UNIVERSITY OF CAMBRIDGE

Proton Decay Search with MicroBooNE and DUNE Experiments

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Natsumi Taniuchi — 03/02/2022 Annual ESR Meeting

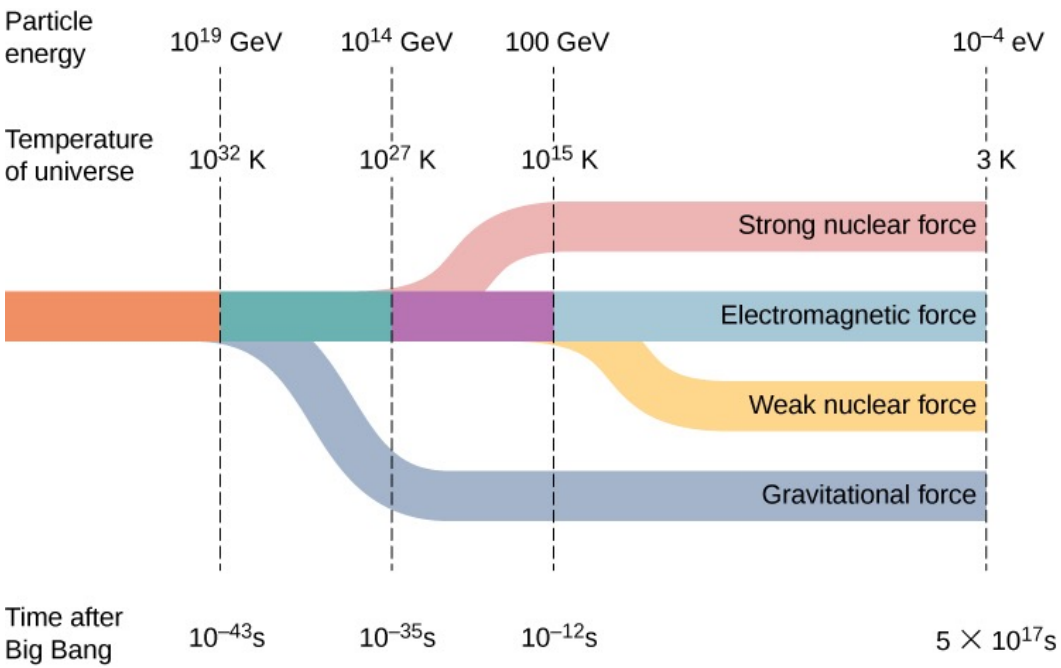
Grand Unified Theory (GUT): Unification of Three Forces

Hypothesis: Fundamental four forces can be unified into one.

✓ Unification of electromagnetic & weak forces proven

Grand Unified Theory (GUT): Unification of electromagnetic, weak, and strong forces.

- Coupling constants merges into one at very high energy (~10^16 GeV).
- Violation of baryon number with low energy.

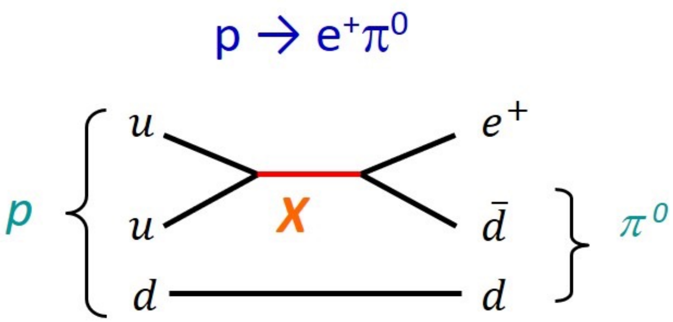


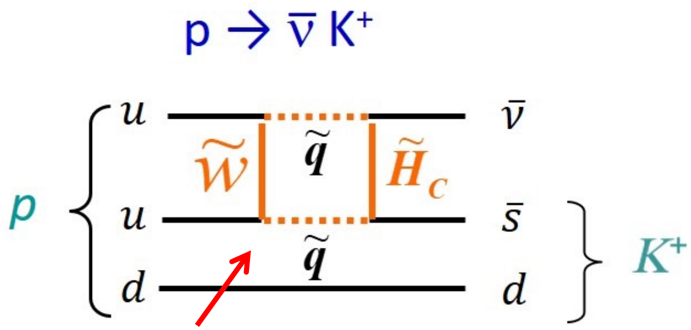
Proton Decay Phenomenon expected by GUTs

GUTs predict protons to decay into lighter particles.

- ✓ Low decay probability & long lifetime: $10^{30}\sim10^{40}$ years.
- ✓ Various decay modes: with/without SUSY
  1. lepton + non-strange meson (e.g.: $p \rightarrow e^{+}\pi^{0}$)
  2. lepton + strange meson: (e.g.: $p \rightarrow \bar{\nu}K^{+}$) → Assume Supersymmetry (SUSY)

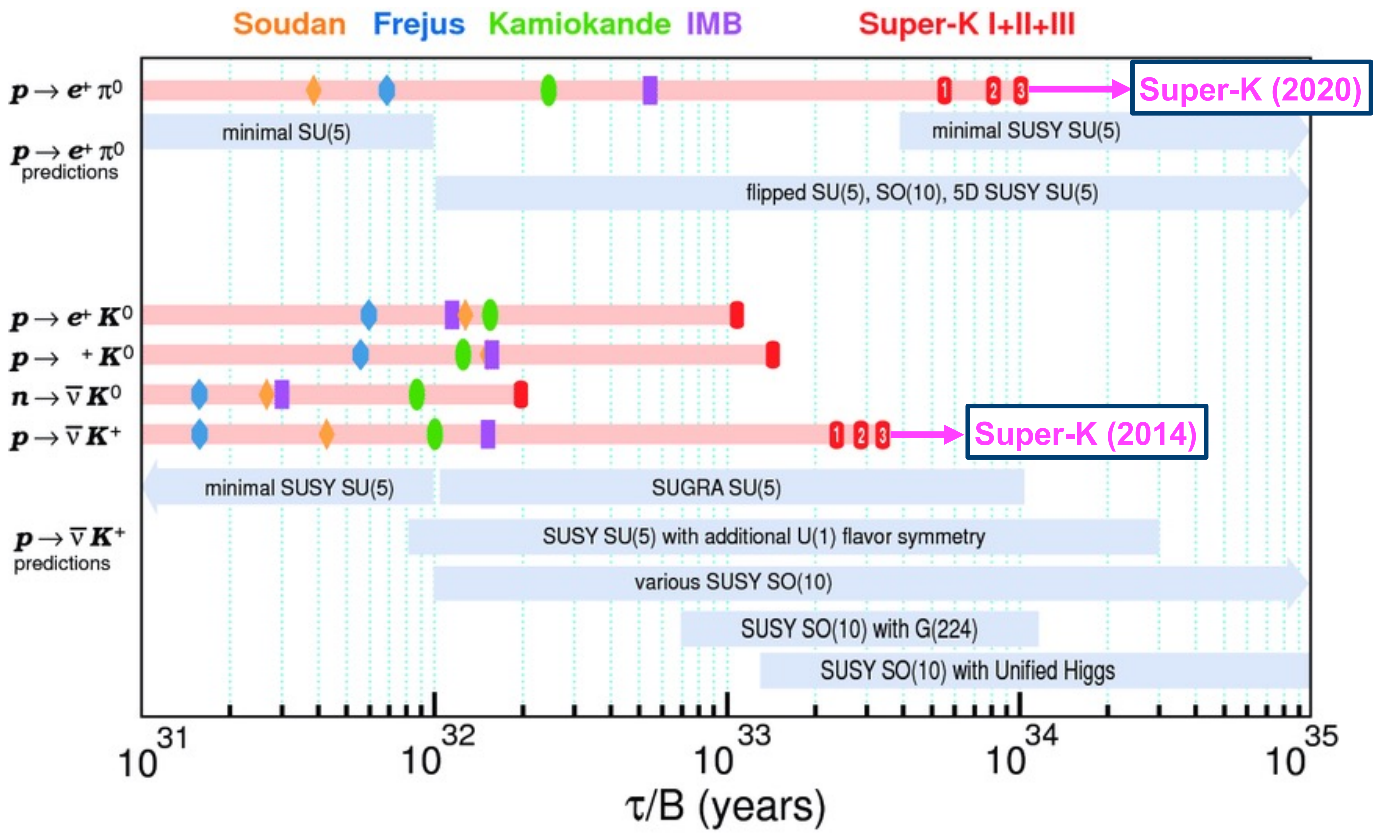
A conjectured symmetry between fermions and bosons.
Particles will have supersymmetric partner.



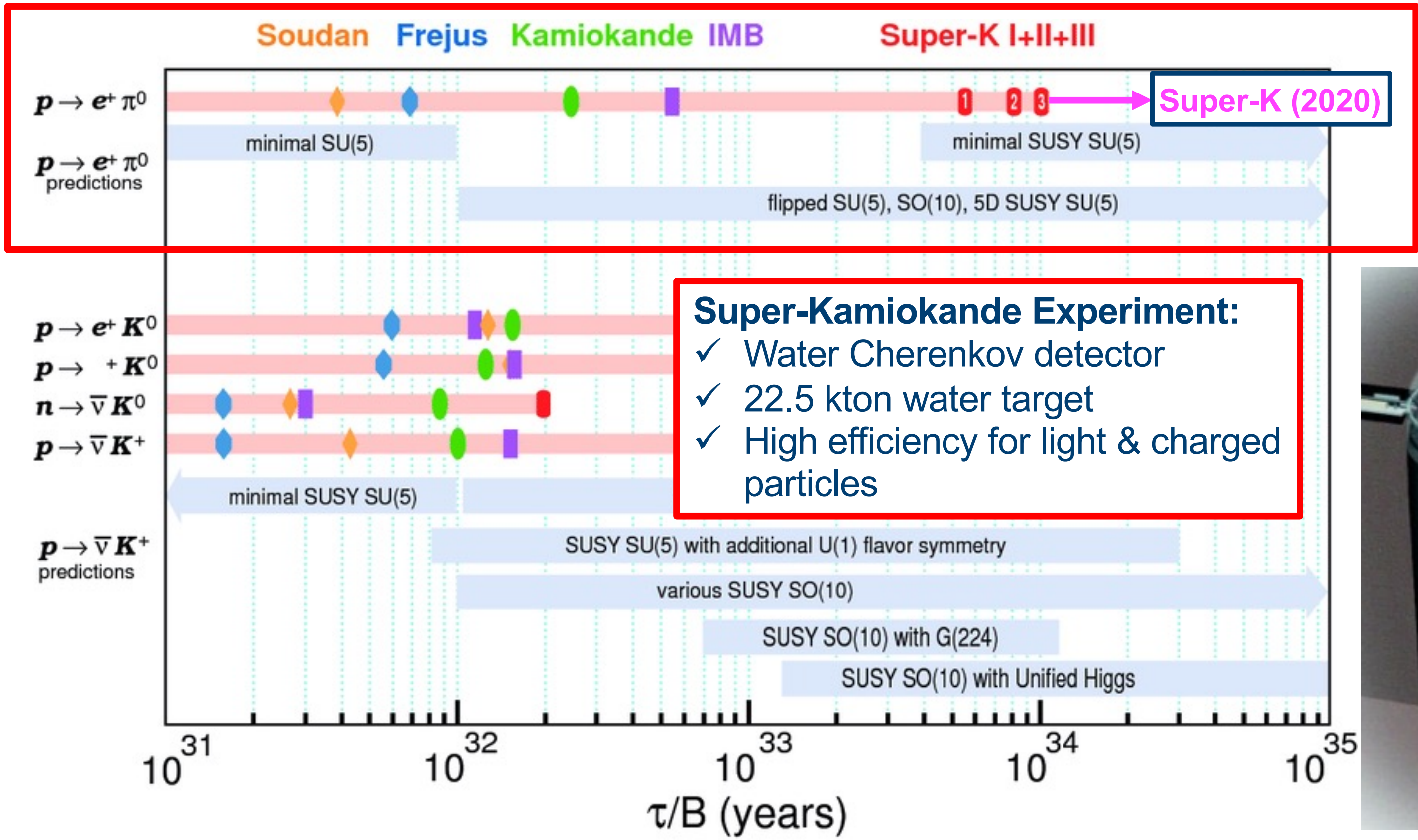


Supersymmetric partners

History of Proton Decay Searches

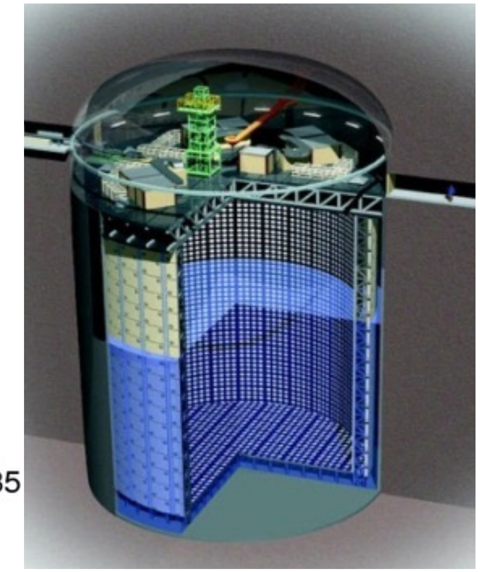


History of Proton Decay Searches



Super-Kamiokande Experiment:

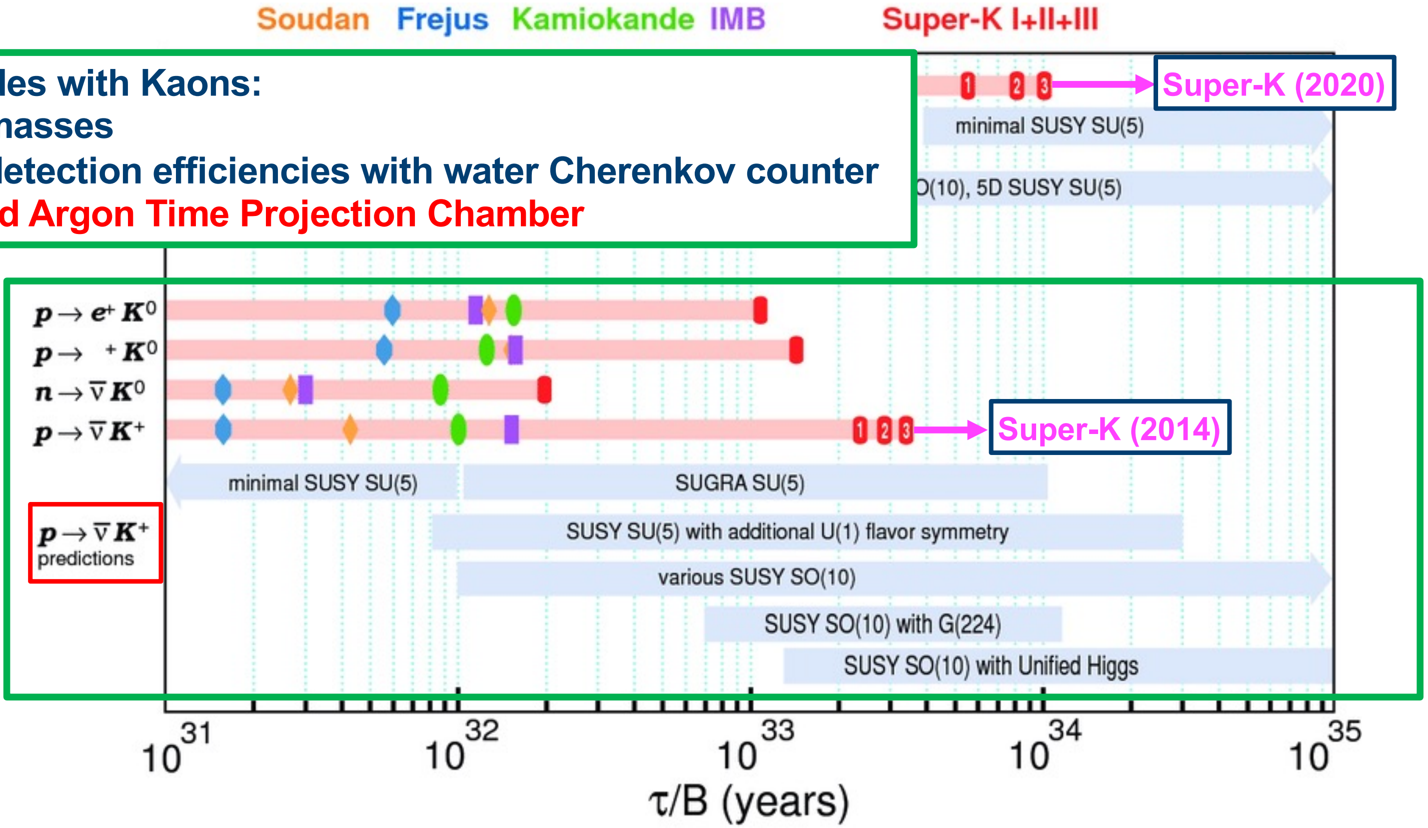
- ✓ Water Cherenkov detector
- ✓ 22.5 kton water target
- ✓ High efficiency for light & charged particles



History of Proton Decay Searches

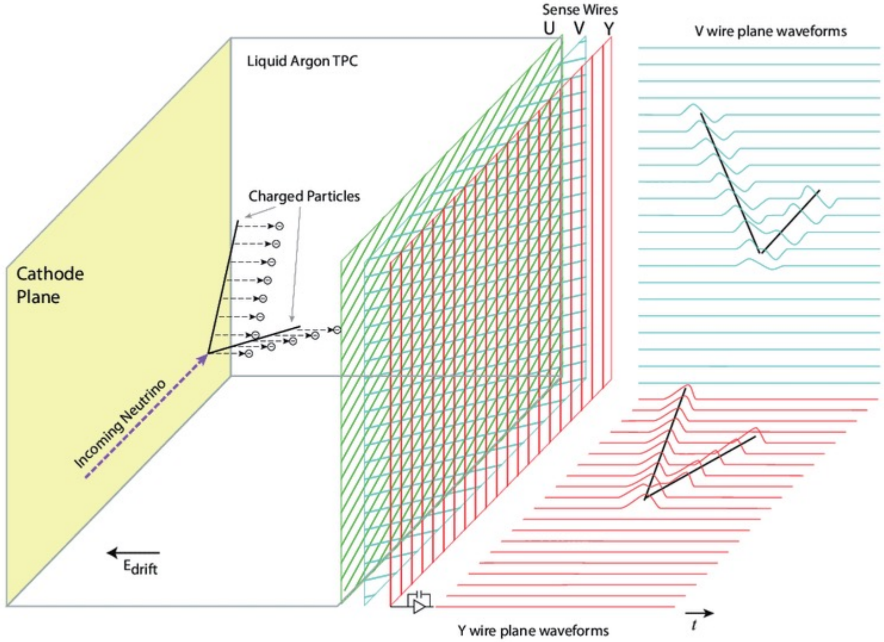
Decay modes with Kaons:

- **Heavy masses**
- **Lower detection efficiencies with water Cherenkov counter**
  → Liquid Argon Time Projection Chamber



LArTPC: Liquid Argon Time Projection Chamber

- Charged particles traversing the medium ionizes atoms to generate electrons along the path
- Deliver precise 3D tracking image with fine-grained wire readouts for various particles including Kaon



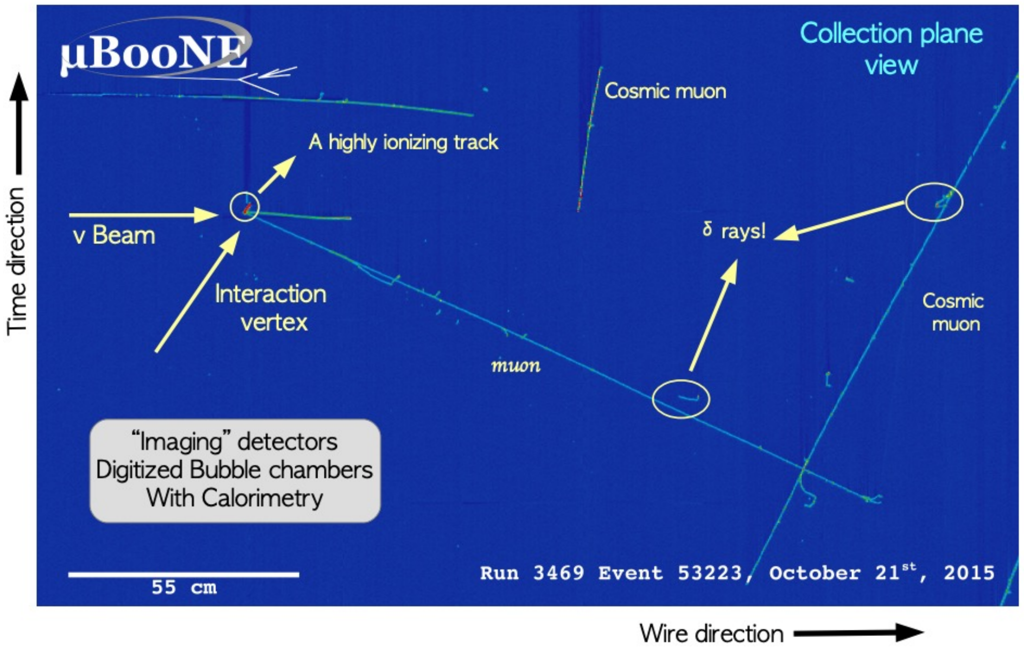
Why liquid argon?

✓ **High density of 1.38 g/cm**
→ Large target mass
→ High statistics for neutrino interaction

✓ **Precise dE/dx measurement**
→ High-accuracy PID

✓ **Abundant and low cost**
→ Creation of huge volume detectors

✓ **Fine grain TPC**
→ Great image resolution of O(5 mm)
→ Reconstruction of multi-prong final states



PANDORA: Reconstructing the LArTPC events

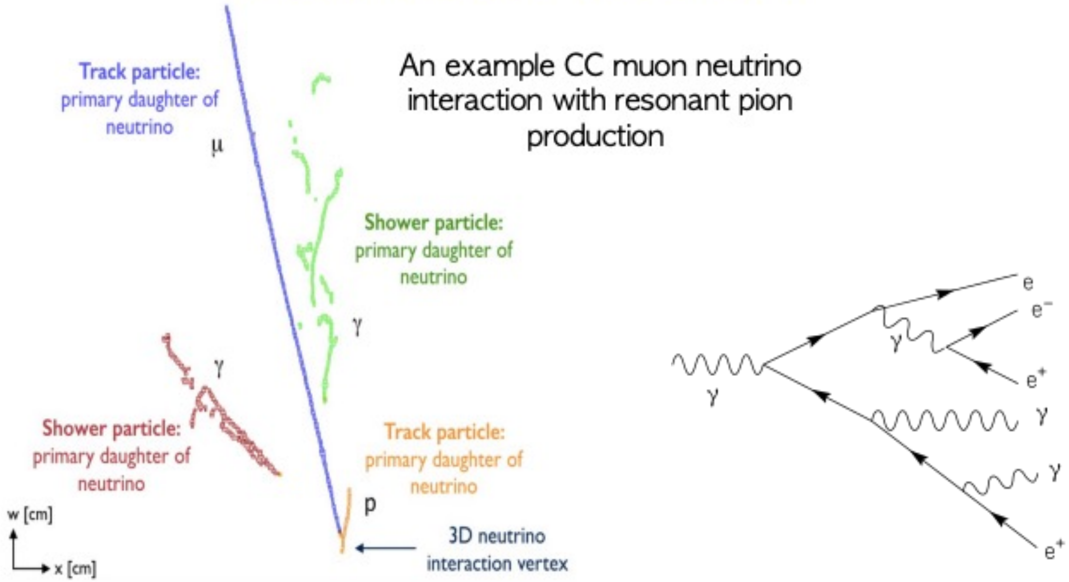
Convert raw LArTPC images into analysis-level physics quantities

✓ **Low-level steps:**
- Signal processing
- Noise filtering

✓ **Pattern recognition:**
- 3*2D images from TPC → 3D trajectories
- Cluster merging
- Track / Shower-like topologies
  - $\mu/K/\pi$: track-like ↔ e/γ: shower-like
- Remove cosmic muons

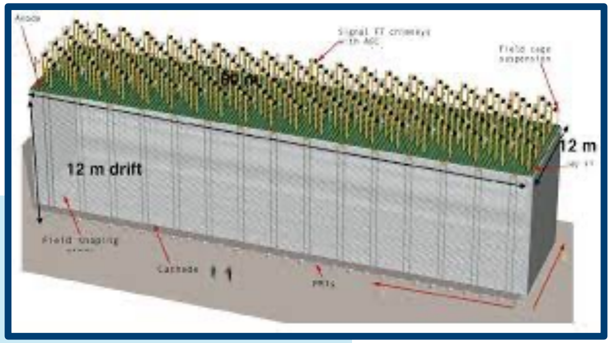
✓ **High-level characterization:**
- Particle identification
- Neutrino interaction

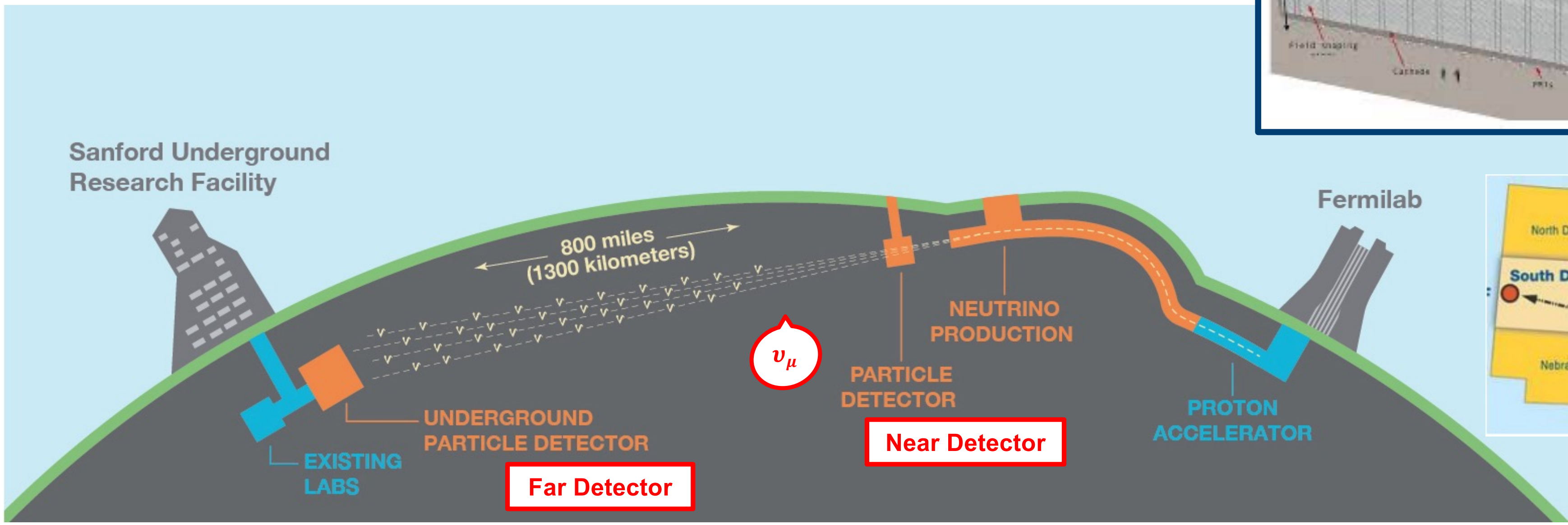
https://arxiv.org/pdf/1708.03135.pdf



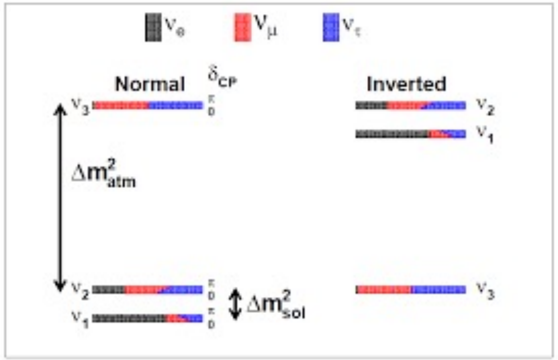
DUNE: Deep Underground Neutrino Experiment under construction

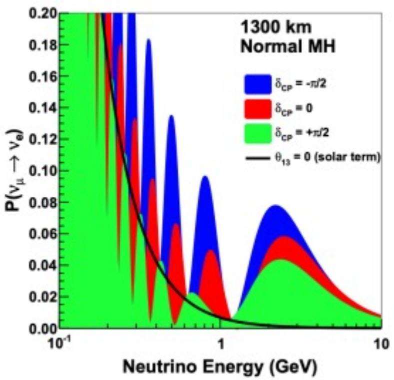
- Detector installation beginning in mid 20s [7]
- Consists of Near and Far detectors located ~1300 km apart
  - Near detector: Complex of particle detectors for neutrino beam properties
  - Far detector: 40 kton LArTPC with ~10^35 of protons

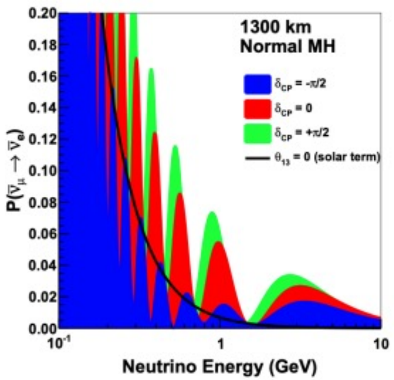




Rich Physical Landscapes: Neutrino and BSM Physics







Precise measurements of:

- Neutrino oscillation: $P(\nu_\mu \to \nu_e)\ vs\ P(\overline{\nu_\mu} \to \overline{\nu_e})$
  - ✓ δ_{CP}: CP violation in lepton sector
  - ✓ Clues of neutrino mass hierarchy

PHYSICS

2-flavour appearance probability

$$P_{\upsilon_\alpha \to \upsilon_\beta}(\mathrm{L,E}) = \sin^2 2\theta \sin^2\left(1.27 \frac{\Delta m^2(\mathrm{eV}^2)\mathrm{L(km)}}{\mathrm{E(GeV)}}\right)$$

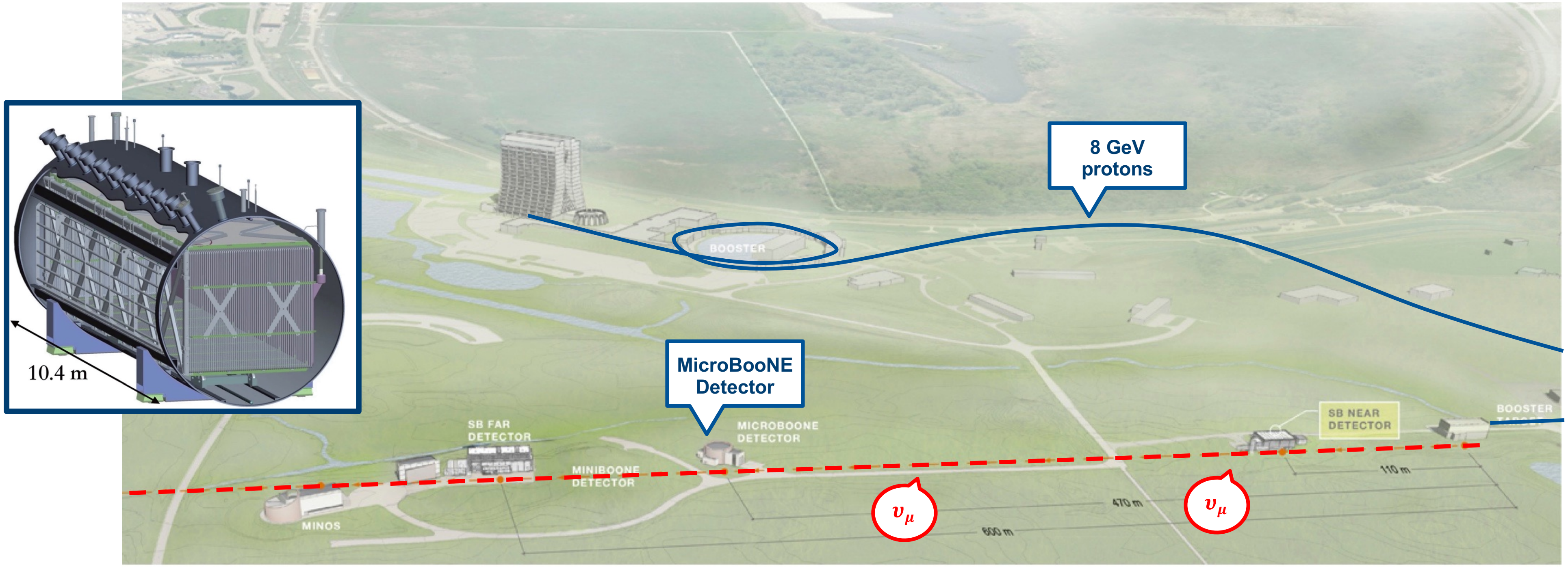
EXPERIMENT

- Supernova neutrinos
- Atmospheric neutrinos
- BSM physics including proton decay

✓ $E_\nu \sim 2.5\ \mathrm{GeV}, L \sim 1300\ km$

MicroBooNE: Micro Booster Neutrino Experiment

- 85 ton LArTPC running from 2015
- 0.25-2 GeV υ beam from the Booster Neutrino Beam (BNB) and the Neutrino Main Injector (NuMI)



Generating Neutrinos from Meson Decays

1. **Primary Beam**

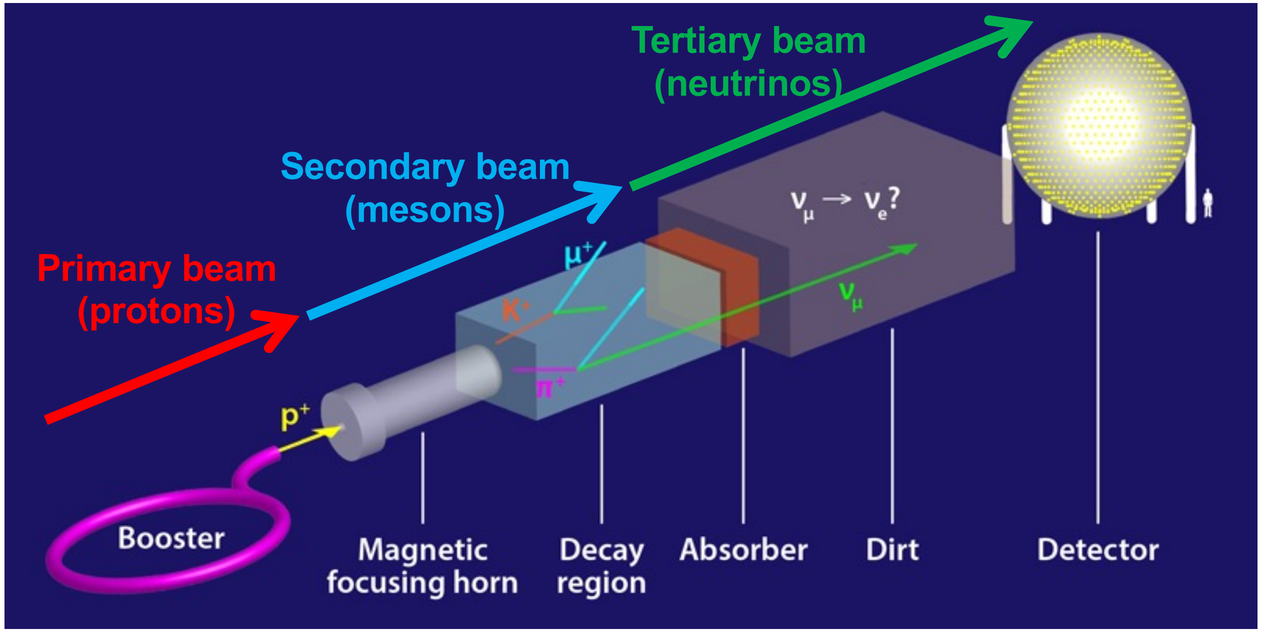
$$p + Be \rightarrow \pi^+, K^+, K_L^0$$

2. **Secondary Beam**

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$
$$K^+ \rightarrow \mu^+ \nu_\mu$$
$$K_L^0 \rightarrow \pi^- \mu^+ \nu_\mu$$

3. **Intrinsic ν_e Beam**

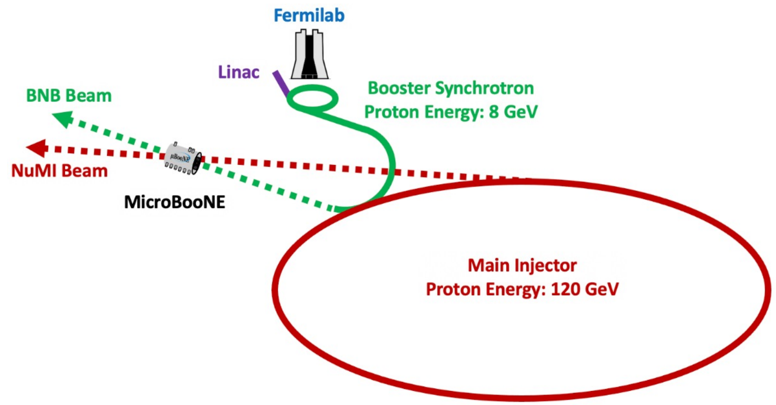
$$\mu^+ \rightarrow e^+ \nu_e \overline{\nu_\mu}$$
$$K^+ \rightarrow \pi^0 e^+ \nu_e$$
$$K_L^0 \rightarrow \pi^- e^+ \nu_e$$



2 neutrino beams in MicroBooNE

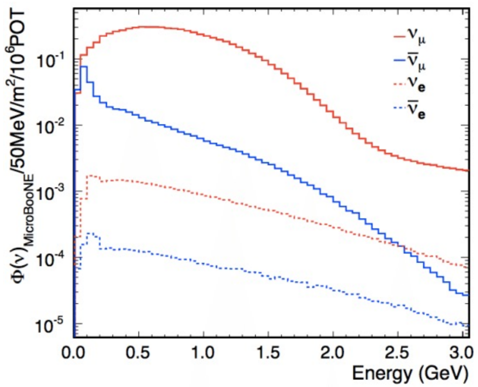
Booster Neutrino Beam (BNB)

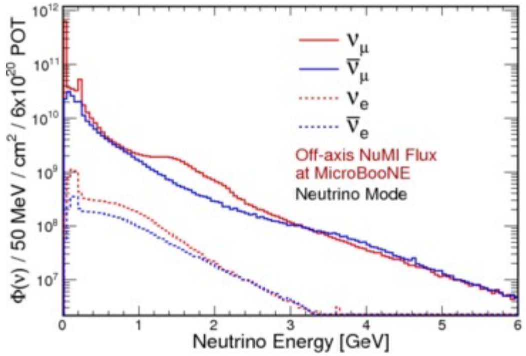
- Dominant flux component: ν_μ
- On-axis beam mainly used for low E excess



Neutrino Main Injector (NuMI)

- Both rich in ν_μ & ν_e with higher energy than BNB
- Off-axis beam suited for cross section measurement of neutrino interactions





Low Energy Excess and Cross Section Studies

It was designed for neutrino oscillation study and investigation on possible excess of low energy ν_e event observed by LSND and MiniBooNE experiments

1. Neutrino oscillation events from $\nu_\mu \rightarrow \nu_e$: MiniBooNE observed an unexpected >4σ (statistical and systematic combined) excess of neutrino interactions producing final state electrons or photons at lower energies.

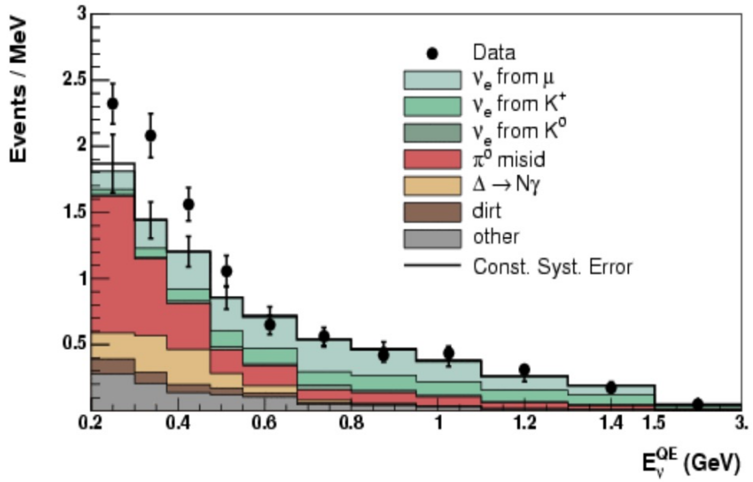
PHYSICS

2-flavour appearance probability

$$P_{\nu_\alpha \rightarrow \nu_\beta}(\mathrm{L,E}) = \sin^2 2\theta \sin^2\left(1.27 \frac{\Delta m^2(\mathrm{eV}^2)\mathrm{L(km)}}{\mathrm{E(GeV)}}\right)$$

EXPERIMENT

$E_\nu \sim 500\ \mathrm{MeV}$,
$L \sim 500\ m$
$L/E_\nu \sim 1$



2. Cross section measurements with neutrino beam

- Neutrino cross section:
  ex. Total and differential $\nu_e + \overline{\nu_e}$ charged-current inclusive
- Hyperon, **kaon**, and η meson production

My study plan: K^+ cross section measurement with MicroBooNE

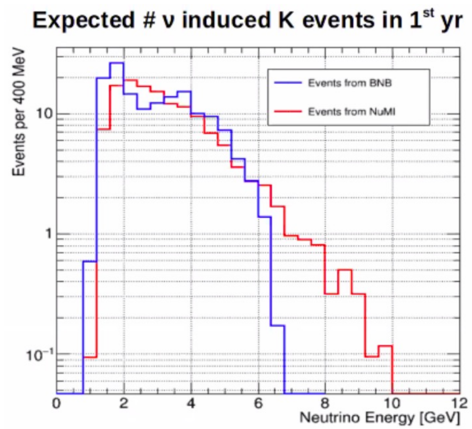
Importance of Kaon study:

- Many GUT models suggest major proton decay modes involving K^+ at final states
- Provide better understanding of backgrounds from atmospheric neutrinos in proton decay searches
- There was no kaon production measurements on Ar or other targets at 1 GeV neutrino energy region

$\rightarrow$ previous analysis: K^+ cross section study with BNB neutrino beam data by MicroBooNE

My research plan:

- K^+ cross section study with NuMI neutrino beam data by MicroBooNE
- Doubles in statistics



K^+ Production by neutrinos

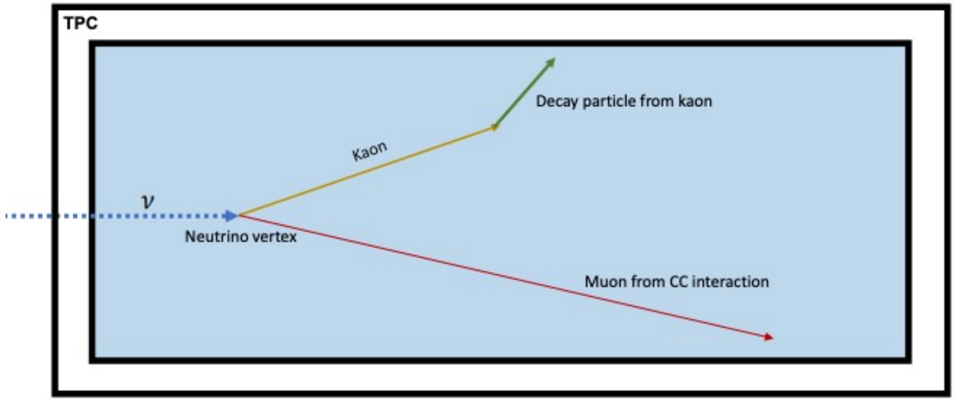
2 modes to produce K^+ by neutrino interactions

✓ **Associated kaon production**:
Kaon accompanied by a hyperon in the final state (E_{thres}: 1.1 GeV)

$$\nu_\mu + n \to \mu^- + K^+ + \Lambda^0 \qquad \nu_\mu + p \to \nu_\mu + K^+ + \Lambda^0$$
$$\nu_\mu + p \to \mu^- + K^+ + \Sigma^+ \qquad \nu_\mu + n \to \nu_\mu + K^+ + \Sigma^-$$
$$\nu_\mu + n \to \mu^- + K^+ + \Sigma^0$$

✓ **Single kaon production**:
Single kaon produced in the final state (E_{thres}: 0.8 GeV)

$$\nu_\mu + p \to \mu^- + K^+ + p$$
$$\nu_\mu + n \to \mu^- + K^+ + n$$



- CC neutrino interaction: $\nu_\mu + \mathrm{Ar} \to \mu^- + K^+ + n/(\mathrm{Hyperons})$
- Kaon decay: $K^+ \to \mu^+\nu_\mu$ (~64%), $K^+ \to \pi^+\pi^0$ (~21%)

→ Detectable as tracks

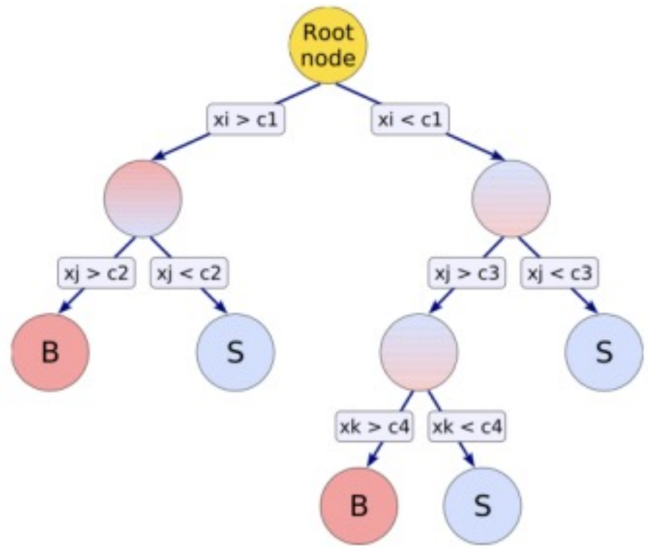
Signal/Background separation with Boosted Decision Tree (BDT)

✓ True signal: $\nu_\mu + \mathrm{Ar} \rightarrow \mu^- + K^+ + \mathrm{nucleons/Hyperon}$

✓ Possible BG events: $\nu_\mu + \mathrm{Ar} \rightarrow \mu^- + \pi^- + \mathrm{nucleons}$

Classify signal/BG events with BDT

- Structured like binary tree: sort events by yes/no decisions upon training variables
  - Keep splitting until all the events are classified as signal or background
  - "Boosted": Add weights for mis-identified events
- Select variables and values for splitting conditions with best separation



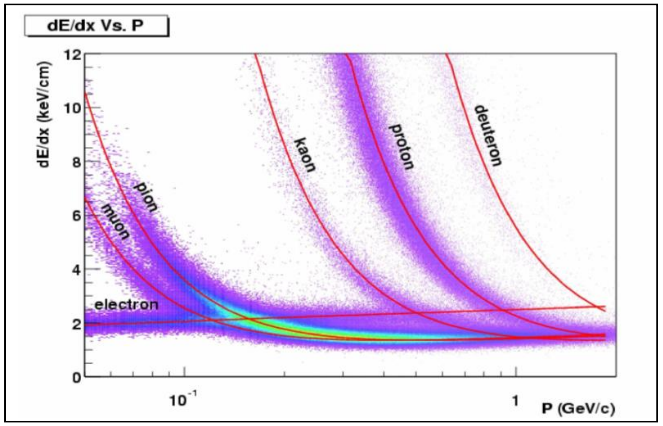
Schematic of decision tree: leaf nodes at bottom are labeled "signal" and "background" after binary splits are made; these labels depend on the majority of events that end up in nodes

https://indico.fnal.gov/event/17409/contributions/42949/attachments/26558/32939/Conley_2018June20_SNBMeeting.pdf

Event selection with BDT training

Slide taken from: previous BNB study

χ^2 **hypothesis** (for kaon, proton, muon and pion for each plane)	**Log-likelihood ratio (LLR) PID** (muon - proton separation and kaon - proton separation)	**Daughter Track length**



Where χ^2 for 3 plane is defined as:

$$\chi^2_{3pl} = \frac{\chi^2_{pl0}\times w_{pl0} + \chi^2_{pl1}\times w_{pl1} + \chi^2_{pl2}\times w_{pl2}}{w_{pl0}+w_{pl1}+w_{pl2}}$$

$$w_{plane} = \begin{cases} 1 \text{ if } \sin^2(\theta_{wire}) \geq 0.05 \\ 0 \text{ if } \sin^2(\theta_{wire}) < 0.05 \end{cases}$$

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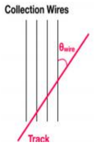
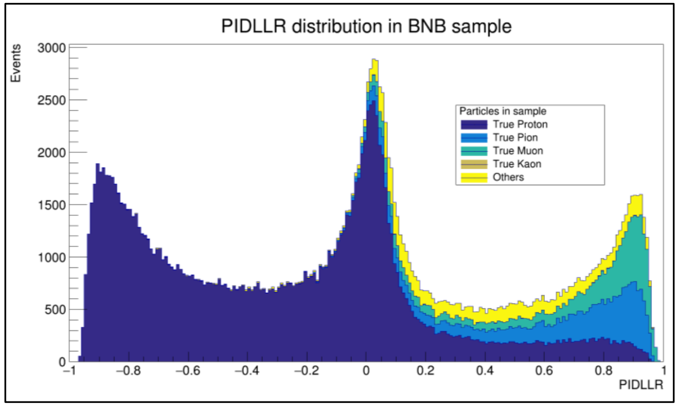
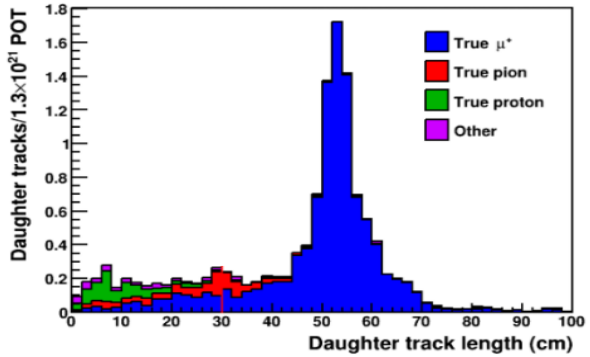
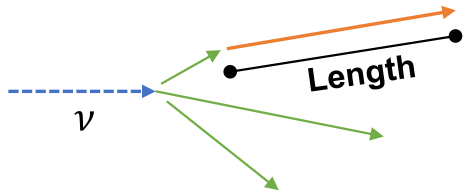




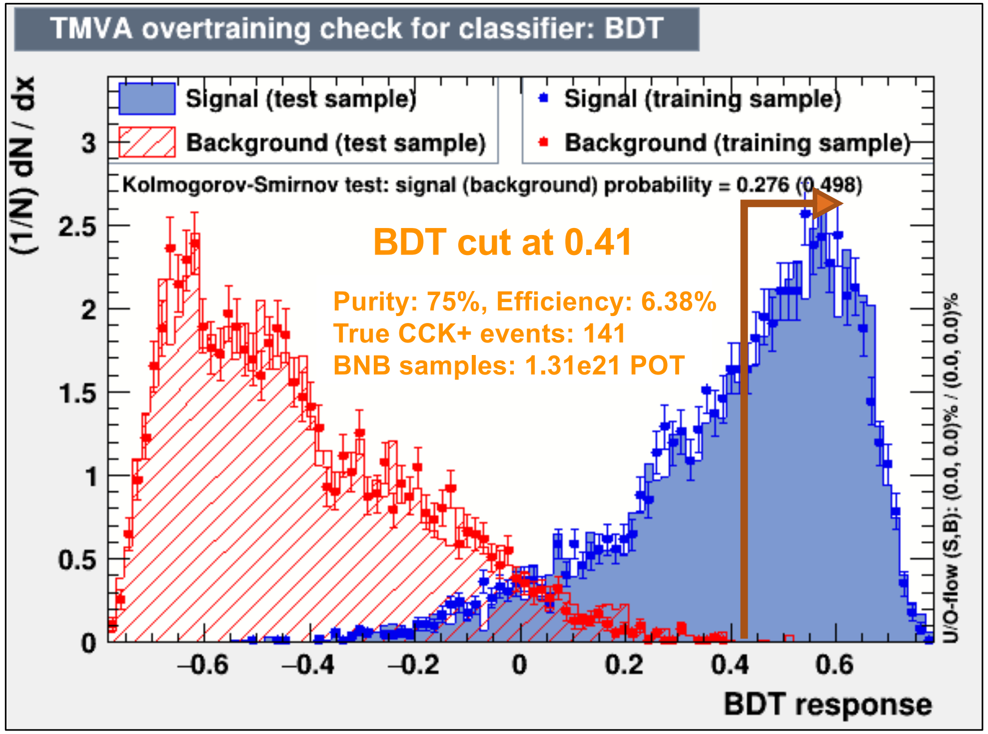
PID score based on dE/dx PDF and wire pitch direction of the tracks.





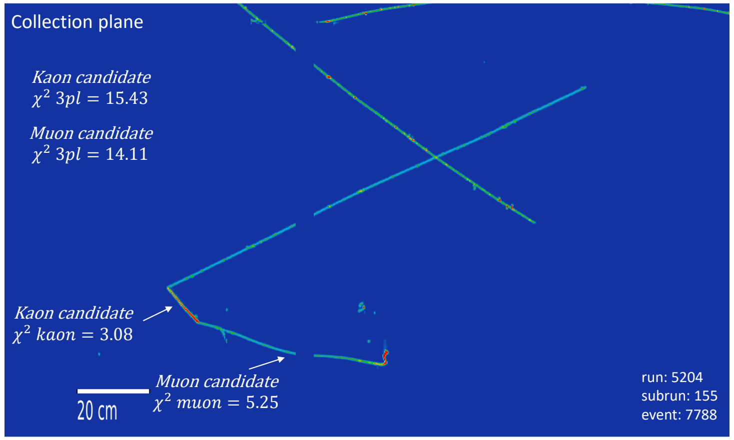
Kaon signal selection with BNB data

Slide taken from:
previous BNB study



Data event candidate (1 of 2)

Event selection (data)



Selected event in both approaches: χ^2 cuts and BDT cut.

Summary and Outlooks

- Kaon detection is crucial for proton decay searches

- Kaon production study with NuMI beam
  - So far: Get used to microboone event generation/reconstruction/ML analysis with previous BNB kaon analysis
  - Current: modifying/writing codes for my NuMI analysis

- Lectures: Particle Physics, machine learning
- Workshop: Pandora event reconstruction