Physics of neutrino experiment DUNE

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Content

- Briefly on neutrino oscillations
- DUNE
- ProtoDUNE
- Proton decay
- Calibrations

Neutrinos and flavour oscillations

- Neutrinos second most abundant particles in the universe
- Carry **three flavours *e*, μ, τ**
- **Flavour oscillations** observed
- Must have **non-zero mass**
- Oscillations only sensitive to Δm^2

Flavour states | Neutrino mixing (PMNS) | Mass states

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

~ Amplitude of transition

Oscillation parameters

- $\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$ (ν_{reactor} –Daya Bay)
- $\sin^2 \theta_{12} = 0.307^{+0.013}_{-0.012}$ (ν_{solar}–SK, SNO, ν_{reactor}–KamLAND)
- $\sin^2 \theta_{23} = 0.546 \pm 0.021$ ($\nu_{\text{accel.}}$–T2K,MINOS,NOvA, $\nu_{\text{atmo.}}$–IceCube, SK)
- $\Delta m^2_{21} = (7.53 \pm 0.18)\times 10^{-5}\ \text{eV}^2$ (ν_{reactor} –KamLAND)
- $\Delta m^2_{32} = (2.453 \pm 0.033)\times 10^{-3}\ \text{eV}^2$ (NO assumed) ($\nu_{\text{accel.}}$–T2K,MINOS,NOvA,$\nu_{\text{atmo.}}$–IceCube, SK, ν_{reactor} –Daya Bay, RENO)

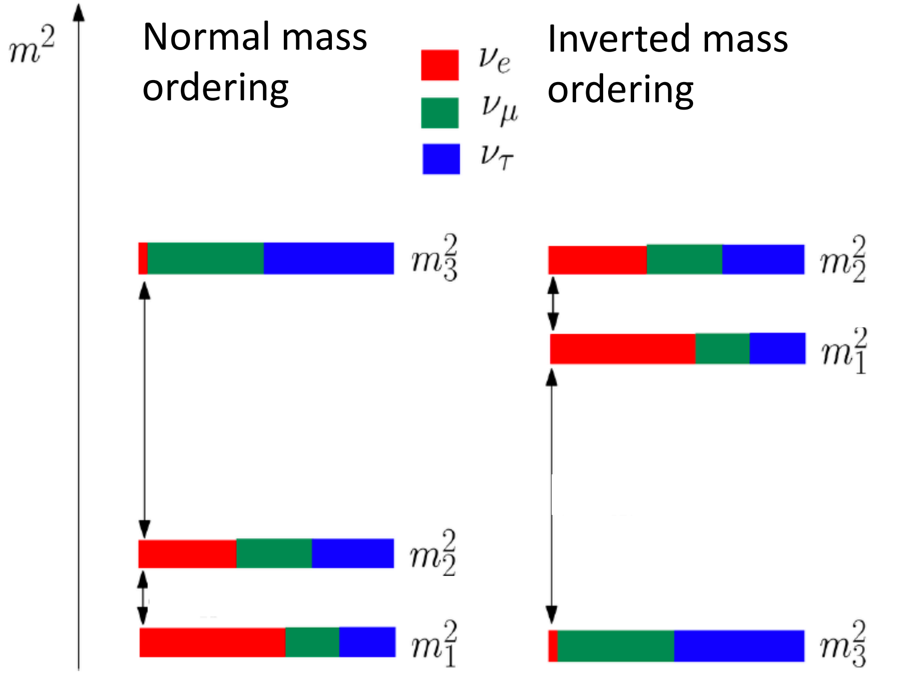
[PDG]

CP symmetry violating term

Parametrisation

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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



[Image credit: MPKI]

Unknown:

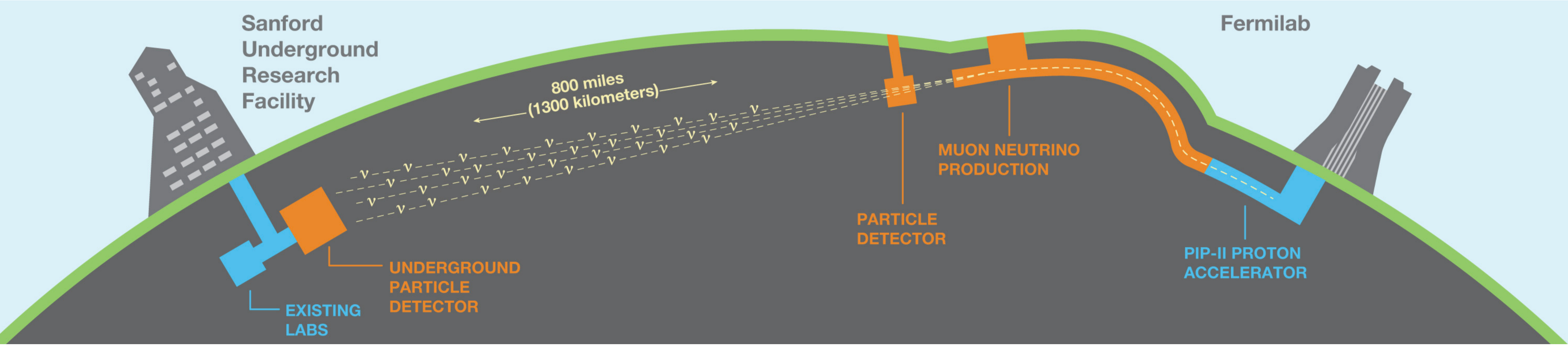
- Mass ordering ($m_3 > m_1$ ‘normal’, $m_3 < m_1$ ‘inverted’)
- CP violation ($\delta \neq 0||\pi$)

DUNE will address both!

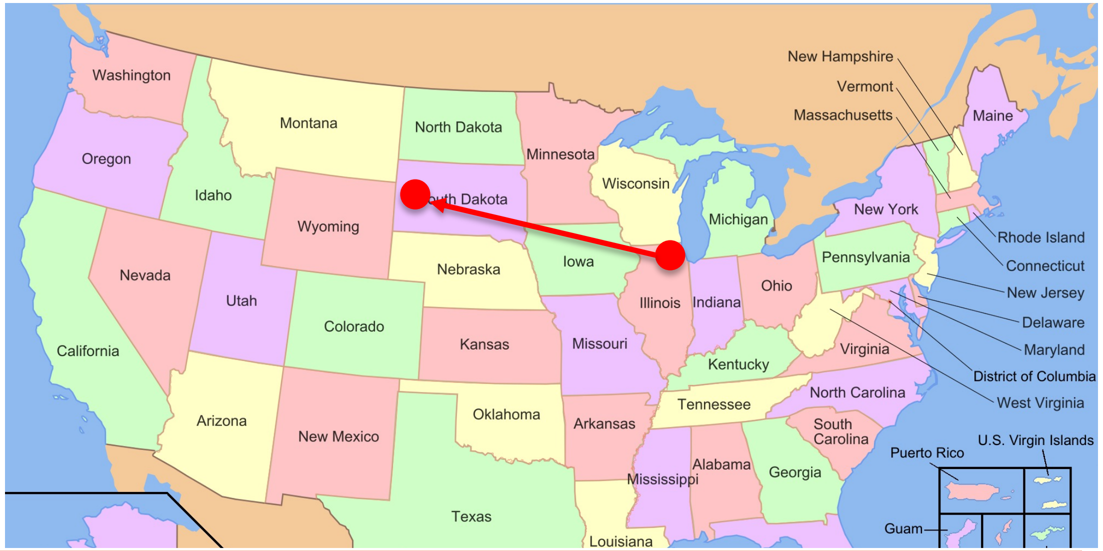
DUNE Physics Programme

- Determination of CP violation in neutrino oscillation
- Determination of neutrino mass ordering
- Precise measurement of mixing parameters
- Detection of neutrinos from core-collapse supernovae
- Proton decay and other BSM studies
- Detection of solar neutrinos

Deep Underground Neutrino Experiment – DUNE

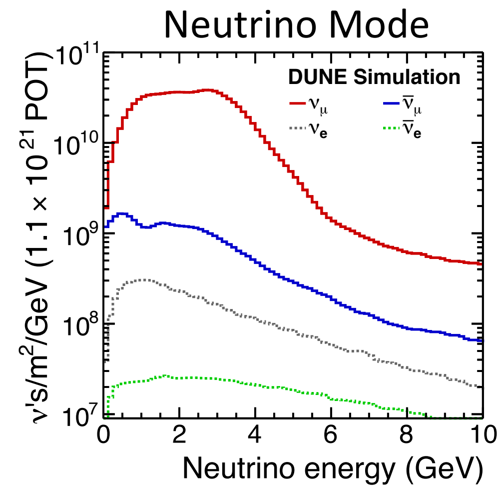


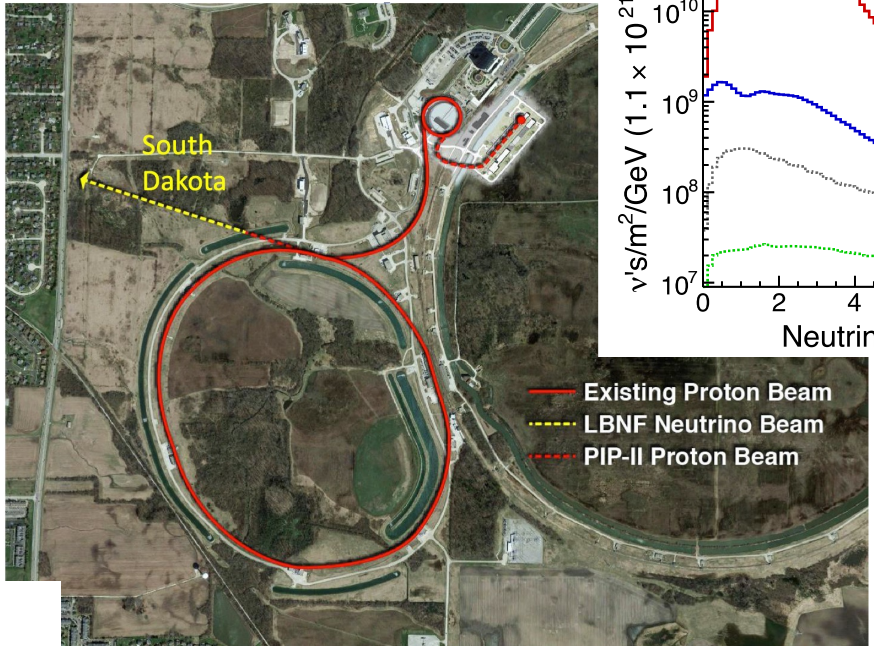
- 3 major components: beam, near detector, far detector
- Fermilab (Chicago, IL) to former Homestake gold mines (Lead, SD)
- International collaboration
- Czech member institutions:
  - FZU
  - Czech Technical University
  - Charles University

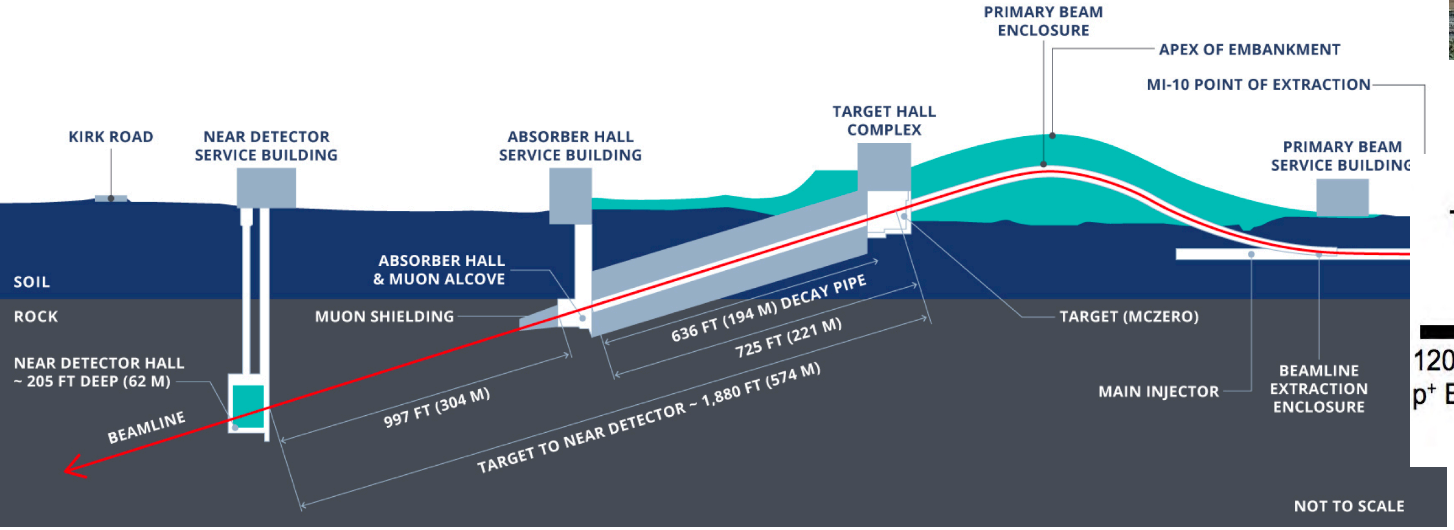


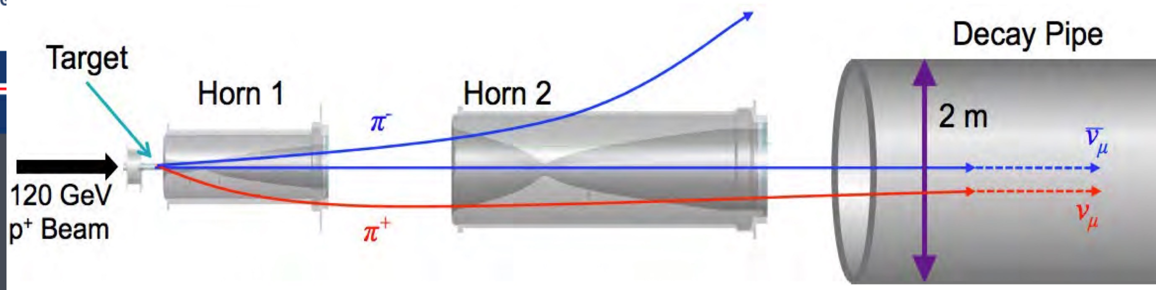
Beam

- Proton Improvement Plan II
- Will produce 1.2 MW proton beam (60–120 GeV) (upgradeable to 2.4 MW)
- Protons on target → pions → muons + neutrinos
- Expected late 2020s



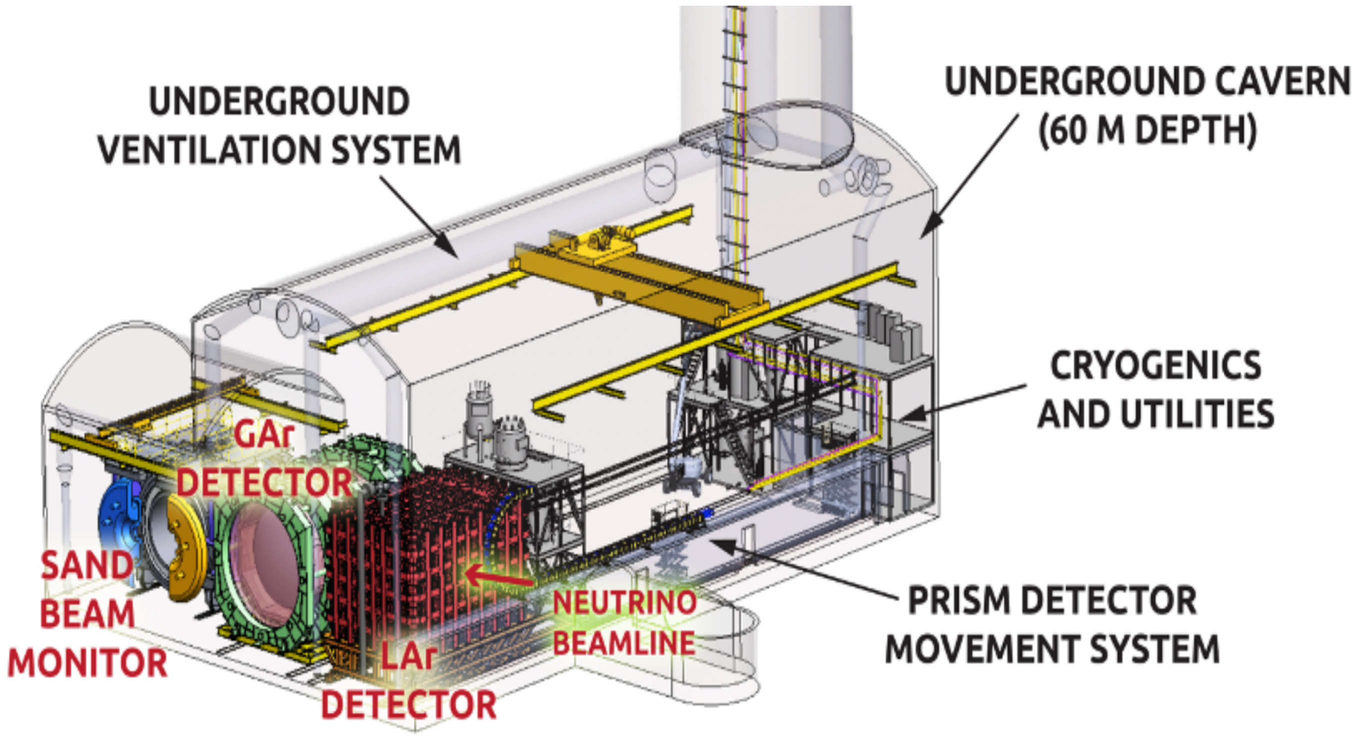






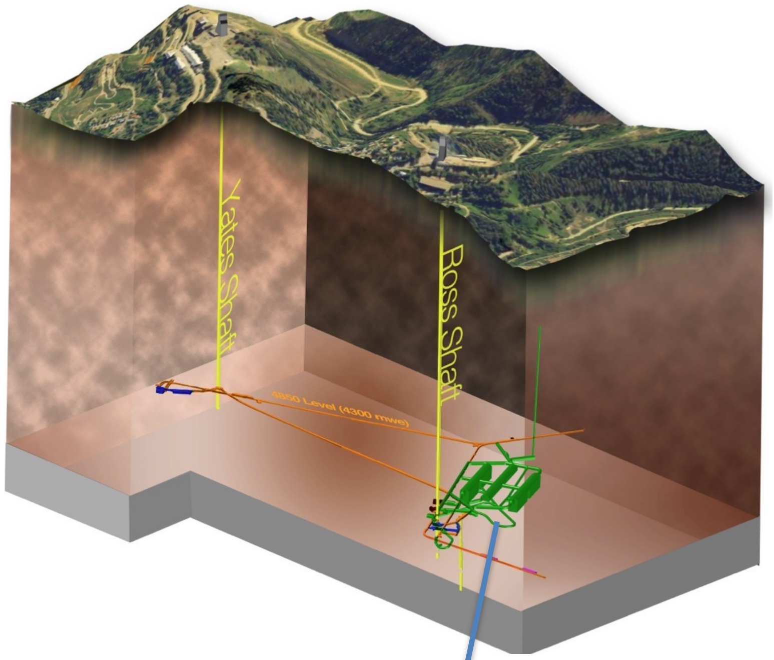
Near Detector

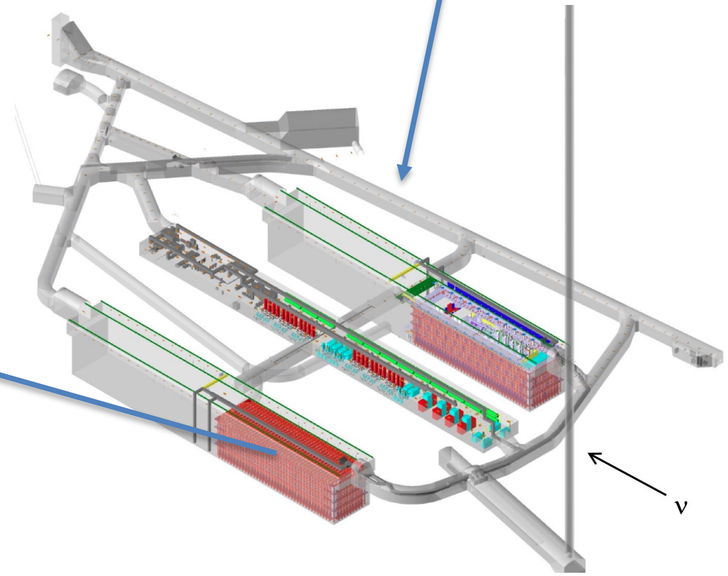
- Cross section measurement
- Flux monitoring
- Constrains on systematics in relative Near – Far Detector measurement
- Three systems
  - LArTPC – primary neutrino target
  - GArTPC – high pressure gas; muon tracker
  - On-axis monitor – inner tracker, ECAL, SC-magnet

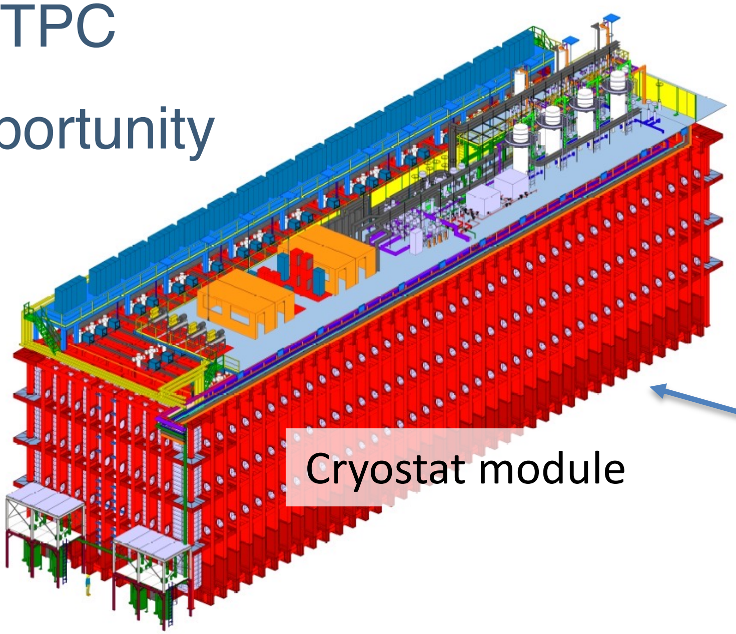


Far Detector

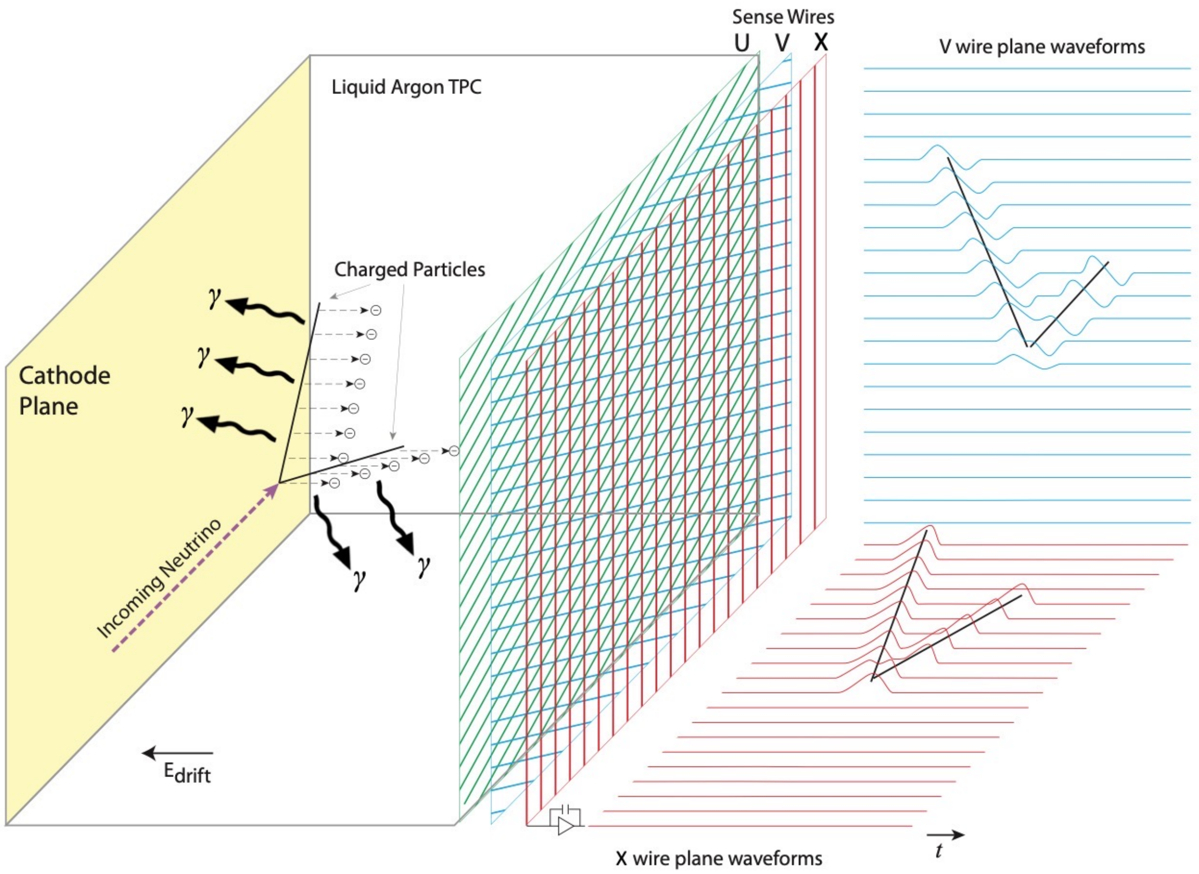
- Sanford Underground Research Facility (SURF)
- 1.5 km underground
- 4 detectors in 2 main caverns
- Instrumented in stages
- Modules 1, 2 and 3 – LArTPC
- Module 4 – module of opportunity



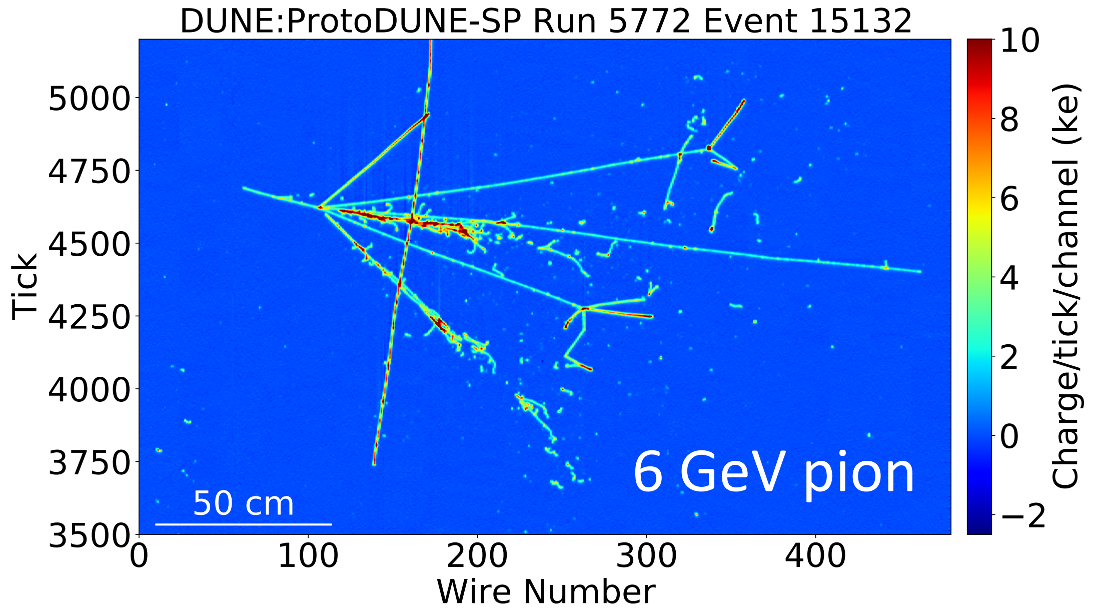




Principles of LArTPC

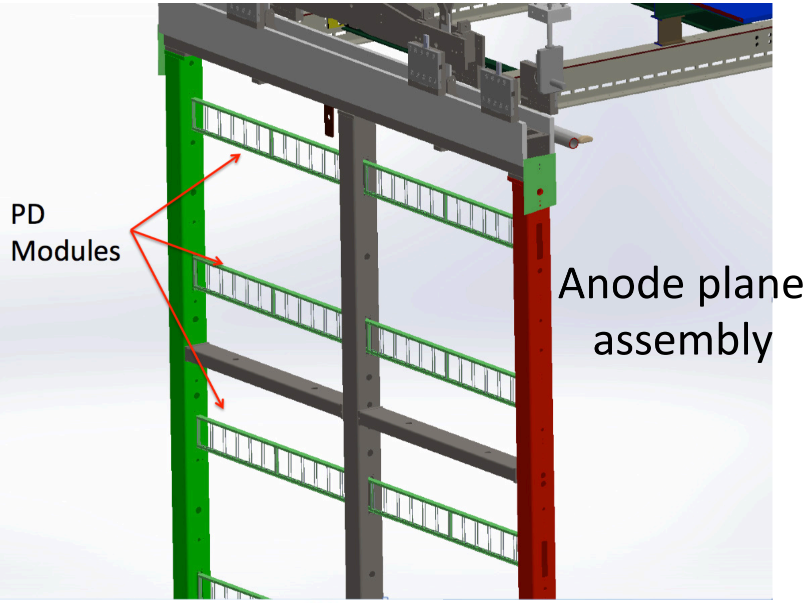


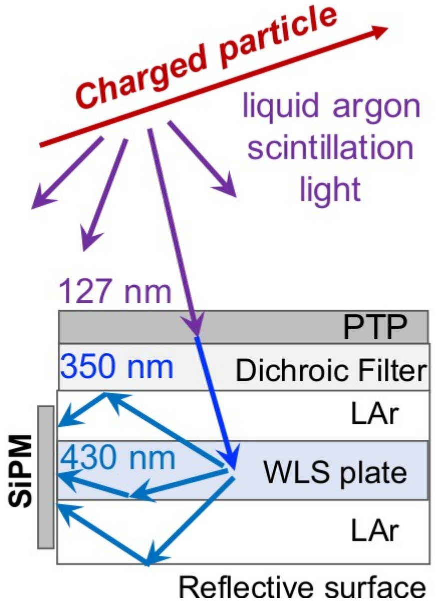
- Liquid Argon Time Projection Chamber
- 3D image – time plays role of 1 coordinate
- Far Detector – multiple readout wire planes → multiple 2D views

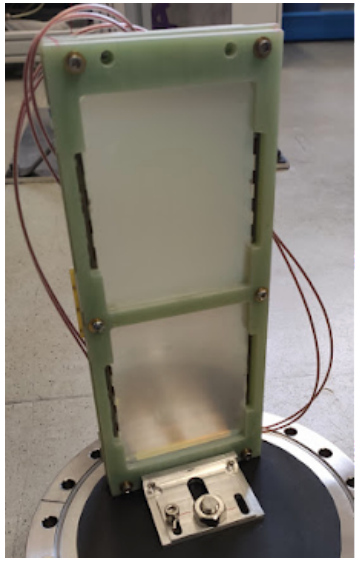


Photon Detection System

- Will provide time information for events
  - Need reference time to know drift distance
  - Crucial for non-beam events
- Calorimetry
  - Aid TPC energy reconstruction
  - Important for low-energy physics (supernova ν)
- Decided to use X-ARAPUCA
- **FZU** has been involved:
  - Installation and commissioning of system in ProtoDUNE
  - Initial tests of SiPM sensors → selection of candidates to be tested in ProtoDUNE
  - Will prepare for mass testing for QA/QC for DUNE Far Detector Module 1





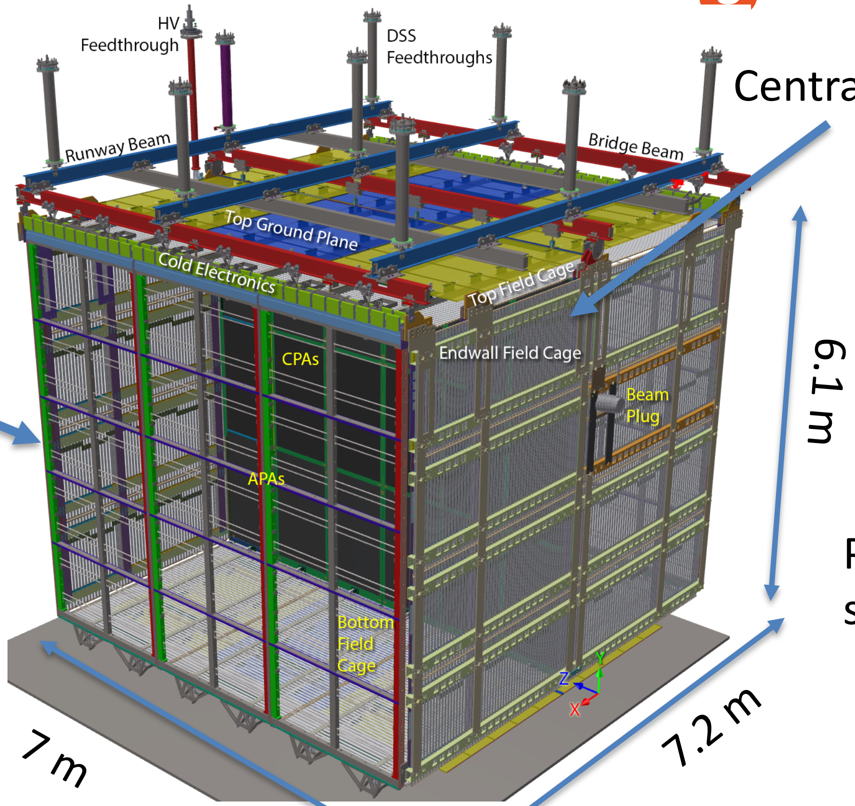


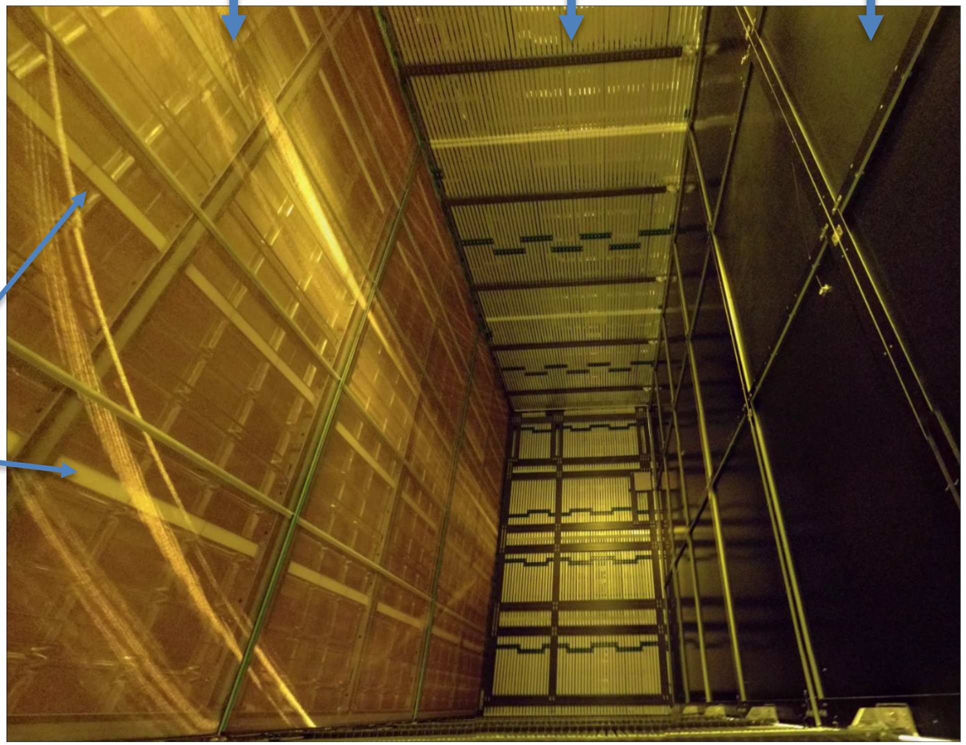
ProtoDUNE at CERN

- Design **validation** and **demonstration** at full scale – same drift distance and E-field
- **Two prototypes** (~1 kt LAr)
  - ‘**Single Phase**’, **horizontal drift**
    - All liquid argon
    - Operational 2018–2020
    - In test beam – p, π, μ, e, K
    - Cosmics
    - Components being upgraded → **‘Phase II’ (start 2022)**
  - ‘**Dual Phase**’, **vertical drift**
    - Liquid argon with gaseous layer on top
    - Drift charge multiplied in gas phase → amazing signal/noise
    - Proved to be difficult at large scale
    - Operational 2019-2020, cosmics
    - Evolved into **‘Single-phase’, vertical drift**

Dual phase cryostat

ProtoDUNE Single Phase





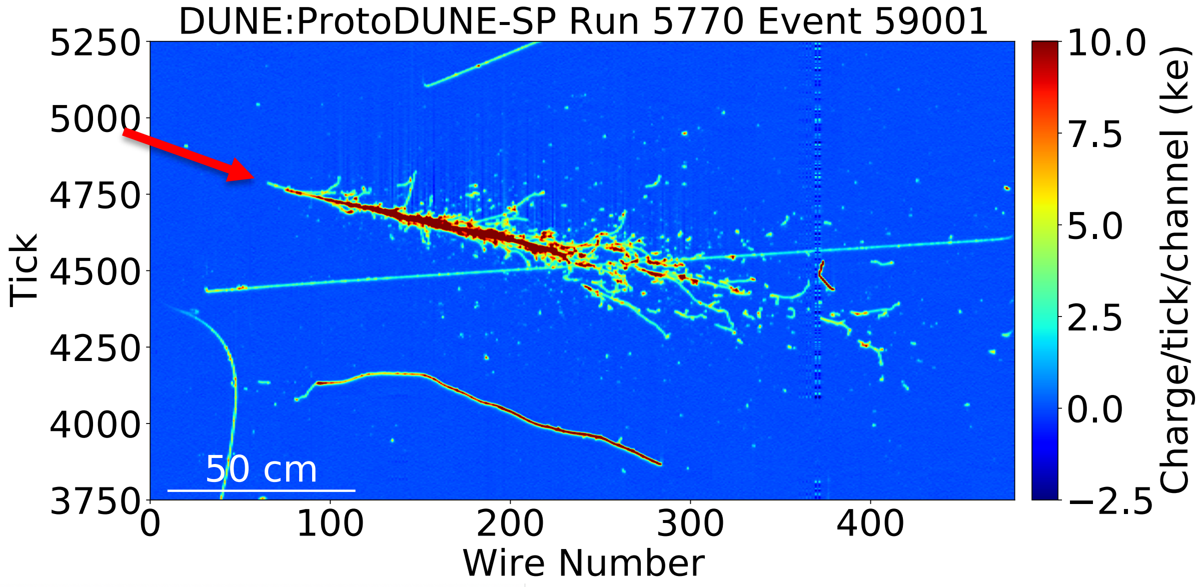
- 2 drift volumes
- Cathode in the middle
- 3 anode assemblies on each side

- Inside view of one drift volume
- Not filled with LAr

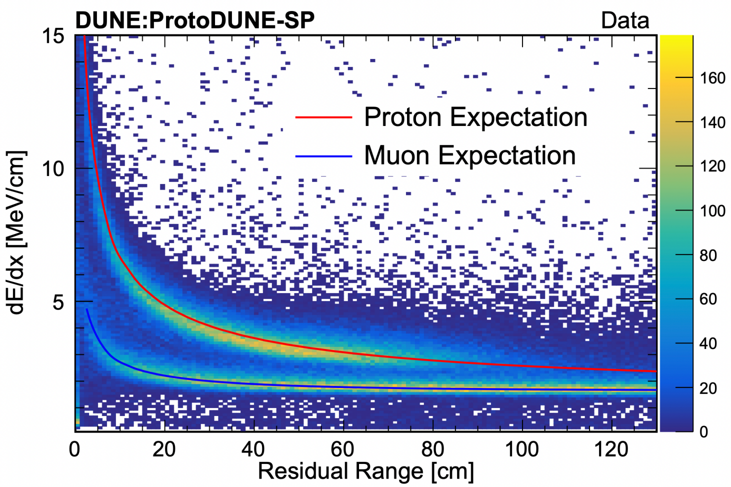
ProtoDUNE Single Phase

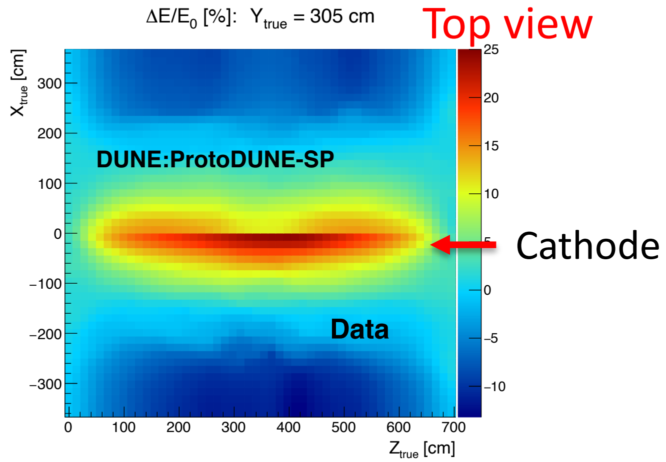
- Successful beam **particle identification and reconstruction**
  - Cross section measurements under way (π, *p*, *K* with Ar)
- Measured distortion of electric field
  - Due to accumulated space charge
- **Stable operation**
  - $>$ 99.5% HV uptime
  - $>$ 99% channels active
- **Photon detectors tested** → final-design considerations

Beam electron, 6 GeV



Energy loss vs residual range for stopping particles
→ Particle identification





Electric field distortion

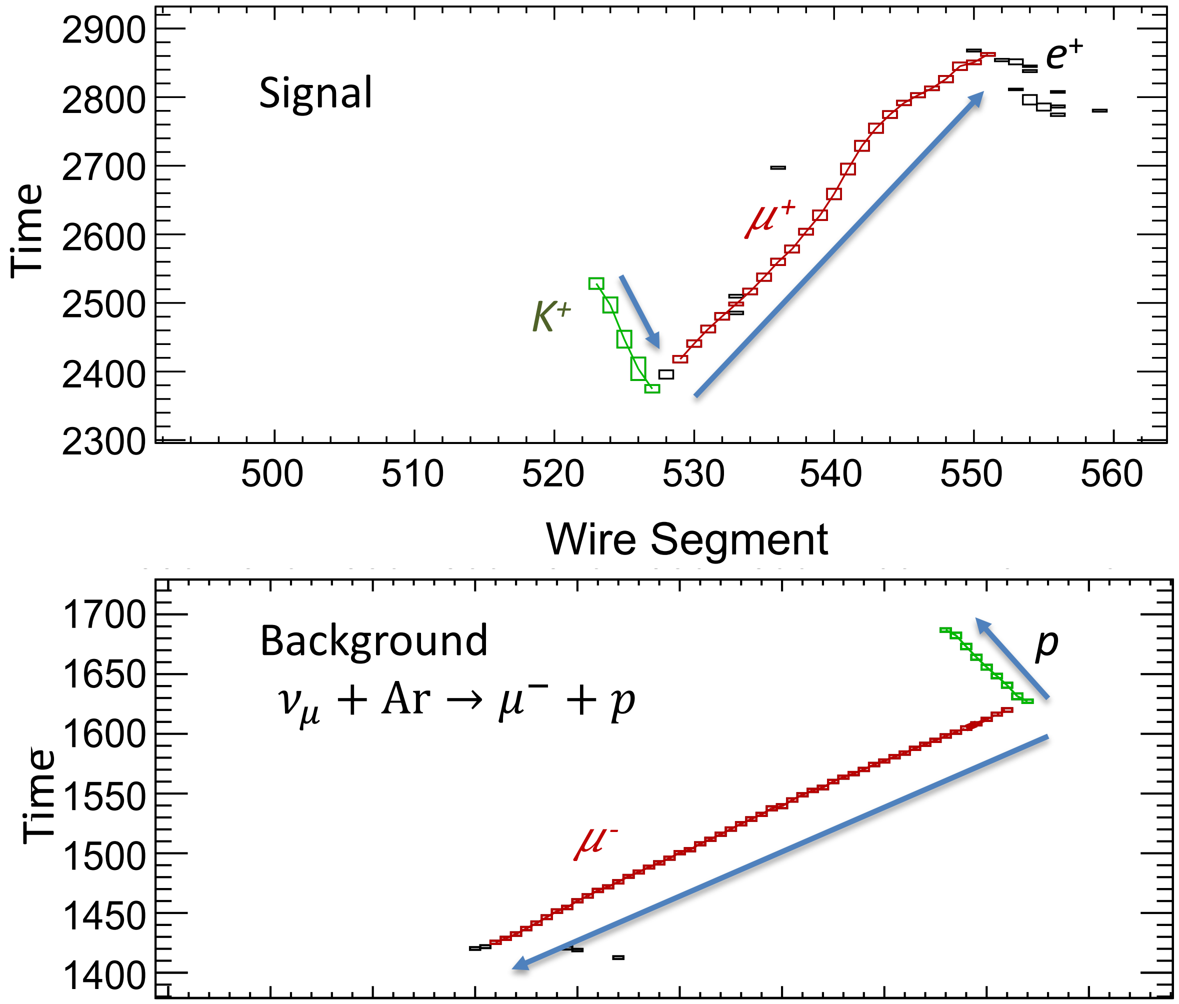
Proton decay

- Potential of DUNE for baryon-number violating decays:
  - $p \rightarrow K^{+}\bar{\nu}$, $n \rightarrow K^{+}e^{-}$, $p \rightarrow e^{+}\pi^{0}$
  - More to be investigated
- Super-Kamiokande biggest player in the game
  - Large water Cherenkov detector
- LArTPC has better particle identification and topology reconstruction → potentially better efficiency in selecting decay signals and background discrimination
- Most promising: $p \rightarrow K^{+}\bar{\nu}$

$p \to K^+ \bar{\nu}$

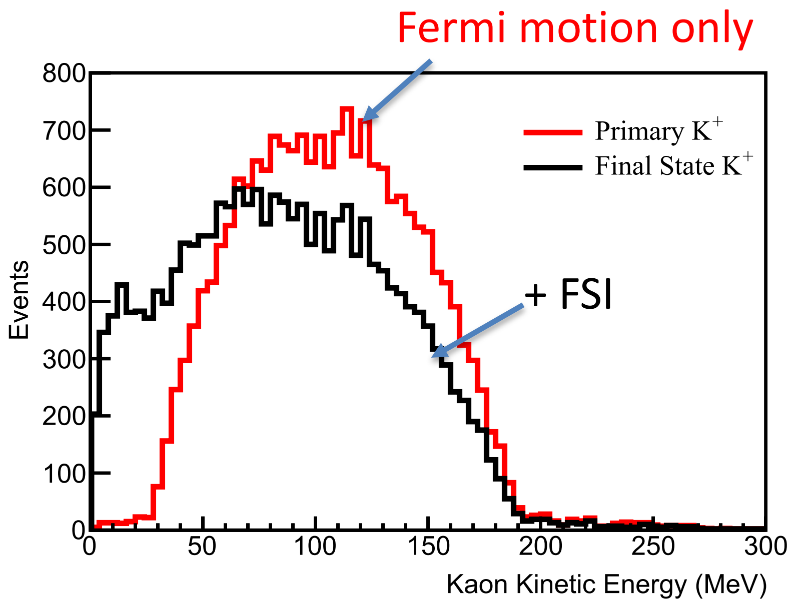
- $\boldsymbol{KE_K = 105}$ **MeV** (~28 cm in LAr; if *p* at-rest)
- $\boldsymbol{K^+ \to \mu^+ \nu_\mu}$ **(64%)**
  - $\boldsymbol{KE_\mu = 153}$ **MeV (~52 cm in LAr**)
- **DUNE will see kaons** (unlike in water Cherenkov detector) and mono-energetic μ
- Major background from **atmospheric** $\boldsymbol{\nu_\mu}$**CC**
  - Similar topology (if μ energy is right)
  - Possible misidentification of **proton as *K***
    - Can discriminate on direction
    - Difficult to distinguish when short tracks
- Caveat: in DUNE *p* decays inside Ar nucleus

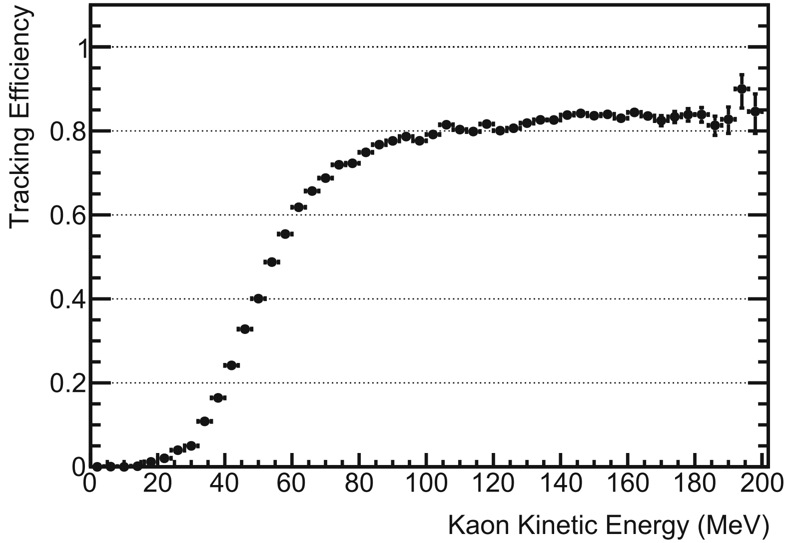
Reconstructed MC events



Effects of Nucleus

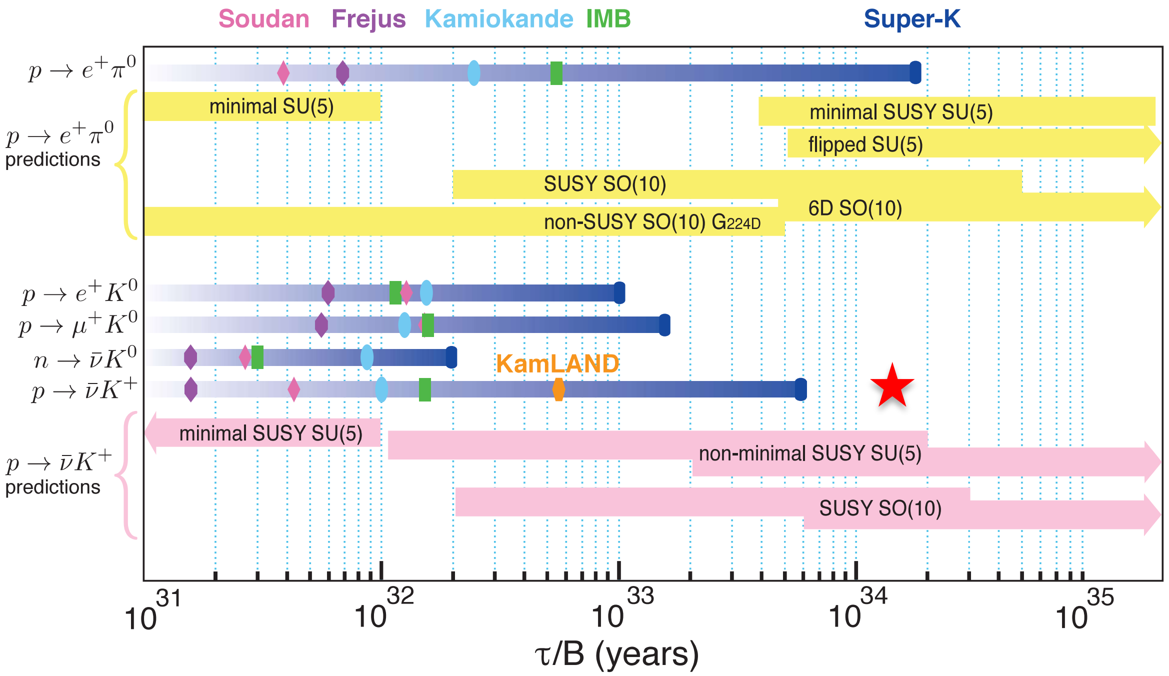
- Energy of outgoing *K* affected by
  - *p* Fermi motion
  - interactions within nucleus (Final State Interactions/FSI)
  - Significant fraction of *K* leave Ar with < 50 MeV
- Current reconstructions have troubles finding short tracks (~4 cm or ~40 MeV)
- Improvements in reconstruction foreseen (visual scanning suggest improvement in tracking efficiency 58% → 80% possible)





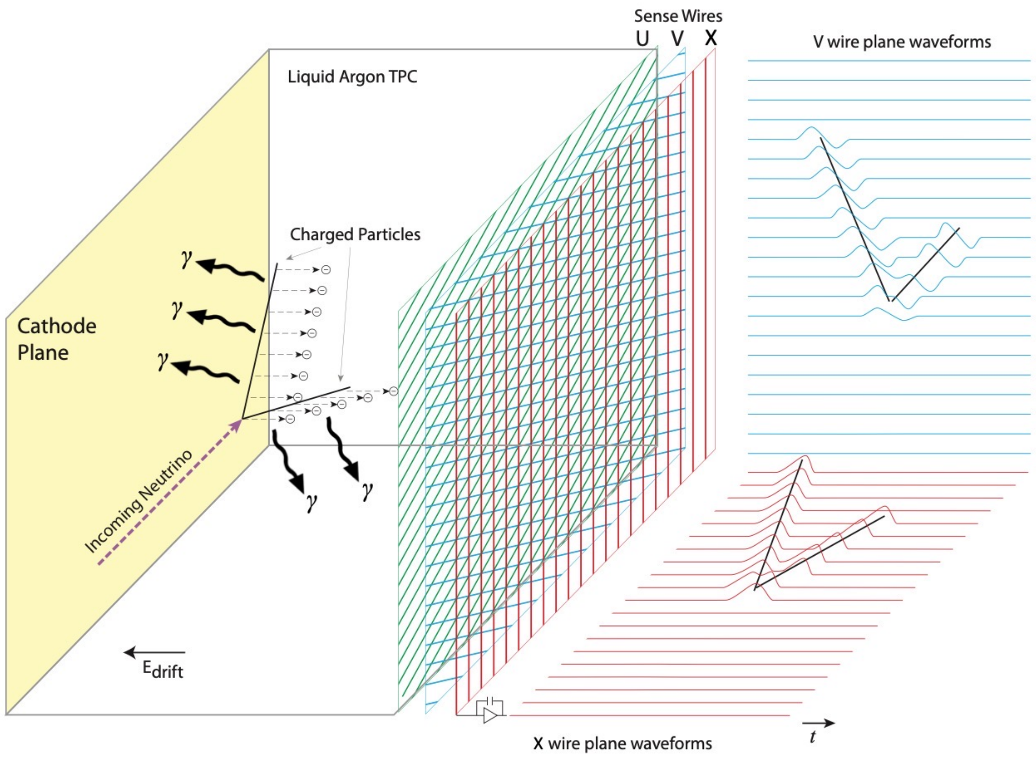
Sensitivity to $p \rightarrow K^+ \bar{\nu}$

- Multi-variate analysis chosen (Boosted Decision Tree) for event classification
- Background suppression to 0.4 events per 400 kt-year (or 10 years with all 4 modules)
- Current reconstruction → 15% signal efficiency
- With improved reco. → 30%
- **→ proton lifetime limit 1.3×10^{34} years (90% CL) if no signal observed**
- FSI model not known well
  - Some constraints from pion data
  - Variations lead to about 2% uncertainty in signal efficiency



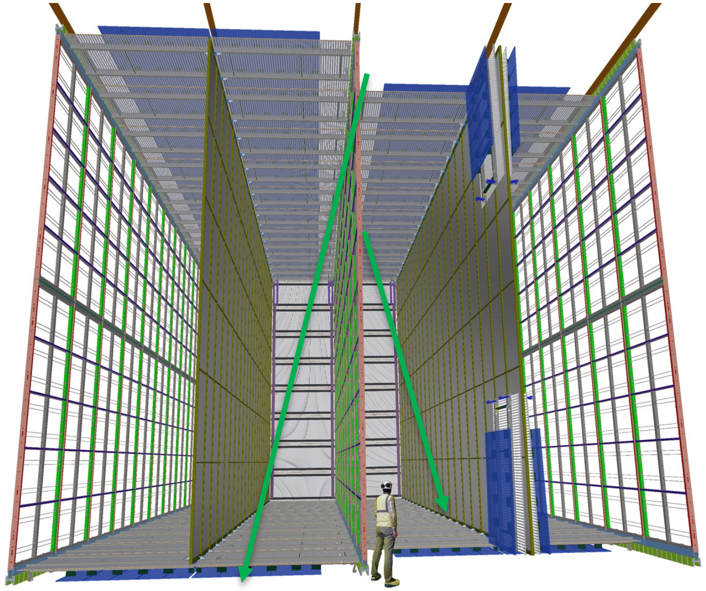
Detector calibration

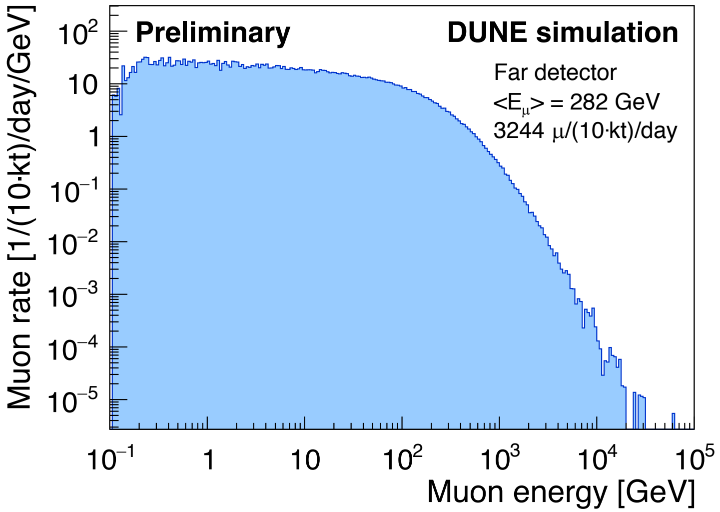
- Need to determine several detector parameters
  - Drifting electron lifetime (attachment to impurities)
  - Electron-ion recombination
  - Electric field / electron drift velocity
  - Electron diffusion
  - Electronics gain
  - Etc.
- Measure detector response to 'standard candles'
- Cosmic ray muons useful source
- Beam neutrino events can be also used
- Some dedicated hardware – laser, neutron source, purity monitors

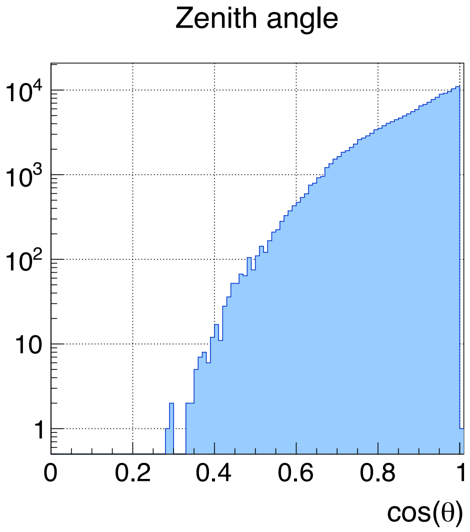


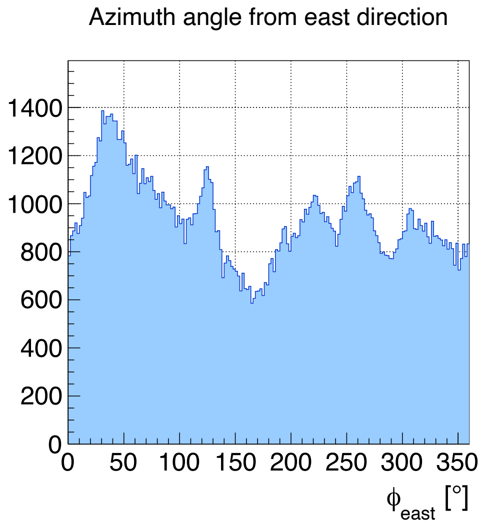
Cosmic ray muons underground

- Not too many at Far Detector (1.5 km underground)
  - ~4700 muons in single module per day
  - Only ~90 stop inside
    - (stopping muons are great for energy calibration)
- Mostly vertical tracks



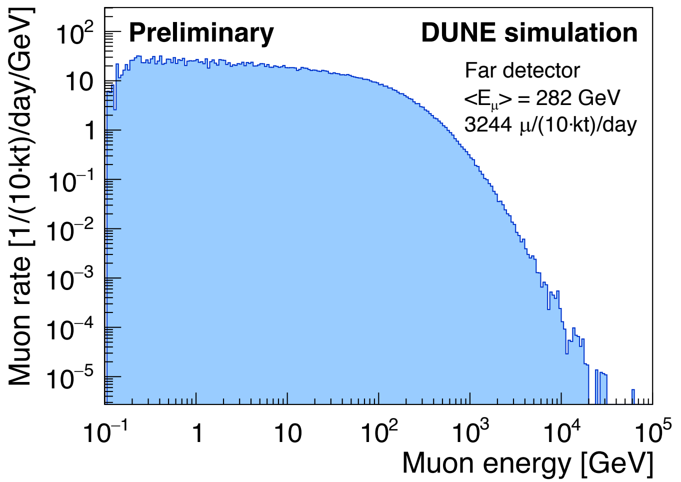


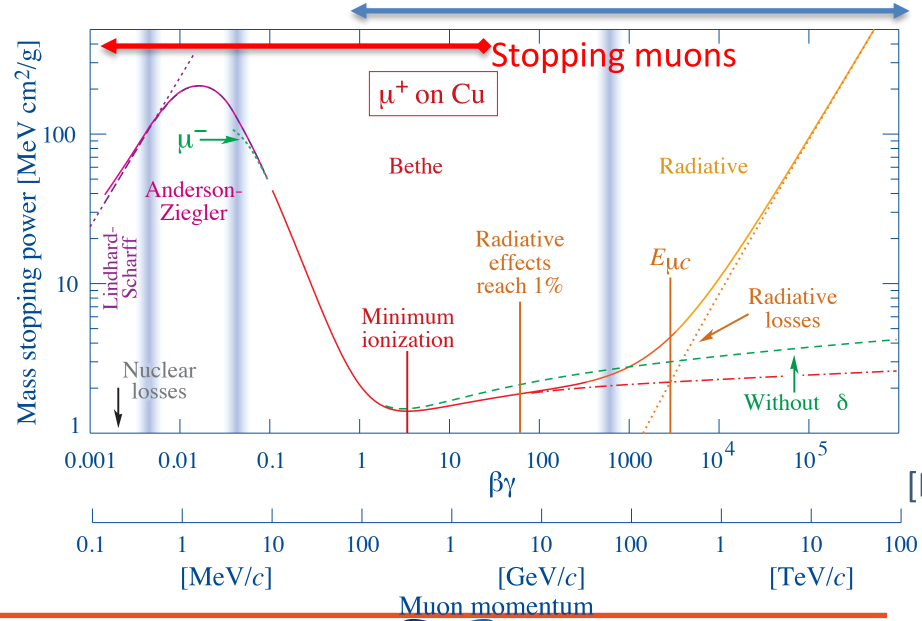




Electron lifetime measurement

- Electrons attenuated along drift due to impurities
- Collected charge dependent on drift distance
- Use cosmic ray muons to measure it
  - Broad E spectrum → varying ionisation loss
  - Reconstruction of charge sensitive to track orientation → response will differ for individual muons
- Enough tacks → variations average out → uniform energy depositions along drift coordinate → can measure effects on drifted charge





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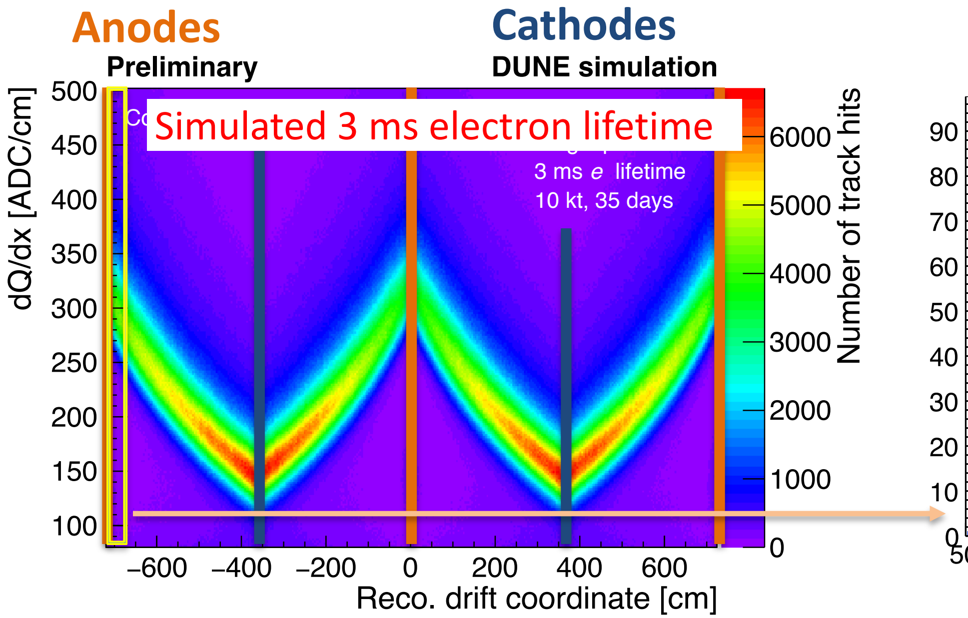
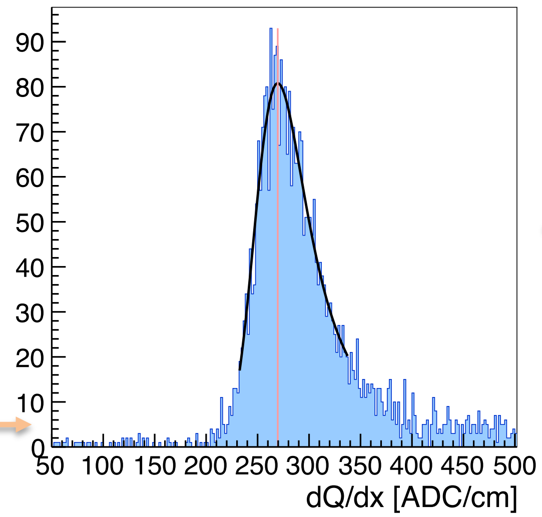
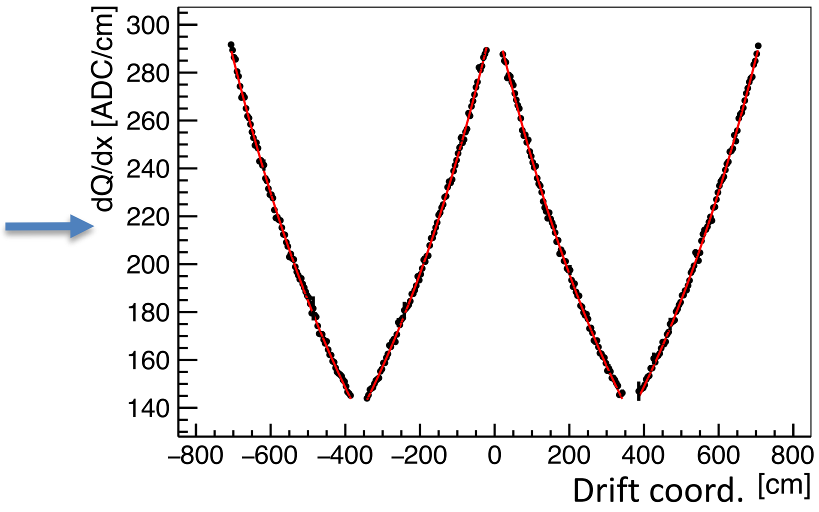
Electron lifetime measurement

- Simulated about 35 days of cosmic ray muons
- Assumed average depositions and charge reco. uniform along drift direction
- dQ/dx – collected charge on each wire / length of corresponding track segment
- Found ~1% uncertainty in corrected dQ/dx achievable with 1-day data – purely statistical
- Systematic effects are being evaluated







FZU DUNE

Conclusion

DUNE programme

- Neutrino oscillations
- Supernova and solar neutrino
- BSM searches – proton decay discussed

Status & Schedule

- ProtoDUNE single phase successfully ran in test beam @ CERN
  - Valuable input for DUNE design and demonstration of similar-scale LArTPC
- ProtoDUNE phase II test beam planned in 2022-2023
- Near and Far site construction/preparation is underway
- First DUNE far detector installation in mid-2020s
- Neutrino beam expected late 2020s

More details on DUNE physics

Deep Underground Neutrino Experiment (DUNE), Far Detector Technical Design Report, Volume II: DUNE Physics, arXiv:2002.03005 [hep-ex]

- Physics papers
  - *Long-baseline neutrino oscillation physics potential of the DUNE experiment*, Eur.Phys.J.C 80 (2020) 10, 978
  - *Low exposure long-baseline neutrino oscillation sensitivity of the DUNE experiment*, arXiv:2109.01304 [hep-ex]
  - *Prospects for beyond the Standard Model physics searches at the Deep Underground Neutrino Experiment*, Eur.Phys.J.C 81 (2021) 4, 322
  - *Supernova neutrino burst detection with the Deep Underground Neutrino Experiment*, Eur.Phys.J.C 81 (2021) 5, 423