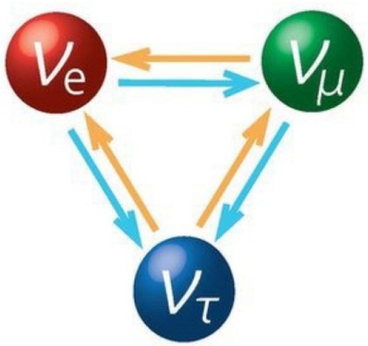
DUNE: Physics program and status

Ryan Patterson
Caltech

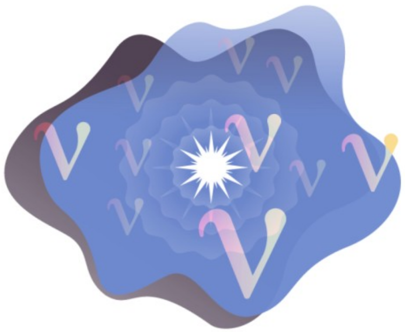
Neutrino Platform Week
CERN

January 29, 2018

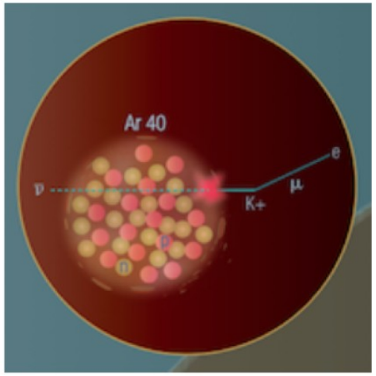
Primary physics program of DUNE



- **Oscillation physics**
  - Search for leptonic *CP* violation
  - Determine the neutrino mass hierarchy
  - Precision PMNS measurements



- **Supernova physics**
  - Observation of time and flavor profile provides insight into collapse and evolution of supernova
  - DUNE will have unique sensitivity to ν_e flavor



- **Baryon number violation**
  - Prediction of many BSM theories
  - LAr TPC technology well-suited to certain proton decay channels (*e.g.*, $p \rightarrow K^+\overline{\nu}$)
  - Δ(B-L) ≠ 0 channels accessible (*e.g.*, $n \rightarrow \overline{n}$)

Neutrinos have mass

But they are very light! See-saw mechanism? – Heavy (possibly GUT-scale) RH neutrinos alongside light LH neutrinos:

$$m_\nu \sim \frac{m_{\rm EW}^2}{m_{\rm GUT}} \sim \frac{(10^2\ {\rm GeV})^2}{10^{15}\ {\rm GeV}}$$

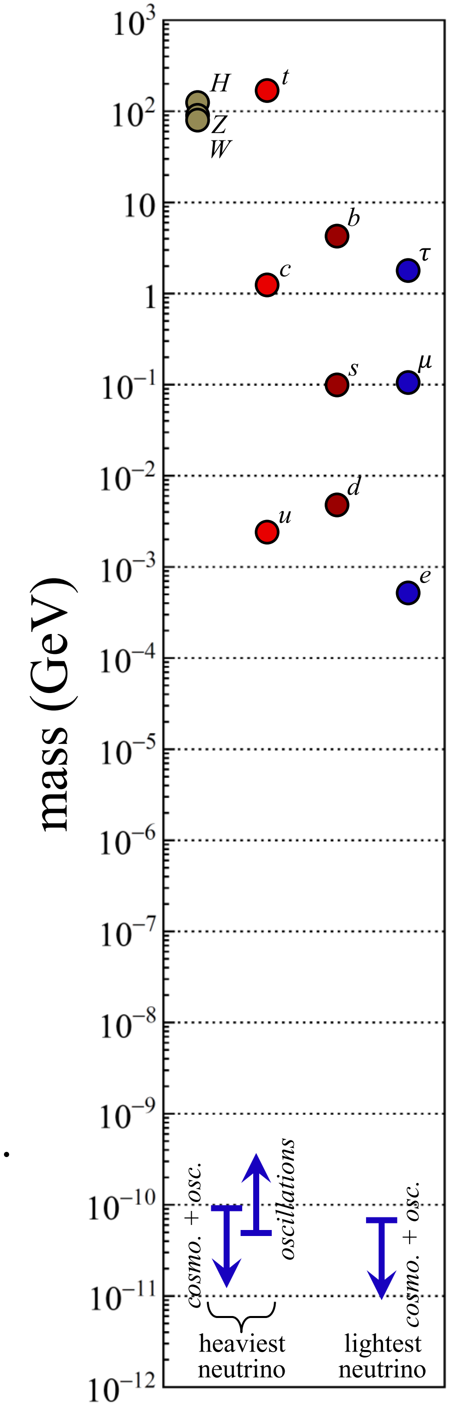
$$\sim 10^{-11}\ {\rm GeV}$$

Would imply that the **physics of neutrino mass** is connected to **extremely high energy scales** (or at least new physics of some kind).

Potential new physics signatures in oscillation expts:

non-unitarity, non-standard interactions, >3 neutrinos, large extra dimensions, effective CPTv, decoherence, neutrino decay, …

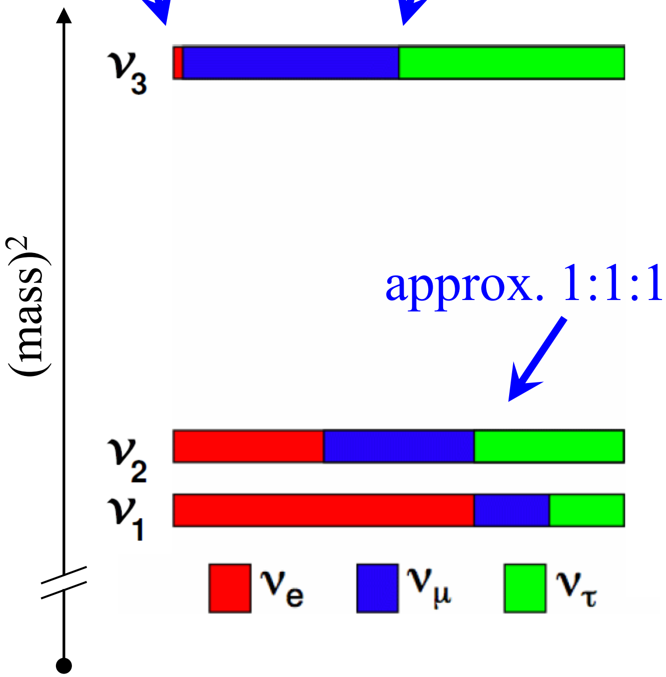
Now textbook material, the see-saw mechanism goes back to P. Minkowski (1977); M. Gell-Mann, P. Ramond and R. Slansky (1979); and T. Yanagida (1979)



Neutrino mixing

$|U_{e3}| \neq 0$
(recent discovery)

$|U_{\mu 3}| = |U_{\tau 3}|$?
("maximal mixing")



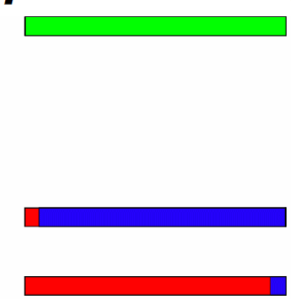
approx. 1:1:1 ratio

Experimental question:

$\sin^2\theta_{23} \neq 0.5$?

Non-maximal mixing?
If so, which way does it break?

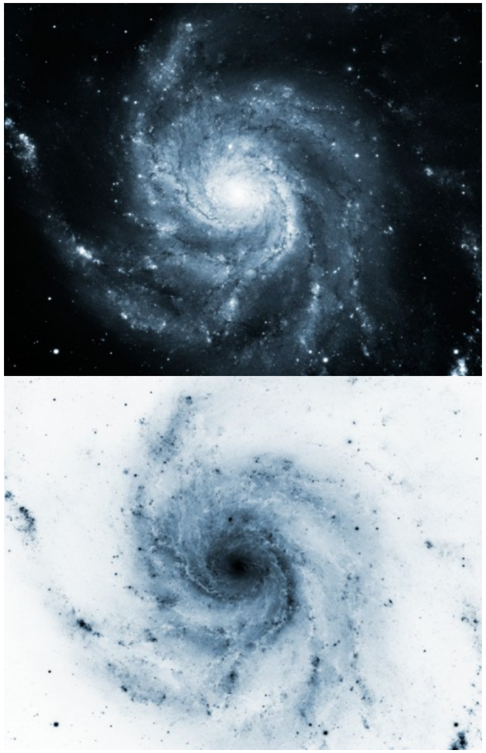
quark mixing:



Standard parametrization of PMNS matrix:

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

CP violation



New source of *CP* violation required to explain baryon asymmetry of universe

part-per-billion level of matter/antimatter asymmetry in early universe

Neutrino *CP*v **allowed in νSM**, but not yet observed

…due so far to the experimental challenge, not physics!

Leptogenesis[1] is a workable solution for the baryon asymmetry, but need to first **find *any* leptonic (neutrino) *CP*v**

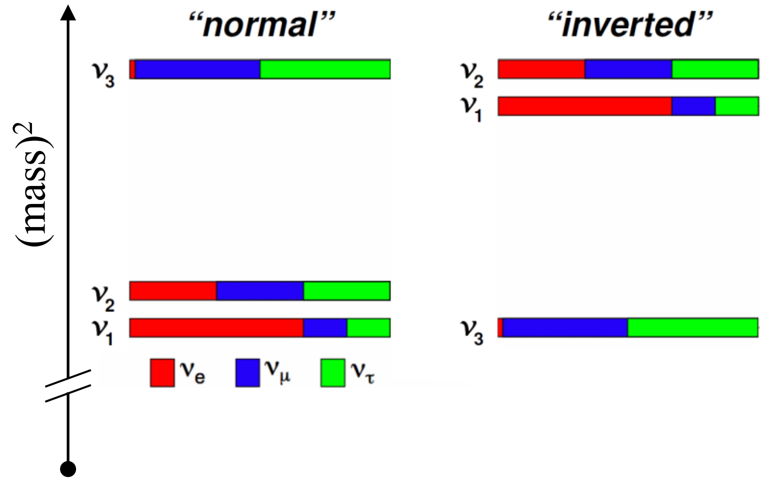
★ $\sin\delta \neq 0$?

Leptonic CP violation?

[1] M. Fukugita and T. Yanagida (1986); rich history since then.

ν mass hierarchy

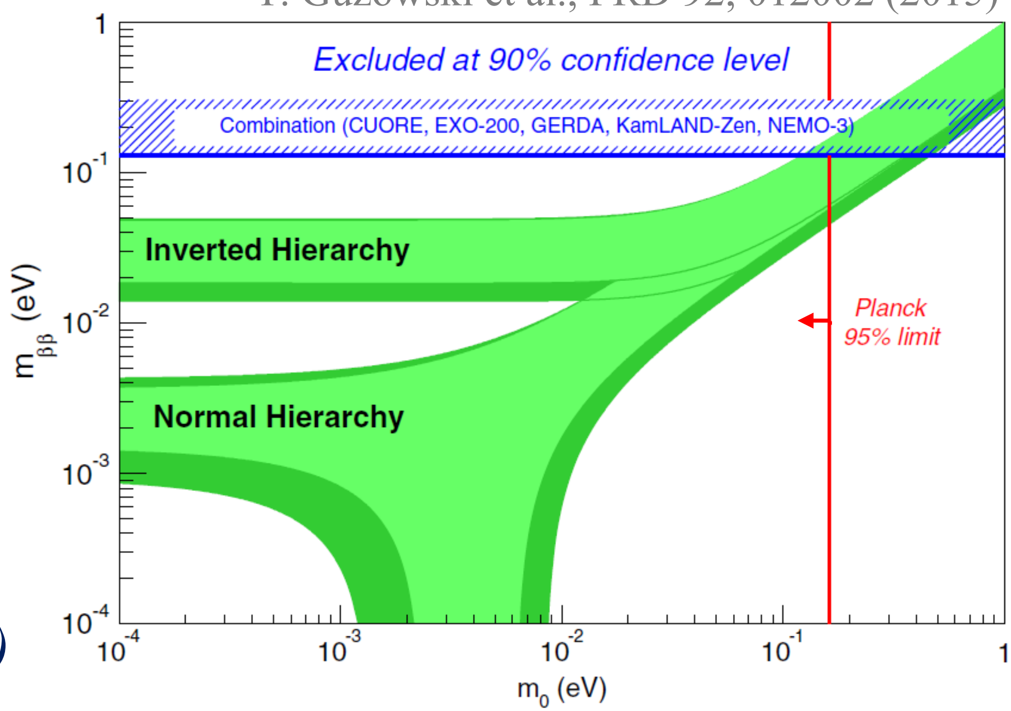
★ Are the electron-rich states ν_1 & ν_2 **heavier or lighter** than ν_3 ?



Far-reaching implications for such a simple question:

- **$0\nu\beta\beta$** and **Majorana nature of ν**
- Experimental approach to and interpretation of m_β
- **Cosmology** and **astrophysics**
- **Theoretical frameworks** for flavor and mass generation

P. Guzowski et al., PRD 92, 012002 (2015)



Notice:

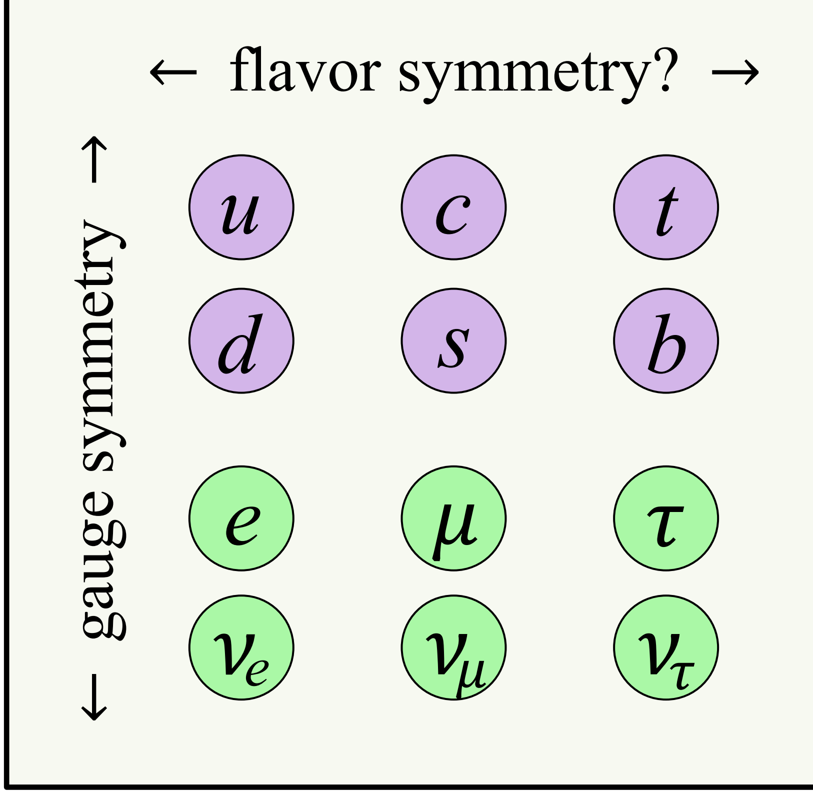
An inverted hierarchy implies **<1.5% mass degeneracy**.

→ *Would hint at…??* *(cf.: π^+/π^0)*

Flavor: A core problem for 21st century particle physics

What **flavor symmetry** can produce the observed pattern of mixings and masses, and how is that symmetry broken?

More broadly: what are the **dynamical origins** of fermion masses, mixings, and *CP* violation?



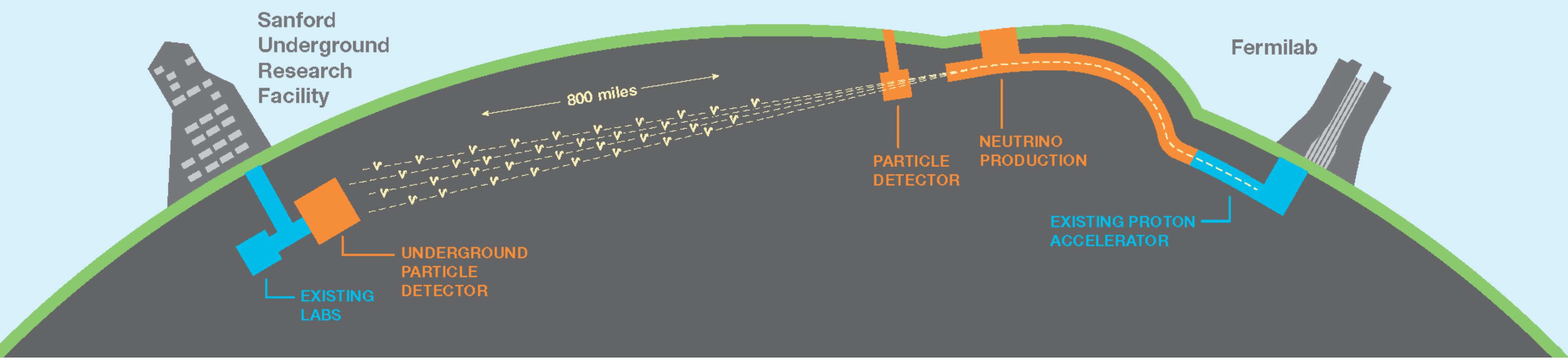
Tackling this problem requires **theoretical and <u>experimental</u> progress.**

Flurry of exciting theoretical work in recent years with emphasis on predictive power and connections between low energy observables and leptogenesis.

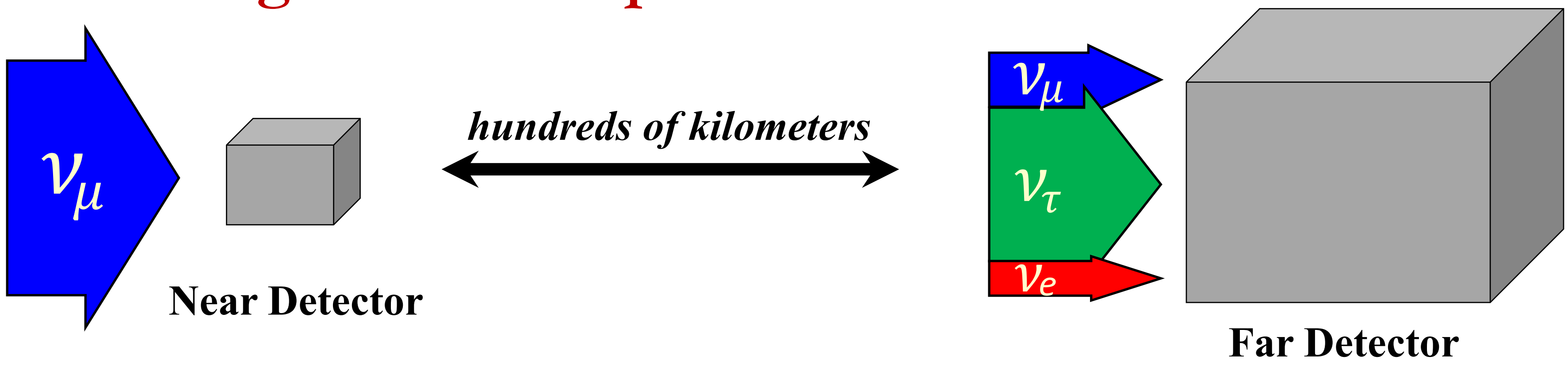
DUNE

Deep Underground Neutrino Experiment

A next generation experiment for **neutrino science, nucleon decay,** and **supernova physics**



Generic long-baseline experiment



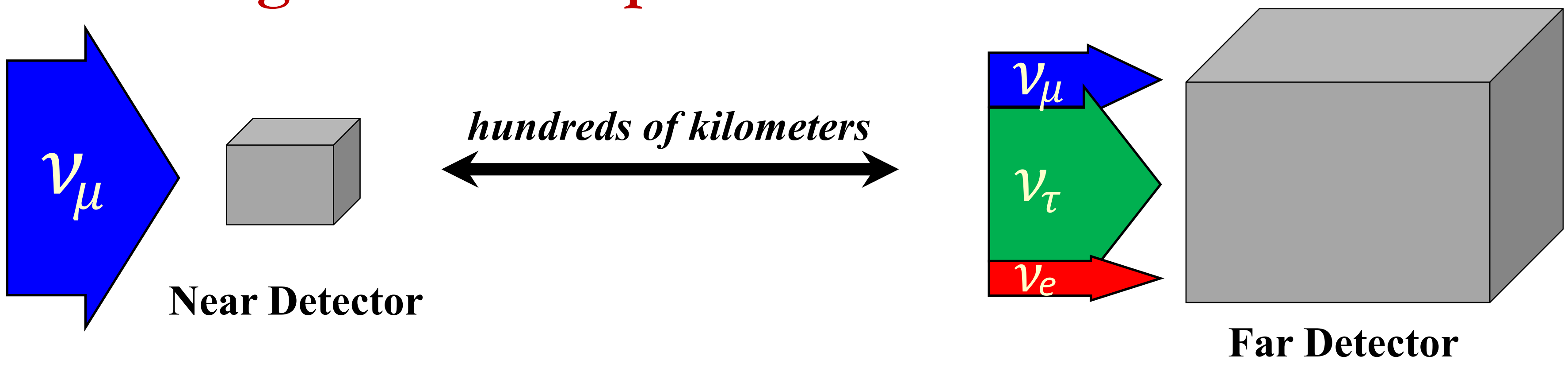
ν_μ survival (or "disappearance"):

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \underbrace{\sin^2 2\theta_{23}} \sin^2(\Delta m^2_{32} L/4E)$$

...to leading order

Experimental data **consistent with unity** (*i.e.*, maximal mixing).

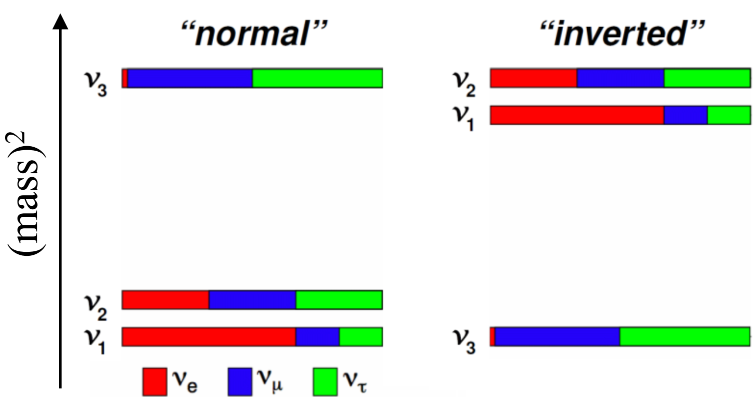
Generic long-baseline experiment



ν_e appearance:

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\,\sin^2 2\theta_{13}\,\sin^2(\Delta m^2_{32} L/4E)$$

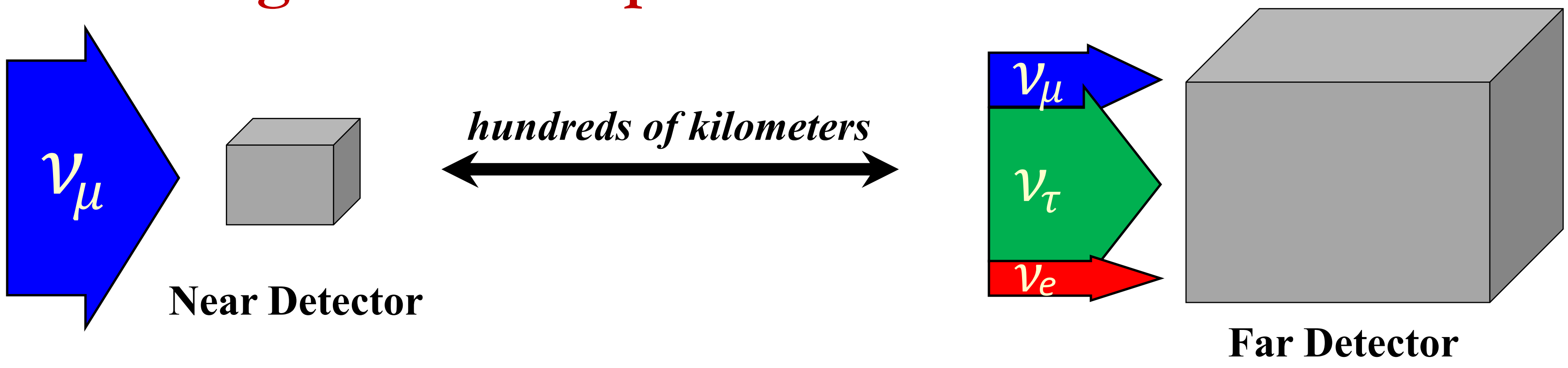
*...plus **potentially large CPv** and **matter effect*** modifications!*



* ν_e see different potential than $\nu_{\mu,\tau}$ when propagating through matter (here, the earth)

⇒ a hierarchy-dependent effect

Generic long-baseline experiment



Importance of Near Detector

Observation:

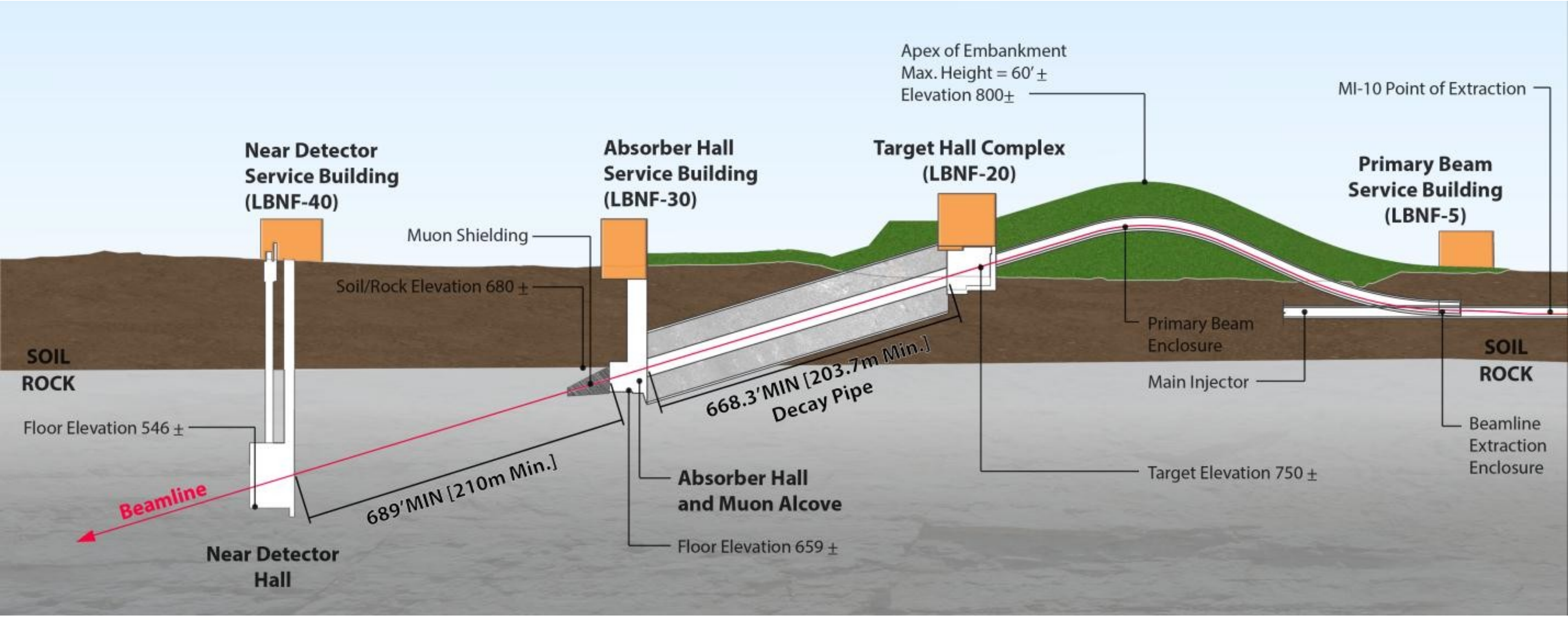
$$[\ \phi(E)\ \sigma(E)\ \varepsilon(E)\ P_{\nu_\mu \to \nu_x}(E)\ + \text{background}\ ] \otimes \{\text{detector effects}\}(E, \ldots)$$

20-50% (flux) 20-50% (cross section) 5-50% (efficiency) 5-50% (background) ← **typical starting uncertainties**

ND allows massive reduction in these uncertainties since they are largely correlated between detectors (esp. if similar detectors)

Long Baseline Neutrino Facility (LBNF)

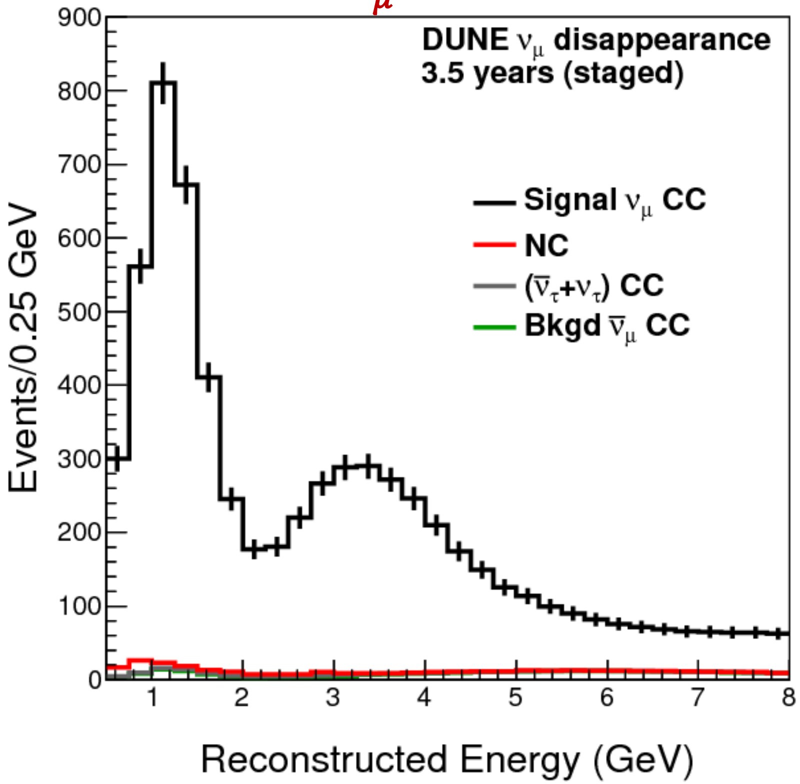
- **DUNE:** The international scientific collaboration
- **LBNF:** DOE/Fermilab-hosted facilities project, with international participation
- **Horn-focused beamline** similar to NuMI beamline
  - 60 – 120 GeV protons from Fermilab's Main Injector
  - 200 m decay pipe at -5.8° pitch, angled at South Dakota (SURF)
  - Initial power 1.1 MW, upgradable to 2.4 MW



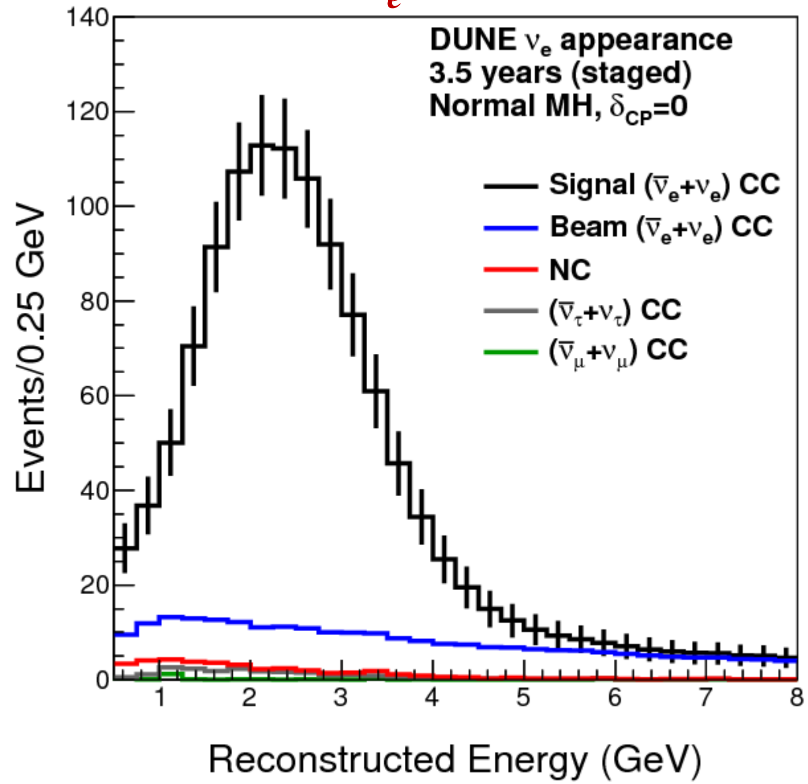
Beamline optimization

- The **LBNF beam design** has evolved since the DUNE CDR nominal
- Genetic algorithm used to explore space of 2- and 3-horn options.
- Result is an **engineered design** with flux and ultimate *CP*v reach similar to earlier "idealized" optimized design. *(Sensitivities here use the latter.)*

ν_μ at FD



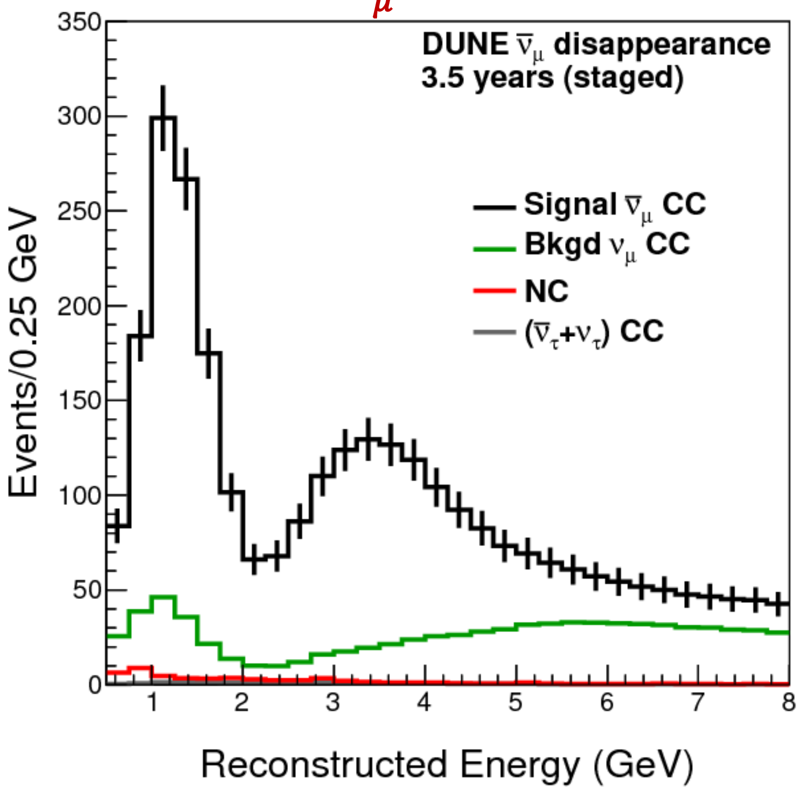
ν_e at FD



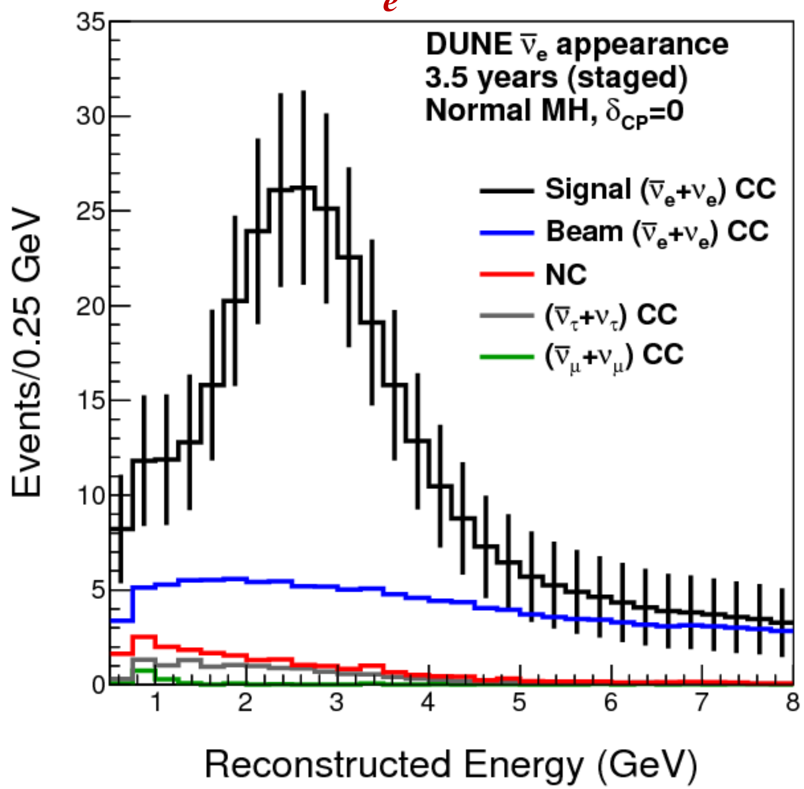
Beamline optimization

- The **LBNF beam design** has evolved since the DUNE CDR nominal
- Genetic algorithm used to explore space of 2- and 3-horn options.
- Result is an **engineered design** with flux and ultimate *CP*v reach similar to earlier "idealized" optimized design. *(Sensitivities here use the latter.)*

$\bar{\nu}_\mu$ at FD

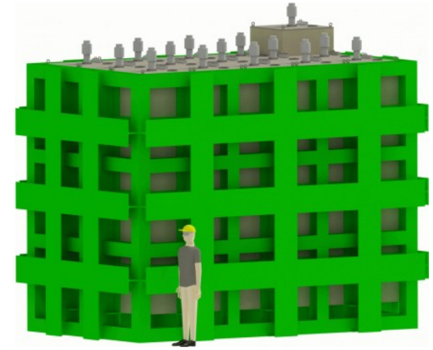


$\bar{\nu}_e$ at FD

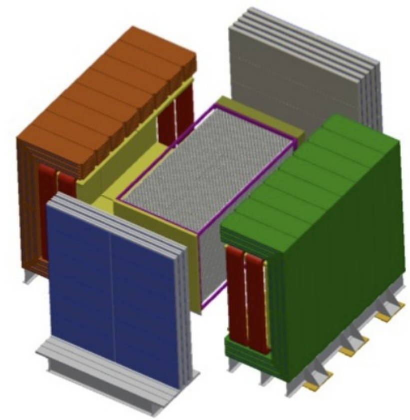


DUNE Near Detector

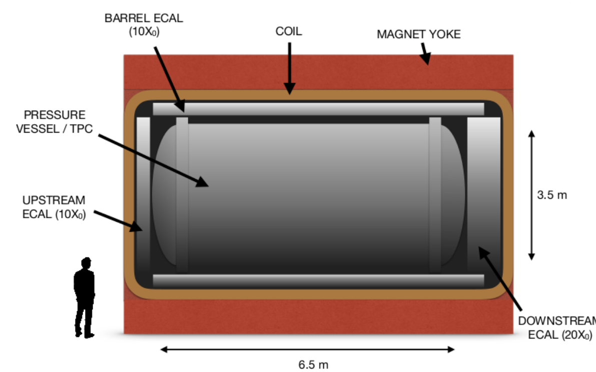
- **DUNE will have a Near Detector**
  - Constrain systematic uncertainties in neutrino flux, neutrino scattering cross sections, and (to some extent) detector response
  - *Also:* allow a program of neutrino-nucleus scattering measurements and BSM searches
- **Hybrid designs under development**
  - LAr TPC plus a downstream magnetized high-pressure GAr TPC or fine-grained tracker
  - Laterally movable detector? ("DUNE-PRISM")



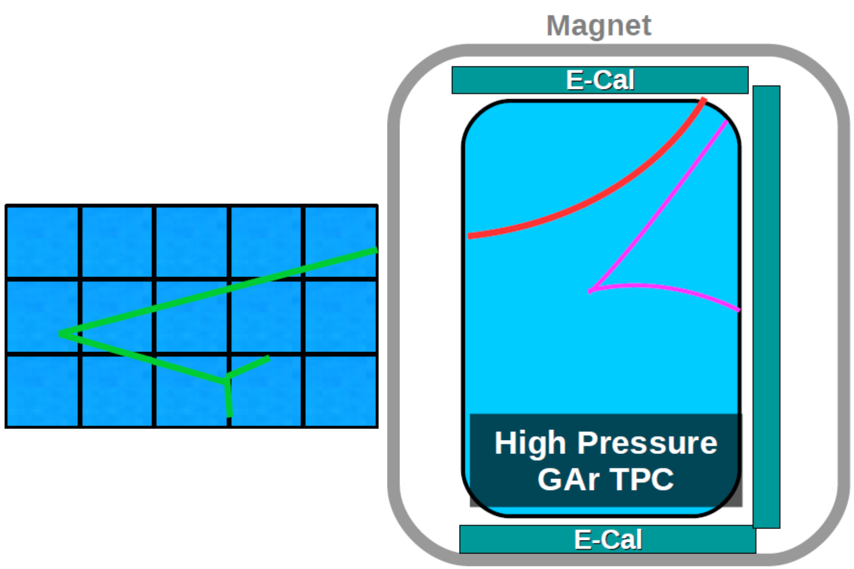
30-ton LAr TPC ("ArgonCube")



Magnetized Straw Tube Tracker

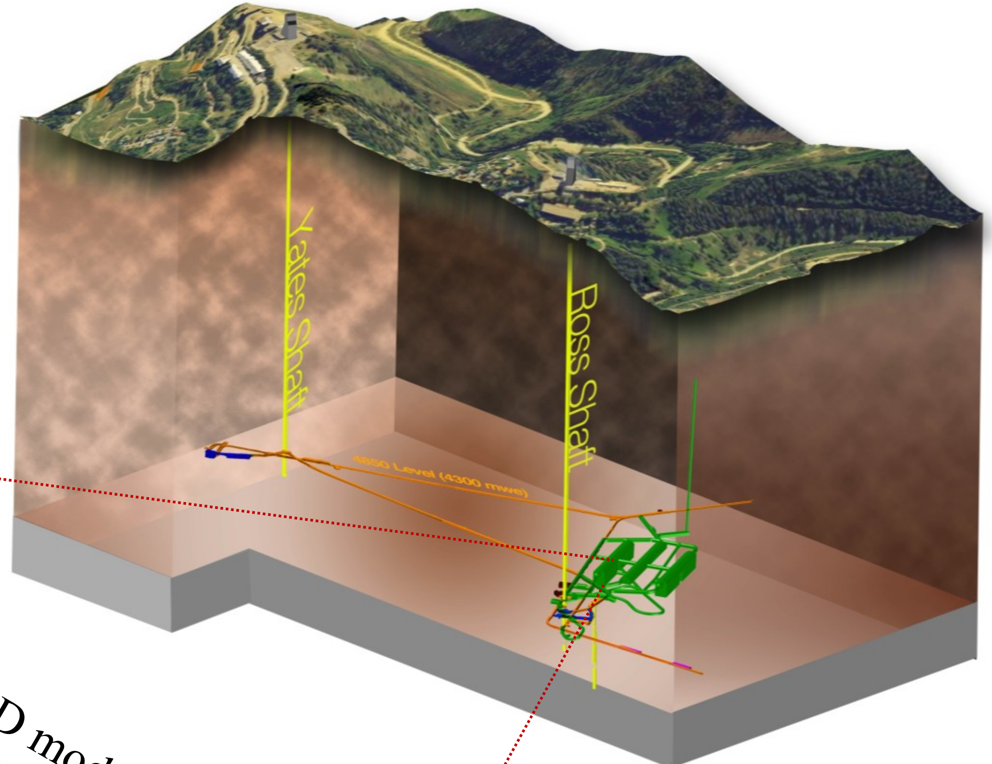


Magnetized HPGAr TPC

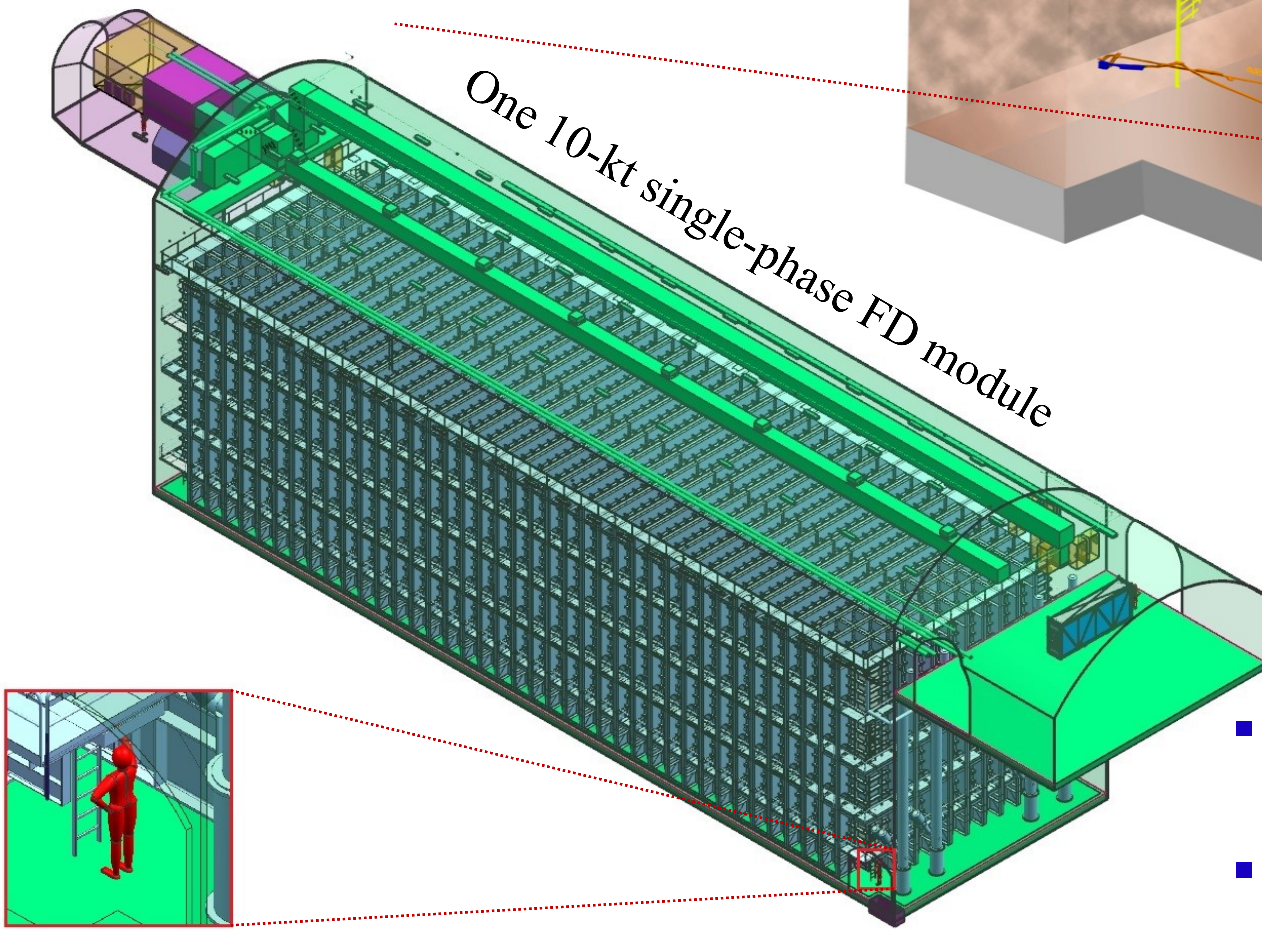


DUNE Far Detector

- **40-kt (fiducial)** LAr TPC
- Installed as four 10-kt modules at 4850’ level of SURF



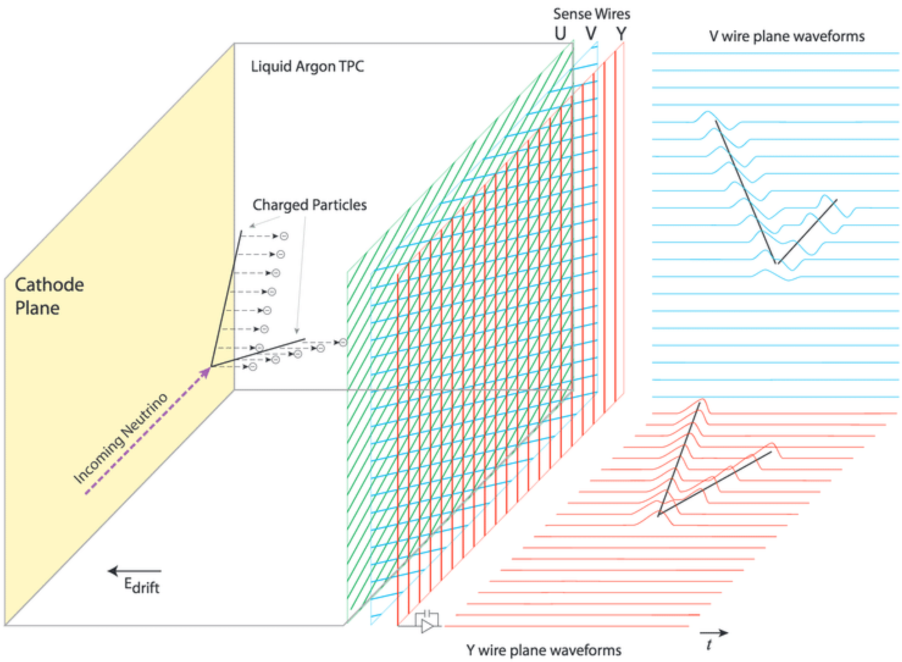
Sanford Underground Research Facility (SURF)



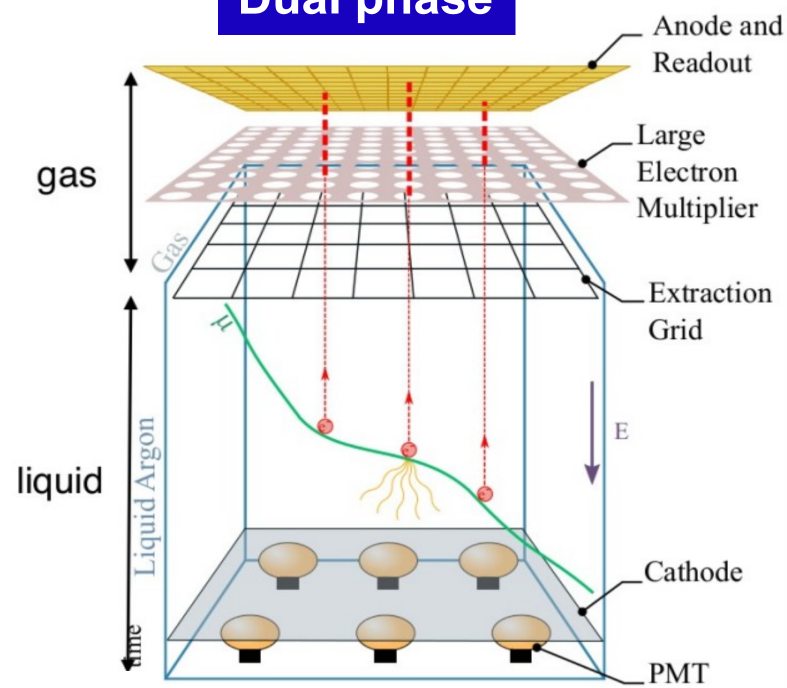
- First module will be a **single phase LAr TPC**
- Modules installed in stages. Not necessarily identical

Single phase (SP) and dual phase (DP) designs

Single phase



Dual phase



- Ionization readout via Anode Plane Assemblies (APA)
- 3 wire planes (2 induction + 1 collection views)
- Four 3.6-m drift regions per TPC
- Scintillation light collected by SiPMs

- Ionization electrons extracted, amplified through gas phase
- Charge readout by 2D segmented anode plane
- Single 12-m drift volume per TPC
- Scintillation light collected by PMTs

DUNE: Key design features

Very long baseline

→ *no osc. parameter ambiguities*

Large detector and powerful beam

→ *high event rate*

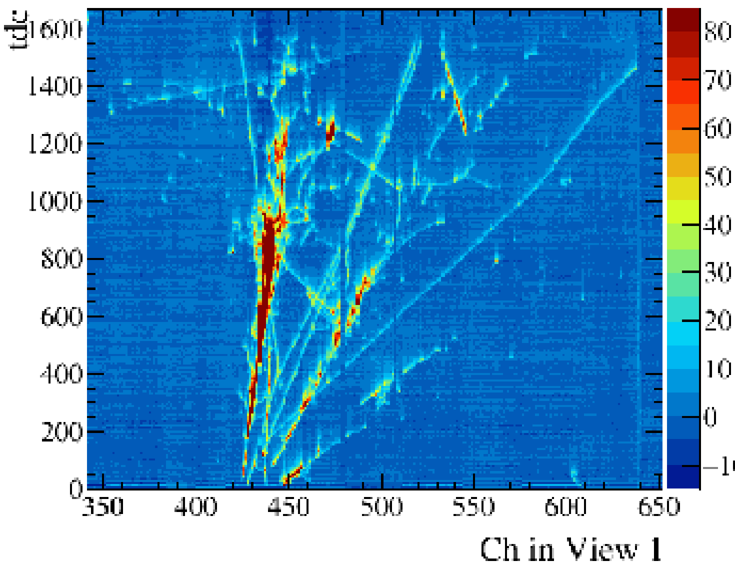
Highly capable LAr TPC

→ *excellent background rejection*

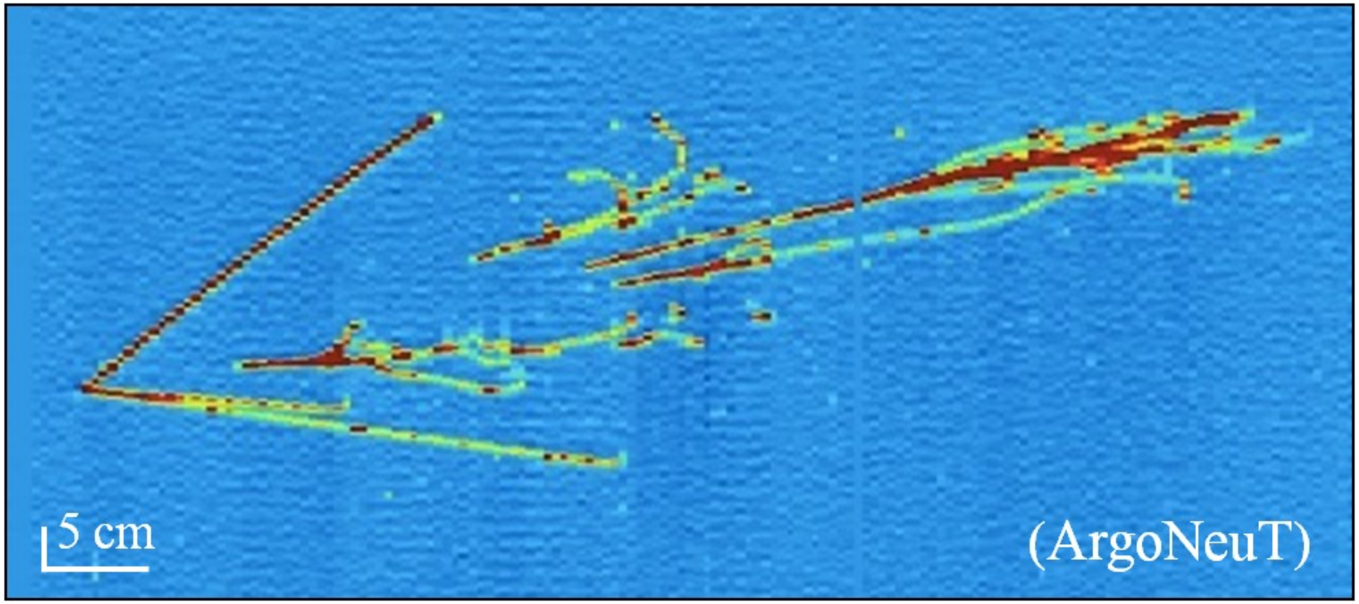
Low energy threshold

→ *rich underground physics program*

3m×1m×1m DP prototype data
(raw output; no noise filtering)

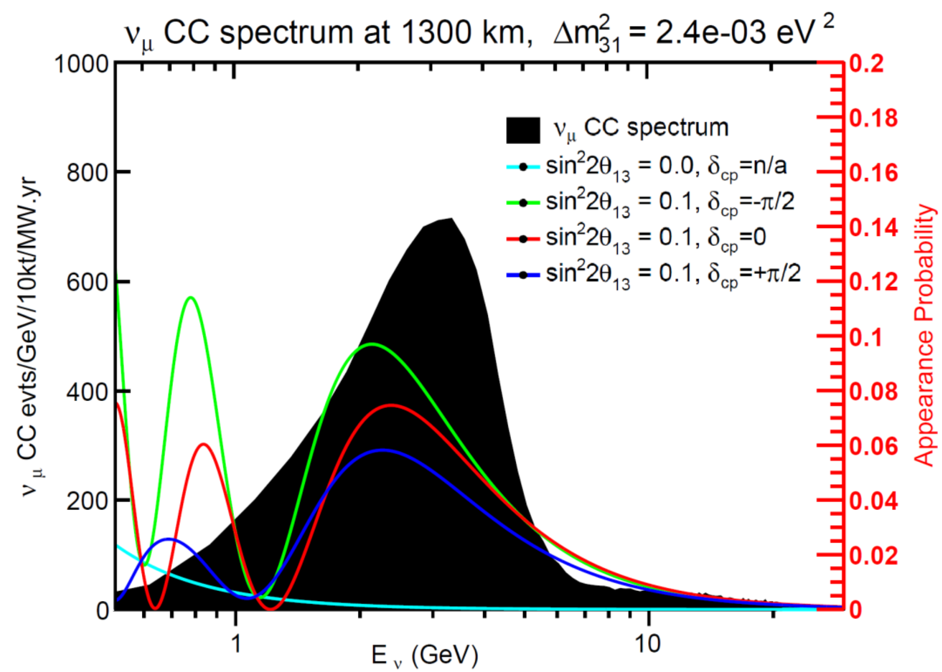


Neutrino event in ArgoNeuT detector

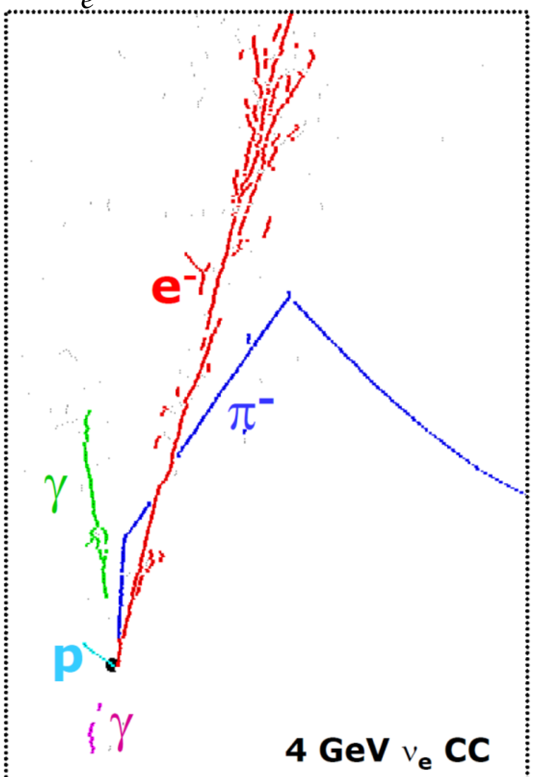


High resolution detectors

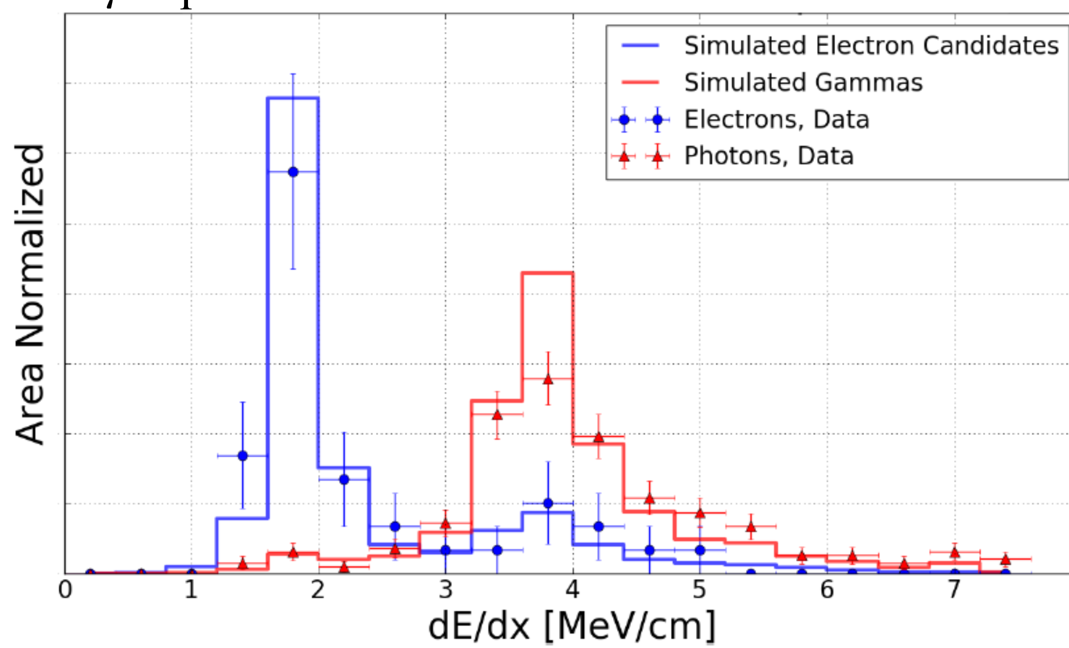
- permits broadband neutrino beam
- *e*-*γ* shower separation via both event topology and early *dE*/*dx*



Simulated and reconstructed
ν_e CC event in DUNE



e/*γ* separation with R&D detector



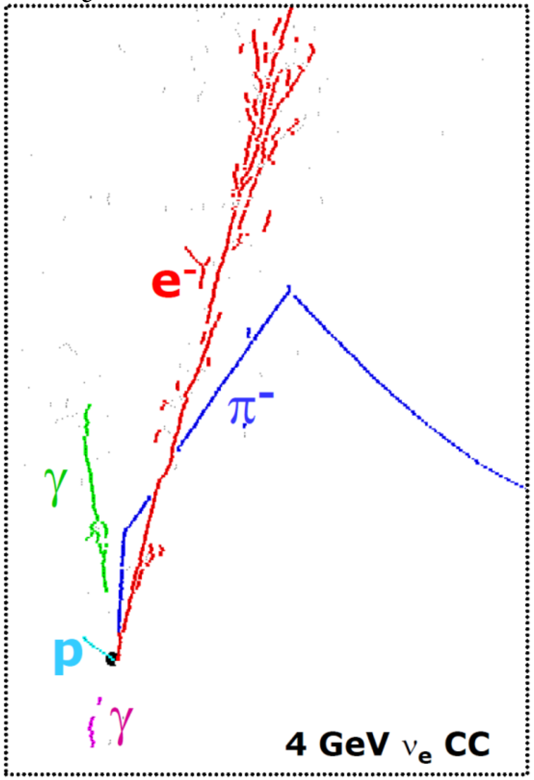
ArgoNeuT, arXiv:1610.04102

Event reconstruction and PID

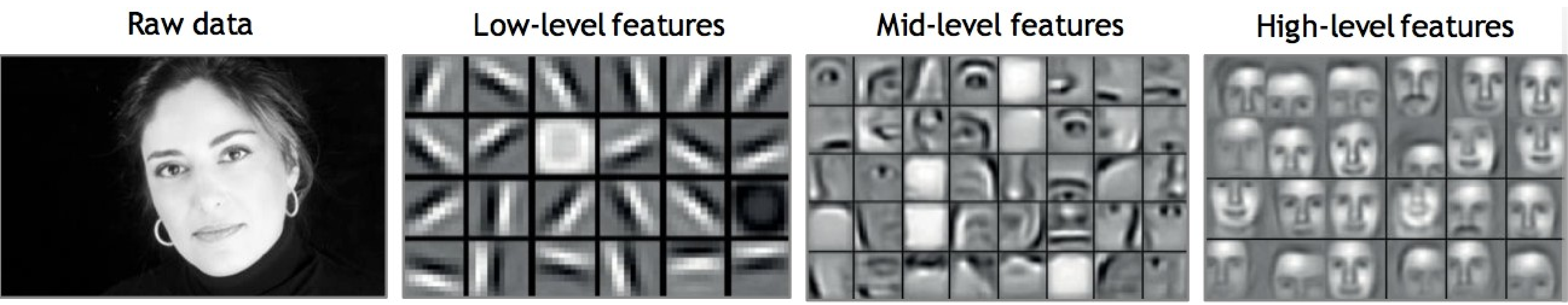
LAr TPC event reconstruction and particle identification continues to enjoy rapid evolution across experiments

- On DUNE, exploring both traditional and modern approaches, including convolutional neural networks and deep learning

Simulated and reconstructed ν_e CC event in DUNE



CNNs: network of weights describing kernel operations, convolving that kernel across the entire image to exaggerate useful features. Inspired by the architecture of the visual cortex.



*(after 7 **years**, staged deployment)*

Observation of leptonic *CP* violation

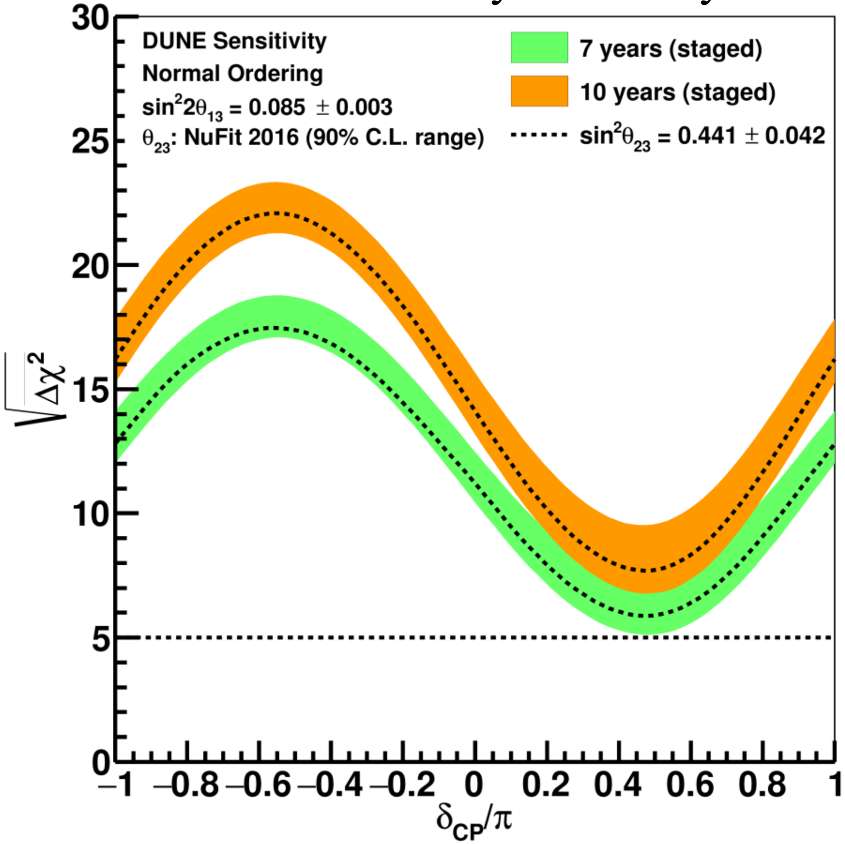
- **5σ** near $\delta = \pi/2$
- **3σ** for 65% of δ range

Definitive hierarchy determination

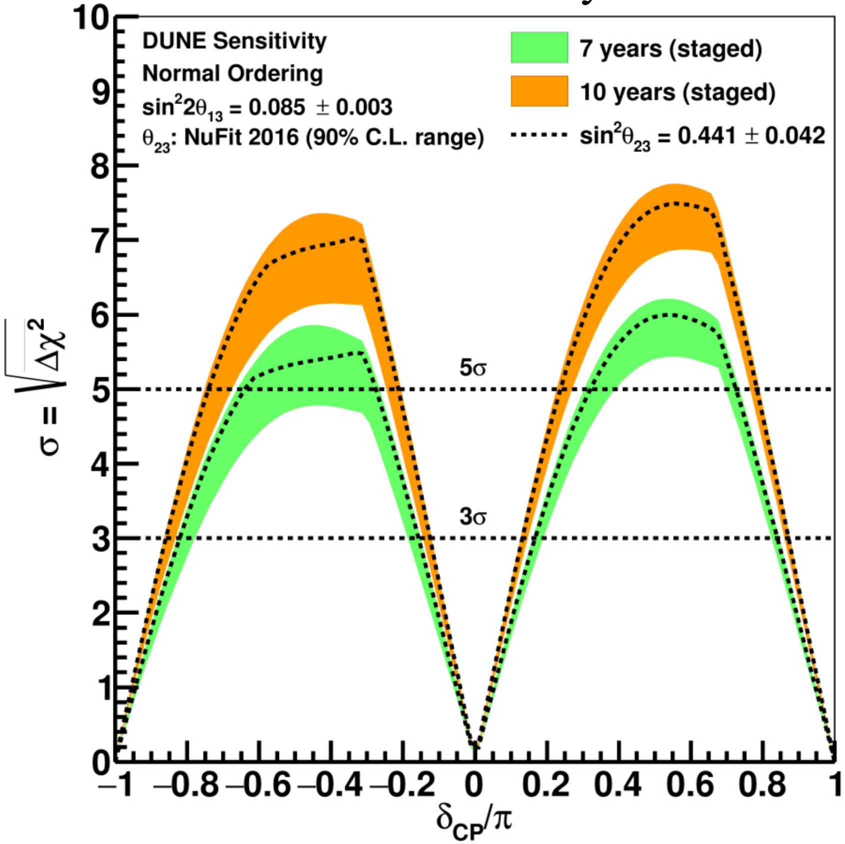
- **>5σ** regardless of other parameter choices

Move quickly to
potential discovery

Mass hierarchy sensitivity



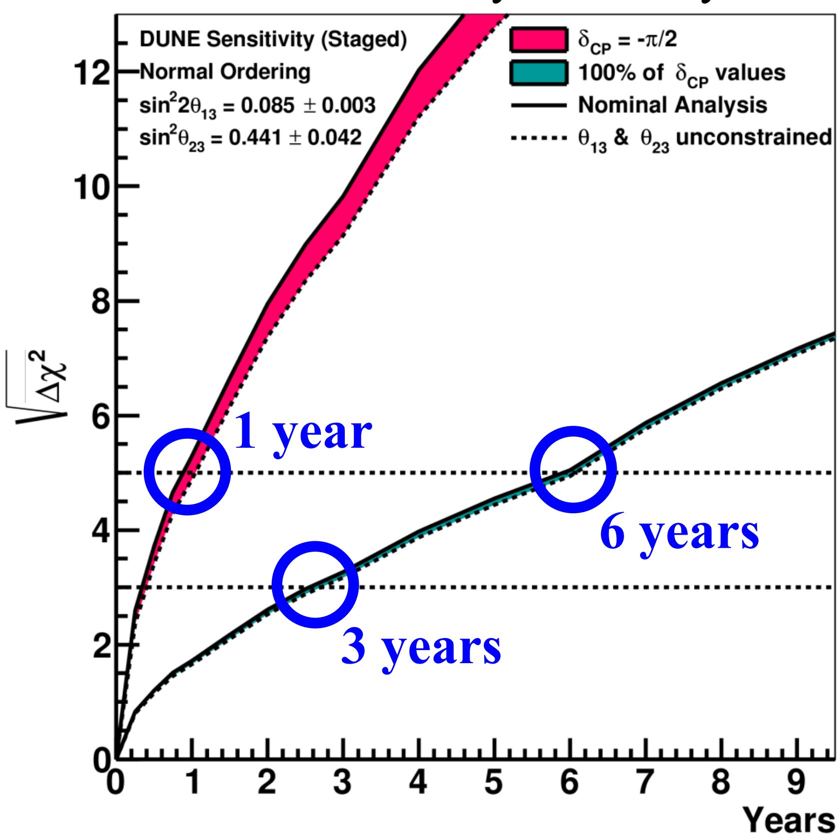
*CP*v sensitivity



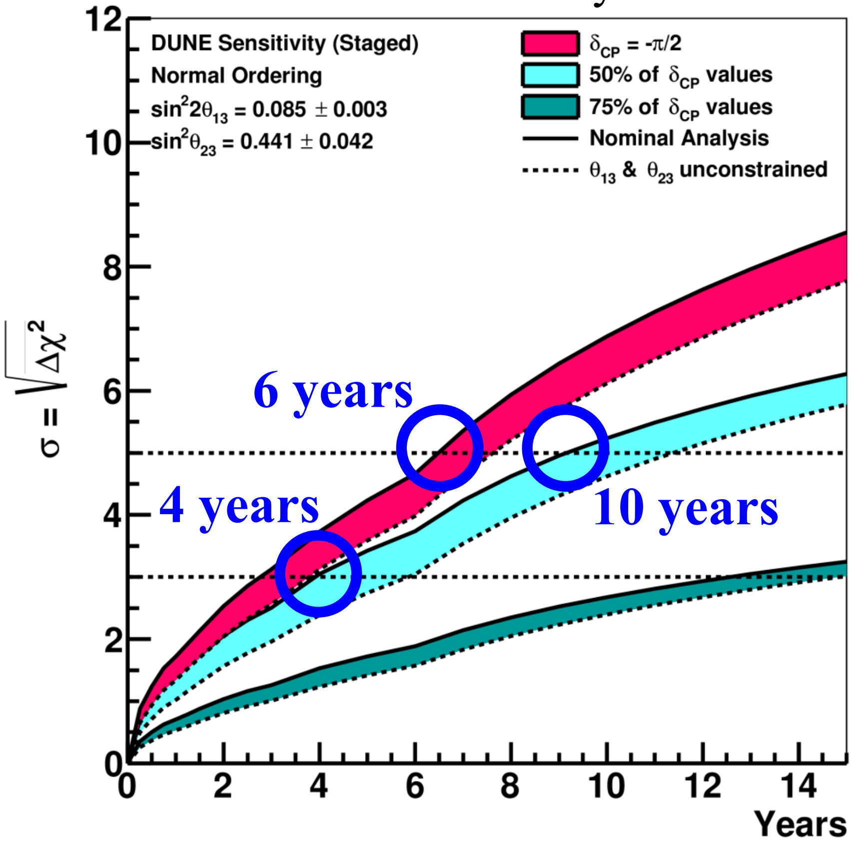
Sensitivity vs. time

→ **Significant milestones** throughout beam-physics program
→ **A few examples** below

Mass hierarchy sensitivity



*CP*v sensitivity



Precision PMNS

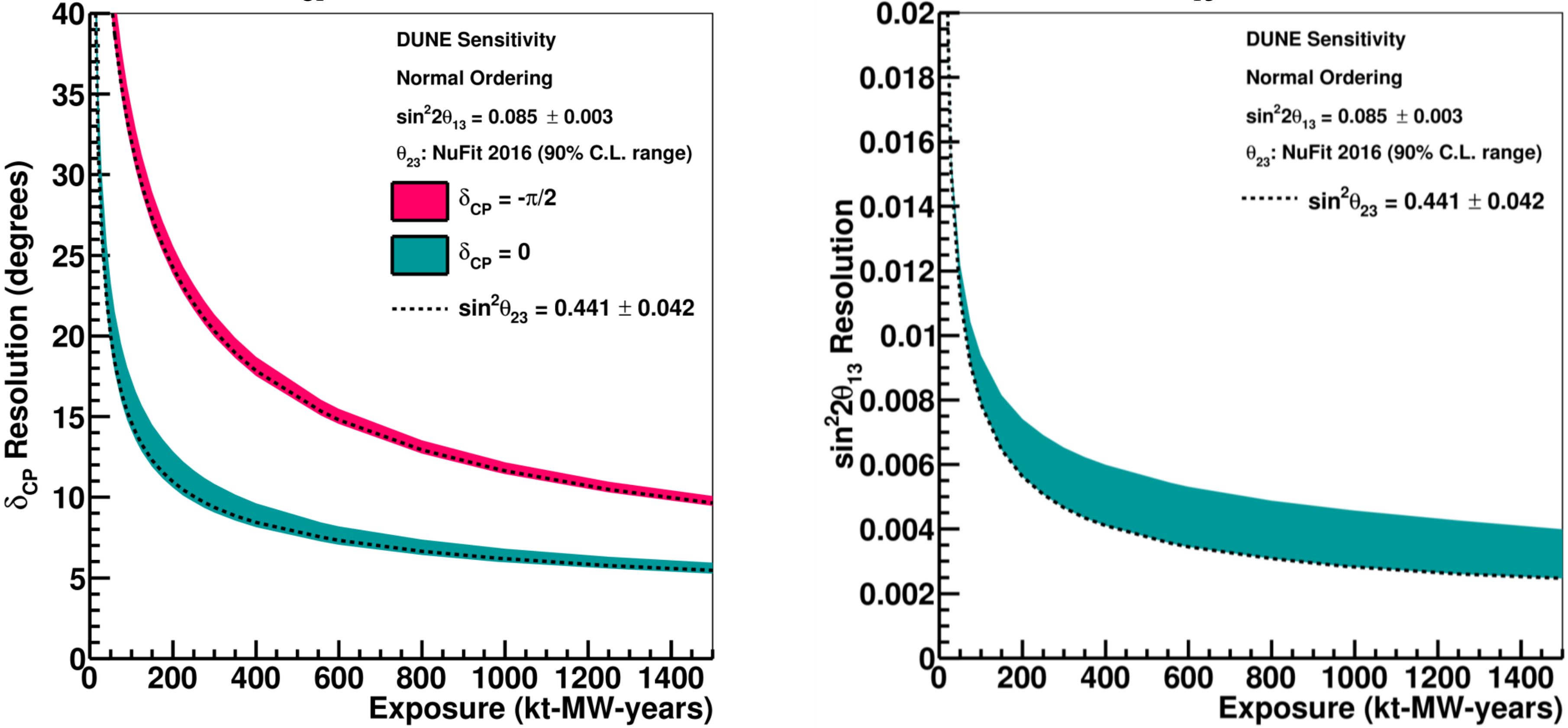
(ultimate precision depends on parameter values themselves)

→ *E.g.:* δ_{CP} to ~10° ; θ_{13}, θ_{23} to ~0.2°

→ A suite of oscillation parameter measurements **in a single experiment**

δ_{CP} resolution

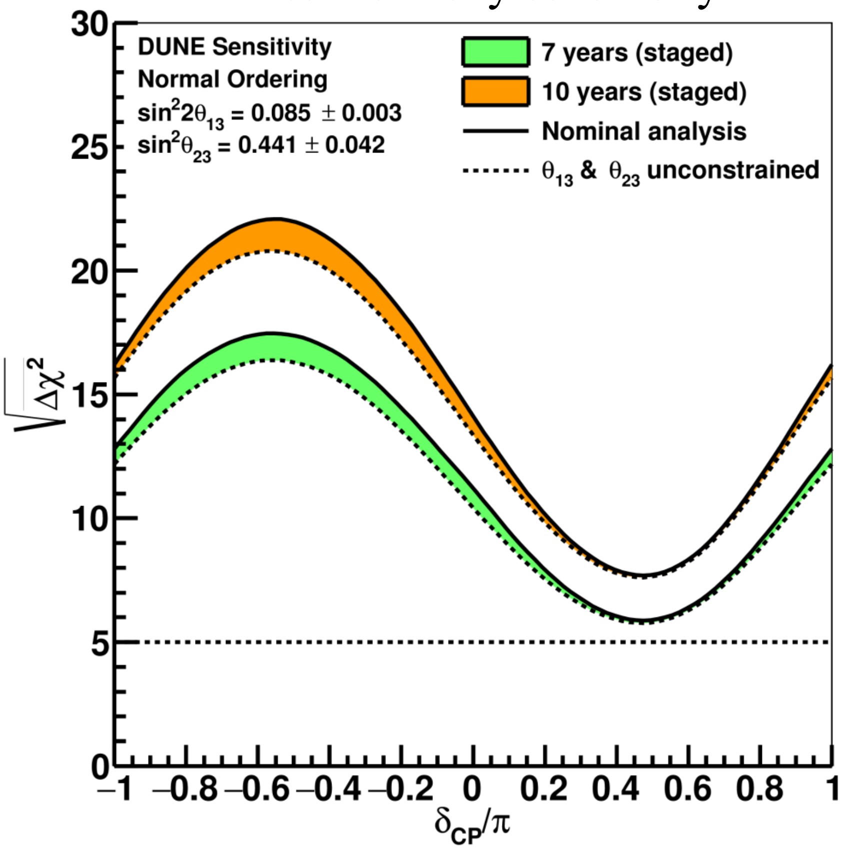
$\sin^2 2\theta_{13}$ resolution



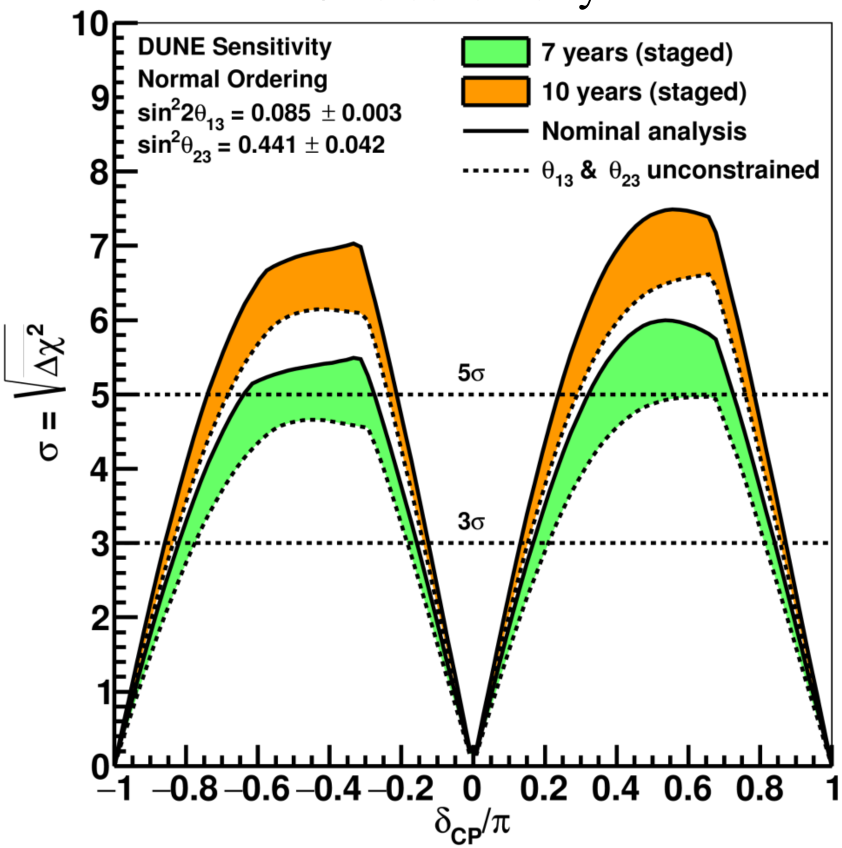
νMH and *CP*v reach with no external constraint on θ_{13} or θ_{23}

→ Neither depends critically on external constraints, though it obviously helps to include them.

Mass hierarchy sensitivity



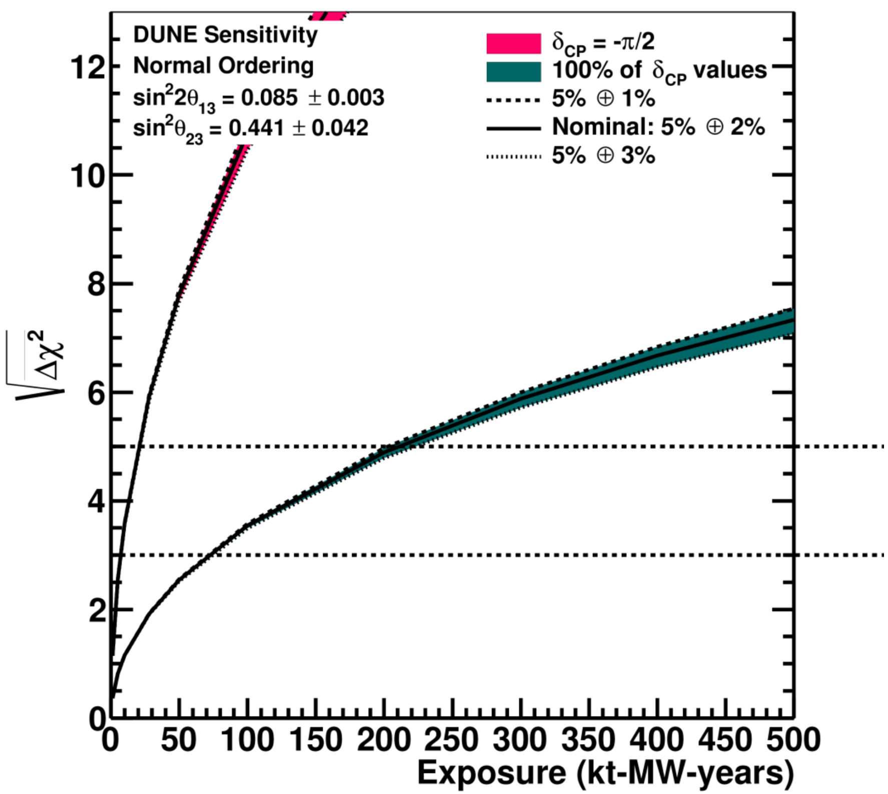
*CP*v sensitivity



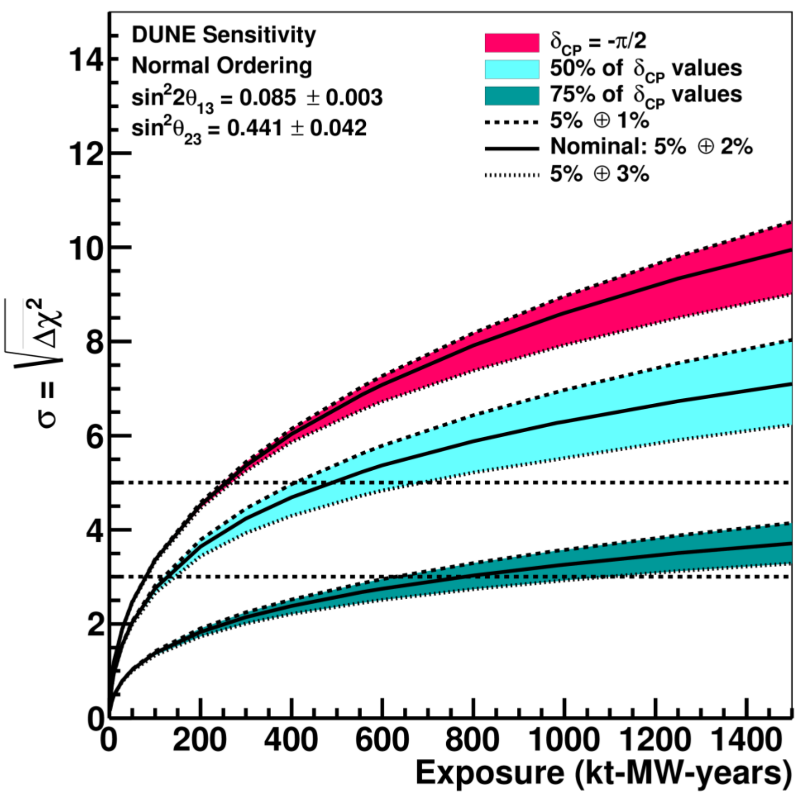
*ν*MH and *CP*v reach with varying assumptions about systematic uncertainties

→ Some movement in *CP*v reach. More sophisticated systematic error treatments under development for upcoming Technical Design Report.

Mass hierarchy sensitivity

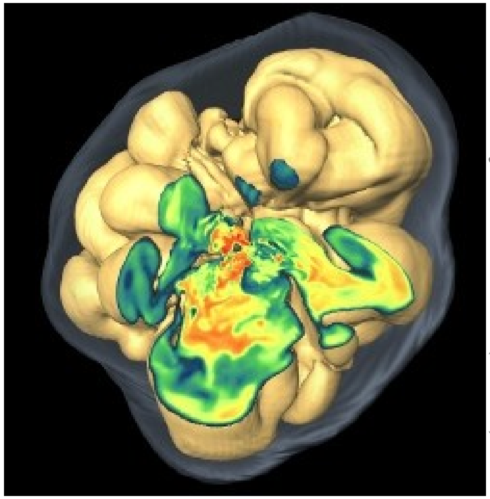


*CP*v sensitivity



Supernova neutrinos

- **99% of energy** released in a core-collapse supernova is **carried away by neutrinos** *(cf.: 0.01% carried away by light)*
- **Rich information** embedded in neutrino signal:
  - **Supernova physics:** core-collapse mechanism, black hole formation, shock stall/revival, nucleosynthesis, cooling, …
  - **Particle physics:** flavor transformations in core, collective effects, mass hierarchy, sterile neutrinos, extra dimensions, …

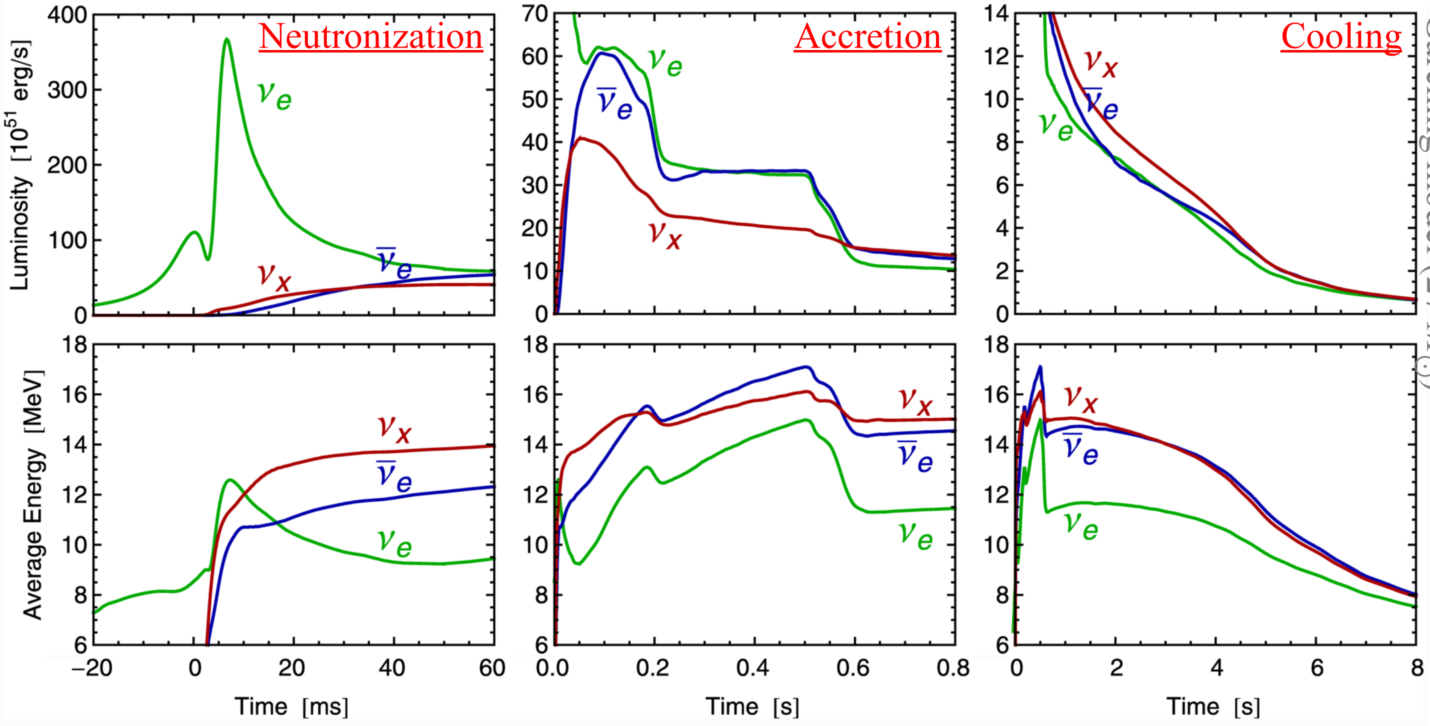


S. Woosley and T. Janka
Nature Physics **1**, 147 (2005)

Argon target:
Unique sensitivity to ν_e flux

DUNE at 10 kpc:
~3000 ν_e events over 10 seconds

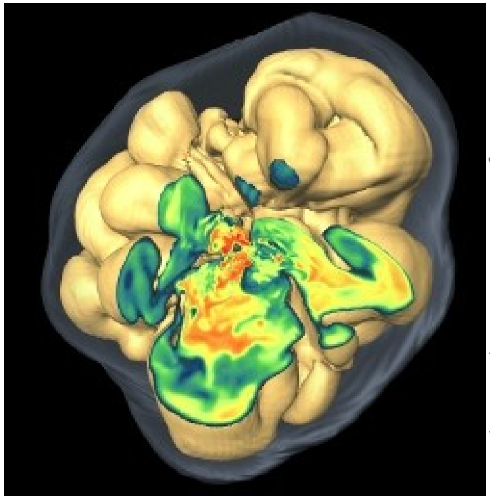
with 5%–10% energy resolution & sub-μs time resolution



Garching model (27 $M_\odot$)

Supernova neutrinos

- **99% of energy** released in a core-collapse supernova is **carried away by neutrinos** *(cf.: 0.01% carried away by light)*
- **Rich information** embedded in neutrino signal:
  - **Supernova physics:** core-collapse mechanism, black hole formation, shock stall/revival, nucleosynthesis, cooling, …
  - **Particle physics:** flavor transformations in core, collective effects, mass hierarchy, sterile neutrinos, extra dimensions, …



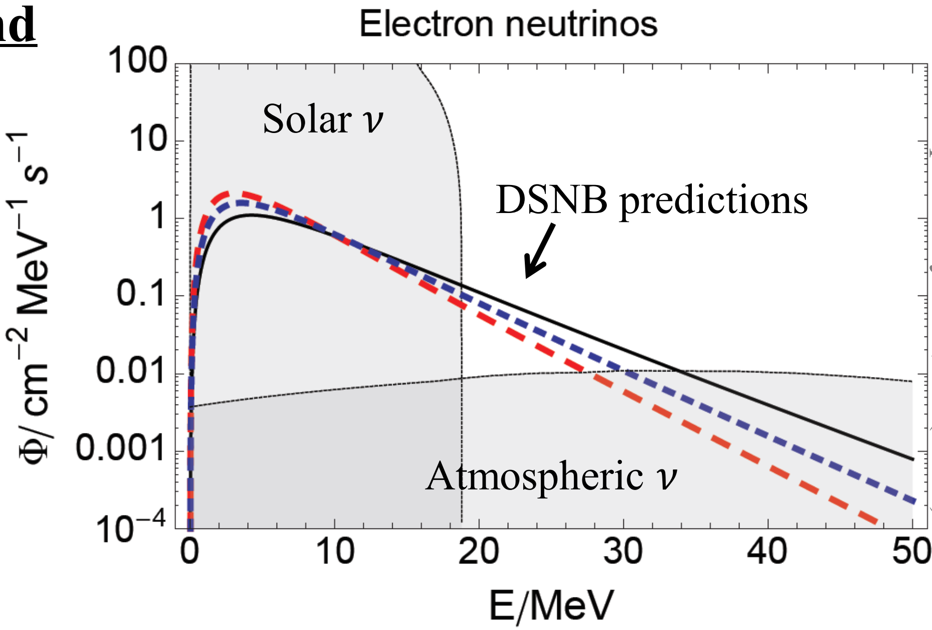
S. Woosley and T. Janka
Nature Physics **1**, 147 (2005)

Diffuse supernova neutrino background

Should be there. *Not yet observed.**

DUNE: Potential for DSNB discovery and rate measurement

(a challenge; stay tuned)



C. Lunardini,
Astropart. Phys. **79**, 49 (2016)

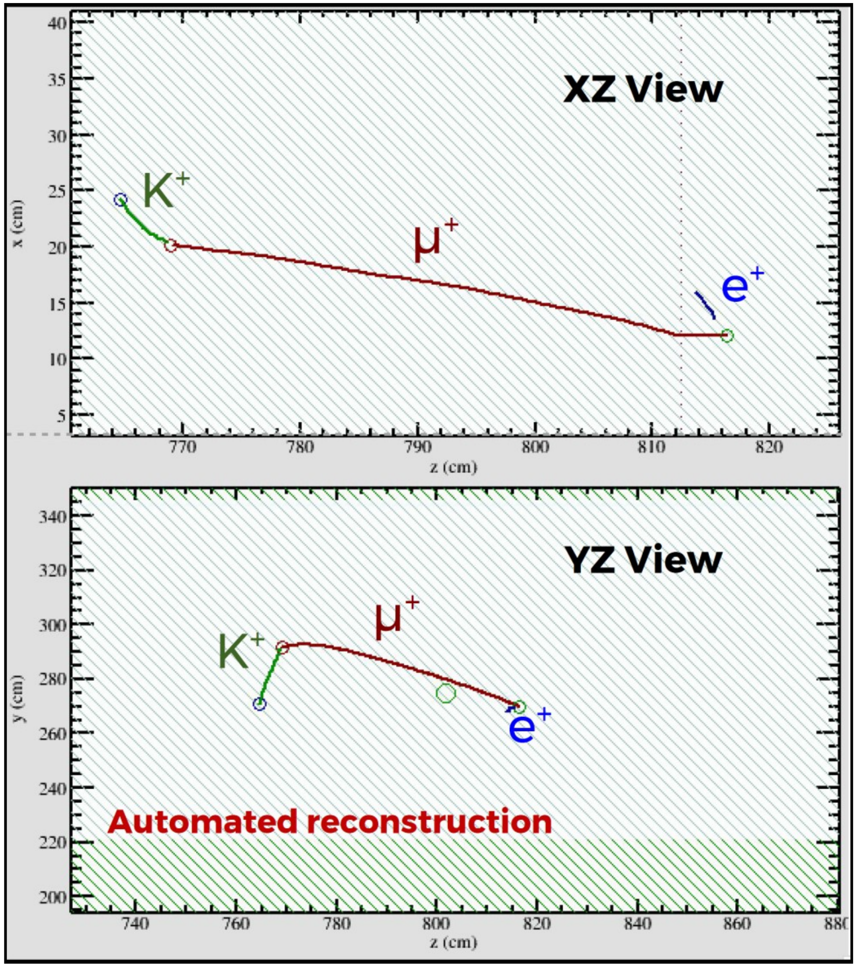
* Present limit from Super-K:
K. Bays *et al.*, Phys. Rev. D **85**, 052007 (2012)

Baryon number violation

Processes with $\Delta B \neq 0$, including **proton decay**, are a general prediction of **grand unified theories**

- An **effective proton decay search** requires (**and DUNE has**)
  - **Large exposure:**
    40 kton, 20+ yr program
  - **Low background rates:**
    Deep underground location
  - **High signal efficiency:**
    Precision LAr TPC tracking

LAr TPC technology **particularly shines** for complex *p* decay modes or modes with **final state kaons**, as **favored by SUSY GUTs**



At right:

***K*±→*μ*→*e* decay sequence**

Clear signature in DUNE

Baryon number violation

Processes with $\Delta B \neq 0$, including **proton decay**, are a general prediction of **grand unified theories**

- An **effective proton decay search** requires (**and DUNE has**)
  - **Large exposure:**
    40 kton, 20+ yr program
  - **Low background rates:**
    Deep underground location
  - **High signal efficiency:**
    Precision LAr TPC tracking

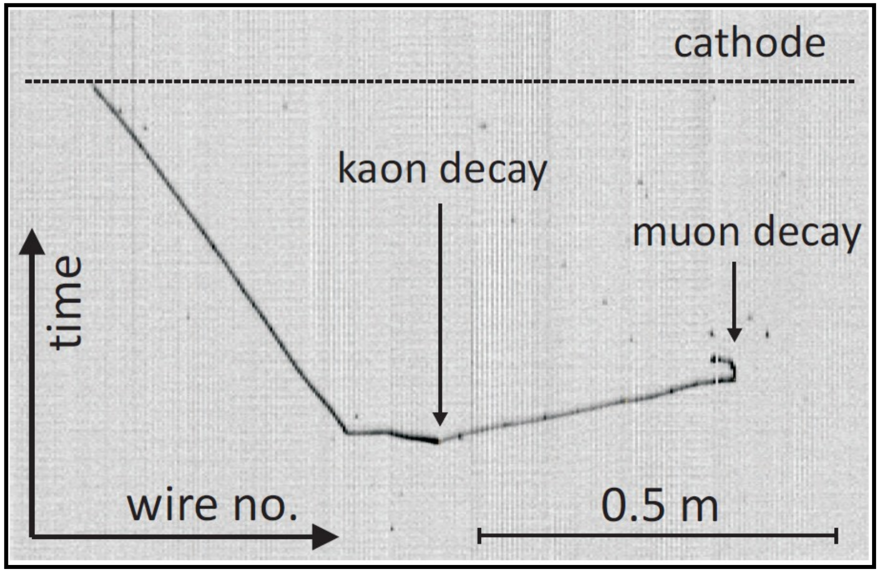
LAr TPC technology **particularly shines** for complex *p* decay modes or modes with **final state kaons**, as **favored by SUSY GUTs**

At right:

***$K^{\pm}\rightarrow\mu\rightarrow e$* decay sequence**

Clear signature in DUNE

ICARUS collab., Adv. HEP, vol. 2013, 260820 (2013)



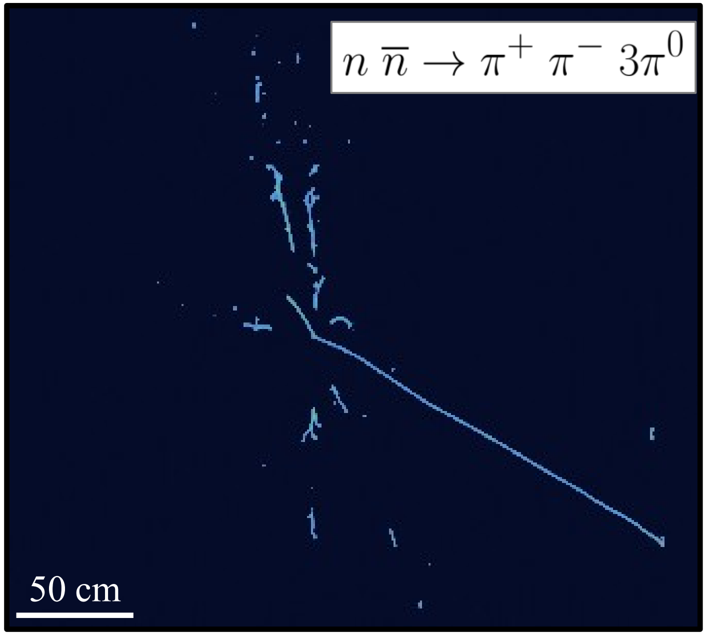
Baryon number violation

Processes with $\Delta B \neq 0$, including **proton decay**, are a general prediction of **grand unified theories**

- An **effective proton decay search** requires (**and DUNE has**)
  - **Large exposure:**
    40 kton, 20+ yr program
  - **Low background rates:**
    Deep underground location
  - **High signal efficiency:**
    Precision LAr TPC tracking

LAr TPC technology **particularly shines** for complex *p* decay modes or modes with **final state kaons**, as **favored by SUSY GUTs**

simulation



At right:

***n*-$\bar{n}$ oscillation** → intranuclear $\bar{n}n$ annihilation

Spherical spray of hadrons with $\boldsymbol{E \approx 2M_n}$ and **net momentum** $\boldsymbol{\lesssim p_F}$ ~ 300 MeV

10-yr sensitivity: $\tau_{free} > 1.6\times 10^9$ s @ 90% C.L. (5× current limit)

More of the physics program beyond "3ν"

Some of the **new physics signatures** accessible with DUNE:

- **Light sterile neutrinos**
  Various experimental anomalies persist. Multiple channels for investigation in a LBL setup.
- **Non-standard interactions**
  Beam and atmospheric neutrinos passing through matter provide access to non-standard couplings. Unique search features: long baselines; appearance channel.
- **Dark matter**
  Astrophysical (*e.g.*, annihilation in the sun; at DUNE, look for up-going neutrinos), beam-induced light dark matter (*e.g.*, $qq \rightarrow V^* \rightarrow \bar{\chi}\chi$ at target), and boosted dark matter
- **And more…**
  Lorentz violation, effective *CPT*v, large extra dimensions, non-unitarity, neutrino tridents (Z' and muon g–2)

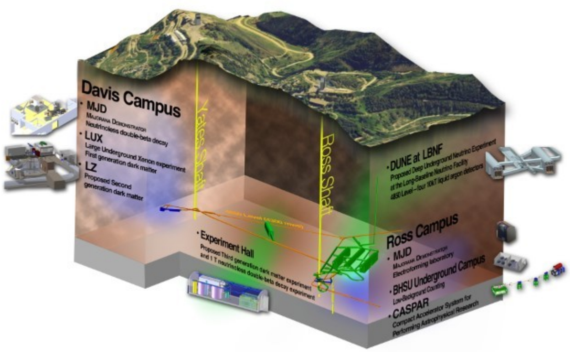
Plus **millions of interactions** in the Near Detector for exploring ν-nucleus scattering: final state interactions, nuclear structure, MEC/2p2h channels, …

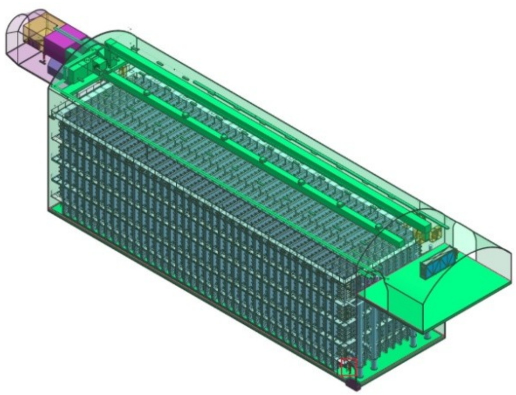
T2HK and DUNE Comparison

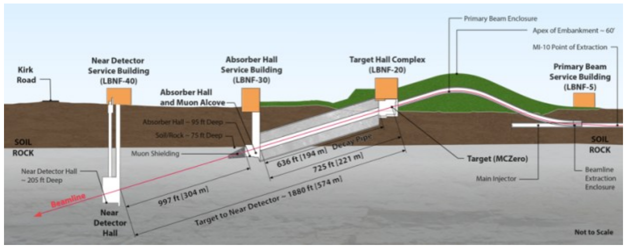
Note: The experiments use a **mix of assumptions** for oscillation parameters, systematic uncertainties, and other relevant quantities. Comparisons should assume **10%-ish uncertainties on stated sensitivities** to absorb such effects.

(10 yrs, staged deployment)		**T2HK**	**DUNE**	
CP violation	δ resolution	7° – 21°	7° – 15°	similar
	3σ coverage	78%	74%	
	5σ coverage	62%	54%	
νMH	sens. range	$5\sigma - 7\sigma$	$8\sigma - 20\sigma$+	DUNE superior
octant	sens. @ 0.45	5.8σ	5.1σ	similar
	5σ outside of…	[0.46, 0.56]	[0.45, 0.57]	
p decay (90% C.L.)	$p \rightarrow \bar{\nu} K^+$	>2.8e34 yrs	>3.6e34 yrs	mode dependent
	$p \rightarrow e^+ \pi^0$	>1.2e35 yrs	>1.6e34 yrs	
supernova ν (10 kpc or relic)	SNB $\bar{\nu}_e$	130k evts		complementary channels (ν_e vs. $\bar{\nu}_e$, though Hyper-K has more SN events total)
	SNB ν_e		3k evts	
	relic $\bar{\nu}_e$	100 evts, 5σ		
	relic ν_e		30 evts, 6σ	
NSI (90% C.L.)	$\lvert\varepsilon_{\mu e}\rvert$	<0.34	<0.05	DUNE superior
	$\lvert\varepsilon_{\mu\tau}\rvert$	<0.27	<0.08	
	$\lvert\varepsilon_{\tau e}\rvert$	<0.98	<0.25	

DUNE Timeline







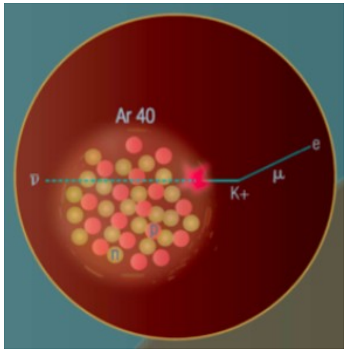
2017: Far Site Construction Began

2018: ProtoDUNEs at CERN

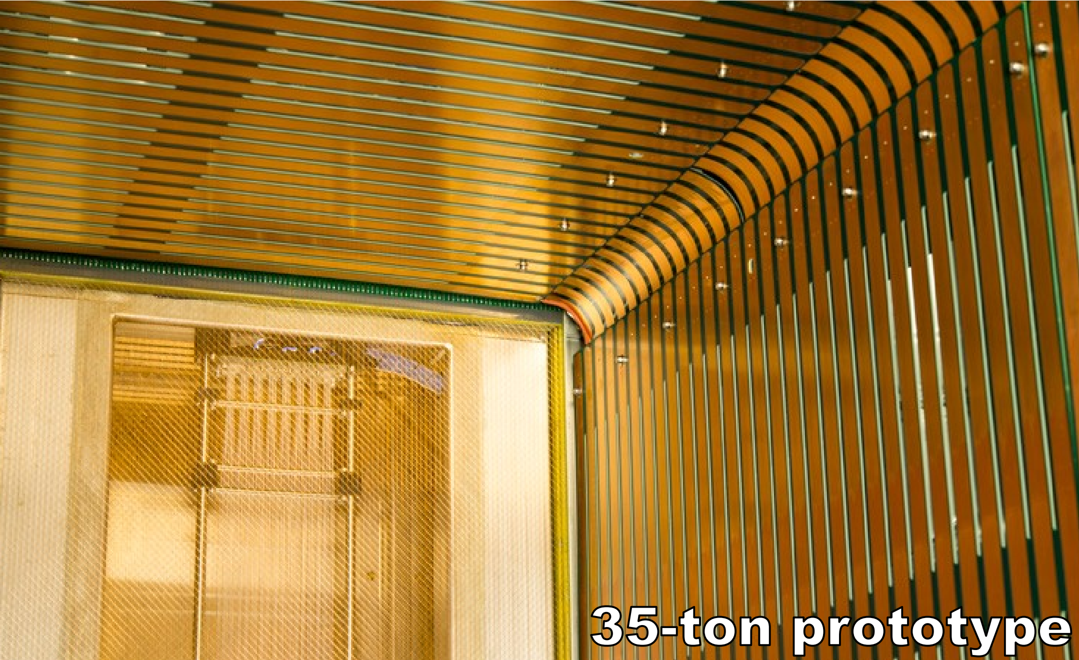
2021: Far Detector Installation Begins

2024: Physics Data Begins (20 kt)

2026: Neutrino Beam Available



40 kton + 2 MW beam to follow in subsequent years



DUNE is a top priority of the international HEP community

Highly internationalized:

- 1061 collaborators
- 175 institutions
- 31 countries

Full-scale component prototypes under construction at CERN

- Single- and dual-phase designs

DUNE in the current neutrino oscillation landscape

(Why you should be excited about DUNE)

The slides that follow aren't DUNE slides. Just me sharing some thoughts…

DUNE's oscillation physics program in in an evolving landscape

- **A question:**

  How does DUNE's neutrino oscillation program connect to the current long-baseline program, given the impressive performance of and projections for the latter?

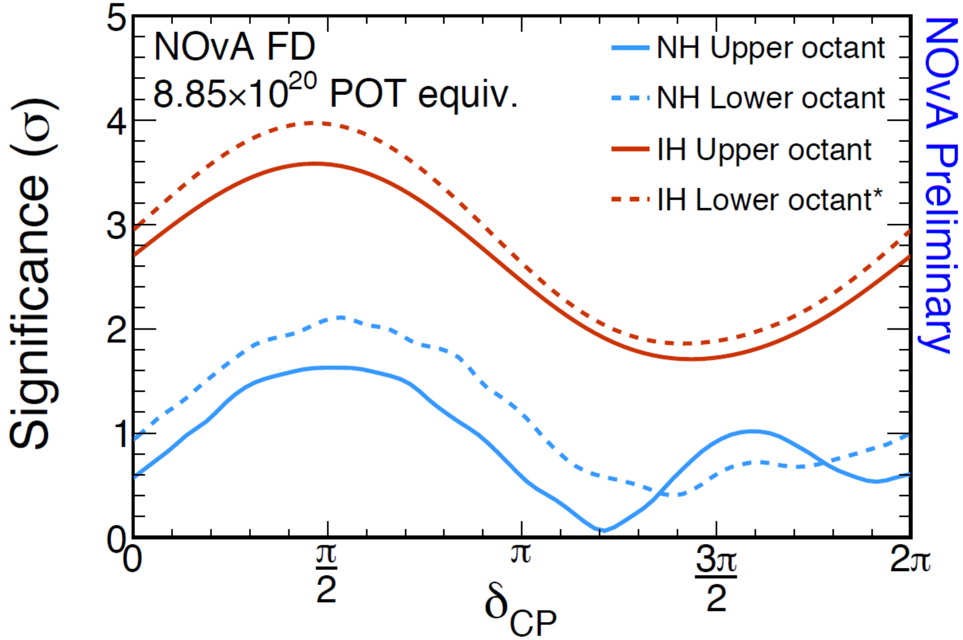
- Indeed, the **current operating program** is impressive:
  - Recent $\nu + \bar{\nu}$ results from **T2K** $\Rightarrow$ 2σ evidence for *CP*v reported
  - First $\nu + \bar{\nu}$ results from **NOvA** to come this summer
  - Aggressive plans for **exposure increases** for both experiments
  - Large **atmospheric** $\boldsymbol{\nu}$ **samples** in hand or possible (Super-K, ν telescopes)

- Currently favored parameters offer **highest sensitivities for *CP*v and $\boldsymbol{\nu}$MH**

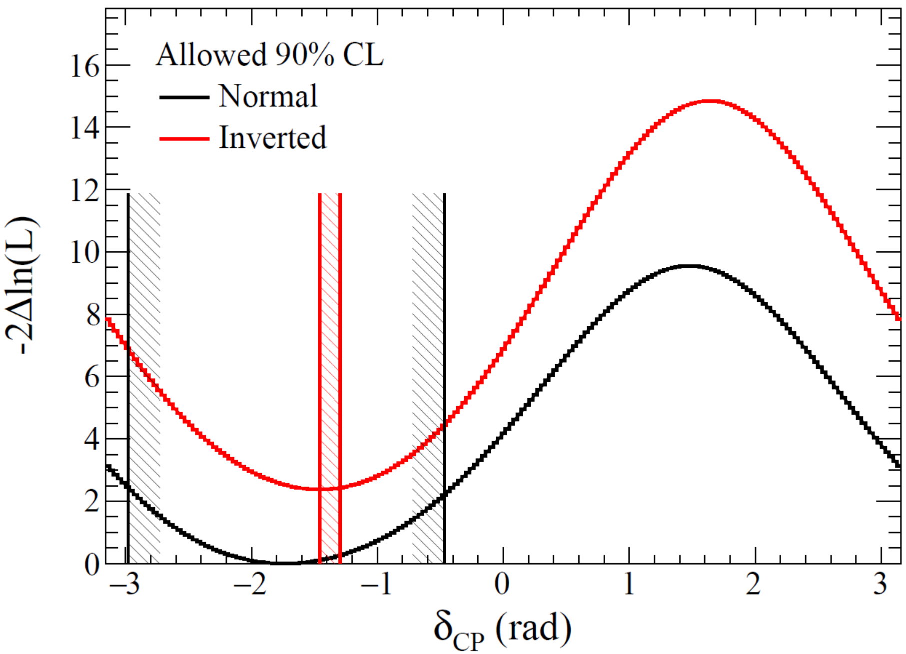
Latest from NOvA, T2K, and one global fitting effort

Inverted hierarchy and
***CP* conservation** each showing
some tension with data

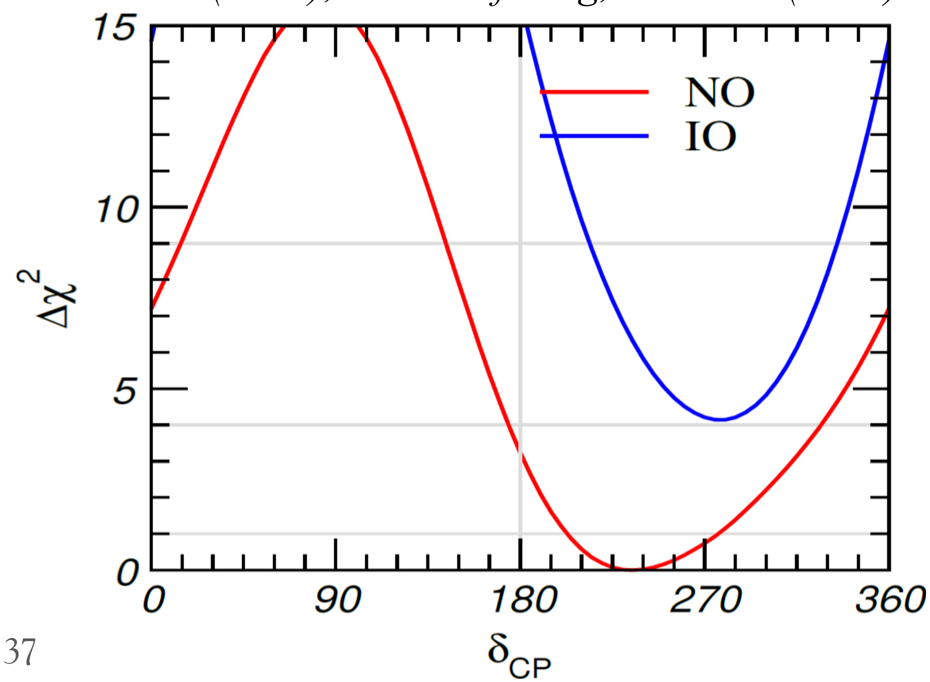
NOvA ν only, FNAL seminar Jan 2018, A. Radovic



*T2K ν+ν̄, PRD **96**, 092006 (2017)*

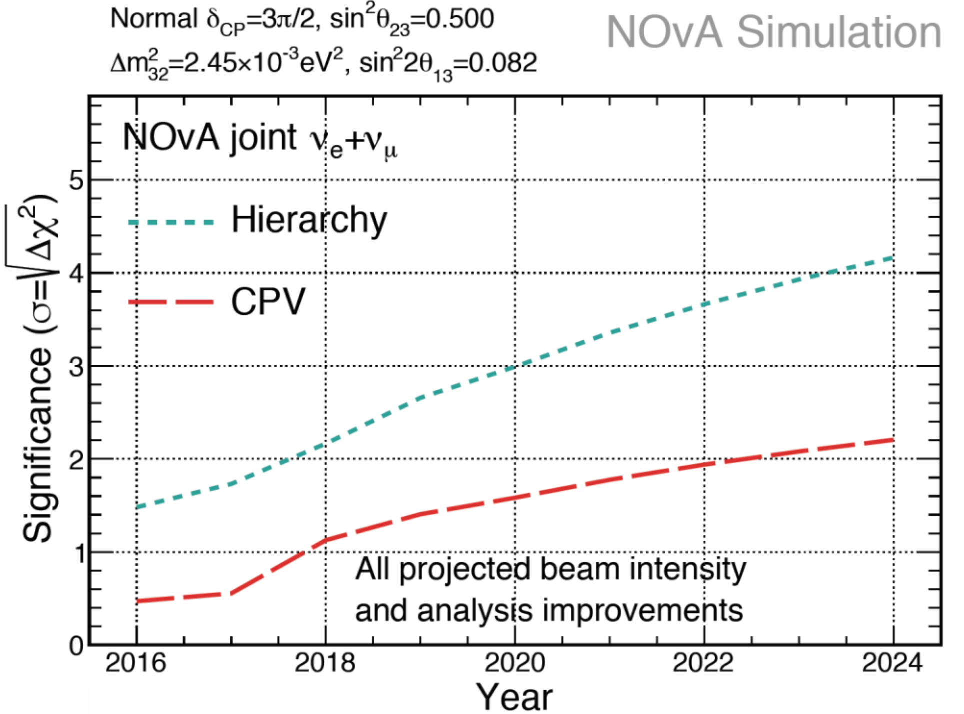


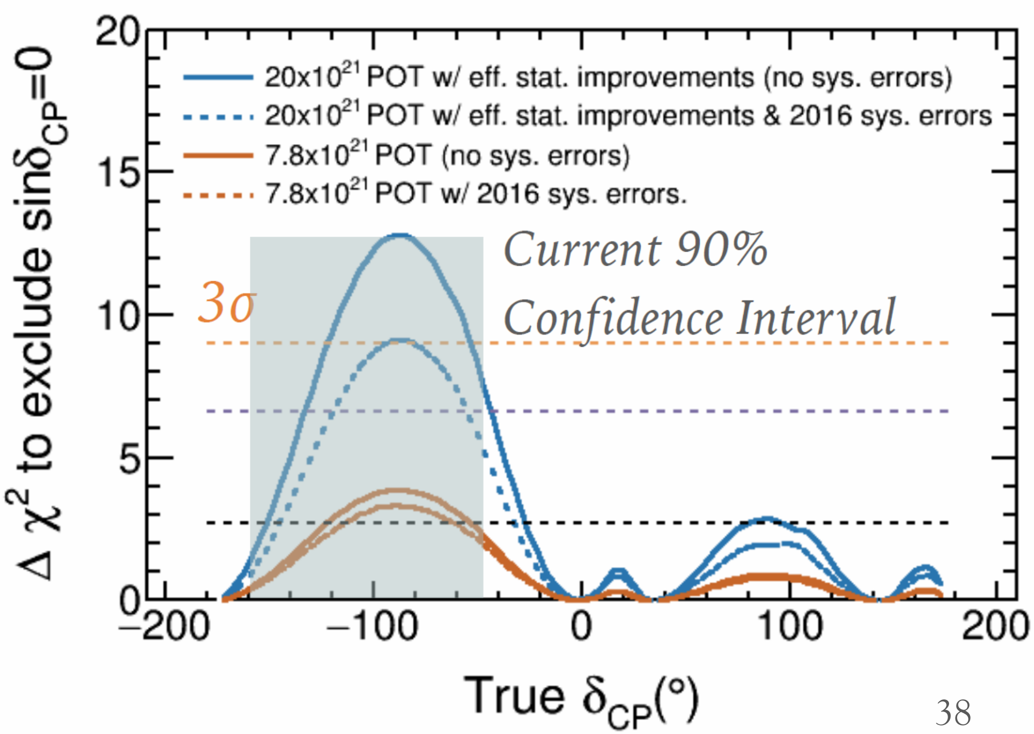
NuFIT 3.2 (2018), www.nu-fit.org, JHEP 01 (2017) 087



Projections for NOvA and T2K

Both forecasts assume reasonable accelerator upgrades





Prior to DUNE start, possibility of 3σ and 4σ sorts of C.L.s for νMH and CPv, assuming best fits don't drift away.

And, can then combine T2K and NOvA results.

Main caveat to these projections: sensitivities **depend greatly** on the parameters nature has actually chosen. *Current best-fit parameters are rather favorable – good! but tenuous.*

- **However**: regardless of the final outcome of current experiments, there is so much more left to do!

All possible outcomes have required next steps:

if ambiguities → **aim for clarity**
if evidence → **aim for discovery**
if discovery → **aim for characterization**

To expand on each line of this "triptych"…

1) If ambiguities → aim for clarity

- **Applies to all questions of "texture"**:

  - νMH is [normal | inverted]
  - mixing is [maximal | non-maximal]
  - octant is [upper | lower]
  - *CP* sym. is [violated | (maybe) respected]

- There is **ample phase space** still allowed to end up with ambiguities in any of these binary questions.

- νMH has well-known **"parameter degeneracies"** at 810 km that are still in play.
  T2K data can help break these degeneracies, but not overwhelmingly.

- Recent tension regarding **maximal mixing** has relaxed somewhat, making this question wide open again.

- **Octant determination highly dependent** on how non-maximally mixed ν_3 is.

2) If evidence → aim for discovery

- **Applies to all questions of "texture".**
- **Nominally an obvious thing: we want to discover *CP*v, νMH, etc…**

Is 2σ / 3σ / Xσ enough?

- **Enough for what purpose?**
  - Enough to guide model building?
  - Enough to motivate experiment directions (*e.g.*, direct ν mass measurements)?
  - Enough to rule out Majorana neutrinos (*e.g.*, when interpreting $0\nu\beta\beta$ results)?
  - Enough to declare leptogenesis viable / non-viable?
  - Enough to hold up to, say, future tension with ΛCDM fits or SNν data?

There will come a time when **each piece of our understanding** will need to be trusted at a very high confidence level ($>5\sigma$).

Lower confidence levels are **invaluable** and **actionable** in many contexts, but not all, especially when confronting the full field of questions.

3) If discovery → aim for characterization

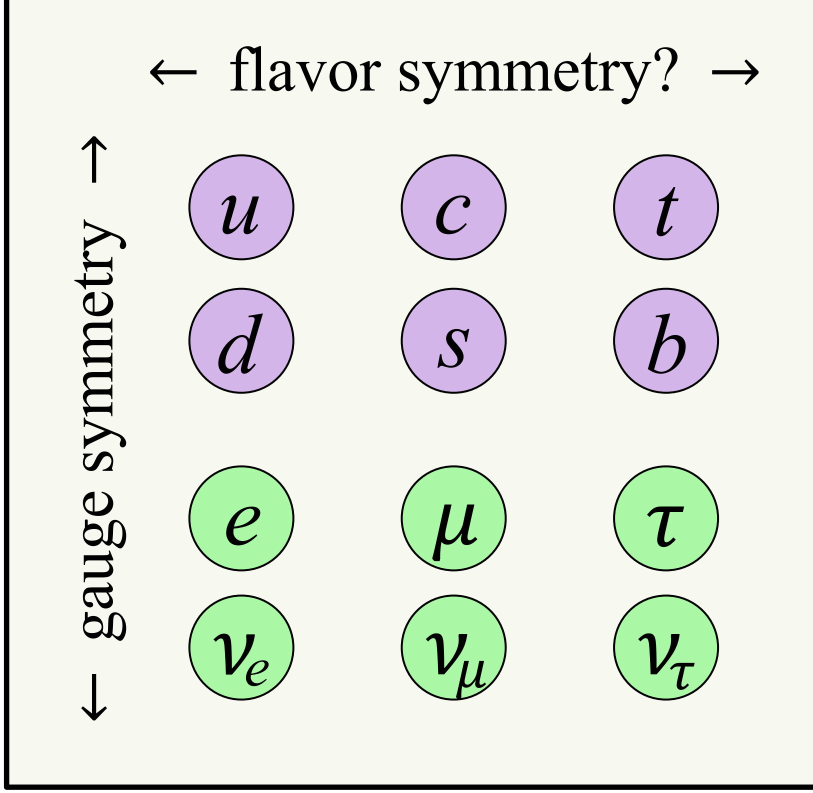
- **Applies to all 3ν parameters** (nevermind BSM)
- This is the precision program that is **inarguably beyond the current experiments**.

- Can compare goals to the **level of precision achieved** in quark flavor physics.
  - *But quark precision measurements are easily connected to specific BSM searches.* Same with neutrinos, just not usually in the form of loop effects.
  - *We haven't learned anything new from quark flavor precision, per se.* Maybe not in the past 10 years, but over the past 50 we sure have.
  - *It's a false analogy since leptons and quarks seem to behave very differently.* All the more reason to measure neutrinos well!

Flavor: A core problem for 21st century particle physics

What **flavor symmetry** can produce the observed pattern of mixings and masses, and how is that symmetry broken?

More broadly: what are the **dynamical origins** of fermion masses, mixings, and *CP* violation?



Tackling this problem requires **theoretical and <u>experimental</u> progress.**

→ **DUNE** will be at the heart of this.

Conclusions

DUNE gearing up

- **ProtoDUNE** installation underway now at CERN
- **Far Detector** site prep work underway now at SURF

A broad physics program

- DUNE will determine the ***ν*MH** and can measure **leptonic *CP*v** at 5σ
- Precision **PMNS**: a new era for understanding flavor
- **Nucleon decay**
- **Supernova** neutrinos
- And a rich **BSM physics** program both inside and outside the neutrino sector