Nucleon Decay Searches in DUNE with K^+ as Final State

Selection Cuts and Preliminary Sensitivities

IFIC Group Meeting

Presented by: **Hamza Amar Es-sghir** & Michel Sorel
Date: September 16, 2026

Outline

Structural roadmap of the presentation

01. Cosmological & Theoretical Foundations

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

02. Experimental Landscape & DUNE Setup

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- 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

- Pandora Vertexing
- Readout Plane Calorimetry & Calibration
- Truth Matching & Primary K+ Tracking
- Daughter Tracking & PIDA

05. Selection Chain & Cuts

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- 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

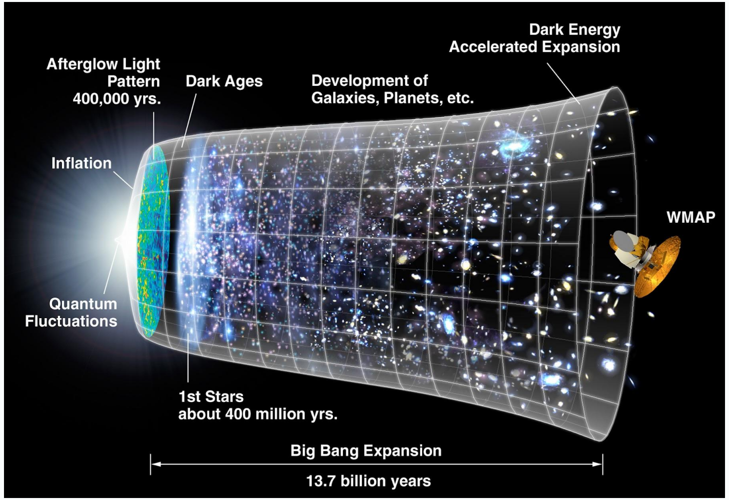
Cosmological & Theoretical Foundations

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.



Cosmological Matter-Antimatter Asymmetry & Observational Evidence

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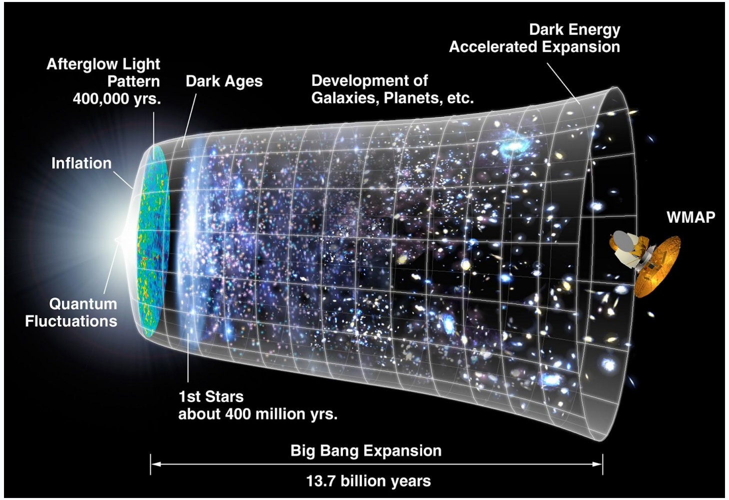


Standard Model Fails to Explain η

Sakharov Conditions, EW Sphalerons & B-L Protection

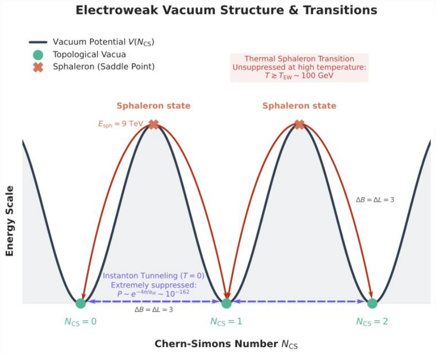
Non-perturbative vacuum transitions and asymmetry survival mechanisms

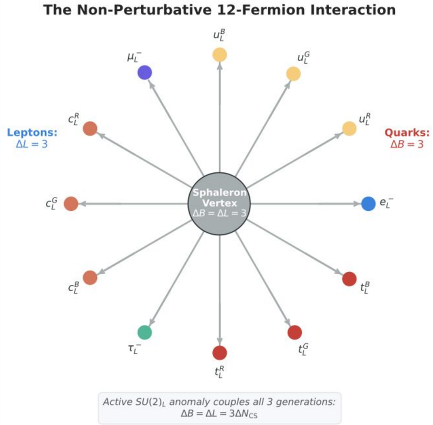
Sakharov's Conditions

1. **Baryon Number Violation**: Required to transition from B = 0 to B ≠ 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 GeV ≤ T ≤ 10^{12} GeV), unsuppressed sphalerons erase baryon asymmetry generated by any primordial $\Delta(B\text{-}L) = 0$ process.
- **B-L Conservation Immunity**: Processes generating $\Delta(B\text{-}L) \neq 0$ survive sphaleron washout and power the observed η.





Grand Unification Theories & Nucleon Decay

Connecting grand unification gauge symmetries to nucleon decay

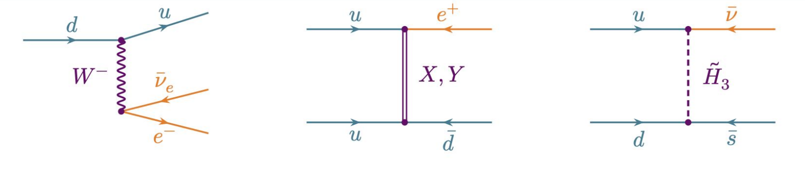
Beyond Standard Model Frameworks

• **Standard Model Limitation**: B & L are strictly conserved accidental global symmetries of the classical SM Lagrangian.

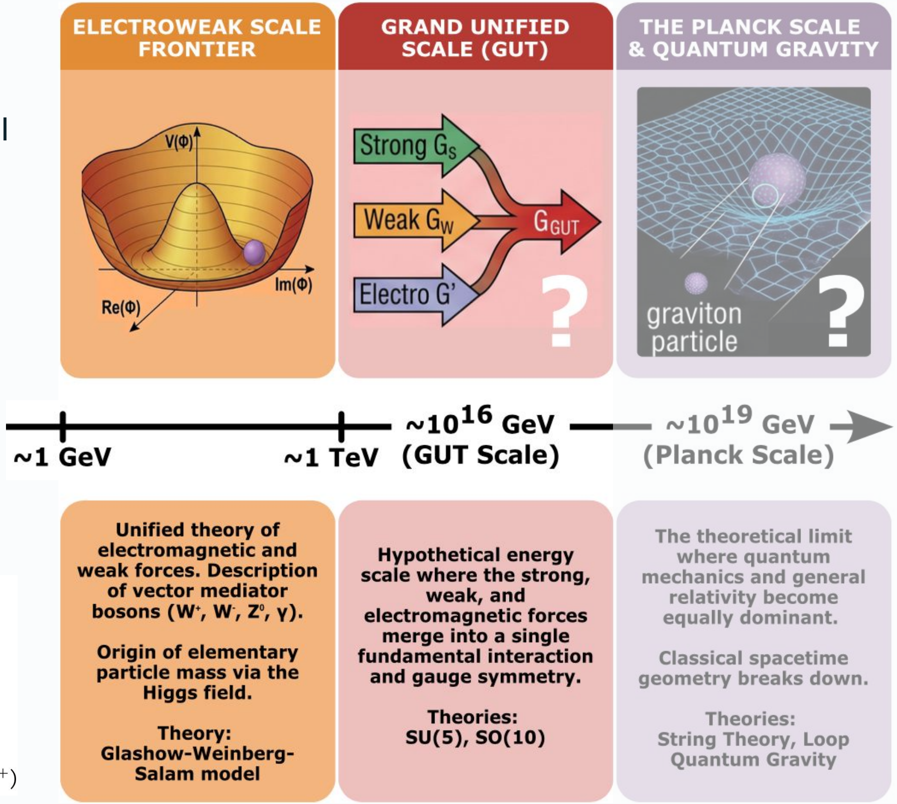
• **GUTs**: Naturally break B and L by placing quarks and leptons into common gauge representations (leptoquarks). Energy scale ~10^{15}–10^{16} GeV.

• **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)* ($p \to e^+\pi^0$) (c) *SUSY GUTs* ($p \to \bar{\nu}K^+$)



Experimental Landscape & DUNE Setup

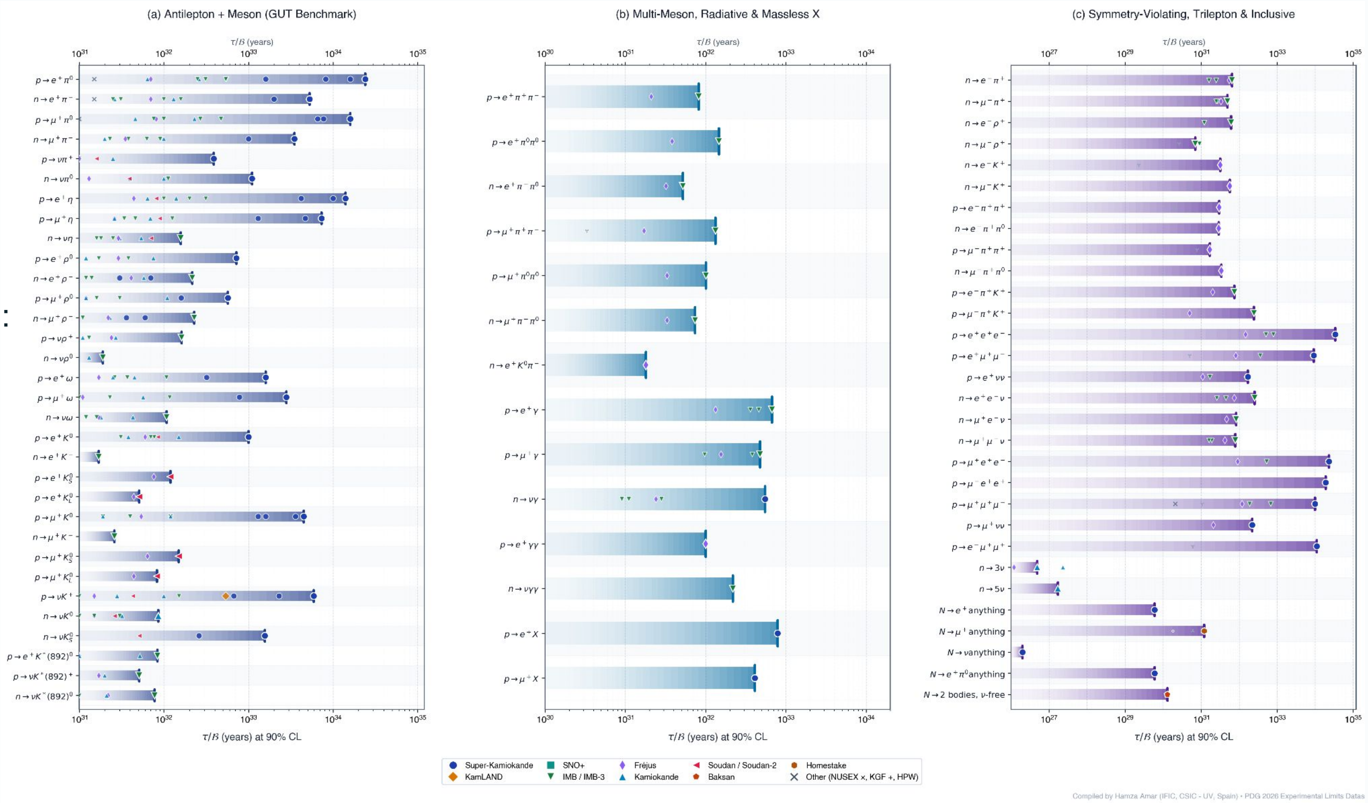
Current Experimental Limits

Global landscape 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 $\times 10^{10}$ years.
- **Three Main Categories**:

(a) **Antilepton + Meson** (GUT Benchmark).
(b) Multi-Meson, Radiative, and Massless X Modes.
(c) **Symmetry-Violating**, Trilepton, and Inclusive Channels.



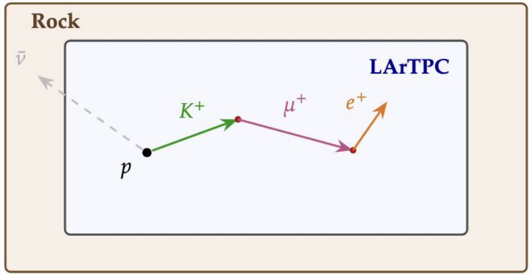
Current Experimental Limits

Decay channels with K^+ as final state

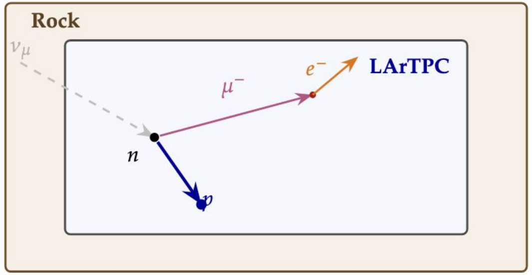
$$N_{\text{decay}} = N_{\text{target}} \frac{\Delta t}{\tau/\mathcal{B}}$$

Partial lifetime ***τ/B*** limit is constrained by detector exposure (mass × time), signal selection efficiency and surviving background rate:
- Atmospheric neutrinos.
- Cosmic ray muons.

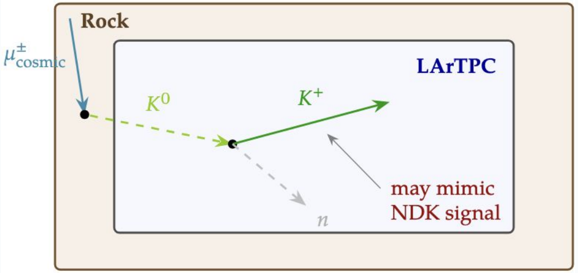
Nucleon Decay Channel°	Δ(*B* - *L*)	Benchmark Limit (yr)
$p \to \bar{\nu} K^+$	0	5.9×10^{33} (Super-K)
$n \to \mu^- K^+$	-2	5.7×10^{31} (Fréjus)
$n \to e^- K^+$	-2	3.2×10^{31} (Fréjus)



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



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



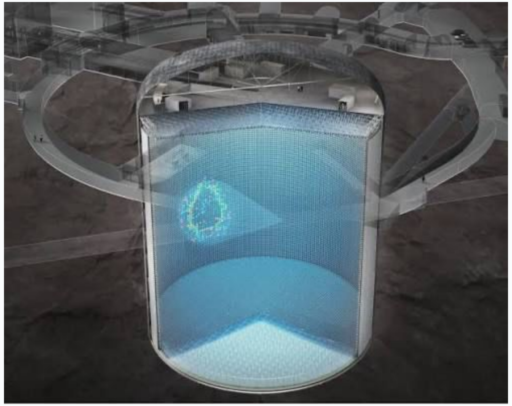
(c) Cosmic $\mu \to K^0$ **in rock,** $K^0 p \to K^+ n$ **in LAr**

Next-Generation Facilities

Underground detectors for nucleon decay searches

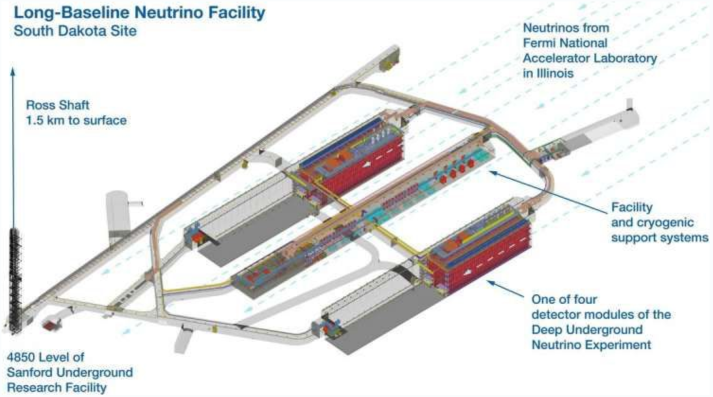
Experiment	Mass (kt)	Main Feature
Hyper-K	216 (Light Water)	Mass
JUNO	20 (Liquid Scintillator)	Timing
DUNE	40 (Liquid Argon)	Imaging

Hyper-K



JUNO

DUNE

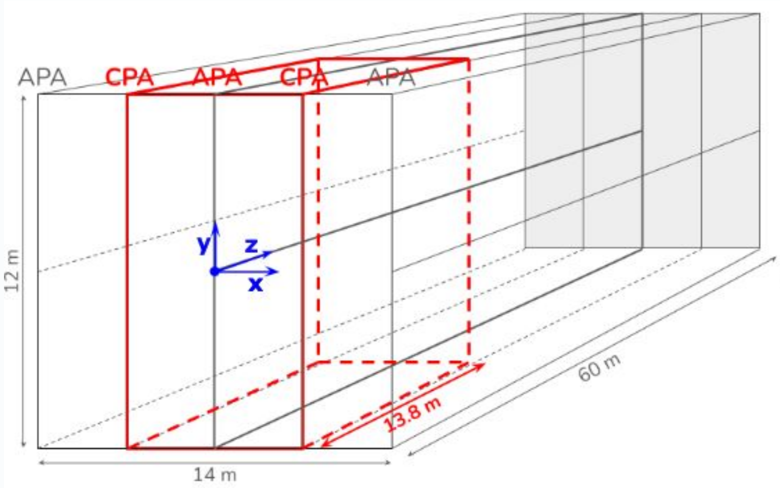


DUNE Simulated Detector Geometries

Reduced FD-HD and FD-VD Modules

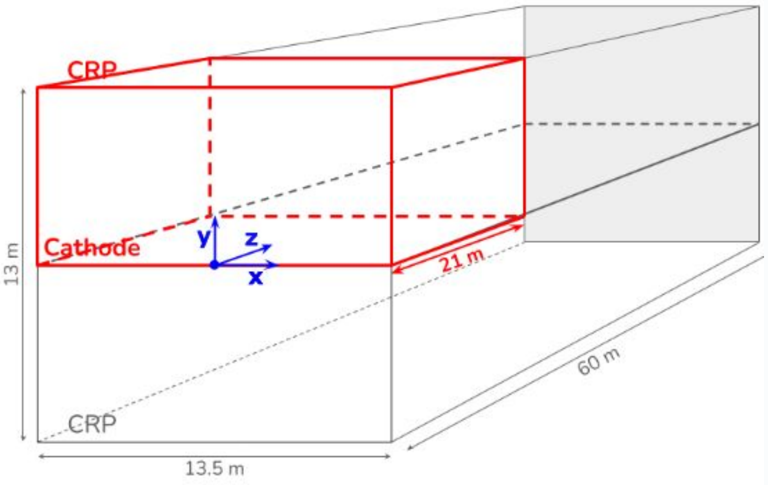
Horizontal Drift (FD-HD 1x2x6)

• *Geometric configuration*: 1×2×6.
• *Active volume dimensions*: 7.2 × 12.0 × 13.9 m^3 (~1.68 kton active LAr mass).



Vertical Drift (FD-VD 1x8x14)

• *Geometric configuration*: 1×8×14.
• *Active volume dimensions*: 6.5 × 13.5 × 21.0 m^3 (~2.57 kton active LAr mass).



Datasets

Simulated samples for partial lifetime sensitivity studies

Generated Event Datasets

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

- 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`)

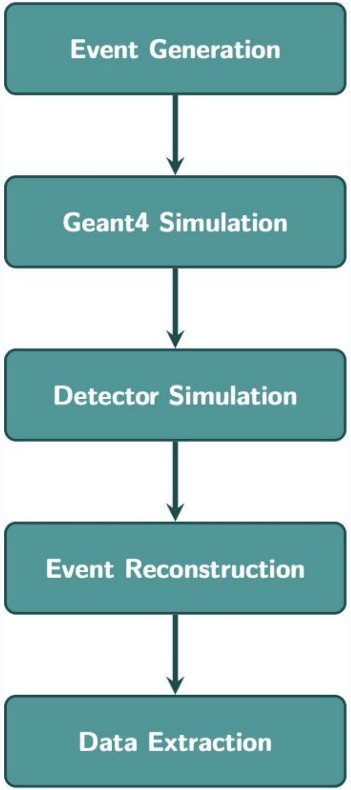
Stage 1 – Event Generation:
Generates primary interaction kinematics. GENIE simulates nucleon decays and atmospheric neutrino backgrounds. MUSUN simulates cosmogenic muons.

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 `atmos` 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.



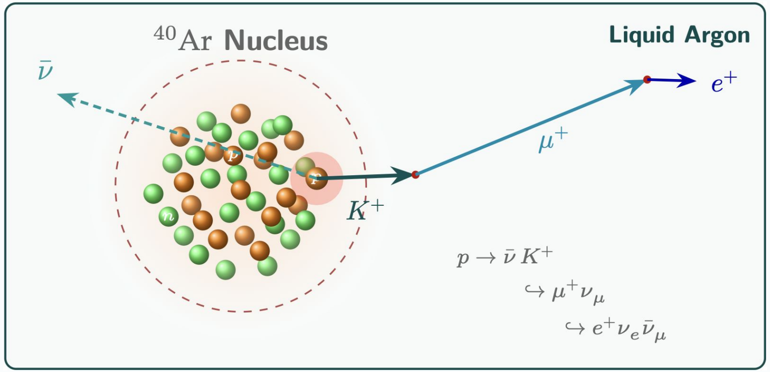
Signal & Background Generation

Nucleon Decay Searches in DUNE

Decay channels with K^+ as final state

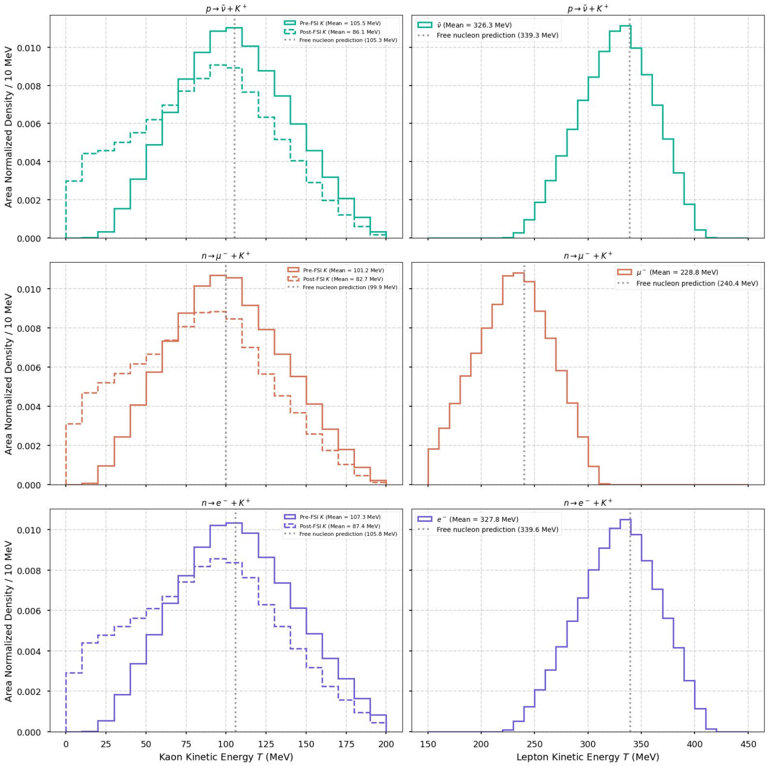
K+ Decay Topology & Kinematics

- **Bound-Proton Decay**: Non-monochromatic kaons due to Fermi momentum of bound protons in ^{40}Ar. Nuclear final state interactions smears the energy distribution.



Kaon Kinetic Energy

Lepton Kinetic Energy



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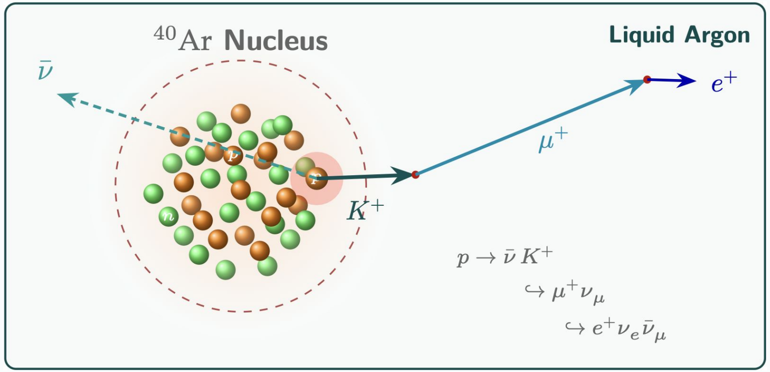
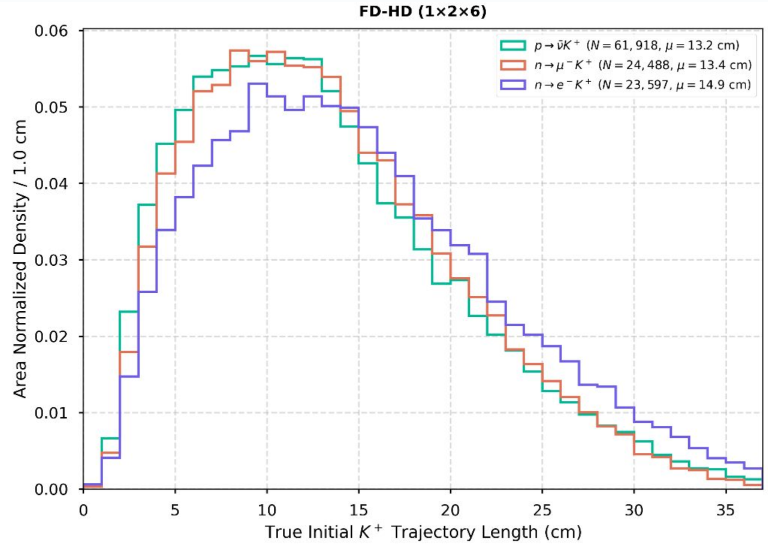
- **K^+ Propagation**: In LAr (ρ = 1.39 g/cm³), K^+ travels mean track length $L_K \approx$ 13-14 cm before stopping, depositing a high *dE/dx* Bragg peak.





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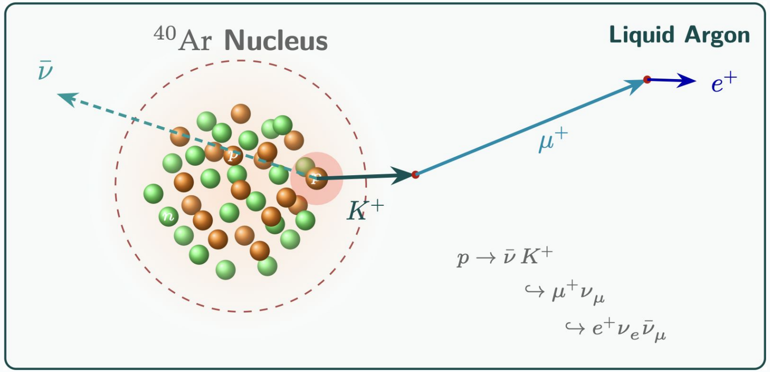
K+ Decay Topology & Kinematics

- **Main Decay Channels (τ_K = 12.38 ns)**:
  - **$K_{\mu 2}$** Branching Ratio (63.56%): $K^+ \rightarrow \mu^+ \nu_\mu$ (T_μ = 152.5 MeV, $L_\mu \approx$ 54 cm at rest).
  - **$K_{\pi 2}$** Branching Ratio (20.67%): $K^+ \rightarrow \pi^+\pi^0$ (T_π = 108.4 MeV, $L_\pi \approx$ 28 cm at rest; $\pi^0 \rightarrow \gamma\gamma$).
- **Daughter Muon Decay (τ_μ = 2.2 μs):** $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ (Michel positron, $T_e \leq$ 52.8 MeV).



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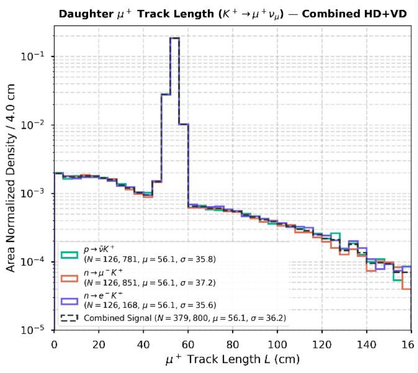

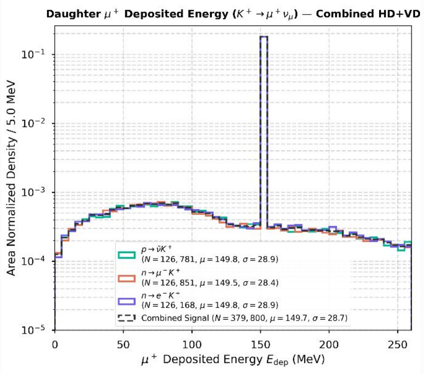

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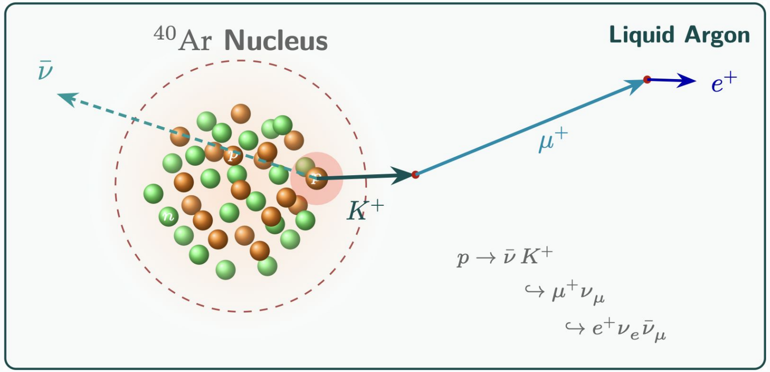

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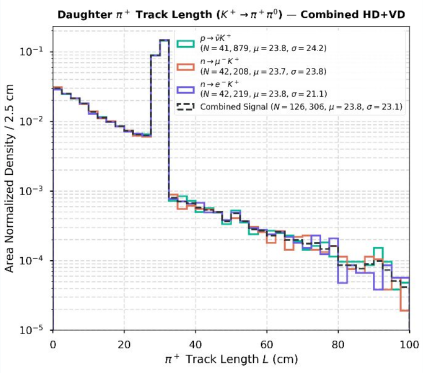

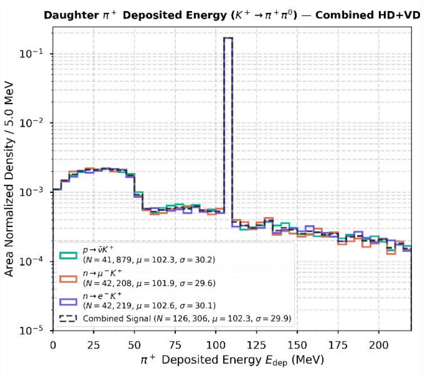

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Decay channels with K^+ as final state

Deposited Energy

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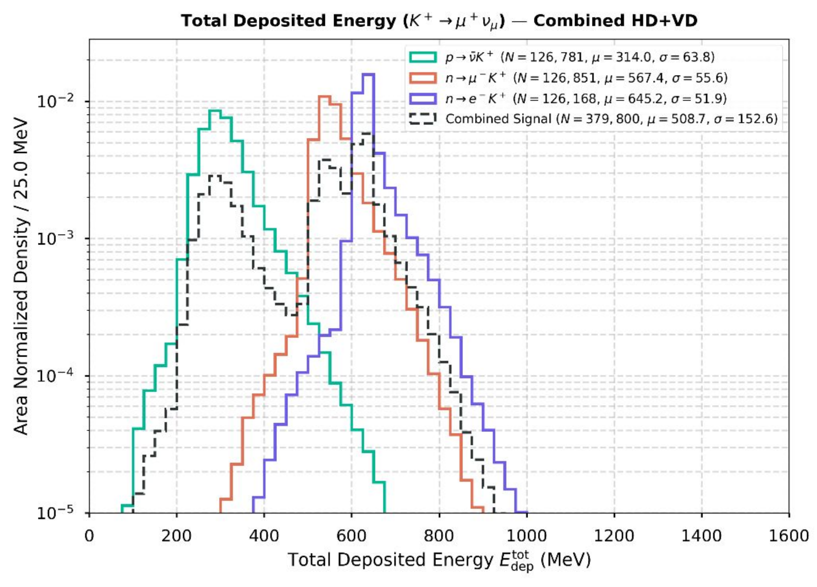

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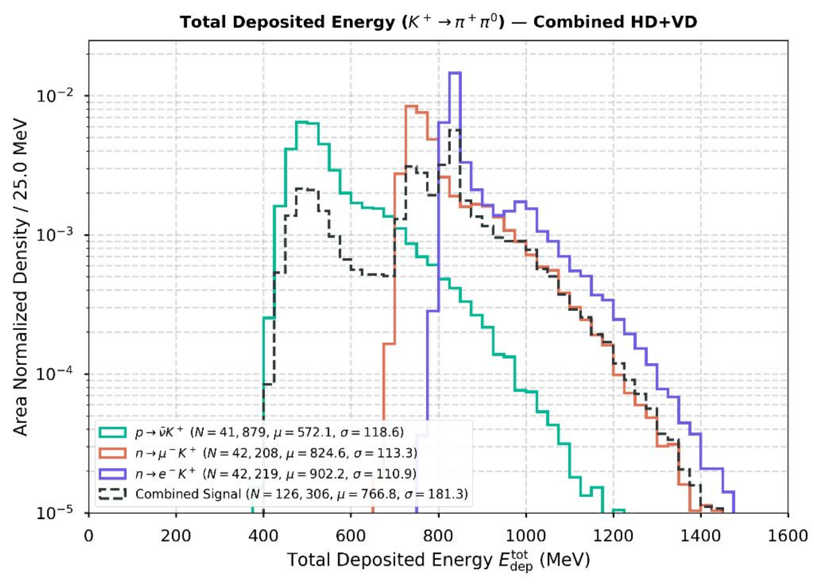
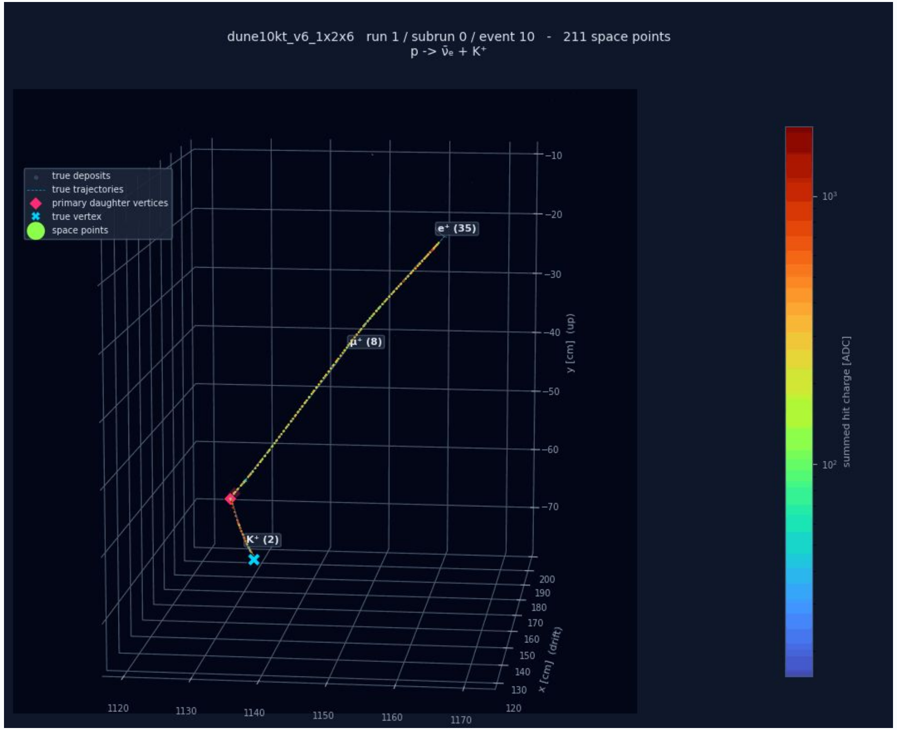


Event Displays

Nucleon Decay Signals



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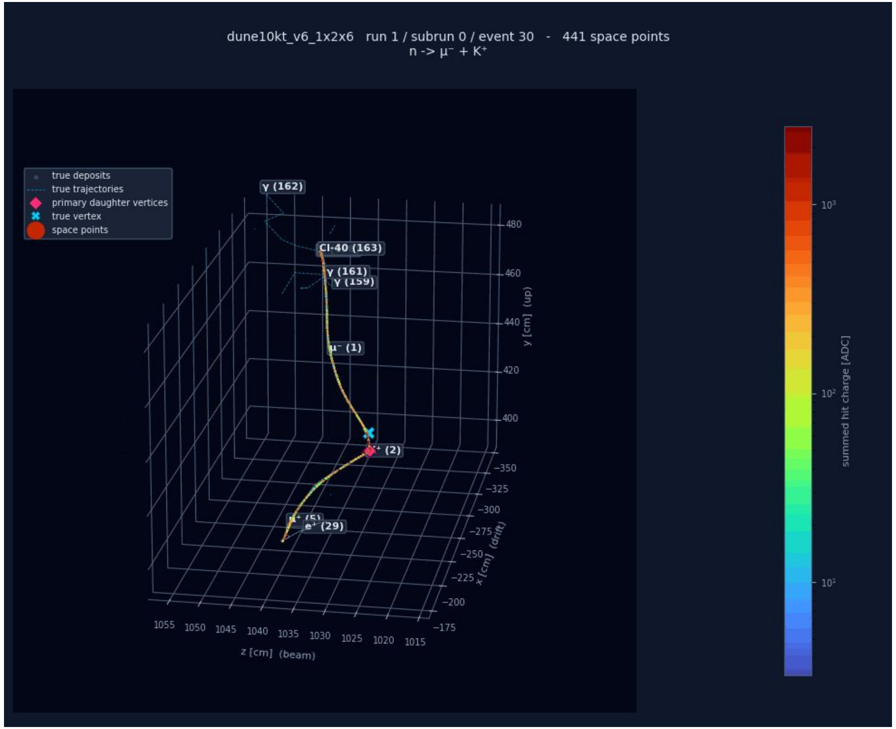
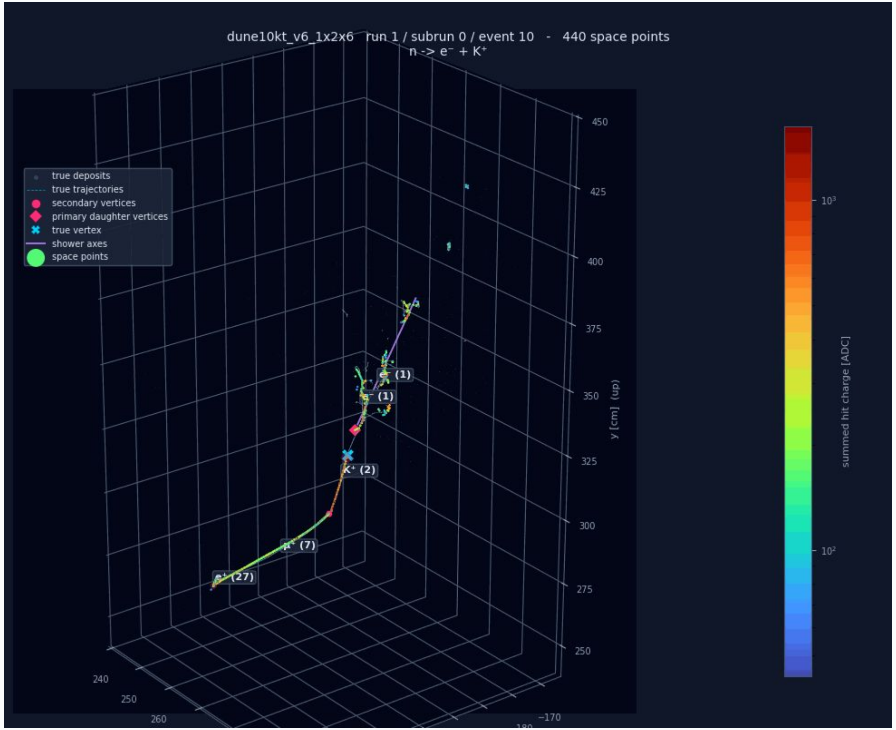




Physics Background: Atmospheric Neutrinos

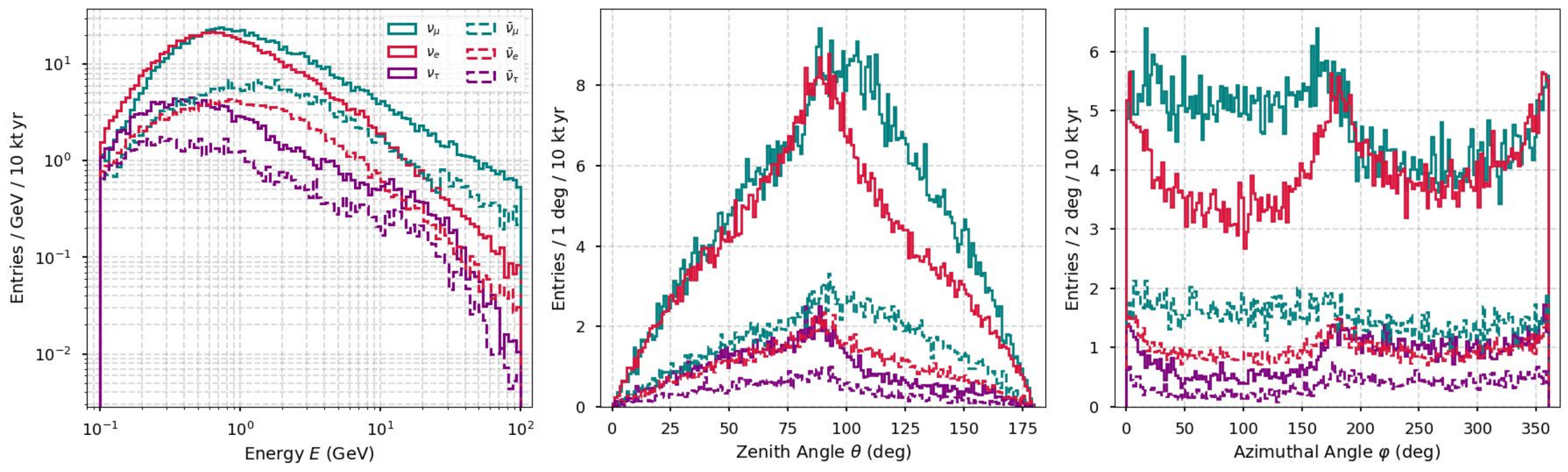
Honda flux simulation, 3-flavor oscillations, and neutrino classification

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.



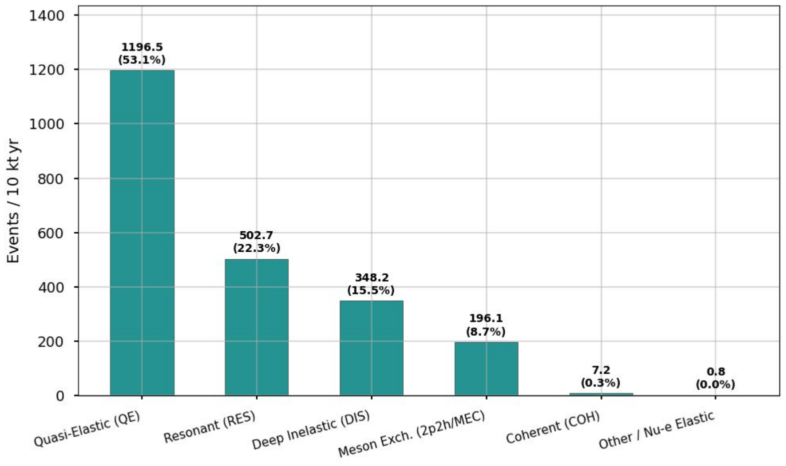
Physics Background: Atmospheric Neutrinos

Honda flux simulation, 3-flavor oscillations, and eutrinonevent 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**

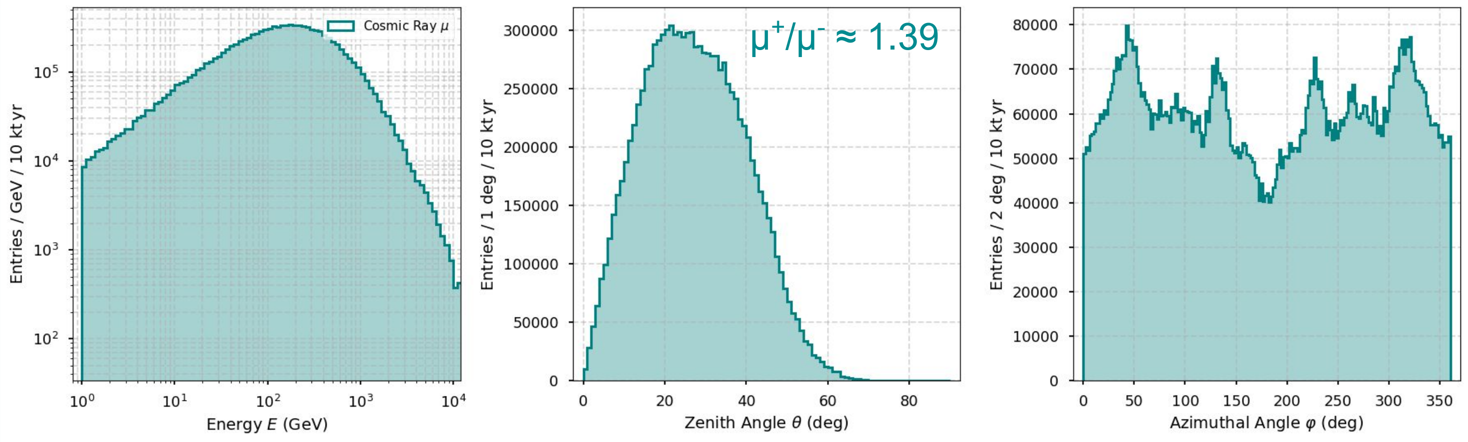


Physics Background: Cosmic Ray Muons

MUSIC/MUSUN simulation at DUNE-SURF underground depth

Underground Overburden & Muon Simulation

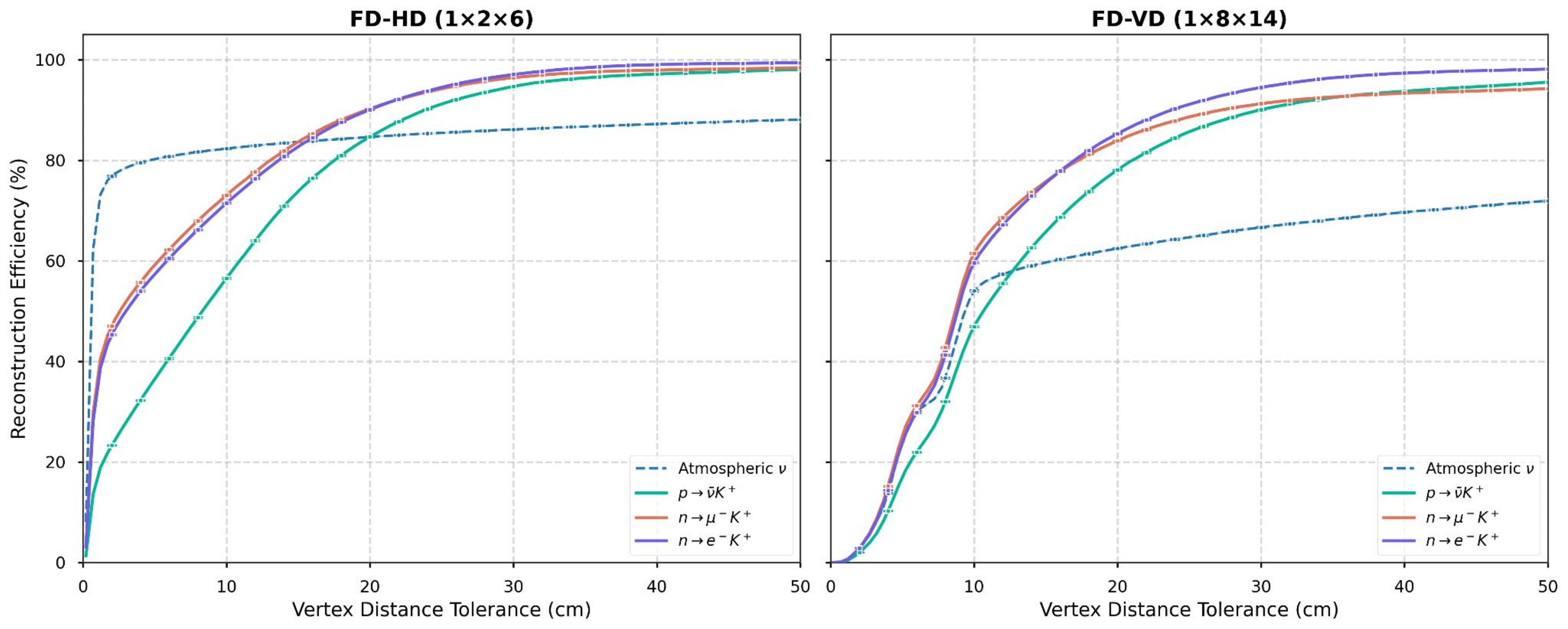
- **SURF Overburden Depth:** 1.48 km cavern depth to shield against muons; very energetic muons reach the Far Detector.
- **Surface-to-Underground Transport (MUSIC):** Simulates stochastic energy loss (pair production, bremsstrahlung, photonuclear) of surface cosmic ray muons traversing the rock.
- **Underground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



Detector Reconstruction Performance

Pandora Reconstruction Performance

Vertex reconstruction

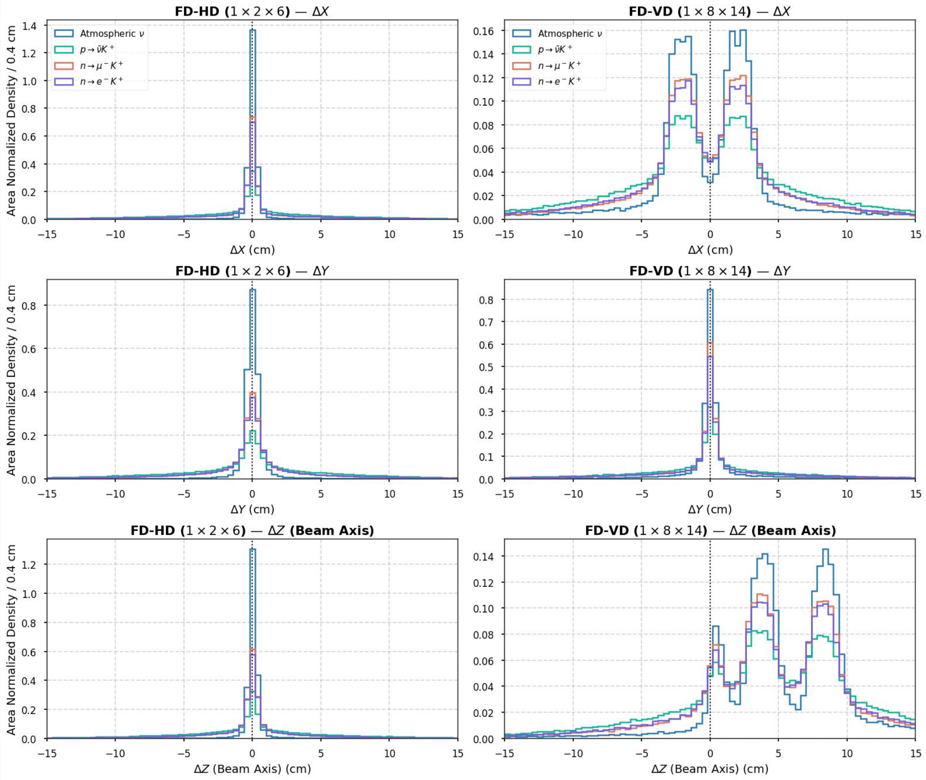


Pandora Reconstruction Performance

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.

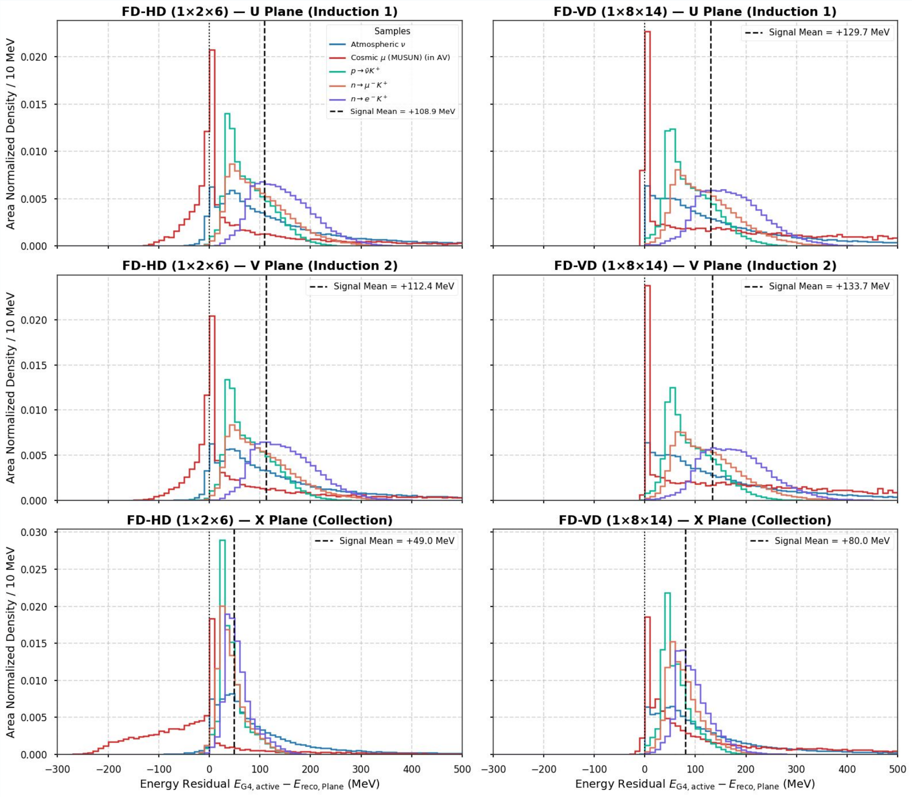


Pandora Reconstruction Performance

Energy reconstruction

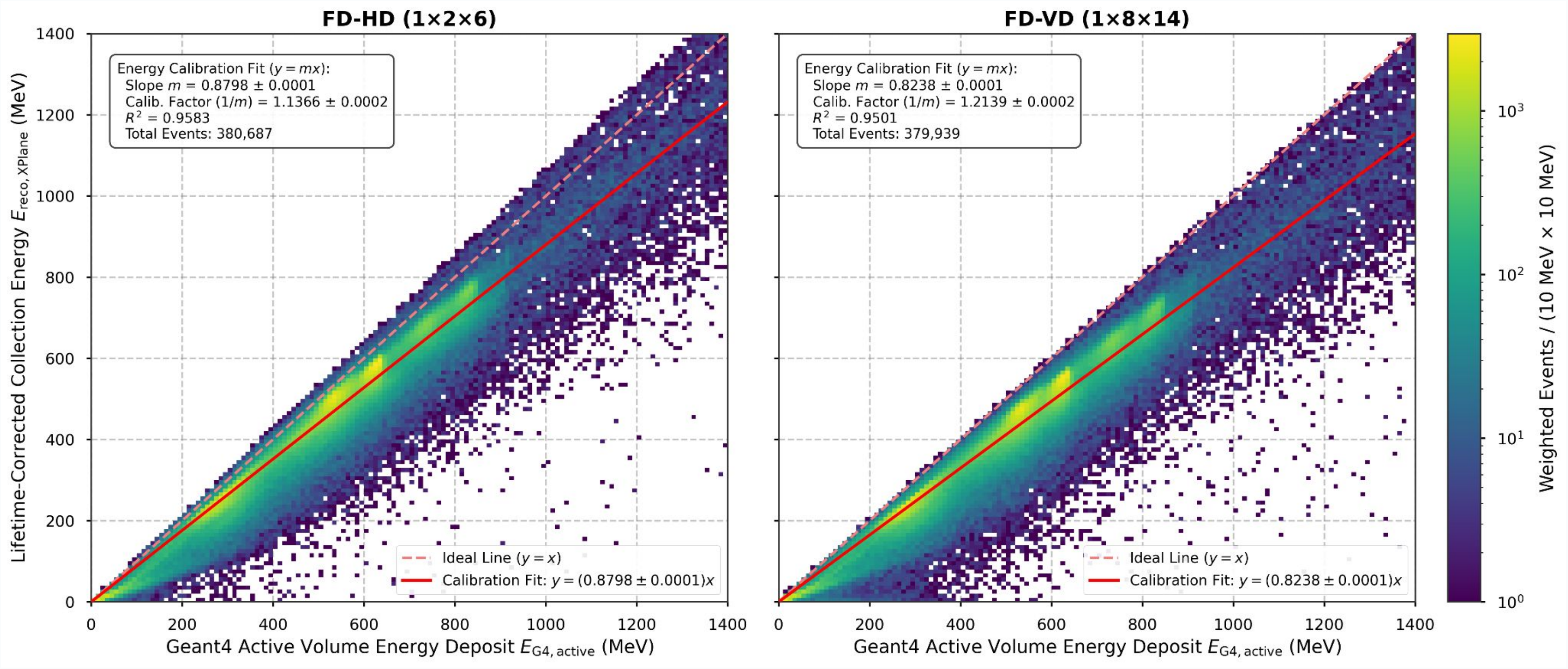
Readout Plane Reconstruction

- **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



Pandora Reconstruction Performance

K^+ tracks

Truth Matching Criteria

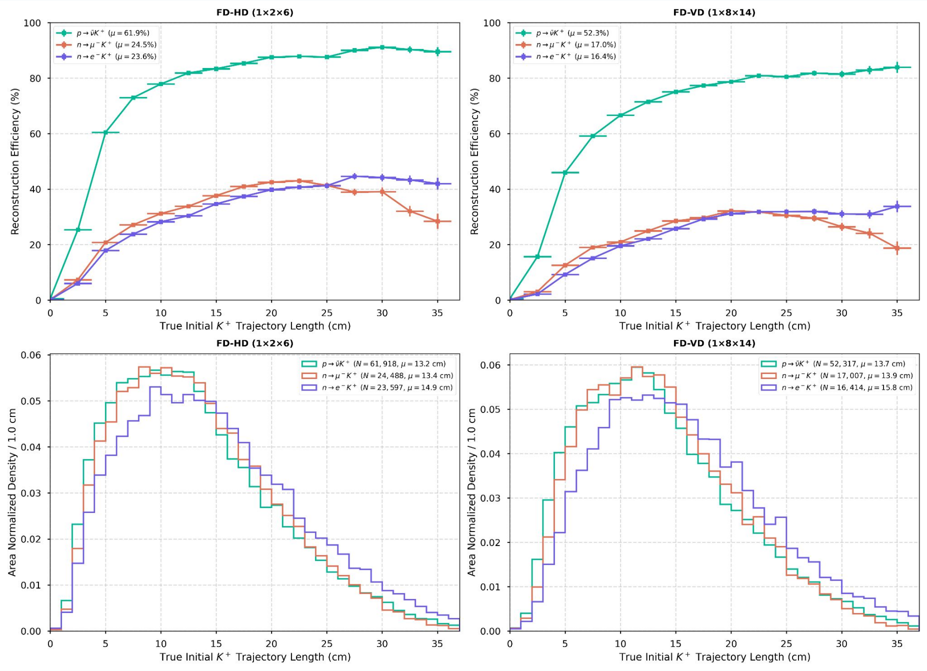
- **Matching Definitions:**

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

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

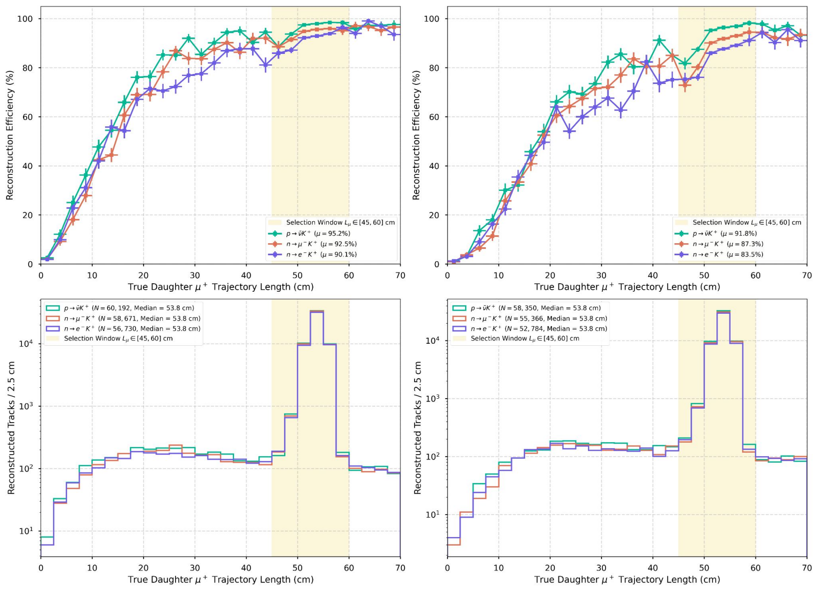
- **Primary Kaon Tracking Efficiency:**
  - Reaches > 86.5% (> 78.5%) tracking efficiency in FD-HD (FD-VD) for primary K^+ with true length $L_K > 20$ cm for the golden channel.
  - Neutron decay modes exhibit lower efficiency due to energy deposits from the charged primary lepton.
- **Short Track Limitations:**

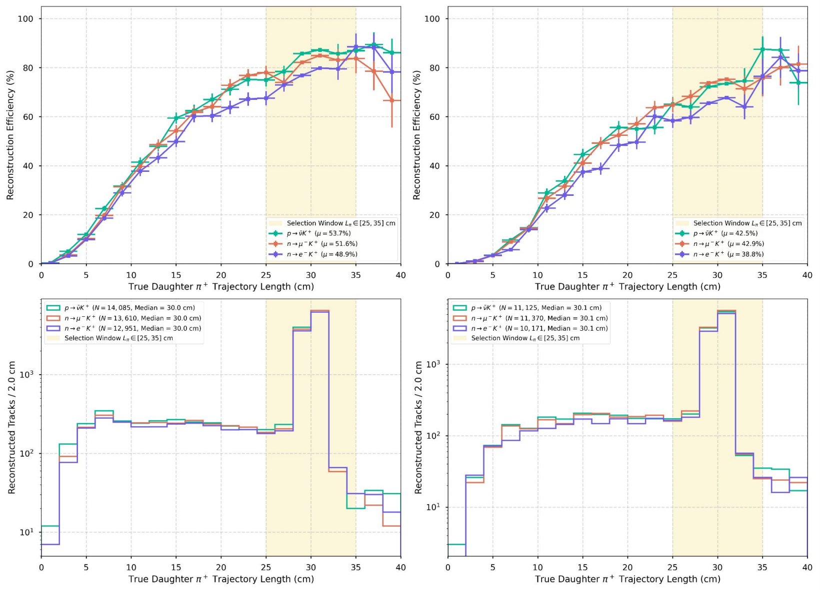
Primary kaons with $L_K < 5$ cm (very low T_K) suffer tracking efficiency drops due to 2D hit clustering limits.



Pandora Reconstruction Performance

μ^+ and π^+ tracks





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

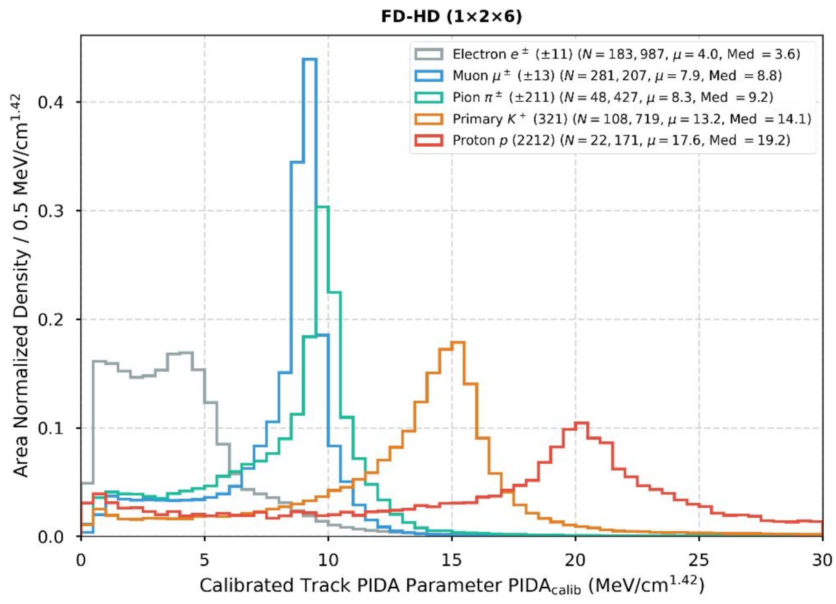
$K_{\pi 2} \in [25, 35]$

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 MeV/cm$^{1.42}$.
  - Kaons: Intermediate PIDA band ∈ [10.0, 17.0] MeV/cm$^{1.42}$.
  - Protons: PIDA > 17.0 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

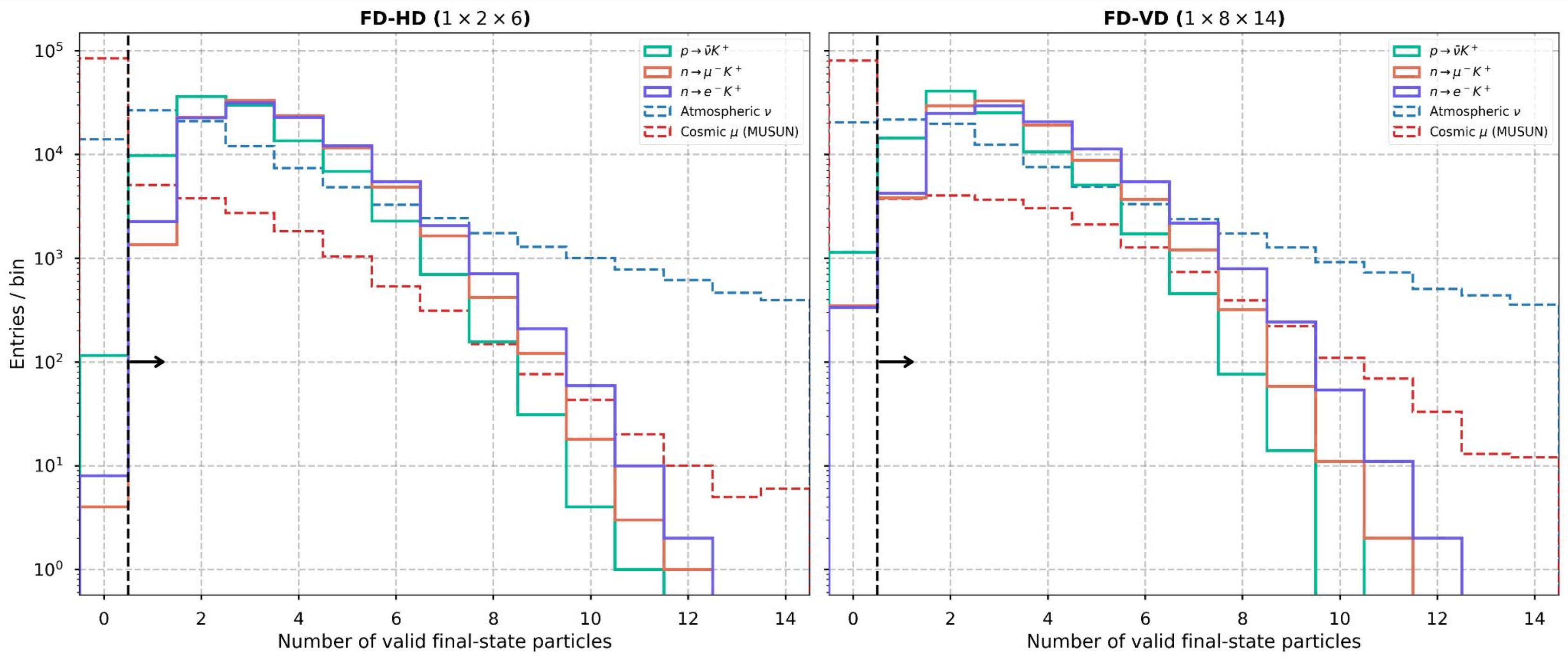
4. Charge ROI ∈ [30, 1000] MeV

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.

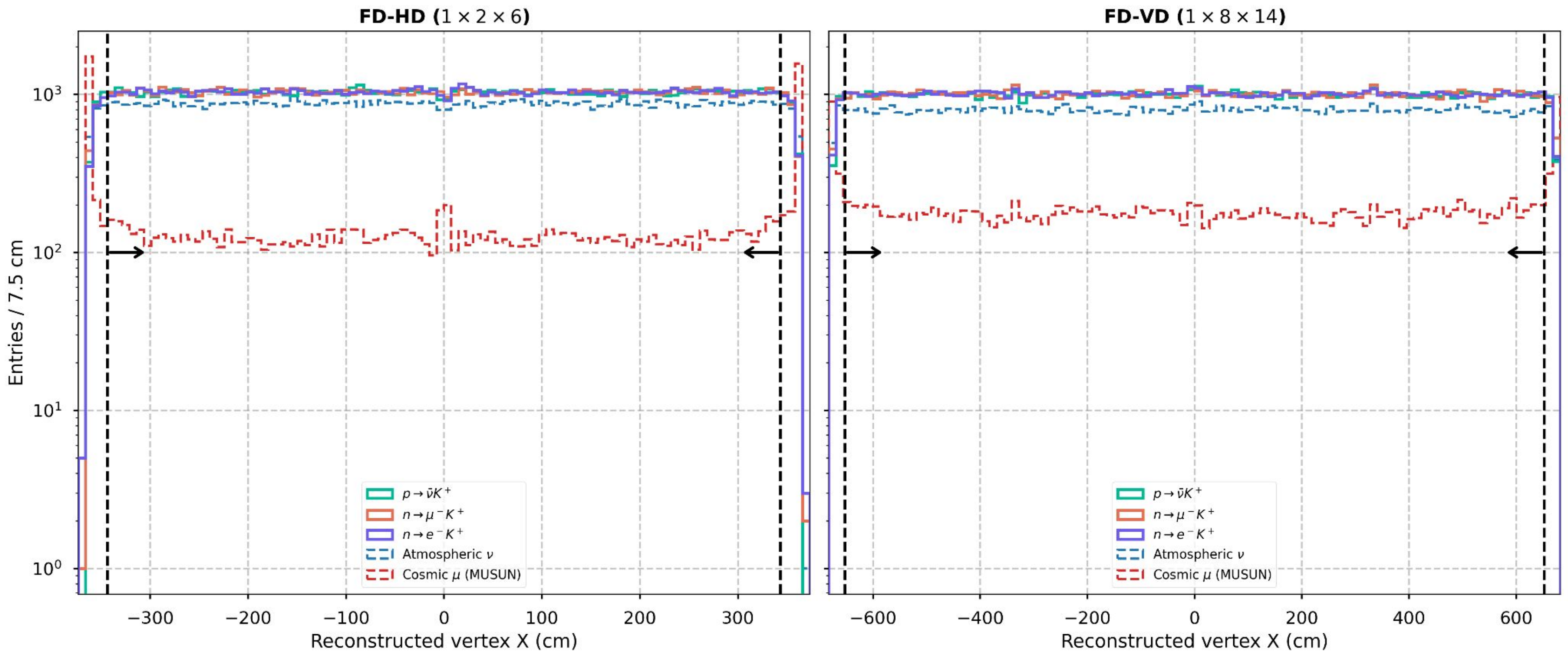
Event Selection

Valid Pandora Fina-State Particle



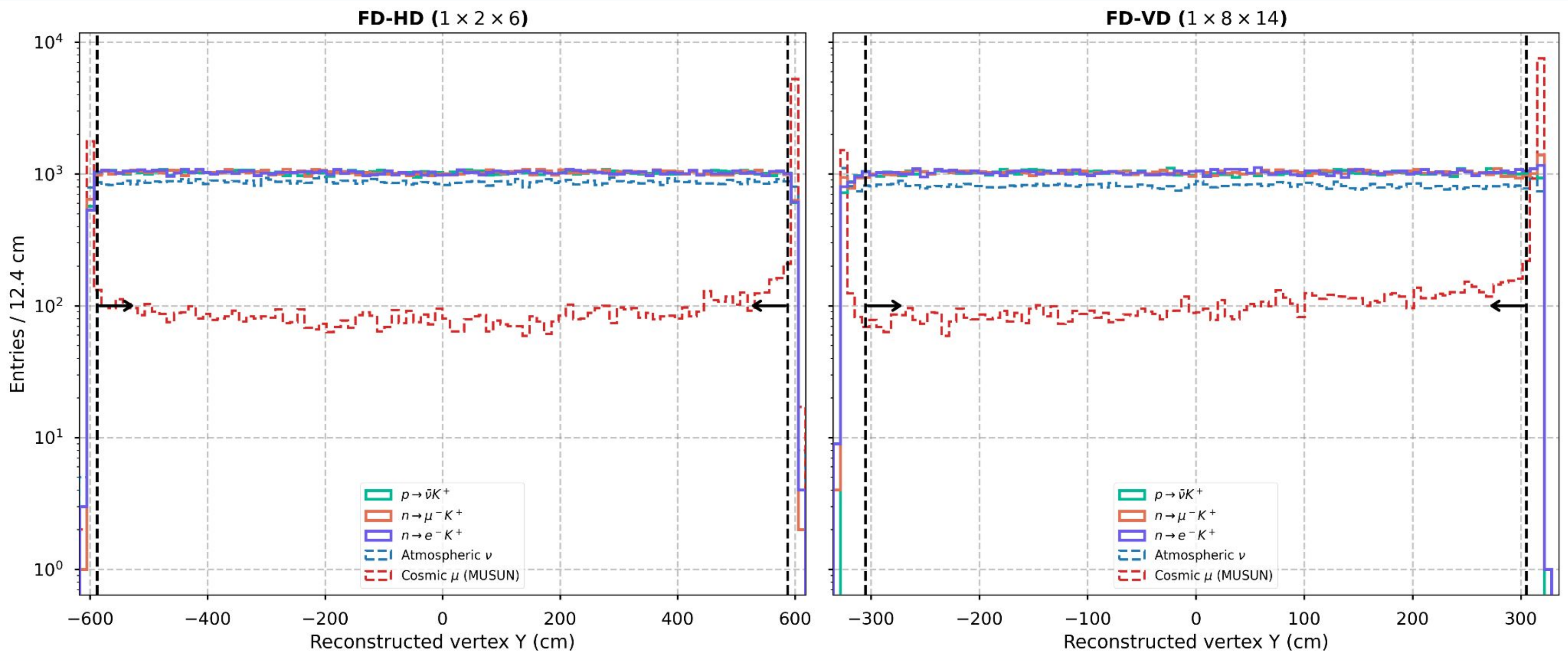
Event Selection

Pandora Vertex in Fiducial Volume (t_0 = 0)



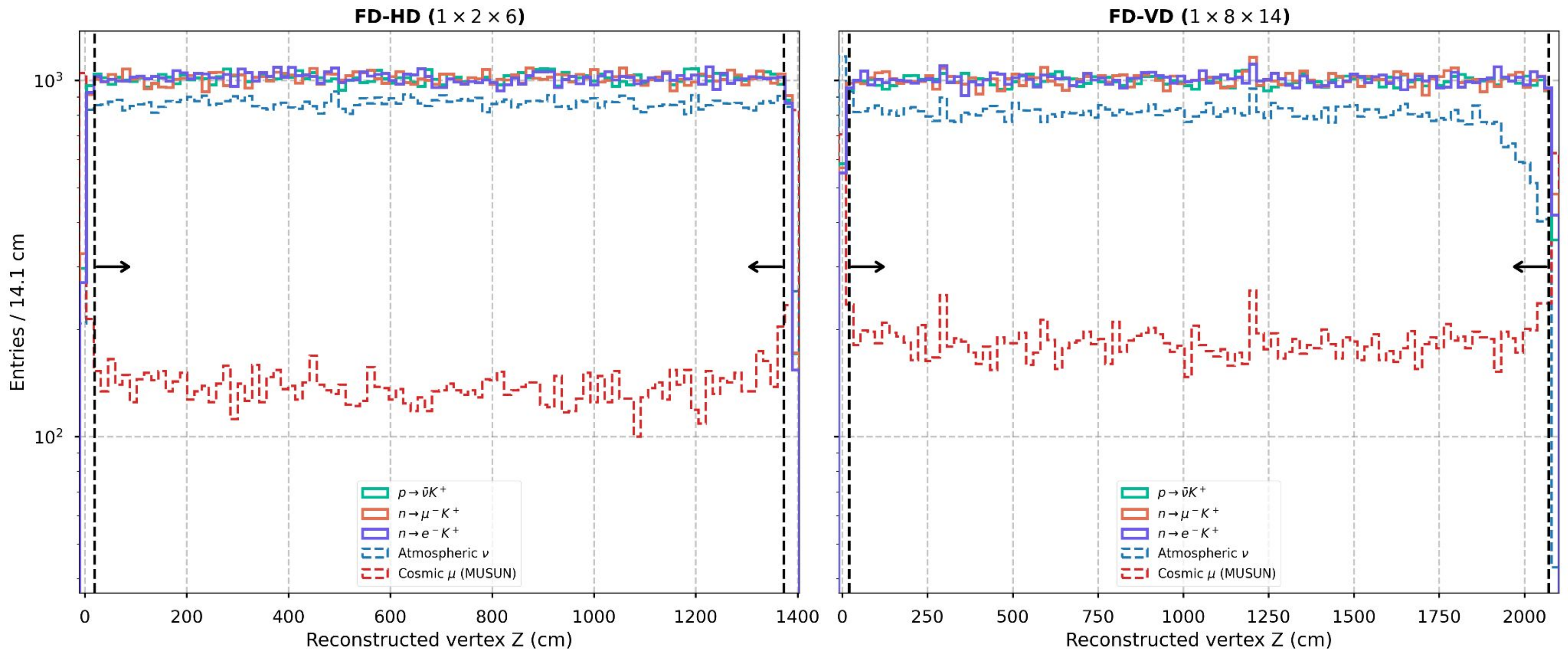
Event Selection

Pandora Vertex in Fiducial Volume (t_0 = 0)



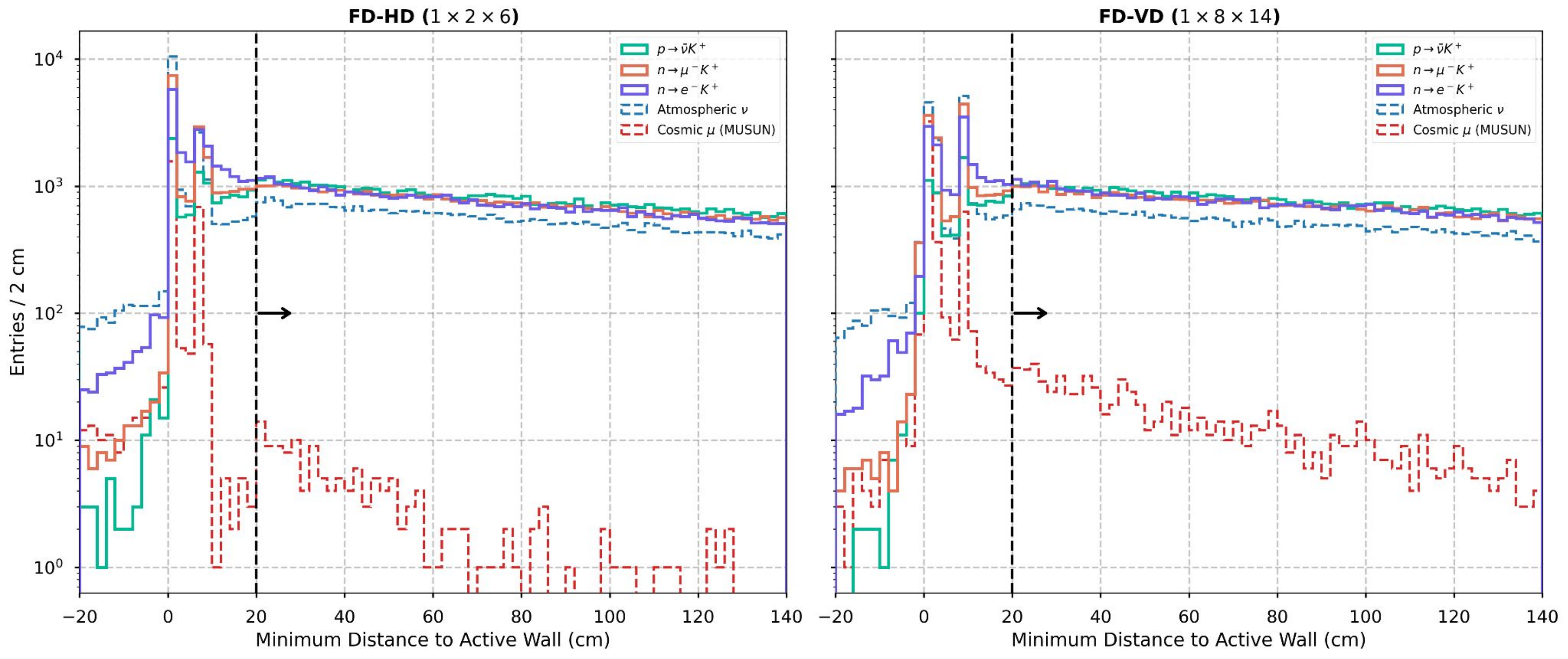
Event Selection

Pandora Vertex in Fiducial Volume (t_0 = 0)



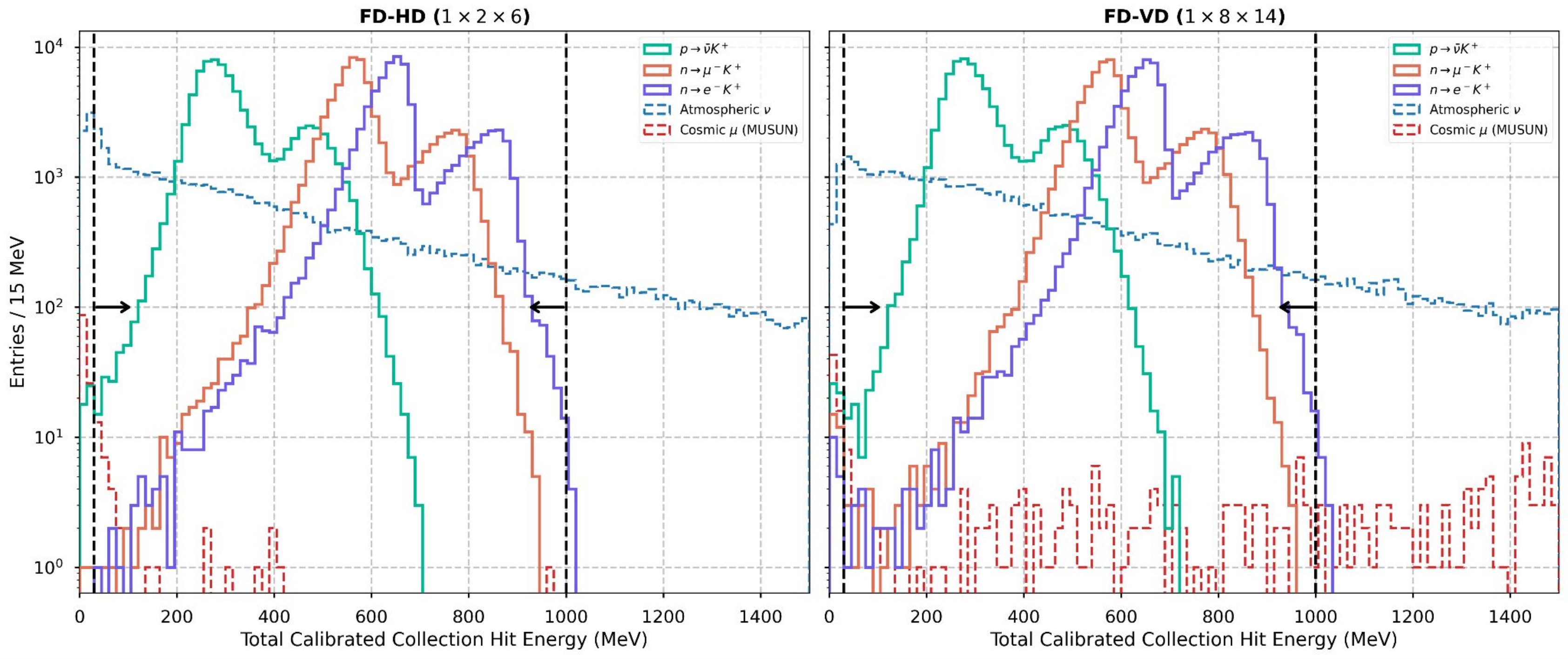
Event Selection

Pandora Space Points in Fiducial Volume



Event Selection

Charge ROI ∈ [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 ∈ [30, 1000] MeV

5. Decay topology

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

7. PIDA Proton Veto

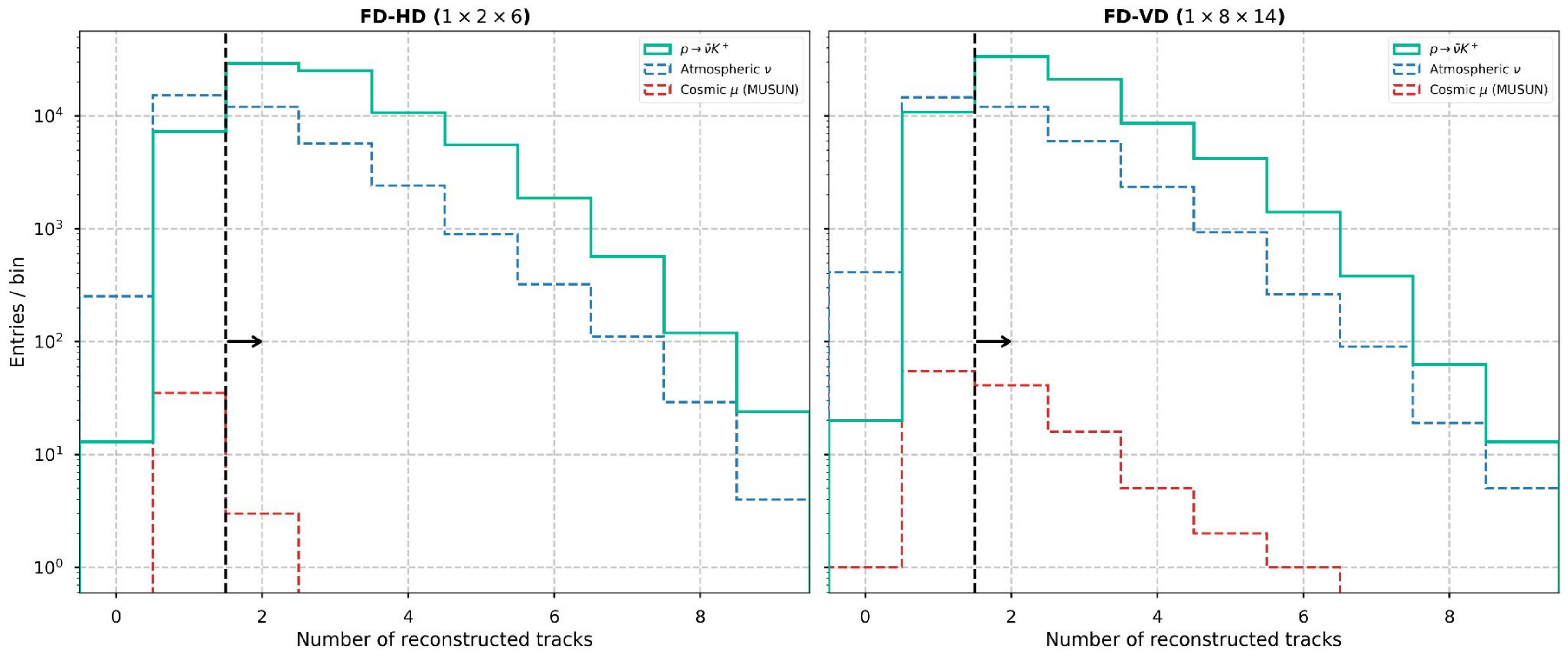
8. Final Charge ROI

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

- 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 ($p \to \bar{\nu} K+$), ≤650 ([650, 1000]) MeV ($n \to \mu- K+$), ≤700 ([700, 1000]) MeV ($n \to e- K+$).

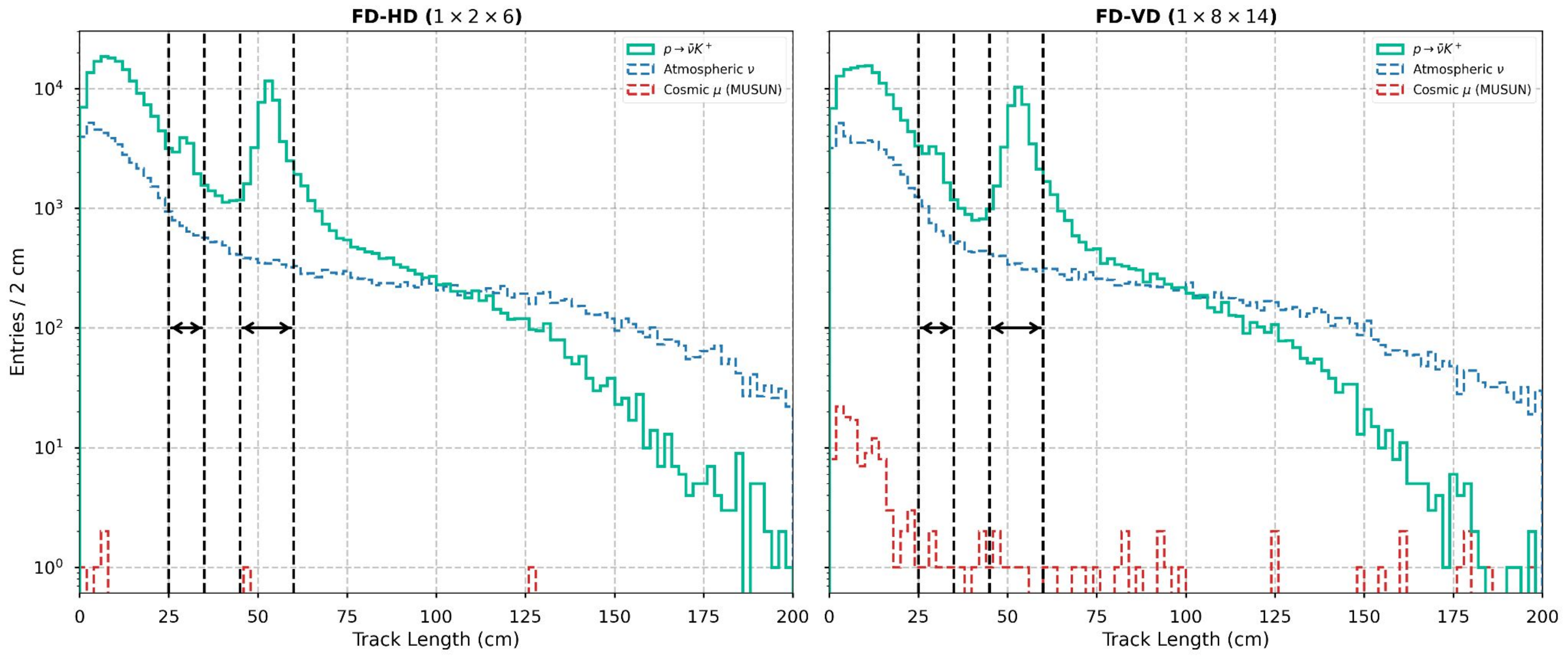
Event Selection: $p \rightarrow \bar{\nu} K^+$

Decay Topology



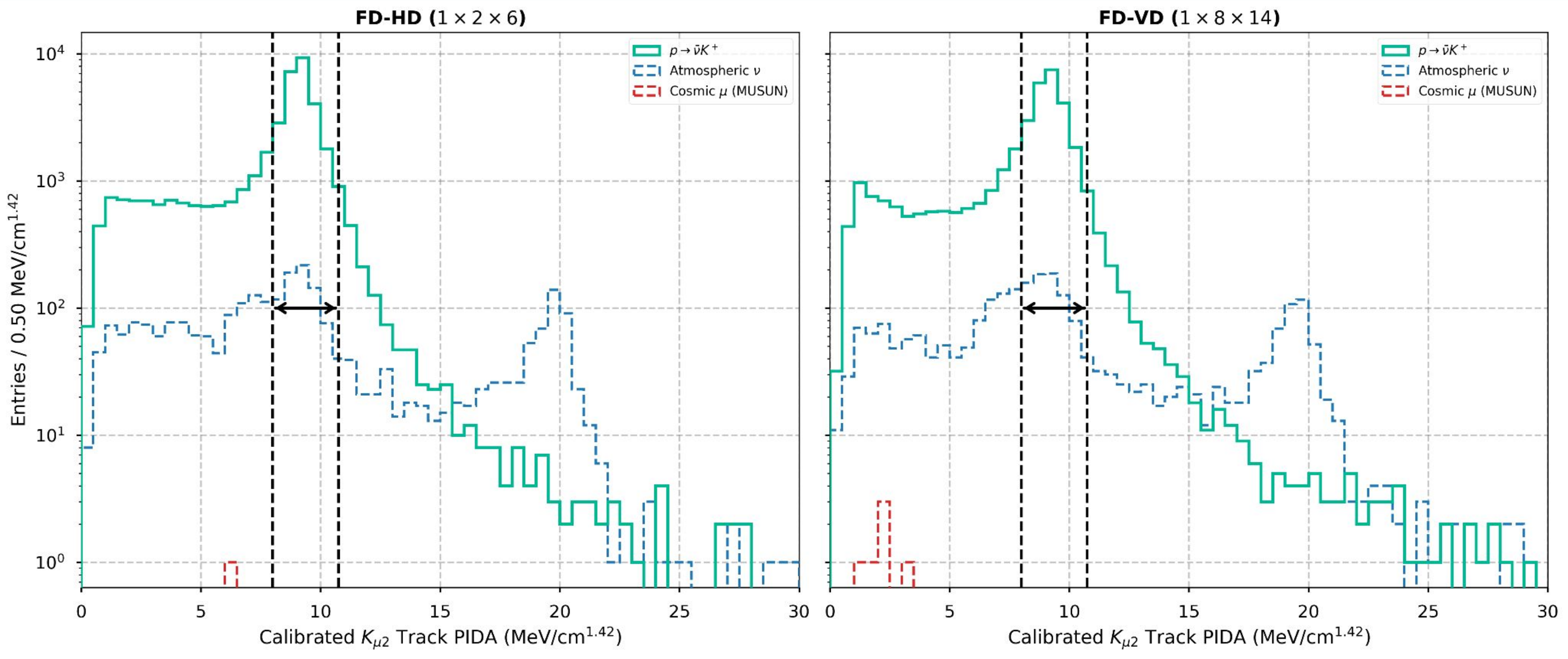
Event Selection: $p \rightarrow \bar{\nu} K^+$

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



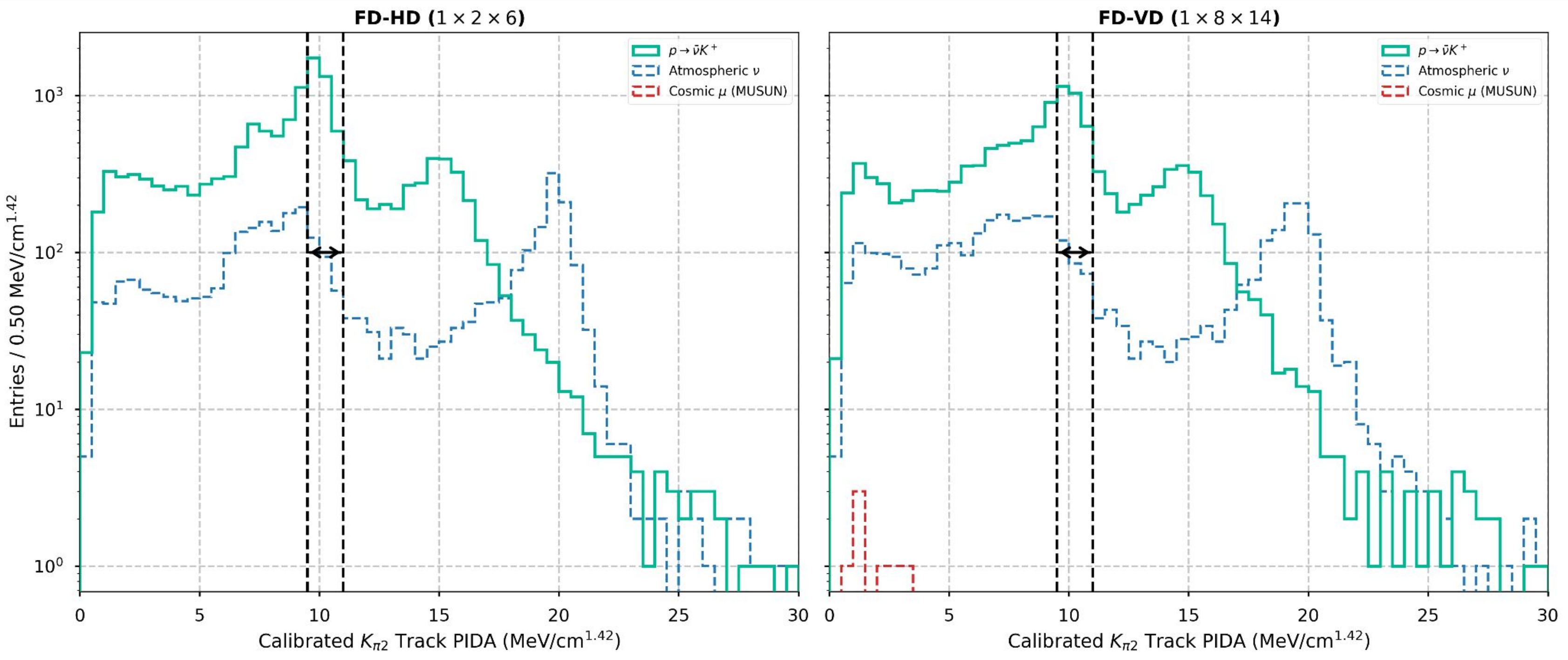
Event Selection: $p \to \bar{\nu} K^+$

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



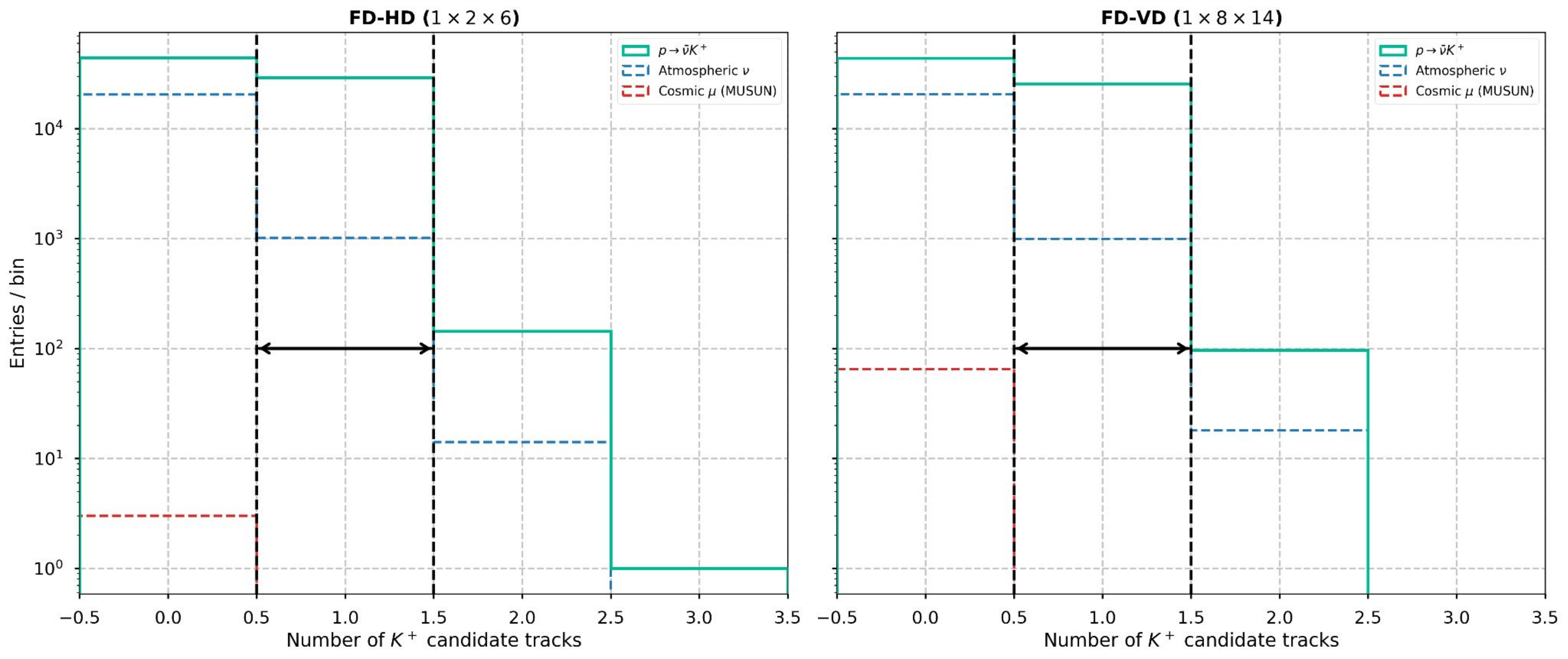
Event Selection: $p \rightarrow \bar{\nu} K^{+}$

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



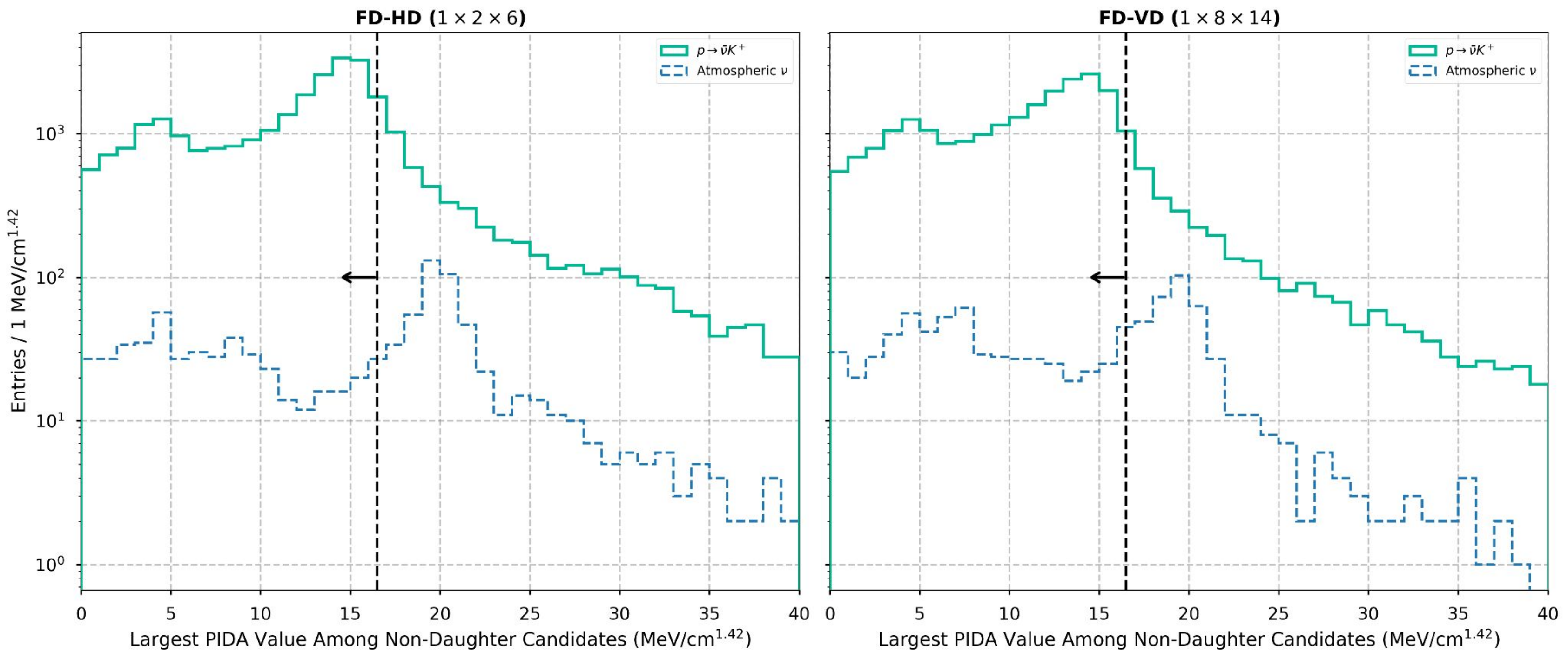
Event Selection: $p \to \bar{\nu} K^+$

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



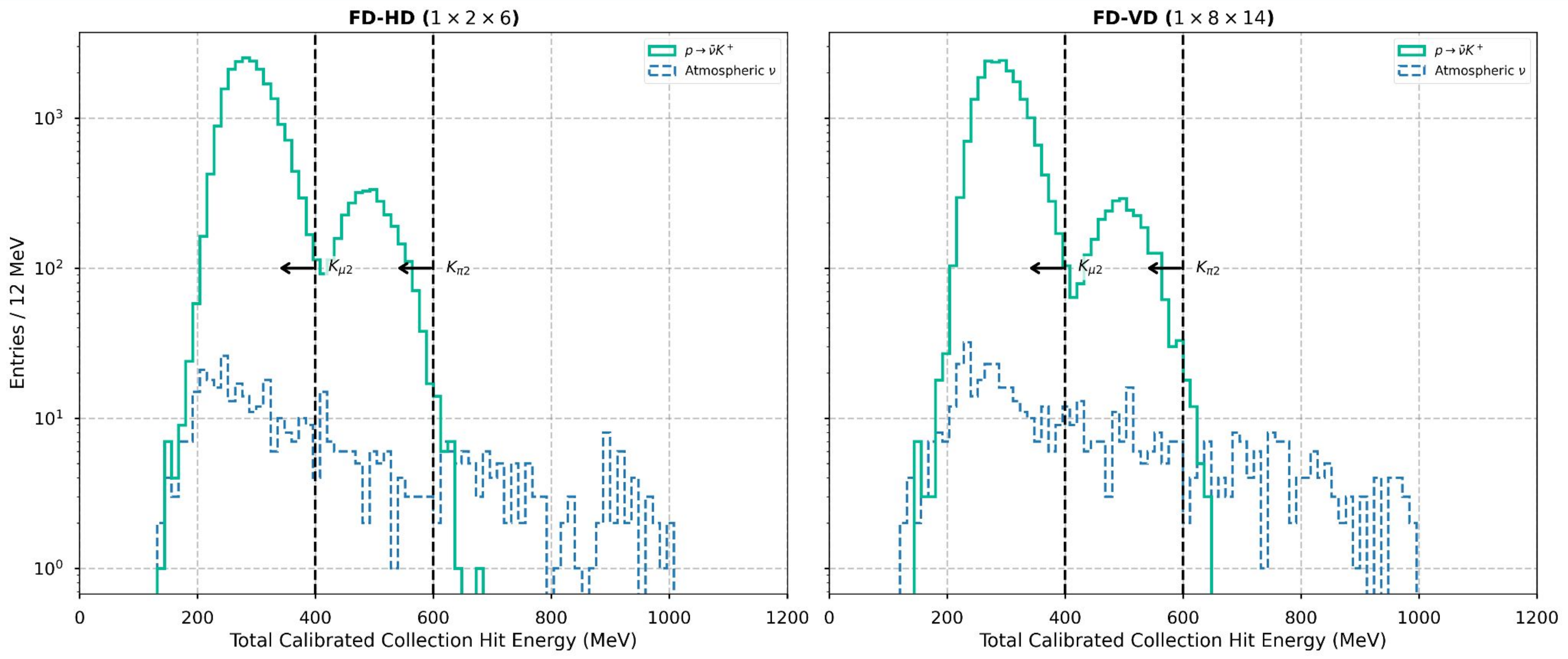
Event Selection: $p \rightarrow \bar{\nu} K^+$

PIDA Proton Veto



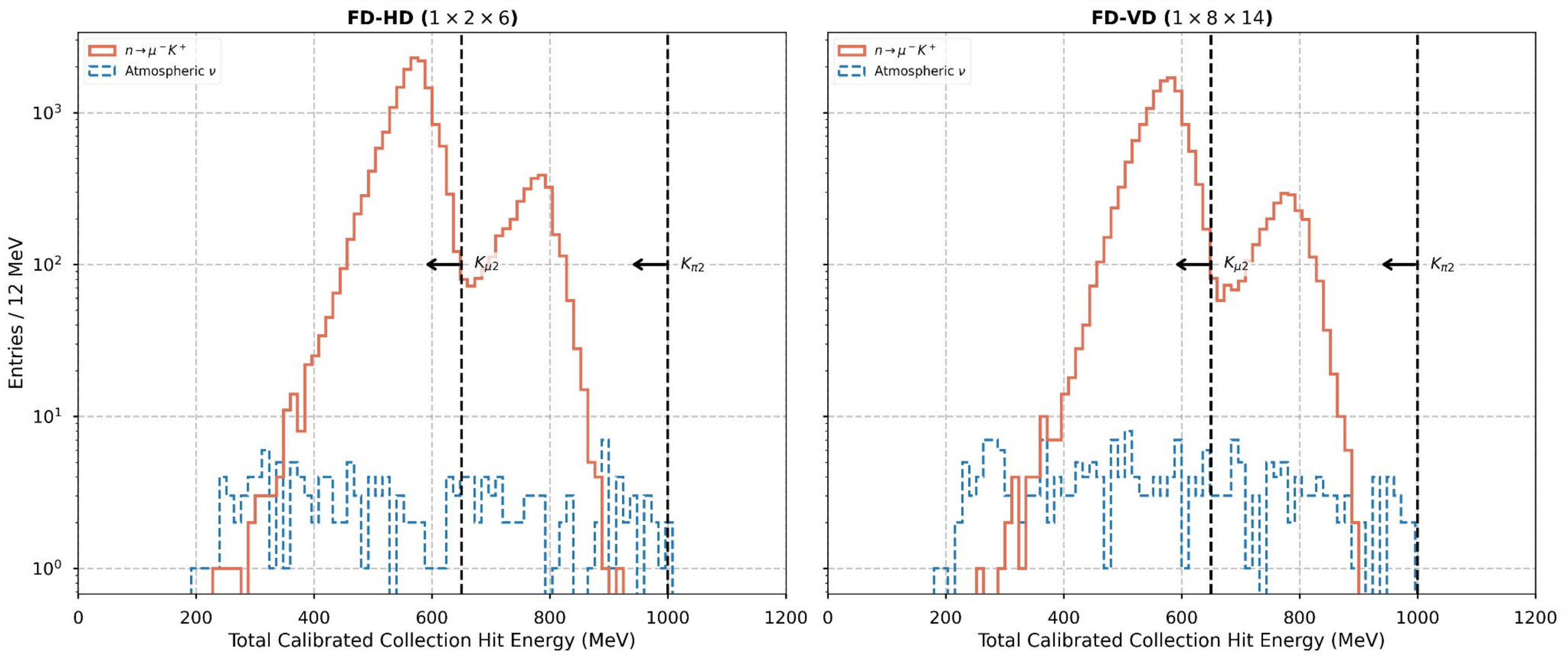
Event Selection: $p \rightarrow \bar{\nu} K^+$

Final Charge ROI



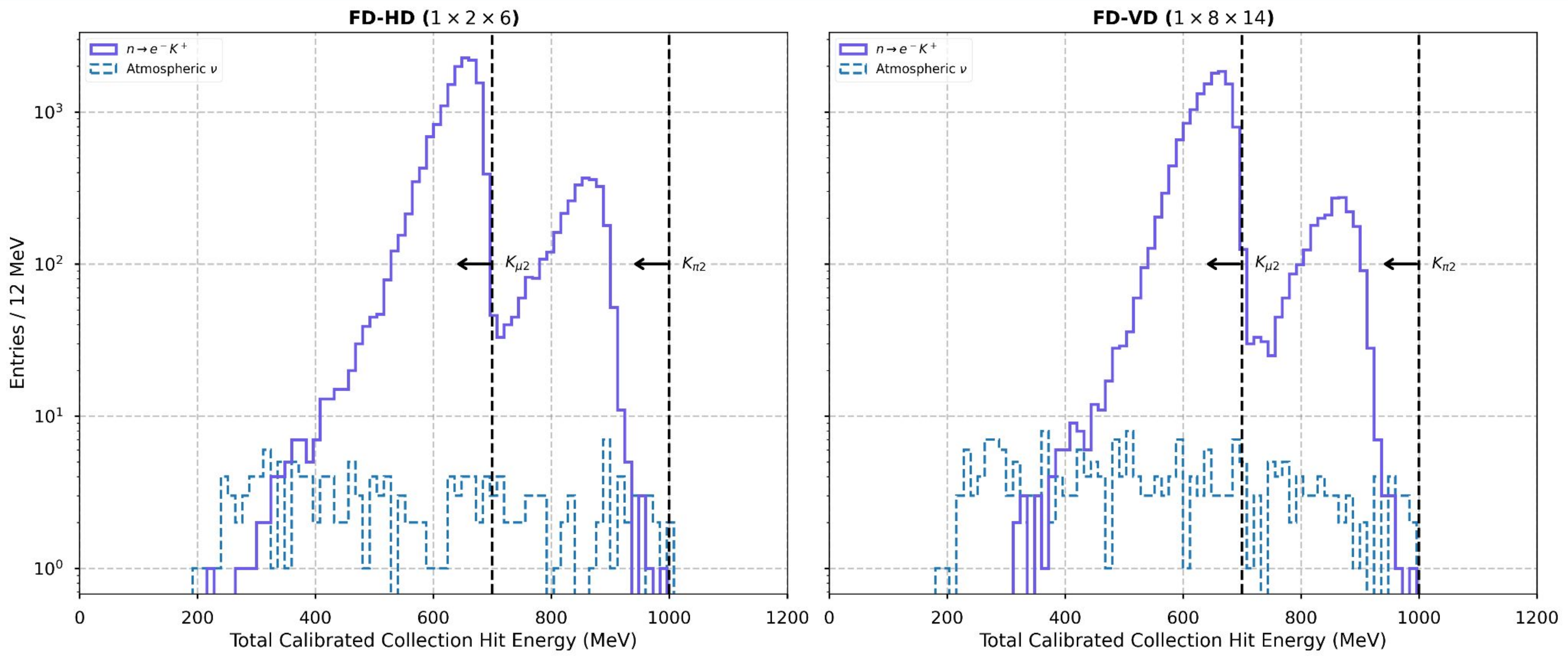
Event Selection: n → $\mu^- K^+$

Final Charge ROI



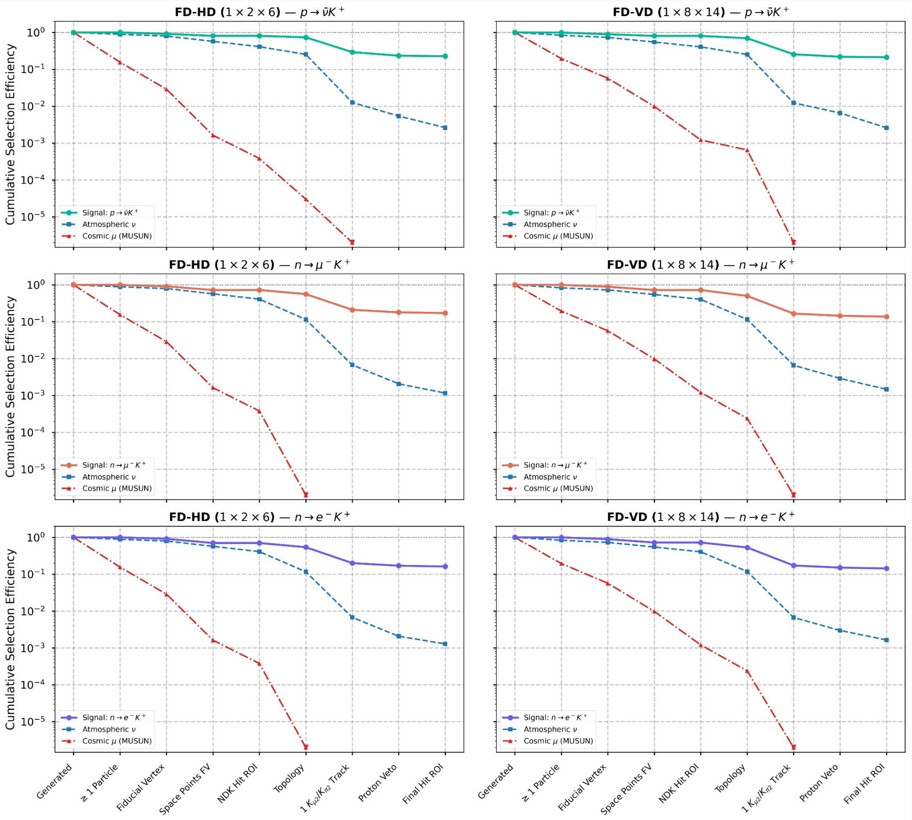
Event Selection: $n \rightarrow e^- K^+$

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 ν / 10 kt year.
- Cosmic Muons: 11 × 10^6 μ / 10 kt year.

Post-Cut Final Annualized Exposures:

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

FD-VD (1x8x14) Module ~ 2.57 kton

Initial Generated Exposures:

- Atmospheric Neutrinos: 2251.4 ν / 10 kt year.
- Cosmic Muons: 11 × 10^6 μ / 10 kt year.

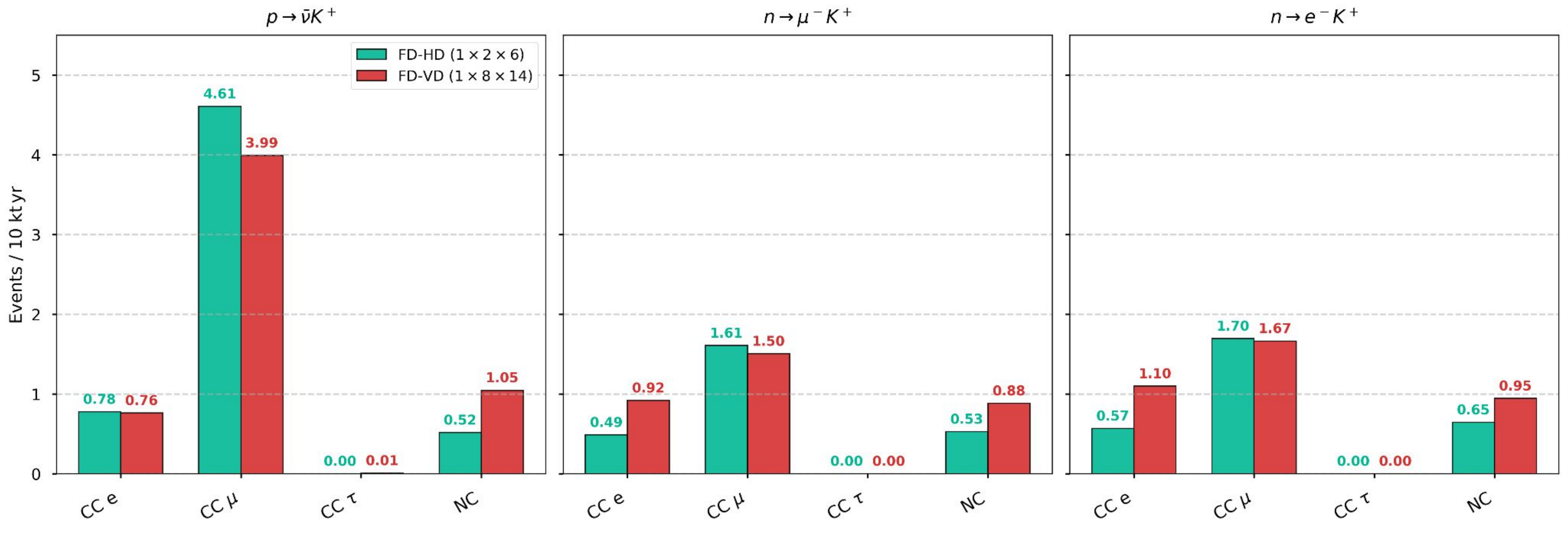
Post-Cut Final Annualized Exposures:

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

Background Composition

Comparative an

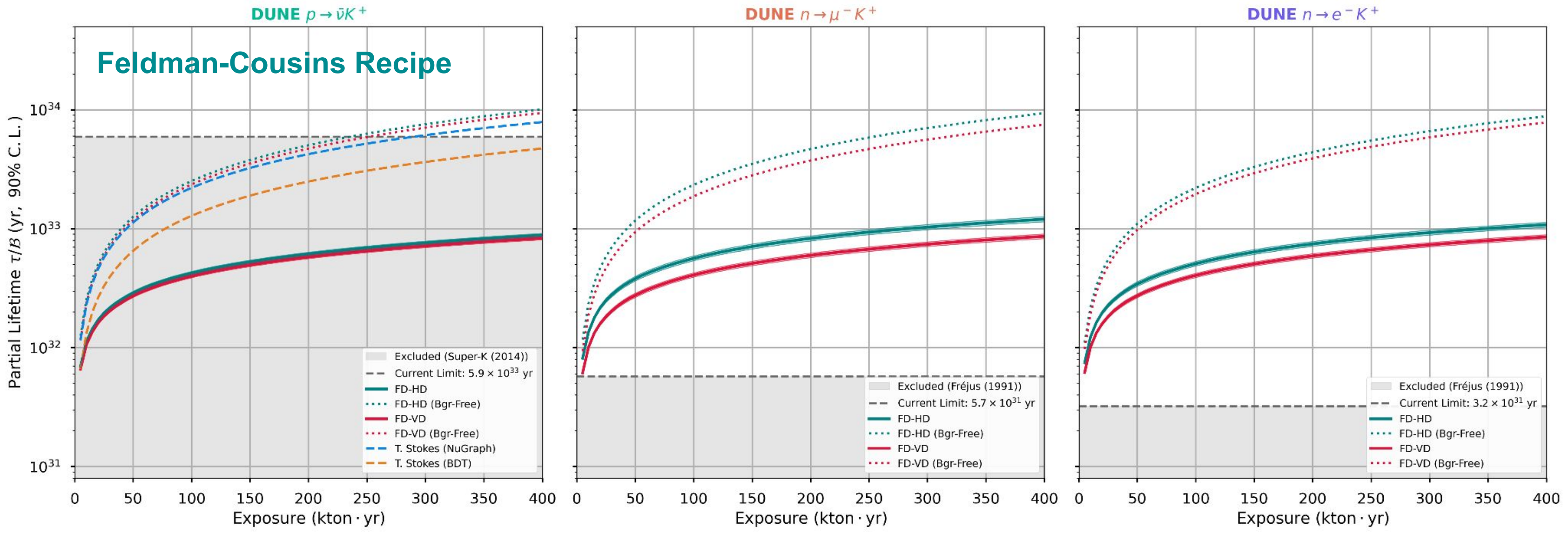
- Dominant background: CC interactions from muon neutrinos and antineutrinos.
- Electron CC and NC interactions are also significant.



Sensitivities & Outlook

Nucleon Decay Sensitivity in DUNE FD

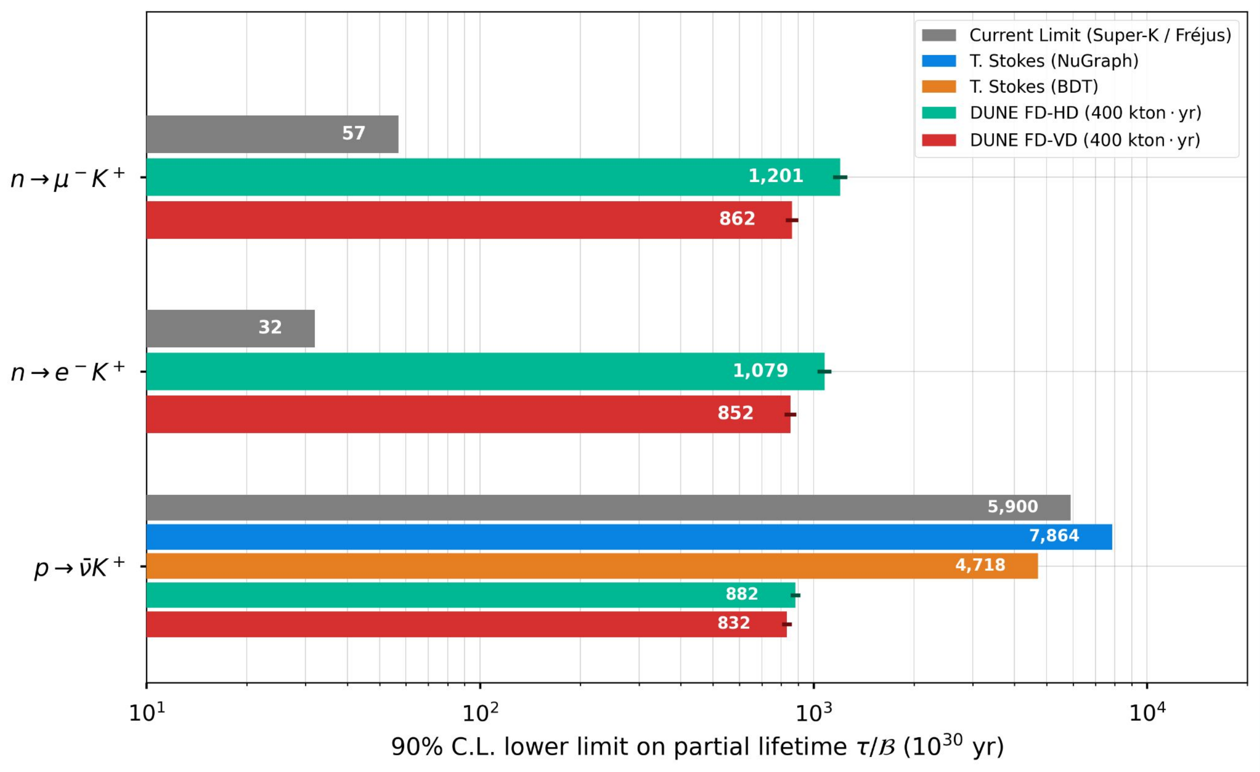
Sensitivity as a function of the exposure in DUNE FD



For more details about the statistical treatment, please refer to: J.J. Gomez-Cadenas, J. Martin-Albo, M. Sorel et al., "Sense and sensitivity of double beta decay experiments," JCAP 1106 (2011) 007, http://arxiv.org/abs/1010.5112

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

A&E/ANOA Working Group Meeting

Presented by: **Hamza Amar Es-sghir** & Michel Sorel
Date: August 26, 2026