Beyond the Standard Model at DUNE

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On behalf of DUNE Collaboration

NuFACT2019, August 26~31, 2019

The Grand Hotel Daegu, Korea

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- DUNE (Deep Underground Neutrino Experiment) Overview
- Beyond Standard Model (BSM) Physics
  - Oscillation effects
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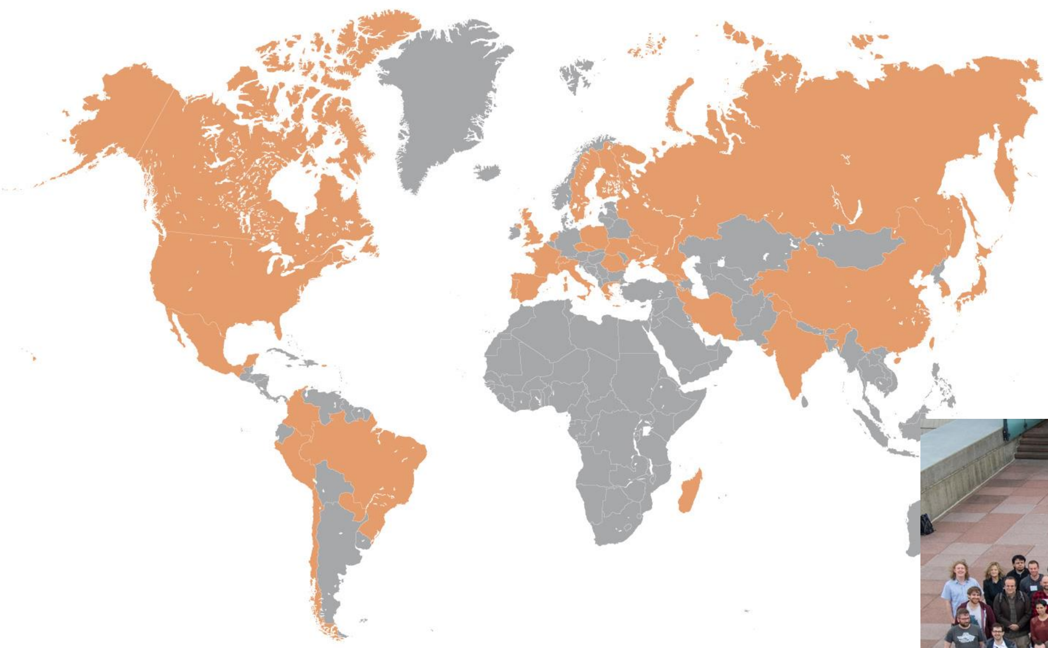
- Summary

DUNE Overview

See Friday 8/30 Plenary 09:00 - DUNE (Jae Yu)

DUNE – a fully international experiment

- 1094 collaborators from 184 institutions in 34 countries
- Growing at a rate of around 100 collaborators/year

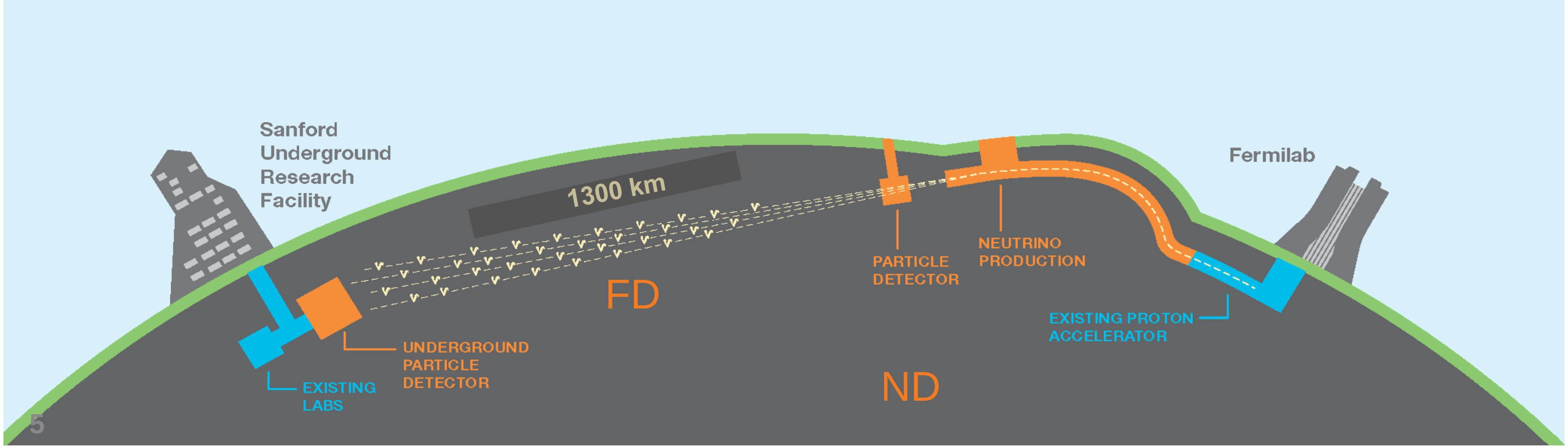


Armenia, Brazil, Bulgaria, Canada, CERN, Chile, China, Colombia, Czech Republic, Spain, Finland, France, Greece, India, Iran, Italy, Japan, Madagascar, Mexico, Netherlands, Paraguay, Peru, Poland, Portugal, Romania, Russia, **South Korea**, Sweden, Switzerland, Turkey, UK, Ukraine, USA.

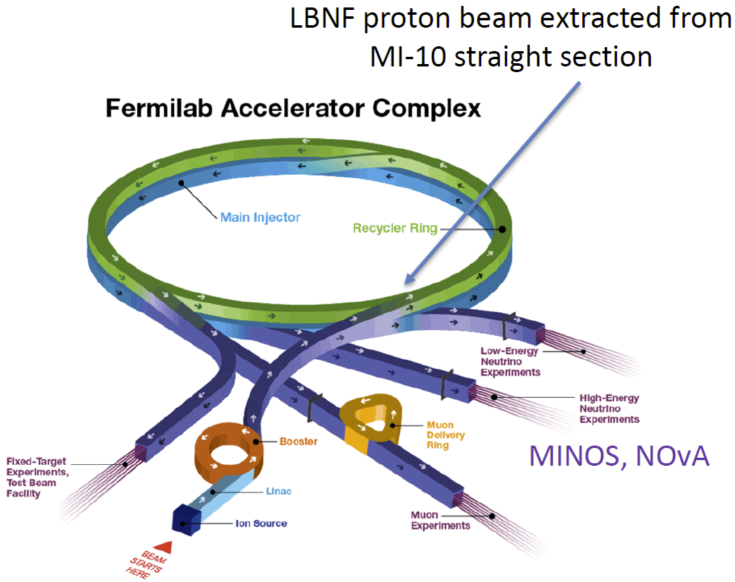
DUNE

- Approximately 4X10 kton fiducial mass liquid-argon Far Detector
  - First 2 modules in 2024, Beam operation in 2026, Final module in 2027
- Located at SURF's 1478 m level with 1300 km baseline
- Near Detector located approximately 575 m from neutrino source
- Wide-band neutrino beam (~ few GeV range)
- Flagship physics topics: CPV, supernova neutrinos and BSM physics

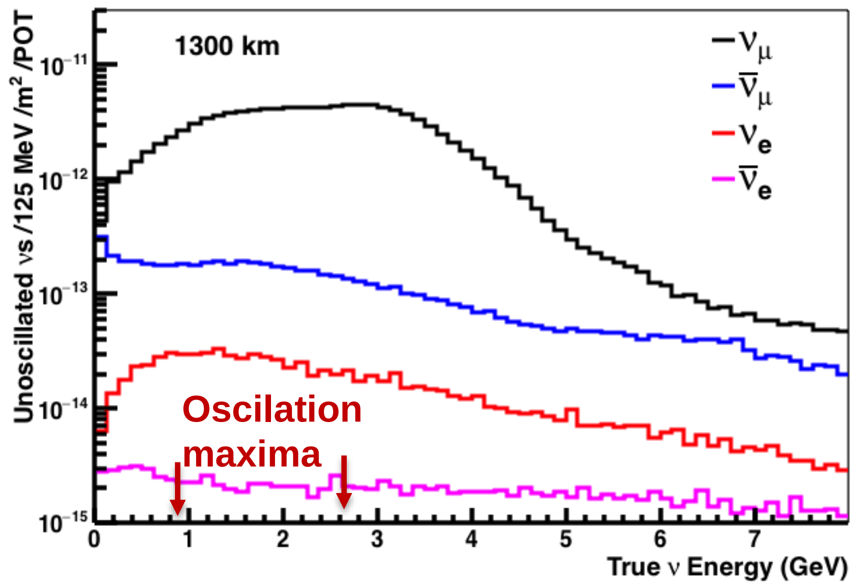
See Friday 8/30 WG1 14:00 - DUNE Oscillation Physics (Kim Siyeon)



The LBNF Beam



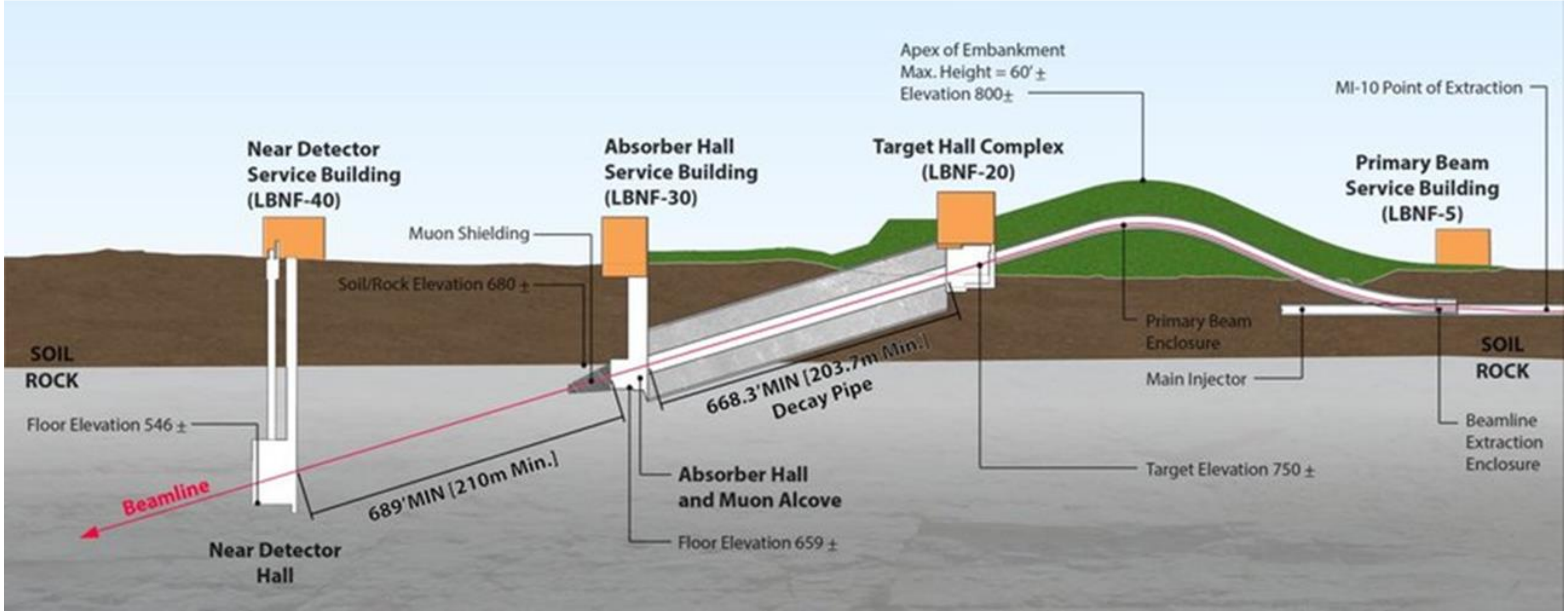
Neutrino Flux at 1300 km
(CDR Optimized Beam)



- The LBNF (Long Baseline Neutrino Facility) beam is produced at Fermilab.
- It will use 60-120 GeV proton beam at 1.2 MW, upgradeable to 2.4 MW.
- It can run in neutrino and anti-neutrino 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 physics.

See Tuesday 8/27 WG3 16:00 - Design Studies of the LBNF/DUNE Target (Chris Densham)

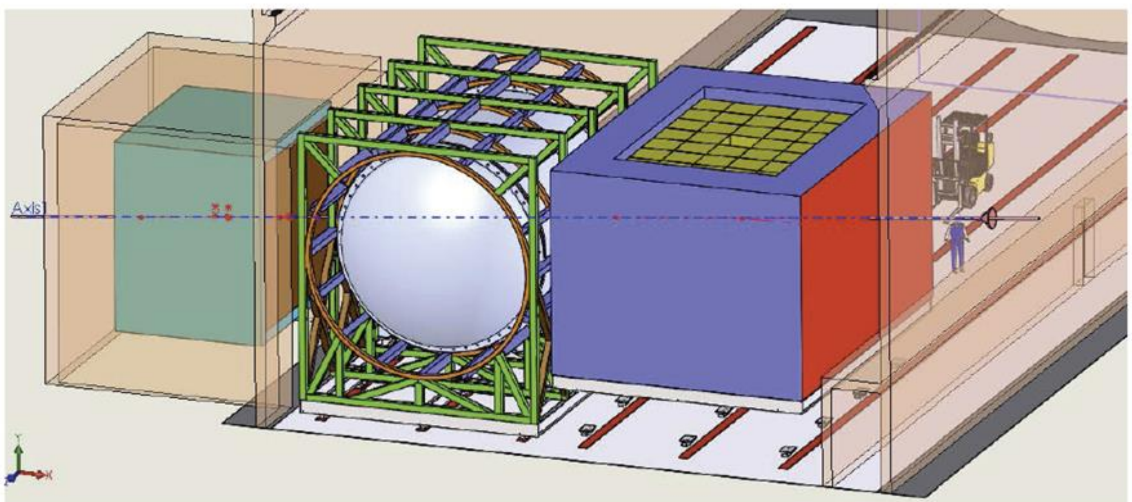
Near Detector (ND)

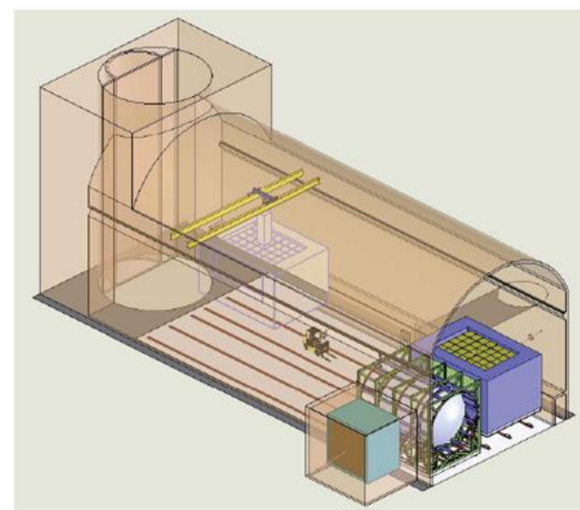


- Control of systematic uncertainties affecting the long-baseline oscillation analysis

Near Detector (ND)

- The preliminary conceptual design includes three sub-detectors (right to left)
  - A LArTPC (50~100 tons) with pixelated readout,
  - A magnetized, high-pressure gaseous TPC (HPgTPC),
  - A magnetized 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 the deconvolution of the neutrino flux and cross-section

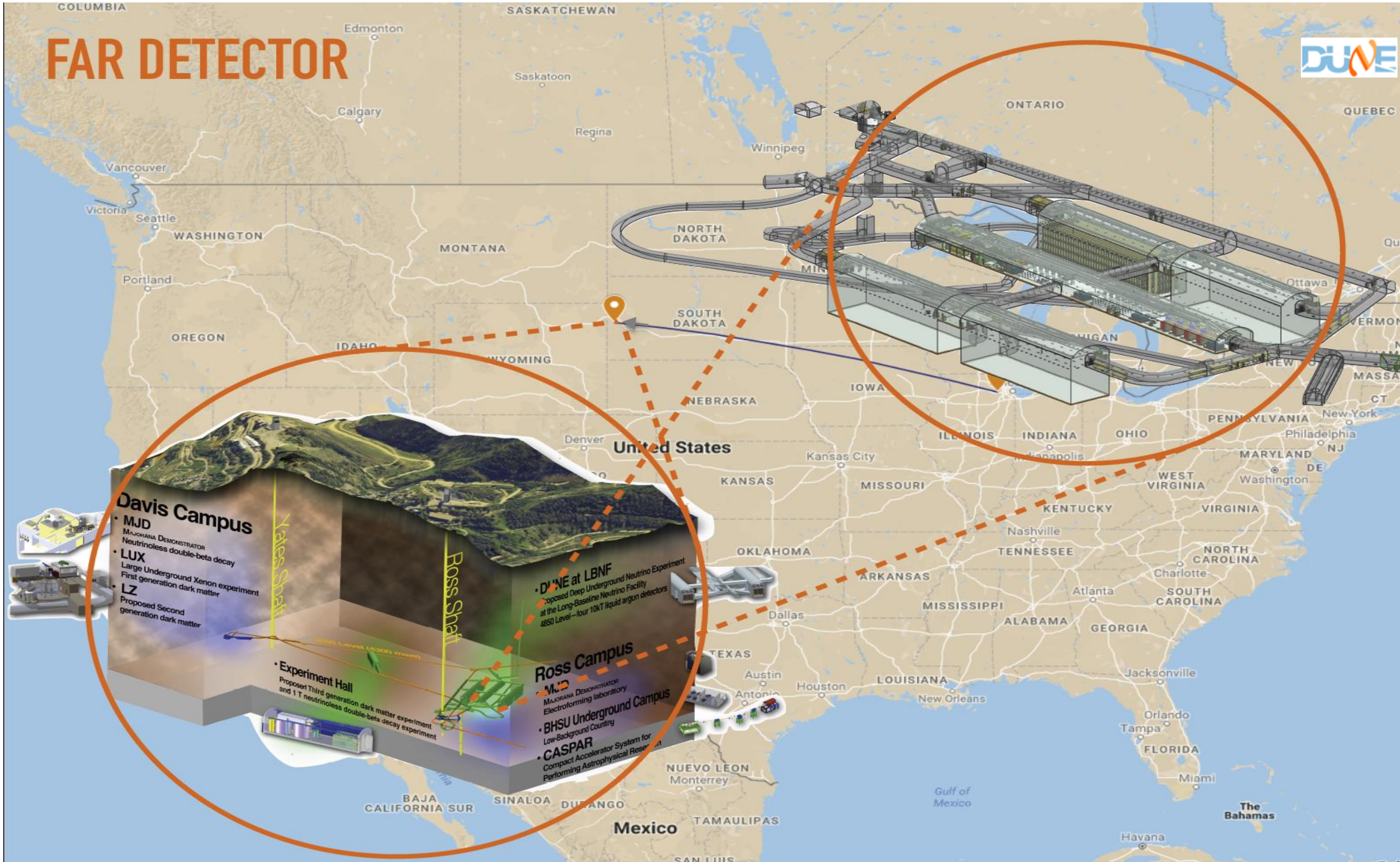




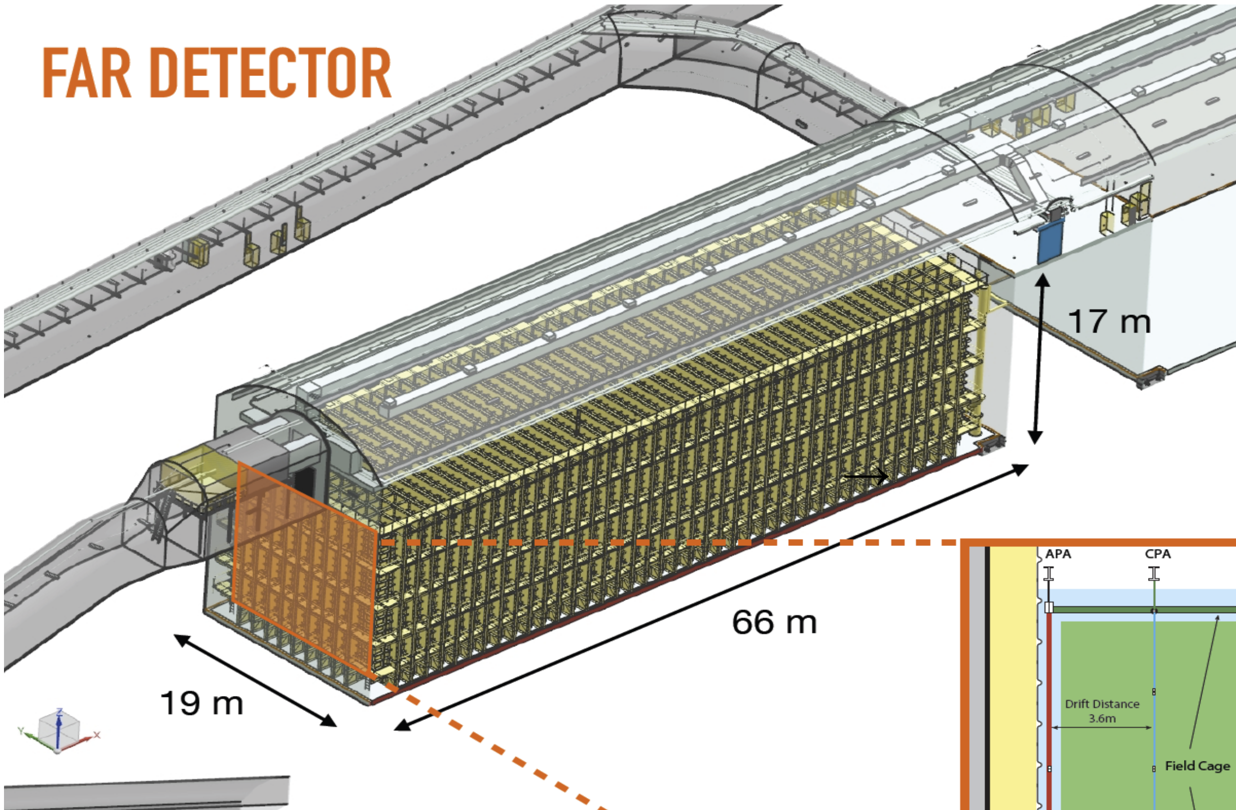
See Monday 8/26 Poster 19:00 - 3DST-S in the DUNE Near Detector (Kim Siyeon)

See Thursday 8/29 WG1+2 14:00 - DUNE ND (Alan Bross)

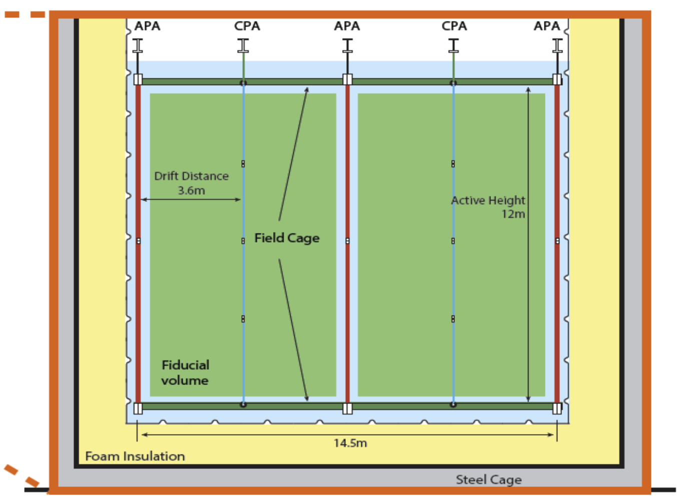
Far Detector (FD)



Far Detector (FD)



APA: Anode Plane Assembly
CPA: Cathode Plane Assembly



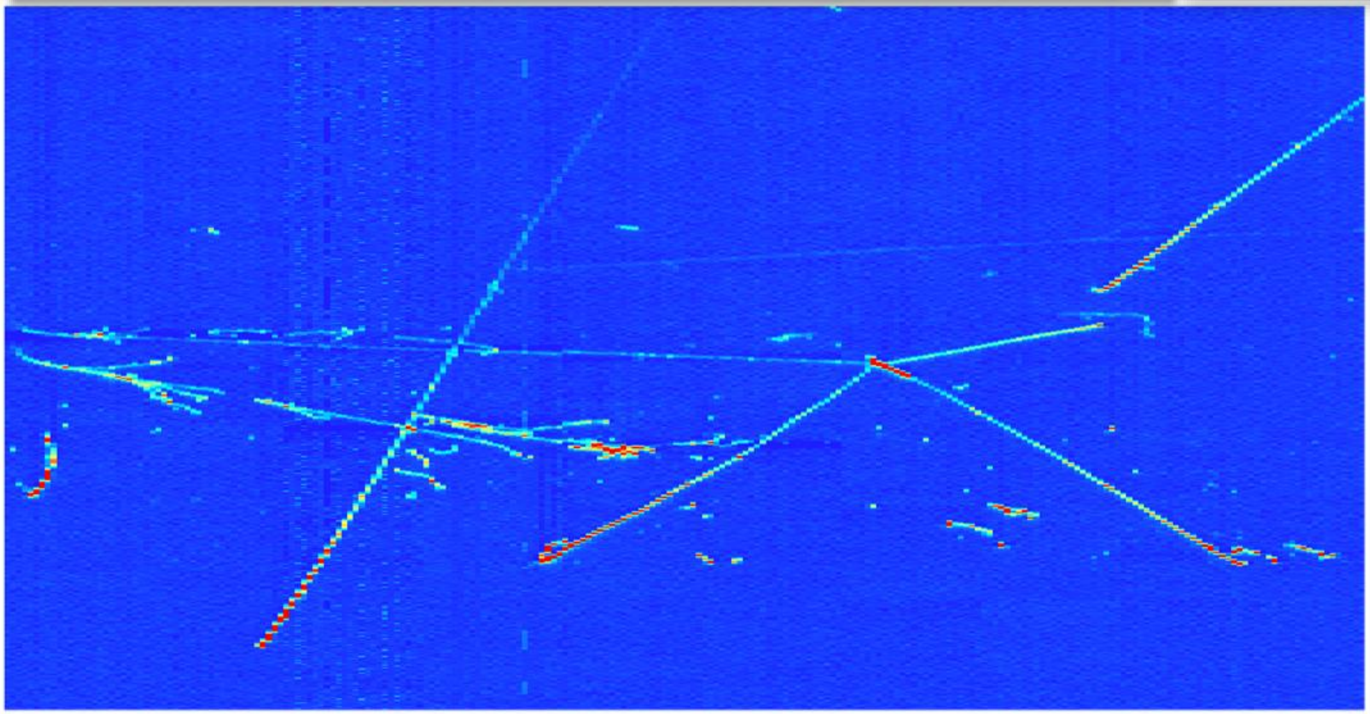
- 4X10-kton (fiducial) LArTPC modules
- Single and dual-phase detector designs
- Integrated photon detection

Single-phase: charge drifts to wire planes (APAs)

A powerful imaging technology

2 EM showers and a pion interaction with 4 prongs

proto DUNE SP



collection view. Run 4696, event 103.

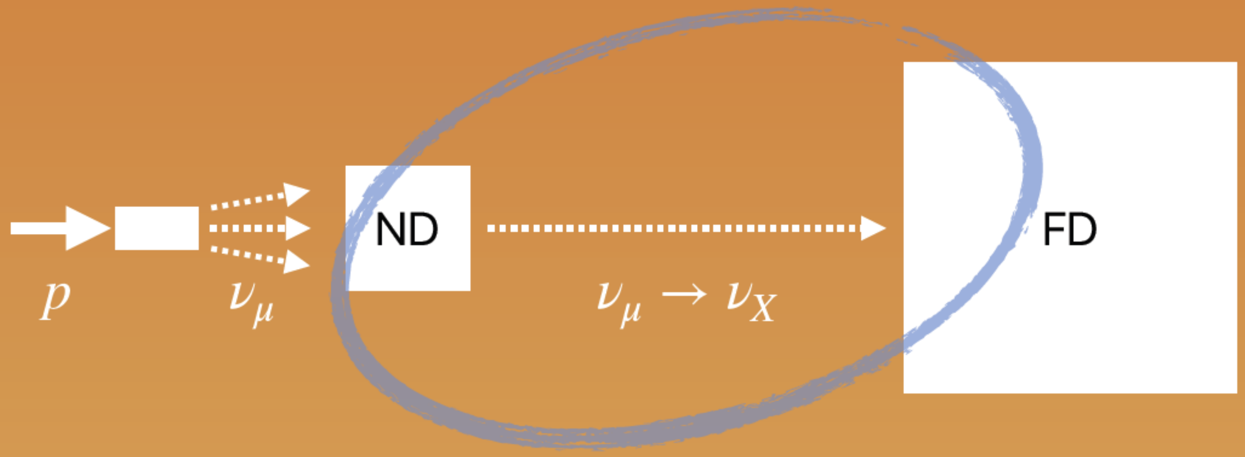
See Monday 8/26 Poster 19:00
Measuring the space charge effect in ProtoDUNE-SP (Joshua Thompson)

See Thursday 8/29 WG1+2 14:22
First Results from Singe-Phase ProtoDUNE at CERN Neutrino Platform (Jianming Bian)

BSM Physics at DUNE

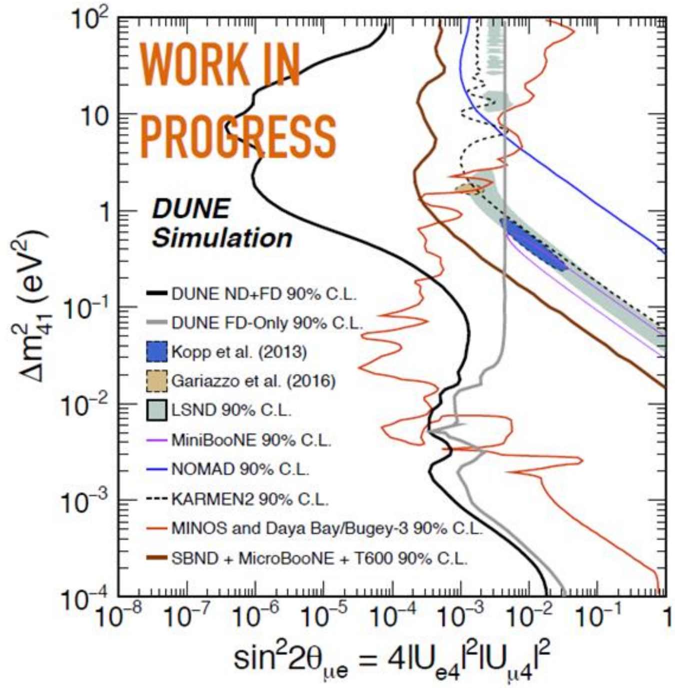
- Topics investigated include:
  - Non-standard short-baseline and long-baseline oscillations phenomena:
    - Sterile neutrino mixing
    - Non-standard interactions (NSI)
    - Non-unitarity mixing
    - CPT violation
    - Tau neutrinos
  - BSM at the ND related to the beam and its interactions with the detector:
    - Low mass dark matter
    - Trident neutrinos
    - Heavy neutral leptons
  - BSM at the FD benefitting from its large mass and resolution:
    - Boosted dark matter
    - Nucleon decay

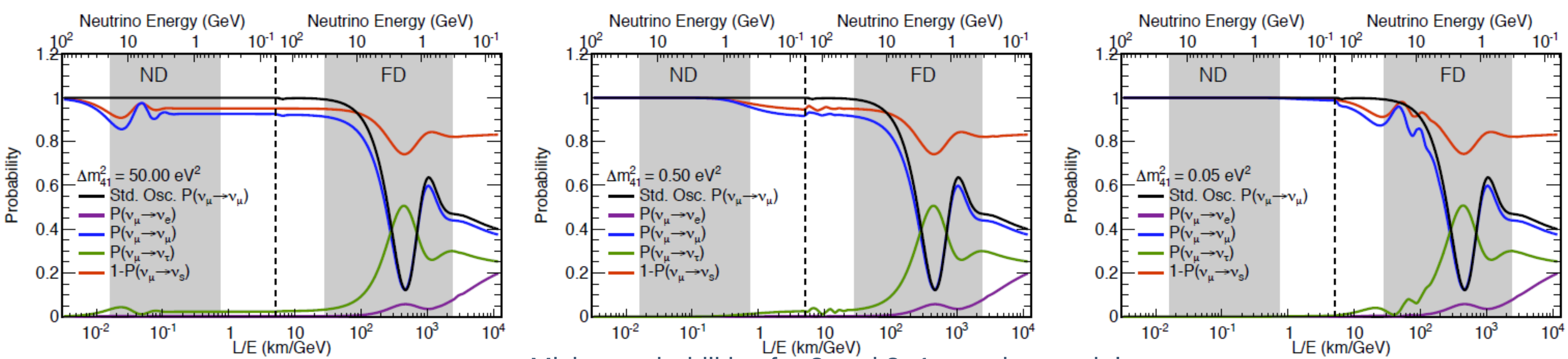
Non-standard Oscillation



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

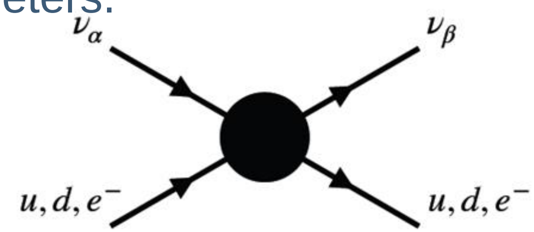




Mixing probabilities for 3 and 3+1 neutrino models

Non-Standard Interactions (NSI)

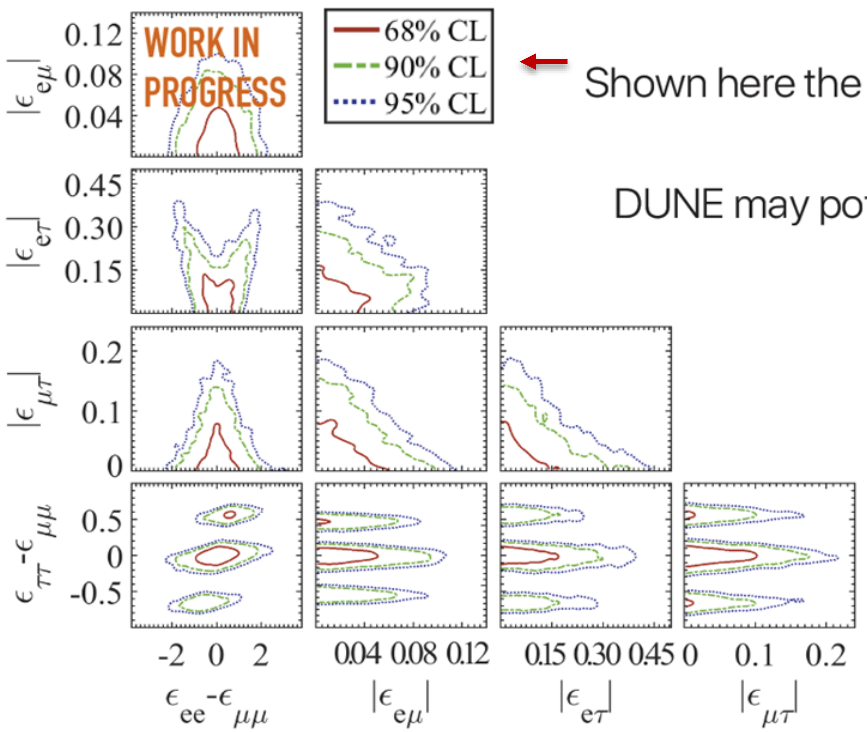
- Projected DUNE has sensitivity to various NSI parameters.



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

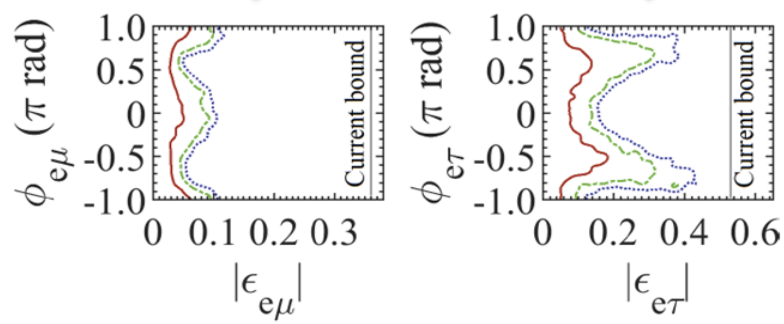
PMNS — **Matter effect (MSW)** — **New Physics**

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



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

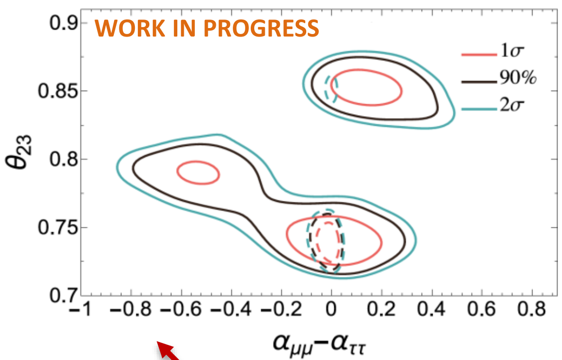
DUNE may potentially improve present constraints on $|\varepsilon_{e\mu}|$ and $|\varepsilon_{e\tau}|$ by at least a factor of 2.

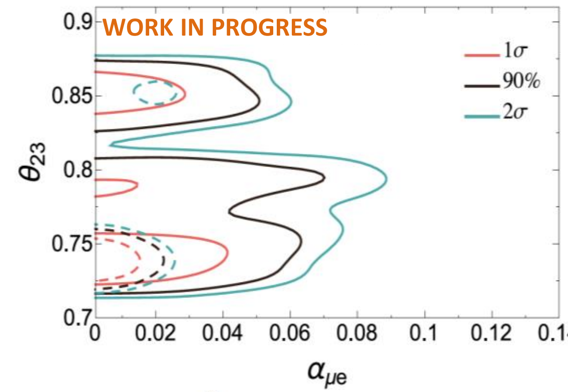


Non-Unitary Mixing

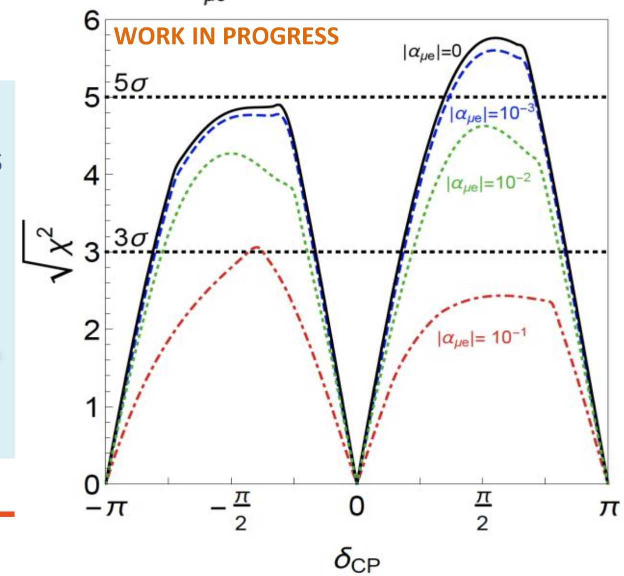
- If neutrinos acquire mass through a (type I) seesaw mechanism, the mixing matrix need not be unitary.
- 300 kton·MW·years with 80 GeV beam flux

$$N = \begin{pmatrix} 1-\alpha_{ee} & 0 & 0 \\ \alpha_{\mu e} & 1-\alpha_{\mu\mu} & 0 \\ \alpha_{\tau e} & \alpha_{\tau\mu} & 1-\alpha_{\tau\tau} \end{pmatrix} U^{3\times 3}$$





- Allowed regions at the 1σ, 90%, 2σ CL for non-unitarity mixing parameters for DUNE-only (solid) and DUNE + present constraints (dashed)
- Impact for non-unitarity on the DUNE CPV discovery portal



CPT Violation

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

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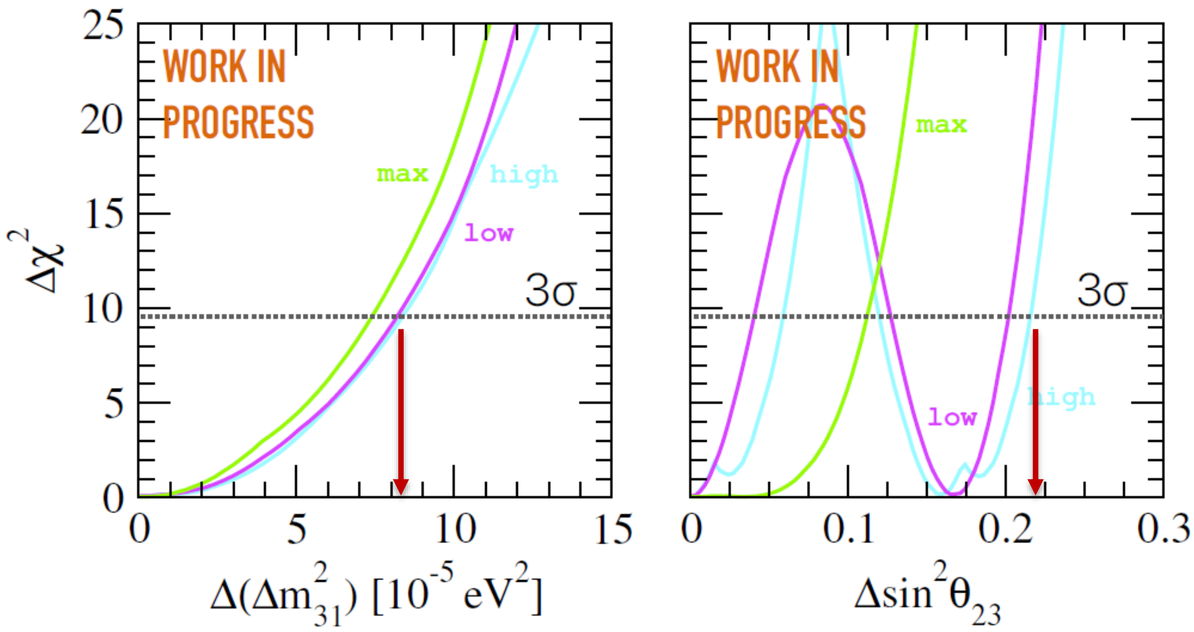
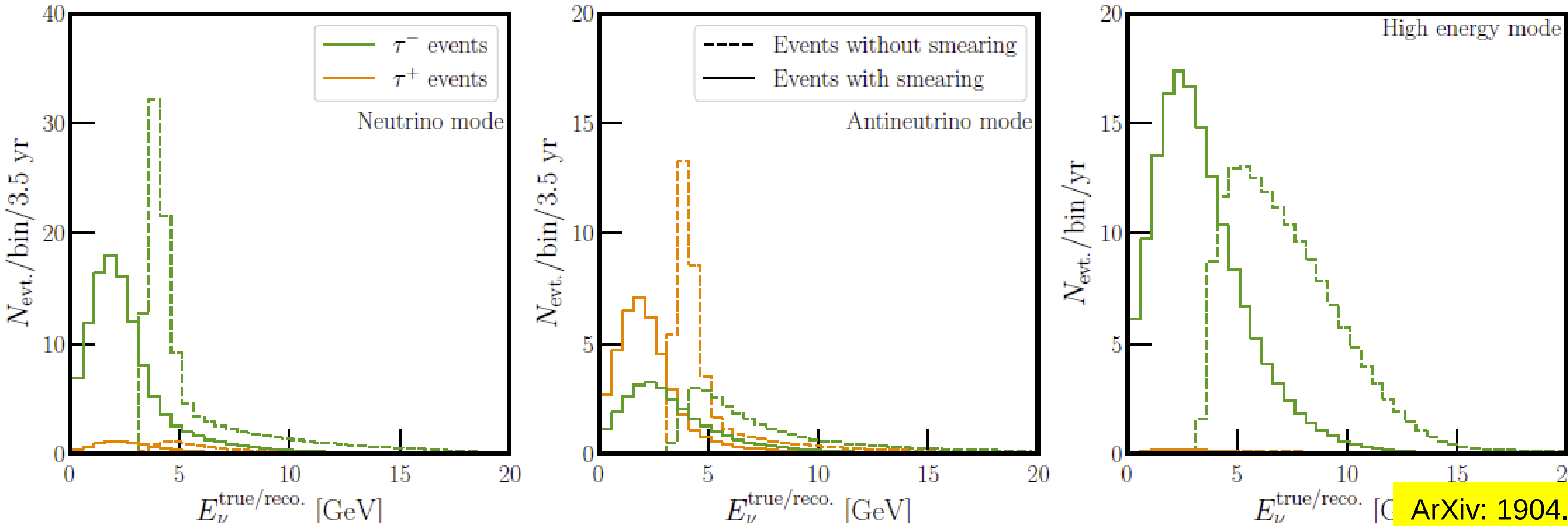


- Projected sensitivity of DUNE to CPT violation for an exposure of 300 kton·MW·year and three different values of θ_{23} mixing angle.
- Current experimental bounds: $\Delta(\Delta m^2_{31}) \equiv \left|\Delta m^2_{31} - \Delta \bar{m}^2_{31}\right| < 3.7 \times 10^{-4}\ \text{eV}^2$
  $\Delta(\sin^2\theta_{23}) \equiv \left|\sin^2\theta_{23} - \sin^2\bar{\theta}_{23}\right| < 0.32$
- DUNE can improve current limit on $\Delta(\Delta m^2_{31})$ by almost one order of magnitude.

ArXiv: 1712.01714

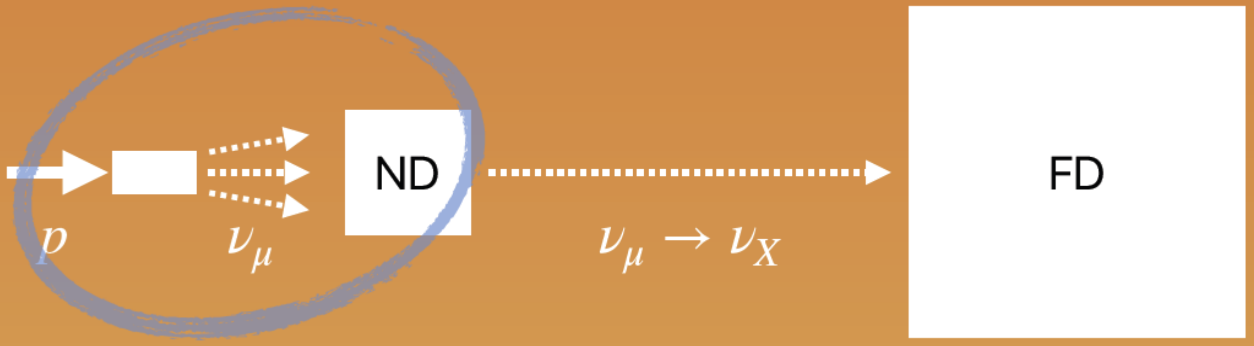
Tau neutrinos

- Currently, almost all of our knowledge from the tau neutrino sector derives from lepton universality of cross-section and PMNS 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.

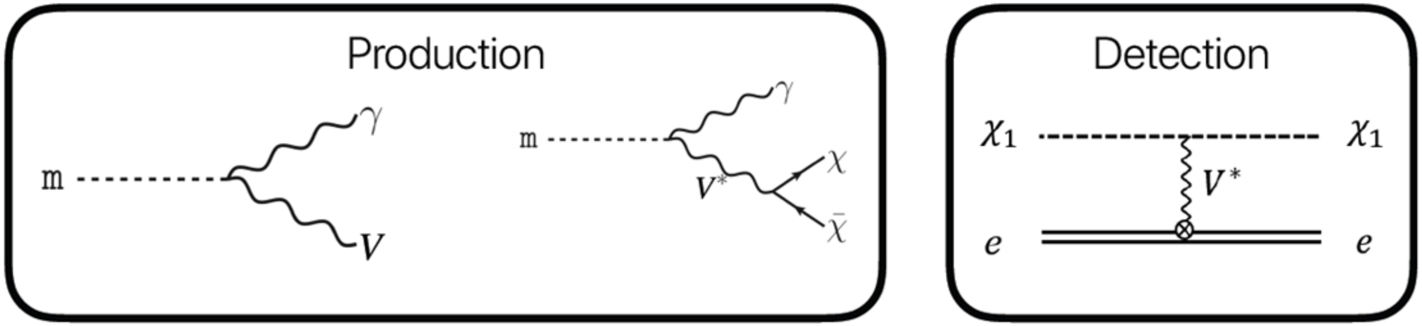


ArXiv: 1904.07265

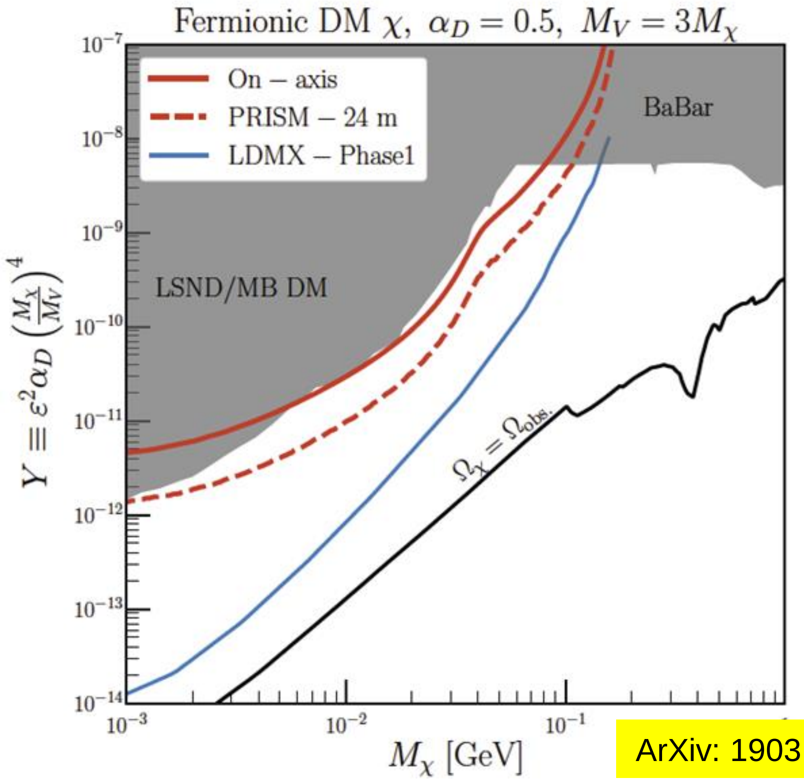
New Physics at the Near Detector



Low-mass Dark Matter



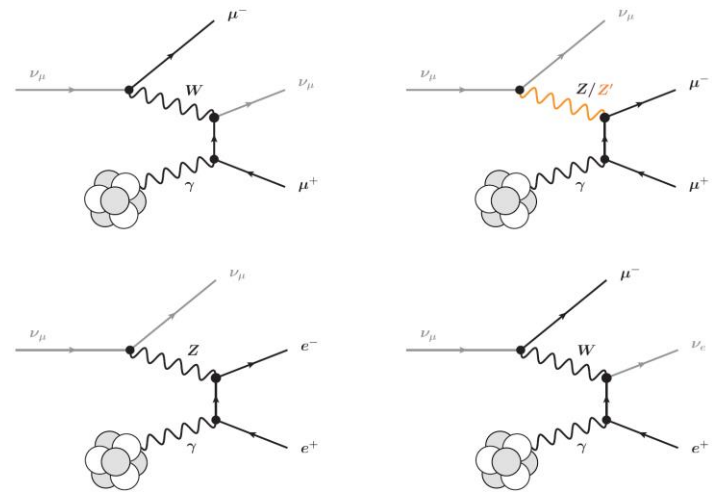
- Dark matter particles produced in the decay of light mesons reach the DUNE ND, where they are detected via electron scattering.
- The main background (neutrino-electron) can be suppressed by taking data off-axis (PRISM).
- Shown here the sensitivity (90% CL) of DUNE for a 7-year (50% neutrino beam, 50% anti-neutrino) run



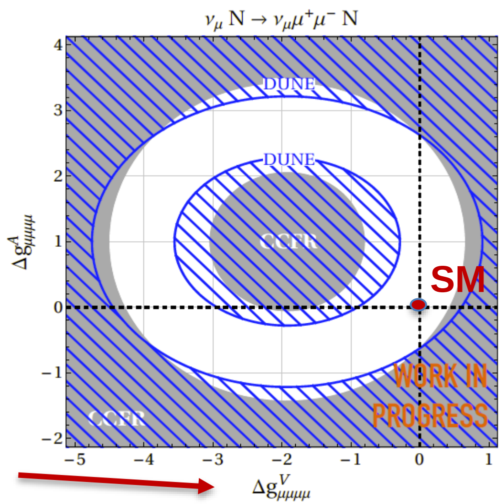
ArXiv: 1903.10505

Trident Neutrinos

- Rare SM process, with one neutrino and two leptons of opposite charge in the final state,
  - has been observed with measured cross-section in good agreement with SM.
- SM cross-section is ~7 orders of magnitude smaller than ν_μCCπ background.
- Trident rate is sensitive to the existence of new forces mediated by a light vector boson that could explain the muon g-2 anomaly.

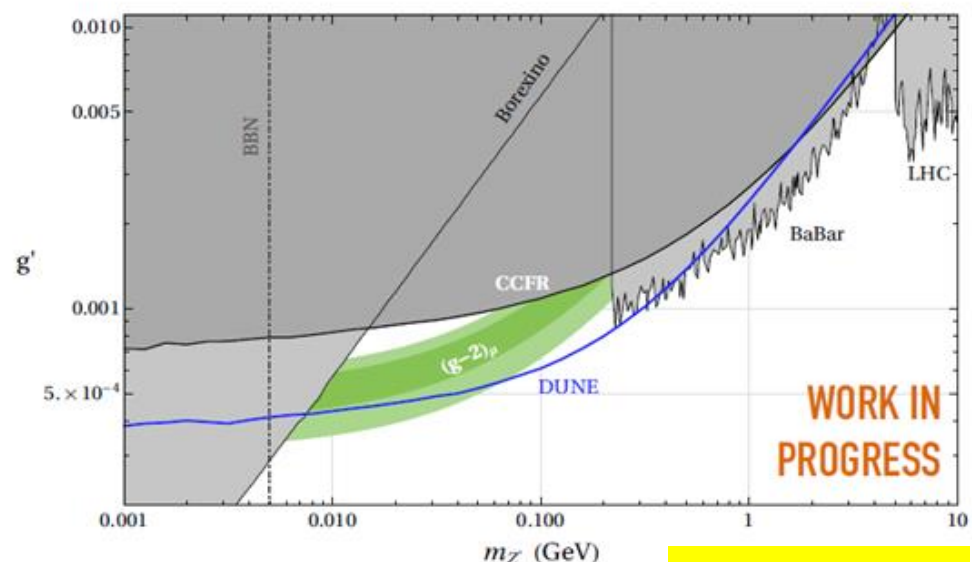


$$\frac{\sigma(\nu_\mu \to \nu_\mu \mu^+\mu^-)_{\rm exp}}{\sigma(\nu_\mu \to \nu_\mu \mu^+\mu^-)_{\rm SM}} = \begin{cases} 1.58 \pm 0.64 & \text{(CHARM II)} \\ 0.82 \pm 0.28 & \text{(CCFR)} \\ 0.72^{+1.73}_{-0.72} & \text{(NuTeV)} \end{cases}$$



New Physics parameters

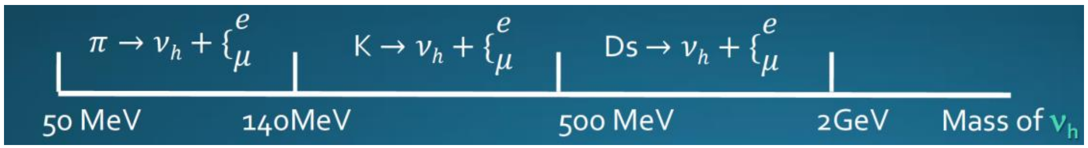
Model Independent Search (95% CL)



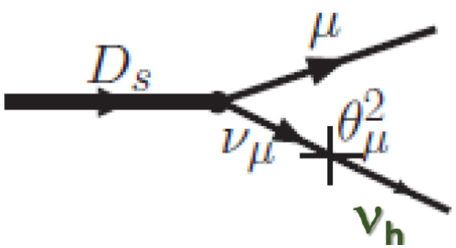
ArXiv: 1902.06765

Heavy Neutral Leptons (HNL)

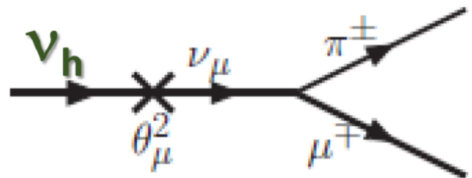
- Neutral portal to Heavy Neutrino
  - The HNL coupling to SM "should not" be more than $U^2 \sim 10^{-7}$



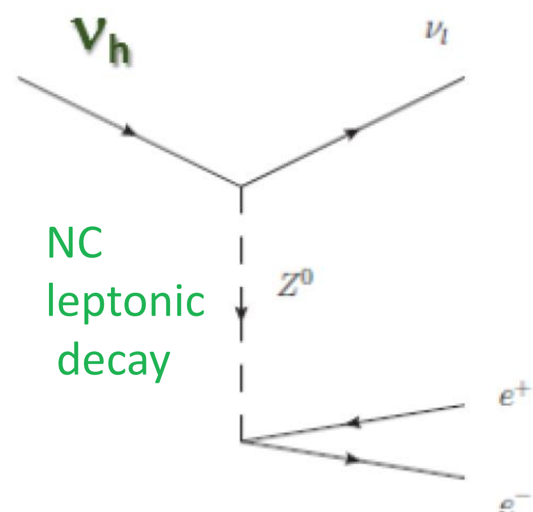
PLB548(2002)204, PRL90(2003)201801 & PRD69(2004)015002



Semi-leptonic decay

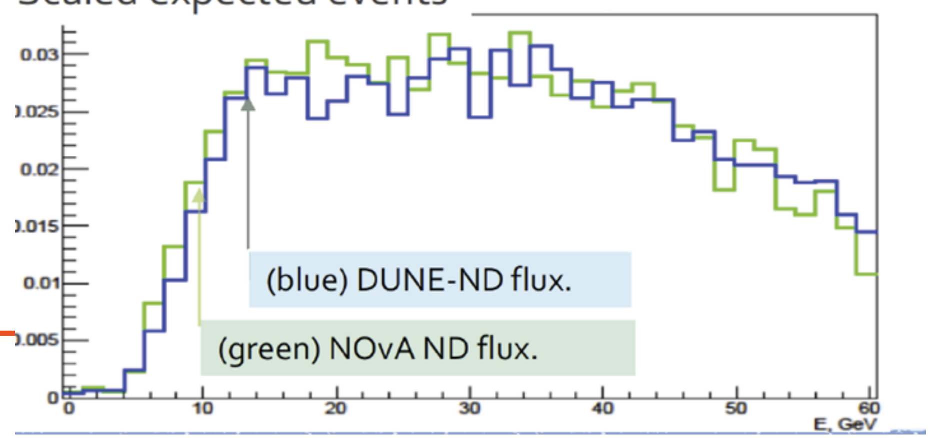


NC leptonic decay

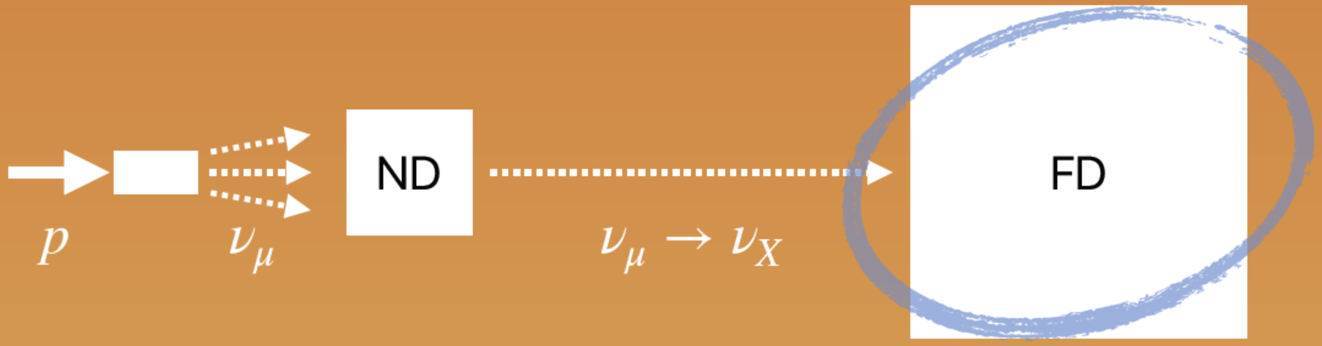


- Ds production of 1μb in NuMI target is likely similar to LBNF target.
- DUNE ND geometry is favorable for GeV masses and ~ 1μs lifetime.

Scaled expected events

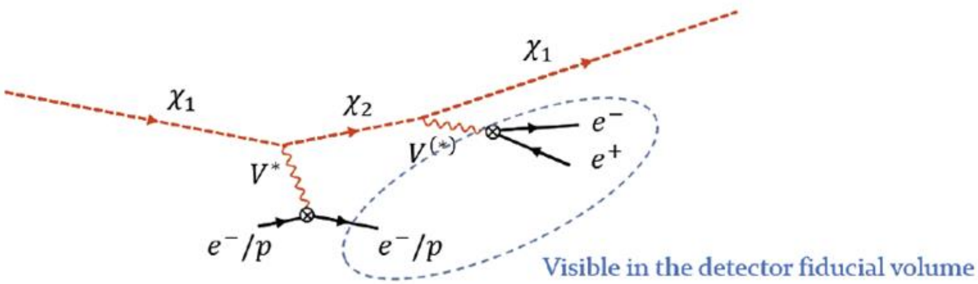


New Physics at the Far Detector

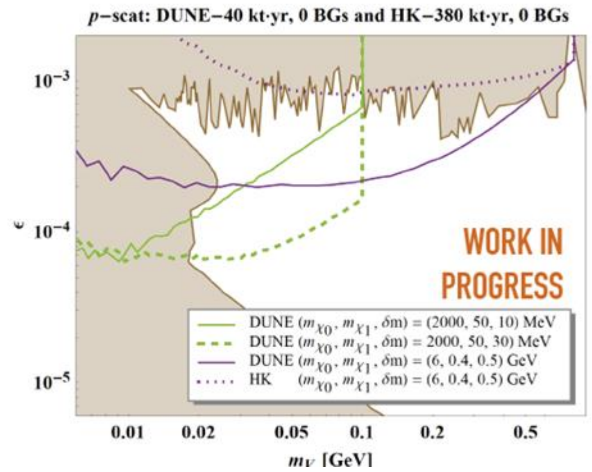


Boosted Dark Matter

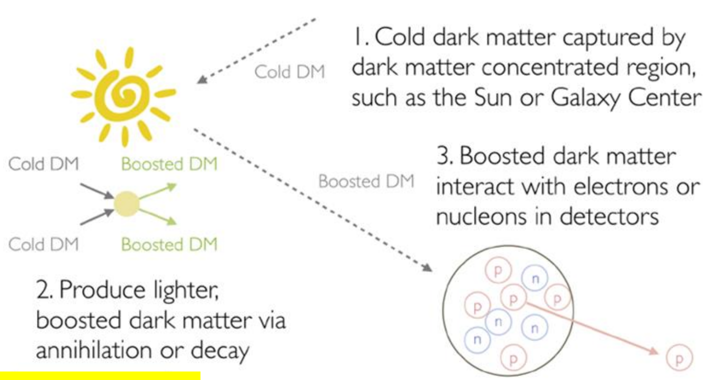
- Case1: Galactic halo can produced dark matter which could interact inelastically in DUNE.
  ⇒ Dark photon



χ_0: heavier dark matter
$\delta m = m_{\chi 2} - m_{\chi 1}$

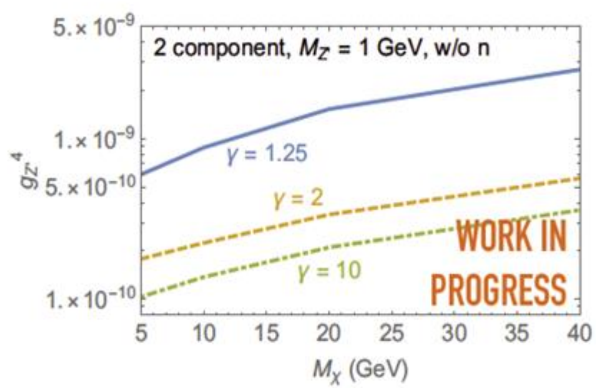


- Case2: Dark matter from the core of Sun could interact elastically with the DUNE.
  ⇒ Lepto-phobic Z'

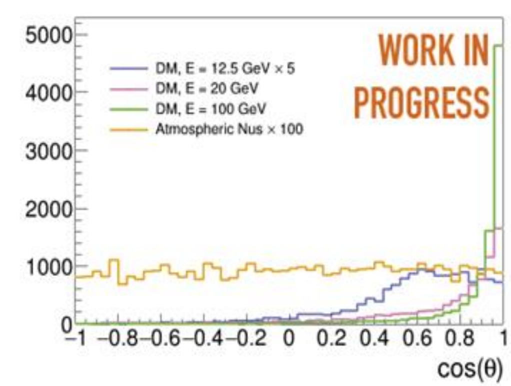


JCAP02(2015)005

4. Look for scattered electrons or recoil protons



Expected 5σ discovery reach with 1year DUNE lifetime

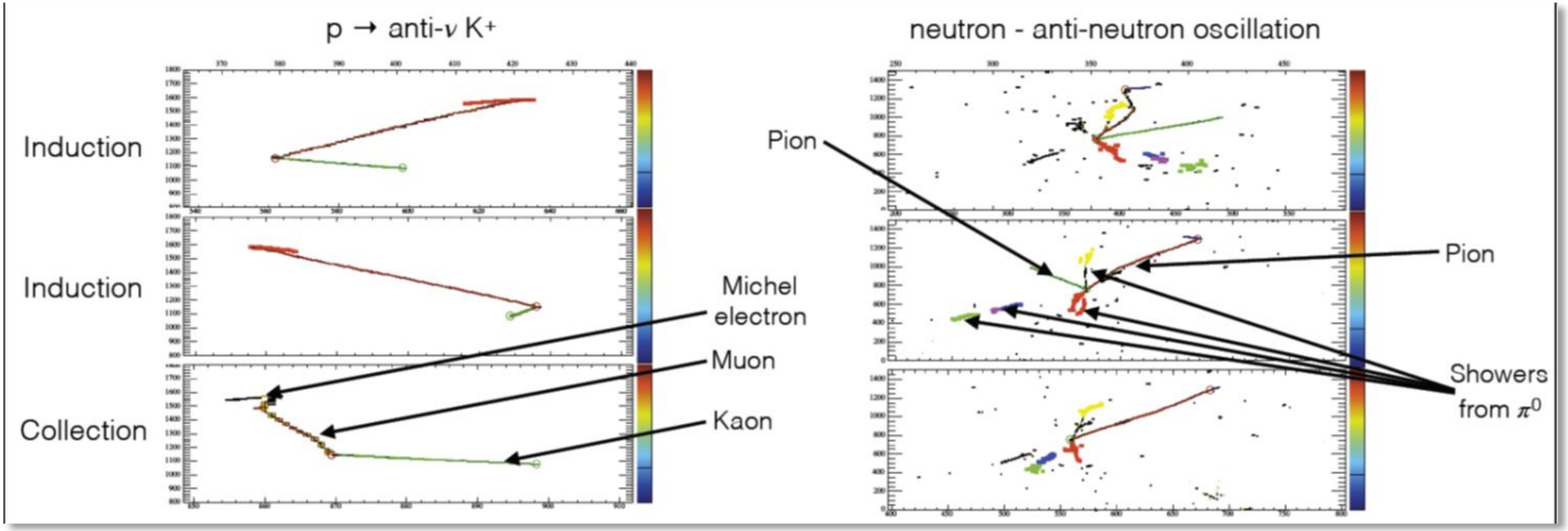


Angle between Sun and particles produced

PRL119(2017)161801, arXiv: 1612.06867, PRD98 (2018) 075027, arXiv: 1803.03264

Nucleon Decay

- DUNE, shielded from cosmic ray, has a high mass and precise particle tracking ⇒ Baryon number violation can be done:
  - Neutron - anti-neutron oscillation
  - $p \to$ anti-ν K^+, $n \to K^+ e^-$
  - $p \to \pi^0 e^+$
- Sensitivity using full simulations (including atmospheric neutrinos and final state interactions with the Argon nucleus) is coming for the TDR.



Summary

- The DUNE detectors and the LBNF beam enable a rich experimental program of BSM physics searches, including
  - Non-standard short-baseline and long-baseline oscillation phenomena;
  - Searches for new phenomena/particle 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.

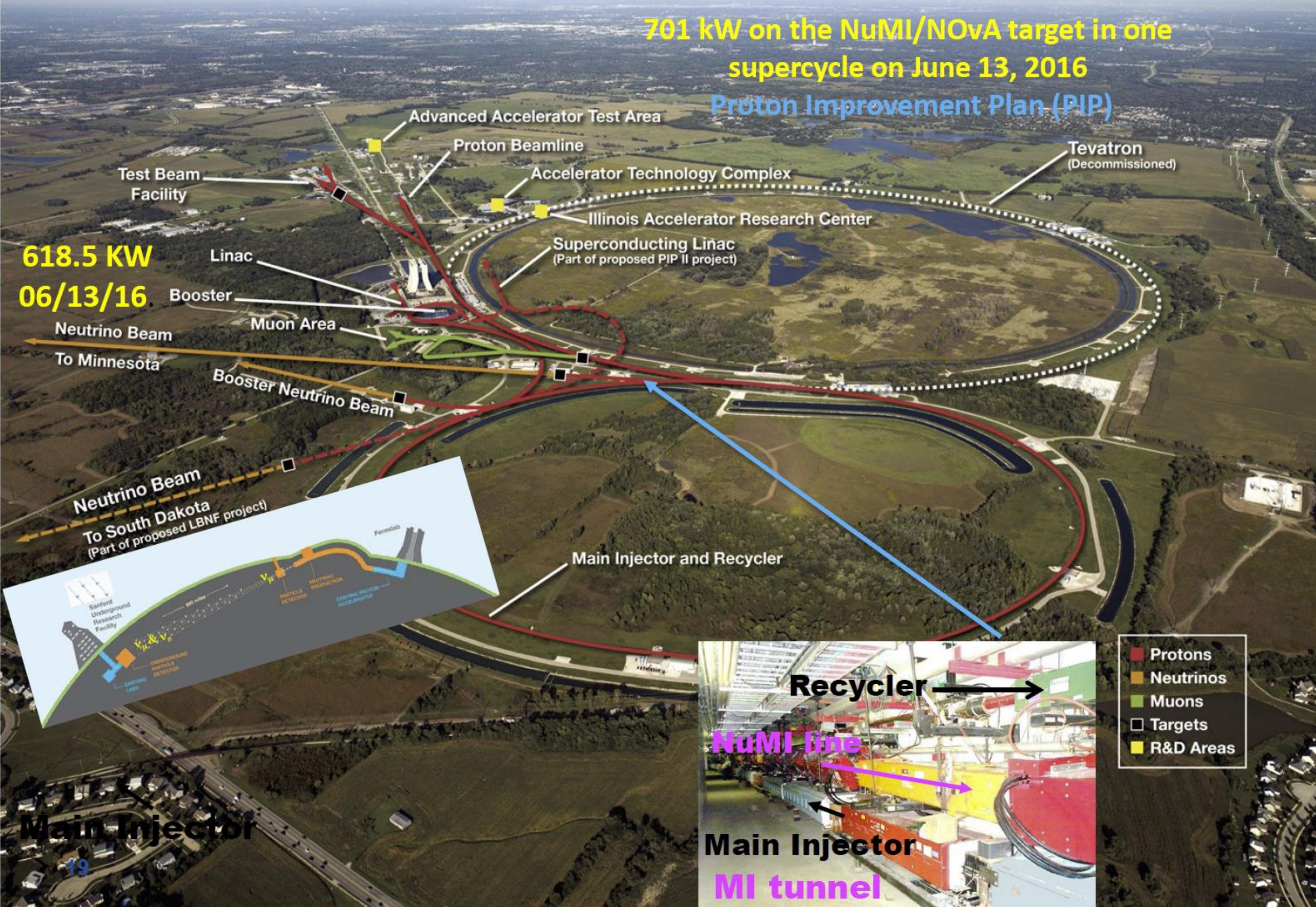
- Look for results from finalized studies in the upcoming DUNE Technical Design Report (TDR) later this year.

Thank you for your attentions.

(cho@kisti.re.kr)

Back-up

Fermilab Accelerator Complex



Testing the standard "three-flavour" paradigm

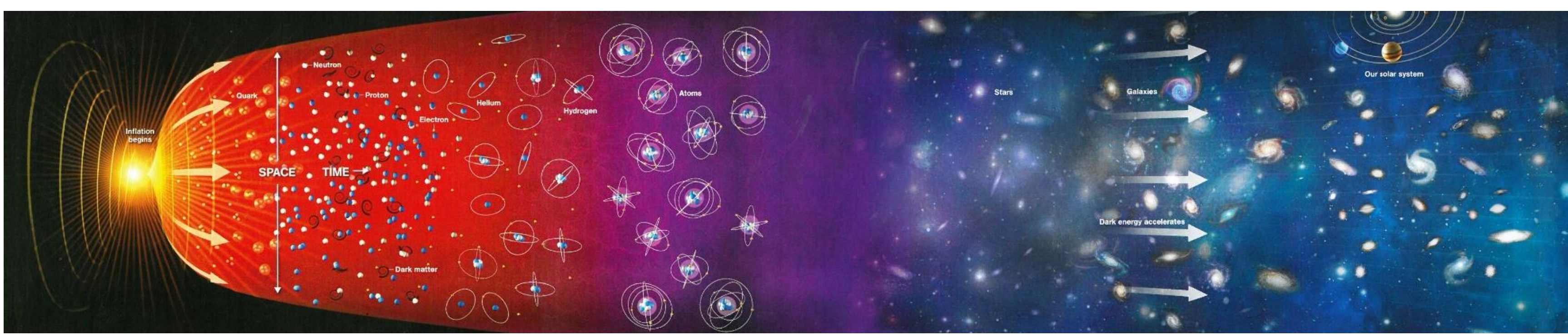
complex phase

$$U_{\mathrm{PMNS}} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

CP Violation in the lepton sector might provide support for *Leptogenesis* as mechanism to generate the Universe's matter-antimatter asymmetry.

CP Violation: $\delta \neq \{0, \pi\}$

$$s_{ij} = \sin\theta_{ij} \; ; \; c_{ij} = \cos\theta_{ij}$$



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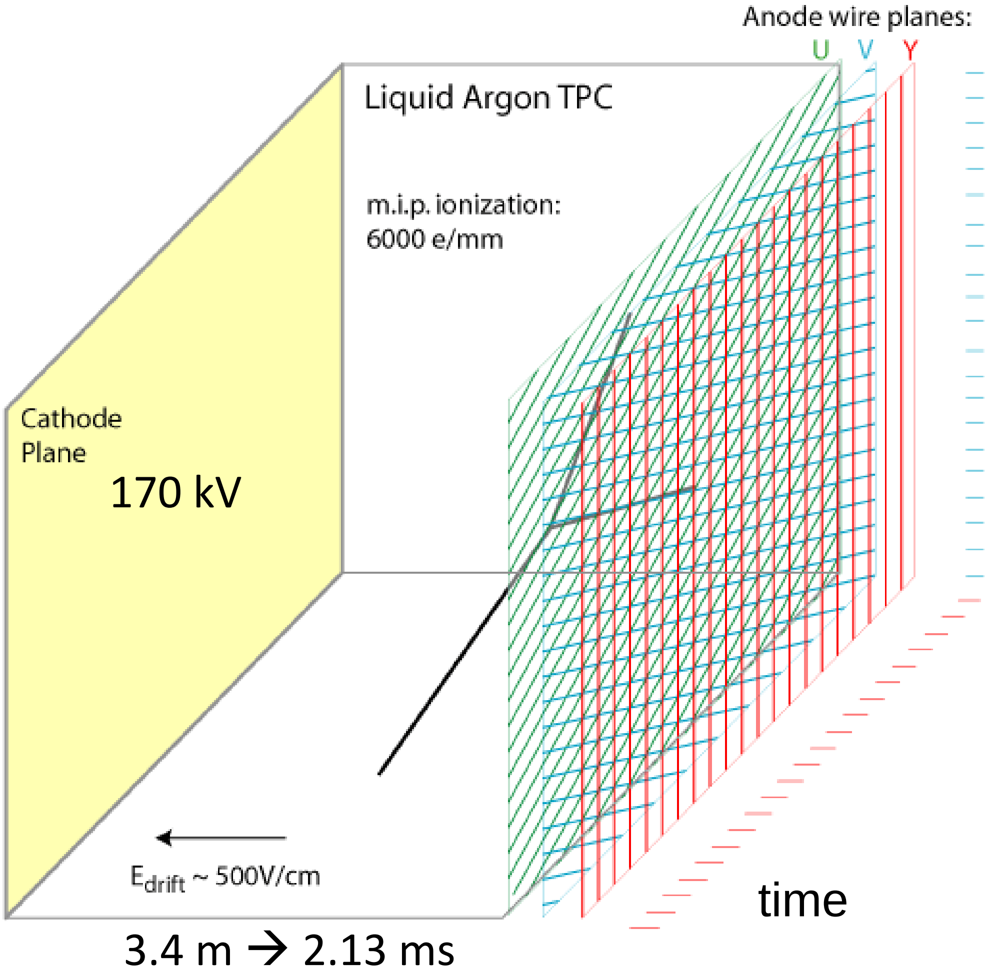
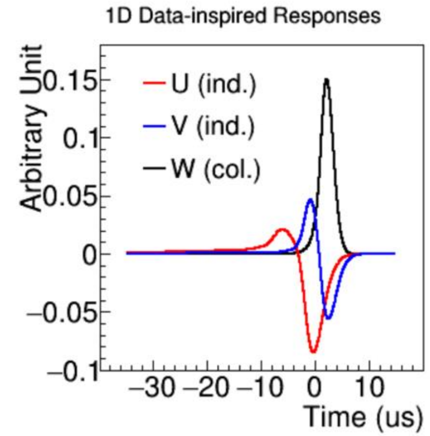
$$s_{ij} = \sin\theta_{ij} \; ; \; c_{ij} = \cos\theta_{ij}$$

Caveat:

No direct evidence for *Leptogenesis*, since a model is needed to connect the low-scale CPV observed here to high-scale CPV for heavy neutrinos that lead to *Leptogenesis*.

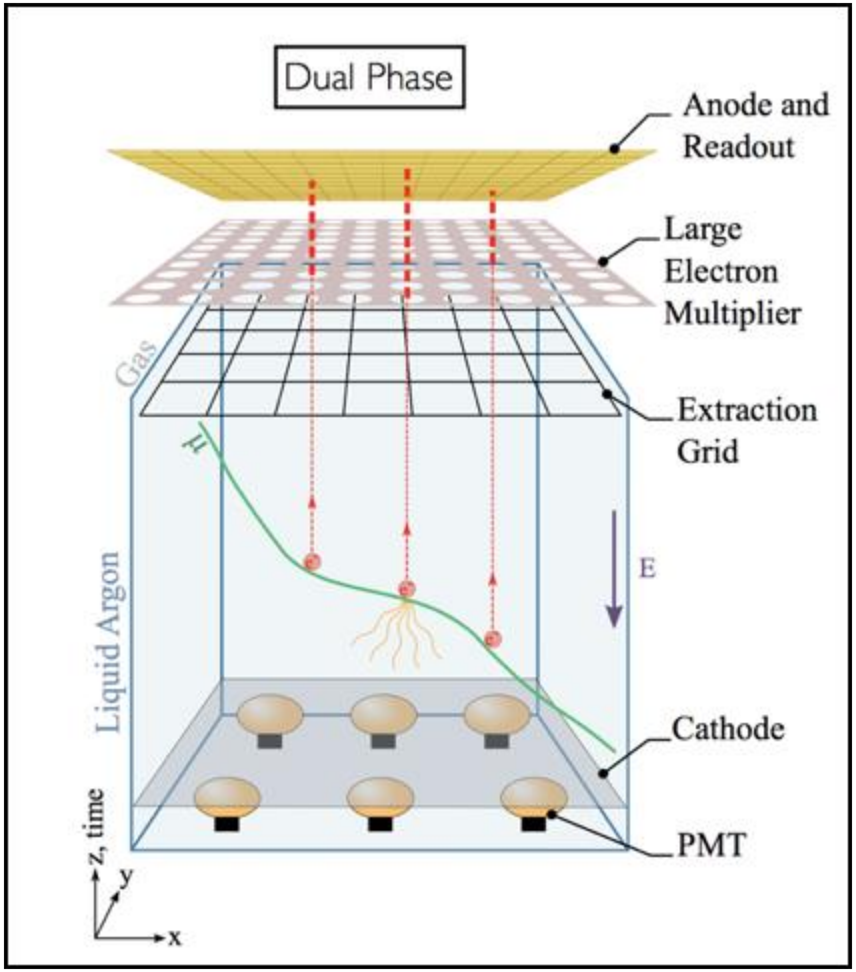
Single Phase Concept



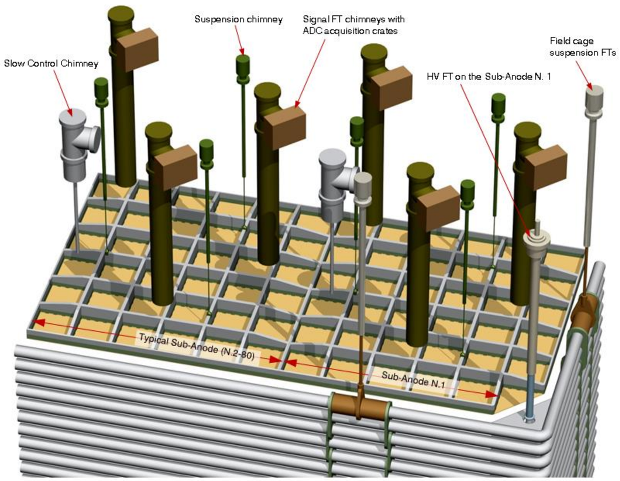


time

Dual Phase TPC



- Larger drift distance (12 m) – higher fields
- Potentially better signal to noise
- Readout/HV access through chimneys on top.



- 153,600 channels
- 80 3x3 m^2 Charge Readout Planes

Thank you for your attentions.

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