BSM Searches at Short Baseline LArTPCs

SLAC NATIONAL ACCELERATOR LABORATORY

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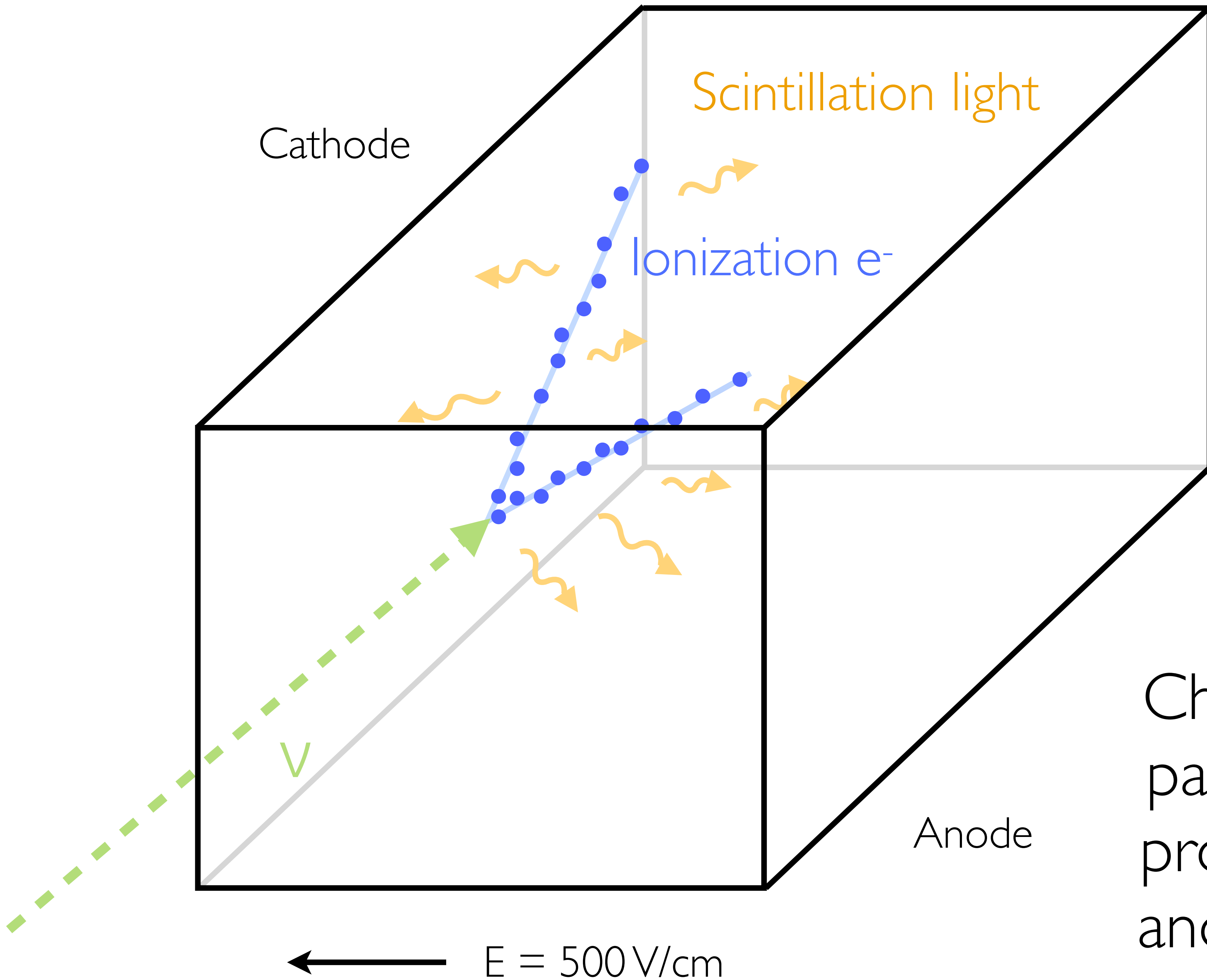
Nu Tools for BSM Workshop
December 15, 2022

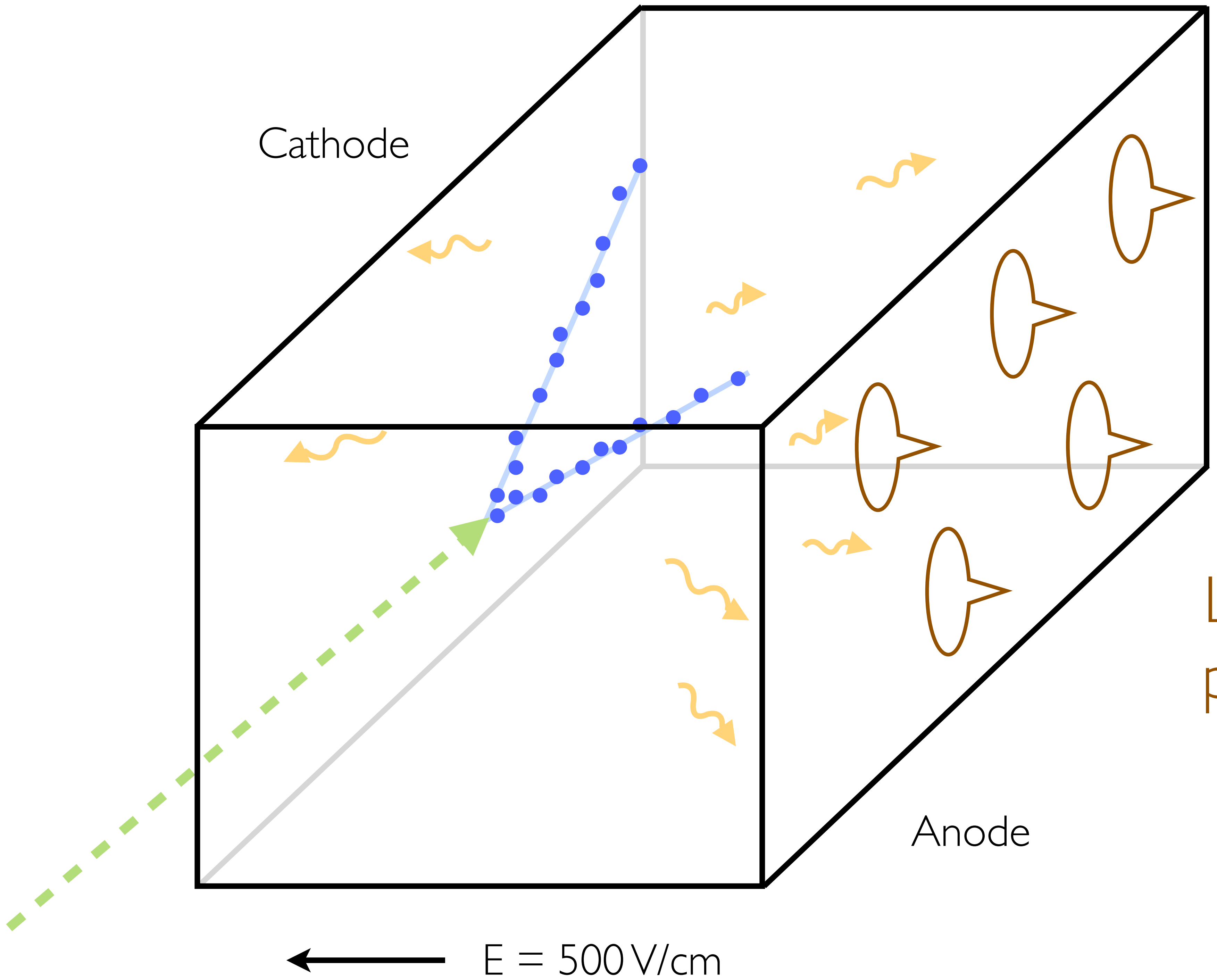
LArTPC



Incoming neutrino interacting with LAr

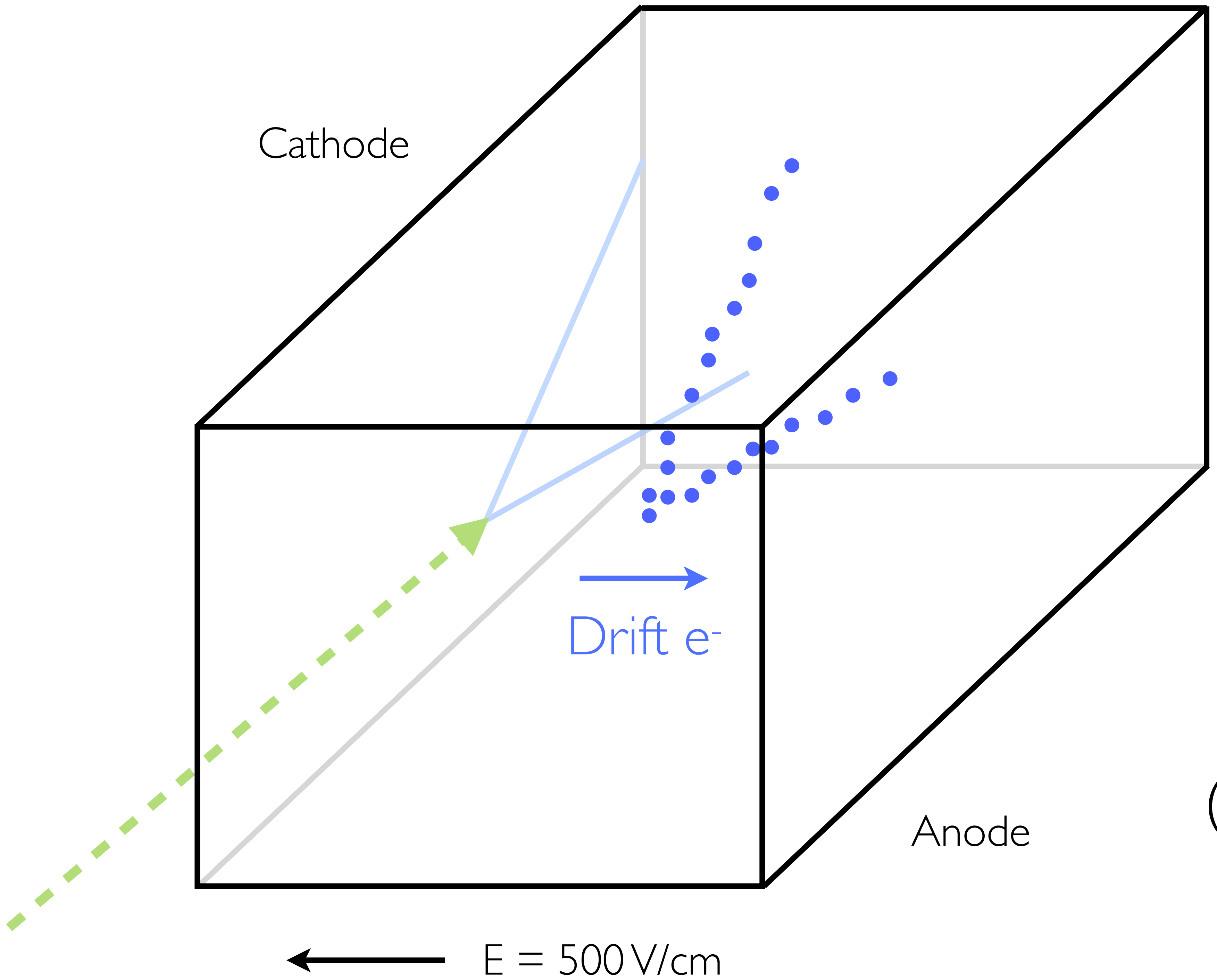
Charged secondary particles ionize LAr, producing electrons and scintillation light

LArTPC



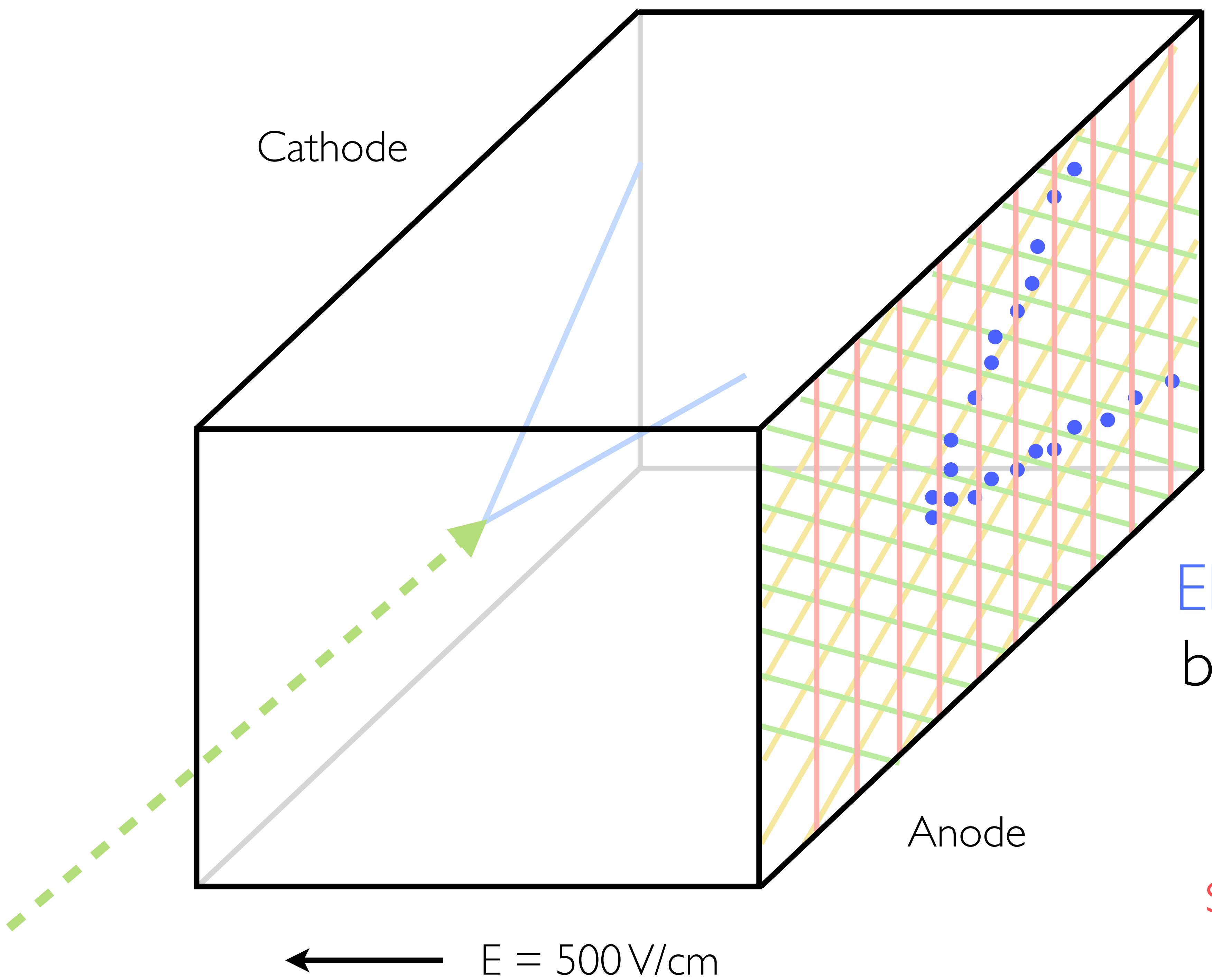
Light collected by photon detectors (10-100ns), determining event time t_0

LArTPC



Electrons drift towards anode (drift time at ms scale)

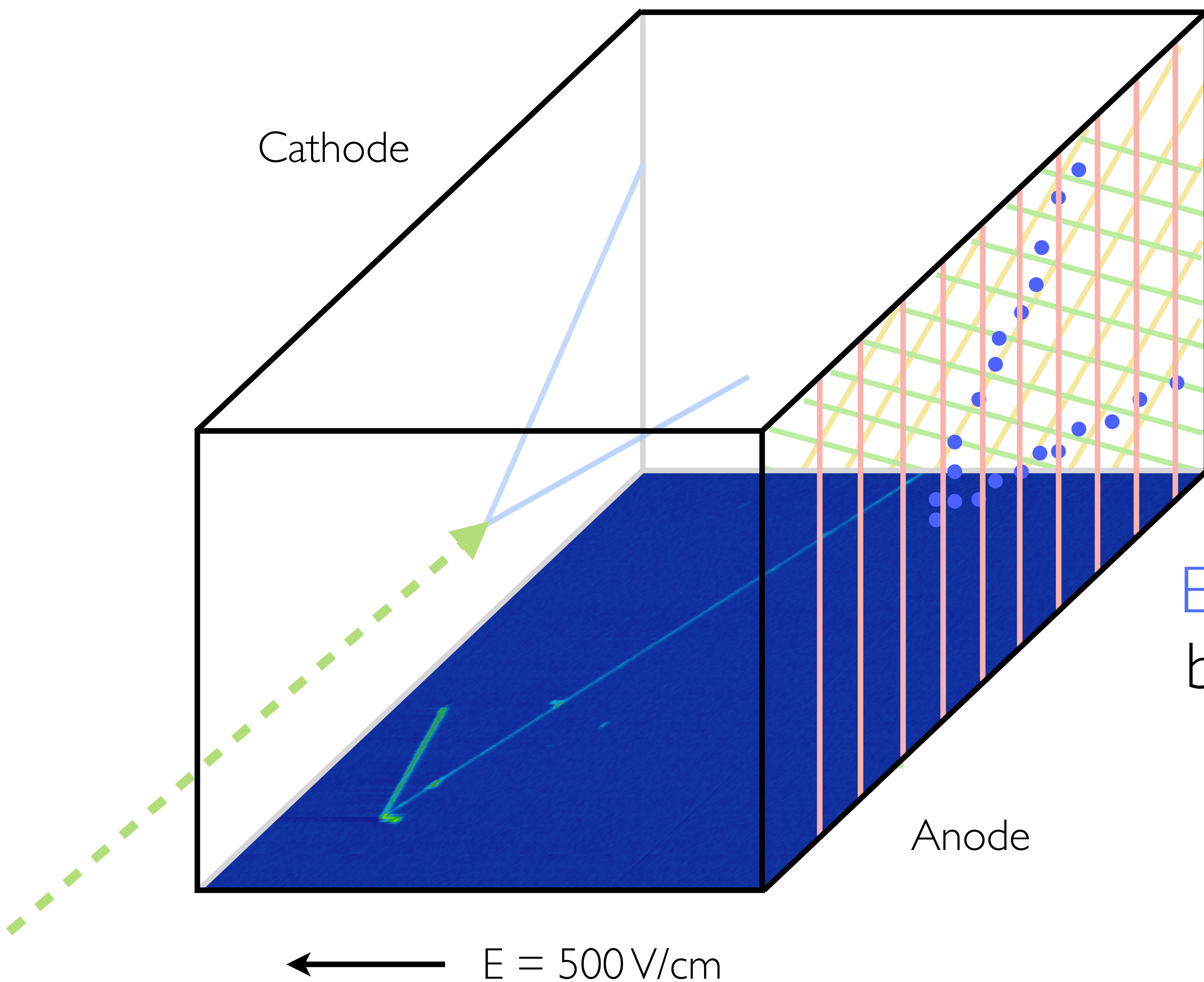
LArTPC



2 induction planes
1 collection plane

Electrons detected by the wire planes at anode, providing the spatial, kinematic information.

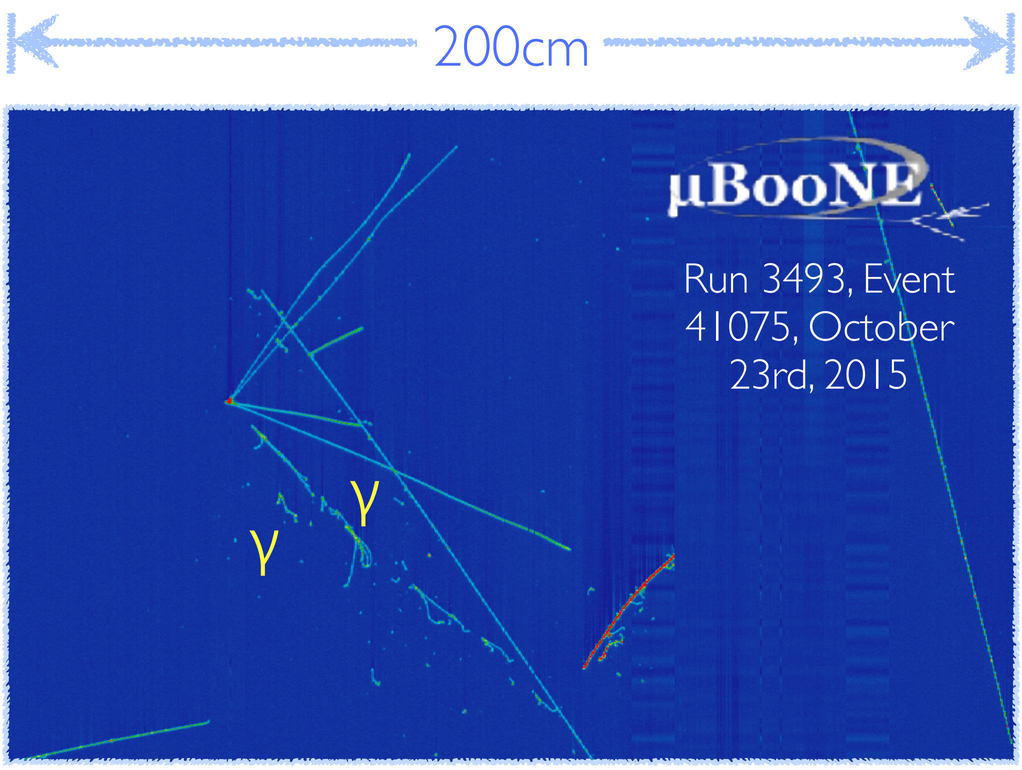
LArTPC

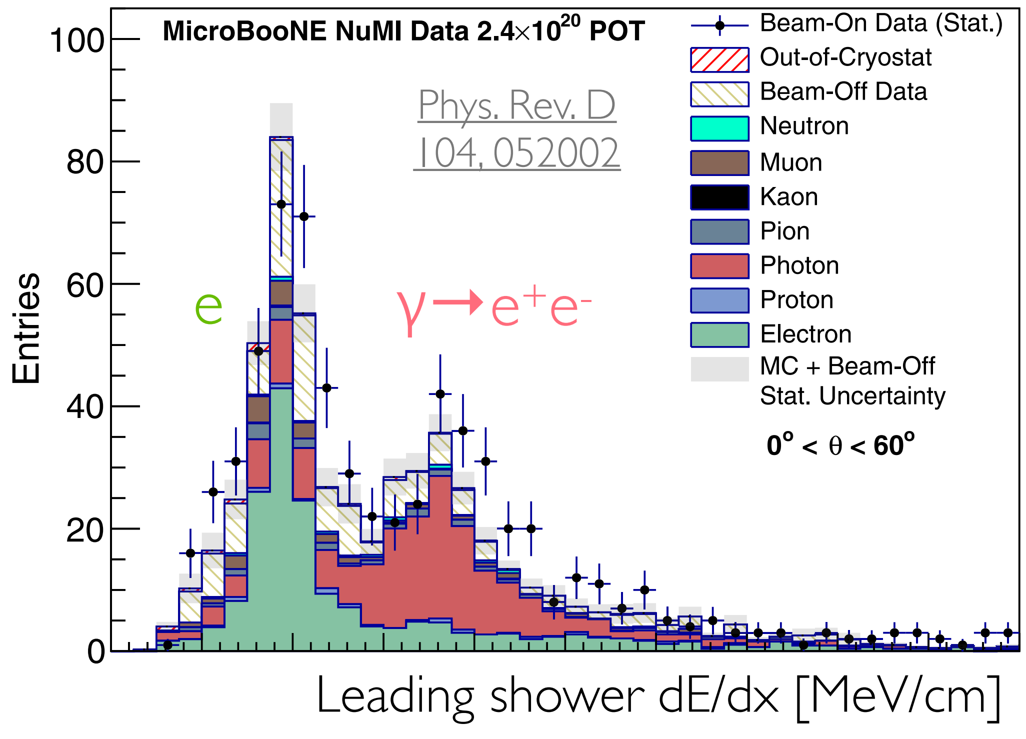


Electrons detected by the wire planes at anode, providing the spatial, kinematic information.

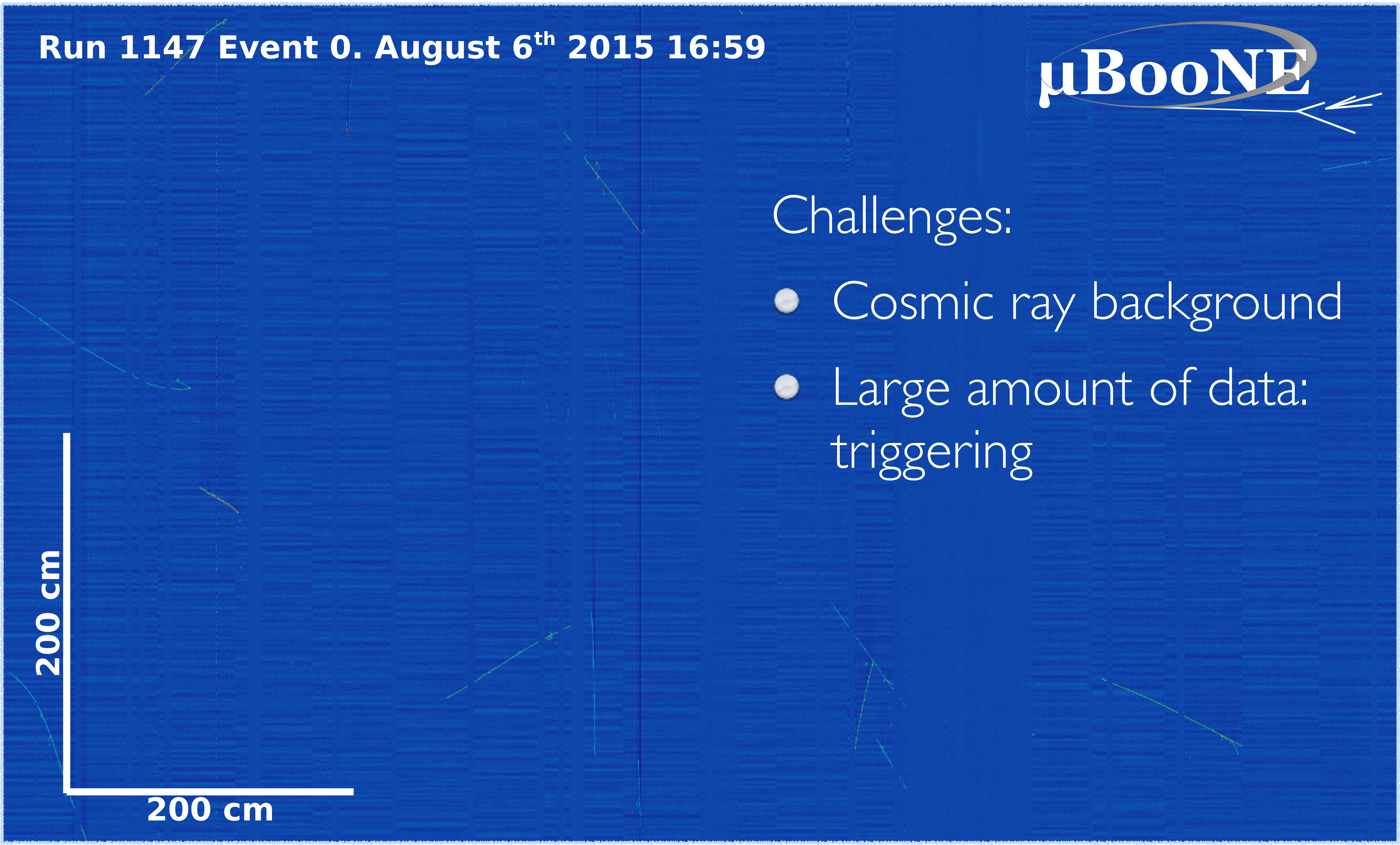
LArTPC Features

- LAr: large interaction rate
- Modular and scalable
- Nearly fully instrumented
- Millimeter resolution
- Calorimetric measurement
  - e/γ separation
- Low detection threshold for protons
- Supernova ν_e (E~10 MeV)
- Charge collection at millisecond time-scale





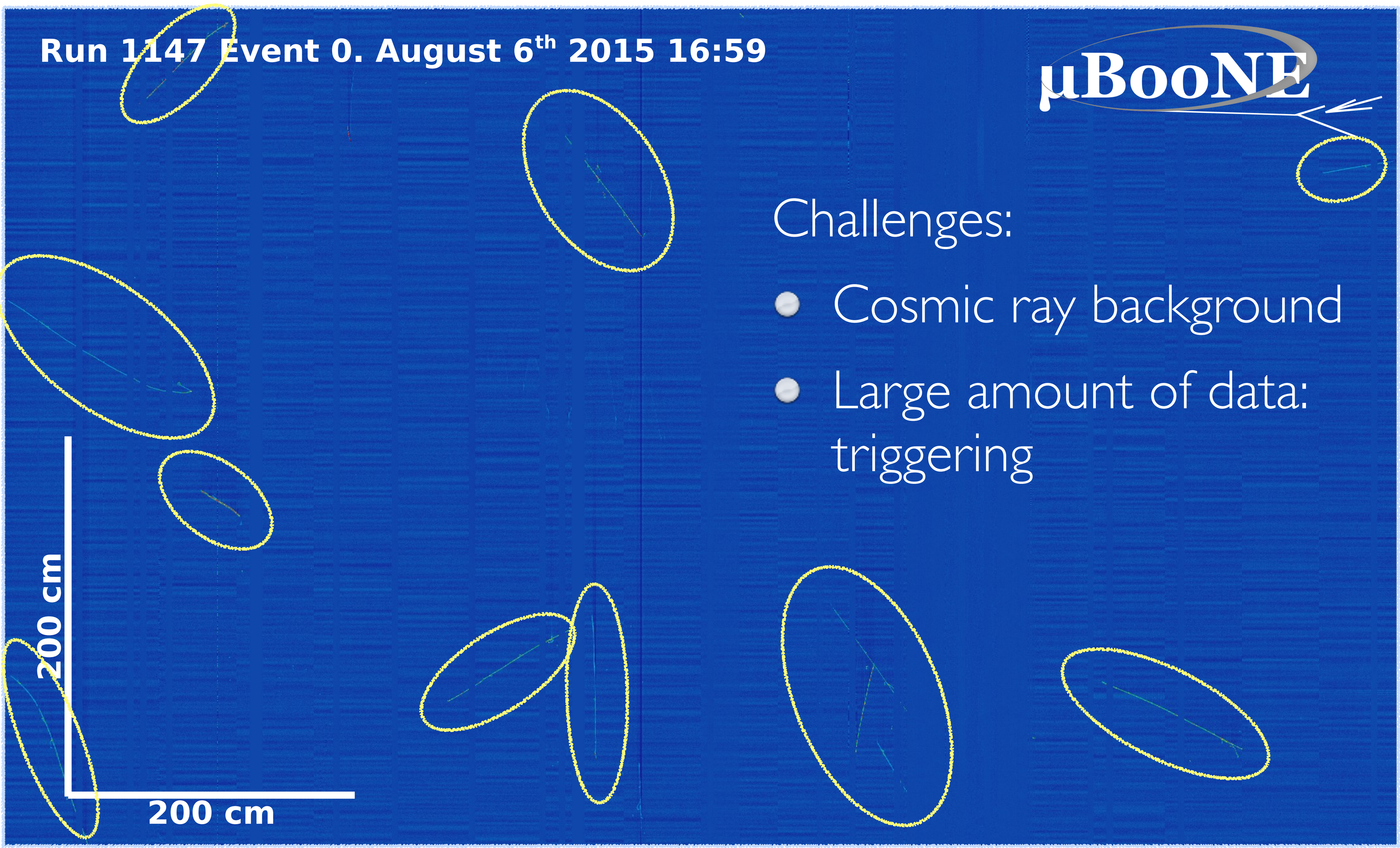
Slow Detector on Surface



Challenges:

- Cosmic ray background
- Large amount of data: triggering

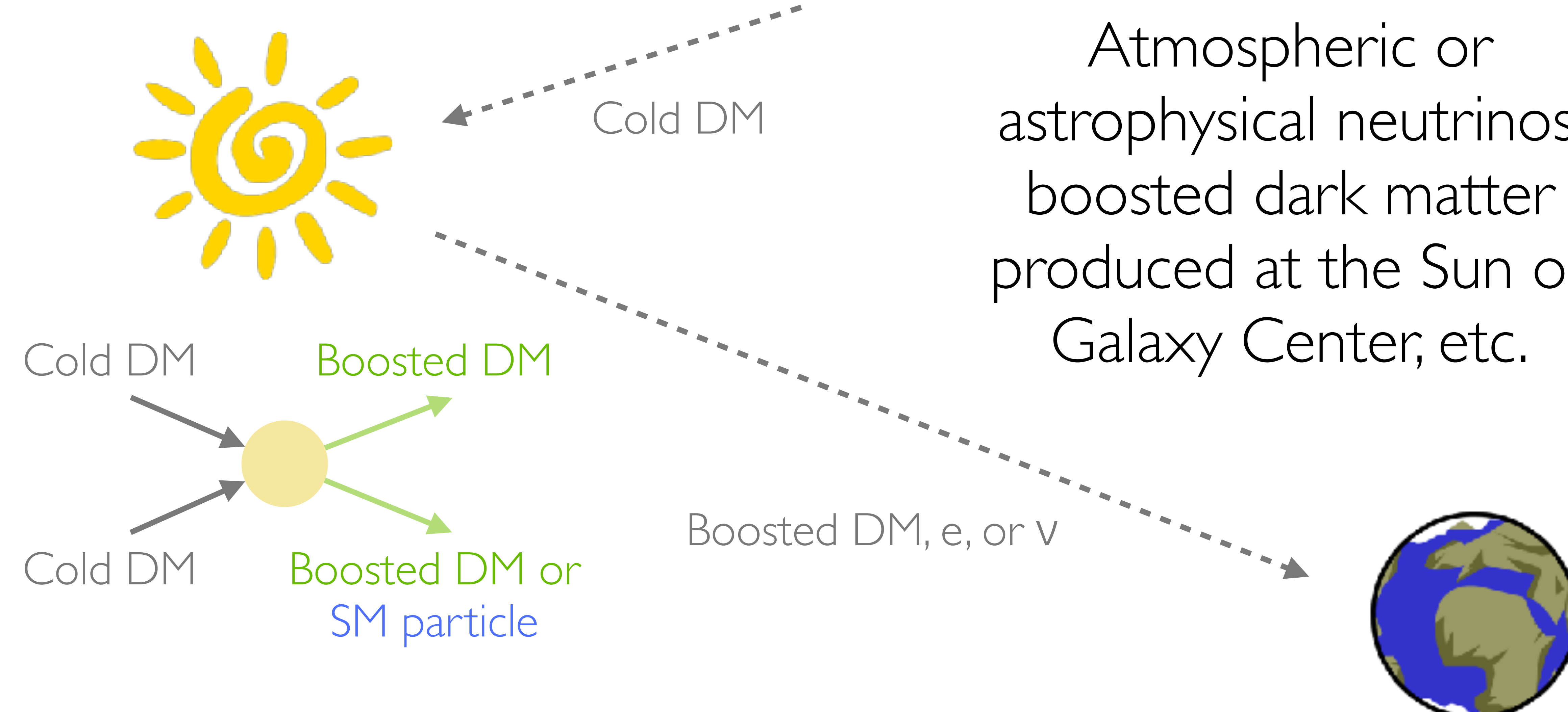
Slow Detector on Surface



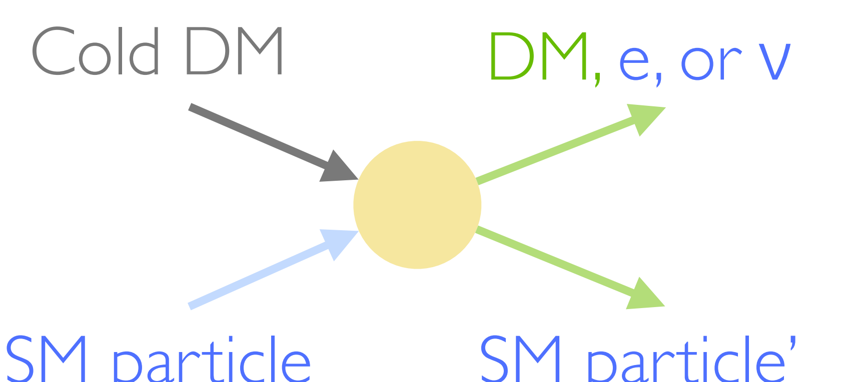
Challenges:

- Cosmic ray background
- Large amount of data: triggering

Not Ideal for Natural Source

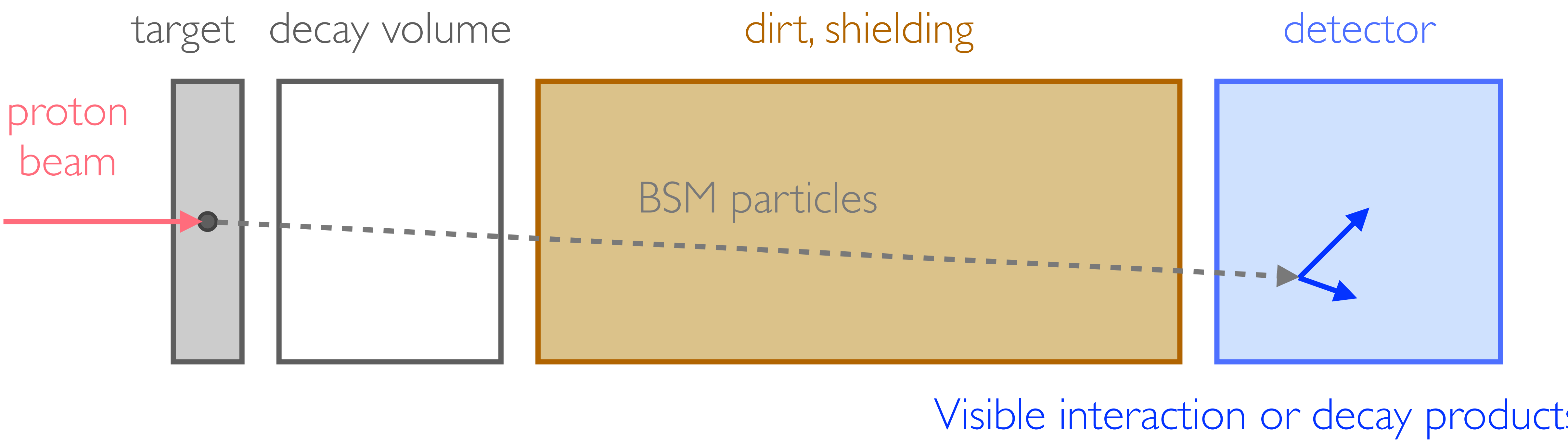


Atmospheric or astrophysical neutrinos, boosted dark matter produced at the Sun or Galaxy Center, etc.



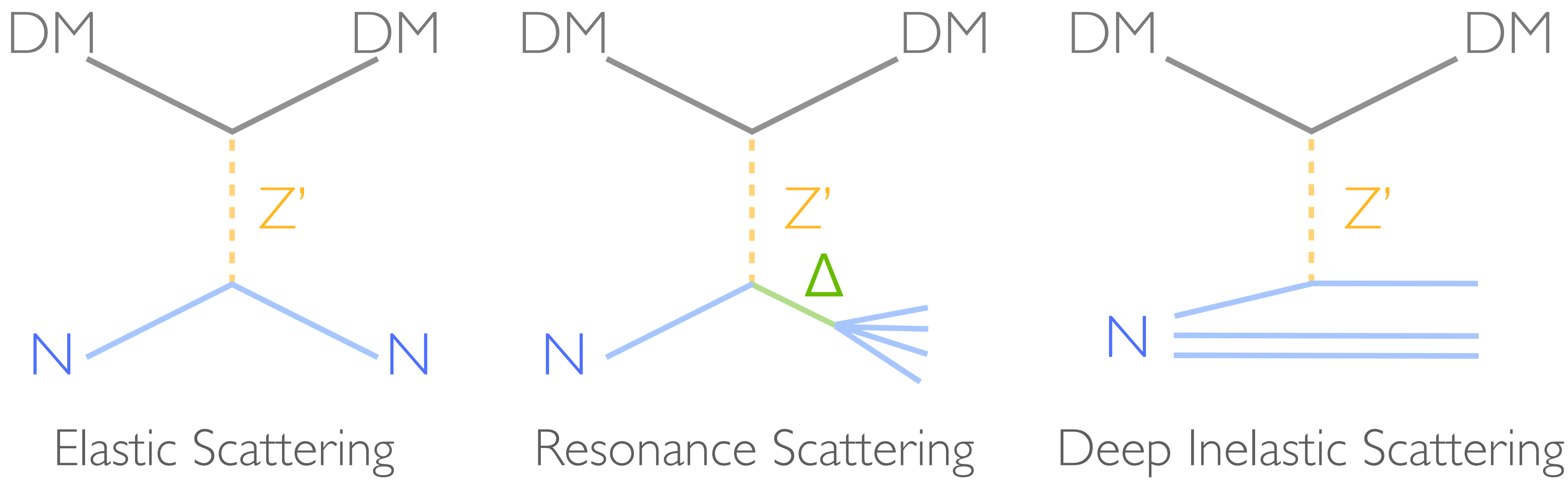
Require massive, underground LArTPCs (i.e. DUNE far detector)

Neutrino Beam



- High intensity proton beam + fixed target
- Produce charged and neutral mesons: $\pi^{\pm}$, $K^{\pm}$, π^{0}, etc.
- BSM particles produced via Higgs, vector, neutrino, ALP portals, dark neutrinos, νphilic mediators, etc.
- Detect SM particles from interactions or decays of the BSM particles

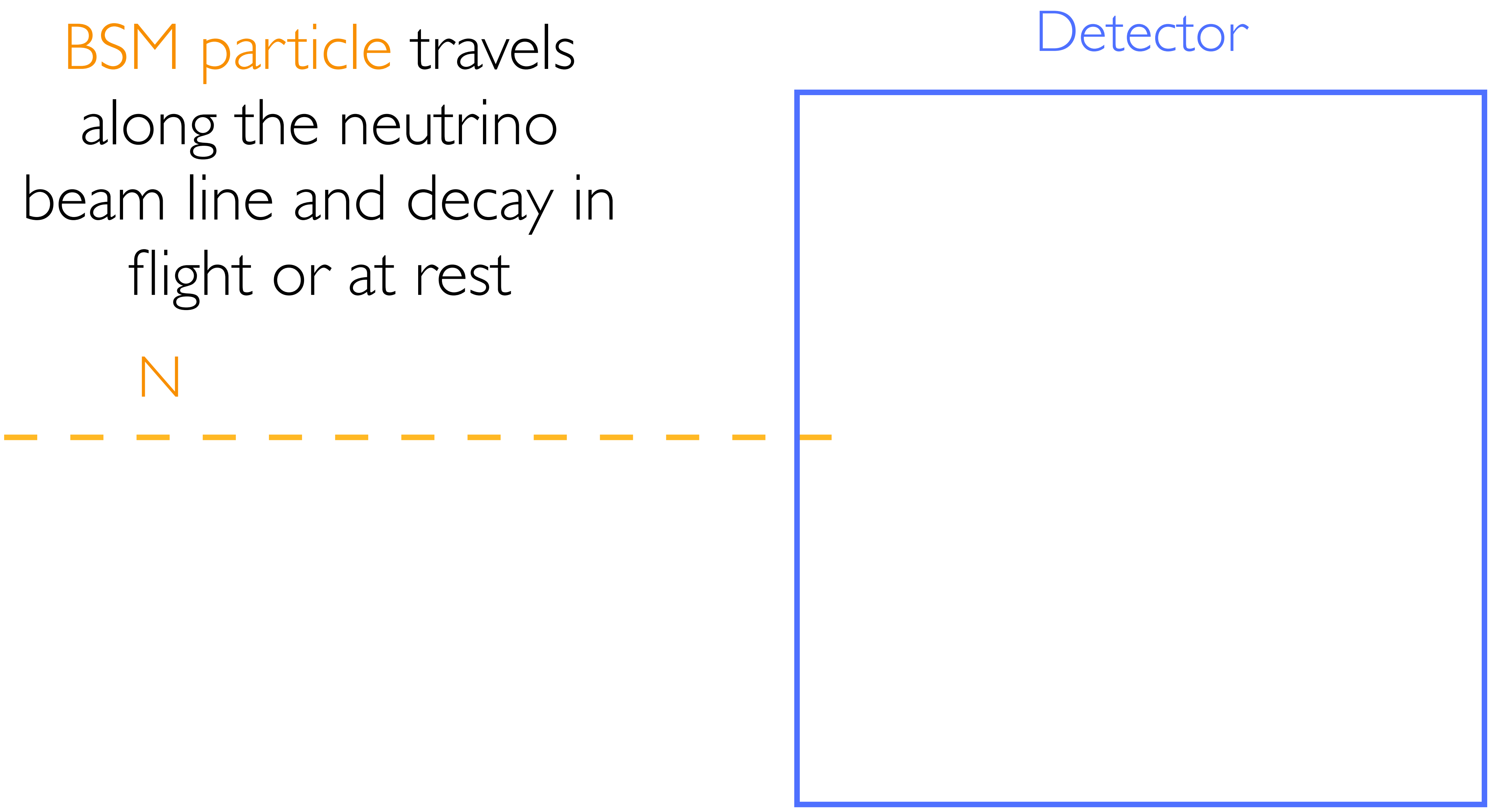
Detection: Interaction



- BSM-electron scattering: e signature
- BSM-nucleon scattering: typically neutral current-like
  - Nuclear effects smear the topology
- Challenging on modeling BSM signals, and reducing and precisely constraining neutrino background

Detection: Decay Products

BSM particle travels along the neutrino beam line and decay in flight or at rest



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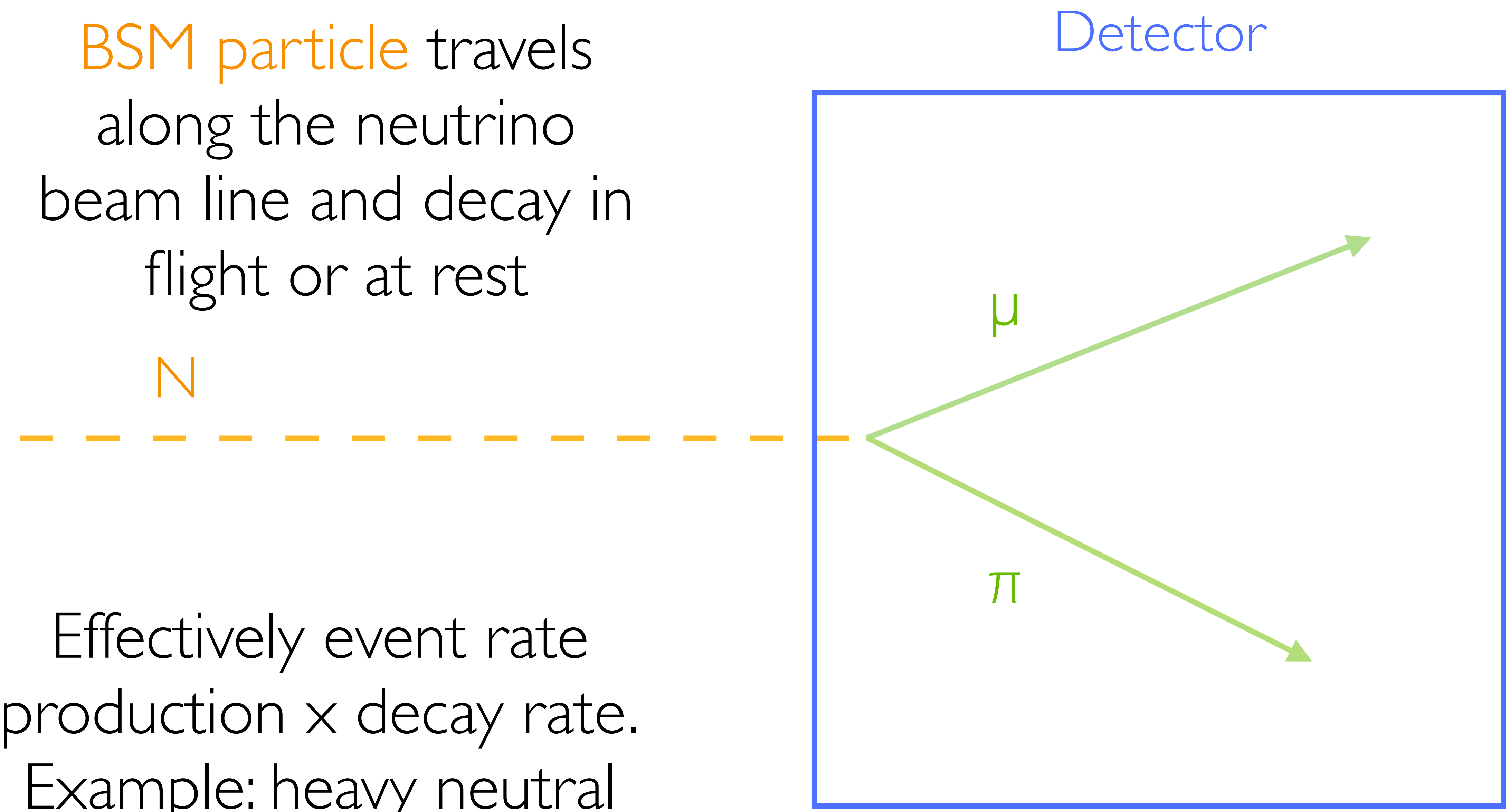
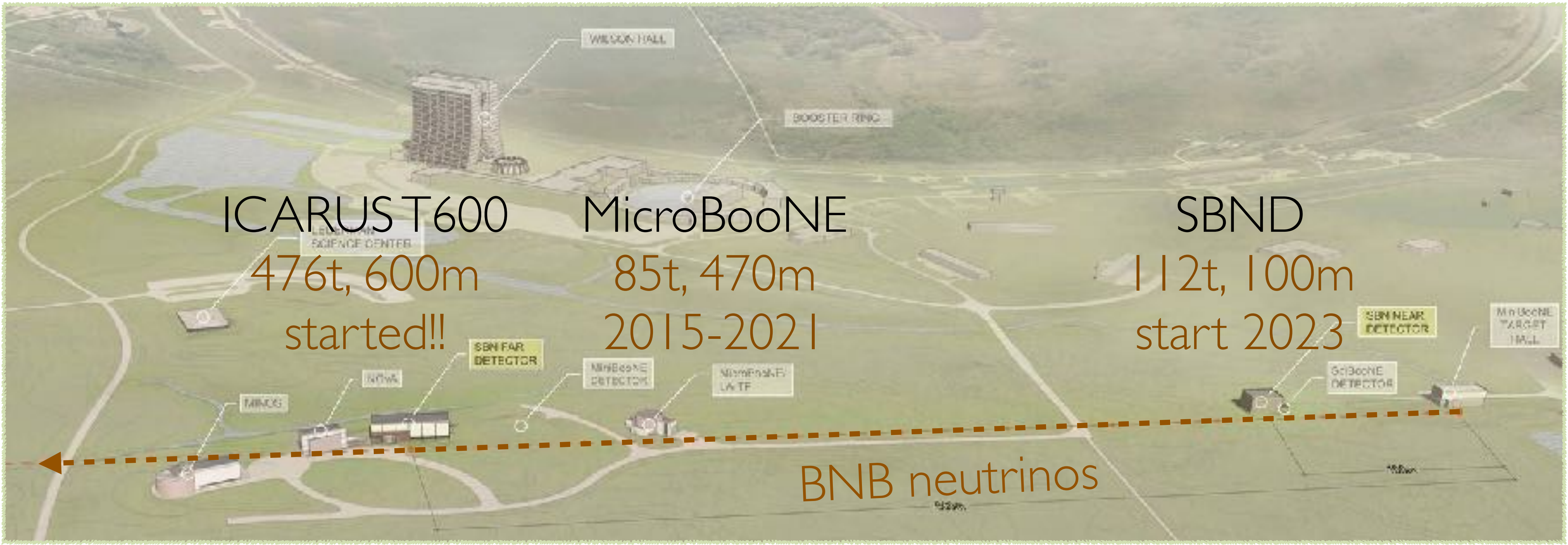


A decay channel

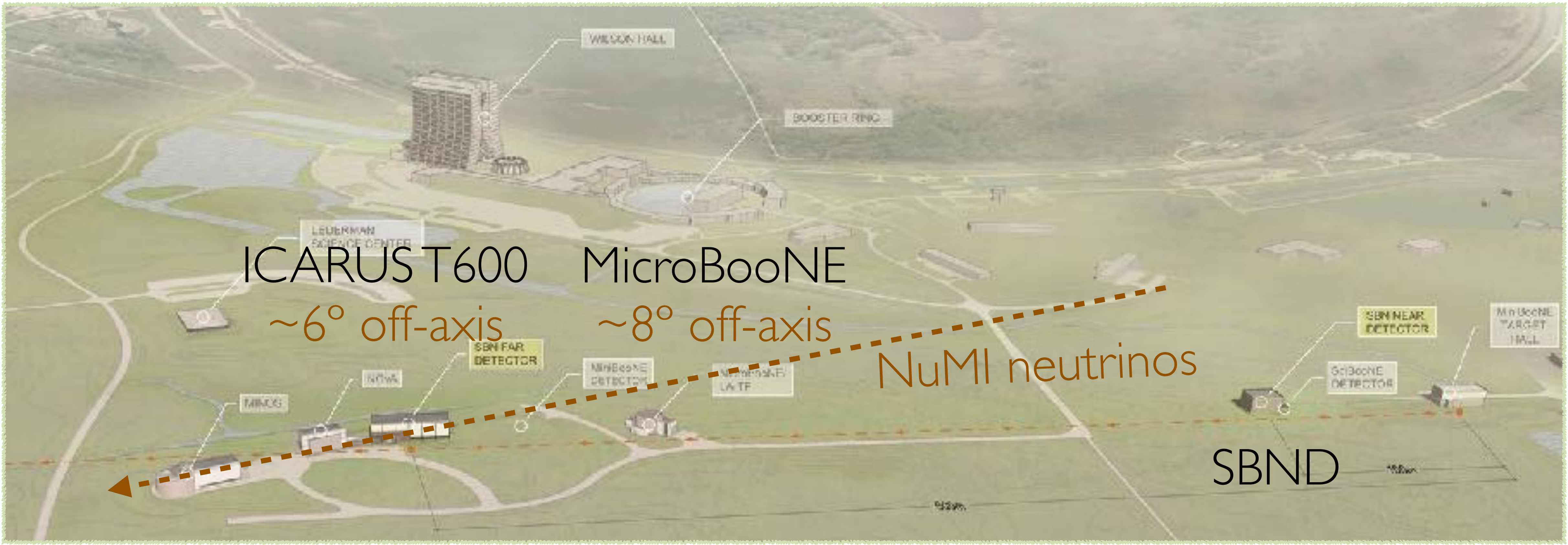
Effectively event rate production x decay rate. Example: heavy neutral lepton (N) decays into μπ

Short Baseline Program



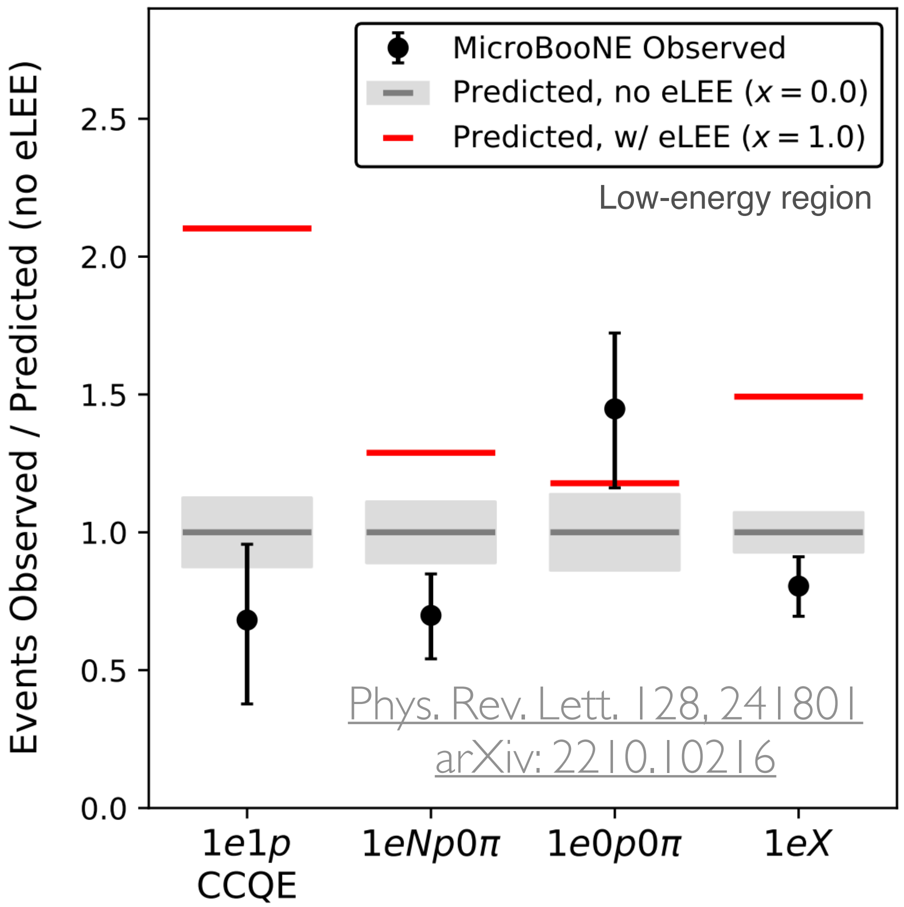
- eV-scale sterile ν: measured by $\nu_\mu \rightarrow \nu_e$ oscillation
- Measure ν-Ar cross section
- BNB ν_μ: 8 GeV protons, ν energy peak at ~600 MeV
- 3 LArTPC detectors on surface in different baselines

Free Neutrinos from NuMI

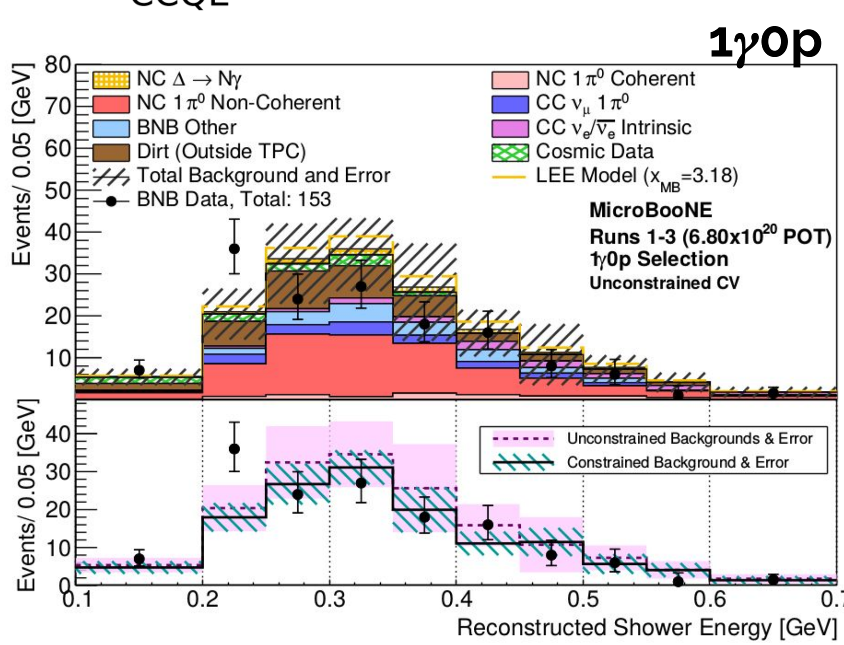


- NuMI ν_μ: 120 GeV protons
- Off-axis neutrino beams for MicroBooNE and ICARUS
- ν-Ar cross section measurements
- BSM searches from both BNB and NuMI

BSM Search@Short Baselines



Phys. Rev. Lett. 128, 241801
arXiv: 2210.10216



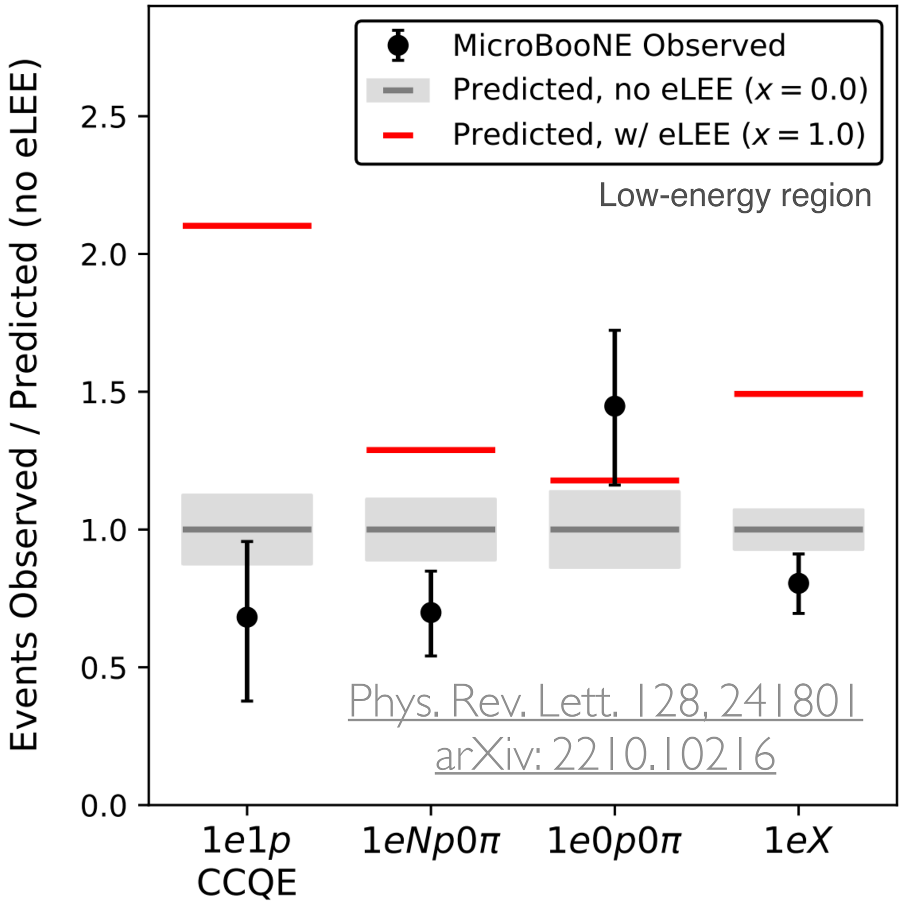
Phys. Rev. Lett. 128, 111801

- eV-scale sterile neutrino search by $\nu_\mu \to \nu_e$
  - LSND & MiniBooNE anomalies
- ν-Ar cross section measurements
- Search for BSM particles
  - Require more dedicated tools

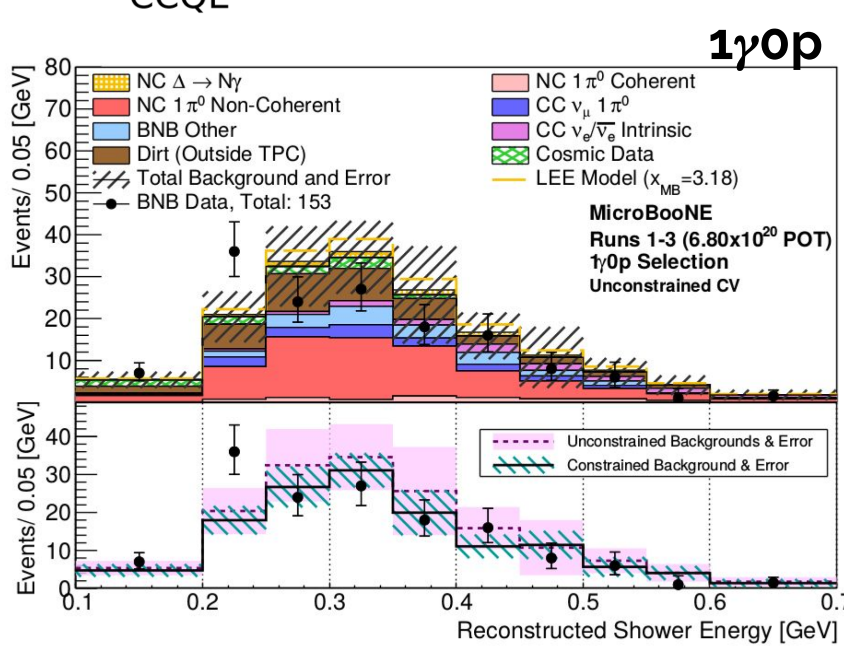
Today's menu

- Neutrino portal: Heavy neutral lepton (HNL)
- Higgs portal scalar particle (HPS)
- Physics motivation in Hostert and Putnam's talks

BSM Search@Short Baselines



Phys. Rev. Lett. 128, 241801
arXiv: 2210.10216



Phys. Rev. Lett. 128, 111801

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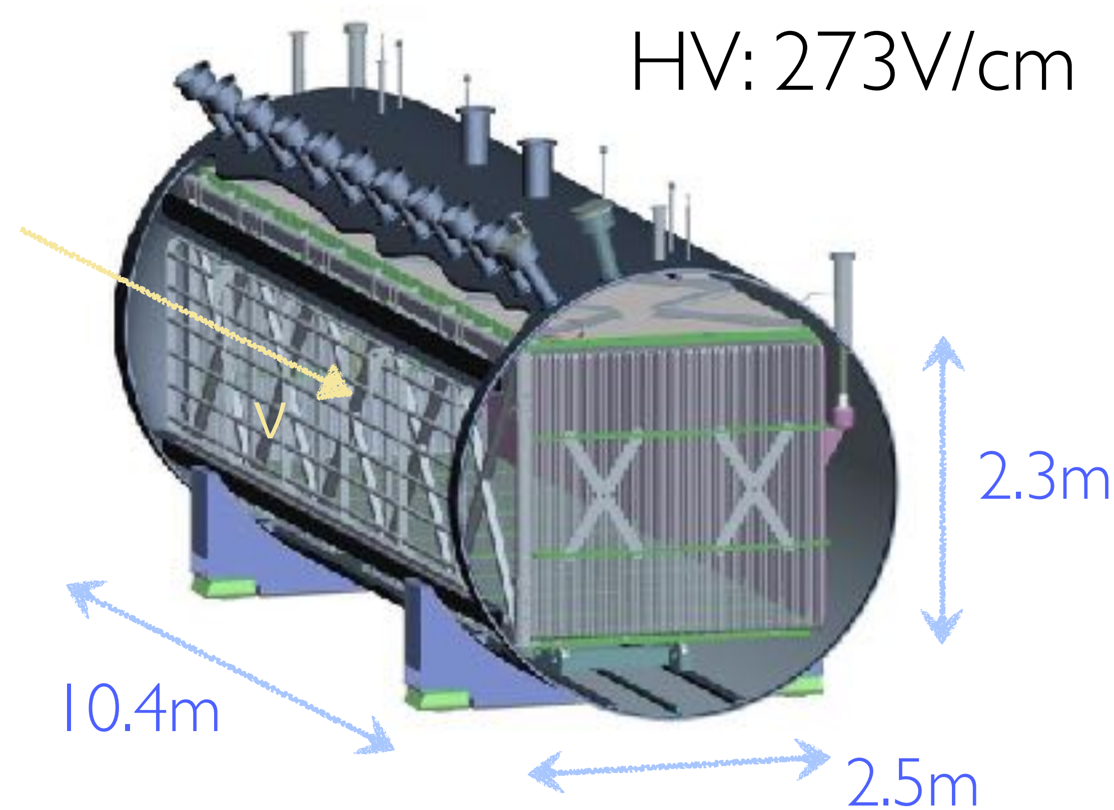
BSM Searches at MicroBooNE

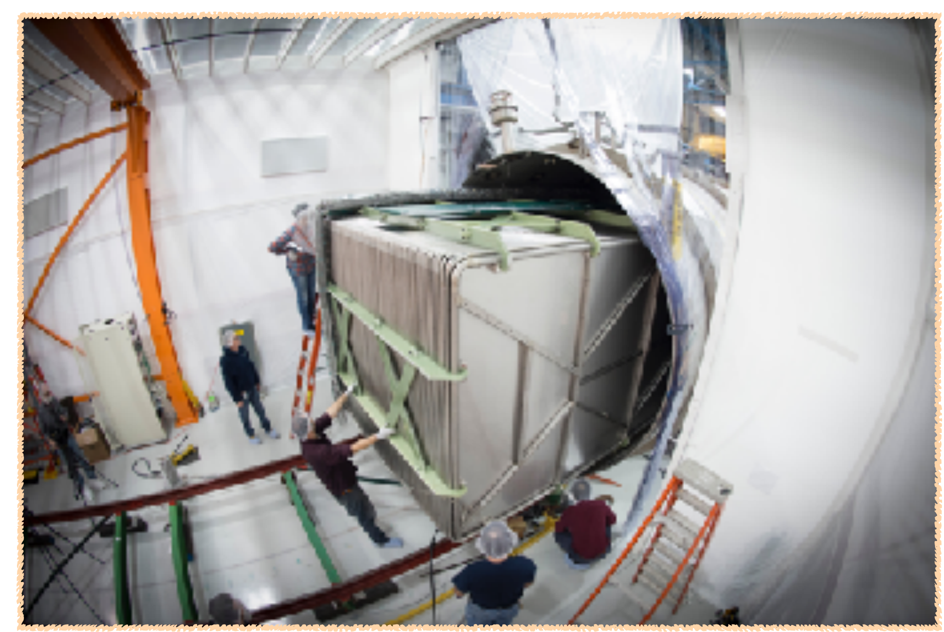
Publication: https://microboone.fnal.gov/documents-publications/

MicroBooNE

- LAr: 85 tons (active)
- 1 TPC: 2.3mx2.5mx10.4m
  - 8192 wires, 3-mm pitch
  - 2MHz sampling rate
- Light collection
  - 32 PMTs+4 paddle PMTs
  - 64MHz sampling rate
- Cosmic ray tagger
- Operation: 2015-2021, collected 1.5×10^{21} POT

HV: 273V/cm





Background: Cosmic Rays

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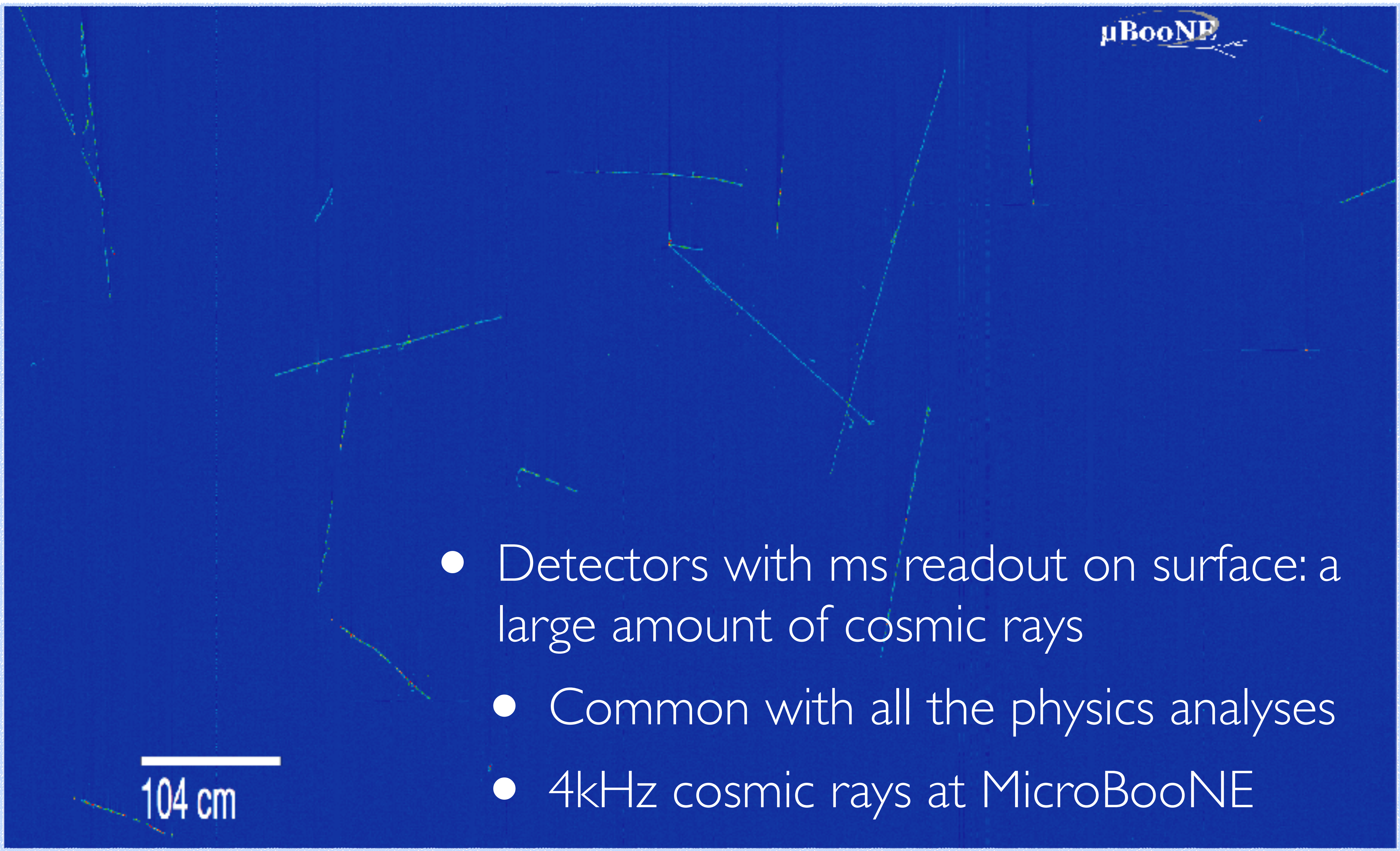
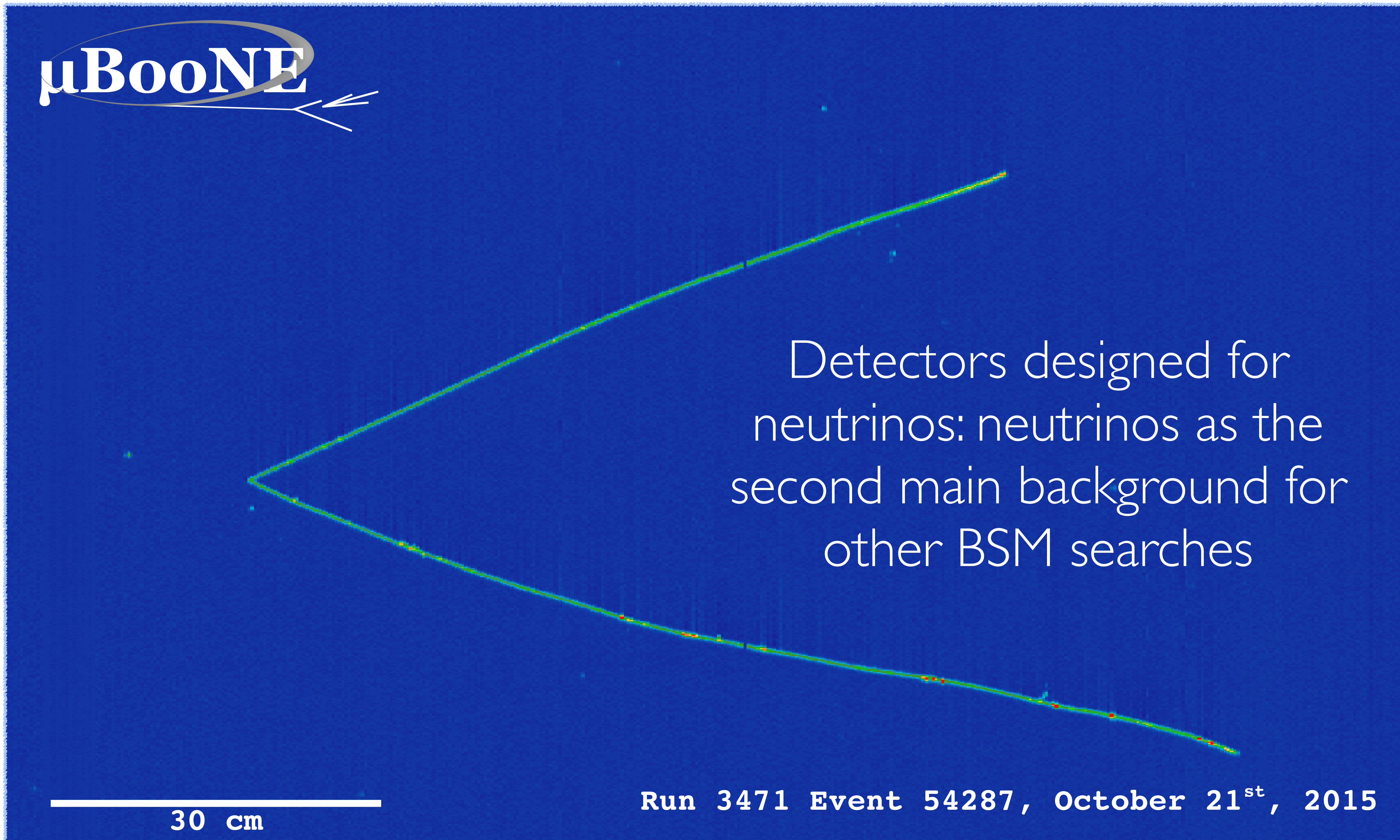


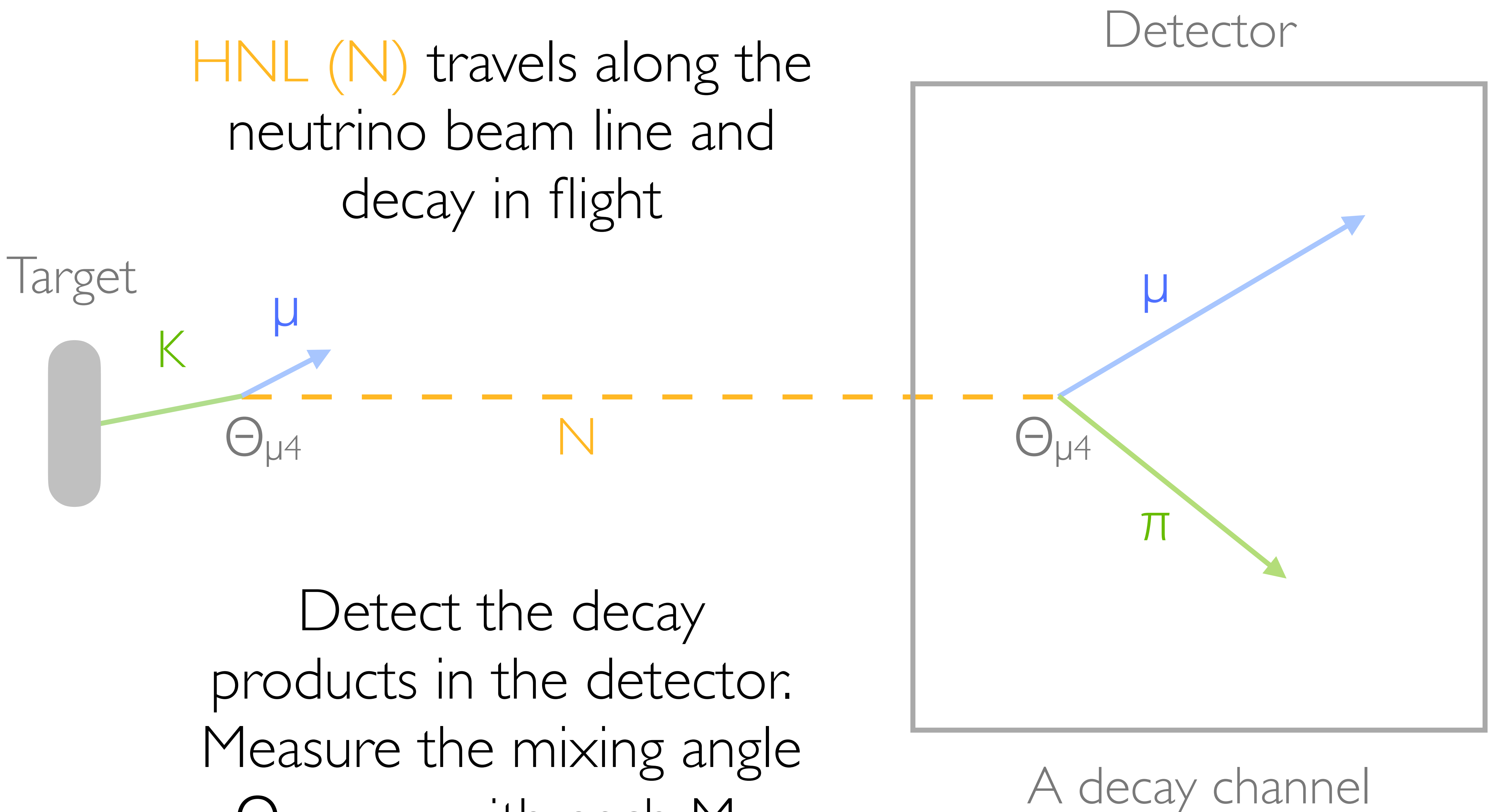
- Detectors with ms readout on surface: a large amount of cosmic rays
  - Common with all the physics analyses
  - 4kHz cosmic rays at MicroBooNE

Background: SM Neutrinos



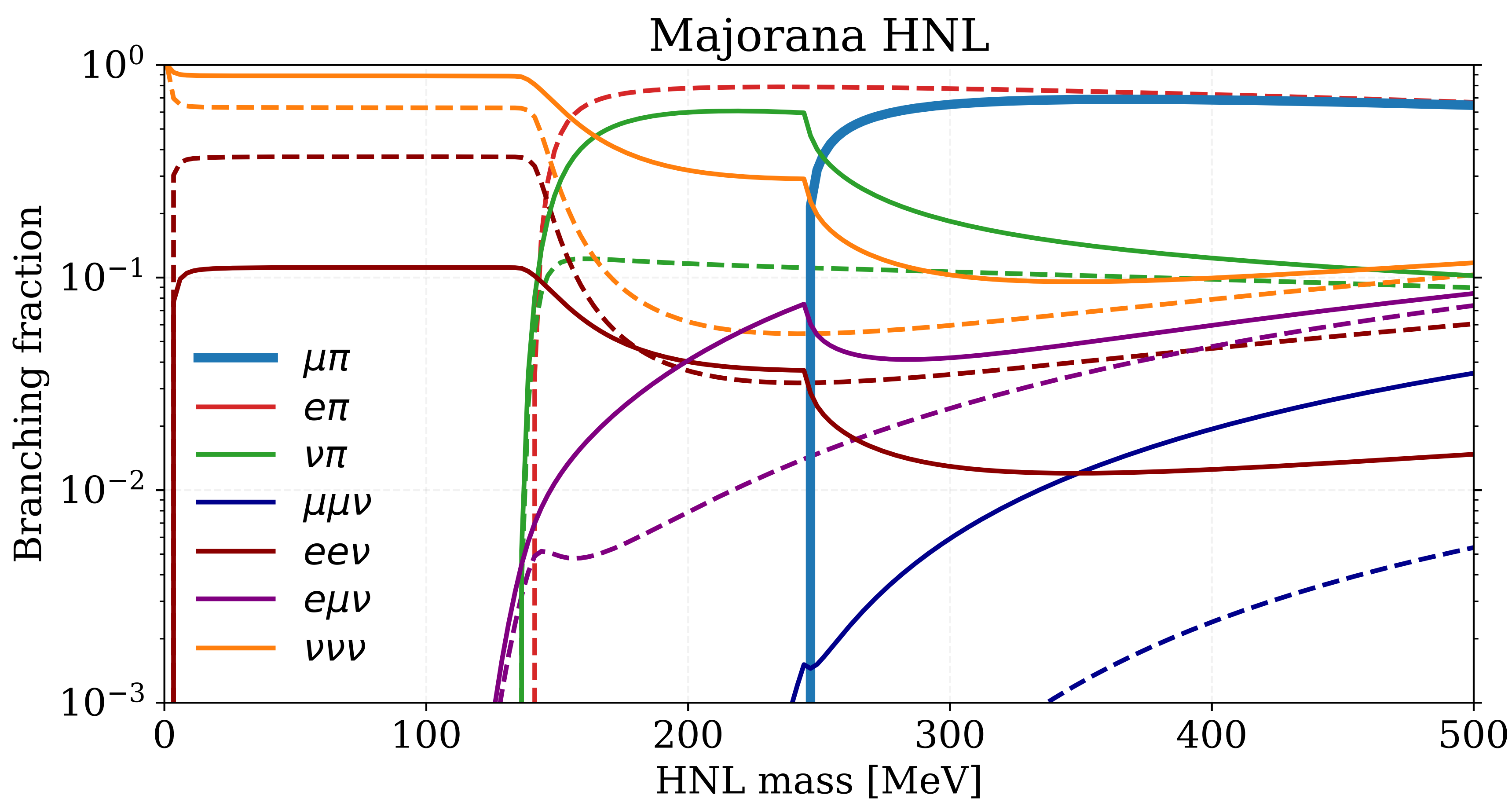
Heavy Neutral Lepton

HNL (N) travels along the neutrino beam line and decay in flight



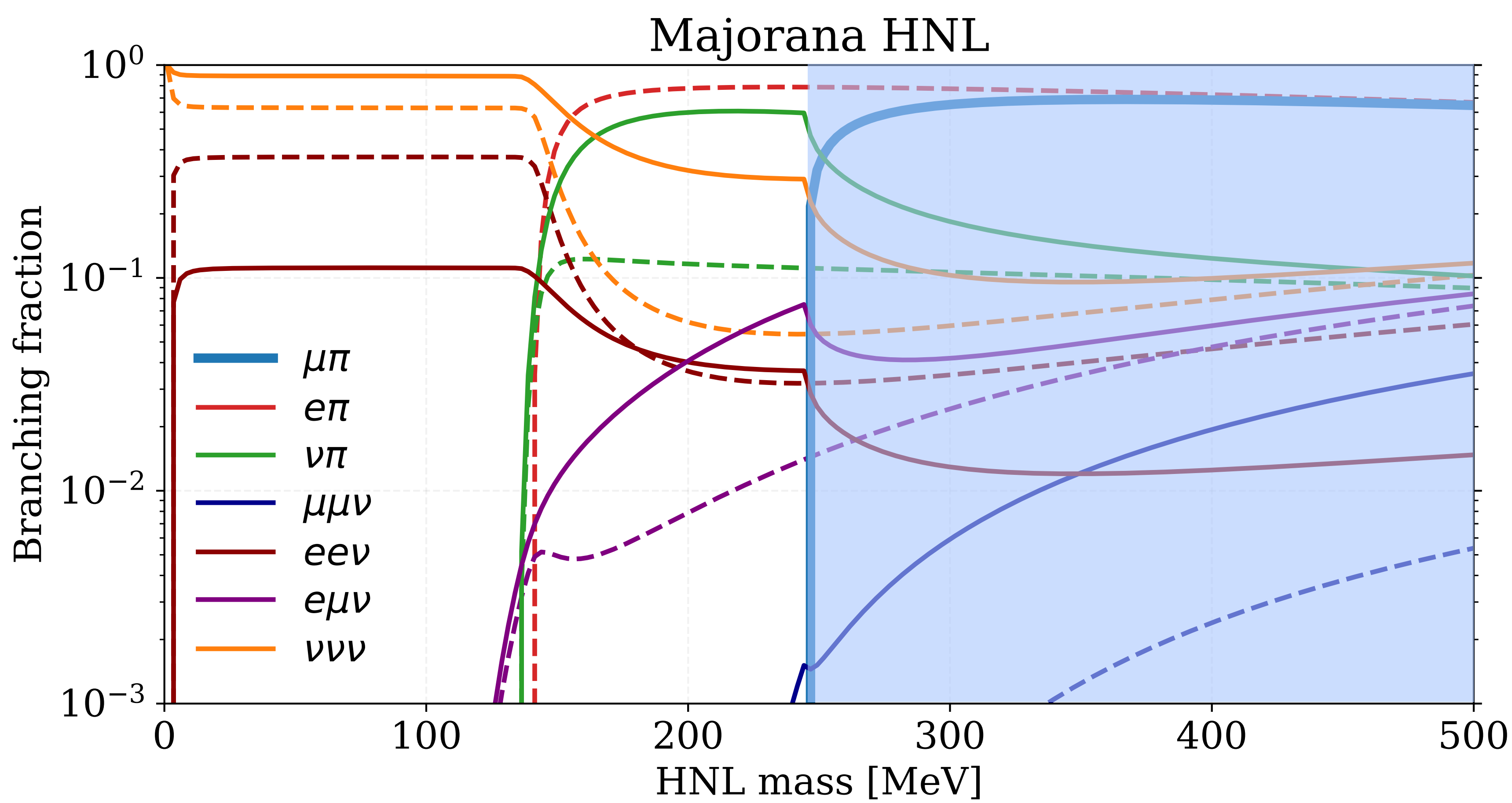
Detect the decay products in the detector. Measure the mixing angle $\Theta_{\mu 4,\, e4,\, \tau 4}$ with each M_N

Decay Channels



- 2 or 3-body decays
- Charged current: N→**γν**, N→**μ**eν, N→eπ, N→**μπ**
- Charged and neutral current: N→3ν, N→eeν, N→**νπ**^{0}, N→**μμν**

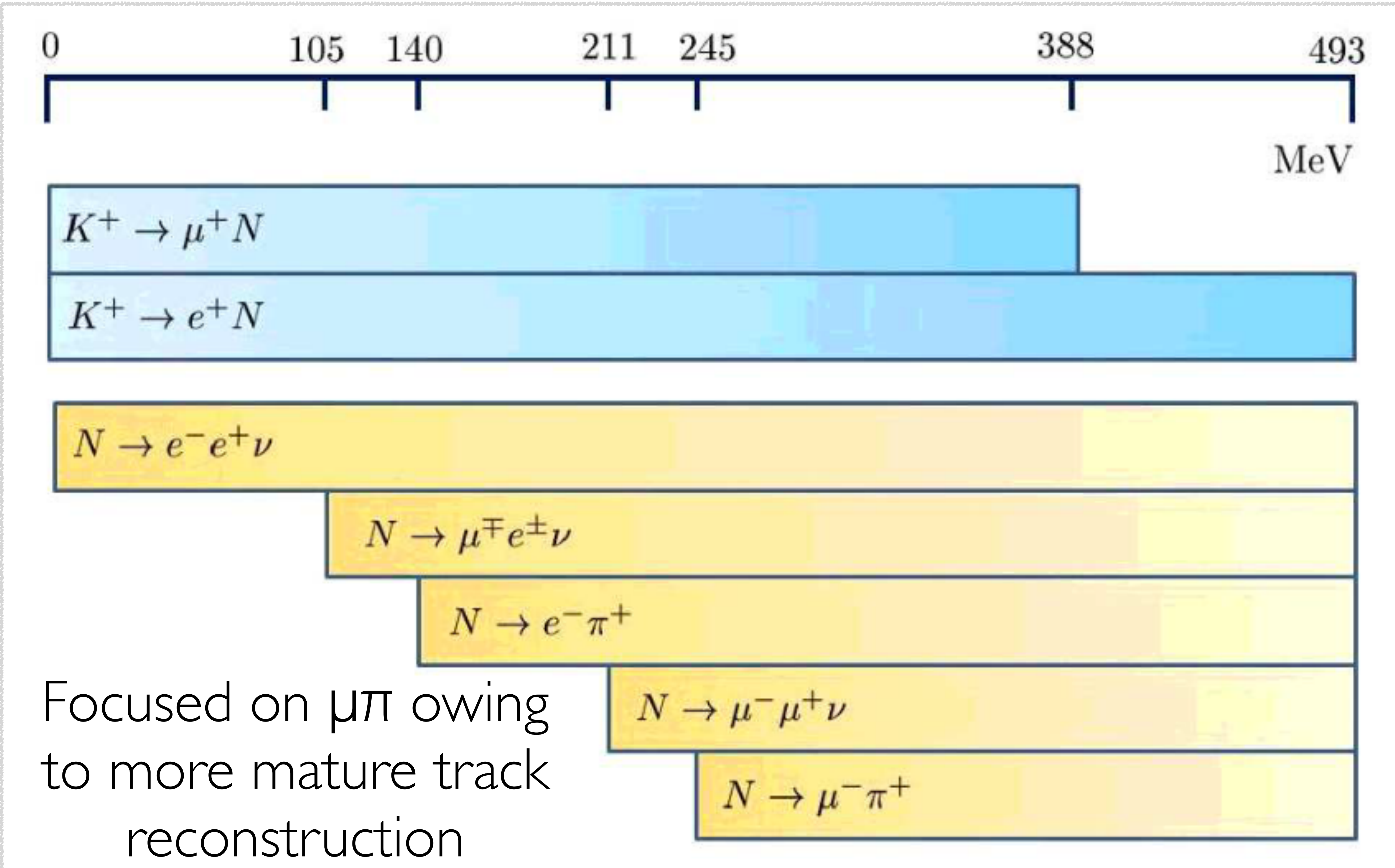
Decay Channels



$N \rightarrow \mu^{\pm}\pi^{\mp}$ dominant at $M_N > 250$ MeV/c^2

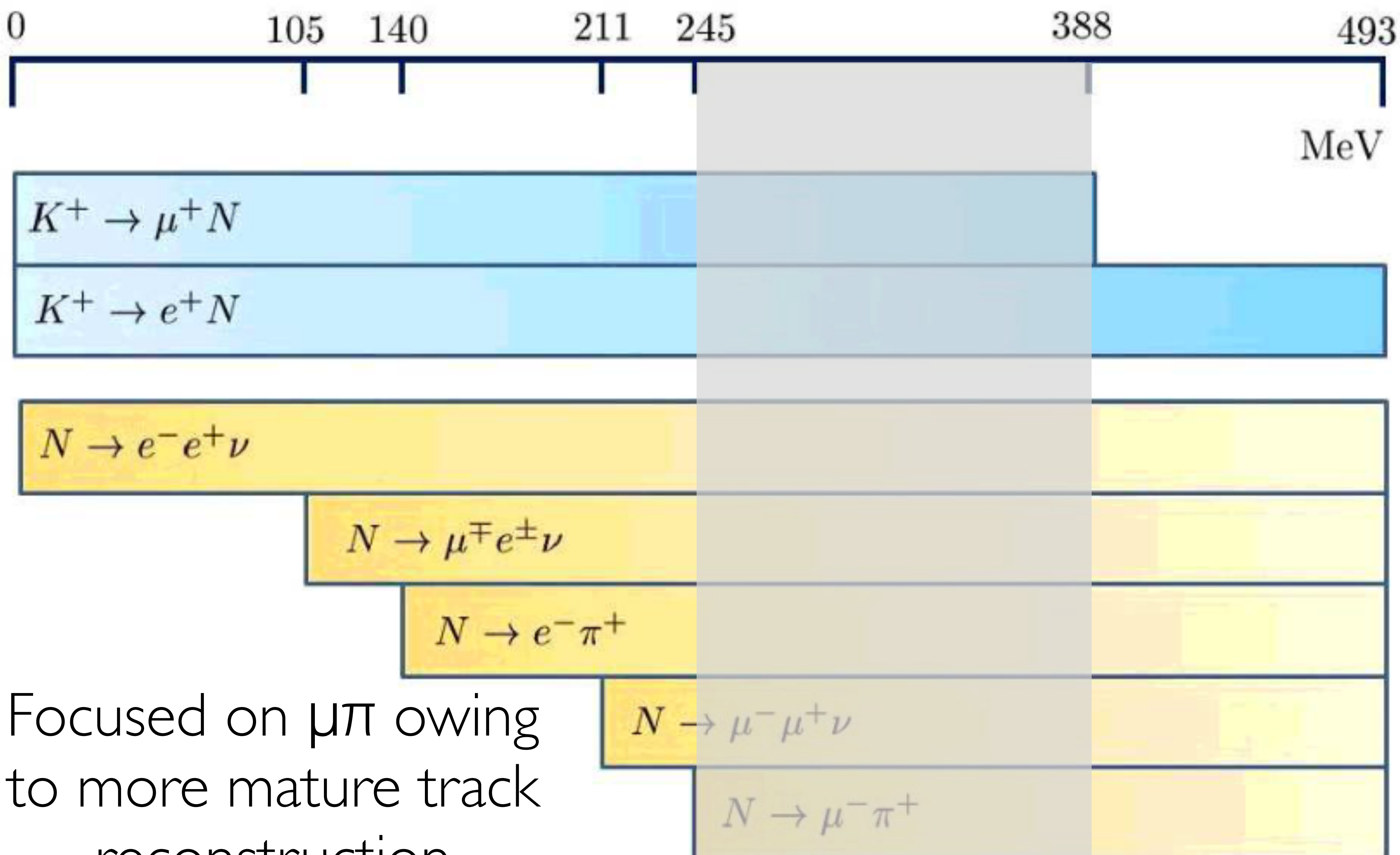
- 2 or 3-body decays
- Charged current: $N \rightarrow \boldsymbol{\gamma\nu}$, $N \rightarrow \boldsymbol{\mu}e\nu$, $N \rightarrow e\pi$, $N \rightarrow \boldsymbol{\mu\pi}$
- Charged and neutral current: $N \rightarrow 3\nu$, $N \rightarrow ee\nu$, $N \rightarrow \boldsymbol{\nu\pi}^0$, $N \rightarrow \boldsymbol{\mu\mu\nu}$

Sensitivity on HNL Mass



Focused on μπ owing to more mature track reconstruction

Sensitivity on HNL Mass

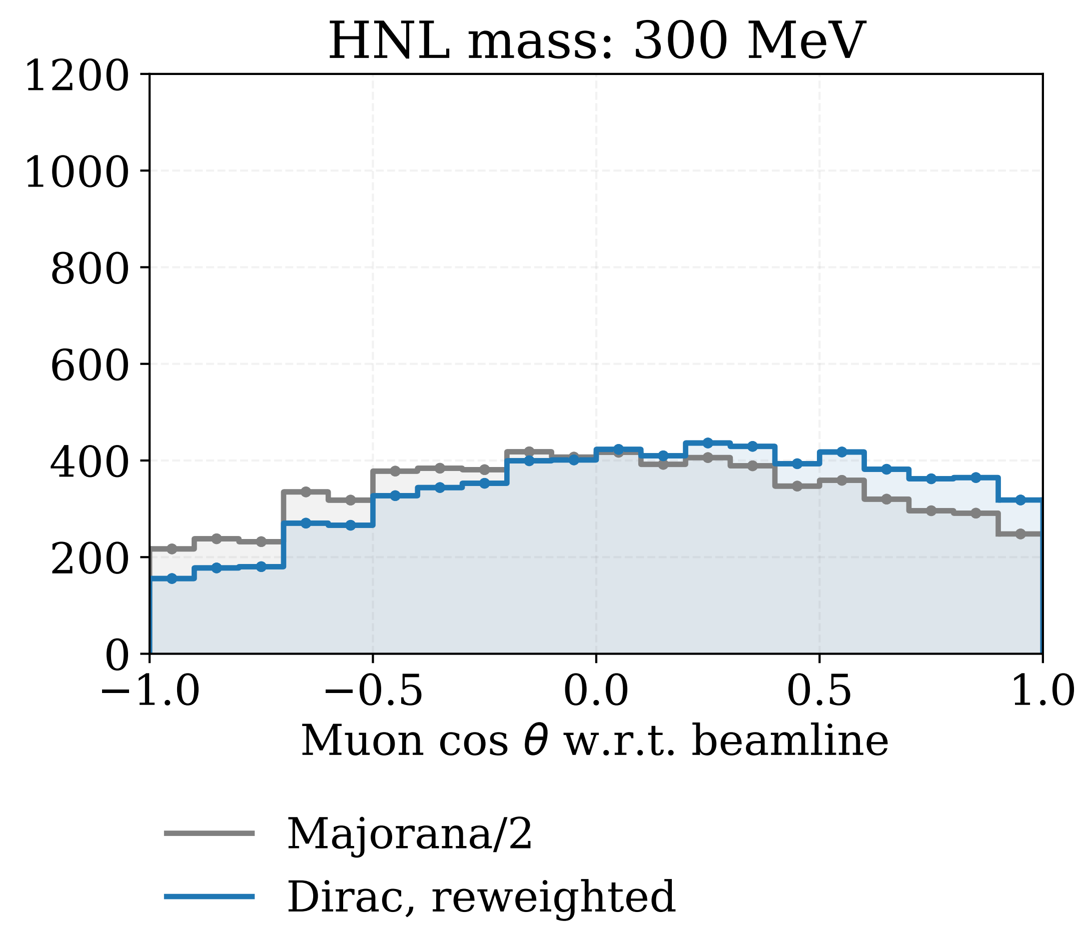


Focused on μπ owing to more mature track reconstruction

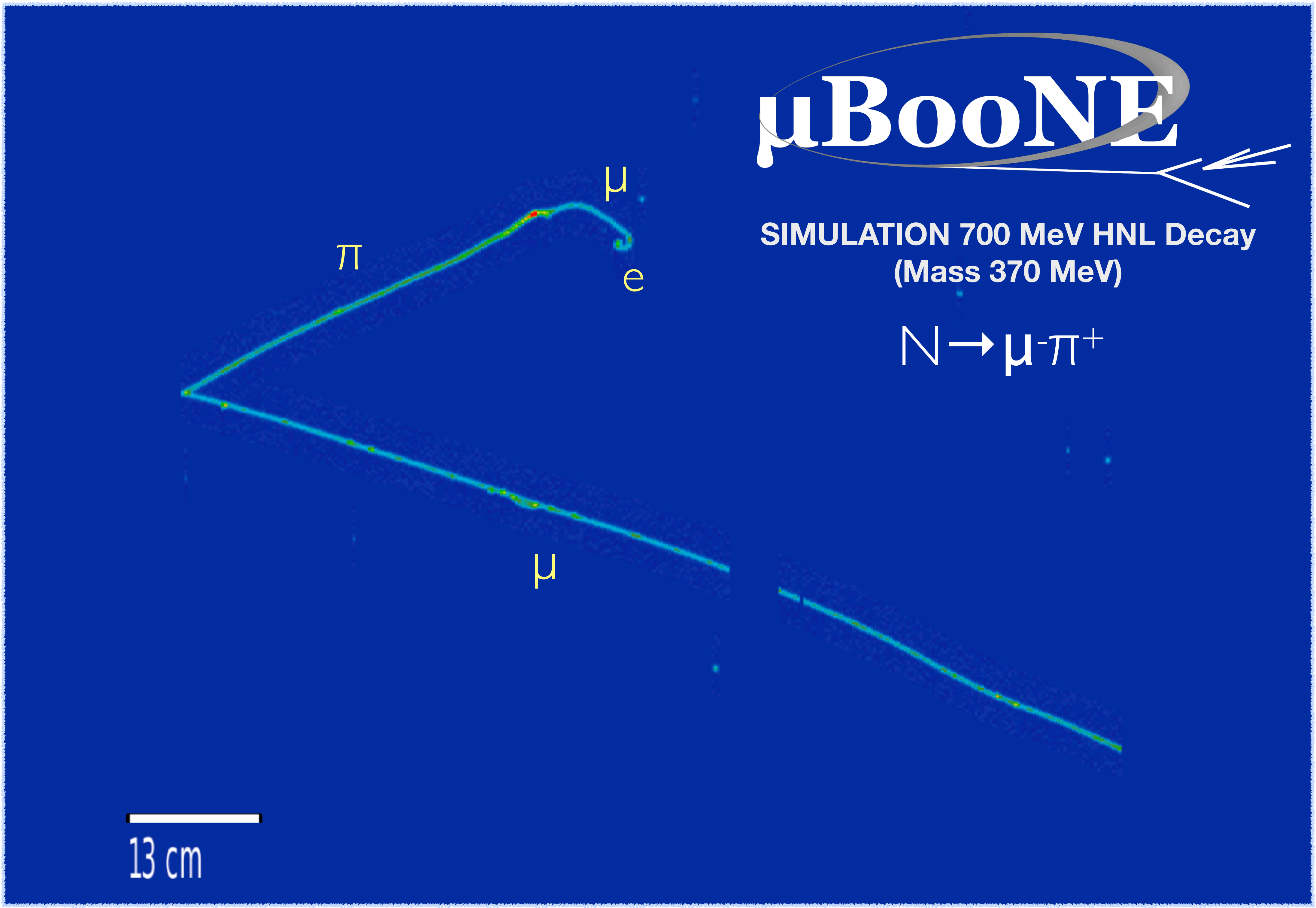
Majorana v.s. Dirac

- HNL can be a Majorana or Dirac particle
- Majorana HNL
  - $N \to \mu^- \pi^+$ and $N \to \mu^+ \pi^-$
  - Sum of $\mu^- \pi^+$ and $\mu^+ \pi^-$ is isotropic in the HNL rest frame
- Dirac HNL
  - $N \to \mu^- \pi^+$ only
  - Half event rate compared to Majorana HNL
  - Asymmetric angular spectrum

We use the Majorana assumption in the following slides, while presenting the results for both the cases



Simulated HNL Event

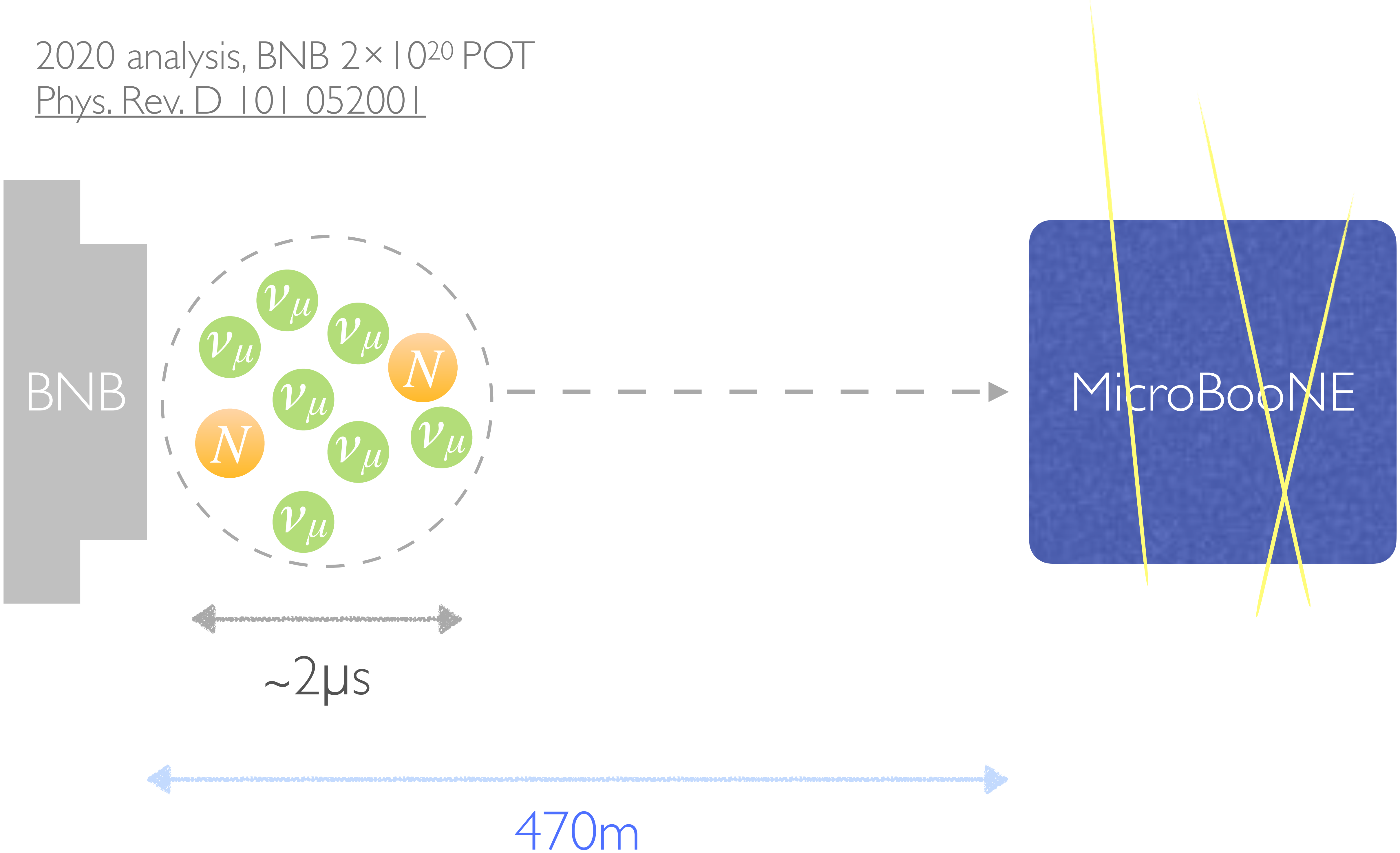


Event with an HNL

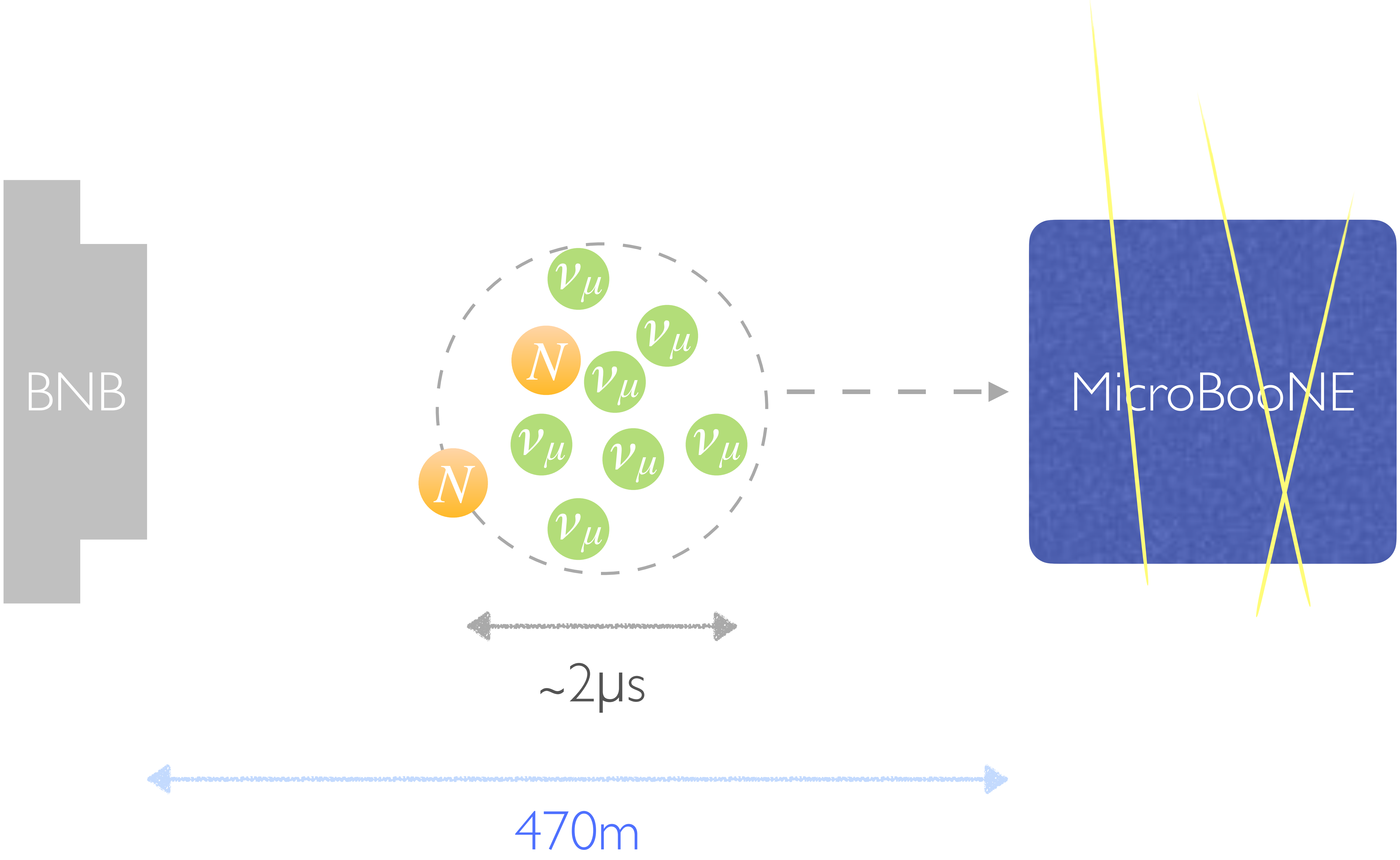
A simulated HNL overlaid with a pure cosmic data event

Time of Flight

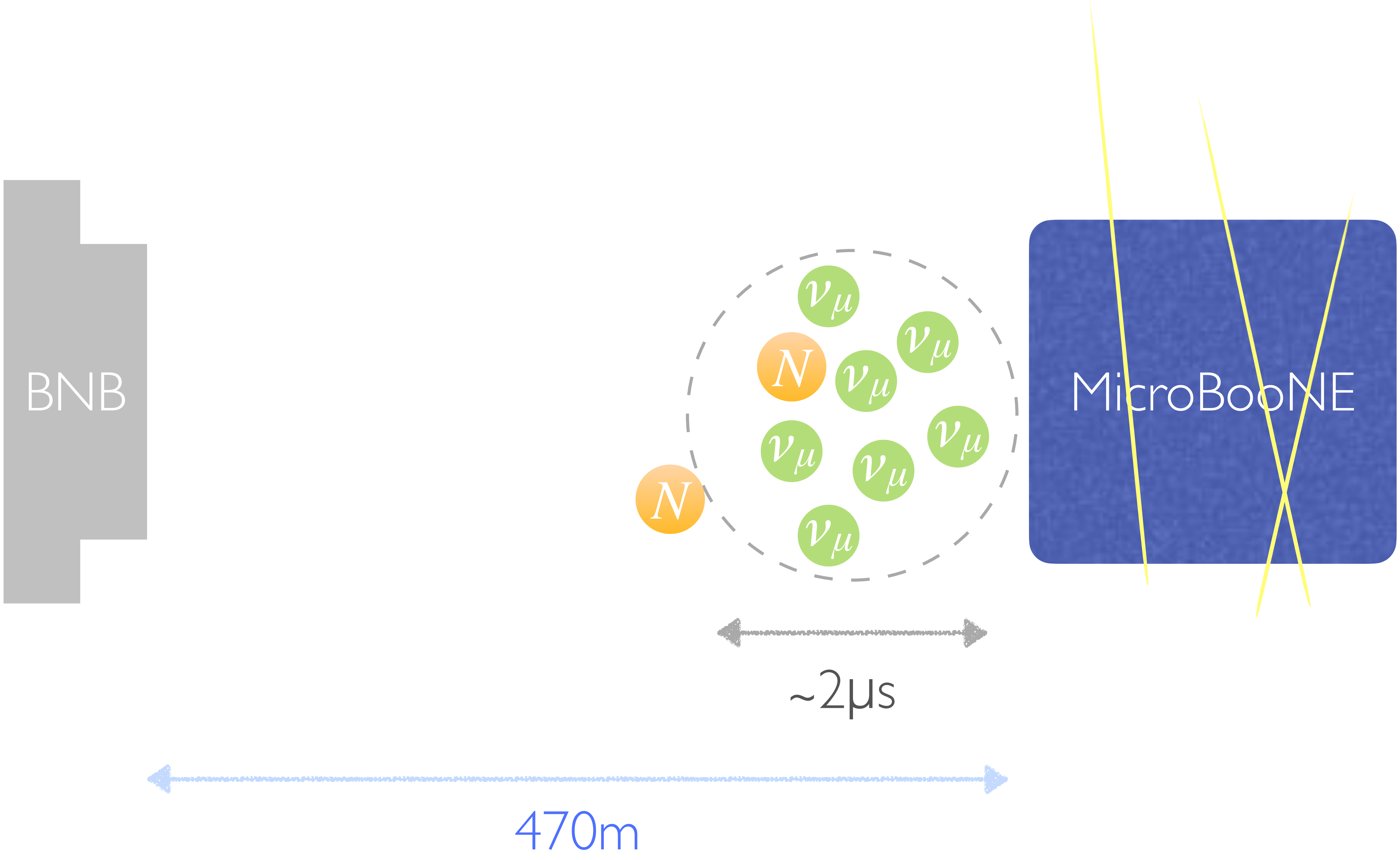
2020 analysis, BNB 2×10^{20} POT
Phys. Rev. D 101 052001



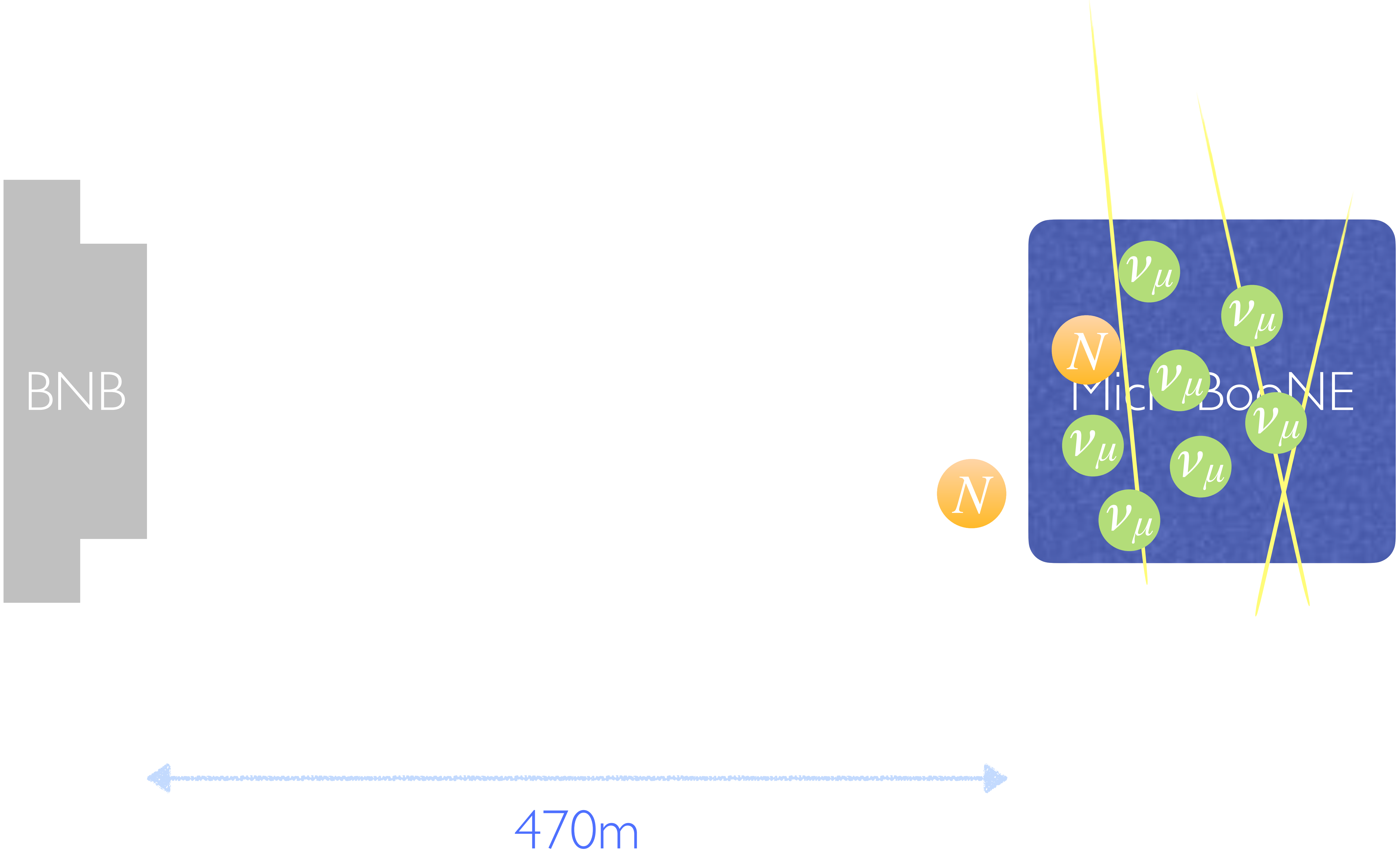
Time of Flight



Time of Flight



Time of Flight



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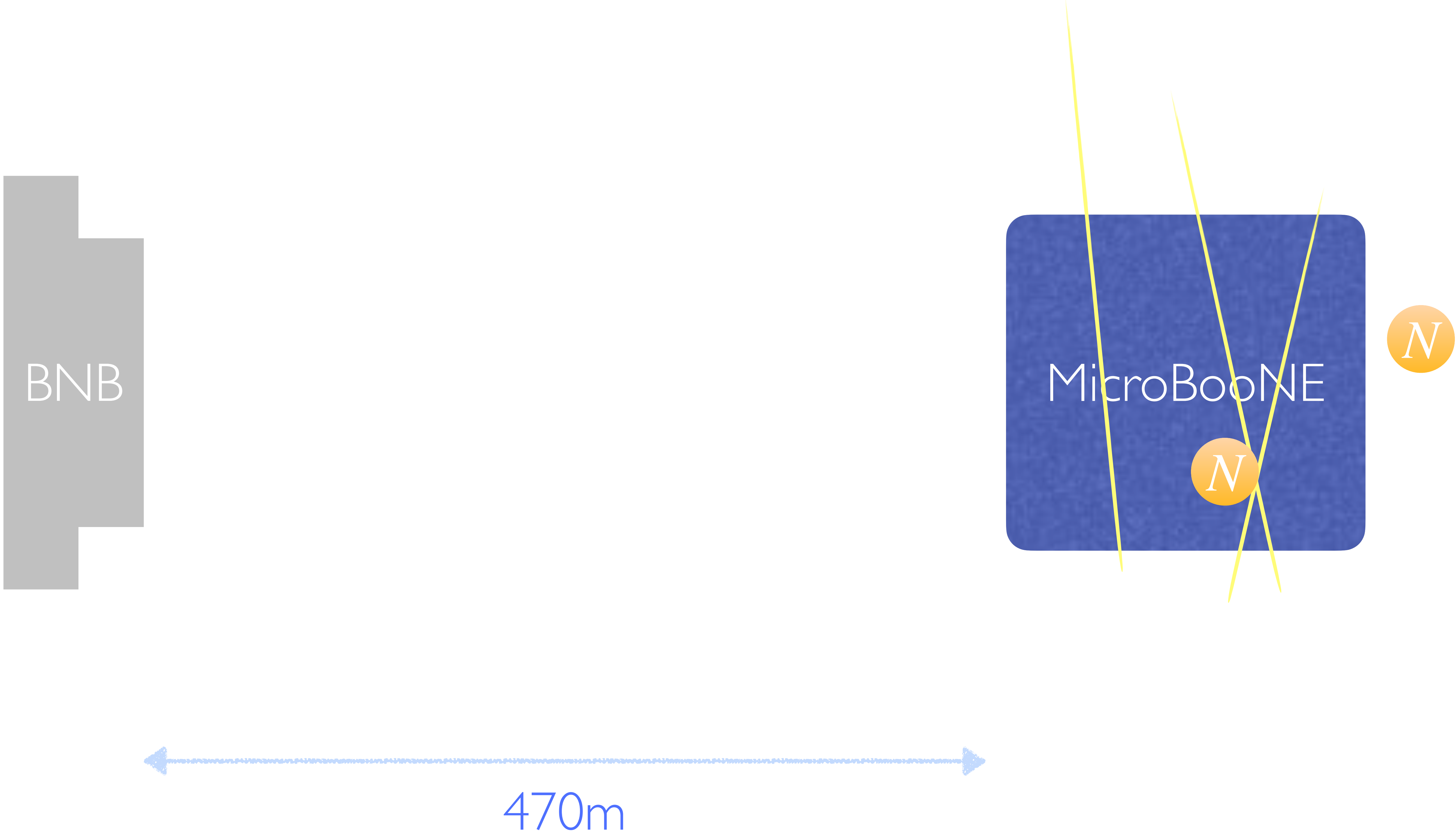
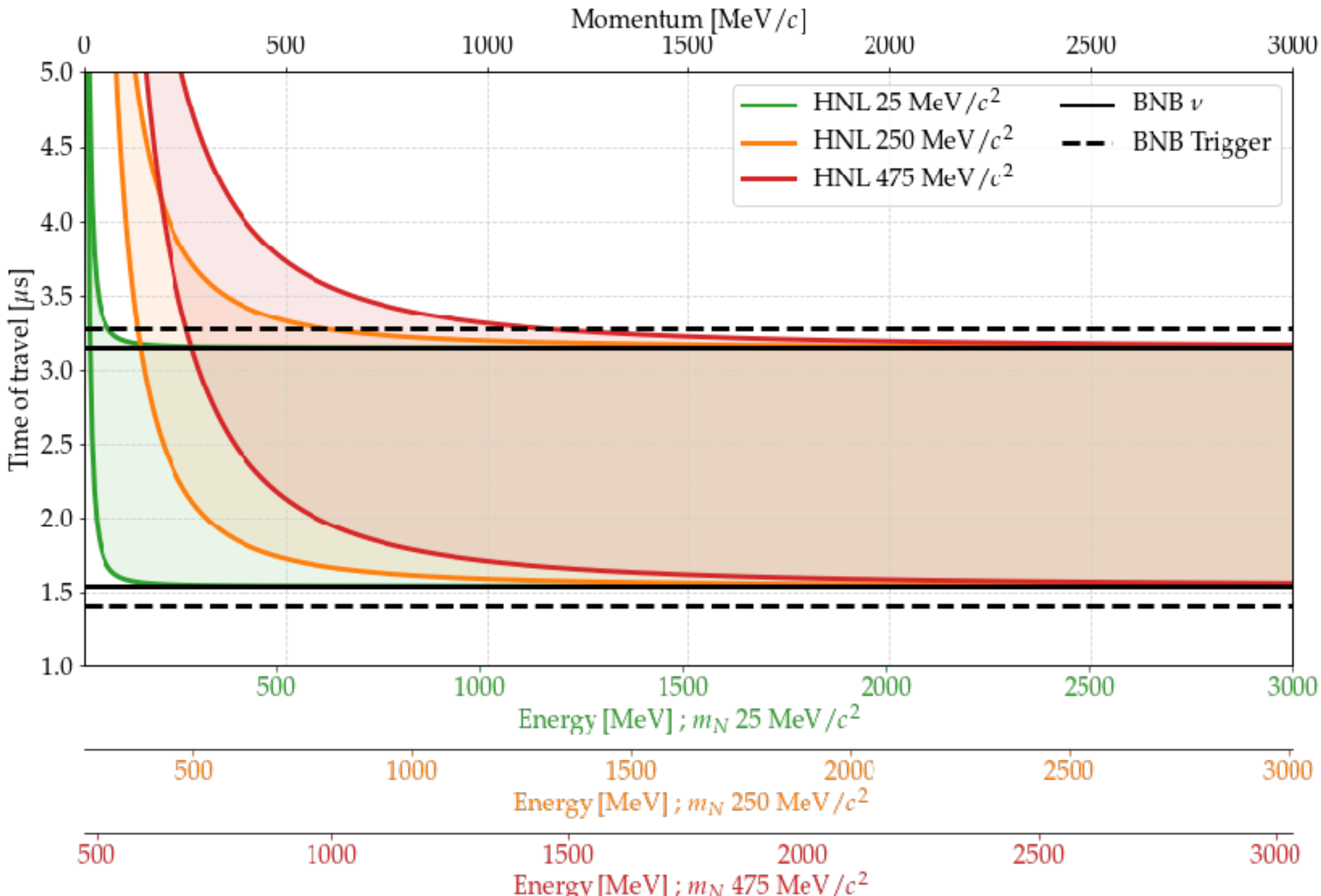
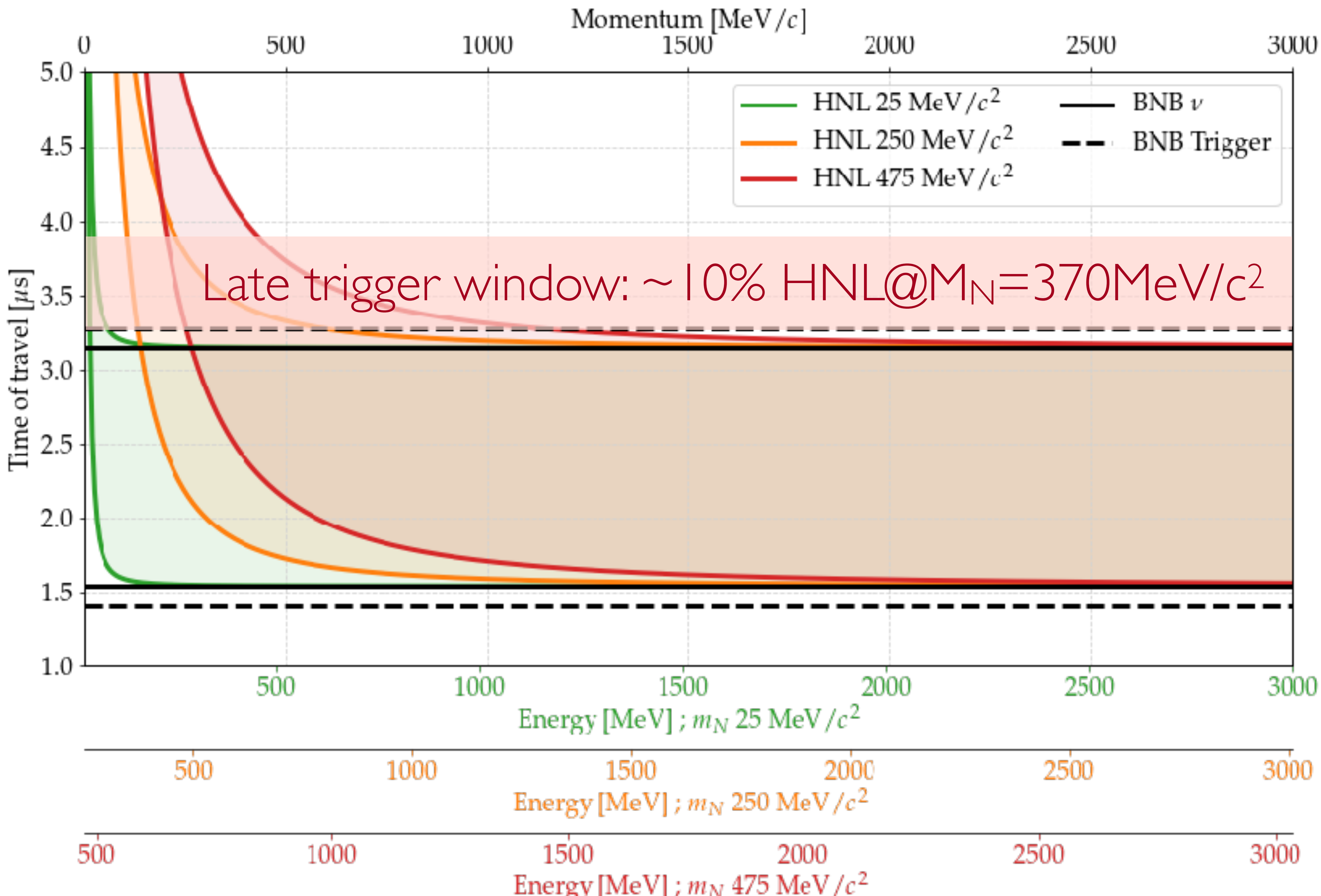


HNL Late Trigger Window



Courtesy of Davide Porzio

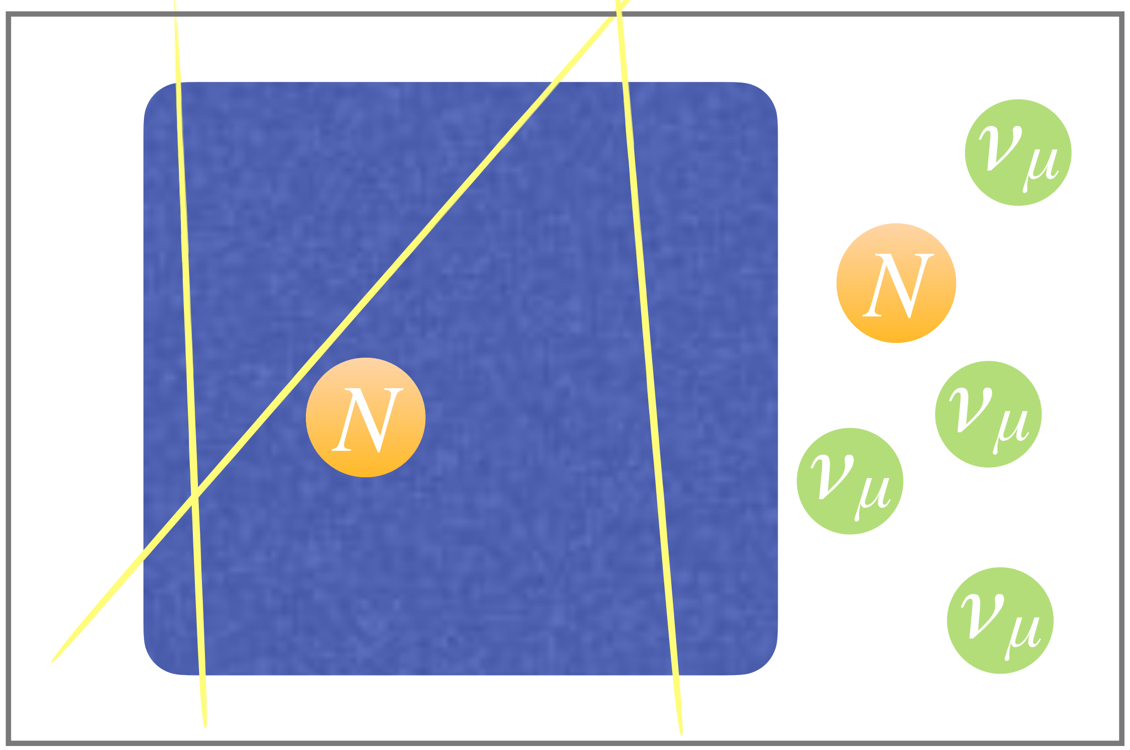
HNL Late Trigger Window



Courtesy of Davide Porzio

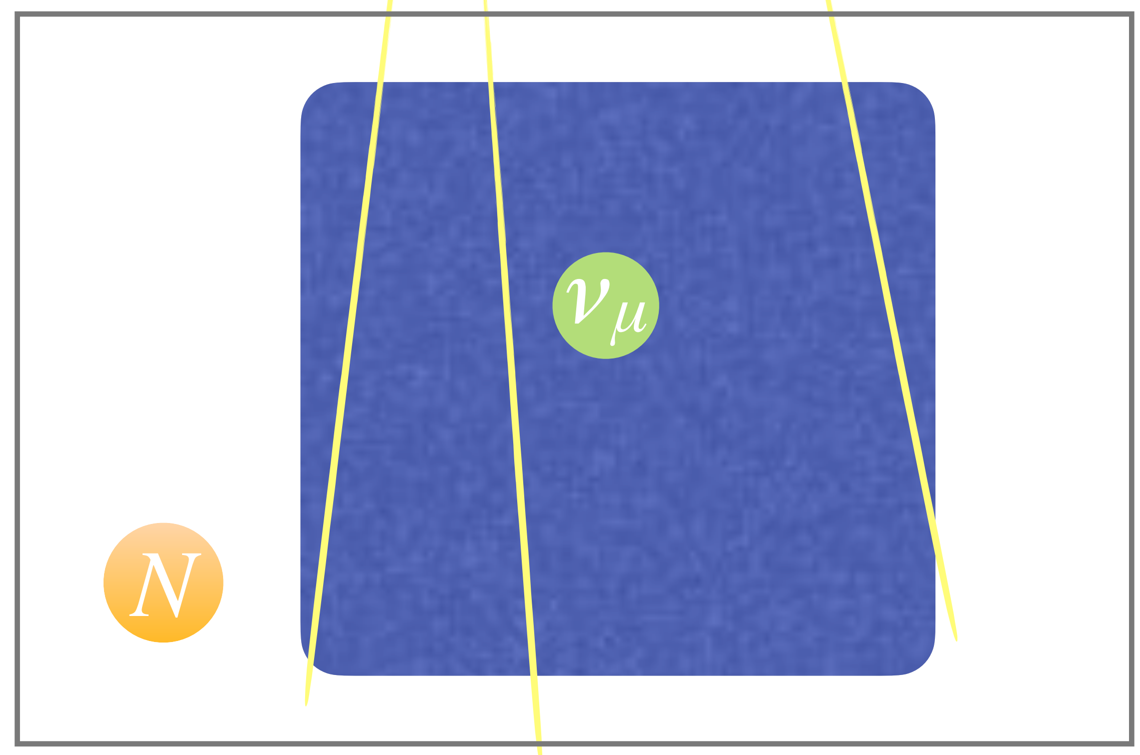
Data-Driven Analysis

Triggered events



Snapshot of the detector

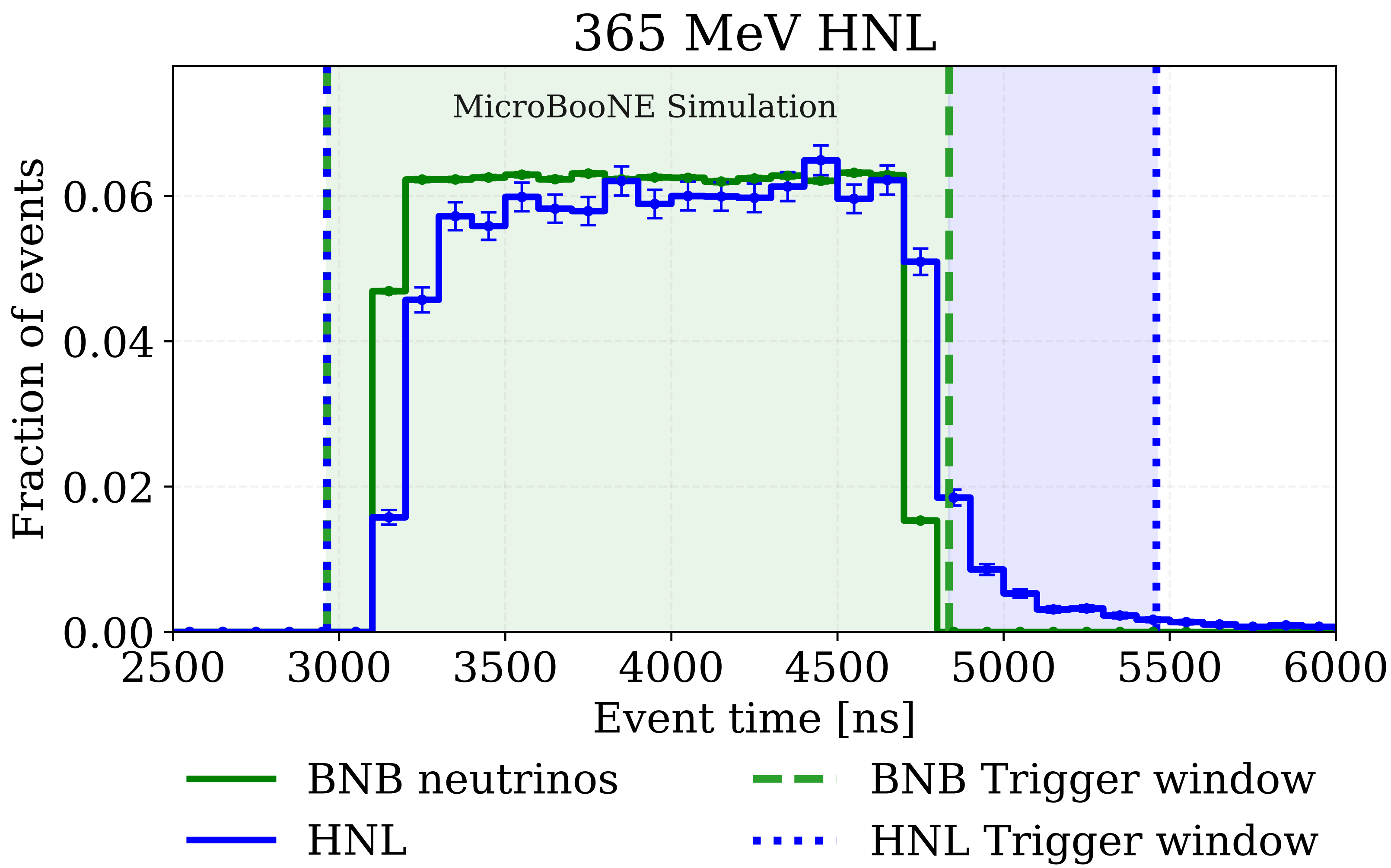
Vetoed events



Snapshot of the detector

- Use the events triggered in late trigger window, but vetoed those triggered in the BNB trigger window
- Measure an excess of events in a data sample containing only cosmic rays

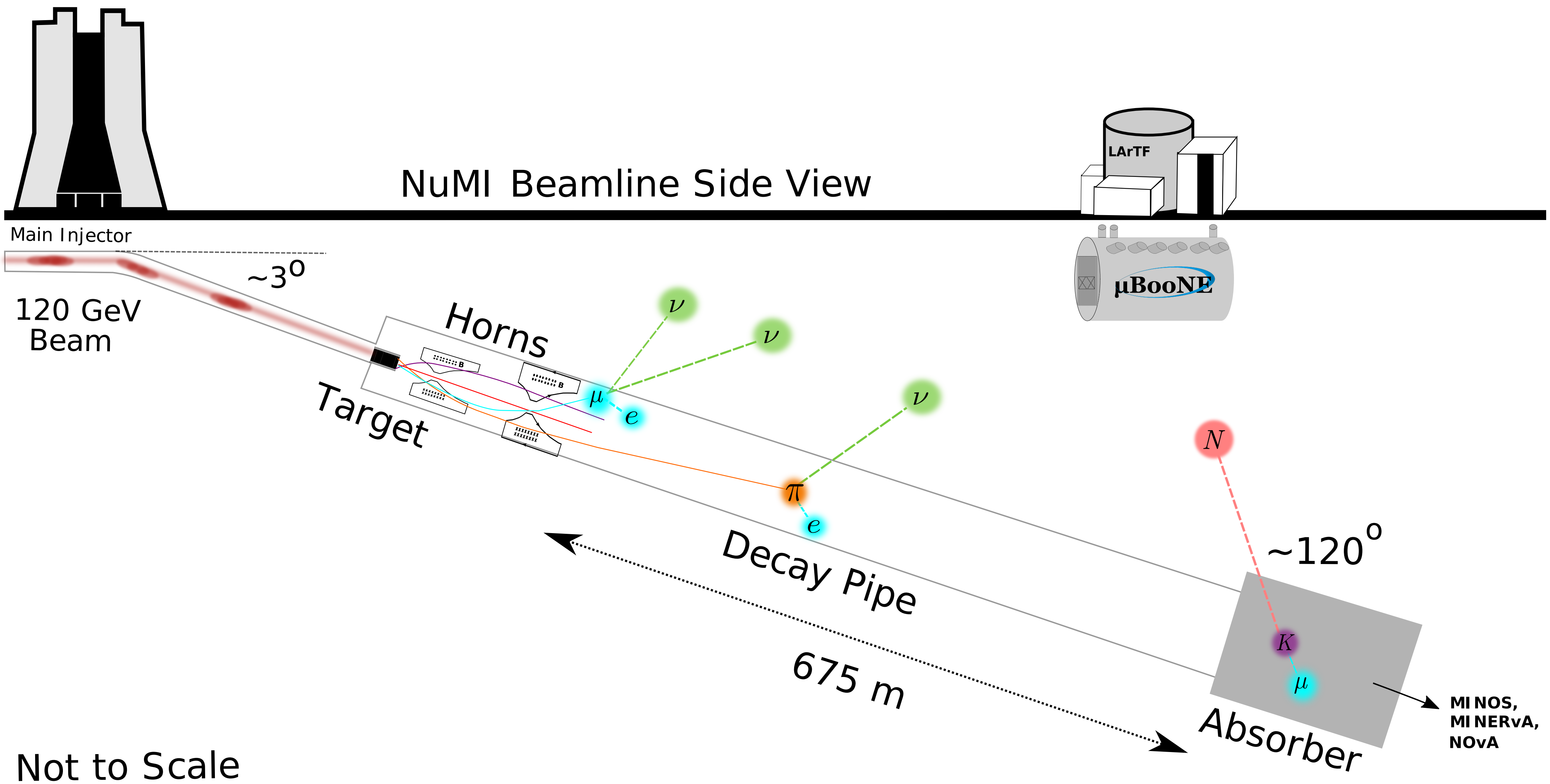
Small Signal Fraction



- Lower kaon production rate at BNB than NuMI
- The analysis strategy yields a small fraction of signals
- Better ν beam structure simulation and reconstruction will improve the sensitivity

K Decays at NuMI Absorber

2022 analysis, NuMI 7×10^{20} POT
Phys. Rev. D 106 092006



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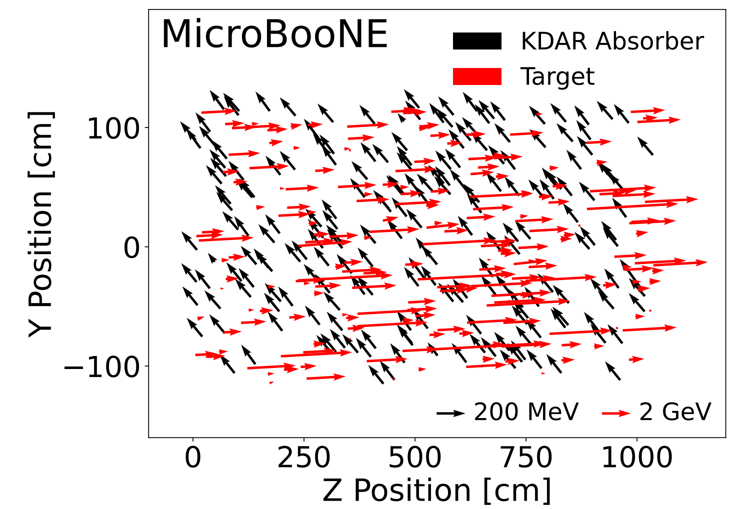
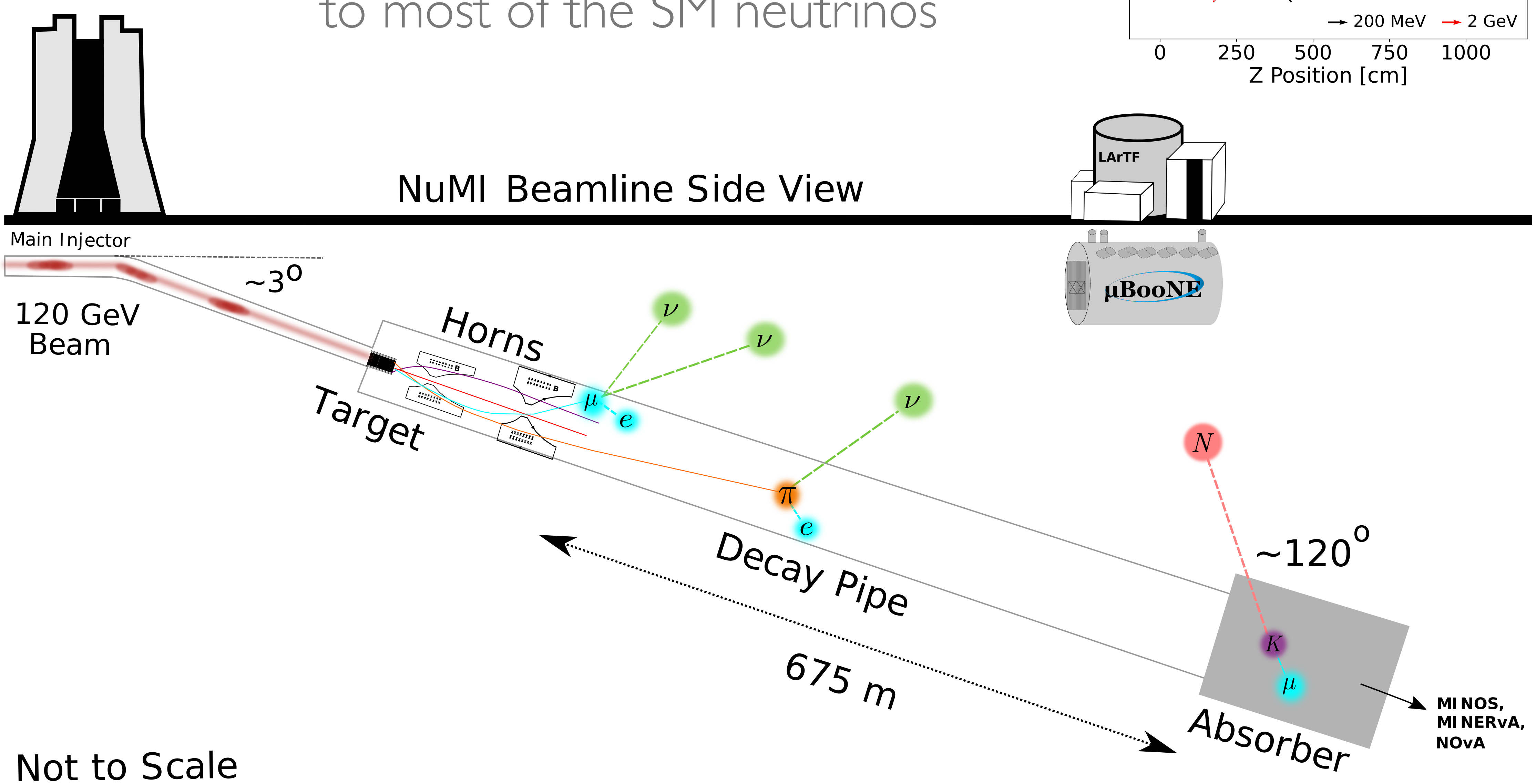


Utilize the different direction to most of the SM neutrinos



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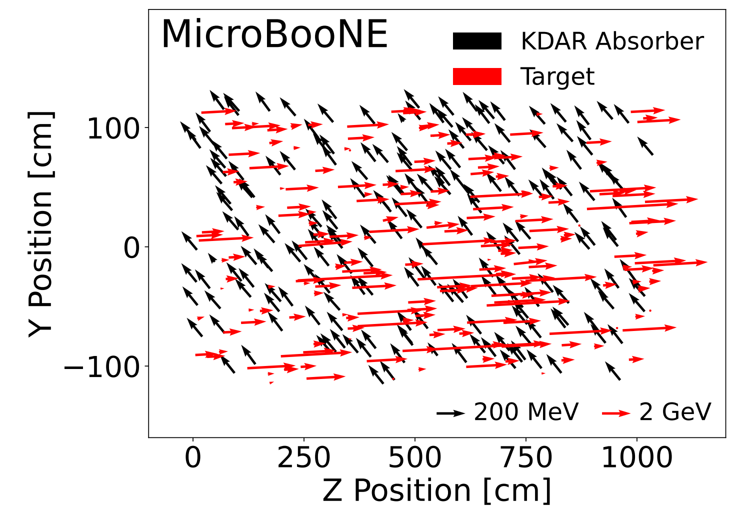

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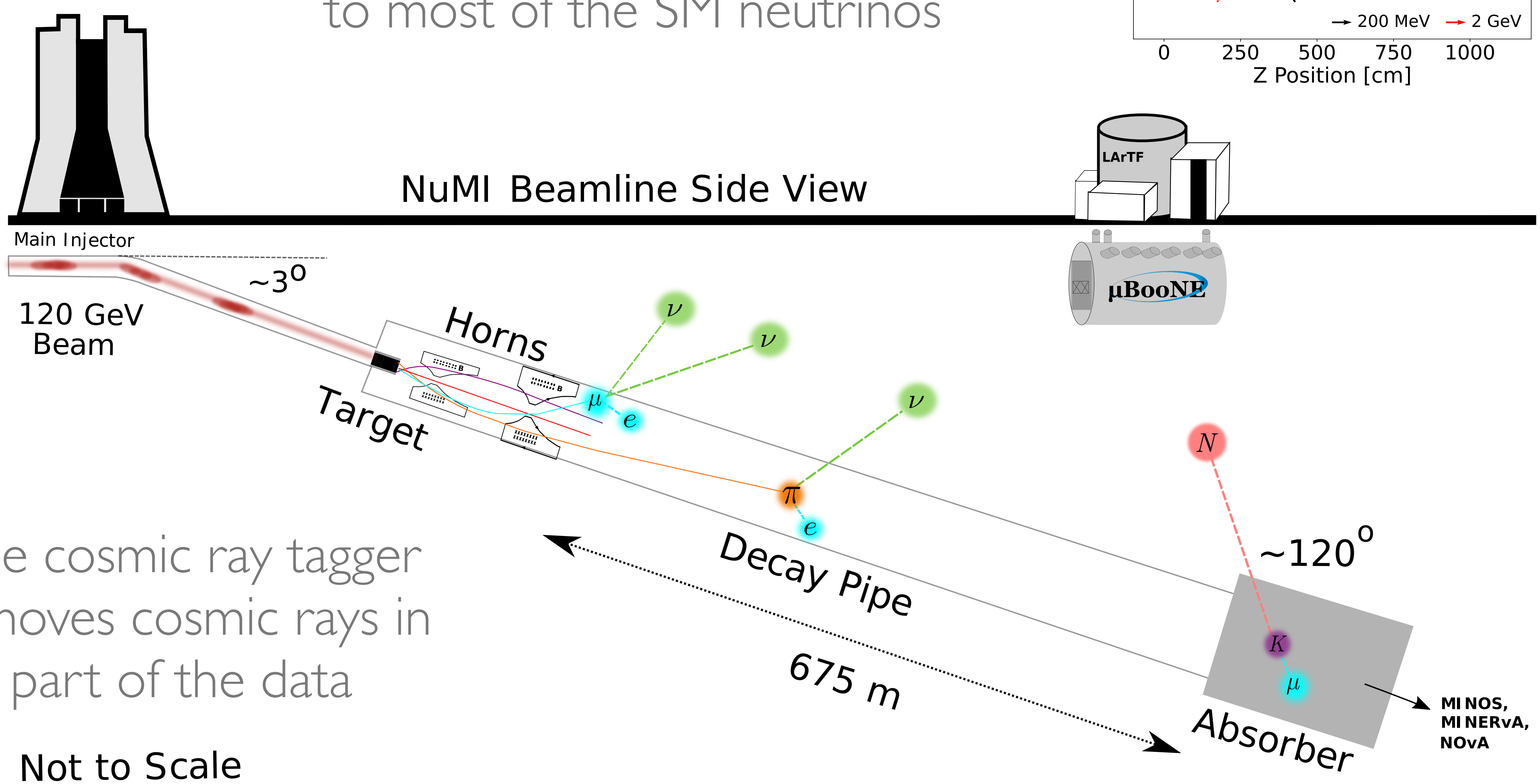
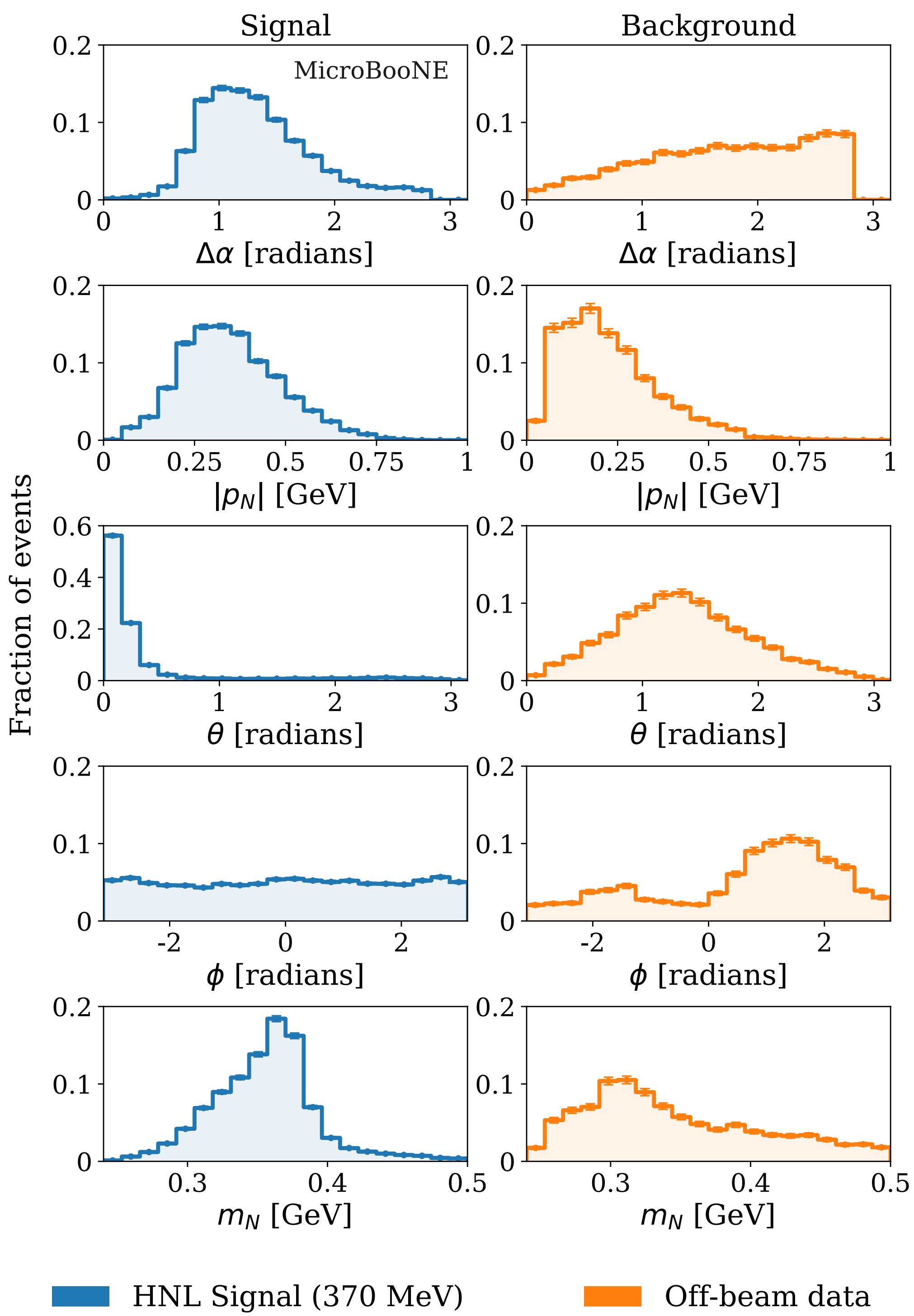


The cosmic ray tagger removes cosmic rays in part of the data

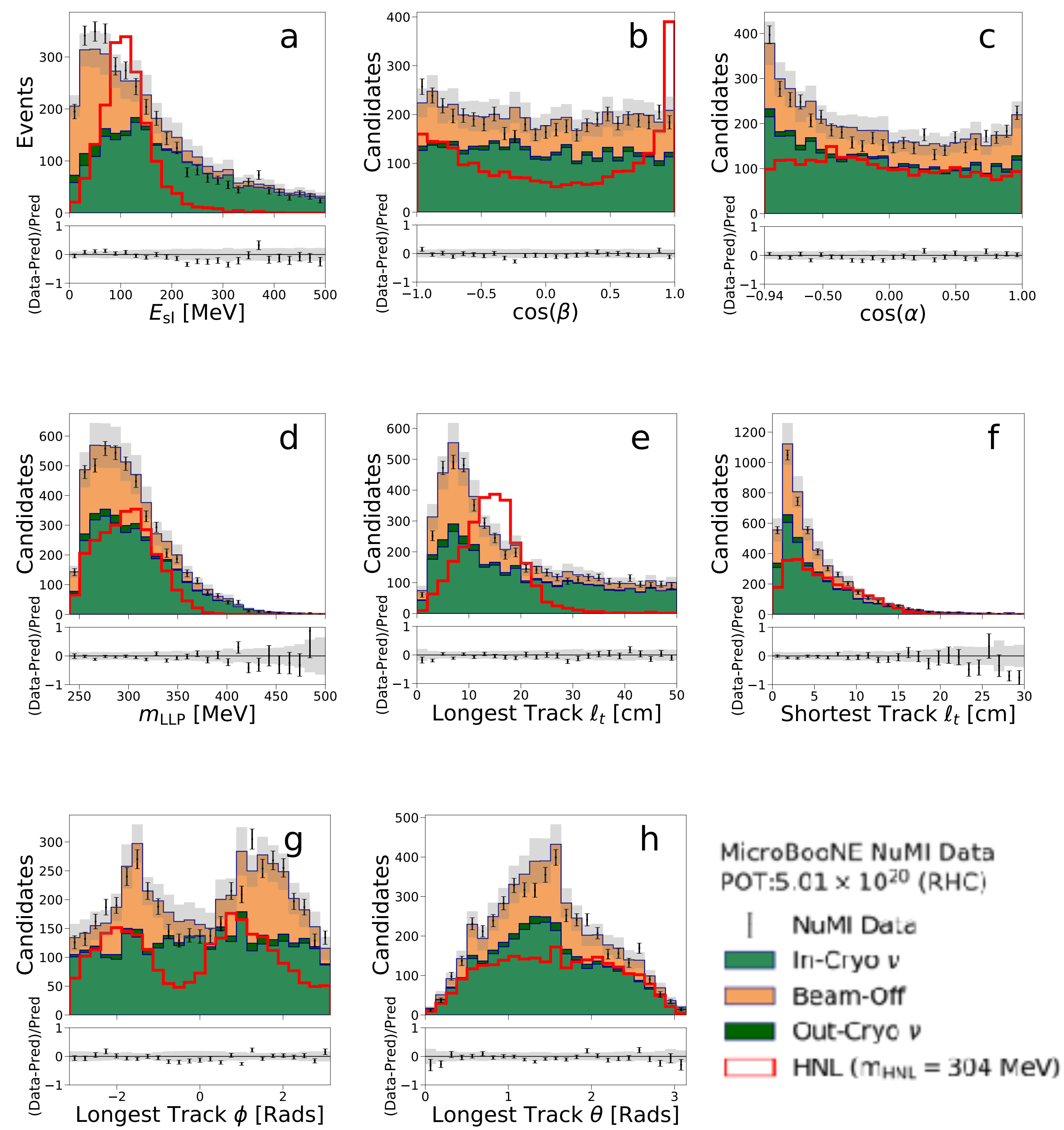
Not to Scale

Kinematic Distributions

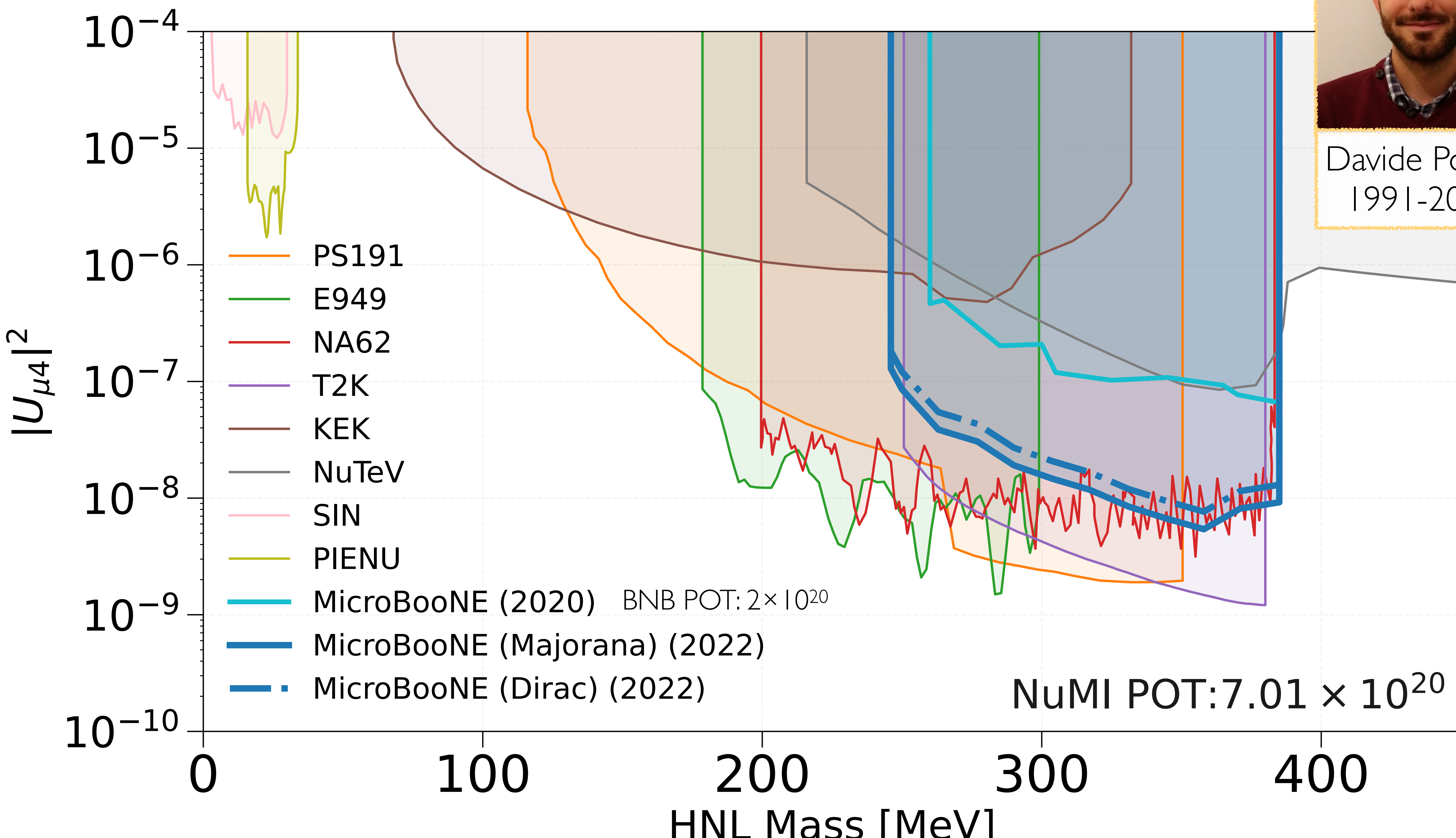
2020 Analysis



2022 Analysis



HNL Sensitivity



Davide Porzio
1991-2021

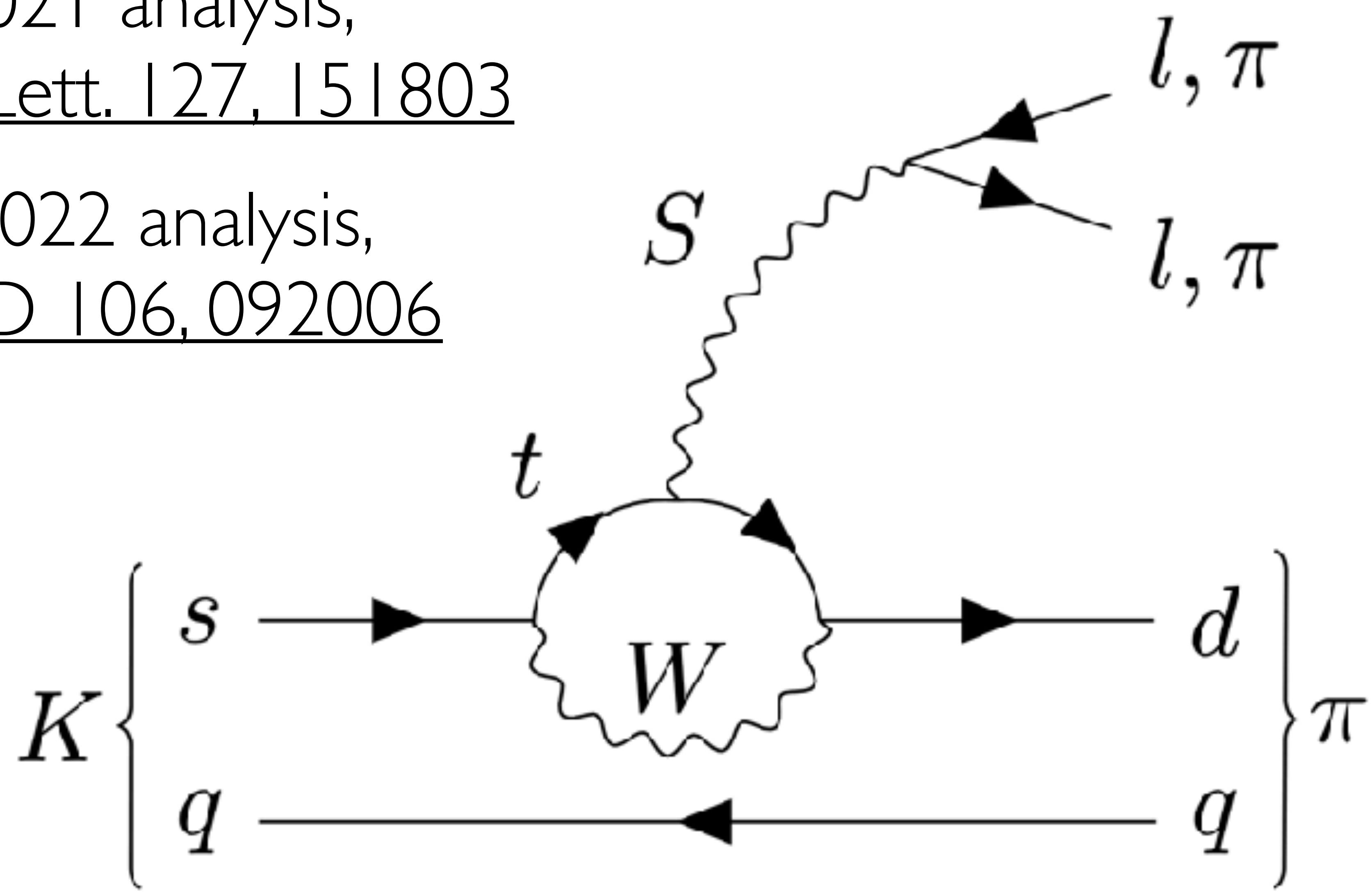
Phys. Rev. D 101, 052001 (2020)
Phys. Rev. D 106, 092006 (2022)

Higgs Portal Scalar Particle

Kaon decays at rest in the NuMI absorber

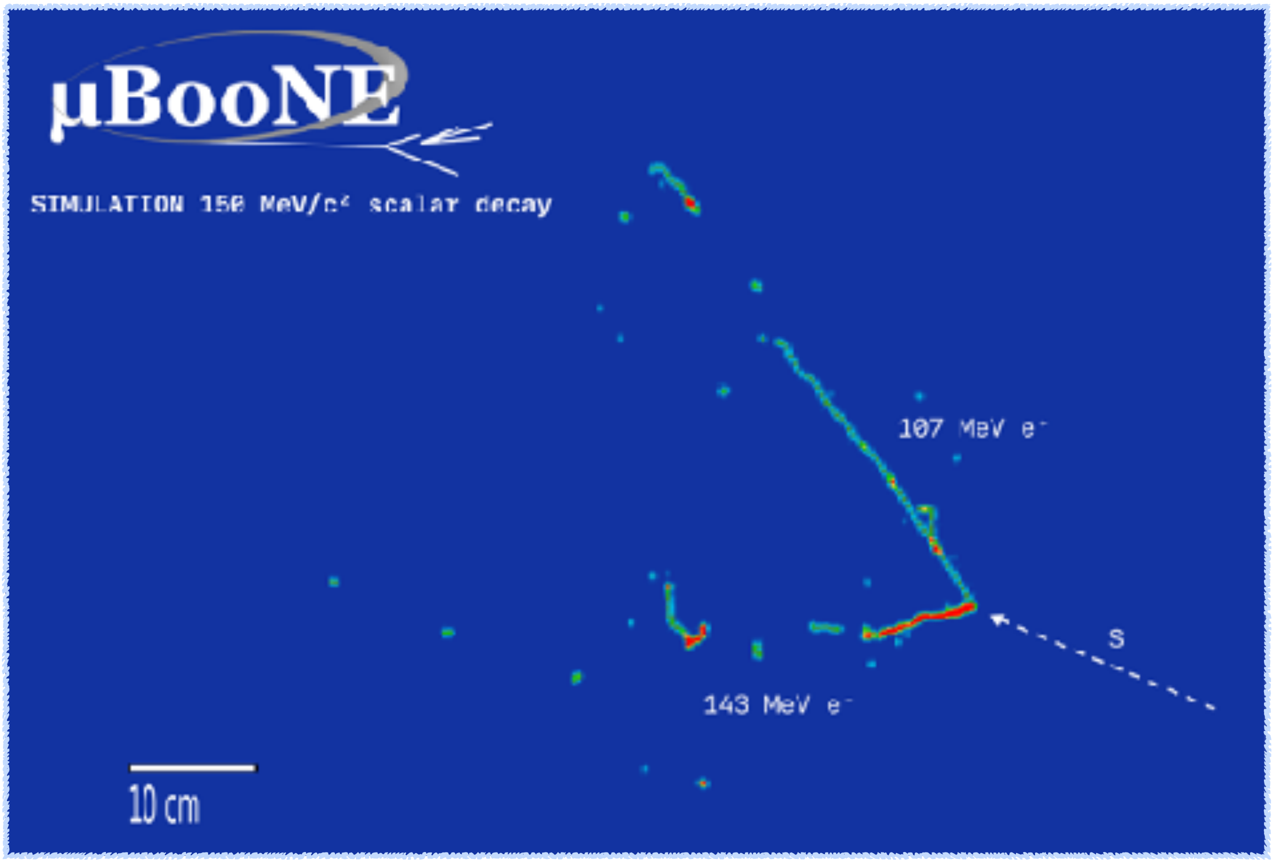
$K^+ \rightarrow \pi^+ S$ (S: HPS)

- $S \rightarrow e^+e^-$: 2021 analysis, Phys. Rev. Lett. 127, 151803
- $S \rightarrow \mu^+\mu^-$: 2022 analysis, Phys. Rev. D 106, 092006



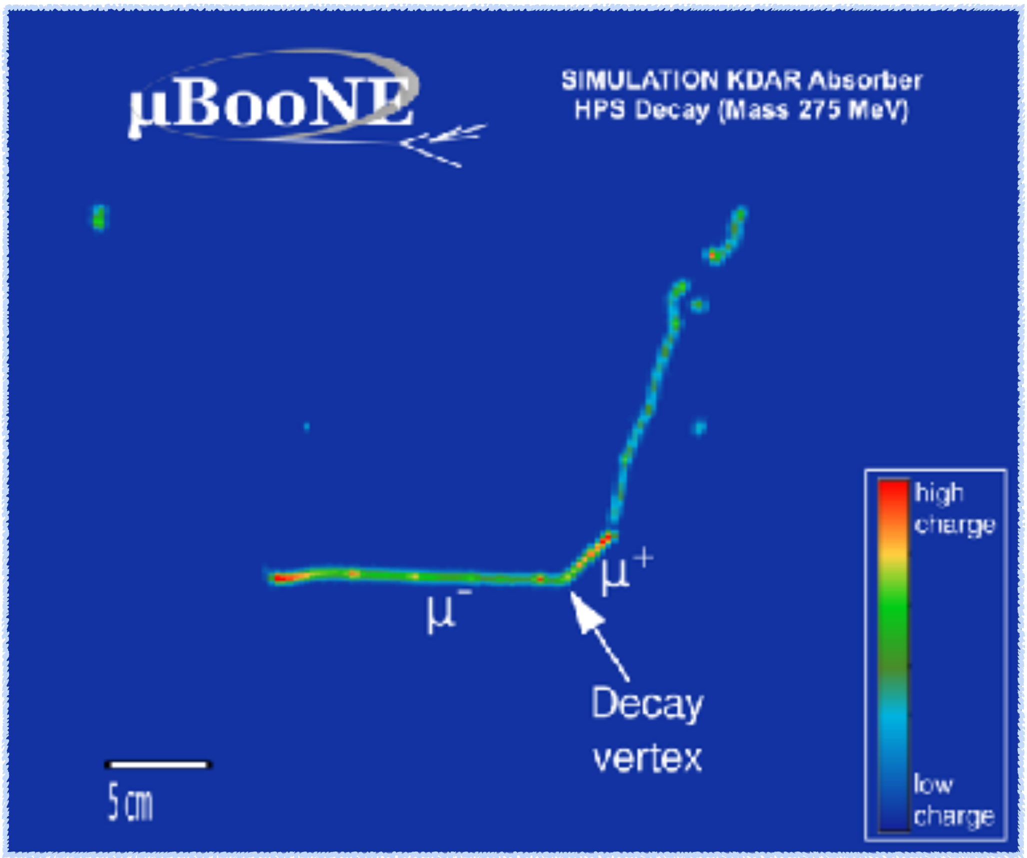
Analysis Strategy

2021 analysis, $S \to e^+e^-$
Sensitive to m_S<212 MeV



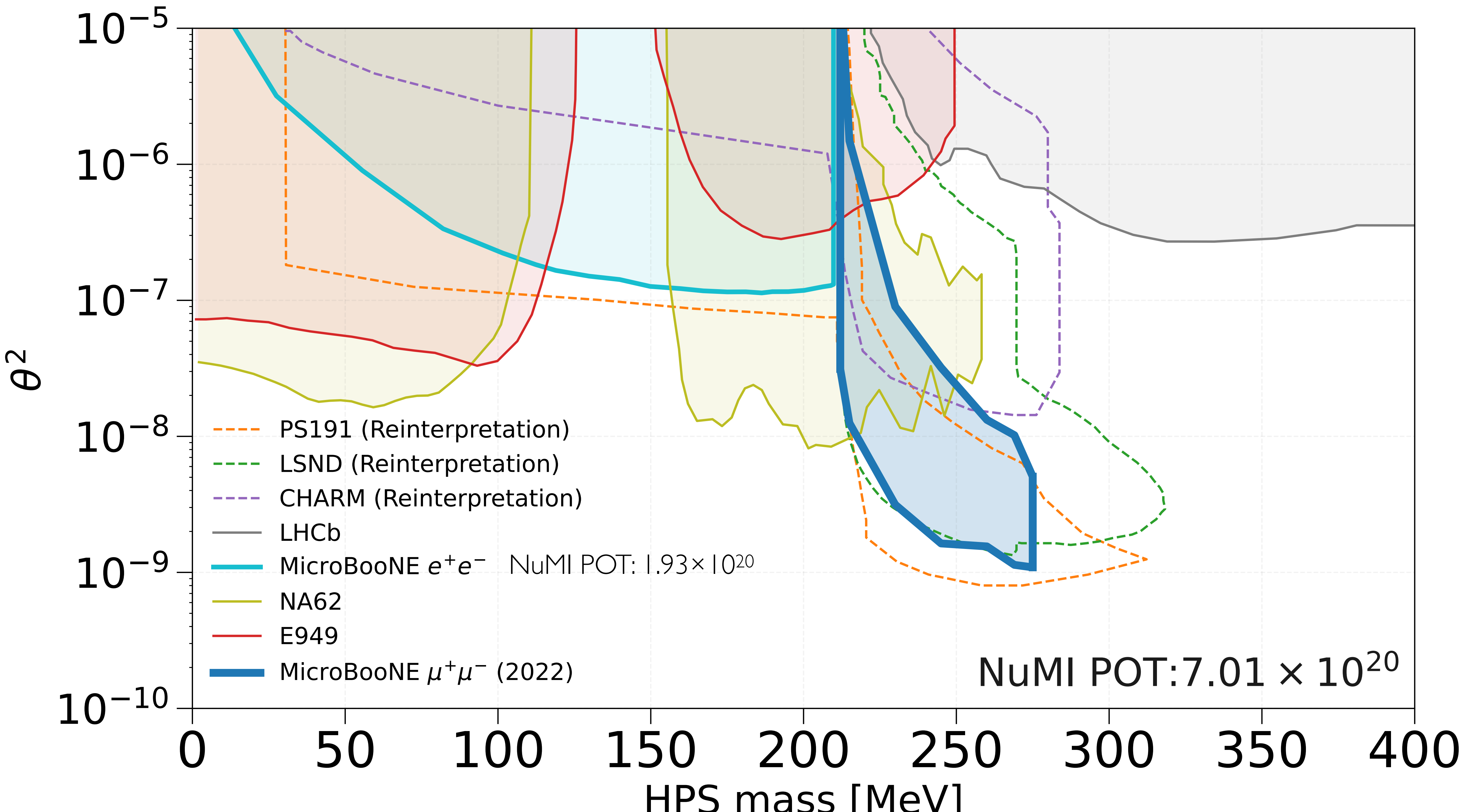
1.93×10^{20} POT
Only geometrical quantities used
(Shower reconstruction less mature)

2022 analysis, $S \to \mu^+\mu^-$
Sensitive to $212 < m_S < 275$ MeV



7×10^{20} POT
Geometrical and kinematic quantities used

HPS Sensitivity



Phys. Rev. Lett. 127, 151803 (2021)
Phys. Rev. D 106, 092006 (2022)

Systematic Uncertainty

Analyses presented today are statistical limited

	HNL 2020	HPS 2021	HNL 2022 HPS 2022
HNL/HPS Flux	8%	30%	30%
SM ν Flux	—	26.6%	(5-10)%
σ(SM ν)	—	33.4%	(5-10)%
Trigger	8%	—	—
Detector	10%	70%	(10-20)%
Simulation Stat.	—	38%/28.2%	(5-42)%

Systematic Uncertainty

Analyses presented today are statistical limited

	HNL 2020	HPS 2021	HNL 2022 HPS 2022
HNL/HPS Flux	8%	30%	30%
SM ν Flux	—	26.6%	(5-10)%
σ(SM ν)	—	33.4%	(5-10)%
Trigger	8%	—	—
Detector	10%	70%	(10-20)%
Simulation Stat.	—	38%/28.2%	(5-42)%

The rate of kaon production at rest in the NuMI absorber

Systematic Uncertainty

Analyses presented today are statistical limited

	HNL 2020	HPS 2021	HNL 2022 HPS 2022
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Detector	10%	70%	(10-20)%
Simulation Stat.	—	38%/28.2%	(5-12)%

The rate of kaon production at rest in the NuMI absorber

Dominated by the sample statistics

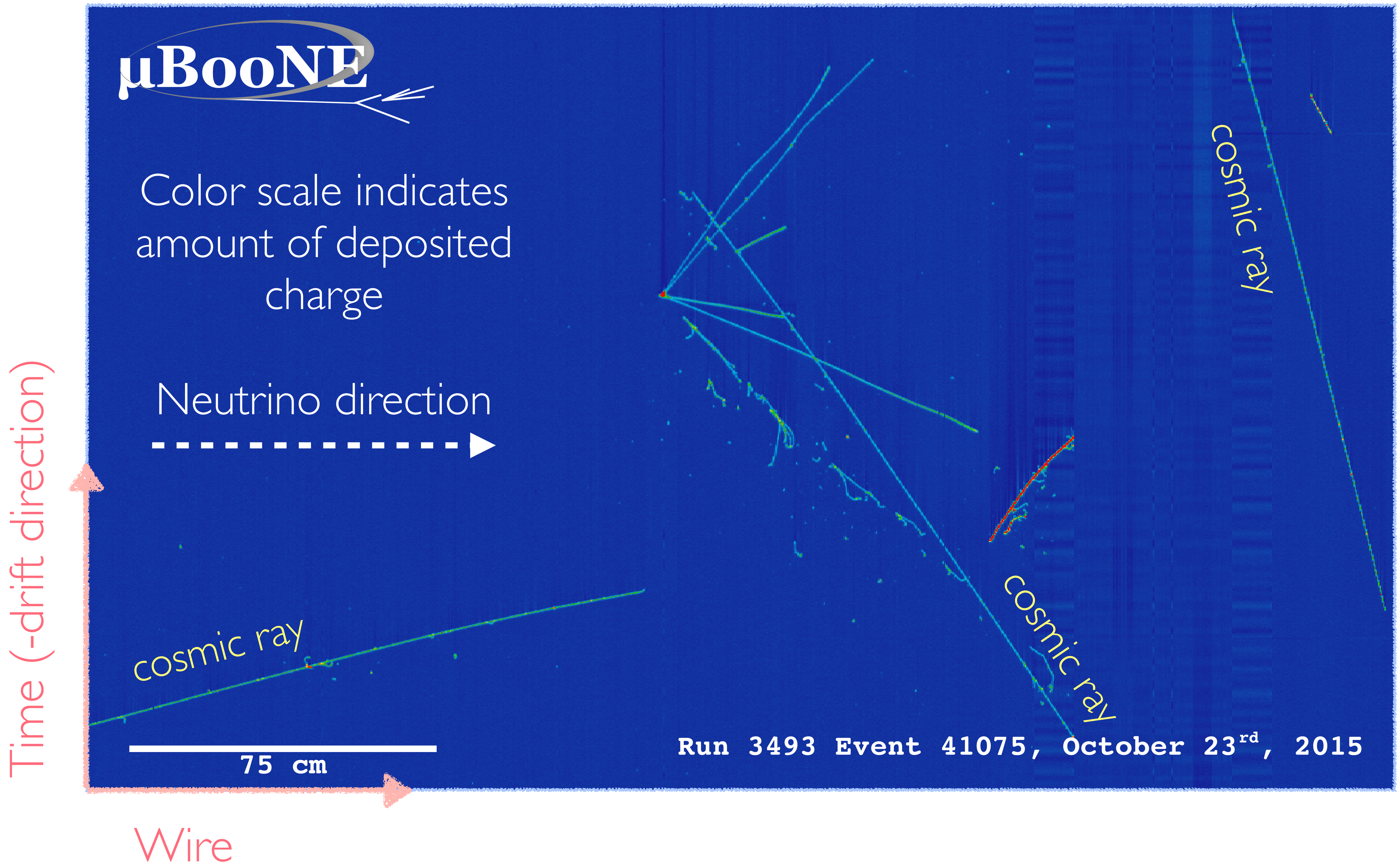
Wish List

- Light detector: high sampling rates and detection efficiency (ICARUS and SBND)
- Light reconstruction: timing, calorimetry
- Light+charge signal matching
- Charge reconstruction: energy of electromagnetic showers, track/shower separation, particle ID, reconstruction optimized to signal directions
- Cosmic ray removal: overburden (ICARUS), cosmic ray taggers (MicroBooNE, ICARUS, SBND), light signal matching
- Detector modeling: more detector measurements
- SM neutrino flux and cross section modeling
- BSM flux and interaction/decay modeling
- High signal/noise for MeV-scale activities

Remark

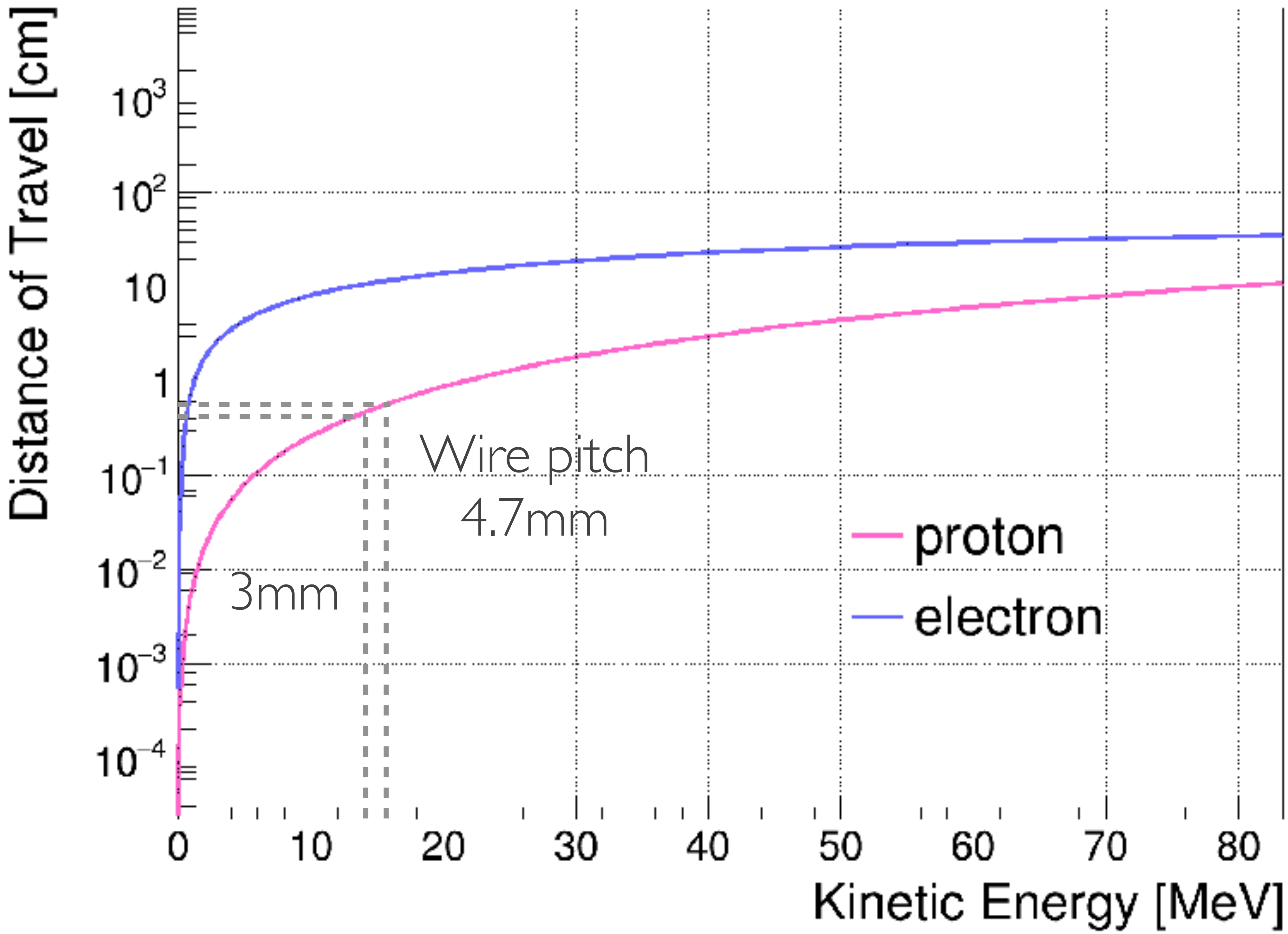
- Search for interactions of BSM particles
  - MC simulation of BSM-Ar interactions required
- Search for decays of BSM particles
  - Easy for signal MC simulation
  - Suffer from the density of LAr
- Most of desired tools also benefit oscillation and σ
- Analysis strategies to discriminate from SM neutrinos required (and from cosmic rays in SBN)
- Other ongoing BSM efforts at MicroBooNE
- Future LArTPCs with high intensity beam (DUNE ND-LAr) require to deal with pile-ups (modular detectors)

Backup



μBooNE
Color scale indicates amount of deposited charge
Neutrino direction
cosmic ray
cosmic ray
cosmic ray
75 cm
Run 3493 Event 41075, October 23rd, 2015
Time (-drift direction)
Wire

Low Energy Threshold

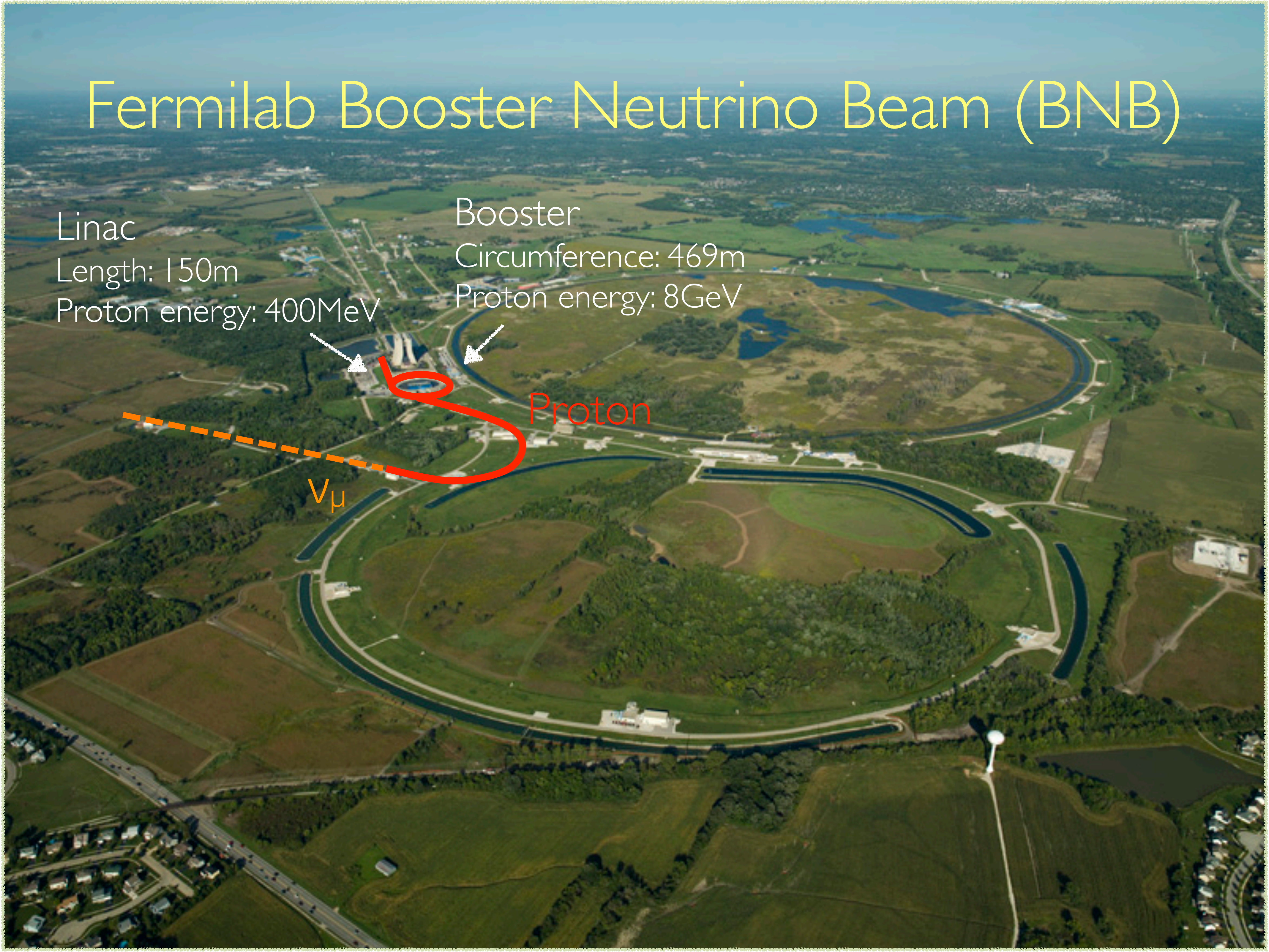


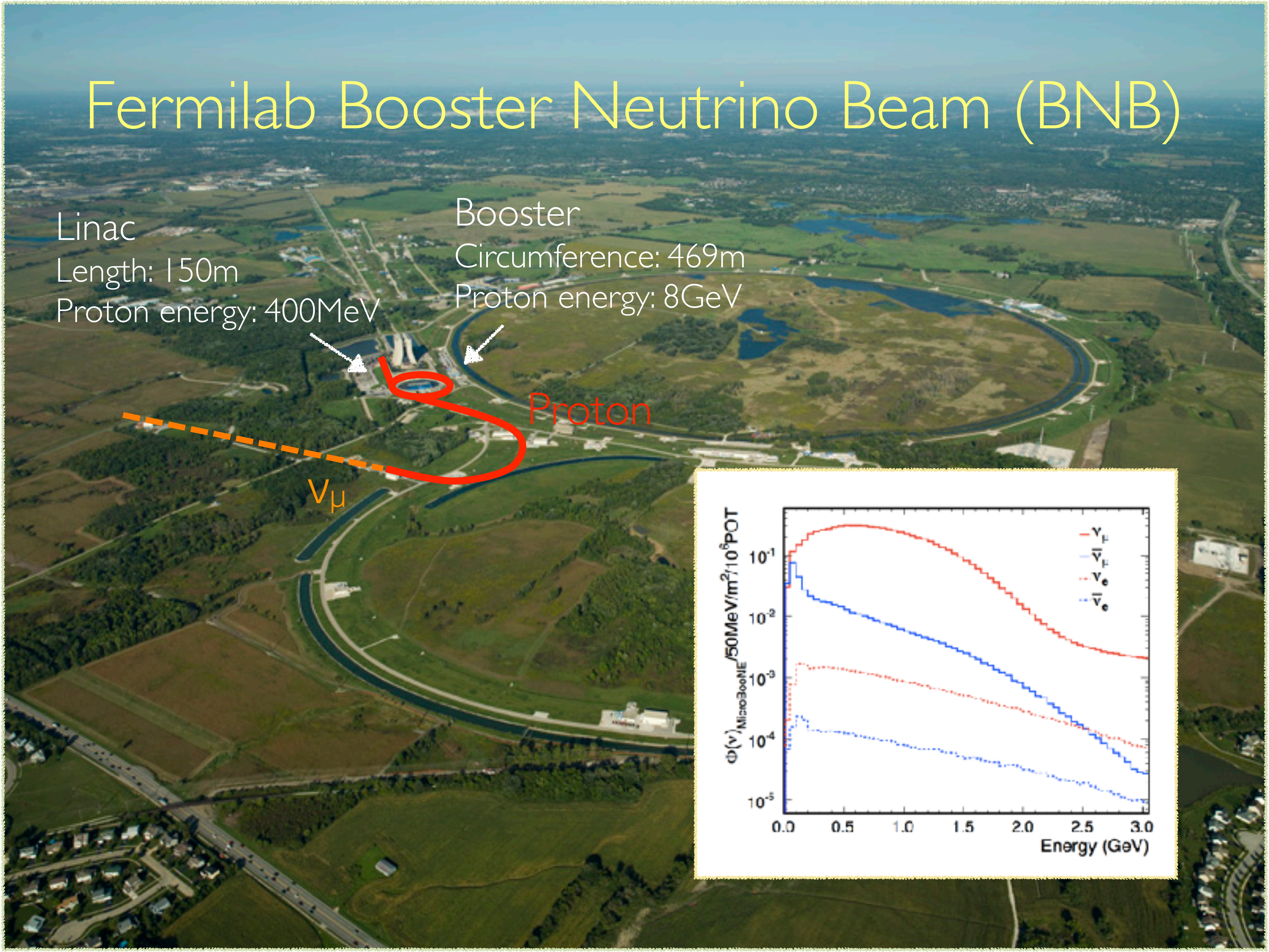
Dark Sector Landscape

Model	Production	Detection
Higgs Portal	K, B decay	Decay ($\ell^+\ell^-$)
Vector Portal	π^0, η Decay Proton Bremmstrahlung Drell-Yan	Scattering (χe^-, χX, Dark Tridents) Decay ($\ell^+\ell^-$, $\pi^+\pi^-$) Inelastic Decay ($\chi \to \chi' \ell^+\ell^-$)
Neutrino Portal	π, K, $D_{(s)}$, B decay	Decay (many final states)
ALP Portal (γ-coupling dominant)	Meson Decay Photon Fusion Primakoff Process	Decay ($\gamma\gamma$) Inverse Primakoff process
Dark Neutrinos Dipole Portal	SM Neutrino Dalitz Decay	Upscattering + Decay ($\nu \to \nu_D$, $\nu_D \to \nu \ell^+\ell^-$) Decay ($\nu_D \to \nu\gamma$)
νphilic Mediators	SM Neutrino	Scattering (Missing $\not{p}_T$, SM Tridents)

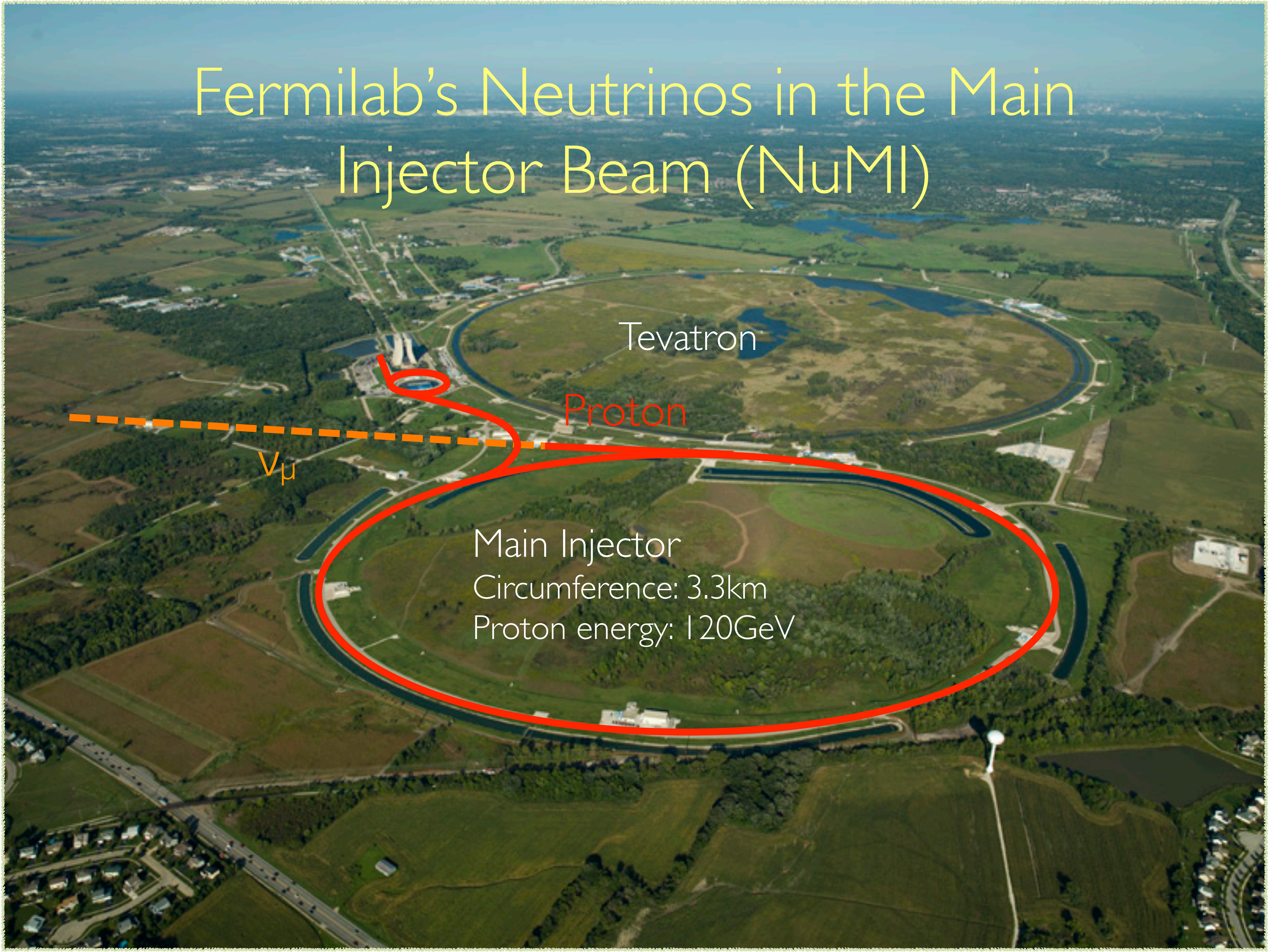
Table 1: A selection of models that can be probed by neutrino beam experiments.

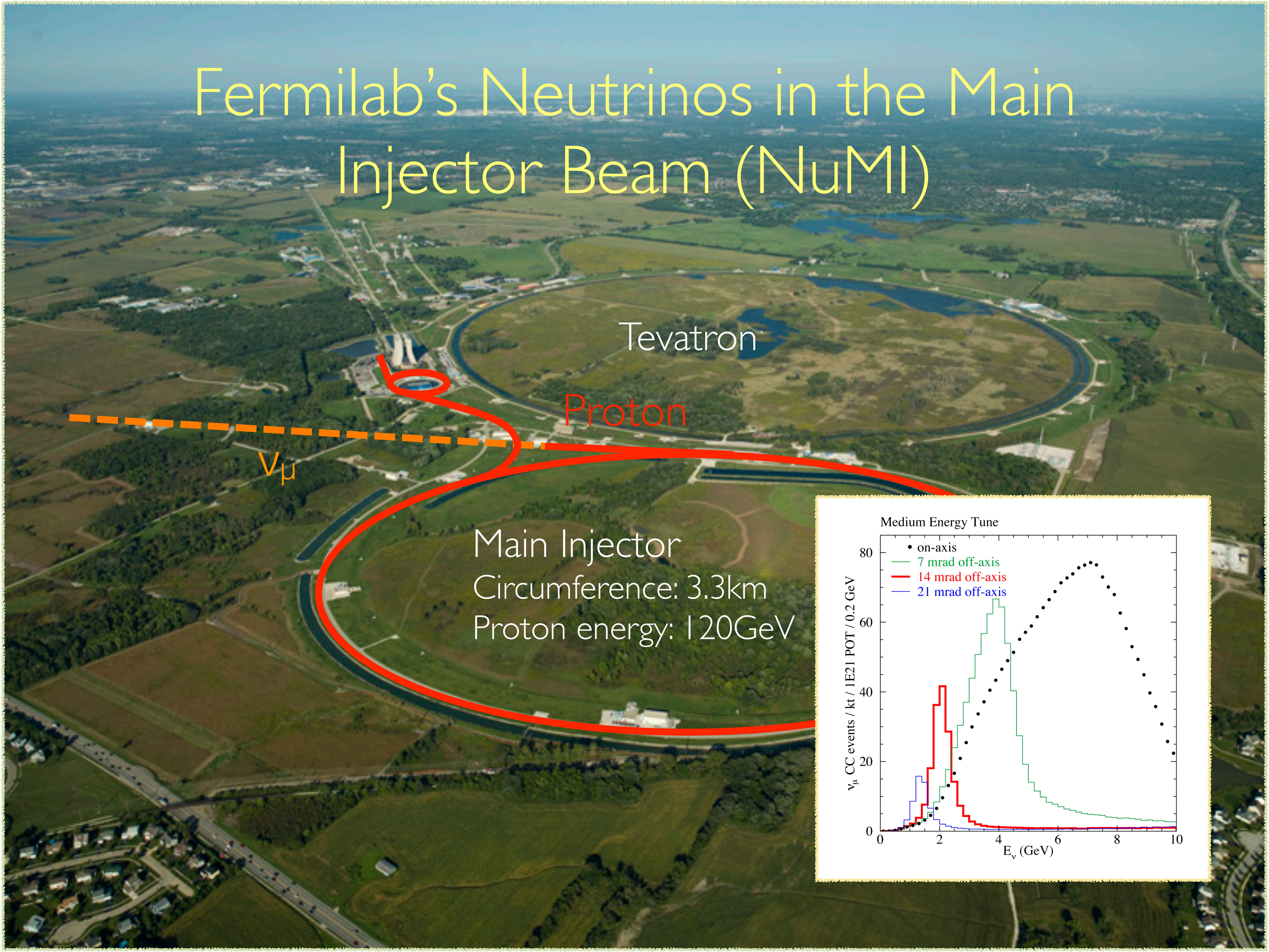
arXiv: 2207.06898


Fermilab Booster Neutrino Beam (BNB)
Linac
Length: 150m
Proton energy: 400MeV
Booster
Circumference: 469m
Proton energy: 8GeV
Proton
νμ


Fermilab Booster Neutrino Beam (BNB)
Linac
Length: 150m
Proton energy: 400MeV
Booster
Circumference: 469m
Proton energy: 8GeV
Proton
νμ
$\Phi(\nu)_{MicroBooNE}$/50MeV/m²/10⁶POT
Energy (GeV)
ν_μ
$\bar{\nu}_\mu$
ν_e
$\bar{\nu}_e$
0.0
0.5
1.0
1.5
2.0
2.5
3.0
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵

Fermilab's Neutrinos in the Main Injector Beam (NuMI)




Fermilab's Neutrinos in the Main Injector Beam (NuMI)
Tevatron
Proton
νμ
Main Injector
Circumference: 3.3km
Proton energy: 120GeV
Medium Energy Tune
on-axis
7 mrad off-axis
14 mrad off-axis
21 mrad off-axis
νμ CC events / kt / 1E21 POT / 0.2 GeV
Eν (GeV)
0
20
40
60
80
0
2
4
6
8
10

Production

Accelerator neutrino beam or fixed target facility produce charged mesons, such as kaons, pions

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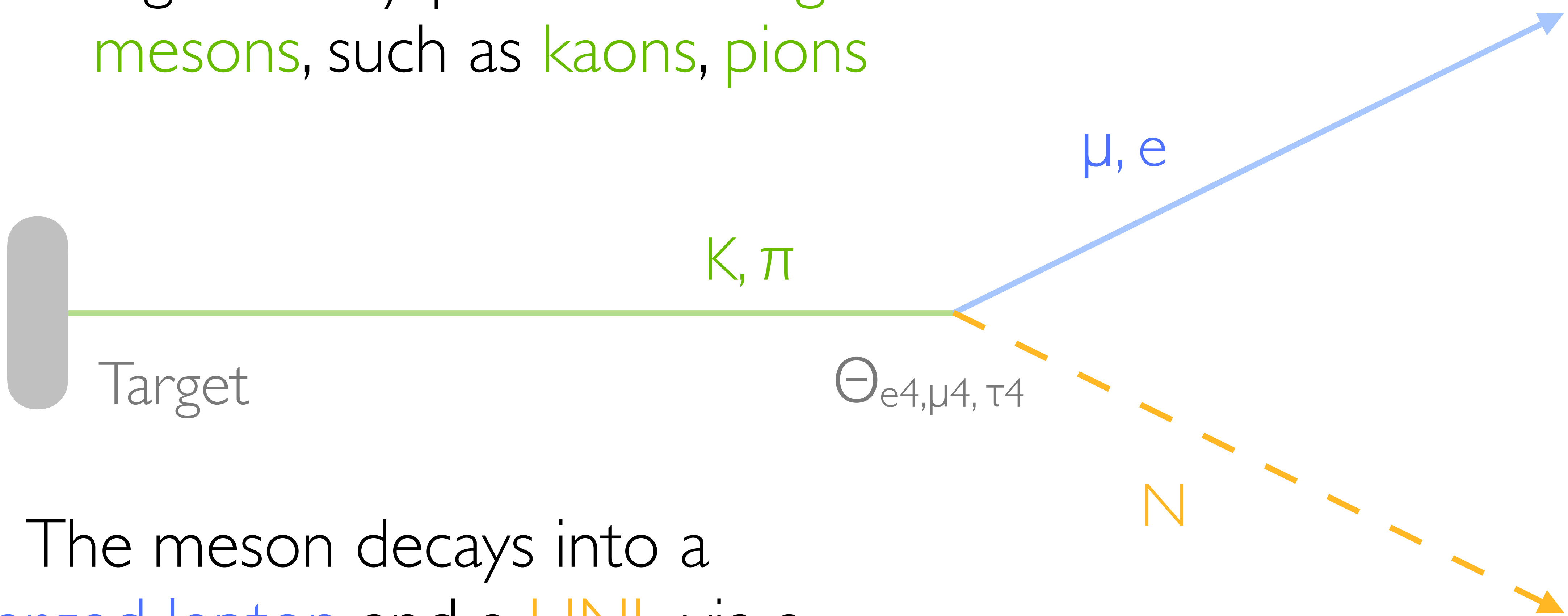
Accelerator neutrino beam or fixed target facility produce charged mesons, such as kaons, pions



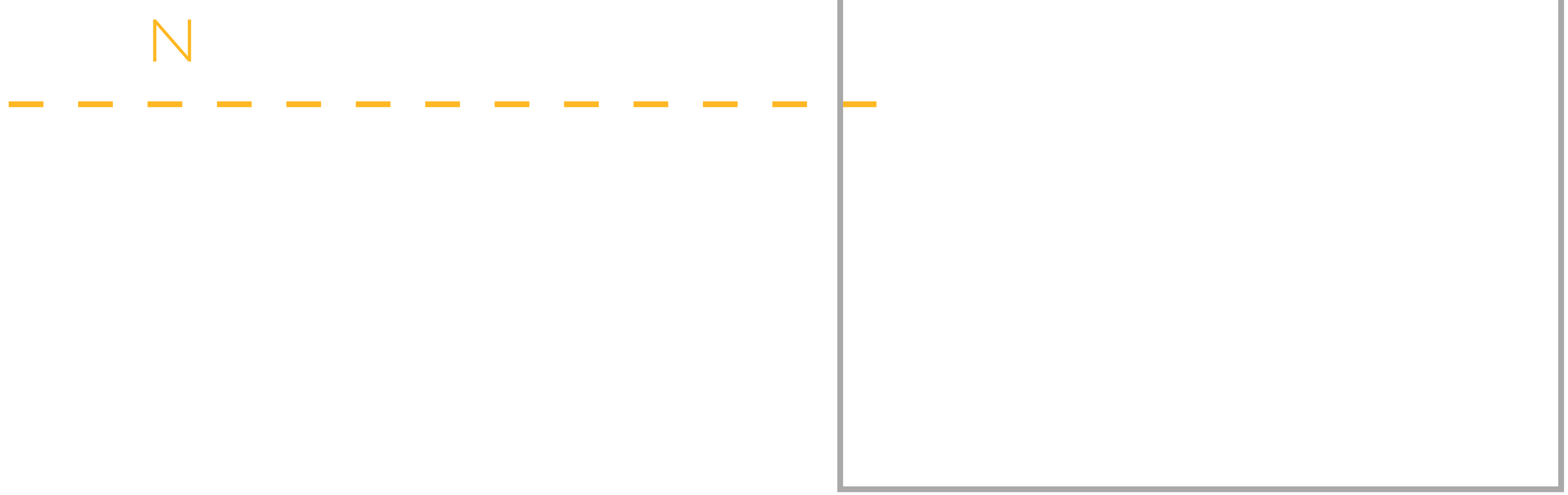
The meson decays into a charged lepton and a HNL via a mixing angle, $\Theta_{e4,\mu4,\tau4}$, between the SM neutrino and the HNL

No helicity suppression

HNL Detection

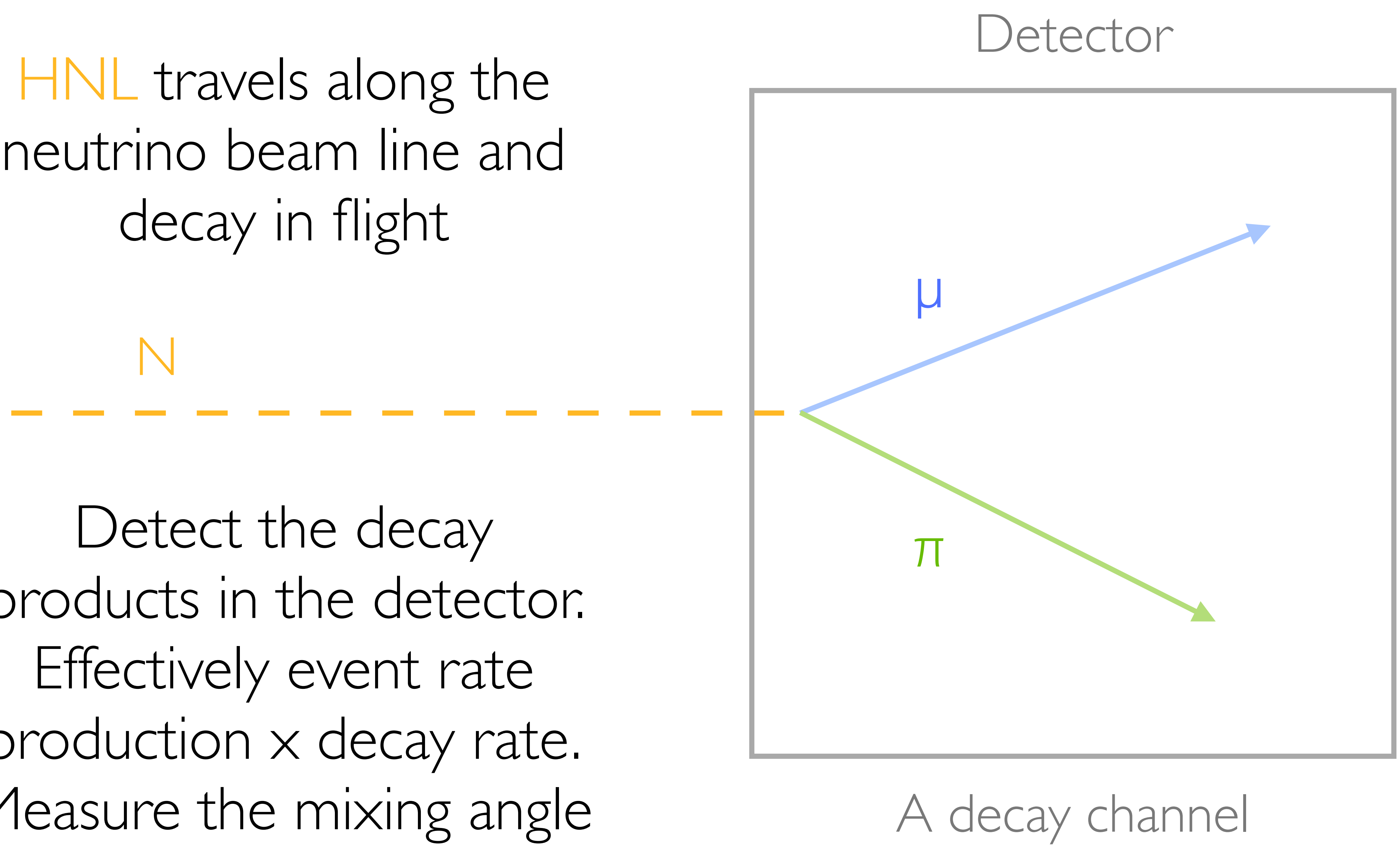
HNL travels along the neutrino beam line and decay in flight

Detector



HNL Detection

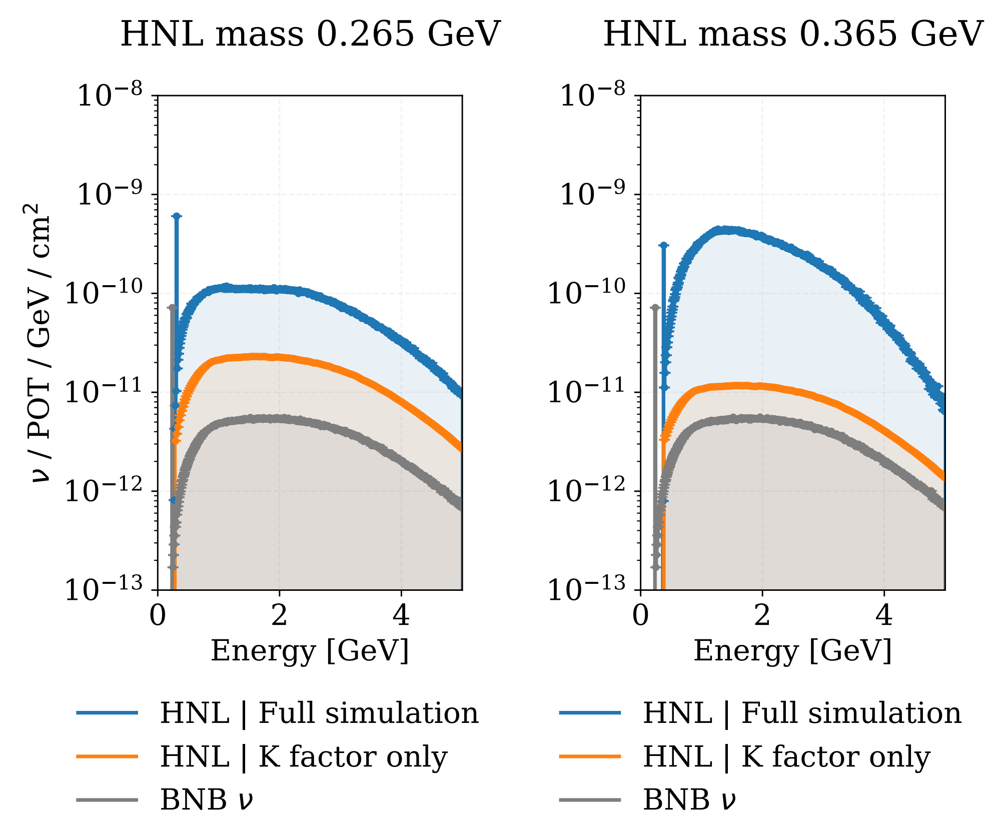
HNL travels along the neutrino beam line and decay in flight

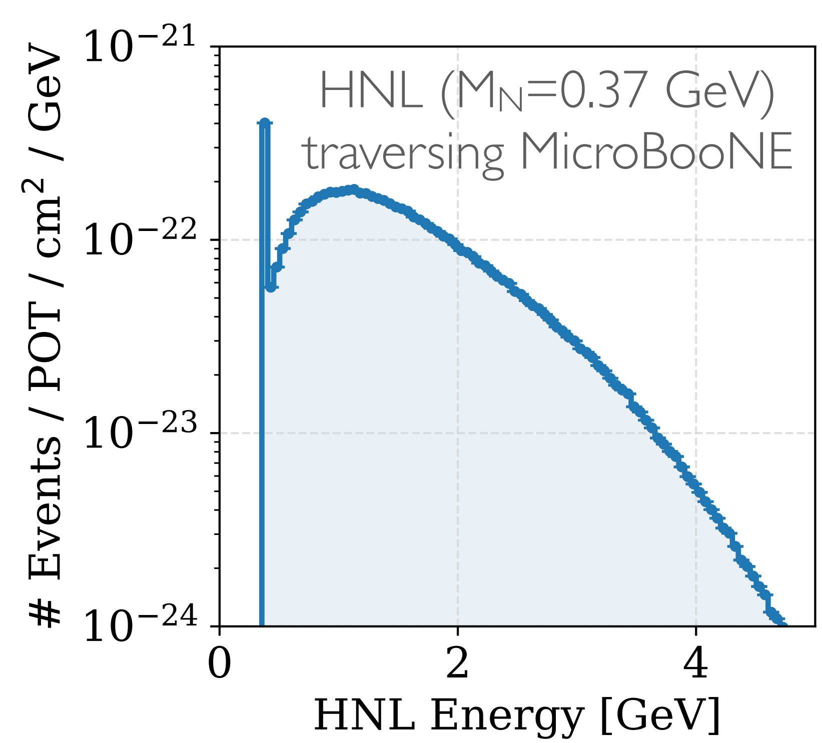


Detect the decay products in the detector. Effectively event rate production x decay rate. Measure the mixing angle $\Theta_{\mu 4,\, e4,\, \tau 4}$ with each M_N

HNL Flux from BNB

- Consider nonzero $\Theta_{\mu 4}$, while $\Theta_{e4} = \Theta_{\tau 4} = 0$
- HNL produced by $K \rightarrow N\mu$
- Fully simulate the HNL flux based on the parent mesons (kaons) of SM neutrino flux simulation
- Number of events traversing MicroBooNE proportional to $\Phi_N(E) \times P_{decay}(E)$

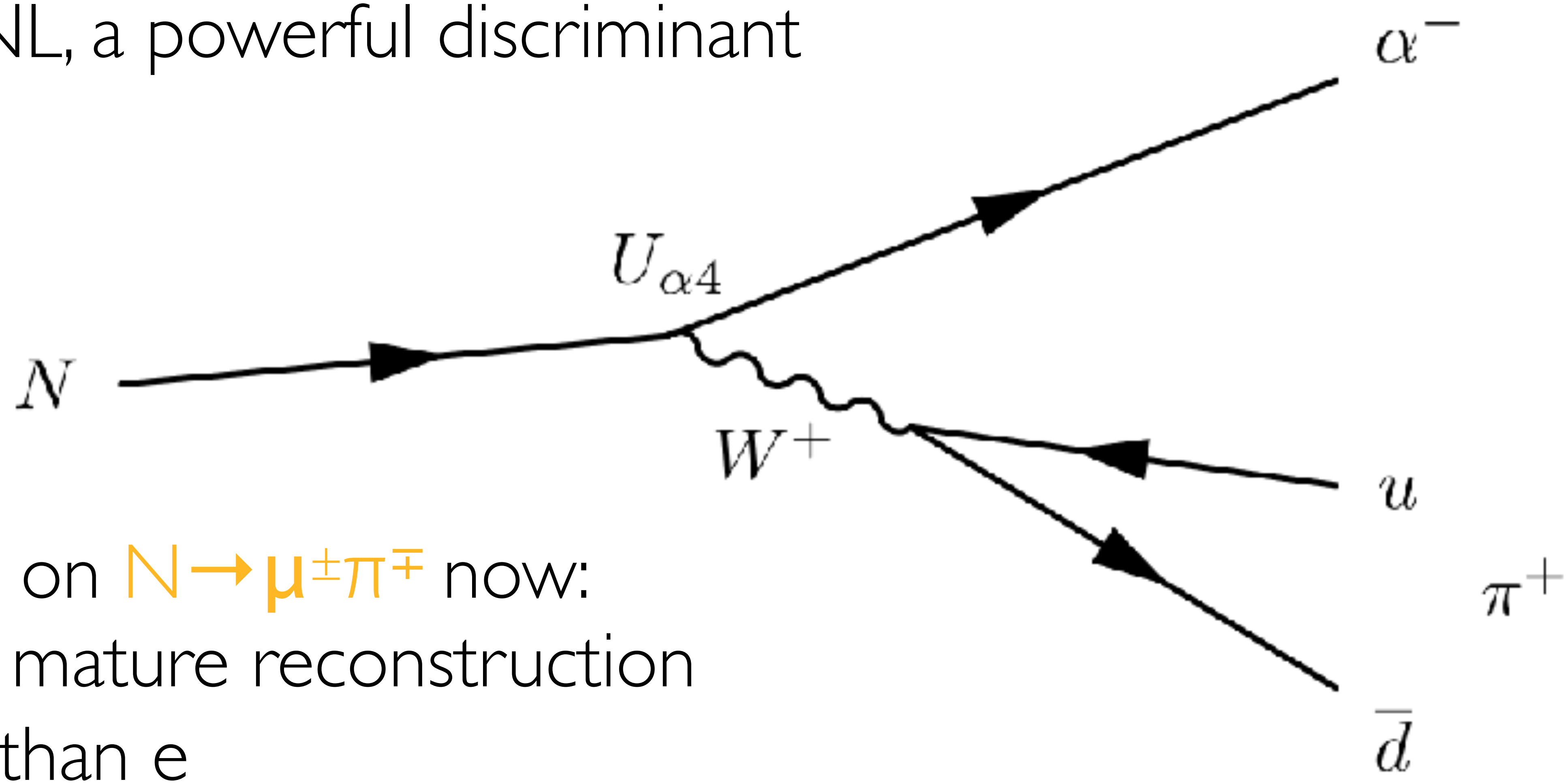




2-body Decay Signature

$N \rightarrow l^{\pm}\pi^{\mp}$

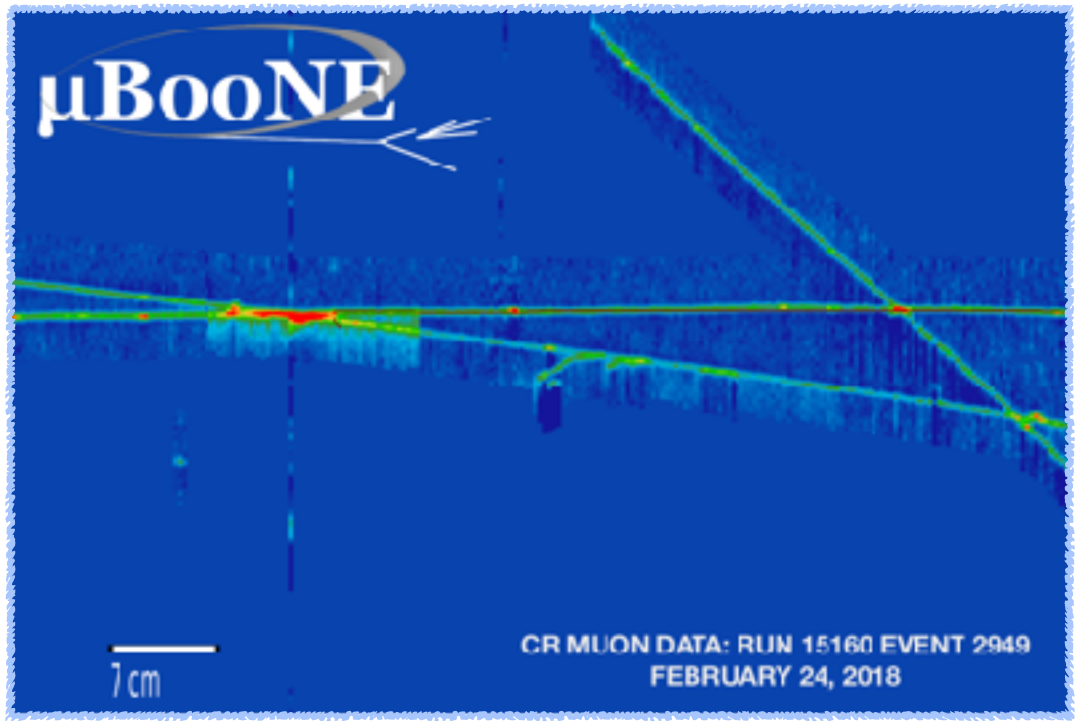
- Fully reconstructed final states
- Able to reconstruct the invariant mass of HNL, a powerful discriminant

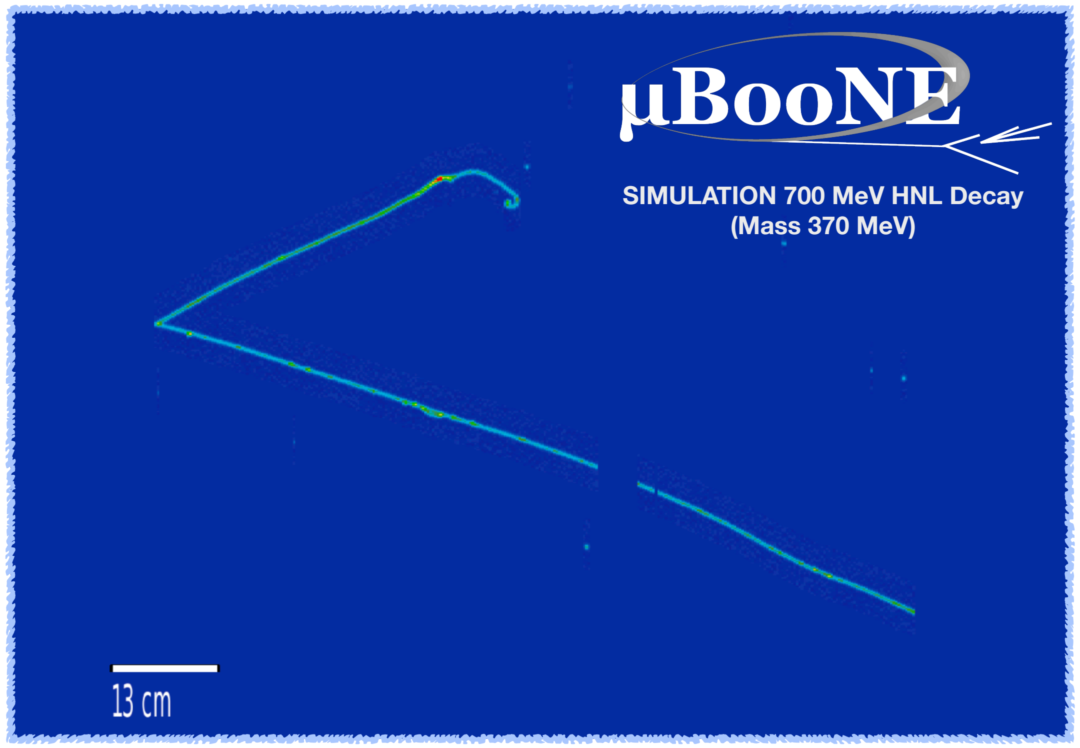


Focus on $N \rightarrow \mu^{\pm}\pi^{\mp}$ now:
more mature reconstruction
for μ than e

Samples

Background sample: pure cosmic rays data fulfilling the same trigger requirement but not in coincidence with BNB

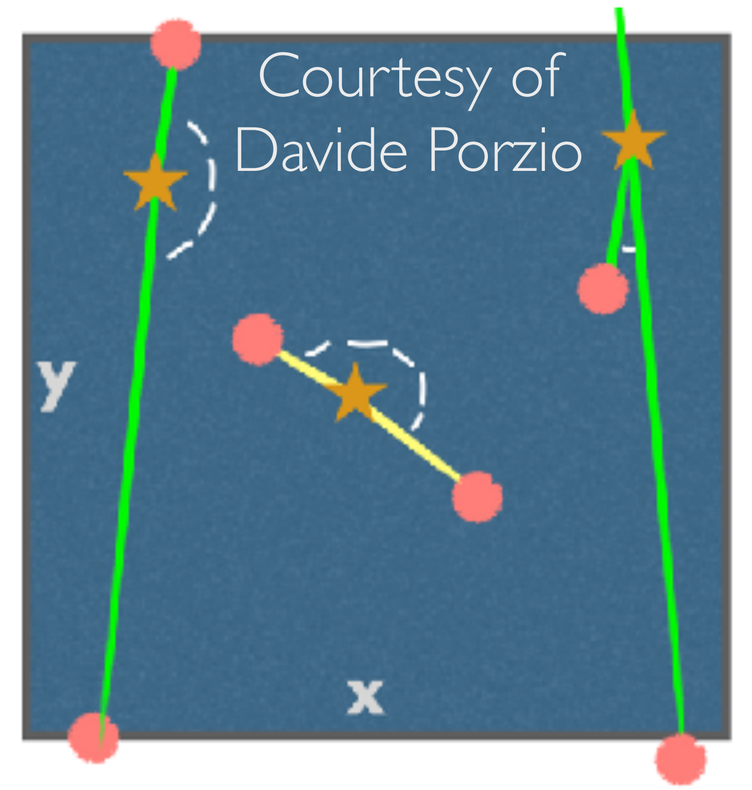


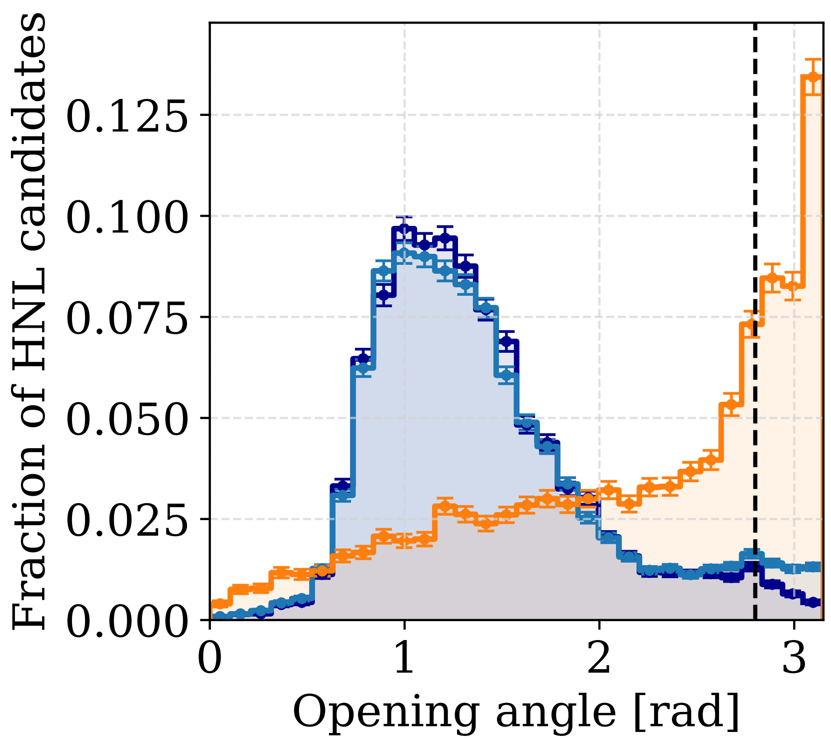


Signal sample for selection optimization and BDT training: pure HNL simulation

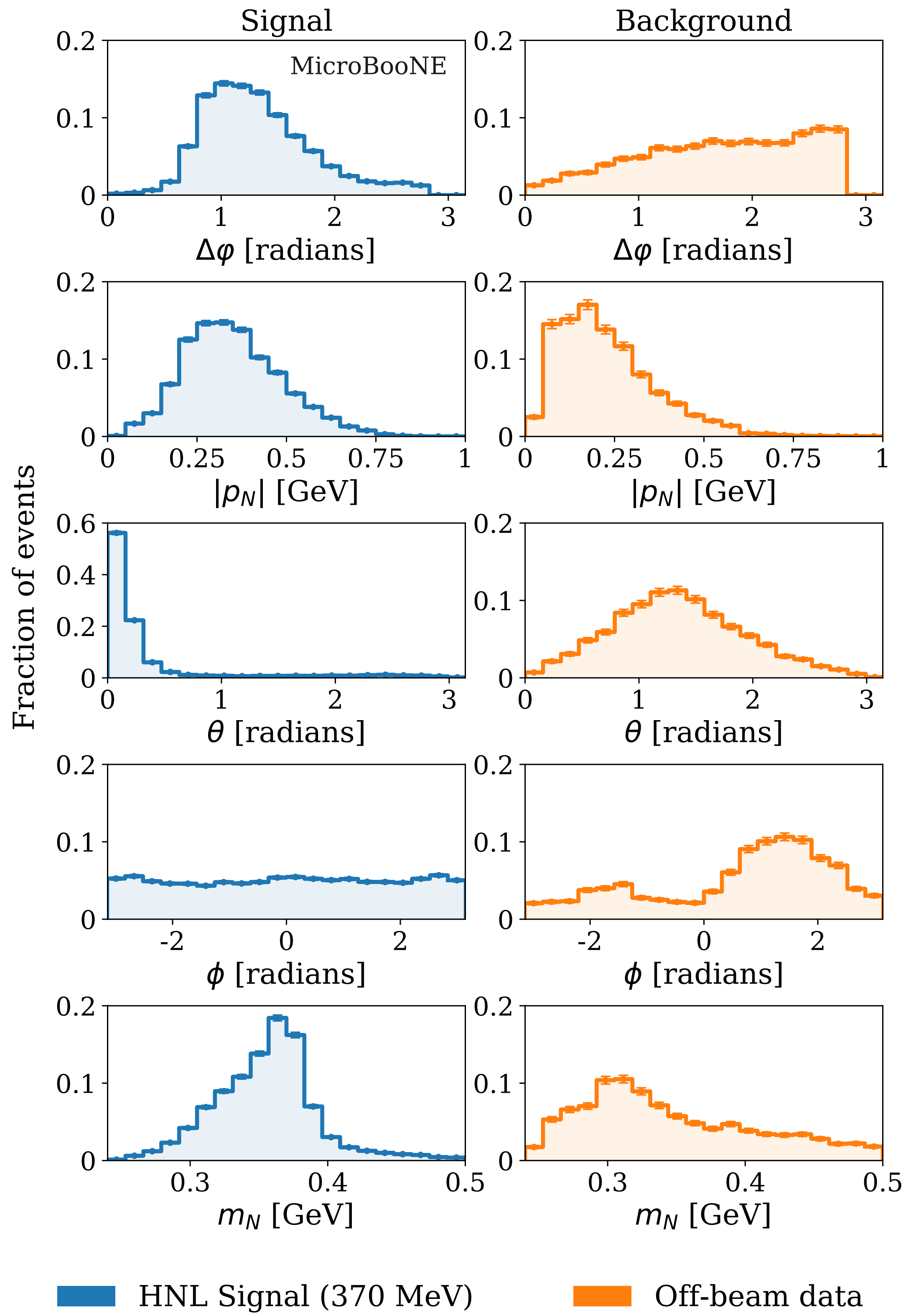
Kinematic Selection

- Cosmic background comes from broken tracks and sometimes delta rays
- Reduce cosmic background
  - Track opening angle $\Delta\phi < 2.8$ rad
  - Invariant mass < 500 MeV
    - Track momentum calculated by its length
- Signal efficiency: (45-50)%
- Background efficiency: 1.6%



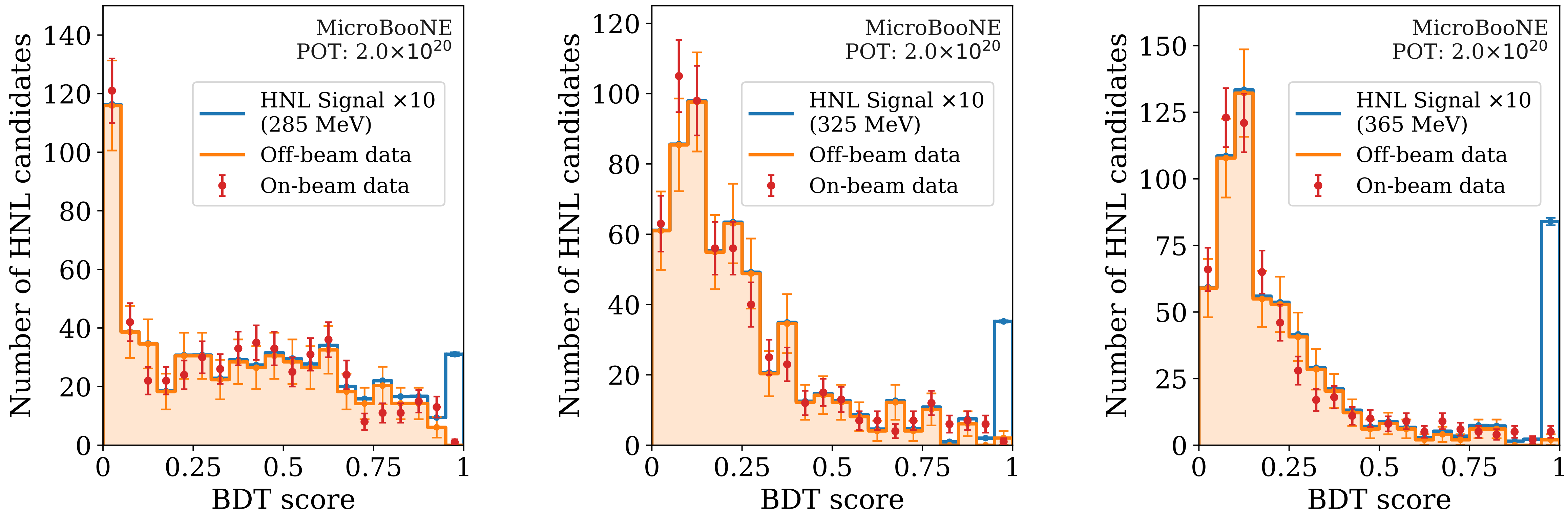


BDT Training



- Five kinematic variables for BDT training
  - Δϕ: 3D opening angle between the two tracks from the HNL decay
  - $|p_N|$: momentum of the HNL candidate
  - θ: polar angle of the HNL candidate
  - Φ: azimuthal angle of the HNL candidate
  - m_N: the invariant mass of the μπ pair

BDT Discriminant



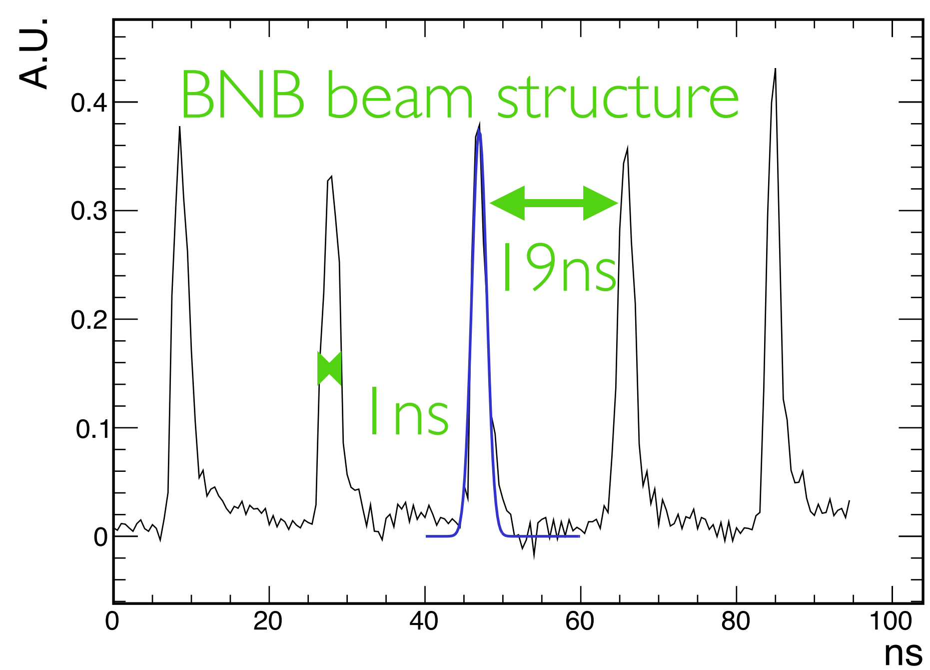
- 5 input variables of reconstructed HNL kinematics for BDT training
- Validate the MC performance with the SM neutrino MC and data samples
- Log-likelihood ratio (LLR) test statistic and set limits at 90% confidence level

Background Reduction

- SM neutrinos
  - 2020 analysis Phys. Rev. D 101 052001
    Utilize the longer time of flight of HNL produced by BNB, 2×10^{20} POT
  - 2022 analysis Phys. Rev. D 106 092006
    Utilize the kaon decaying at rest in the hadron absorber of NuMI, 7×10^{20} POT
    - Off-axis of the NuMI neutrinos
    - Almost opposite direction to most of neutrinos
- Cosmic rays
  - The cosmic ray tagger removes cosmic rays for part of the data used in the 2022 analysis

Outlook at SBN

- $N \to e^{\pm}\pi^{\mp}$ larger parameter space
- Higher sampling rate of light systems in ICARUS and SBND
    - Events outside beam buckets
- Better sensitivity & cross check



Courtesy of En-Chuan Huang