DUNE Recombination Measurement with ProtoDUNE

Abbey Waldron

RAL Seminar

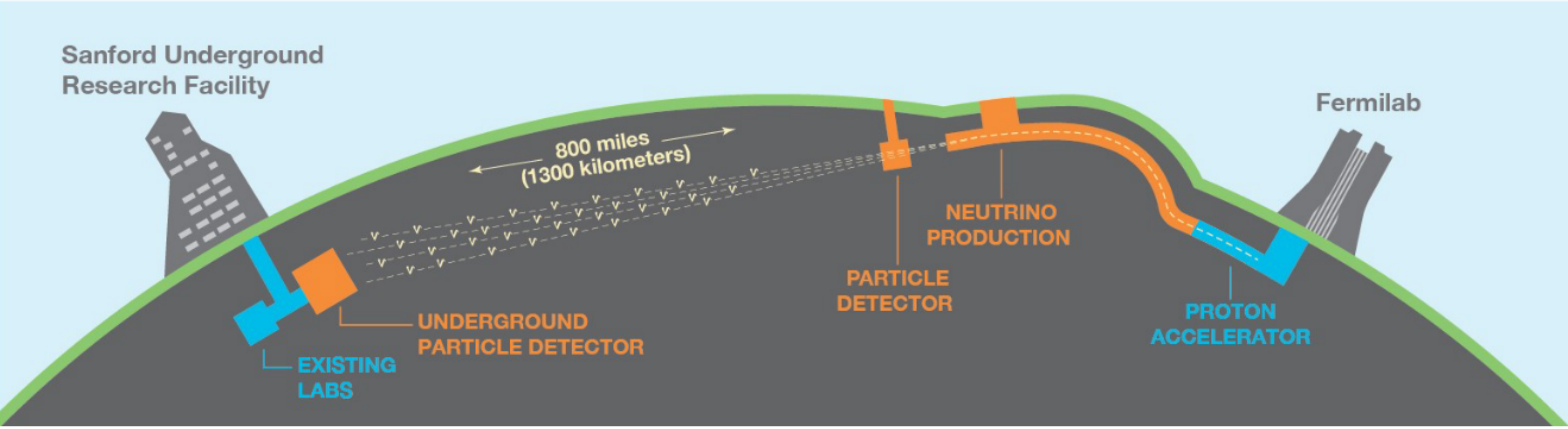
May 1st, 2024

Overview

- DUNE’s Physics Goals
- ProtoDUNE
- Measuring electron-ion recombination at ProtoDUNE

DUNE

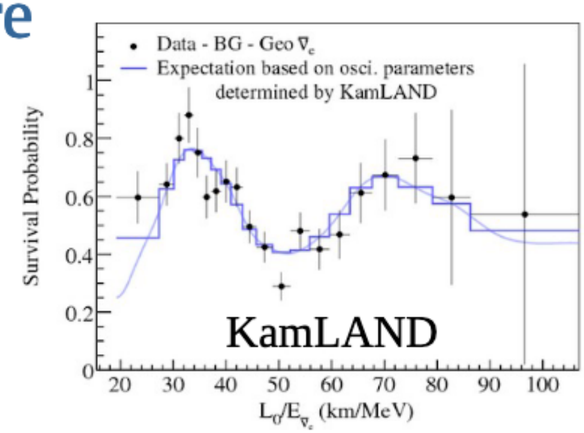
DEEP UNDERGROUND NEUTRINO EXPERIMENT

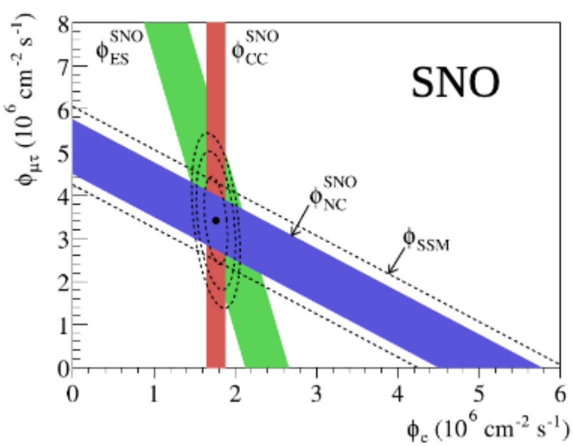


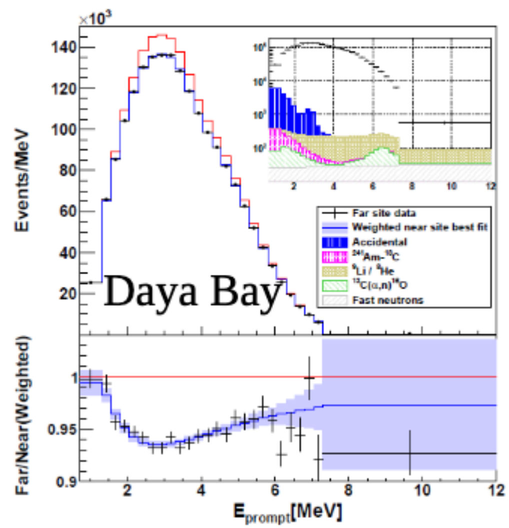
- Next-generation international neutrino & underground science experiment hosted in the United States (37 countries + CERN)
- High intensity neutrino beam, near detector complex at Fermilab
- Large, deep underground LArTPC far detectors at SURF
- Precision neutrino oscillation measurements, MeV-scale neutrino physics, broad program of physics searches beyond the Standard Model

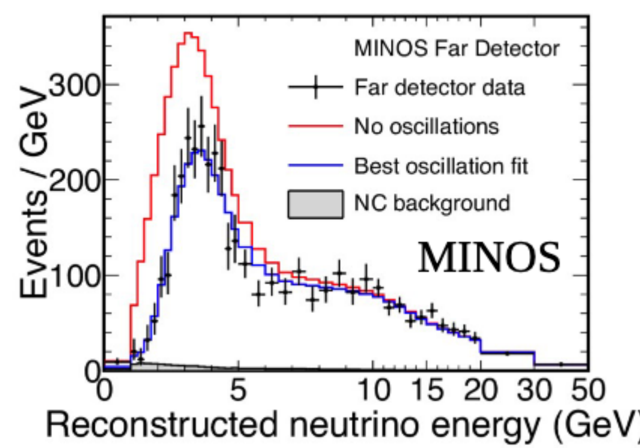
Neutrino oscillation: motivation

- We know neutrinos oscillate… but what is the origin of neutrino mixing? Is there an underlying flavor symmetry?









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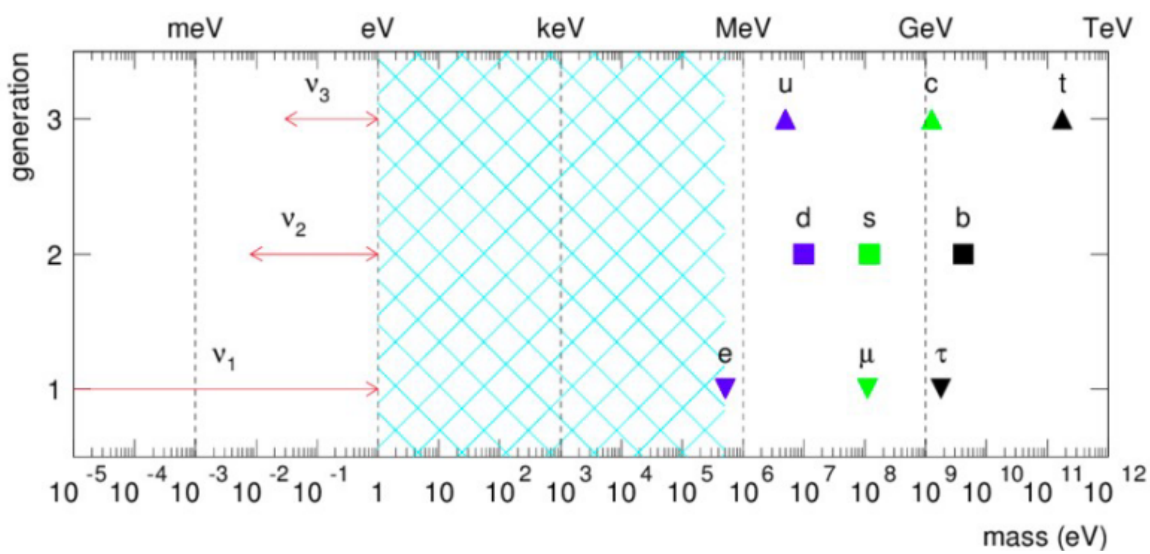
Neutrino oscillation: motivation

- We know neutrinos oscillate… but what is the origin of neutrino mixing? Is there an underlying flavor symmetry?
- We know neutrinos have mass… but what is the origin of neutrino mass? Why are the neutrinos so light?



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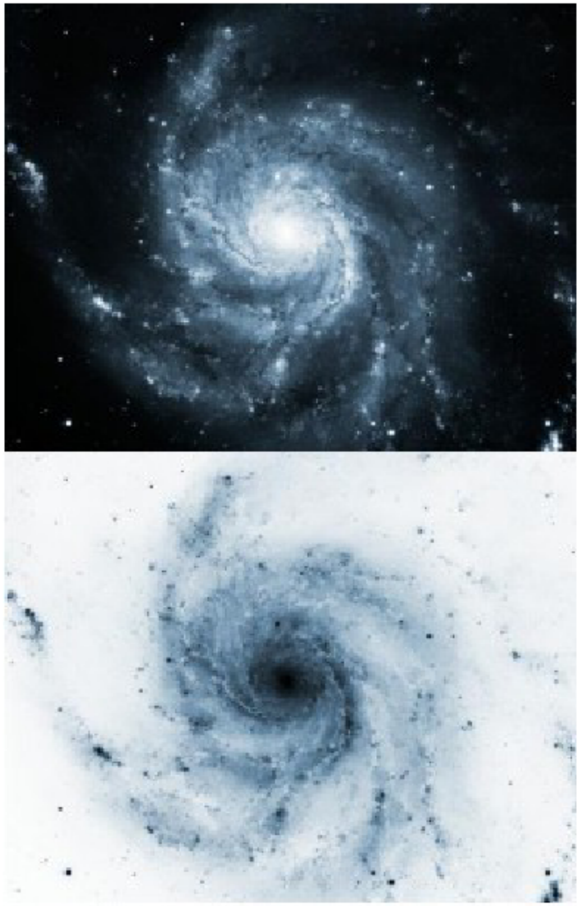

Neutrino oscillation: motivation

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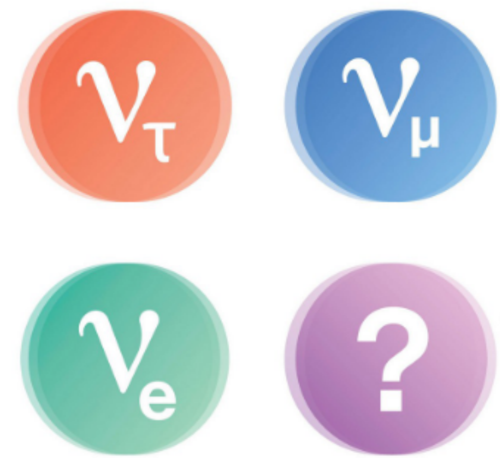
- We know neutrinos have mass… but what is the origin of neutrino mass? Why are the neutrinos so light?
- We know there is a baryon asymmetry… but is leptogenesis a viable explanation?
- We know there are at least three neutrino states… but are there exactly three? Is the νSM complete? Is the PMNS matrix unitary?



$$U_{\text{PMNS}}^{\text{Extended}} = \begin{pmatrix} \overbrace{\begin{matrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{matrix}}^{U_{\text{PMNS}}^{\text{3x3}}} & \begin{matrix} \cdots & U_{en} \\ \cdots & U_{\mu n} \\ \cdots & U_{\tau n} \end{matrix} \\ \begin{matrix} \vdots & \vdots & \vdots \\ U_{s_n 1} & U_{s_n 2} & U_{s_n 3} \end{matrix} & \begin{matrix} \ddots & \vdots \\ \cdots & U_{s_n n} \end{matrix} \end{pmatrix}$$

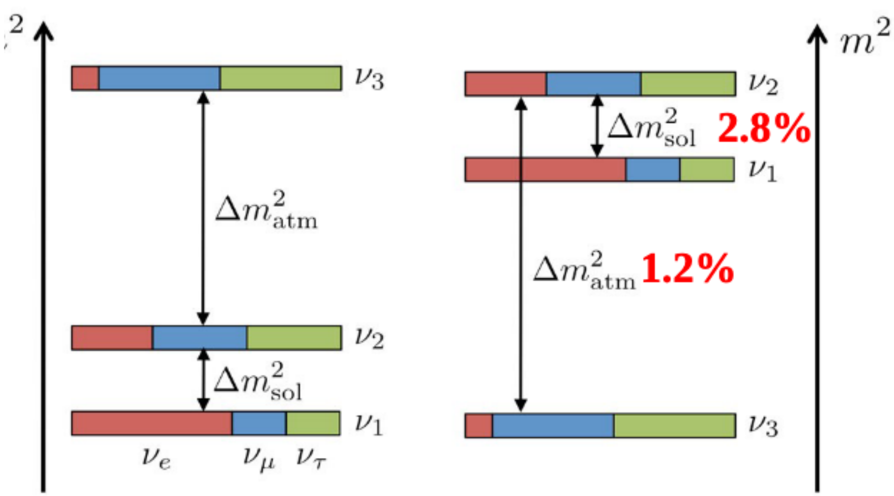
Phys. Rev. D 93, 113009 (2016)

What we know now

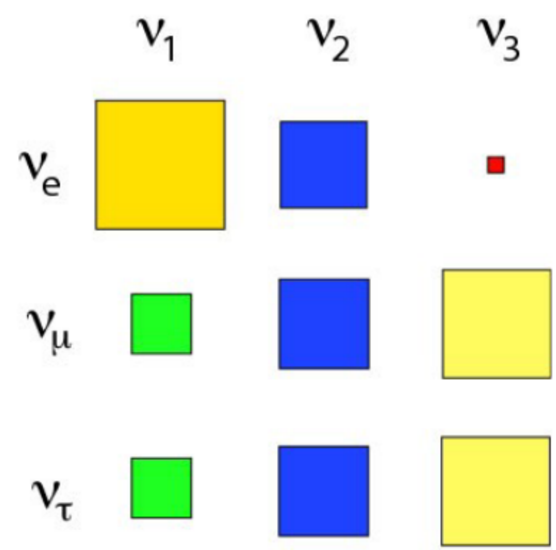
$$U_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta_{\mathrm{CP}}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{\mathrm{CP}}} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12}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

2.3%

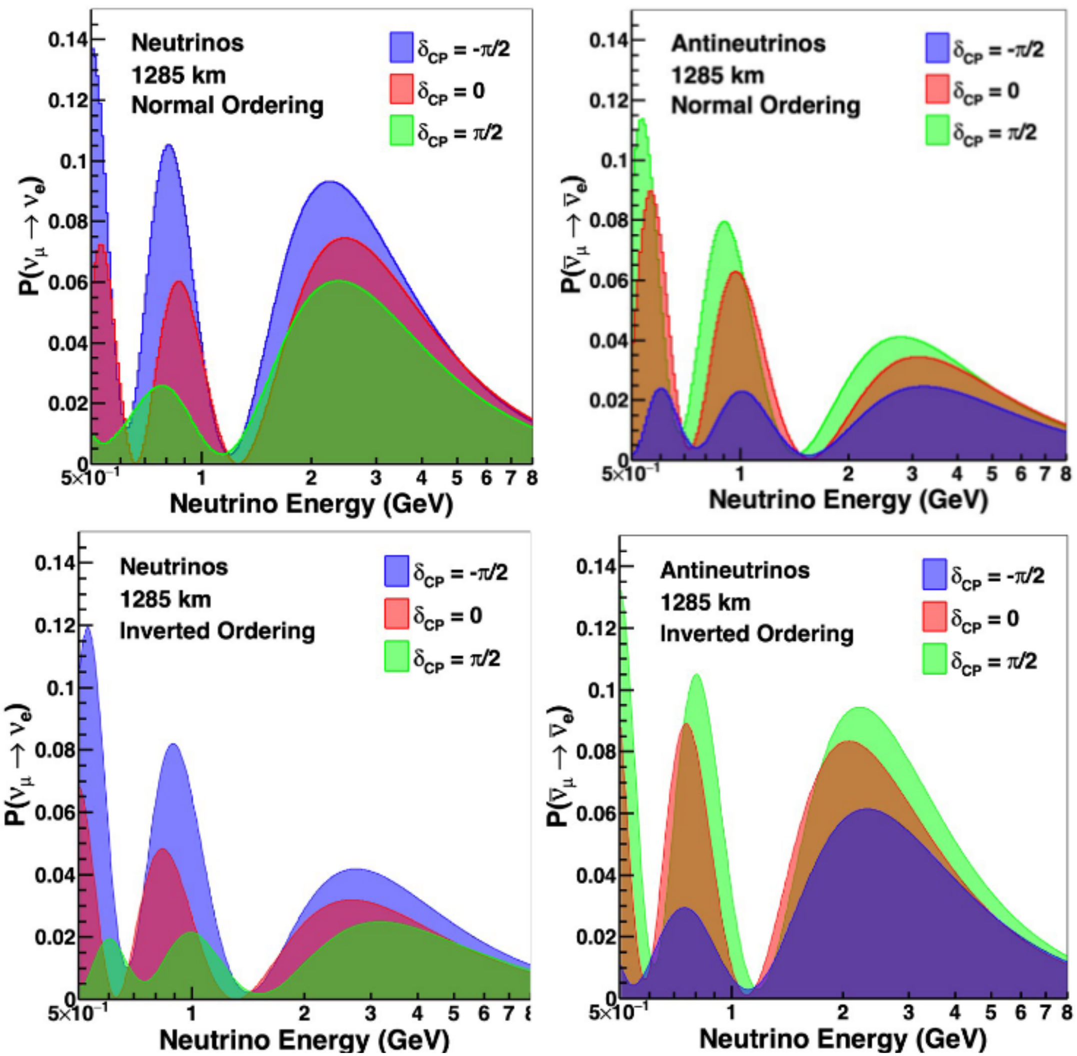
$\sin^2\theta_{23} = 0.5 \pm 0.1$ **?** **2.7%**



Mass ordering unknown



DUNE measures oscillations over more than a full period

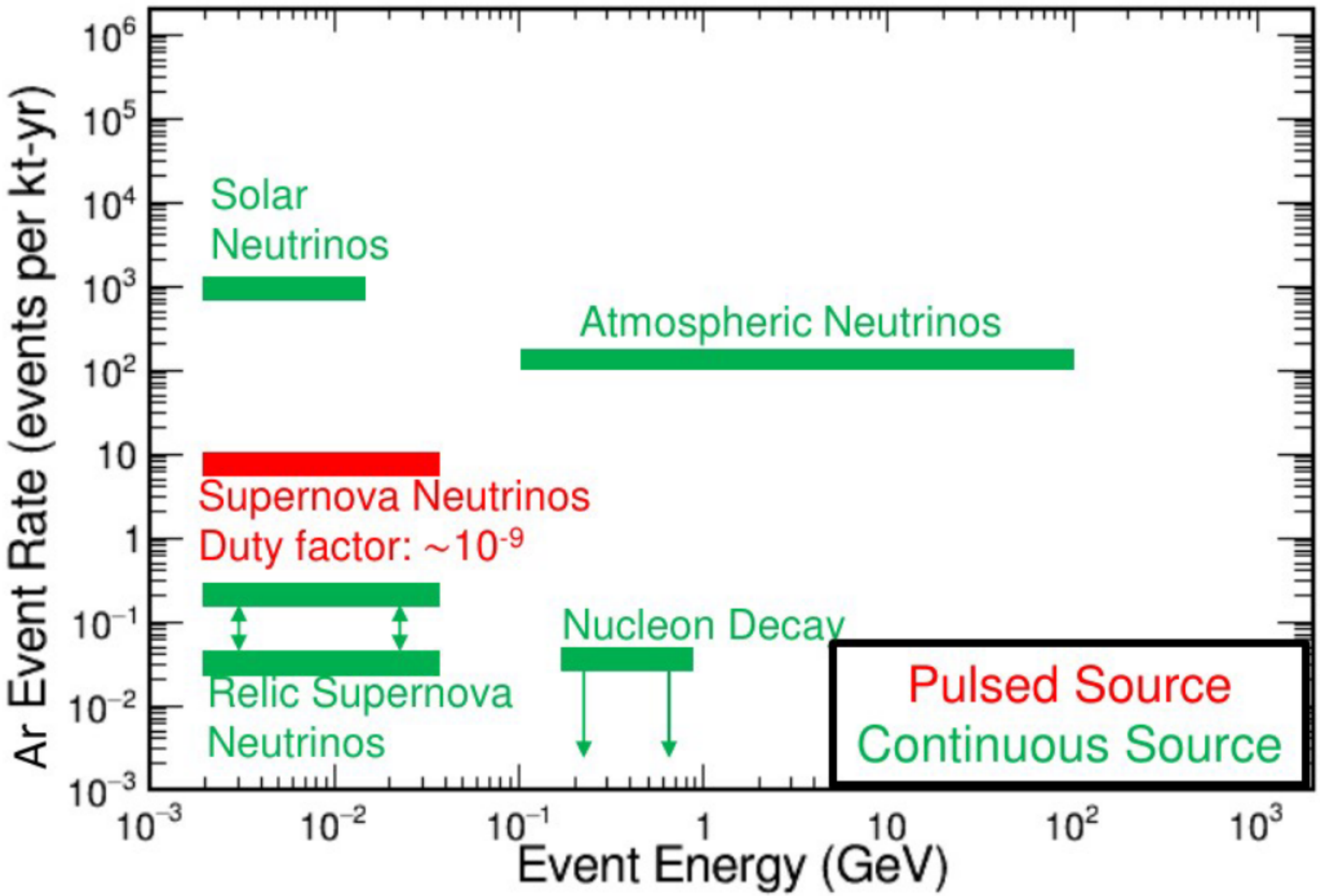


- Effect of mass ordering, CP violation, θ_{23} octant have *different shape* as a function of L/E
- Measuring oscillations as a continuous function of energy helps resolve degeneracies
- This is unique to DUNE, and complementary to other experiments with narrow flux spectra (e.g. Hyper-K)

Neutrino oscillation is part of a broad physics program

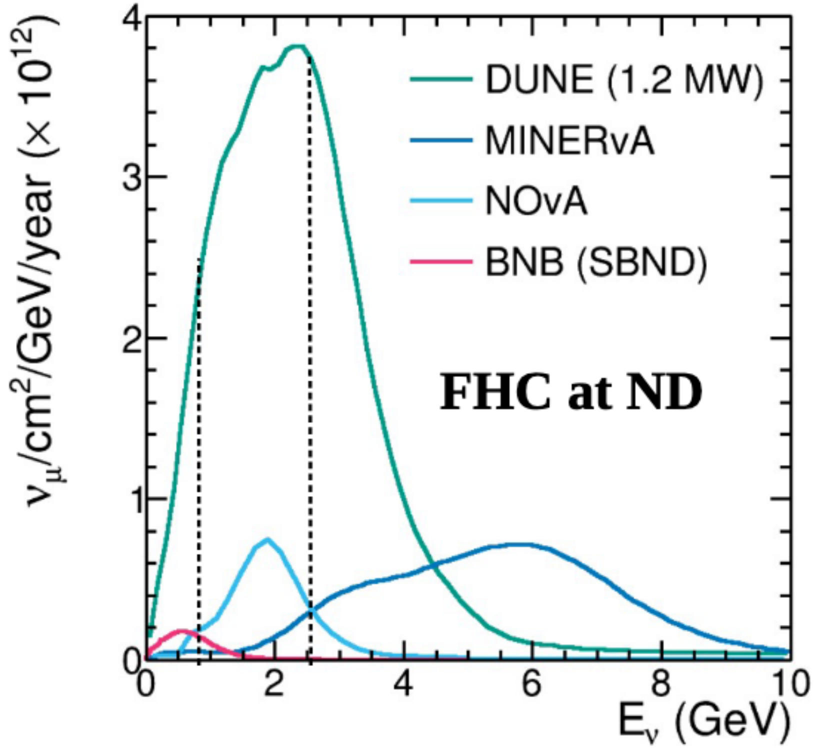
- DUNE FD has excellent BSM sensitivity:
  - Large mass
  - Deep underground
  - High resolution
  - Low thresholds
- Boosted BSM searches → high intensity beam and capable ND

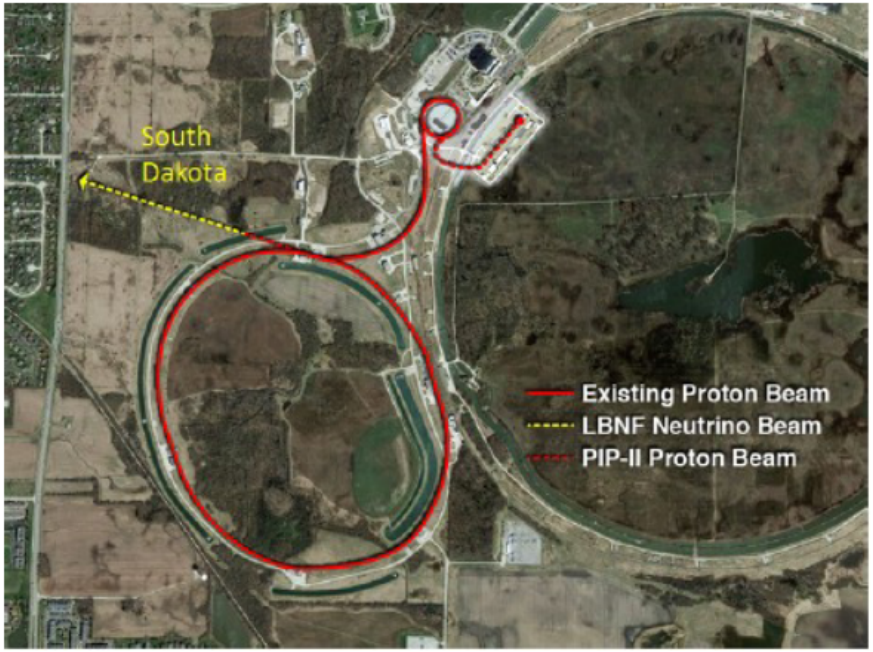
Astroparticle events in DUNE: several decades in energy & rate



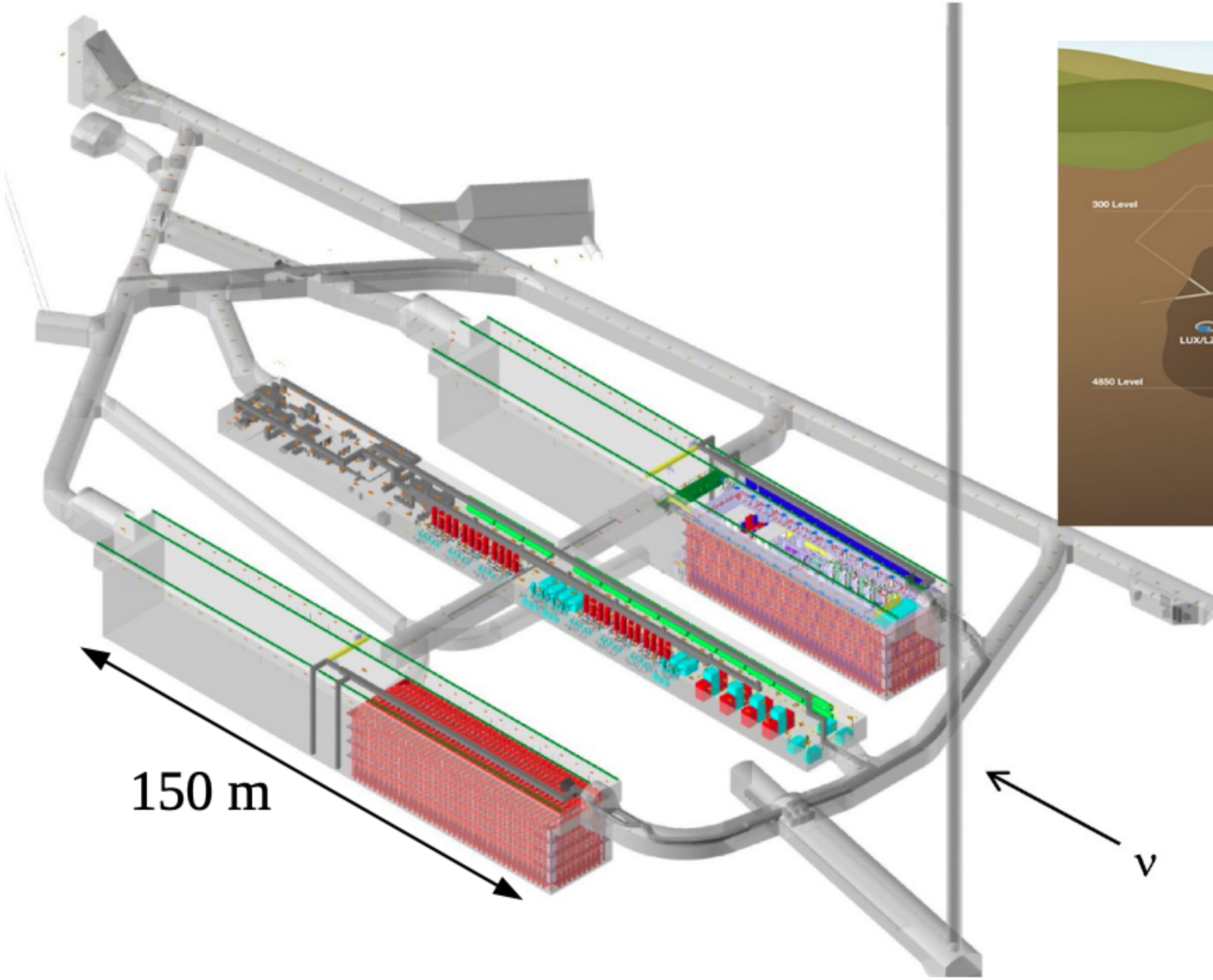
LBNF: lots and lots of neutrinos

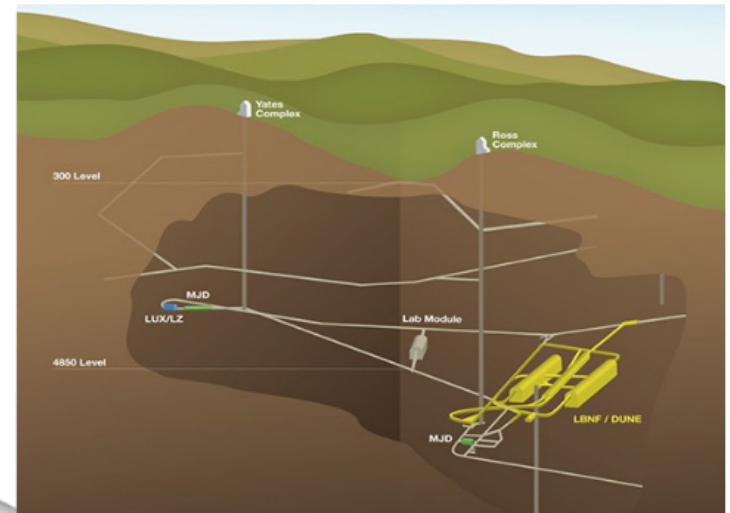
- 1.2 MW proton beam, upgradeable to 2.4 MW
- Peak at 1st maximum (2.5 GeV), with substantial flux between first and second maximum (0.8 GeV)





Deep underground far detector site at SURF (Lead, South Dakota)



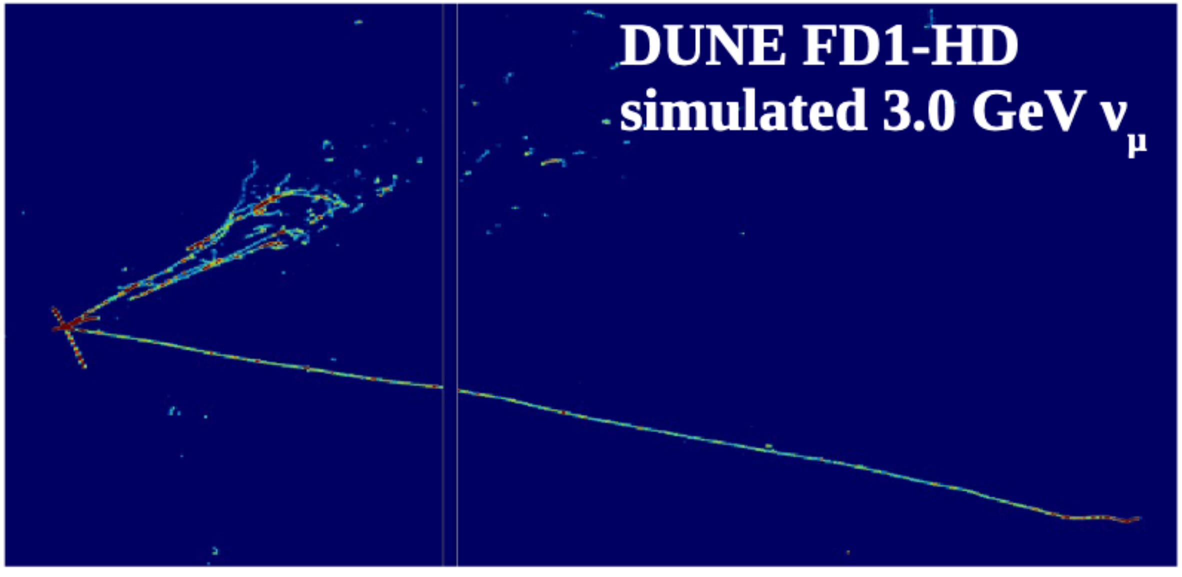


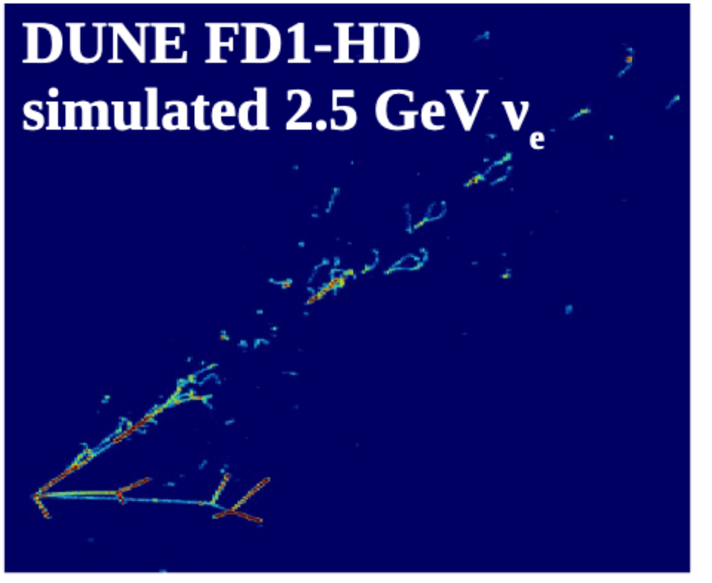
- 1490m underground (4300 mwe)
- Space for 70kt LAr detector

Far Detector – Site of Original Davis Experiment!

Image: Brookhaven

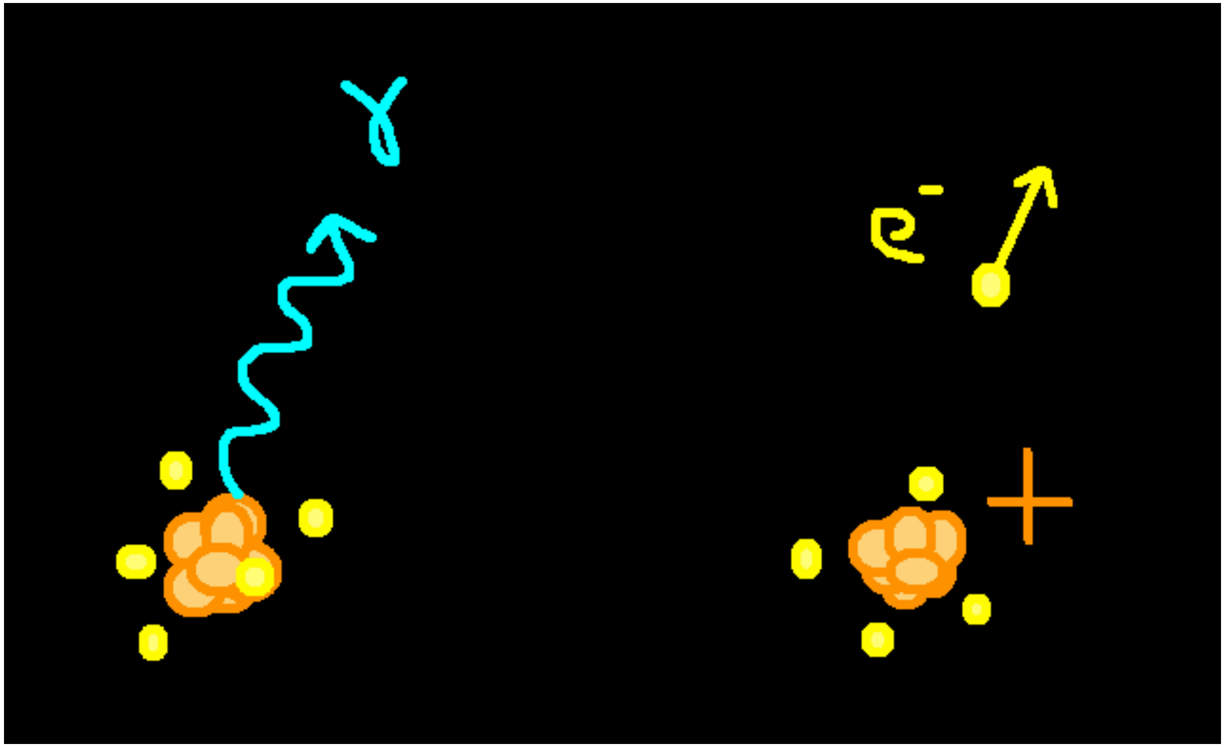
Why LAr: exquisite imaging for flavor ID, energy reconstruction





- Clean separation of ν_μ and ν_e charged currents
- Low thresholds for charged particles → precise reconstruction of lepton and hadronic energy → E_ν reconstruction over broad energy range

Why LAr: Nobel Elements



- Transparent to their own scintillation light
- No electron attachment*, long drift distances

Why LAr: Transparent

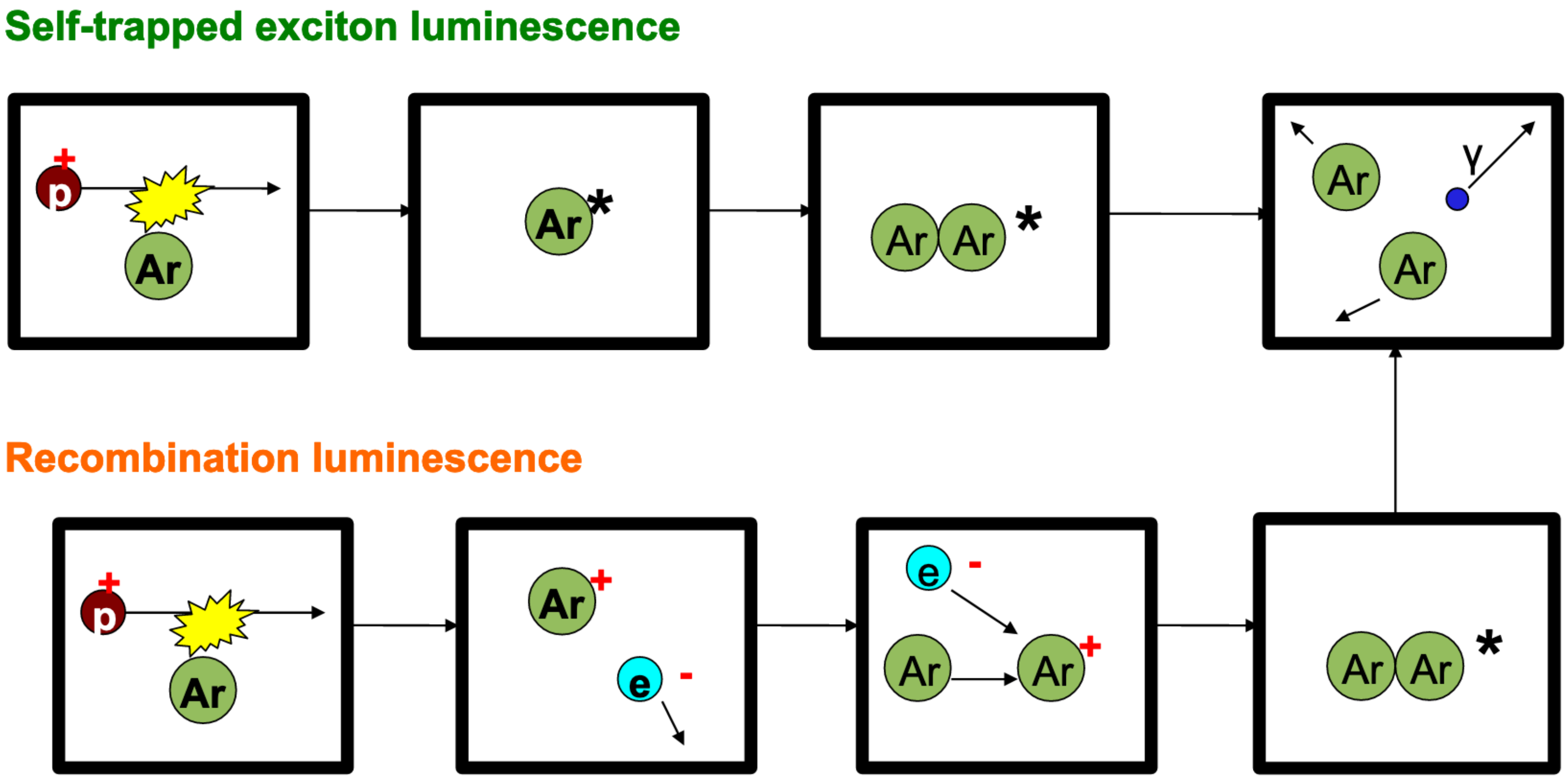
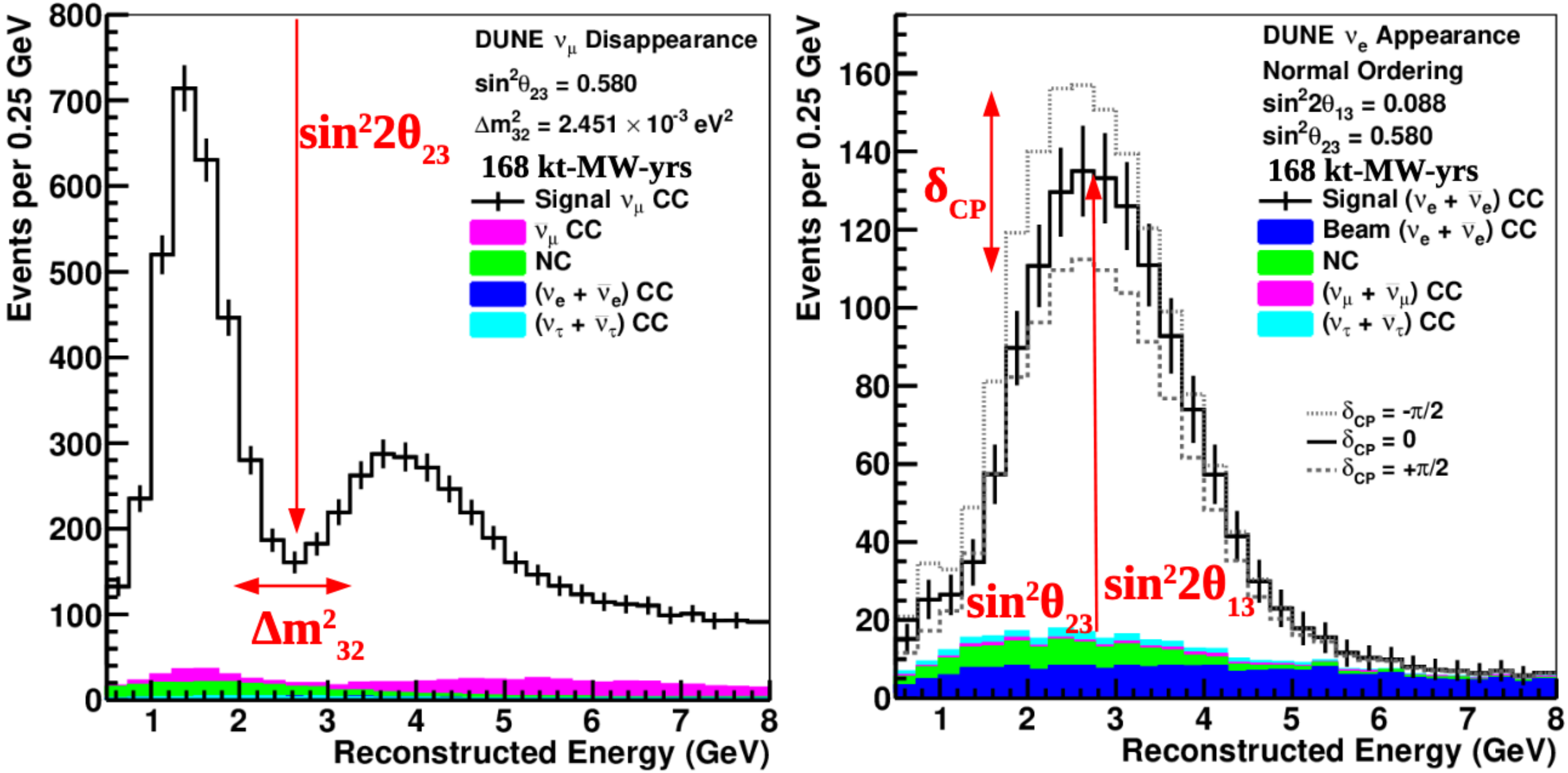


Image: Ben Jones

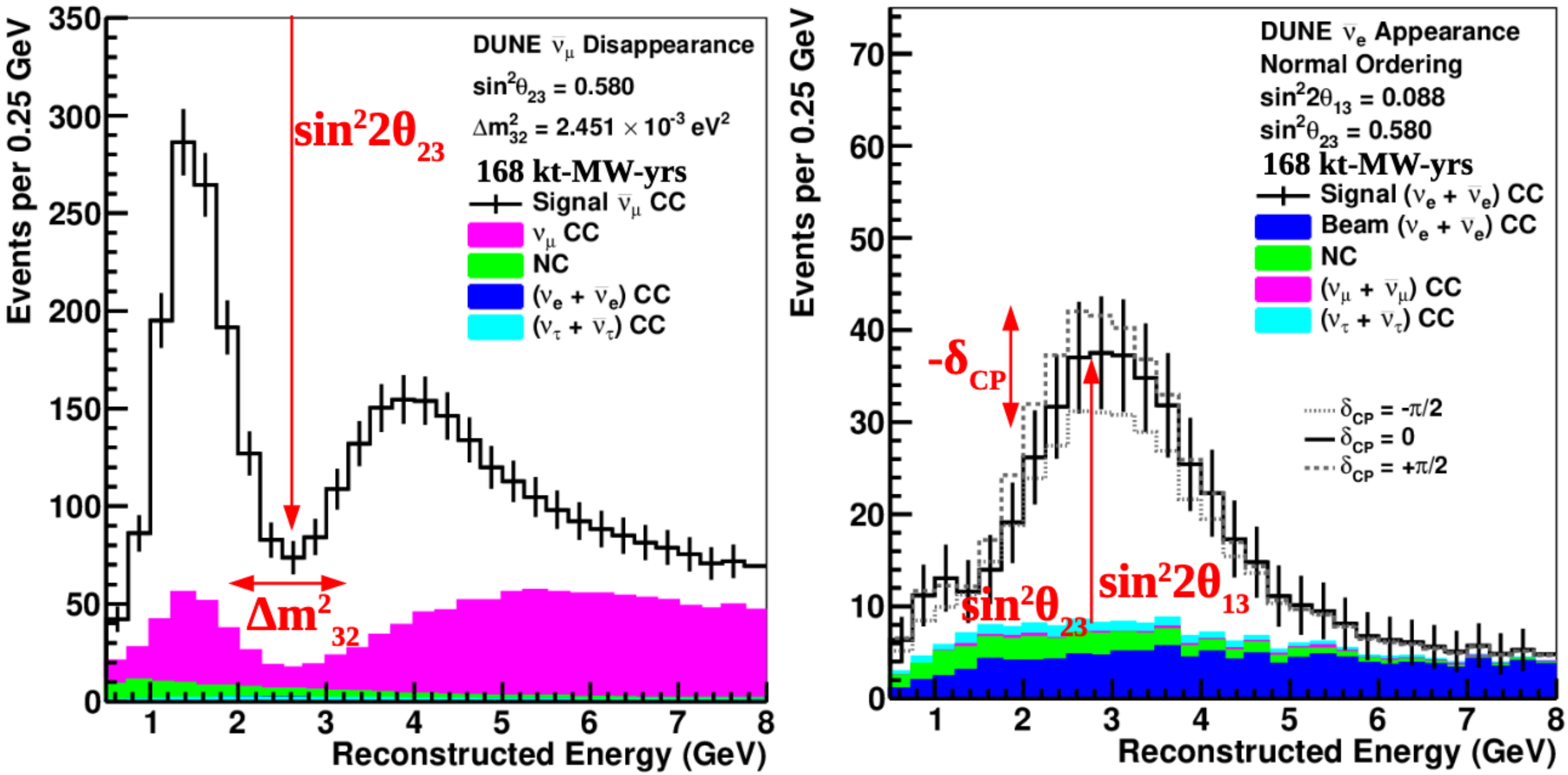
- Scintillation from decay of eximers
- Reverse process to absorb light requires two atoms in close proximity
- Argon unbound in ground state, atoms typically around 4 Å apart

What DUNE actually measures: Events vs. reco energy



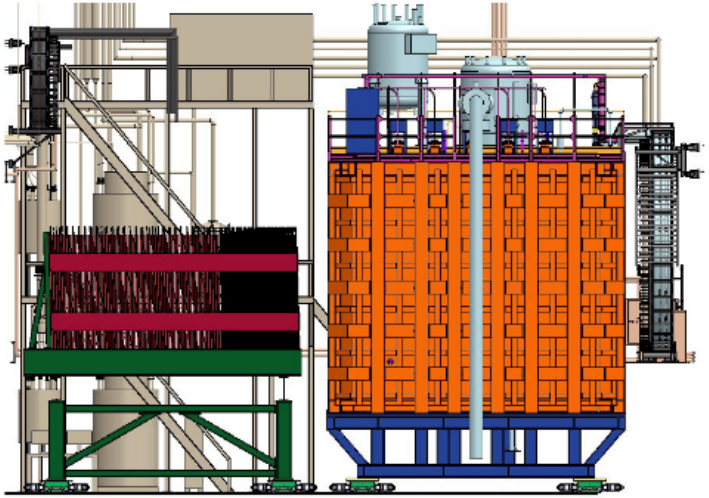
FHC = neutrinos

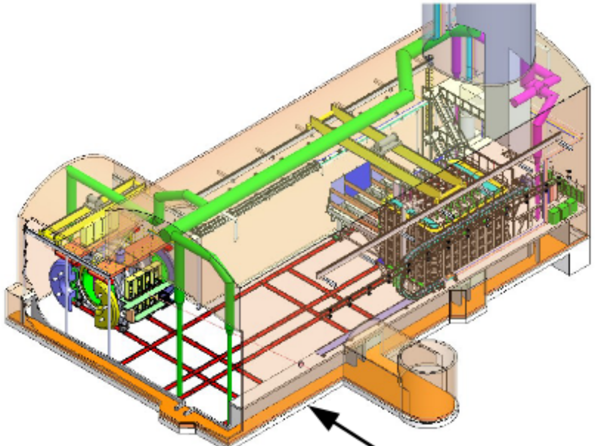
What DUNE actually measures: Events vs. reco energy



RHC = antineutrinos

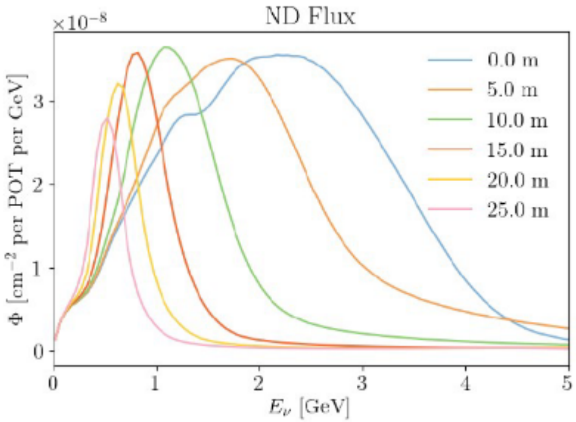
The DUNE ND provides critical constraints on systematics



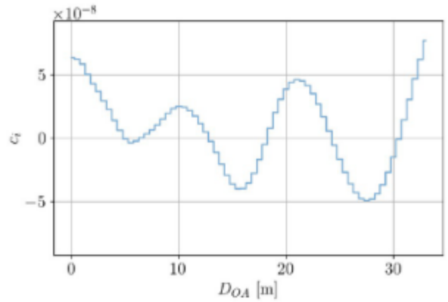


- Large uncertainties on flux, cross sections, and detector response require are constrained to the few percent level by the ND
- ND-LAr+TMS: measure neutrino interactions on the same Ar target, with same detector technology as FD
  - Some differences in design to mitigate beam pile-up
  - Steel+scintillator spectrometer to measure forward muons
- System moves up to 30m off axis (next slide)
- On-axis detector (SAND) measures neutrino interactions on various targets and monitors beam stability

PRISM plays a critical role in enabling DUNE's precision



x



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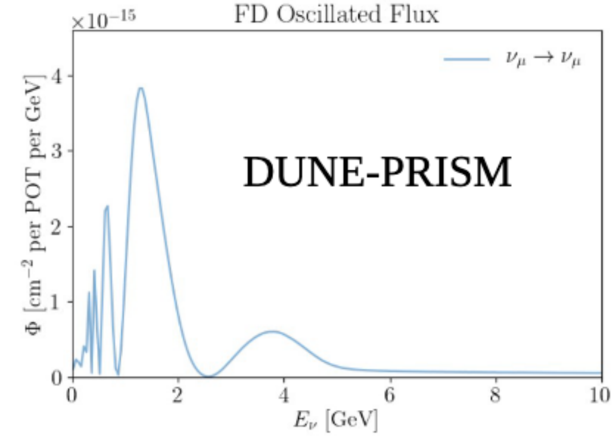
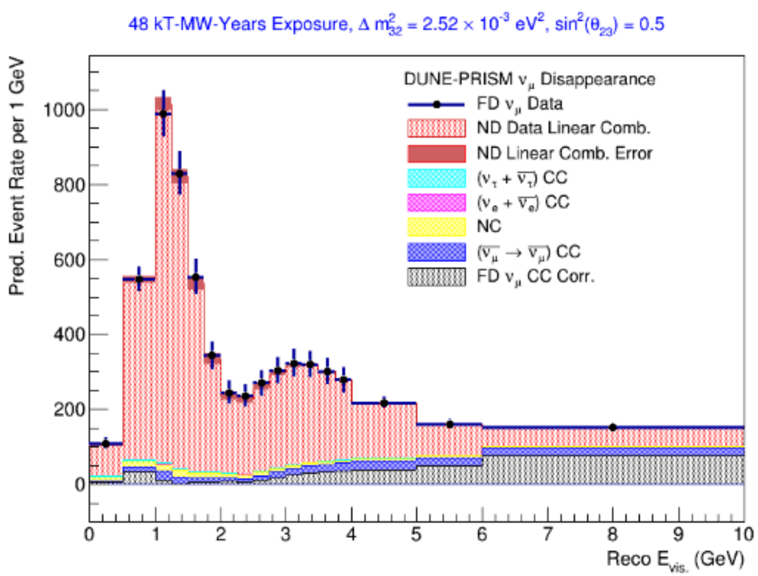
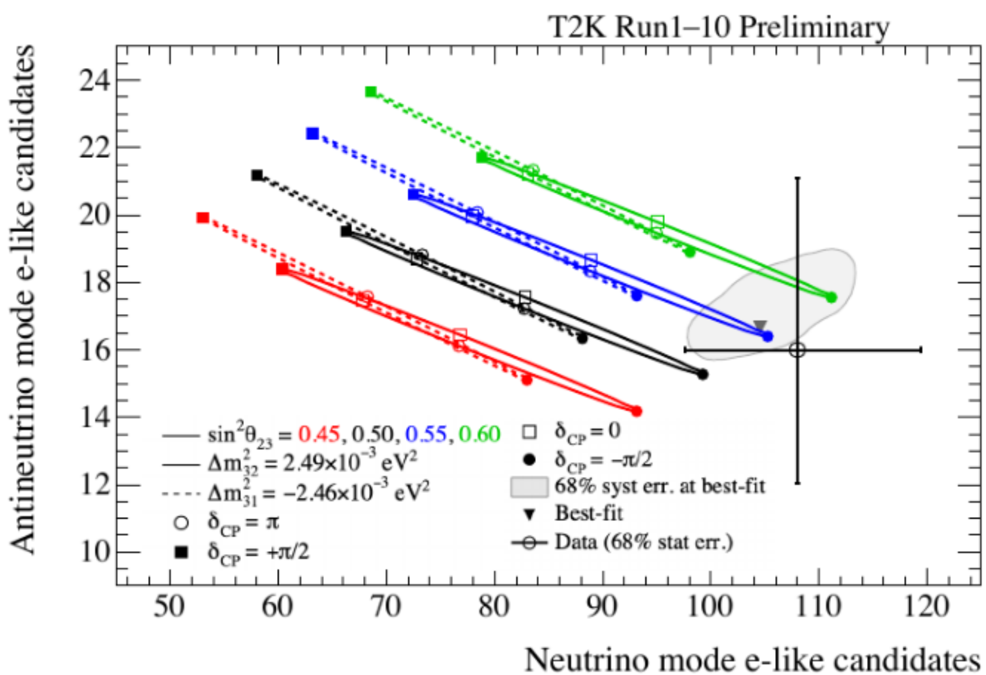


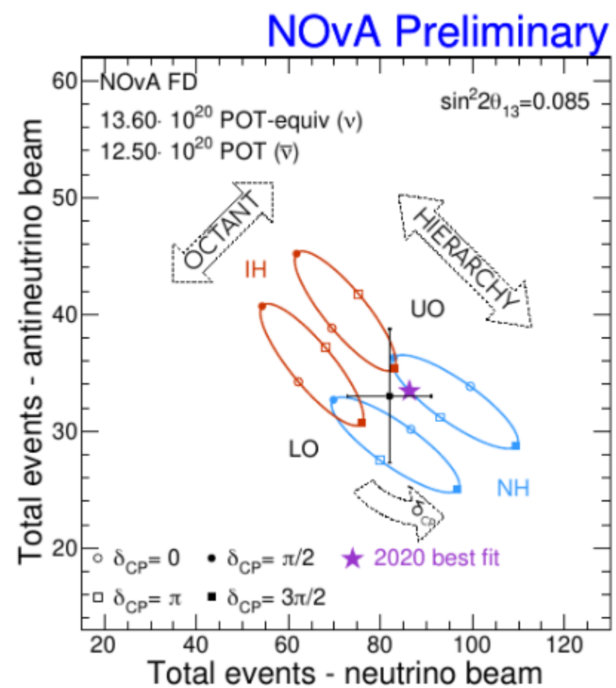


- FD flux ≠ ND flux → uncertainties in **energy dependence** of cross sections, response, etc.
- ND flux changes with angle due to pion decay kinematics
- Take ND data in different fluxes → build linear combination to match FD *oscillated* spectra
- Robust analysis approach with very minimal dependence on interaction modeling

Current measurements of $\nu_\mu \rightarrow \nu_e$ (T2K and NOvA)

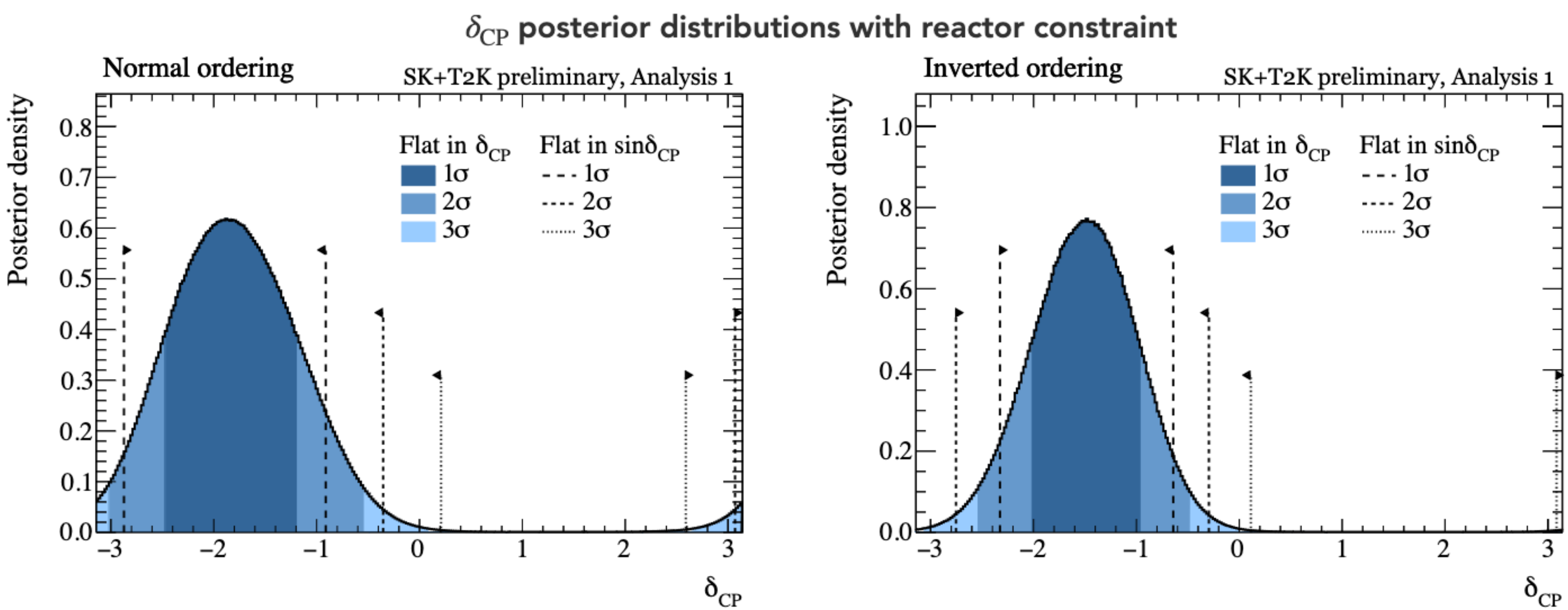
- Narrow-band neutrino flux at the oscillation maximum
- Number of observed ν_e and $\bar{\nu}_e$ events is related to the oscillation parameters, but effects are degenerate, and data are not precise enough to resolve everything



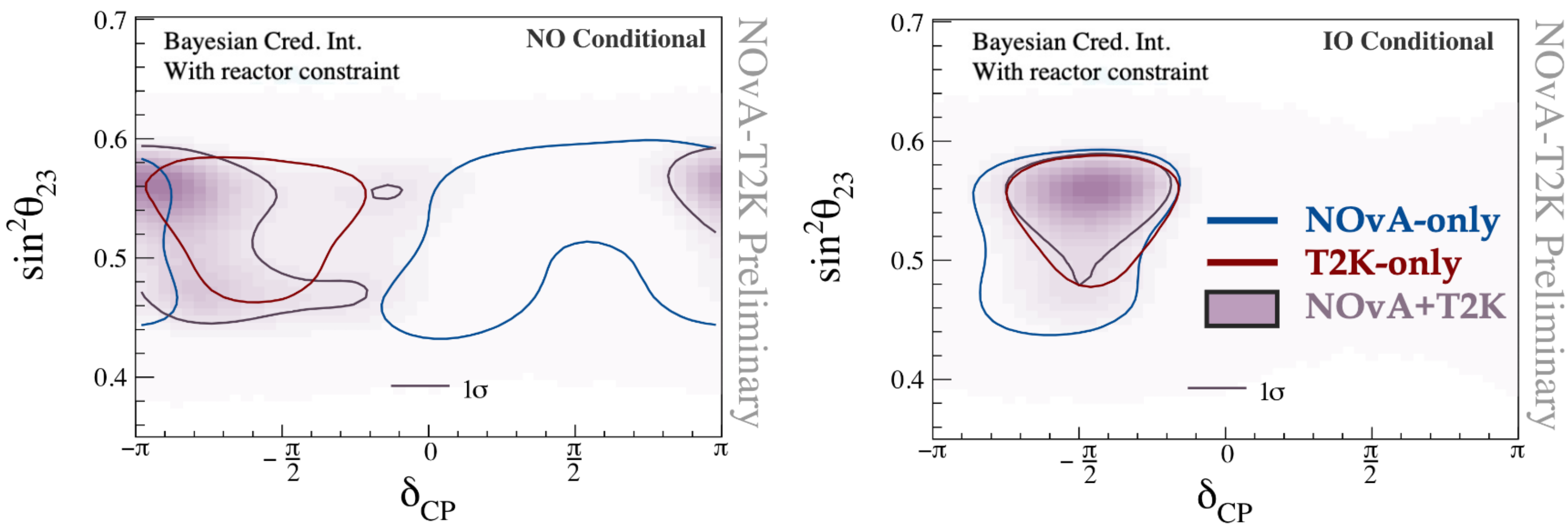


Current Measurements (T2K + SK)

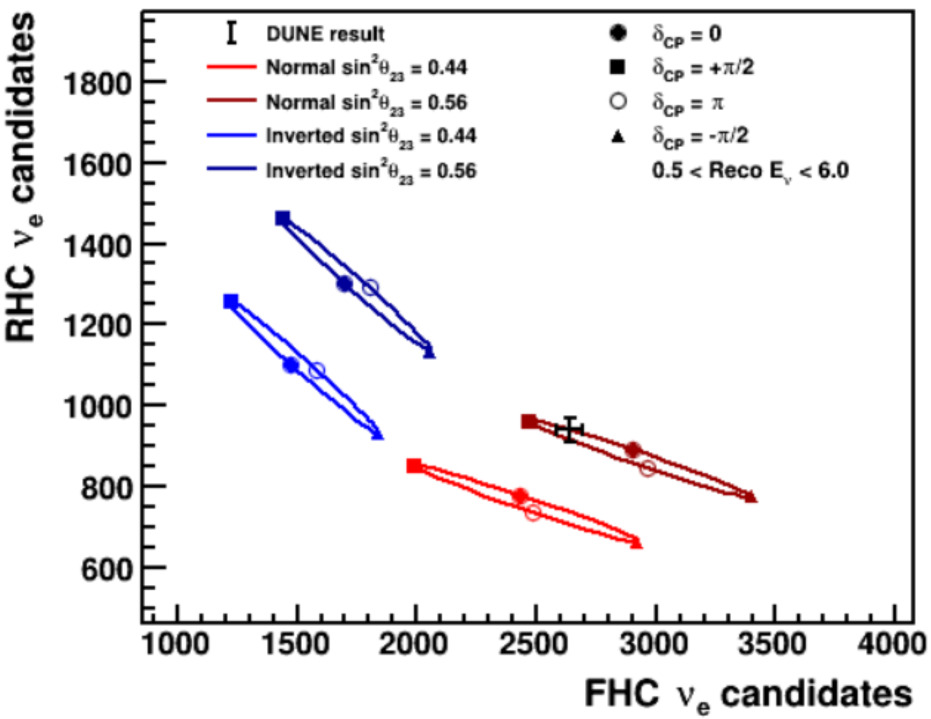
- For inverted neutrino mass ordering, CP-conservation excluded at 3σ
- However, neutrino mass orderings cannot be distinguished



Current Measurements (NOvA+T2K)

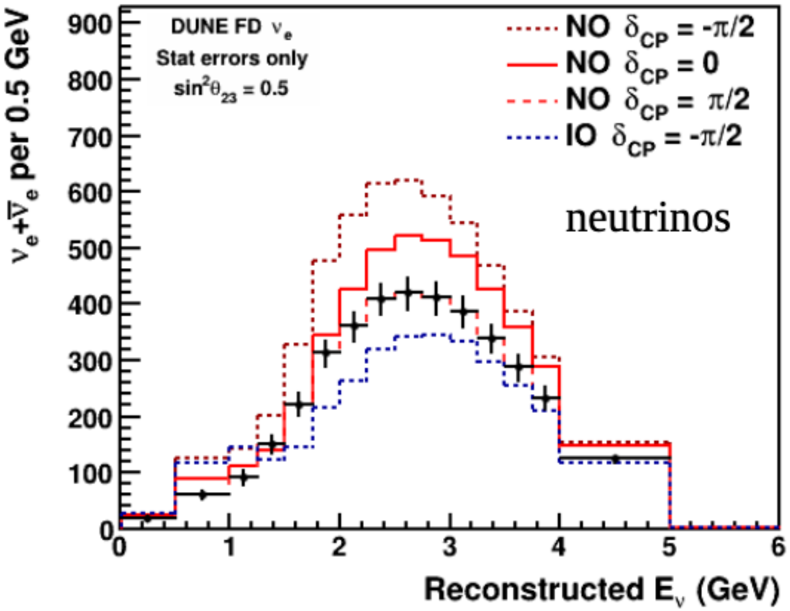


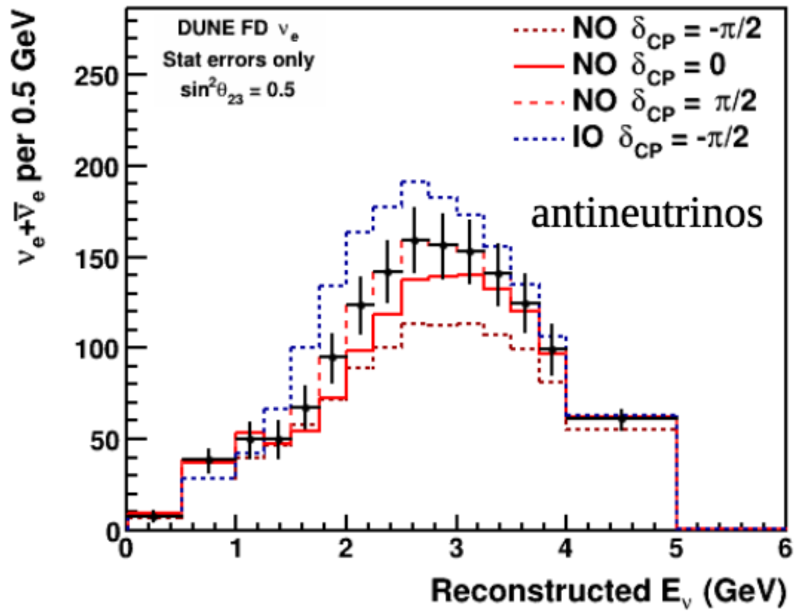
DUNE's large matter effect makes CPV and MO effects separable



- Key feature very long baseline → no overlap between NO and IO
- Data point shows long-term reach of DUNE if we ignored spectral information and just counted events
- This is a really, really bad way to show the reach of DUNE...

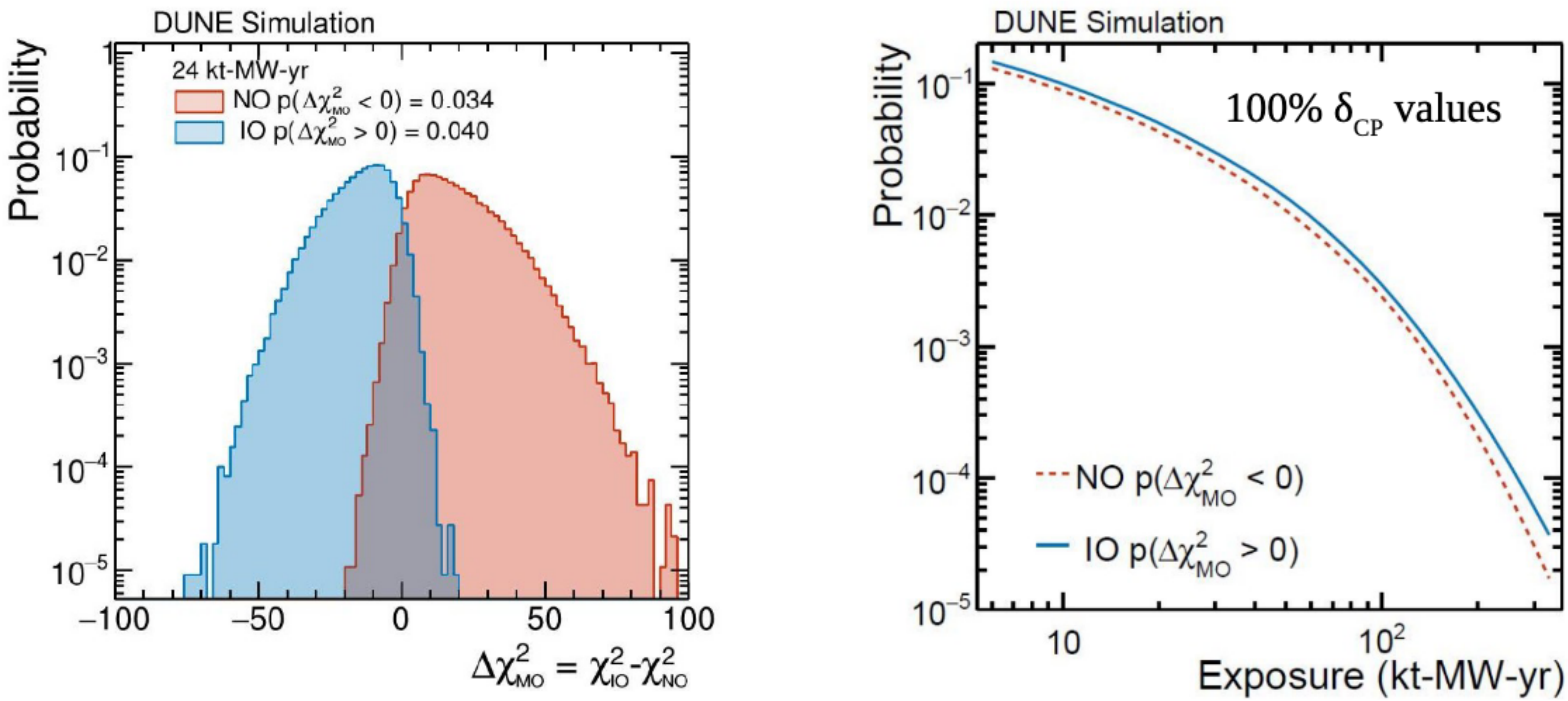
DUNE measures oscillations over more than a full period





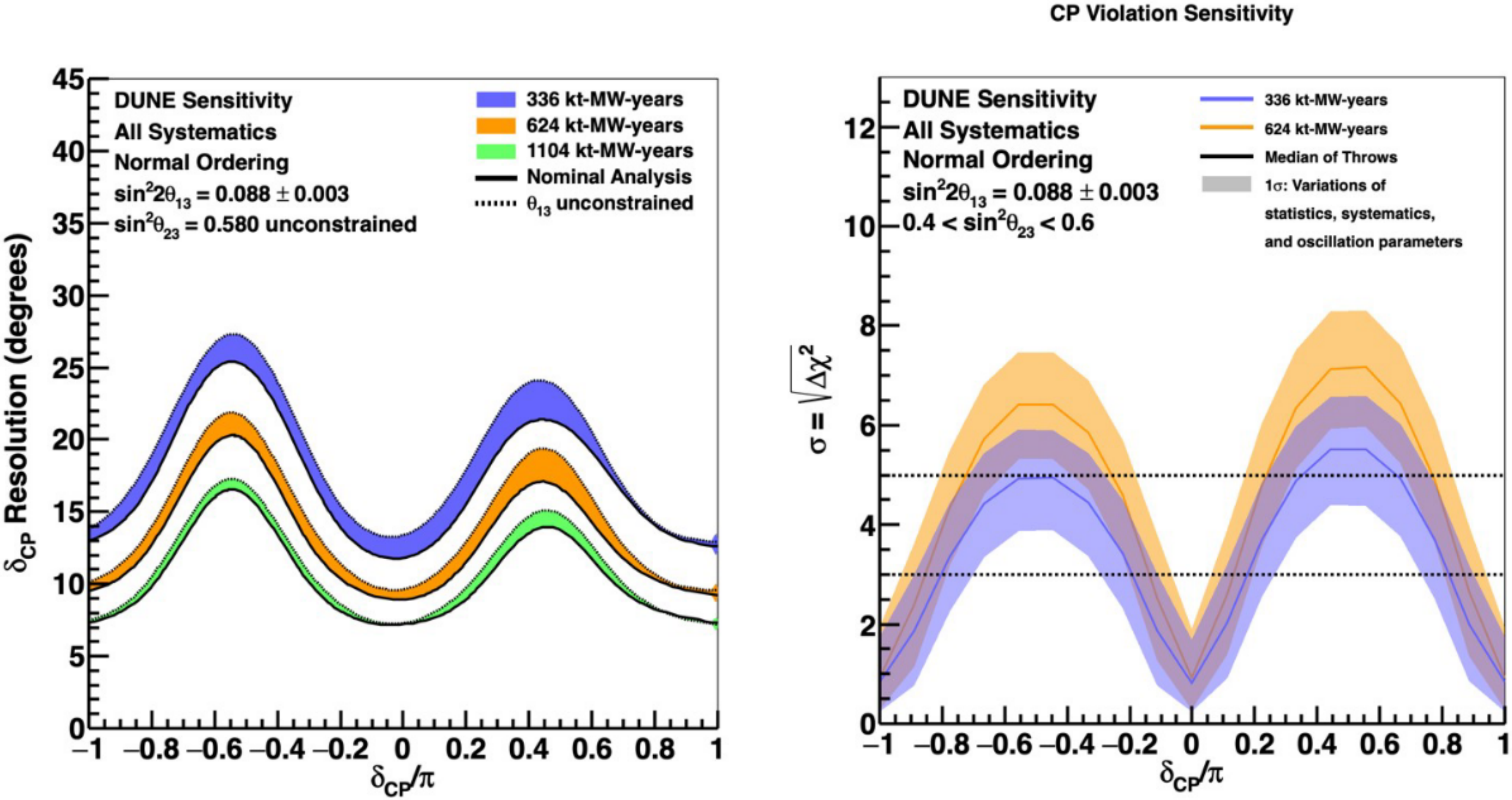
- Broadband neutrino beam → measure oscillations vs. L/E
- Oscillation parameters affect the spectral shape as well as the rate
- We might see that our data fits nicely with a particular set of 3-flavor parameters over many energy bins…and we might not

Mass ordering: definitive resolution



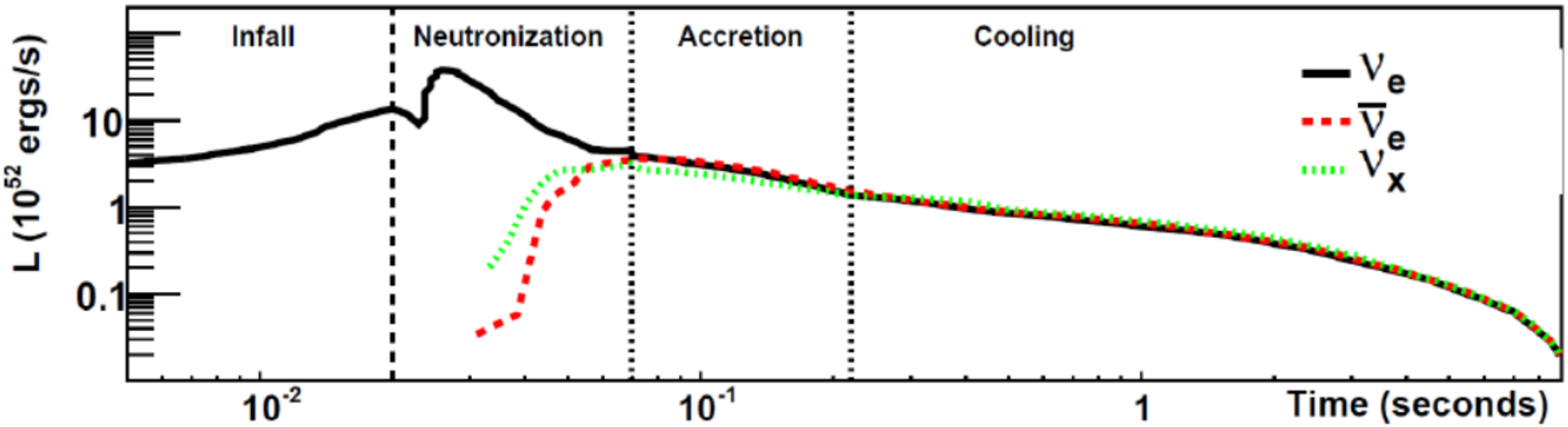
- Significant mass ordering sensitivity very quickly: ~97% correct after ~1-2 years
- Long term → >10σ for any parameter combination

CP violation: δ resolution 6-16°



- 6°-16° resolution to δ_{CP} without dependence on other experiments, discovery sensitivity to CP violation over a broad range of possible values

DUNE has unique sensitivity to supernova electron neutrinos



- Neutronization burst is entirely ν_e
- Complementary with other sensitive large detectors
- SNB is driving the design of the DAQ and trigger system

	ν_e	$\bar{\nu}_e$	ν_x
DUNE	89%	4%	7%
SK[1]	10%	87%	3%
JUNO[2]	1%	72%	27%

[1]Super-Kamiokande, *Astropart. Phys.* **81** 39-48 (2016)
[2]Lu, Li, and Zhou, *Phys Rev. D* **94** 023006 (2016)

ProtoDUNE

ProtoDUNE

- Prototype for the first far detector module of DUNE
- Liquid argon TPC, active volume of 7.2 m x 6.1 m x 7.0 m and photon detection system
- Incorporates full-sized components designed for the far detector
- First physics run, mixed particle test beam with momenta in range 0.3 GeV/c to 7 GeV/c at CERN neutrino platform in 2018-2019

ProtoDUNE Physics Goals

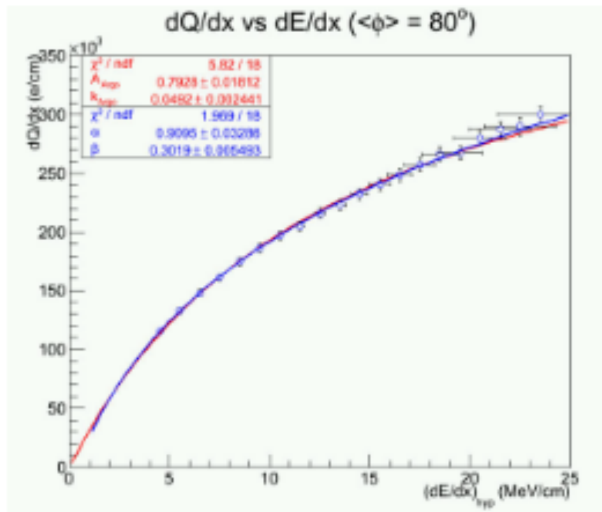
- Improve pion and proton cross section measurements
- Enable development of liquid argon simulations before DUNE main physics running
- **Measure electron-ion recombination in liquid argon** crucial for neutrino energy reconstruction in DUNE

Recombination Measurement

- Want to know energy deposited in our detectors to measure neutrino oscillation parameters
- What we actually measure is the charge read out from the electrons drifting to the anodes
- To do our physics we need to convert between the two -> recombination modelling!
- One of the main systematics for neutrino oscillation measurements at DUNE

Recombination

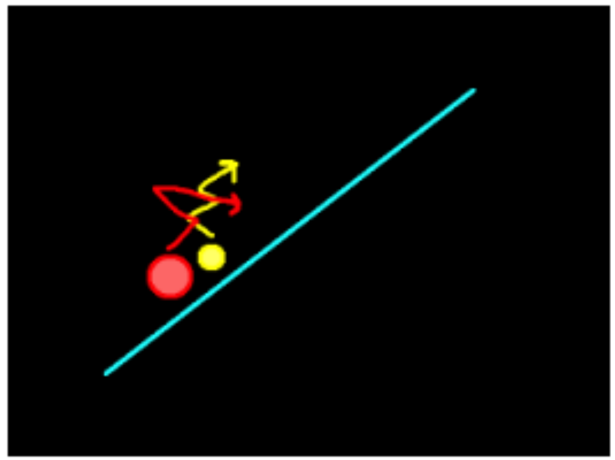
Relationship between the observed charge, dQ/dx, and the deposited energy, dE/dx, is non-linear due to electron-ion recombination, dQ/dx saturates at higher values of dE/dx and varies as a function of electric field



JINST 8 (2013) P08005 (ArgoNeuT)

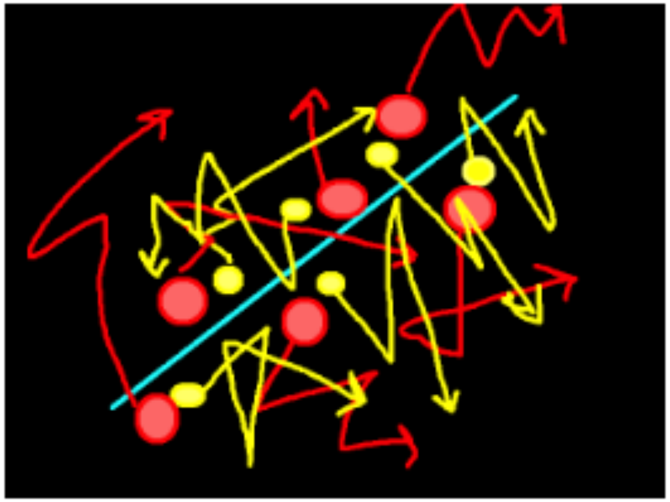
- Investigate two different models of recombination using stopping proton tracks: Birks' model and Modified Box model

Recombination Modeling: Onsager geminate theory



- Assumes electron recombines with parent ion
- Electron ion separation small compared to ion spacing

Recombination Modeling: Jaffé columnar model



- Assumes separation of ions (W/(dE/dx)) is small compared to electron ion distance
- Gaussian profile about track assumed
- Introduces angular dependence if electric field present (perpendicular vs parallel to drift direction)

Birks' Model

$$\frac{dQ}{dx} = \frac{A_B}{W} \frac{\frac{dE}{dx}}{1 + \frac{k_B}{\rho\epsilon}\frac{dE}{dx}}$$

Where A_B and k_B are free parameters to be fit. Other parameters from nature or detector:

- $W = 23.6$ eV/electron (average energy to ionise argon atom)
- $\epsilon = 0.553[0.4867]$ kV/cm (average drift electric field, ProtoDUNE-SP in this analysis [MC])
- $\rho = 1.383$ g/cm^3 (density of liquid argon at 124.106 kPa)

Modified Box Model

$$\frac{dQ}{dx} = \frac{1}{\beta W} \log\left(\beta \frac{dE}{dx} + \alpha\right)$$

Where $\beta' = \rho\epsilon\beta$ and α and β' are free parameters to be fit. Other parameters from nature or detector:

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- $\epsilon = 0.553[0.4867]$ kV/cm (average drift electric field, ProtoDUNE-SP in this analysis [MC])
- $\rho = 1.383$ g/cm^3 (density of liquid argon at 124.106 kPa)

Notes about these models

These models are purely empirical and the "constants" are not parameters of nature but rather contain secret detector physics:

- electric field
- track angle with respect to the drift direction
- impurities
- delta ray modeling

As such it is important to measure for each detector and check reasonable compared to similar detectors, but bear the above in mind.

Uncertainty on dE/dx

Using the Modified Box model, we can solve for dE/dx:

$$\frac{dE}{dx} = \frac{1}{\beta}\left(\exp\left(\beta W \frac{dQ}{dx}\right) - \alpha\right)$$

ProtoDUNE Results

How we make this Measurement

- Compare calibrated charge deposits with expected energy deposit deduced from residual range of the proton track

Method: Selecting the Stopping Protons

Some basic cuts applied (the same as far as possible in data and MC):

- Primary track contains hits
- Reconstructed track length consistent with stopping 1 GeV proton
- Beamline instrumentation PID = proton
- Track start position and angle consistent with beam
- Additional cleaning cuts

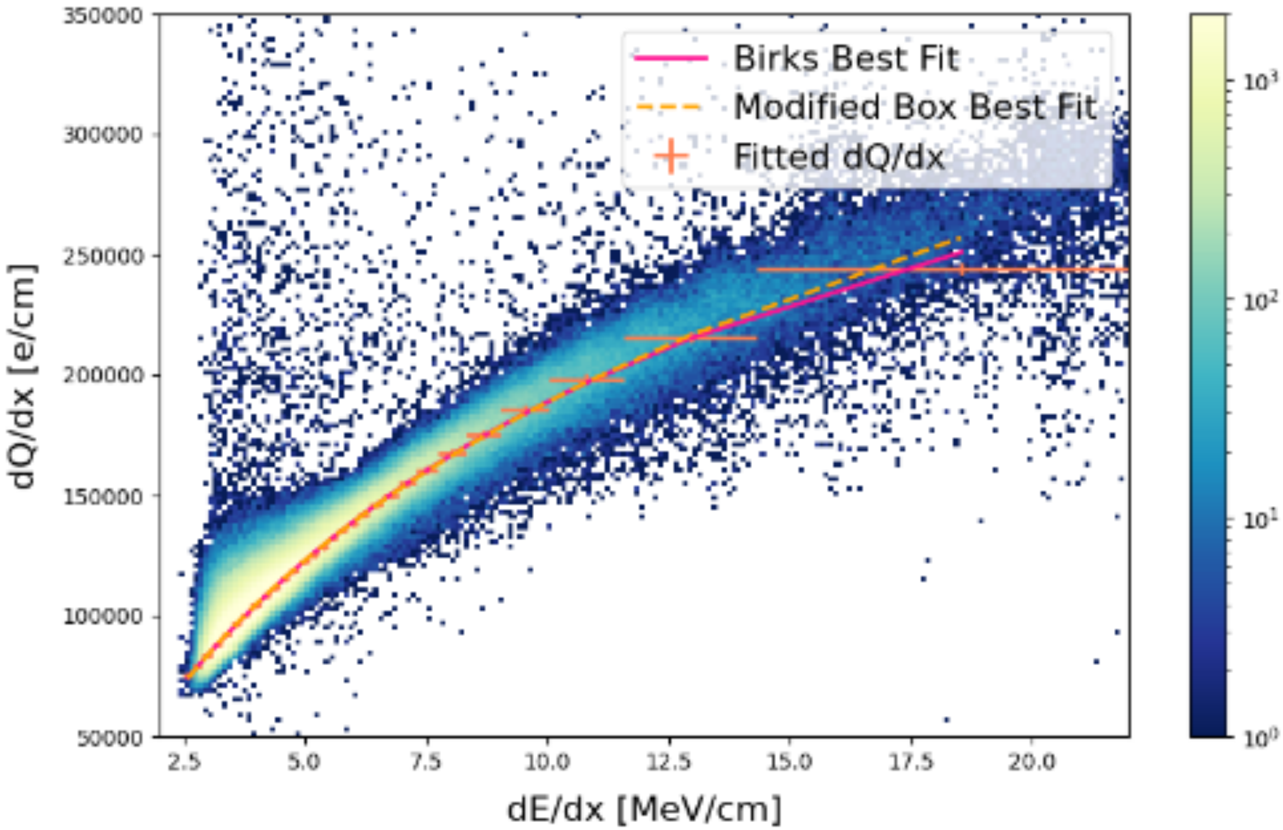
Method: Get dQ/dx and dE/dx

For all the hits along the primary track need to get dQ/dx, dE/dx and residual range:

- Residual range (R): directly from track reconstruction
- dQ/dx: uniformity calibration applied
- dE/dx: most probable value calculated from track reconstructed residual range via Landau-Vavilov distribution [1]

[1] root.cern.ch/doc/master/classROOT_1_1Math_1_1VavilovAccurate.html

Validation with MC



Abbey Waldron

Validation with MC

Modified Box Model:

- $\alpha = 0.920 \pm 0.015$ (Input: 0.93)
- $\beta' = 0.212 \pm 0.005$ (Input: 0.212) $(\text{kV}/\text{cm})(\text{g}/\text{cm}^2)/\text{MeV}$
- $\chi^2/\text{ndof} = 1.07$

Uncertainties

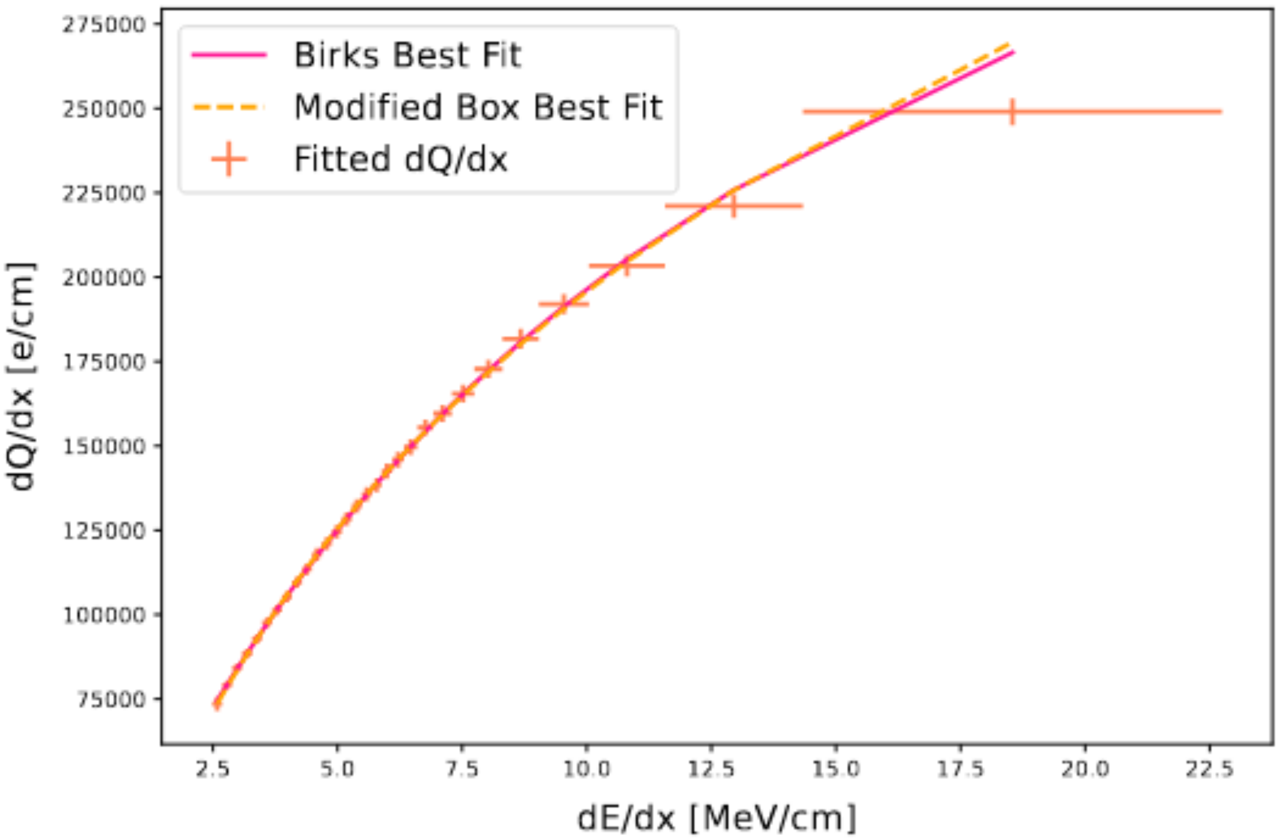
dE/dx

- 0.5 cm from end point finding [we are working to reduce]

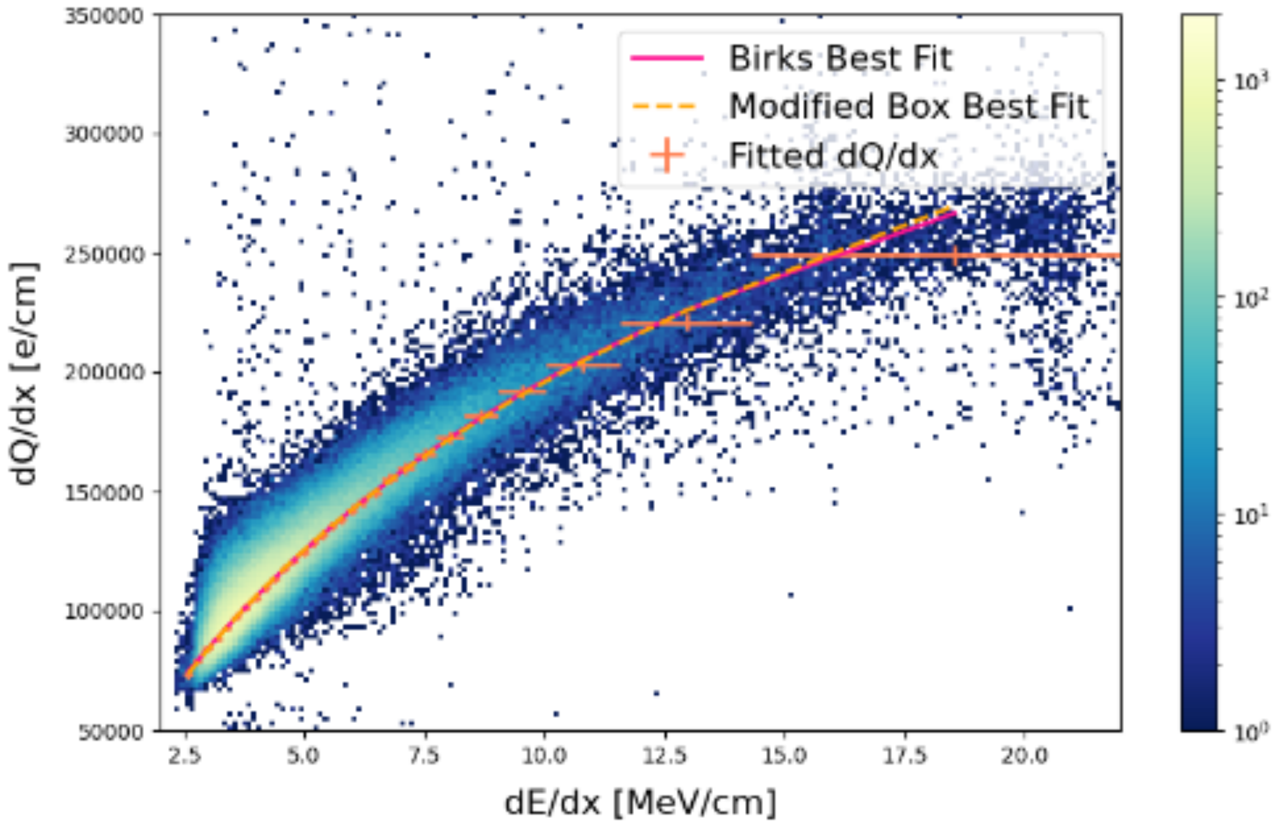
dQ/dx

- Statistical uncertainty from peak finding (varies by bin, small)
- Uniformity correction, drift direction (0.3% data, 0.3% MC)
- Uniformity correction, plane perpendicular to drift direction (1.5% data, 1.0% MC)
- Additional space charge systematic uncertainty (calculated, not included in these results)
- Additional systematic due to electric field non-uniformity (calculated, not included in these results)

Fit Results: Data



Fit Results: Data



Global Results Summary

	ArgoNeuT, ICARUS	μBooNE	ProtoDUNE
Modified Box Model α	0.93 ± 0.02	0.92 ± 0.02	0.905 ± 0.014
Modified Mox Model β' (kV/cm)(g/cm^2)/MeV	0.212 ± 0.002	0.184 ± 0.002	0.194 ± 0.005
Birks' Model A_B	0.800 ± 0.003	0.816 ± 0.012	0.813 ± 0.018
Birks' Model β' (kV/cm)(g/cm^2)/MeV	0.0486 ± 0.0006	0.045 ± 0.001	0.051 ± 0.004

JINST 8 (2013) P08005, NIM A 523 (2004) 275-286, JINST 15 (2020) 03, P03022, this work

Fit Results: Data

Modified Box Model:

- $\alpha = 0.905 \pm 0.014$ (ArgoNeuT: 0.93 ± 0.02)
- $\beta' = 0.194 \pm 0.005$ (ArgoNeuT: 0.212 ± 0.002) $(\mathrm{kV/cm})(\mathrm{g/cm^2})/\mathrm{MeV}$
- $\chi^2/\mathrm{ndof} = 1.04$

Birks' Model:

- $A_B = 0.813 \pm 0.018$ (ICARUS: 0.8 ± 0.003)
- $k_B = 0.051 \pm 0.004$ (ICARUS: 0.0486 ± 0.0006) $(\mathrm{kV/cm})(\mathrm{g/cm^2})/\mathrm{MeV}$
- $\chi^2/\mathrm{ndof} = 0.77$

Summary

- DUNE will resolve the neutrino mass ordering, and measure δ_{CP} with CP-violation sensitivity over a broad range of parameter space
- DUNE will precisely measure θ_{13}, θ_{23} and Δm^2_{32}, and 3-flavor oscillations to test the 3-flavor paradigm
- DUNE has unique sensitivity to low-energy neutrinos from a galactic supernova burst
- ProtoDUNE provides a vital measurement for the energy reconstruction via electron-ion recombination
- A lot of exciting physics lies ahead!