DUNE

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Fermilab Users' Meeting
13 June, 2019

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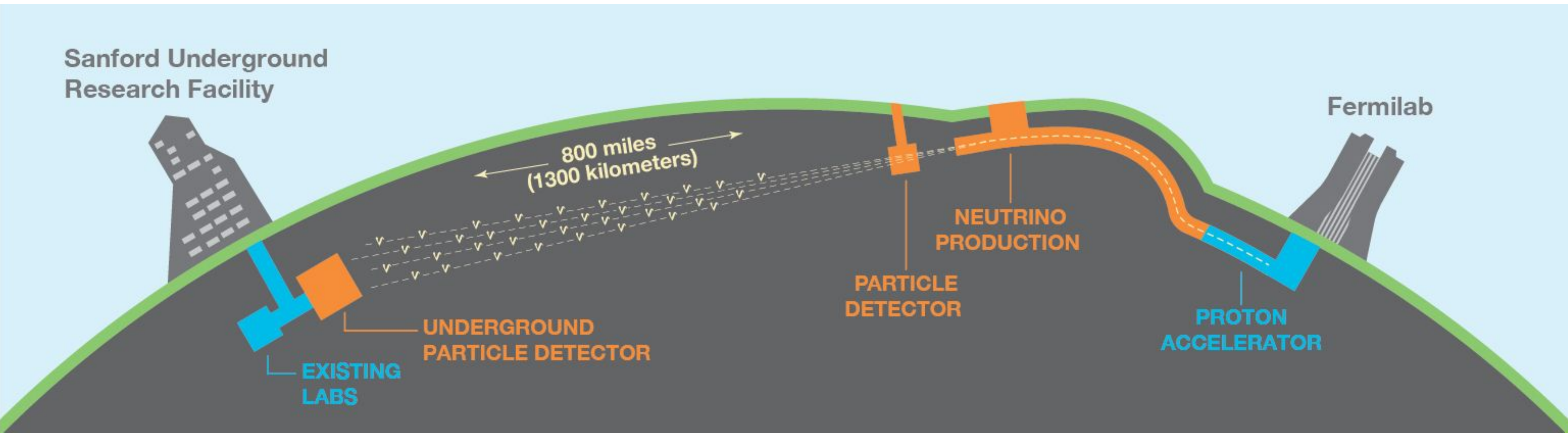
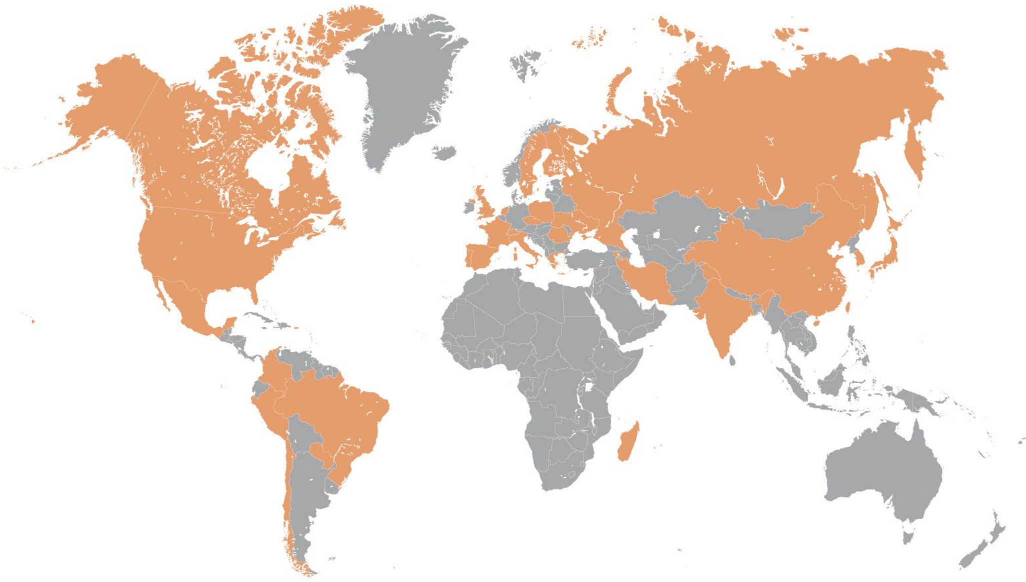
DEEP UNDERGROUND NEUTRINO EXPERIMENT



- 40 kt fiducial volume liquid argon TPC far detector at SURF, 1300 km baseline
- Near detector system at Fermilab, 574 m baseline
- Wide-band neutrino beam from Fermilab Main Injector
- Primary physics goal: neutrino oscillations (including CP violation, mass ordering)
- Also nucleon decay, supernova neutrinos, BSM physics, ν cross sections

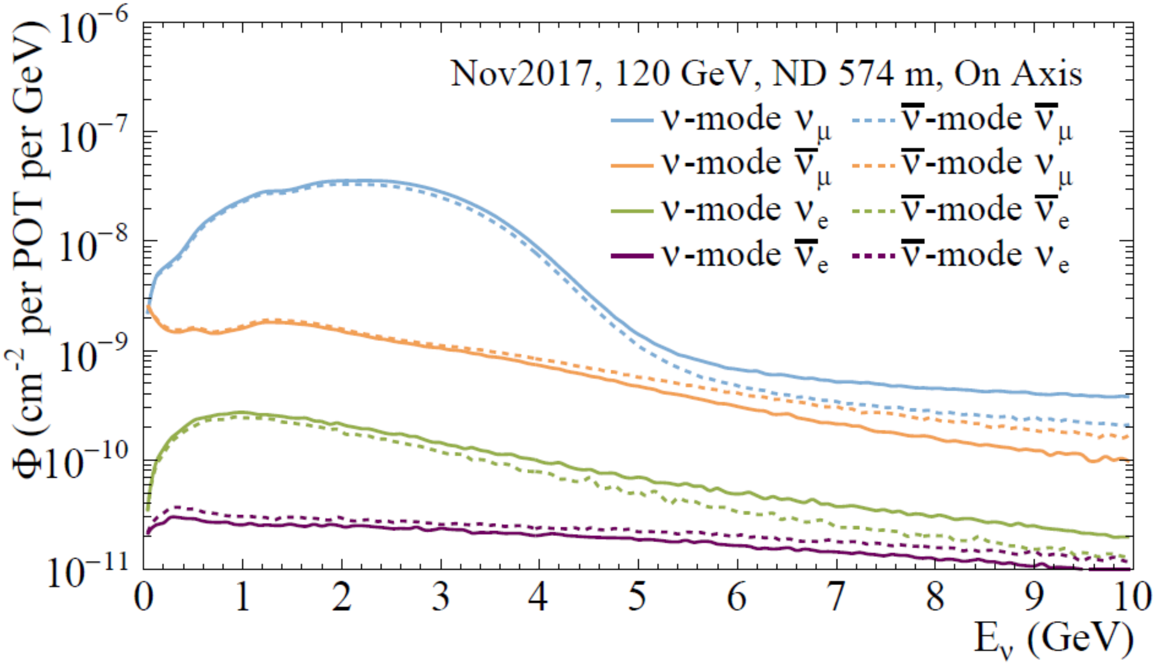
DUNE: international collaboration

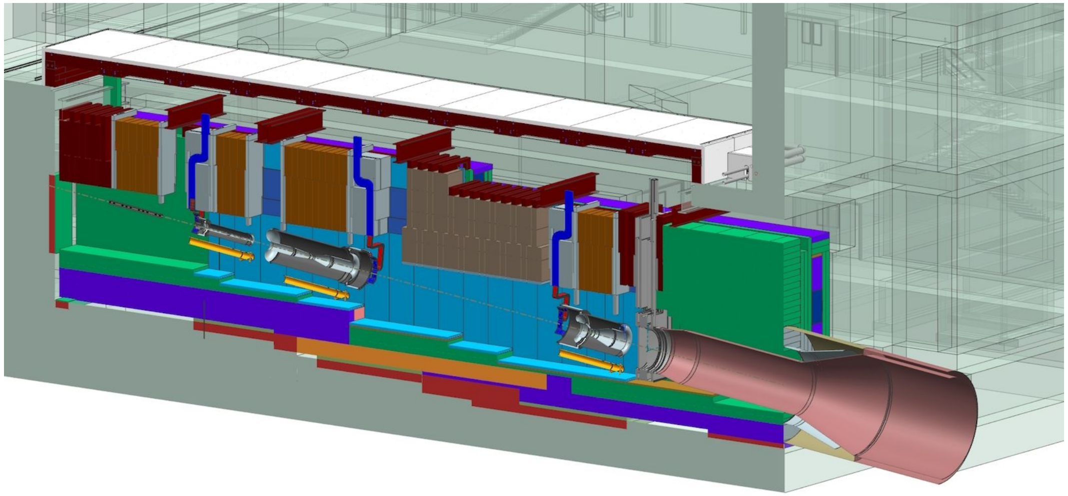
- 1069 collaborators from 177 institutions in 31 countries
- 578 faculty, 184 postdocs, 109 engineers, 198 Ph.D. students



Armenia (3), Brazil (31), Canada (1), CERN (37), Chile (3), China (2), Colombia (8), Czech Republic (11), Spain (35), Finland (4), France (38), Greece (5), India (44), Iran (2), Italy (66), Japan (7), Madagascar (4), Mexico (10), The Netherlands (6), Paraguay (4), Peru (7), Poland (6), Portugal (6), Romania (7), Russia (10), South Korea (5), Sweden (1), Switzerland (30), UK (146), Ukraine (4), USA (528)

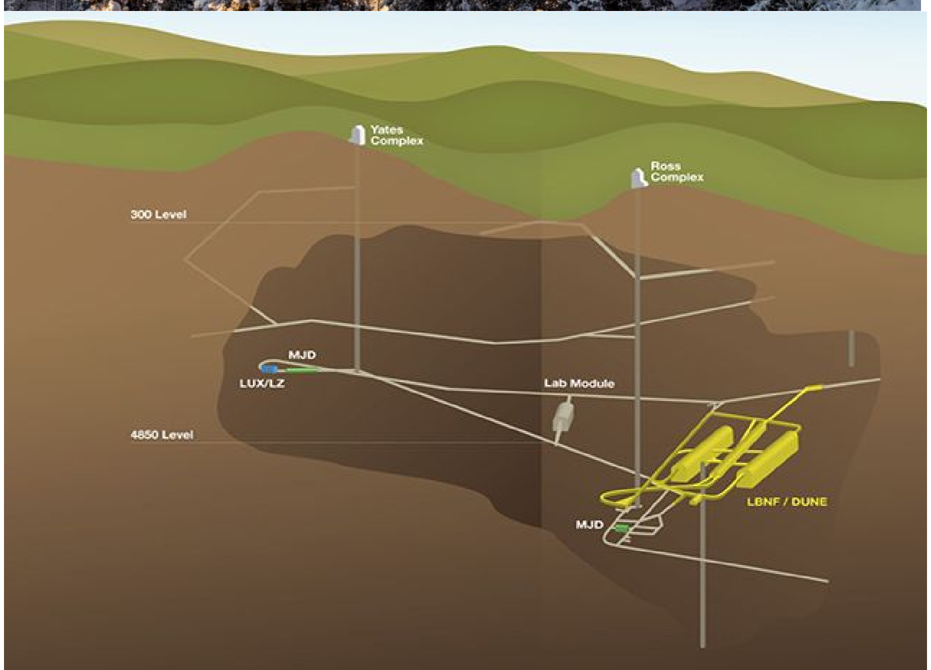
LBNF: intense neutrino beamline



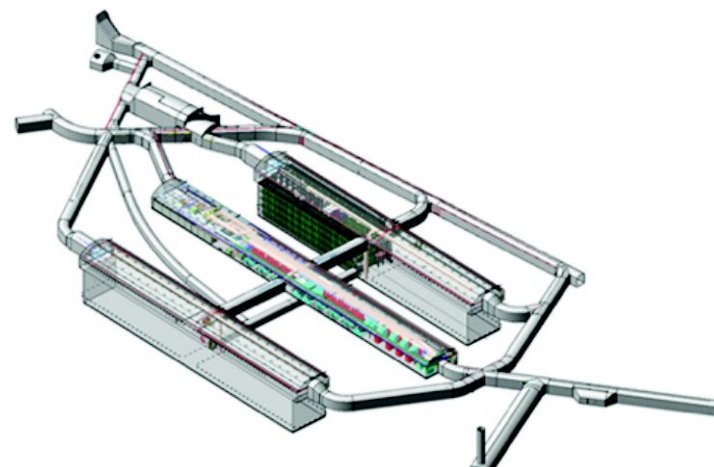


- 120 GeV Main Injector proton beam
- 1.2 MW initial beam power, upgradeable to 2.4 MW
- Beamline and focusing system optimized for CP violation sensitivity

Far detector at SURF

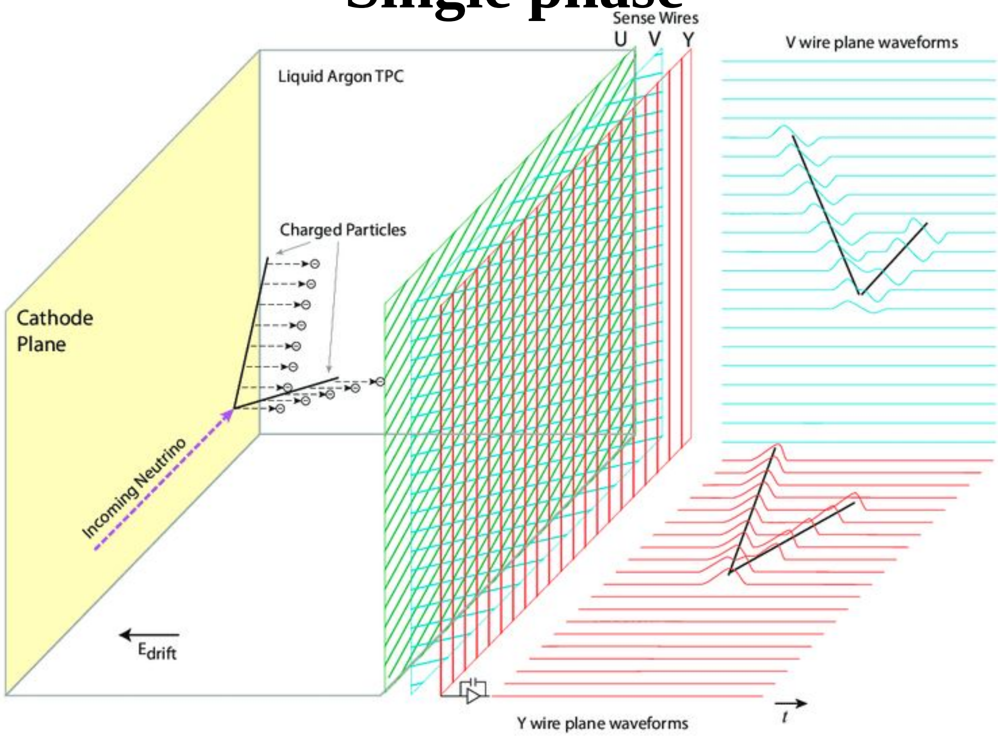


- Sanford Underground Research Facility in Lead, South Dakota
- Four 10-kt F.V. LAr TPC modules, located 4,850 ft. underground (1,480m)
- Pre-excavation underway, excavation in 2019, first module operational in 2024

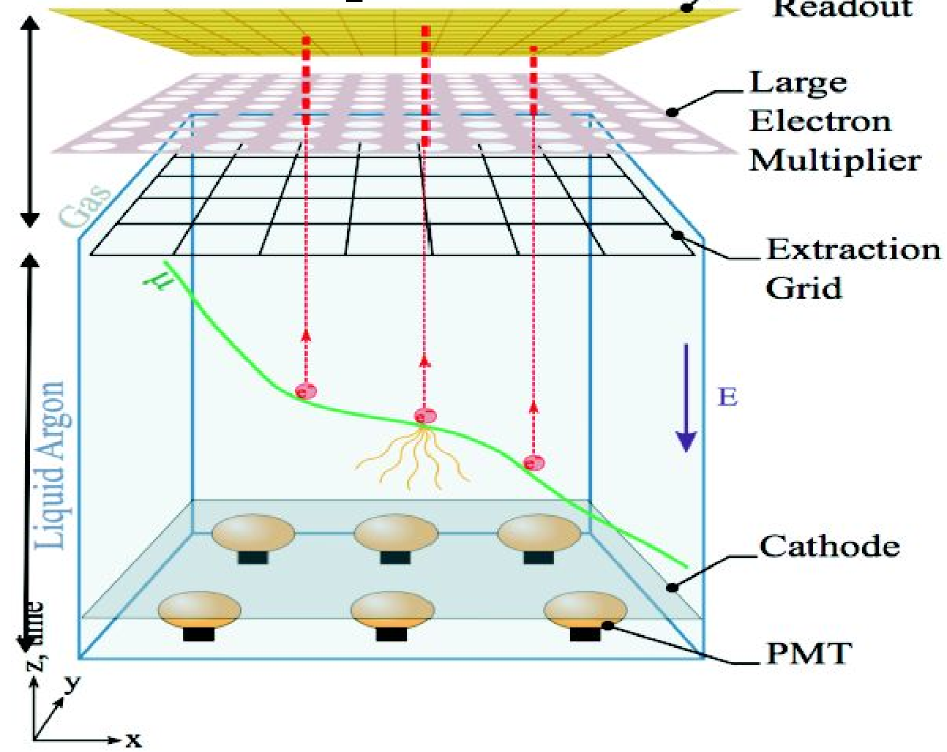


Two detector technologies

Single phase

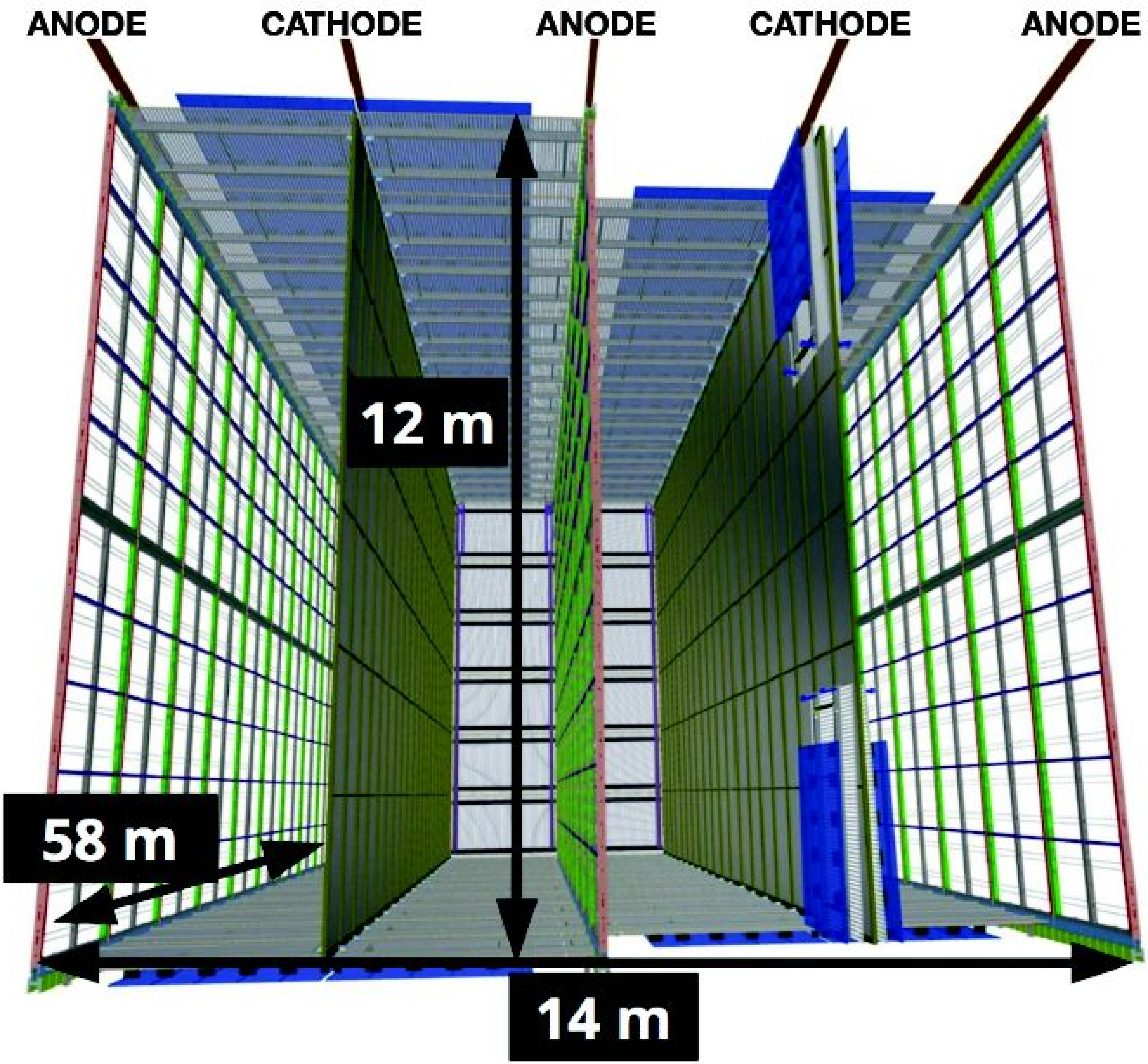


Dual phase



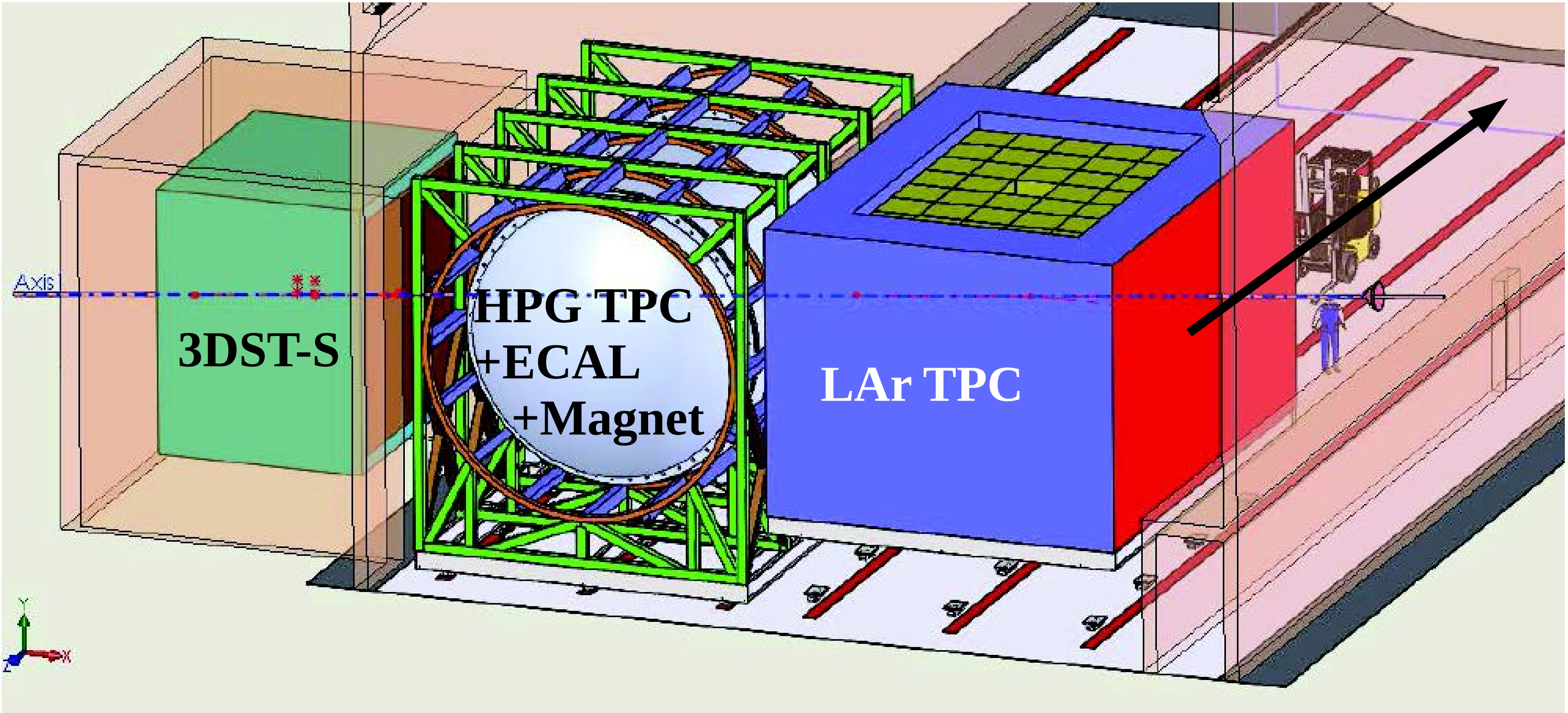
- Single phase: all liquid, charge read out by two induction wire planes and one collection plane
- Dual phase: Charge drifts vertically, amplified and read out in gas phase for larger signal/noise

First 10kt module: single phase



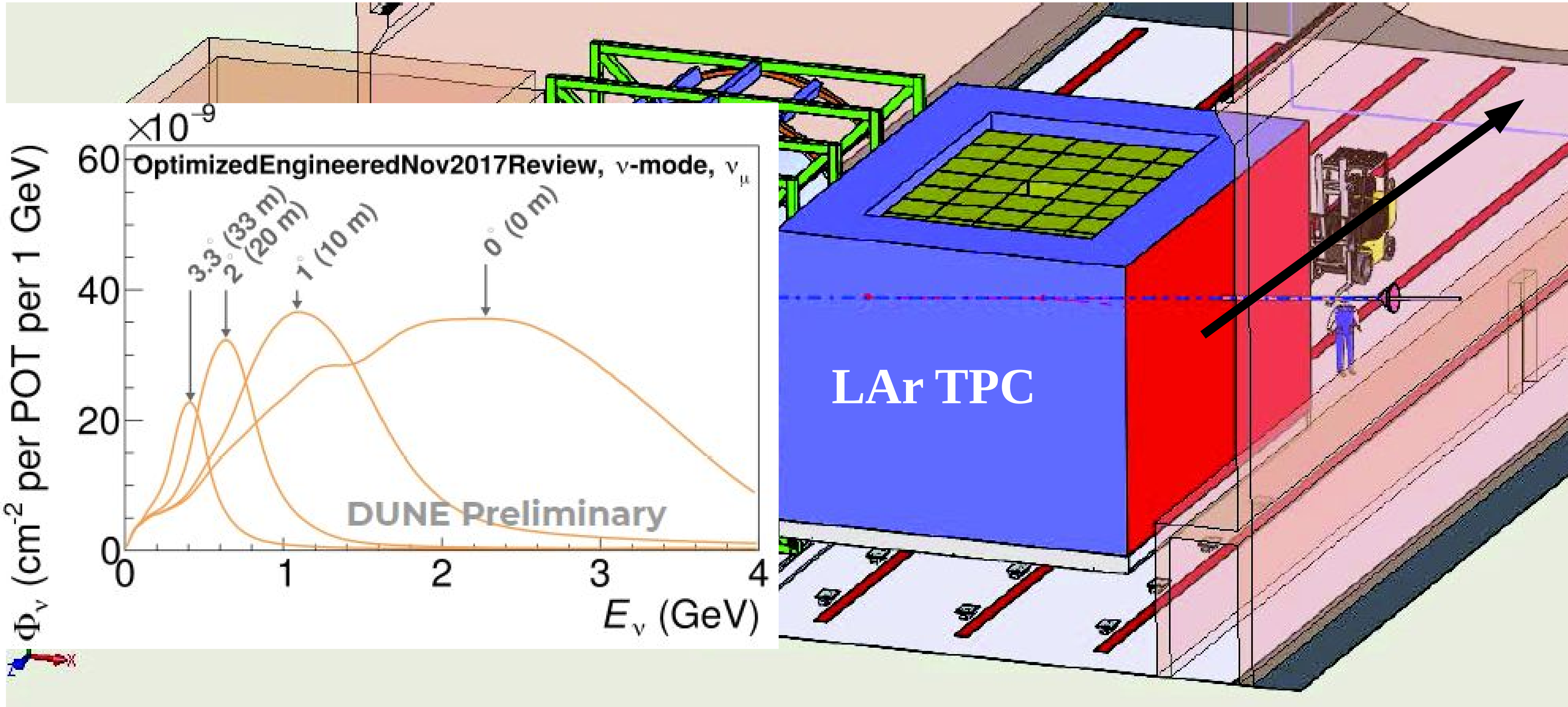
- 2 cathode planes → 4 drift regions each ~3.6m
- 500 V/cm field = 180 kV potential
- Photon detectors integrated into the anode planes to detect scintillation light

Near detector system at Fermilab



- Reduce systematic uncertainties in oscillation analysis by measuring the neutrino flux and neutrino-argon interactions with high precision
- Monitor the neutrino beam rate and spectrum

Near detector system at Fermilab



- Flux changes as you move off-axis → probe energy dependence of neutrino interactions, relationship between E_ν and detector observables

Primary DUNE physics motivation: Neutrino oscillations

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"

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

Neutrino oscillation measurements & unknowns

Neutrino oscillation unknowns:

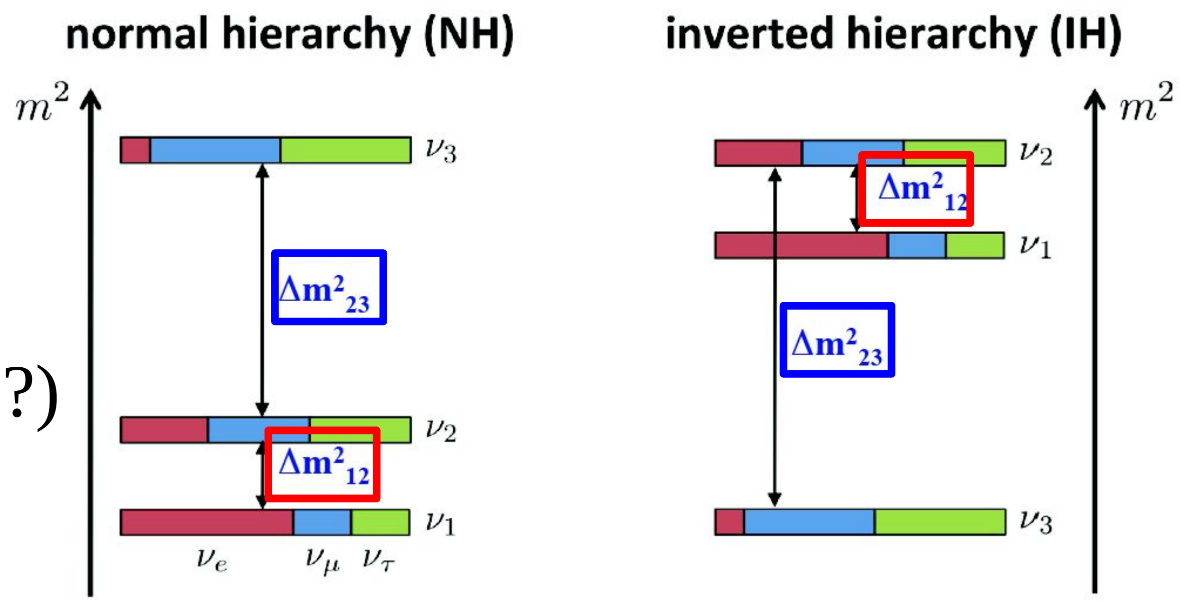
- CP violating phase δ_{CP}
- Mass ordering
- Octant of θ_{23} ($\sin^2\theta_{23} < 0.5$?)

Measured by:

Solar/reactor

Atmospheric/accelerator

Reactor/accelerator



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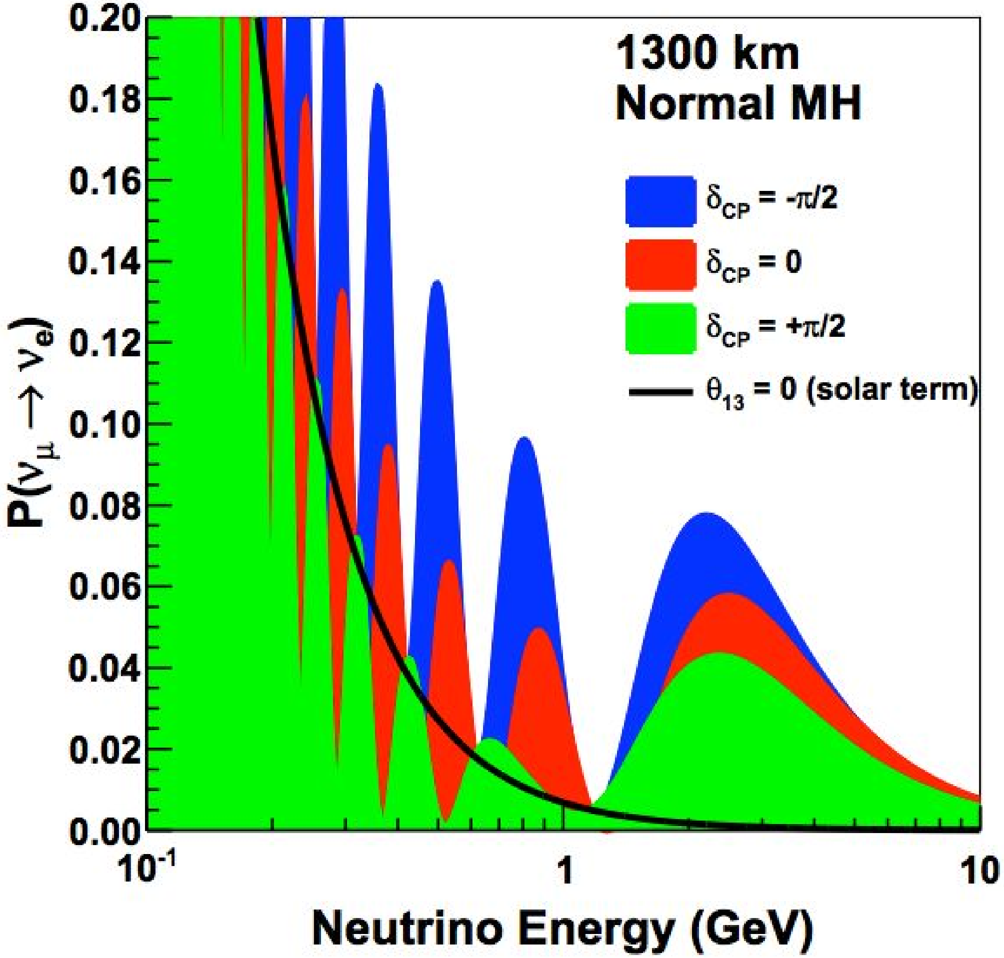
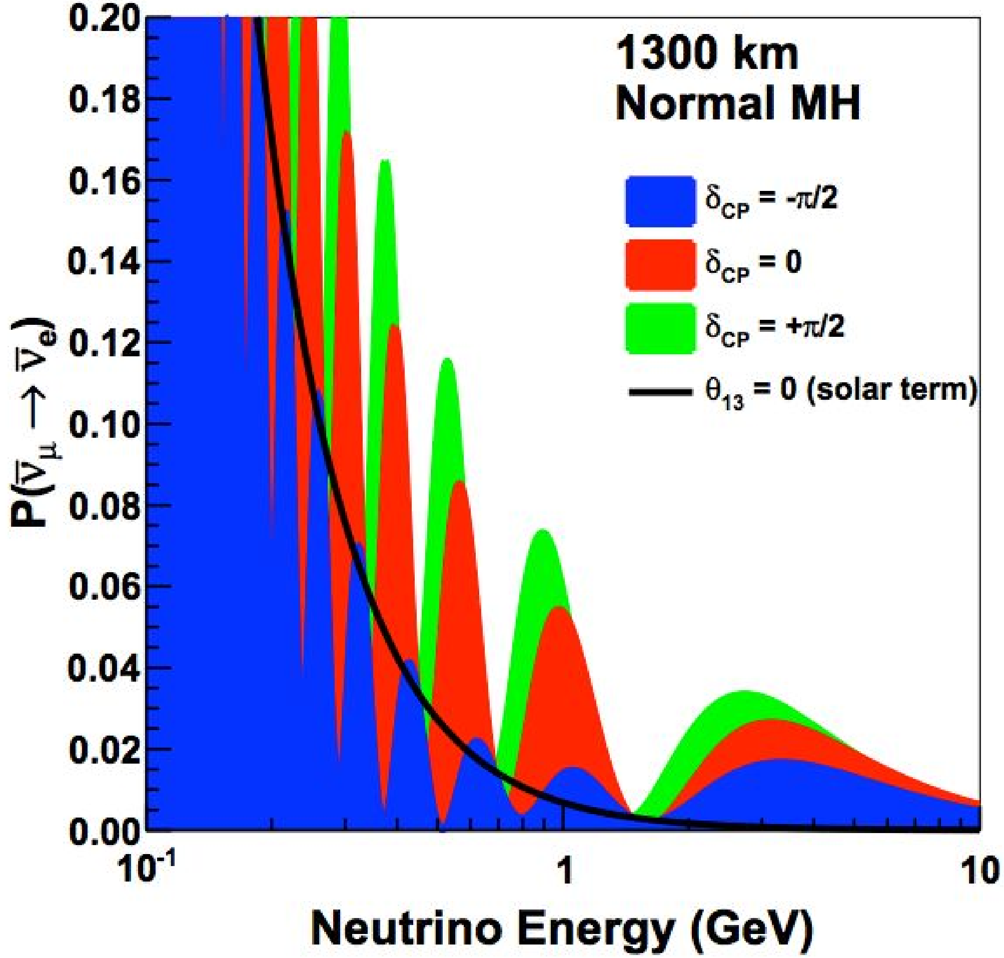
Non-zero δ_{CP} changes oscillation probabilities for ν and $\bar{\nu}$

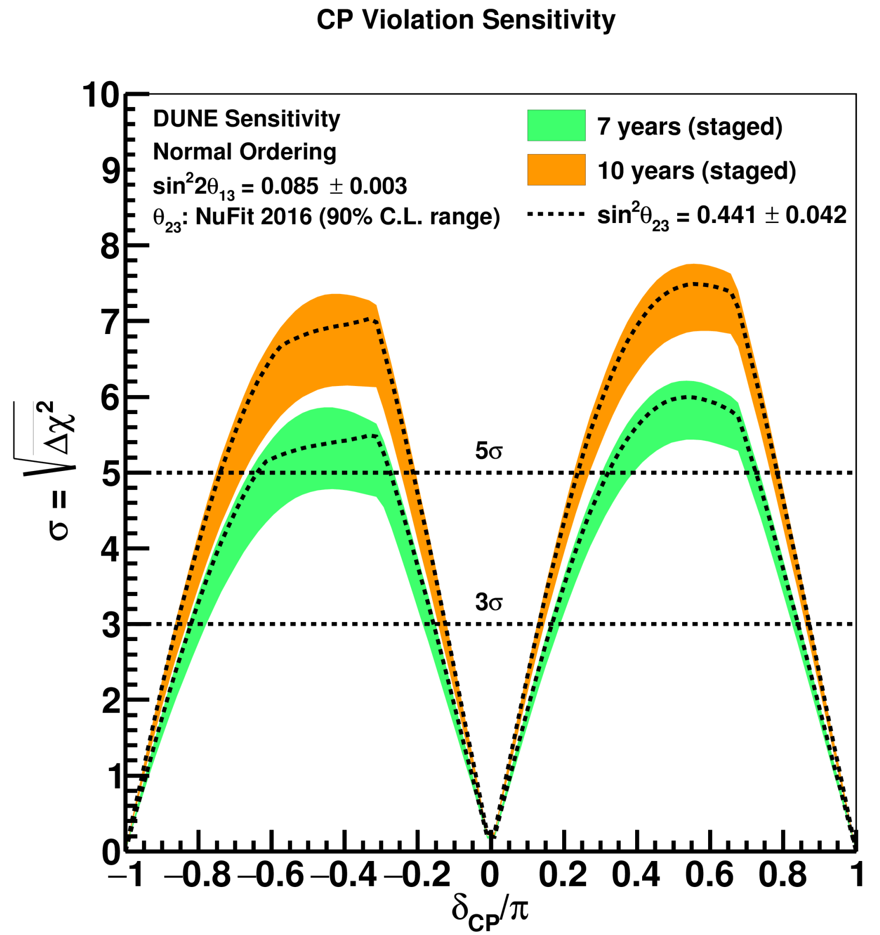
Neutrino

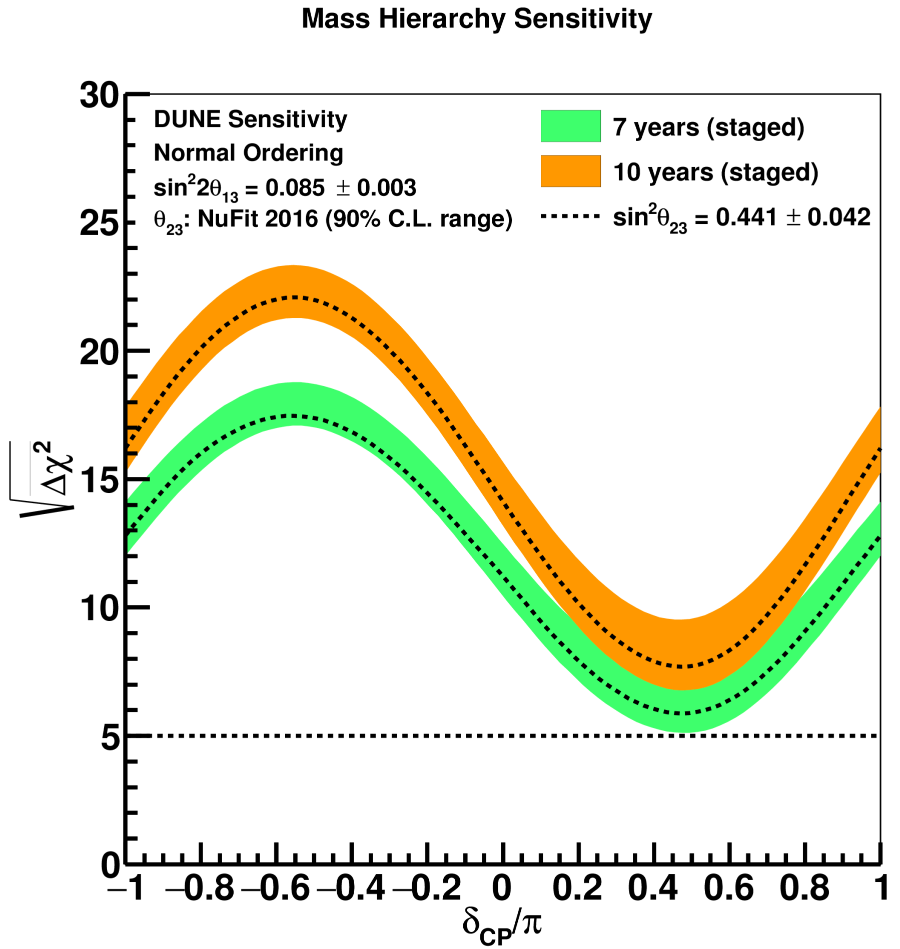


Antineutrino



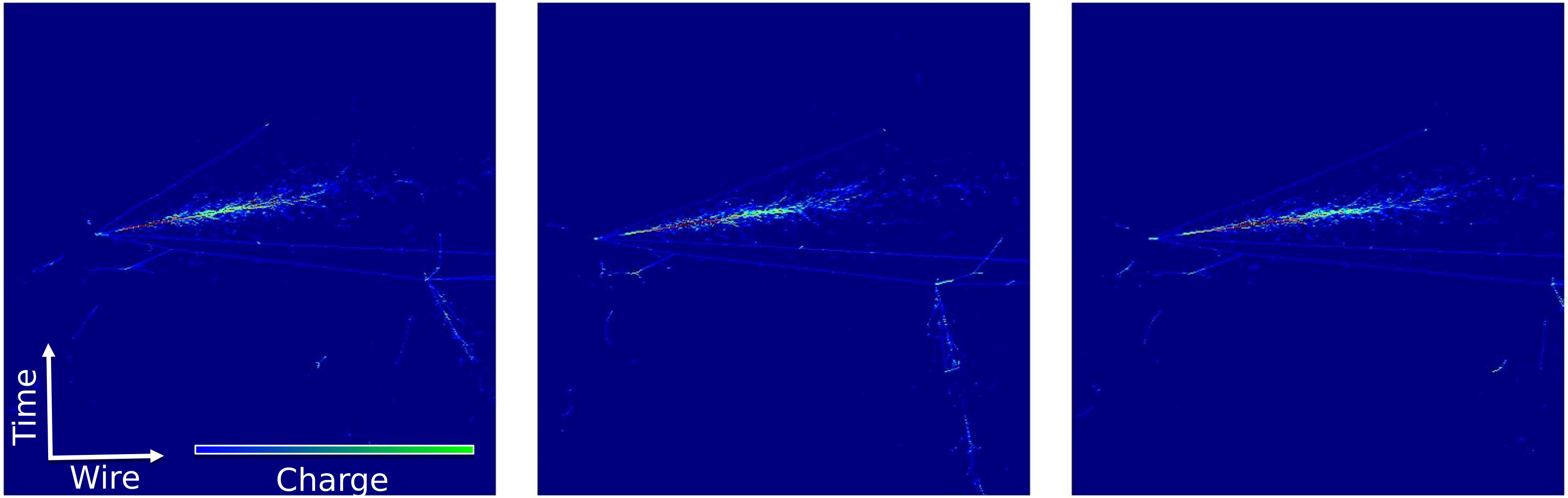
CPV and MH sensitivity





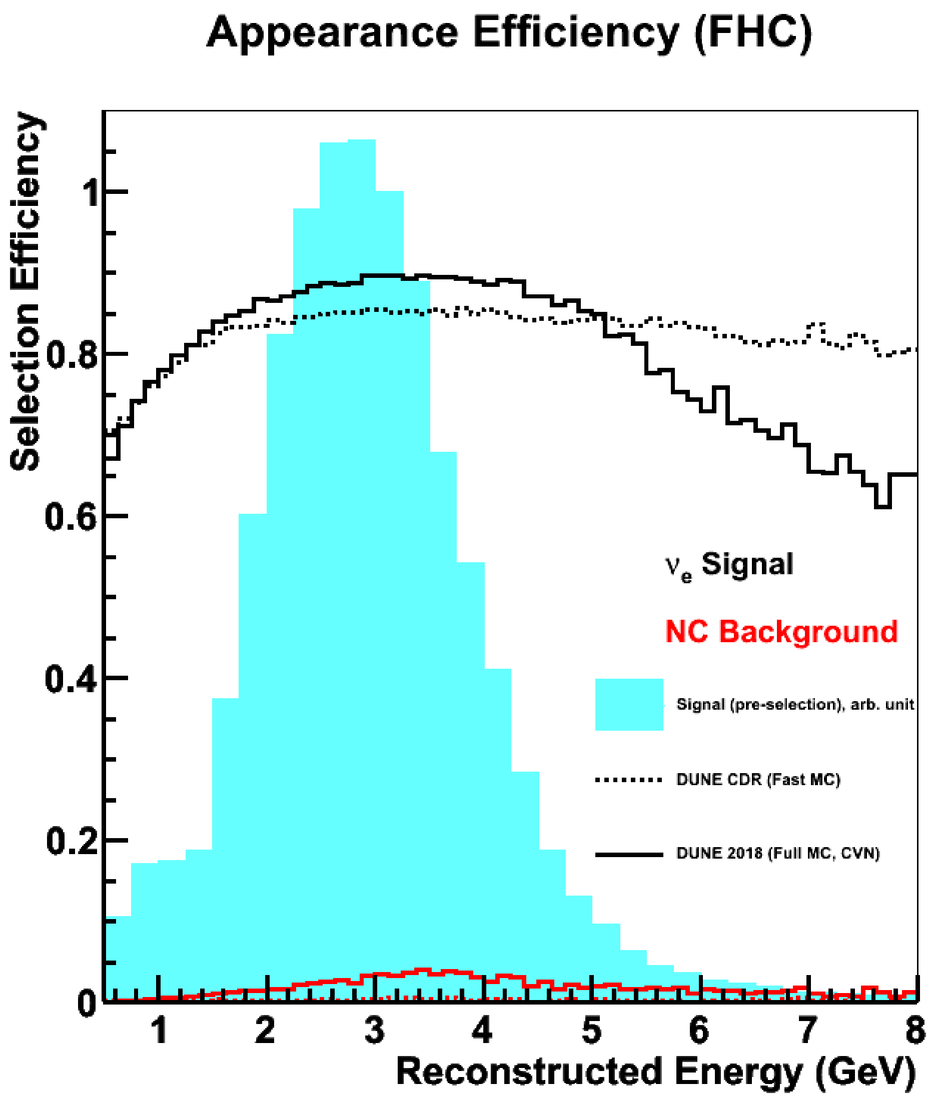
- Updated analysis with full FD simulation & reconstruction, detailed systematic uncertainties, including ND samples in progress, will be included in TDR (July 2019)

Far detector simulation, reconstruction, CVN event selection



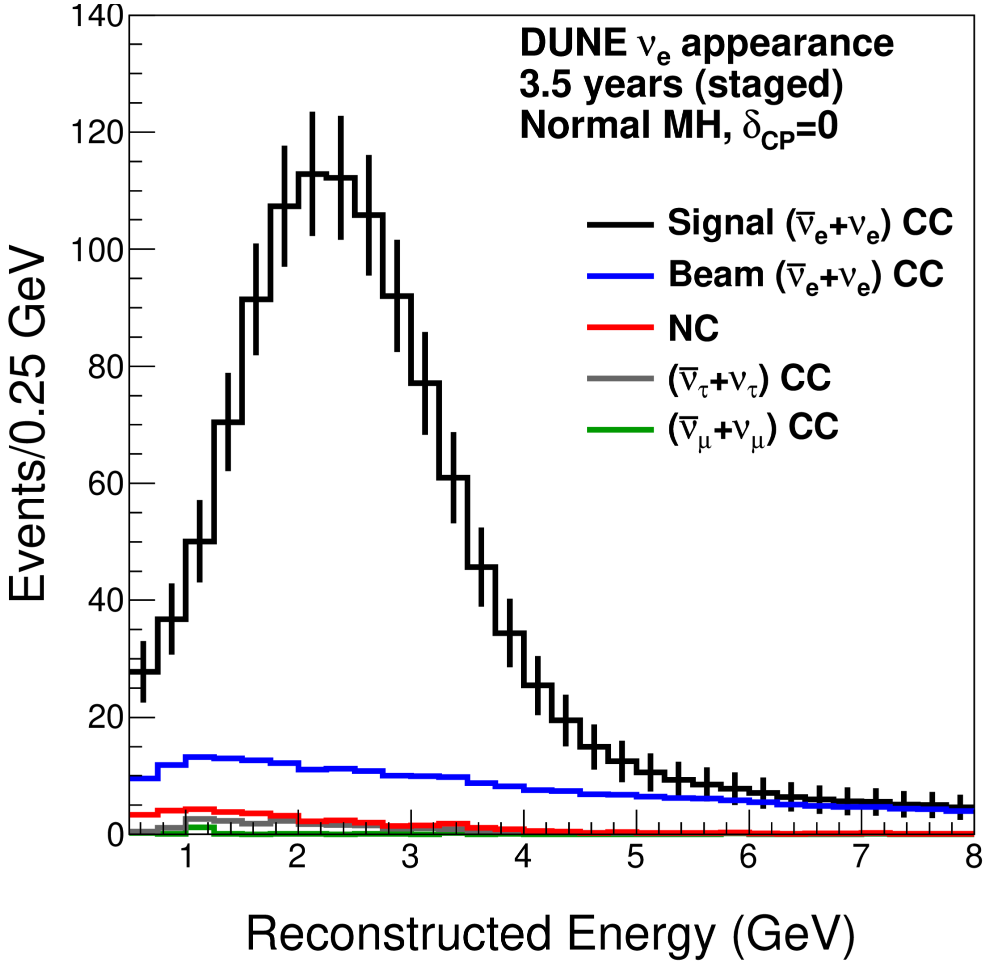
- CVN algorithm trained on event images (simulated ν_e CC shown)
- Three wire readout planes in far detector → three 2-dimensional "images" of each interaction
- Classifier output is ν_e CC and ν_μ CC probabilities

ν_e selection efficiency



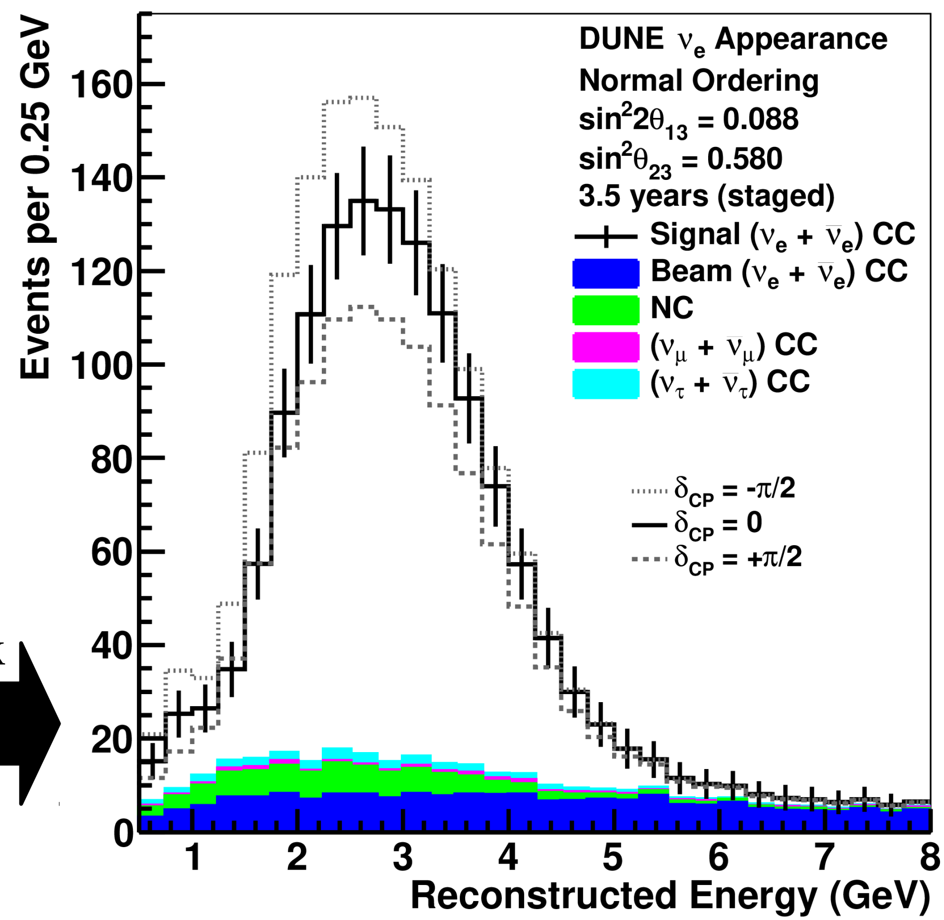
- Selection of oscillated ν_e CC events with full simulation and reconstruction achieves similar performance to what was assumed in CDR
- ~90% efficiency in flux peak
- Work is ongoing to ensure robustness to modeling uncertainties

ν_e appearance sample with updated analysis



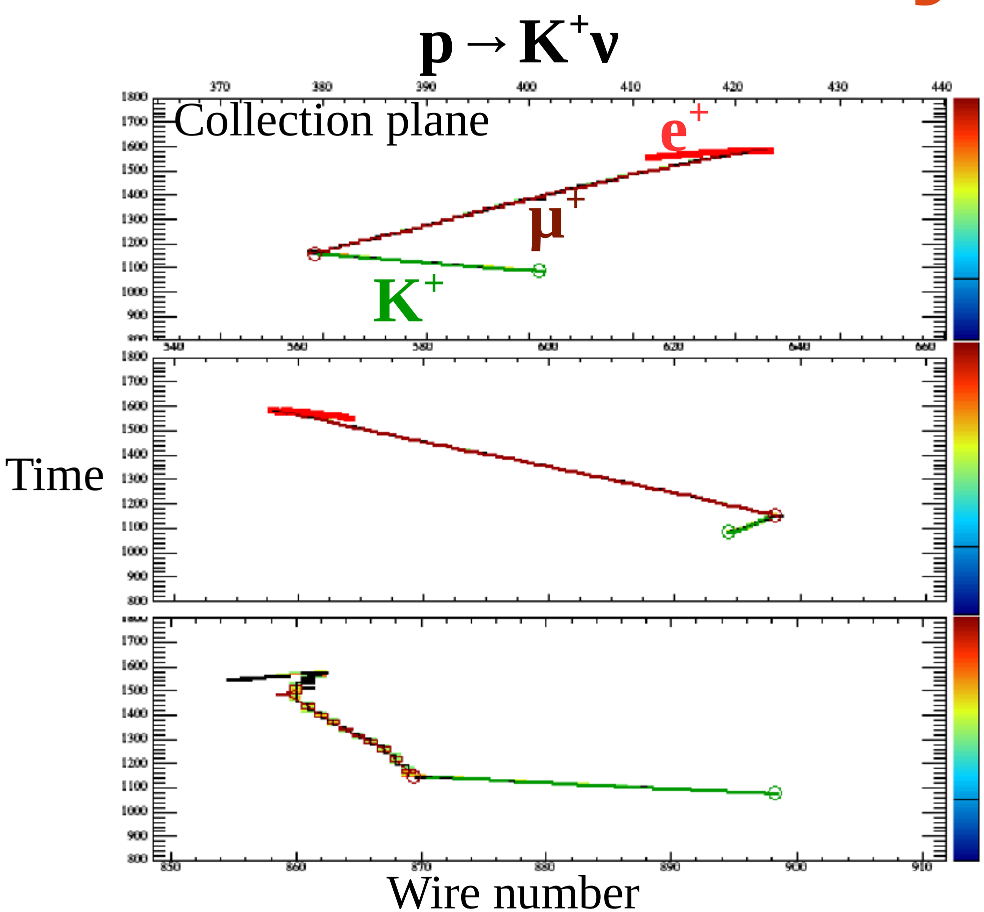
2017 analysis (Fast MC)

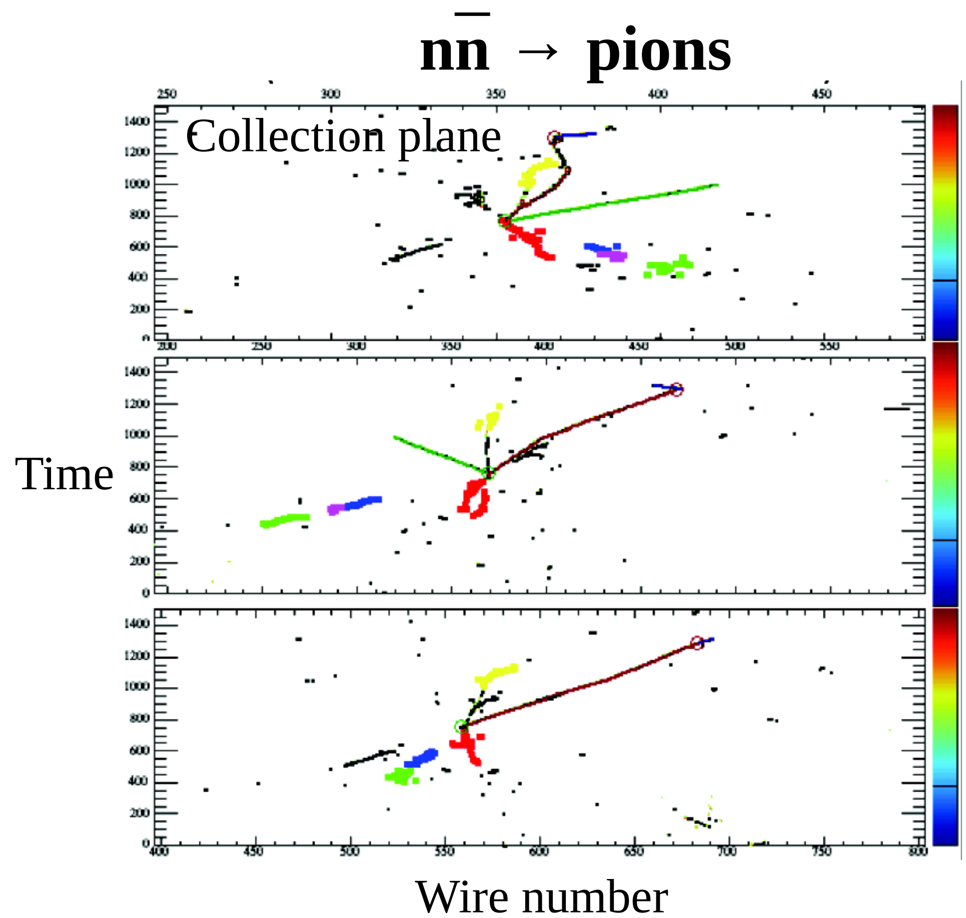
tons of work



2019 TDR sneak preview
(Full sim+Reco+selection)

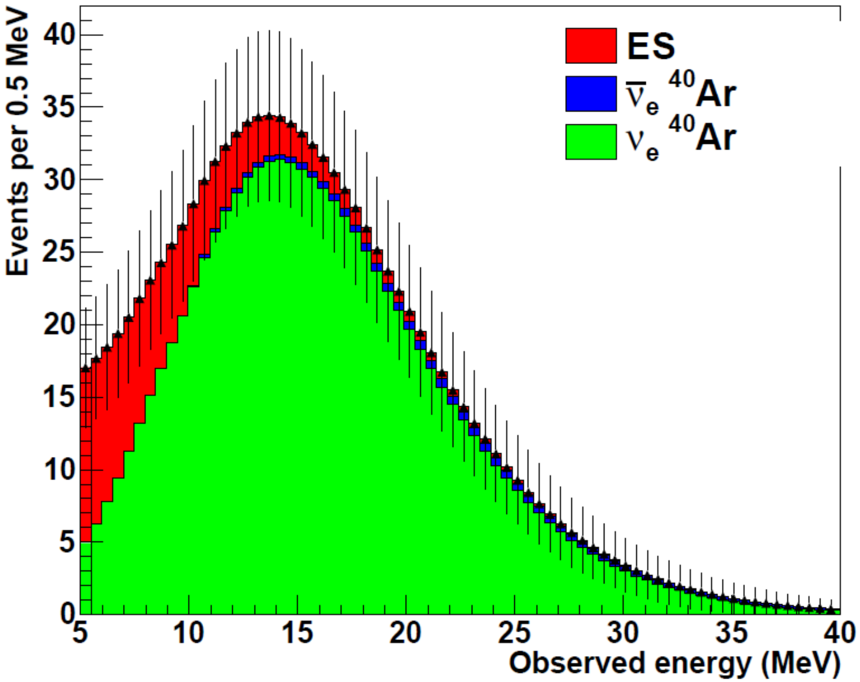
Nucleon decay & $n\bar{n}$ oscillations



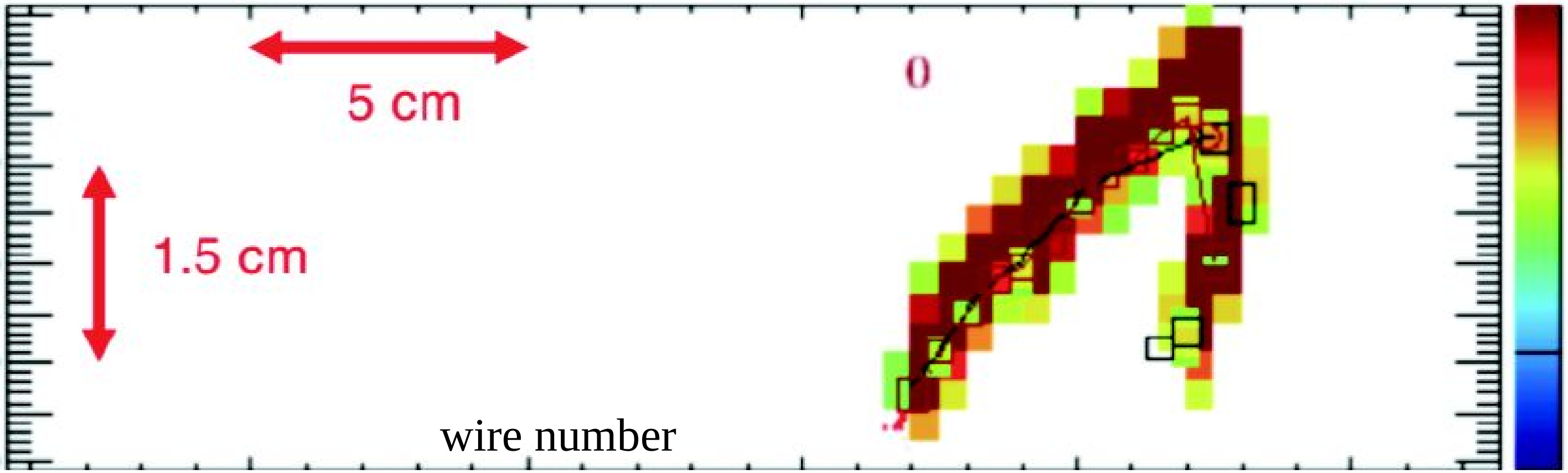


- Updated analyses with full simulation & reconstruction will be presented in upcoming TDR

Supernova burst neutrinos

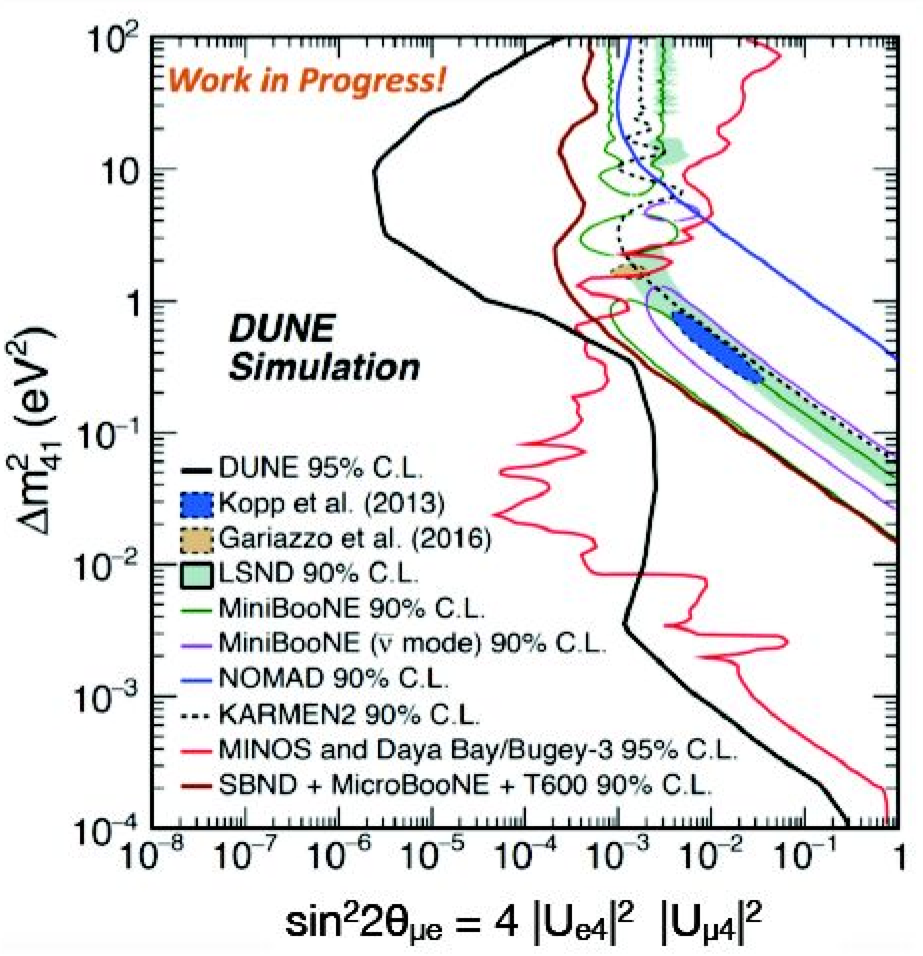


- DUNE will see 100s to 1000s of neutrinos from a supernova burst
- Primary channel in LAr is $\nu_e\,^{40}Ar \rightarrow e^-\,^{40}K^*$



BSM searches

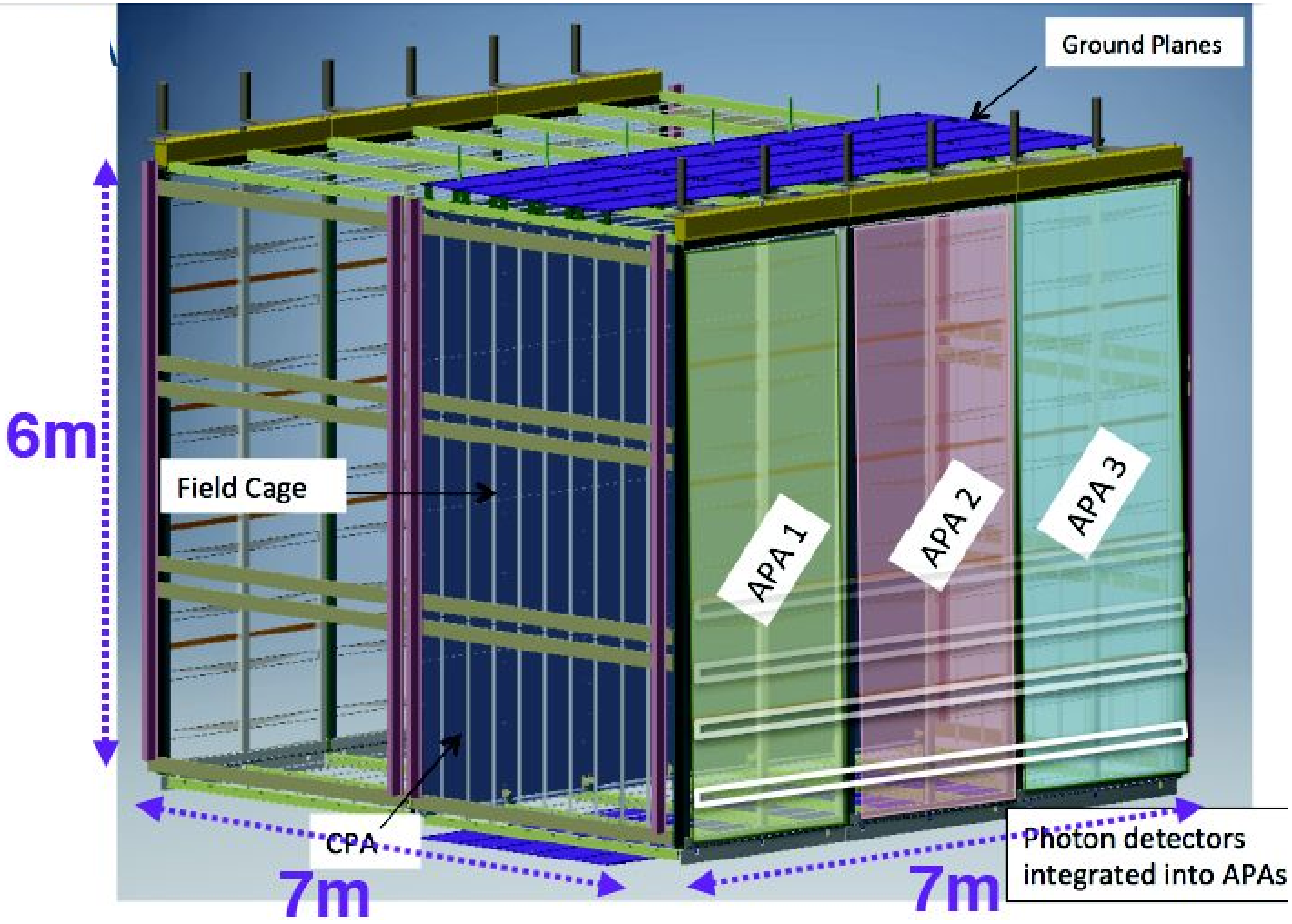
- Sterile neutrinos
- Light dark matter
- Boosted dark matter
- Non-standard interactions
- Neutrino tridents
- Large extra dimensions
- Likely much more!



ProtoDUNE: prototyping the DUNE far detector design

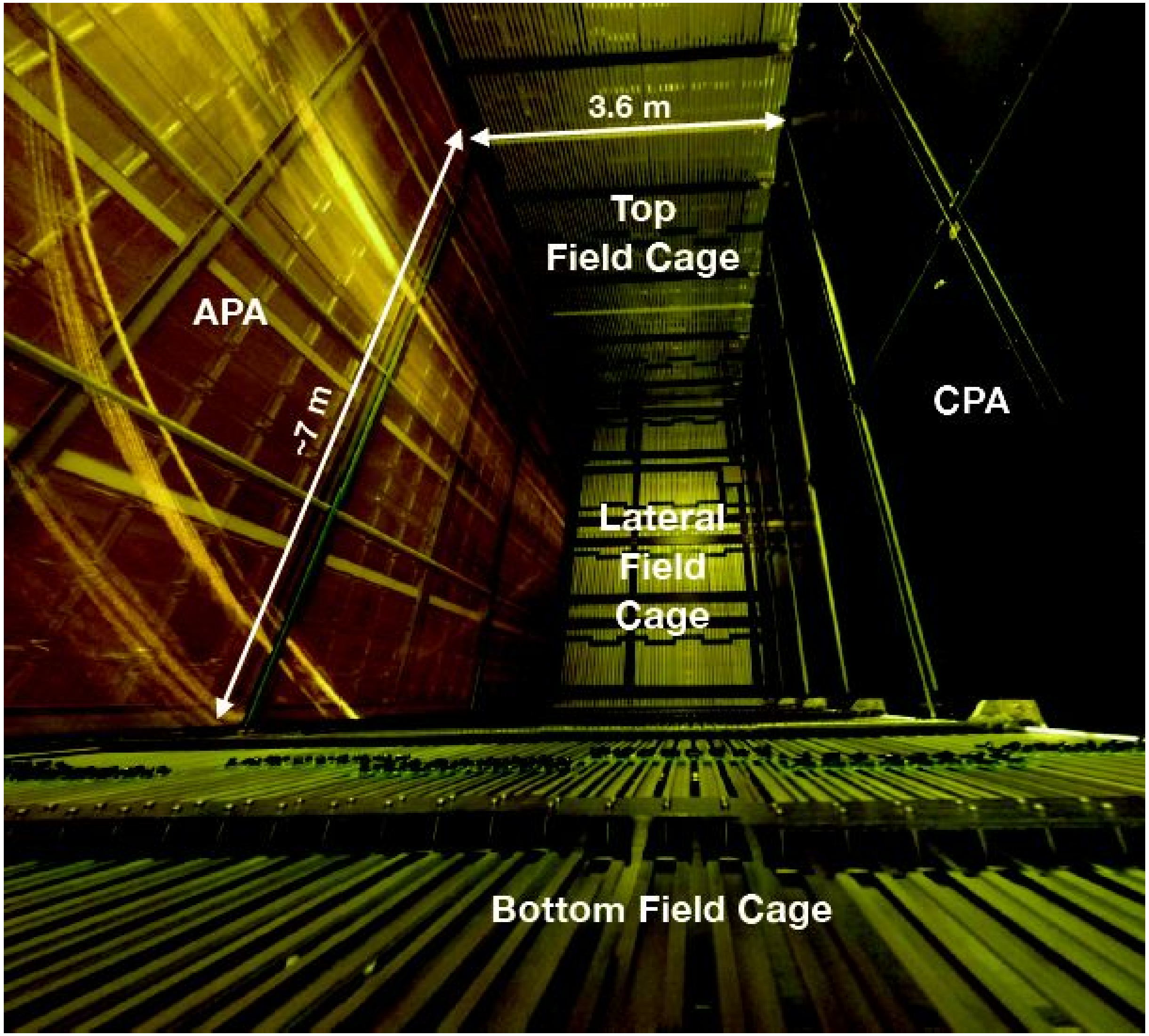
- Two prototype detectors located at CERN neutrino platform
- Single phase and dual phase
- Test detector engineering, and also hadron beam physics program

ProtoDUNE-SP



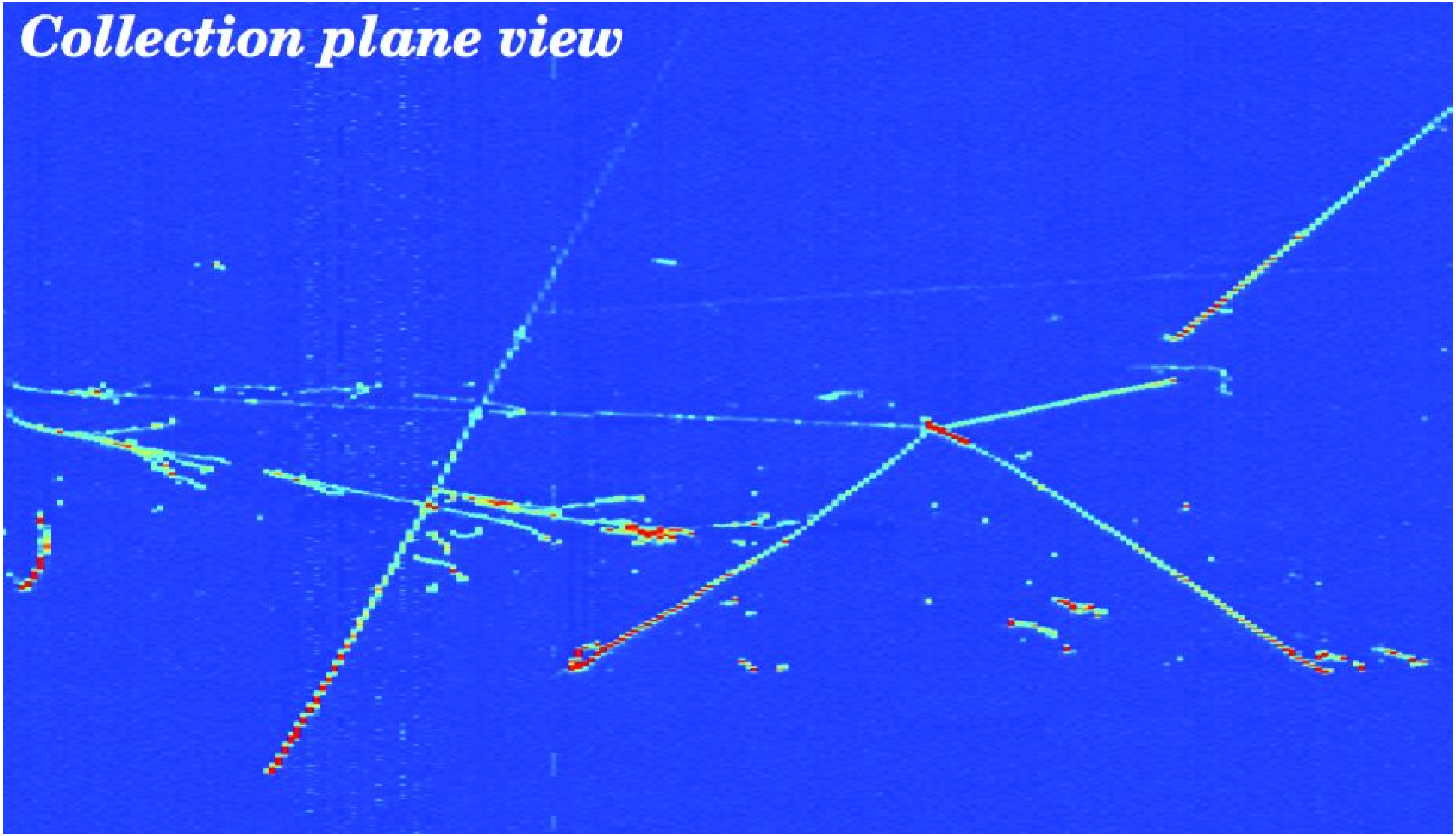
- Full scale prototype – same voltage, drift distance as DUNE SP
- Test of design, installation, operation, stability
- Measure hadron response in LAr

ProtoDUNE-SP



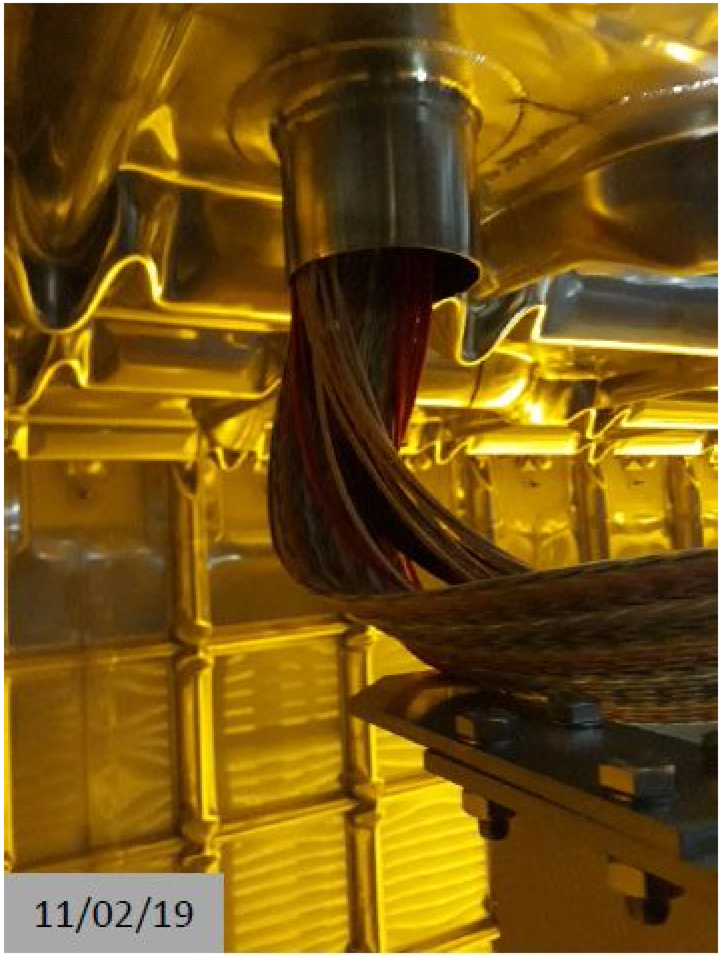
- Beam physics run Sep 21 – Nov 11
- Pions, protons, electrons, kaons from 0.3-7 GeV, total ~4M triggers
- Achieved stable running at 180kV, ~8ms electron lifetime, ~600 ENC noise → S/N ~ 38

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



Summary

- DUNE is designed for discovery sensitivity to CP-violation in neutrinos, and neutrino mass ordering
- Precise measurements of θ_{13}, θ_{23}, Δm^2_{32}
- Sensitivity to baryon number violation (nucleon decay, neutron-antineutron oscillations), supernova burst neutrinos
- Full scale prototype has been completed with successful ProtoDUNE-SP run last fall
- TDR is coming in late July

Thanks for listening!

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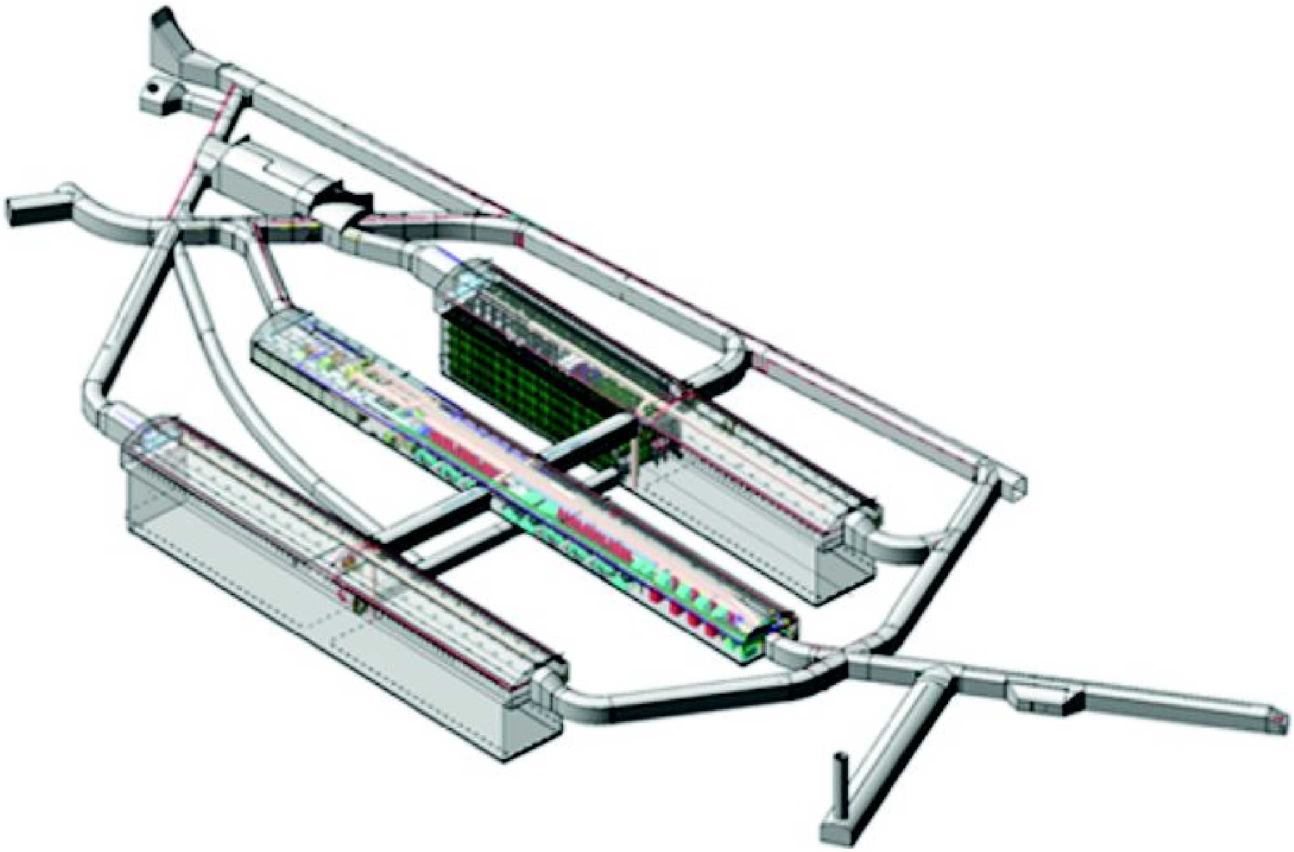
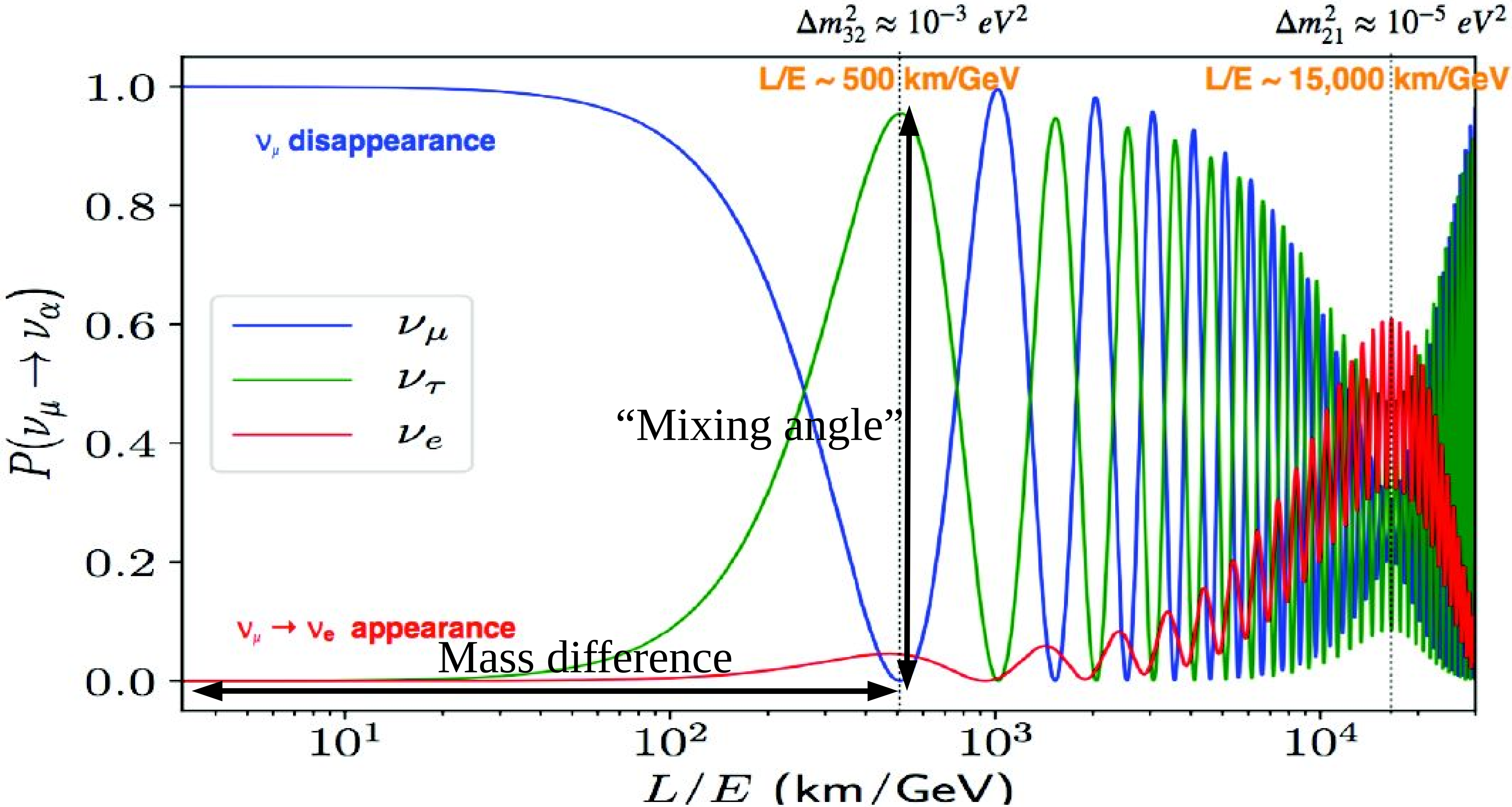
Backups

Staging plan

- Start of run: 2 FD modules (20 kt total fiducial mass), 1.2 MW beam power, with ND
- After one year: 3 FD modules (30 kt total fiducial)
- After three years: 4 FD modules (full 40 kt fiducial)
- After six years: upgrade to 2.4 MW beam



Neutrinos oscillate



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3-flavor oscillations in matter

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

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

- $\nu_\mu \to \nu_e$ oscillation probability depends on all three mixing angles, both mass differences, matter effects, and CP-violating phase!
- Must measure all other parameters to access δ_{CP}

Antineutrino oscillations in matter

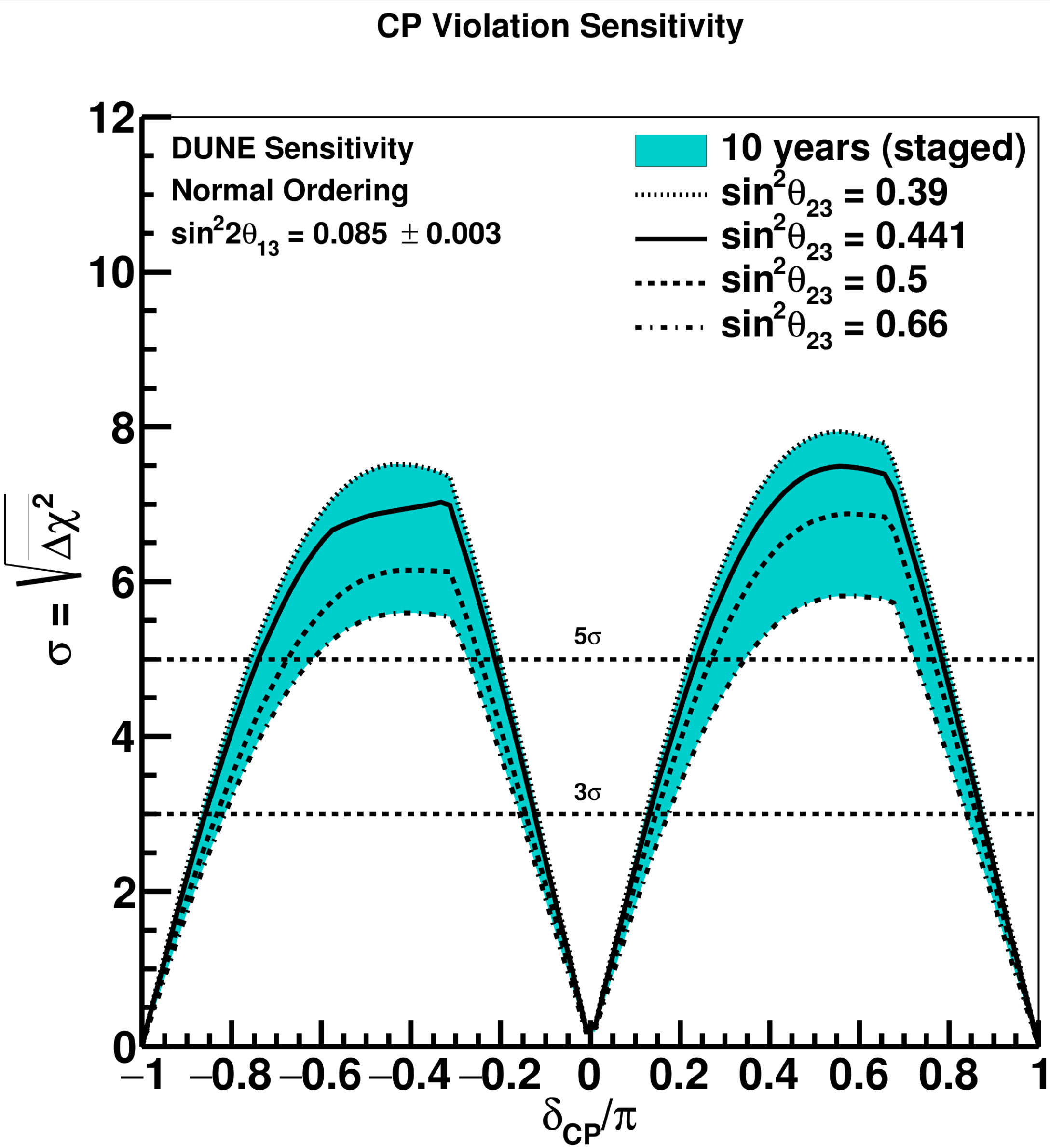
$$P(\overline{\nu}_\mu \to \overline{\nu}_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2$$
$$+\sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}-\delta_{CP})$$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

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

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

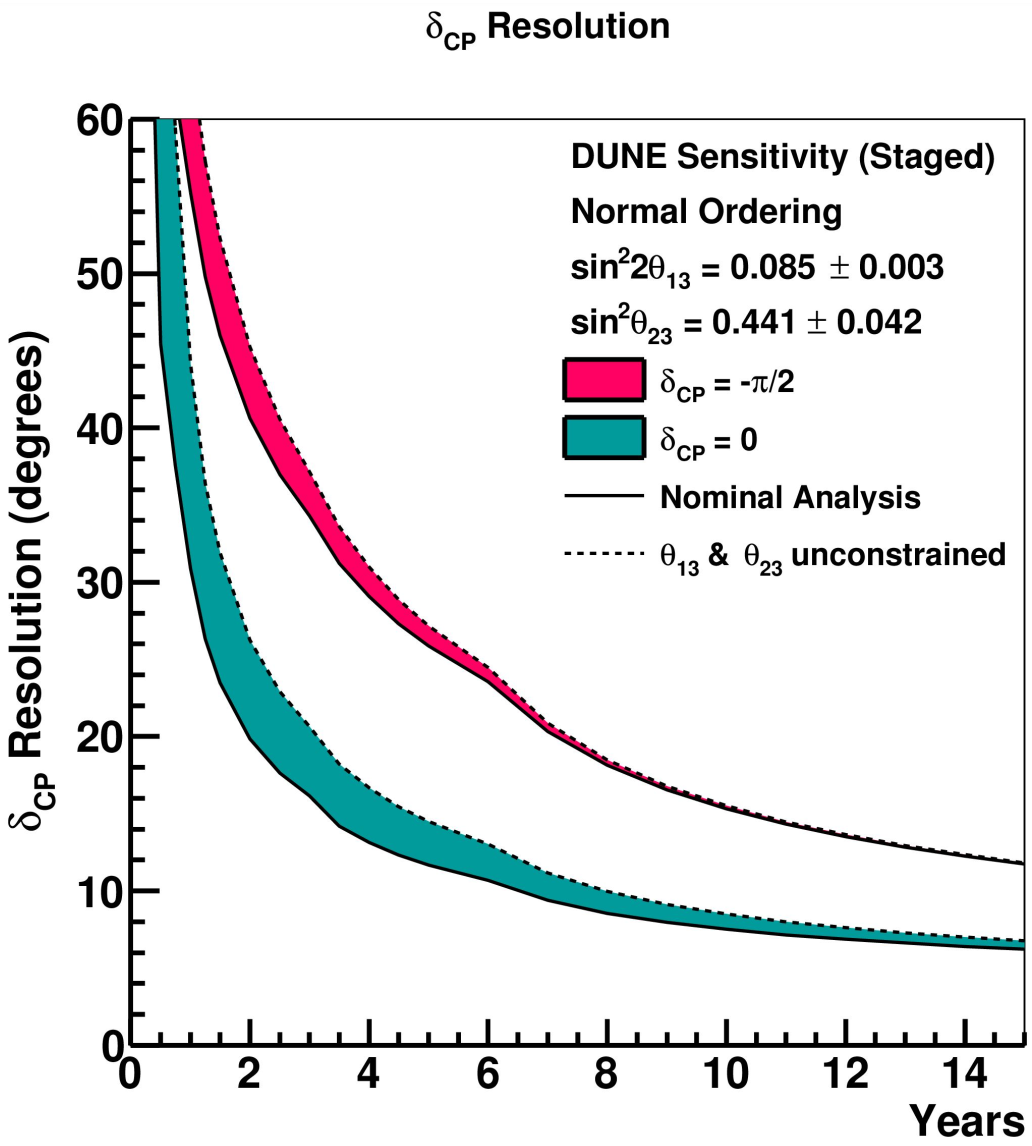
- For antineutrinos, matter effects and CP violating effect have opposite sign
- Causes $\nu_\mu \to \nu_e$ and $\overline{\nu}_\mu \to \overline{\nu}_e$ to be different!

CPV sensitivity vs θ_{23}



- θ_{23} (including octant) also affects the rate of ν_e at FD
- CP violation sensitivity is best if true value of θ_{23} is in lower octant

δ_{CP} resolution



- DUNE will do more than just measure if δ != 0 → precise measurement of δ
- Sensitivity is best when δ is near CP-conserving values 0,π
- Long term resolution is between 8-15 degrees depending on true value of δ chosen by nature

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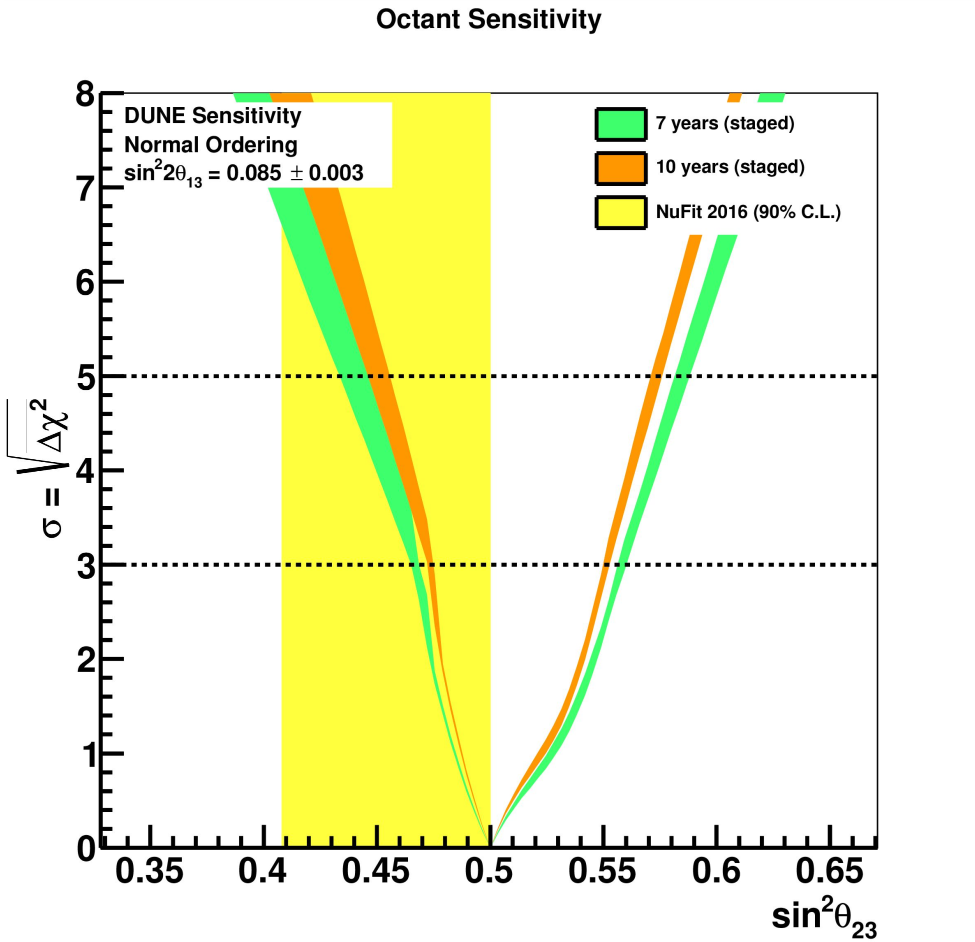
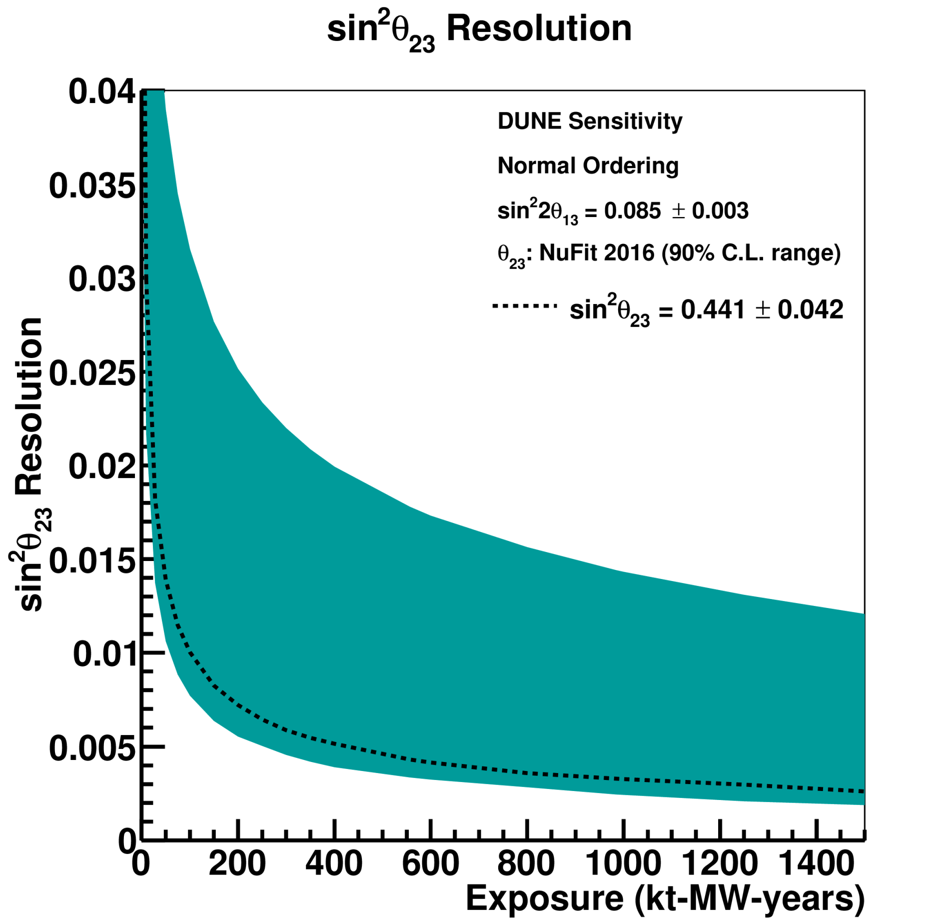
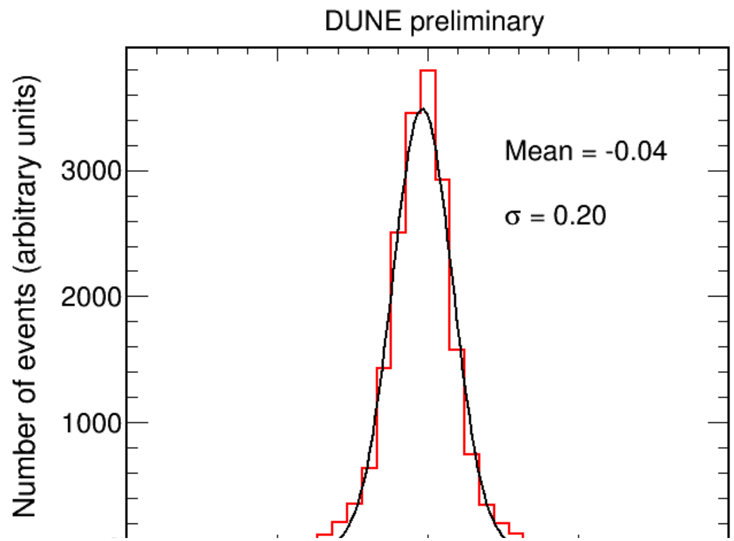
$\sin^2\theta_{23}$ and octant resolution (CDR)

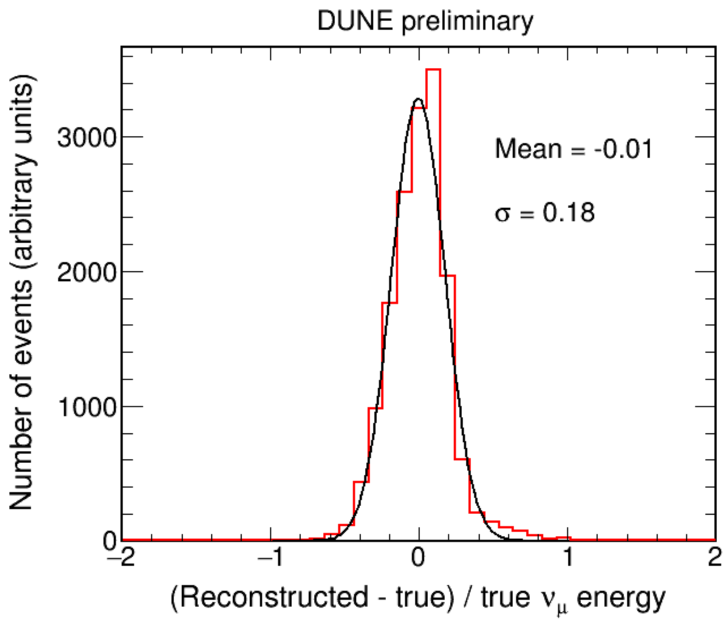


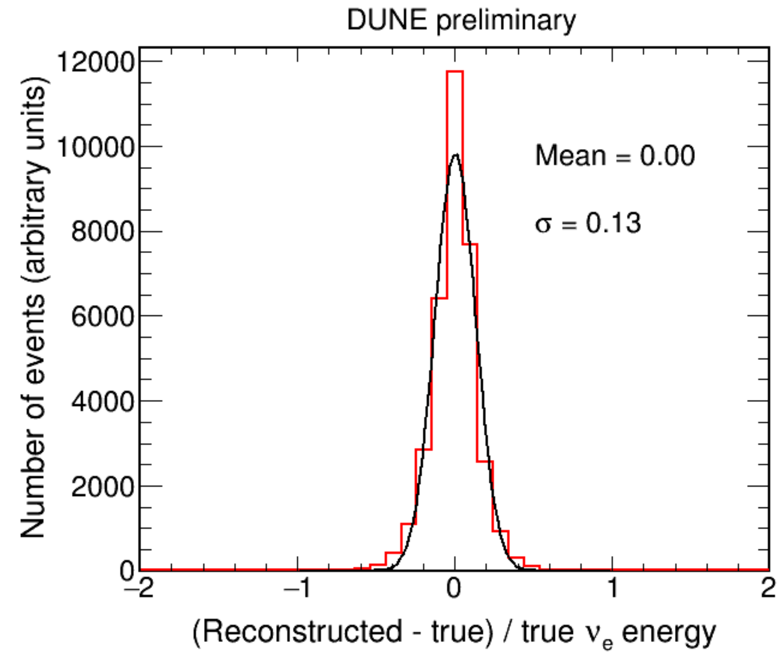


- Simulation and analysis update for TDR: full end-to-end simulation, reconstruction, event selection in FD
- Geant4 simulation of near detector, detailed systematic uncertainties

Neutrino energy resolution

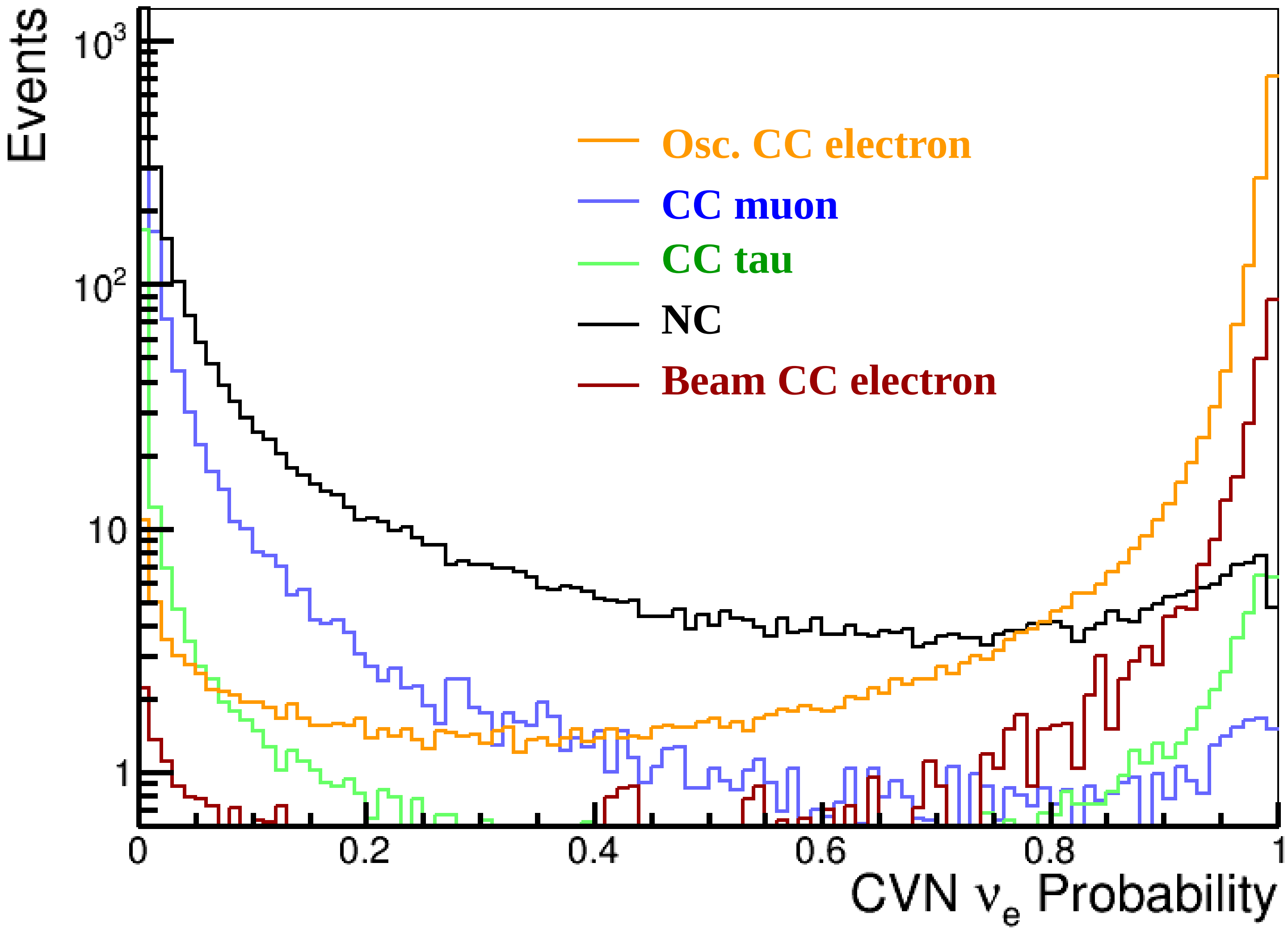






- Muons ~ 18% for contained tracks, 20% for exiting
- Electrons ~ 13%

ν_e charged-current selection



- Selects both oscillated and intrinsic ν_e
- Backgrounds include $\pi^0 \to \gamma\gamma$, $\tau \to e$

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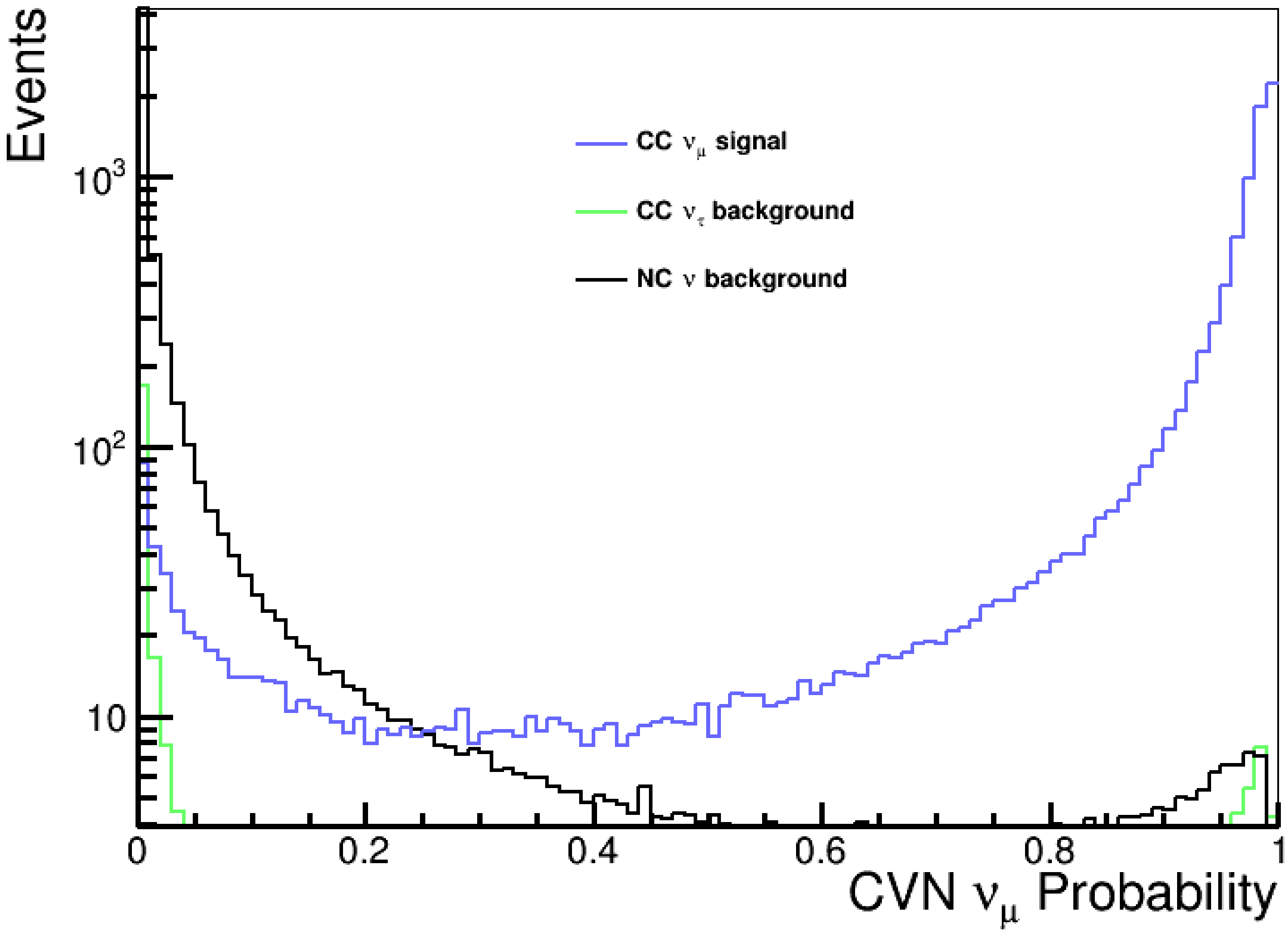
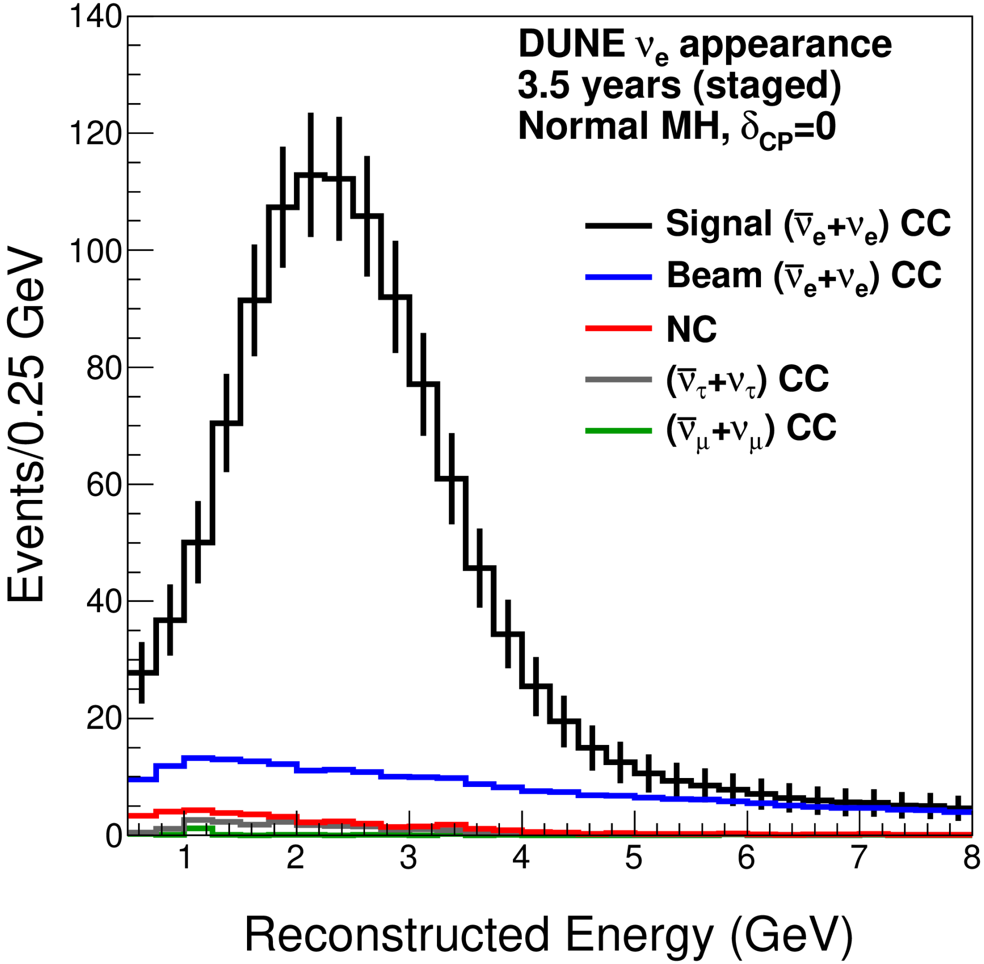
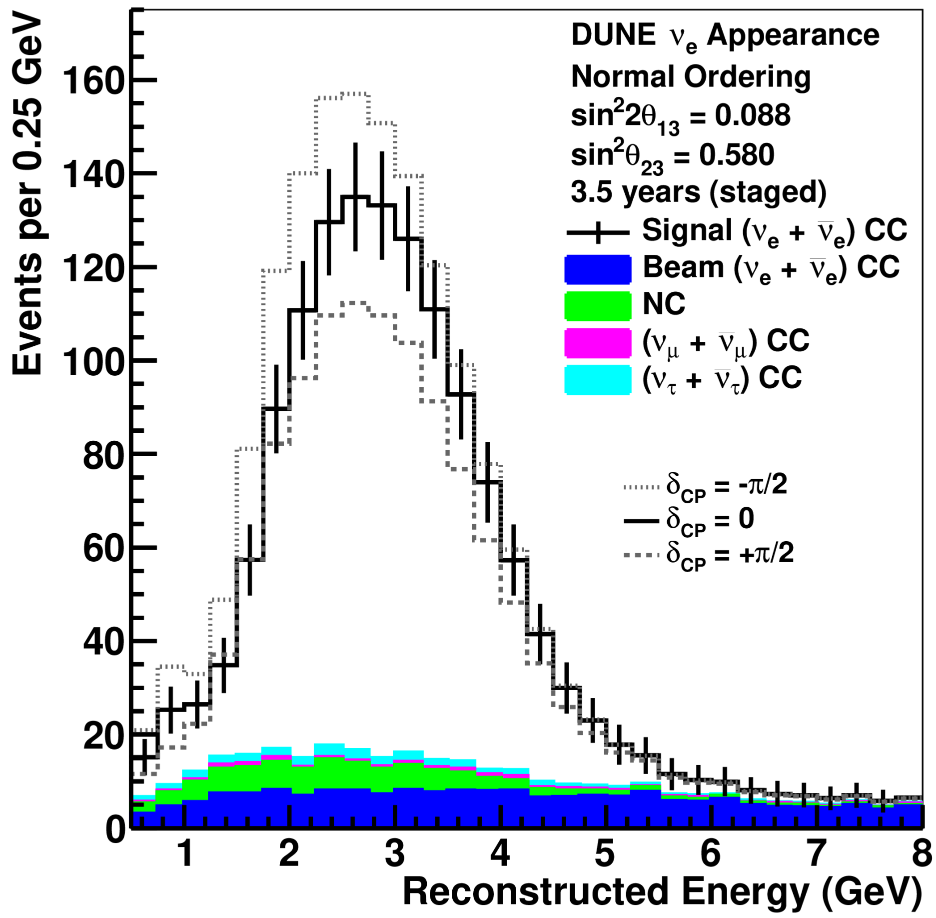
CVN output for ν_μ CC event selection



FD FHC $\nu_e+\bar{\nu}_e$

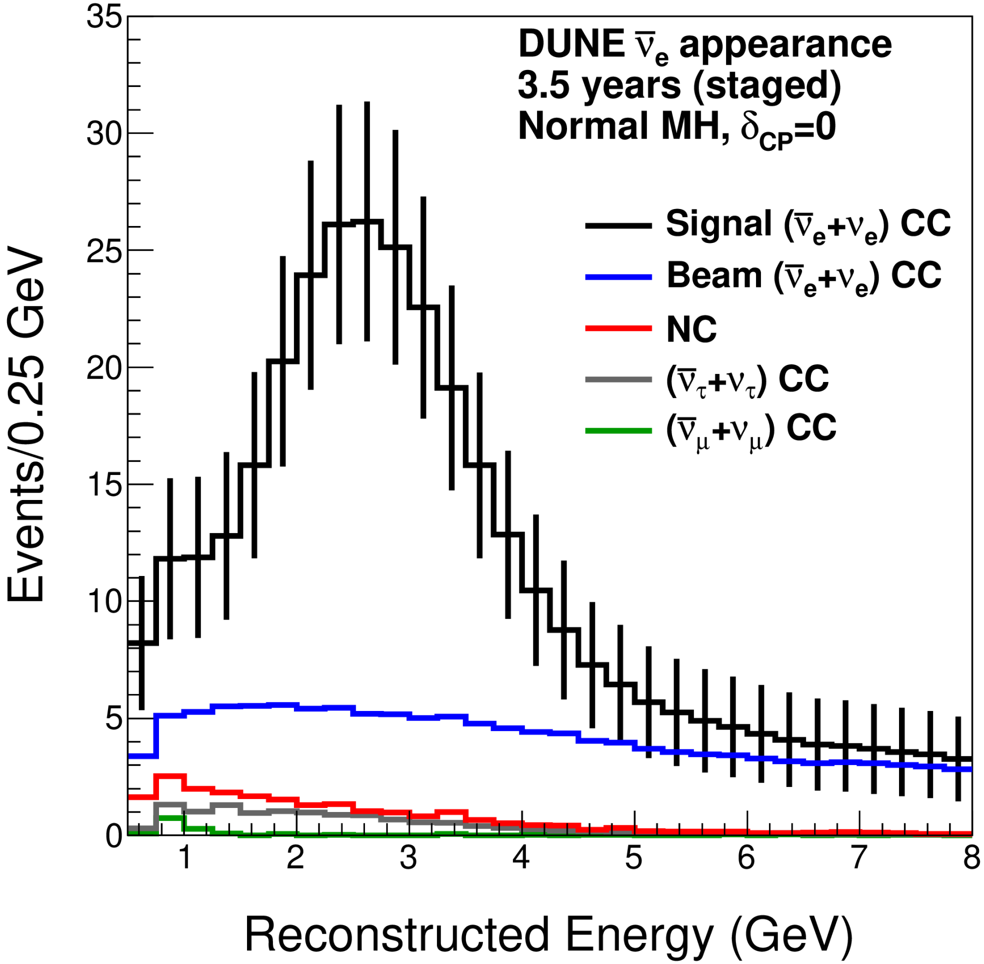


2017 CDR update

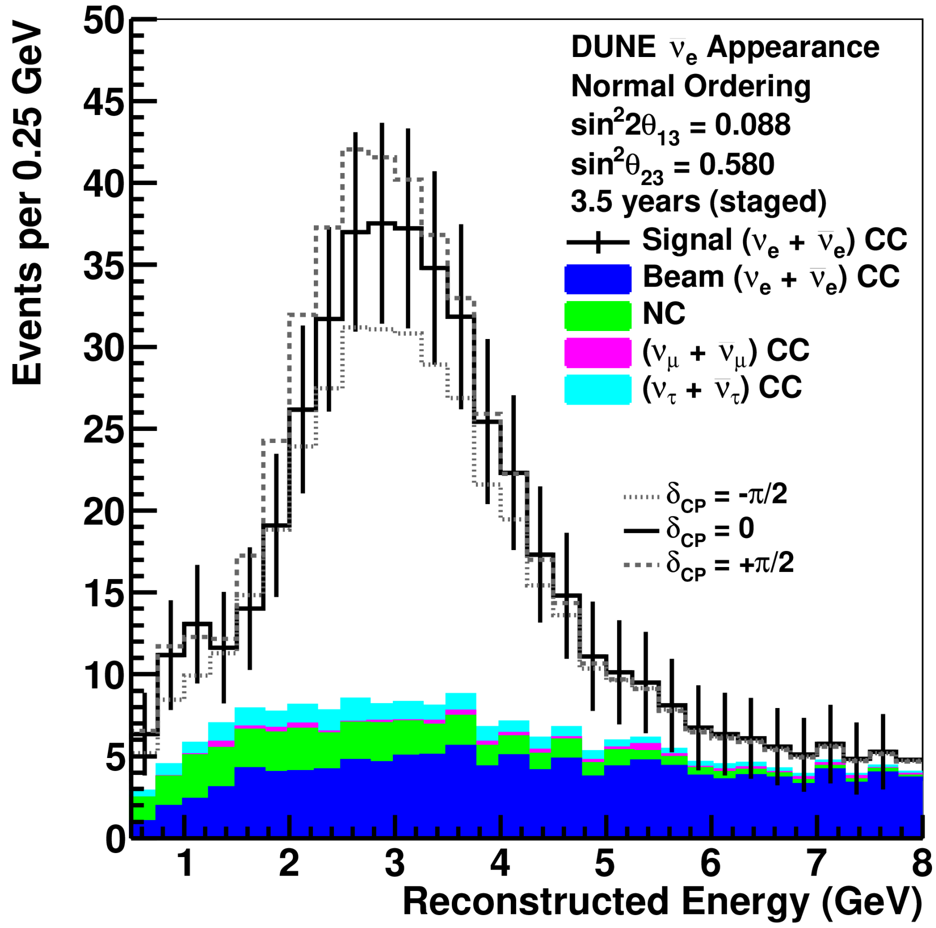


2019 TDR

FD RHC $\nu_e+\bar{\nu}_e$

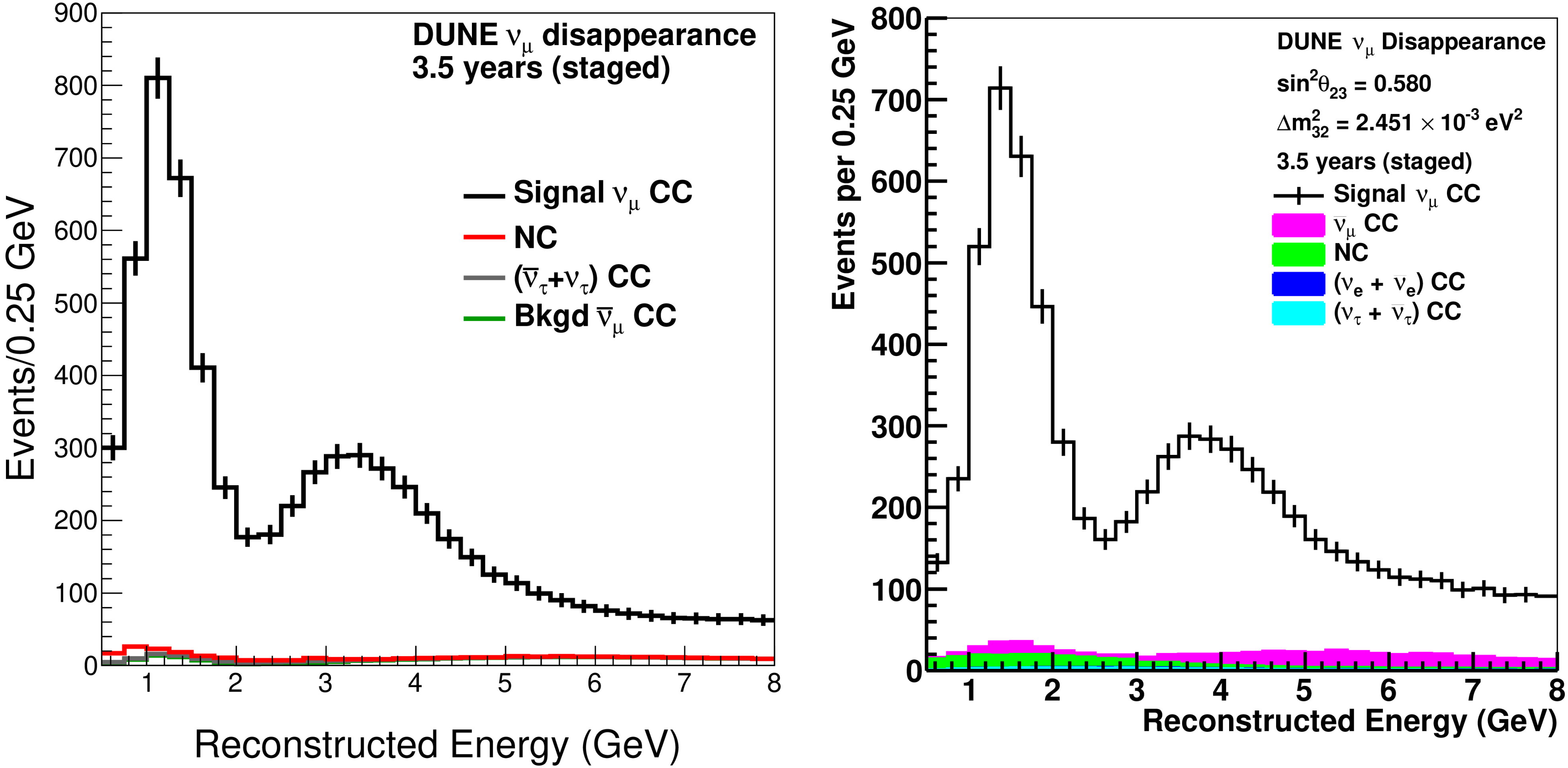


2017 CDR update



2019 TDR

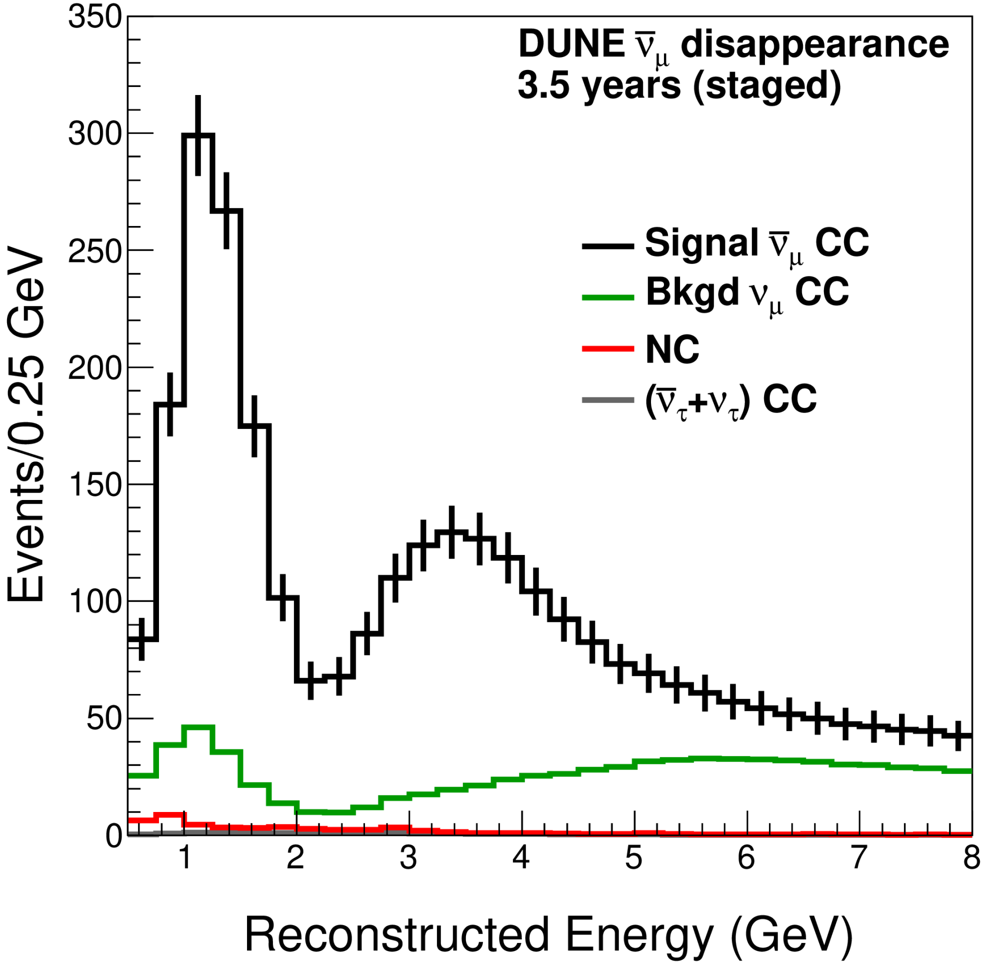
FD FHC $\nu_\mu+\bar{\nu}_\mu$



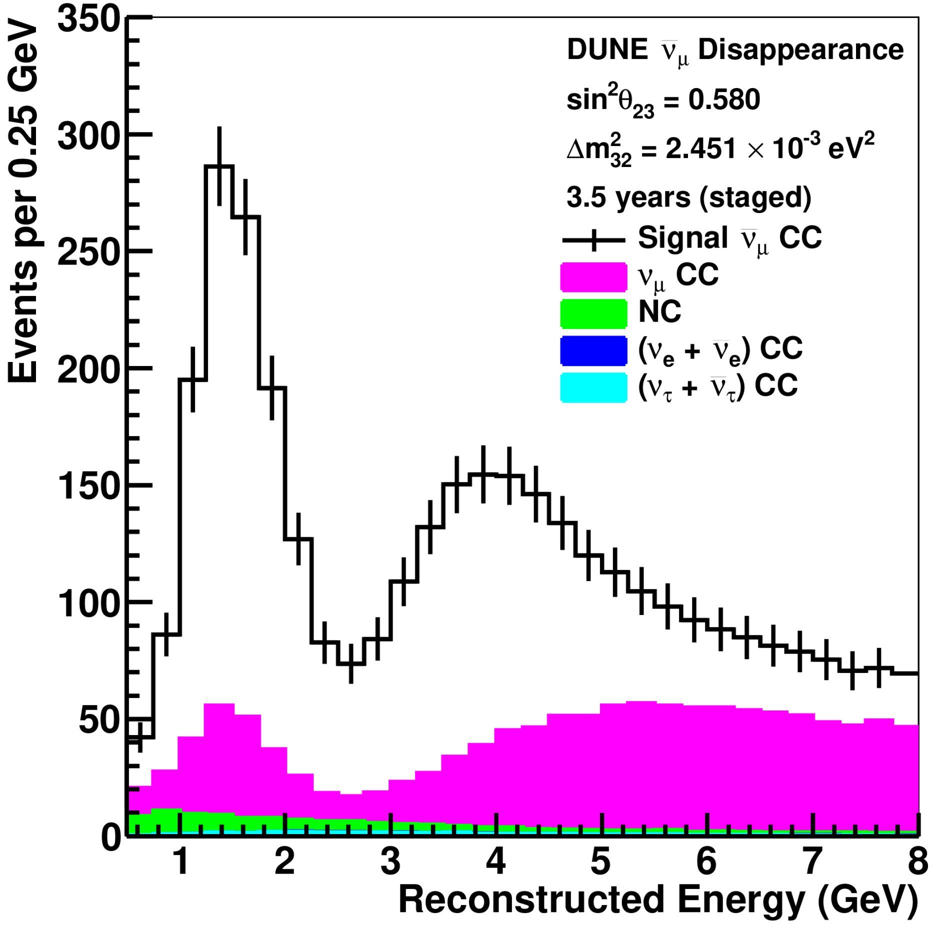
2017 CDR update

2019 TDR

FD RHC $\nu_\mu+\bar{\nu}_\mu$

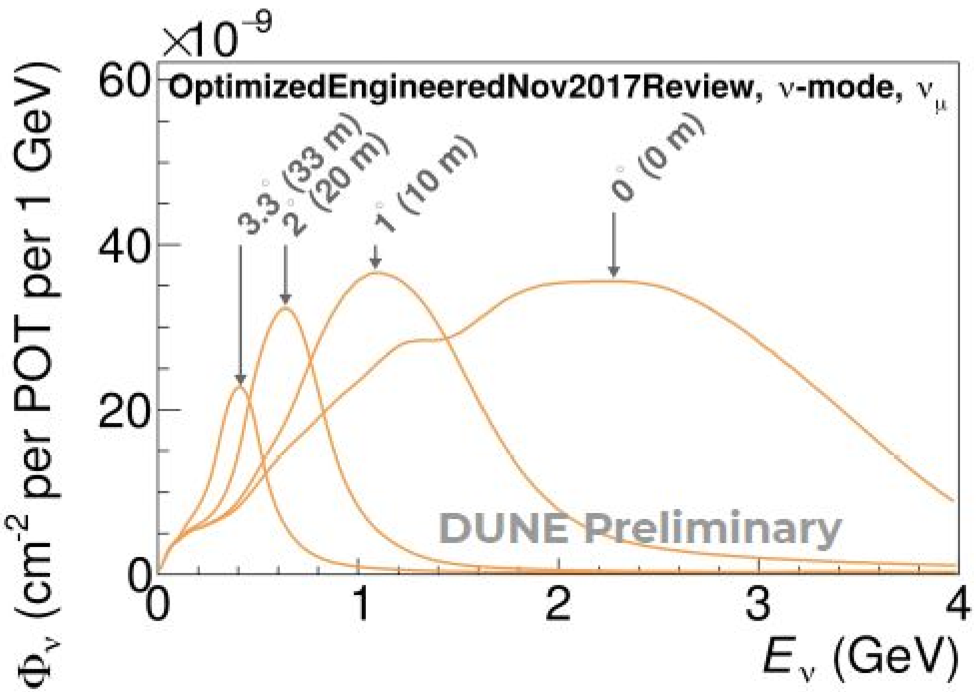


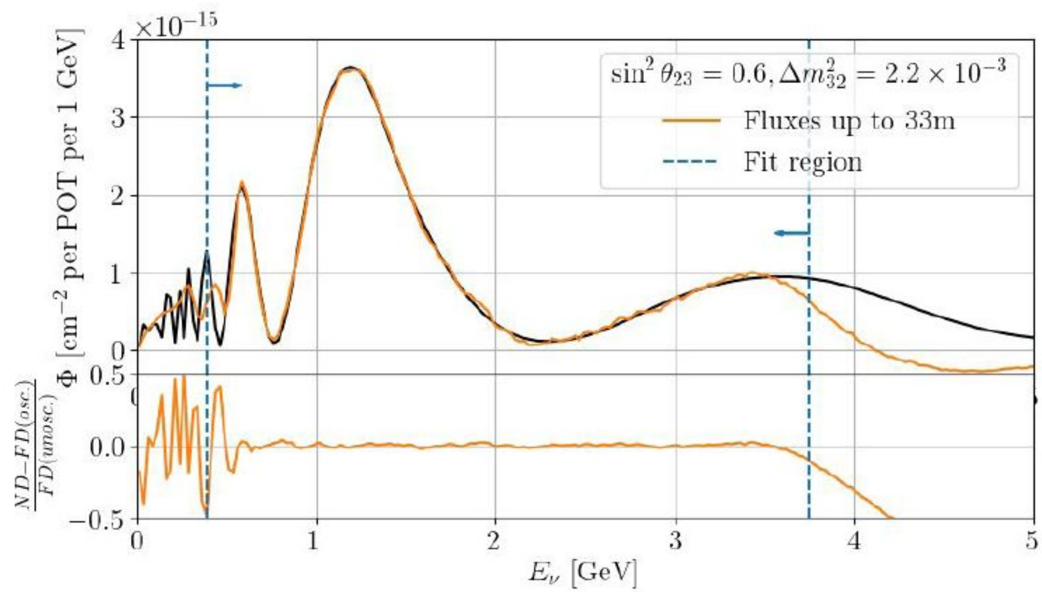
2017 CDR update

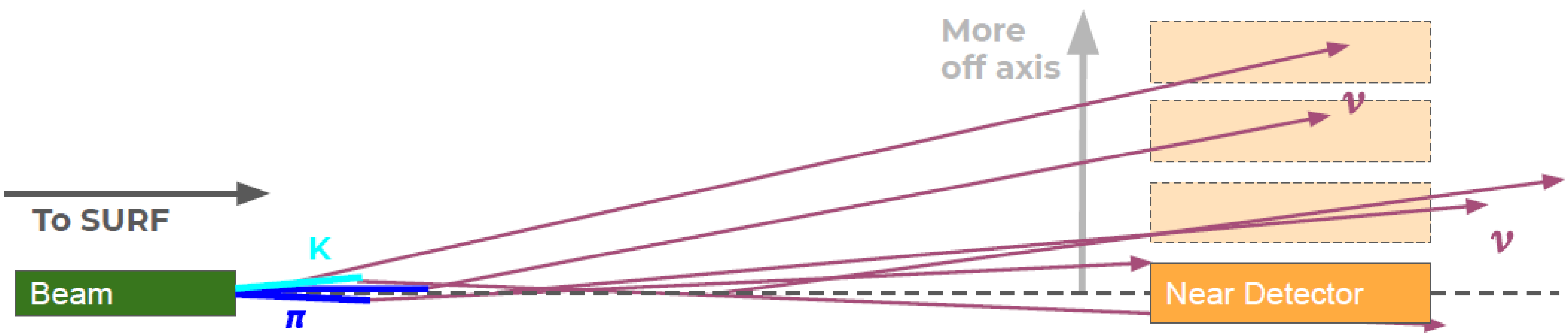


2019 TDR

DUNE-PRISM: off-axis ND

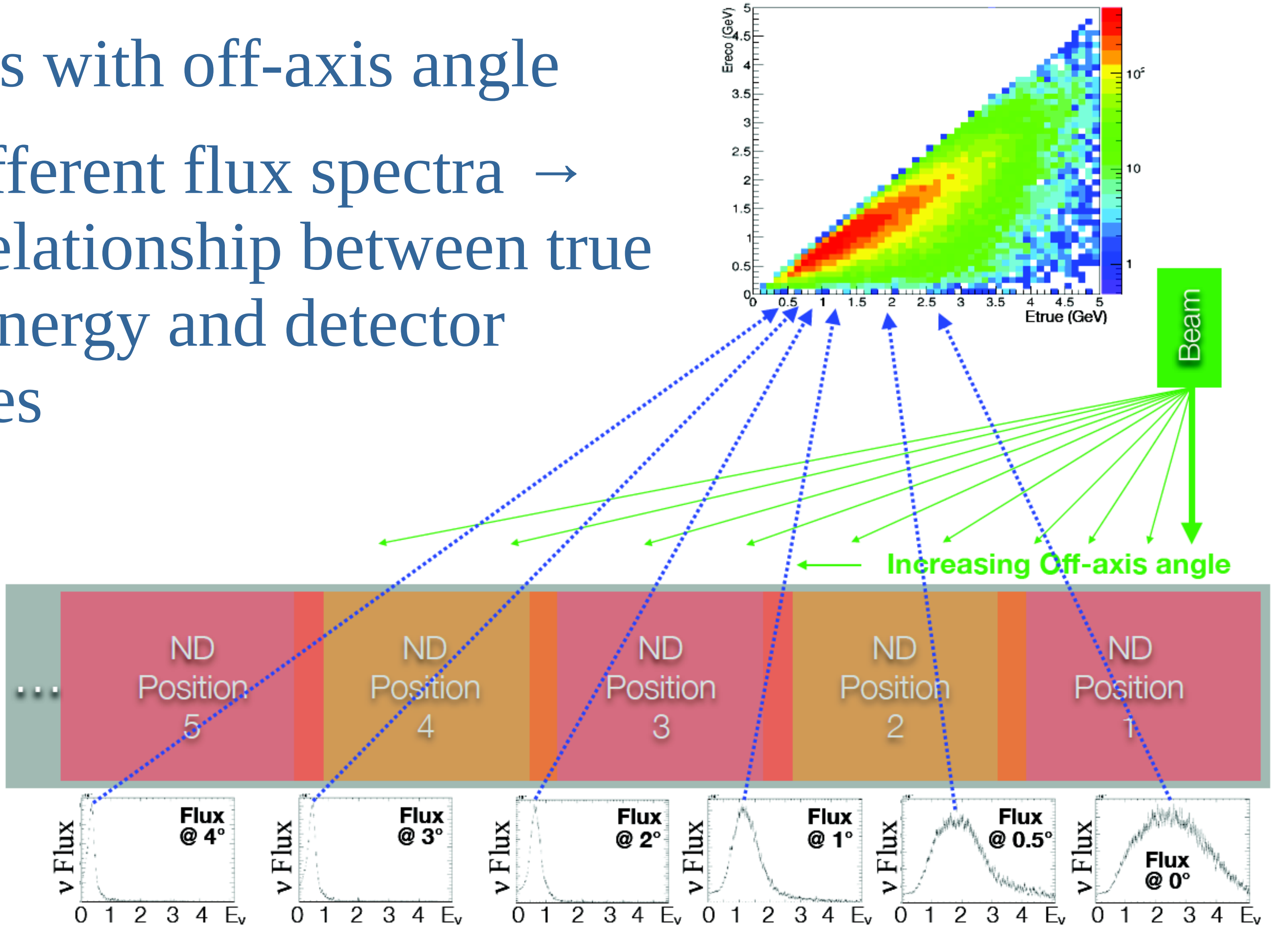




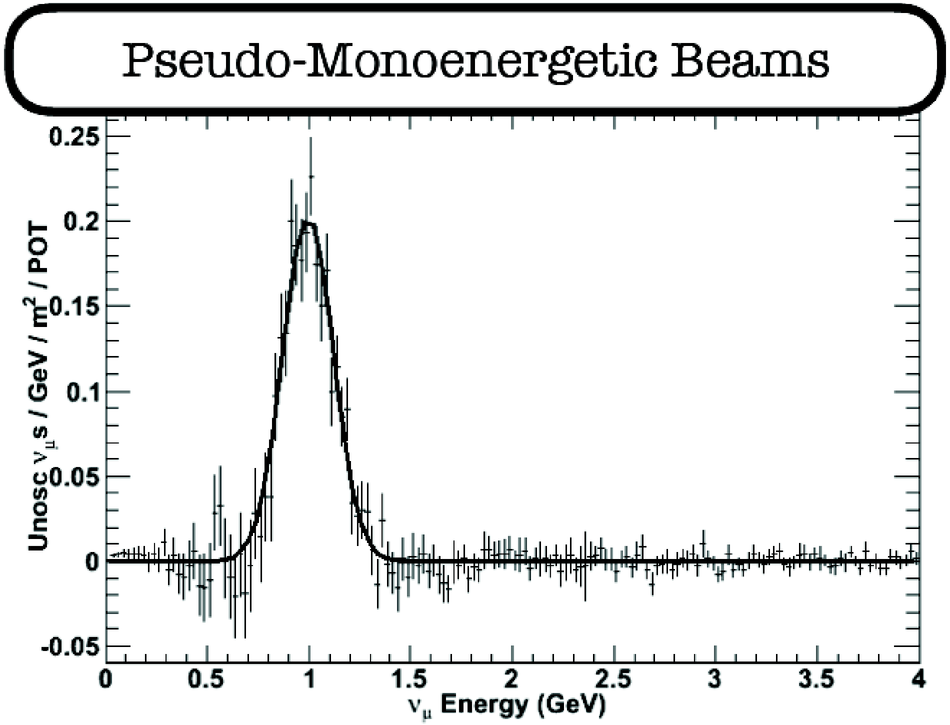


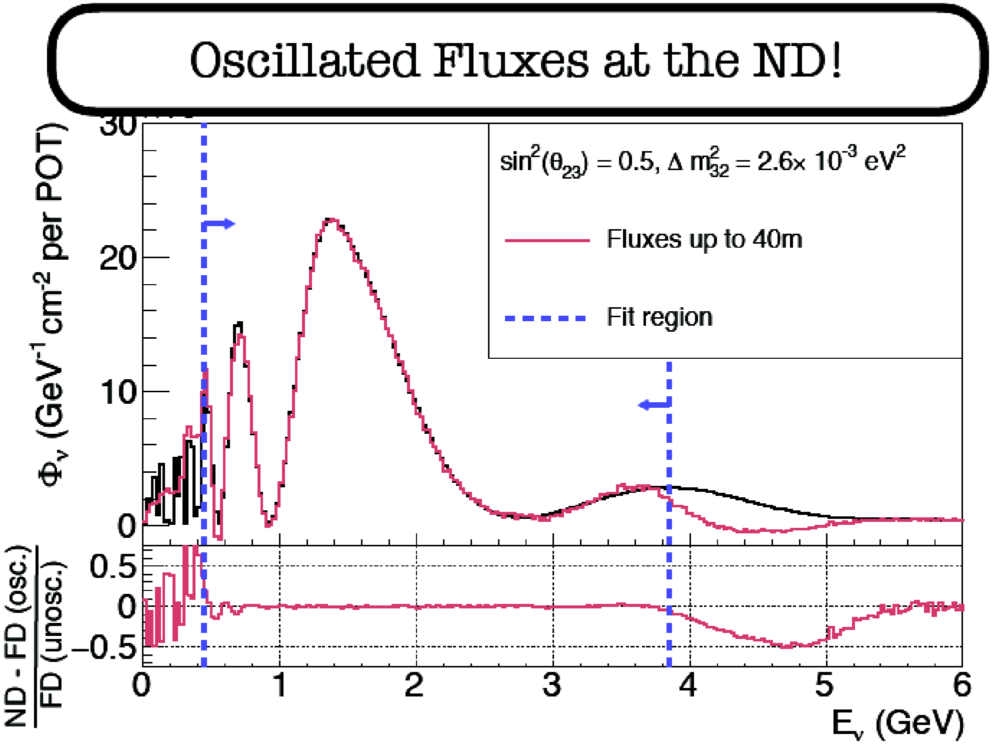
One solution: make ND measurements with many different fluxes

- Flux varies with off-axis angle
- Access different flux spectra → map out relationship between true neutrino energy and detector observables



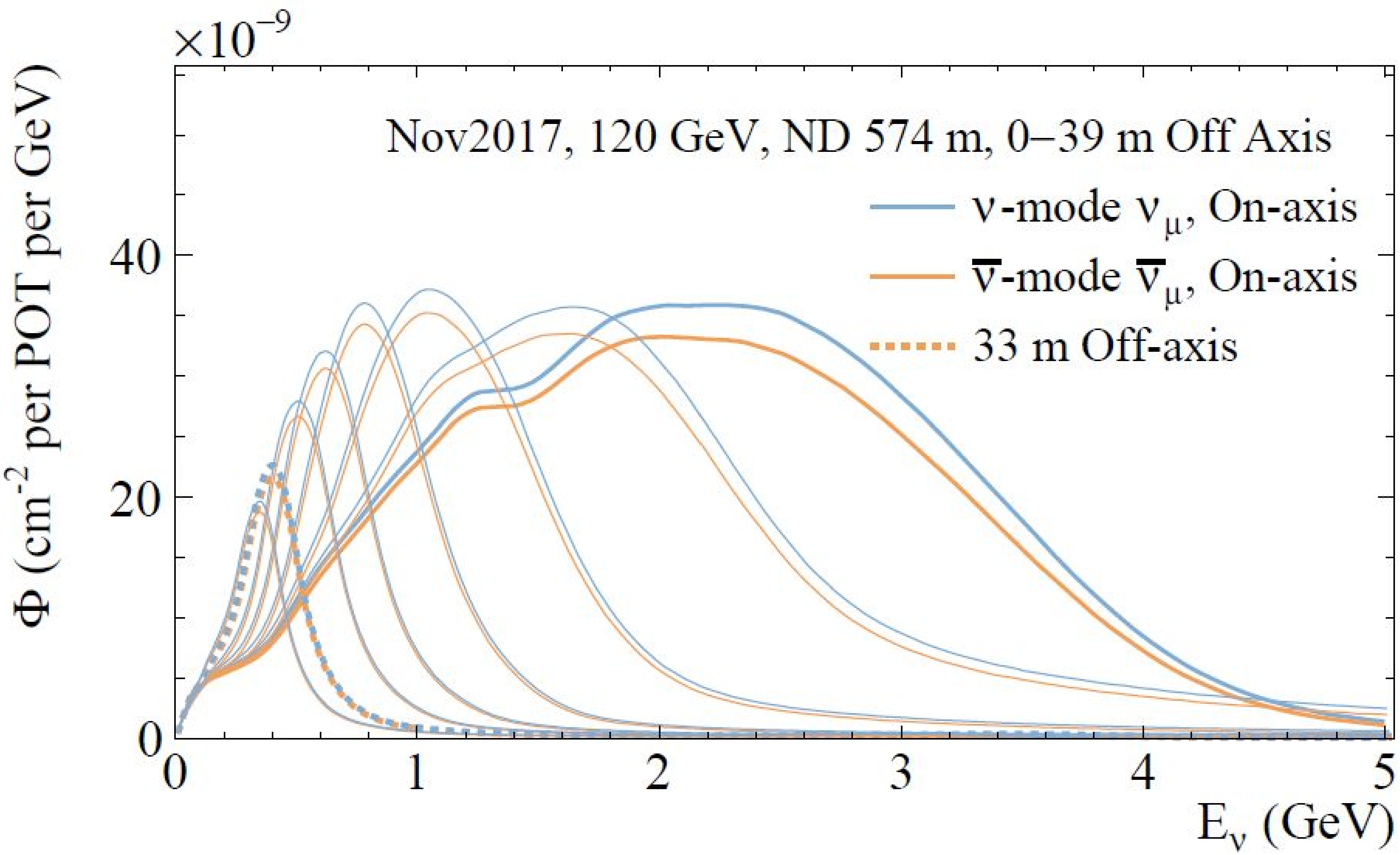
Reproduce FD flux with linear combinations of ND samples



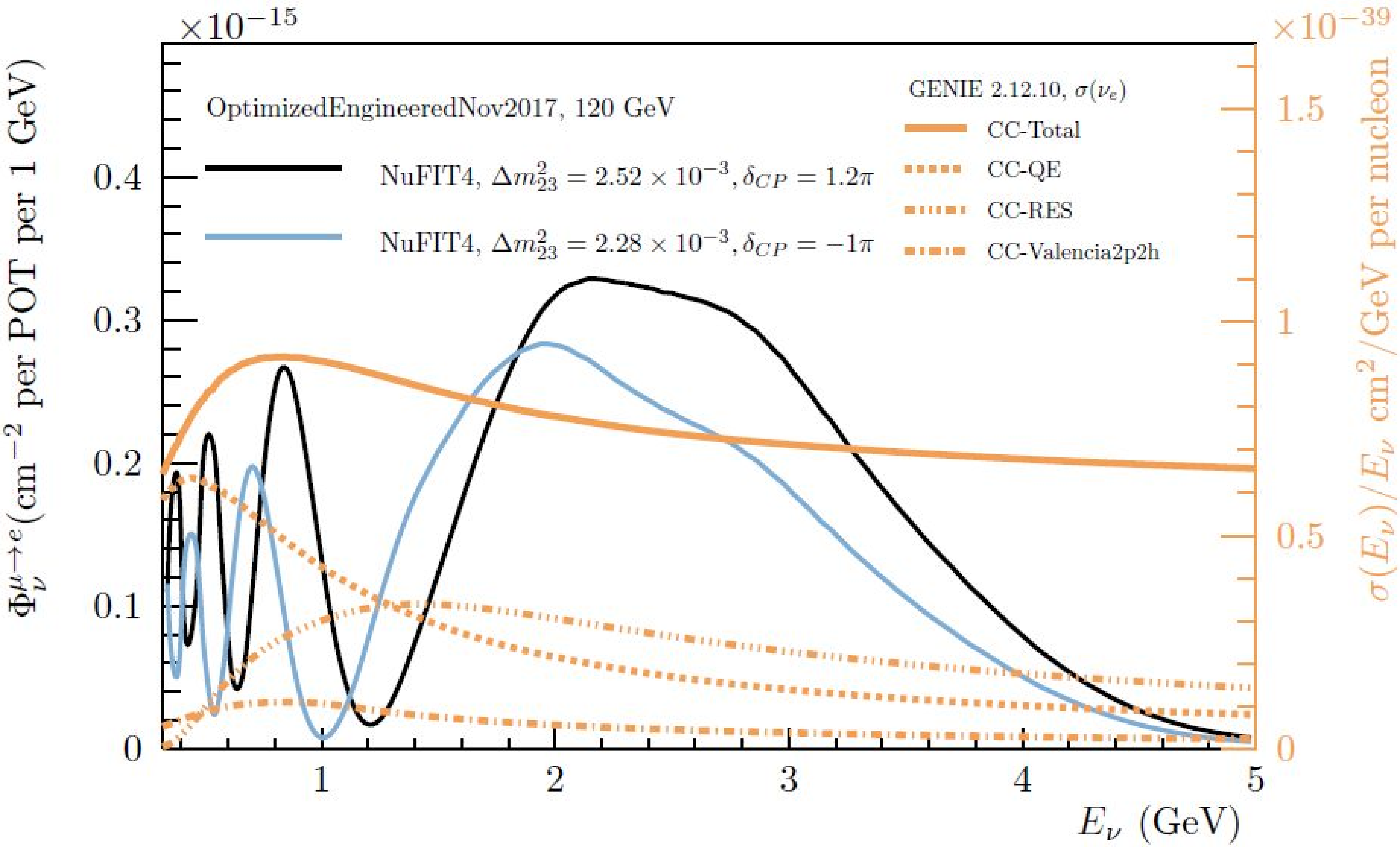


- By taking linear combinations of spectra at different off-axis angles, we can create pseudo-monoenergetic beams
- Or we can create a replica oscillated FD flux for some set of oscillation parameters

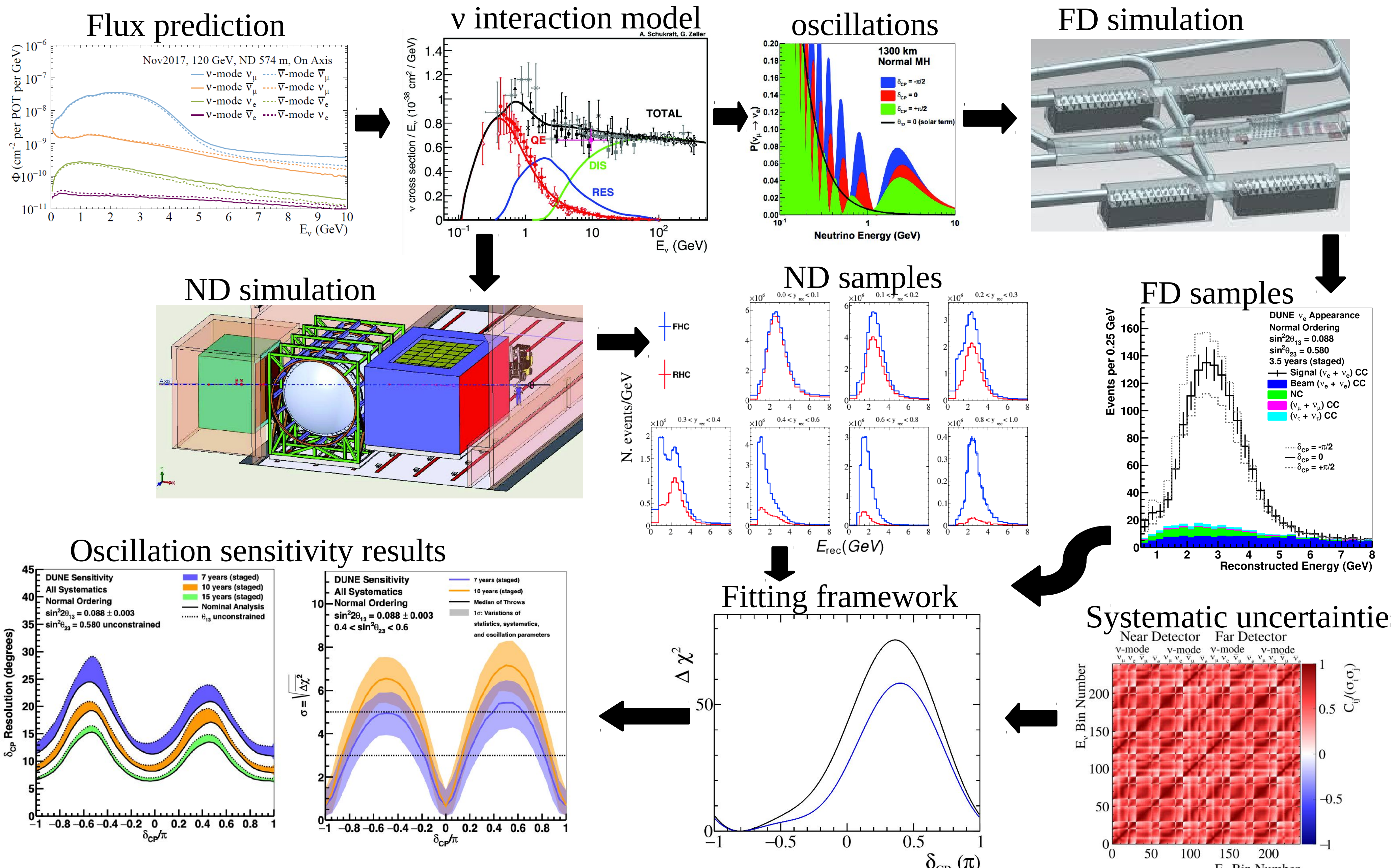
Flux predictions up to 39m off axis: peaks from 2.5 down to 0.4 GeV



Far detector spectra, with cross section predictions vs. energy

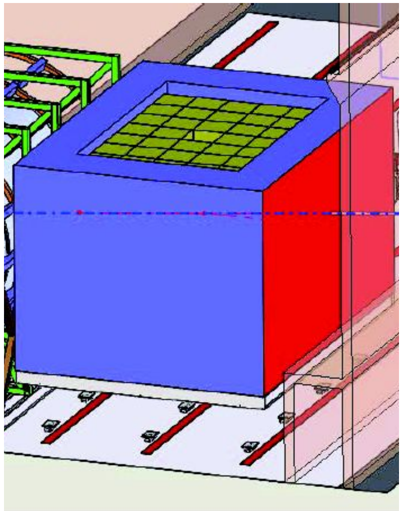


DUNE long-baseline oscillation analysis

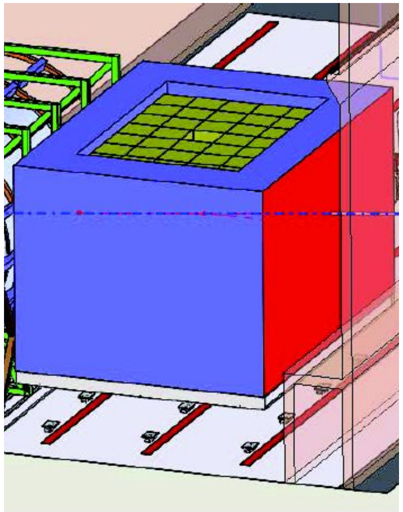


ND: LAr TPC

- Measure ν-Ar interactions with same technology as far detector
- Direct flux constraint with ν+e → ν+e



ND: Multi-purpose detector



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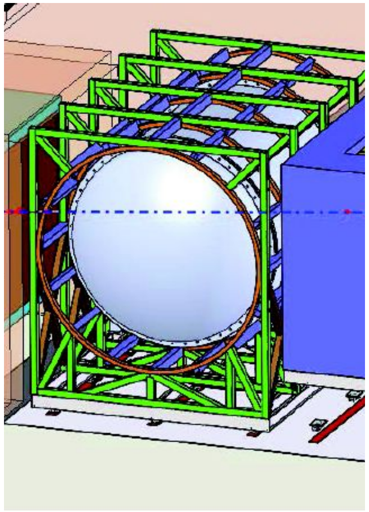
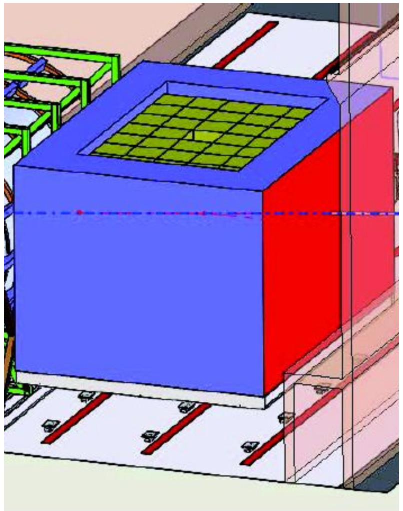


- Measure ν-Ar interactions with low thresholds, exquisite PID, same target nucleus as FD
- Reconstruct muons exiting LAr TPC

ND: 3DST-S



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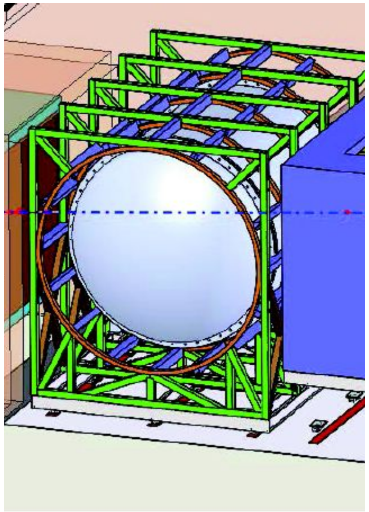

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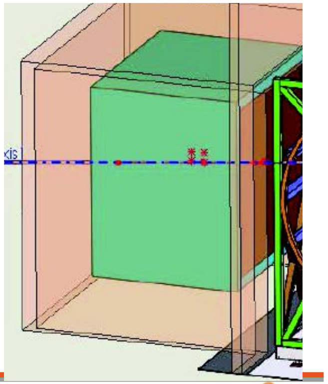
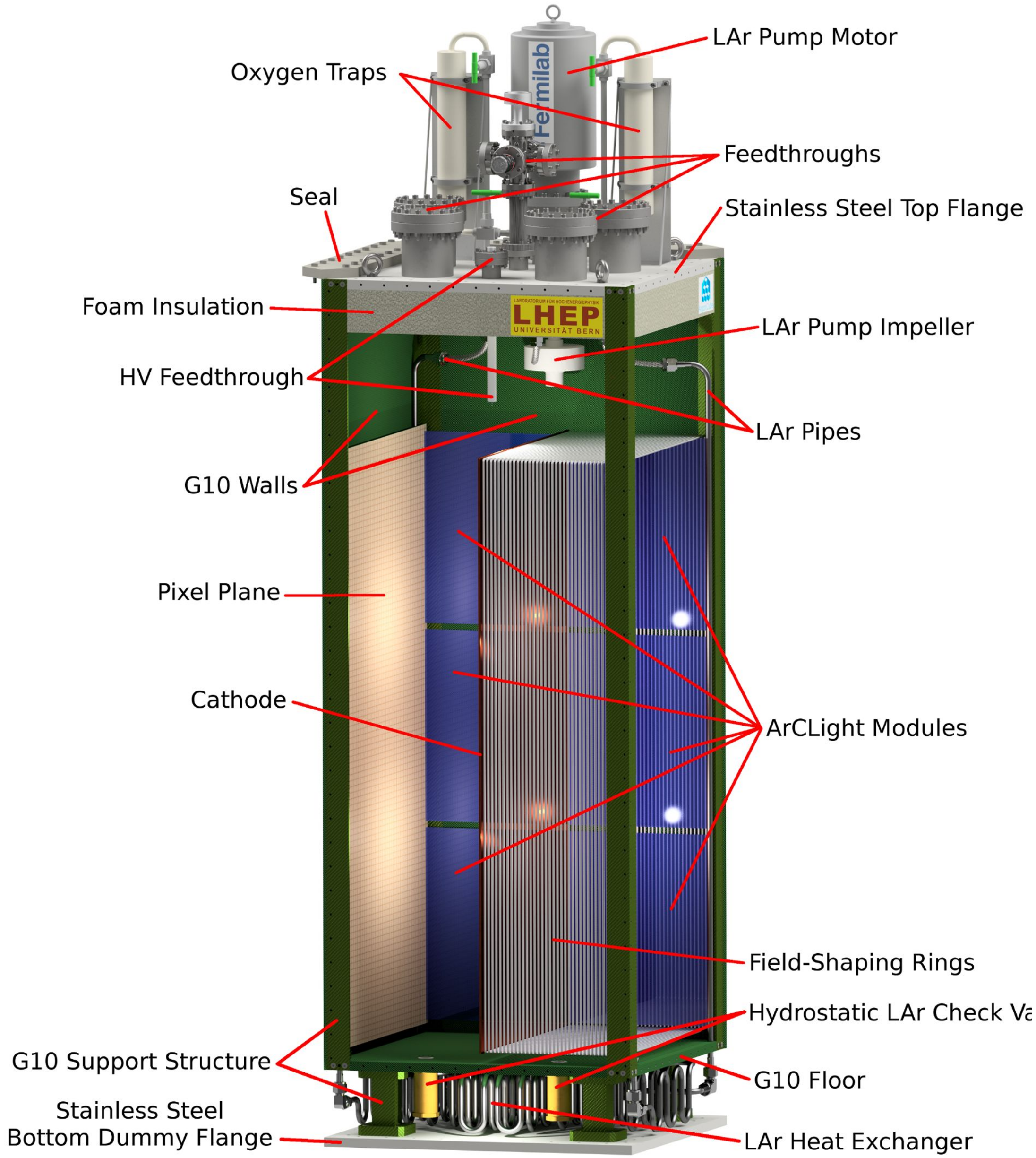
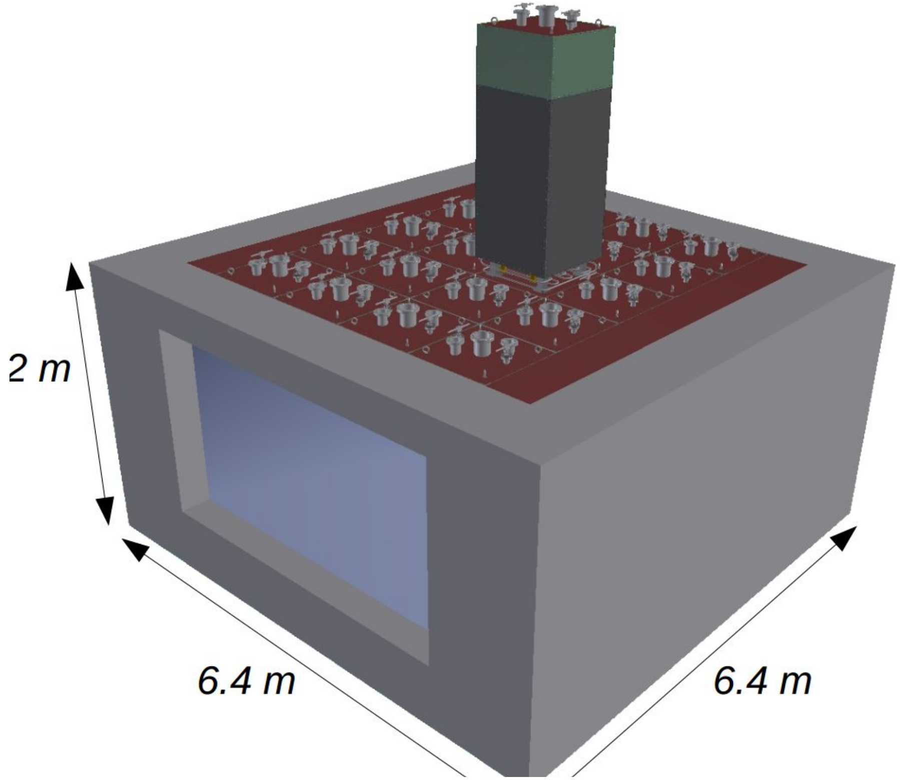


- Monitor the neutrino beam on-axis
- Direct measurement of neutrons with time-of-flight

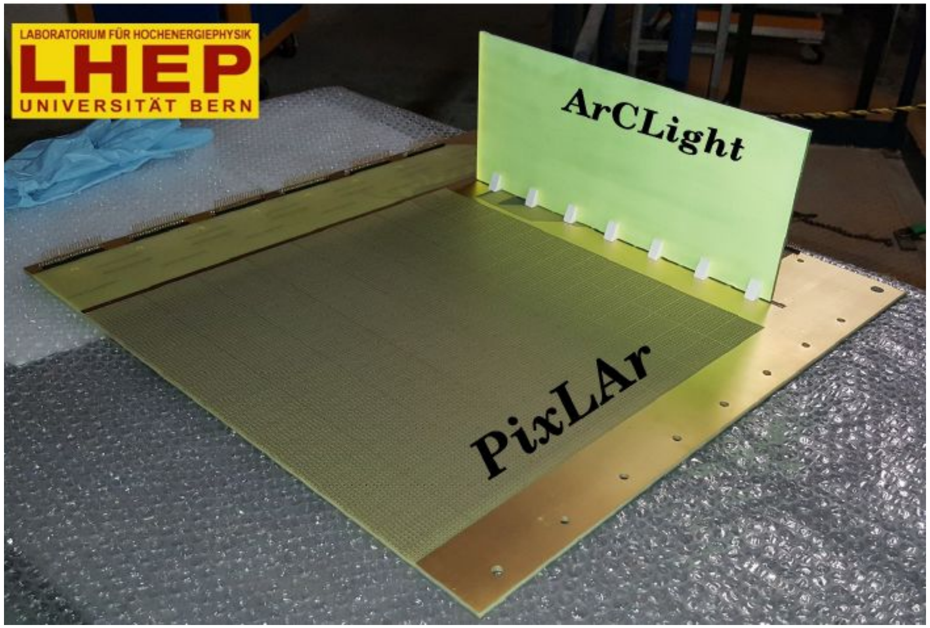
ArgonCube ND concept





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



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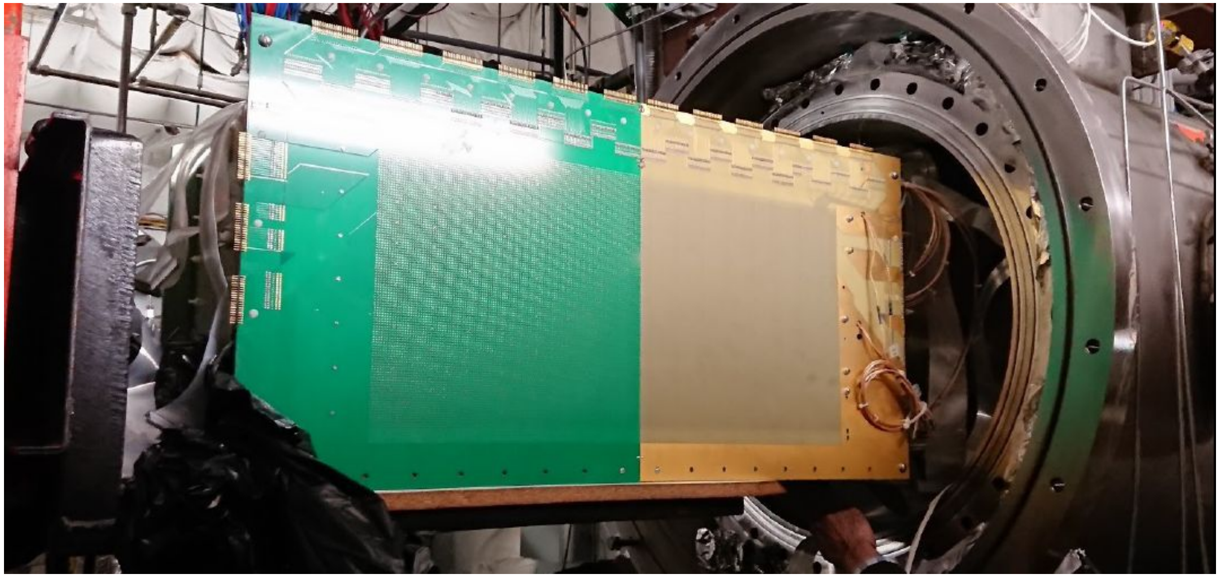
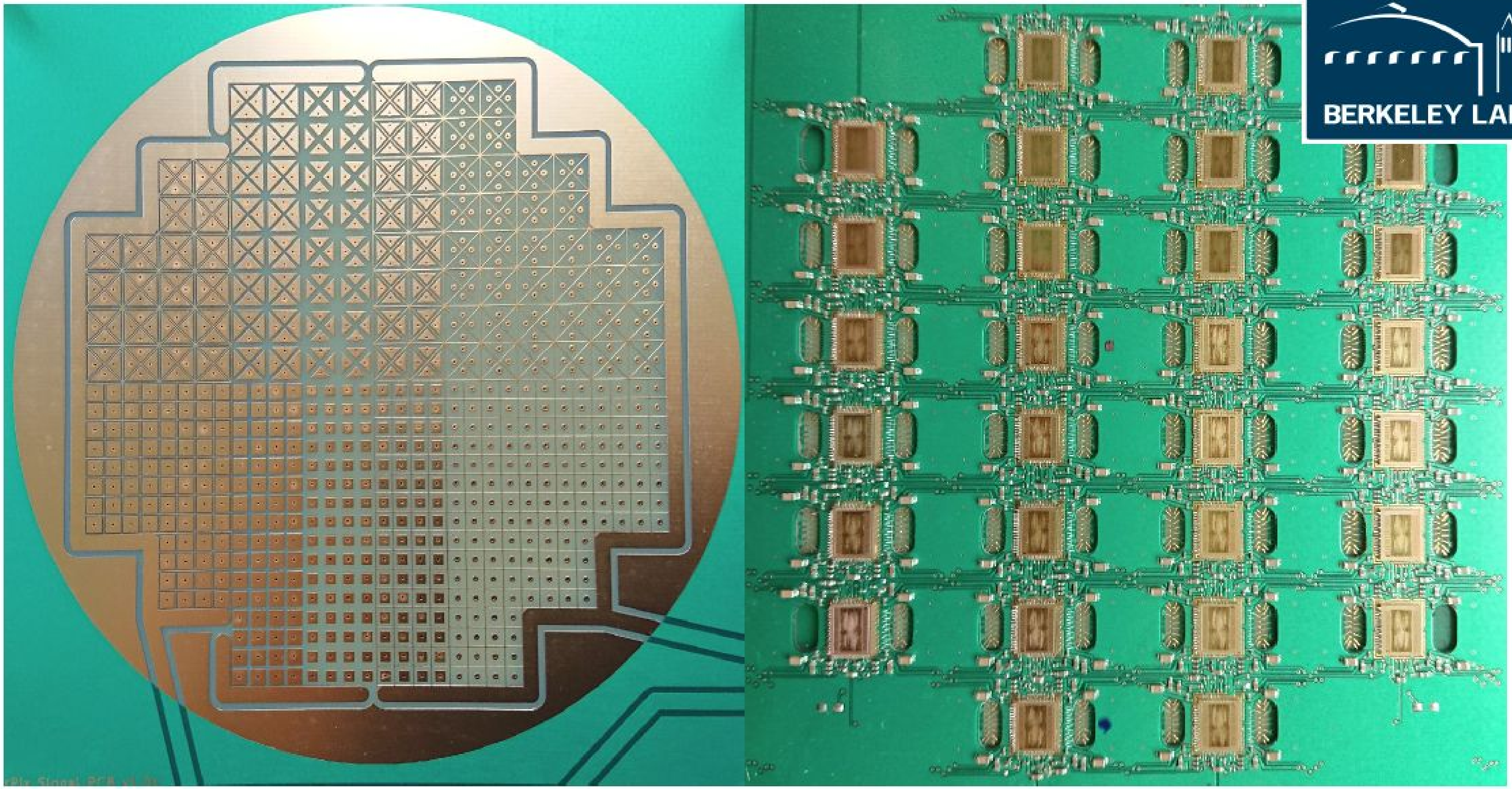
PixLAr tests at Fermilab



- 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

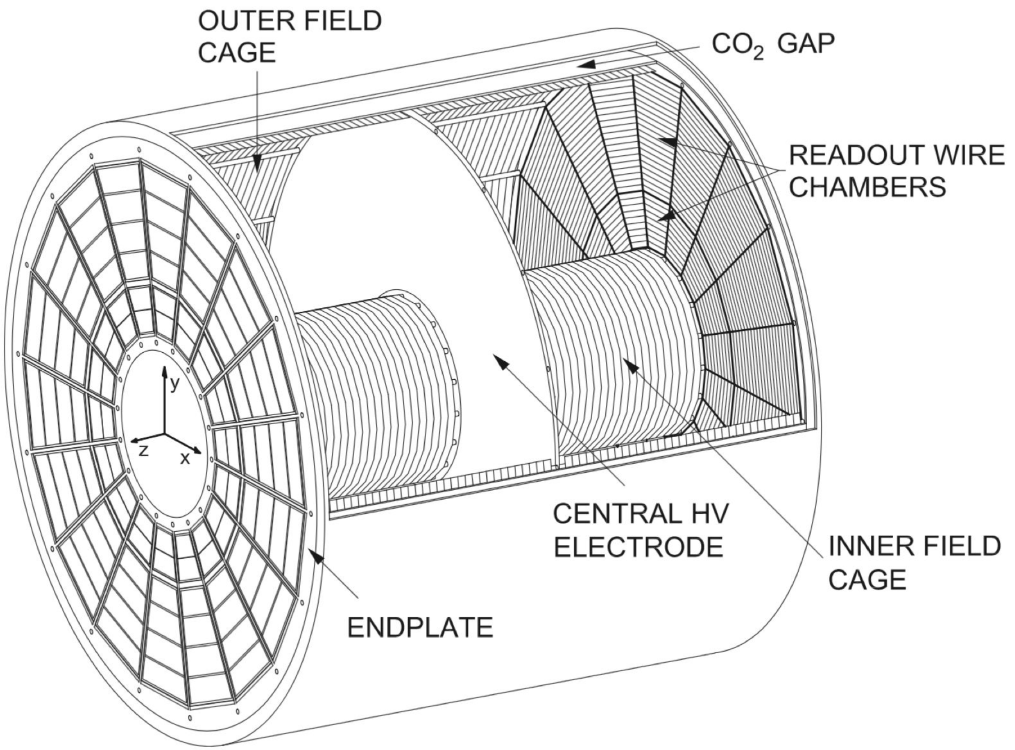


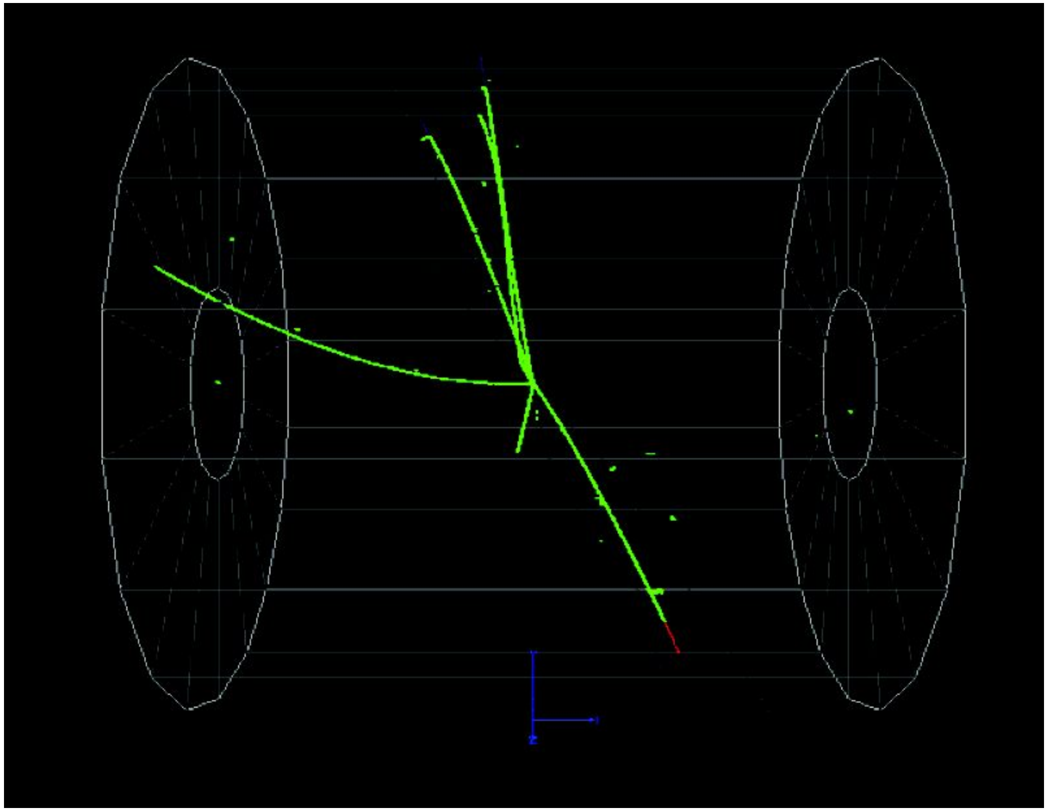
- Low-power, single-channel readout developed at LBNL, tested at LBNL and Bern

High-pressure gas TPC

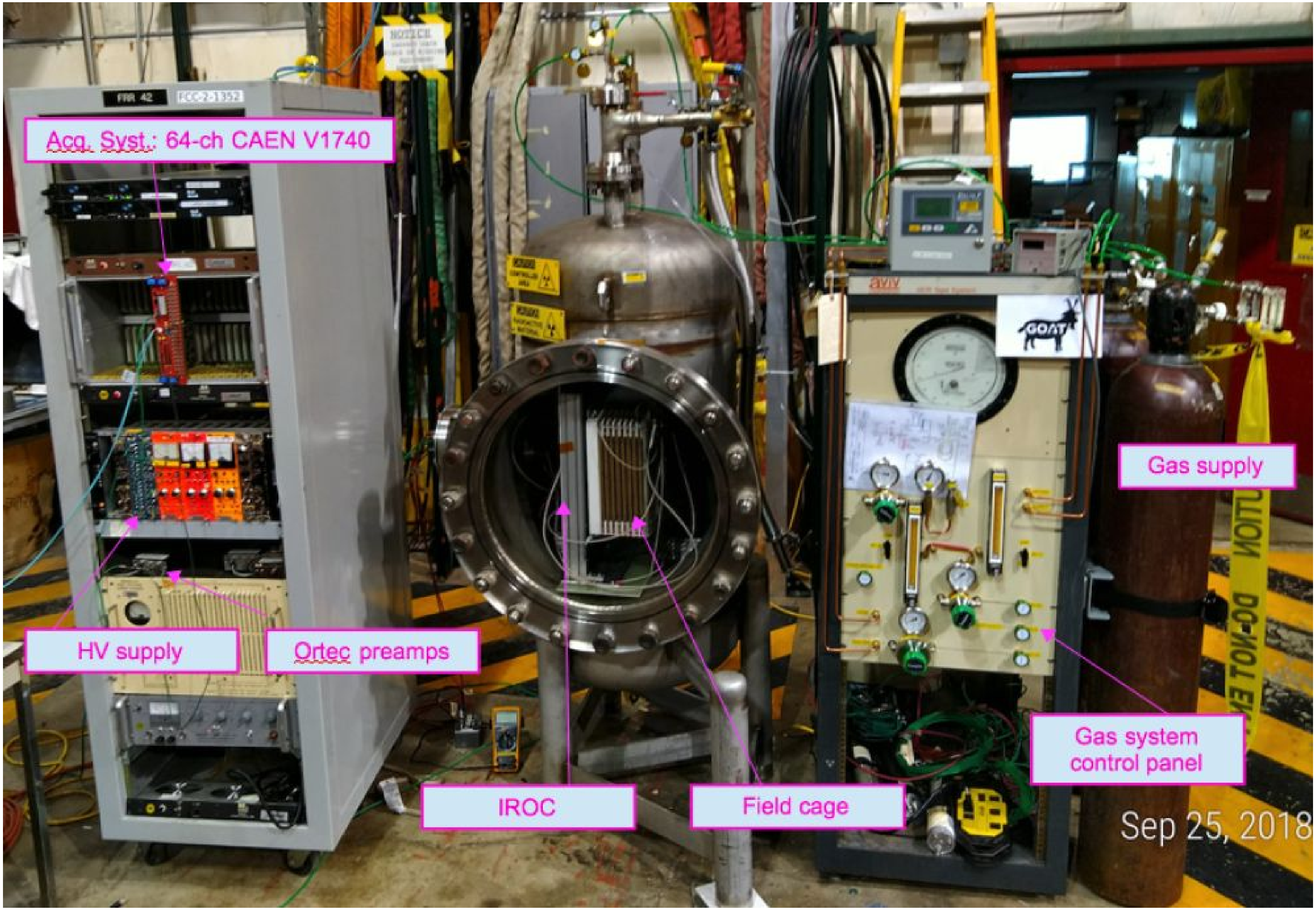
- 10bar 90-10 Ar-CH_4 mixture
- Repurpose ALICE readout chambers (available in 2019), filling central hole with new chamber
- New front-end electronics

New software: GArSoft



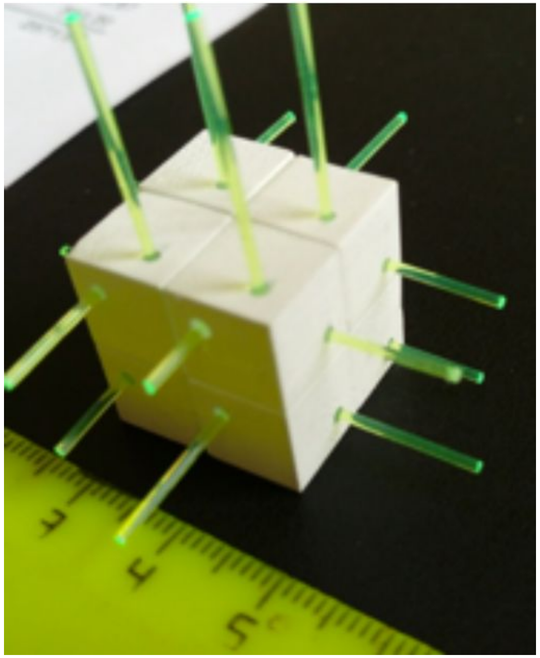


Gas TPC test stand @Fermilab



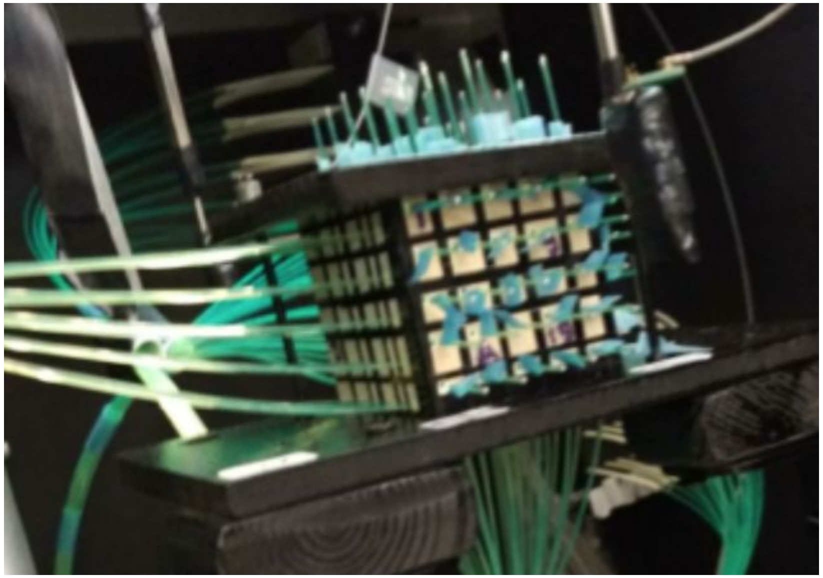
3D scintillator tracker (3DST)

- 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

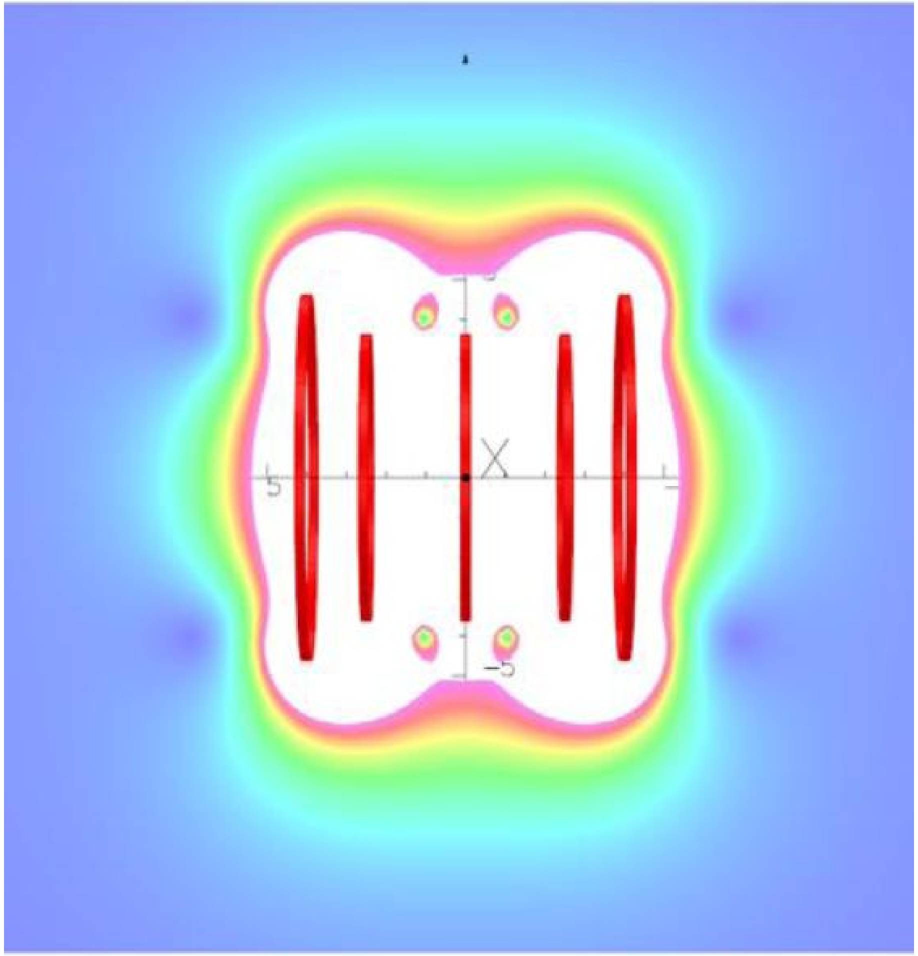


3DST prototypes

- Testing and prototyping is shared with T2K ND upgrade
- O(100) cube prototypes operated in test beams at CERN and Japan in 2017
- O(10000) cube prototype at CERN summer 2018
- Planned 2019 neutron beam run at Los Alamos



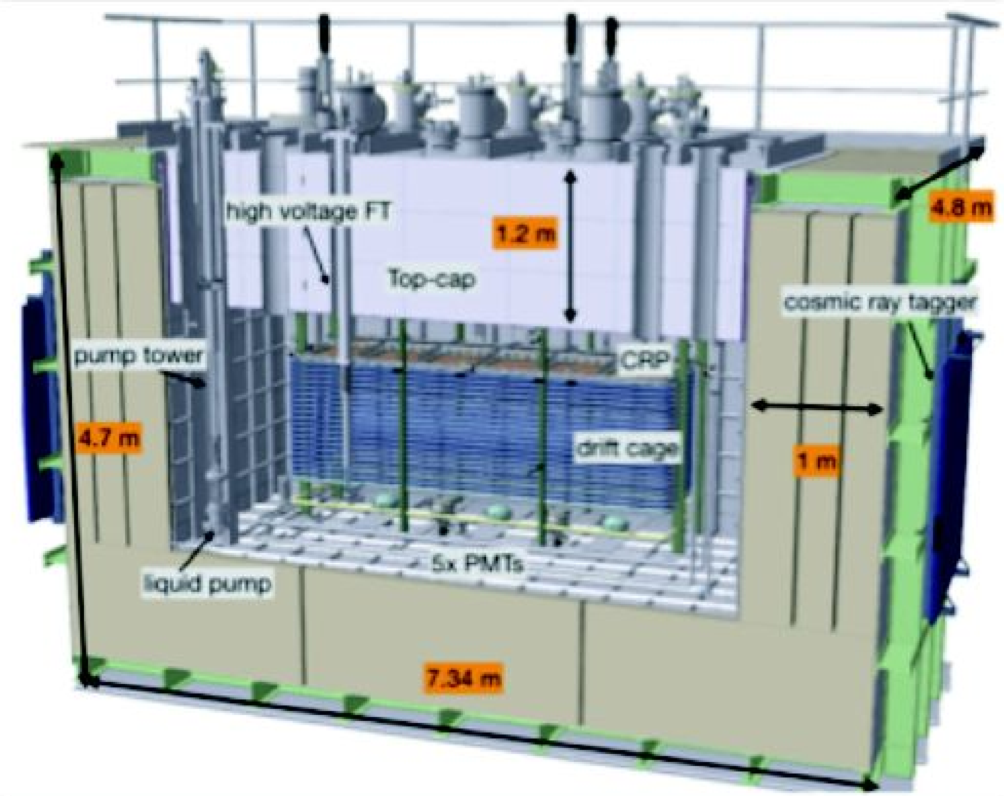
Near detector MPD magnet



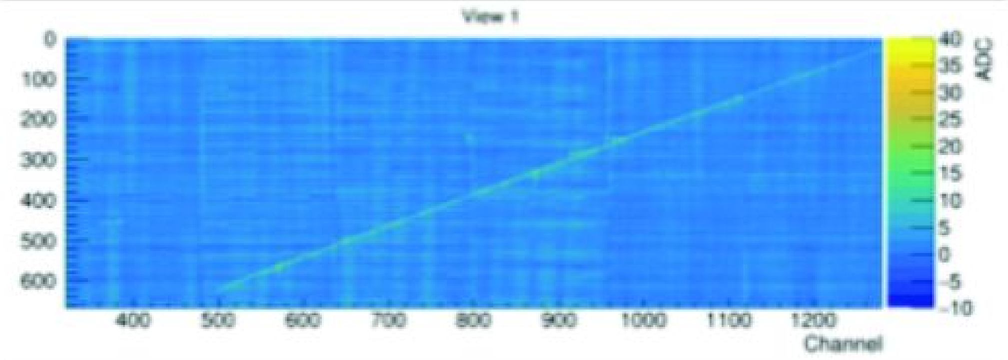
3 superconducting coils with 2 bucking coils to actively cancel stray fields to ~50 gauss

DP 3x1x1 prototype

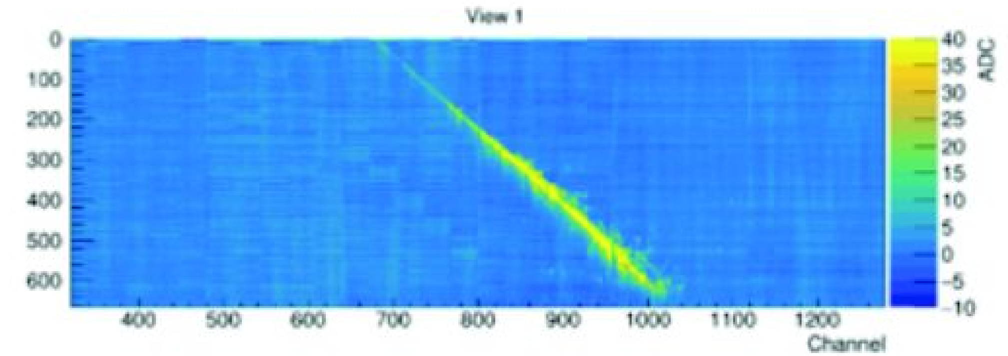
- Ran at CERN June-November 2017, demonstrating dual-phase LAr TPC concept
- Achieved S/N ~ 100 for MIP



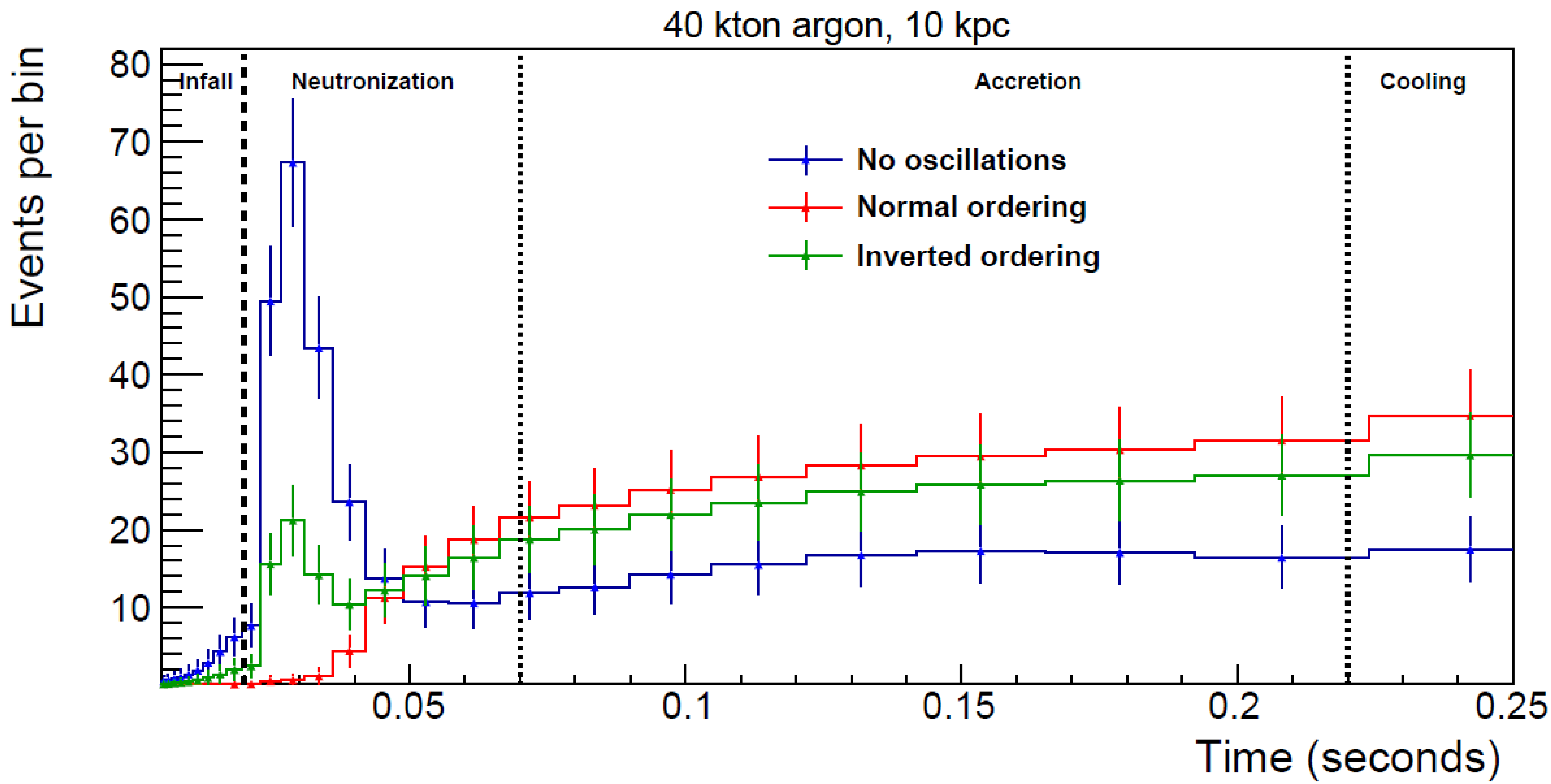
Muon



EM Shower



Mass ordering sensitivity from SNB



- In addition to astrophysics, time profile of SNB gives sensitivity to neutrino oscillations, including mass ordering