BSM physics and DUNE

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for the DUNE collaboration

Atomic nuclei as laboratories for BSM Physics
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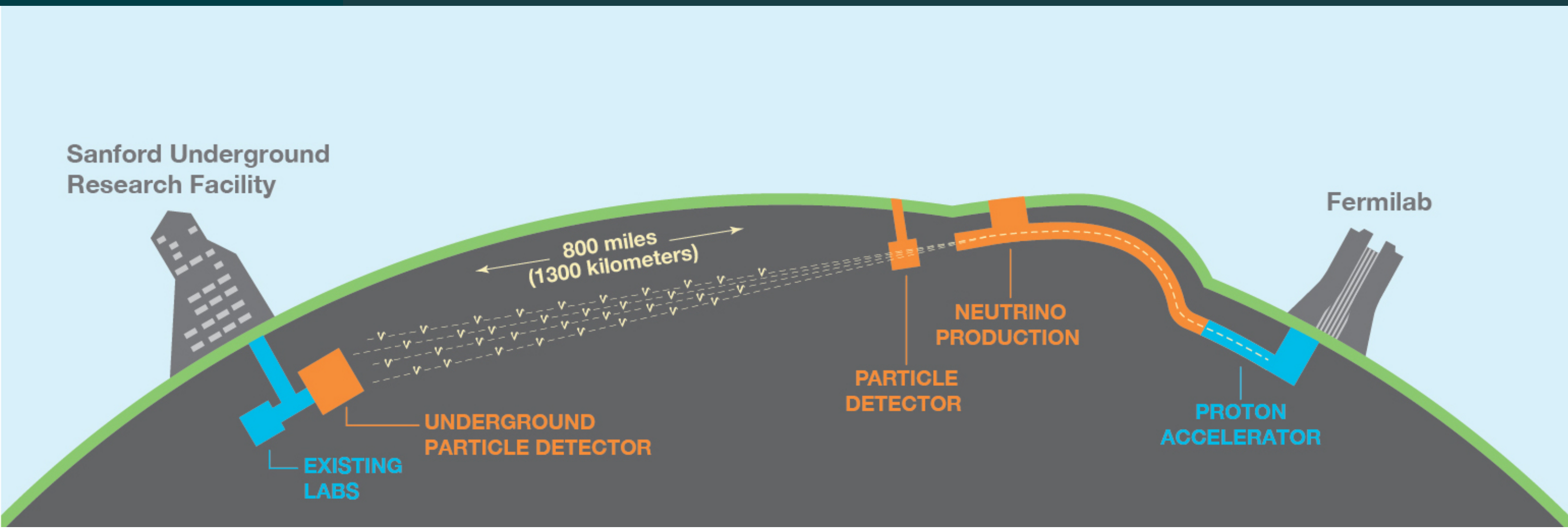
Content

- DUNE experiments
- Neutrino oscillation physics
- Beyond Standard Model (BSM) Physics
  - Oscillation effects
    - Sterile neutrinos
    - Non Standard Interaction (NSI)
    - CPT violation
    - (Tau neutrino appearance, extra dimensions, …)
  - New signals
    - Nucleon decay
    - Dark sector
    - Neutrino trident
    - (Heavy neutral lepton, …)

DUNE Goals



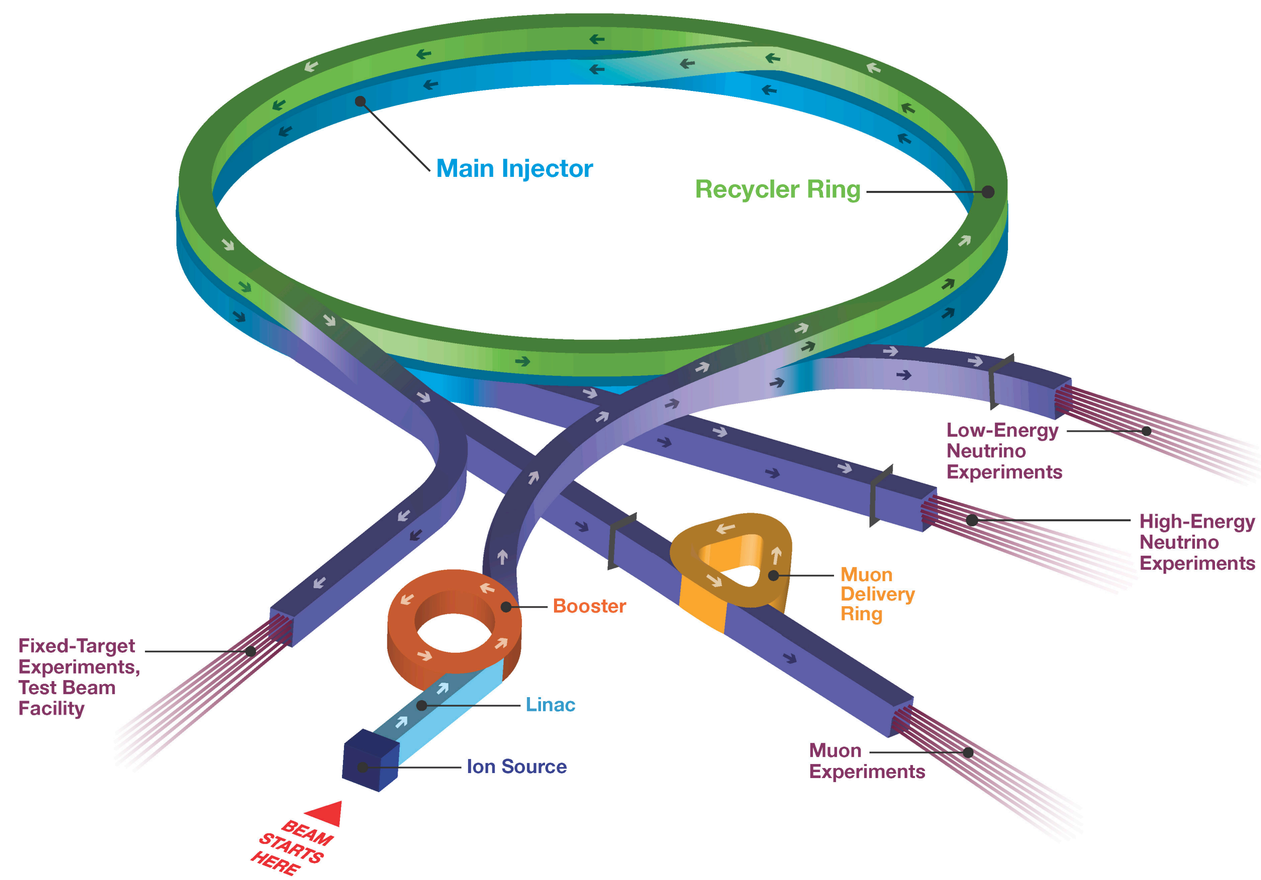
- Primary goals of DUNE:
  - Accelerator neutrino oscillation program:
    - Discover δ_{CP} in the neutrino sector
    - Neutrino mass ordering
    - θ_{23} octant
  - Supernova neutrino burst
  - Proton decay

- Secondary goals of DUNE (ancillary science program):
  - BSM:
    - Non standard interactions
    - Lorentz violation, CPT violation
    - Extra dimensions
    - Heavy neutral lepton
    - Sterile neutrinos
    - Neutrino trident
    - Dark matter
    - …
  - Atmospheric oscillations program
  - Neutrino cross sections
- Solar neutrinos arXiv:1808.08232v1, arXiv:1702.06097v2

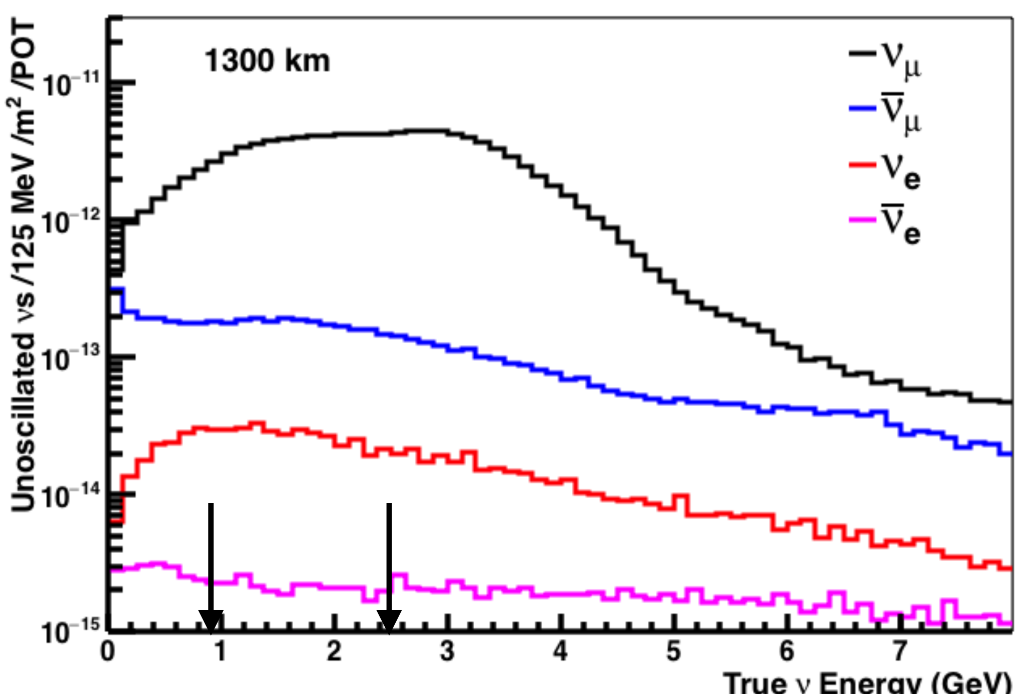
Beam

- Neutrino beam produced at Fermilab:
  - 60 - 120 GeV proton beam
  - Upgrade of the main injector (PIP-II)
  - 1.2 MW, upgradable to 2.4 MW (PIP-III)
  - Horn and magnetic field select the sign of pions (and neutrinos)
- At the Far Detector, wide ν_μ beam:
  - Low beam ν_e background (on-axis)

Fermilab Accelerator Complex

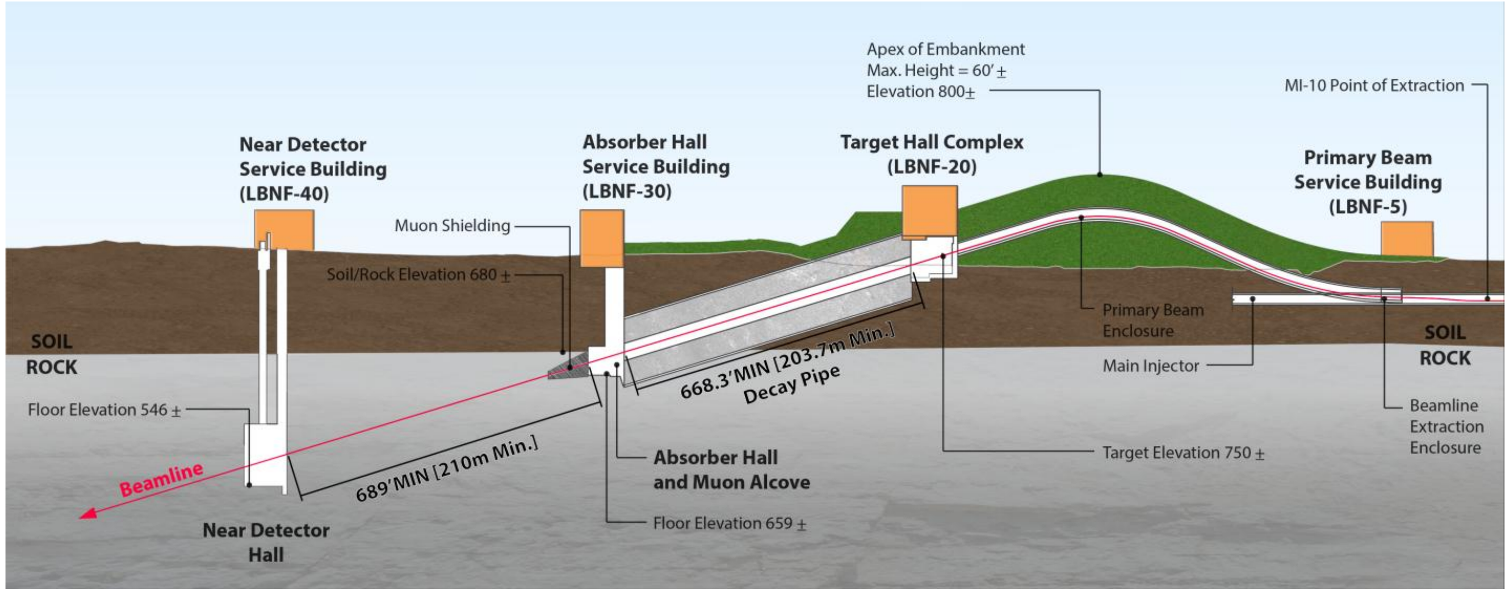


FD ν beam (unoscillated) in neutrino mode



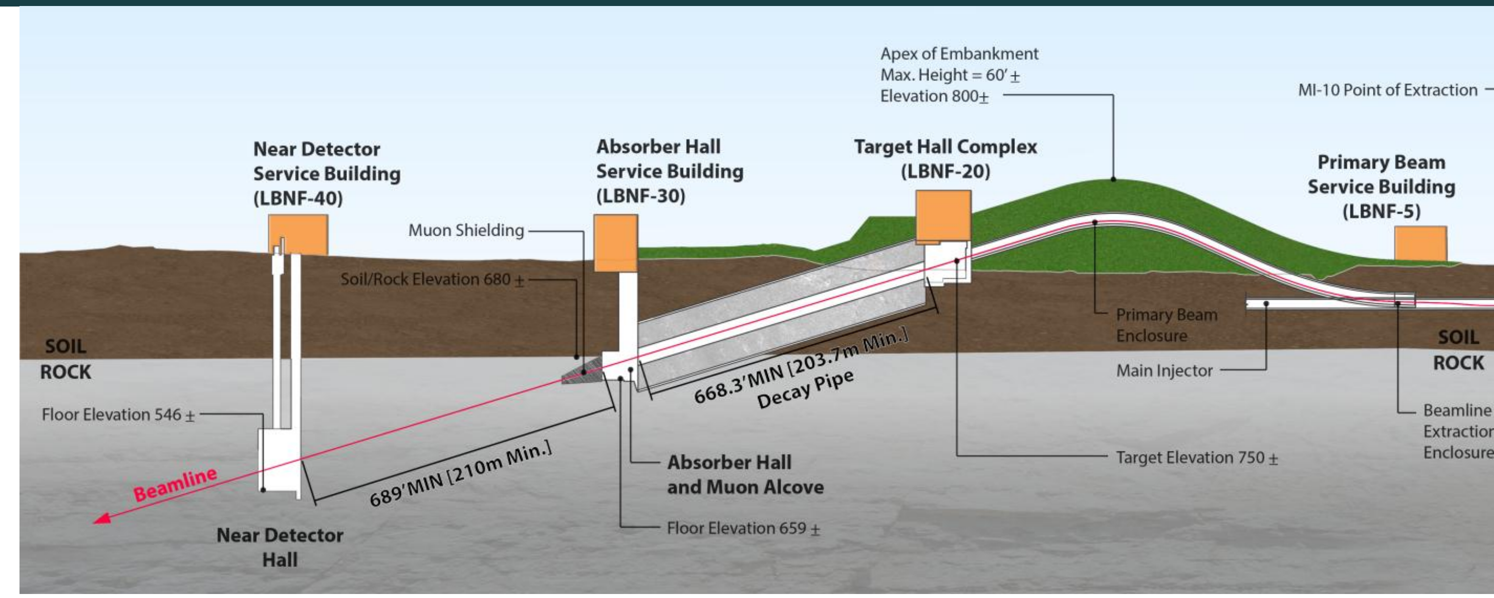
Oscillation maxima

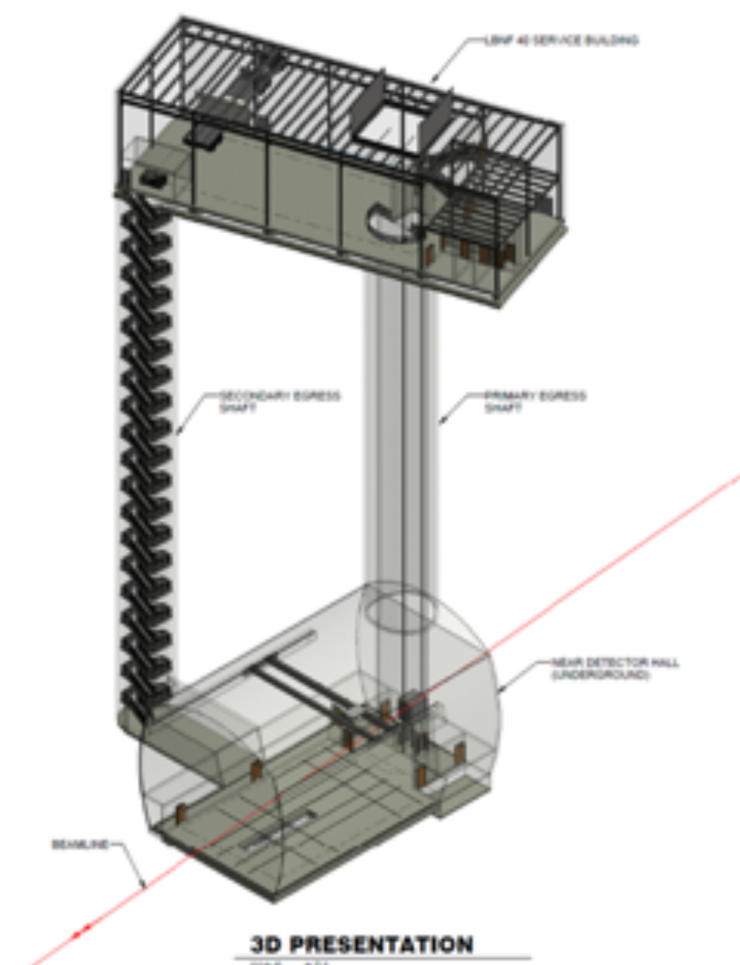
Secondary beamline



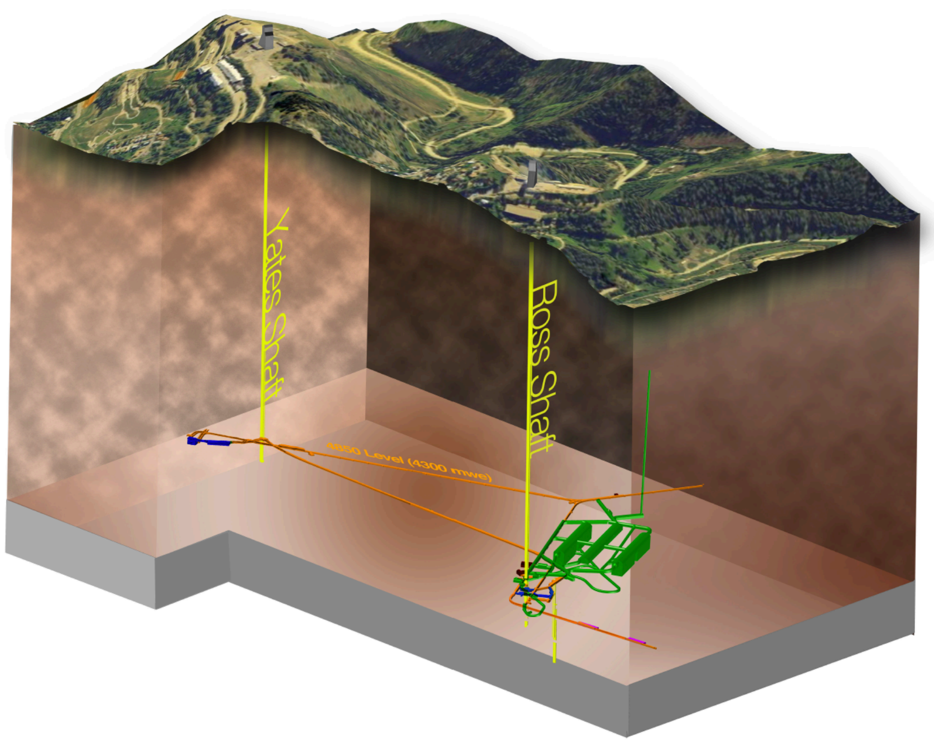
Near Detector

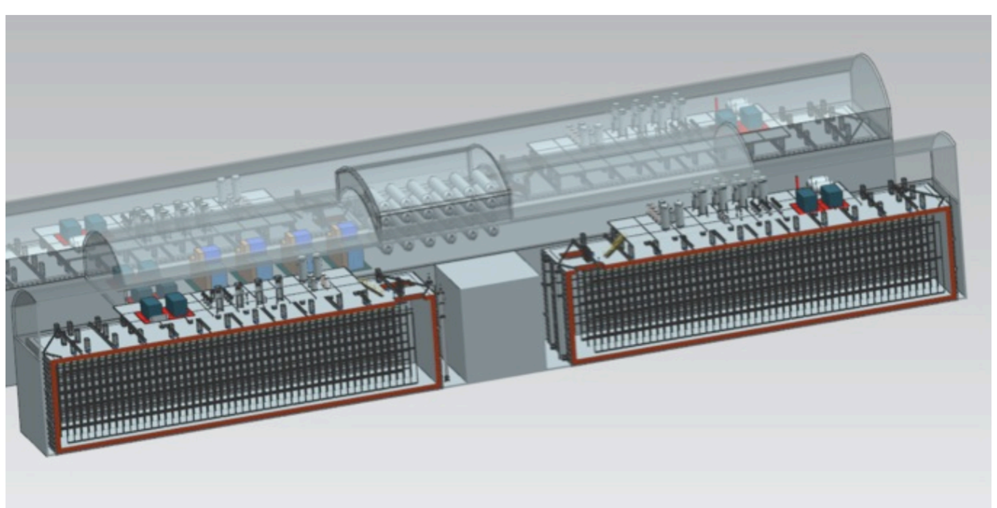
- Near detector at 575 m from the target:
  - Ar TPC detector
  - Magnetised tracker
  - Calorimeter
  - Muon chamber
- Design near final (expected 2019)
  - Conceptual design still allows for a PRISM option for off-axis flux measurement
  - Better constraints for oscillation measurements
- Aim: inform the oscillation measurement at the far, constrain all of the main systematics:
  - Measure the neutrino flux
  - Measure neutrino cross sections
  - Measure detector uncertainties





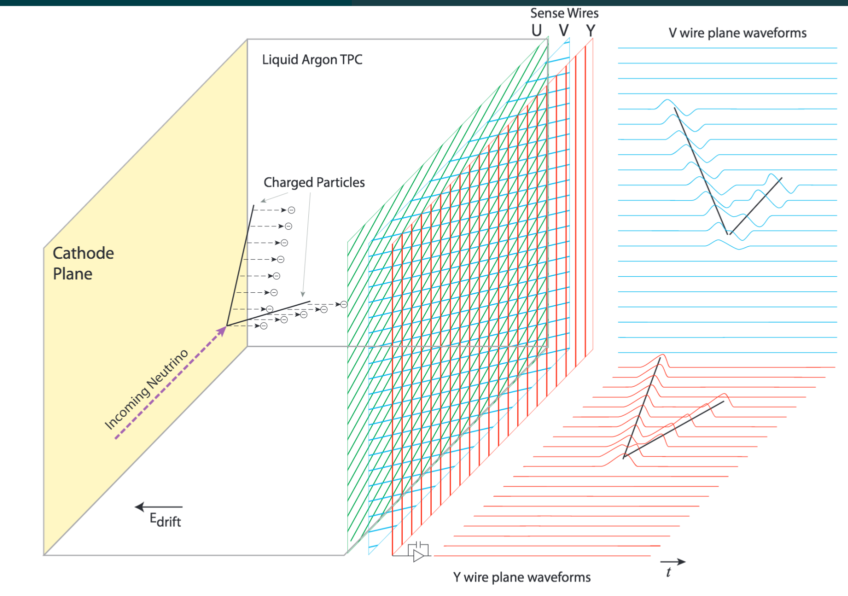
DUNE Far Detectors

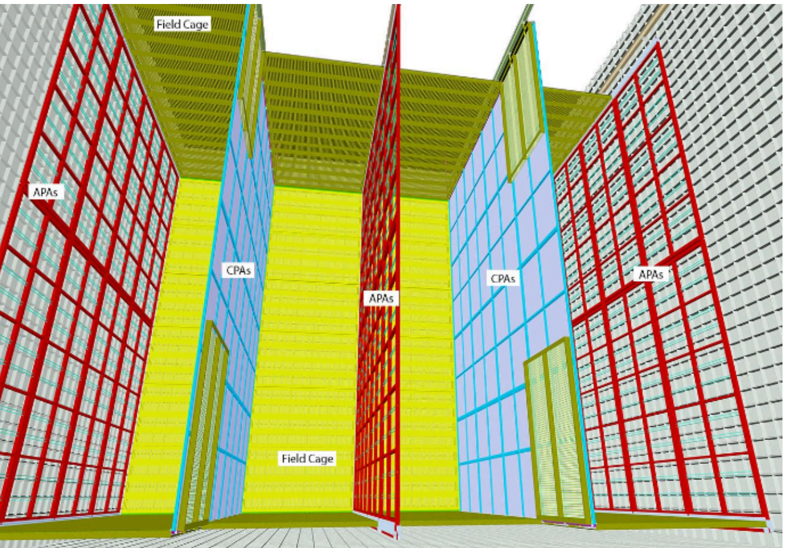


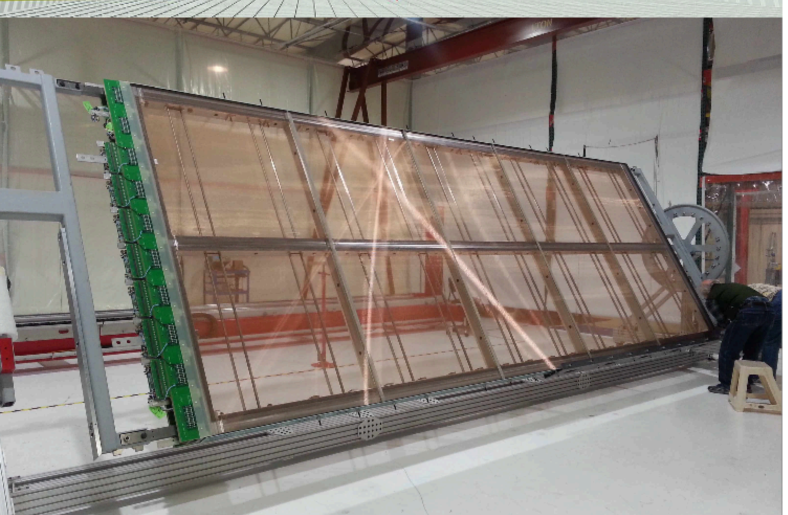


- Liquid Argon Time Projection Chambers (LArTPC):
  - Collect drift electrons with wires (anode plane wires):
    - PID, energy reconstruction, topology…
  - Measure scintillation light with photon detector (T_0).
- Far detector:
  - Sanford underground research facility
  - 4 x 10kT (beam fiducial) of Liquid Argon: ~15 x 14 x 60 m^3
    - 2 single phase
    - 1 dual phase (additional gaseous phase)
    - 1 “opportunity” module
  - 1.5 km underground (~ 4300 m.w.e.) → low cosmogenic background

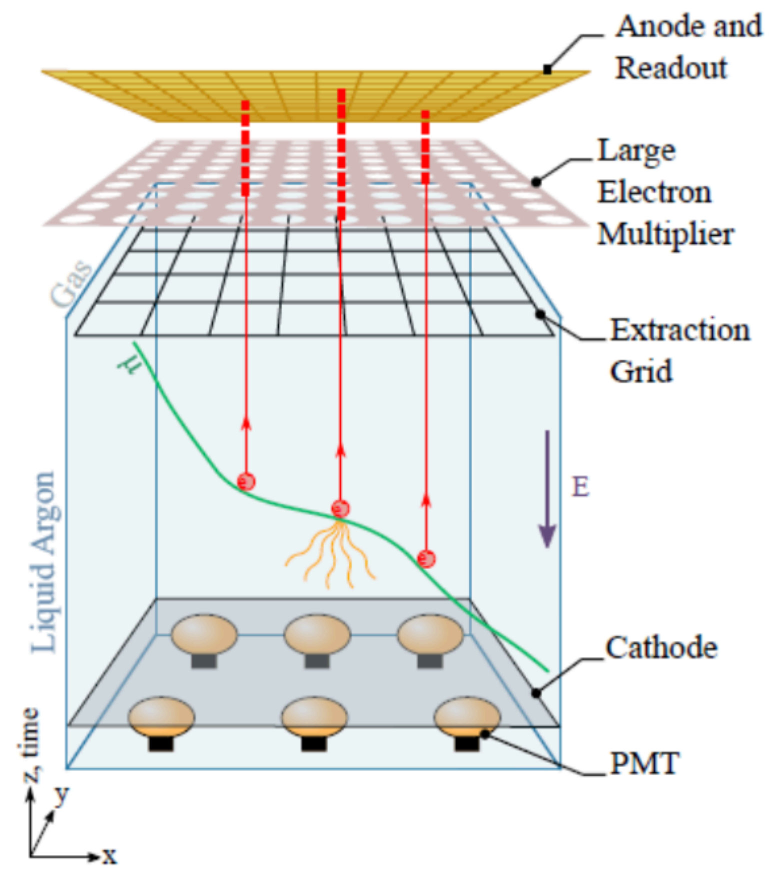
Detector technology: Single/Dual Phase

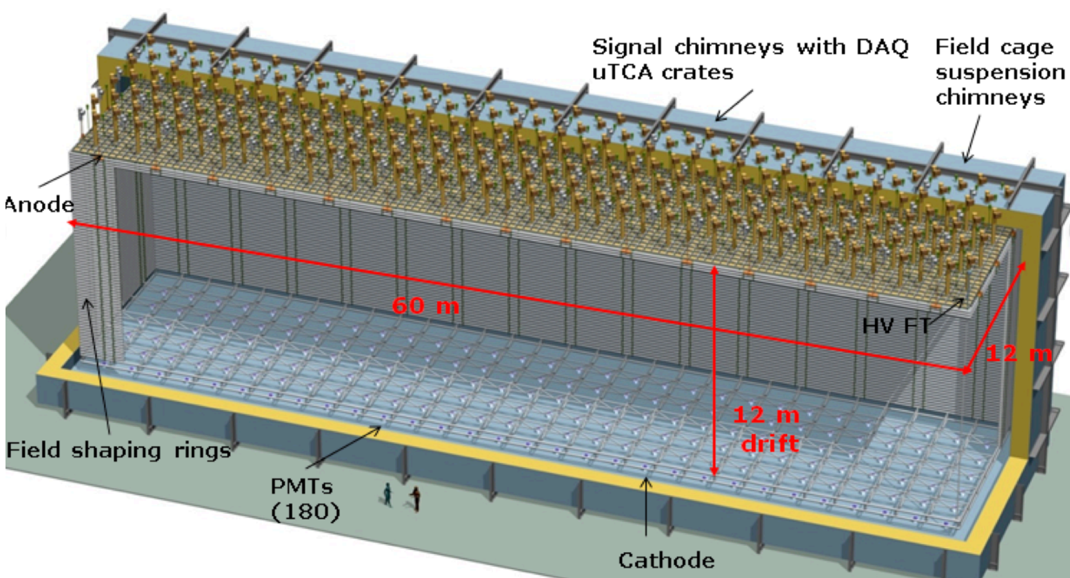






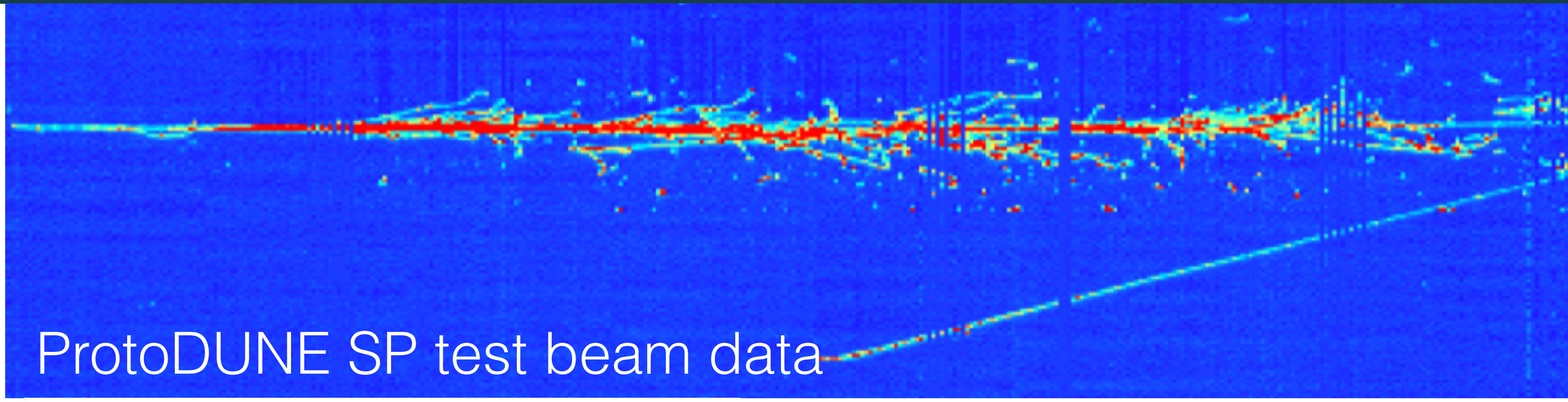
- Single phase:
  - Horizontal drift direction
  - Modular building blocks for each 10 kT module = APA (Anode Plane Assembly)
  - Design tested at CERN (autumn 2018) ProtoDUNE.
- Dual phase:
  - Vertical drift direction
  - Module = CRP (Charge Readout Plane)

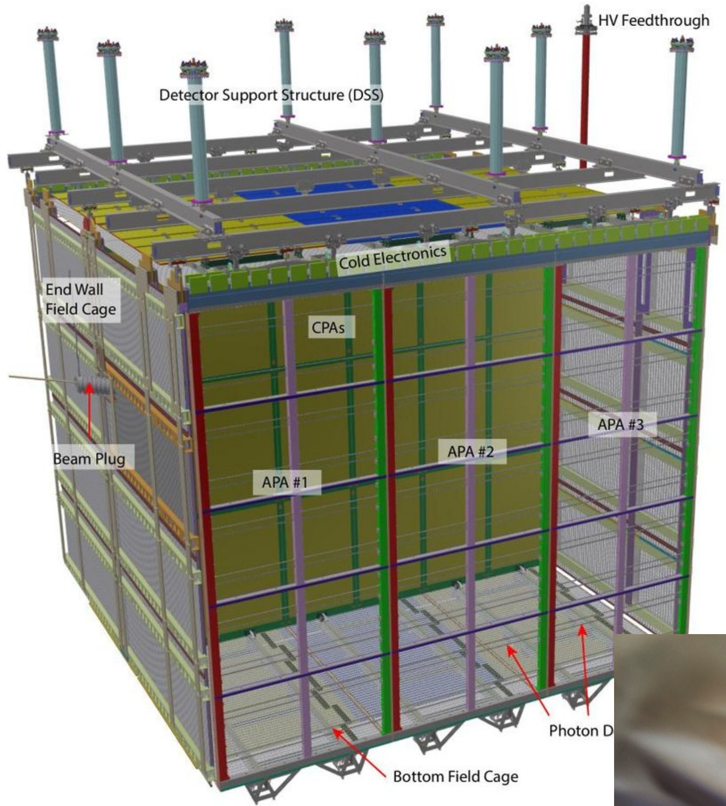




ProtoDUNEs

- SP ProtoDUNE:
  - Took beam data
    - Measured pions, kaons, muons, protons and electrons at energies interesting for neutrino oscillation analyses.
  - Now taking cosmics (LHC Long Shutdown 2).
  - Resume test beam after LS2.
- DP ProtoDUNE:
  - Being assembled as we speak.
  - Will start to take cosmics.
  - Test beam after LS2.



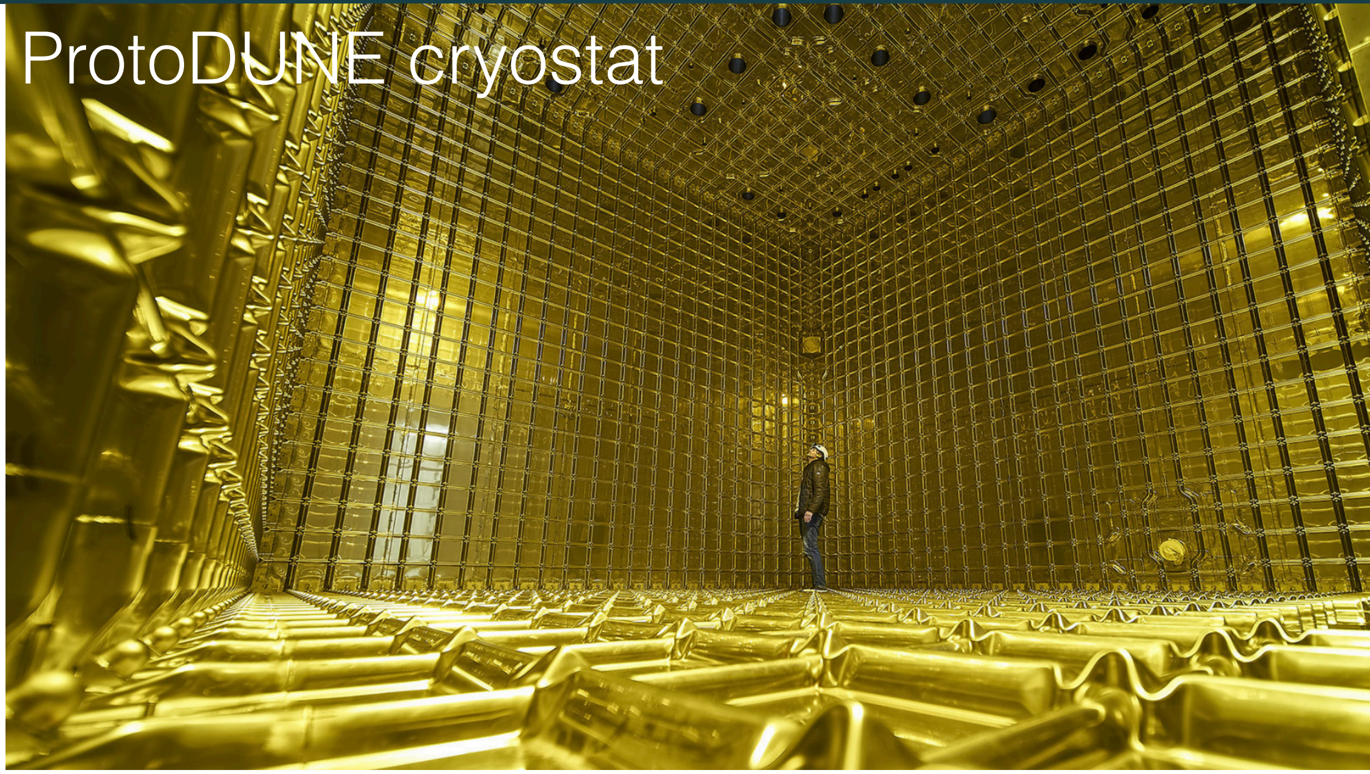


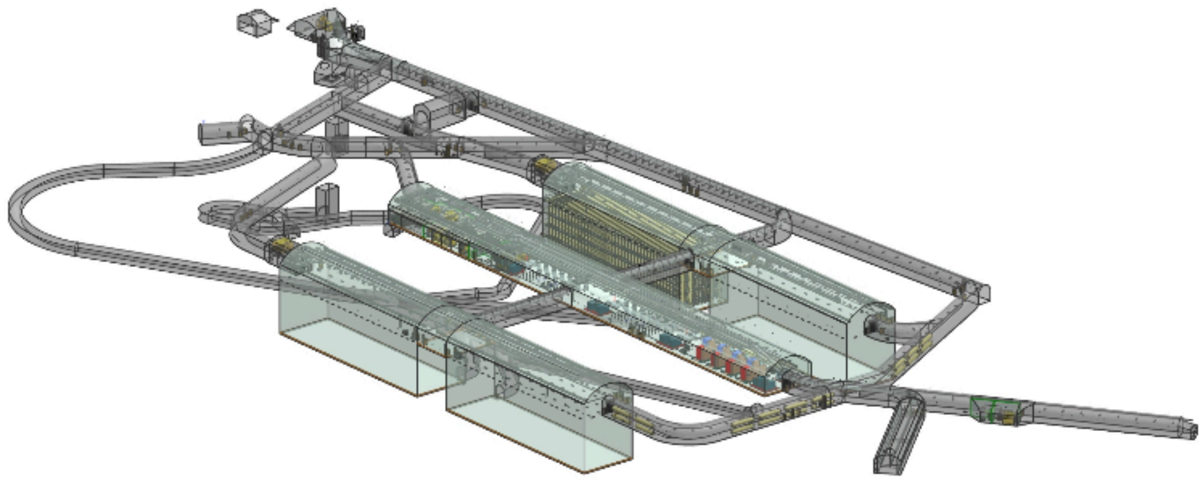
ProtoDUNE SP

ProtoDUNE DP

DUNE status and timeline

- ProtoDUNE experiments:
  - 2018: Single Phase ProtoDUNE took test beam data at CERN
    - Expect result soon
  - 2019: Dual Phase coming up soon
  - 2019: Cosmic runs for ProtoDUNE SP/DP
  - 2021 (after LS2): Test beam
- 2019: Far site excavation starts
- 2019: FD TDR + ND CDR
- Oct 2019: DOE CD2/3b
- August 2024: First module construction starts
- August 2025: Second module construction starts





DUNE far site excavation

“Standard” oscillations

$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = \begin{bmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{bmatrix} \times \begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix}$$

Interacting states — PMNS — Mass states

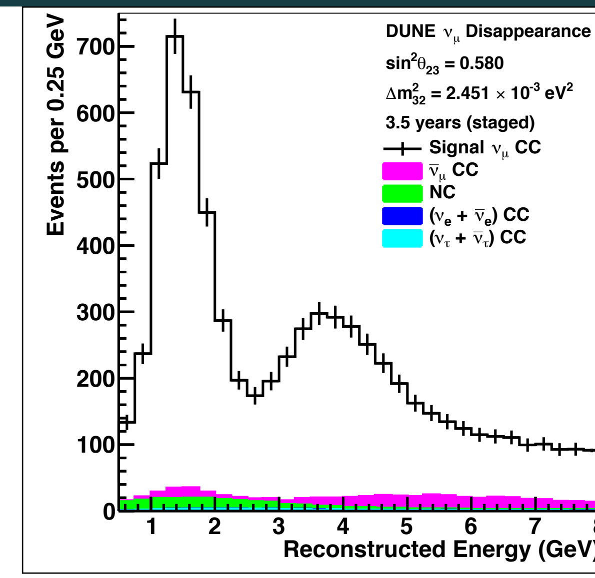
Matter effect: $a = G_F N_e/\sqrt{2}$

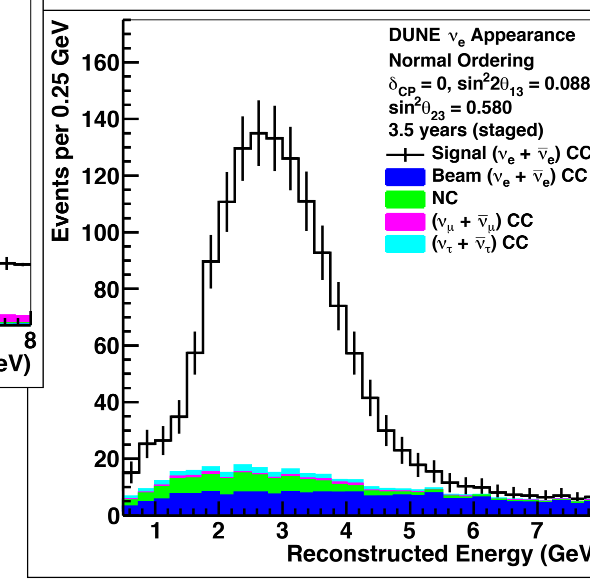
Difference of mass squared: $\Delta_{ij} = \Delta m^2_{ij} L/4E_\nu$

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

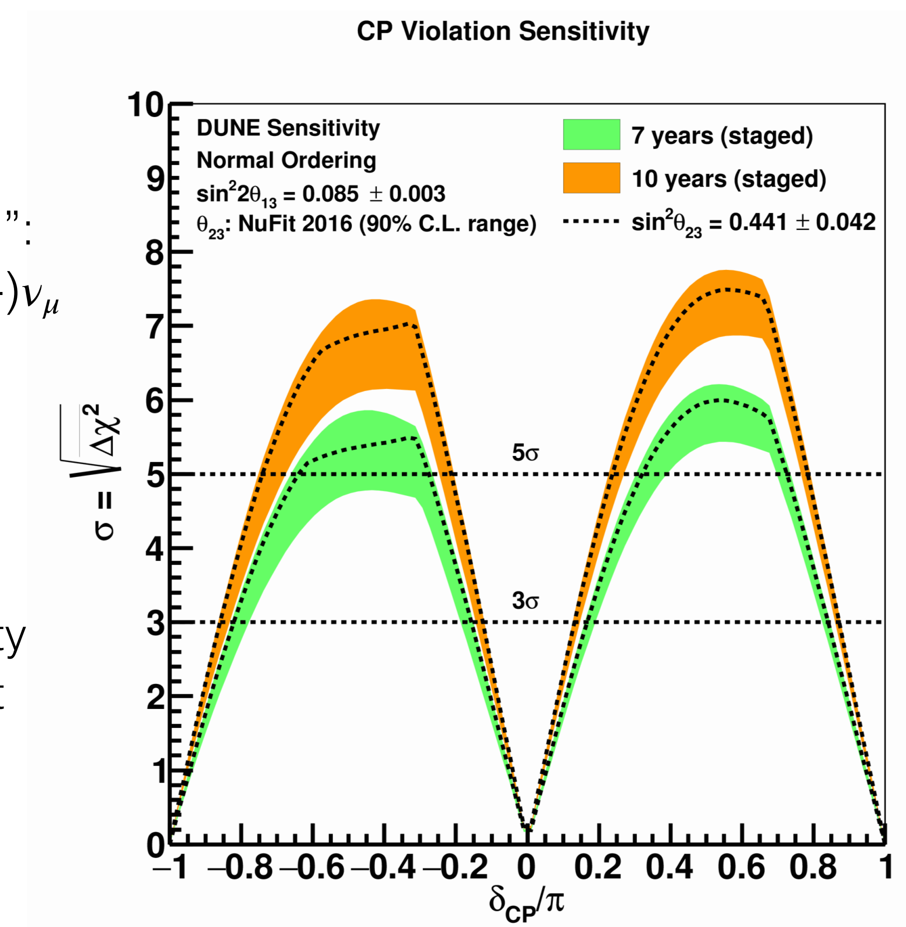
CP Phase

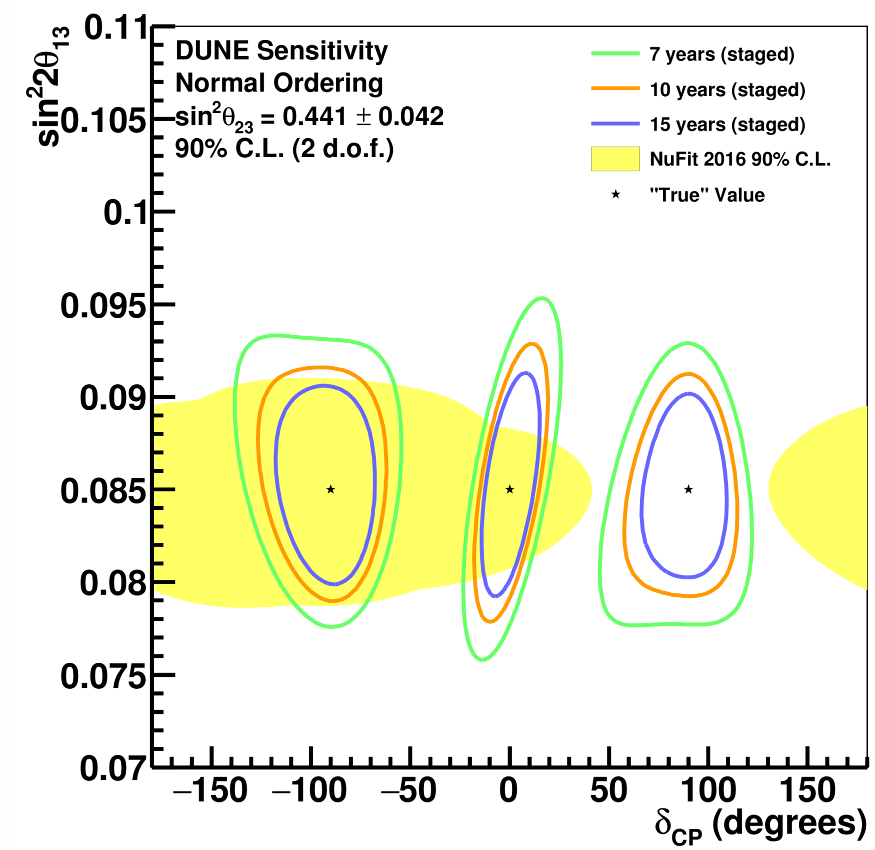
Angles from PMNS matrix





- Neutrino oscillations, “golden channel”: measure (anti-)ν_e appearance in (anti-)ν_μ beam.
    - δ_{CP} sensitivity
    - Good δ_{CP} resolution
    - Octant and mass ordering sensitivity via ν_μ disappearance measurement
        - Large matter effect helps disentangling the mass ordering





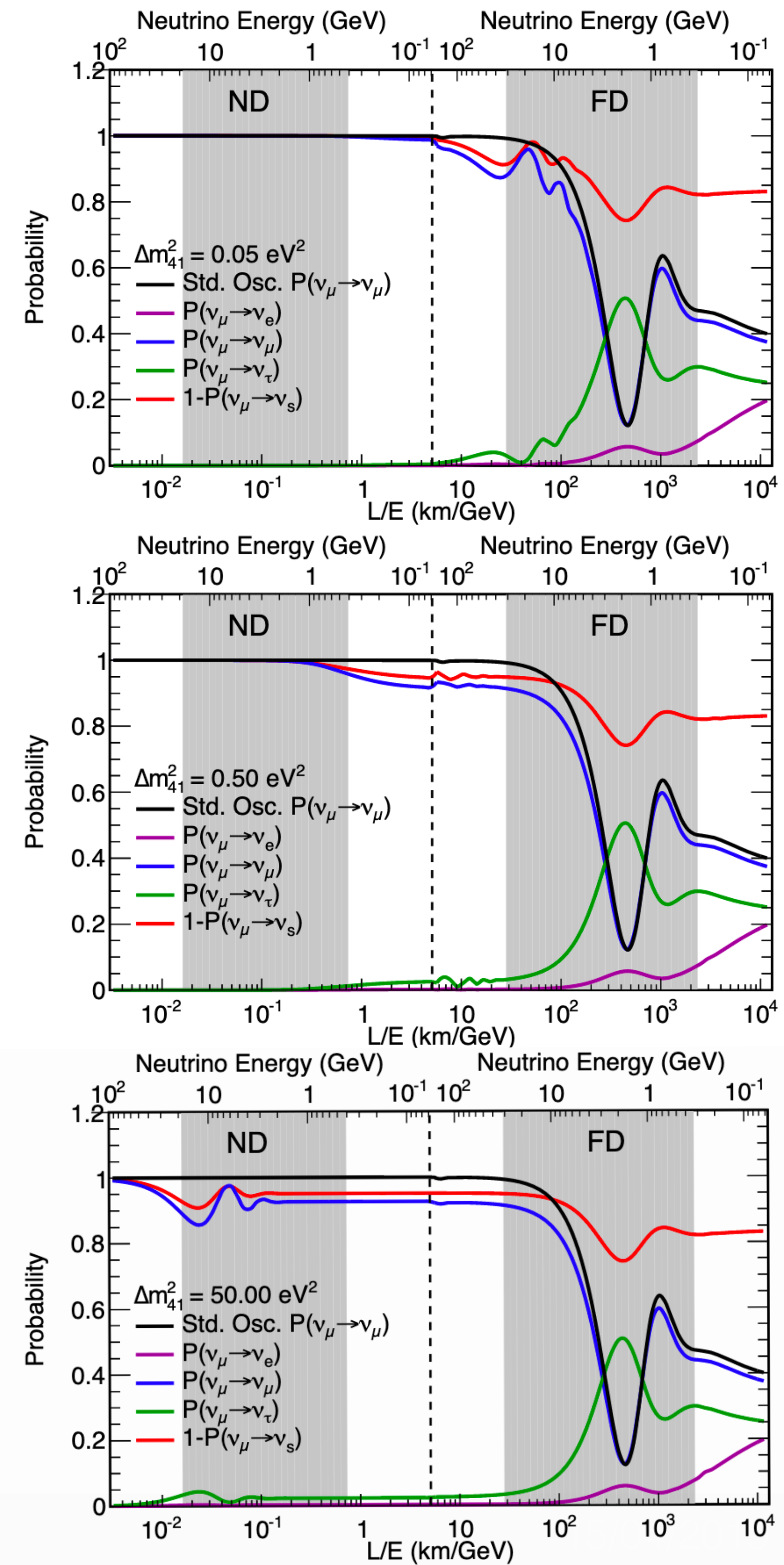
BSM physics

- Non standard oscillation effects
  - Sterile neutrinos
  - NSI
  - CPT violation
- New signals
  - Nucleon decay
  - Dark matter
  - Neutrino trident

Non standard oscillation effects

Sterile neutrinos

- "Simplest" extension to the standard three neutrino oscillations scheme, so called 3+1 model
  - MiniBooNE/LSND excess
- Makes use the broad band DUNE flux, near and far detectors.
- Different measurements possible:
  - Muon CC (ND/FD)
  - Electron CC (ND/FD)
  - NC signal (FD/ND)
- Depending how you combine these you get sensitivity to different parameter of the 3+1 sterile neutrino model.

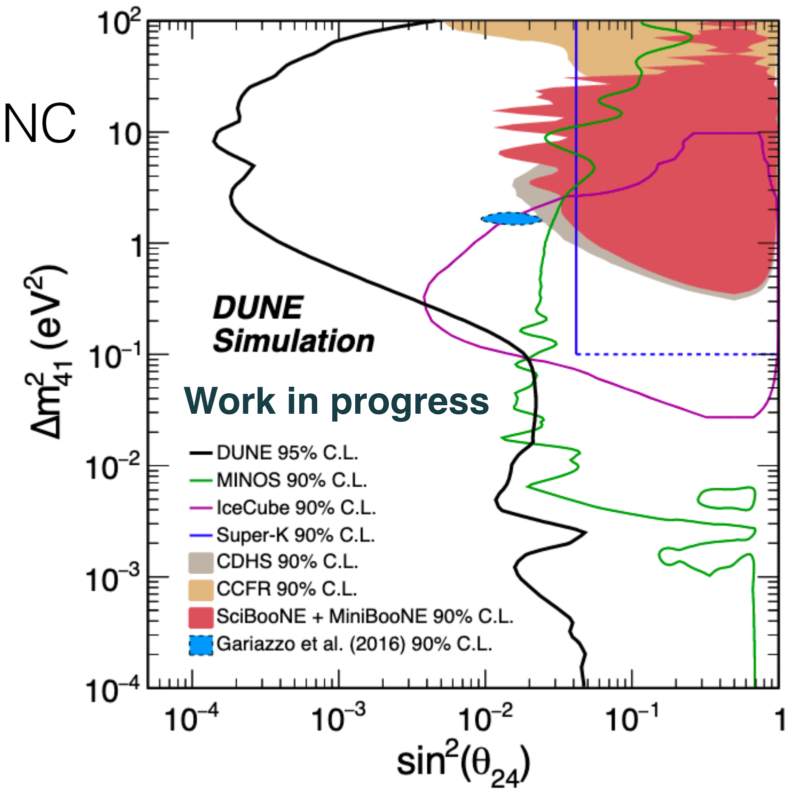


Sterile neutrinos

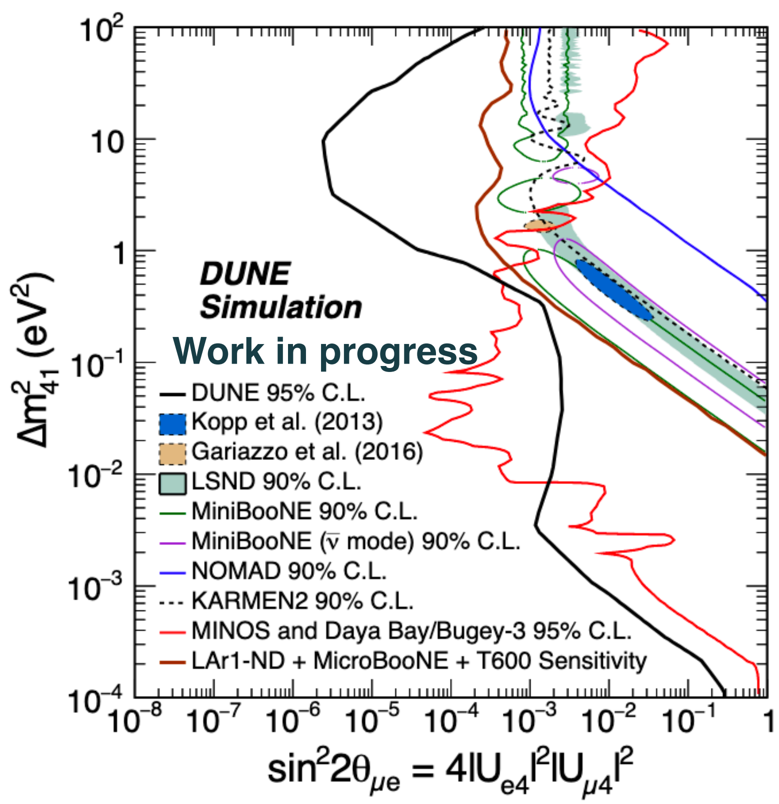
- Sensitivity to sterile neutrinos: 300 kt.MW.years
  - Muon neutrino disappearance
  - Electron neutrino disappearance
  - Neutral current disappearance
  - Electron appearance
- Best contours, **with normalisation systematics only**

$\nu_\mu \rightarrow \nu_\mu$

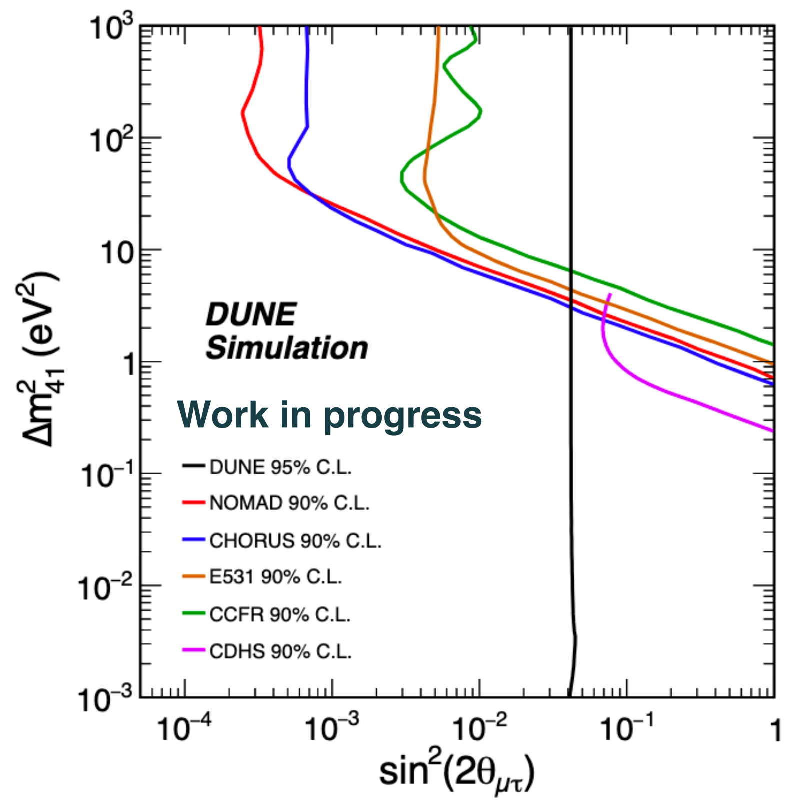
All active $\nu \rightarrow$ NC



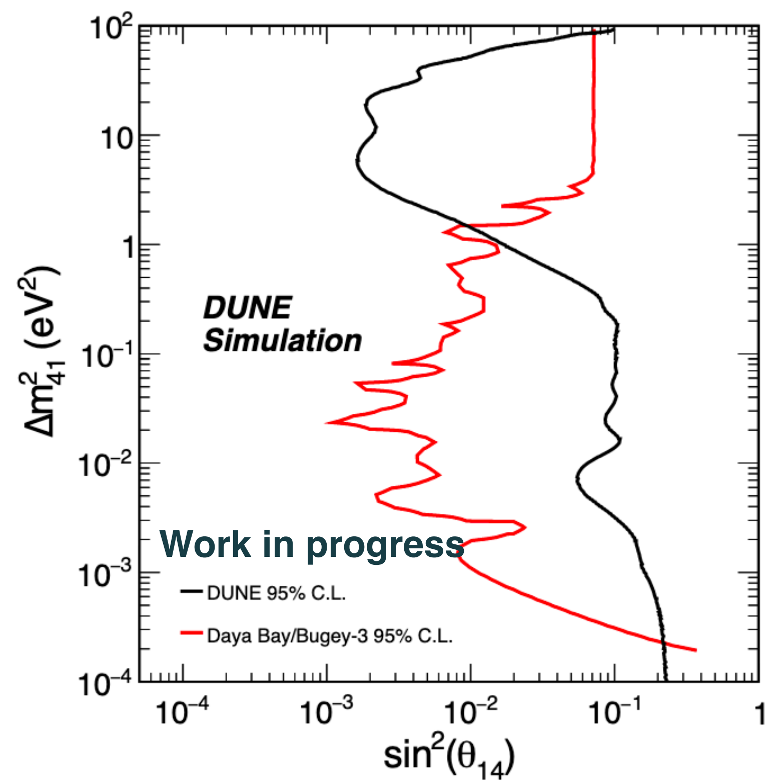
$\nu_\mu \rightarrow \nu_e$



All active $\nu \rightarrow$ NC



$\nu_e \rightarrow \nu_e$



Non-Standard Interactions (NSI)

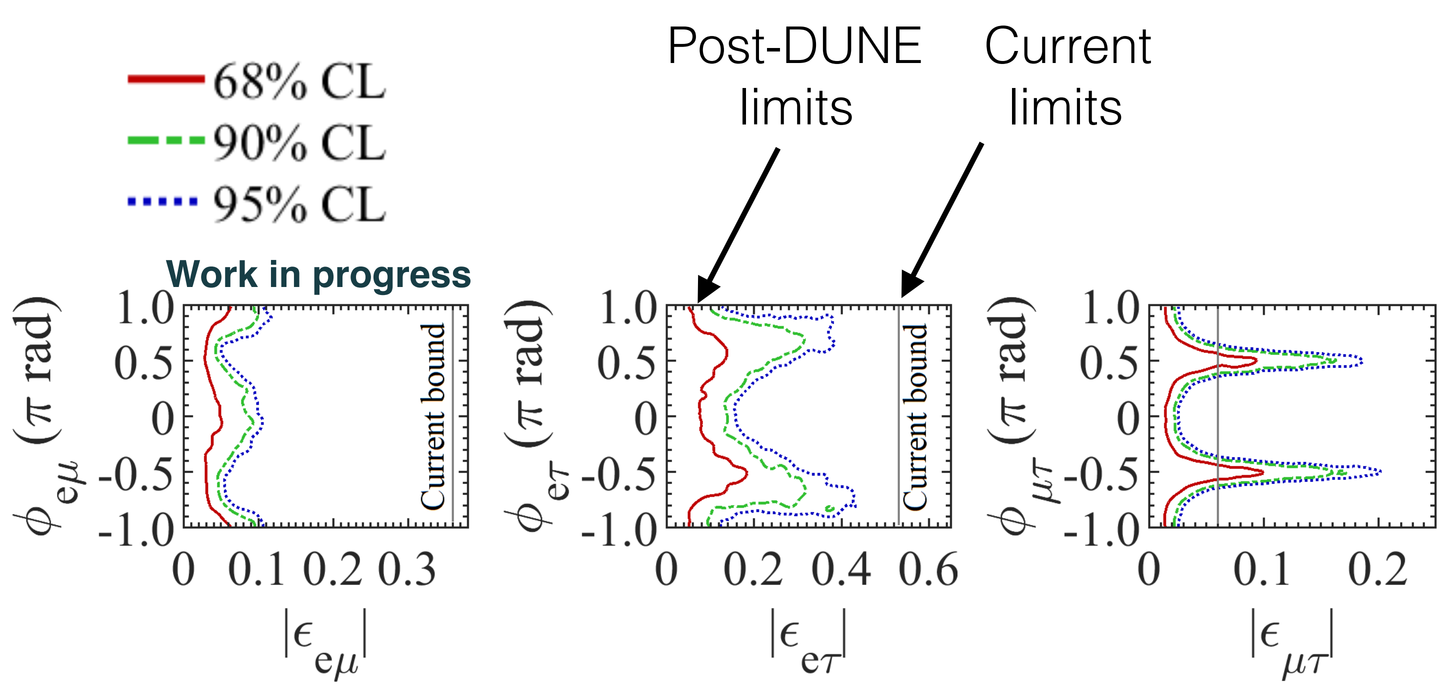
- Neutrinos propagate over a long baseline from the target to the FD can interact on there way with:
  - Dark energy: arXiv:0010126
  - Fuzzy dark matter (DM): arXiv:1608.01307v2
  - Any stand-alone particle which only interacts with neutrinos: arXiv:9610317

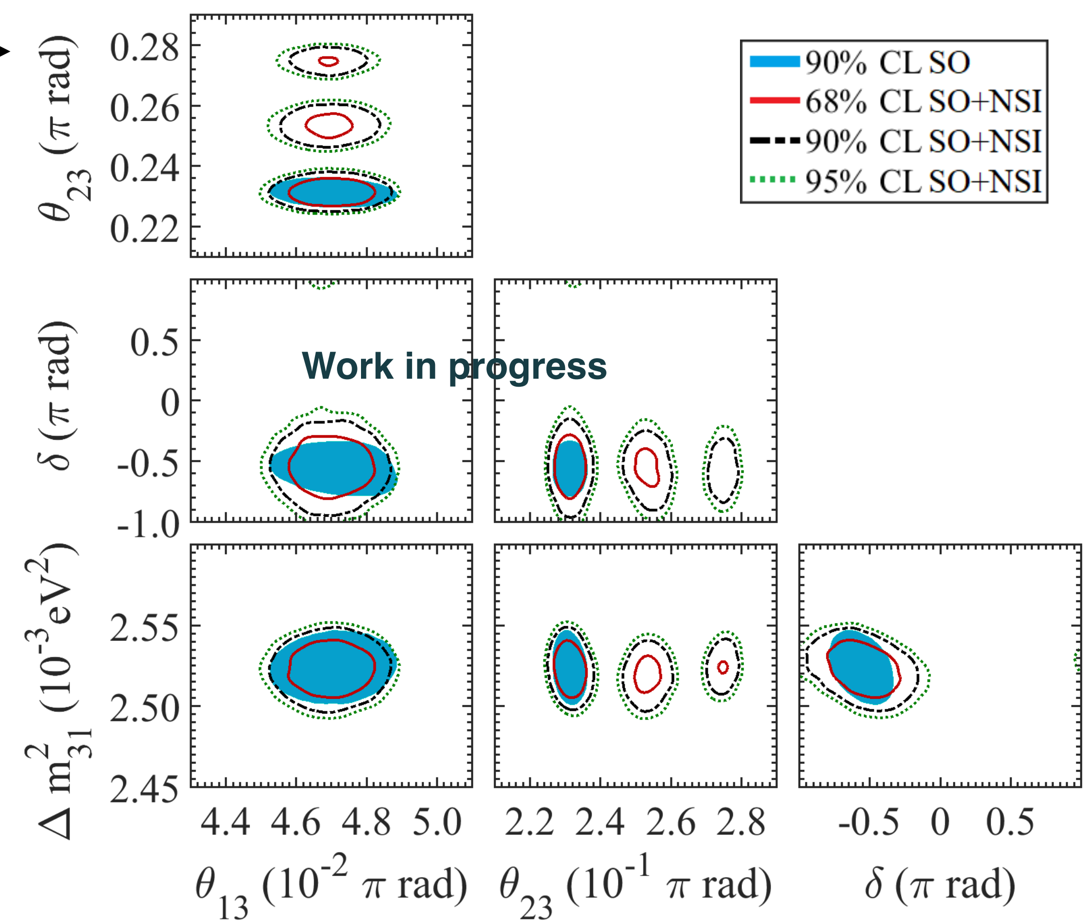
$$H = U \begin{pmatrix} 0 & & \\ & \Delta m^2_{21}/2E & \\ & & \Delta m^2_{31}/2E \end{pmatrix} U^\dagger + \tilde{V}_{\mathrm{MSW}}$$

PMNS | Matter effect (MSW) | New physics

$$\tilde{V}_{\mathrm{MSW}} = \sqrt{2} G_F N_e \begin{pmatrix} 1+\epsilon^m_{ee} & \epsilon^m_{e\mu} & \epsilon^m_{e\tau} \\ \epsilon^{m*}_{e\mu} & \epsilon^m_{\mu\mu} & \epsilon^m_{\mu\tau} \\ \epsilon^{m*}_{e\tau} & \epsilon^{m*}_{\mu\tau} & \epsilon^m_{\tau\tau} \end{pmatrix}$$

- DUNE has a longer baseline than other upcoming neutrino experiments.
- Effect on measured oscillation parameters
- Improved limits:

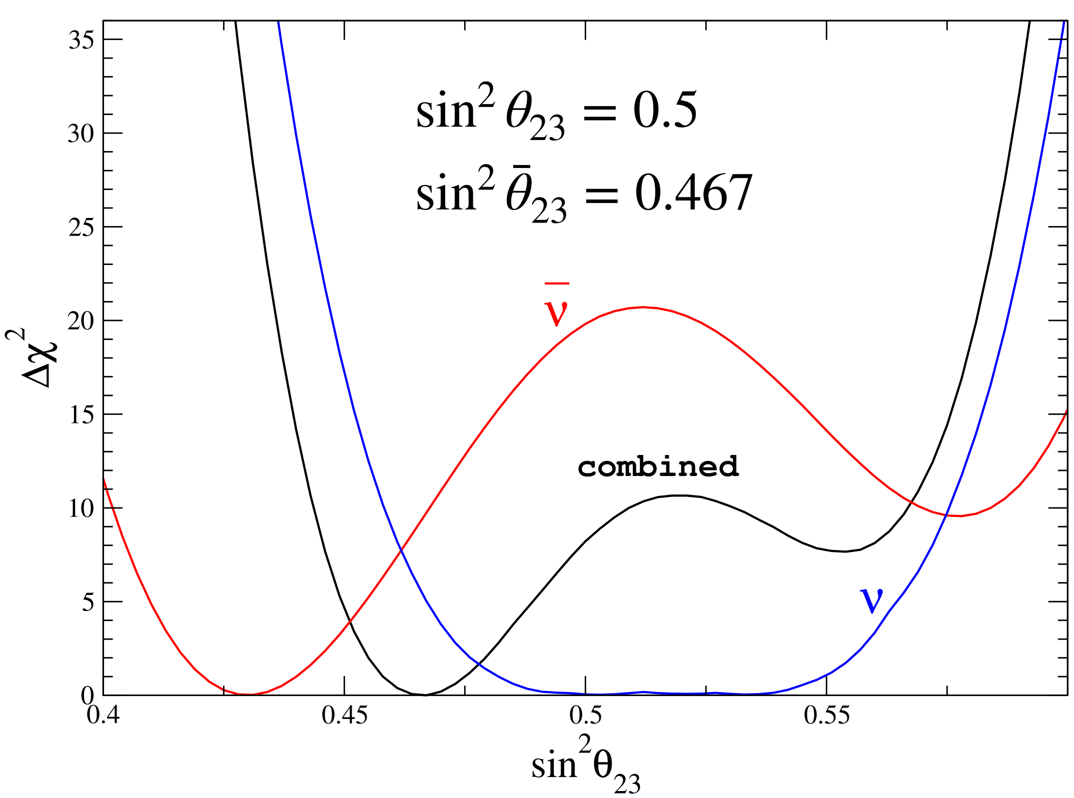




CPT violation

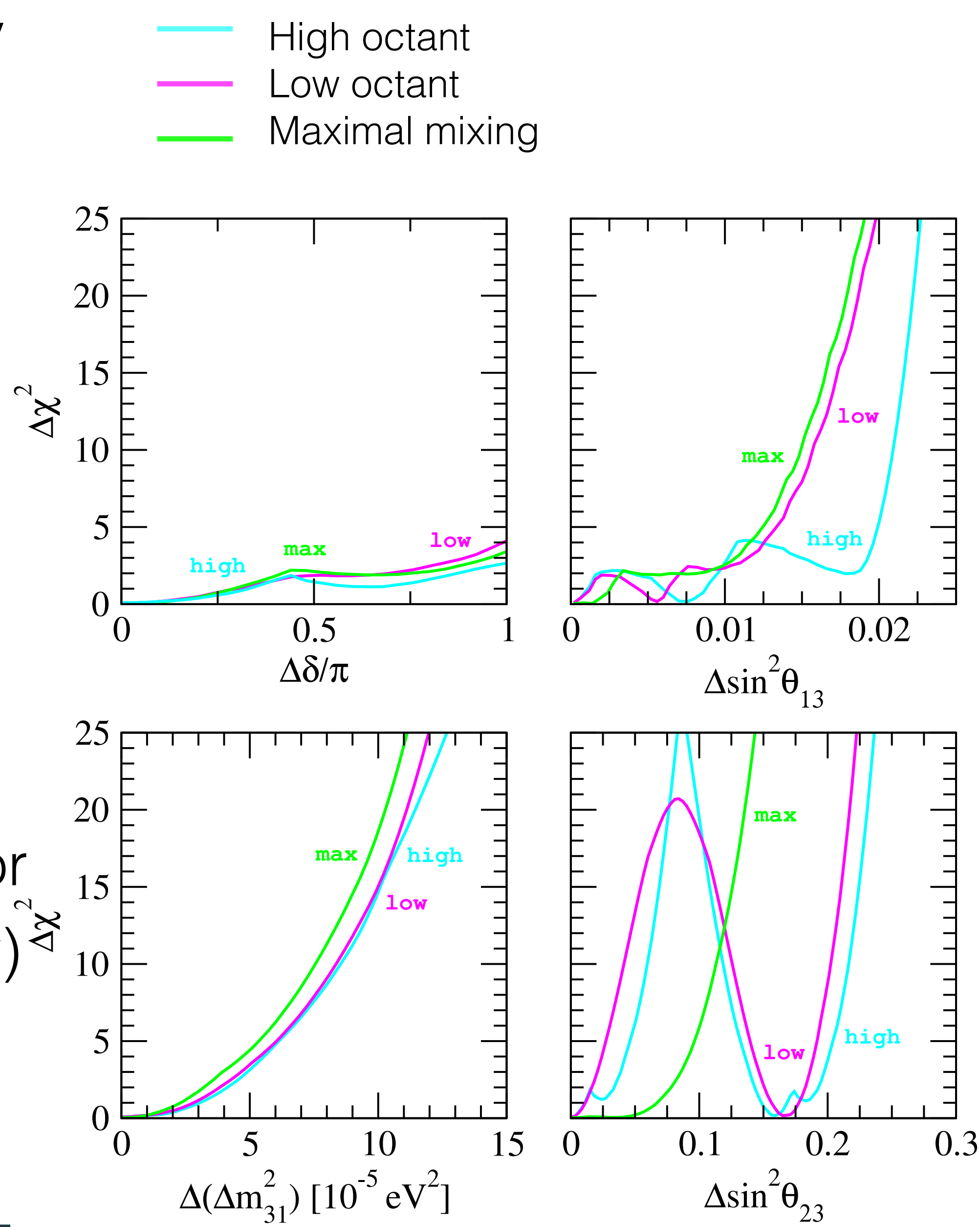
arXiv:1712.01714v2

- $P\left(\nu_\mu \to \nu_e\right) \neq P\left(\bar{\nu}_\mu \to \bar{\nu}_e\right)$ → CP violation
- $P\left(\nu_\mu \to \nu_\mu\right) \neq P\left(\bar{\nu}_\mu \to \bar{\nu}_\mu\right)$ → CPT violation
- Huge disappearance stats at DUNE.
- Any difference between ν_μ and anti-ν_μ should be clearly visible:



ν_e appearance sector (low sensitivity)

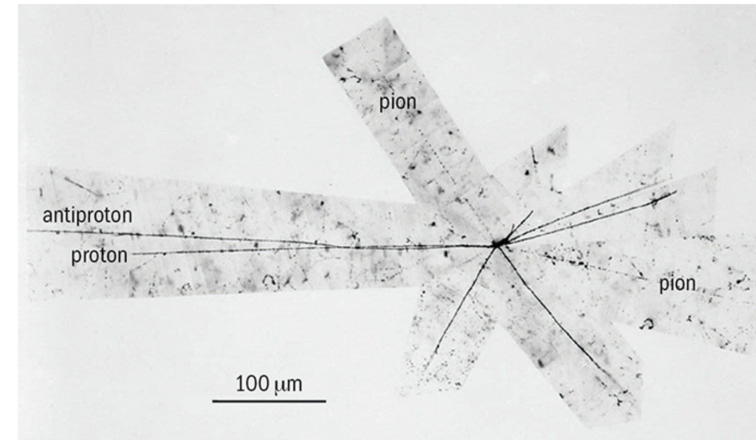
ν_μ disappearance sector (much better sensitivity)



New signals

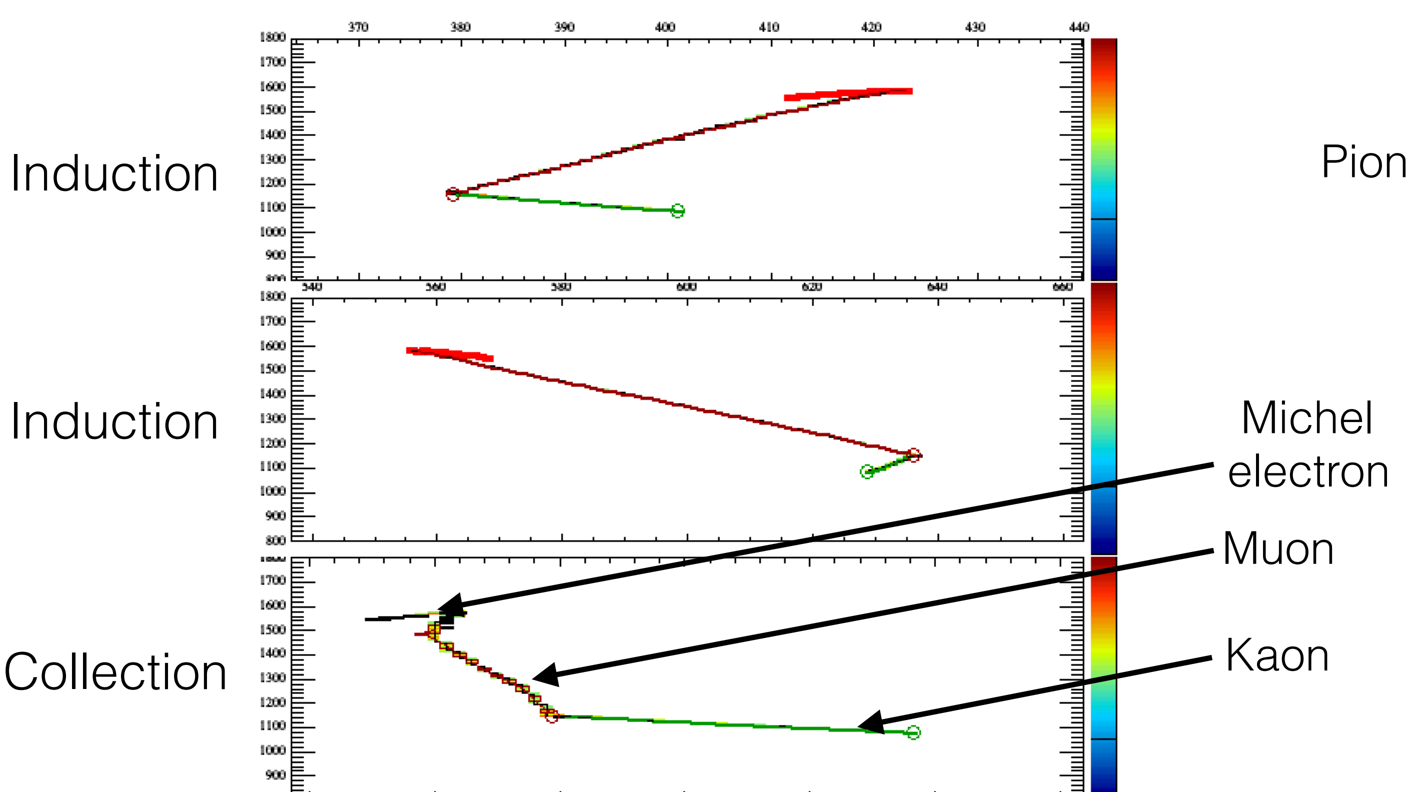
Nucleon decay

- DUNE is shielded from cosmic, has a high mass and precise particle tracking → Baryon number violation can be done:
  - neutron - anti-neutron oscillation
  - p → anti-ν K^+, n → K^+ e^-
  - p → π^0 e^+

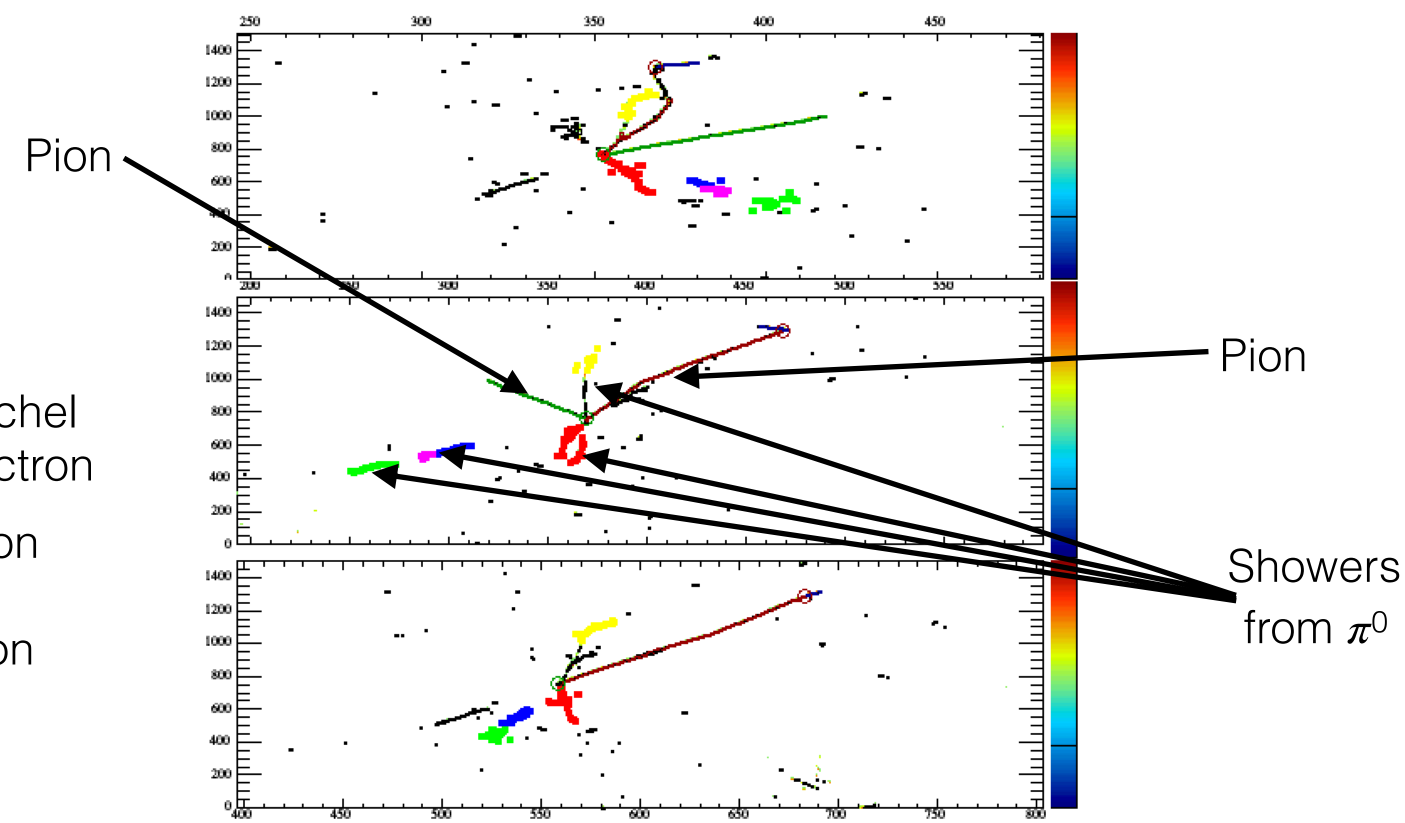


- Sensitivity using full simulation (including atmospheric neutrinos and final state interactions with the Argon nucleus) is coming for the TDR (summer 2019).

p → anti-ν K^+



neutron - anti-neutron oscillation



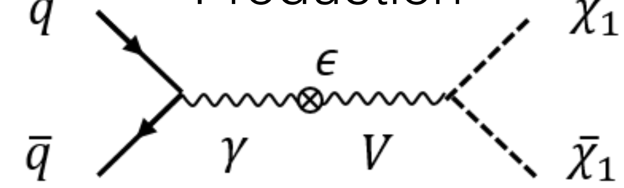
Dark Sector

- 2 benchmark models studied:
  - Vector portal-type scenario with a massive dark photon (V) mixes with SM photon

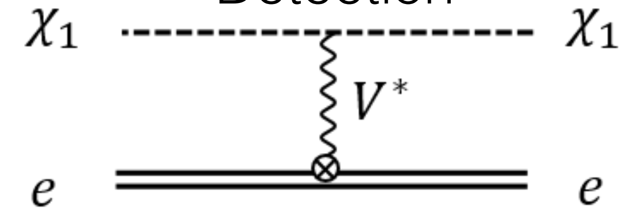
$$\mathscr{L}_{\rm int} \ni -\frac{\epsilon}{2}V_{\mu\nu}F^{\mu\nu} + g_{11}\bar{\chi}_1\gamma^\mu\chi_1 V_\mu + g_{12}\bar{\chi}_2\gamma^\mu\chi_1 V_\mu + \text{h.c.}$$

    - ϵ kinetic mixing parameter, χ_1, χ_2 dark matter particles

Production



Detection



  - Lepto-phobic Z' scenario:

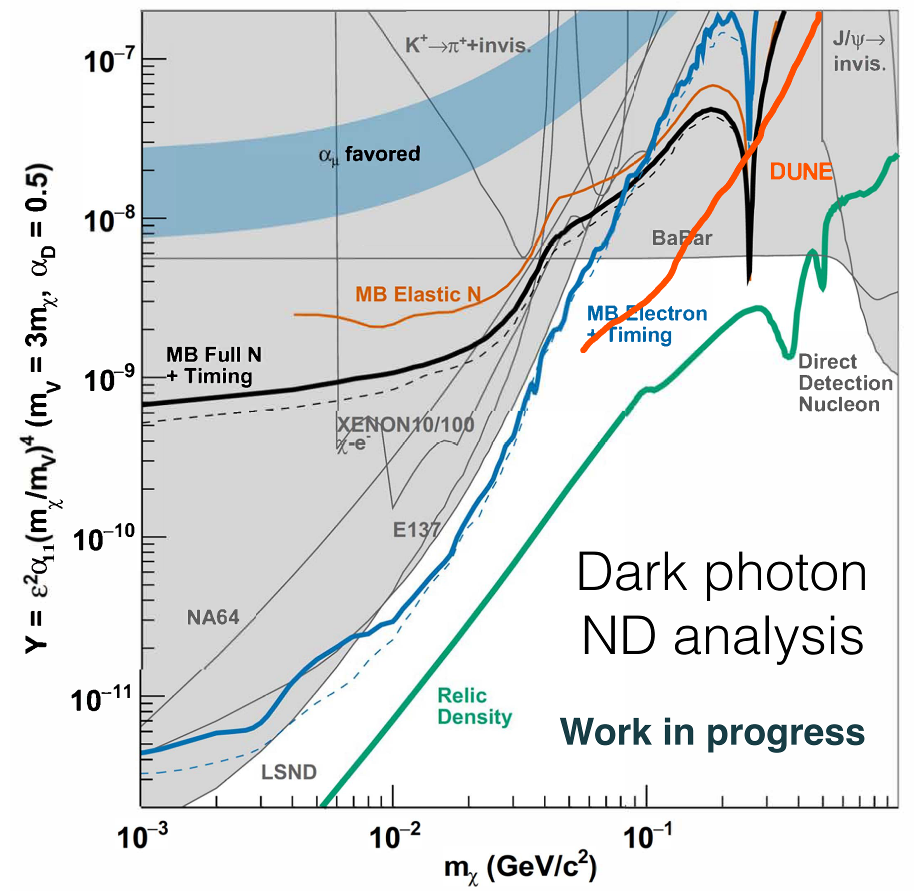
$$\mathscr{L}_{\rm int} \ni -g_{Z'}\sum_f Z'_\mu\bar{q}_f\gamma^\mu\gamma^5 q_f - g_{Z'}Z'_\mu\bar{\chi}\gamma^\mu\gamma^5\chi - Q_\psi g_{Z'}Z'_\mu\bar{\psi}\gamma^\mu\gamma^5\psi$$

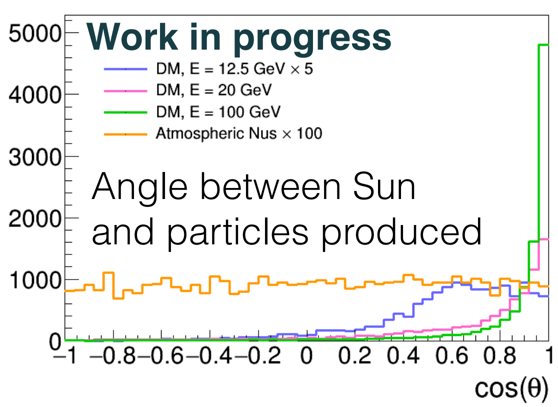
    - χ, ψ dark matter states

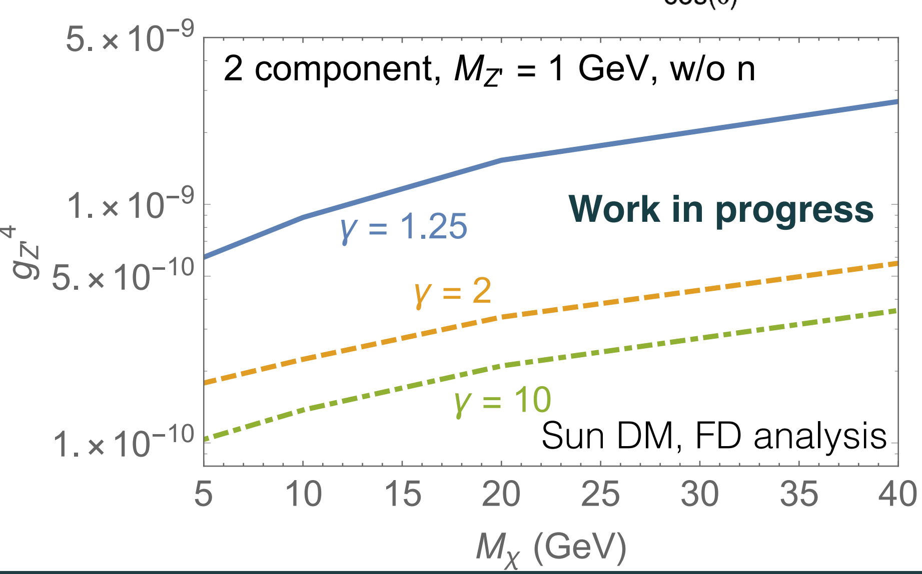
- 3 types of sources:
  - Beam / Target interactions
  - Galactic halo
  - Sun core

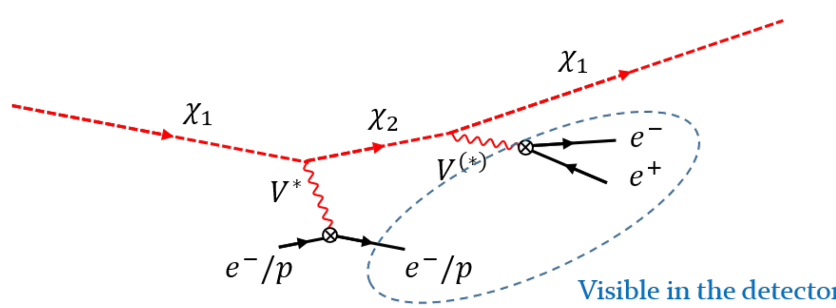
Dark Sector

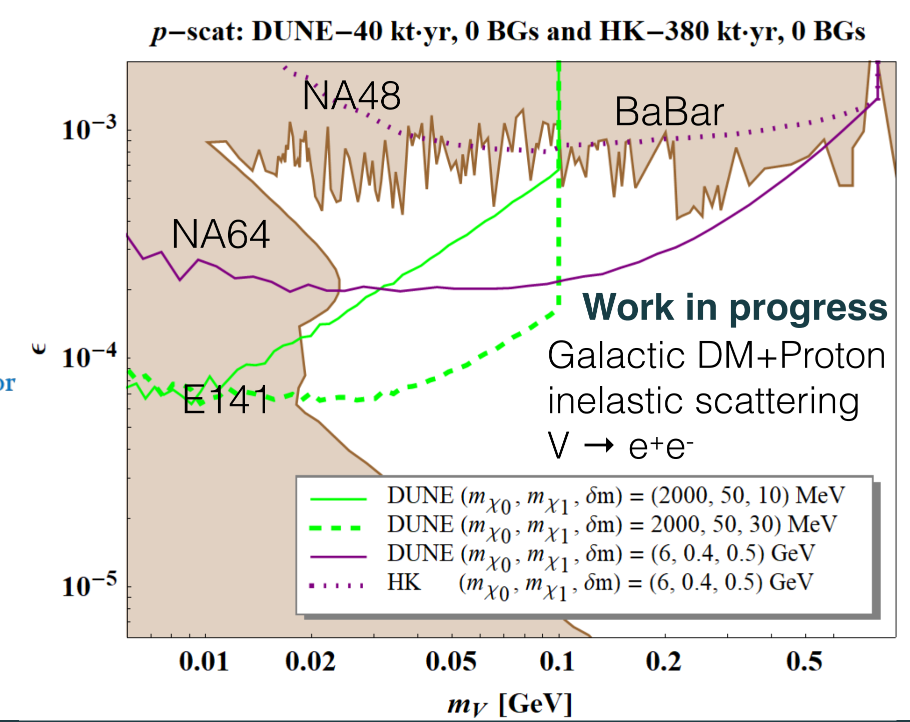
- DM comes from the target (Photon oscillates to Dark Photon)
  - “Internal” source (beam), closer to the target is better → ND analysis.
  - Main background is from ν NC
  - Significant improvement is expected to come from ND-PRISM option: arXiv:1903.10505v1
- Galactic halo can produce DM which could interact inelastically in DUNE (dark matter annihilation) - Dark photon
- DM from the core of the Sun could interact elastically with the DUNE (dark matter annihilation) - Lepto-phobic Z’
  - External sources (Sun, Galaxy halo), so bigger mass is better → FD analysis.











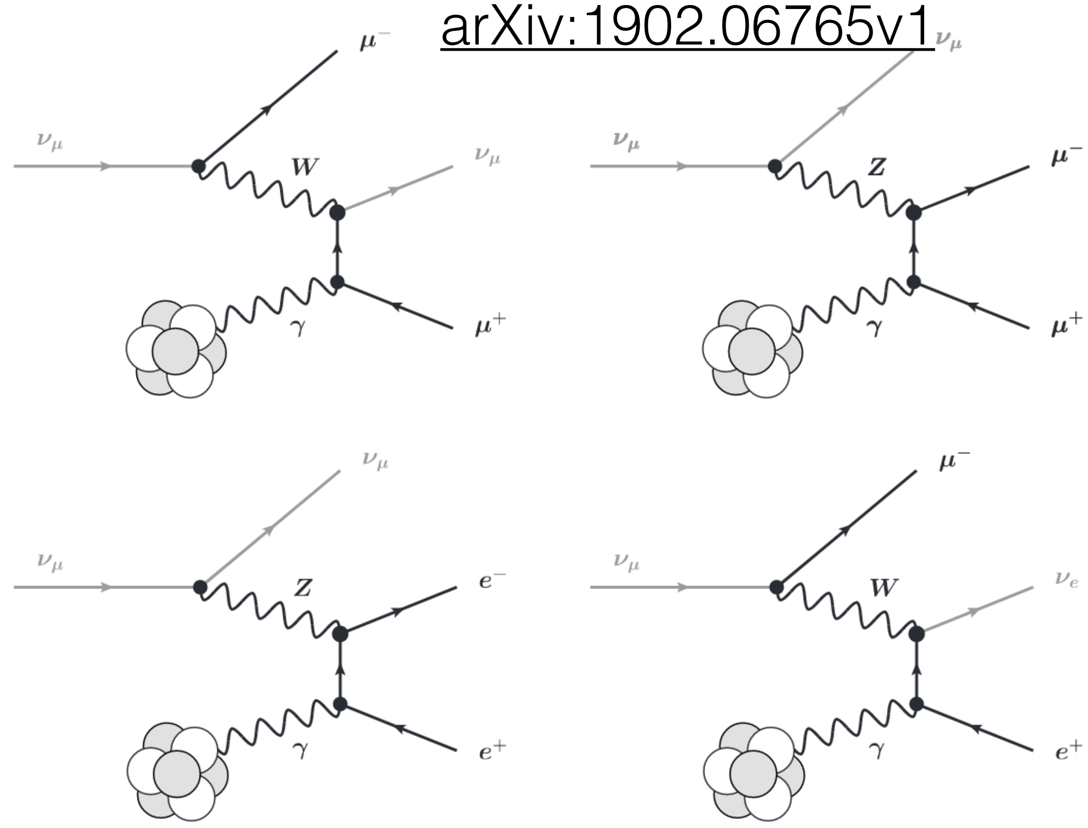
Neutrino trident

arXiv:1902.06765v1

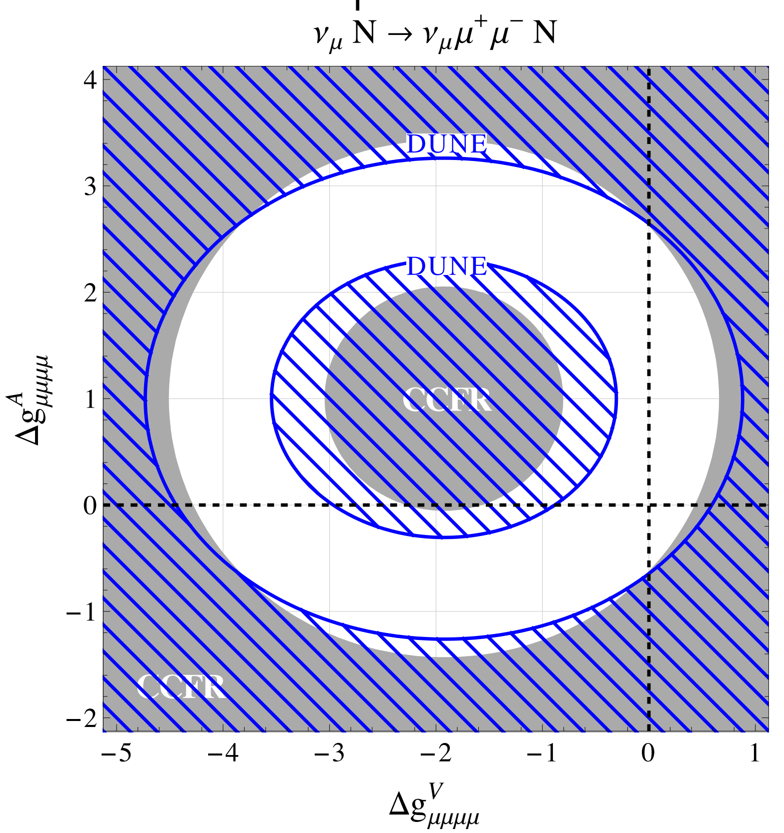
- Source are the neutrinos from the beam → ND analysis
- Process allowed by SM
  - Measurement by CHARM-II, CCFR, NuTeV

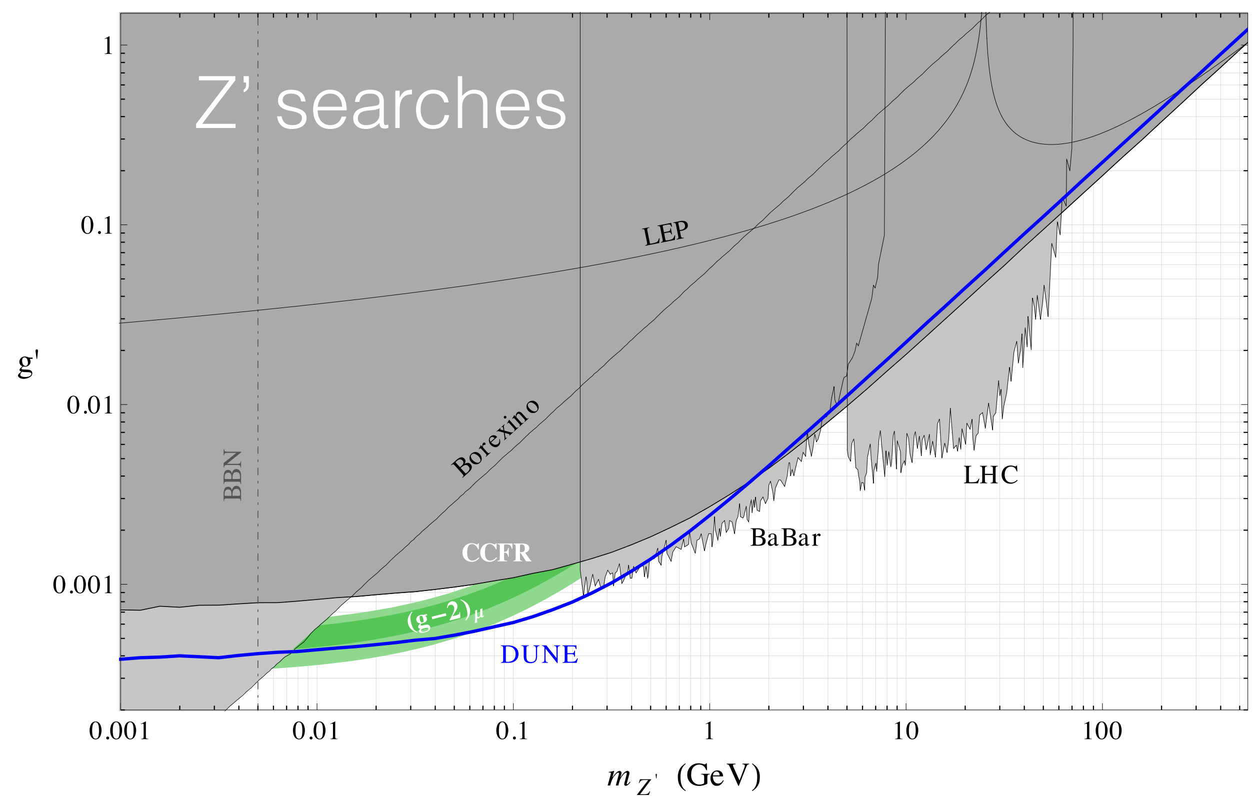
$$\frac{\sigma(\nu_\mu \to \nu_\mu \mu^+ \mu^-)_{\rm exp}}{\sigma(\nu_\mu \to \nu_\mu \mu^+ \mu^-)_{\rm SM}} = \begin{cases} 1.58 \pm 0.64 & \text{(CHARM-II)} \\ 0.82 \pm 0.28 & \text{(CCFR)} \\ 0.72^{+1.73}_{-0.72} & \text{(NuTeV)} \end{cases}$$

- Main background is ν_μ CC 1π



Model independent searches





Conclusion

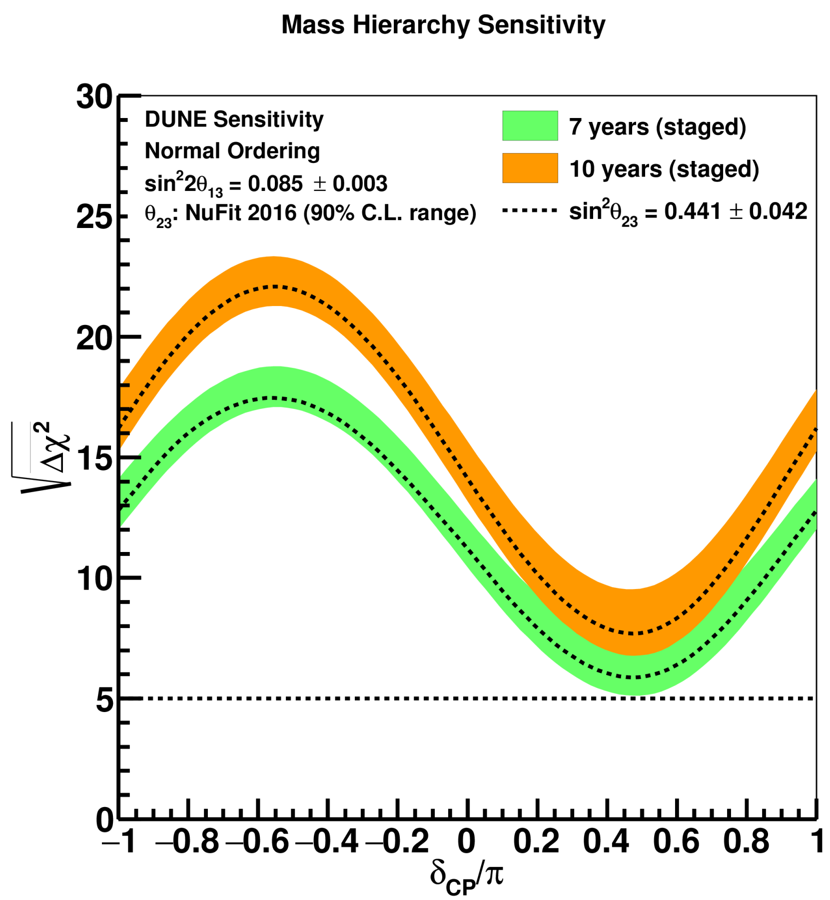
- DUNE is an upcoming neutrino experiment aimed at measuring CP violation in the neutrino sector, proton decay and neutrinos from supernova explosions.
- Shown that DUNE has an extensive BSM physics program, sterile neutrino searches, NSI, CPT violation, dark matter, neutrino tridents, nucleon decay…
  - Direct example of the versatility of the LAr detector and, for me, one of the main advantages of this detector technology.
    - Analyses with very different threshold, topology statistics… lead to very competitive results.
  - Convinced that new ideas will come and we will be able to have many other interesting results.
- In recent time, DUNE has been able to prove its feasibility:
  - Building on experience from the SBN program and previous LAr experiments.
  - ProtoDUNE program is a success, now able to use a smaller replica of DUNE for physics.

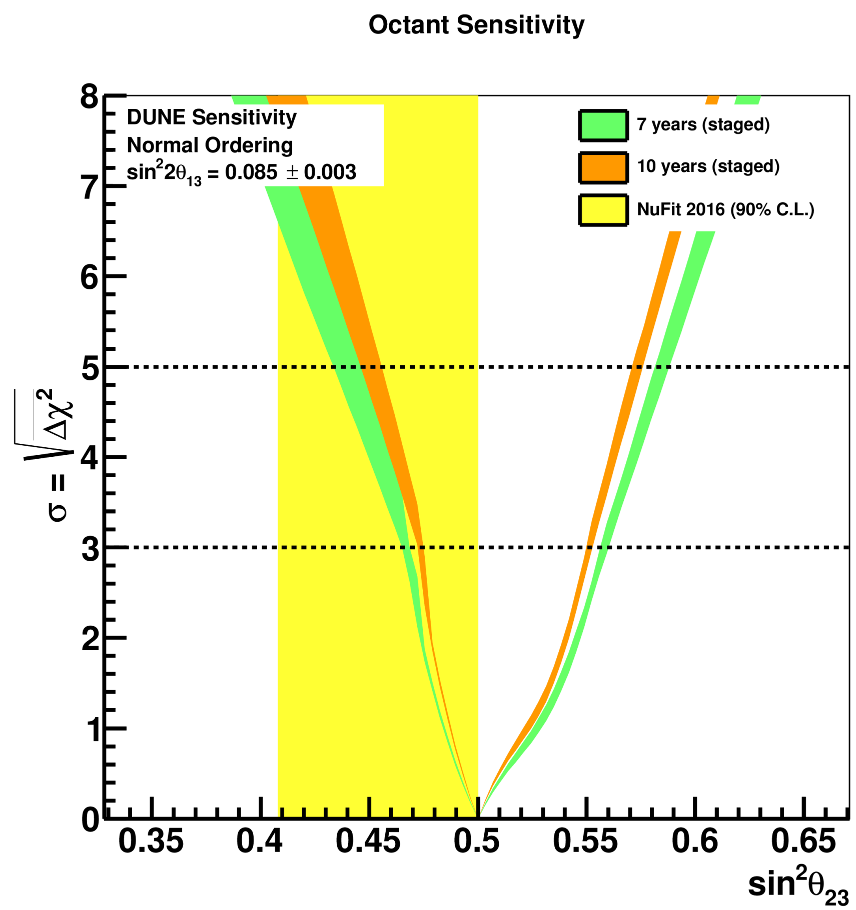
Thanks!

Backup

"Standard" oscillations

- Octant and mass ordering sensitivity via ν_μ disappearance measurement
  - Large matter effect helps disentangling the mass ordering



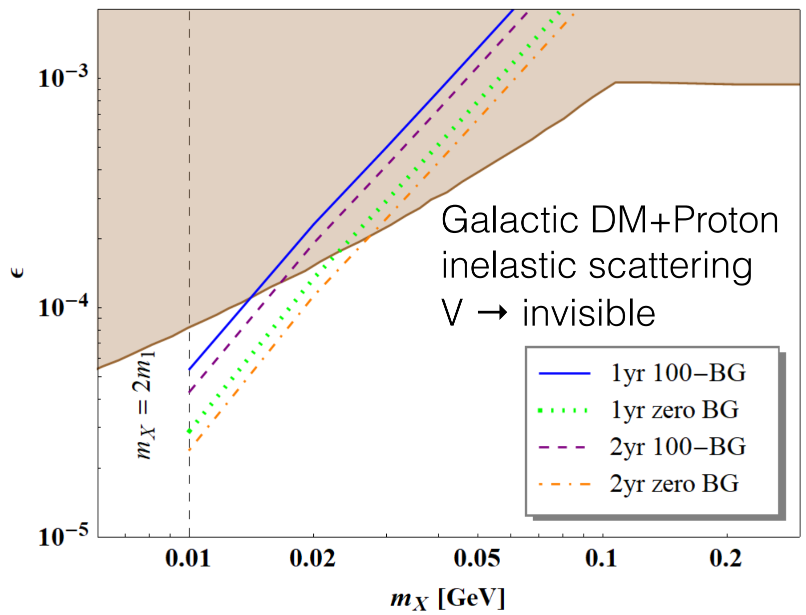


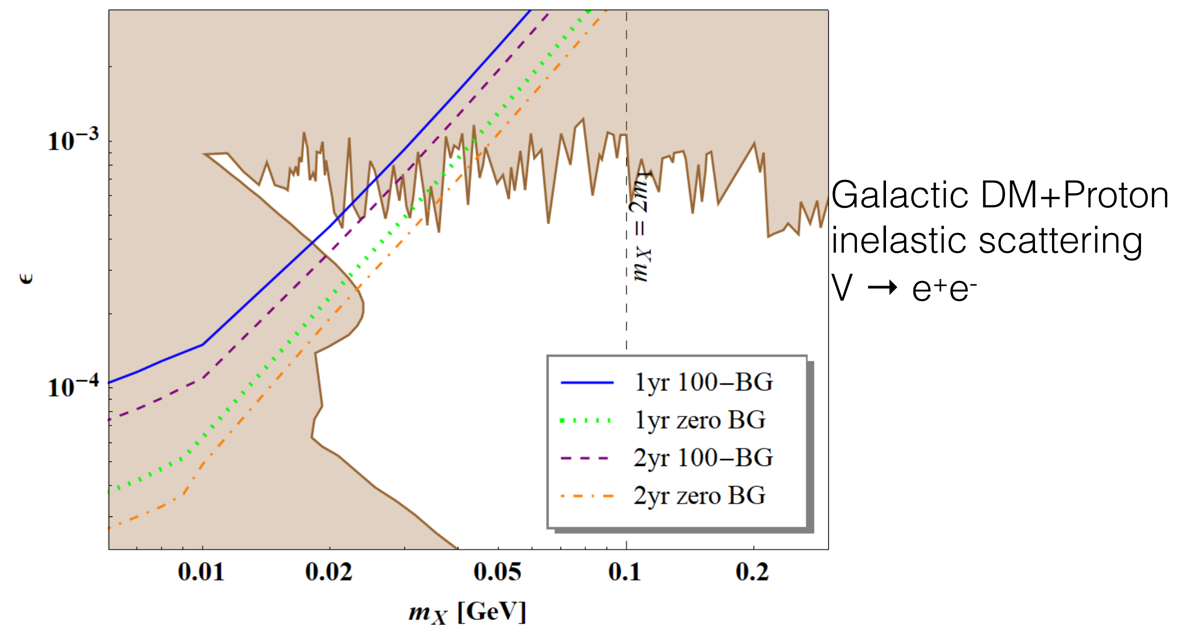
Sterile neutrino
Fits description

Source	Systematic uncertainty
Signal flux	8%
Background flux	15%
F/N flux electron neutrino	2%
F/N flux muon neutrino	0.4%
CC cross section	15%
NC cross section	25%
F/N cross section (separated between flavour and sign)	2%
Fiducial volumes	1%

- GLoBES fit
- Pluggin for steriles and NSI from JKopp
- 300 kT.MW.years
- 80 GeV proton beam
- Same reconstruction efficiency as CDR
- Larger systematics than CDR
- Neutrino decay point uncertainty → 20% smearing in E_{true}/E_{reco}

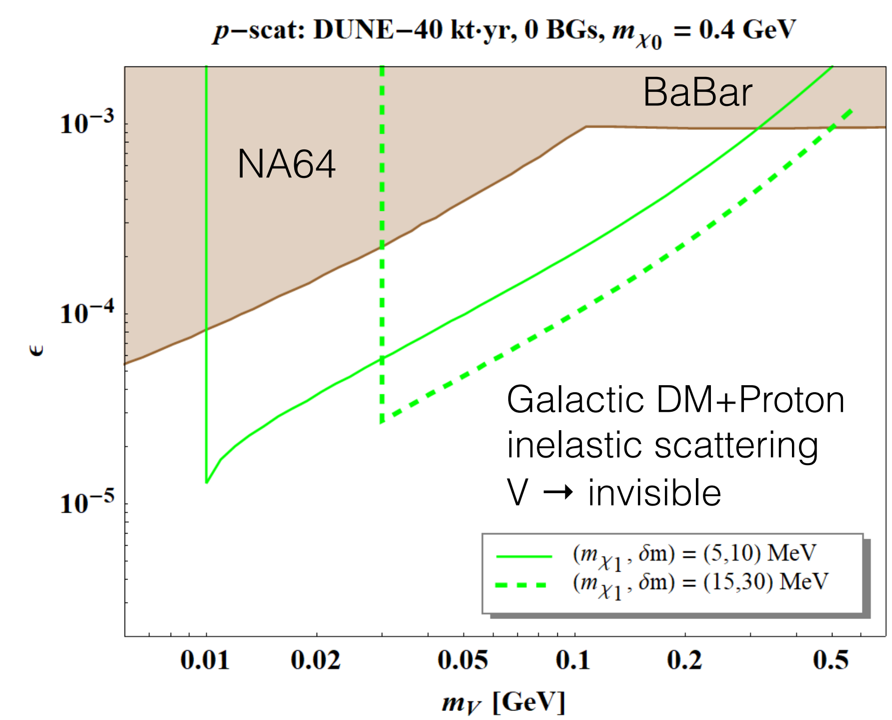
ProtoDUNE DM





- Sensitivity for ProtoDUNE: arXiv:1803.03264v2

- DUNE sensitivity to DM with invisible V decay.



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Staging

- Year 1 (2026): 20-kt FD with 1.07 MW (80-GeV) beam and initial ND constraints
- Year 2 (2027): 30-kt FD
- Year 4 (2029): 40-kt FD and improved ND constraints
- Year 7 (2032): upgrade to 2.14 MW (80-GeV) beam

Exposure [years]	Exposure [kT.MW.years]
5	171
7	300
10	556
15	984