

Potential of the DUNE Experiment for Nucleon Decay Searches

Student Seminar - Experimental Particle Physics

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Outline

Structural roadmap of the presentation

01. Cosmological & Theoretical Foundations

- Matter-Antimatter Asymmetry & Planck η
- Sakharov Conditions & EW Sphalerons
- Grand Unification Theories

02. Experimental Status & DUNE Setup

- Global Nucleon Decay Limits (PDG)
- Kaon Decay Topology ($p \rightarrow \bar{\nu} K^+$)
- LArSoft Simulation & Reconstruction
- Reduced FD Geometries (HD & VD)

03. Signal & Background Generation

- GENIE Signal & Local Fermi Gas Model
- Intranuclear FSI & Hadronic Rescattering
- Atmospheric Neutrinos
- Cosmogenic Ray Muons

04. Detector Reconstruction Performance

- Truth Matching & Primary K^+ Tracking
- Daughter Tracking & PIDA

05. Selection Chain & Cuts

- Agnostic Preselection Chain
- Exclusive Selection
- Cumulative Selection Efficiencies
- Background Normalization at 10 kt yr

06. Sensitivities & Outlook

- Partial Lifetime Sensitivity
- Projected Lifetime Sensitivities at 400 kt yr
- Future Research

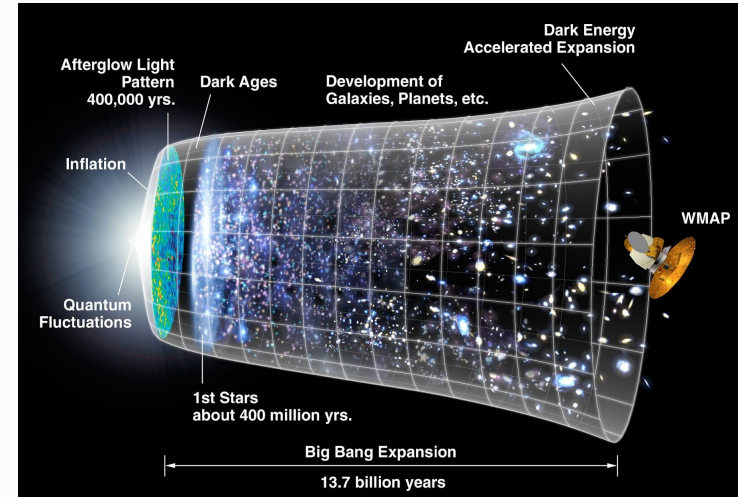
Cosmological & Theoretical Foundations

Cosmological Matter-Antimatter Asymmetry & Observational Evidence

Quantifying the primordial baryon excess

Observational Evidence & Cosmological Asymmetry

- **Observed Universe is Matter-Dominated:** No evidence for primordial antimatter domains on cosmological scales; complete annihilation would leave a dark universe.
- **Baryon-to-Photon Density Ratio (η):** Precision measurement by Planck satellite from CMB anisotropies and BBN:
$$\eta = (n_b - n_{\bar{b}}) / n_\gamma = (6.12 \pm 0.04) \times 10^{-10}.$$
- **Physical Implication:** For every 10 billion baryon-antibaryon pairs in the hot early plasma, a tiny excess of ~ 6 baryons survived the annihilation epoch.
- **Inflationary Dilution:** Rapid cosmic inflation dilutes any initial primordial asymmetry to zero, requiring dynamic generation in the early cosmos.



Sakharov Conditions, EW Sphalerons & B-L Protection

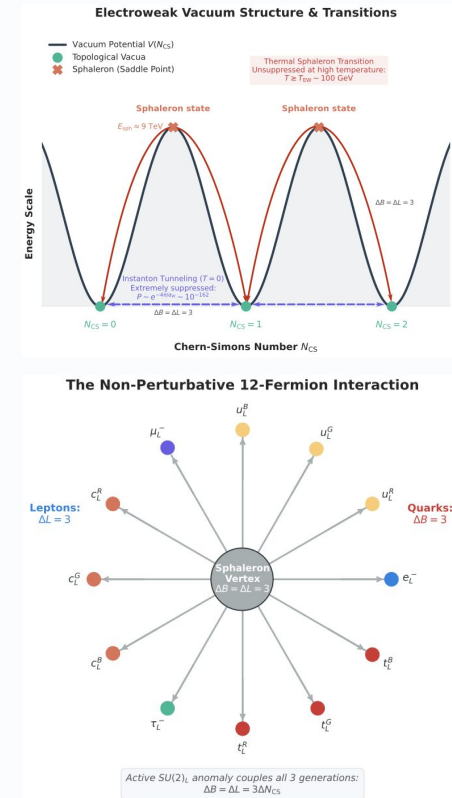
Non-perturbative vacuum transitions and asymmetry survival mechanisms

Sakharov's Conditions

1. **Baryon Number Violation:** Required to transition from $B = 0$ to $B \neq 0$.
2. **C and CP Violation:** Prevents equal rates between baryon and antibaryon production.
3. **Departure from Thermal Equilibrium:** Prevents CPT-driven inverse reaction washout.

Non-Perturbative Electroweak Sphalerons & B-L Protection

- **$SU(2)_L$ Topological Vacuum Structure:** Sphalerons are static, unstable saddle-point field configurations connecting degenerate sectors.
- **B+L Anomaly:** Sphaleron transitions violate B and L individually ($\Delta B = \Delta L = 3$) while strictly conserving $B - L$.
- **Sphaleron Washout:** In the early universe ($10^2 \text{ GeV} \leq T \leq 10^{12} \text{ GeV}$), unsuppressed sphalerons erase baryon asymmetry generated by any primordial $\Delta(B-L) = 0$ process.
- **B-L Conservation Immunity:** Processes generating $\Delta(B-L) \neq 0$ survive sphaleron washout and power the observed η .

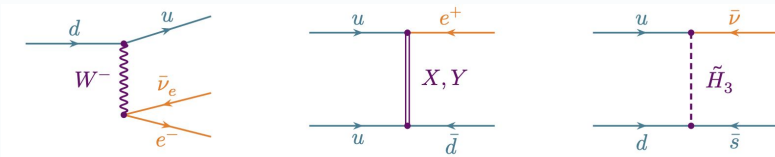


Grand Unification Theories & Nucleon Decay

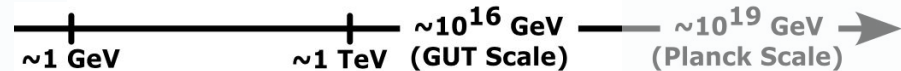
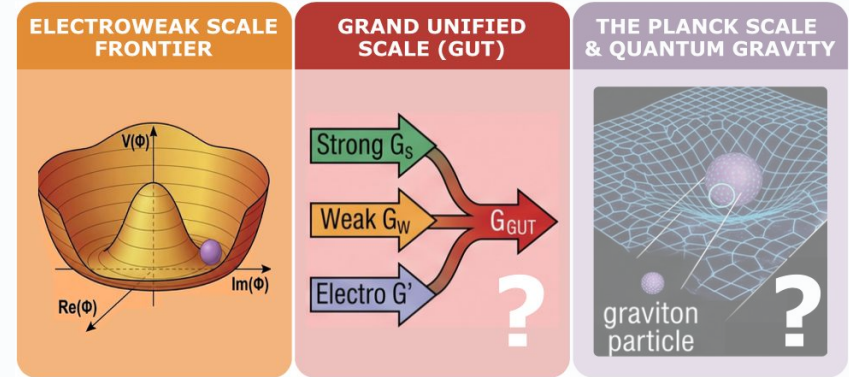
Connecting grand unification gauge symmetries to nucleon decay

Beyond Standard Model Frameworks

- **Standard Model Limitation:** B & L are strictly conserved accidental global symmetries of the classical SM Lagrangian.
- **GUTs:** Naturally break B and L by placing quarks and leptons into common gauge representations (leptoquarks). Energy scale $\sim 10^{15} - 10^{16}$ GeV.
- **Nucleon Decay:** Becomes the primary probe of physics in the primordial Universe.
- **Gauge Groups:** Minimal $SU(5)$ (ruled out by SK), SUSY $SU(5)/SO(10)$, non-SUSY $SO(10)$...
 $SO(10)$ predicts nucleon decay with $\Delta(B - L) = -2$, not washed out by sphalerons.



(a) SM free neutron β -decay (b) Non-SUSY $SU(5)$ ($p \rightarrow e^+ \pi^0$) (c) SUSY GUTs ($p \rightarrow \bar{\nu} K^+$)



Unified theory of electromagnetic and weak forces. Description of vector mediator bosons (W^+ , W^- , Z^0 , γ).

Origin of elementary particle mass via the Higgs field.

Theory:
Glashow-Weinberg-Salam model

Hypothetical energy scale where the strong, weak, and electromagnetic forces merge into a single fundamental interaction and gauge symmetry.

Theories:
 $SU(5)$, $SO(10)$

The theoretical limit where quantum mechanics and general relativity become equally dominant.

Classical spacetime geometry breaks down.

Theories:
String Theory, Loop Quantum Gravity

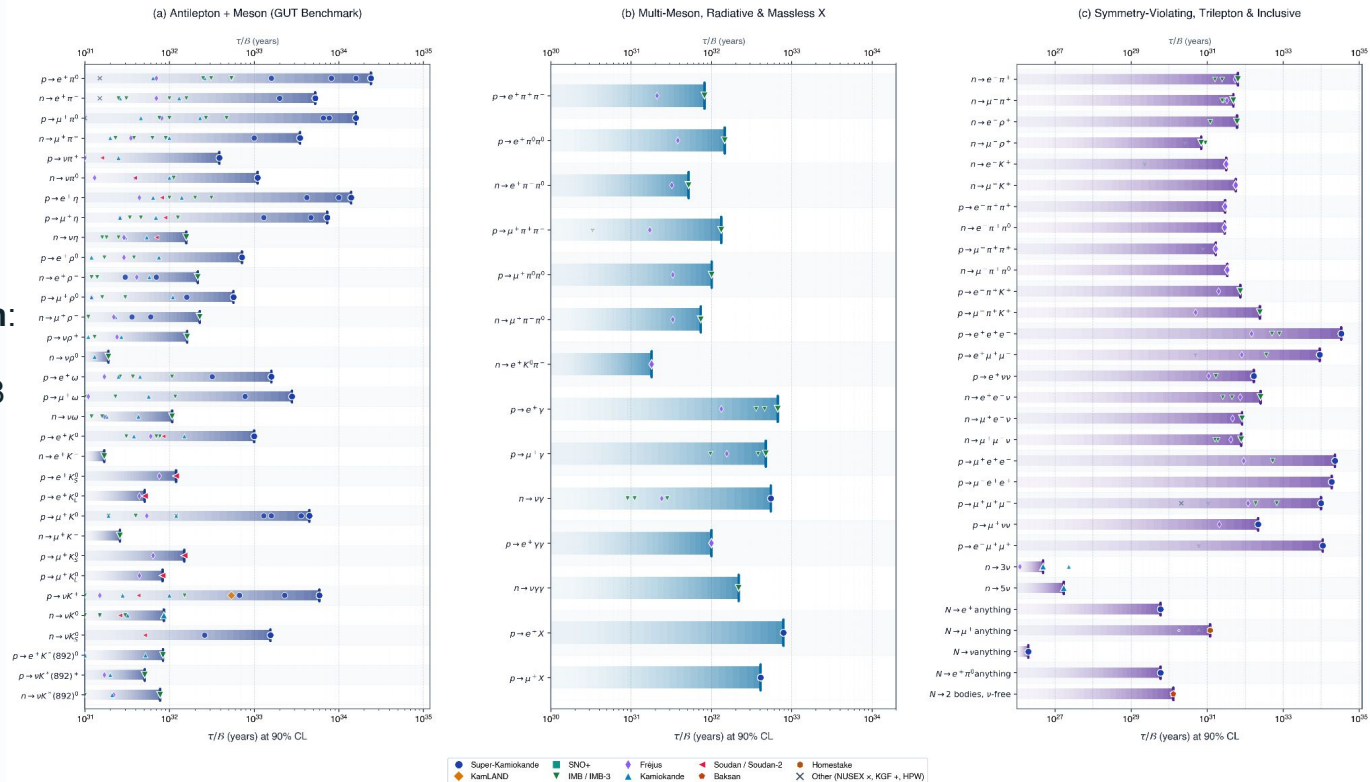
Experimental Status & DUNE Setup

Current Experimental Limits

Global status of single-nucleon decay

Nucleon decay partial lifetime lower limits (90% CL)

- **76 physical channels:** 374 historical experimental measurements.
- **Heavy decay suppression:** Lifetime limits way beyond the age of the Universe: 1.38×10^{10} years.
- **Three Main Categories:**
 - Antilepton + Meson (GUT Benchmark).**
 - Multi-Meson, Radiative, and Massless X Modes.**
 - Symmetry-Violating, Tripleton, and Inclusive Channels.**



Current Experimental Limits

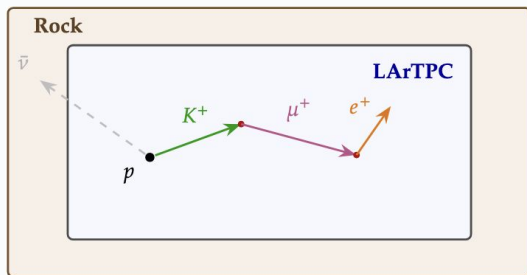
Decay channels with K^+ as final state

$$N_{\text{decay}} = N_{\text{target}} \frac{\Delta t}{\tau/\mathcal{B}}$$

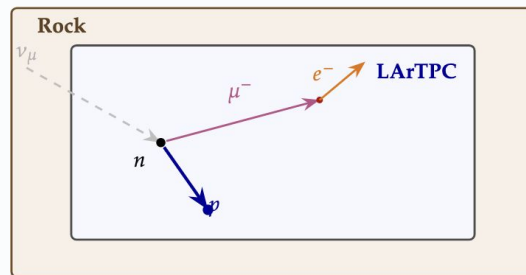
Partial lifetime $\tau/\mathcal{B}$ limit is constrained by detector exposure (mass $\times$ time), signal selection efficiency and surviving background rate:

- Atmospheric neutrinos.
- Cosmic ray muons.

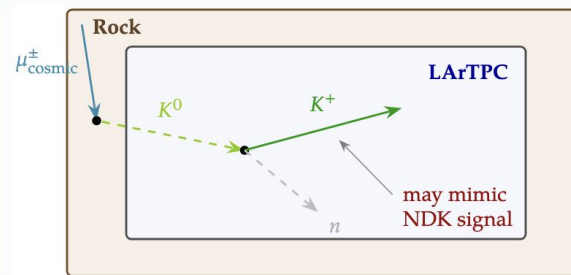
Nucleon Decay Channel ^o	$\Delta(B - L)$	Benchmark Limit (yr)
$p \rightarrow \bar{\nu} K^+$	0	5.9×10^{33} (Super-K)
$n \rightarrow \mu^- K^+$	-2	5.7×10^{31} (Fréjus)
$n \rightarrow e^- K^+$	-2	3.2×10^{31} (Fréjus)



(a) $p \rightarrow \bar{\nu} K^+, K^+ \rightarrow \mu^+ \nu_\mu, \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$



(b) $\nu_\mu + n \rightarrow \mu^- + p, \mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$



(c) Cosmic $\mu \rightarrow K^0$ in rock, $K^0 p \rightarrow K^+ n$ in LAr

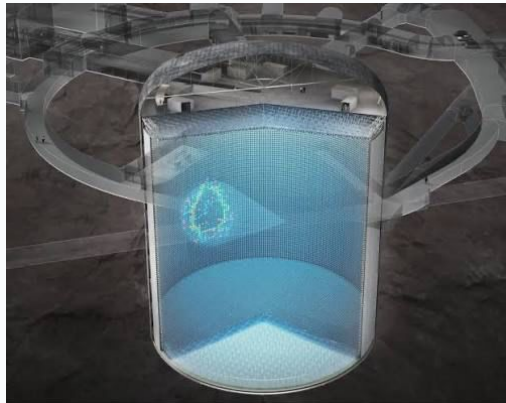
→ K^+ → $\mu^\pm$ → $e^\pm$ → p → K^0 → n, ν

Next-Generation Facilities

Underground detectors for nucleon decay searches

Experiment	Mass (kt)	Main Feature
Hyper-K	216 (Light Water)	Mass
JUNO	20 (Liquid Scintillator)	Timing
DUNE	40 (Liquid Argon)	Imaging

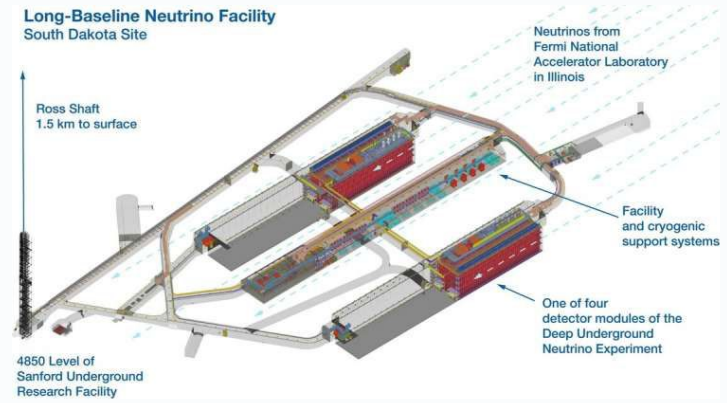
Hyper-K



JUNO



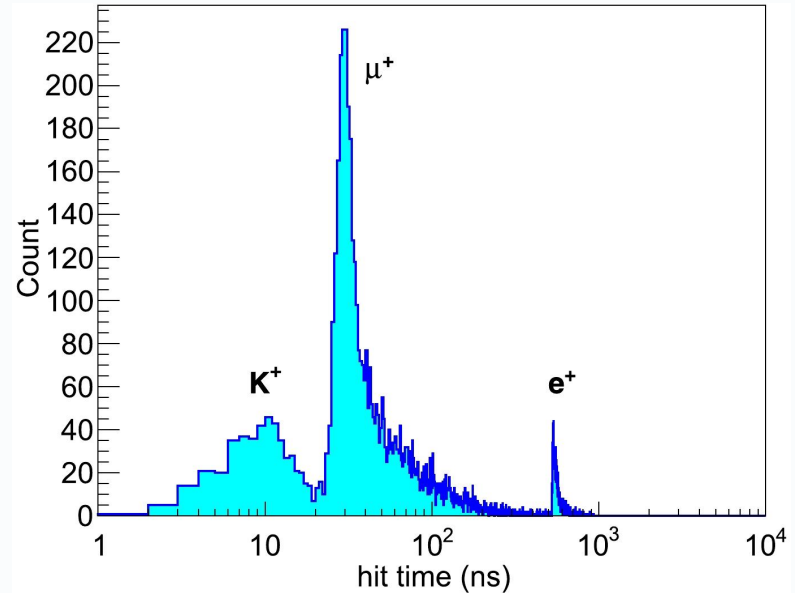
DUNE



Next-Generation Facilities

Underground detectors for nucleon decay searches

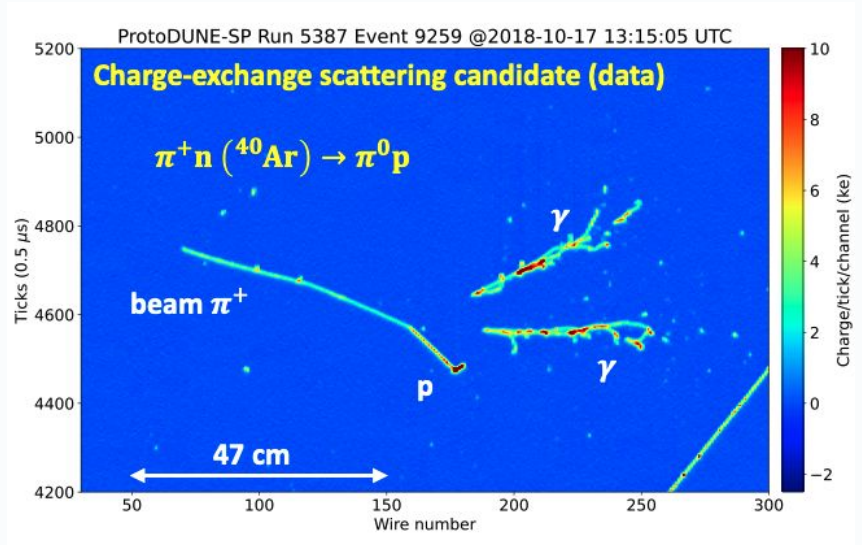
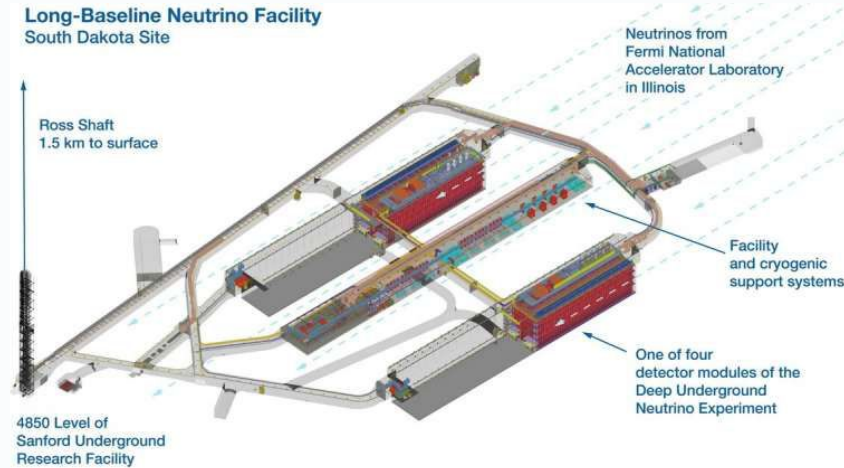
JUNO



Next-Generation Facilities

Underground detectors for nucleon decay searches

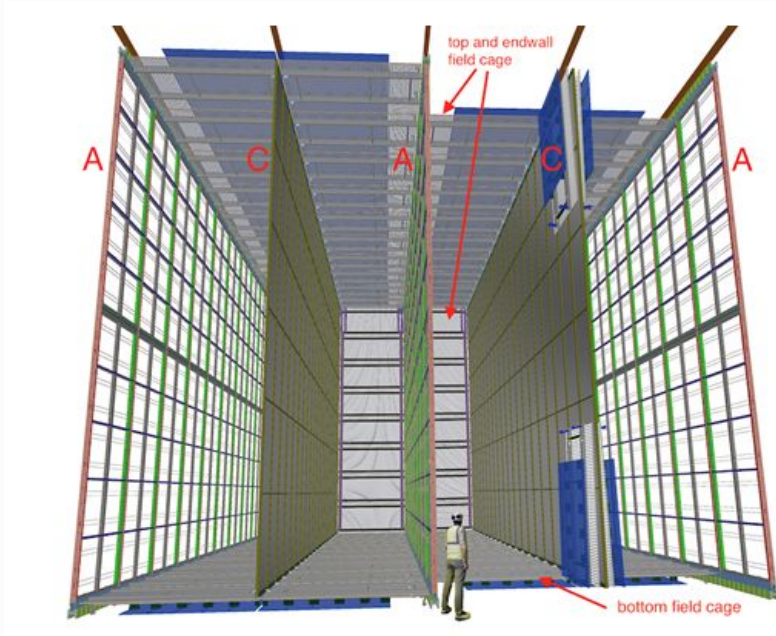
DUNE



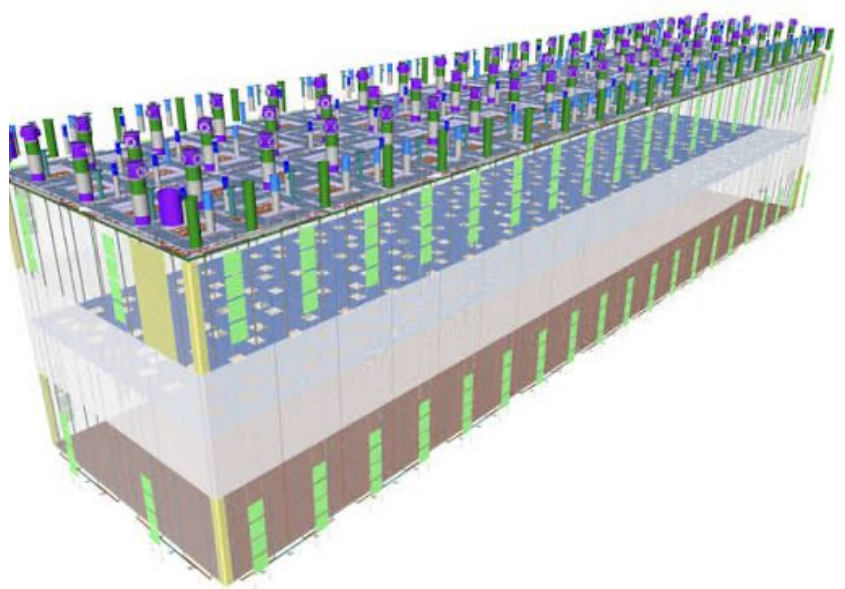
DUNE Simulated Detector Geometries

Reduced FD-HD and FD-VD Modules

Horizontal Drift



Vertical Drift

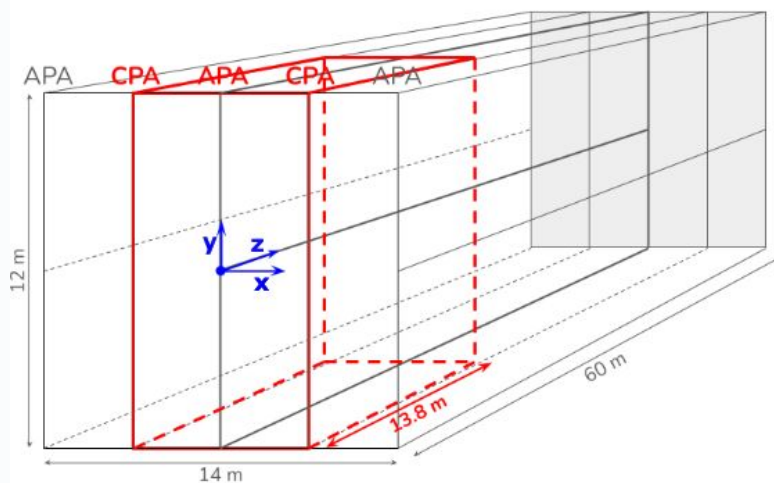


DUNE Simulated Detector Geometries

Reduced FD-HD and FD-VD Modules

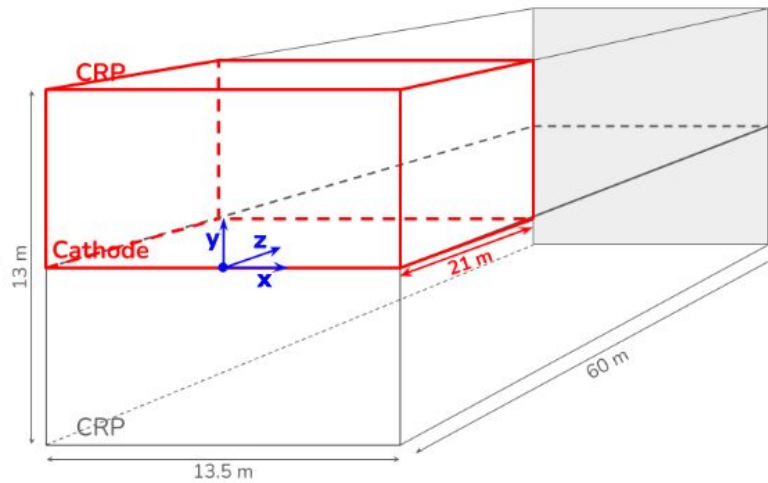
Horizontal Drift (FD-HD 1x2x6)

- *Geometric configuration:* $1 \times 2 \times 6$.
- *Active volume dimensions:* $7.2 \times 12.0 \times 13.9 \text{ m}^3$ (~1.68 kton active LAr mass).



Vertical Drift (FD-VD 1x8x14)

- *Geometric configuration:* $1 \times 8 \times 14$.
- *Active volume dimensions:* $6.5 \times 13.5 \times 21.0 \text{ m}^3$ (~2.57 kton active LAr mass).



Datasets

Simulated samples for partial lifetime sensitivity studies

Generated Event Datasets

1. Signals (NDK): $p \rightarrow \bar{\nu} K^+$, $n \rightarrow \mu^- K^+$, $n \rightarrow e^- K^+$

- Golden channel decay configuration simulated using GENIE
- v3.04.00 with configuration tune AR23_20i_00_00a.
- 100,000 events per channel and module.

2. Atmospheric Neutrino Background (ATM)

Simulated using previous GENIE configuration, representing the dominant physical background after selection.

99,150 (90187.8 weighted) events in FD-HD.

99,550 (89927.8 weighted) events in FD-VD.

3. Cosmic Ray Muon Background (COS)

100,000 events per module.

LArSoft Simulation and Reconstruction Framework

End-to-end art architecture from event generation to data extraction

Five-Stage Modular LArSoft Software Framework (v10_08_01d00)

Stage 1 – Event Generation:

Generates primary interaction kinematics. GENIE simulates nucleon decays and atmospheric neutrino backgrounds. MUSUN simulates cosmogenic muons.

Stage 2 – Geant4:

Simulates ionization and scintillation step-by-step through LAr and handles optical photon transport to PDS.

Stage 3 – TPC Detector Response & Readout (Wire-Cell):

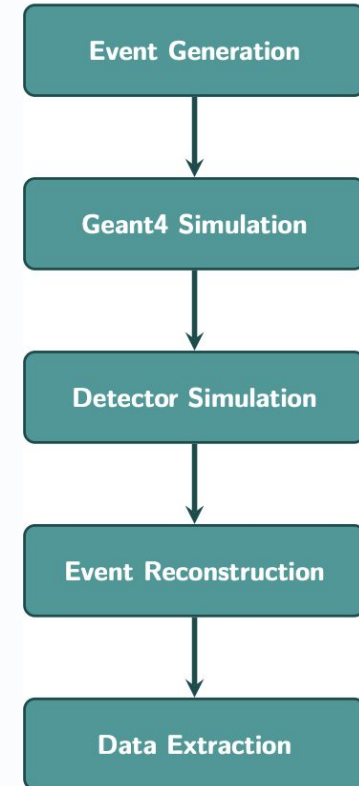
Simulates drift electron attenuation, longitudinal/transverse diffusion, wire field response functions, thermal noise, and ADC digitization.

Stage 4 – Automated Pattern Recognition (Pandora):

Pandora atmospheric pattern recognition clusters 2D wire hits, builds 3D space points, reconstructs interaction vertices, and forms track/shower hierarchies.

Stage 5 – High-Level Analysis (NDKAnalysis Module):

Custom C++/art module extracts truth matching, calorimetry, track lengths, PIDA PID parameters, and candidate selection cuts into flat ROOT TTrees.



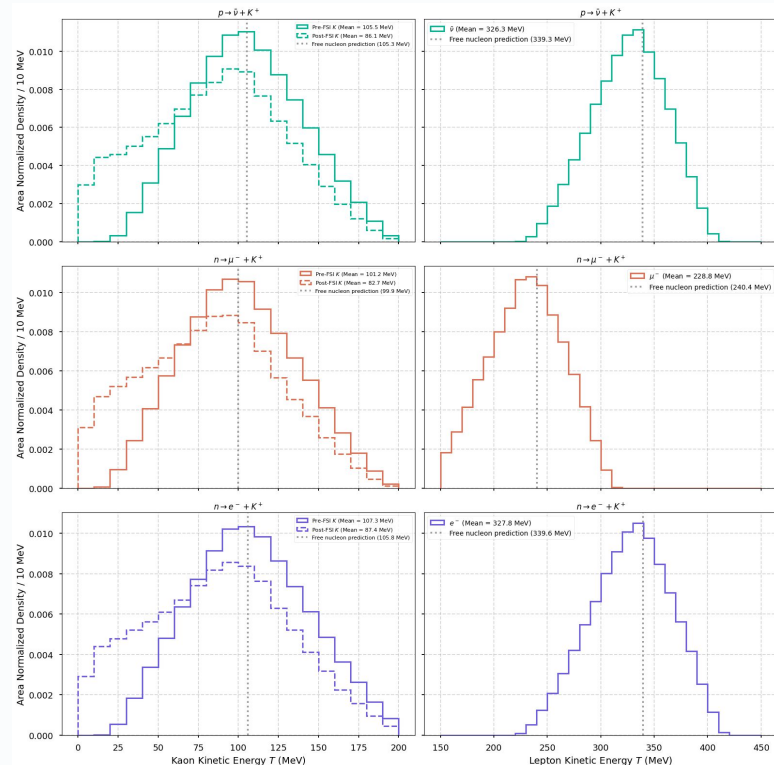
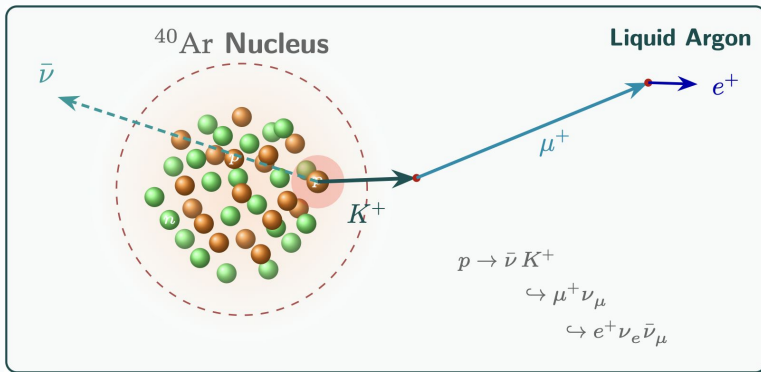
Signal & Background Generation

Nucleon Decay Searches in DUNE

Decay channels with K^+ as final state

K⁺ Decay Topology & Kinematics

- **Bound-Proton Decay:** Non-monochromatic kaons due to Fermi momentum of bound protons in ^{40}Ar . Nuclear final state interactions smears the energy distribution.
- **K⁺ Propagation:** In LAr ($\rho = 1.39 \text{ g/cm}^3$), K^+ travels mean track length $L_K \approx 13\text{-}14 \text{ cm}$ before stopping, depositing a high dE/dx Bragg peak.



Nucleon Decay Searches in DUNE

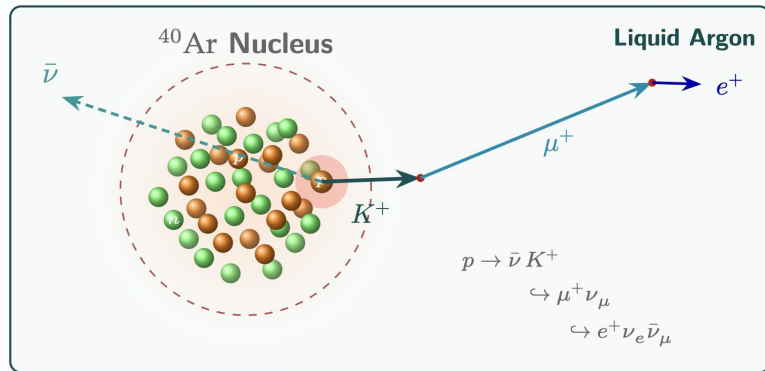
Decay channels with K^+ as final state

K+ Decay Topology & Kinematics

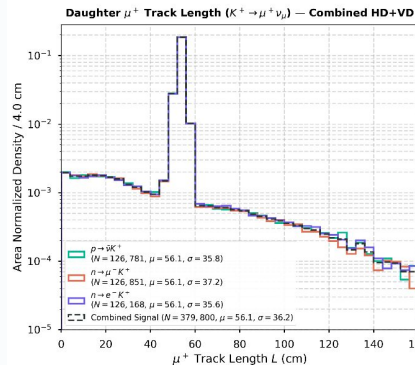
• Main Decay Channels ($\tau_K = 12.38$ ns):

- $K_{\mu 2}$ Branching Ratio (63.56%): $K^+ \rightarrow \mu^+ \nu_\mu$
($T_\mu = 152.5$ MeV, $L_\mu \approx 54$ cm at rest).
- $K_{\pi 2}$ Branching Ratio (20.67%): $K^+ \rightarrow \pi^+ \pi^0$
($T_\pi = 108.4$ MeV, $L_\pi \approx 28$ cm at rest; $\pi^0 \rightarrow \gamma\gamma$).

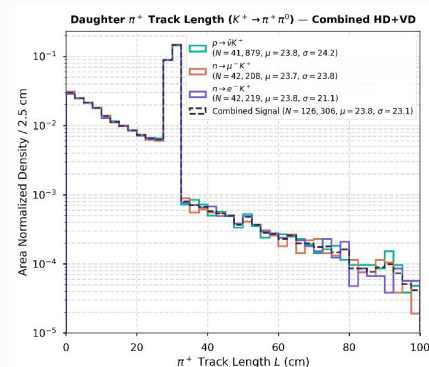
• Daughter Muon Decay ($\tau_\mu = 2.2$ μ s): $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ (Michel positron, $T_e \leq 52.8$ MeV).



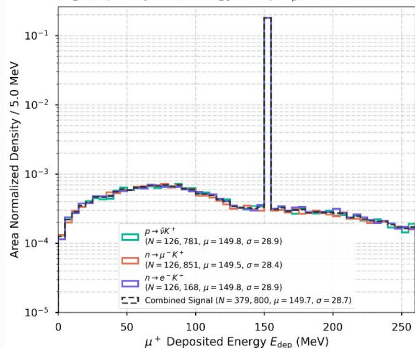
$$K^+ \rightarrow \mu^+ \nu_\mu$$



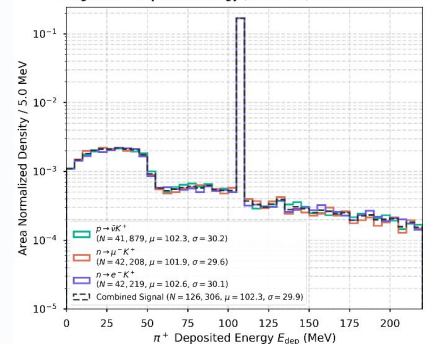
$$K^+ \rightarrow \pi^+ \pi^0$$



Daughter μ^+ Deposited Energy ($K^+ \rightarrow \mu^+ \nu_\mu$) — Combined HD+VD

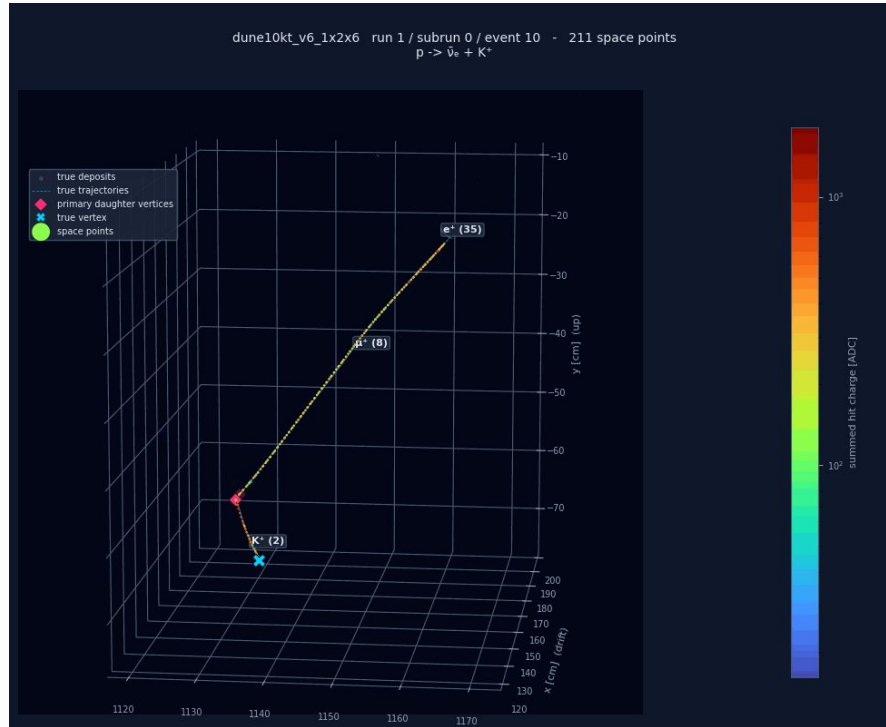


Daughter π^+ Deposited Energy ($K^+ \rightarrow \pi^+ \pi^0$) — Combined HD+VD



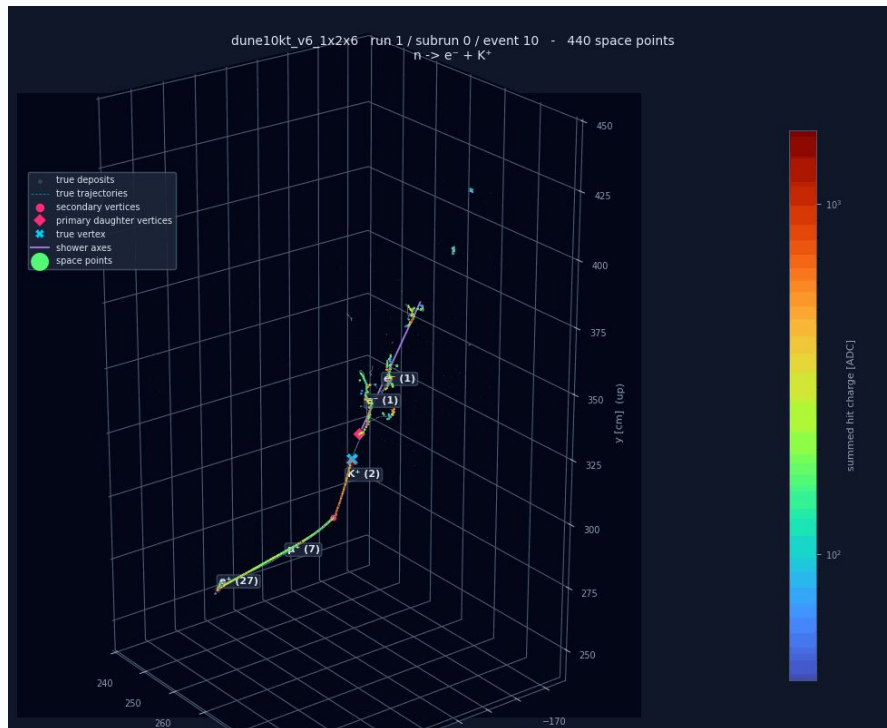
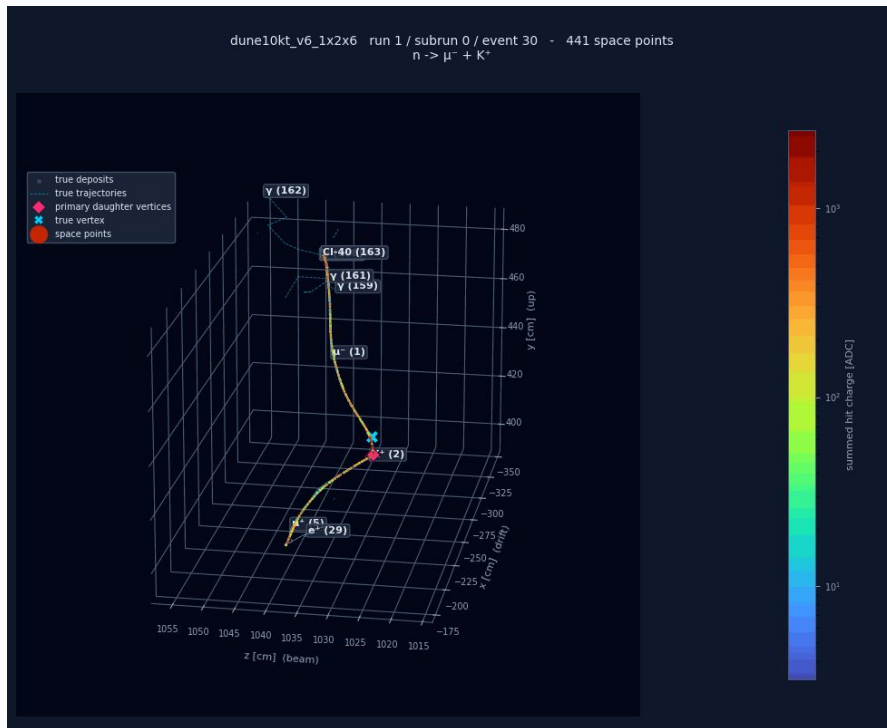
Event Displays

Nucleon Decay Signals



Event Displays

Nucleon Decay Signals

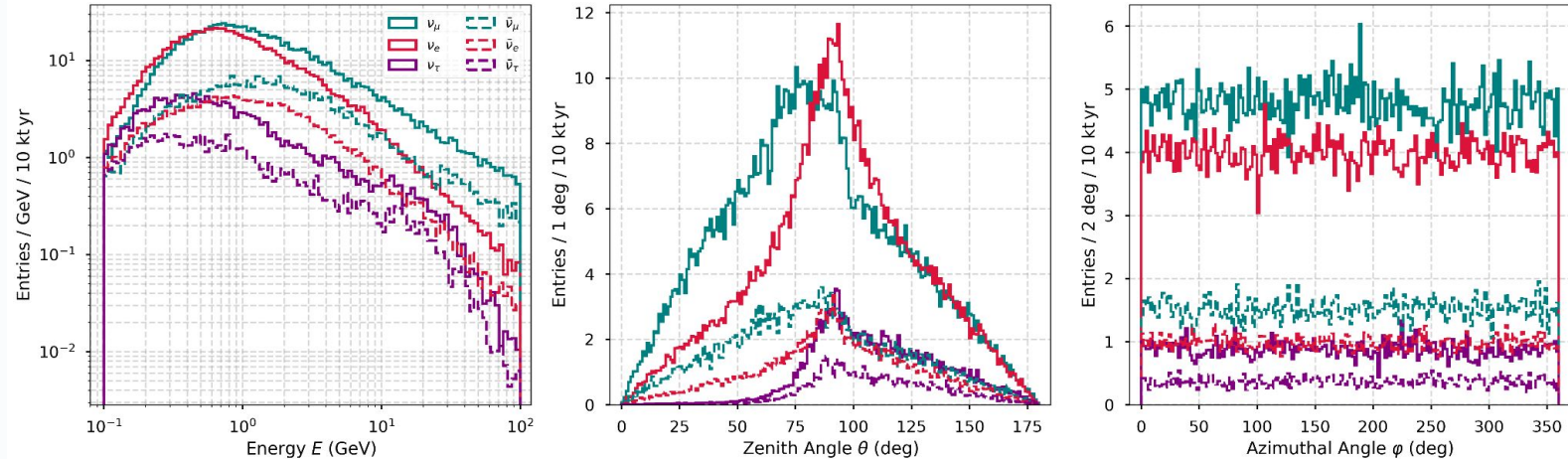


Physics Background: Atmospheric Neutrinos

Honda flux simulation, 3-flavor oscillations, and neutrino classification

Atmospheric Neutrino Simulation in GENIE

- **Flux Input Model:** Honda atmospheric neutrino flux (solar maximum) calculated specifically for SURF (using Homestake data).
- **Neutrino Oscillations:** 3-flavor oscillations applied using NuFit 5.2 global fit parameters.
- **Fully oscillated weight factors:** Applied for each event, corresponding to a exposure of 400 kt yr.

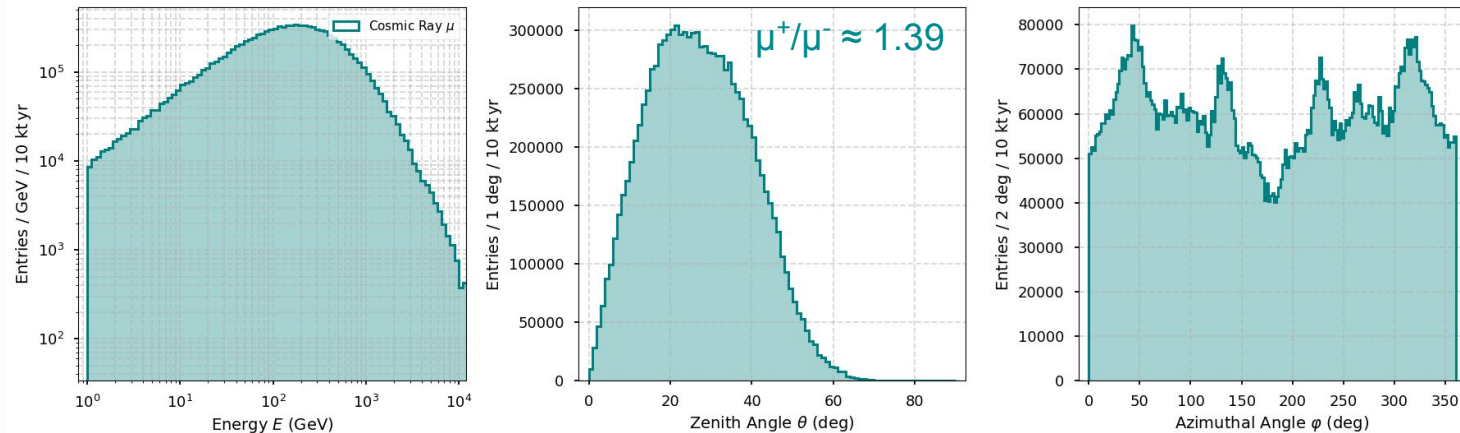


Physics Background: Cosmic Ray Muons

MUSIC/MUSUN simulation at DUNE-SURF underground depth

Underground Overburden & Muon Simulation

- **SURF Overburden Depth:** 1.48 km cavern depth to shield against muons; very energetic muons reach the Far Detector.
- **Surface-to-Underground Transport (MUSIC):** Simulates stochastic energy loss (pair production, bremsstrahlung, photonuclear) of surface cosmic ray muons traversing the rock.
- **Underground Generator (MUSUN):** Samples underground muon flux energy and zenith angle distribution toward the detector. Muon exposure is $11 \times 10^6 \mu$ per 10 kt yr.



Physics Background: Cosmic Ray Muons

MUSIC/MUSUN simulation at DUNE-SURF underground depth



Physics Background: Cosmic Ray Muons

MUSIC/MUSUN simulation at DUNE-SURF underground depth



Physics Background: Cosmic Ray Muons

MUSIC/MUSUN simulation at DUNE-SURF underground depth



Detector Reconstruction Performance

Pandora Reconstruction Performance

K^+ tracks

Truth Matching Criteria

• Matching Definitions:

$$\text{Purity} = \frac{N_{\text{matched}}}{N_{\text{recoHits}}}, \quad \text{Completeness} = \frac{N_{\text{matched}}}{N_{\text{genHits}}}$$

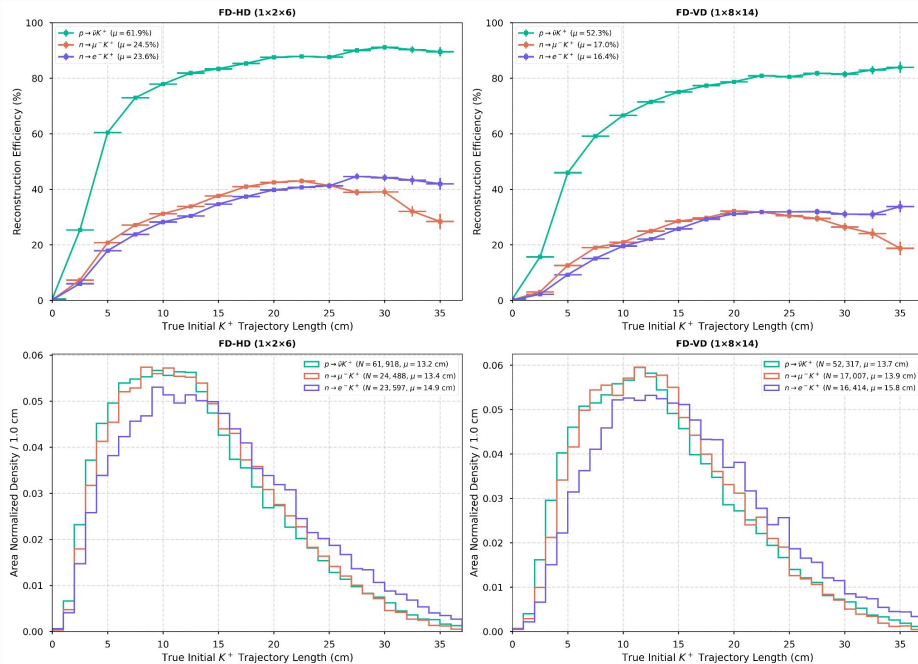
$$N_{\text{matched}} \geq 5, \quad \text{Purity} \geq 0.50, \quad \text{Completeness} \geq 0.50.$$

• Primary Kaon Tracking Efficiency:

- Reaches > 86.5% (> 78.5%) tracking efficiency in FD-HD (FD-VD) for primary K^+ with true length $L_K > 20$ cm for the golden channel.
- Neutron decay modes exhibit lower efficiency due to energy deposits from the charged primary lepton.

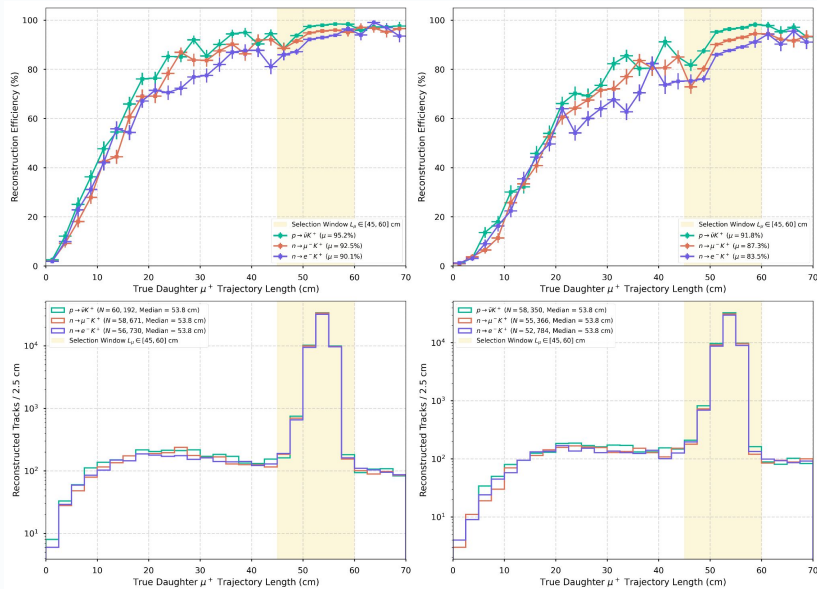
• Short Track Limitations:

Primary kaons with $L_K < 5$ cm (very low T_K) suffer tracking efficiency drops due to 2D hit clustering limits.

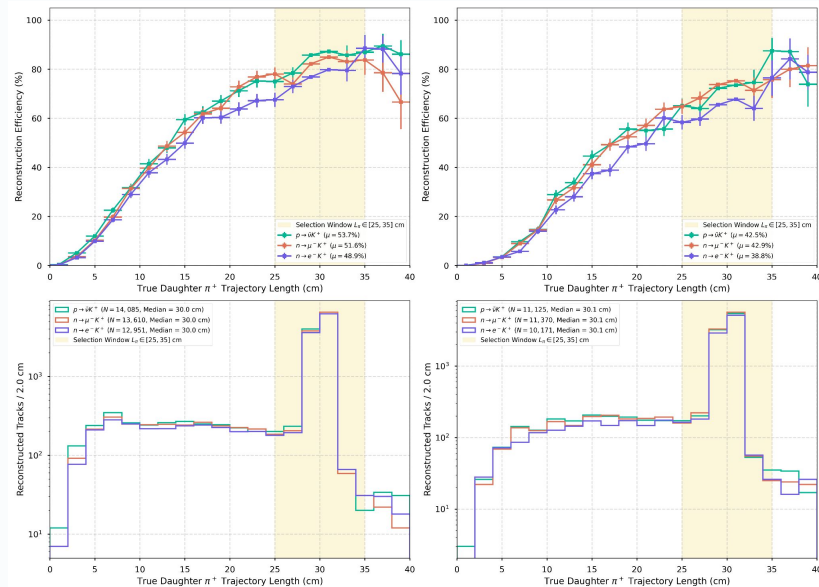


Pandora Reconstruction Performance

μ^+ and π^+ tracks



$K_{\mu 2} \in [45, 60]$ cm.



$K_{\pi 2} \in [25, 35]$ cm.

Calorimetric Particle Identification

Calorimetric dE/dx residual range profiling for species separation

Calorimetric PIDA Formulation & Species Separation

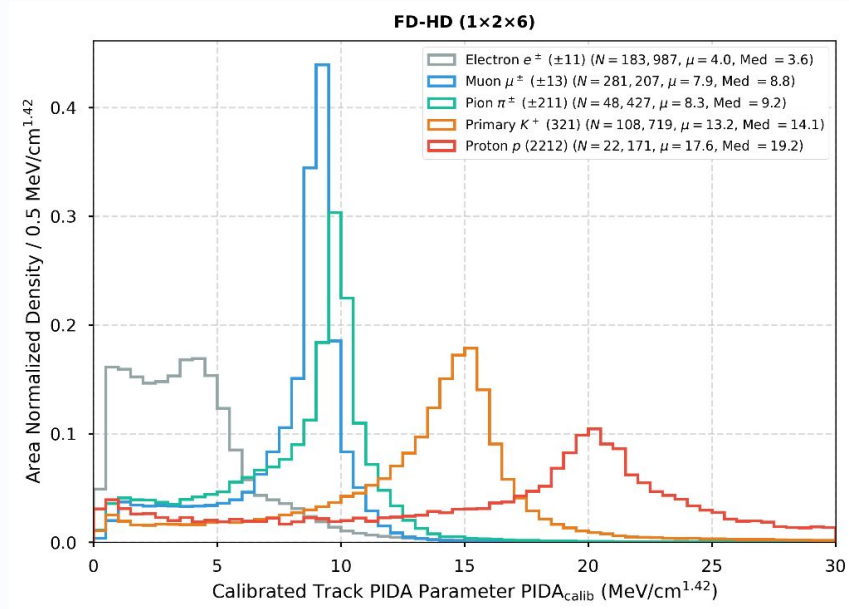
- **Bethe-Bloch Residual Range Parameterization:**
 $dE/dx = A R^{-b}$, where R is residual range from track end and $b = 0.42$ for LAr.

- **PIDA Parameter:**

$PIDA = (1 / N_{hits}) \sum_i (dE/dx)_i \times R_i^{0.42}$, evaluated over the last 30 cm of stopping tracks.

- **Characteristic PIDA Bands:**

- MIP (μ , π): $PIDA < 11.0 \text{ MeV/cm}^{1.42}$.
- Kaons: Intermediate PIDA band $\in [10.0, 17.0] \text{ MeV/cm}^{1.42}$.
- Protons: $PIDA > 17.0 \text{ MeV/cm}^{1.42}$.



Selection Chain & Cuts

Applied Preselection Cuts

Final-state independent filtering strategy for background mitigation

1. Valid Pandora
Final-State Particle

2. Pandora Vertex
in Fiducial Volume ($t_0 = 0$)

3. Pandora Space Points in
Fiducial Volume

4. Charge ROI
 $\in [30, 1000]$ MeV

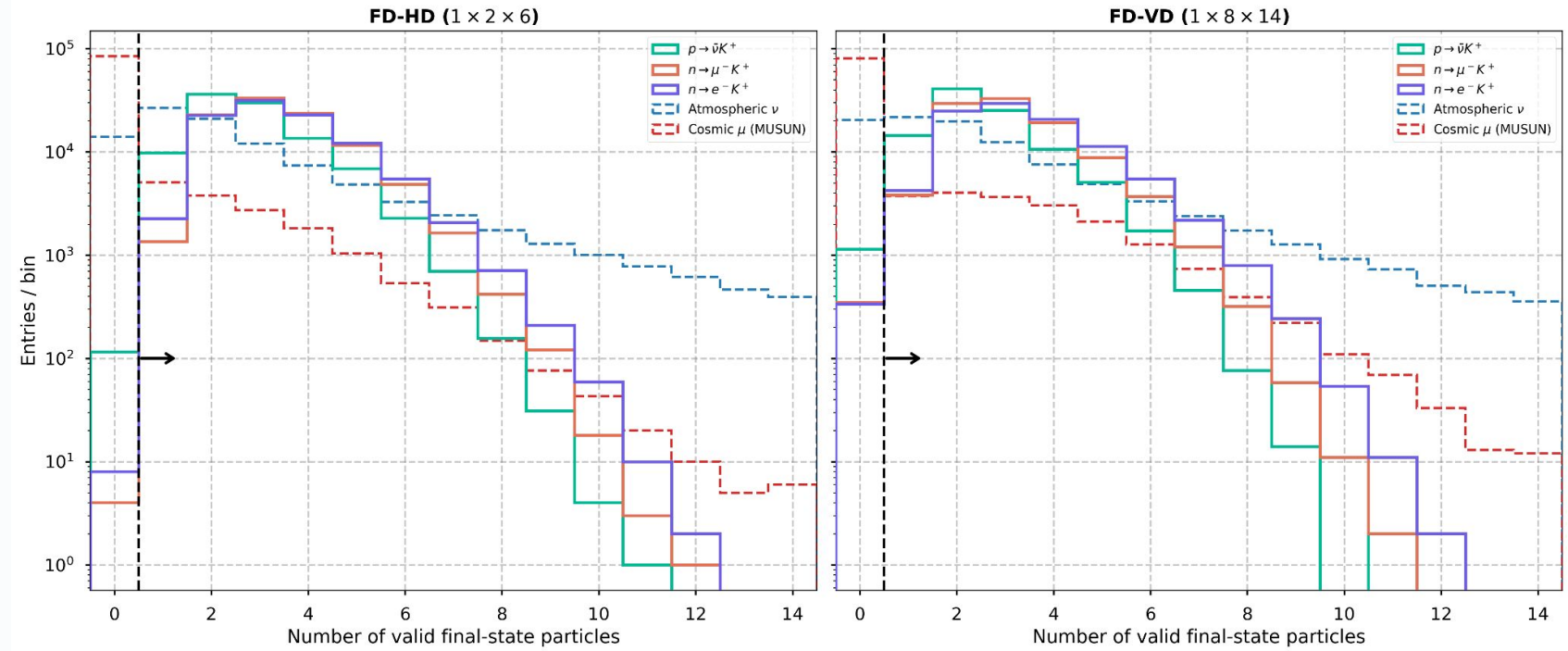
Technical Cut Specifications

- *Valid Final-State Particle Criterion*: At least, one track or shower is reconstructed by the Pandora software. A shower is classified as valid if its vertex is well-defined.
- *Fiducial Volume and Full Containment Restrictions*: A 20 cm minimum spatial buffer is required from all active volume boundaries.
- *t_0 Generation Assumption*: $t_0 = 0$ (event generation time) is assumed perfectly reconstructed for all events.
- *Charge Region of Interest (ROI) Filter*: Total integrated deposited energy is restricted to $[30, 1000]$ MeV. This eliminates low-energy radiological noise (not simulated) and vetoes high-energy background events.

Event Selection

Valid Pandora Final-State Particle

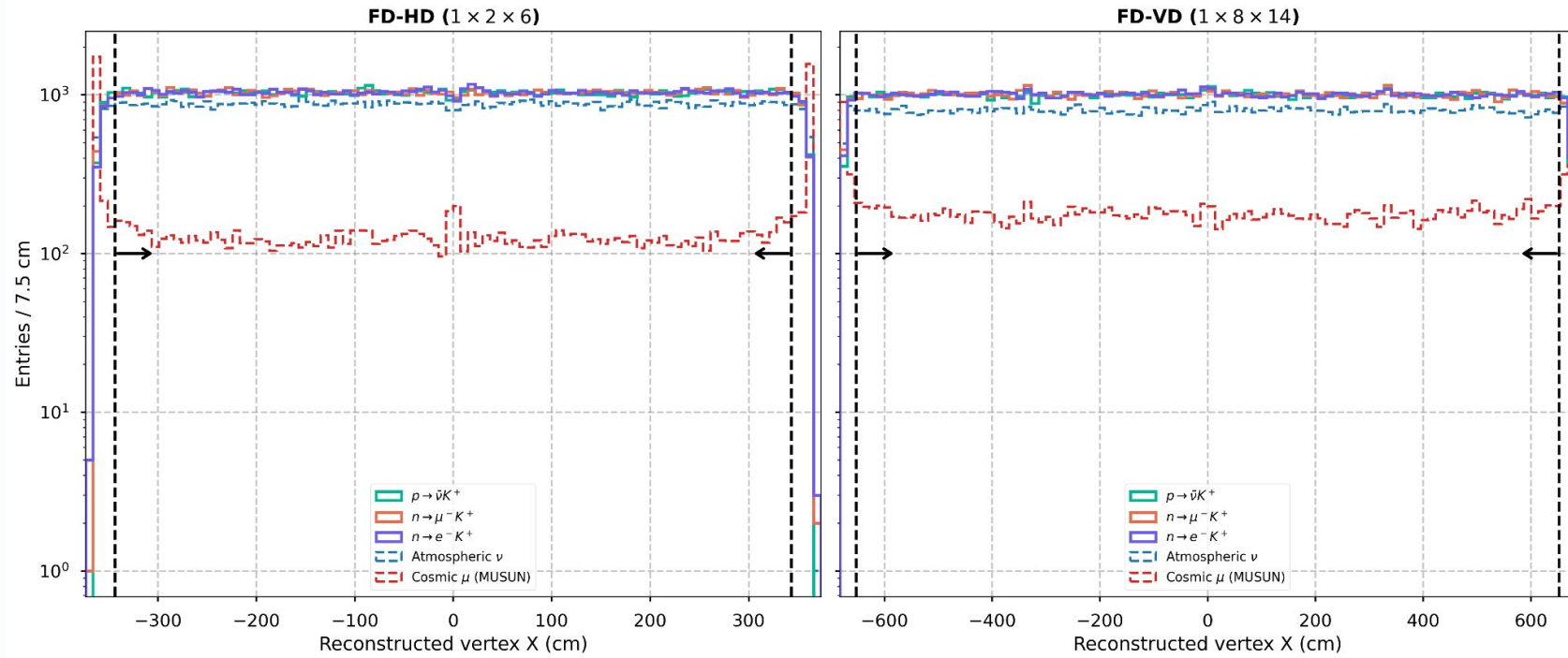
1. Valid Pandora Final-State Particle



Event Selection

Pandora Vertex in Fiducial Volume ($t_0 = 0$)

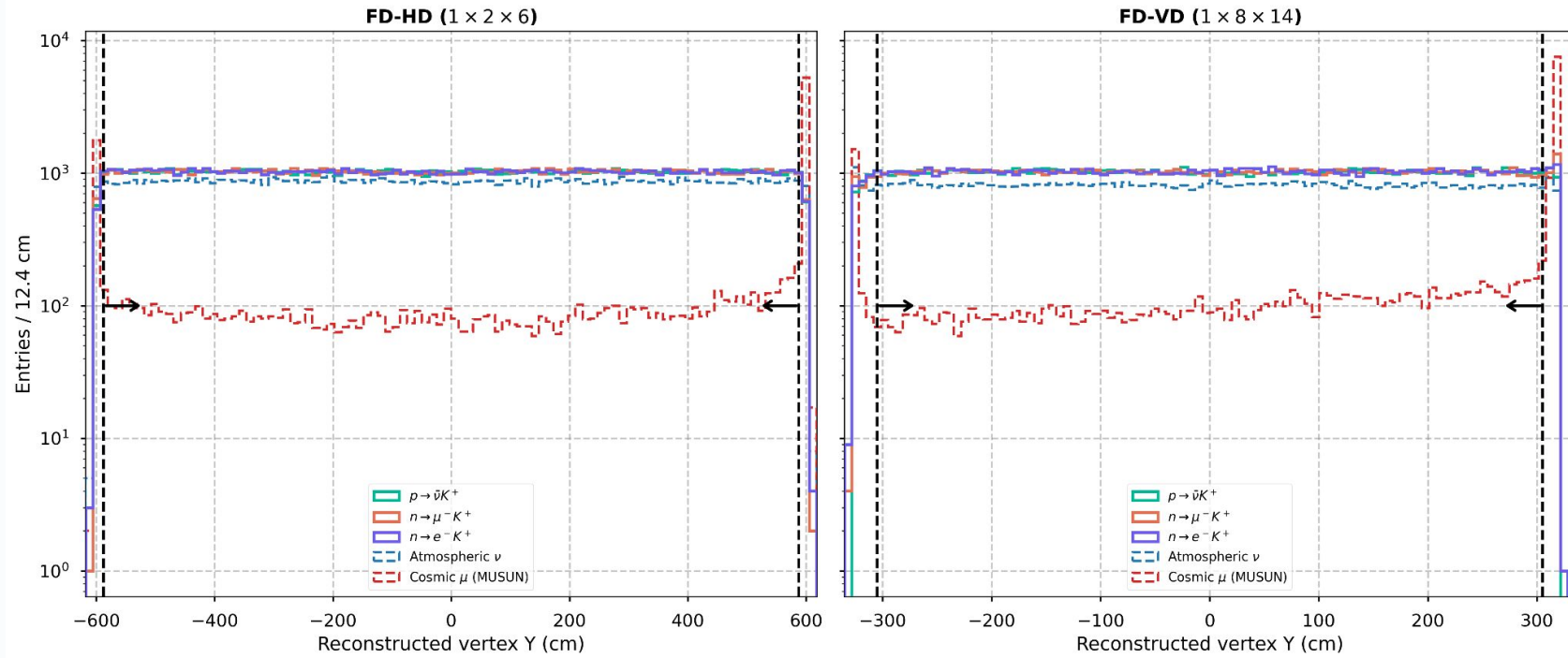
2. Pandora Vertex
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Event Selection

Pandora Vertex in Fiducial Volume ($t_0 = 0$)

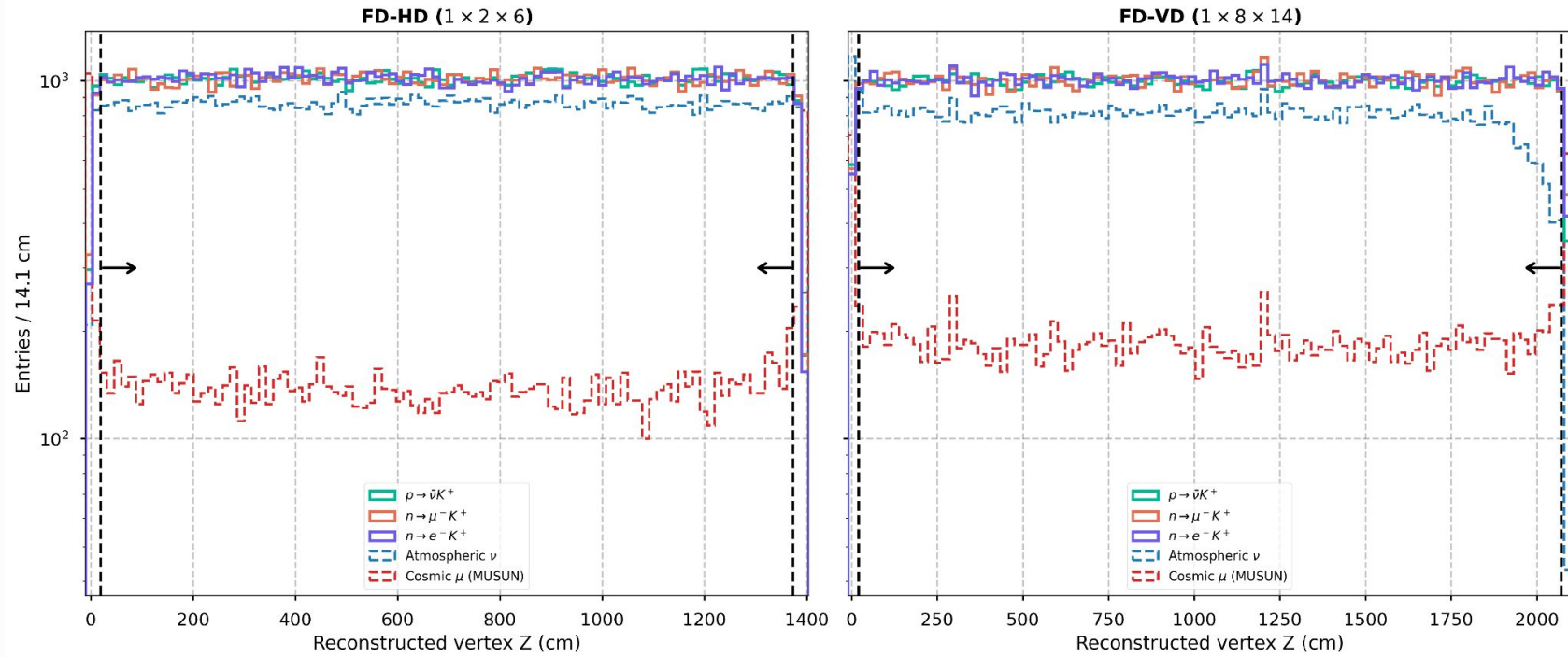
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Event Selection

Pandora Vertex in Fiducial Volume ($t_0 = 0$)

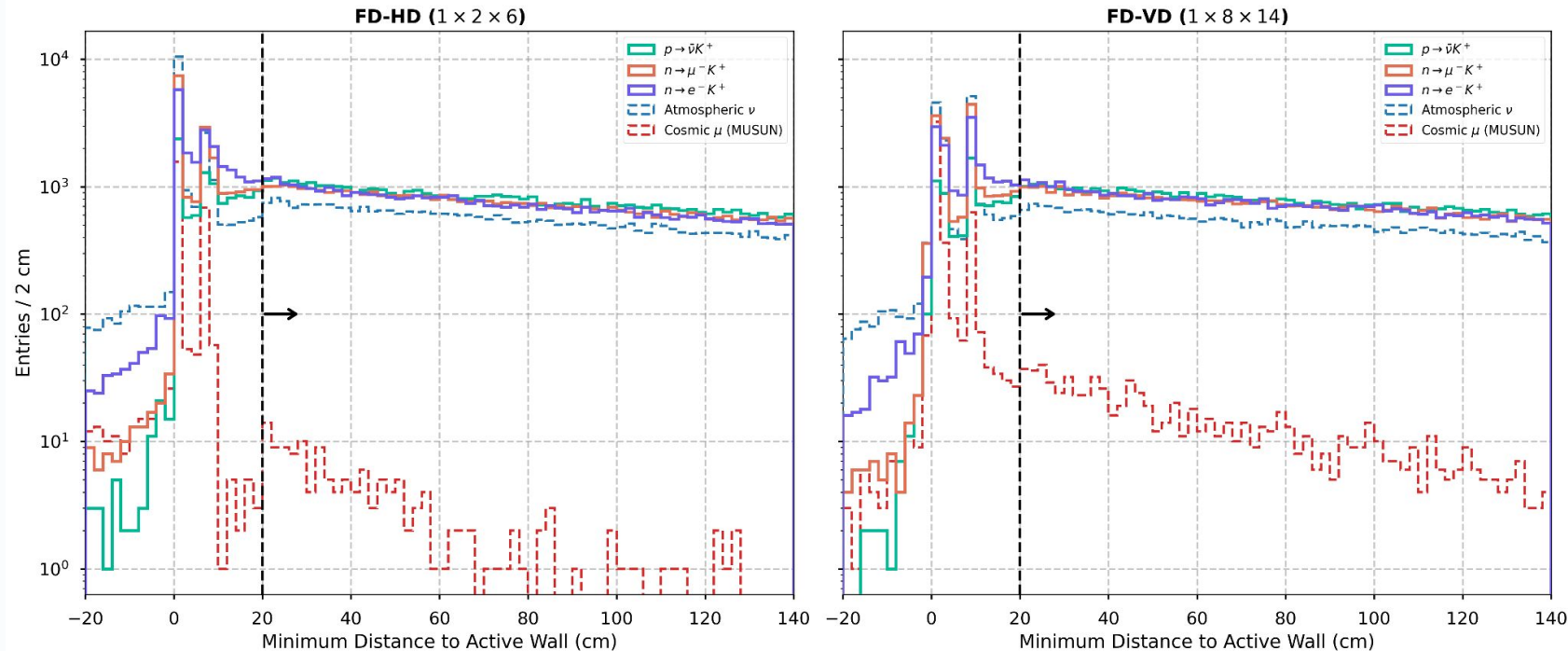
2. Pandora Vertex
in Fiducial Volume ($t_0 = 0$)



Event Selection

Pandora Space Points in Fiducial Volume

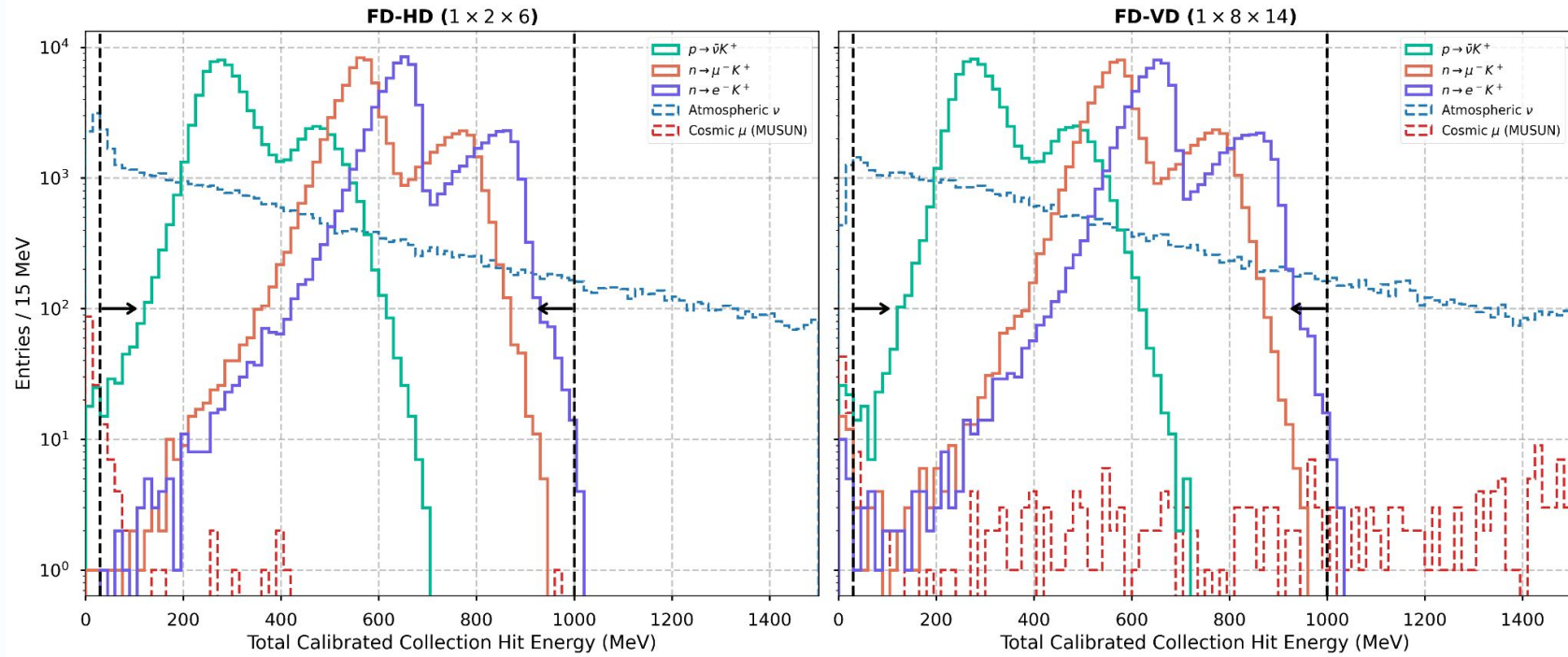
3. Pandora Space Points in Fiducial Volume



Event Selection

Charge ROI $\in [30, 1000]$ MeV

4. Charge ROI
 $\in [30, 1000]$ MeV



Applied Cuts

Golden channel selection strategy

1. Valid Pandora
Final-State Particle

2. Pandora Vertex
in Fiducial Volume ($t_0 = 0$)

3. Pandora Space Points in
Fiducial Volume

4. Charge ROI
 $\in [30, 1000]$ MeV

5. Decay topology

6. 1 $K_{\mu 2}$ | $K_{\pi 2}$ track

7. PIDA Proton Veto

8. Final Charge ROI

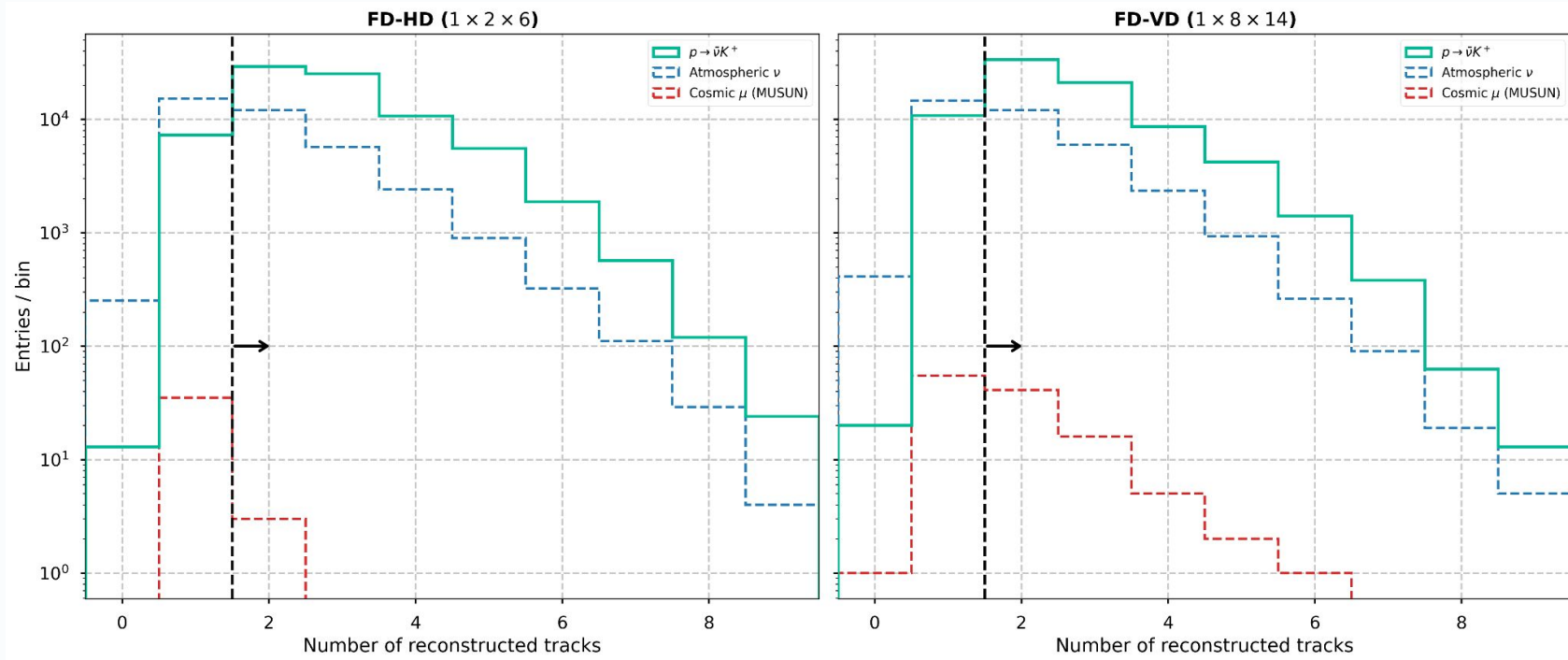
Technical Cut Specifications Based on Unified Optimization from Figure of Merit $\epsilon_s/\sqrt{B}$

- At least 2 tracks for the golden channel (K^+ & μ^+); 3 tracks (K^+ , μ^+ , & (μ^- | e^-)), or 2 tracks & 1 shower (K^+ , μ^+ , & e^-) for neutron decay.
- $K_{\mu 2}$: $L_\mu \in [45, 60]$ cm & $PIDA_\mu \in [8.00, 10.75]$; $K_{\pi 2}$: $L_\pi \in [25, 35]$ cm & $PIDA_\pi \in [9.50, 11.00]$.
- *Veto proton background using PIDA < 16.50.*
- *Final Charge ROI:* Total collection plane hit energy must not exceed upper thresholds for $K_{\mu 2}$ ($K_{\pi 2}$): ≤ 400 ([400, 600]) MeV ($p \rightarrow \bar{\nu} K^+$), ≤ 650 ([650, 1000]) MeV ($n \rightarrow \mu^- K^+$), ≤ 700 ([700, 1000]) MeV ($n \rightarrow e^- K^+$).

Event Selection: $p \rightarrow \bar{\nu} K^+$

Decay Topology

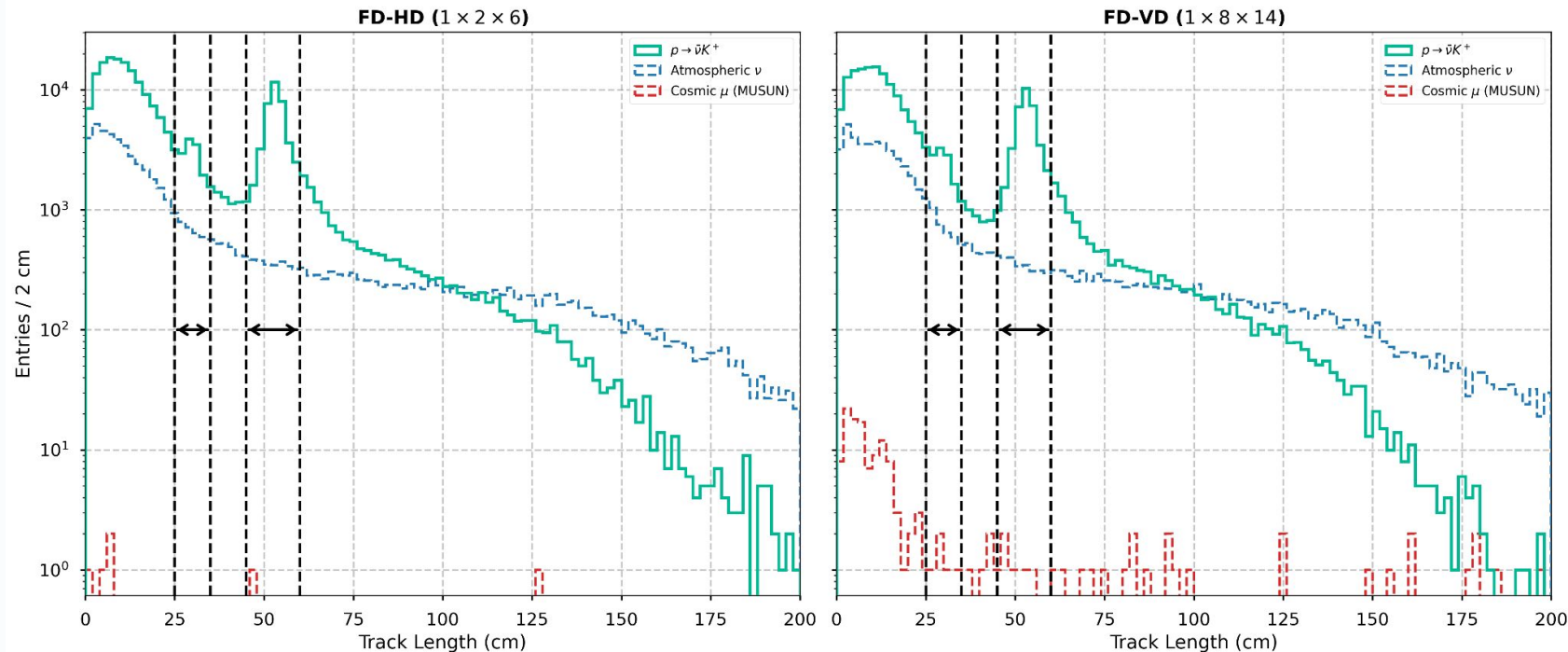
5. Decay topology



Event Selection: $p \rightarrow \bar{\nu} K^+$

$1 K_{\mu 2} \mid K_{\pi 2}$ track

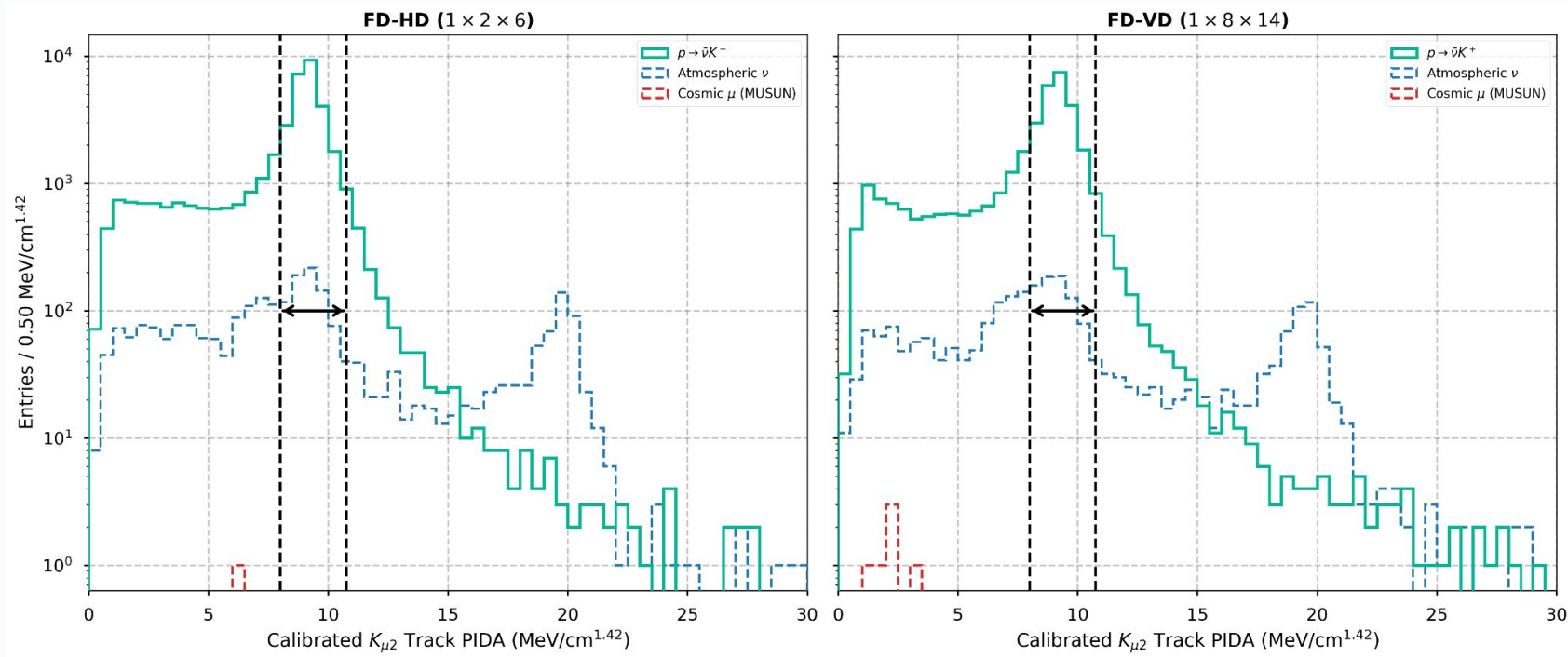
6. $1 K_{\mu 2} \mid K_{\pi 2}$ track



Event Selection: $p \rightarrow \bar{\nu} K^+$

$1 K_{\mu 2} \mid K_{\pi 2}$ track

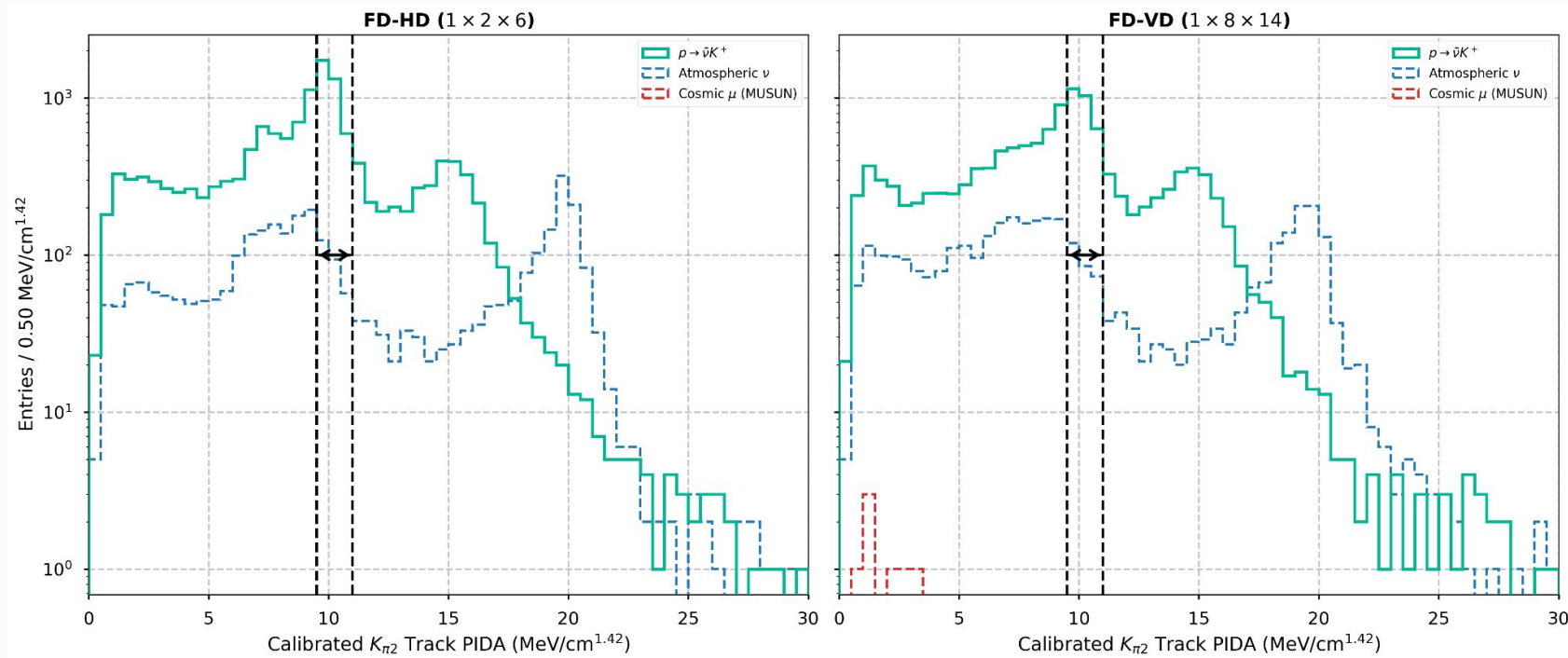
6. $1 K_{\mu 2} \mid K_{\pi 2}$ track



Event Selection: $p \rightarrow \bar{\nu} K^+$

$1 K_{\mu 2} \mid K_{\pi 2}$ track

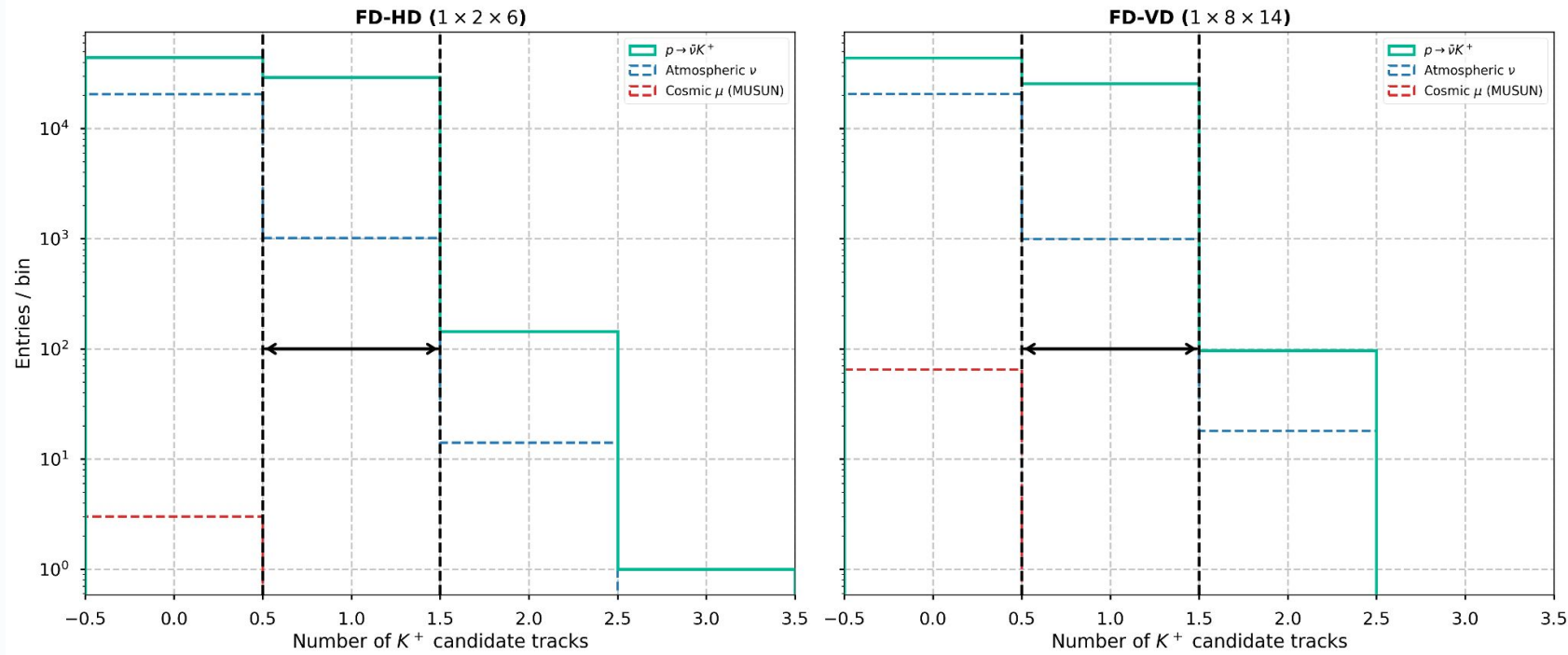
6. $1 K_{\mu 2} \mid K_{\pi 2}$ track



Event Selection: $p \rightarrow \bar{\nu} K^+$

$1 K_{\mu 2} \mid K_{\pi 2}$ track

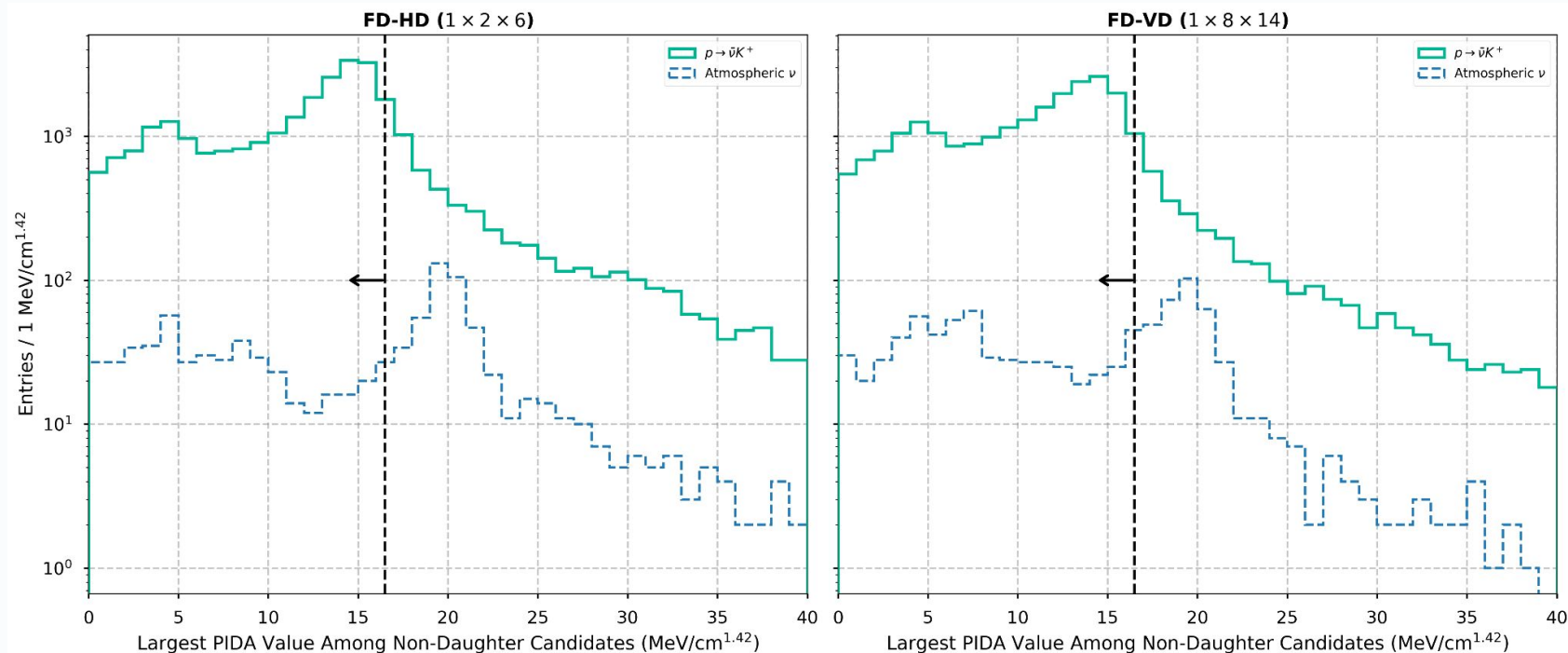
6. $1 K_{\mu 2} \mid K_{\pi 2}$ track



Event Selection: $p \rightarrow \bar{\nu} K^+$

PIDA Proton Veto

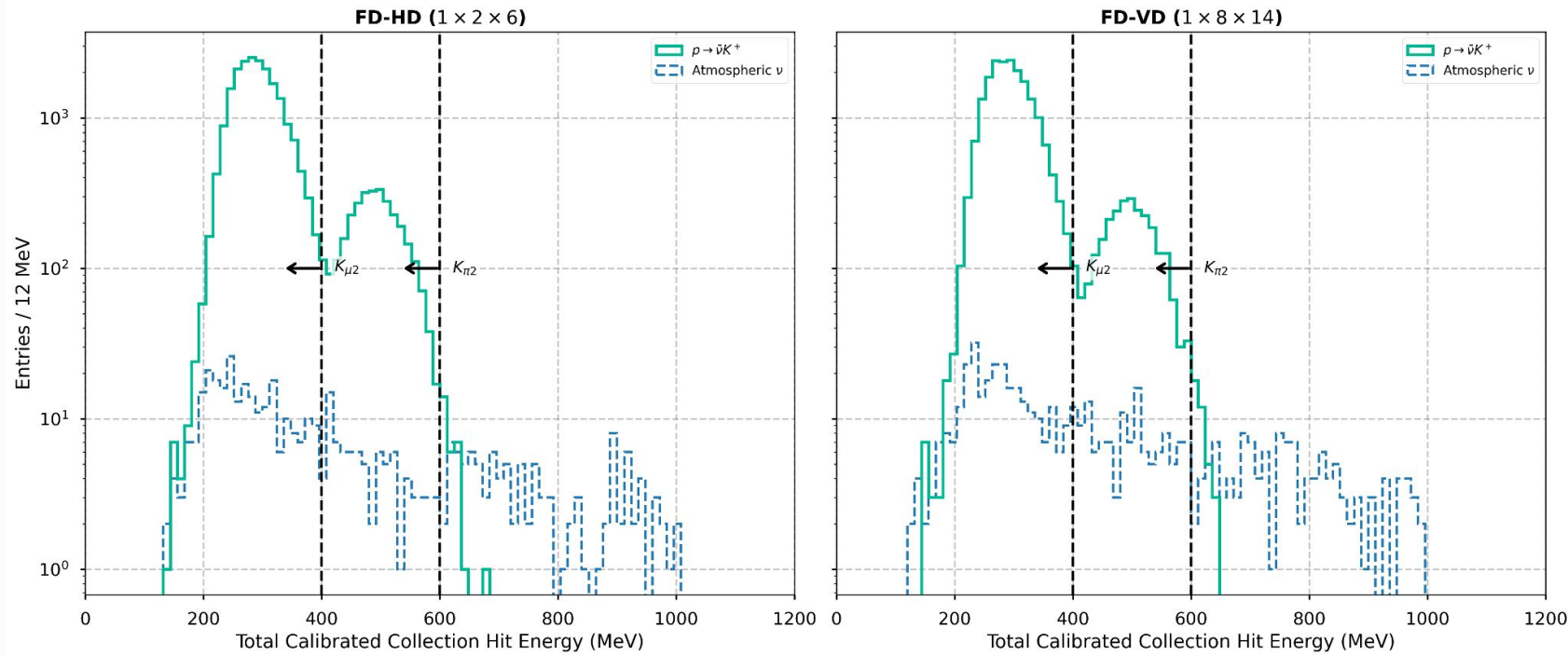
7. PIDA Proton Veto



Event Selection: $p \rightarrow \bar{\nu} K^+$

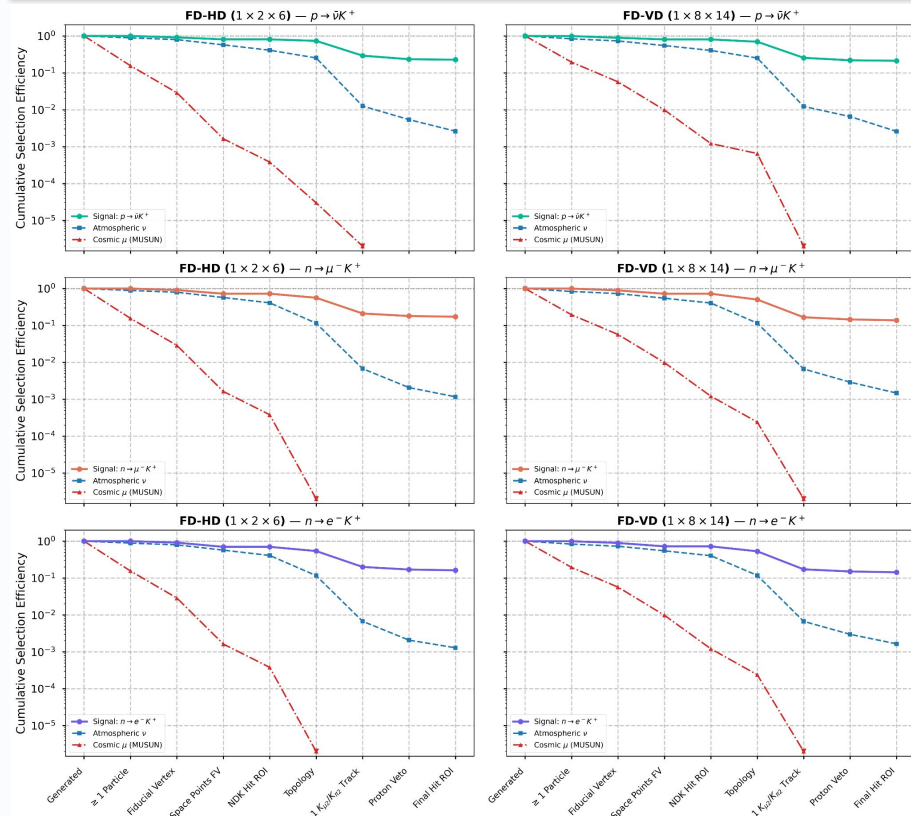
Final Charge ROI

8. Final Charge ROI



Selection Cut Performance

Selection efficiencies for nucleon decay channels vs. atmospheric neutrino and cosmic ray muon backgrounds in DUNE FD



Detector Configuration	$p \rightarrow \bar{\nu} K^+$	ATM	COS
FD-HD	22.637%	0.262%	0.000%
FD-VD	21.187%	0.258%	0.000%

Detector Configuration	$n \rightarrow \mu^- K^+$	ATM	COS
FD-HD	17.204%	0.116%	0.000%
FD-VD	13.772%	0.147%	0.000%

Detector Configuration	$n \rightarrow e^- K^+$	ATM	COS
FD-HD	16.217%	0.129%	0.000 %
FD-VD	14.364%	0.165%	0.000%

Background Event Rates Per Year

Comparative annual rate analysis before and after preselection cuts

FD-HD (1x2x6) Module ~ 1.68 kton

Initial Generated Exposures:

- Atmospheric Neutrinos: $2251.4 \nu / 10 \text{ kt yr}$.
- Cosmic Muons: $11 \times 10^6 \mu / 10 \text{ kt yr}$.

Post-Cut Final Annualized Exposures:

- ν_{μ} :
 - 5.9 events / 10 kt yr ($p \rightarrow \bar{\nu} K^+$).
 - 2.6 events / 10 kt yr ($n \rightarrow \mu^- K^+$).
 - 2.9 events / 10 kt yr ($n \rightarrow e^- K^+$).
- μ : 0 events / 10 kt yr.

FD-VD (1x8x14) Module ~ 2.57 kton

Initial Generated Exposures:

- Atmospheric Neutrinos: $2251.4 \nu / 10 \text{ kt yr}$.
- Cosmic Muons: $11 \times 10^6 \mu / 10 \text{ kt yr}$.

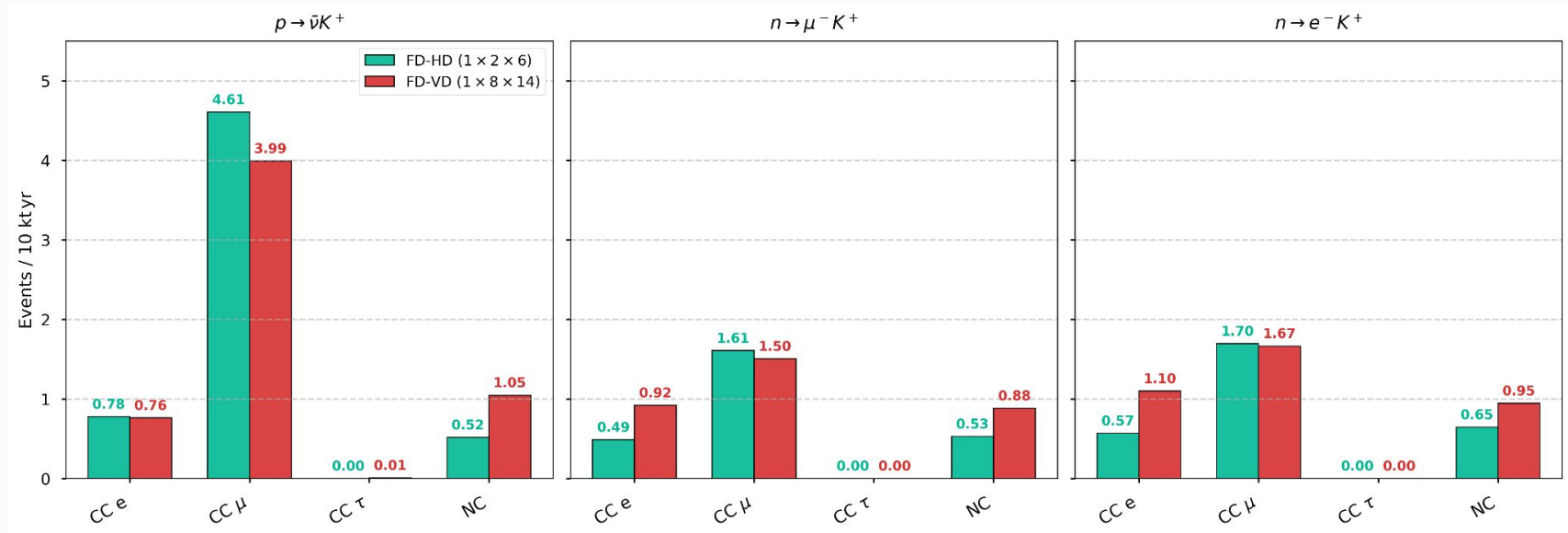
Post-Cut Final Annualized Exposures:

- ν_{μ} :
 - 5.8 events / 10 kt yr ($p \rightarrow \bar{\nu} K^+$).
 - 3.3 events / 10 kt yr ($n \rightarrow \mu^- K^+$).
 - 3.7 events / 10 kt yr ($n \rightarrow e^- K^+$).
- μ : 0 events / 10 kt yr.

Background Composition

Accepted Atmospheric Neutrino Background

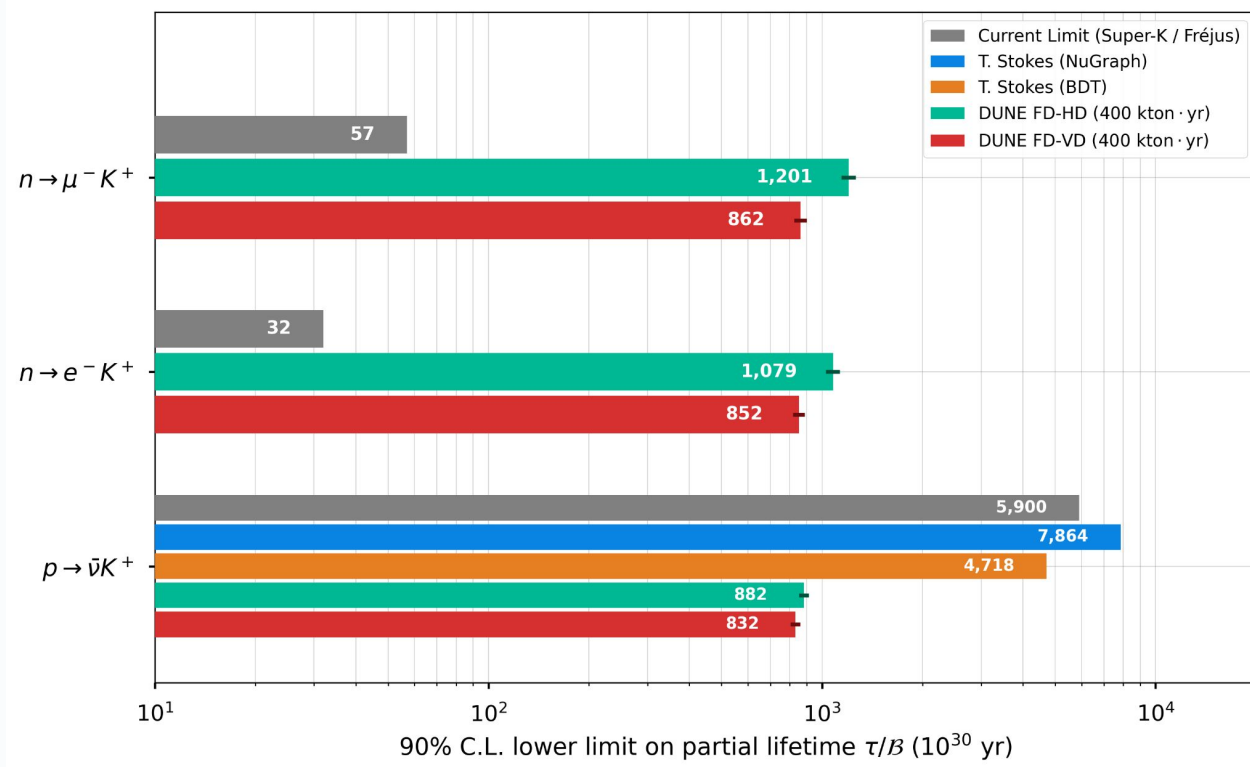
- Dominant background: CC interactions from muon neutrinos and antineutrinos.
- Electron CC and NC interactions are also significant.



Sensitivities & Outlook

Nucleon Decay Sensitivity in DUNE FD

Sensitivity as a function of the exposure in DUNE FD



Future Outlook

- ***Full 10 kt Module Geometry Scaling***

Transition from reduced geometries (1x2x6 / 1x8x14) to full 10 kt layouts will minimize edge effects and improve containment.

- ***Pandora Pattern Recognition Tuning***

Calibrate FD-VD spatial residuals to eliminate systematic vertex offsets.

- ***t_0 Reconstruction***

A perfect t_0 reconstruction is currently assumed. A critical step is integrating a realistic PDS t_0 reconstruction with radiological backgrounds.

- ***Machine Learning Multi-Variate Analysis***

Implementing BDTs or GNNs on 3D Bragg dE/dx profiles to exploit multi-dimensional hit correlations.

Backup Slides

Student Seminar - Experimental Particle Physics

Presented by: **Hamza Amar Es-sghir**

Date: September 28, 2026



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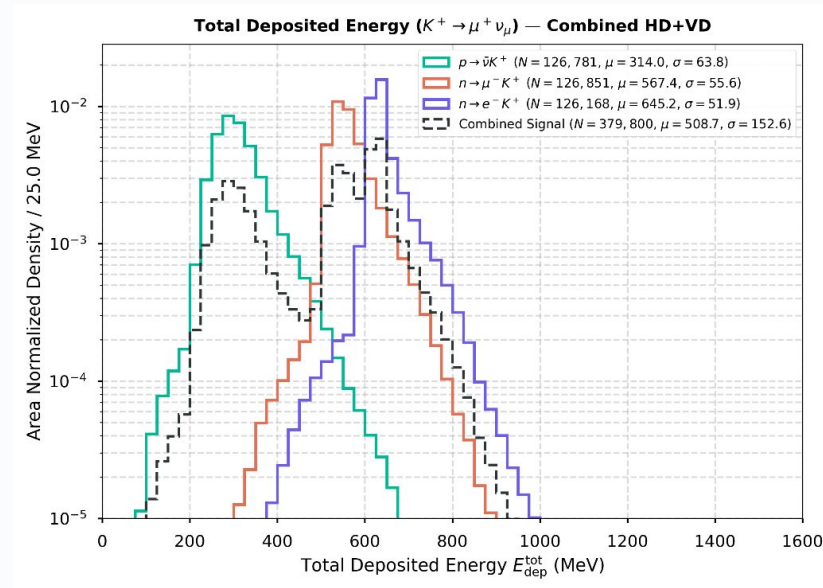
Nucleon Decay Searches in DUNE

Decay channels with K^+ as final state

Deposited Energy

- Main Decay Channels ($\tau_K = 12.38$ ns):

- $K_{\mu 2}$ Branching Ratio (63.56%): $K^+ \rightarrow \mu^+ \nu_\mu$ ($T_\mu = 152.5$ MeV, $L_\mu \approx 54$ cm at rest).



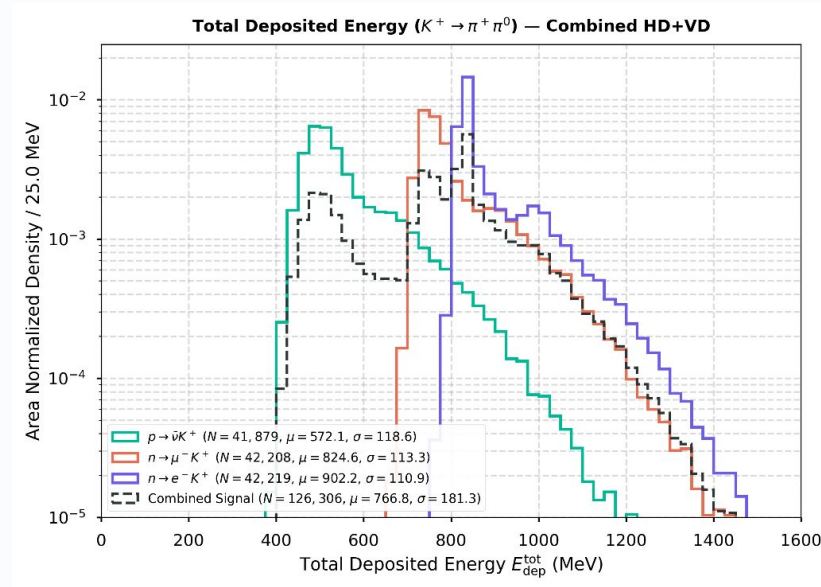
Nucleon Decay Searches in DUNE

Decay channels with K^+ as final state

Deposited Energy

- Main Decay Channels ($\tau_K = 12.38$ ns):

- K_{π^2} Branching Ratio (20.67%): $K^+ \rightarrow \pi^+ \pi^0$ ($T_\pi = 108.4$ MeV, $L_\pi \approx 28$ cm at rest; $\pi^0 \rightarrow \gamma\gamma$).



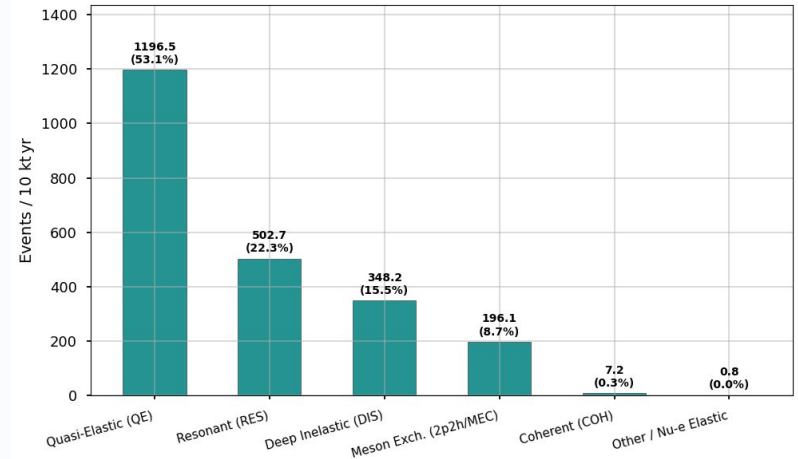
Physics Background: Atmospheric Neutrinos

Honda flux simulation, 3-flavor oscillations, and event classification

Atmospheric Neutrino Simulation in GENIE

Totals per 10 kt · yr
Honda Solar Maximum, NuFIT 5.2, GENIEv3.4.0 AR23 Base Tune

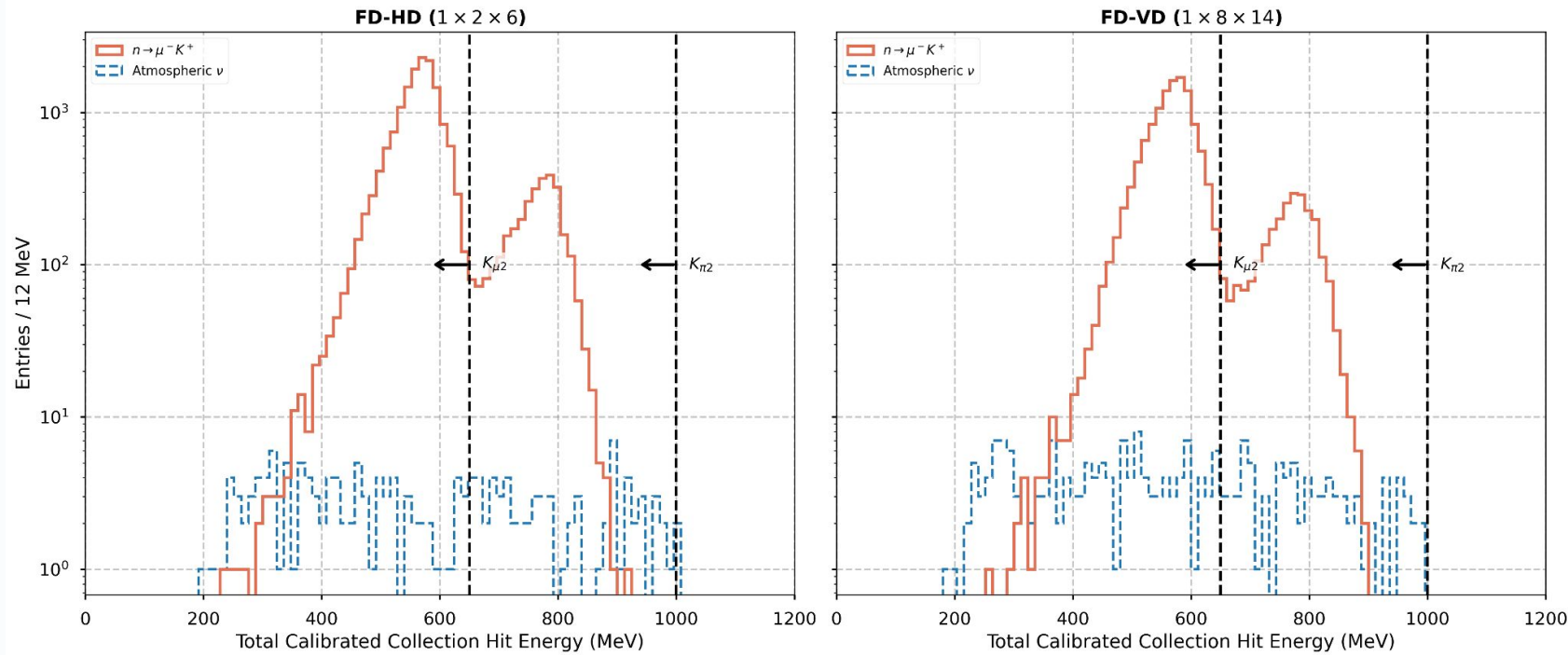
	Sub-GeV [0.1 - 1] GeV	Multi-GeV [1 - 10] GeV	High-GeV [10 - 100] GeV	Total [0.1 - 100.0] GeV
ν_e CC	291.9	196.9	13.74	502.5
ν_μ CC	262.5	284.1	42.14	588.8
ν_τ CC	0.0	2.1	3.89	5.9
$\bar{\nu}_e$ CC	46.9	53.5	4.71	105.1
$\bar{\nu}_\mu$ CC	49.7	94.1	15.77	159.6
$\bar{\nu}_\tau$ CC	0.0	0.8	1.78	2.6
NC	556.9	297.5	32.48	886.9
All	1208.0	929.0	114.51	2251.4



Event Selection: $n \rightarrow \mu^- K^+$

Final Charge ROI

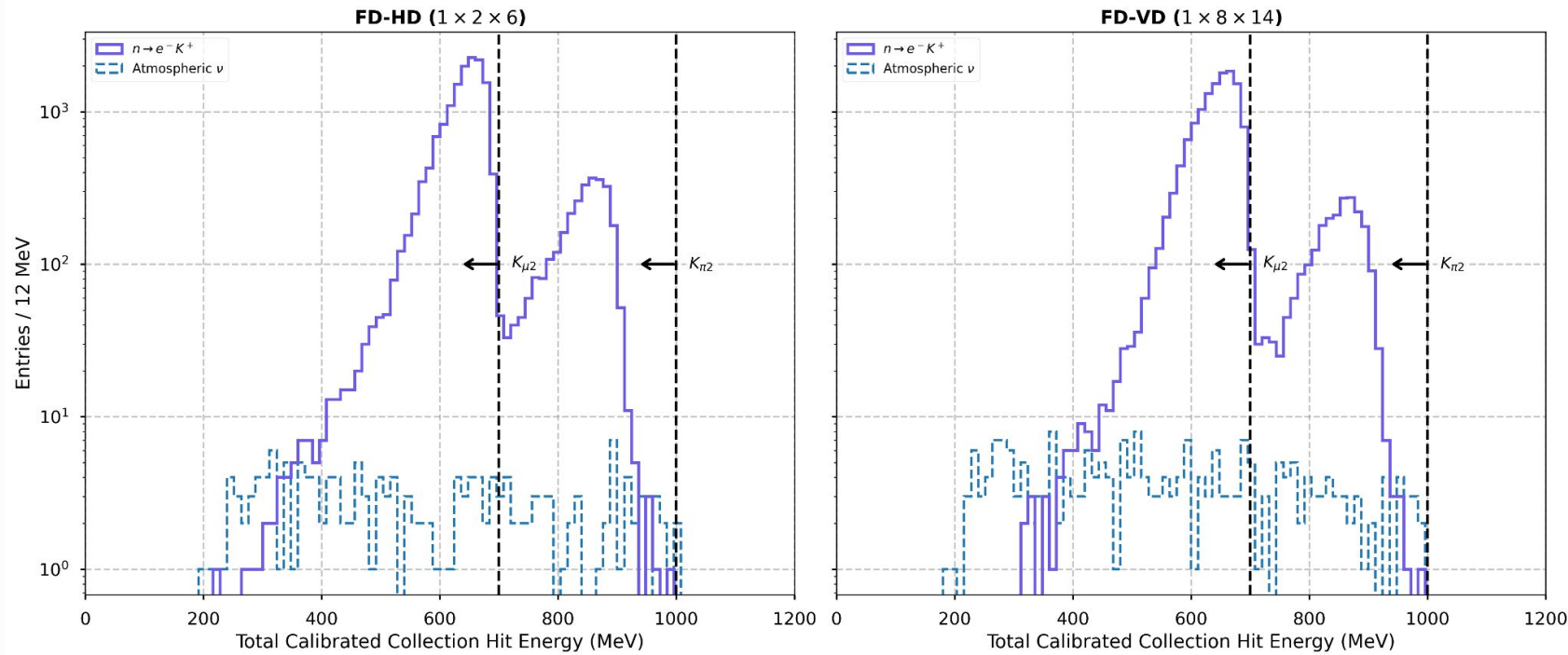
8. Final Charge ROI



Event Selection: $n \rightarrow e^- K^+$

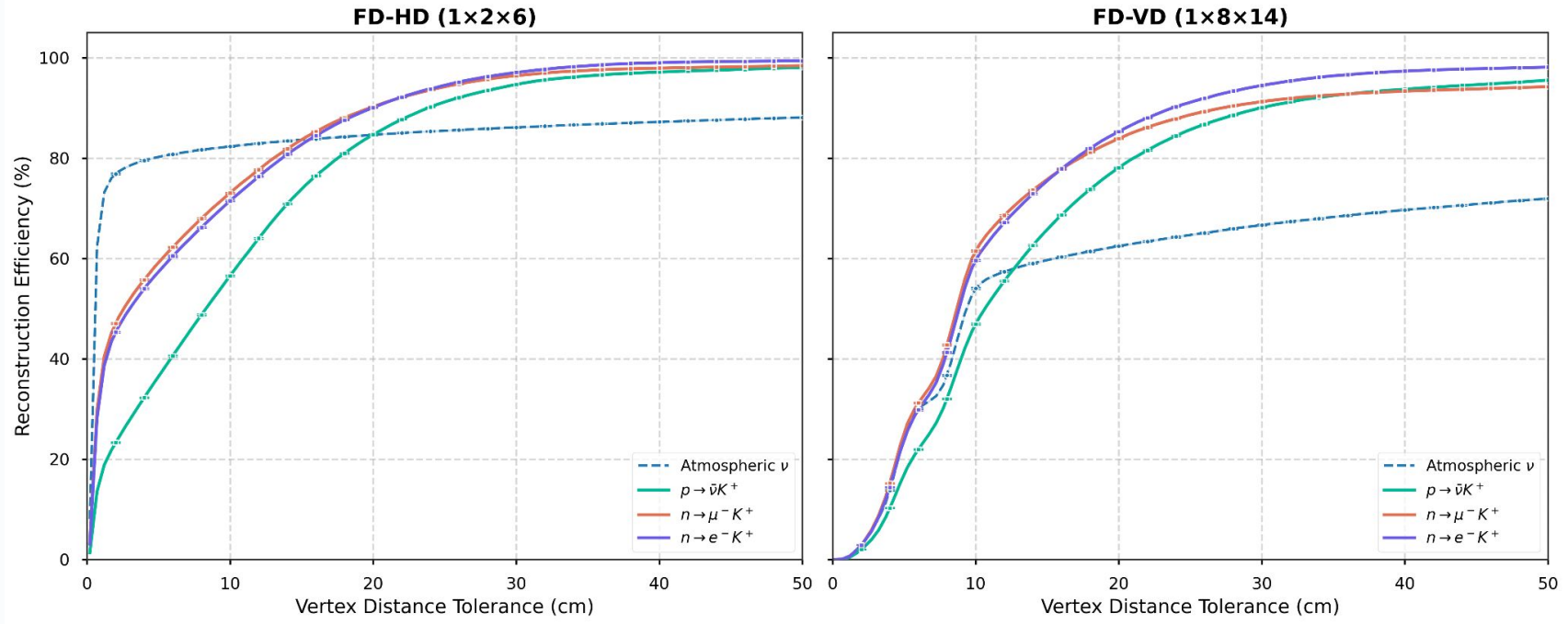
Final Charge ROI

8. Final Charge ROI



Pandora Reconstruction Performance

Vertex reconstruction

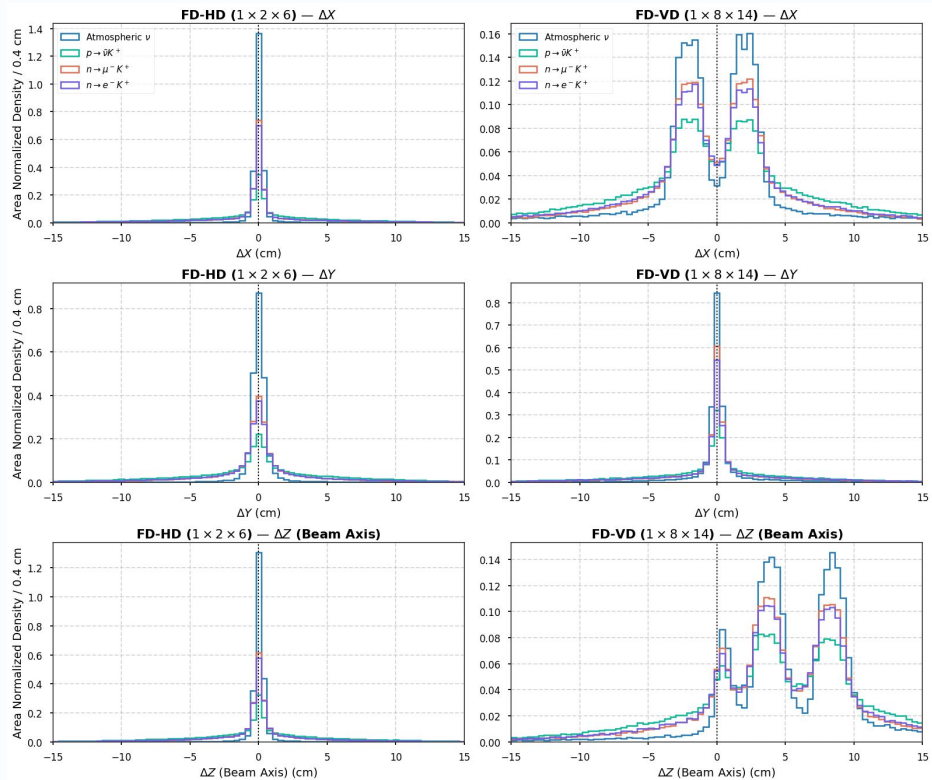


Pandora Reconstruction Performance

Vertex reconstruction

Pandora Vertexing for Non-Beam Events

- Correct reconstruction in FD-HD.
- Biased reconstruction in FD-VD due to unsuitable neural network training (recycled from HD).
- Drift direction reconstructed assuming perfect t_0 reconstruction from the PDS.

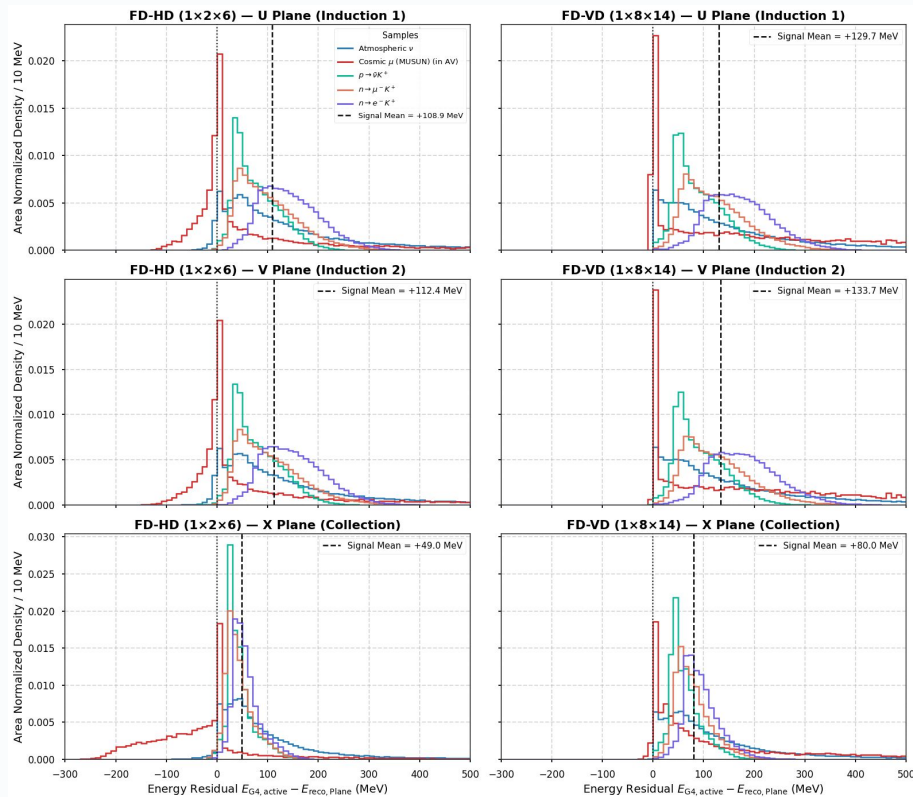


Pandora Reconstruction Performance

Energy reconstruction

Readout Plane Reconstruction

- **Best Plane:** Collection plane, as expected by the lowest signal to noise ratio.
- **Detector behavior:** Both modules exhibit distinct reconstructed energy distributions.



Pandora Reconstruction Performance

Collection plane energy calibration

