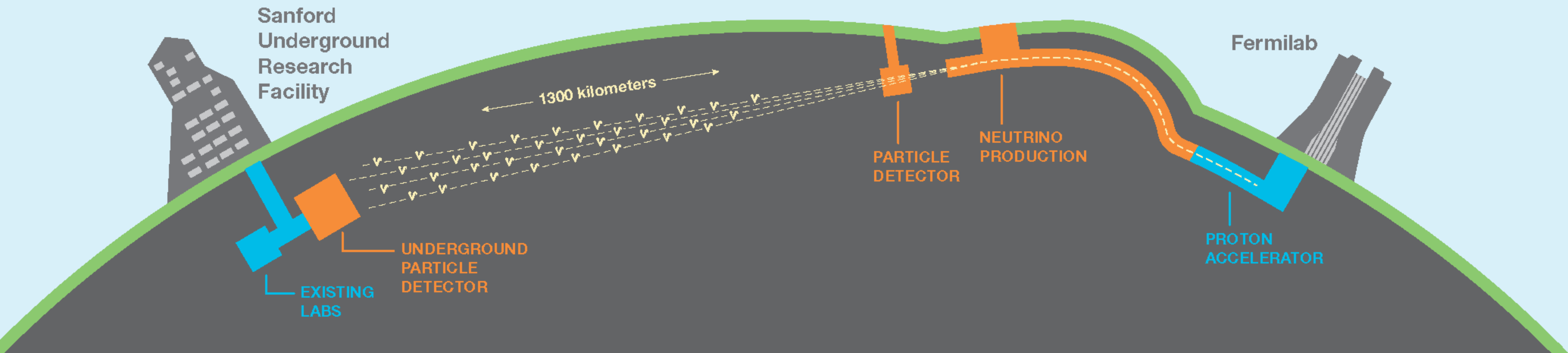
SEARCHING FOR PHYSICS BEYOND THE STANDARD MODEL WITH DUNE

Justo Martín-Albo (Harvard University)
for the DUNE Collaboration

DPF2019 • Northeastern University, 31 July 2019

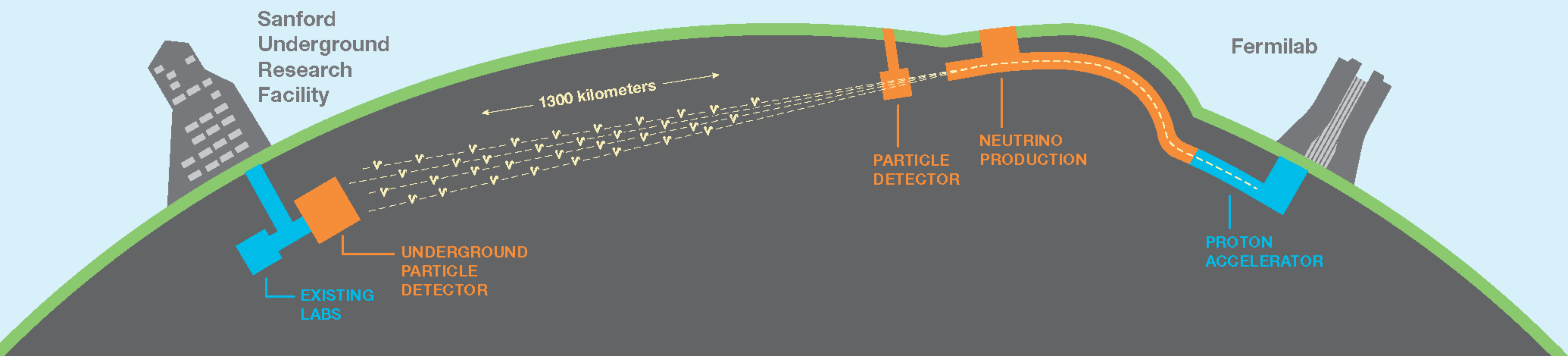
The *Deep Underground Neutrino Experiment* is a next-generation long-baseline oscillation experiment between Fermilab (Illinois) and the *Sanford Underground Research Facility* (South Dakota) consisting of

- a new MW-scale neutrino beamline (LBNF);
- a 4×10-kiloton (fiducial) liquid argon far detector;
- a high-resolution, high-rate near detector.



The science program of DUNE includes:

- Long-baseline neutrino oscillations.
  - Leptonic CP violation.
  - Neutrino mass ordering.
  - Precision test of the 3-neutrino mixing framework.
- Neutrino astrophysics (detection of core-collapse supernovae).
- Nucleon decay and other searches for physics beyond the Standard Model (BSM).

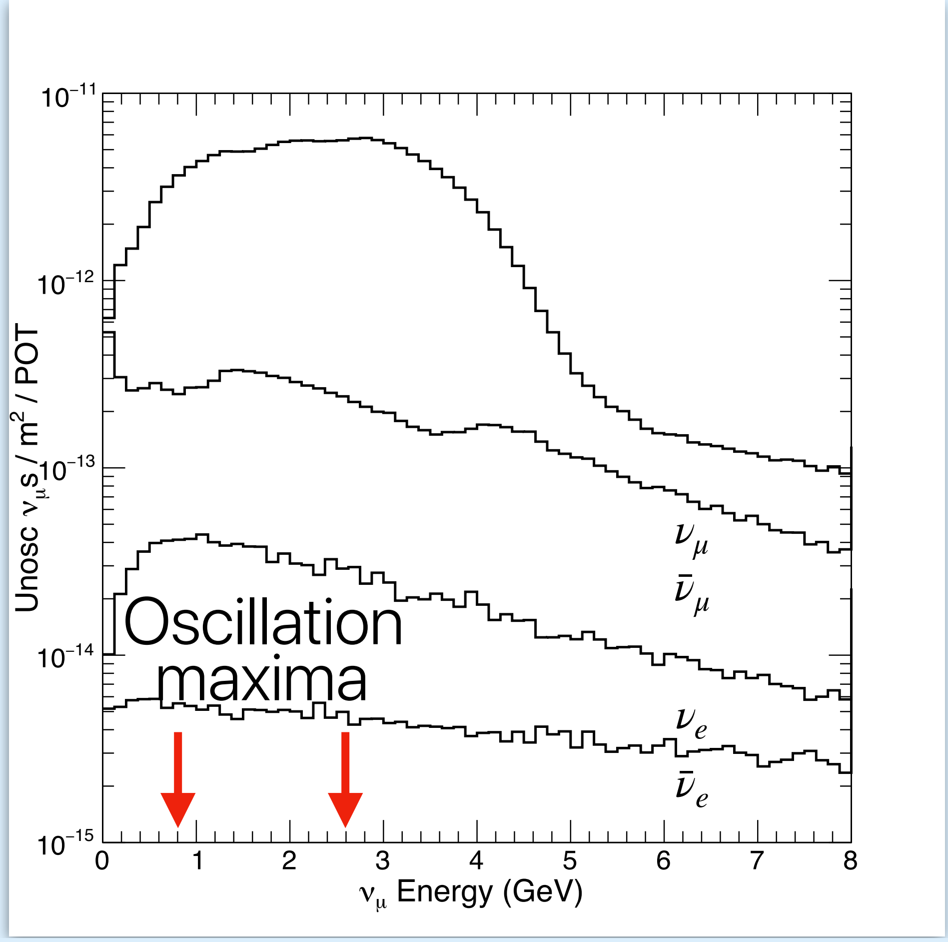


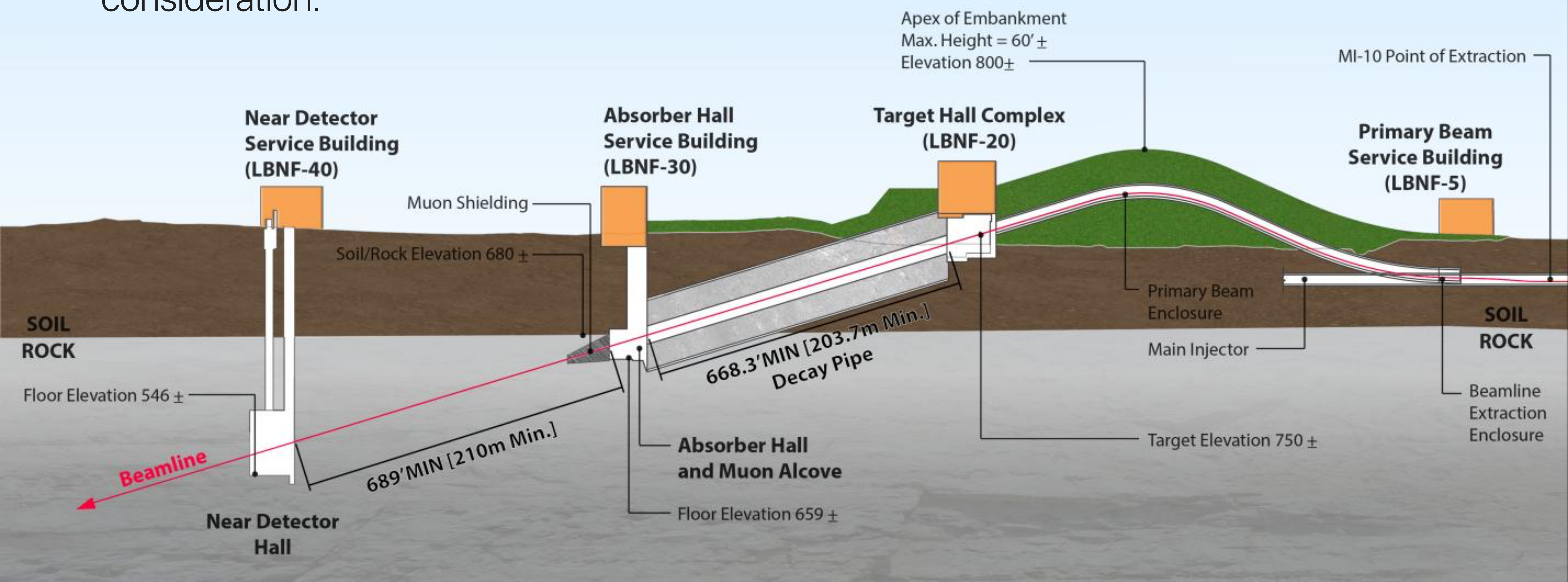
LBNF NEUTRINO BEAM

It will use protons (60–120 GeV) from Fermilab's Main Injector with an initial power of 1.2 MW (~10^{14} POT/s), upgradeable later to 2.4 MW.

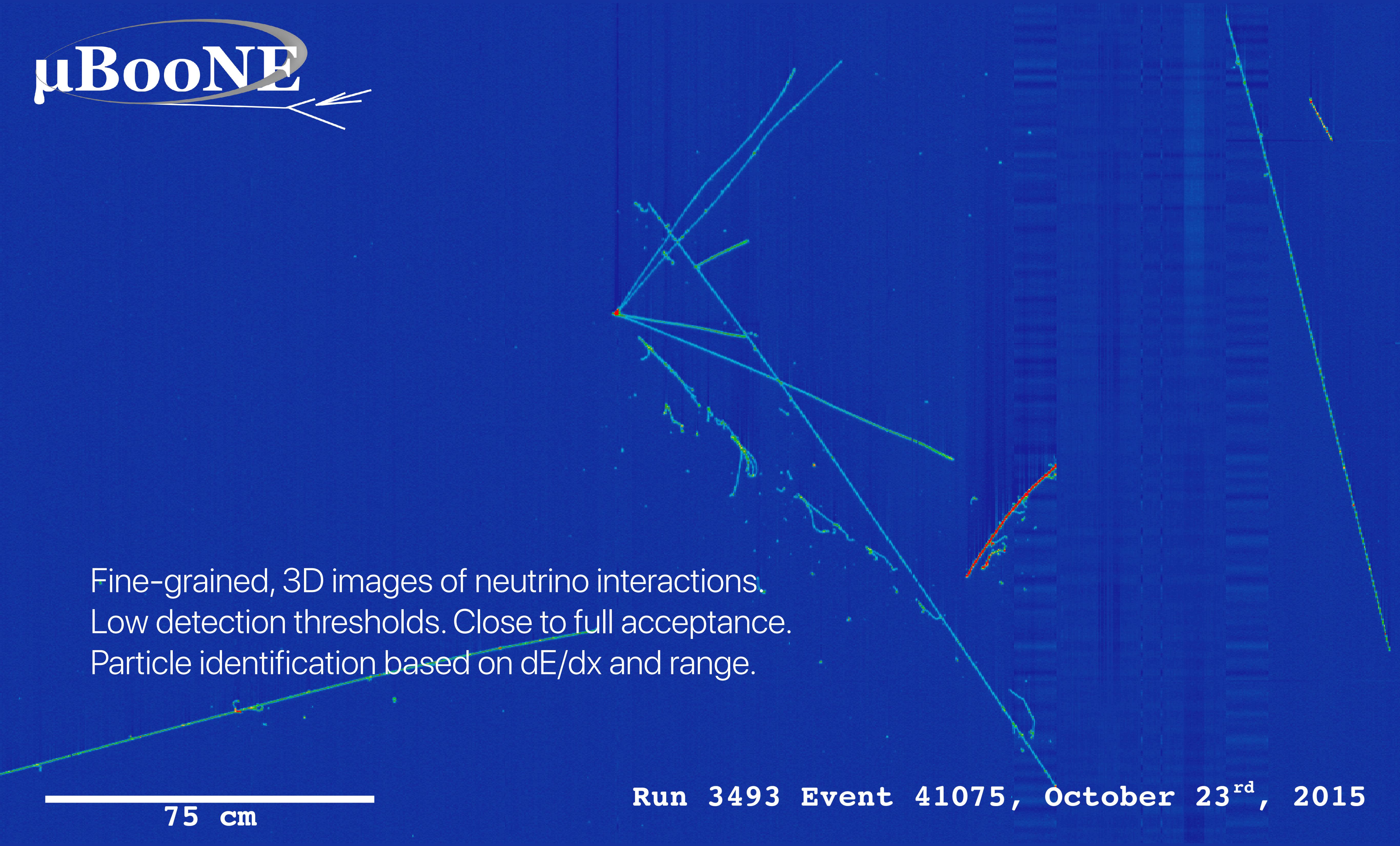
It can run in neutrino and antineutrino modes by switching the polarity of the magnetic horns.

The wide-band beam enables the use of the first and second oscillation maxima and enhances probing of new BSM phenomena. A higher-energy tune is under consideration.



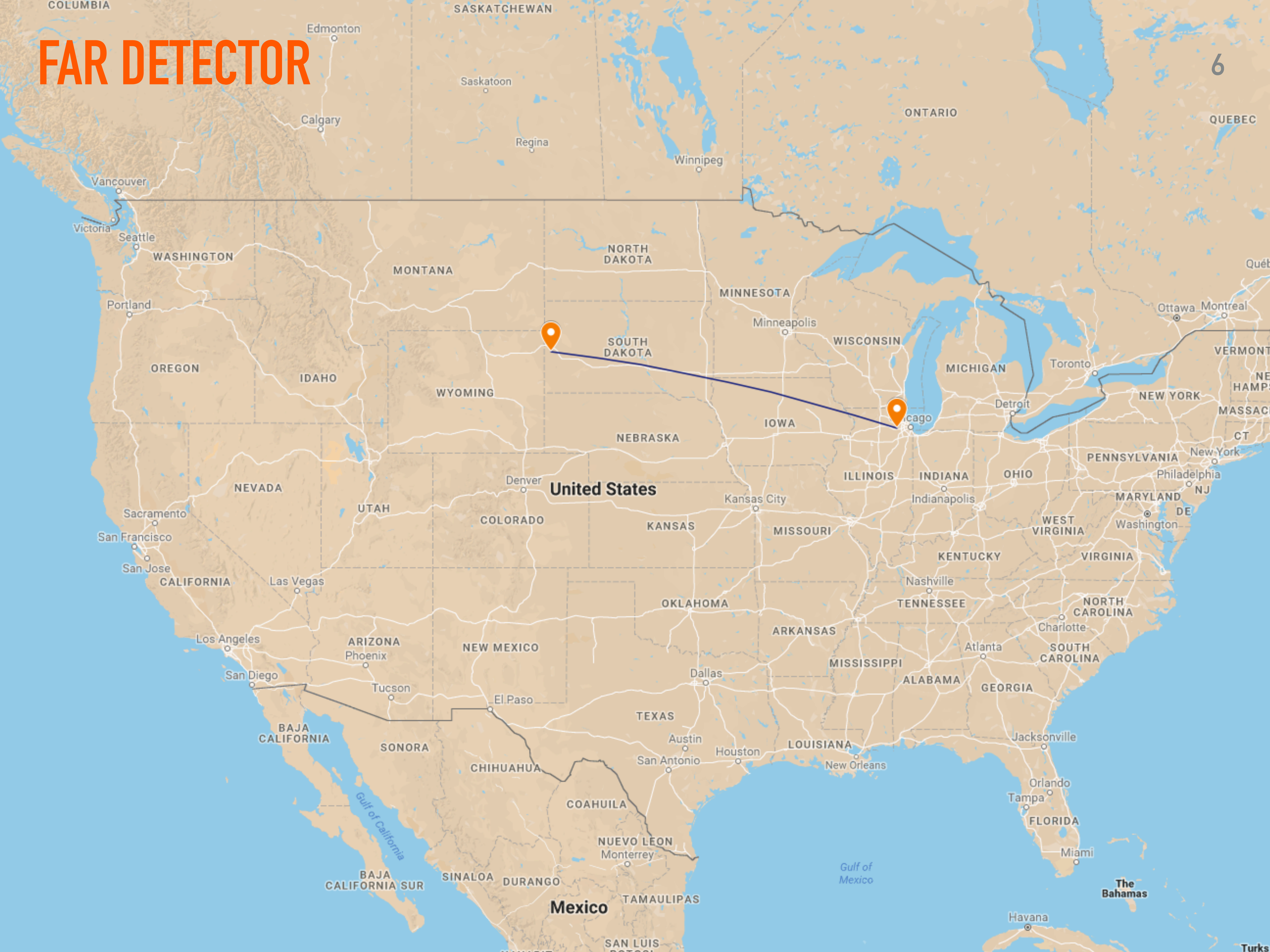


FAR DETECTOR: LIQUID ARGON TPC

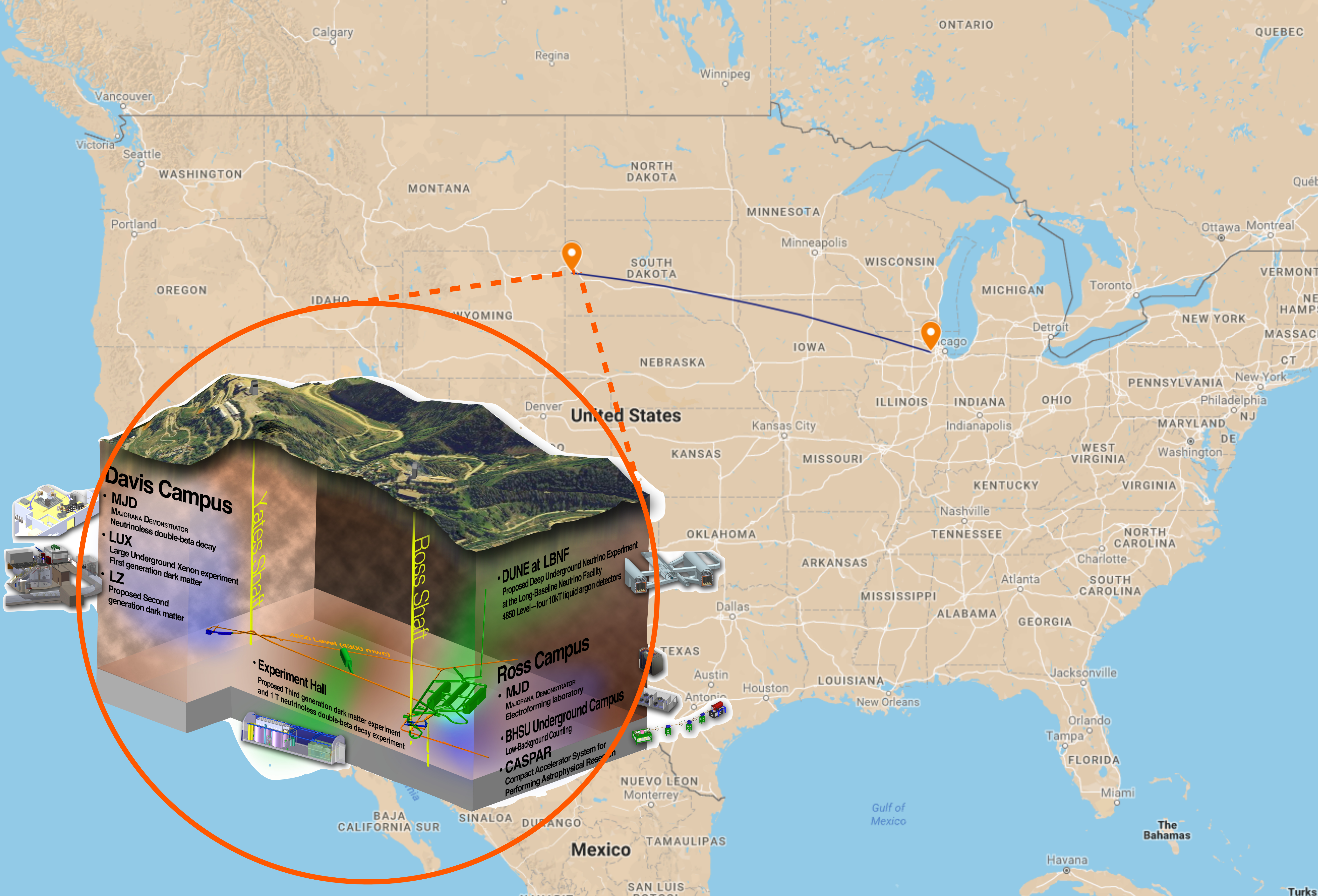


Fine-grained, 3D images of neutrino interactions.
Low detection thresholds. Close to full acceptance.
Particle identification based on dE/dx and range.

FAR DETECTOR

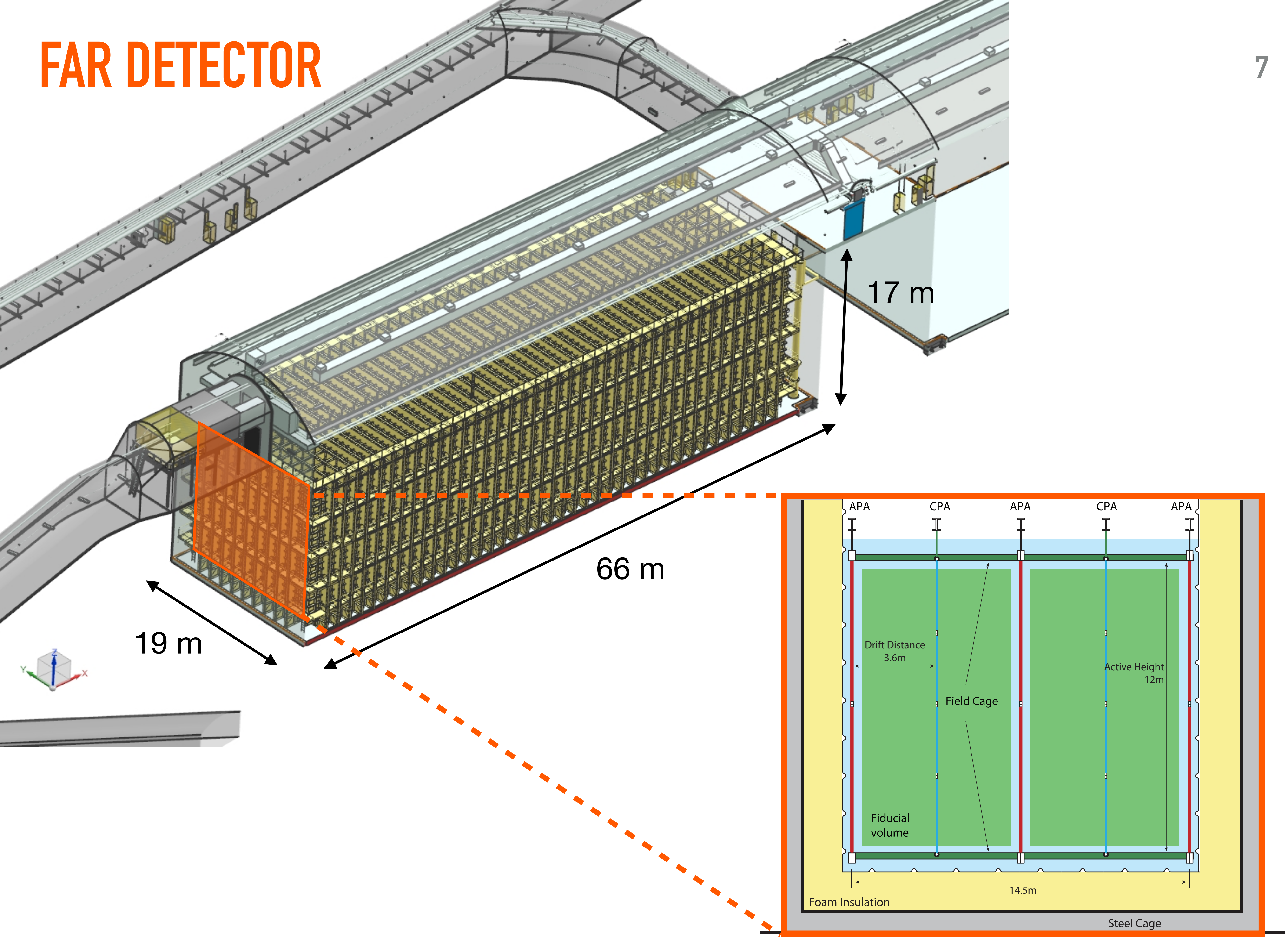


FAR DETECTOR



FAR DETECTOR

FAR DETECTOR



NEAR DETECTOR

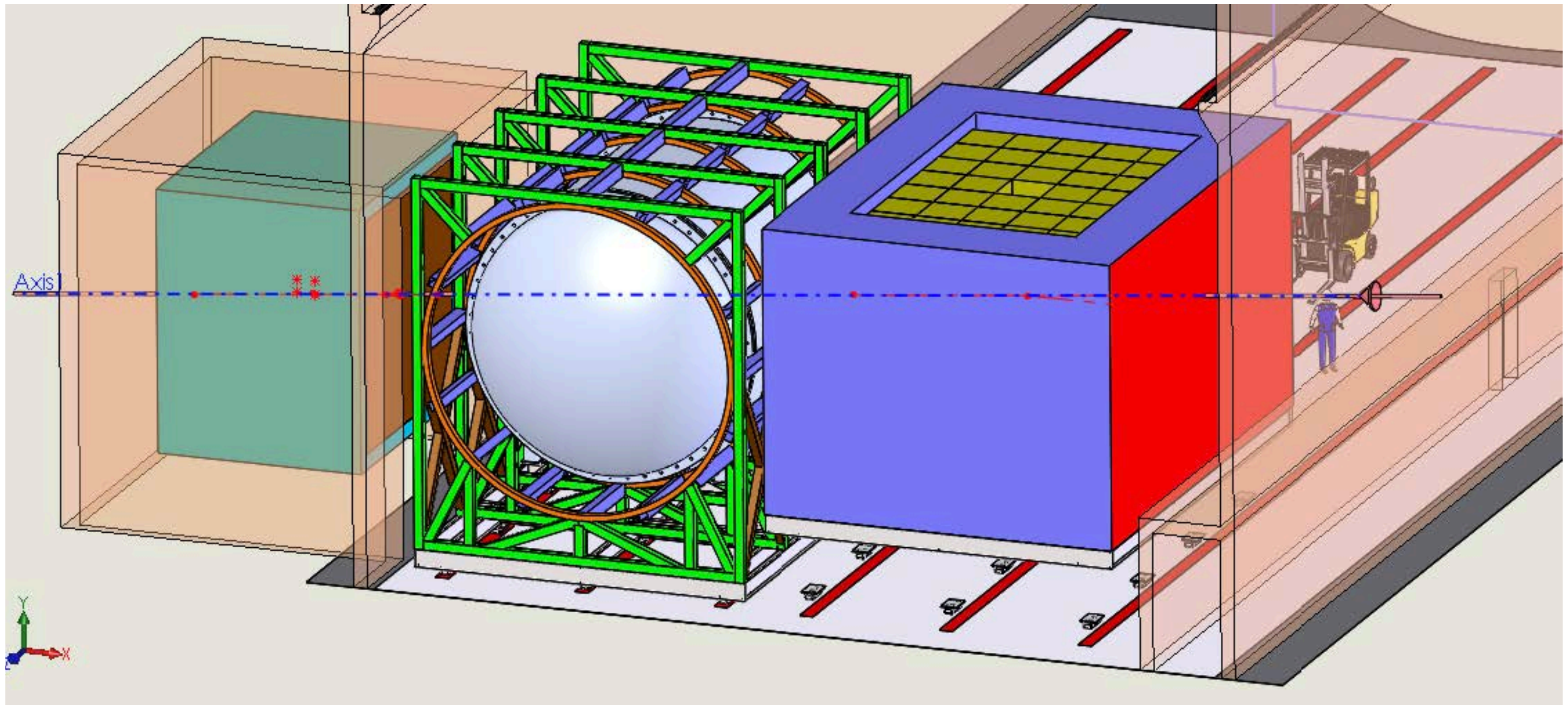
Control of systematic uncertainties affecting the long-baseline oscillation analysis by precise measurements of the neutrino flux and interaction cross sections.

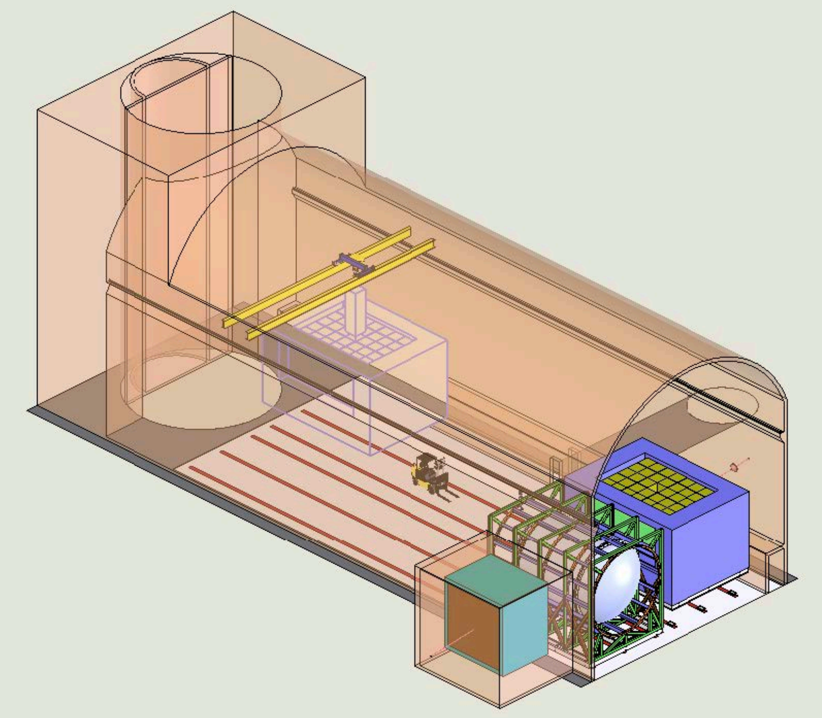
The preliminary conceptual design includes three sub-detectors (right to left):

- A LArTPC (50–100 tonnes) with pixelated readout.
- A magnetised, high-pressure gaseous TPC (HPgTPC).
- A magnetised three-dimensional scintillator tracker (3DST).

The design includes the possibility of taking data at varying off-axis positions, exposing the ND to neutrino fluxes with different spectra.

- Handle to deconvolve the neutrino flux and cross section.





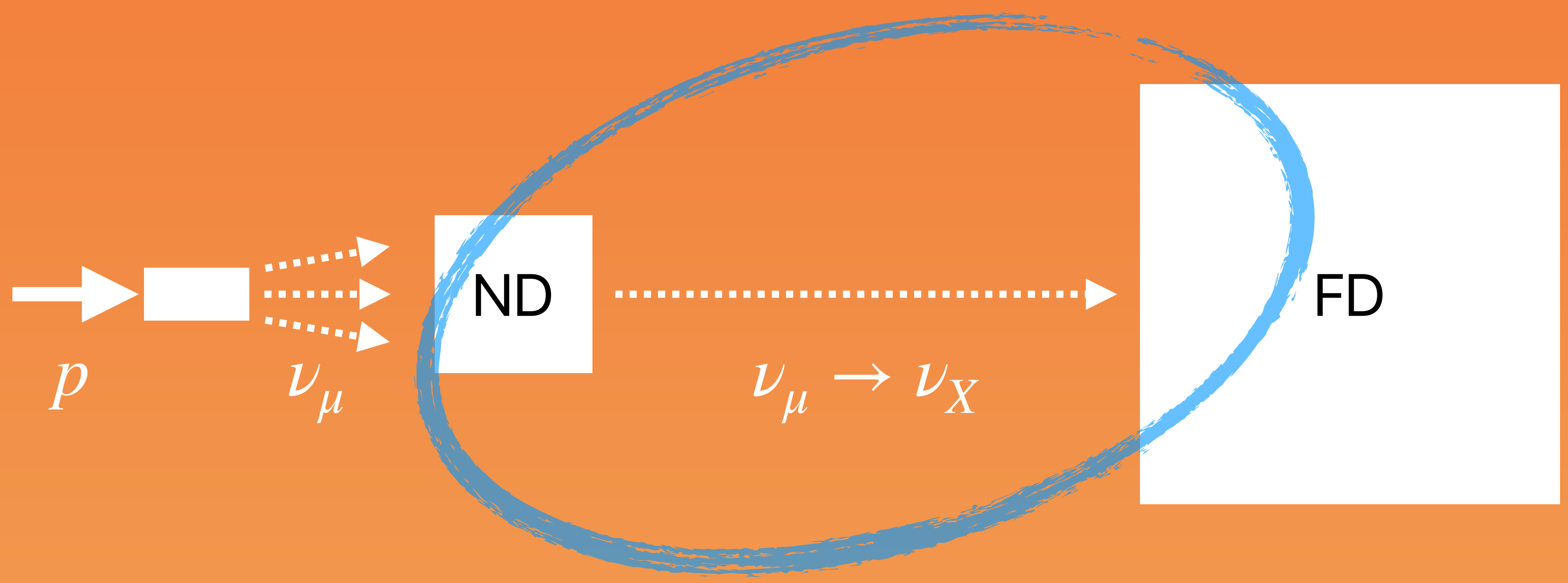
BSM PHYSICS IN DUNE

Topics investigated include:

- Non-standard short-baseline and long-baseline oscillation phenomena: mixing with sterile neutrinos, non-standard neutrino interactions, non-unitarity of the mixing matrix*, CPT violation.
- Searches for new phenomena at the FD benefitting from its large mass and resolution: boosted dark matter, nucleon decay*.
- Searches for new phenomena/particles at the ND related to the beam and its interactions with the detector: trident interactions, heavy neutral leptons*, low-mass dark matter.

(*Not discussed in this talk.)

NON-STANDARD
NEUTRINO OSCILLATIONS

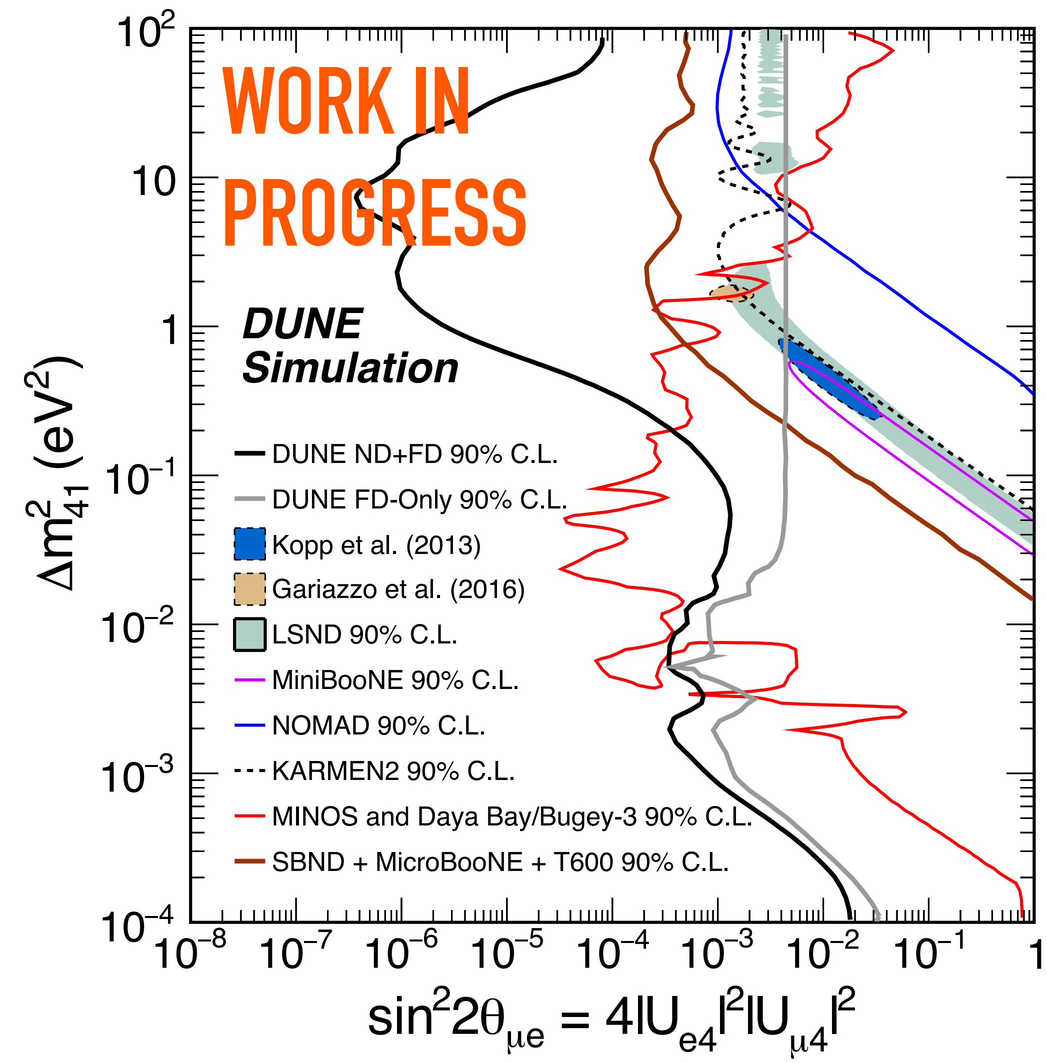


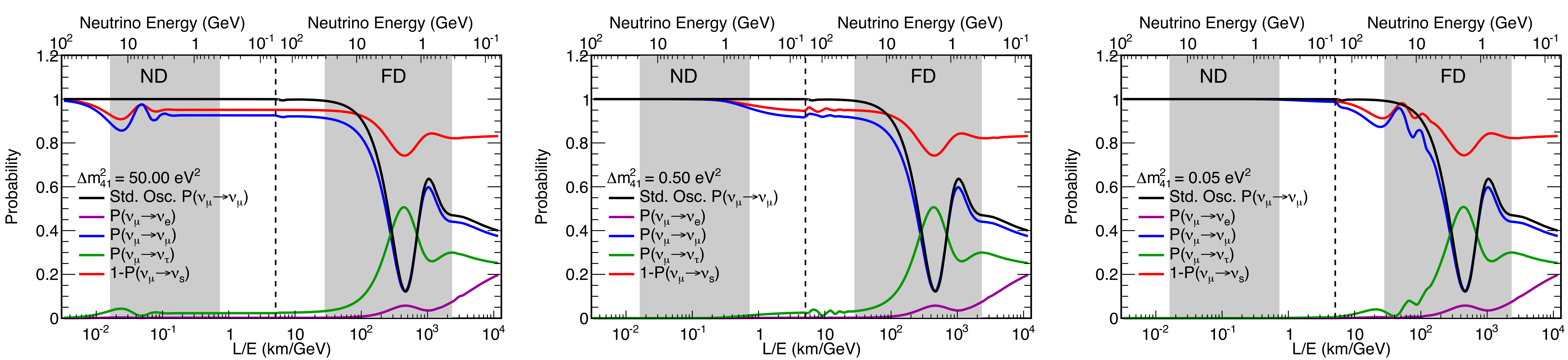
STERILE NEUTRINO MIXING

Sterile (right-handed) neutrinos are a prediction of many BSM models explaining the origin of neutrino masses.

Active-to-sterile neutrino mixing distorts the standard oscillation probabilities. DUNE will be sensitive to this effect through the combined analysis of the ν_μ and ν_e spectra from both the near and far detectors.

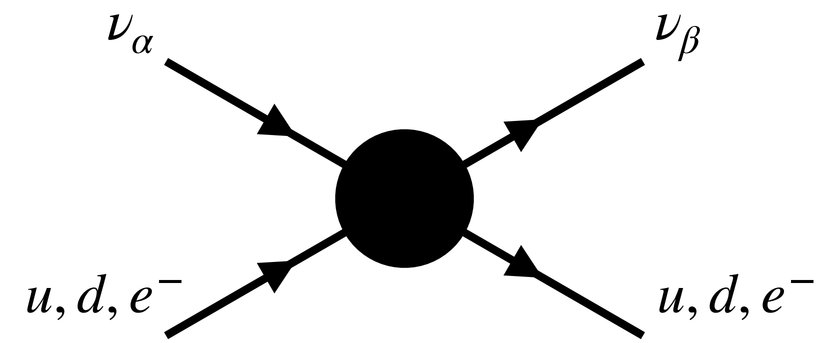
Potentially, DUNE could look as well for non-standard ν_τ appearance or use the atmospheric sample from the far detector.



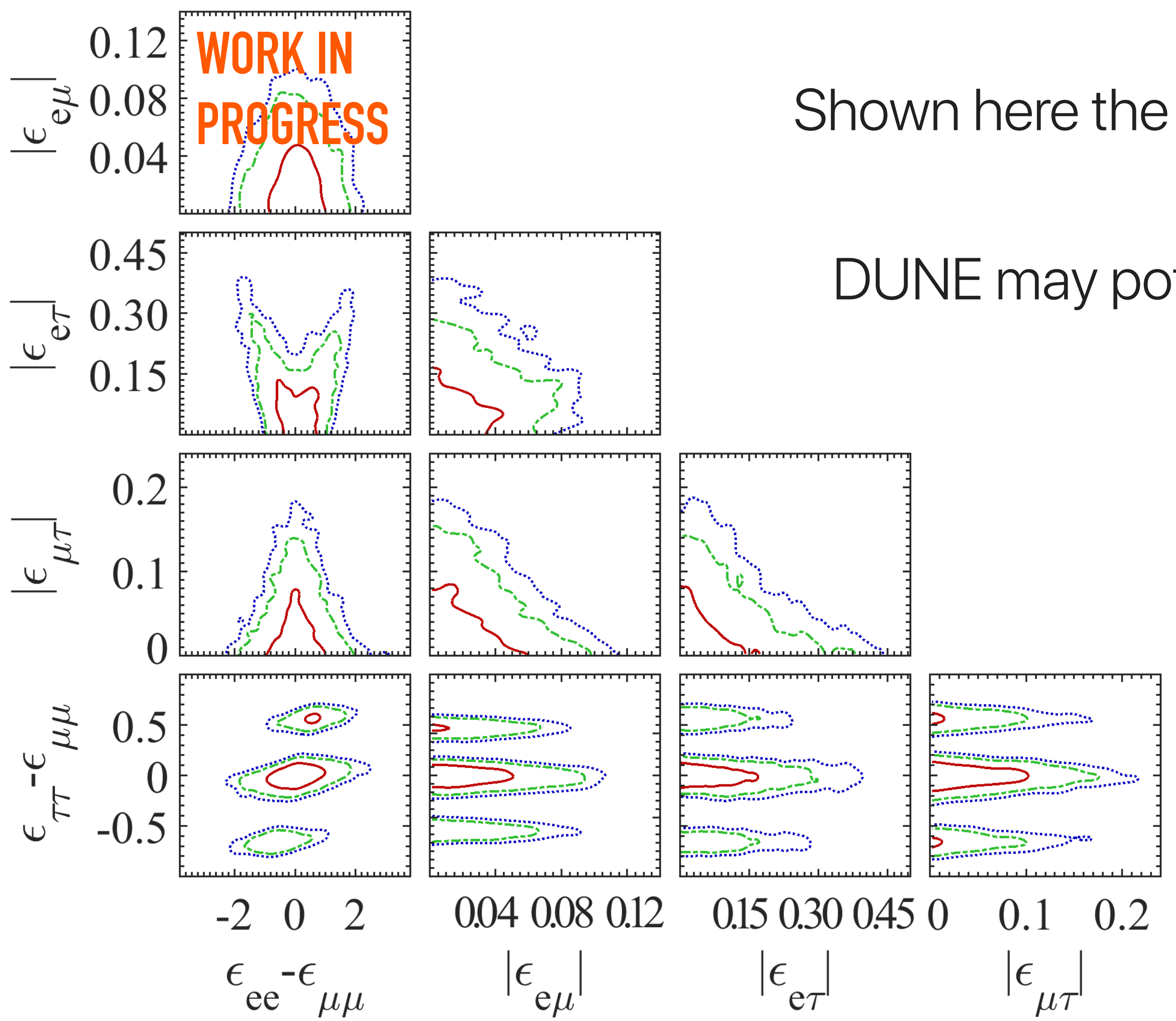


NON-STANDARD NEUTRINO INTERACTIONS

Non-standard interactions (NSI) in propagation can be described as new contributions to the MSW effect:

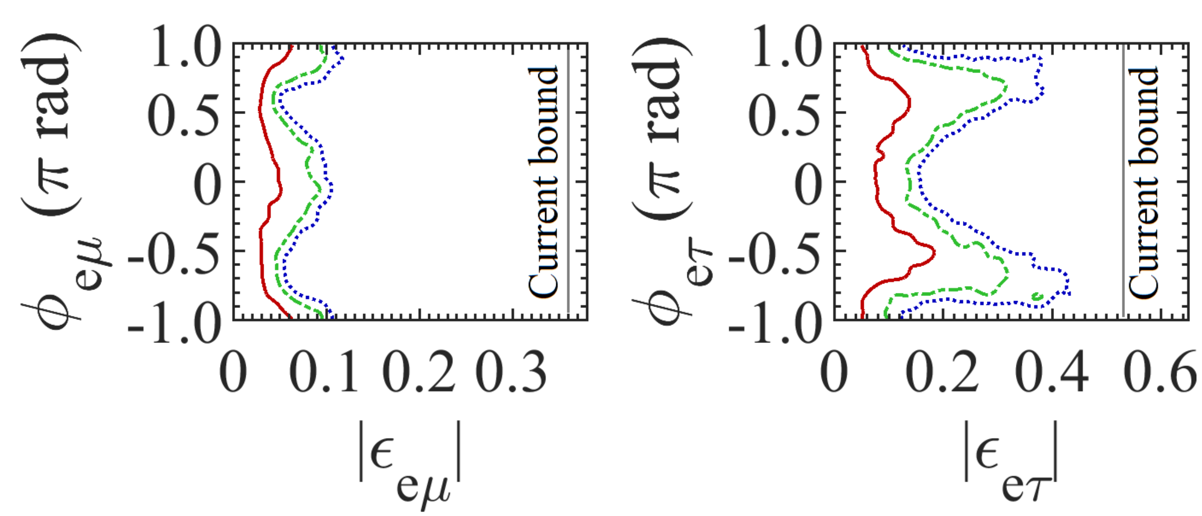


$$H = U \begin{pmatrix} 0 & & \\ & \Delta m^2_{21}/2E & \\ & & \Delta m^2_{31}/2E \end{pmatrix} U^\dagger + \tilde{V}_{\mathrm{MSW}}\,, \quad \tilde{V}_{\mathrm{MSW}} = \sqrt{2} G_F N_e \begin{pmatrix} 1+\epsilon^m_{ee} & \epsilon^m_{e\mu} & \epsilon^m_{e\tau} \\ \epsilon^{m*}_{e\mu} & \epsilon^m_{\mu\mu} & \epsilon^m_{\mu\tau} \\ \epsilon^{m*}_{e\tau} & \epsilon^{m*}_{\mu\tau} & \epsilon^m_{\tau\tau} \end{pmatrix}$$



Shown here the allowed regions (68, 90 and 95% CL) for an exposure of 300 kton·MW·year.

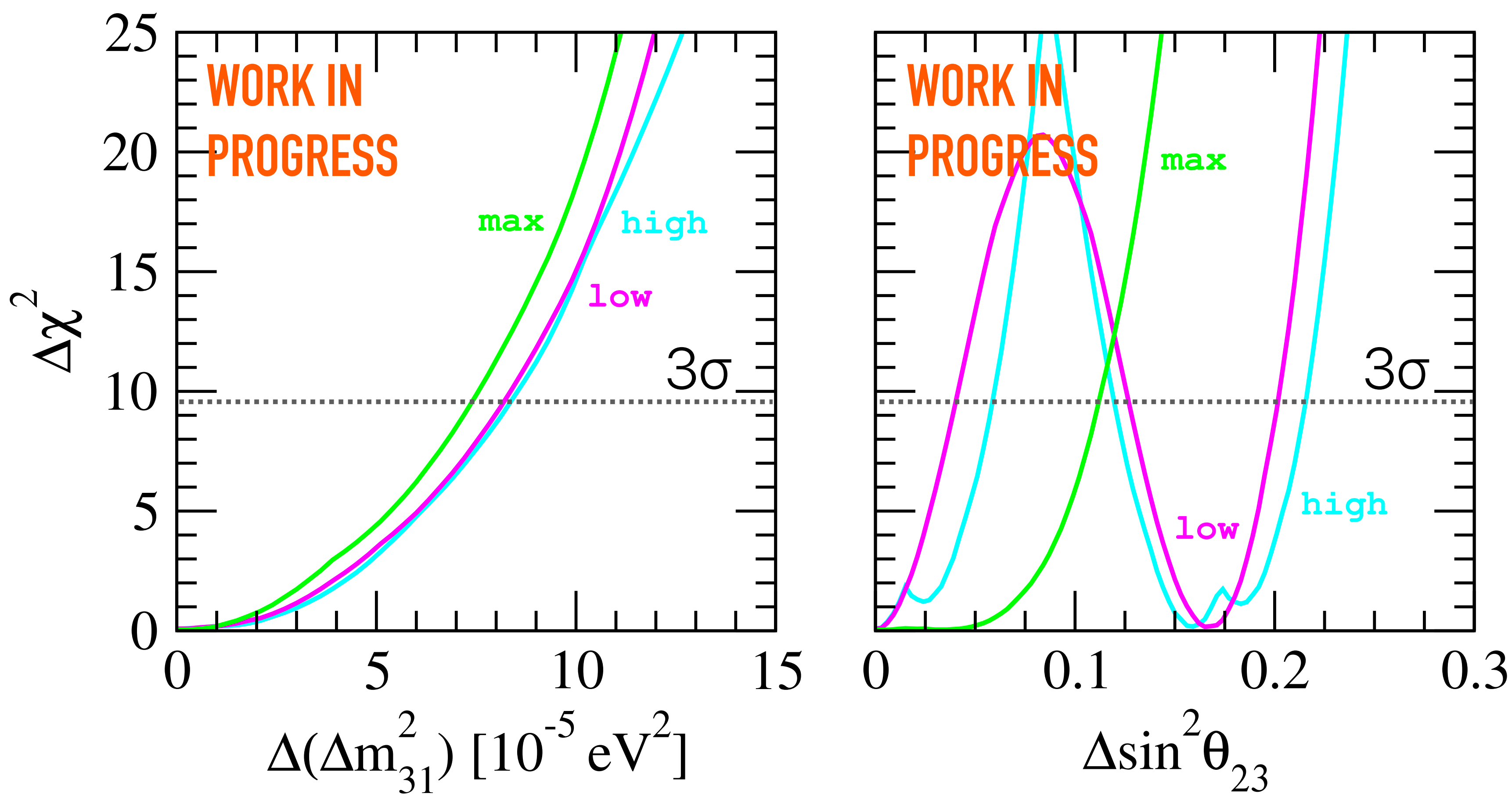
DUNE may potentially improve present constraints on $|\varepsilon_{e\mu}|$ and $|\varepsilon_{e\tau}|$ by at least a factor of 2.



CPT VIOLATION

$$P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e) \Rightarrow \text{CP violation}$$

$$P(\nu_\mu \to \nu_\mu) \neq P(\bar{\nu}_\mu \to \bar{\nu}_\mu) \Rightarrow \text{CPT violation}$$



Projected sensitivity of DUNE to CPT violation for an exposure of 300 kton·MW·year and three different values of the θ_{23} mixing angle: maximal mixing (green), lower octant (magenta) and upper octant (blue).

Current experimental bounds: $\Delta(\Delta m^2_{31}) \equiv \left| \Delta m^2_{31} - \Delta \bar{m}^2_{31} \right| < 3.7 \times 10^{-4}\ \text{eV}^2$

$$\Delta(\sin^2\theta_{23}) \equiv \left| \sin^2\theta_{23} - \sin^2\bar{\theta}_{23} \right| < 0.32$$

(arXiv:1712.01714)

TAU NEUTRINOS

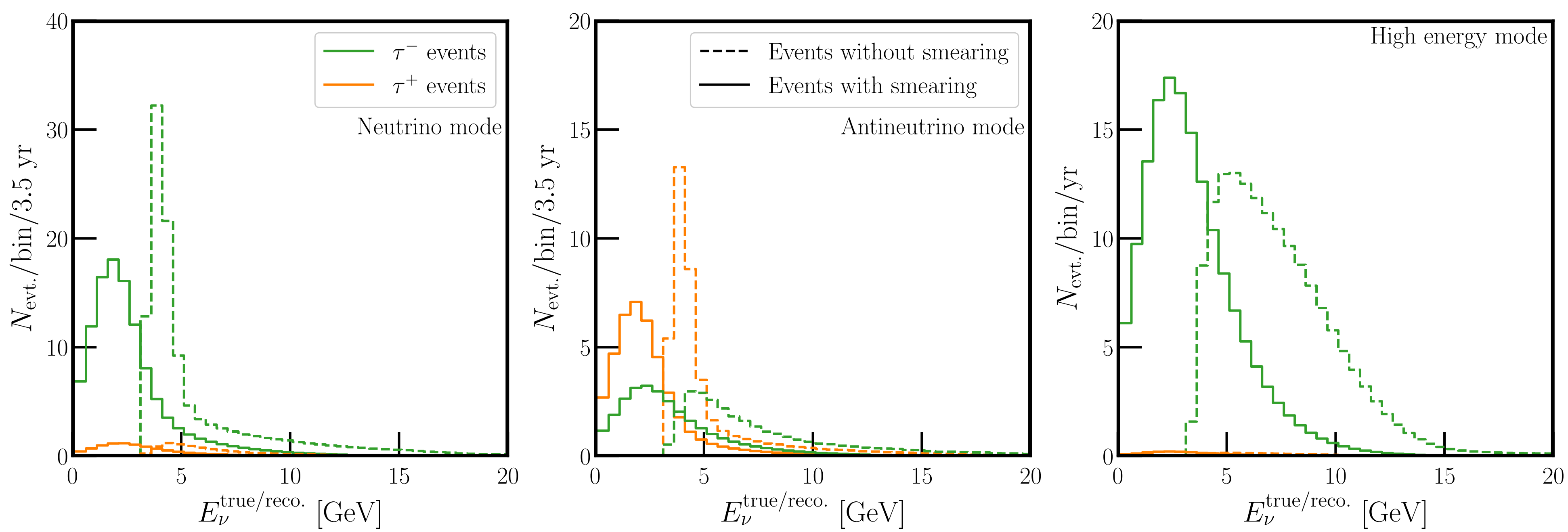
Currently, almost all of our knowledge from the tau neutrino sector derives from lepton universality and the unitarity of the mixing matrix.

Tau neutrinos are challenging to select and reconstruct, but they could provide valuable complementary information for BSM physics searches.

Beam event statistics (for a flat efficiency of 30%):

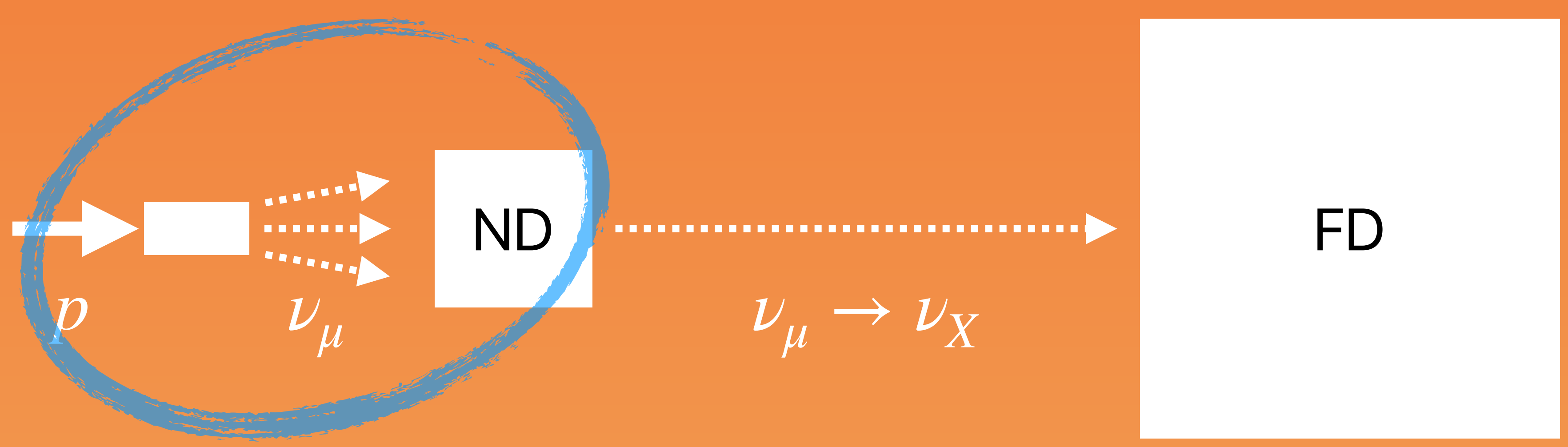
- ~130 ν_τ/year and ~30 anti-ν_τ/year;
- ~800 ν_τ/year for the high-energy tune of the beam.

The atmospheric sample gives access to the full first oscillation maximum, improving constraints on the atmospheric parameters.



(arXiv:1904.07265)

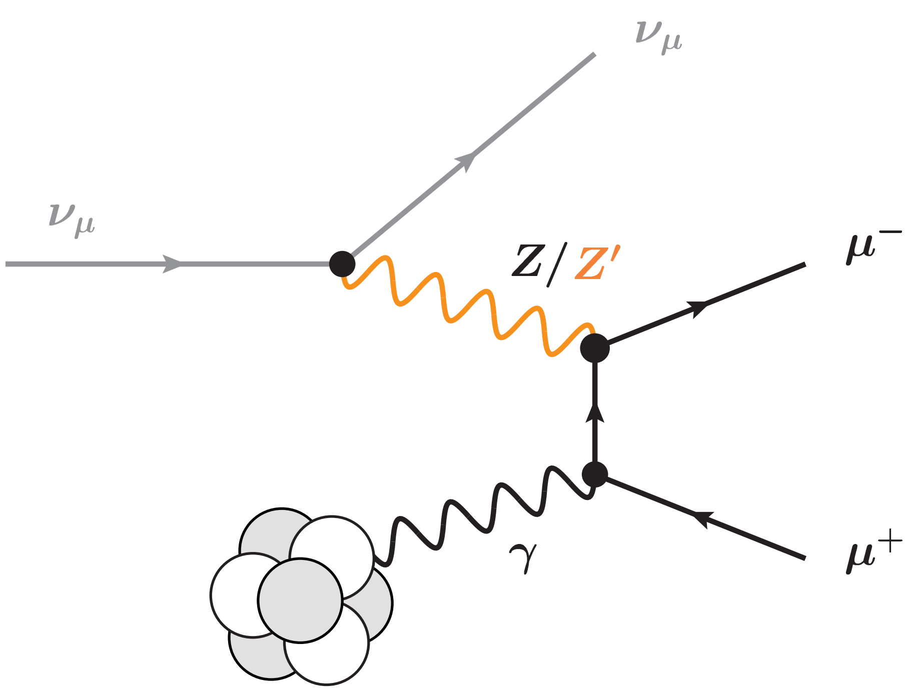
NEW PHYSICS
AT THE NEAR DETECTOR

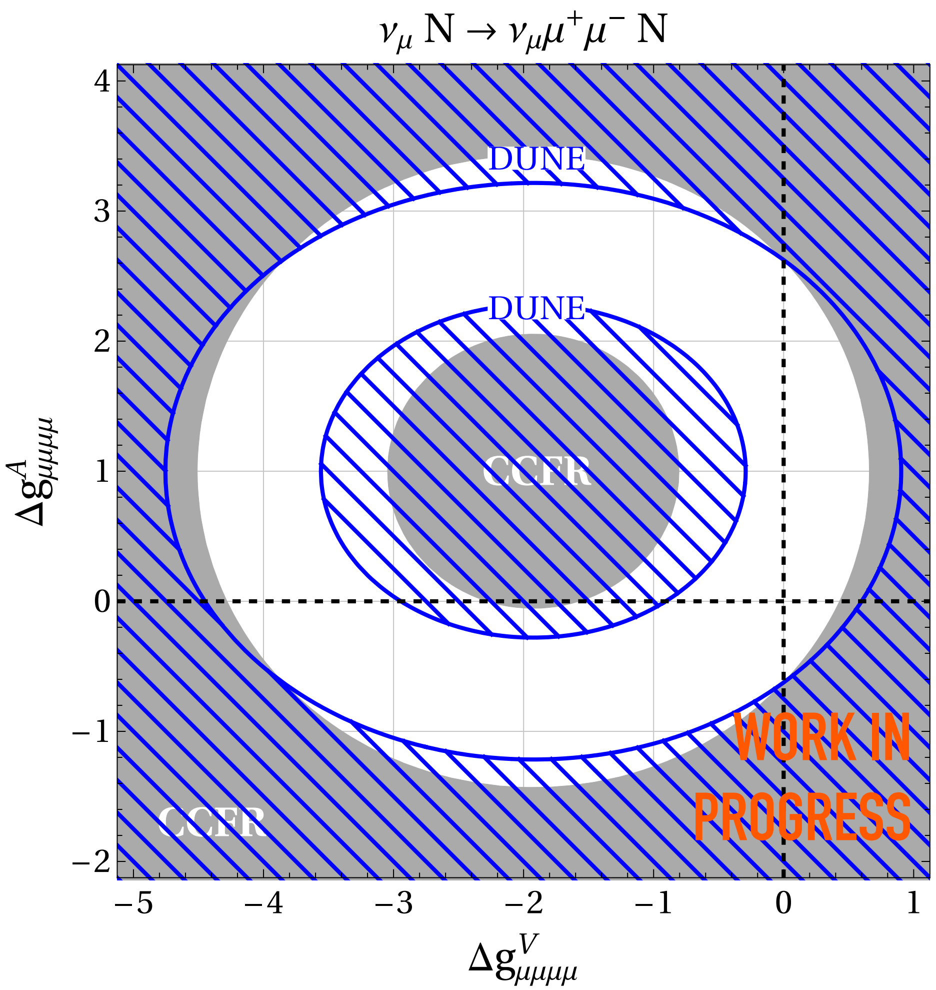


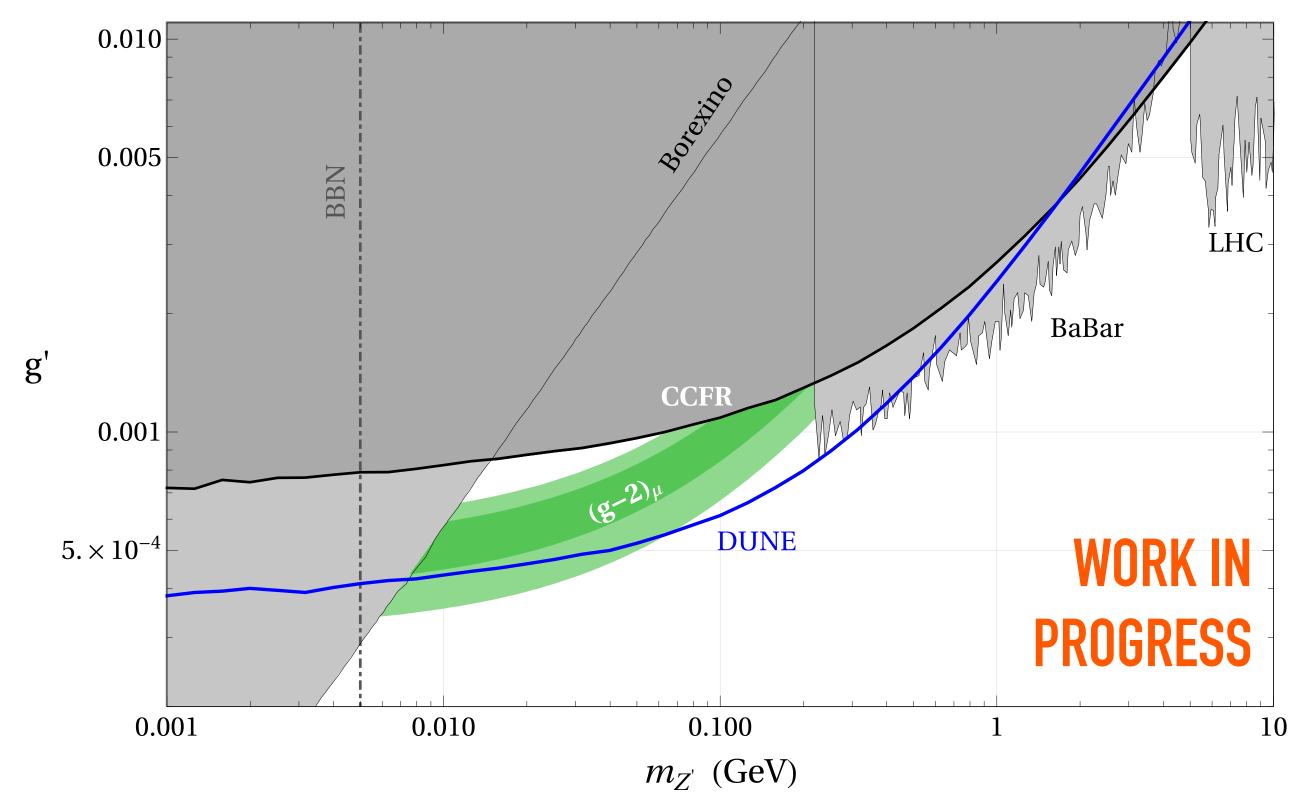
TRIDENT NEUTRINOS

Very rare process: cross section ~7 orders of magnitude smaller than CC one. A few tens of events observed in previous experiments.

Trident rate sensitive to the existence of new forces forces mediated by a light vector boson that could explain the muon g–2 anomaly.

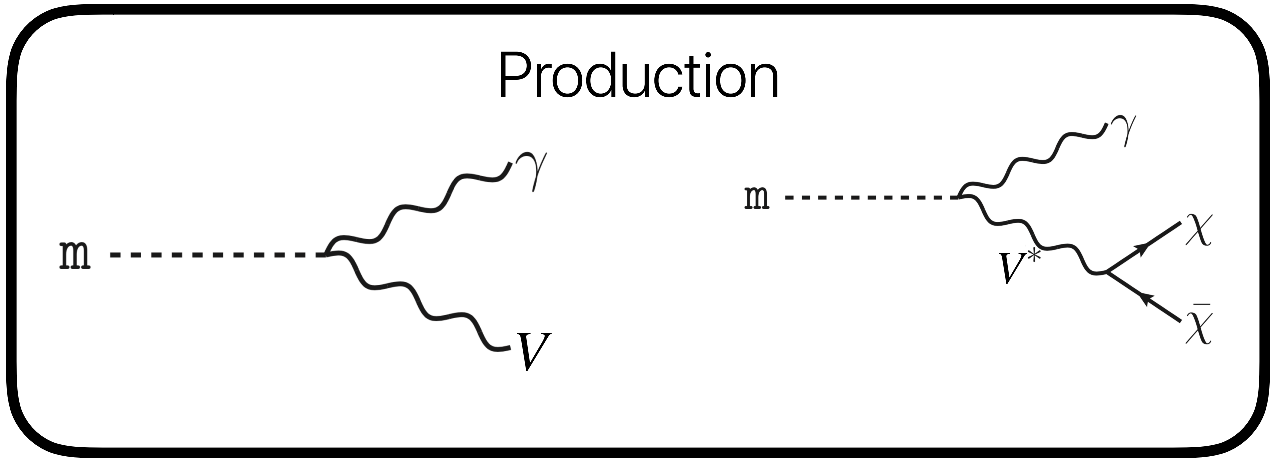


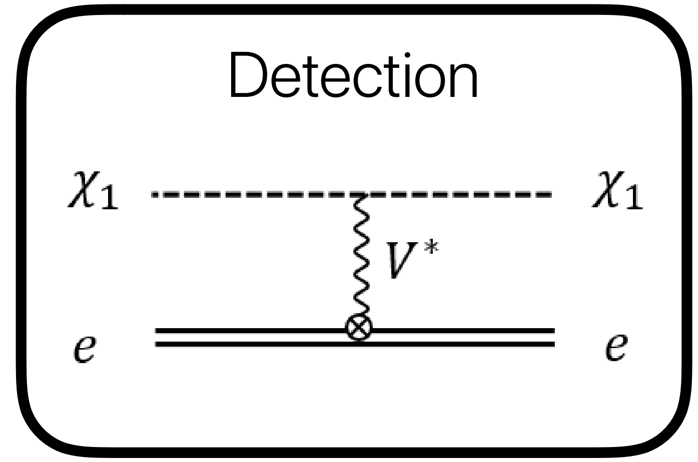




(arXiv:1903.10505)

LOW-MASS DARK MATTER

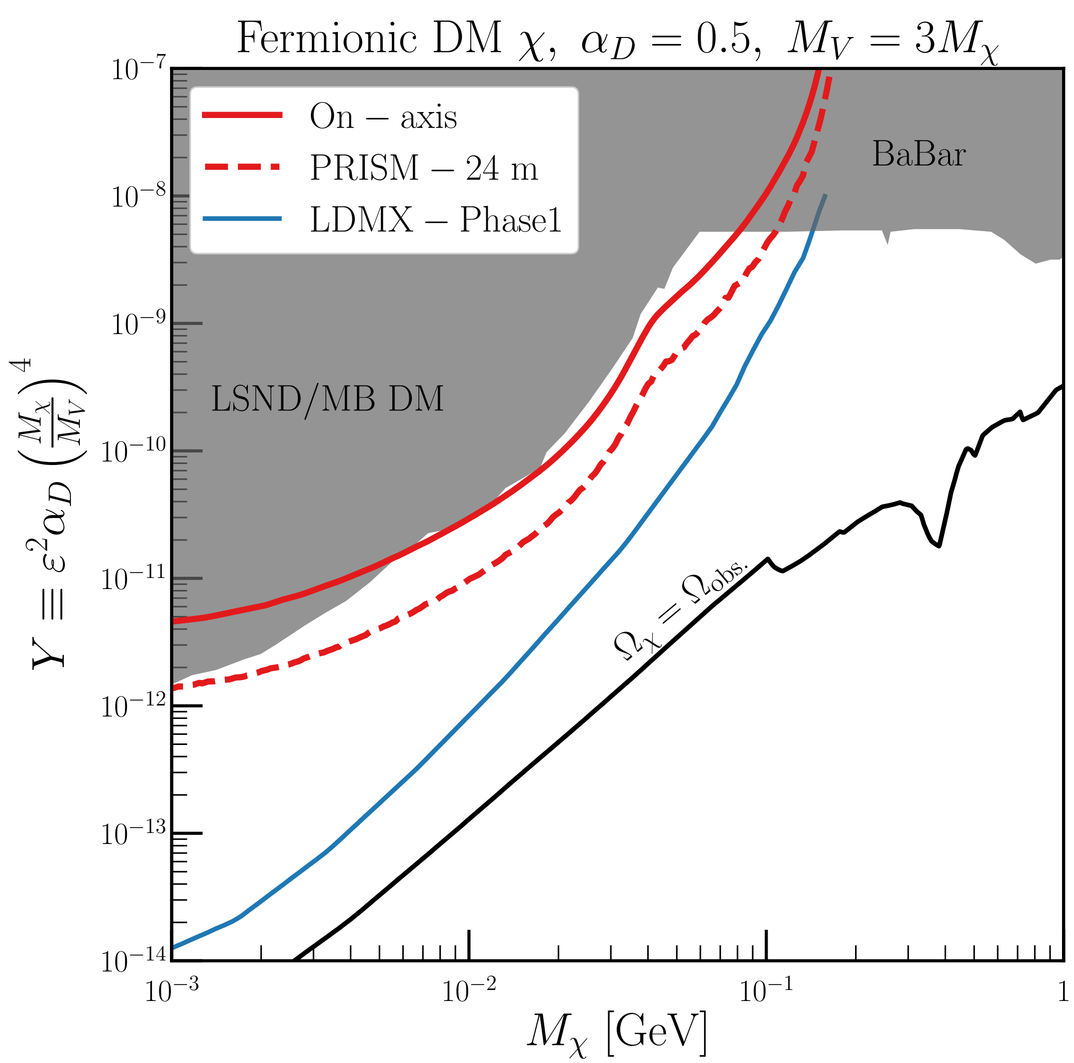




Dark matter particles produced in the decay of light mesons reach the DUNE ND, where they are detected via electron scattering.

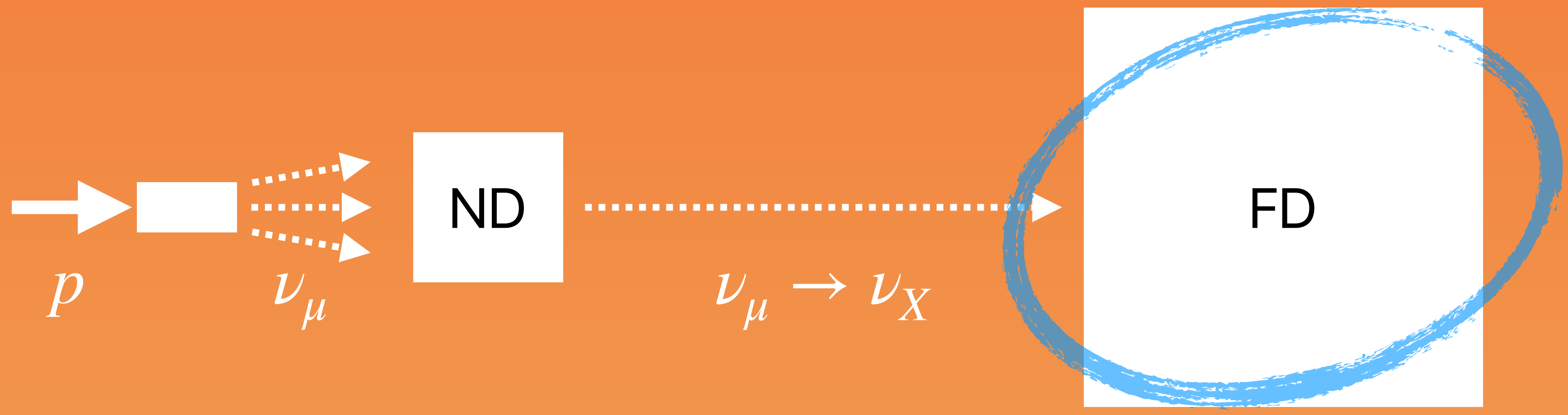
The main background (neutrino-electron scattering) can be suppressed taking data off-axis (PRISM).

Shown here the sensitivity (90% CL) of DUNE for a 7-year (50% neutrino beam, 50% antineutrino) run.

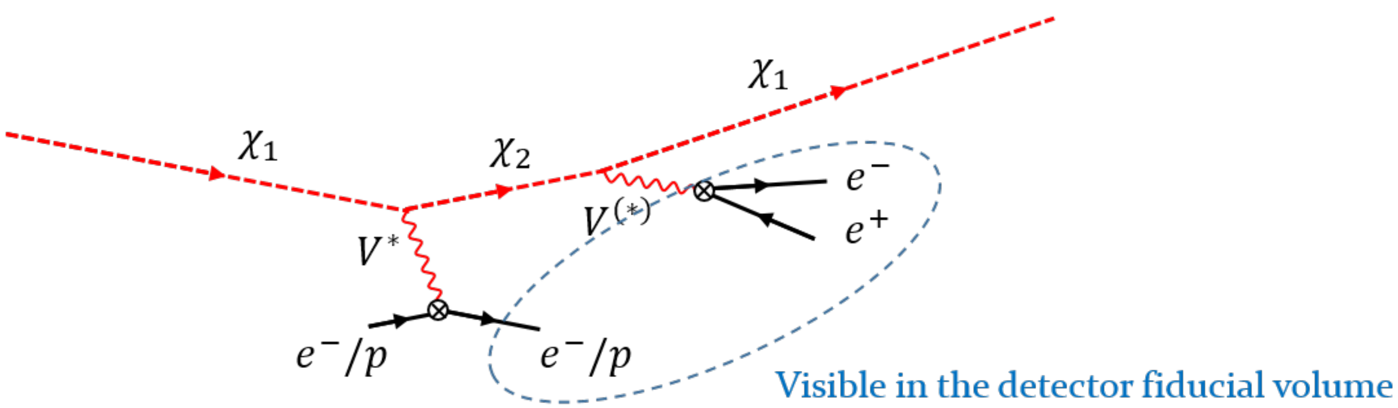


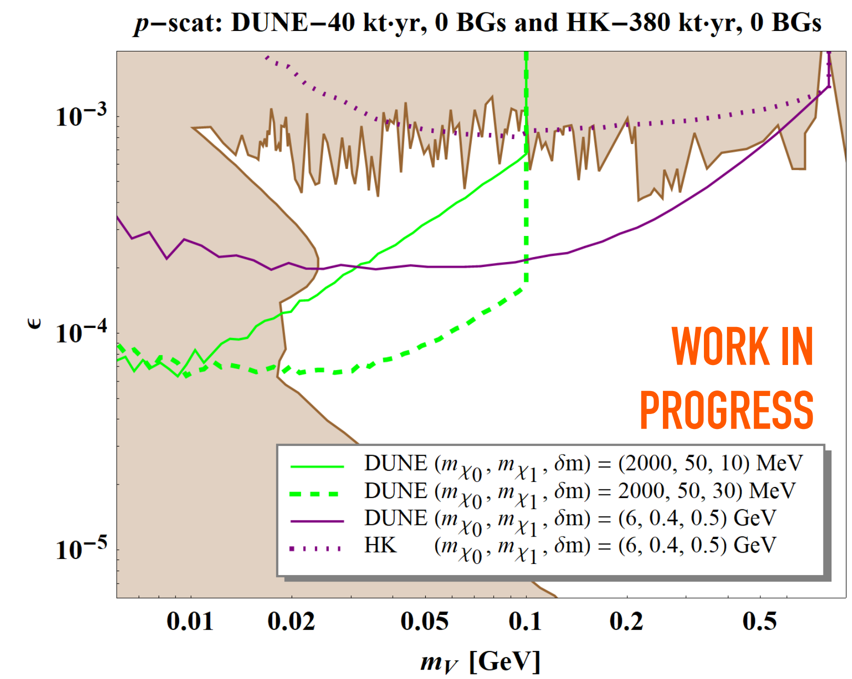
(arXiv:1903.10505)

NEW PHYSICS AT THE FAR DETECTOR

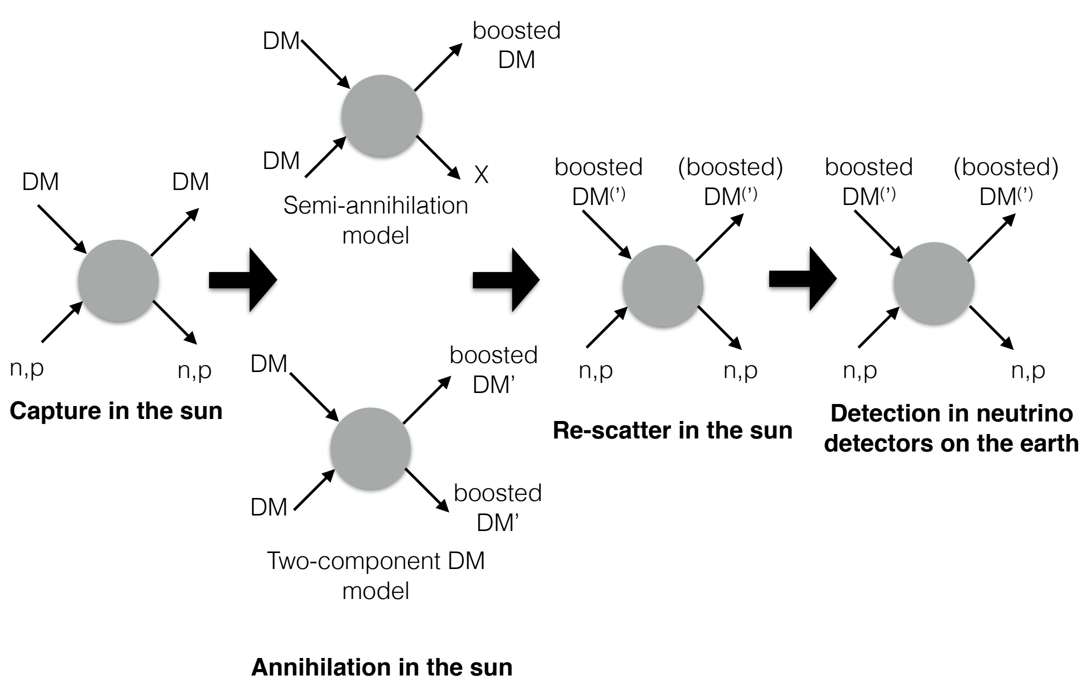


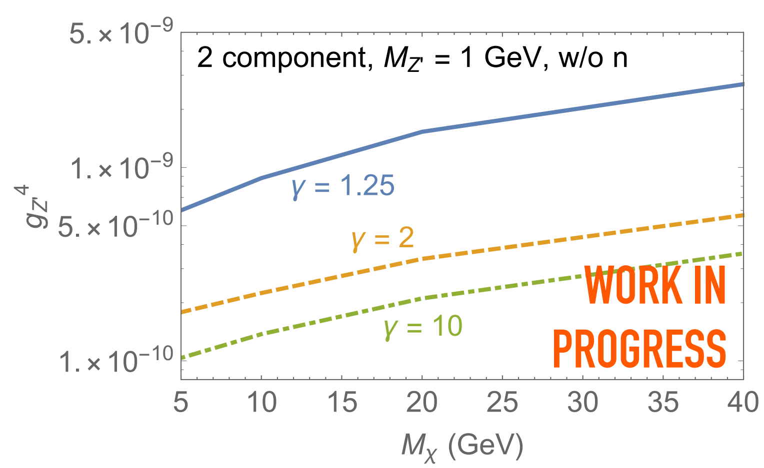
BOOSTED DARK MATTER

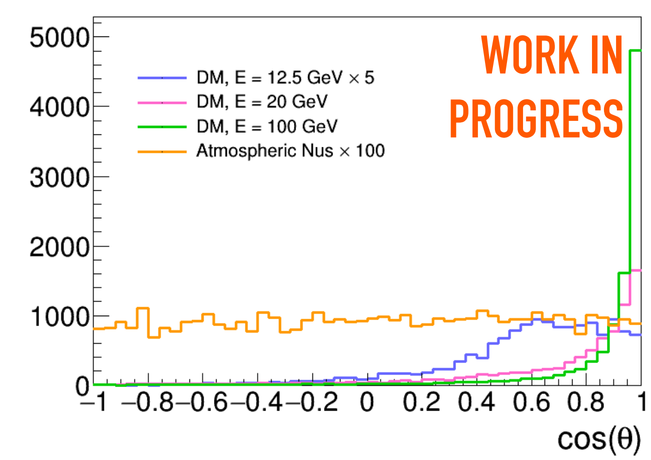




The DUNE FD, with a fiducial mass of 40 kton and high-resolution tracking, will be sensitive to dark matter from astrophysical sources such as the galactic halo (above) or the Sun (below).







CONCLUSIONS

DUNE is gearing up:

- More than 1000 collaborators in 175 institutions in 31 different countries.
- Data taking starts in 2024. Neutrino beam available by 2026.
- ProtoDUNE underway now at CERN.

The capable DUNE detectors and the powerful LBNF beam enable a rich experimental program of (neutrino and non-neutrino) BSM physics searches, including

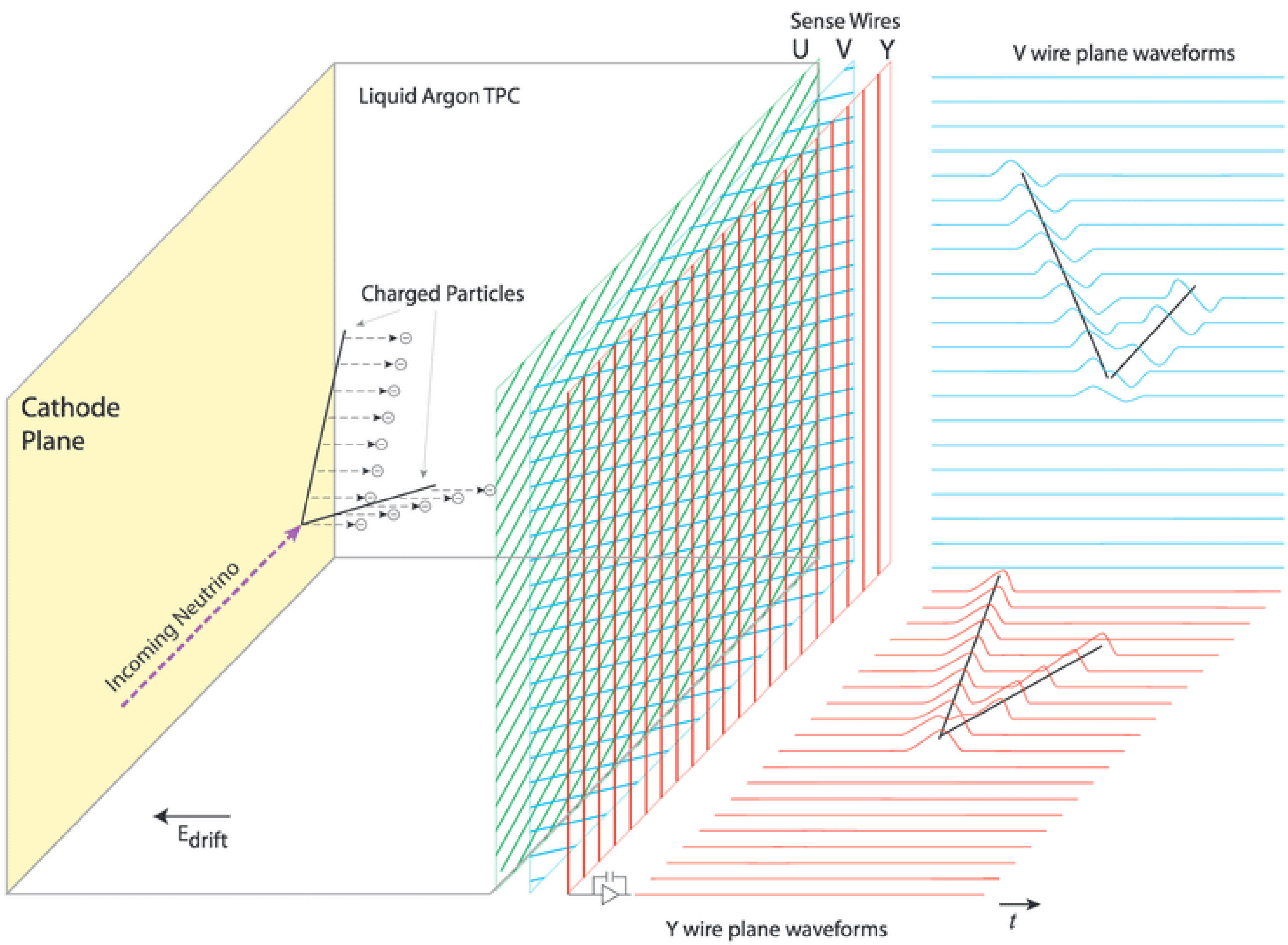
- non-standard short-baseline and long-baseline oscillation phenomena;
- searches for new phenomena/particles at the ND related to the beam and its interactions with the detector;
- searches for new phenomena at the FD benefitting from its large mass;

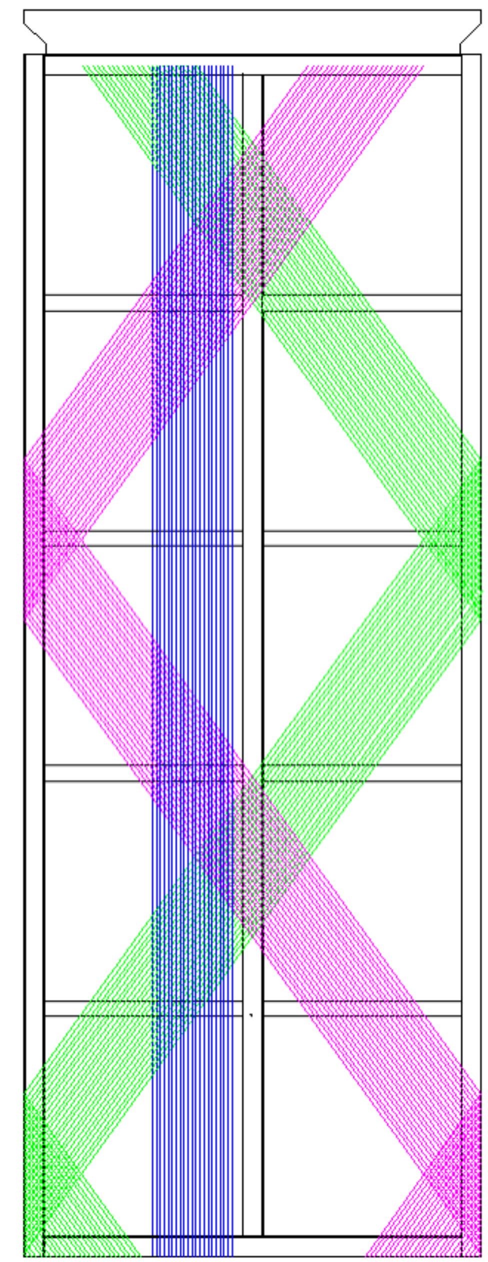
This is a very active and exciting area of collaboration between experimentalists and theorists/phenomenologists. New ideas welcome!

Look for results from finalized studies in the upcoming DUNE Technical Design Report (TDR) later this year.

BACKUP SLIDES

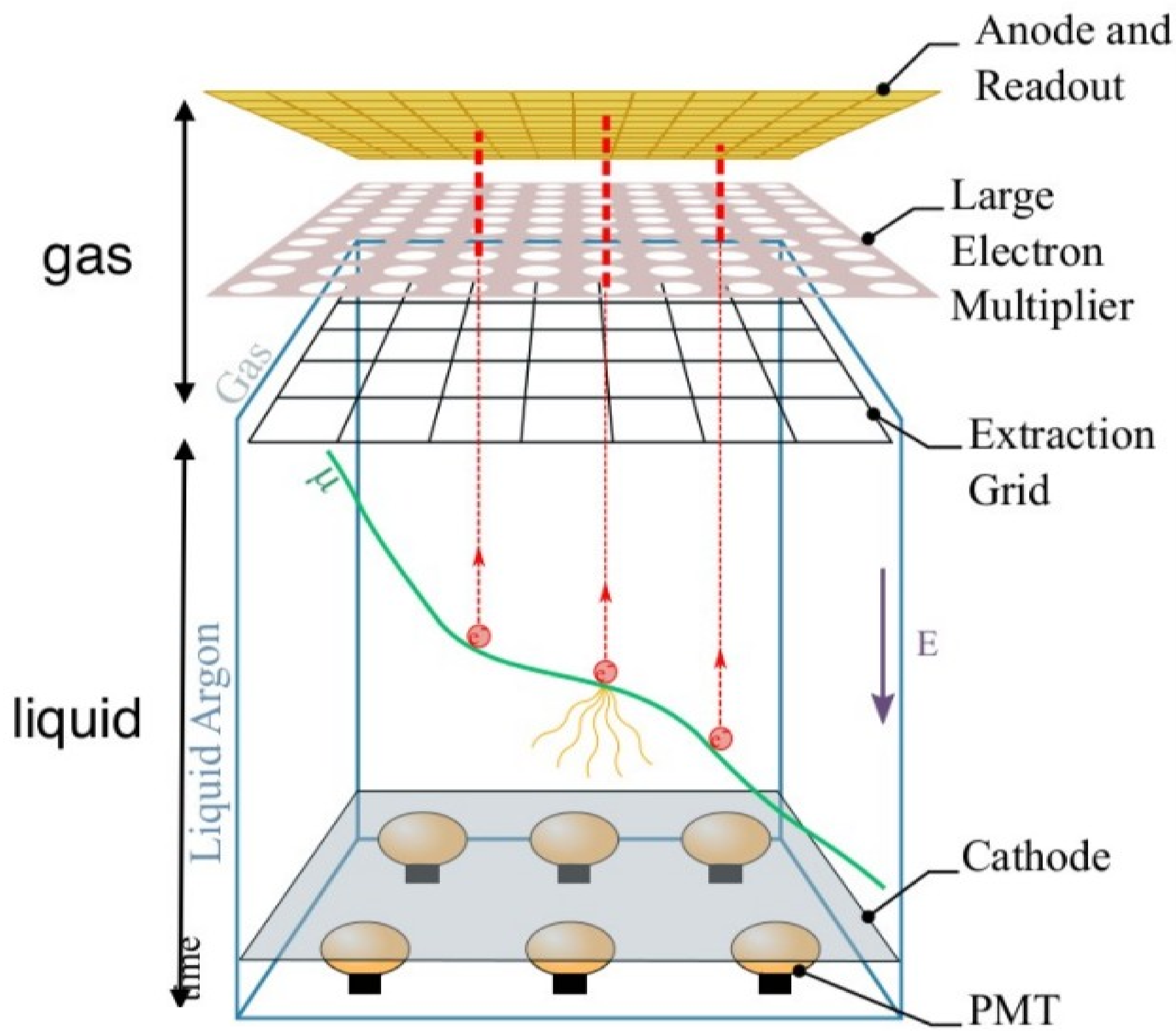
FAR DETECTOR: SINGLE-PHASE LArTPC





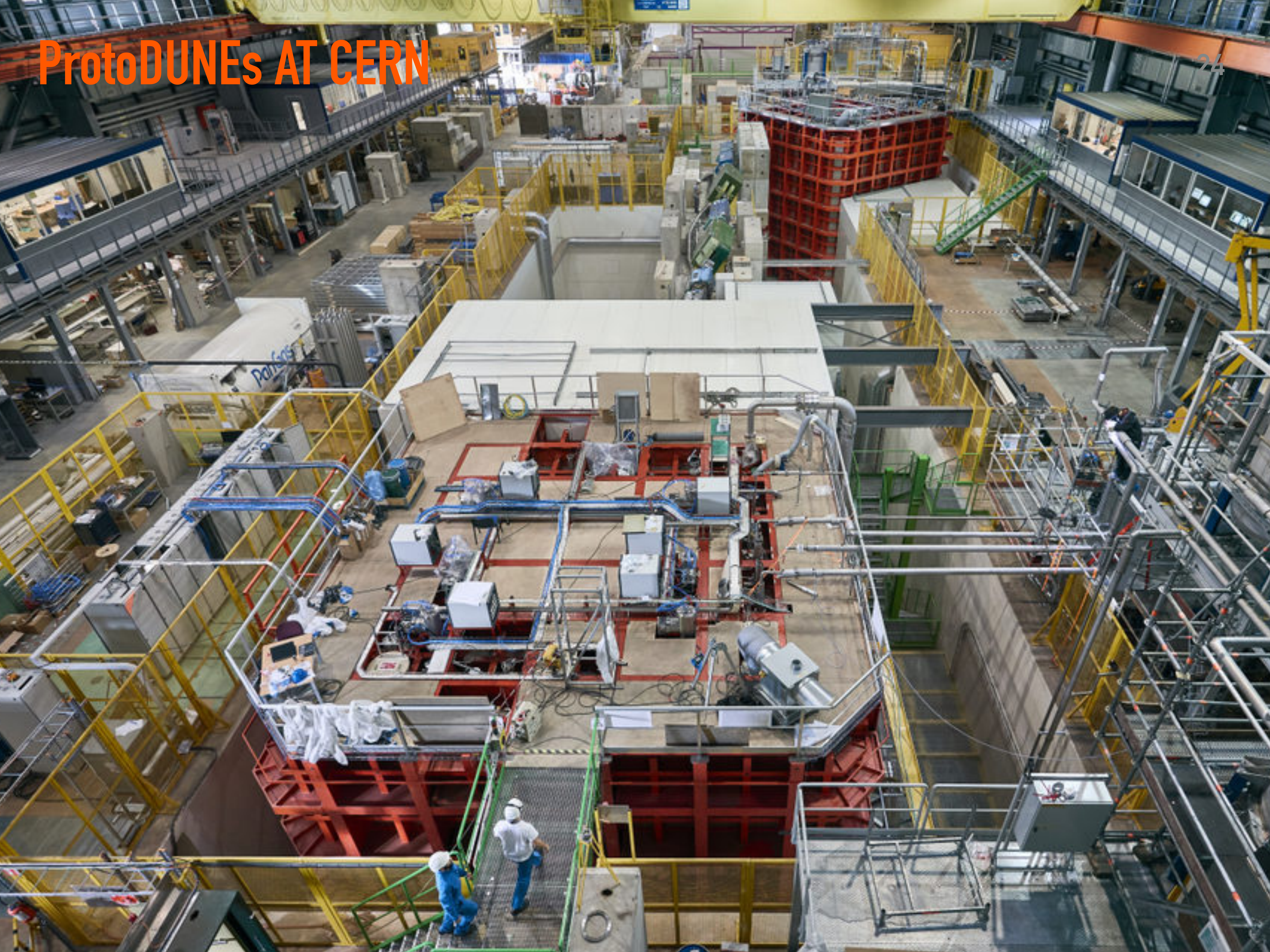
Ionisation readout via *Anode Plane Assemblies* (APA) consisting of 3 wire planes (2 induction views, 1 collection). Four 3.6-m drift regions per TPC. Scintillation light collected by SiPM-based photodetectors.

FAR DETECTOR: DUAL-PHASE LArTPC

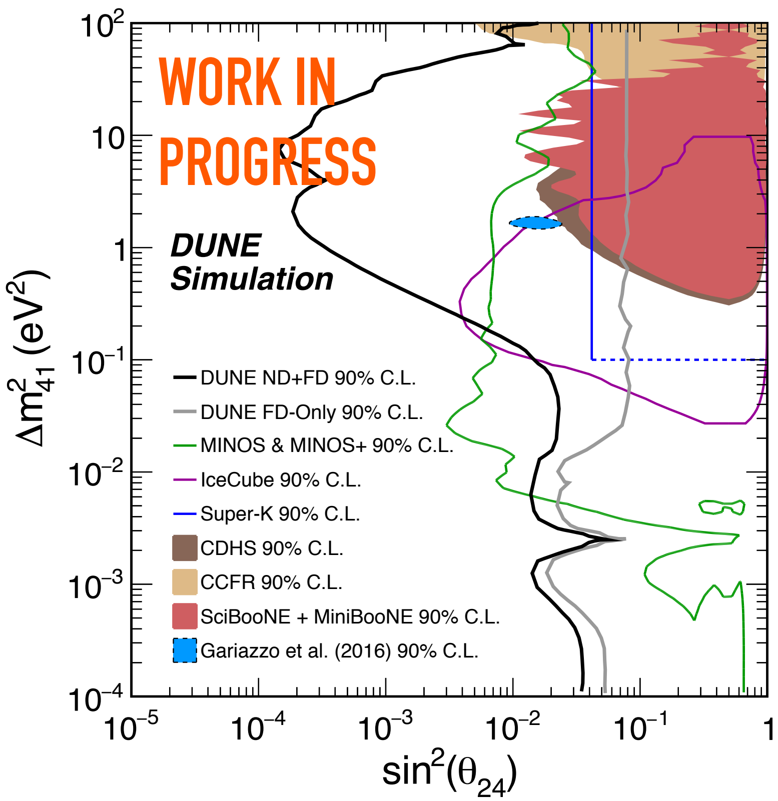


Ionisation electrons extracted to and amplified in gas phase. Charge readout by segmented (strips) anode plane. Single 12-m drift volume per TPC. Scintillation light collected by PMTs.

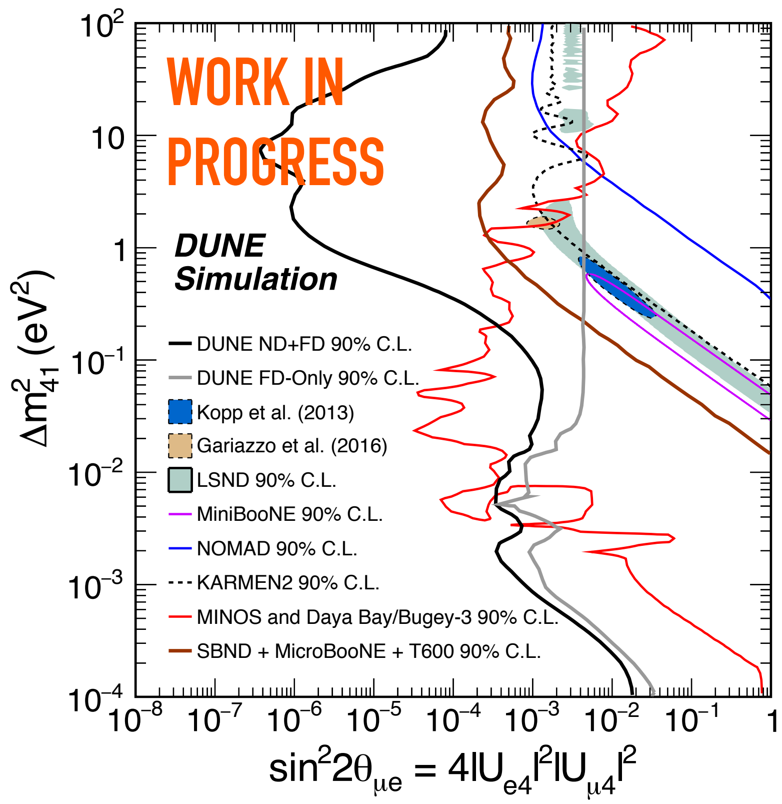
ProtoDUNEs AT CERN



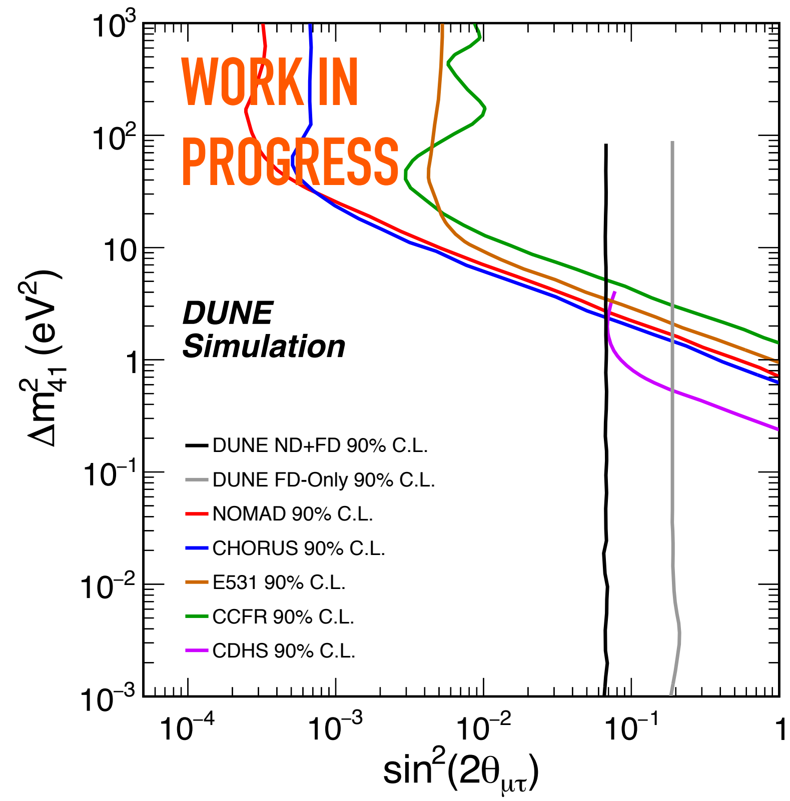
STERILE NEUTRINO MIXING



ν_μ CC+NC disappearance



ν_e CC app./disapp.
+ ν_μ CC disapp.



NC disappearance

DUNE sensitivities to a 3+1 mixing model for an exposure of 300 kton·MW·year.