DUNE Recombination Measurement with ProtoDUNE

Abbey Waldron

Birmingham Seminar
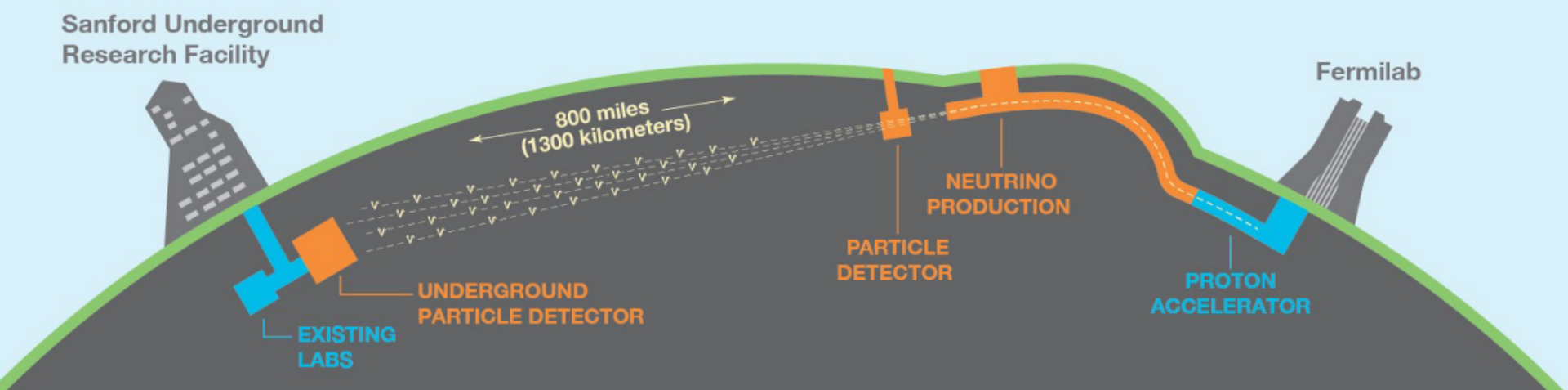
November 8th, 2023

Overview

- DUNE's Physics Goals

- ProtoDUNE
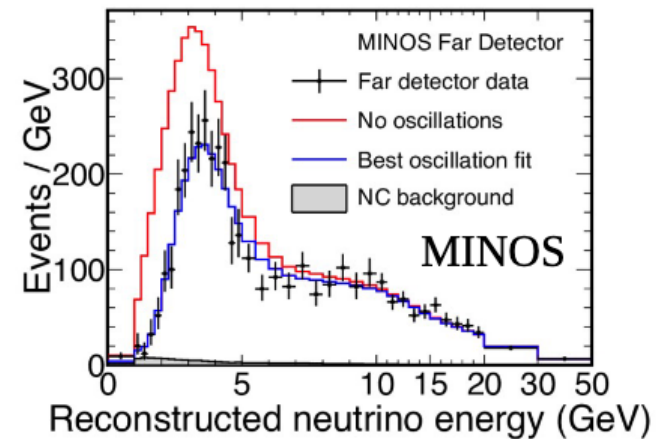
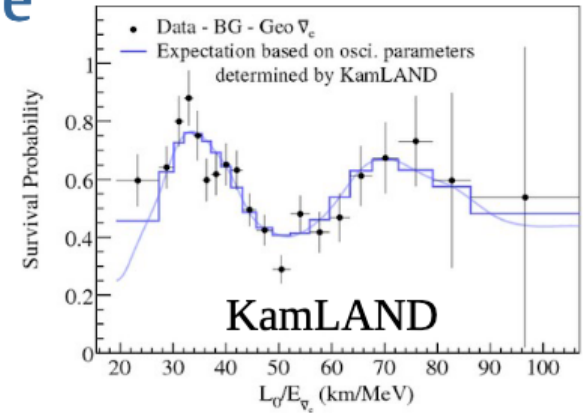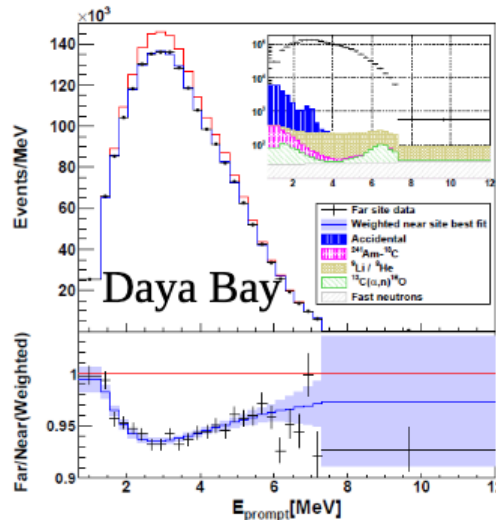- Measuring electron-ion recombination at ProtoDUNE

DUNE

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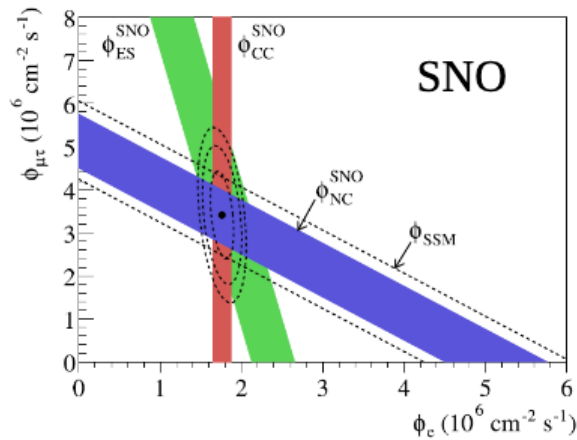- Next-generation international neutrino & underground science experiment hosted in the United States (37 countries + CERN)

- 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

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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?

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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?
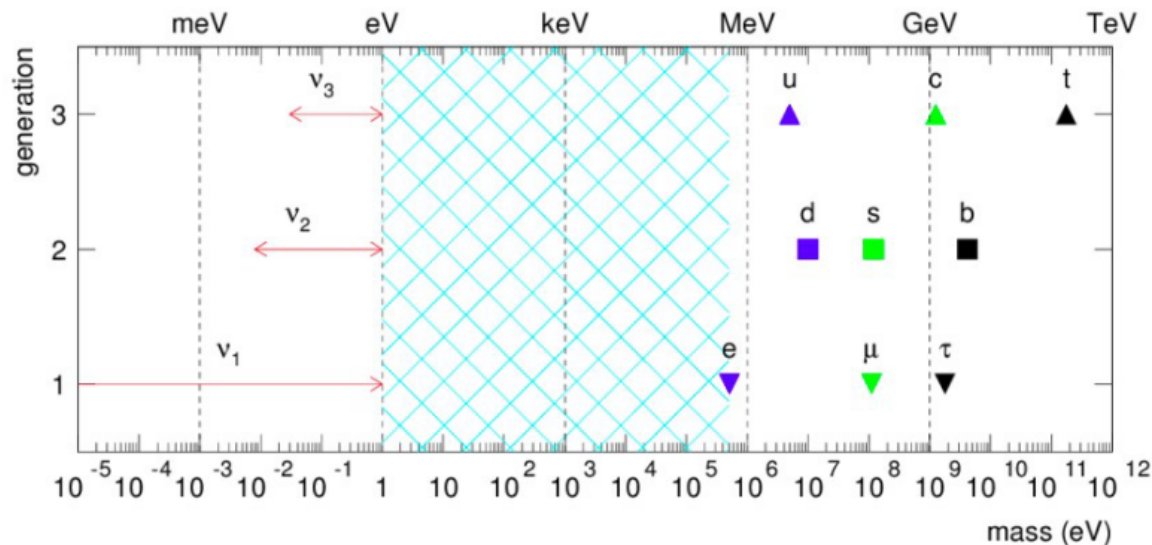

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Neutrino oscillation: motivation

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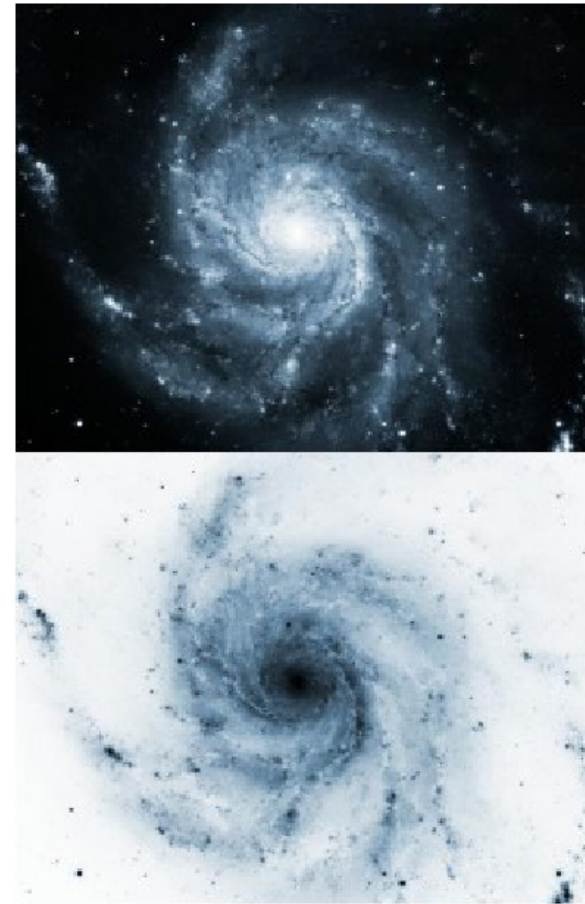- We know there is a baryon asymmetry… but is leptogenesis a viable explanation?

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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?

- 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?
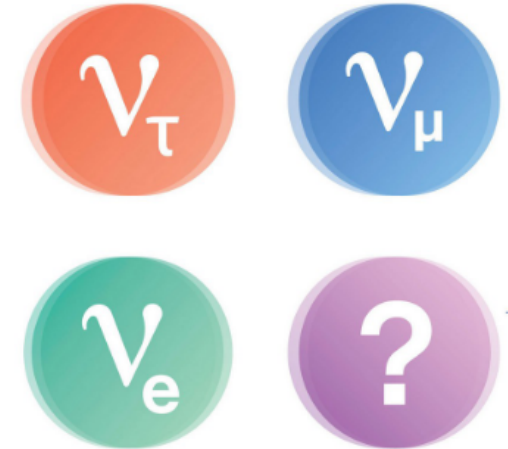
$$U_{\mathrm{PMNS}}^{\mathrm{Extended}} = \begin{pmatrix} \overbrace{U_{e1} \quad U_{e2} \quad U_{e3}}^{U_{\mathrm{PMNS}}^{3\times3}} & \cdots & U_{en} \\ U_{\mu 1} \quad U_{\mu 2} \quad U_{\mu 3} & \cdots & U_{\mu n} \\ U_{\tau 1} \quad U_{\tau 2} \quad U_{\tau 3} & \cdots & U_{\tau n} \\ \vdots \quad\quad \vdots \quad\quad \vdots & \ddots & \vdots \\ U_{s_n 1} \quad U_{s_n 2} \quad U_{s_n 3} & \cdots & U_{s_n n} \end{pmatrix}$$

Phys. Rev. D 93, 113009 (2016)

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What we know now
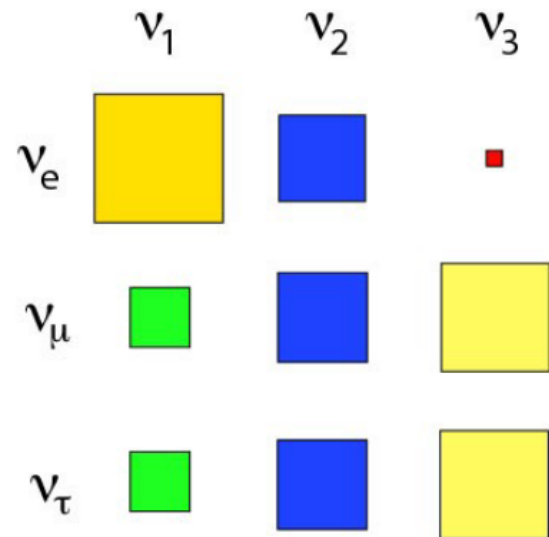
$$U_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta_{\mathrm{CP}}}s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{\mathrm{CP}}}s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$
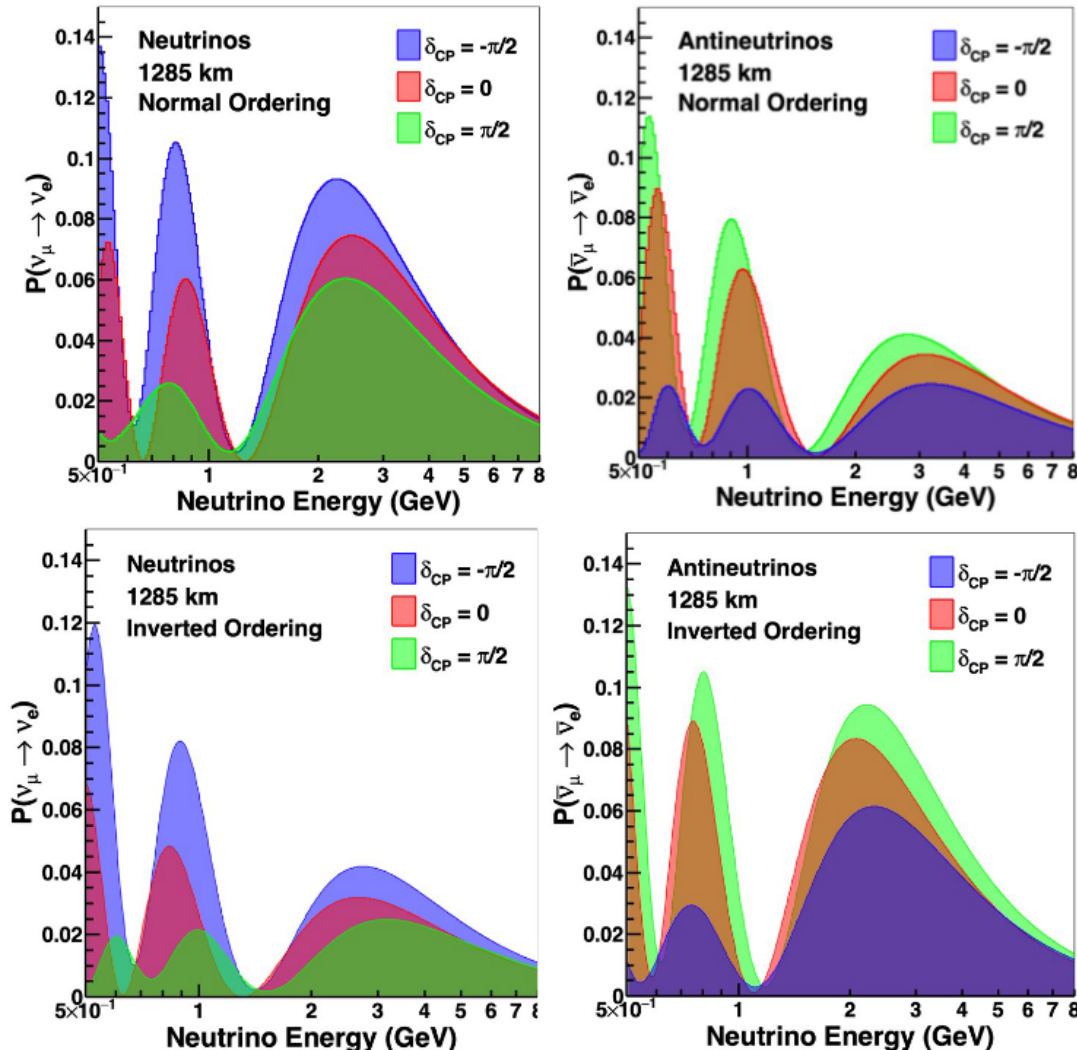
2.3%

$\sin^2\theta_{23} = 0.5 \pm 0.1$

? 2.7%

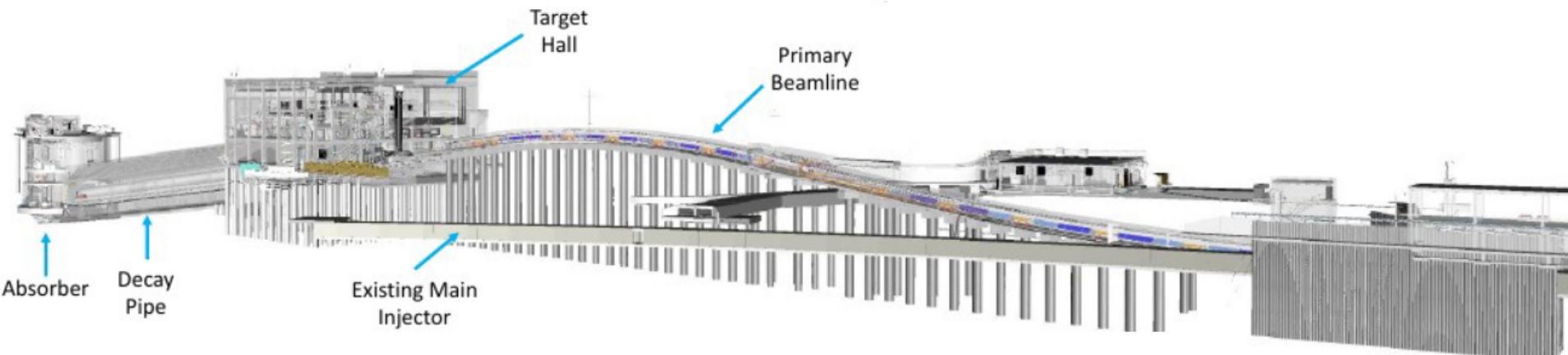**$\Delta m_{\mathrm{sol}}^2$ 2.8%**

$\Delta m_{\mathrm{atm}}^2$ 1.2%
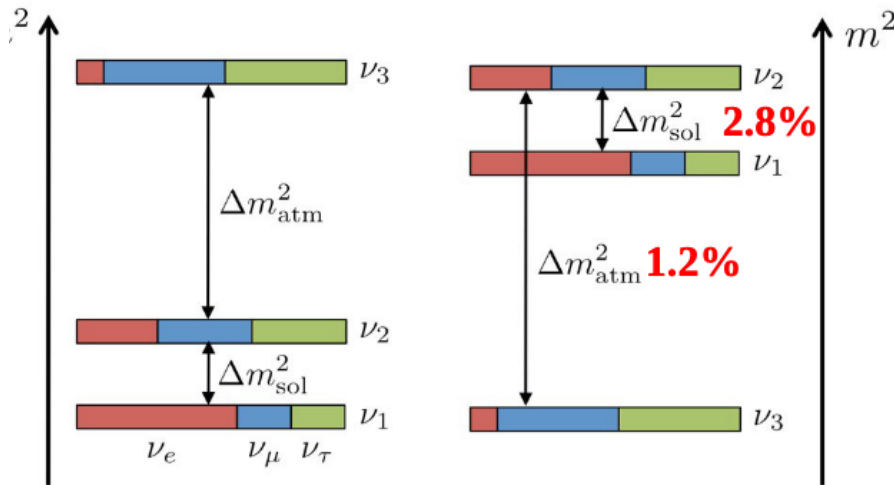
Mass ordering unknown

DUNE measures oscillations over more than a full period

Neutrinos 1285 km Normal Ordering; $\delta_{CP} = -\pi/2$, $\delta_{CP} = 0$, $\delta_{CP} = \pi/2$; $P(\nu_\mu \to \nu_e)$ vs Neutrino Energy (GeV)

Antineutrinos 1285 km Normal Ordering; $\delta_{CP} = -\pi/2$, $\delta_{CP} = 0$, $\delta_{CP} = \pi/2$; $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ vs Neutrino Energy (GeV)

Neutrinos 1285 km Inverted Ordering; $P(\nu_\mu \to \nu_e)$ vs Neutrino Energy (GeV)

Antineutrinos 1285 km Inverted Ordering; $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ vs Neutrino Energy (GeV)
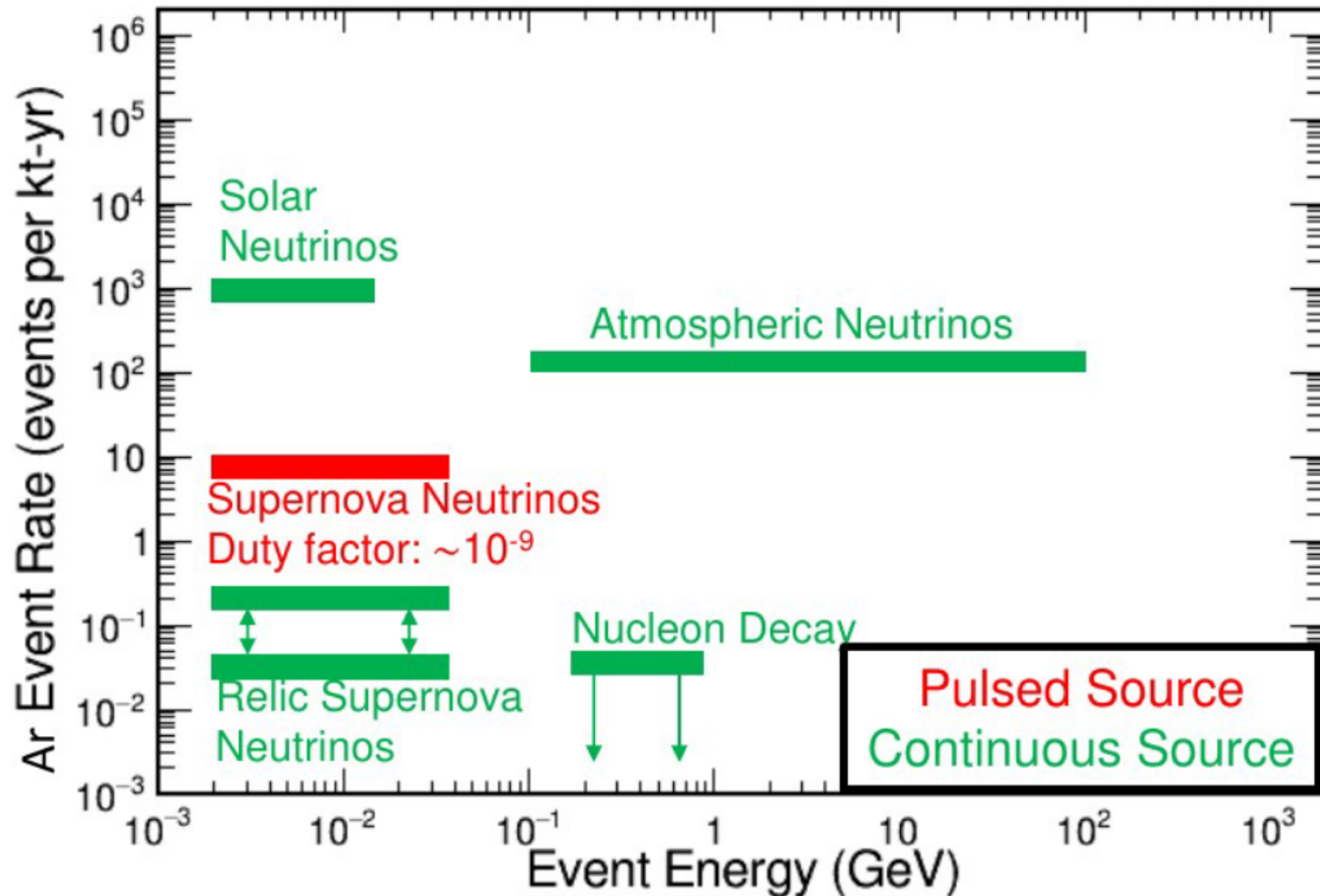
- Effect of mass ordering, CP violation, θ_{23} octant have *different shape* as a function of L/E

- 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)

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Queen Mary University of London   DUNE

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

Target Hall

Primary Beamline

Absorber

Decay Pipe

Existing Main Injector

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Astroparticle events in DUNE: several decades in energy & rate
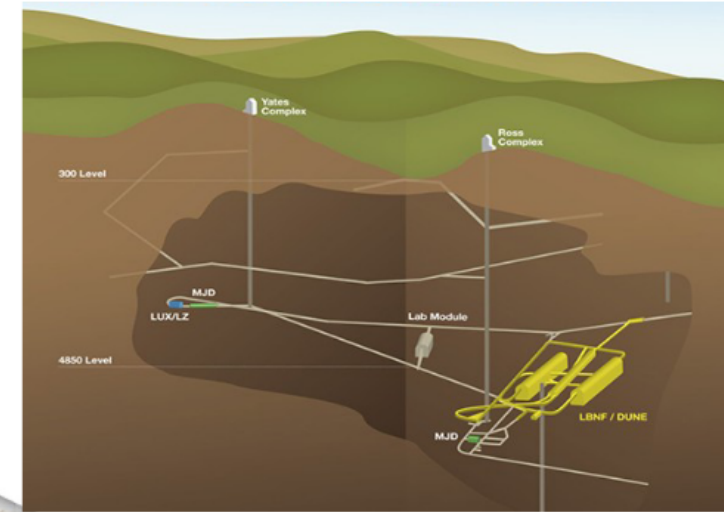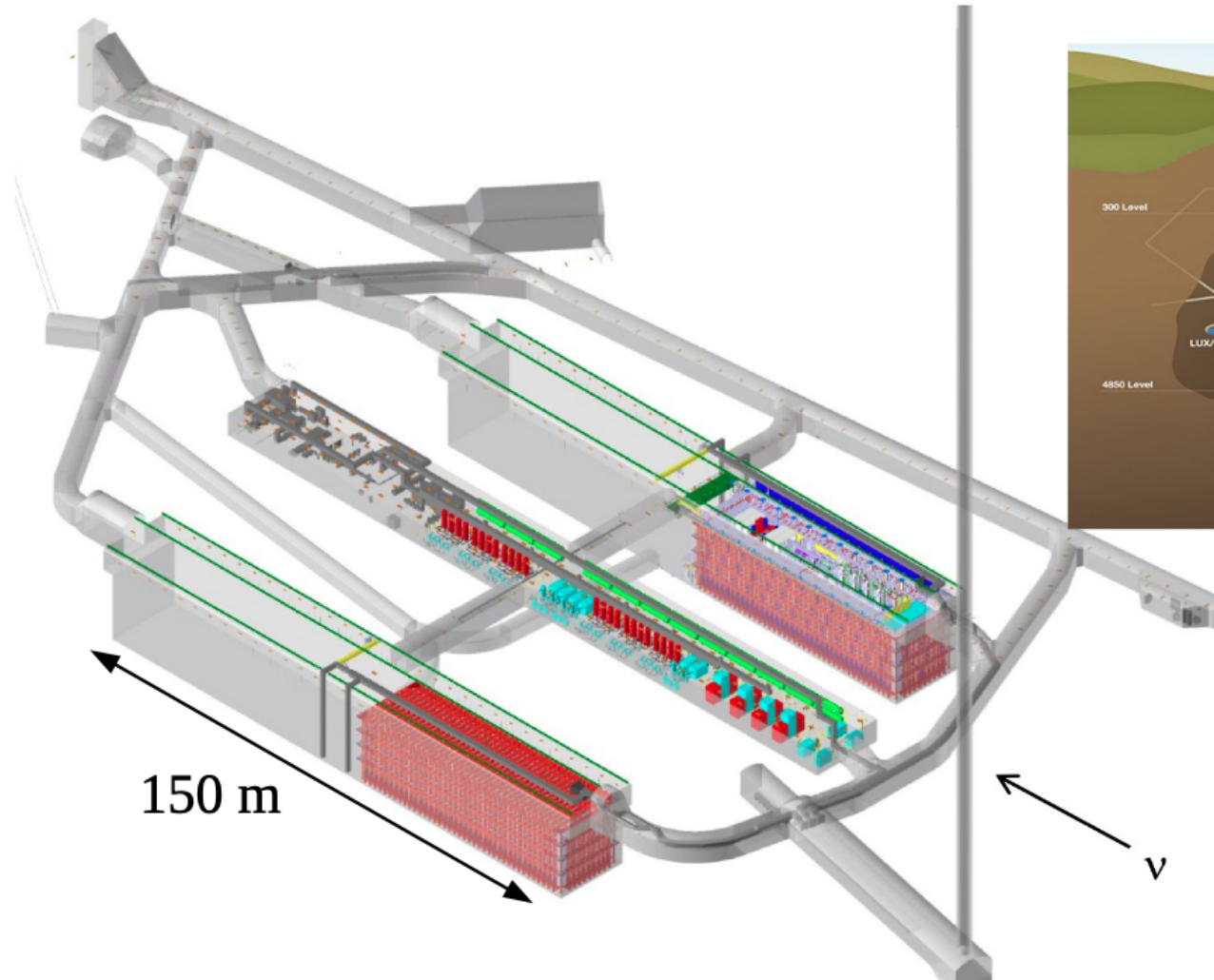

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LBNF: lots and lots of neutrinos

- 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)

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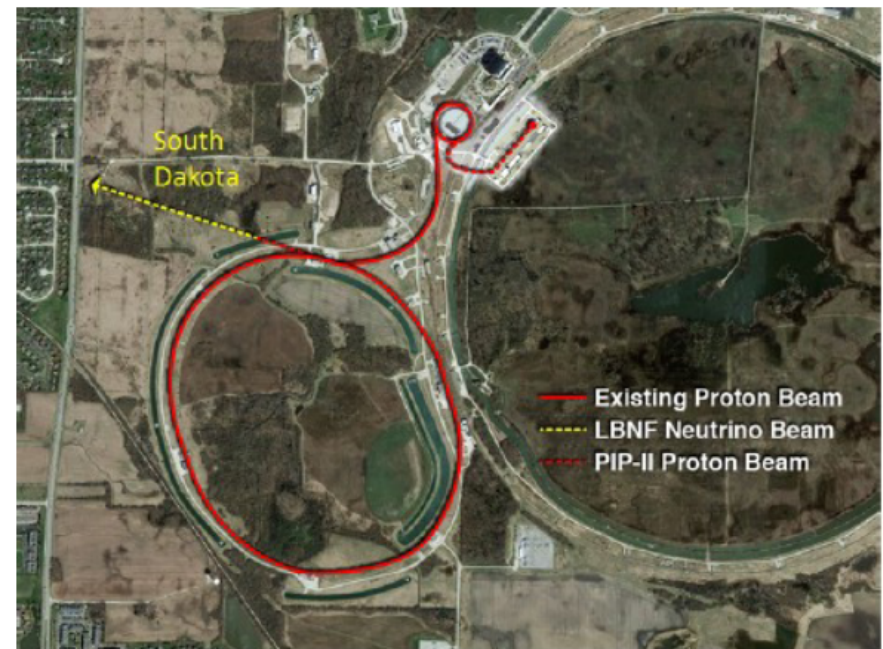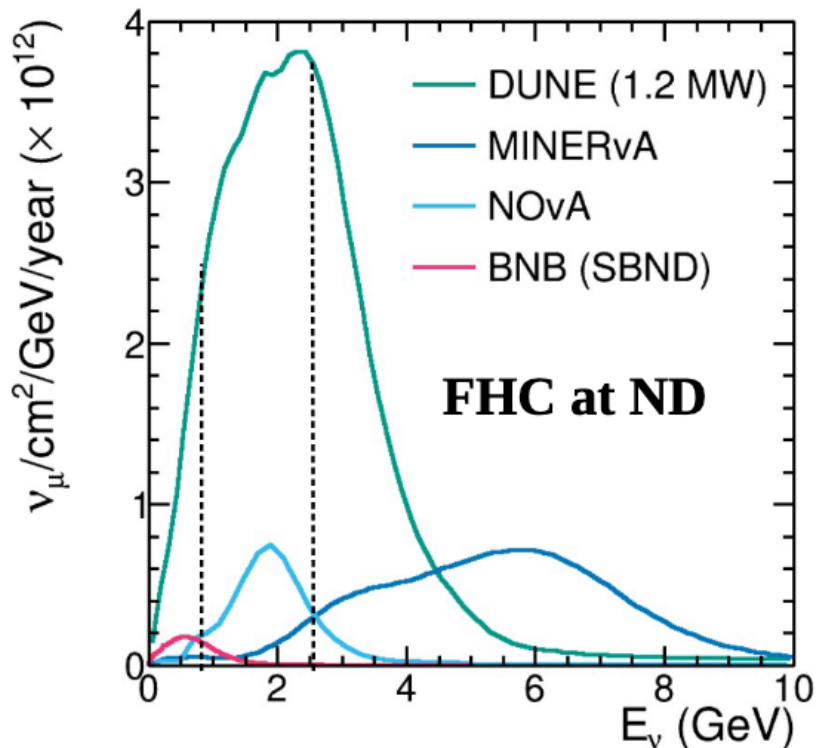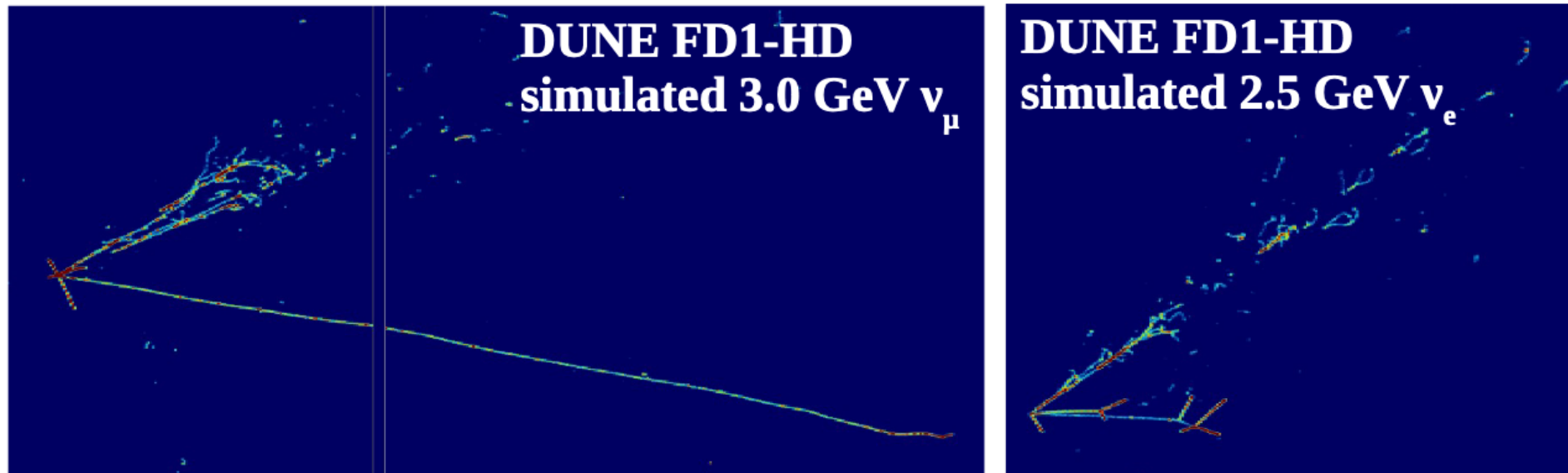
Deep underground far detector site at SURF (Lead, South Dakota)

150 m

ν

- 1490m underground (4300 mwe)

- Space for 70kt LAr detector

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Far Detector – Site of Original Davis Experiment!

Image: Brookhaven

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Why LAr: exquisite imaging for flavor ID, energy reconstruction

DUNE FD1-HD simulated 3.0 GeV ν_μ

DUNE FD1-HD simulated 2.5 GeV ν_e

- Clean separation of ν_μ and ν_e charged currents

- Low thresholds for charged particles $\rightarrow$ precise reconstruction of lepton and hadronic energy $\rightarrow$ E_ν reconstruction over broad energy range
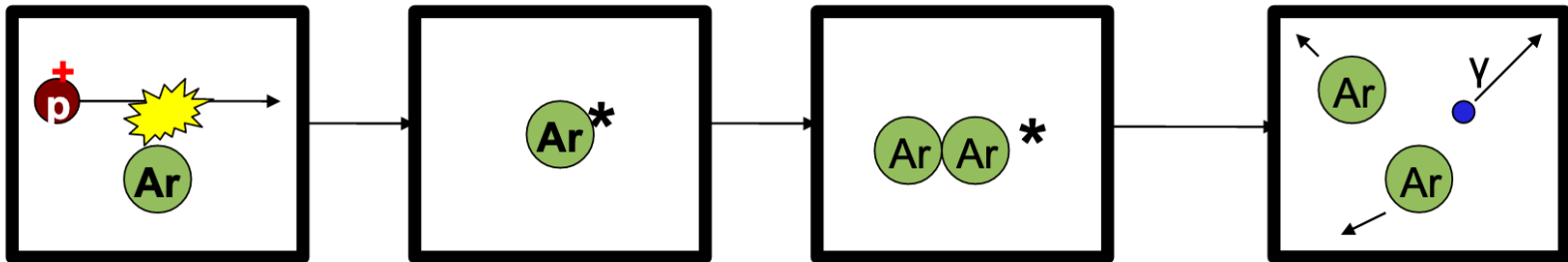
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Why LAr: Nobel Elements
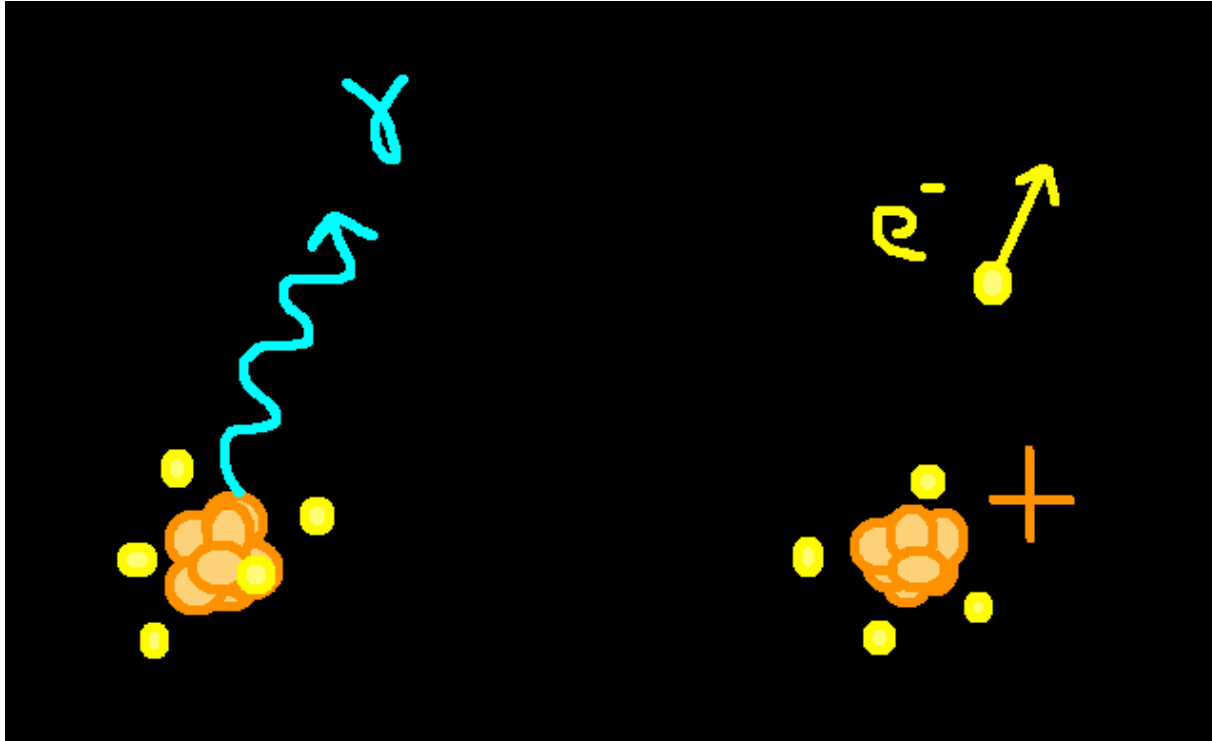
- Transparent to their own scintillation light
- No electron attachment*, long drift distances

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Why LAr: Transparent

Self-trapped exciton luminescence

Recombination luminescence
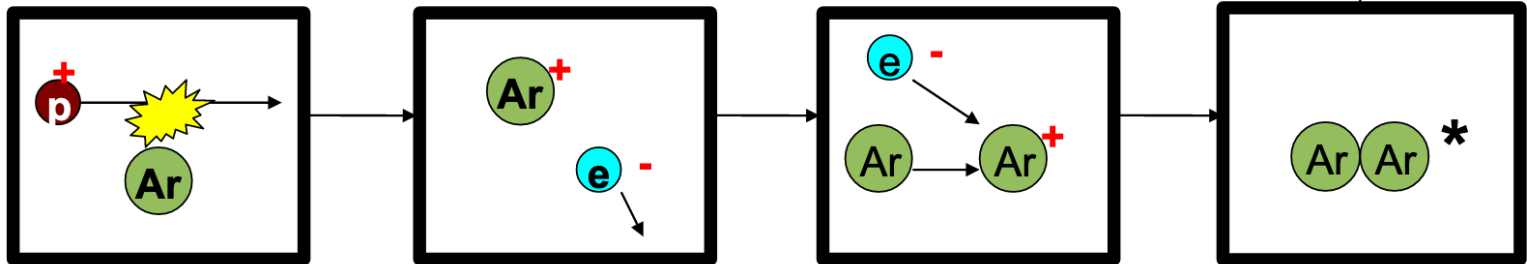
Image: Ben Jones

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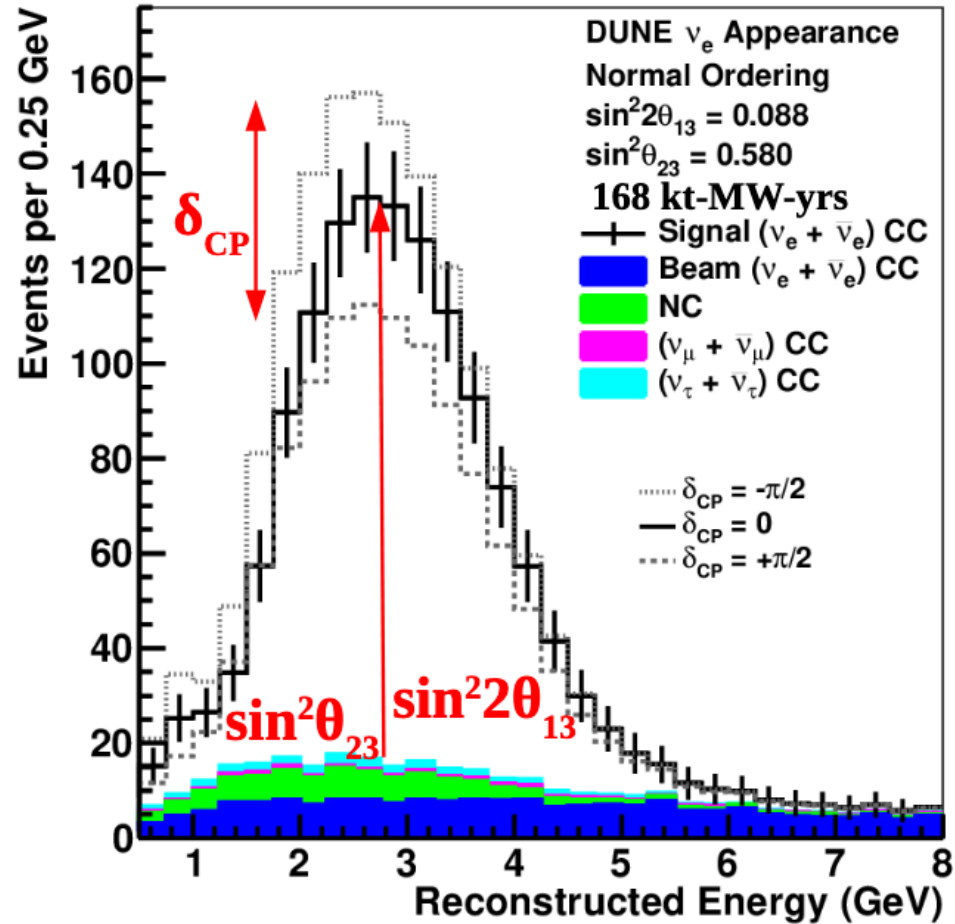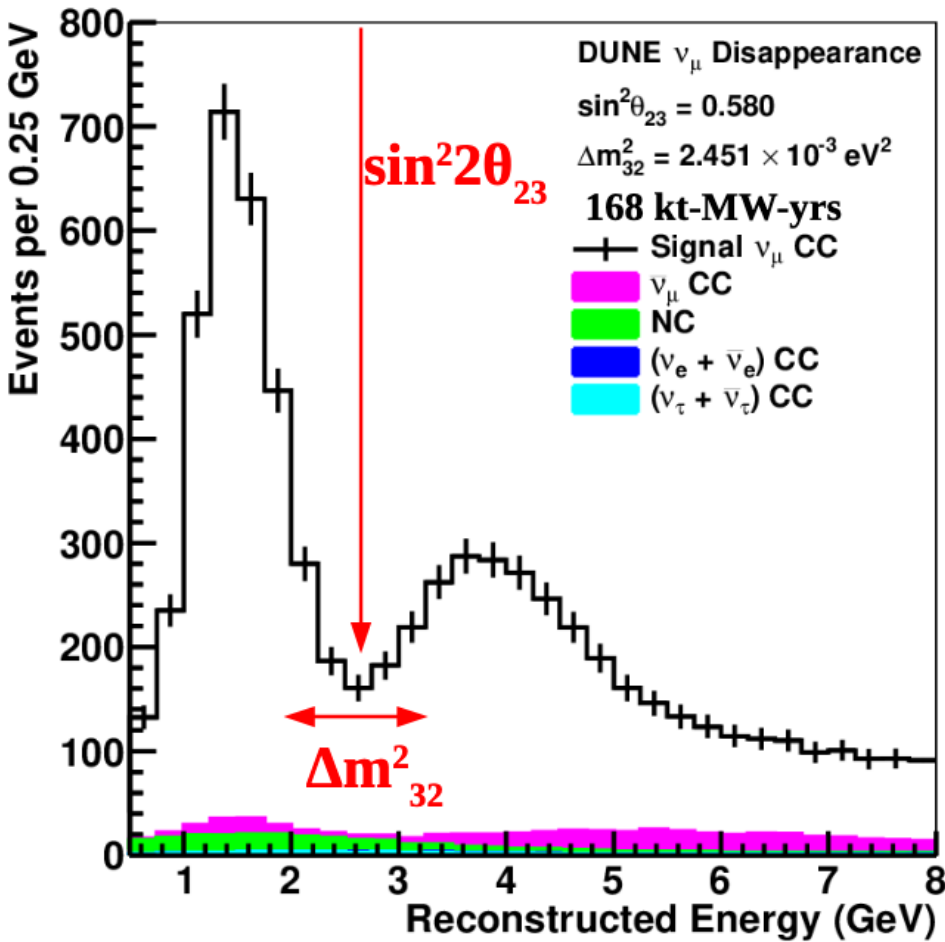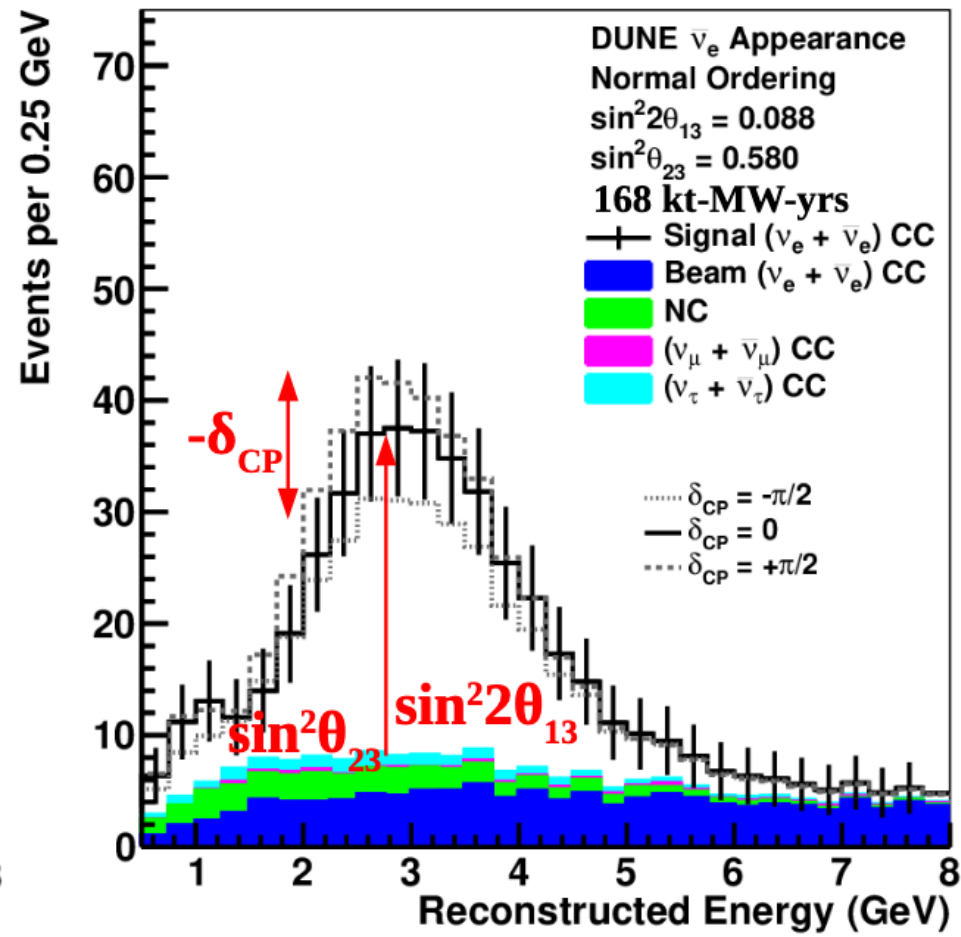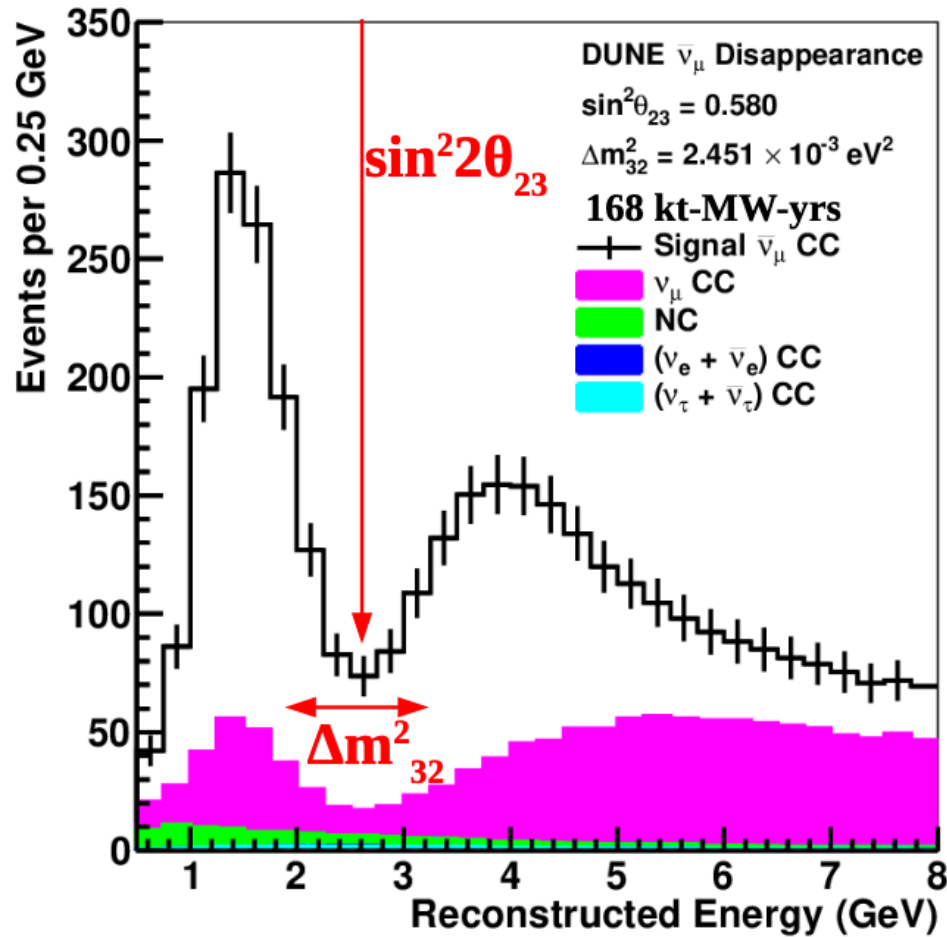- Reverse process to absorb light requires two atoms in close proximity
- Argon unbound in ground state, atoms typically around 4 Å apart

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What DUNE actually measures: Events vs. reco energy

FHC = neutrinos

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What DUNE actually measures: Events vs. reco energy

RHC = antineutrinos

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The DUNE ND provides critical constraints on systematics
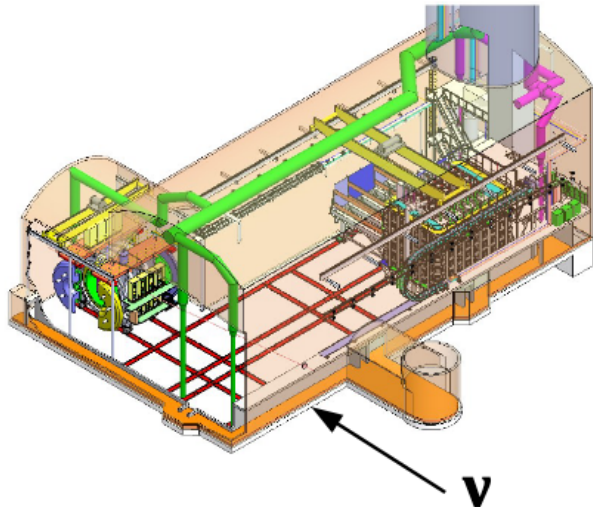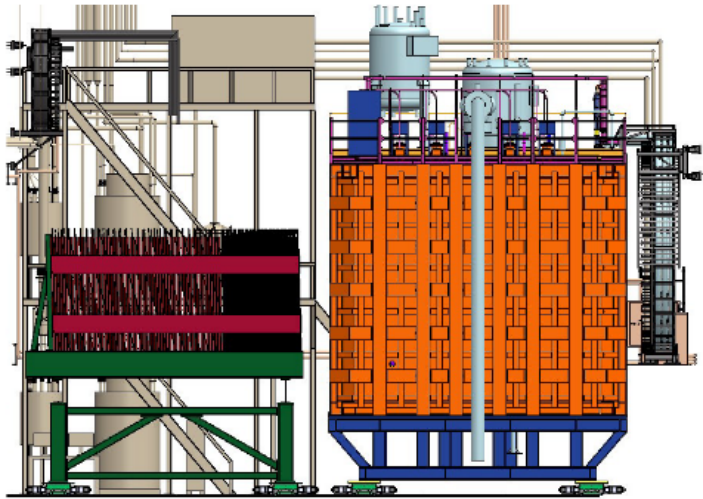
- Large uncertainties on flux, cross sections, and detector response require are constrained to the few percent level by the ND

- 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

ND Flux × (oscillation) → FD Oscillated Flux — DUNE-PRISM

48 kT-MW-Years Exposure, $\Delta m^2_{32} = 2.52 \times 10^{-3}$ eV^2, $\sin^2(\theta_{23}) = 0.5$

DUNE-PRISM ν_μ Disappearance
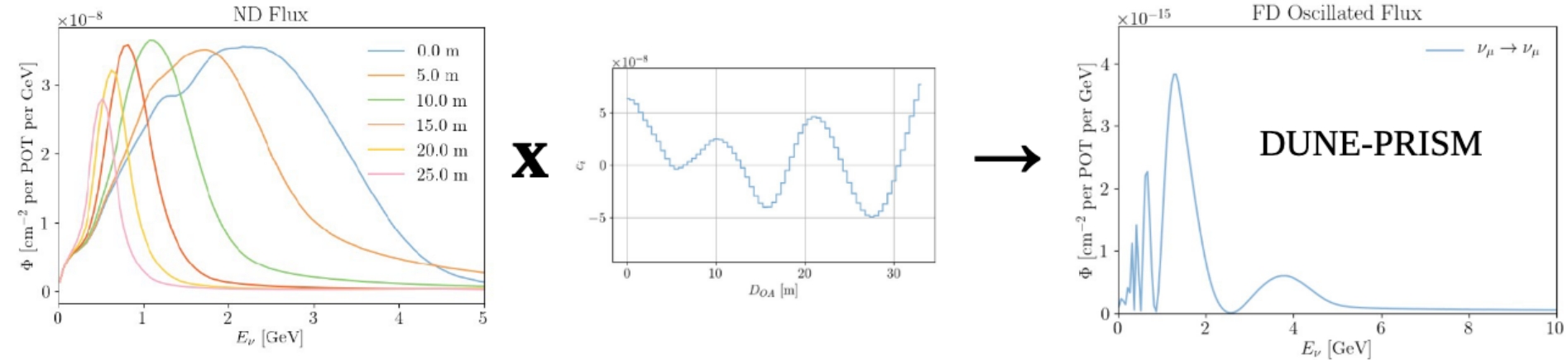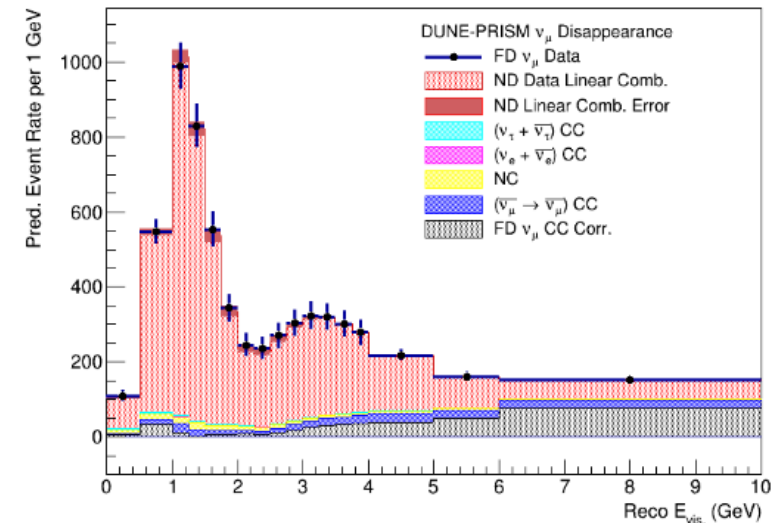
- FD flux ≠ ND flux → uncertainties in **energy dependence** of cross sections, response, etc.

- 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 $\nu_\mu \to \nu_e$ (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

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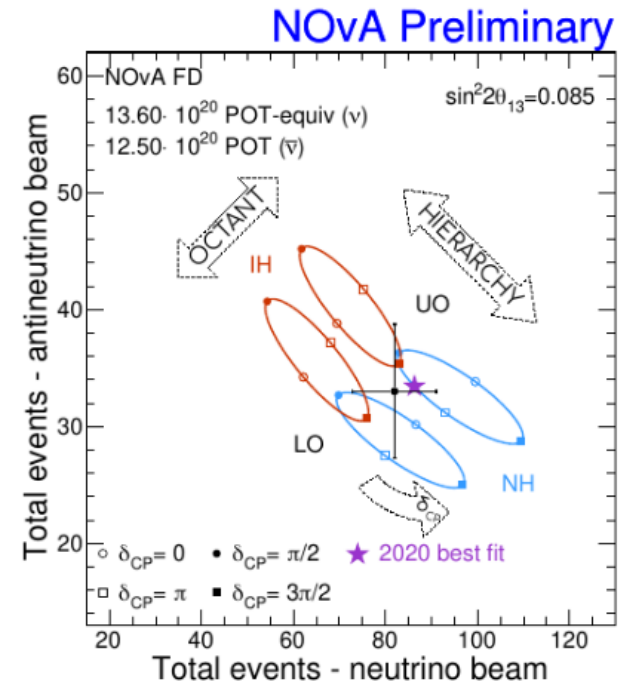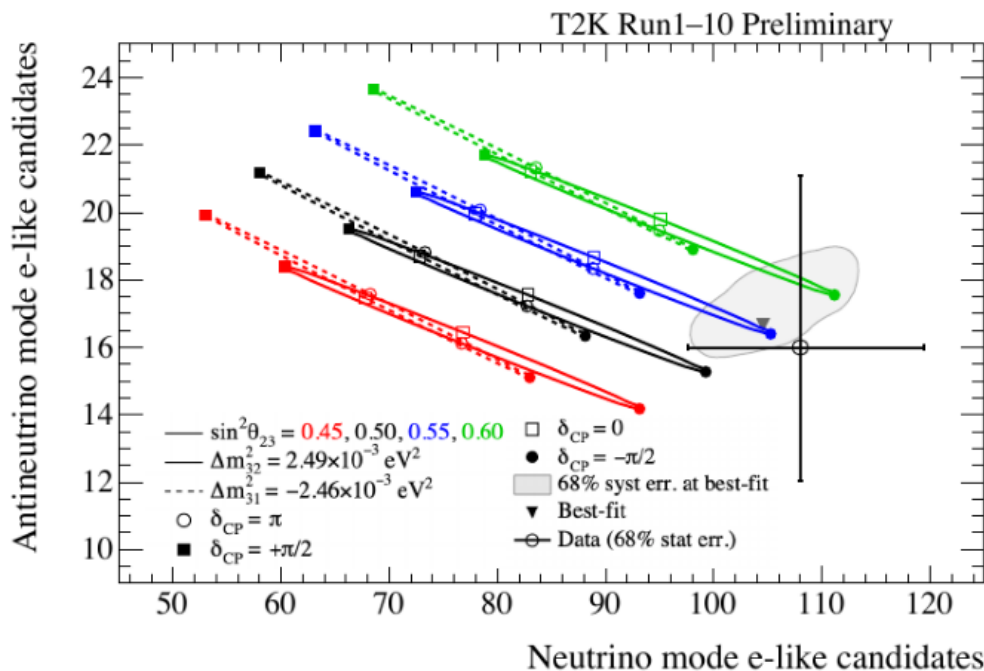
Current Measurements (T2K + SK)

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

δ_{CP} **posterior distributions with reactor constraint**
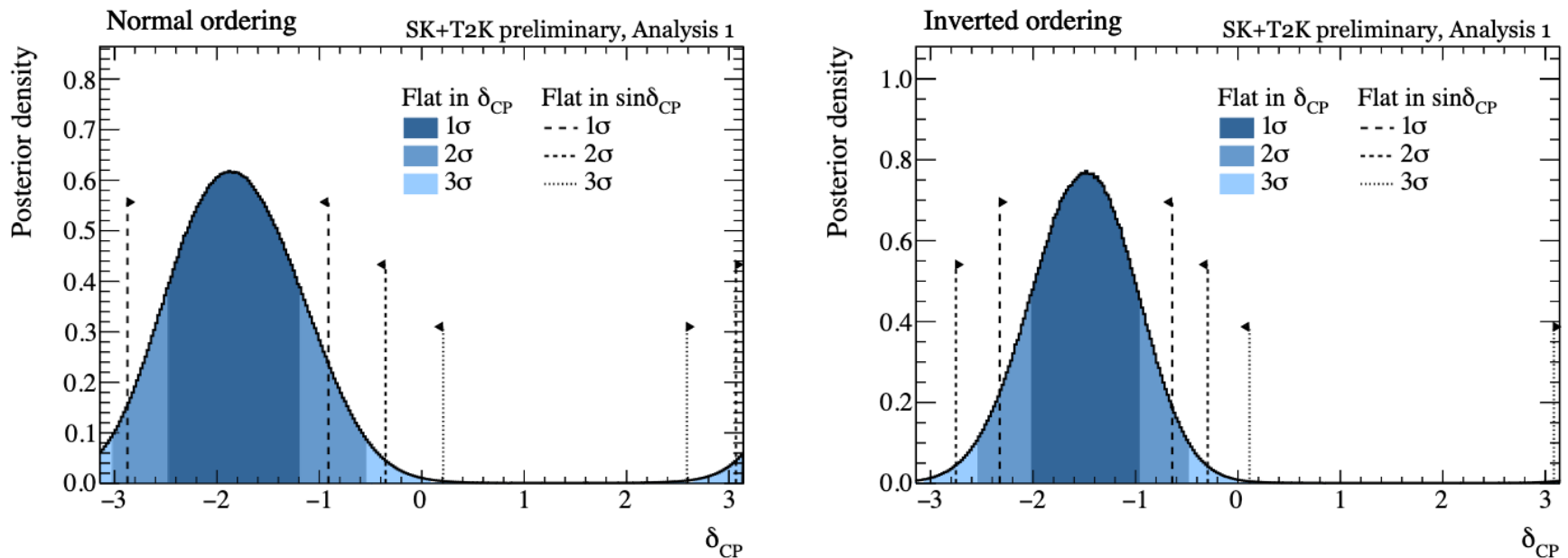
DUNE's large matter effect makes CPV and MO effects separable
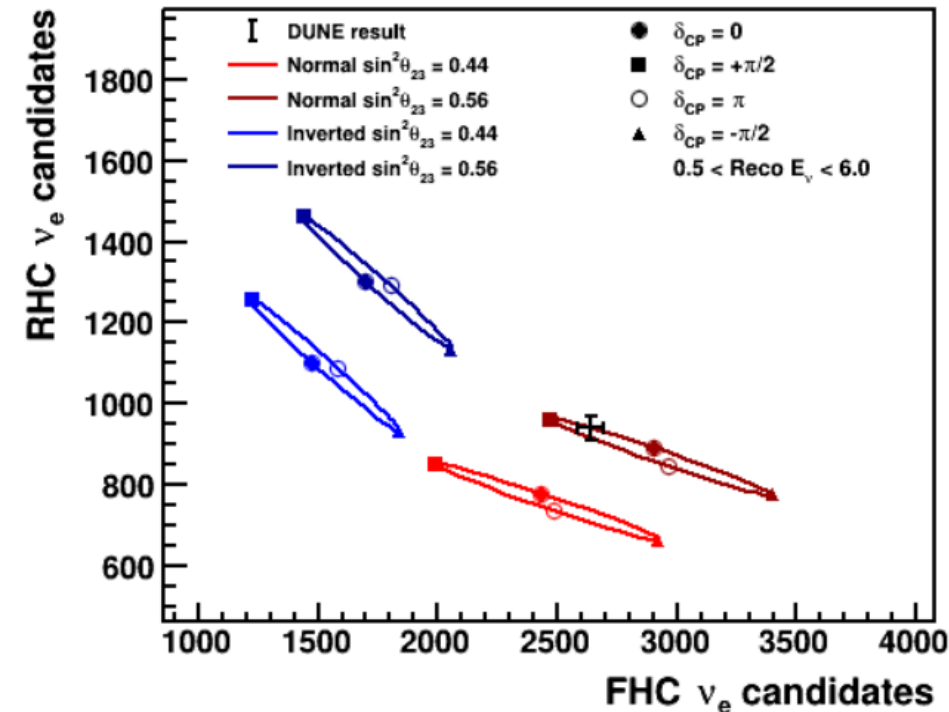
- Key feature very long baseline → no overlap between NO and IO

- 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...

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DUNE measures oscillations over more than a full period
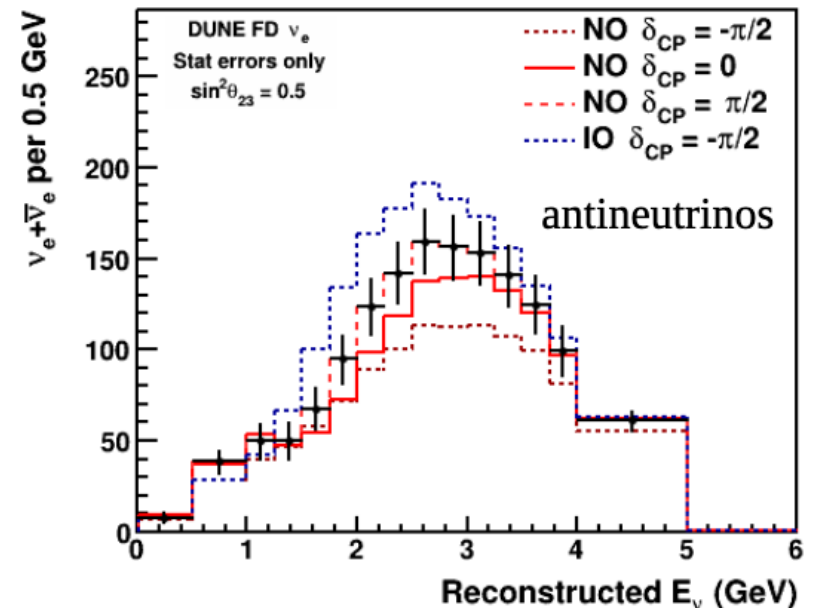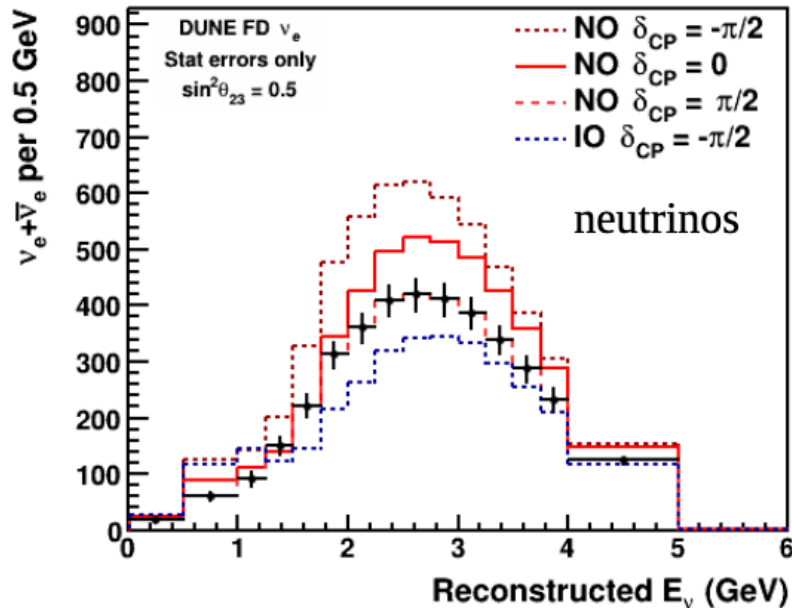
- Broadband neutrino beam → measure oscillations vs. L/E

- 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

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Mass ordering: definitive resolution

DUNE Simulation

24 kt-MW-yr
NO $p(\Delta\chi^2_{MO} < 0) = 0.034$
IO $p(\Delta\chi^2_{MO} > 0) = 0.040$

$\Delta\chi^2_{MO} = \chi^2_{IO} - \chi^2_{NO}$

DUNE Simulation

100% δ_{CP} values

NO $p(\Delta\chi^2_{MO} < 0)$
IO $p(\Delta\chi^2_{MO} > 0)$

Exposure (kt-MW-yr)
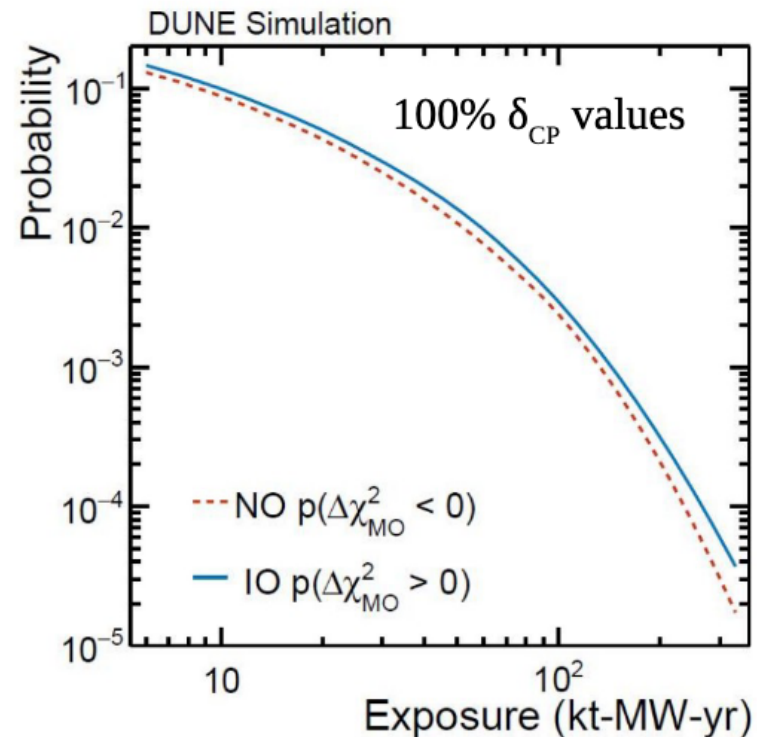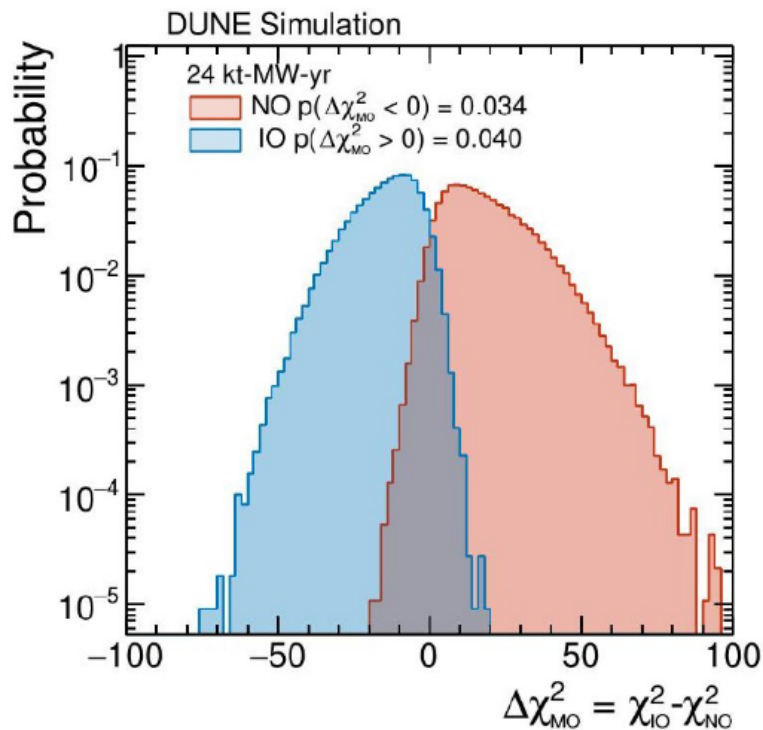
- Significant mass ordering sensitivity very quickly: ~97% correct after ~1-2 years

- Long term → >10σ for any parameter combination

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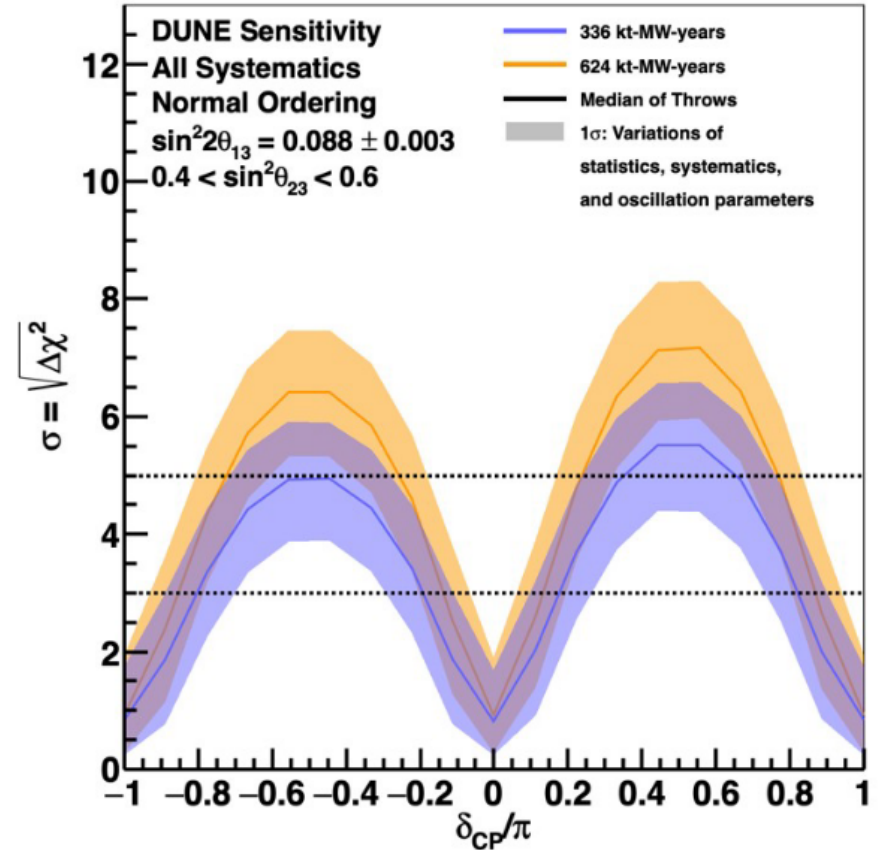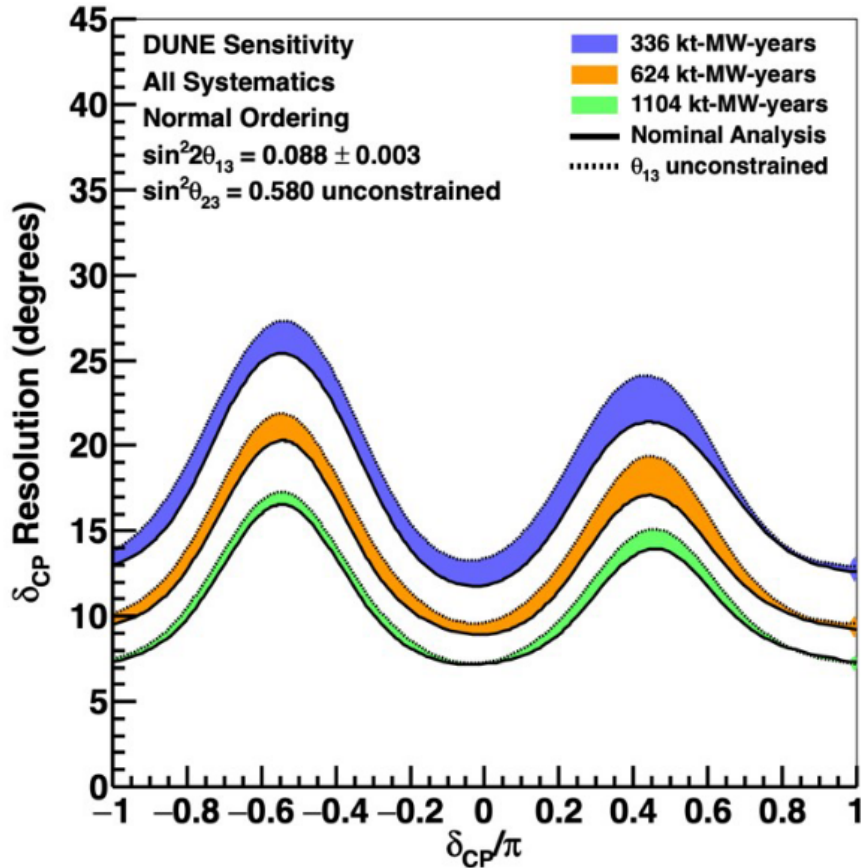
- 6°-16° resolution to δ_{CP} without dependence on other experiments, discovery sensitivity to CP violation over a broad range of possible values

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DUNE has unique sensitivity to supernova electron neutrinos
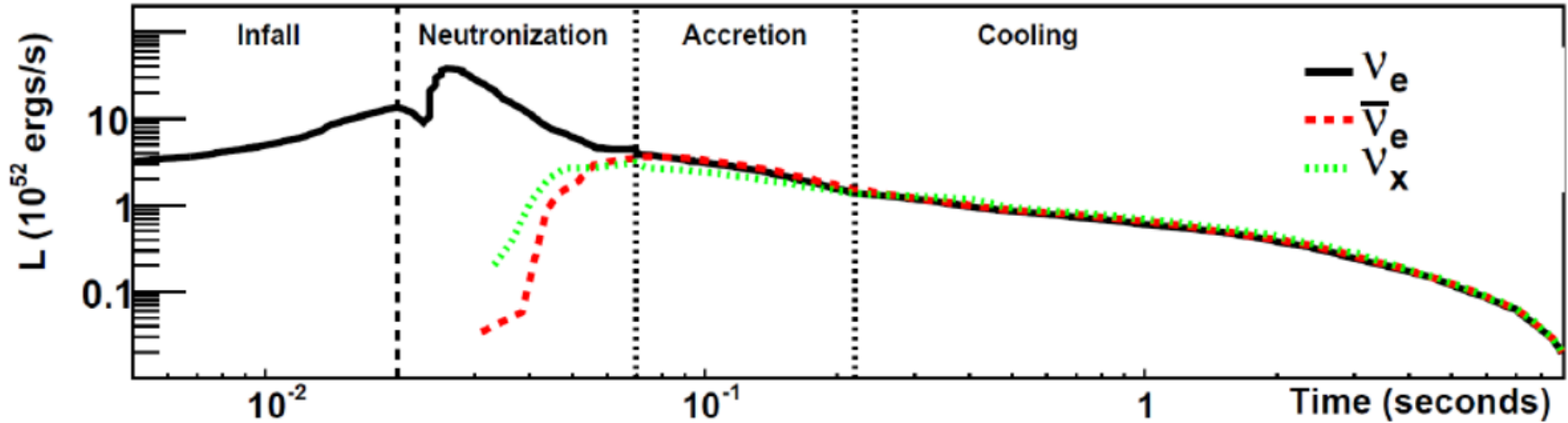
- Neutronization burst is entirely ν_e

- 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)

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ProtoDUNE

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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

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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

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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

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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

dQ/dx vs dE/dx (<φ> = 80°)
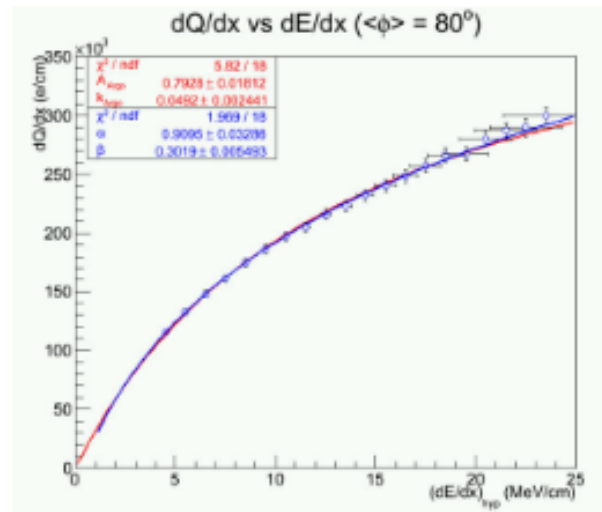
JINST 8 (2013) P08005 (ArgoNeuT)

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

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Recombination Modeling: Onsager geminate theory
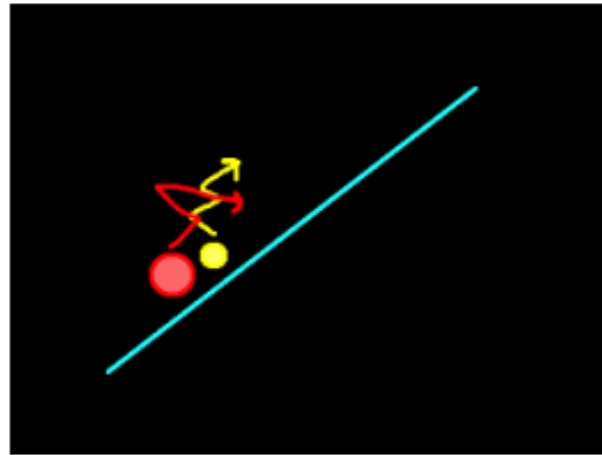
- ► Assumes electron recombines with parent ion
- ► Electron ion separation small compared to ion spacing

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Recombination Modeling: Jaffé columnar model
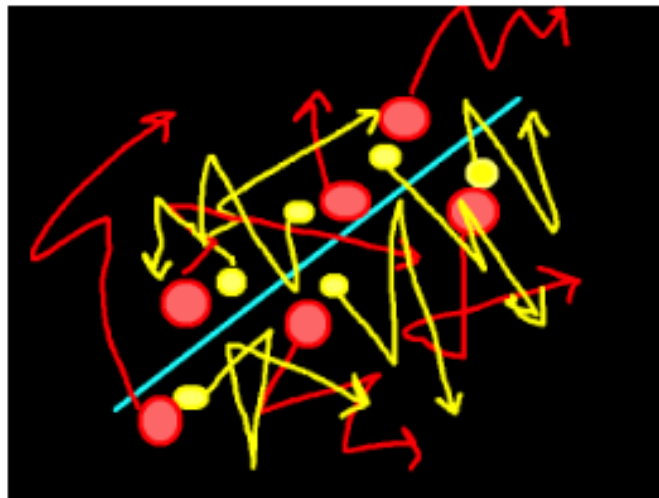
- ▶ Assumes separation of ions $(W/(dE/dx))$ is small compared to electron ion distance

- ▶ Gaussian profile about track assumed

- ▶ Introduces angular dependence if electric field present (perpendicular vs parallel to drift direction)

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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)

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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:

- ▶ $W = 23.6$ 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)

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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.

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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

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How we make this Measurement

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

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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

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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]

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

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Validation with MC

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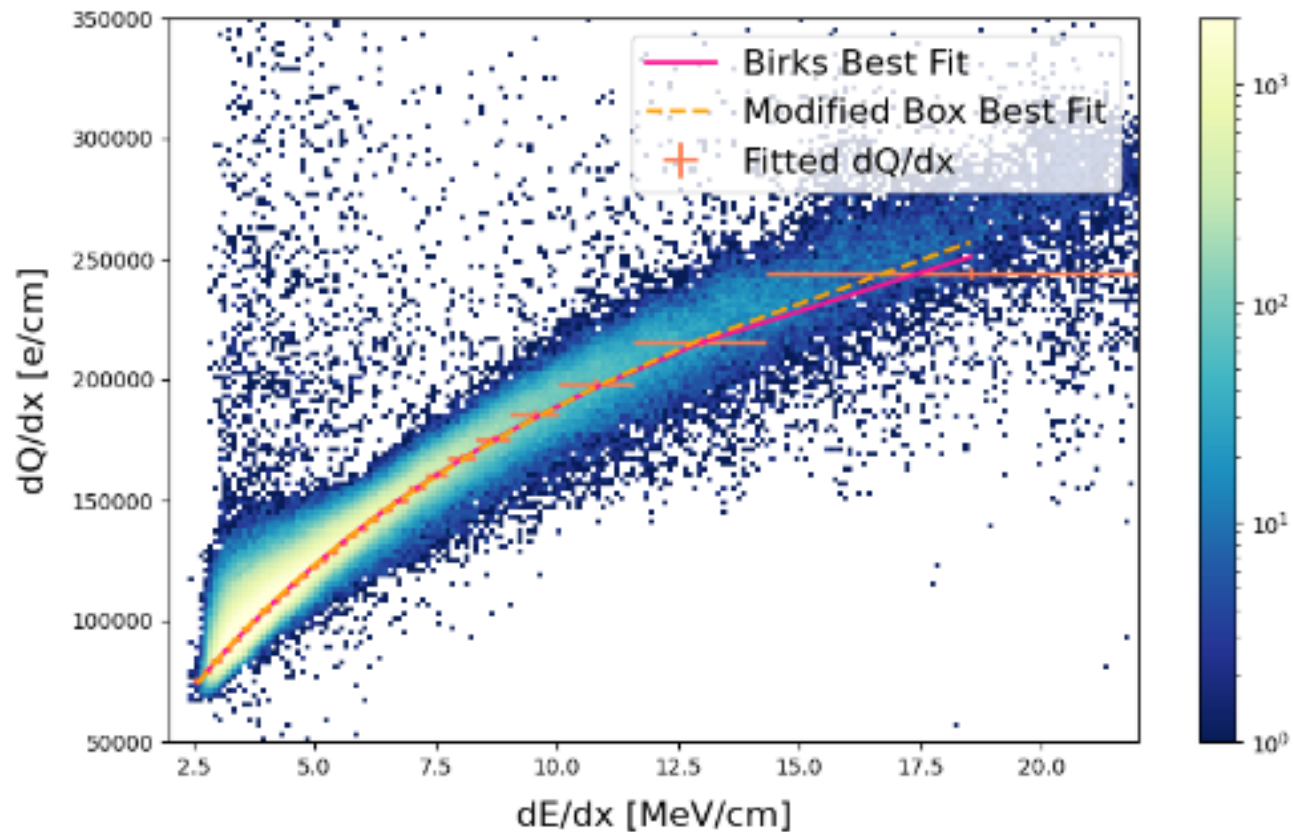
Validation with MC

Modified Box Model:

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

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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)

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Fit Results: Data

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Fit Results: Data

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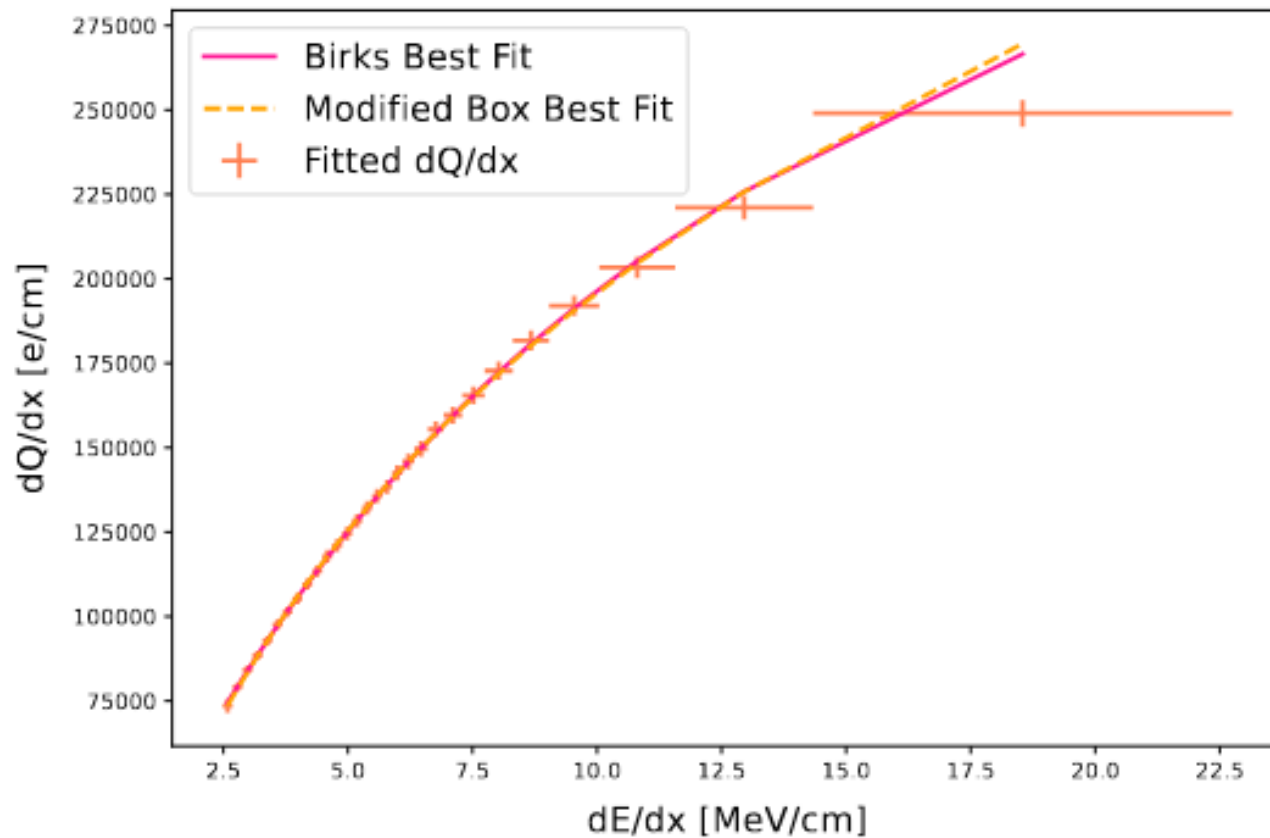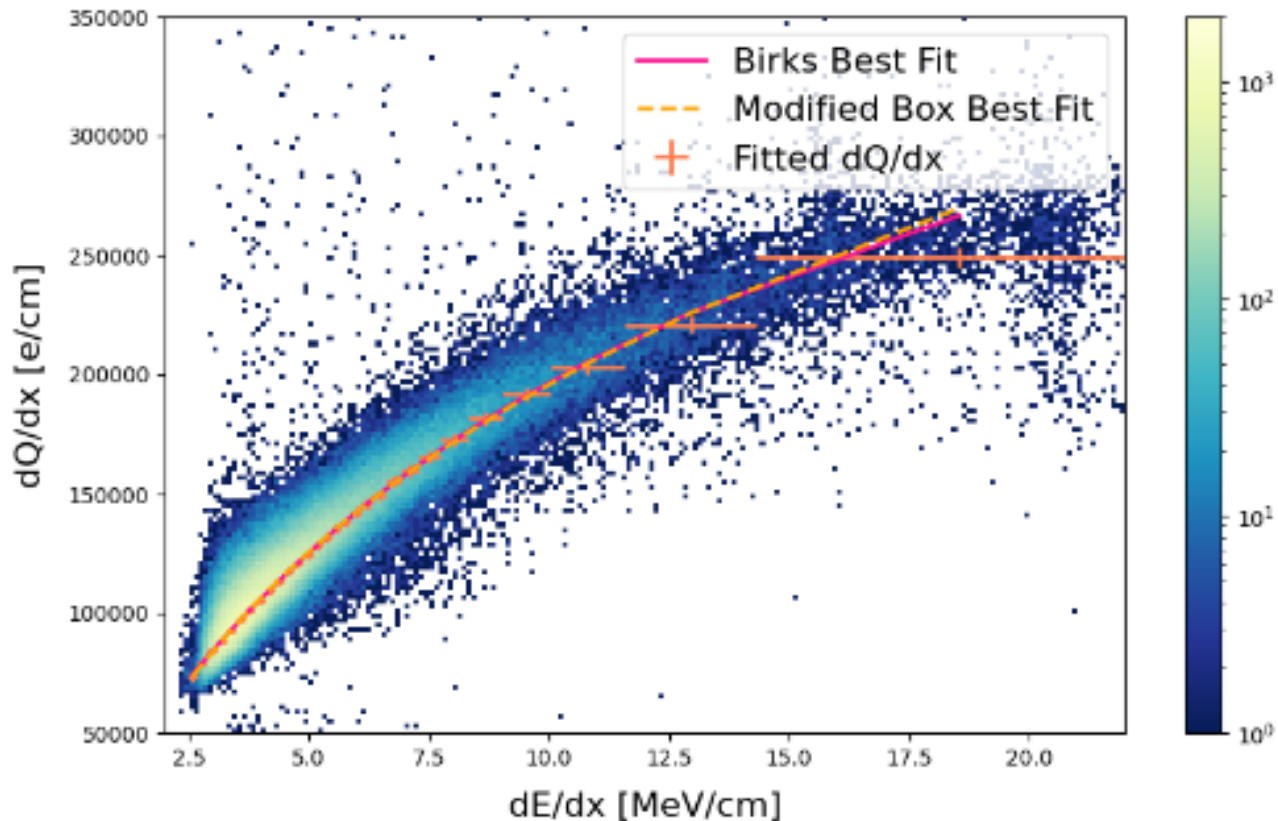
Global Results Summary

	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

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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) $(kV/cm)(g/cm^2)/MeV$
- ▶ $\chi^2/ndof = 1.04$

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) $(kV/cm)(g/cm^2)/MeV$
- ▶ $\chi^2/ndof = 0.77$

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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!