The DUNE Near Detector

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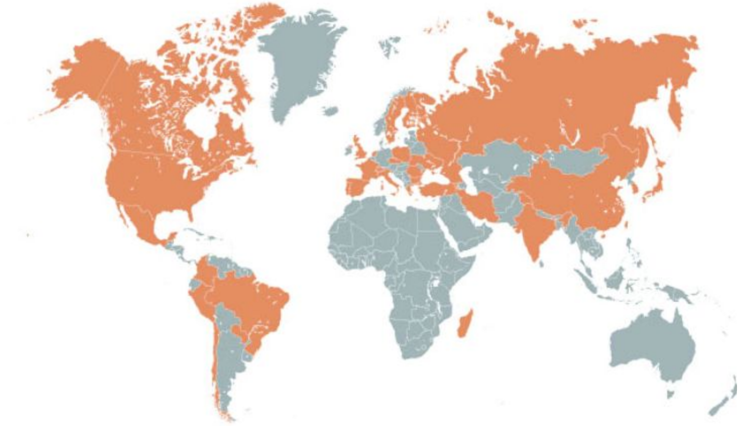
for the DUNE collaboration

NNN18 Vancouver
3 November, 2018

The DUNE collaboration

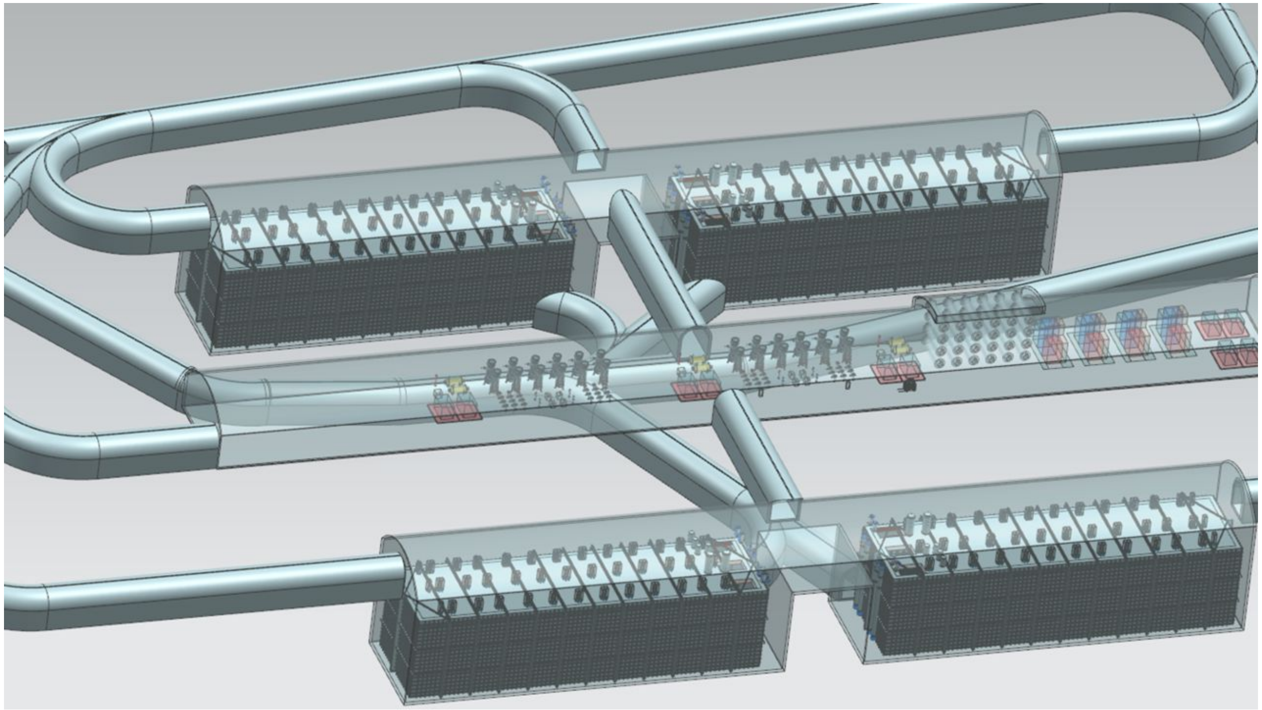


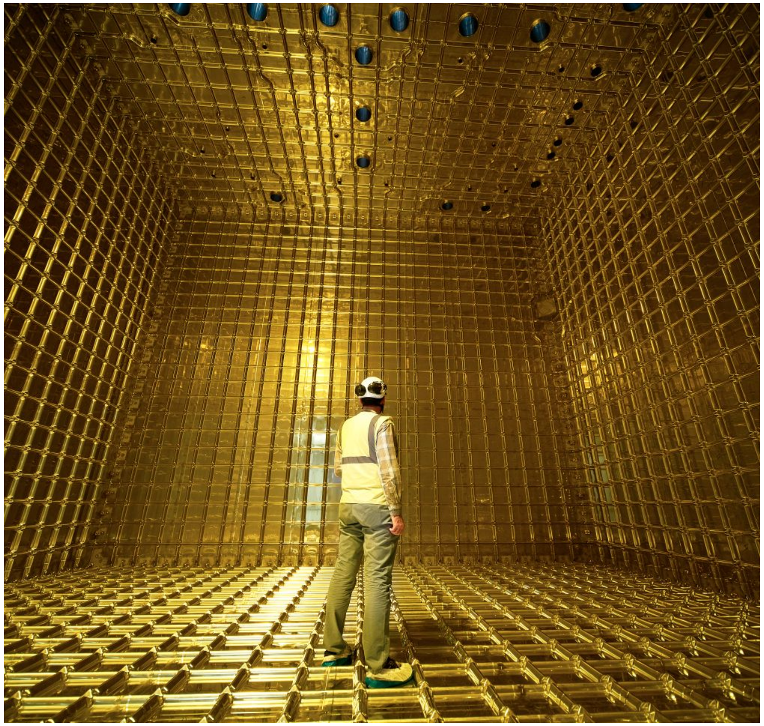
Armenia (3), Brazil (29), Bulgaria (1), Canada (1), CERN (32), Chile (3), China (5), Colombia (13), Czech Republic (11), Spain (34), Finland (4), France (23), Greece (4), India (45), Iran (2), Italy (63), Japan (7), Madagascar (8), Mexico (8), The Netherlands (4), Paraguay (4), Peru (8), Poland (6), Portugal (7), Romania (7), Russia (10), South Korea (4), Sweden (1), Switzerland (35), Turkey (2), UK (136), Ukraine (4), USA (621)

- Large international collaboration of over 1000 people from 175 institutions
- 32 countries + CERN
- Photo and map as of May 2018

The DUNE experiment

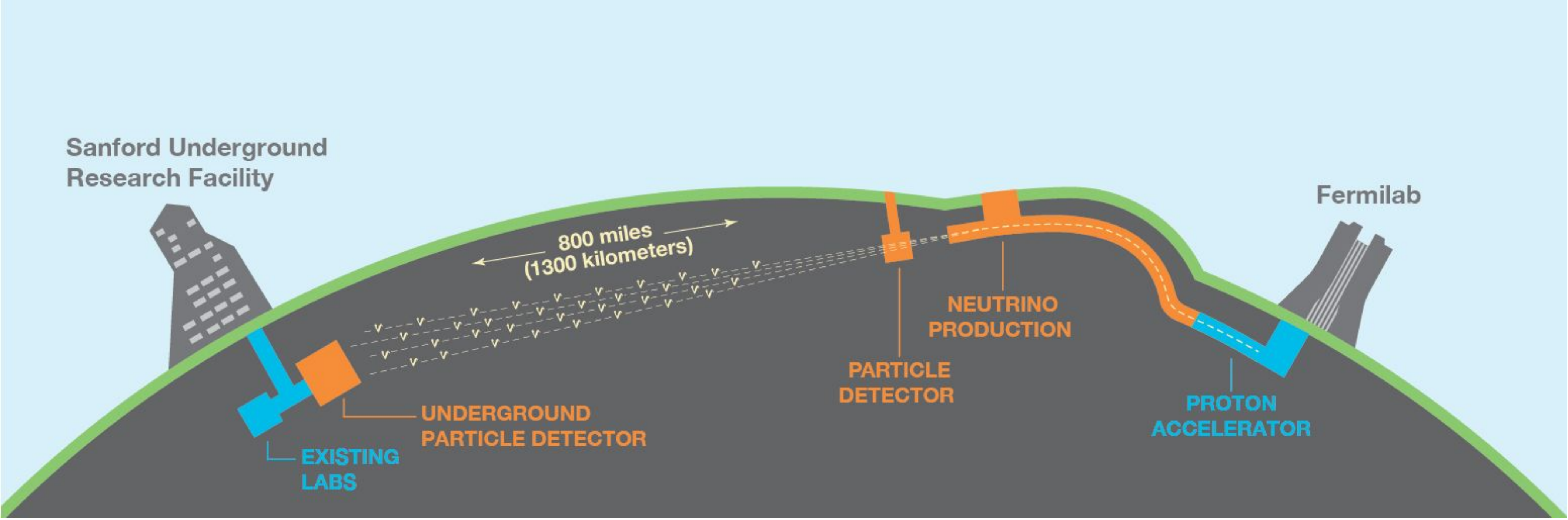
See plenary talk Friday morning by Alex Sousa





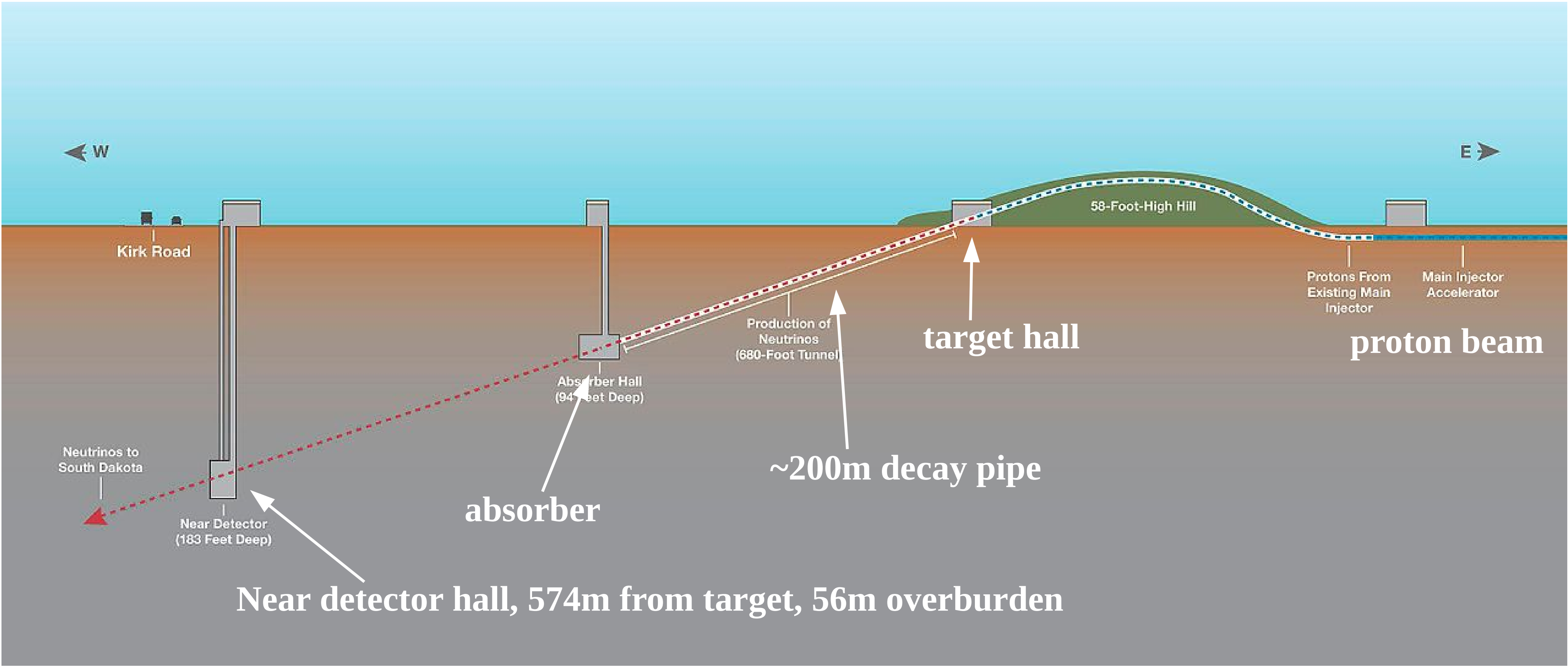
- Four 10kt LAr TPCs at SURF in Lead, South Dakota
- Neutrino oscillations, including CP violation, mass hierarchy
- Also proton decay, supernova neutrinos, atmospheric neutrinos

LBNF beamline



- High-intensity proton beam at Fermilab Main Injector
- Near detector facility at Fermilab with baseline ~ 574m
- Far detector facility at SURF with baseline ~ 1300km

LBNF beamline and DUNE near detector facility at Fermilab



target hall

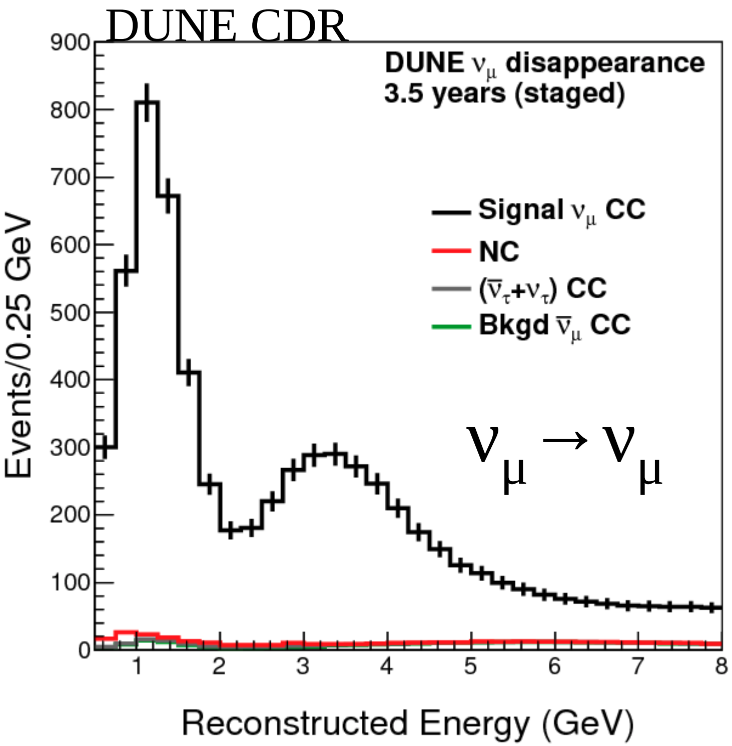
proton beam

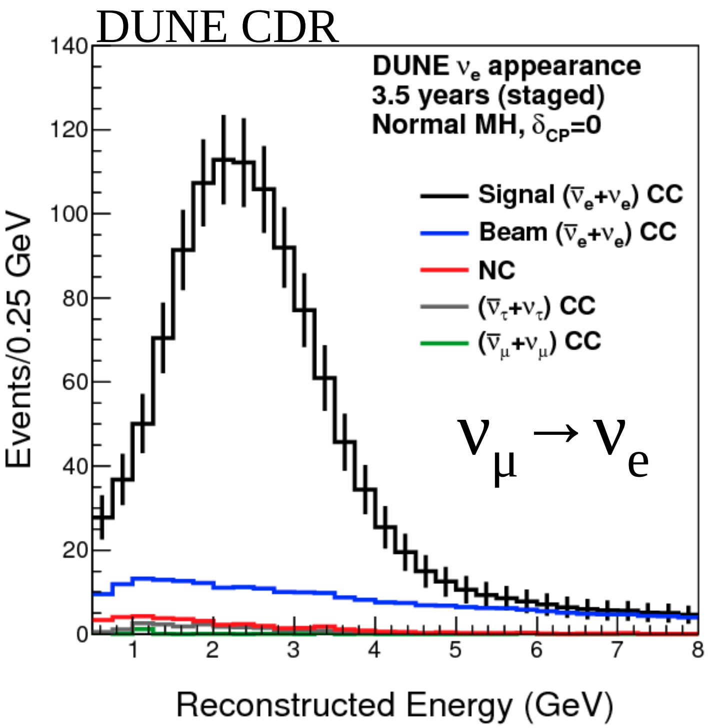
~200m decay pipe

absorber

Near detector hall, 574m from target, 56m overburden

Far detector neutrino spectra





- Wideband neutrino beam peaked at oscillation maximum ~ 2.5 GeV
- Expect O(1000) far detector ν_e → ~3% statistical uncertainty

Requirements for ND

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

Observed far detector spectra depend on:

Neutrino flux prediction

Neutrino-Argon interaction cross sections

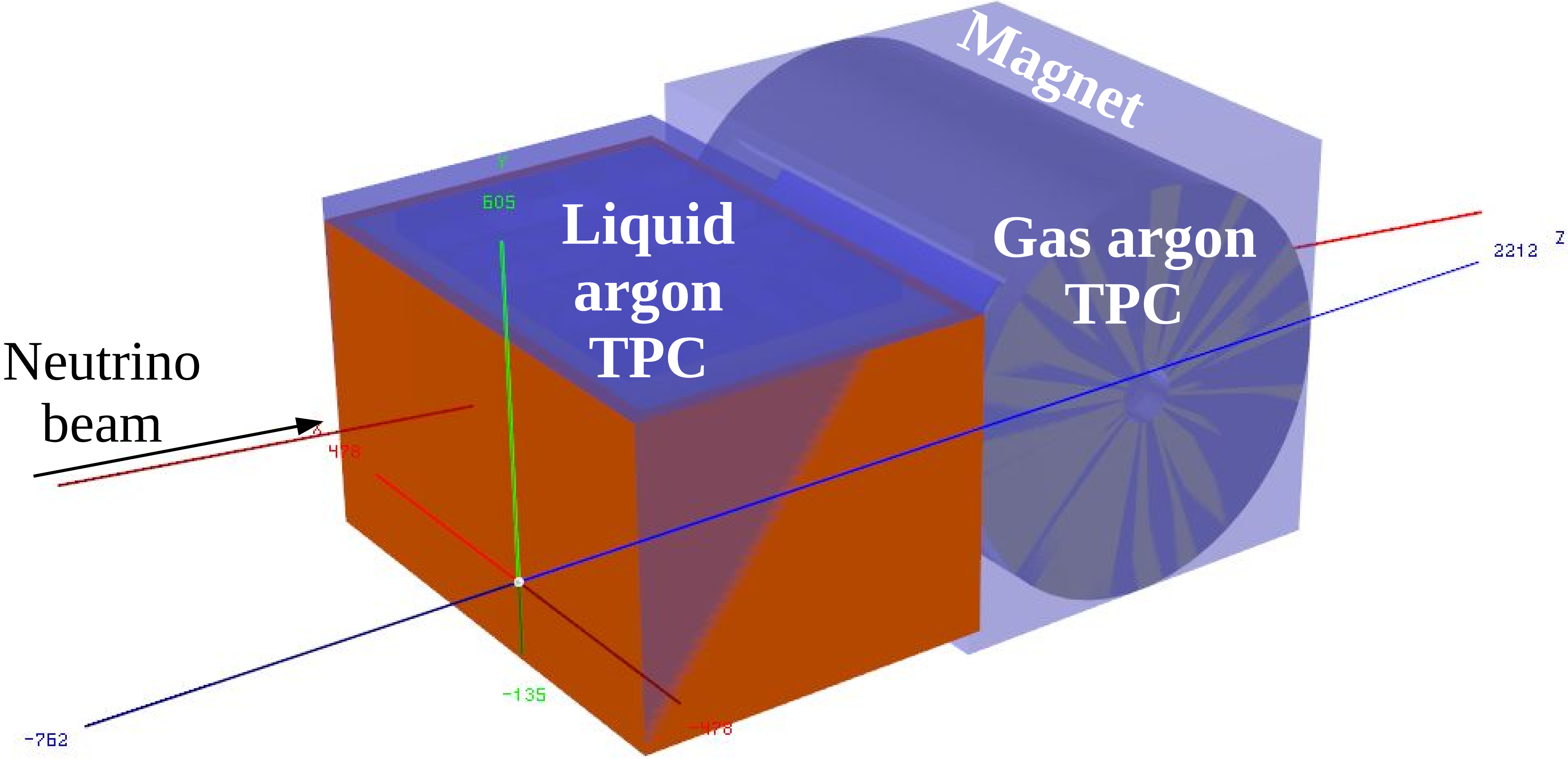
Detector acceptance

True → Reconstructed energy smearing

“Out-of-the-box” predictions have 10s% uncertainty →

Need highly capable ND to constrain to ~3%

Near detector concept: Modular LAr TPC & Magnetized high-pressure gas Ar TPC



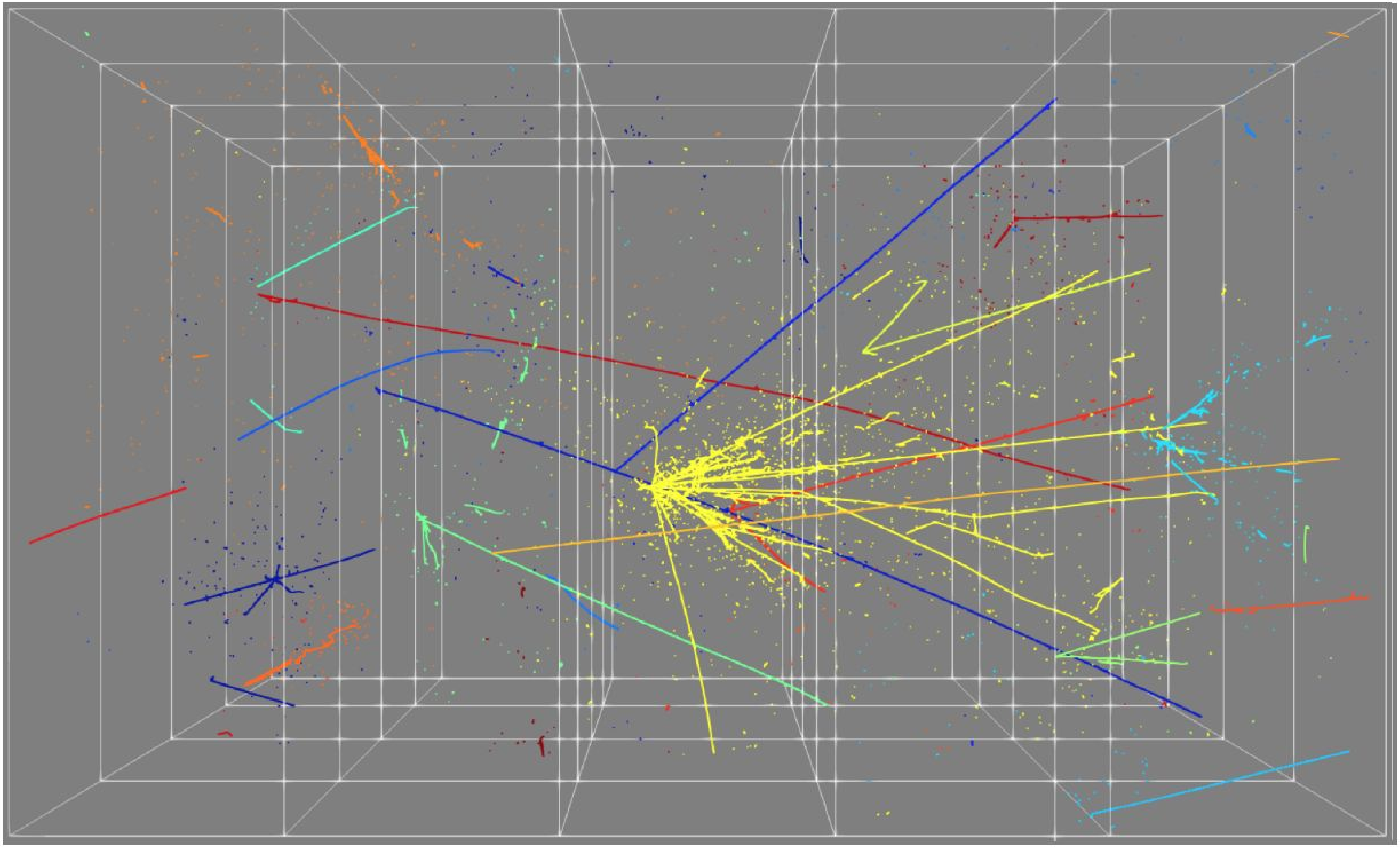
Magnet

Liquid argon TPC

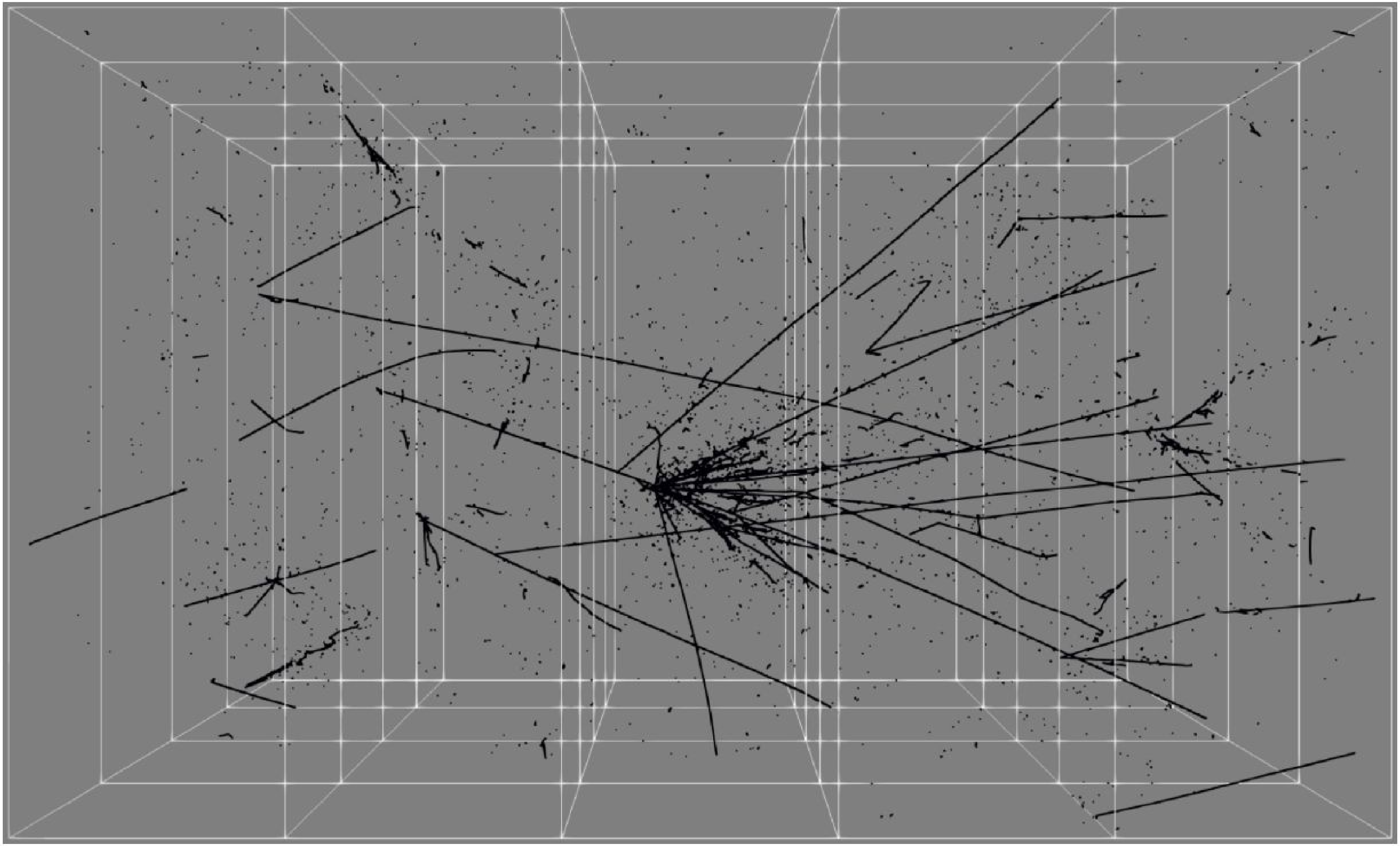
Gas argon TPC

Neutrino beam

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



...without timing resolution



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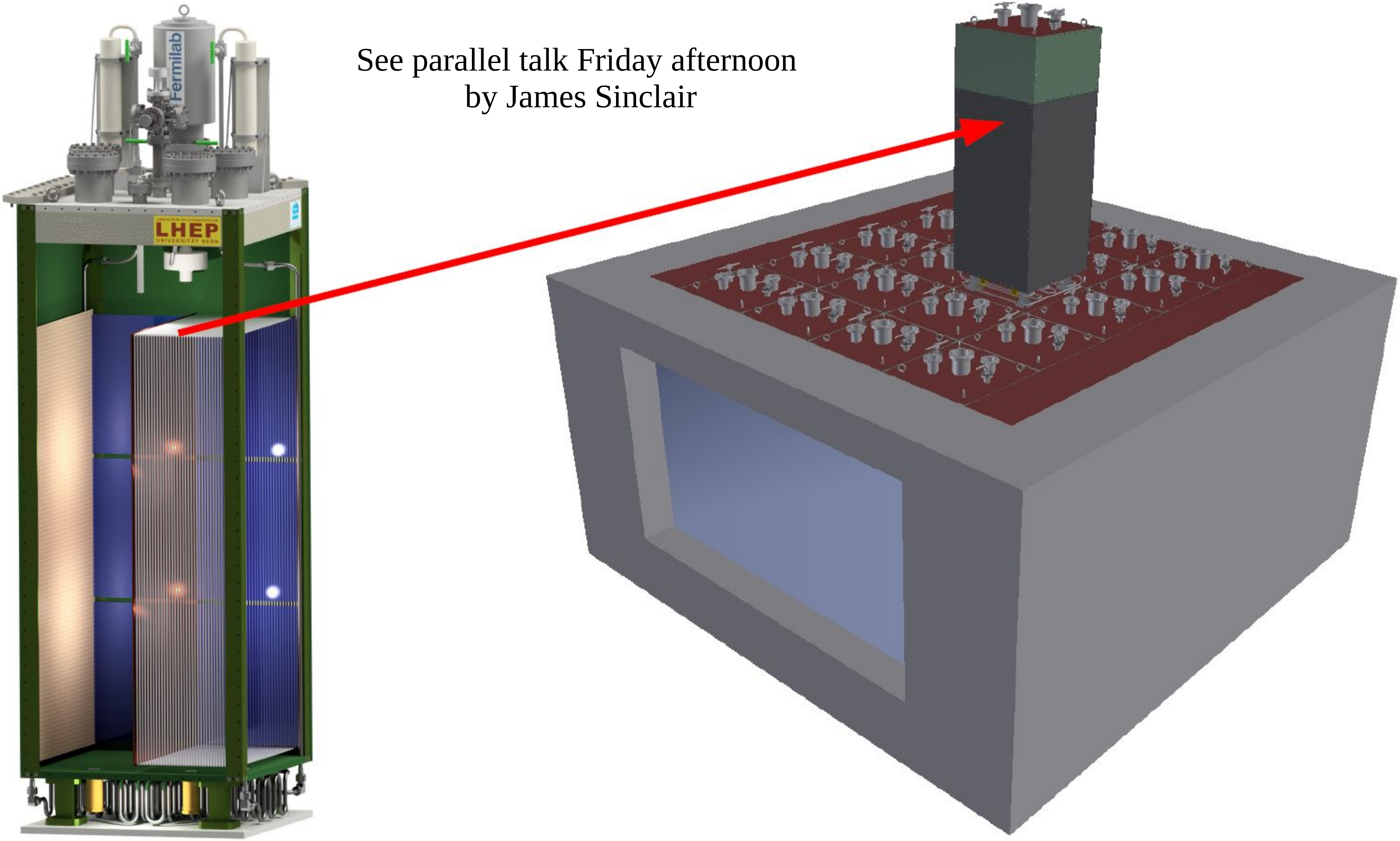
Need highly capable ND to constrain to ~3%

while operating in high-intensity environment

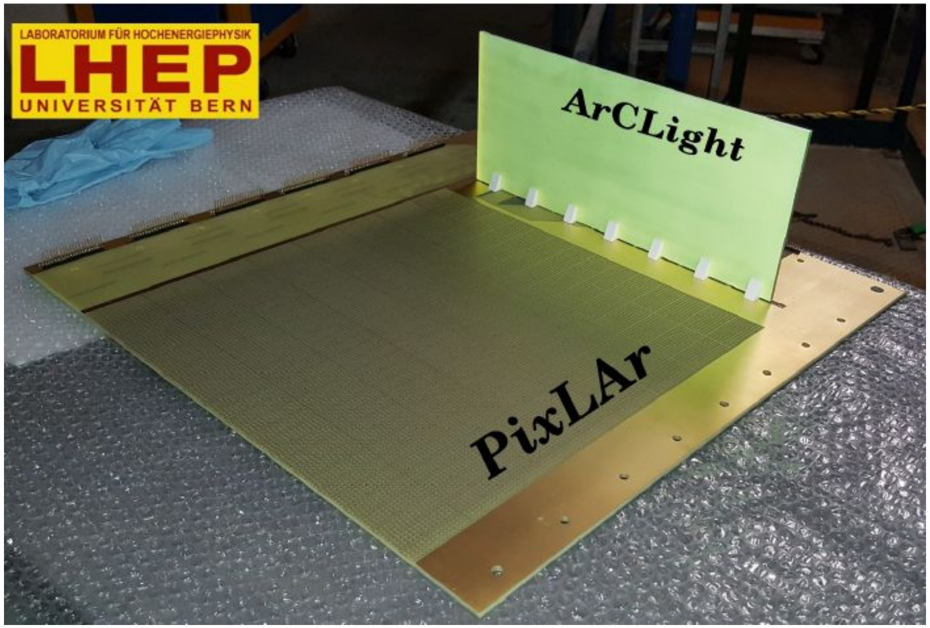
ArgonCube concept for ND



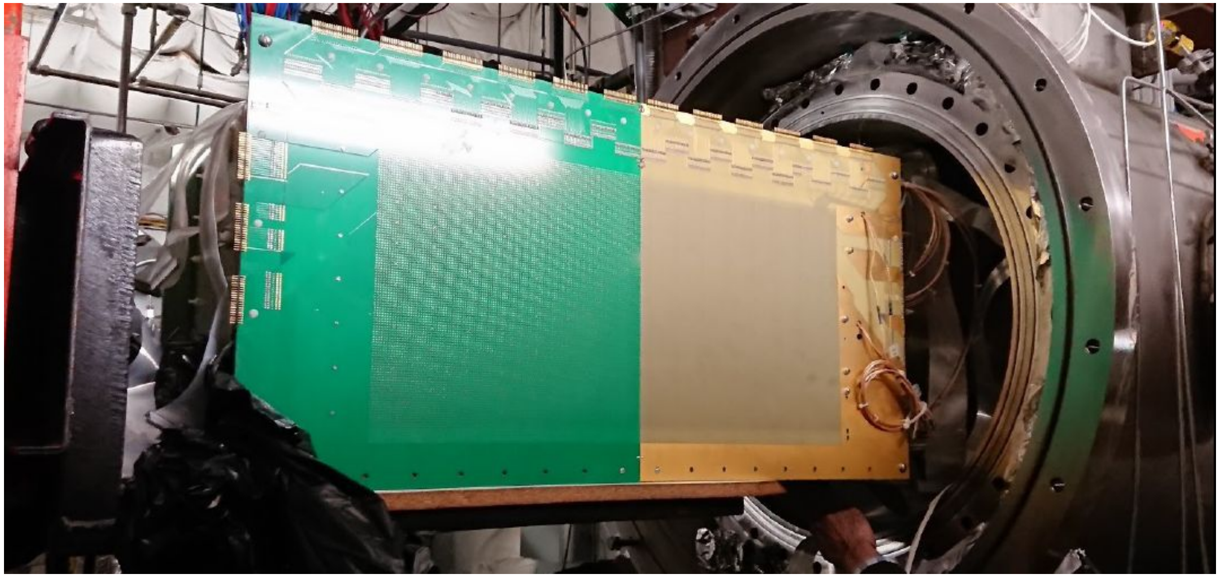
See parallel talk Friday afternoon
by James Sinclair

ArgonCube concept

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



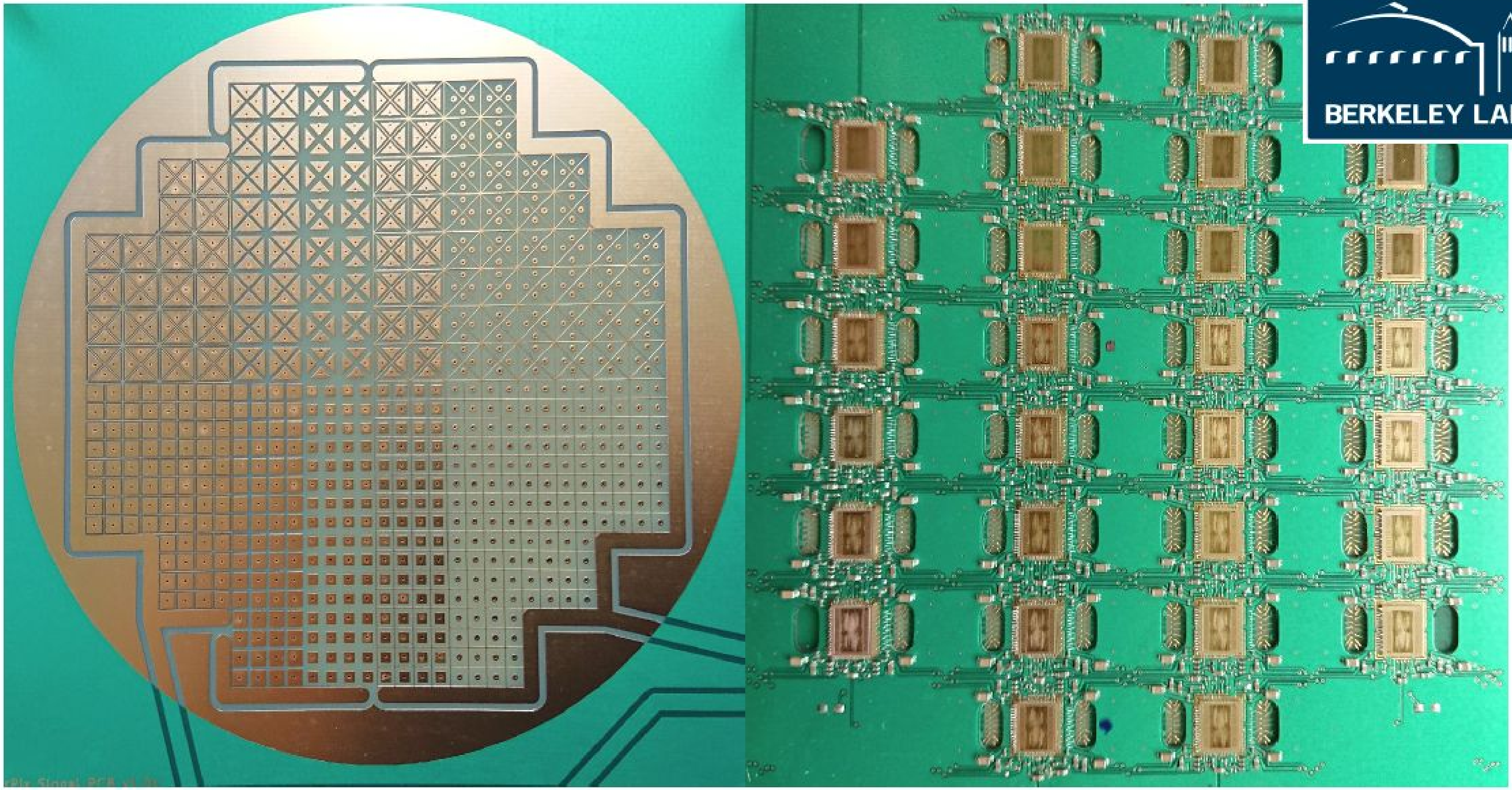
PixLAr tests at Fermilab



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

LArPix: dedicated pixel electronics for LAr TPCs

See parallel talk Friday afternoon by Dan Dwyer



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

ArgonCube 2x2

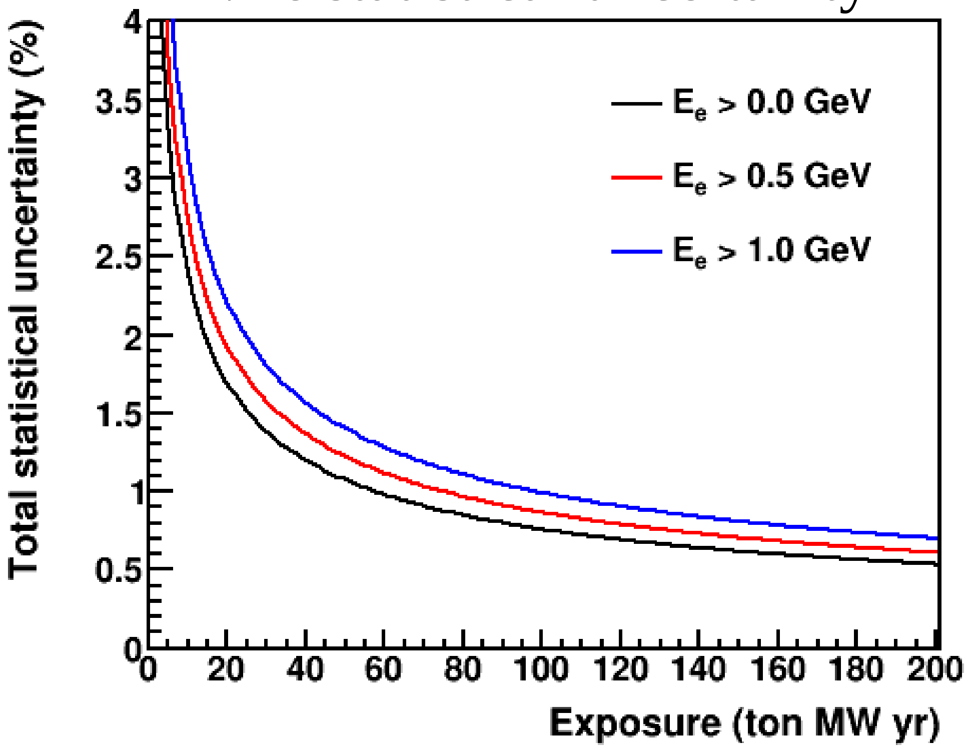
- 2x2 module prototype, each 70x70x140cm^3
- Plan to run with cosmic rays in 2019 at Bern
- Move to Fermilab and run in NuMI in 2020 as part of protoDUNE-ND

ArgonCube

LAr size and event rates

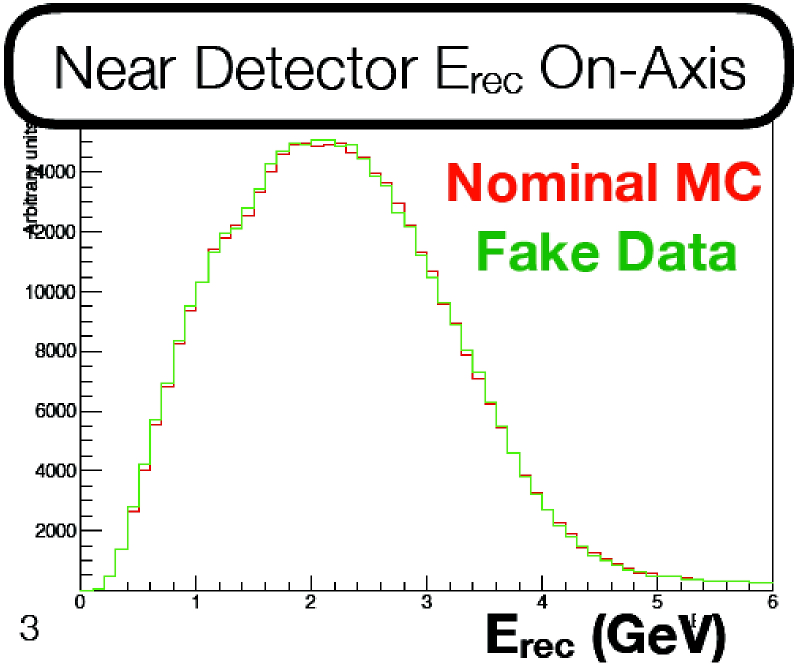
- Nominal detector size is 4x3x5m^3 active LAr, driven by hadronic shower containment
- Rates per year in FHC mode:
    - 37M ν_μ CC
    - 0.5M ν_e CC
    - 3,500 ν+e elastic scattering

ν+e statistical uncertainty

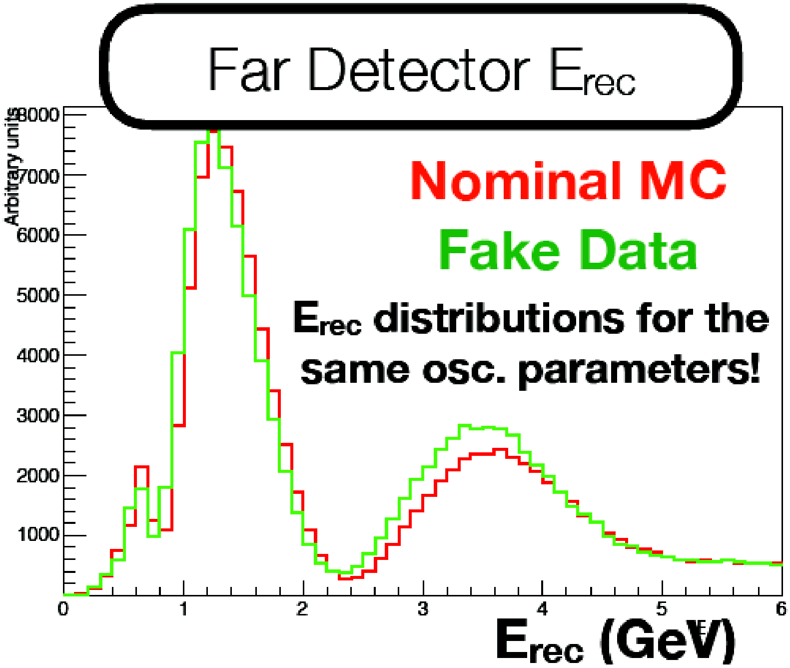


DUNE-PRISM: movable ND

- Measuring neutrino energy is complicated (neutrals, etc.)
- Neutrino-nucleus interactions have many uncertain parameters
- Possible to fit near detector data with many degenerate combinations of parameters
- But far detector has different flux, and choosing the wrong set of parameters can lead to biased oscillation parameters



Near Detector E_{rec} On-Axis

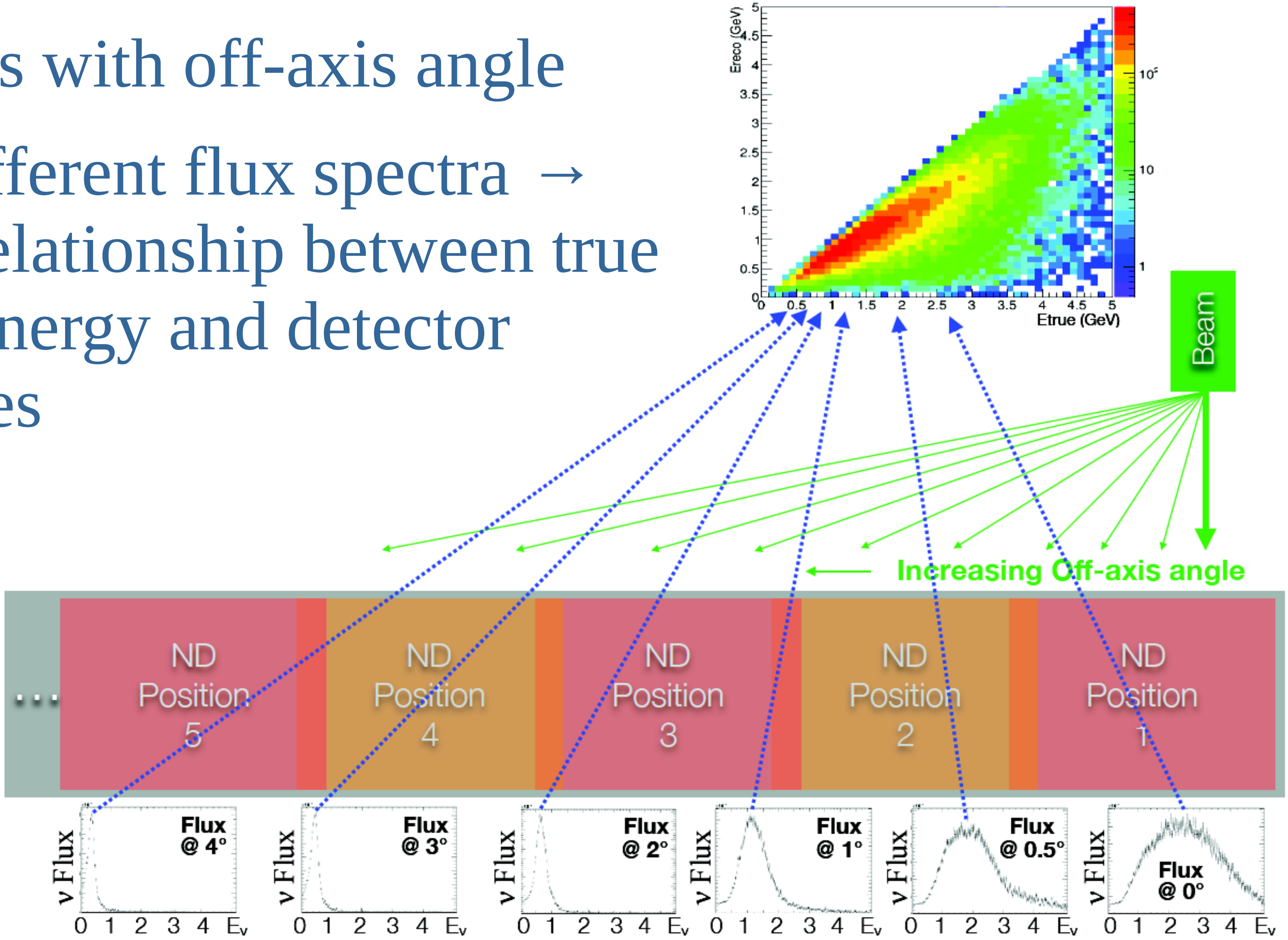


Far Detector E_{rec}

E_{rec} distributions for the same osc. parameters!

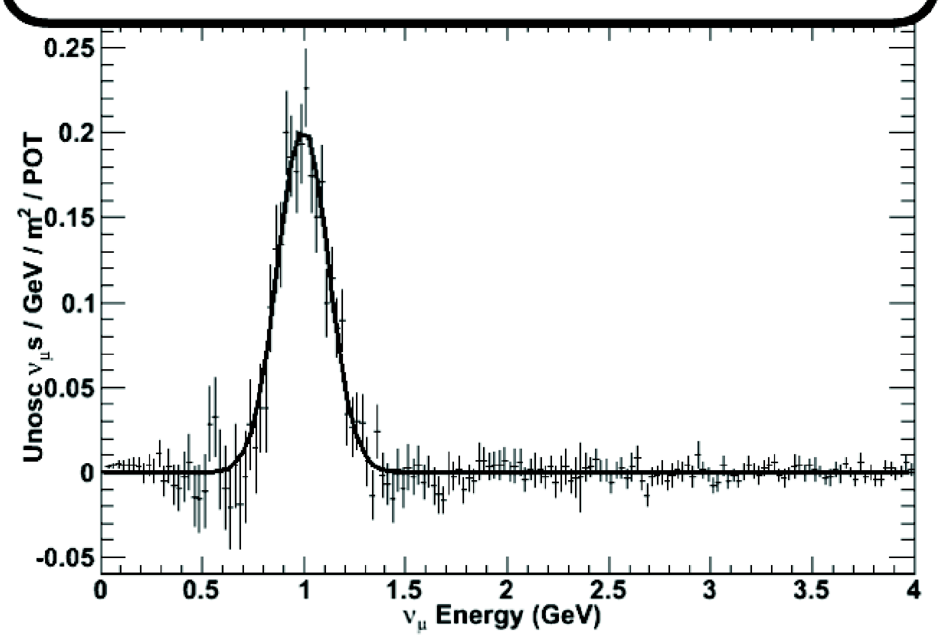
One solution: make ND measurements with many different fluxes

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

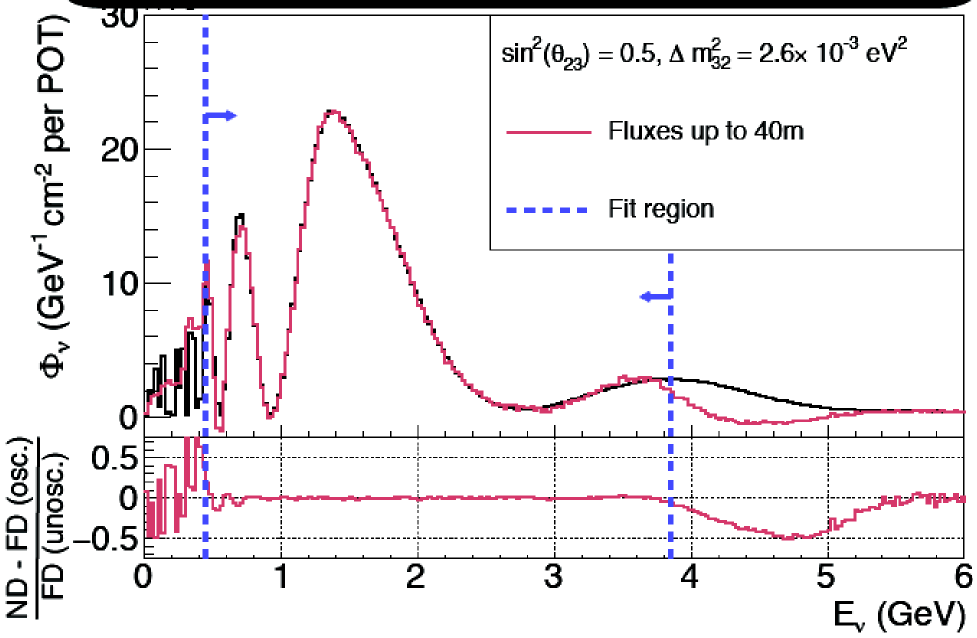


Reproduce FD flux with linear combinations of ND samples

Pseudo-Monoenergetic Beams



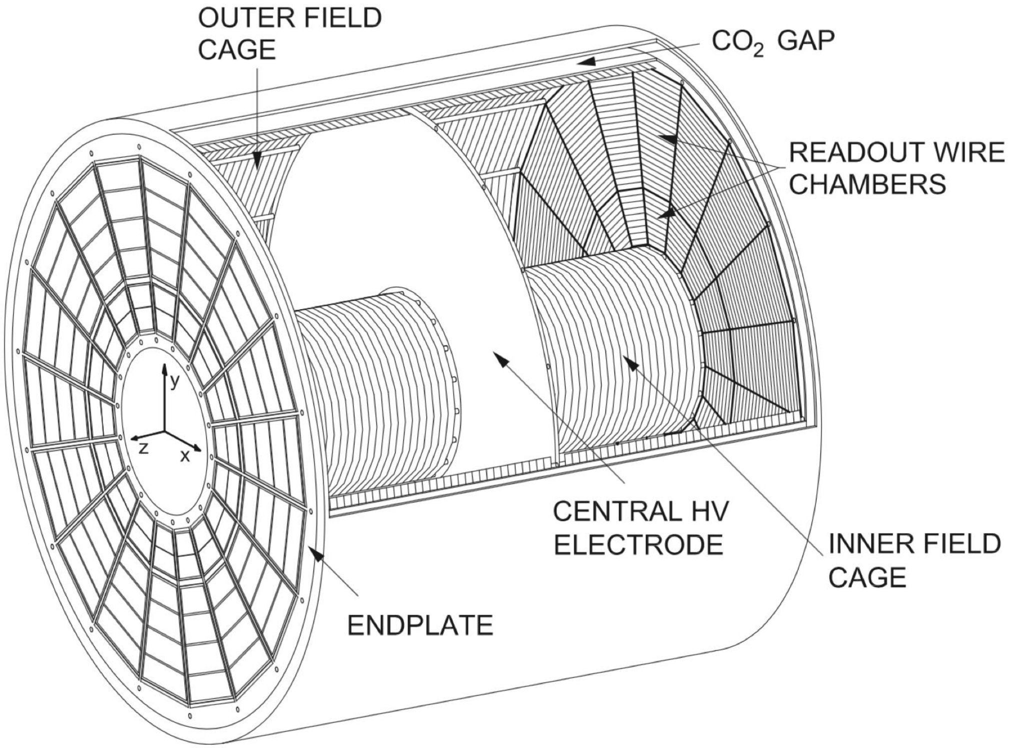
Oscillated Fluxes at the ND!



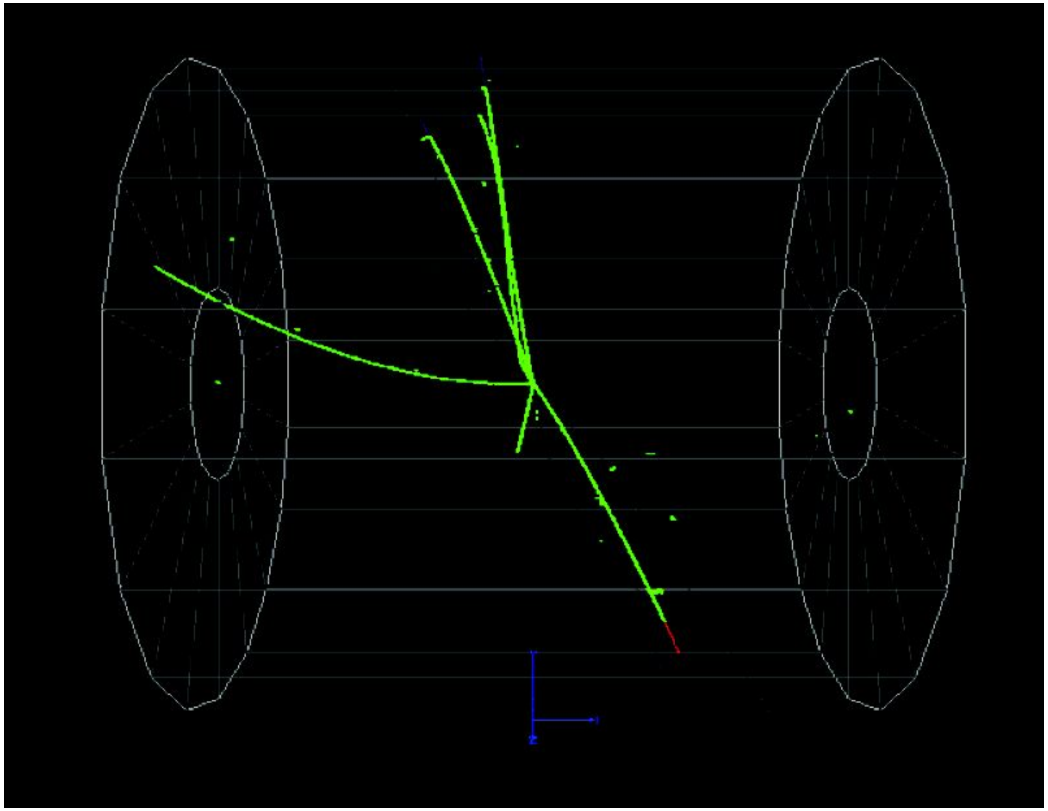
- By taking linear combinations of spectra at different off-axis angles, we can create pseudo-monoenergetic beams
- Or we can create a replica oscillated FD flux for some set of oscillation parameters

High-pressure gas TPC

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



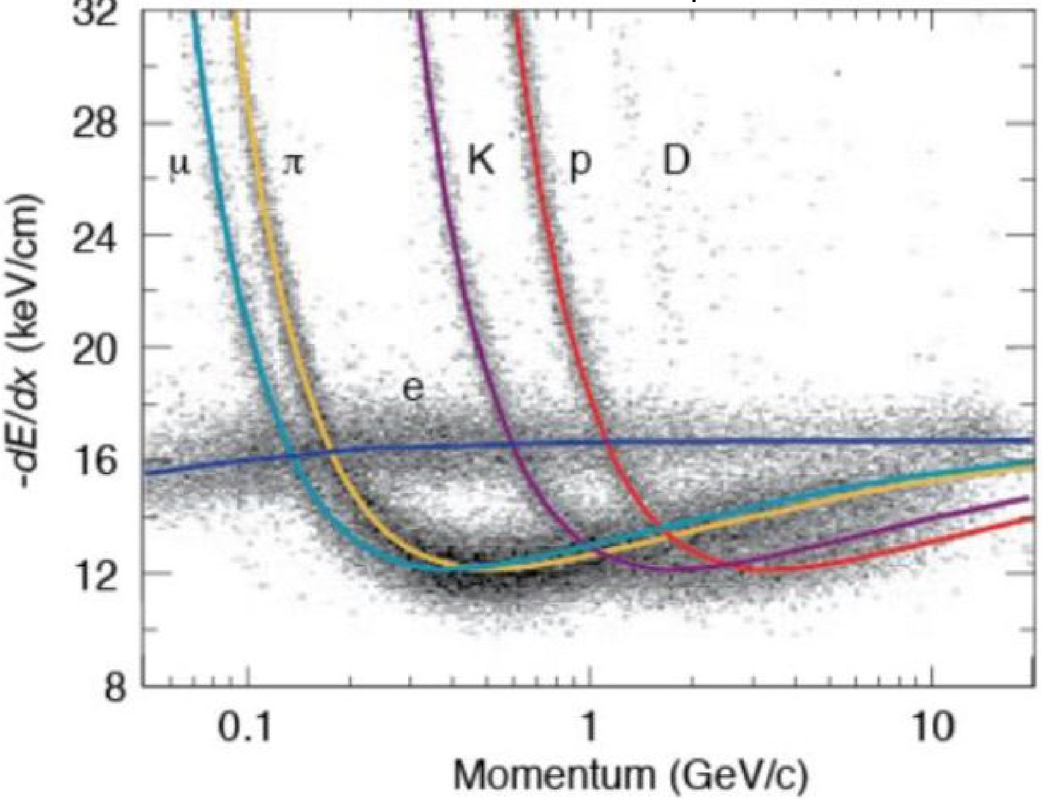
New software: GArSoft



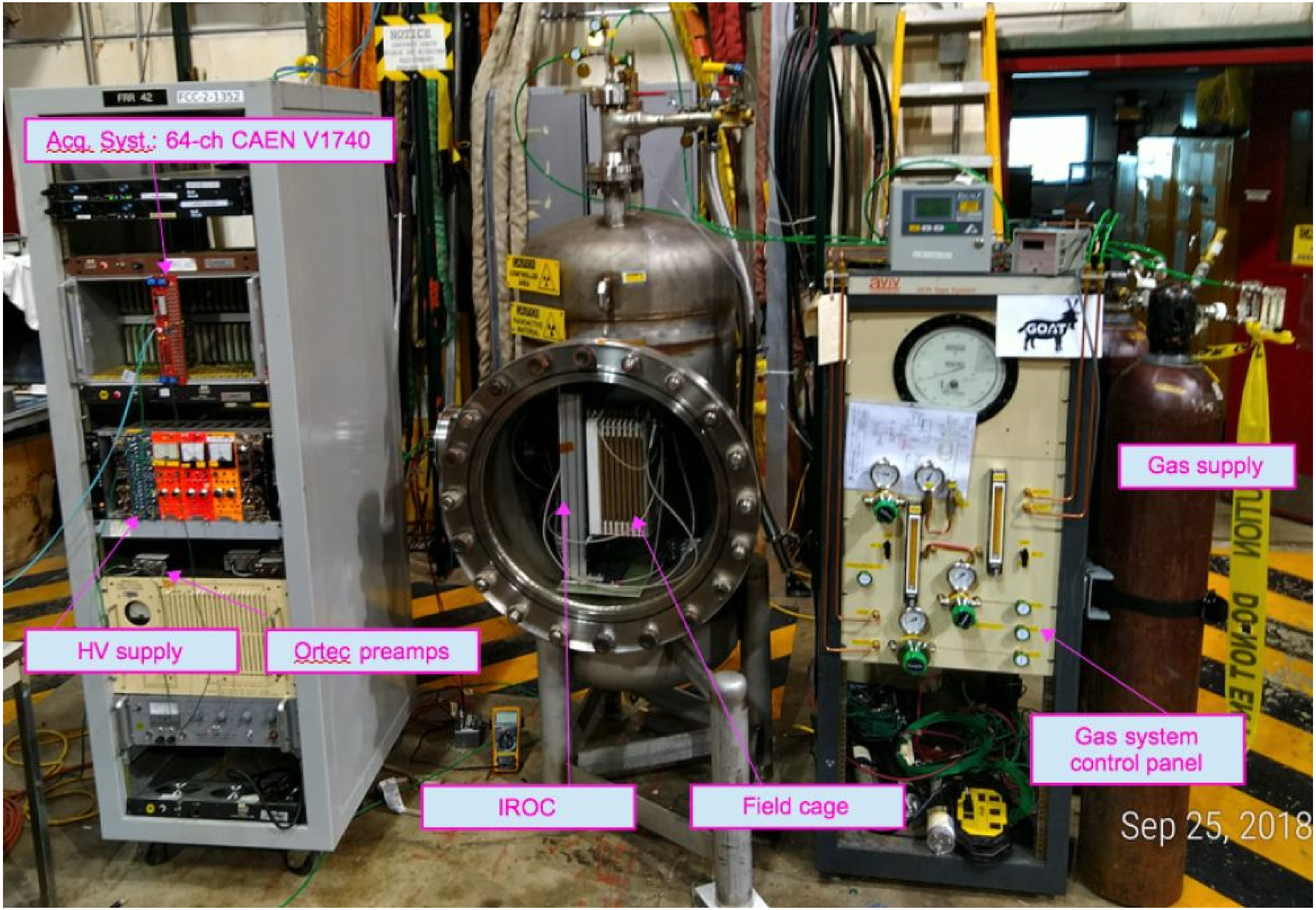
Expected performance of gas TPC based on ALICE & PEP-4 experience

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

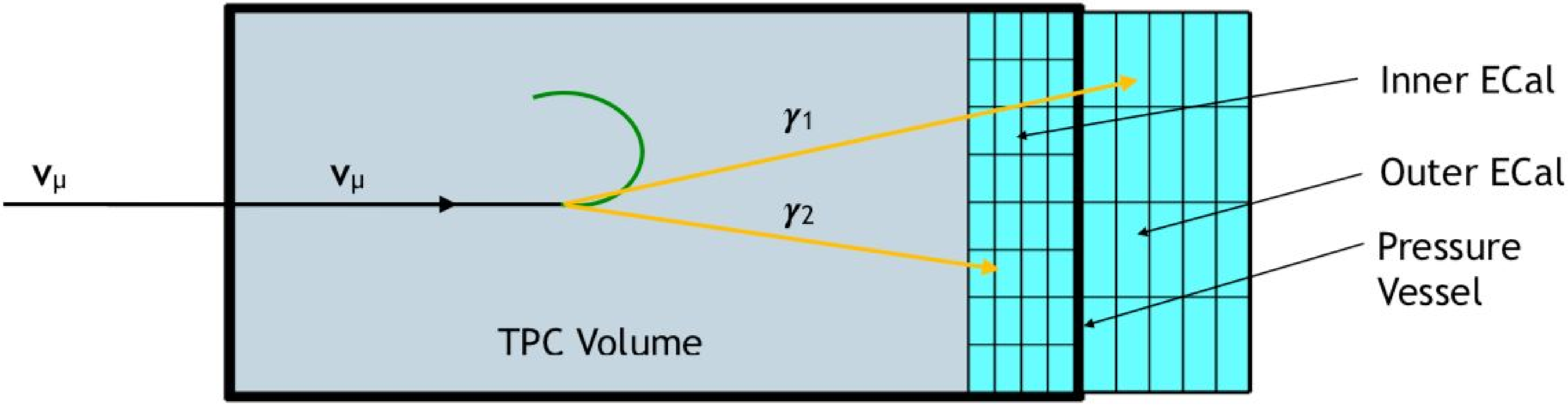
PEP-4, 80/20 Ar-CH_4 at 8.5 atm



Gas TPC test stand @Fermilab

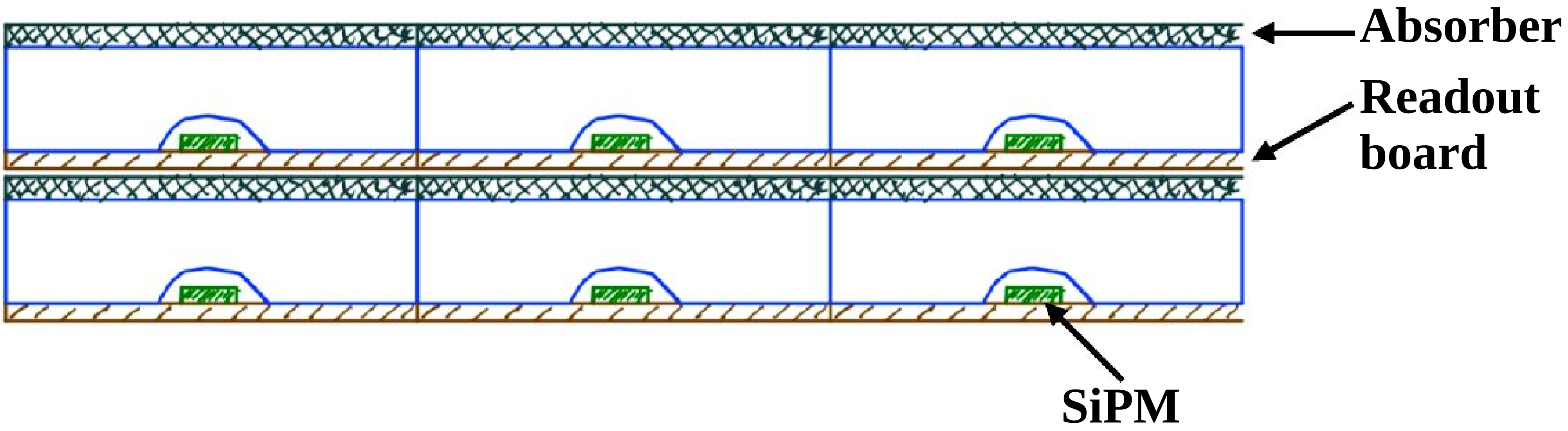


High-performance ECal



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

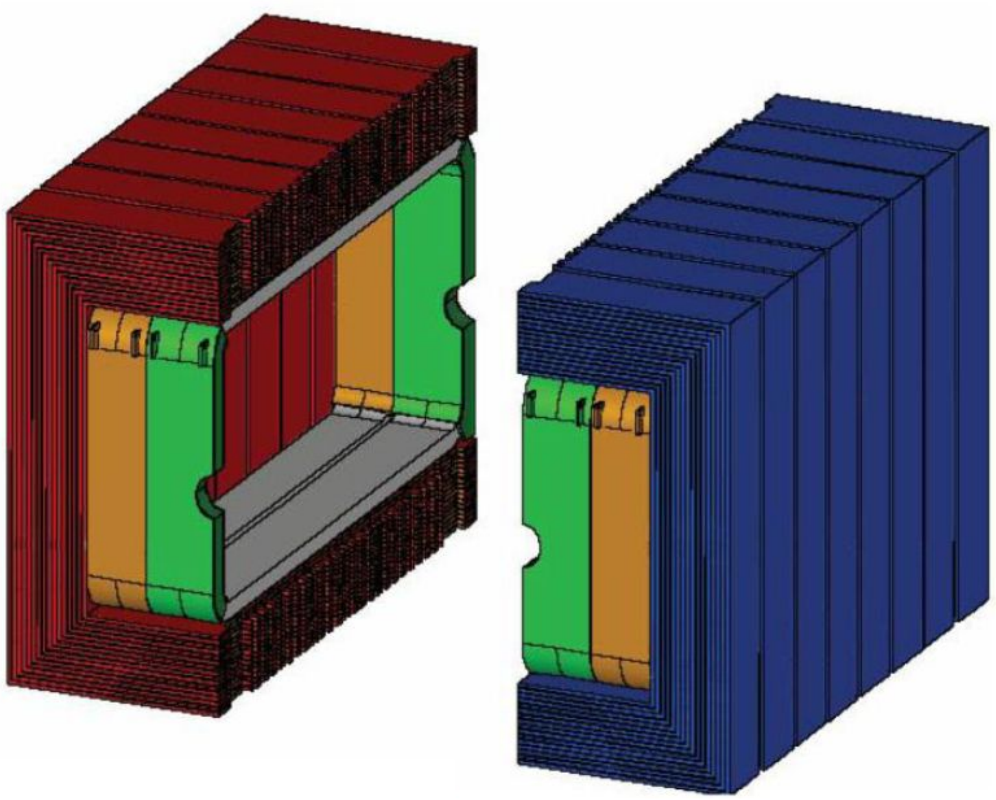
DUNE ND ECal concept

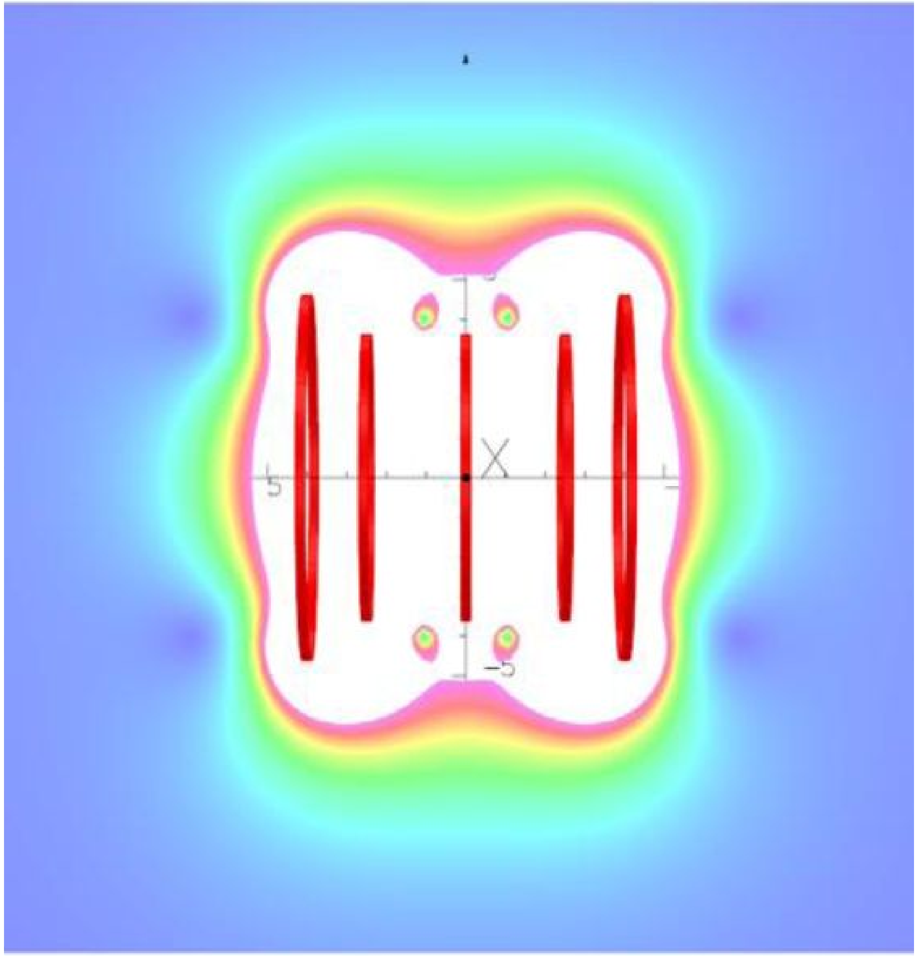


- Based on CALICE AHCAL concept
- Layers of scintillator tiles read out by SiPM
- Optimizations being performed at MPI-Munich, Mainz, DESY

Magnet

CDR reference design is UA1-like warm dipole with central field of ~0.4T, but superconducting designs are also being considered

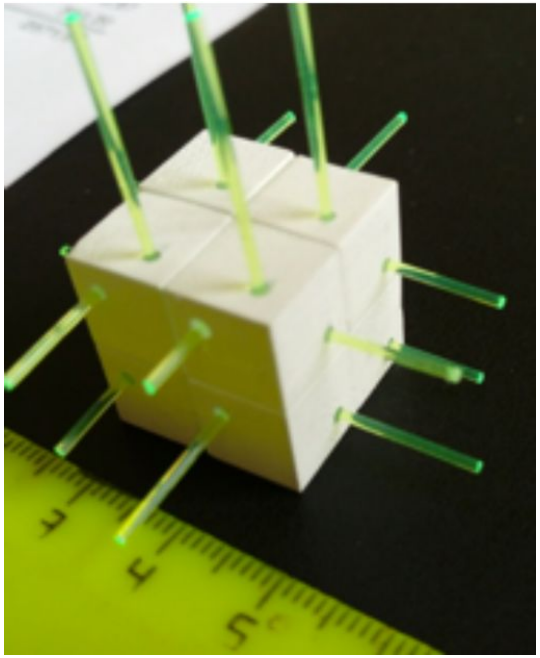




3 superconducting coils with 2 bucking coils to actively cancel stray fields to ~50 gauss

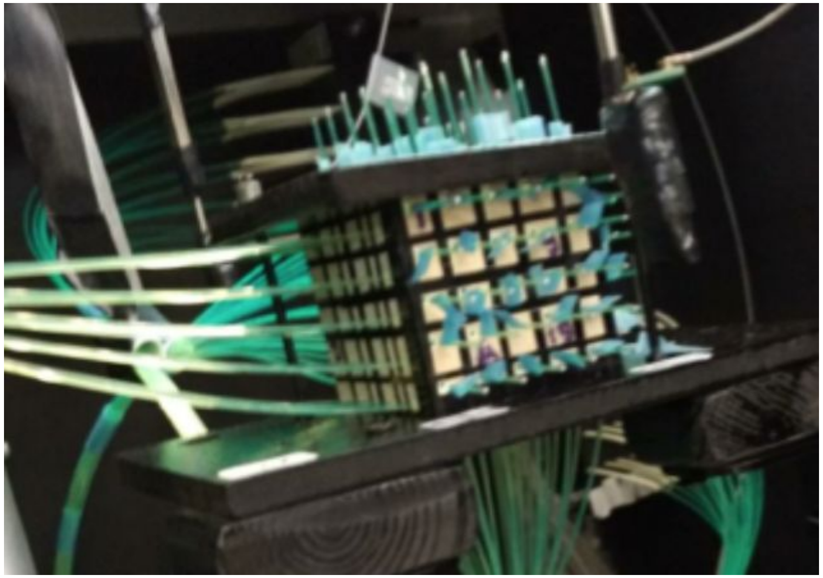
3D scintillator tracker (3DST)

- 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



Recap

- Liquid Argon TPC
  - Modular design, pixelated readout, optically segmented
  - Functionally coupled to magnetized multi-purpose tracker for muon reconstruction
  - High-statistics measurements of neutrino-Argon scattering
  - Exclusive-channel measurements at high statistics
  - Neutrino-electron elastic scattering for flux constraint
  - DUNE-PRISM: movable detector to probe $E_{true} \rightarrow E_{reco}$ by exposure to different off-axis angles

Recap

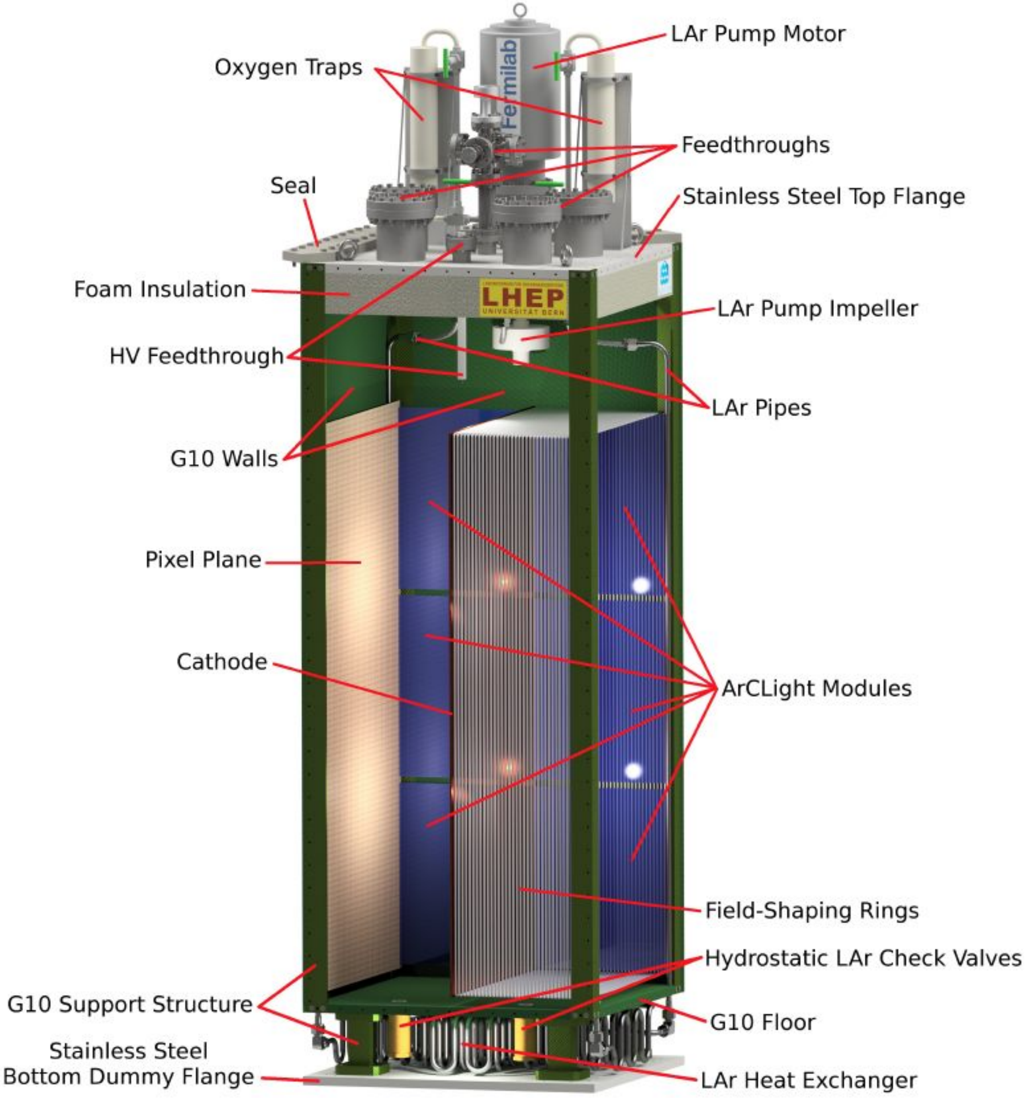
- Magnetized multi-purpose tracker
  - High-pressure gas Ar TPC: very low threshold, high-fidelity measurements of neutrino interaction vertex region
  - Excellent particle ID, energy resolution, charge selection over full phase space
  - Measure same ν-Ar interaction as in LAr TPC with very different reconstruction, systematics
  - High-performance, granular ECal for π^0 reconstruction
- 3D scintillator tracker
  - CH target, with good efficiency to detect neutrons
  - Not clear how it integrates with MPT

ND design status and next steps

- Near Detector Concept Study, Feb 2017 – Aug 2018
  - Recommendations of the group accepted by collaboration
  - Forms the basis for the concept presented in this talk
- Near Detector Design Group working toward full conceptual design report in spring 2019

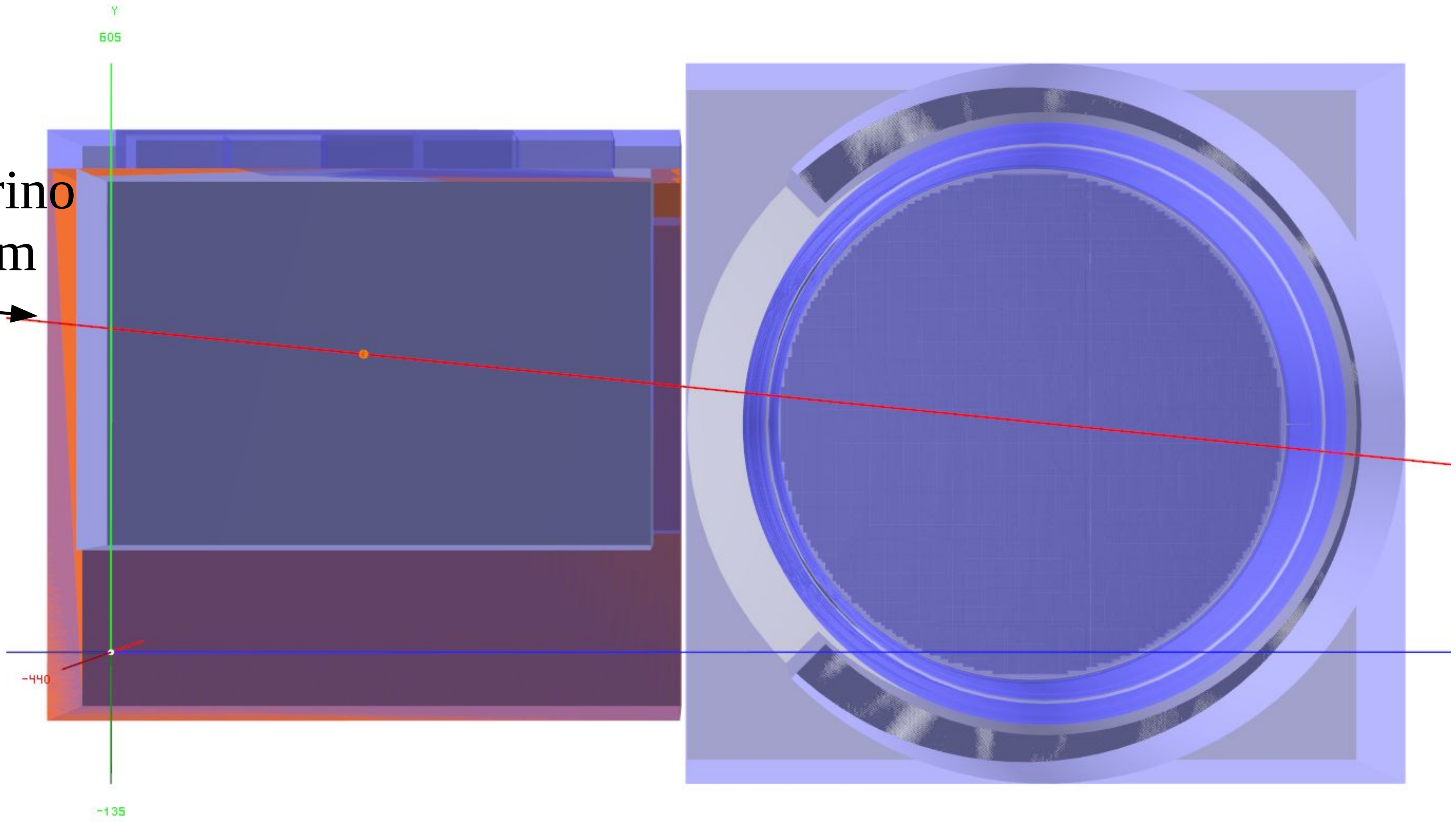
Backups

ArgonCube module



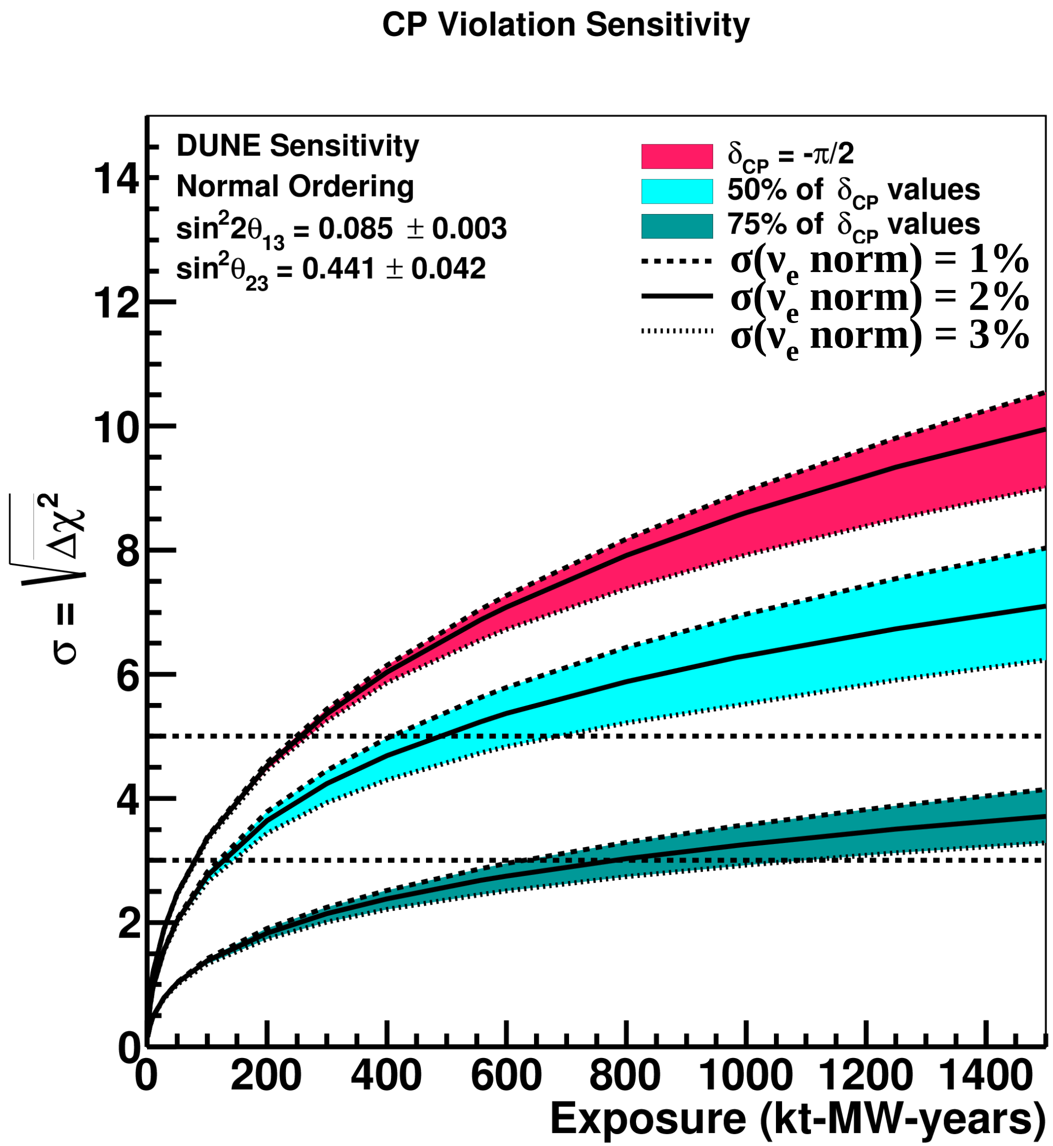
2x2 Demonstrator module.
Note, ND modules will not have individual pumps & filters

Near detector concept: Modular LAr TPC & Magnetized high-pressure gas Ar TPC



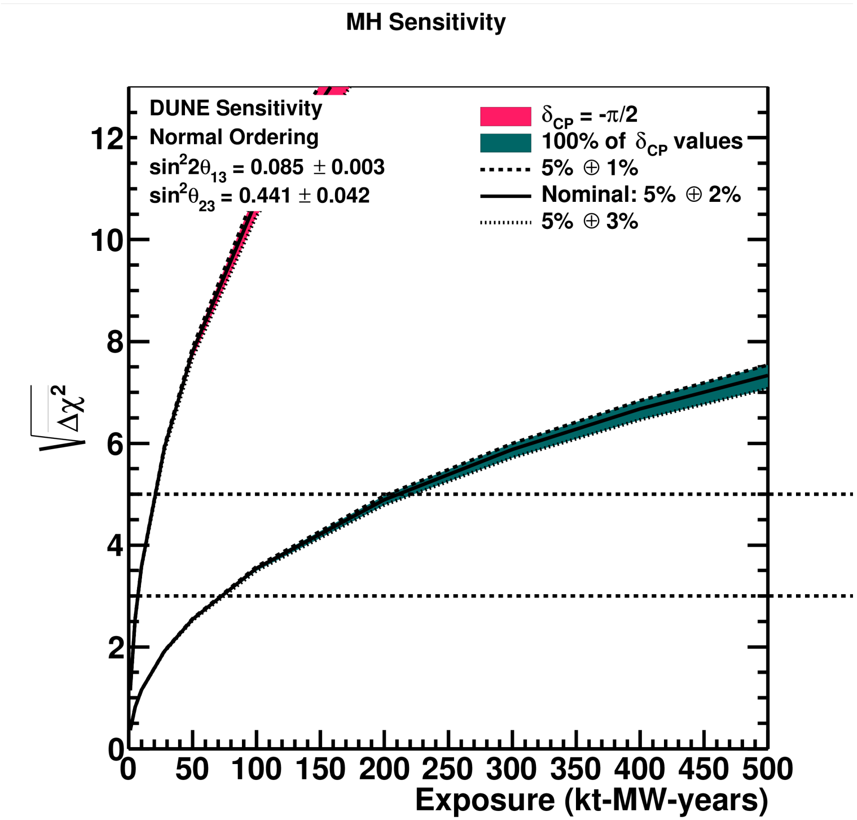
Neutrino beam

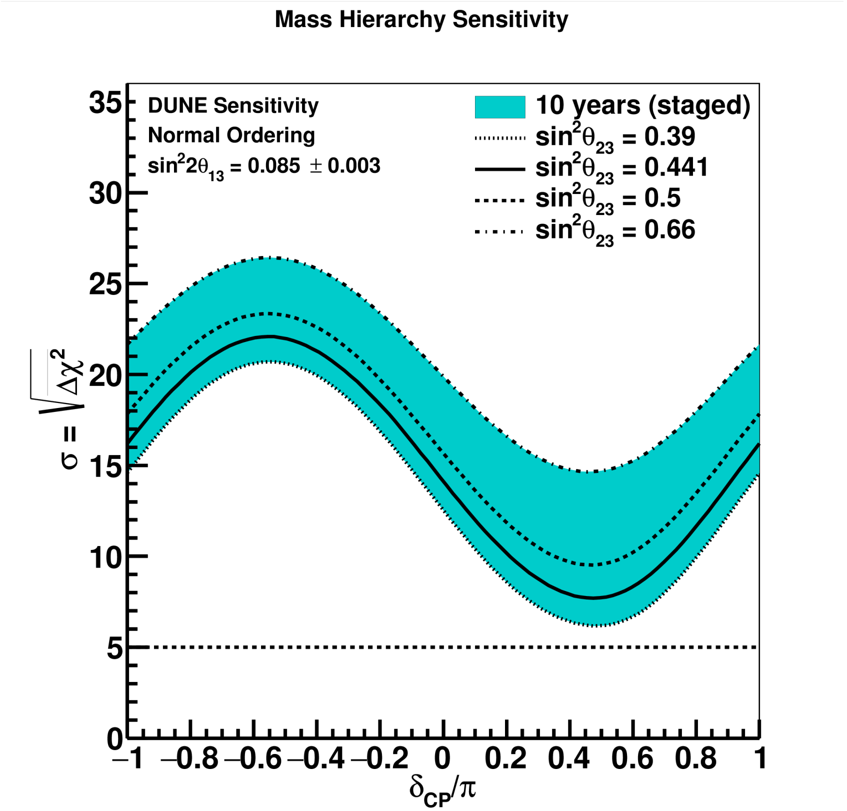
CP violation sensitivity



- 5% normalization uncertainty on ν_e sample fully correlated with ν_μ
- Shown: additional 1, 2, or 3% uncertainty on ν_e sample uncorrelated
- Going from 1% to 3% ~doubles the exposure required for 5σ measurement over 50% of δ values

Effect of systematics on MH





- Systematics have much smaller impact on mass ordering sensitivity
- CP violation is much tougher constraint – any ND that meets CP sensitivity requirements will also easily support MH measurement

Oscillation measurements

You would like to measure:

$$P(\nu_\mu \to \nu_e) = \frac{\Phi_{\nu_e}(E_{true}, L)}{\Phi_{\nu_\mu}(E_{true}, 0)}$$

$$N_{\nu_e}^{far}(E_{reco}) = \int dE_{true} \Phi_{\nu_e}(E_{true}, L) \times \sigma_{\nu_e}(E_{true}) \times \epsilon^{far}(E_{true}) \times \mathbf{D}_{\nu_e}^{far}(E_{true}, E_{reco})$$

$$N_{\nu_\mu}^{near}(E_{reco}) = \int dE_{true} \Phi_{\nu_\mu}(E_{true}, 0) \times \sigma_{\nu_\mu}(E_{true}) \times \epsilon^{near}(E_{true}) \times \mathbf{D}_{\nu_e}^{near}(E_{true}, E_{reco})$$

Oscillation measurements

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But what you actually see in the far detector is:

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The flux you want is only part of the equation...

Oscillation measurements

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σ is the neutrino-Argon interaction cross section

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ε is the detector acceptance

Oscillation measurements

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And you have to correct your observed reconstructed energy spectrum to the true energy, using a model of your detector performance

Oscillation measurements

You would like to measure:

$$P(\nu_\mu \to \nu_e) = \frac{\Phi_{\nu_e}(E_{true}, L)}{\Phi_{\nu_\mu}(E_{true}, 0)}$$

But what you actually see in the far detector is:

$$\frac{N_{\nu_e}^{far}(E_{reco}) = \int dE_{true} \Phi_{\nu_e}(E_{true}, L) \times \sigma_{\nu_e}(E_{true}) \times \epsilon^{far}(E_{true}) \times \mathbf{D}_{\nu_e}^{far}(E_{true}, E_{reco})}{N_{\nu_\mu}^{near}(E_{reco}) = \int dE_{true} \Phi_{\nu_\mu}(E_{true}, 0) \times \sigma_{\nu_\mu}(E_{true}) \times \epsilon^{near}(E_{true}) \times \mathbf{D}_{\nu_\mu}^{near}(E_{true}, E_{reco})}$$

The near detector partially cancels many uncertainties by measuring the same beam on the same target
Systematics on the differences between ND and FD remain

ND/FD differences

$$\frac{N^{far}_{\nu_e}(E_{reco}) = \int dE_{true}\,\Phi_{\nu_e}(E_{true},L)\times\sigma_{\nu_e}(E_{true})\times\epsilon^{far}(E_{true})\times\mathbf{D}^{far}_{\nu_e}(E_{true},E_{reco})}{N^{near}_{\nu_\mu}(E_{reco}) = \int dE_{true}\,\Phi_{\nu_\mu}(E_{true},0)\times\sigma_{\nu_\mu}(E_{true})\times\epsilon^{near}(E_{true})\times\mathbf{D}^{near}_{\nu_\mu}(E_{true},E_{reco})}$$

Solid angle effects make the flux different at ND and FD

ND measures ν_μ cross sections, FD measures ν_e scattering
Lepton mass differences give different allowed phase space

ND is smaller, so acceptance may be less than at FD, and acceptance may be different for μ and e

Reconstruction differences may give rise to differences in the reco → true energy relationship

Staging plan

- Year 0: 2 modules (20kt), 1.2 MW beam
- Year 1-2: 3 modules (30kt), 1.2 MW beam
- Year 3-9: 4 modules (40kt), 1.2 MW beam
- Year 10+: 4 modules (40kt), 2.4 MW beam