# Beyond the Standard Model Physics Prospects at DUNE

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for the DUNE Collaboration

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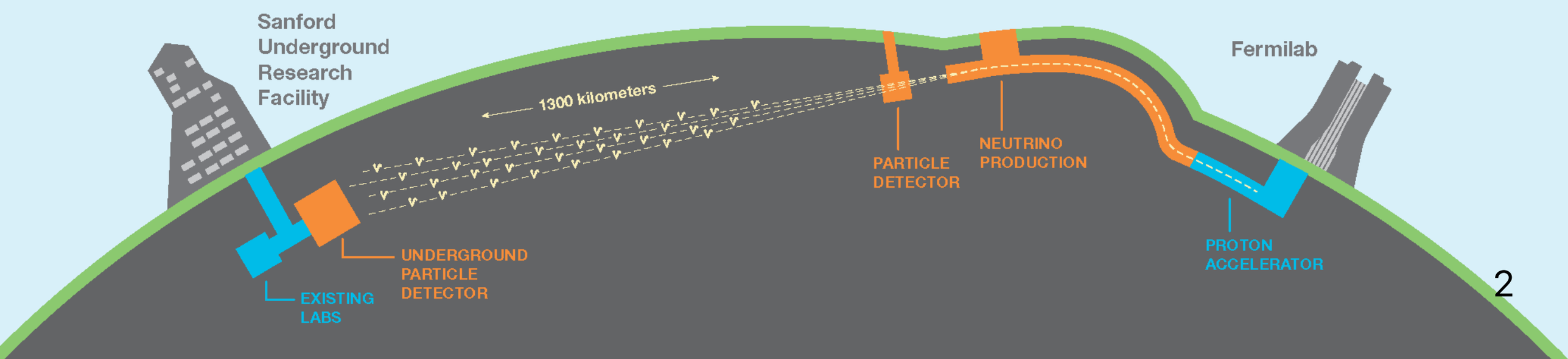
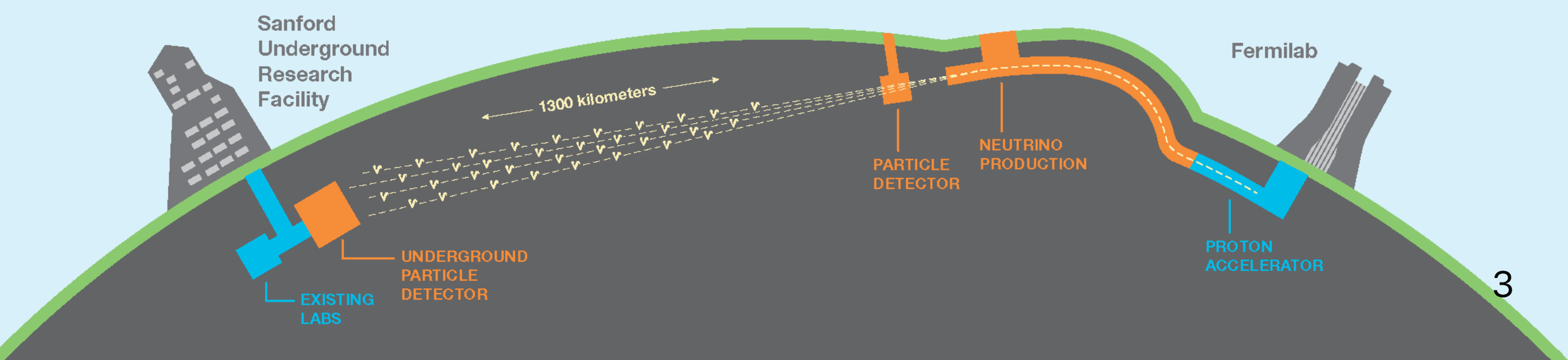
The **Deep Underground Neutrino Experiment** is a next-generation long-baseline neutrino oscillation experiment between Fermilab (Illinois, USA) and the Sanford Underground Research Facility (South Dakota, USA) consisting of

- a new MW-scale neutrino beamline (LBNF);
- a far detector consisting of four 17-kiloton liquid argon TPC modules;
- 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 (e.g. detection of core-collapse supernovae).
- Nucleon decay and other searches for physics beyond the Standard Model (BSM).

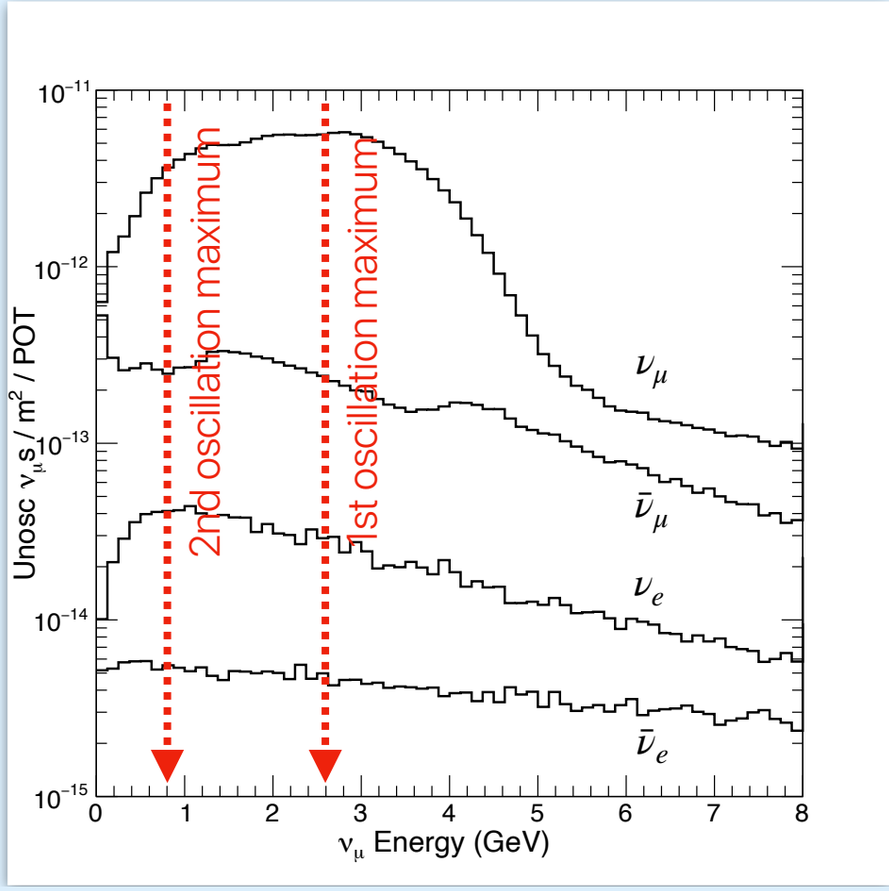


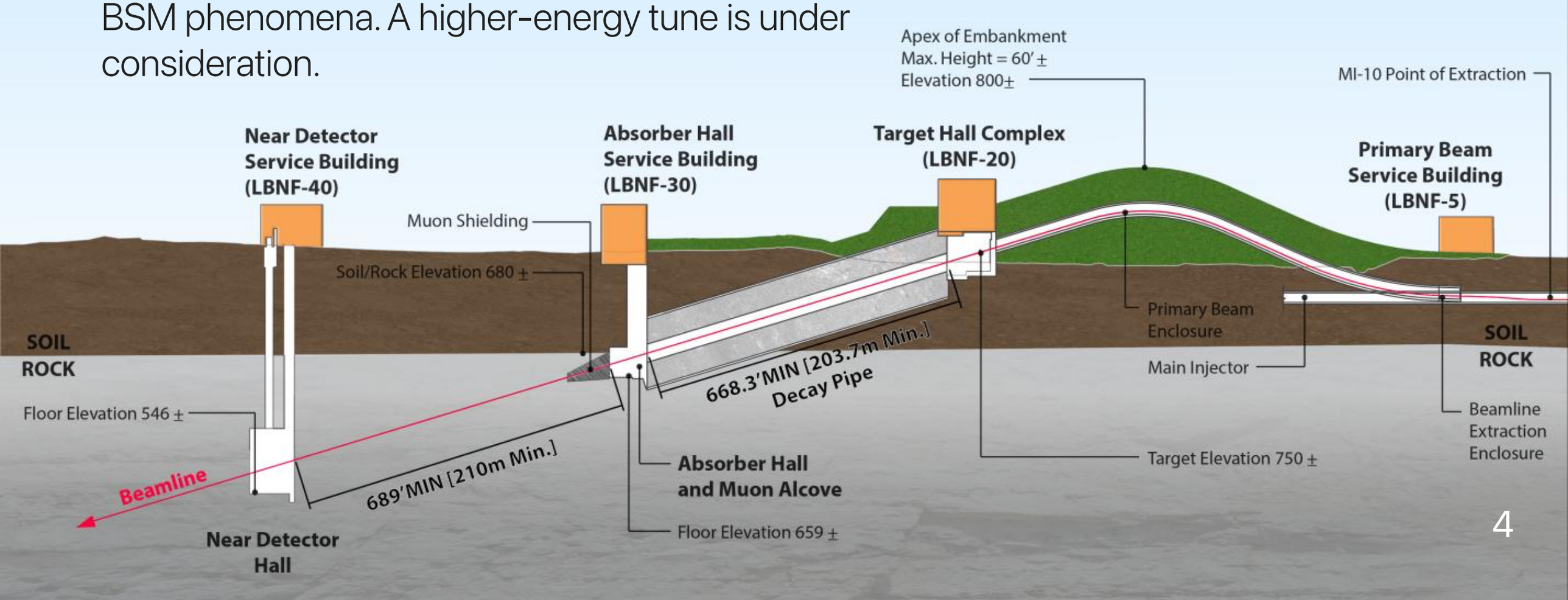
# LBNF Neutrino Beam

It will use protons (60–120 GeV) from Fermilab's Main Injector with an initial power of 1.2 MW (~$10^{21}$ POT/yr), upgradeable later to 2.4 MW.

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

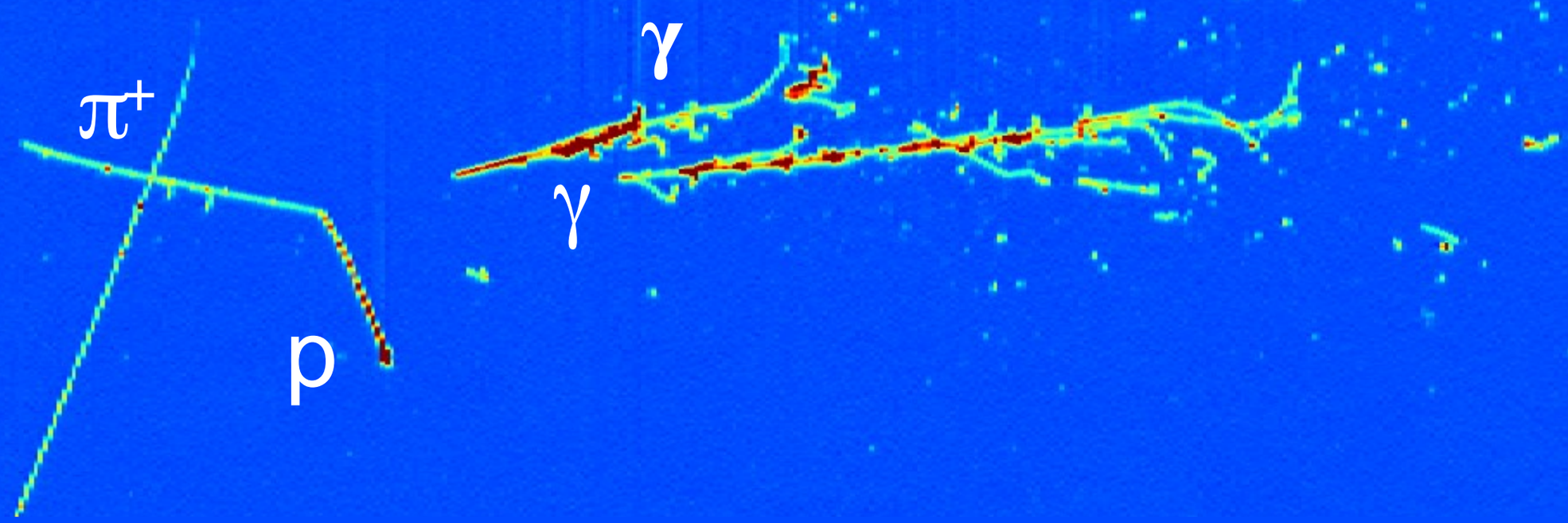
The wide-band beam enables the use of the 1st and 2nd oscillation maxima and enhances probing of new BSM phenomena. A higher-energy tune is under consideration.



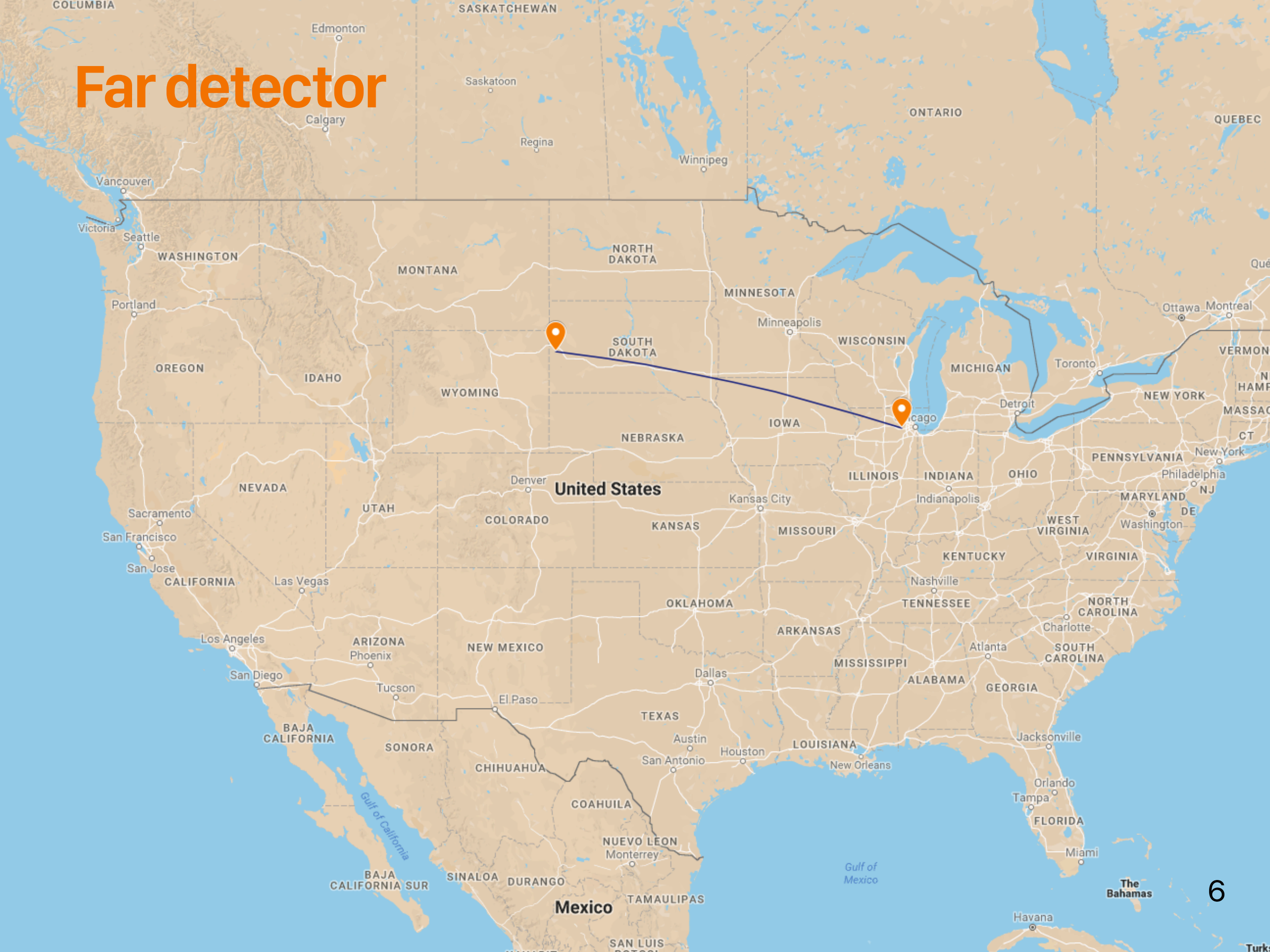
# Far detector: Liquid argon TPC

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




[ProtoDUNE-SP Run 5779 Event 12360]

# Far detector



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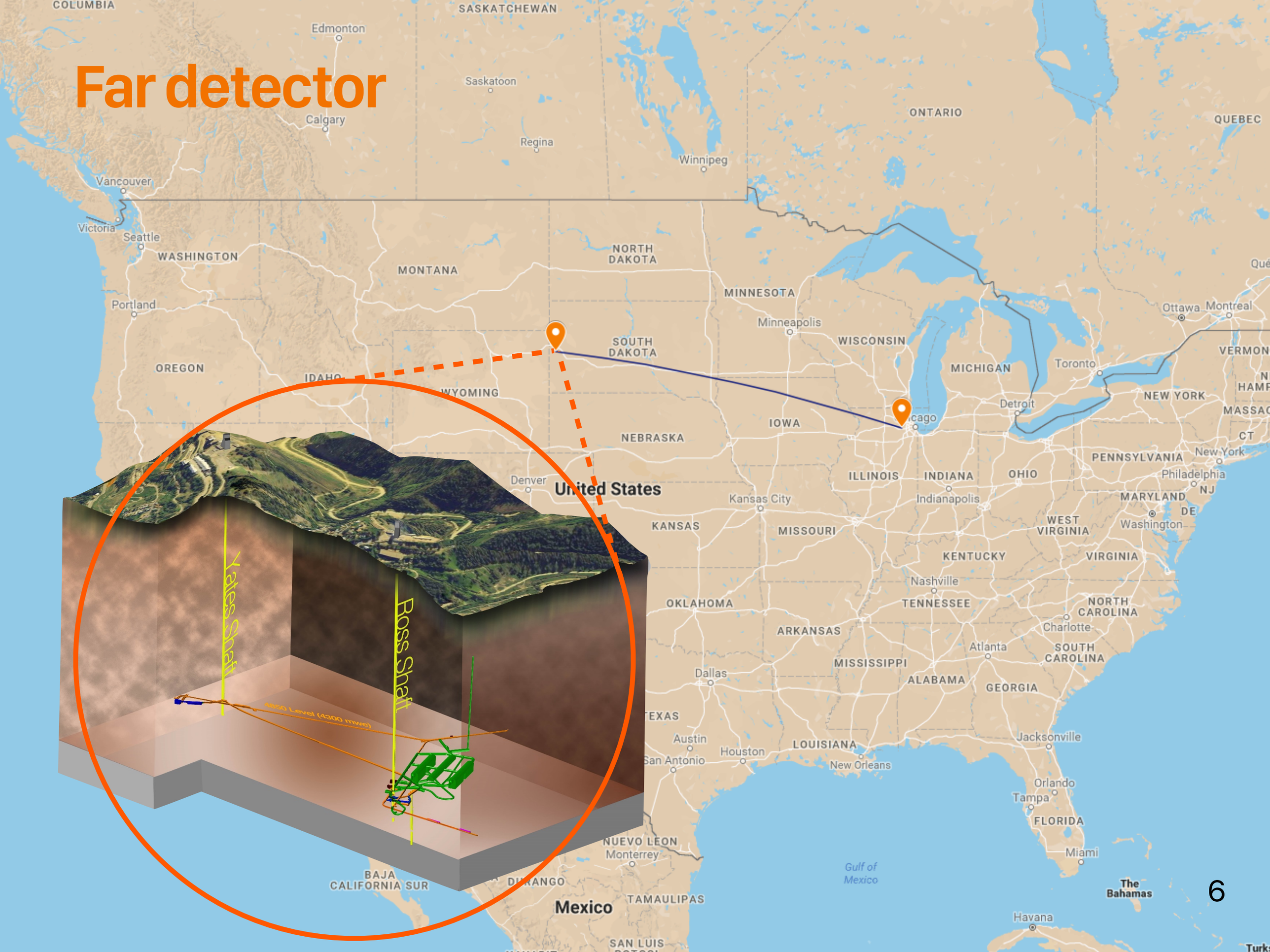

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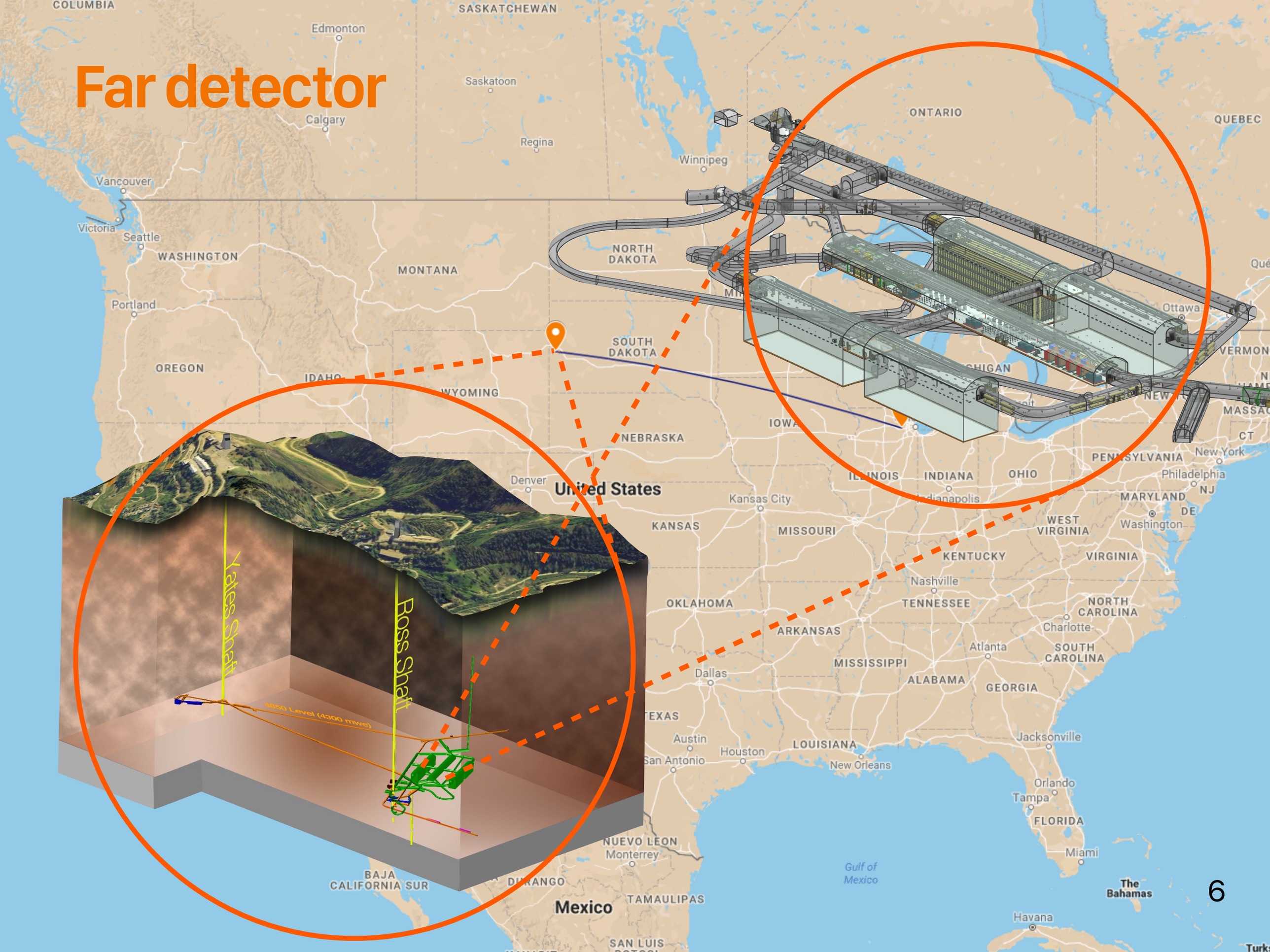

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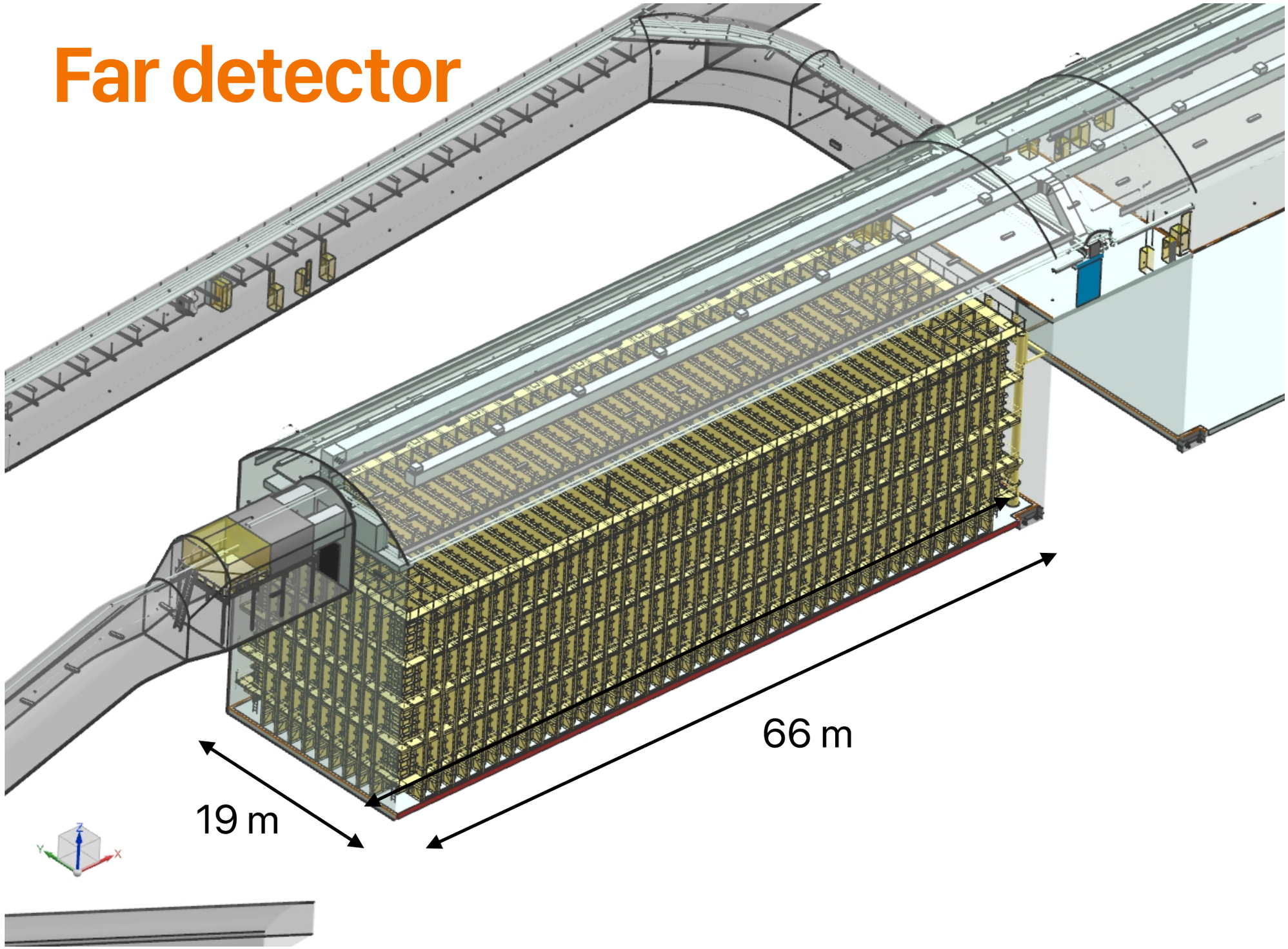

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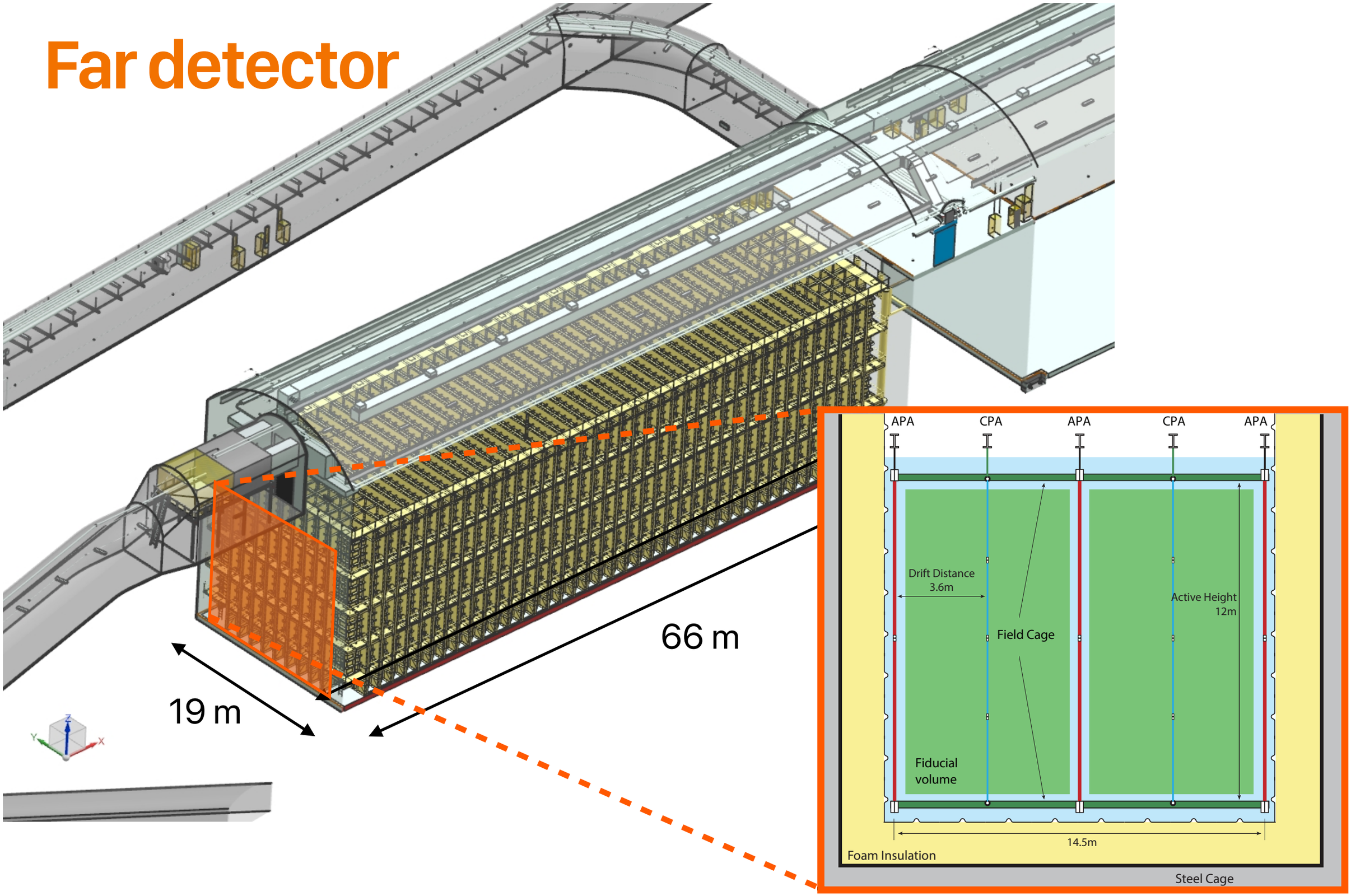


# Near detector

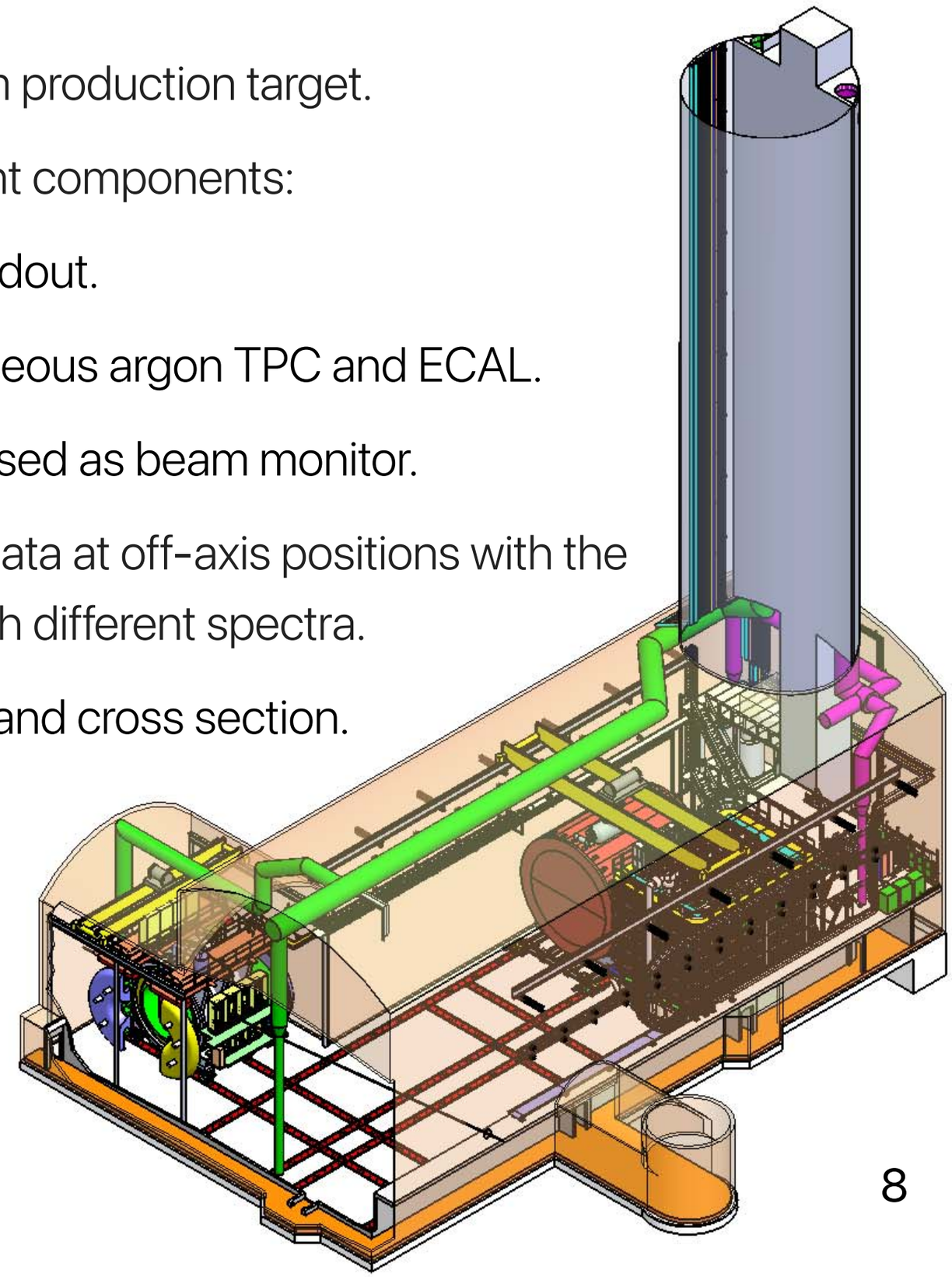
Located 574 m downstream of neutrino beam production target.

The conceptual design includes three different components:

- NDLAr: 150 t LArTPC with pixelated readout.
- NDGAr: magnetised, high-pressure gaseous argon TPC and ECAL.
- SAND: magnetised tracker and ECAL used as beam monitor.

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

- Handle to deconvolve the neutrino flux and cross section.



# BSM physics in DUNE

Topics investigated include the following:

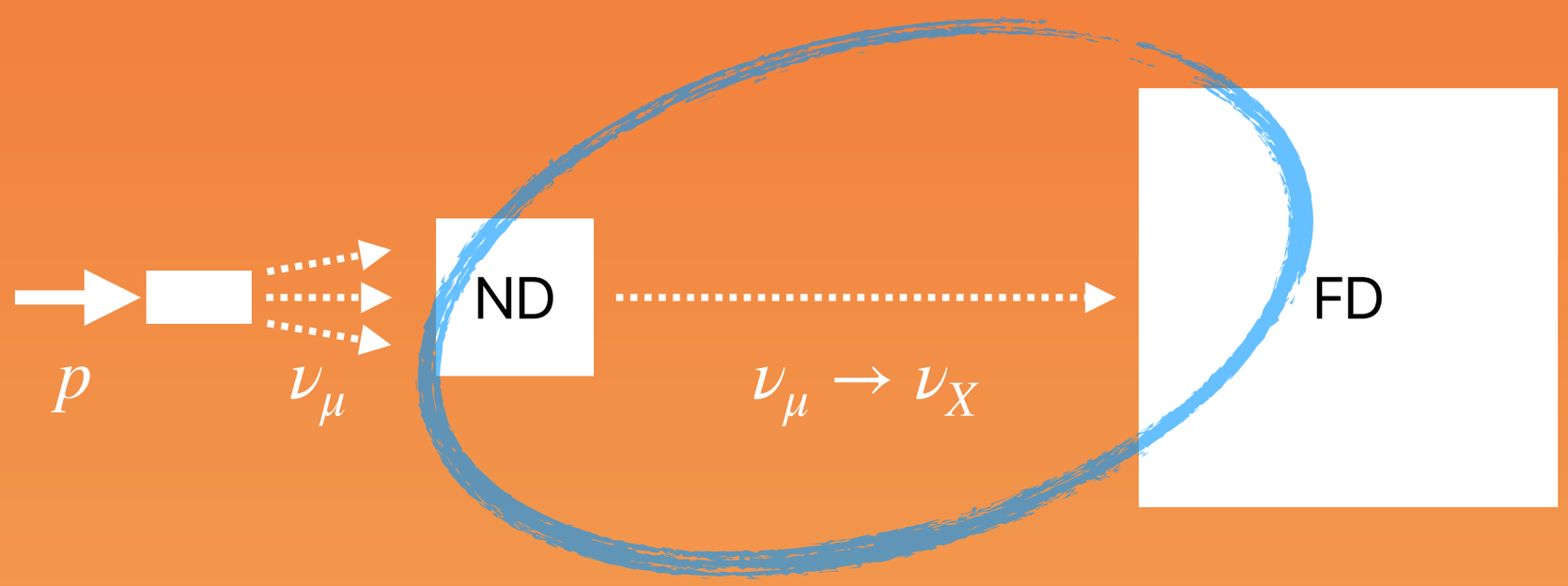
- Non-standard short-baseline and long-baseline oscillation phenomena: sterile neutrino mixing, non-standard neutrino interactions, non-unitarity*, CPT violation.
- Searches at the FD: baryon number violation, boosted dark matter.
- Searches at the ND: trident interactions, heavy neutral leptons*, low-mass dark matter.

(*Not discussed in this talk.)

More details:

- B. Abi et al. (DUNE Collaboration), Eur. Phys. J. C **81** (2021) 322.

# Non-Standard Neutrino Oscillations

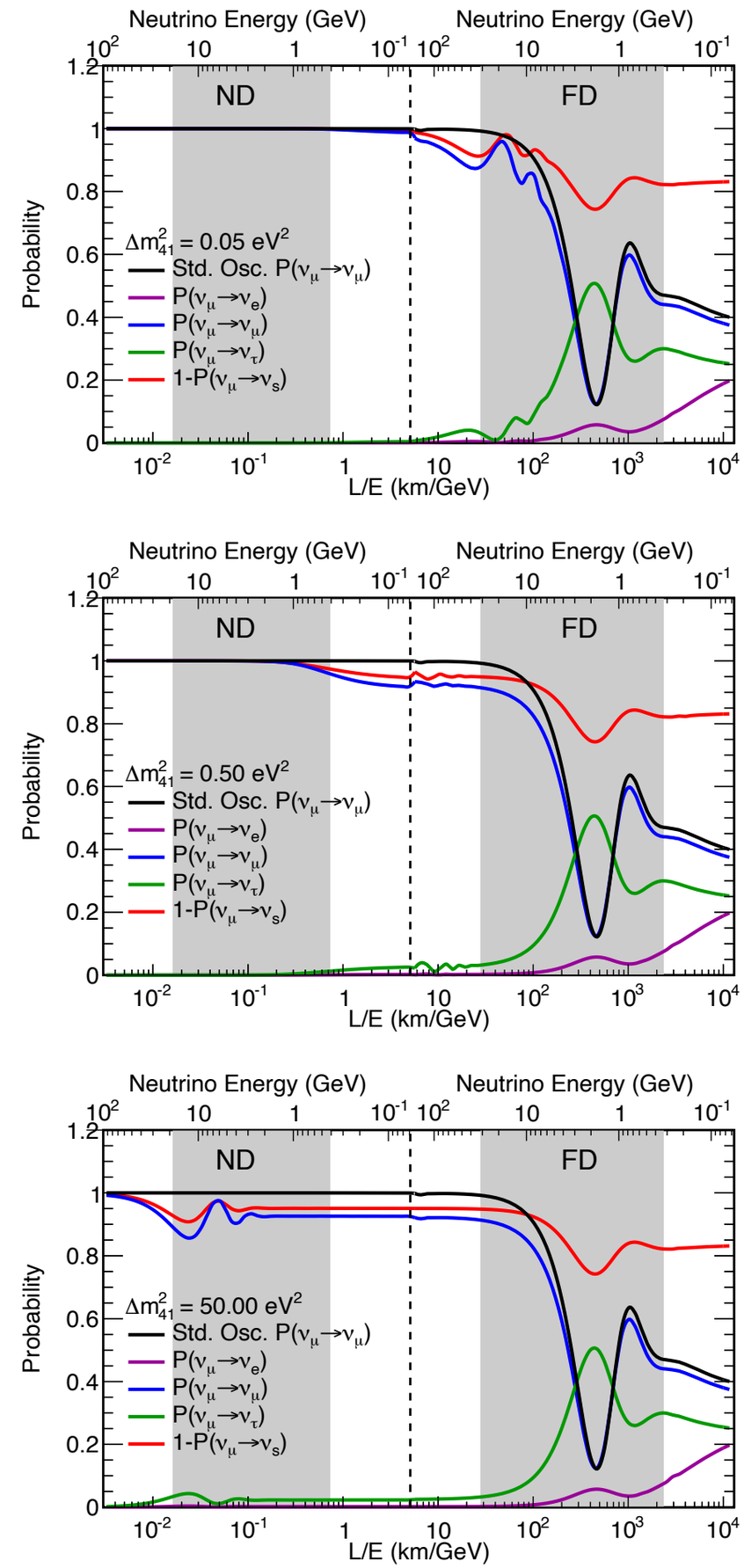


# Sterile neutrino mixing

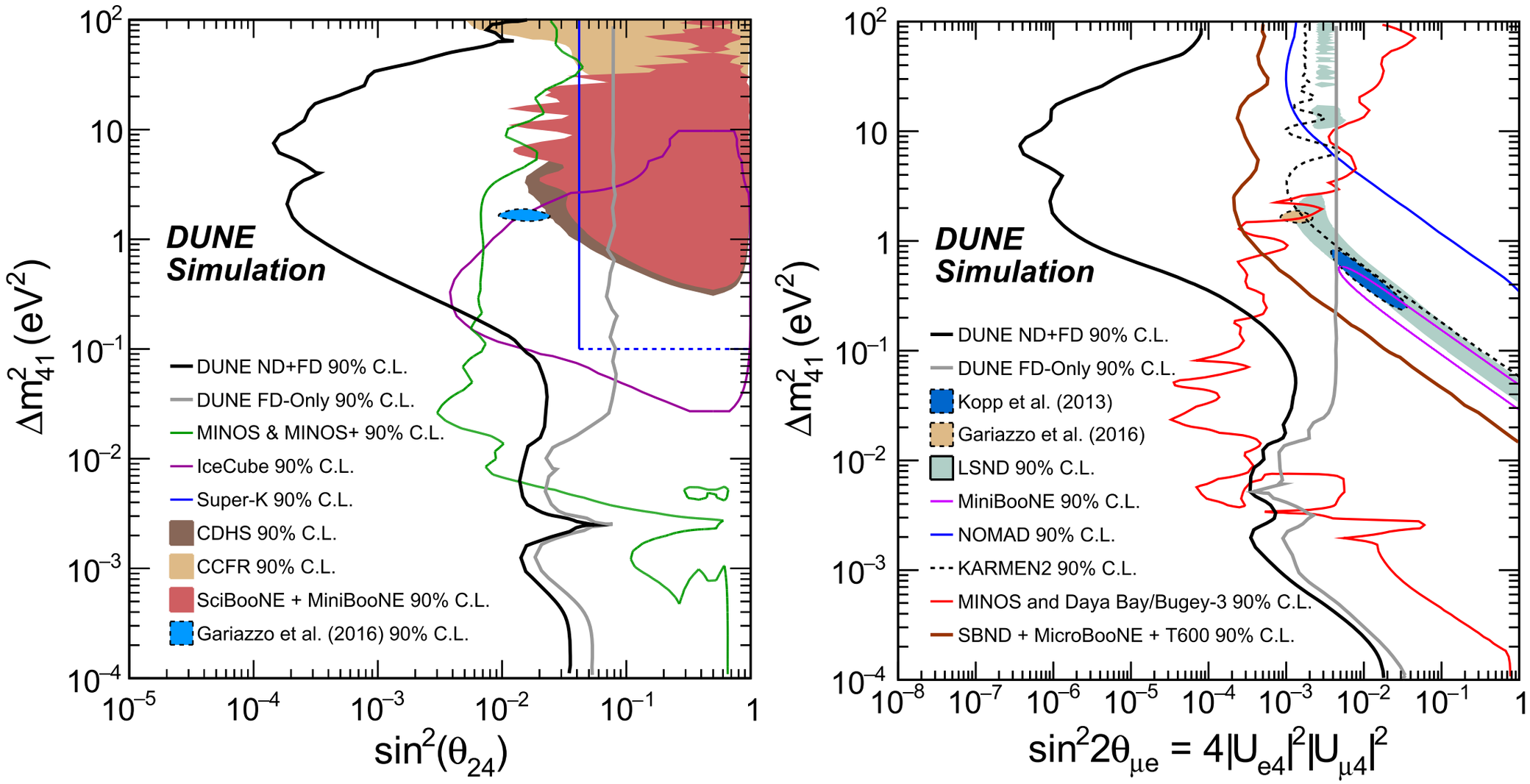
Sterile (right-handed) neutrinos are a prediction of many BSM models explaining the origin of neutrino masses.

Oscillations between active and new light sterile neutrino states would distort the standard oscillation probabilities (see plots).

DUNE will be sensitive to this effect through the combined analysis of the $\nu_\mu$ and $\nu_e$ spectra from both the near and far detectors. The wide span of neutrino energies from LBNF beam enables probes over large regions of parameter space.



# Sterile neutrino mixing




Assuming 300 kton MW yr exposure (staged 7 year running) for 3+1 model with oscillations in ND and FD:

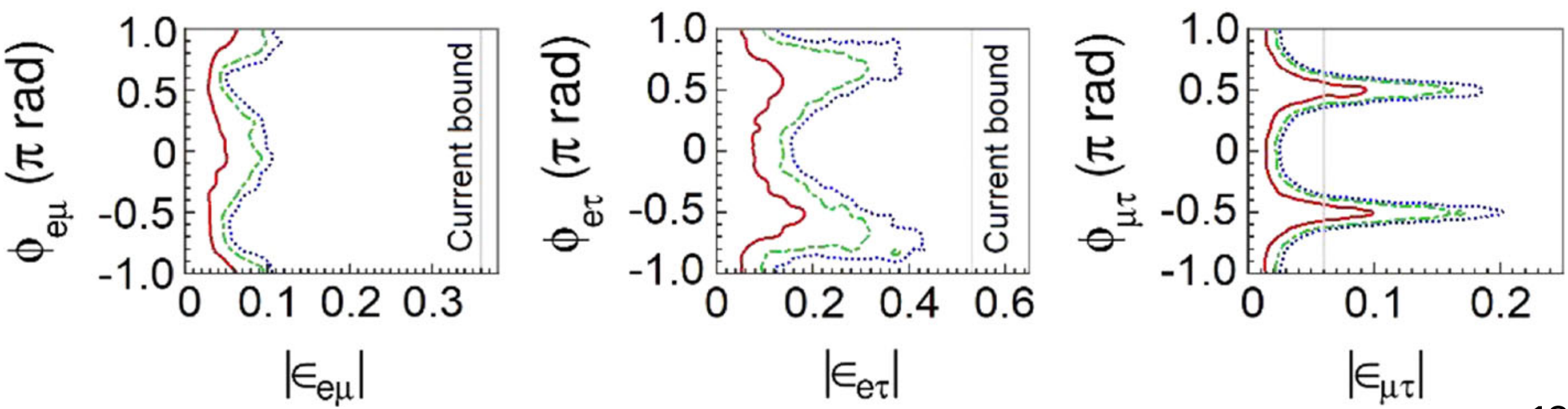
- On its own, DUNE can potentially probe the sterile mixing parameter space at same level or better than present and future experiments.
- Sensitivities include normalization-only systematics, so the two DUNE lines represent best (black) and worst (grey) scenarios.

# Non-standard interactions (NSI)

Non-standard neutrino interactions during propagation can be described as new contributions to the MSW effect:

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

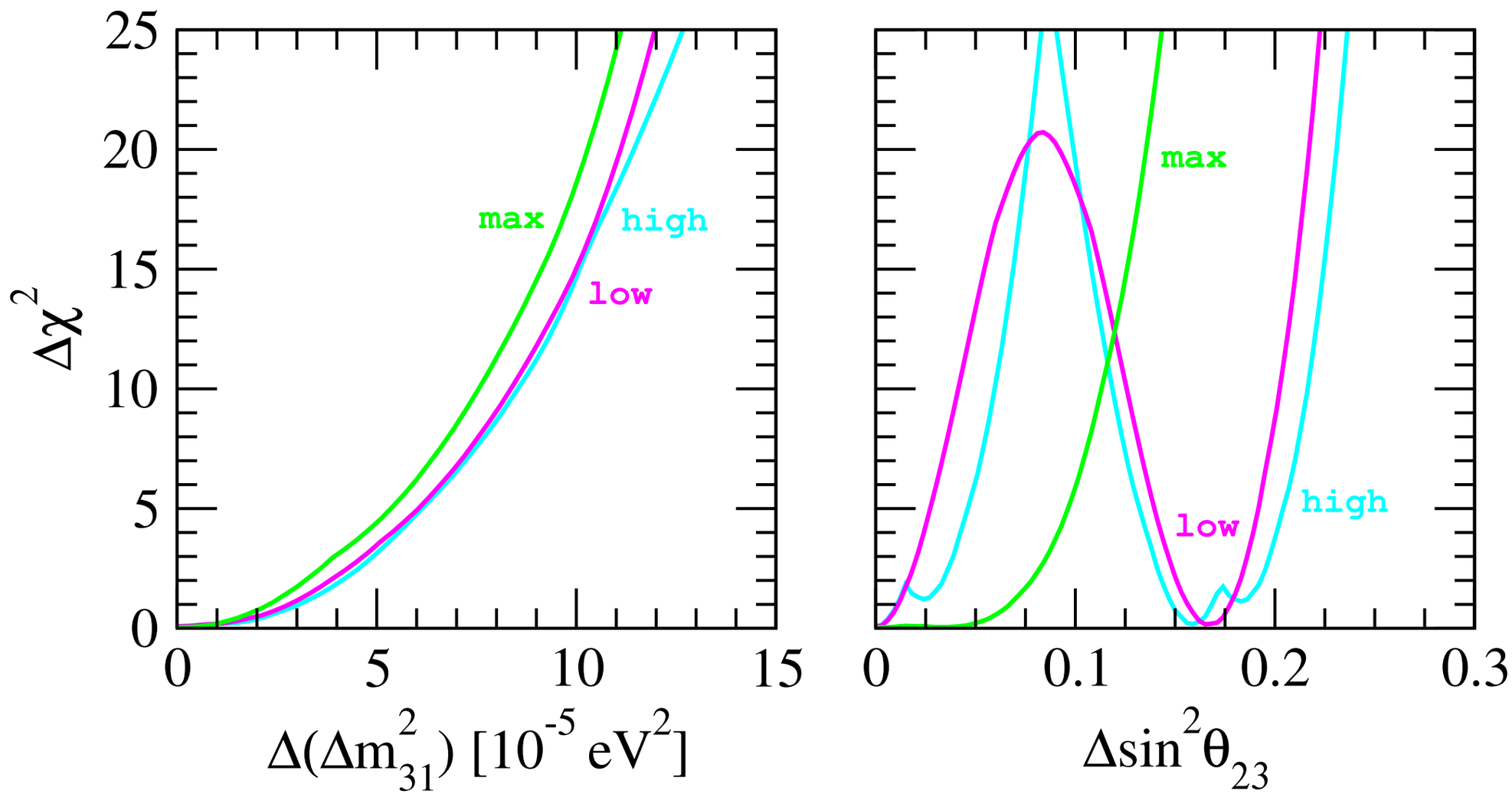
DUNE might improve current constraints on the electron flavour-changing NSI intensity parameters by a factor 2-5. Shown here the allowed regions (68, 90 and 95% CL) for an exposure of 300 kton MW year.



# CPT violation

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

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



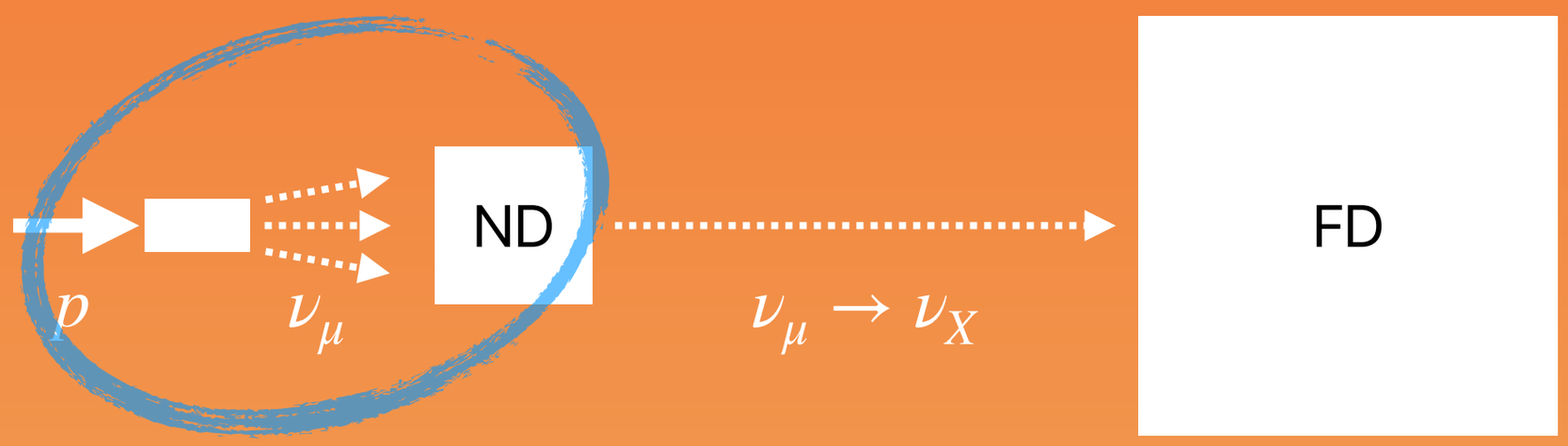

Barenboim, Ternes Tórtola, Phys. Lett. B **780** (2018) 631

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

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

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

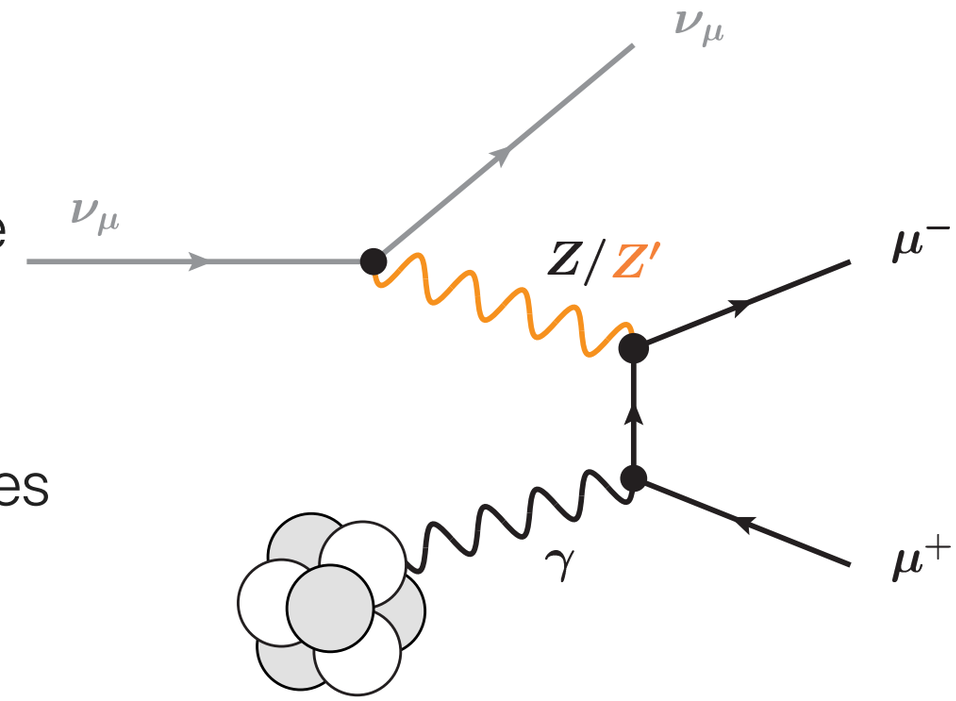
# Searches at the Near Detector

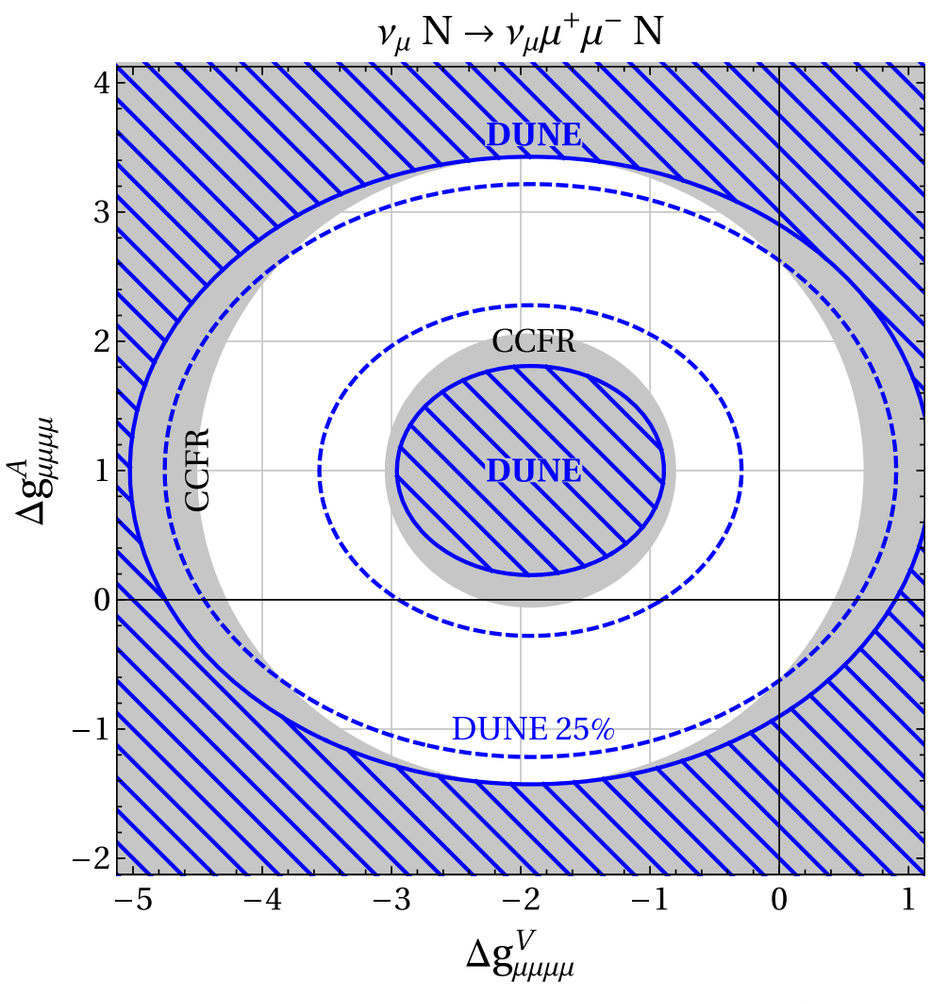


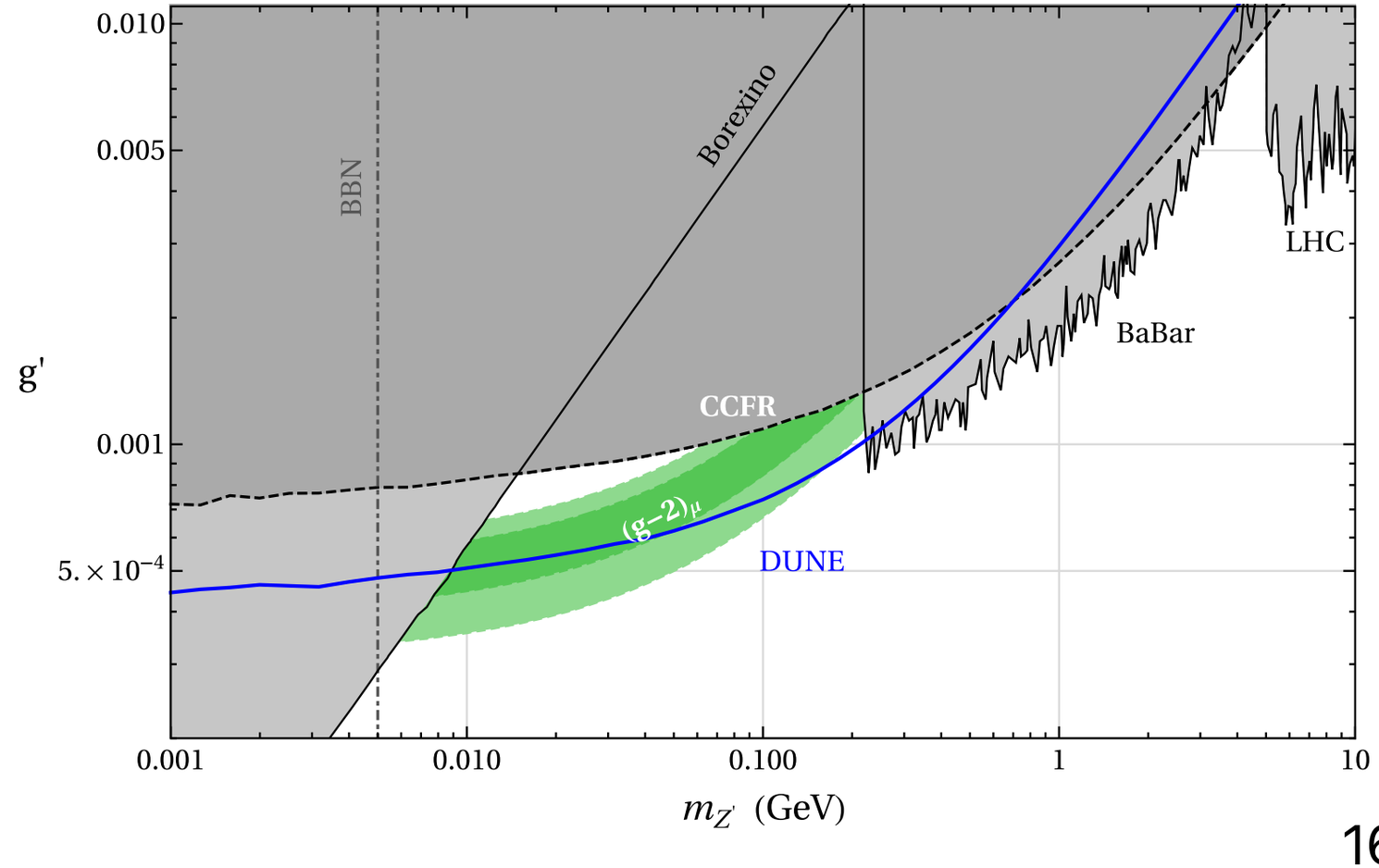
# Neutrino trident

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.



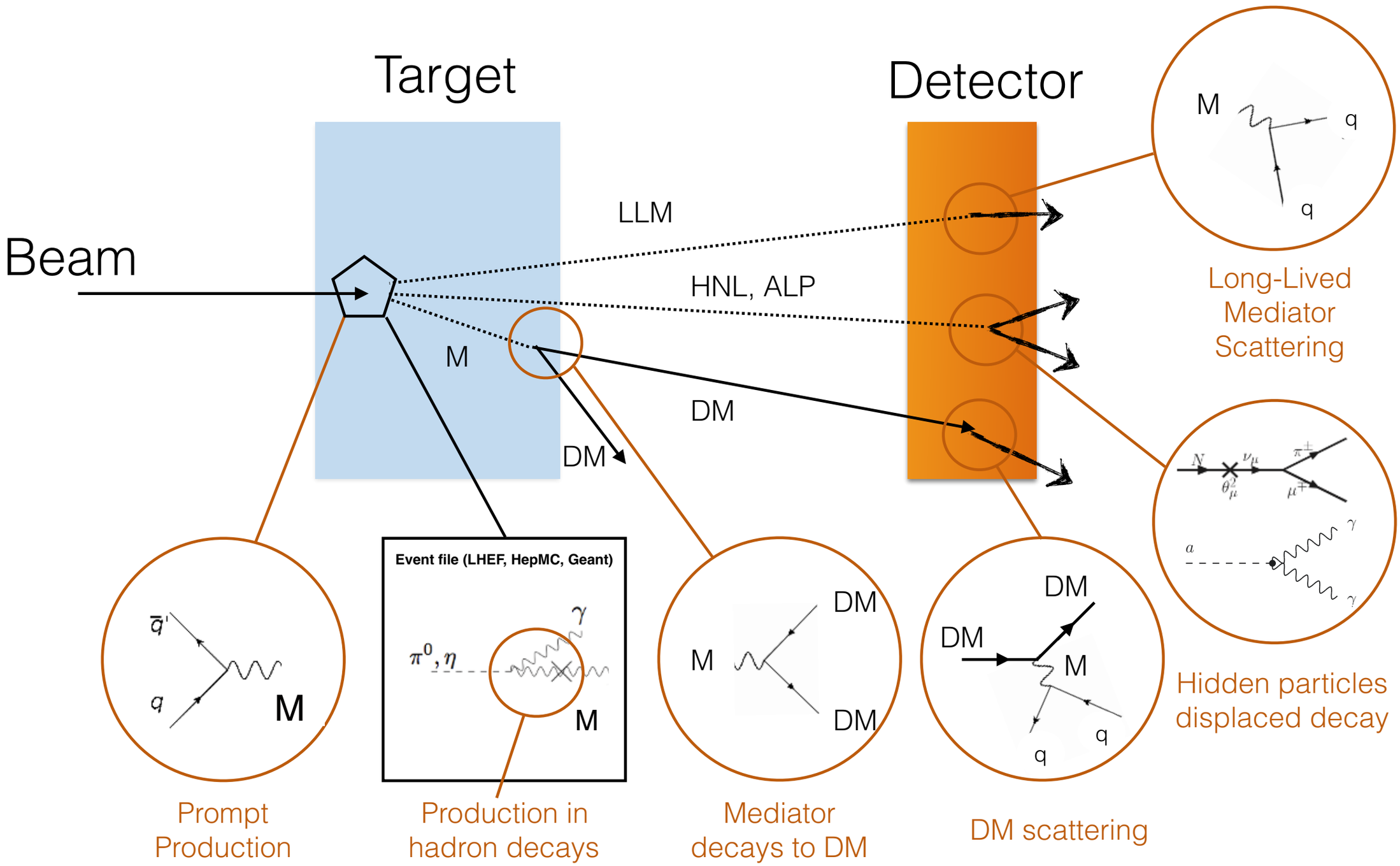






Altmannshofer, Gori, M-A, Sousa, Wallbank, Phys. Rev. D **100** (2019) 115029

# Beam dump



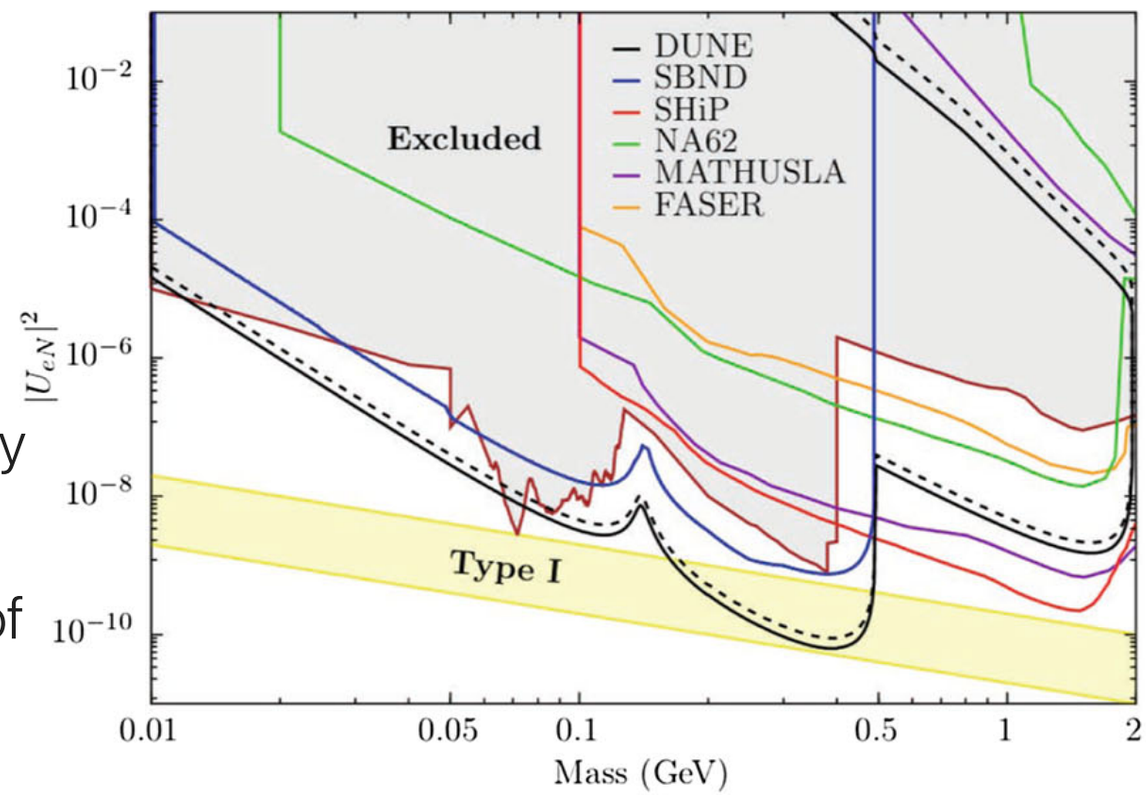

Buonocore, Frugiuele, Maltoni, Mattelaer, Tramontano, JHEP **05** (2019) 028

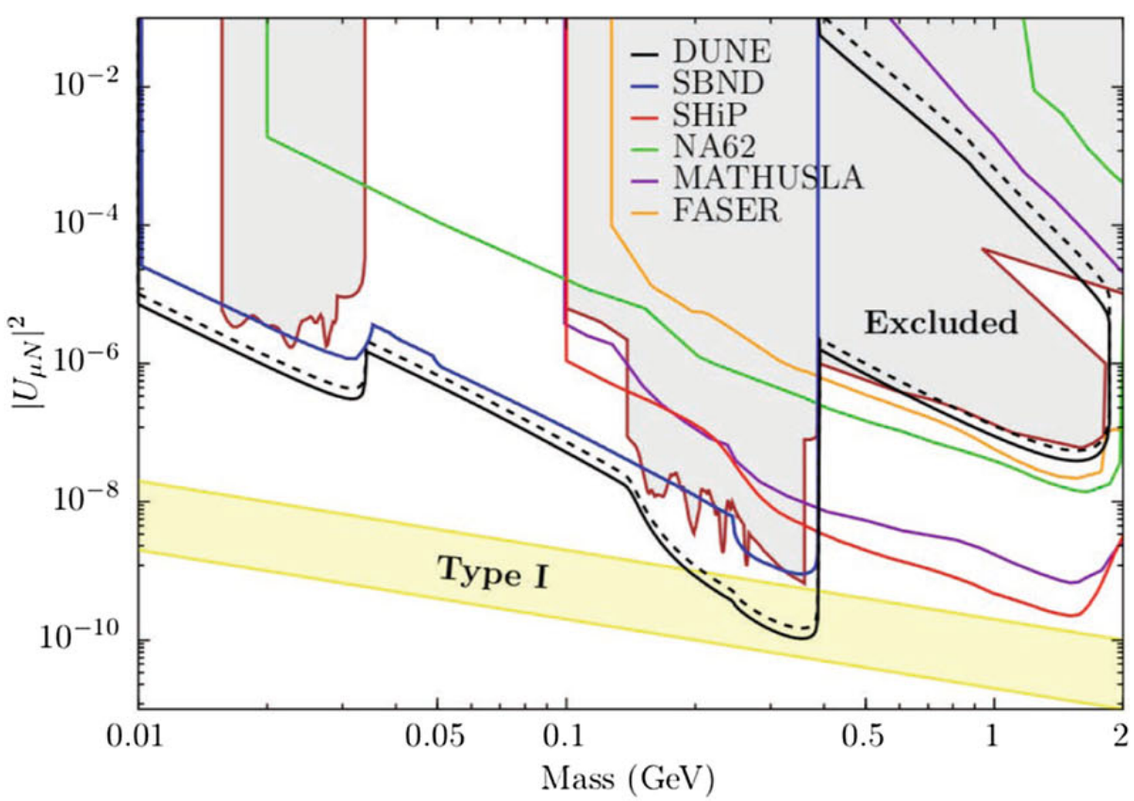
# Heavy neutral leptons

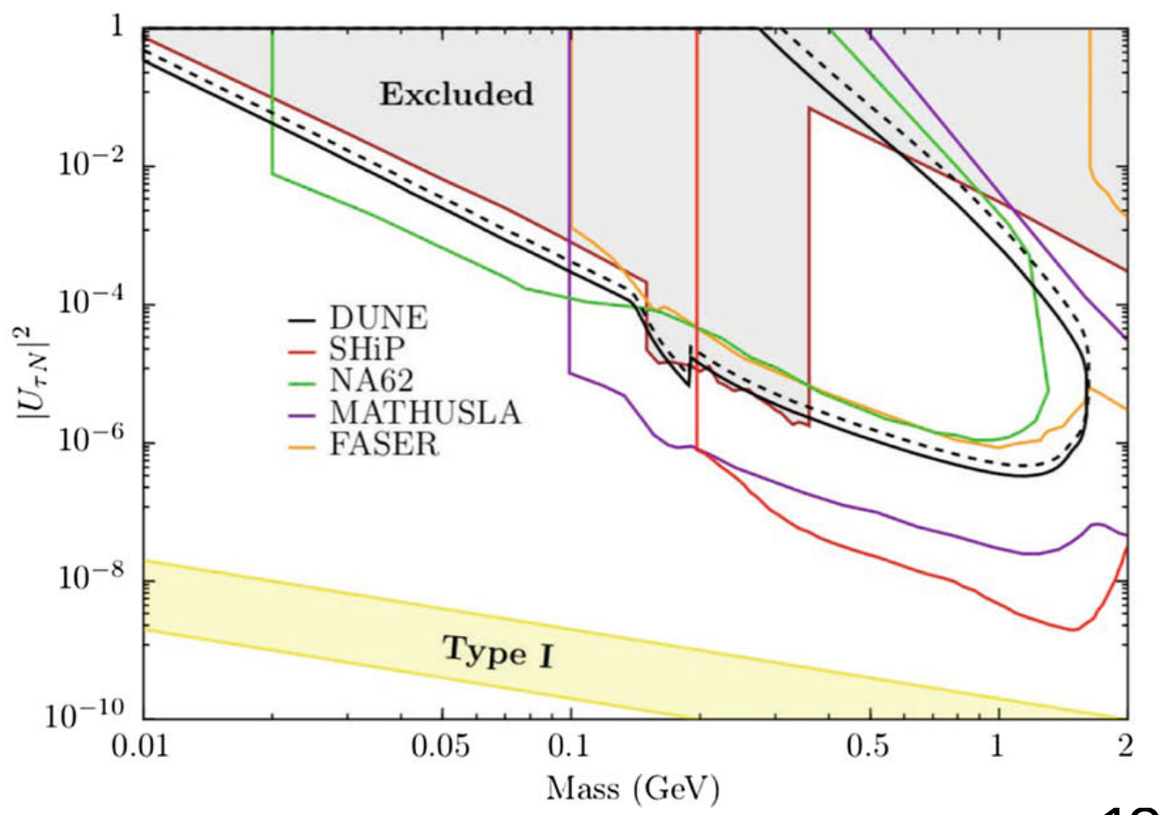
Heavy right-handed singlets predicted in many extensions of the SM may be produced by the LBNF beam.

The HNLs could reach the DUNE ND, where they would be detected via their decay products.

Shown here the sensitivity (90% CL) for a total of total of $1.32\times10^{22}$ POT.



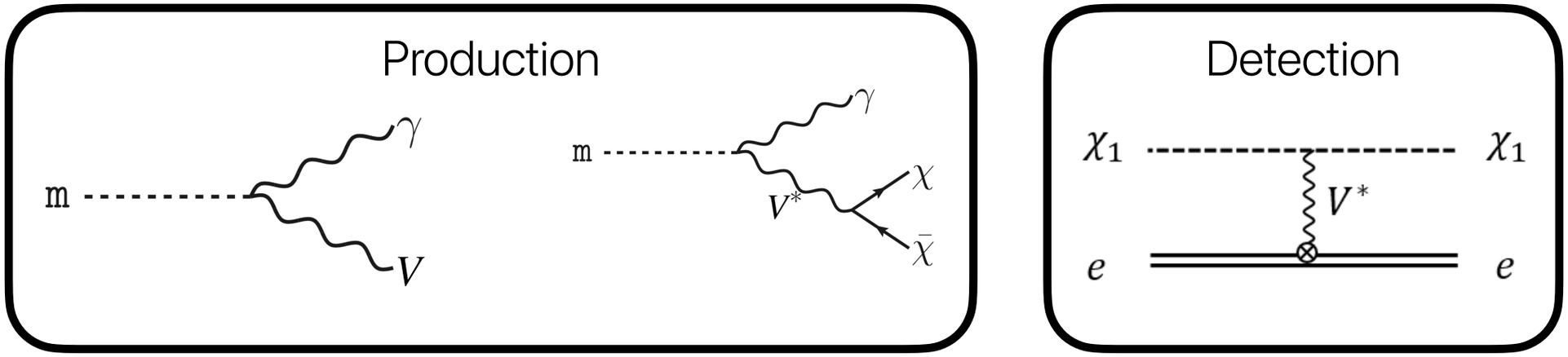



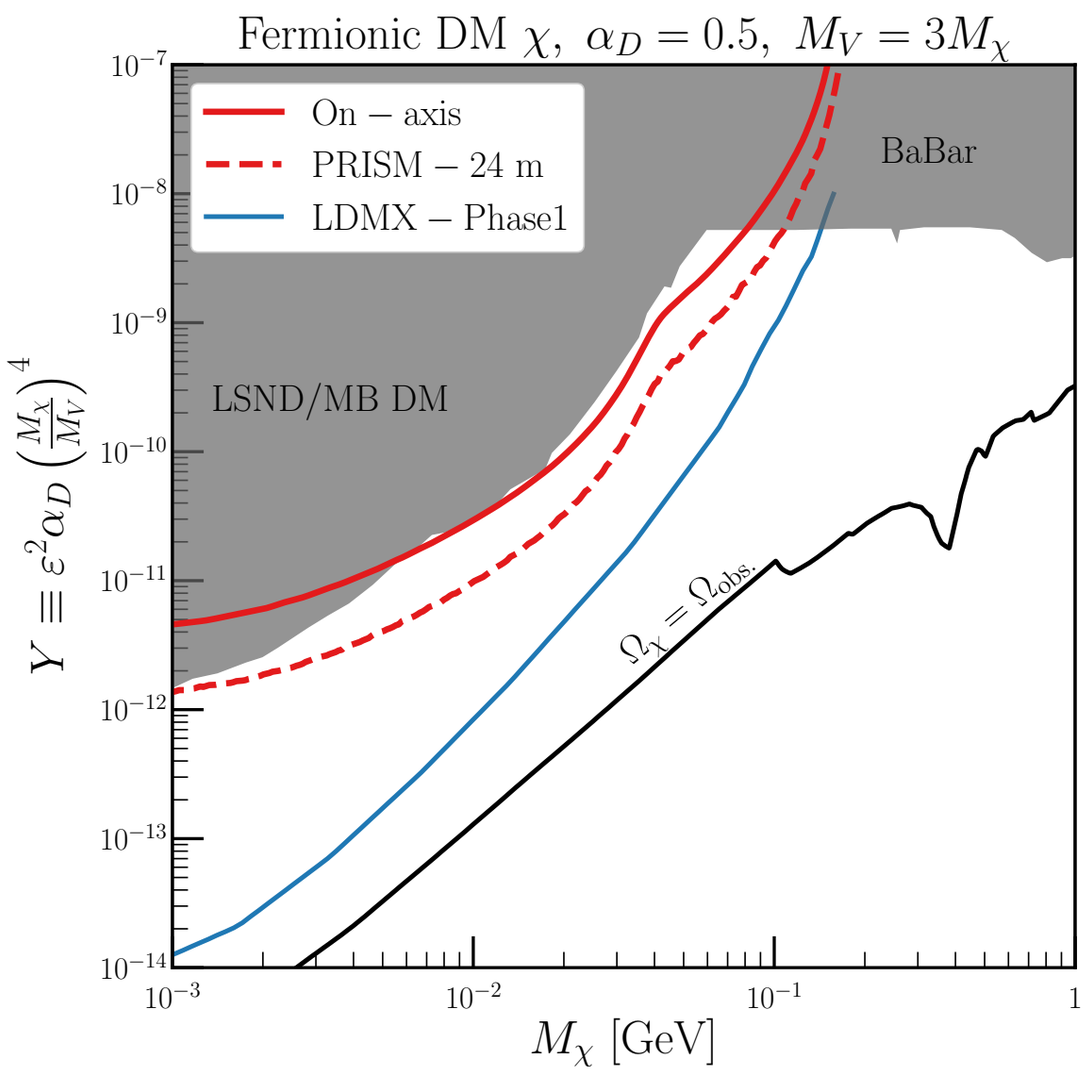






Ballett, Boschi, Pascoli, JHEP **03** (2020) 111

# Low-mass dark matter



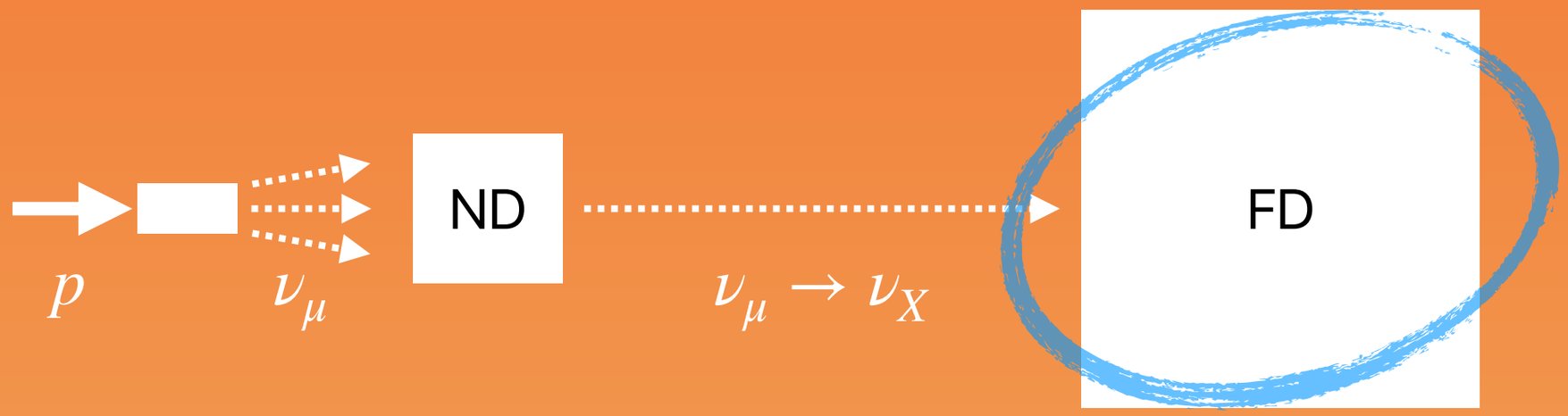

Dark matter particles produced in the decay of light mesons reach the DUNE ND, where they are detected via electron scattering.

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.

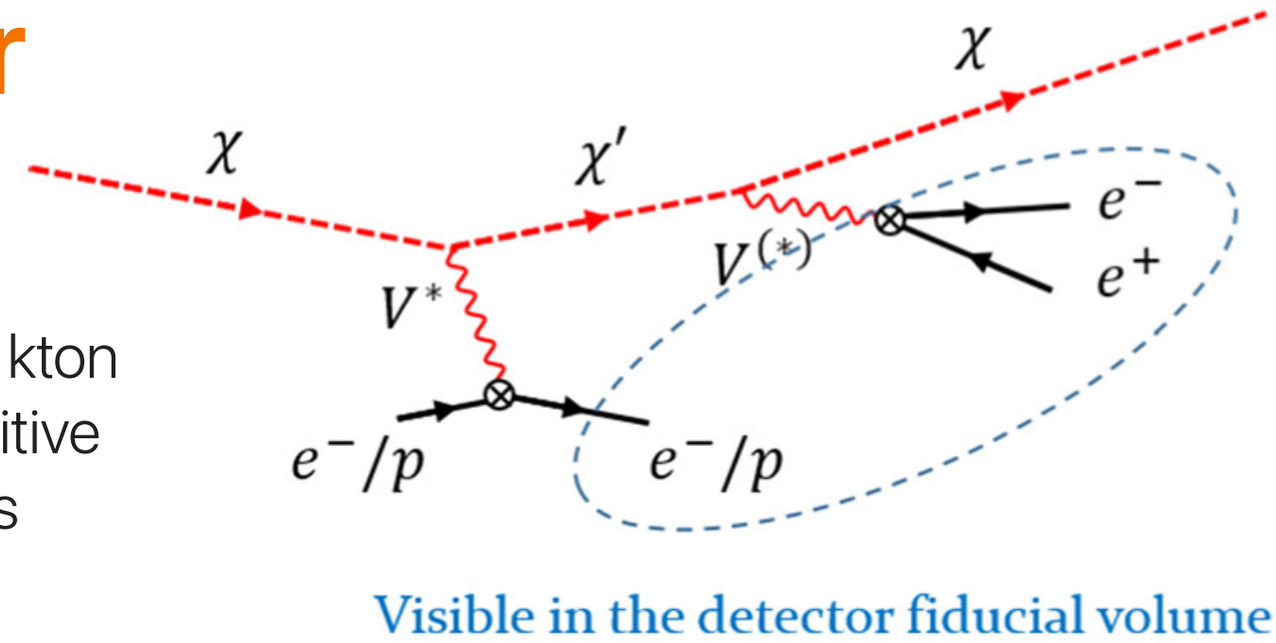
De Romeri, Kelly, Machado, Phys. Rev. D **100** (2019) 095010

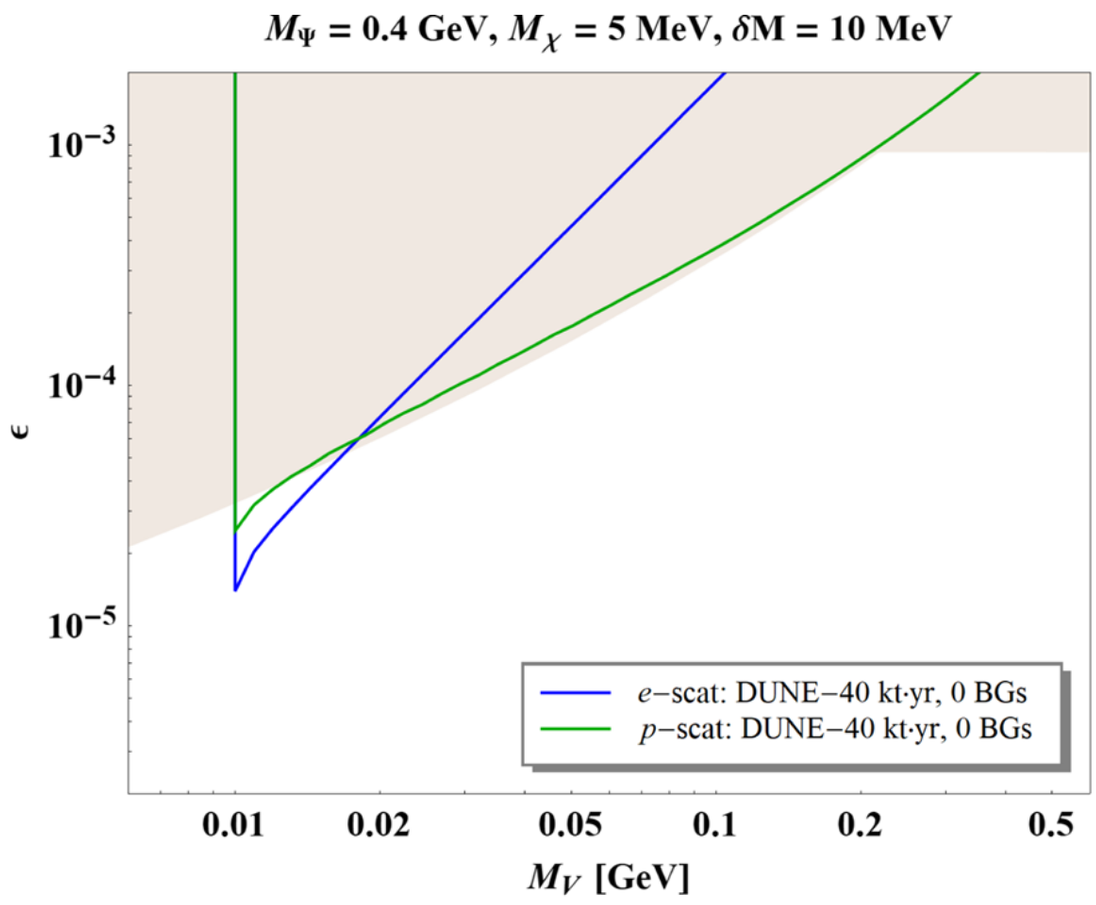
# Searches at the Far Detector

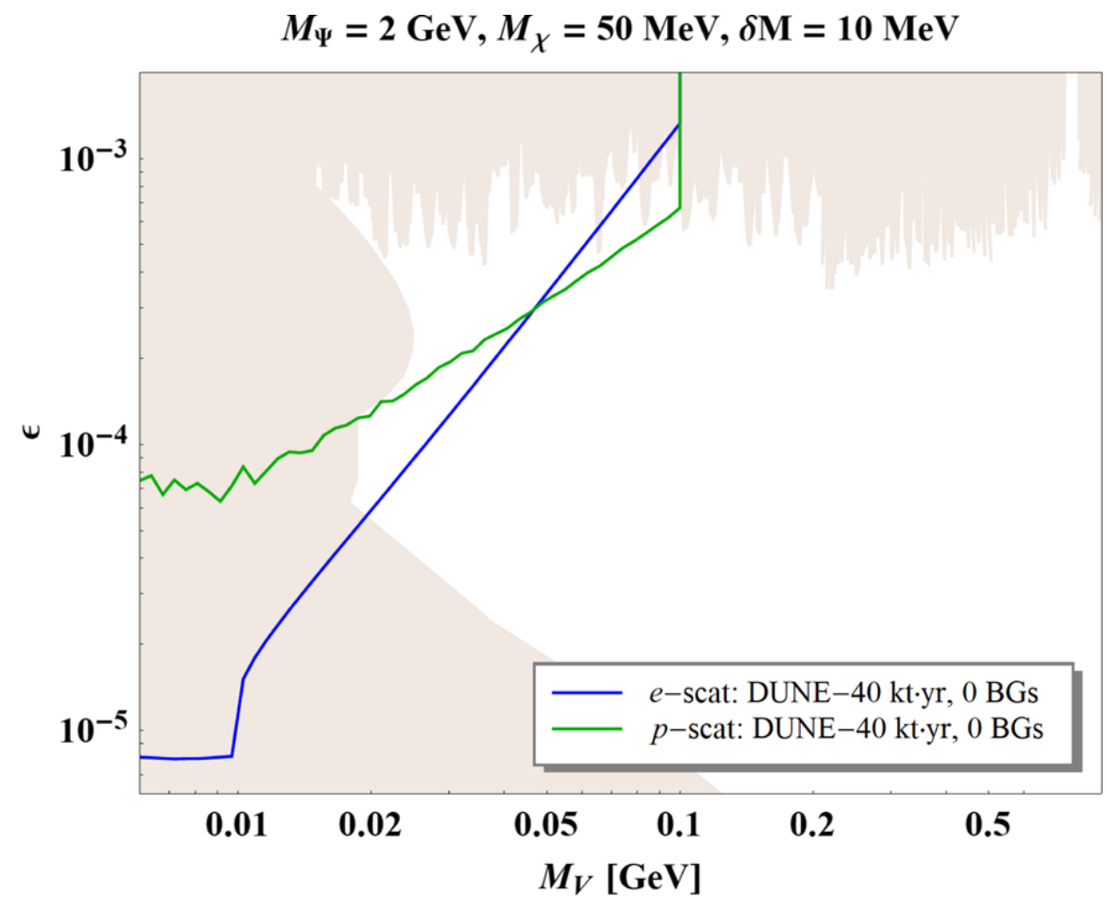


# Boosted dark matter

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.



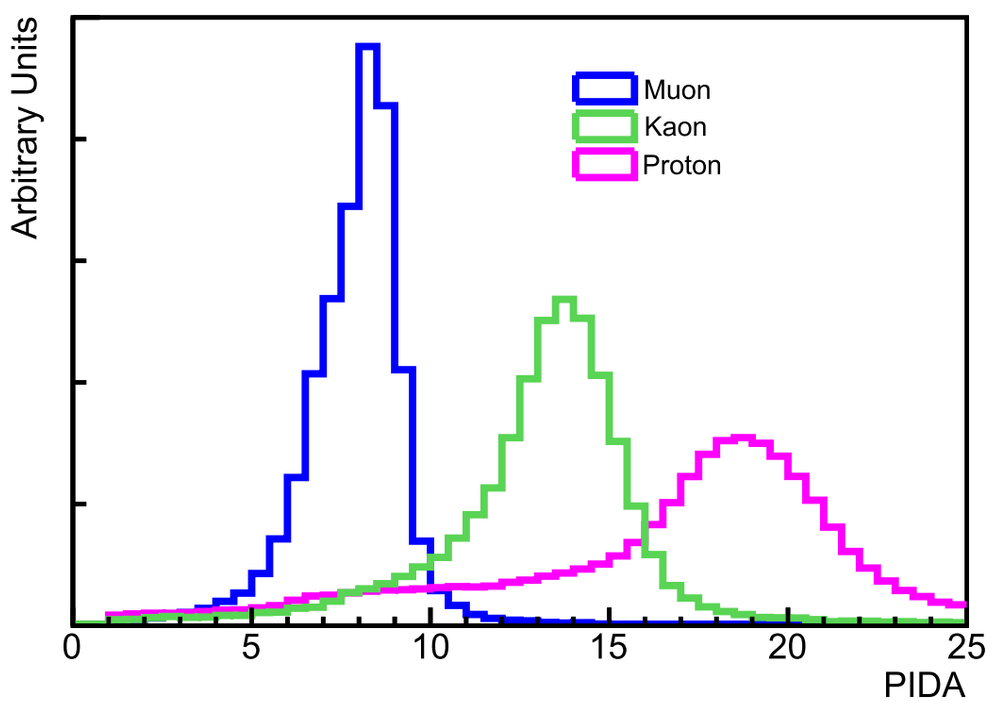

De Roeck, Kim, Moghaddam, Park, Shin, Whitehead, JHEP **11** (2020) 043

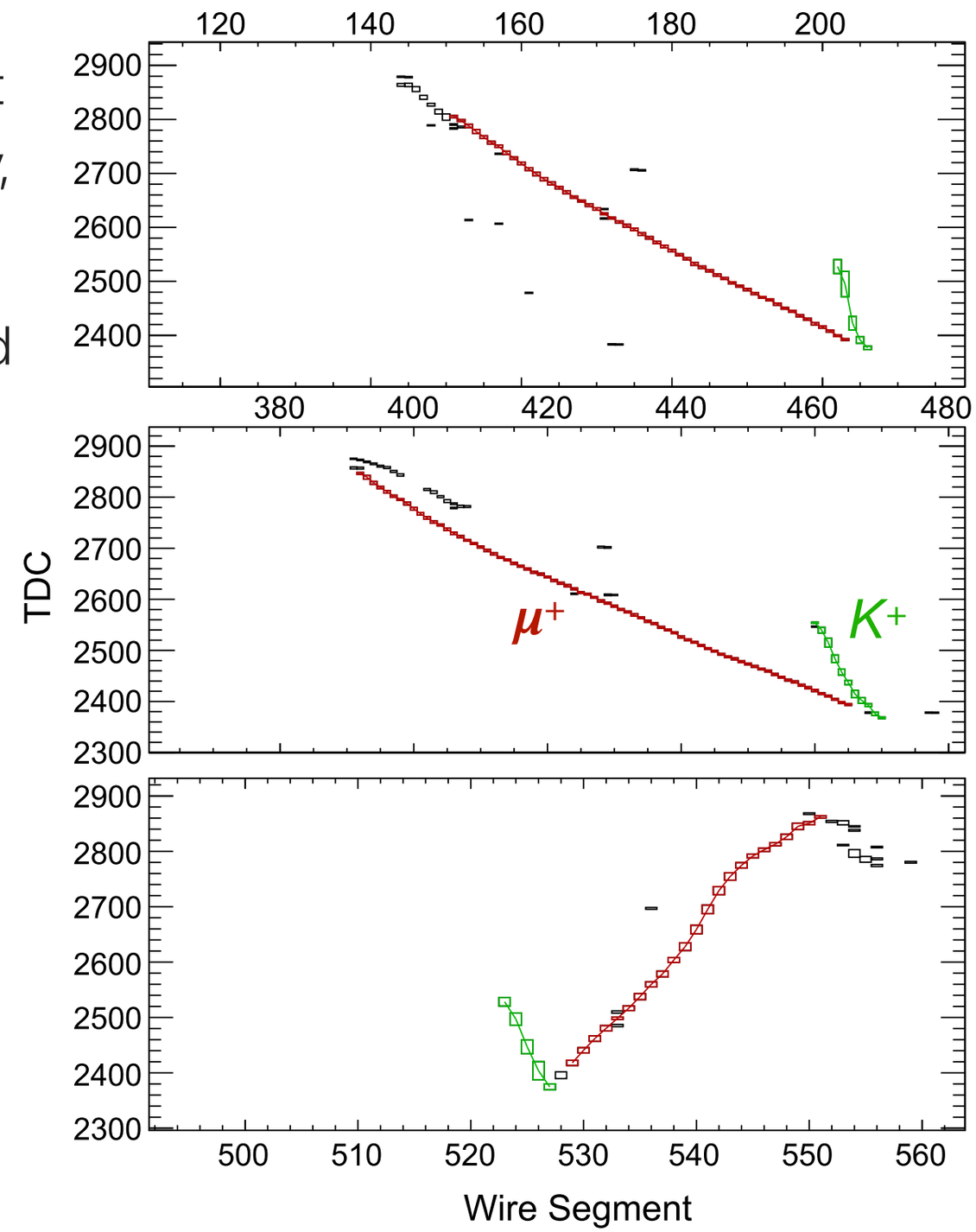
# Proton decay

Grand unified theories extending the SM predict low-energy observables such as nucleon decay, including the decay of the proton into a kaon.

The DUNE FD has the unique ability to track and identify the kaons produced in those decays.

A lower limit on the proton lifetime of $1.3\times10^{34}$ years is expected if no signal is observed in 10 years.



# Outlook

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!