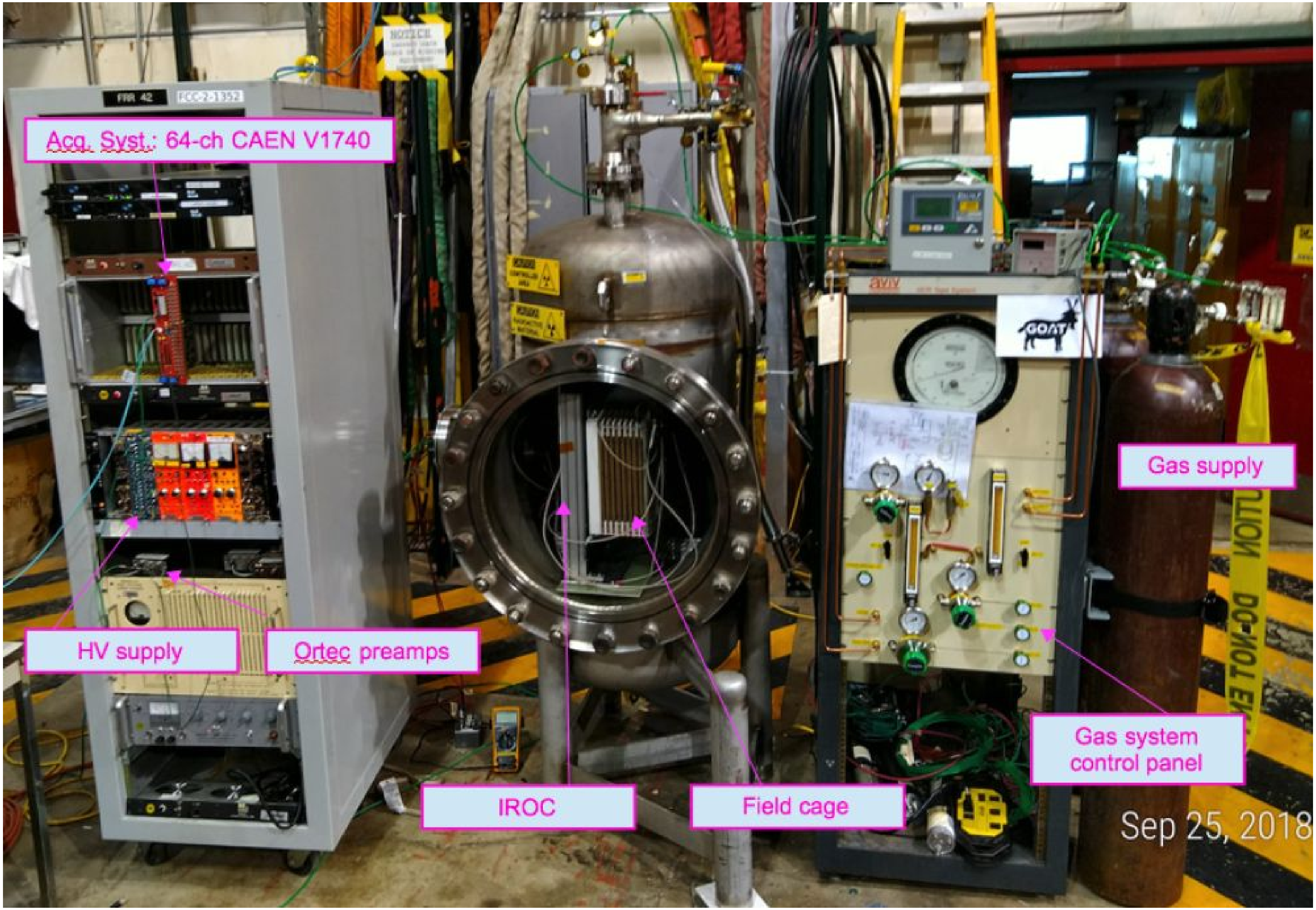
- ~250μm transverse position resolution
- 2-4 mrad angular resolution
- ~0.7% δp/p above 1 GeV/c, and ~1-2% down to 0.1 GeV/c
- Energy scale uncertainty at or below 1%
- ~5 MeV threshold for charged particle detection
- ~1t fiducial volume = ~1M neutrino interactions per year

PEP-4, 80/20 Ar-CH_4 at 8.5 atm

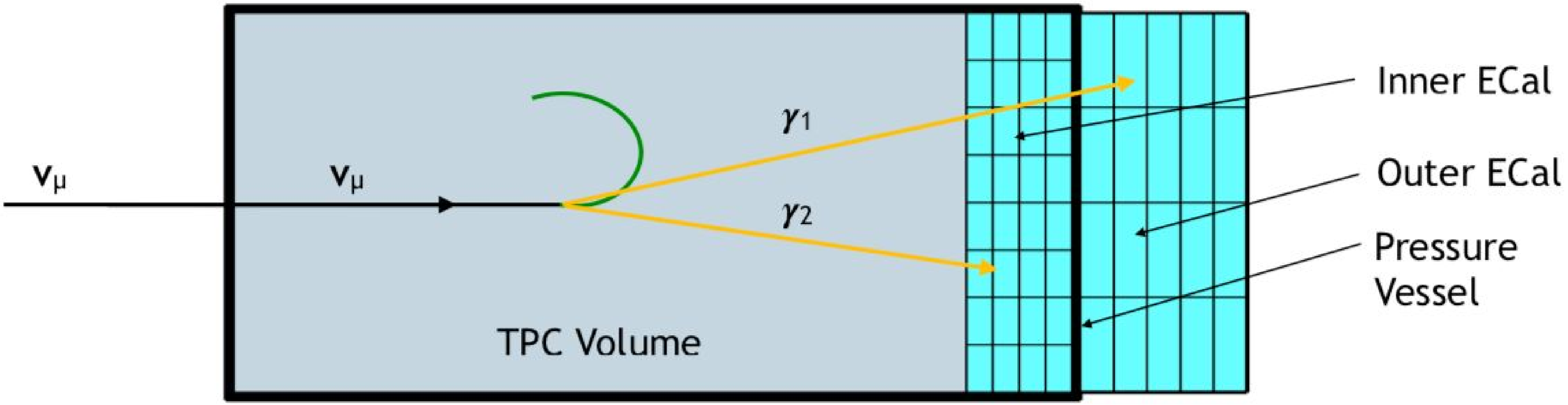


 Chris Marshall (LBNL)

Gas TPC test stand @Fermilab

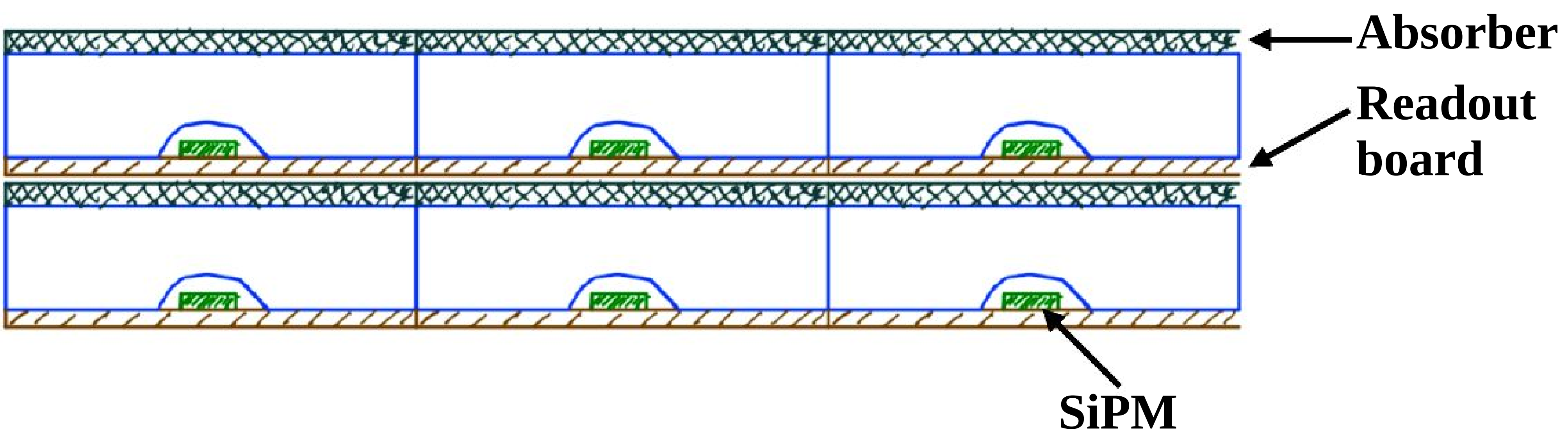


High-performance ECal



- Gas TPC provides exquisite resolution for charged tracks, including electrons
  - But photons will rarely convert in gas volume
- π^0 reconstruction requires high-performance ECal, with excellent energy and angular resolution for photon conversions

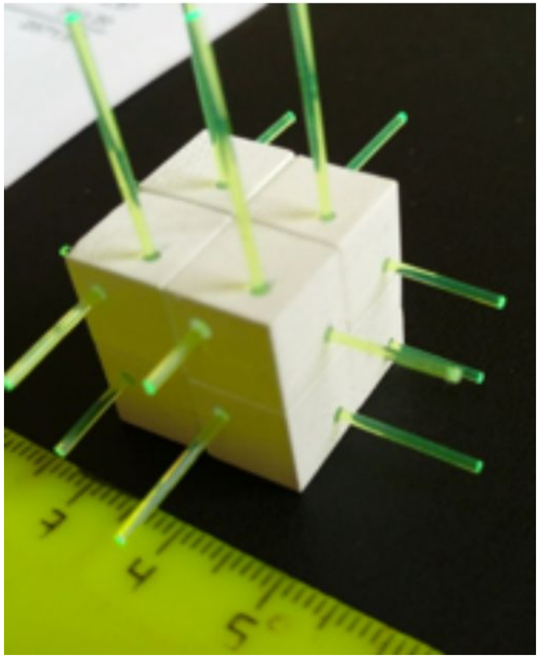
DUNE ND ECal concept



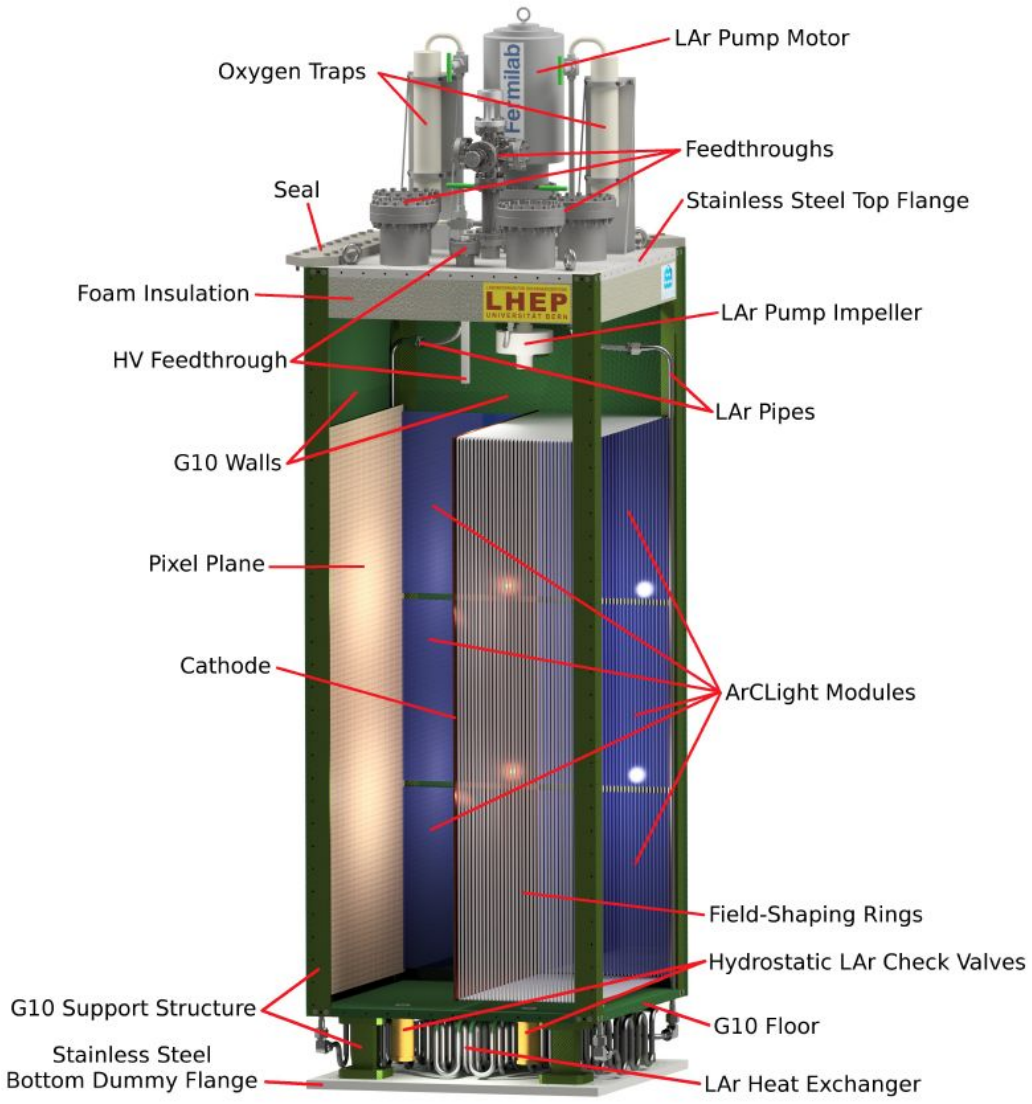
- Based on CALICE AHCAL concept
- Layers of scintillator tiles read out by SiPM
- Optimizations being performed at MPI-Munich, Mainz, DESY

3D scintillator tracker (3DST)

- 1 cm^3 scintillator cubes in a large array, read out with orthogonal optical fibers in three dimensions
- Same concept being pursued by T2K ND280 upgrade, called "Super-FGD"
- Excellent 4π acceptance –no hole at 90°
- Very fast timing: capable of tagging neutrons from recoils, and measuring energy from time-of-flight
- Could be placed in front of (or inside?) gas TPC, or operated in its own magnet with muon spectrometer

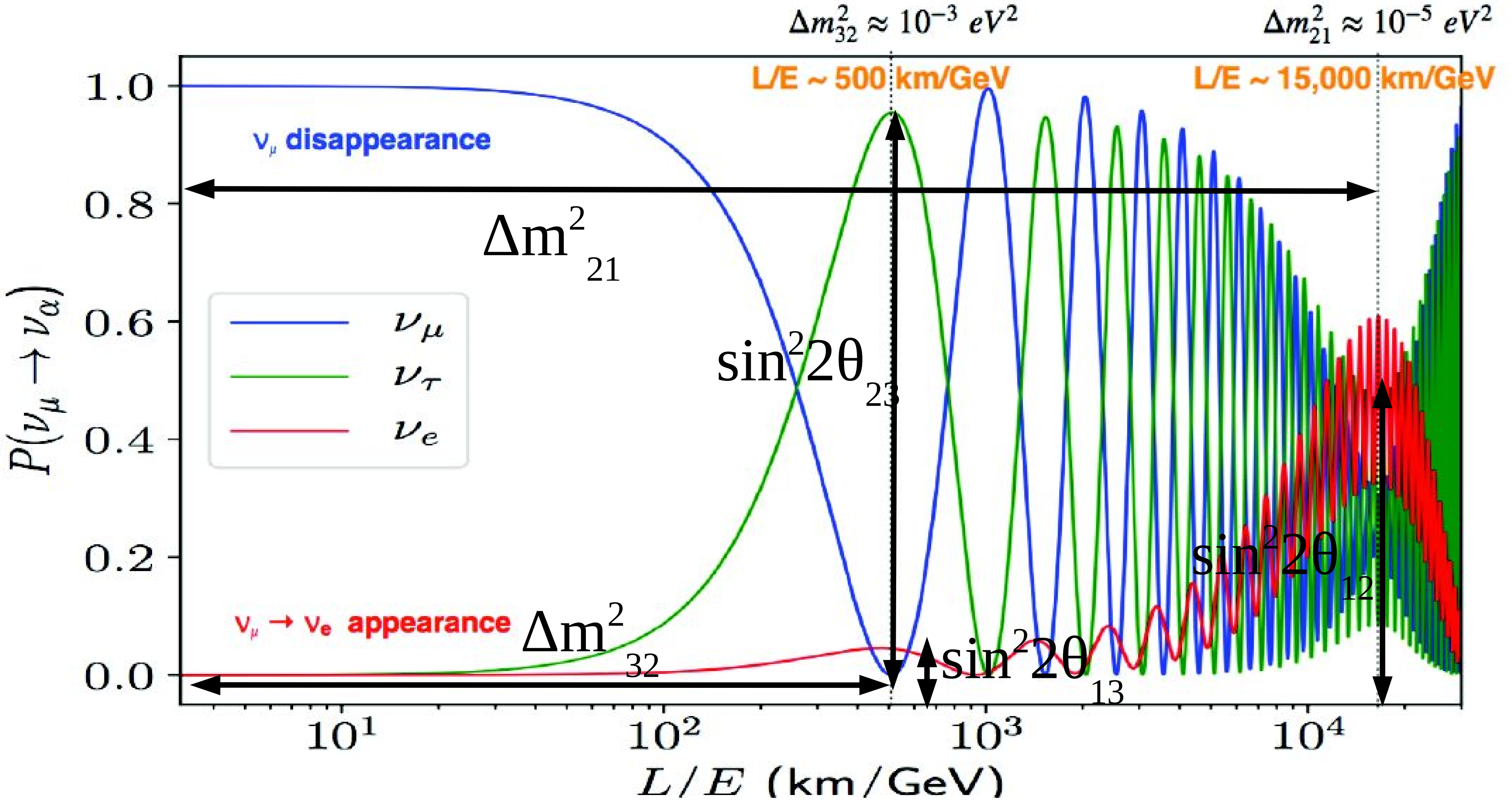


ArgonCube module



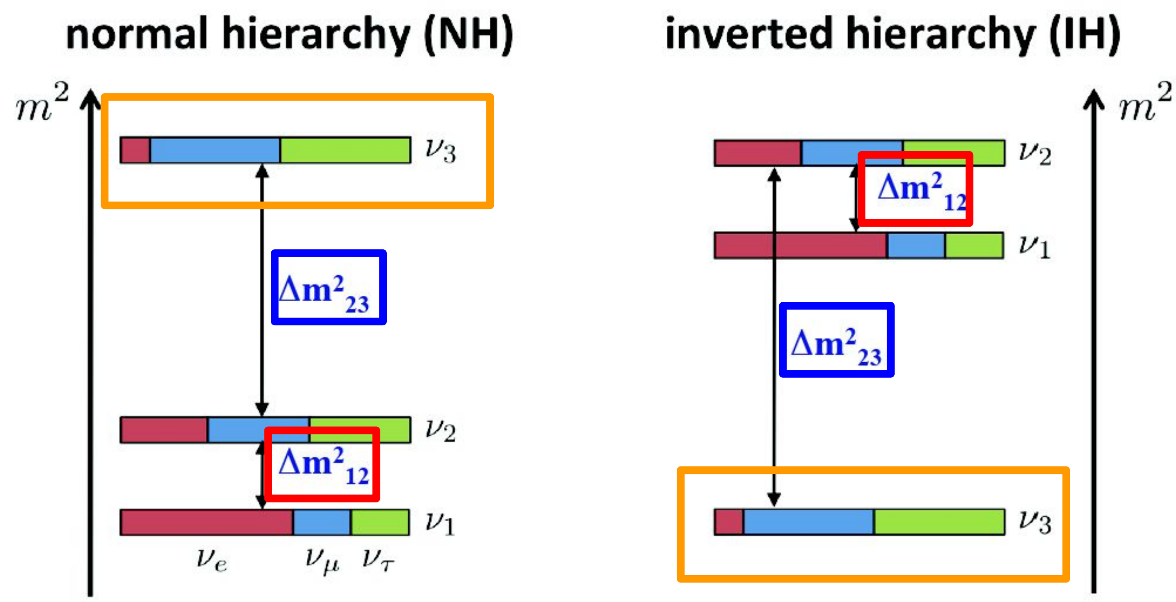
2x2 Demonstrator module.
Note, ND modules will not have individual pumps & filters

There are actually three neutrinos (3 θs, 2 independent Δm^2s)



Is θ_{23} "maximal?"

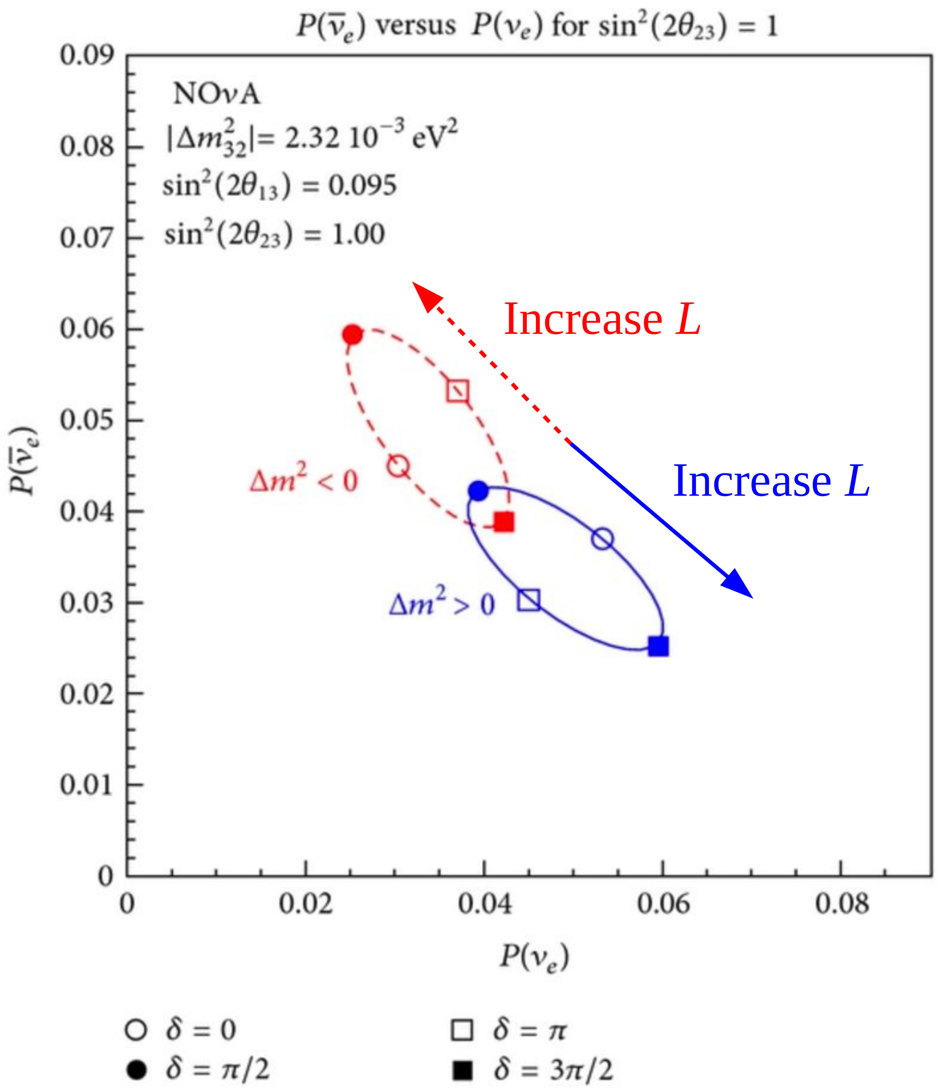
- ν_3 has (almost) the same amount of ν_μ and ν_τ, i.e. $\sin^2 2\theta_{23} \approx 1$
- Is it exactly 1? Could this be a hint of a flavor symmetry?
- If not, which way does it break? Is $\sin^2\theta_{23}$ greater or less than 0.5?



"atmospheric" $\qquad c_{ij} = \cos\theta_{ij}$ $\qquad$ "solar"

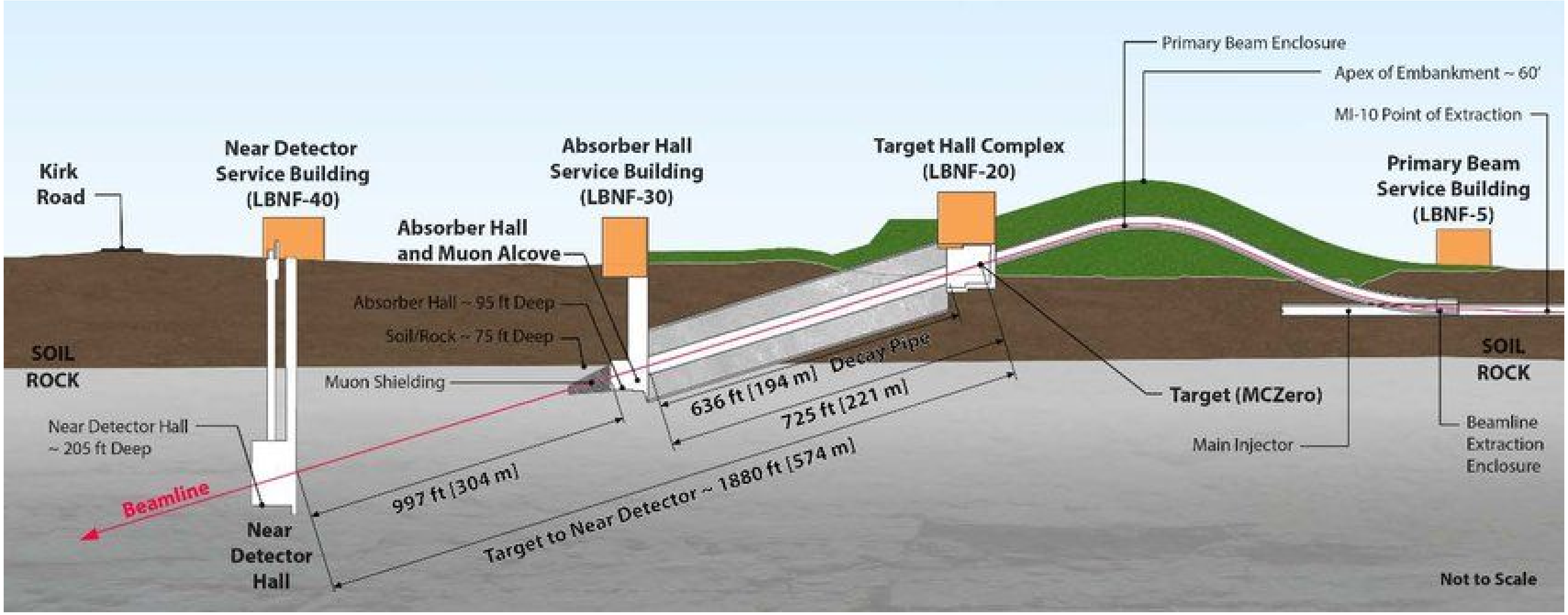
$$U_{\text{PMNS}} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{I}} \underbrace{\begin{pmatrix} c_{13} & 0 & e^{-i\delta_{\text{CP}}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{\text{CP}}} s_{13} & 0 & c_{13} \end{pmatrix}}_{\text{II}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{III}}$$

Neutrino oscillation "biprobability"



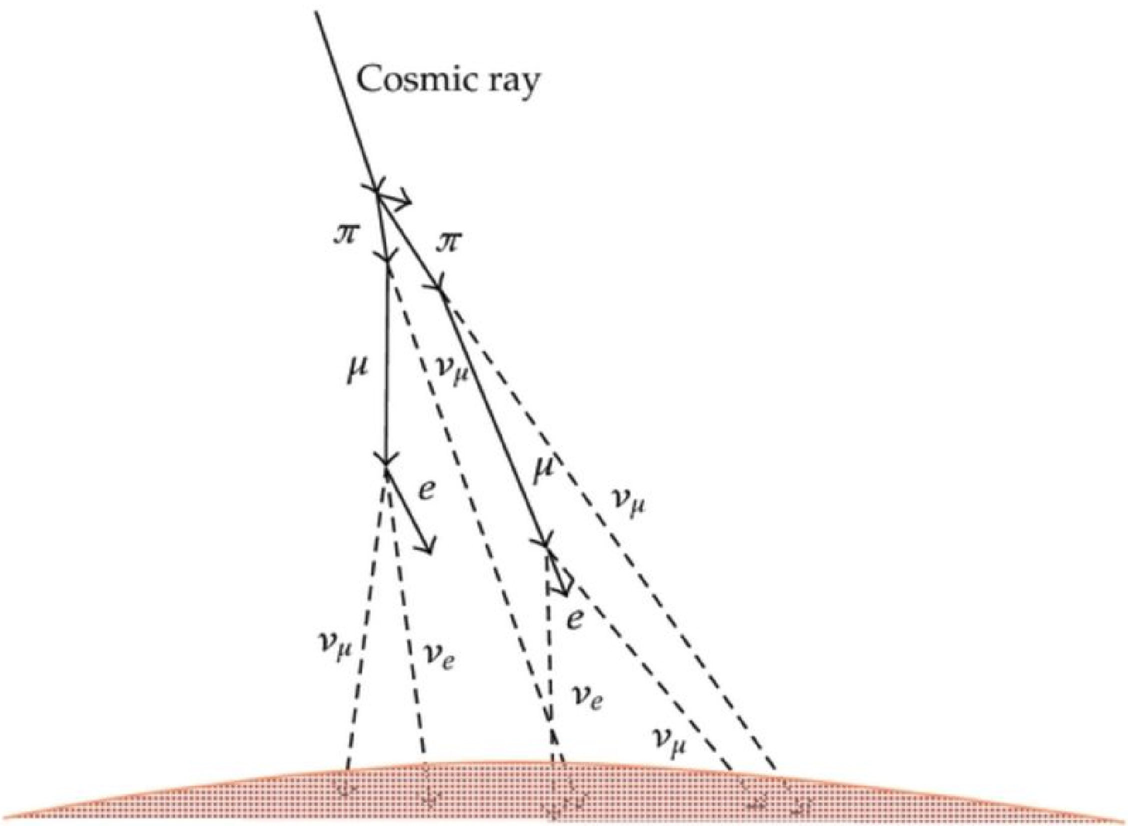
- Experiment essentially measures a point in this space
- Shown here for L = 810 km
- Increased L moves the red and blue ellipses further apart – by 1200km they do not overlap, meaning that the mass ordering and δ can be measured simultaneously

Making neutrinos



- Beam is pointed downward 6° so that the neutrinos go to South Dakota

Pions produced in the atmosphere decay into neutrinos

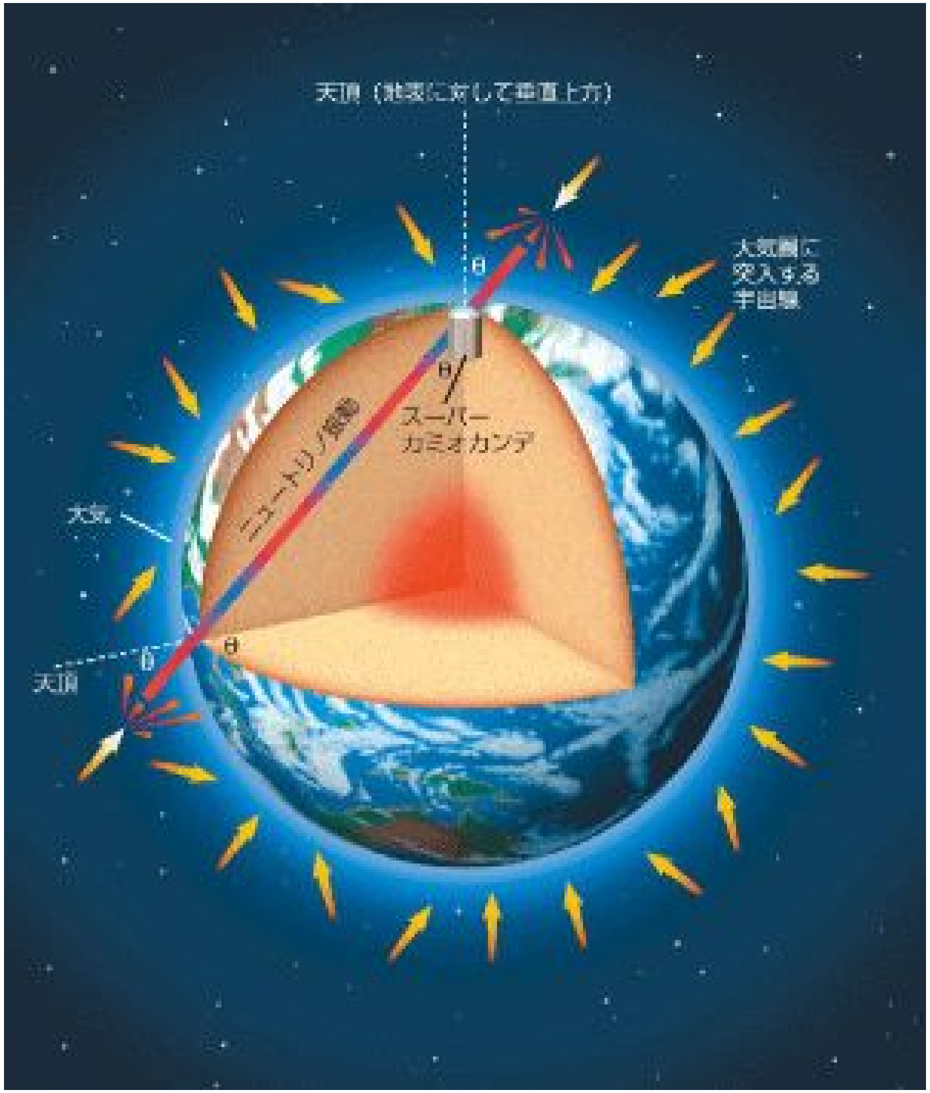


- Cosmic ray interactions in the atmosphere produce pions

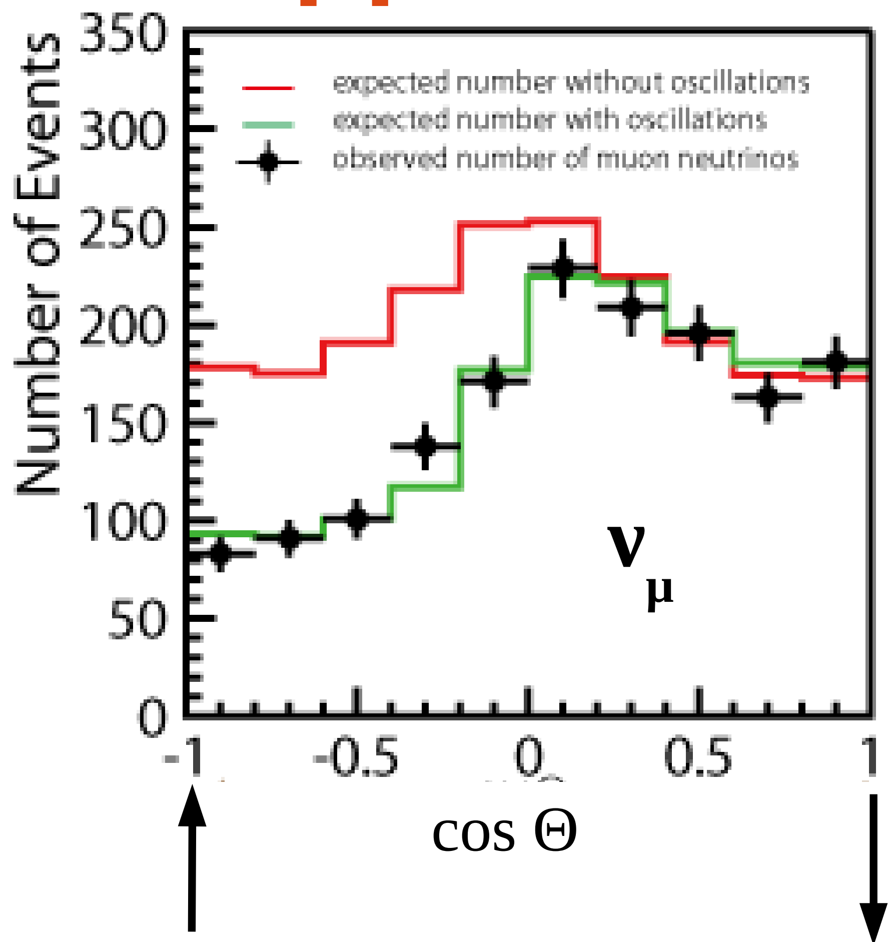
$$\pi \to \mu\ \nu_\mu$$

$$\mu \to e\ \nu_e\ \nu_\mu$$

Upward-going ν_μs traverse the earth, and "disappear"



Super-Kamiokande, U Tokyo

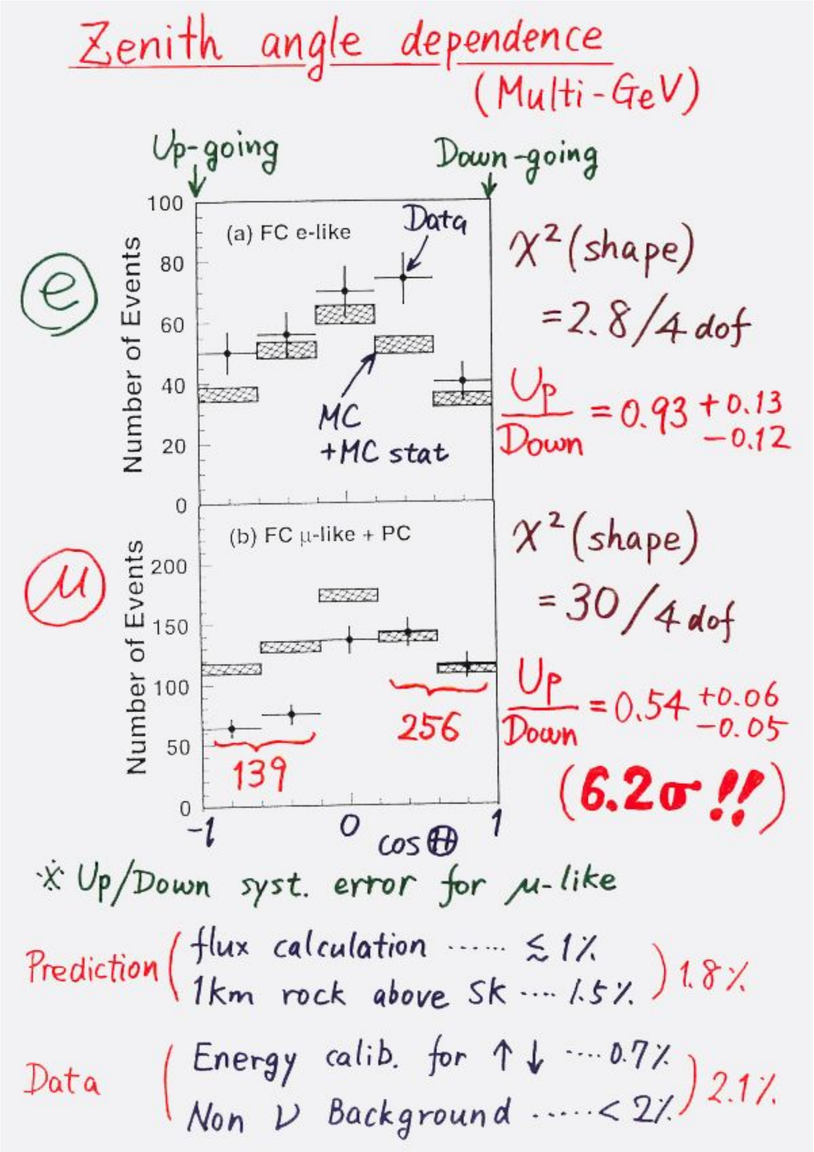


Upward-going
(long distance)

Downward-going
(short distance)

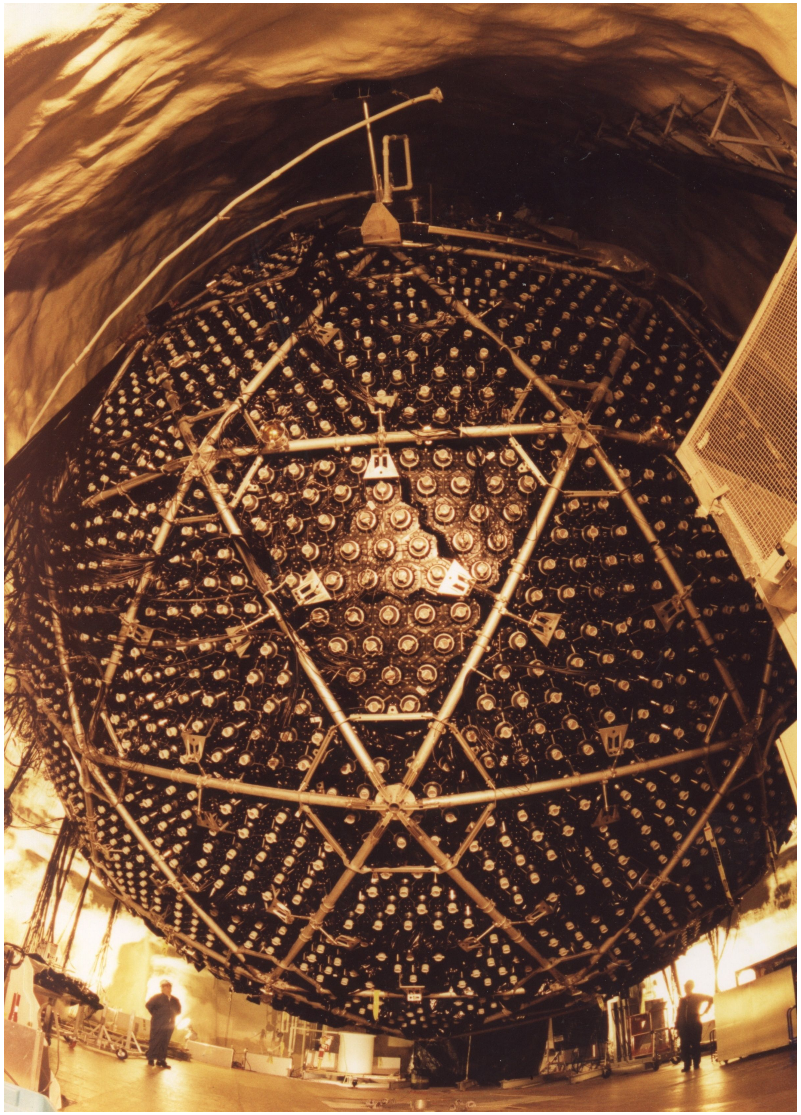
First evidence of neutrino oscillation, reported 5 June, 1998

- The upward-going ν_μ "disappear"
- Downward-going ν_μ do not – the oscillation depends on the distance traveled by the neutrino
- T. Kajita reported the result on behalf of the Super-Kamiokande collaboration at the NEUTRINO98 conference in Takayama, Japan



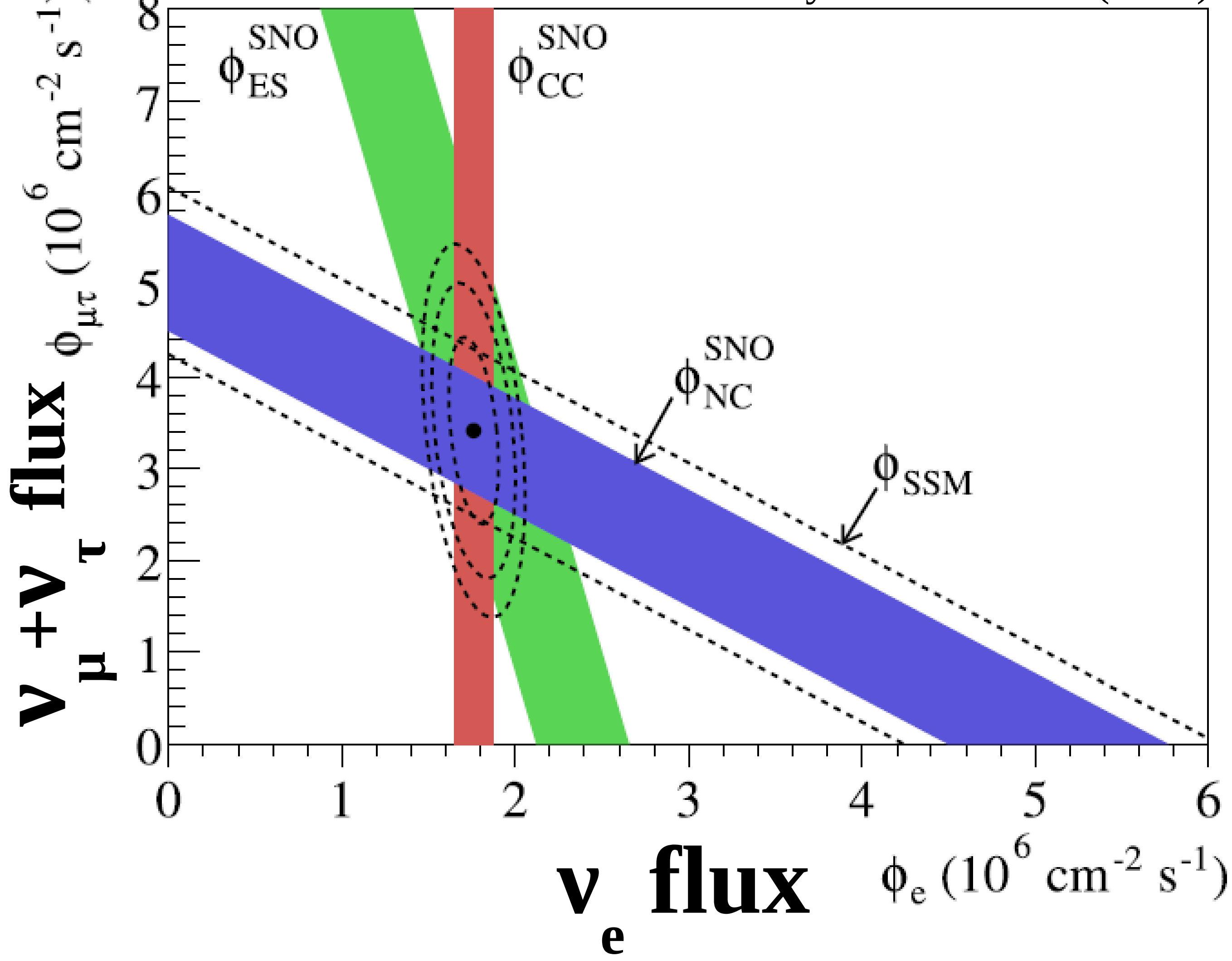
SNO measured solar neutrinos three different ways

- The sun produces ν_es, about 100 billion per cm²/s on earth
- Sudbury Neutrino Observatory (SNO) is sensitive to three different types of interaction:
  - $\nu_e n \rightarrow e^- p$ (ν_e only)
  - $\nu_\alpha d \rightarrow \nu_\alpha n p$ (all flavors equal)
  - $\nu_\alpha e \rightarrow \nu_\alpha e$ (all flavors, but higher rate for ν_e)

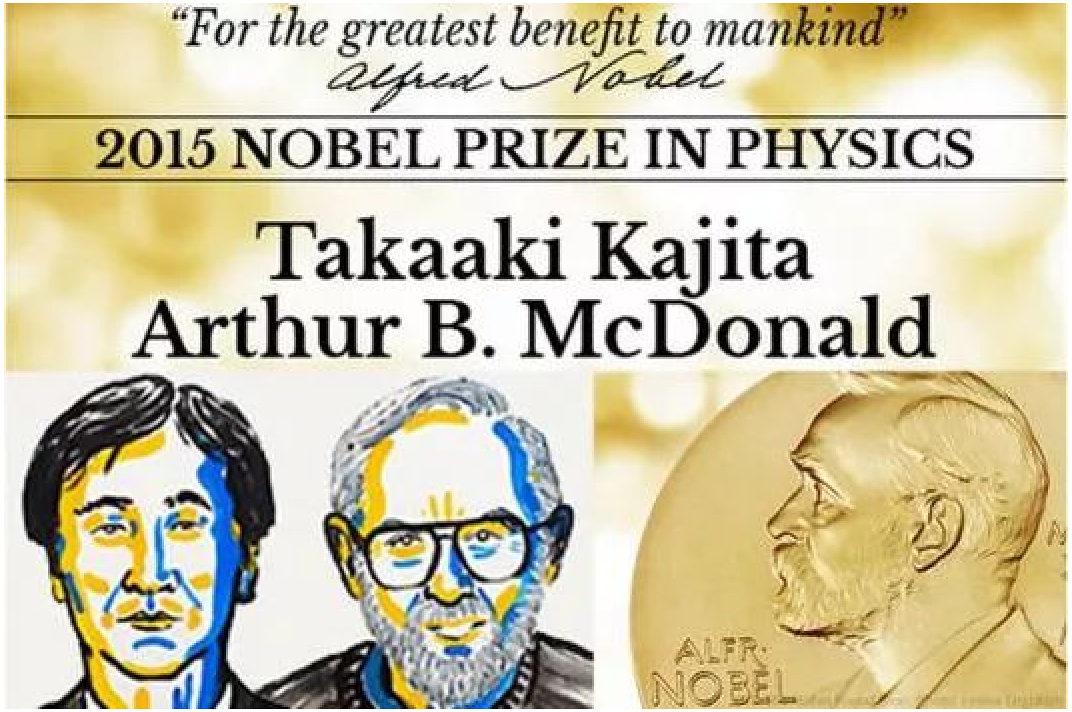


SNO showed that ~2/3 of the solar ν_e are detected as ν_μ and ν_τ

Nuc. Phys. B 908 30-51 (2016)



The discovery of neutrino oscillations lead to the 2015 Nobel Prize



Direct flux constraint with ν-electron elastic scattering

- Elastic scattering of a neutrino with an atomic electron:

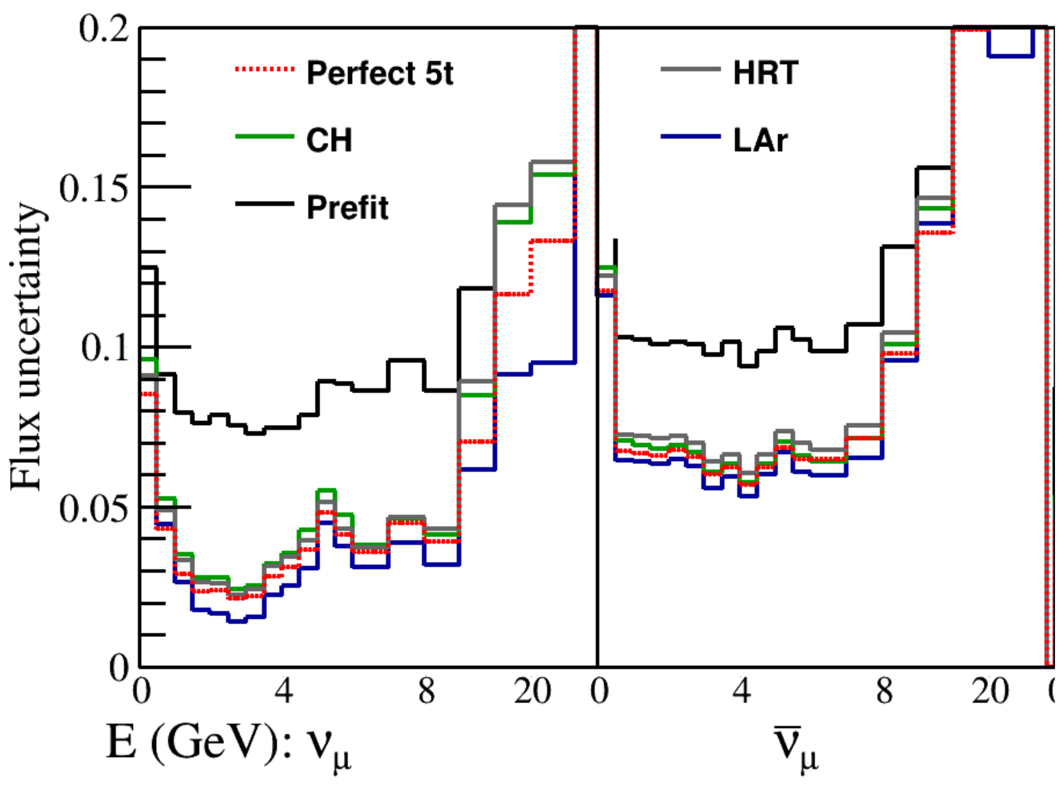
$$\nu + e \rightarrow \nu + e$$

- Unlike neutrino-nucleus scattering, this is a pure electroweak process, and the cross section can be calculated:

$$\frac{d\sigma(\nu_\mu e^- \rightarrow \nu_\mu e^-)}{dy} = \frac{G_F^2 m_e E_\nu}{2\pi}\left[\left(\frac{1}{2} - \sin^2\theta_W\right)^2 + \sin^4\theta_W (1-y)^2\right]$$

- It can be measured in a detector and used to infer the (uncertain) neutrino flux

Direct flux constraint at <2% level: ν-electron elastic scattering



- Detailed study to show how LAr TPC can measure this signal
- Reduce flux uncertainty from 8% → 2%

Measure initial ν flux

Direct flux constraint at <2% level: ν-electron elastic scattering

PHYSICAL REVIEW D **101**, 032002 (2020)

Neutrino-electron elastic scattering for flux determination at the DUNE oscillation experiment

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today!

(Received 25 October 2019; accepted 9 January 2020; published 5 February 2020)

We study the feasibility of using neutrino-electron elastic scattering to measure the neutrino flux in the DUNE neutrino oscillation experiment. The neutrino-electron scattering cross section is precisely known, and the kinematics of the reaction allow the determination of the incoming neutrino energy by precise measurement of the energy and angle of the recoiling electron. For several possible near detectors, we perform an analysis of their ability to measure neutrino flux in the presence of backgrounds and uncertainties. With realistic assumptions about detector masses, we find that a liquid argon detector, even with limitations due to angular resolution, is able to perform better than less dense detectors with more precise event-by-event neutrino energy measurements. We find that the absolute flux normalization uncertainty can be reduced from ~8% to ~2%, and the uncertainty on the flux shape can be reduced by ~20%–30%.