Collider Neutrinos in Lake Geneva

Physics Opportunities Enabled by Kiloton-Scale Detectors

Nicholas Kamp | nkamp@g.harvard.edu

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In collaboration with…

J. Thomas

A. Karle

C. Argüelles

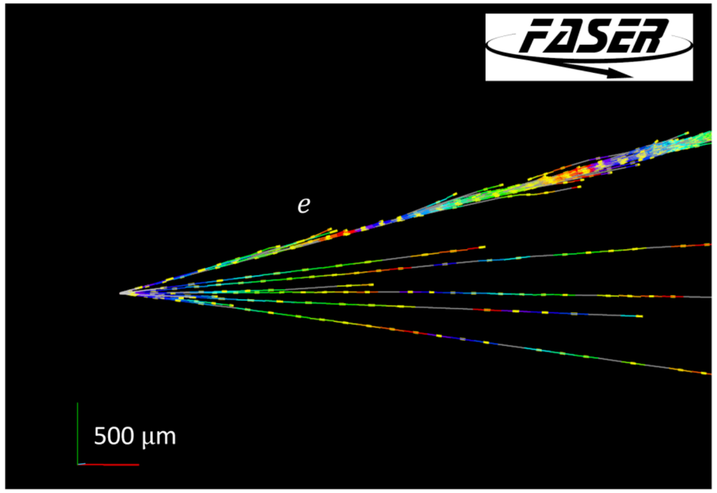
T. Yuan

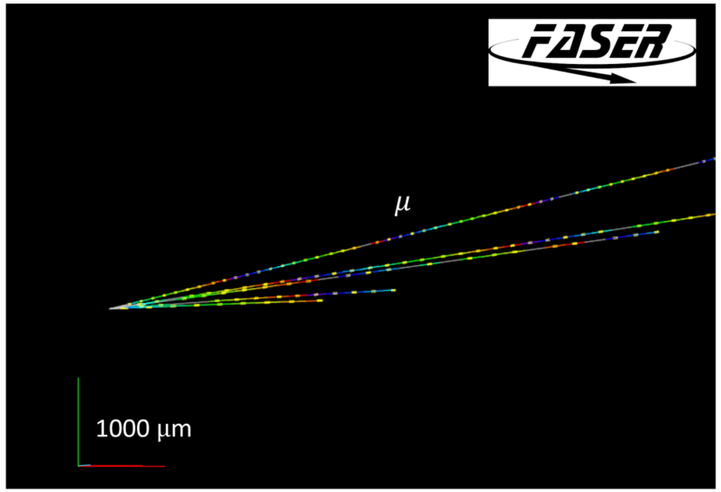
the David & Lucile Packard FOUNDATION

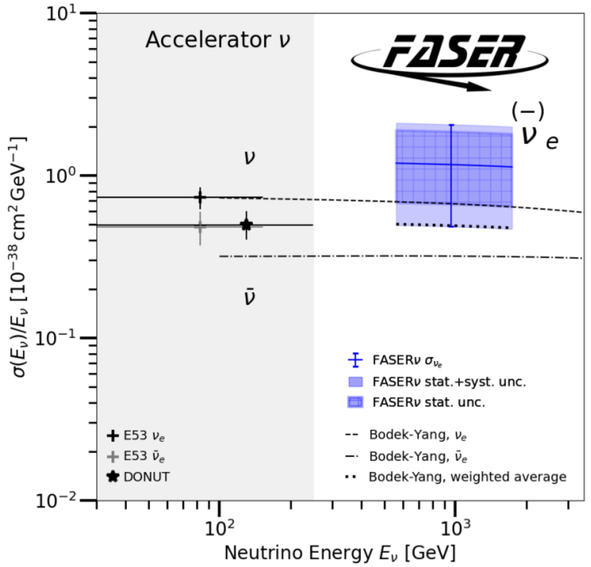
NSF

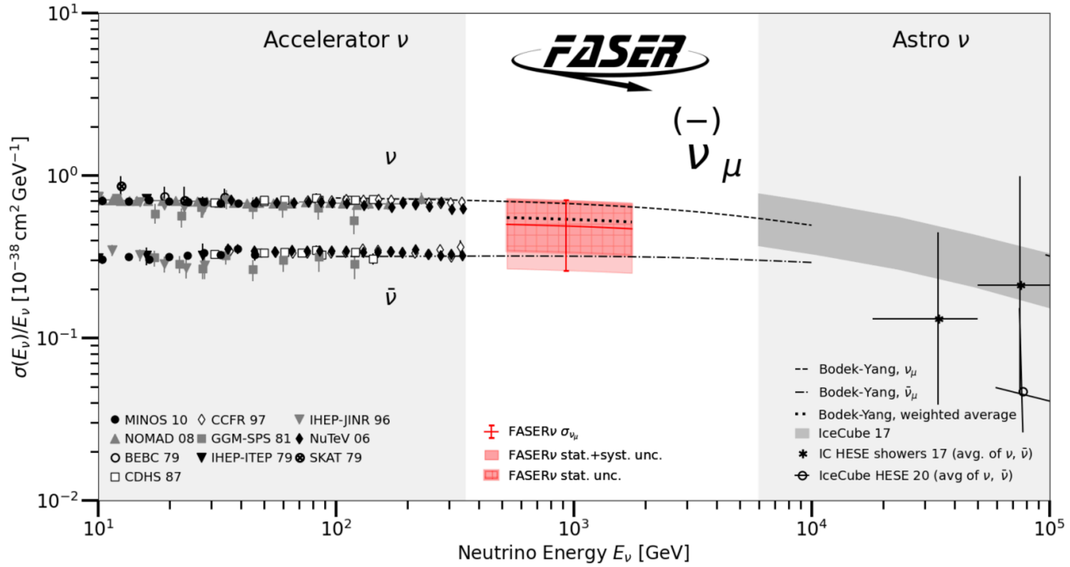
The Dawn of Collider Neutrino Physics

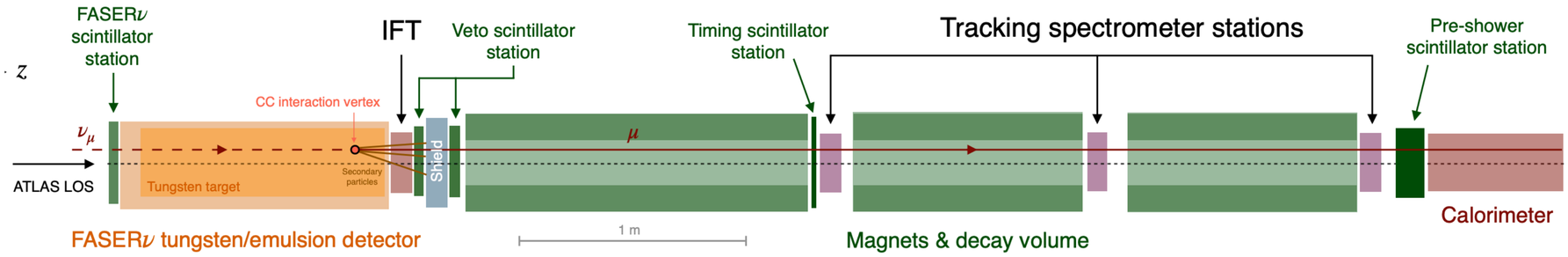
Unique sensitivity to TeV-scale neutrinos and long-lived particles produced in the forward direction at the LHC







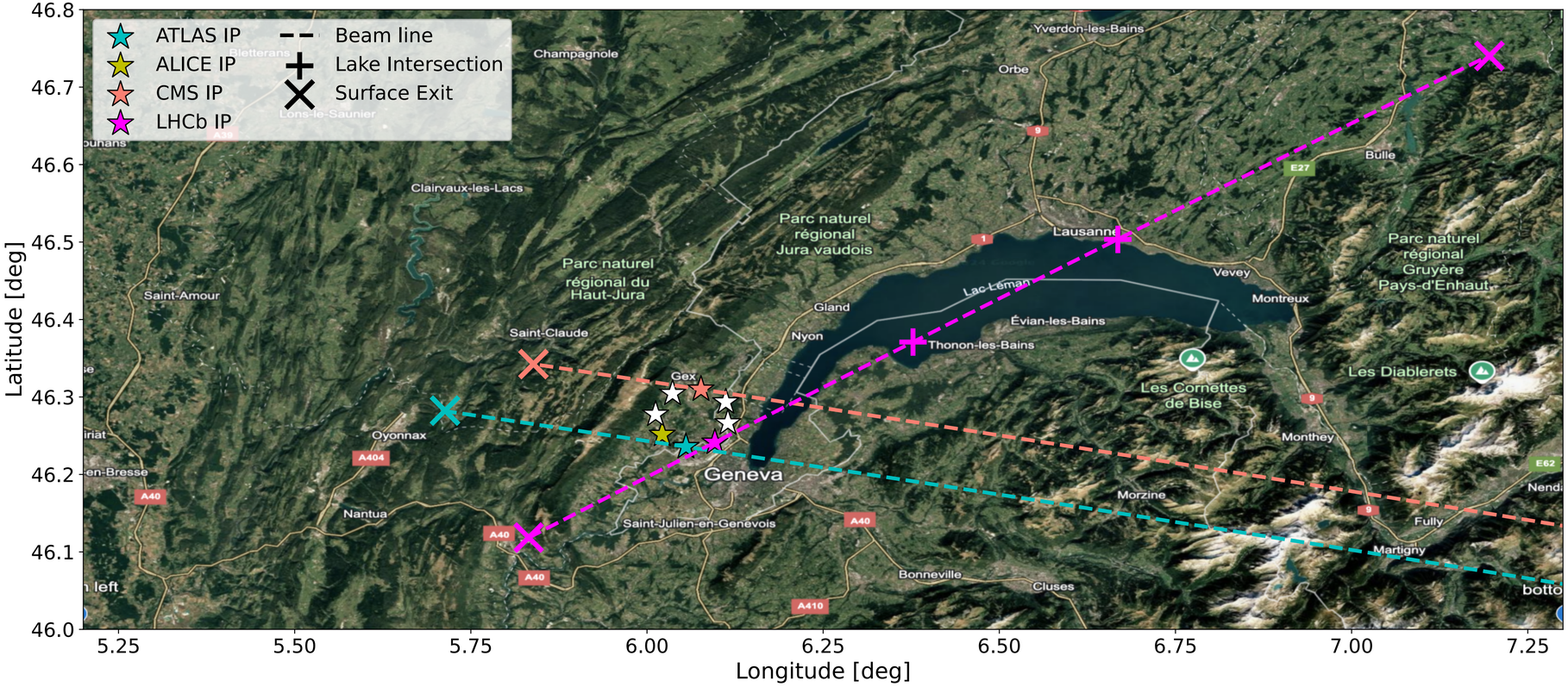




FASER Collab. 2023

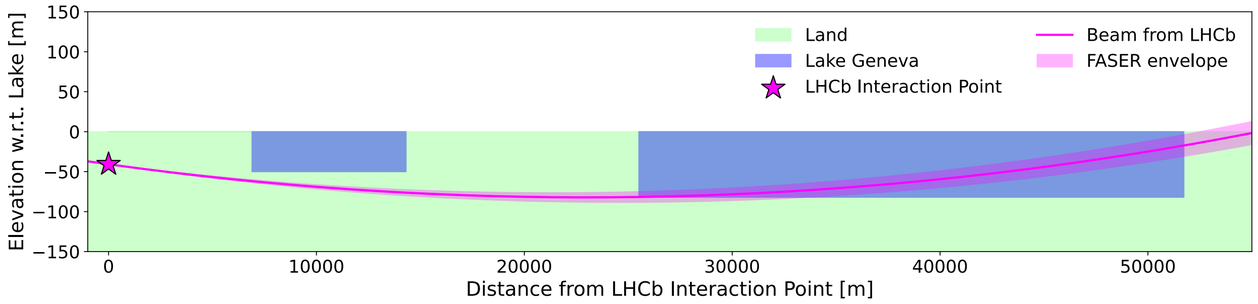
FASER Collab. 2024

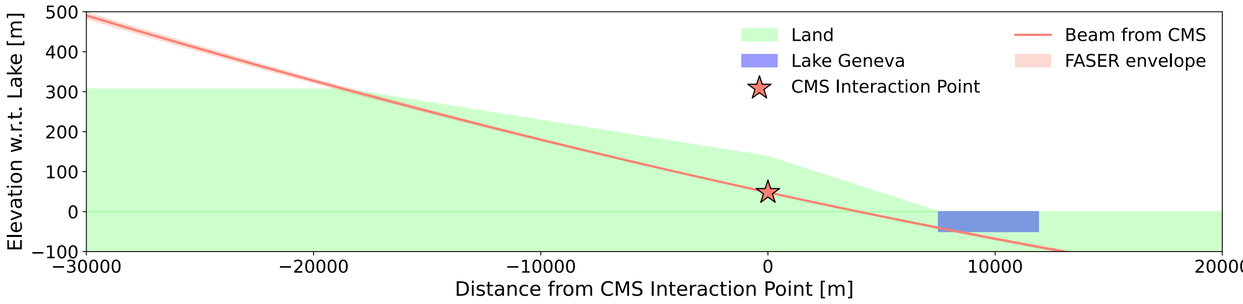
LHC Neutrinos pass through Lake Geneva



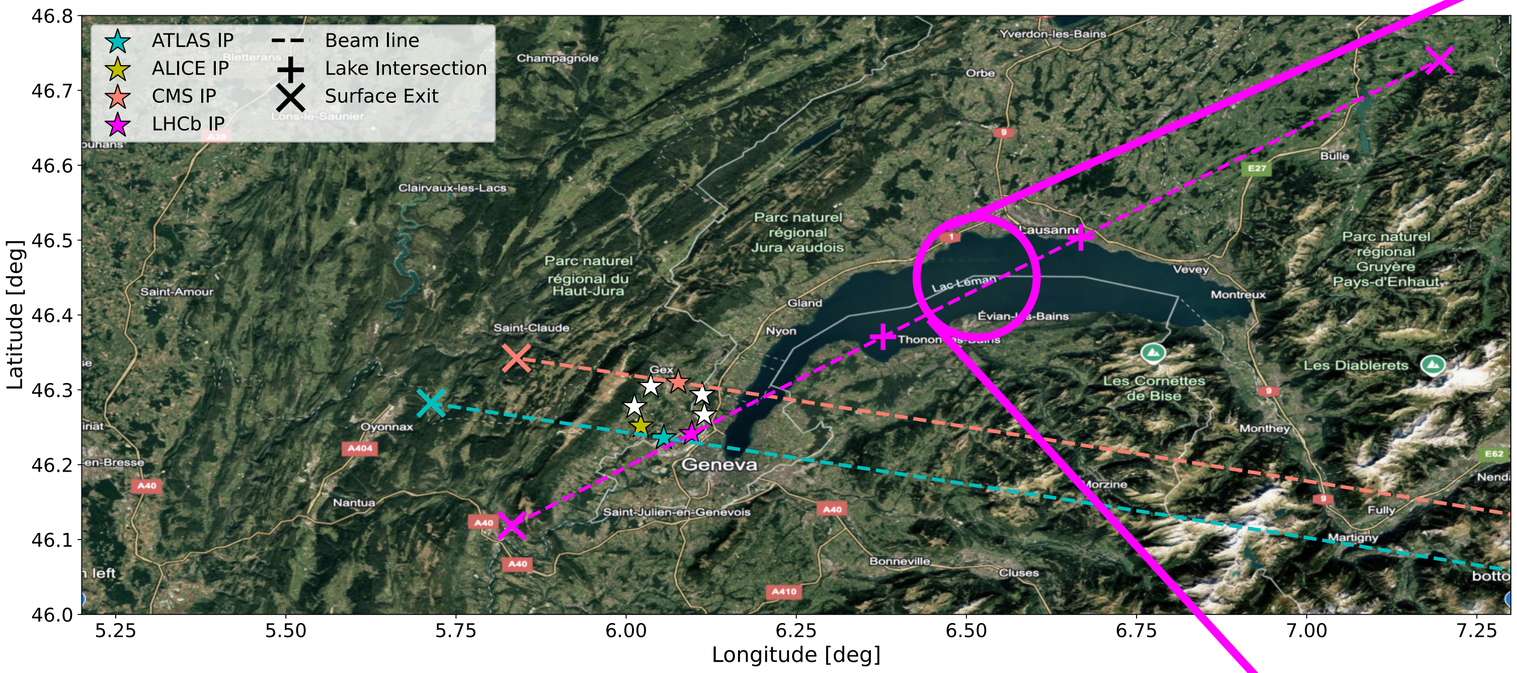
This enables the construction of large-scale lake-and-surface-based detectors that evade muon backgrounds from the p-p collision

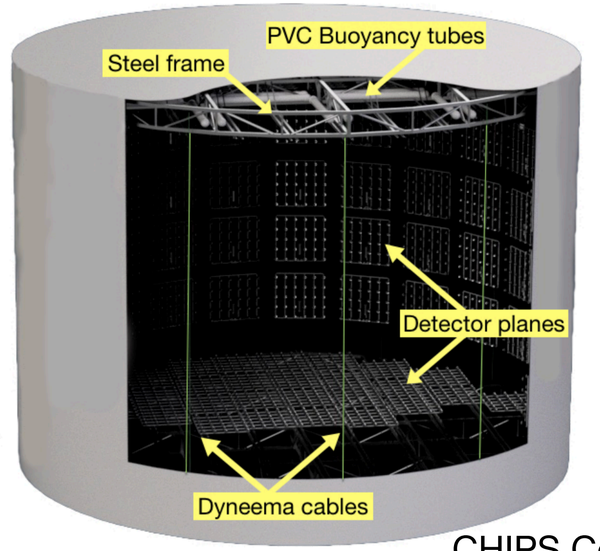
Thanks to Benjamin Weyer and Albert De Roeck for discussions on neutrino beam geometry





UNDINE: UNDerwater Integrated Neutrino Experiment

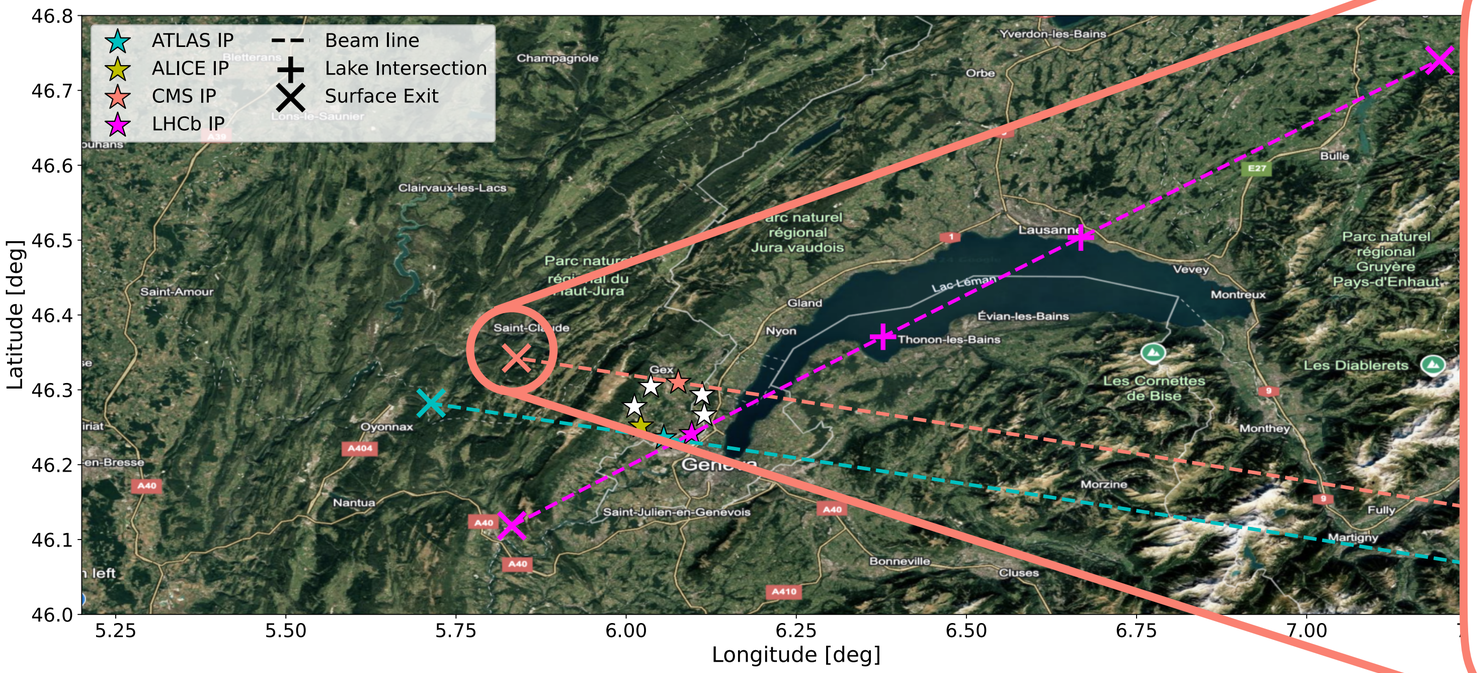


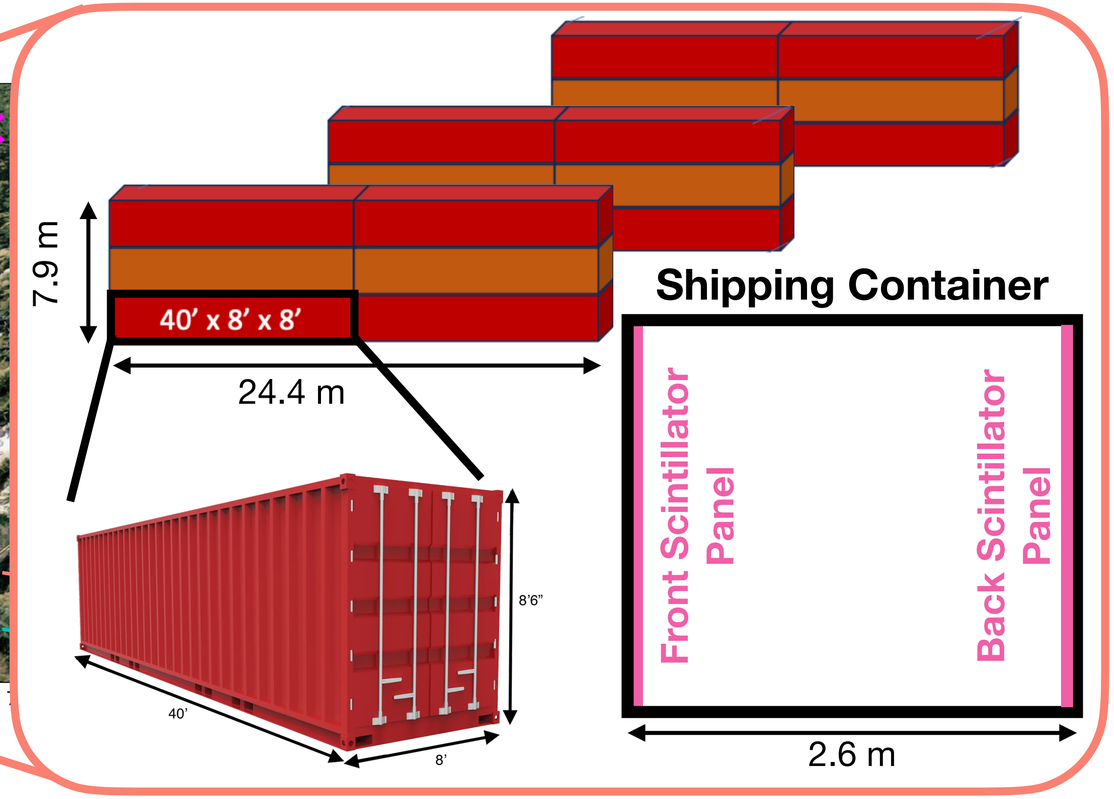


CHIPS Collab. 2024

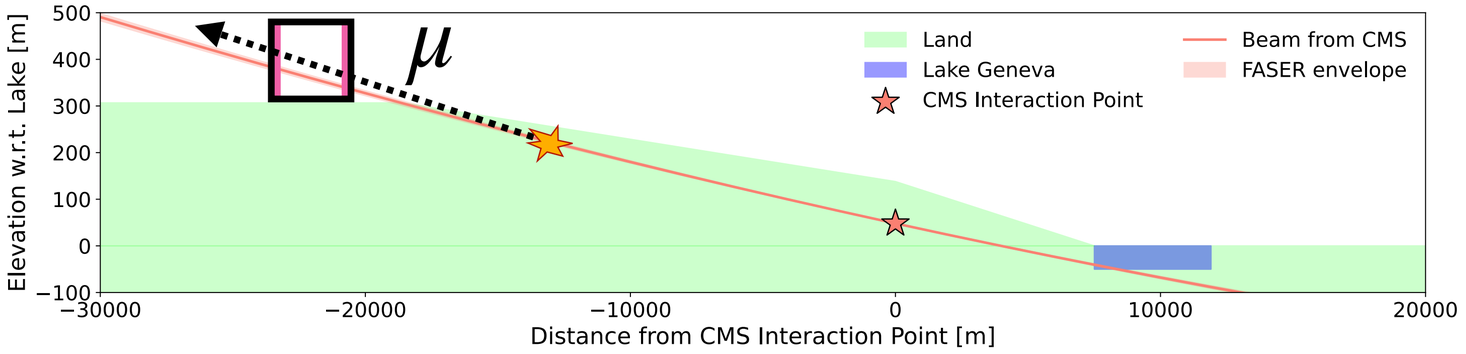
- A suite of CHIPS-style water Cherenkov detectors deployed in a modular fashion
- Benchmark lake detector: 5 CHIPS modules (~30 kT)

SINE: Surface-based Integrated Neutrino Experiment



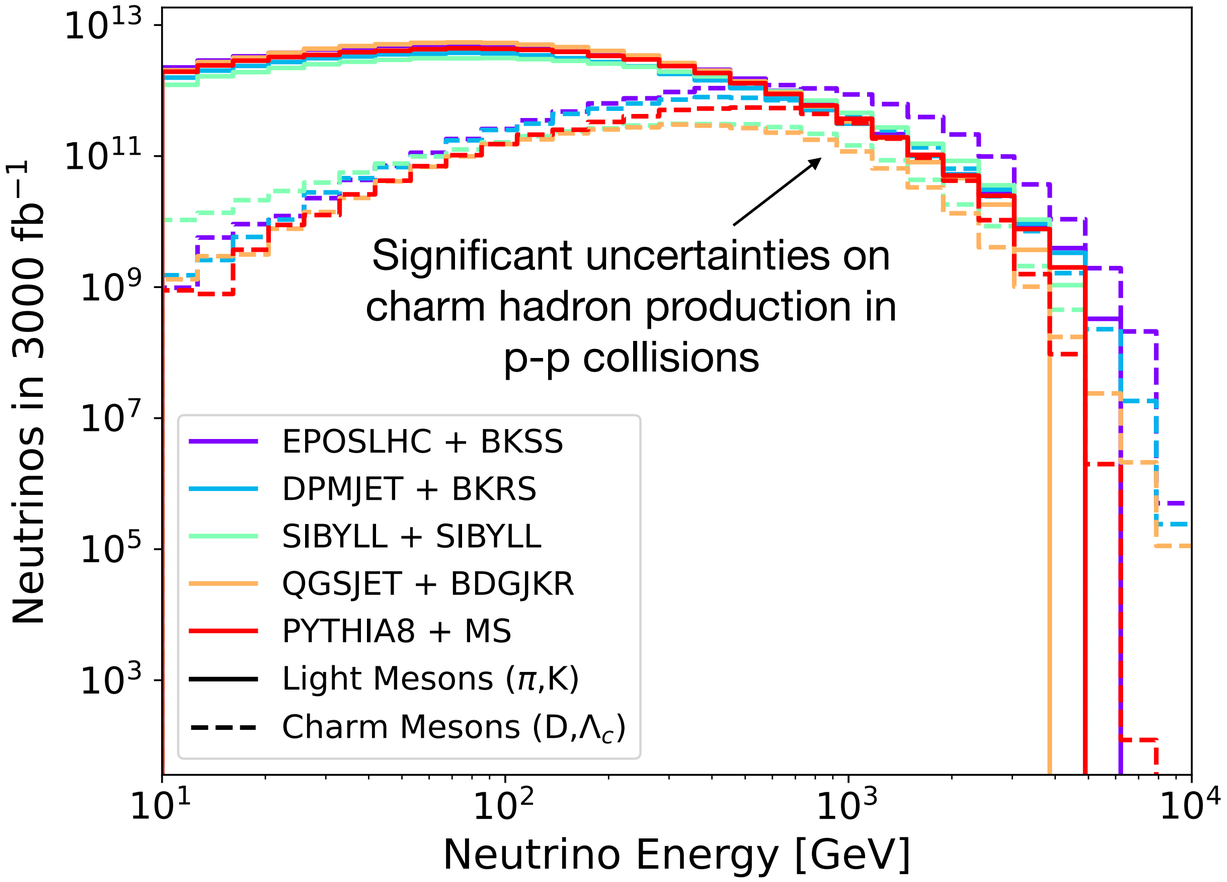


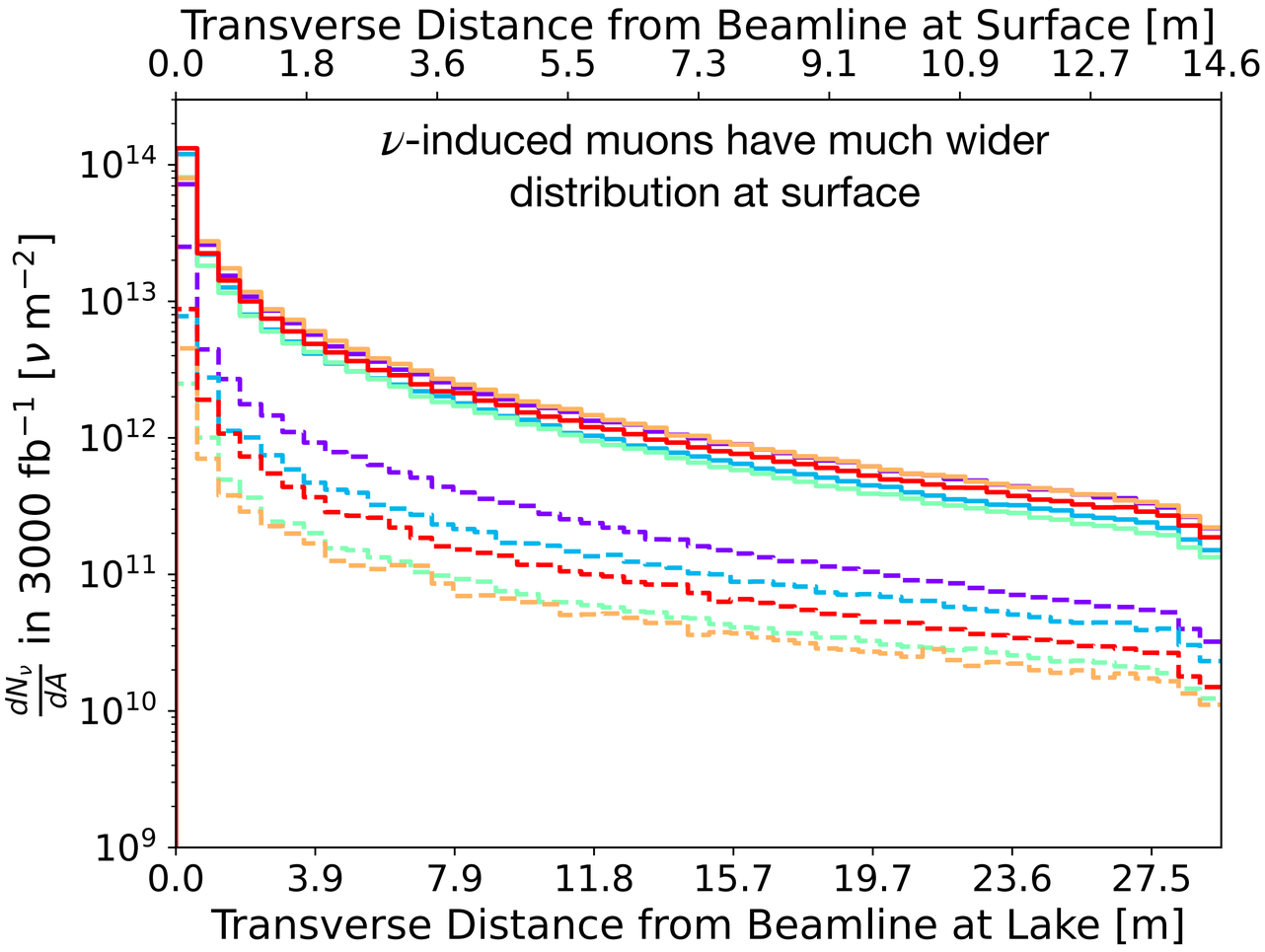
- Scintillator panels arranged along the front and back of shipping crates
- Arranged in three sets of 3x2 crates
- **Signal definition:** up-going muons from neutrino interactions in bedrock



LHC Forward Neutrino Flux

We use github.com/makelat/forward-nu-flux-fit for simulated samples of forward neutrinos produced in ATLAS





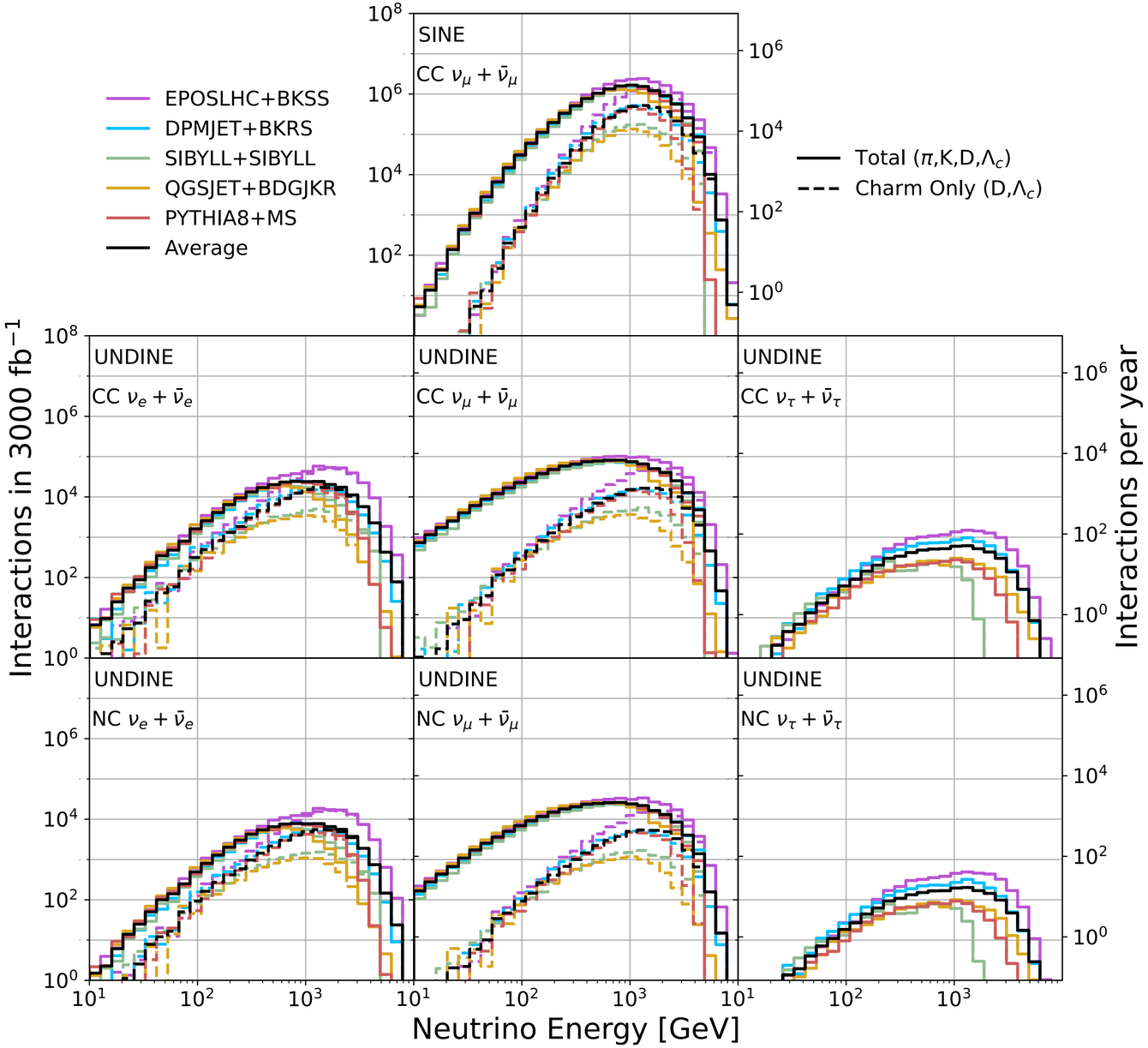
Event Rates

- We simulate DIS neutrino interactions along the LHCb beamline using the SIREN simulation toolkit [1]
- Some flavor identification possible in the lake detector using topology of Cherenkov rings

These detectors offer a cost-effective opportunity to collect large samples of TeV-scale collider neutrino interactions

Dataset	Total	π, K	D, Λ_c
SINE (CC $\nu_\mu + \bar{\nu}_\mu$)	$10^{7.09}$	$10^{6.96}$	$10^{6.50}$
UNDINE (CC $\nu_e + \bar{\nu}_e$)	$10^{5.36}$	$10^{5.02}$	$10^{5.10}$
UNDINE (CC $\nu_\mu + \bar{\nu}_\mu$)	$10^{5.96}$	$10^{5.90}$	$10^{5.09}$
UNDINE (CC $\nu_\tau + \bar{\nu}_\tau$)	$10^{3.76}$	0	$10^{3.76}$
UNDINE (NC $\nu_\alpha + \bar{\nu}_\alpha$)	$10^{5.56}$	$10^{5.45}$	$10^{4.91}$

TABLE I. Event rates for SINE and UNDINE in 3000 fb^{-1}

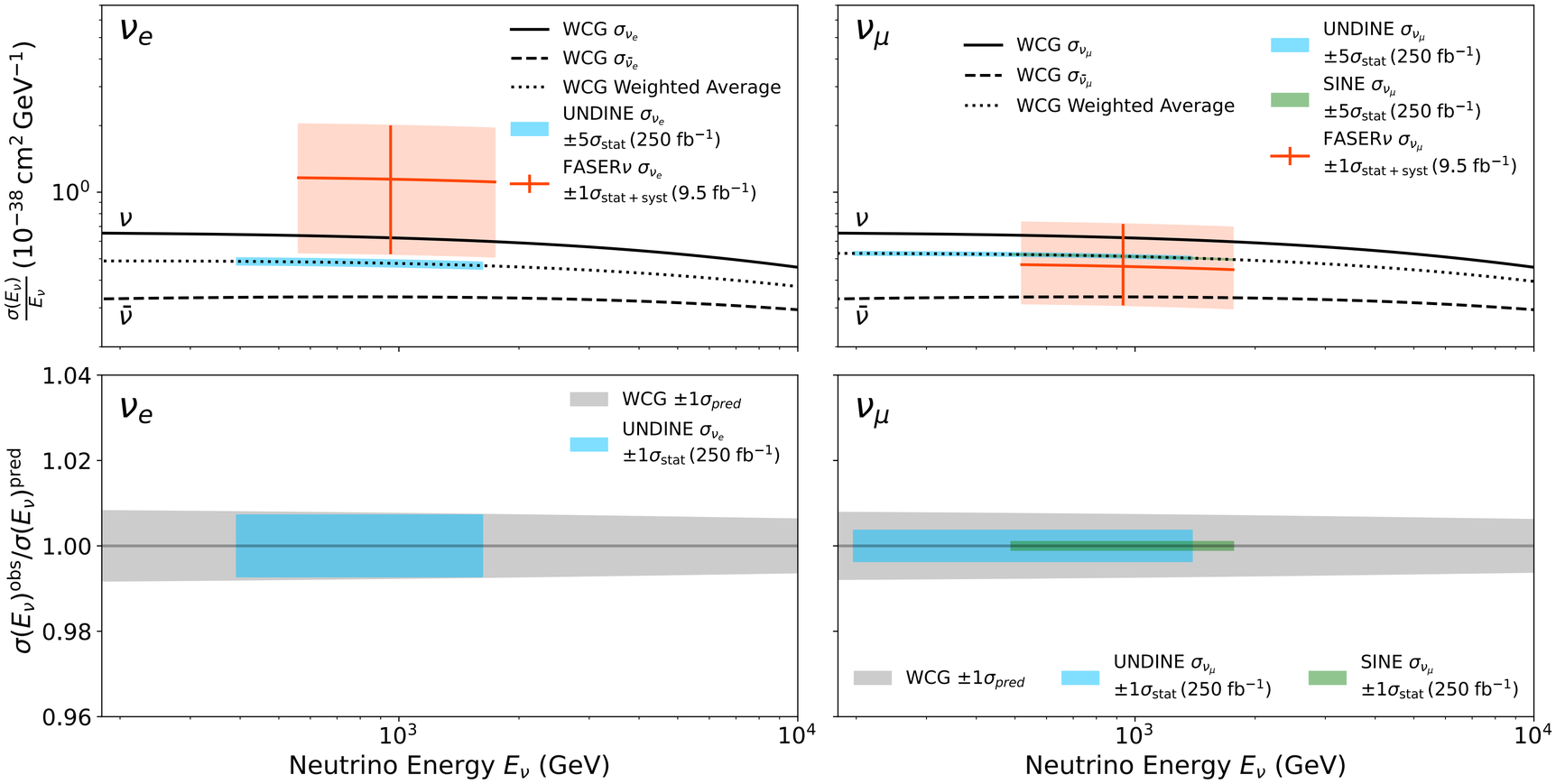


[1] A. Schneider, NK, A. Wen 2024

What can we do with over a million collider neutrinos?

Neutrino Cross Sections

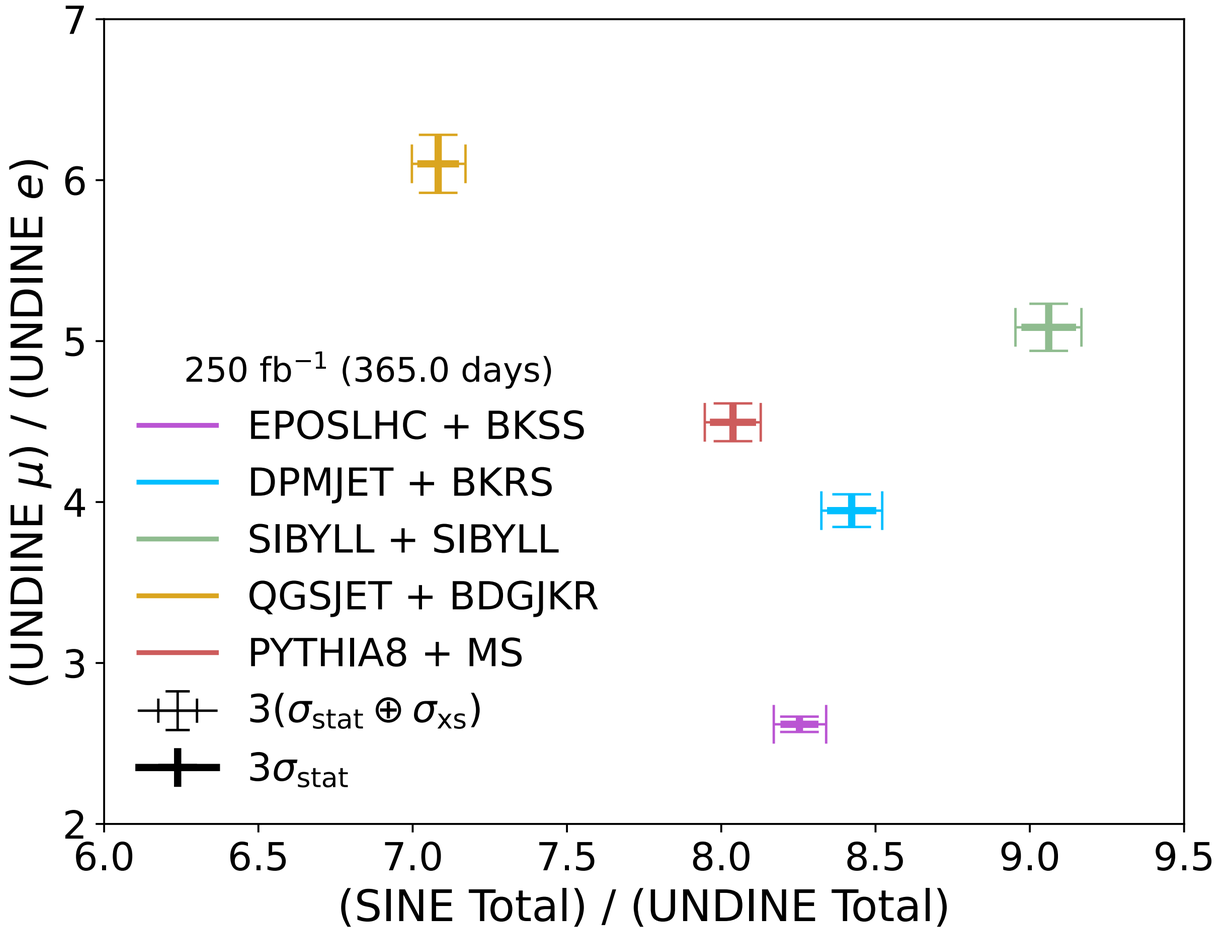
- FASER recently reported first measurements of the total neutrino cross section at the TeV scale [1]
- SINE and UNDINE can make complimentary measurements
- **Sub-percent statistical uncertainty after 1 year of HL-LHC operation**
  - Comparable to theoretical uncertainty [2]



[1] FASER Collab. 2024 [2] Weigel+ 2024

Forward Charm Production in p-p Collisions

- Order-of-magnitude uncertainties
- Increasing forward charm production rates corresponds to…
  1. **More high-energy muon neutrinos**
  2. **More electron and tau neutrinos**
- Ratio measurements can distinguish between charm production models after 1 year
- Important implications for **intrinsic charm content of the proton [1]** and the **prompt atmospheric neutrino flux [2]**

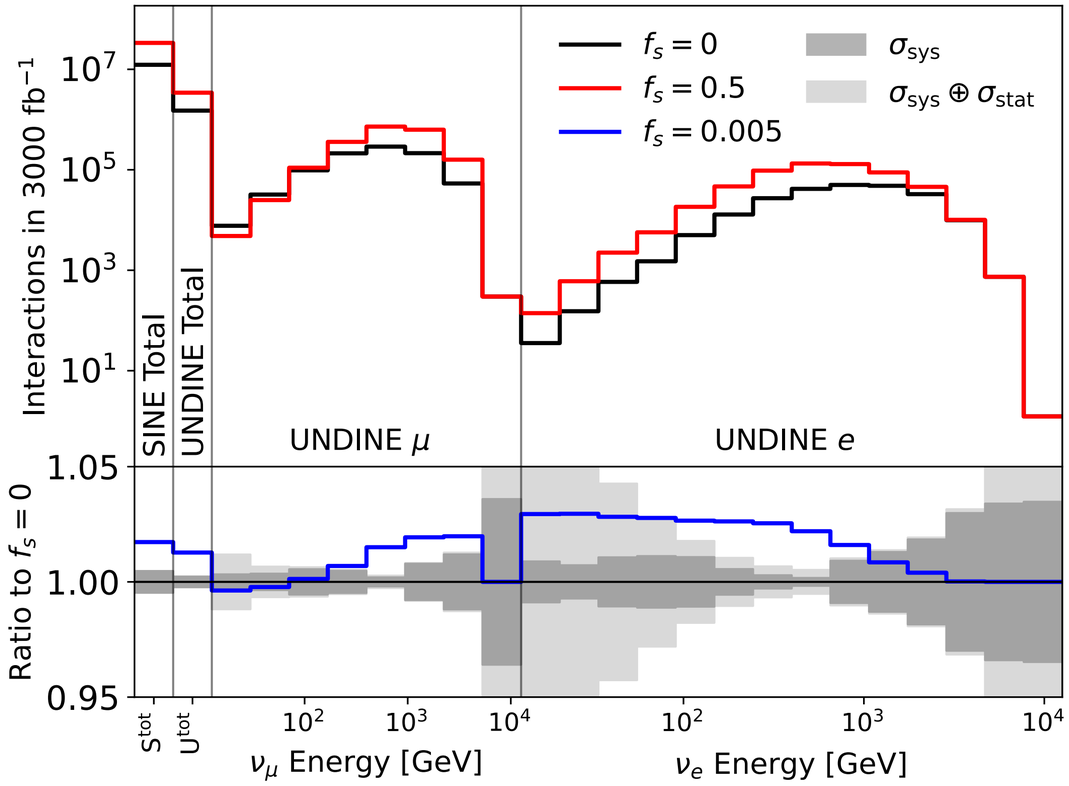


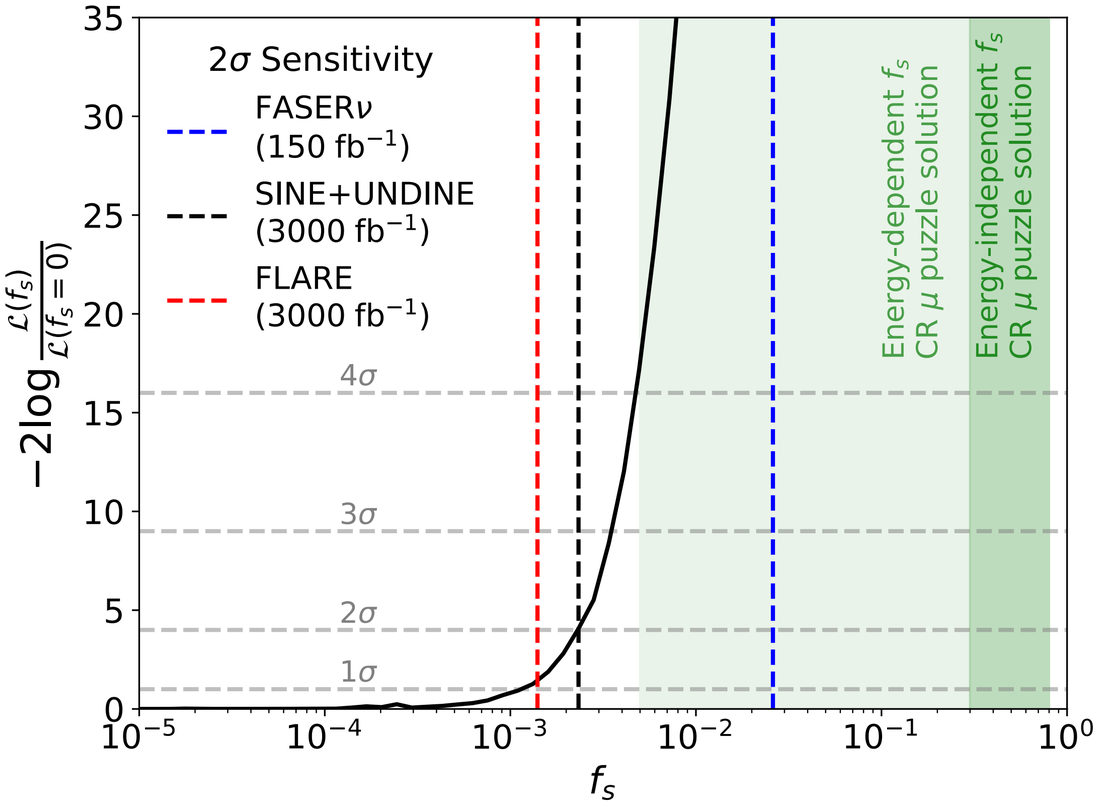
[1] Maciula+ 2022 [2] Jeong+ 2023

Cosmic Muon Puzzle

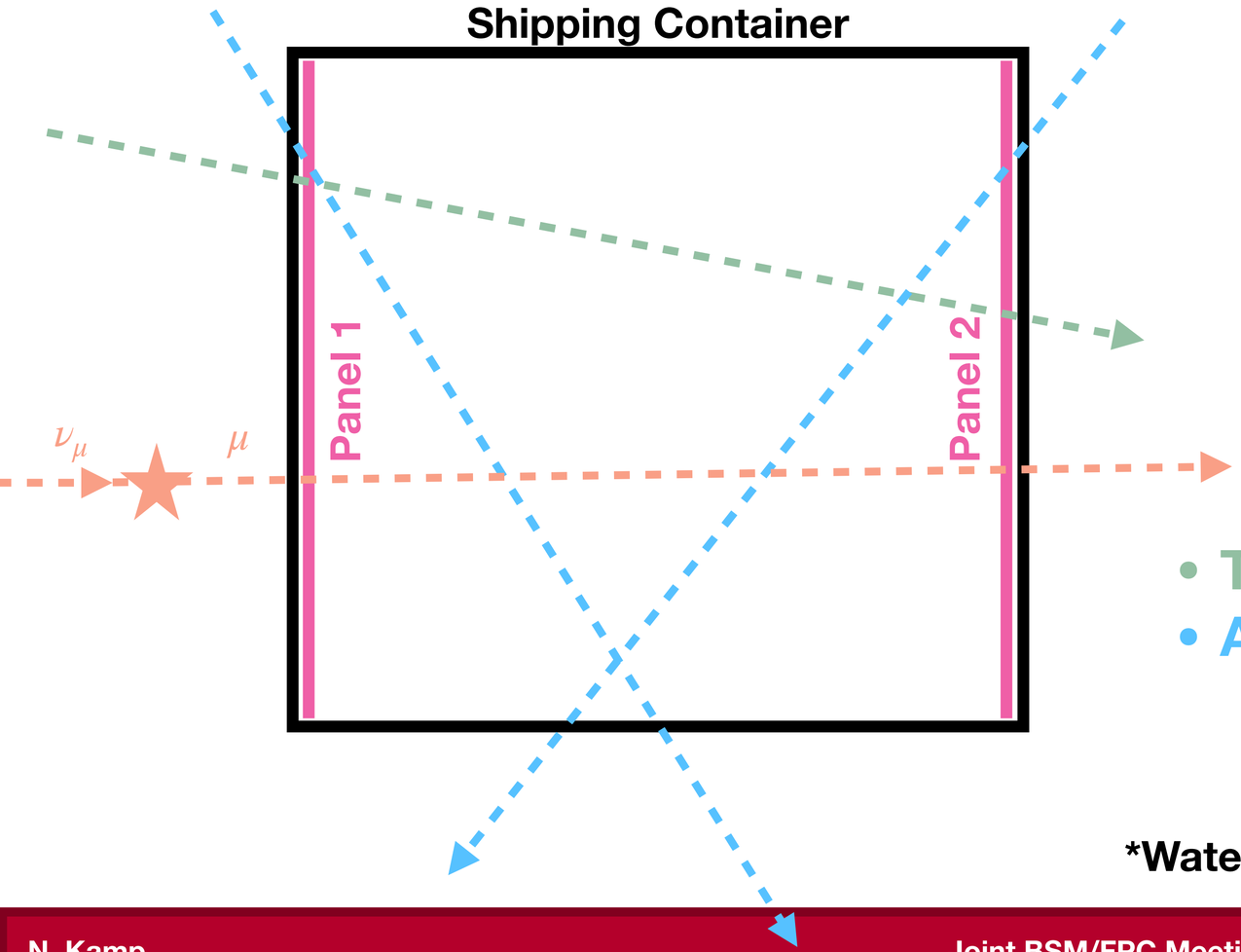
[1] Albrecht+ 2021
[2] Anchordoqui+ 2022
[3] Kling+ 2023

- Excess of muons observed in cosmic ray air showers [1]
- **Hypothesis:** swapping probability f_s between pions and kaons in hadronic showers [2]
- SINE and UNDINE have comparable sensitivity to future FPF experiments [3]





Surface Detector Background



Signal

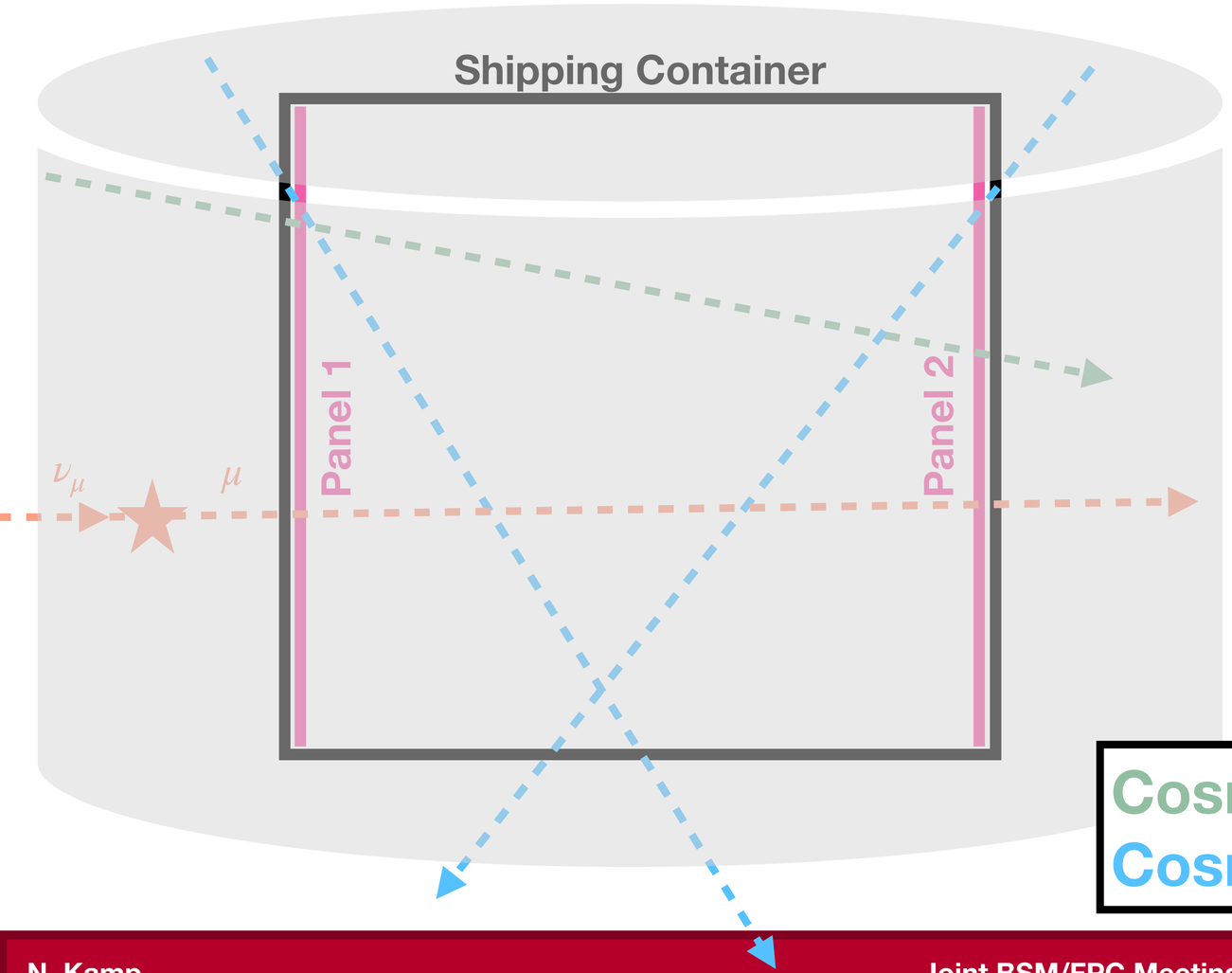
- True coincidence from a ν-induced muon
  ~11 mHz per surface detector

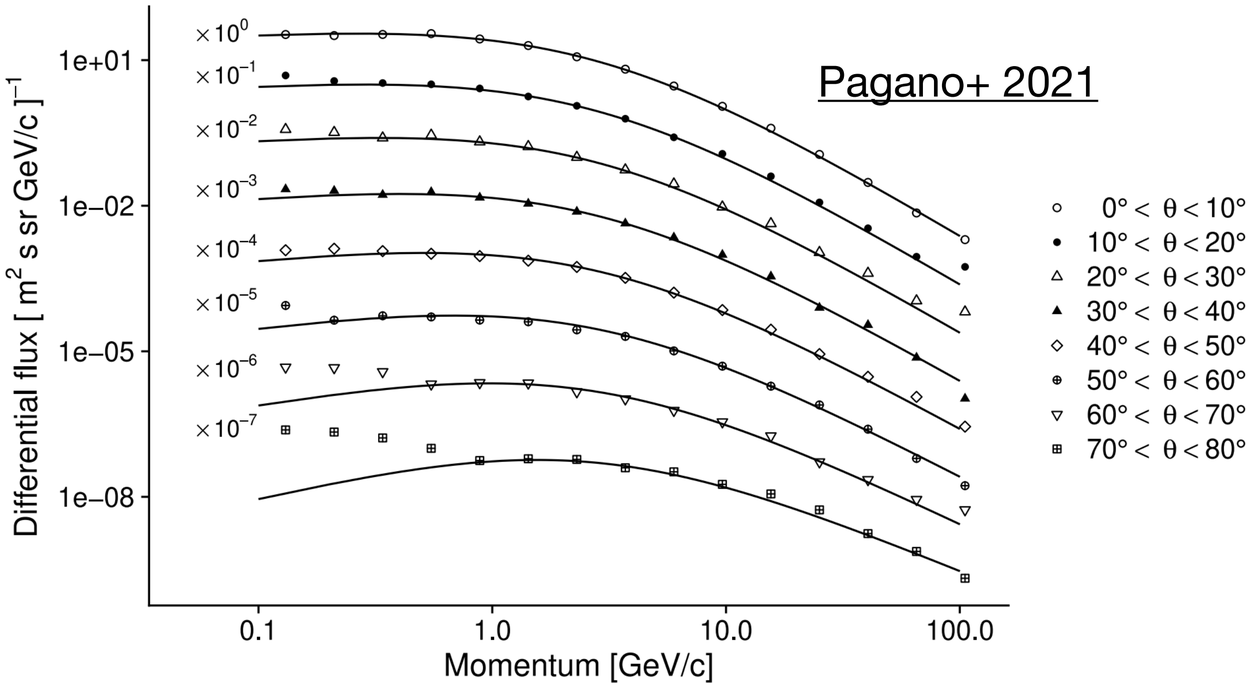
Background

- True coincidence from a single cosmic muon
- Accidental coincidence from two cosmic muons

*Water overburden reduces cosmic backgrounds in lake detector

Surface Detector Background





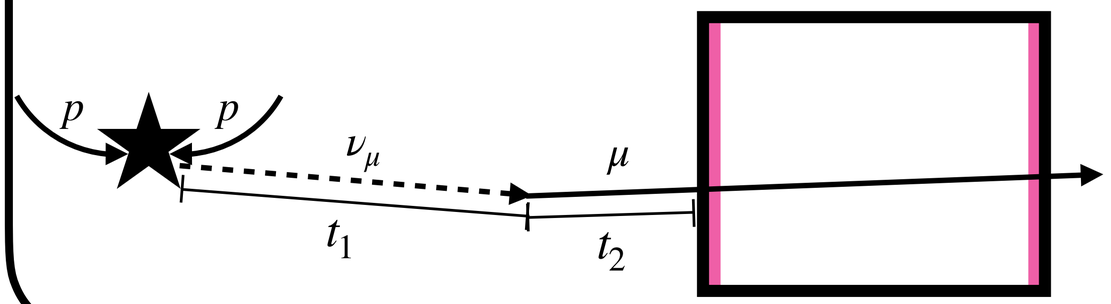
We use EcoMug to generate cosmic muons in a cylinder surrounding one of the shipping containers

Cosmic muon true coincidence rate: 1.67 kHz

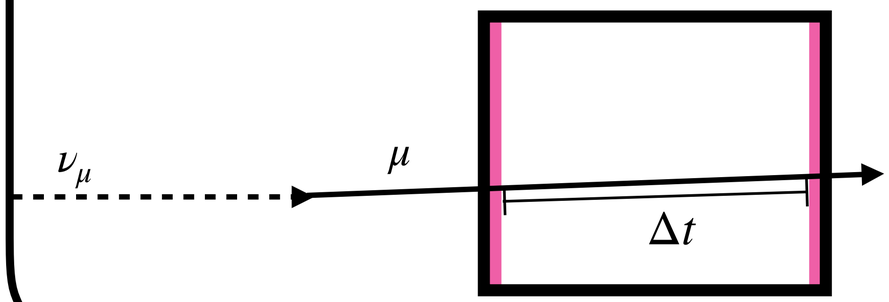
Cosmic muon single panel rate: 1.62 kHz

Four Strategies for Background Rejection

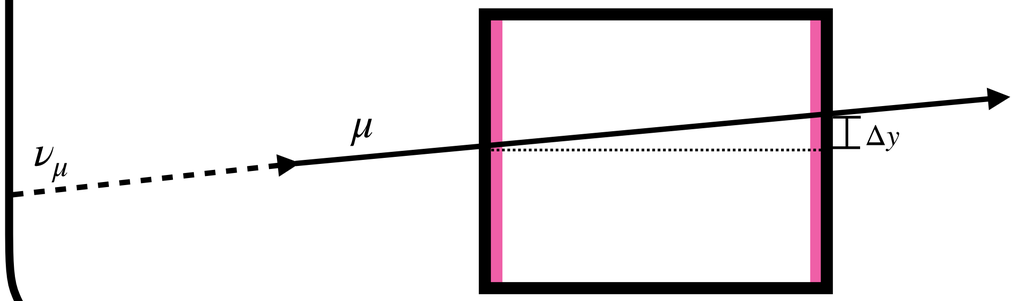
1. Timing with respect to proton collision



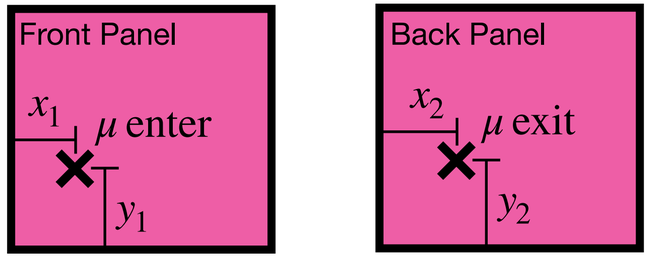
2. Time difference between scintillator panels



3a. Up-going spatial information



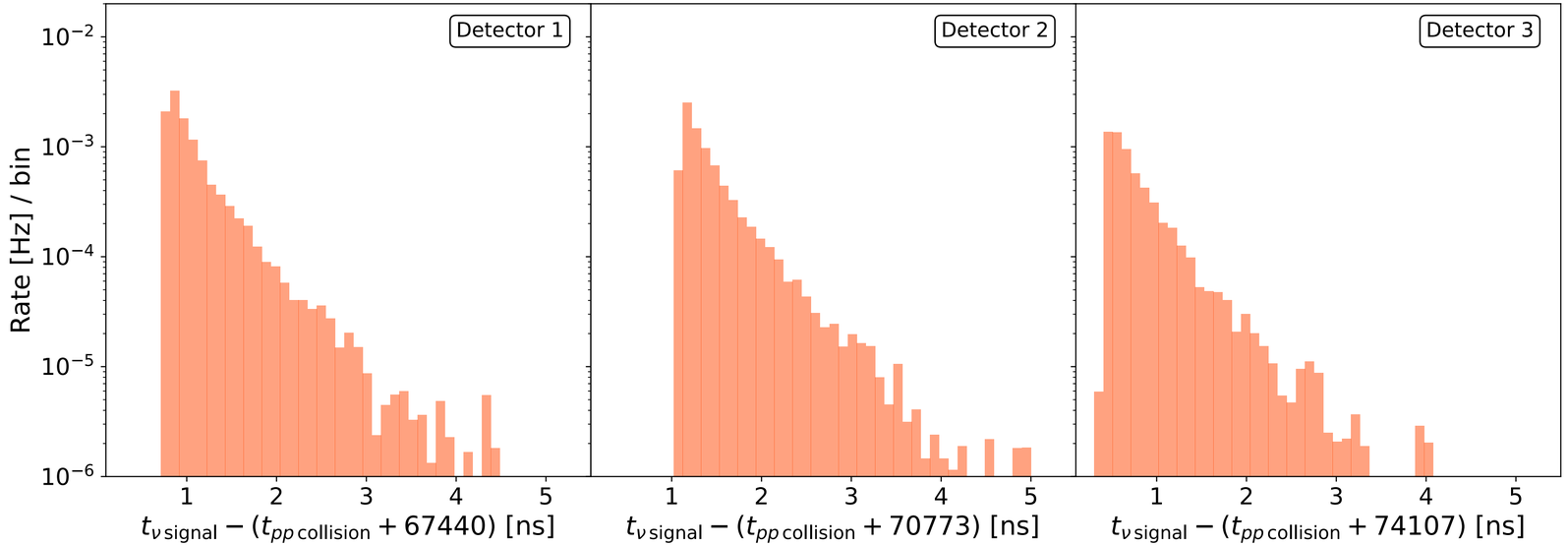
3b. Two-dimensional spatial information

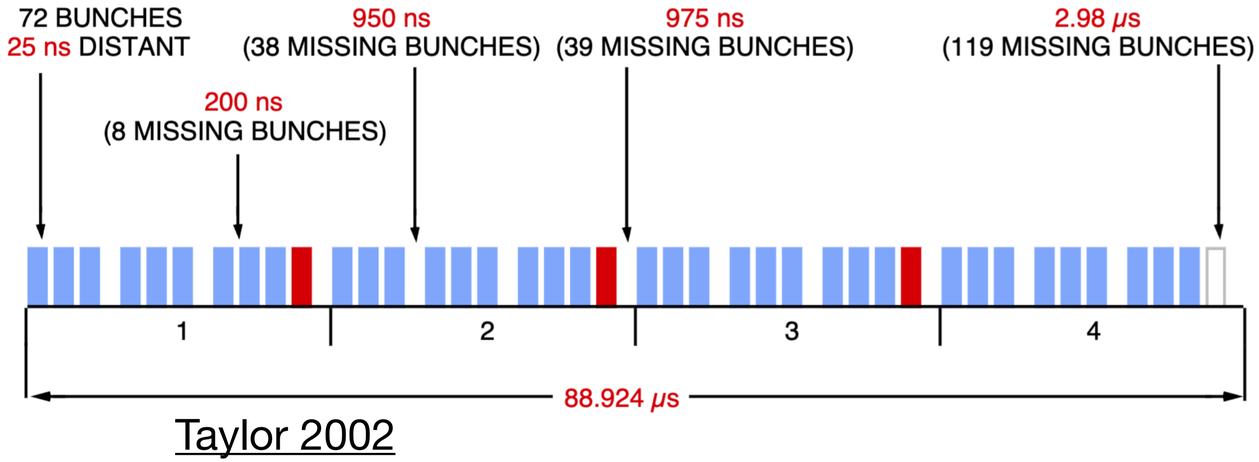


1. Timing with respect to proton collision

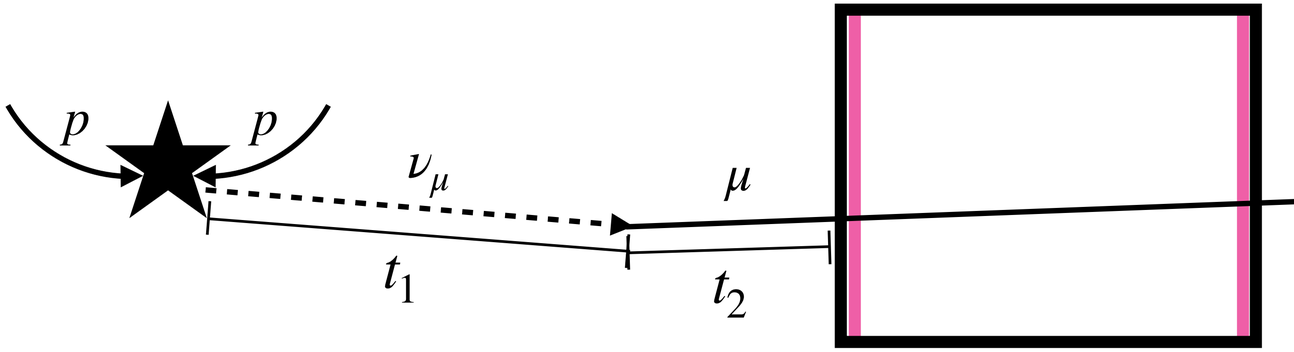
- The LHC has an inherent duty factor of 78.9%
- Within each 25 ns bunch, >99% of neutrino signal events arrive within a 2.5 ns window

Effective duty factor: 7.9%





Taylor 2002



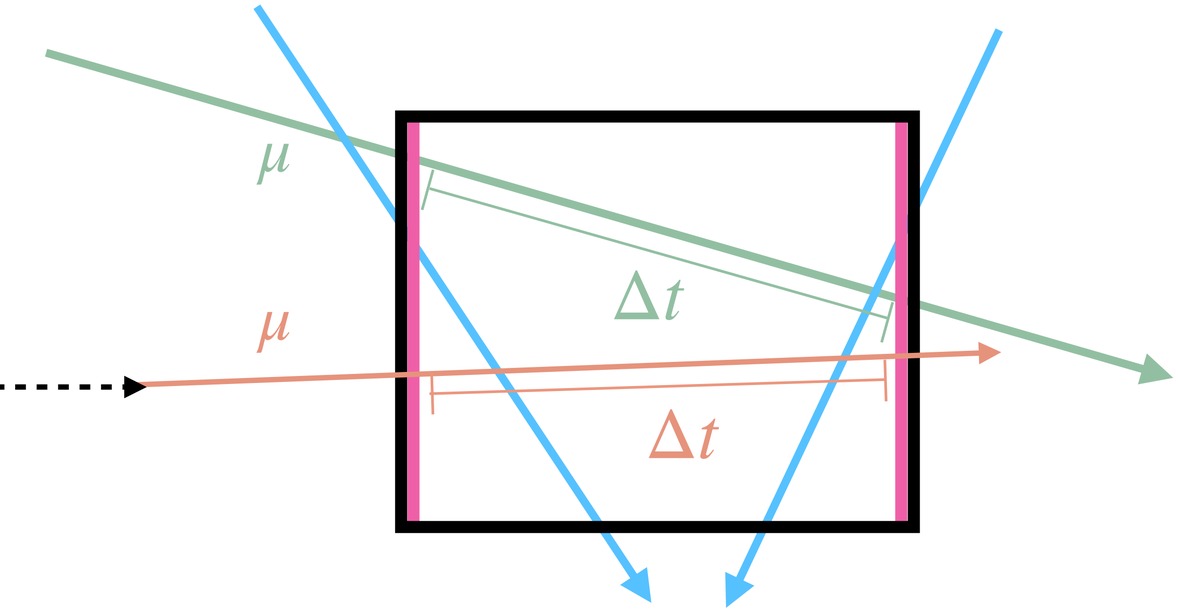
ν-induced muon rate: 11 mHz

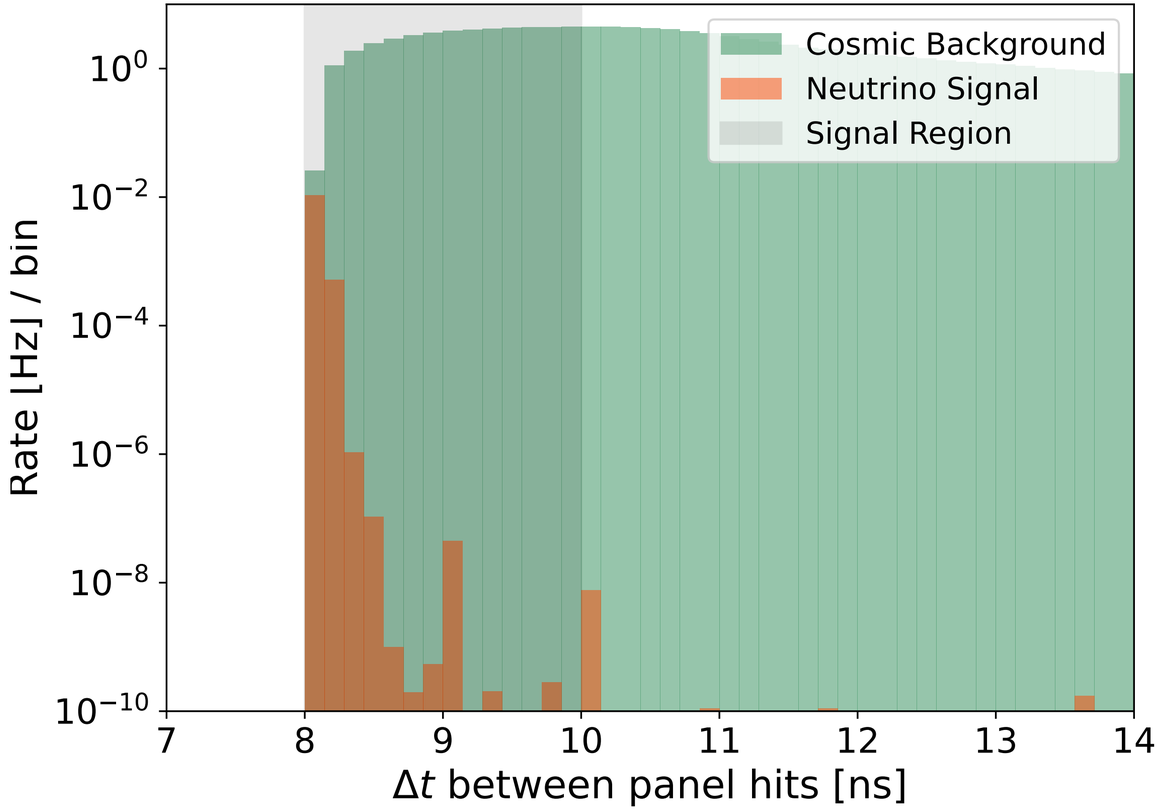
Cosmic muon true coincidence rate: 132 Hz

Cosmic muon single panel rate: 128 Hz

2. Time difference between scintillator panels

- Neutrino-induced muons tend to travel transverse to the scintillator plane, while cosmic muons pass through at larger angles on average
- **Strategy: only keep events any events for which $8 < \Delta t/\mathrm{ns} < 10$**

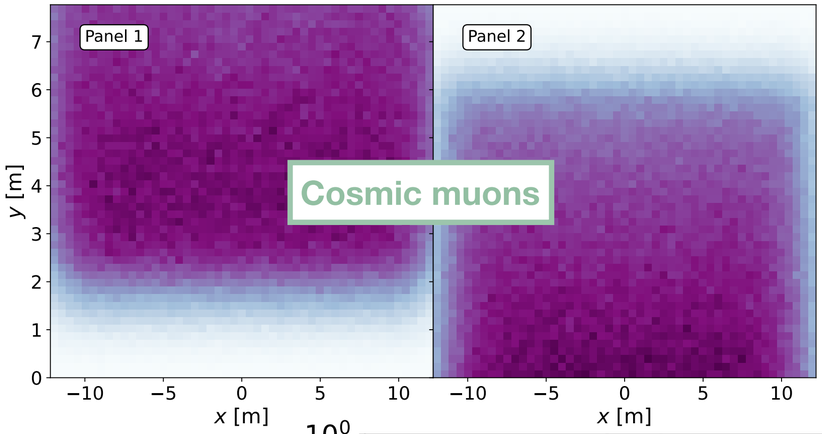


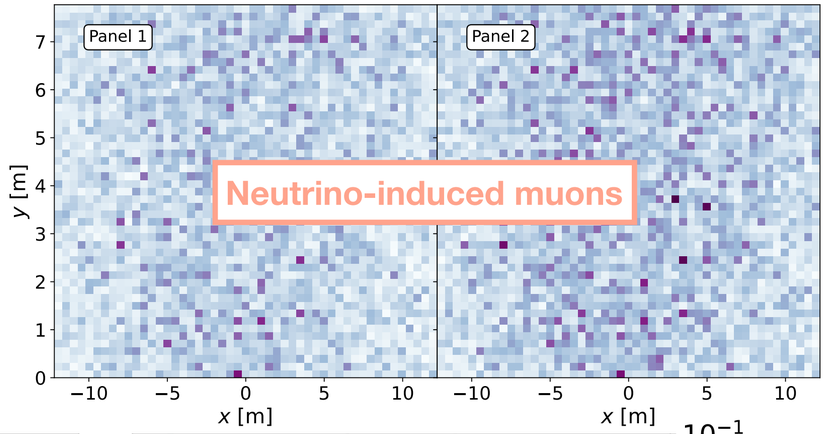


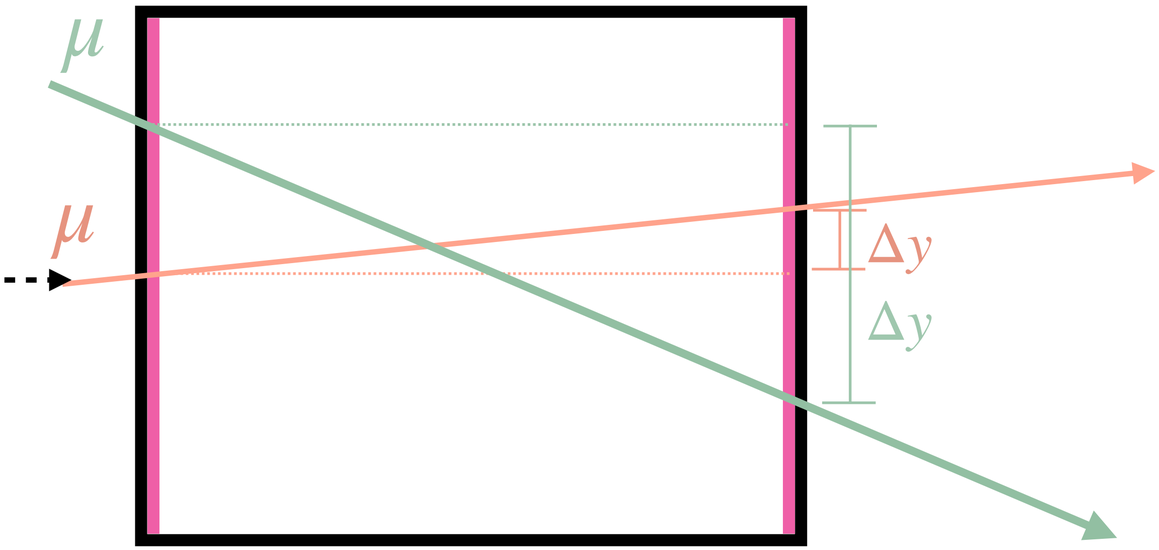
ν-induced muon rate: 11 mHz
Cosmic muon true coincidence rate: 45 Hz
Cosmic muon accidental coincidence rate:
128 Hz $\times$ (1.62 kHz $\times$ 2 ns) = 0.4 mHz

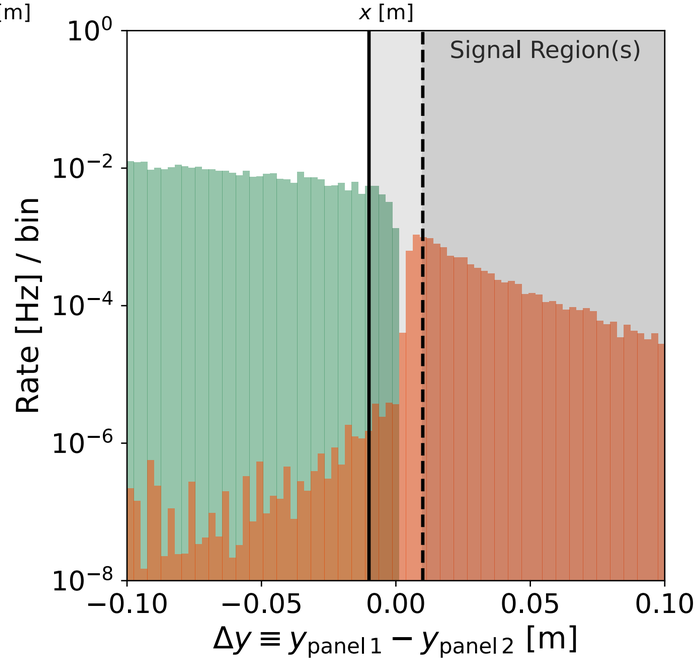
3a. Up-going spatial information

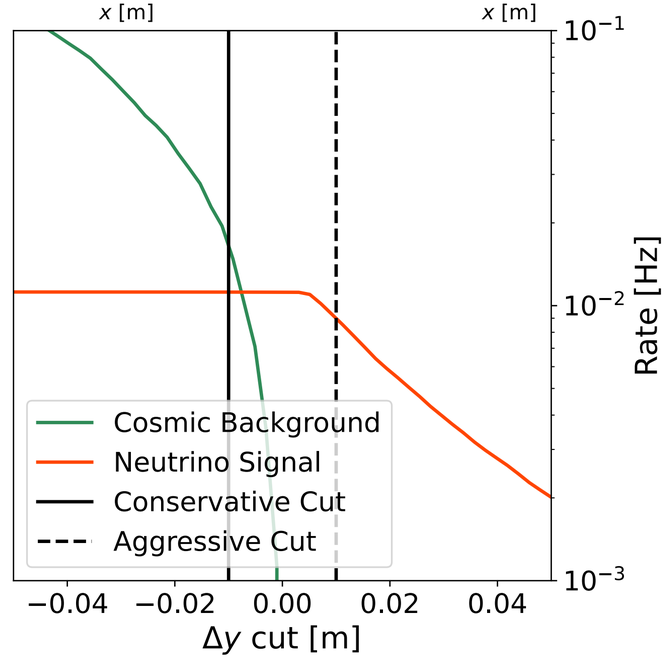
- Neutrino-induced (cosmic) muons tend to travel upward (downward)
- **Strategy: only keep events for which $\Delta y > -1$ cm**
- A more aggressive cut is possible but will reduce signal efficiency









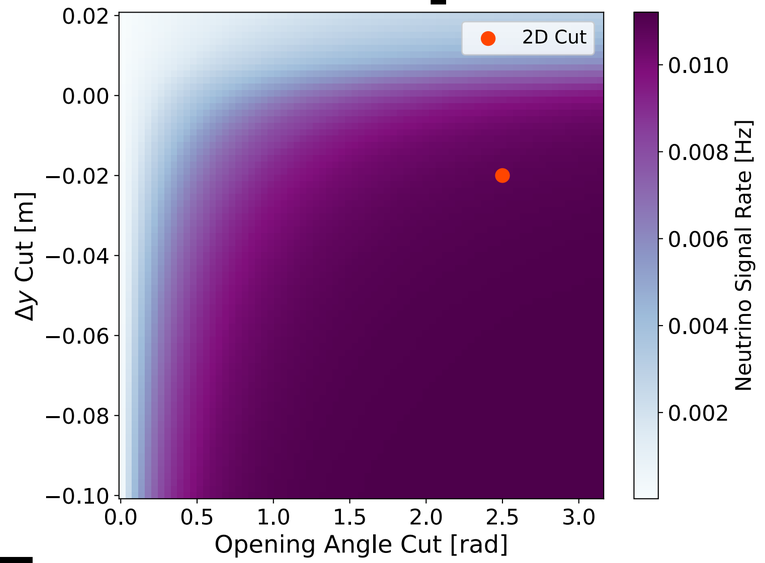


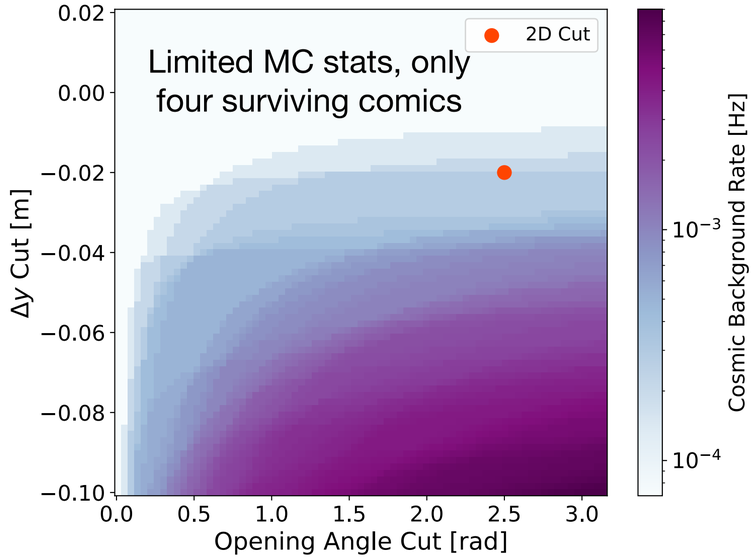
ν-induced muon rate: 11 mHz

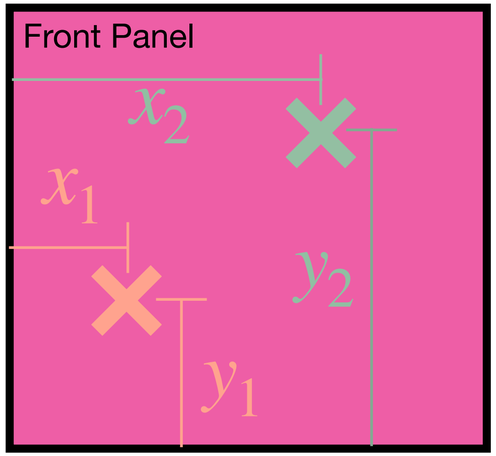
Cosmic muon true coincidence rate: 17 mHz

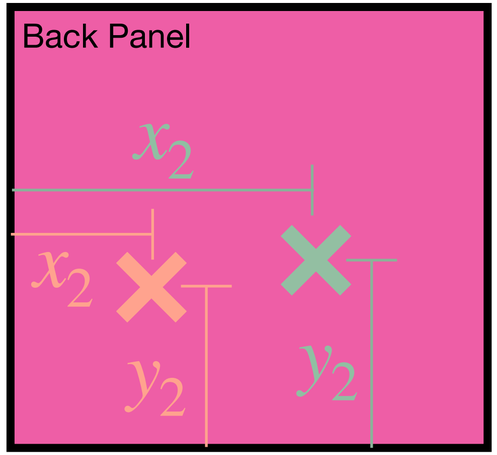
3b. Two-dimensional spatial information

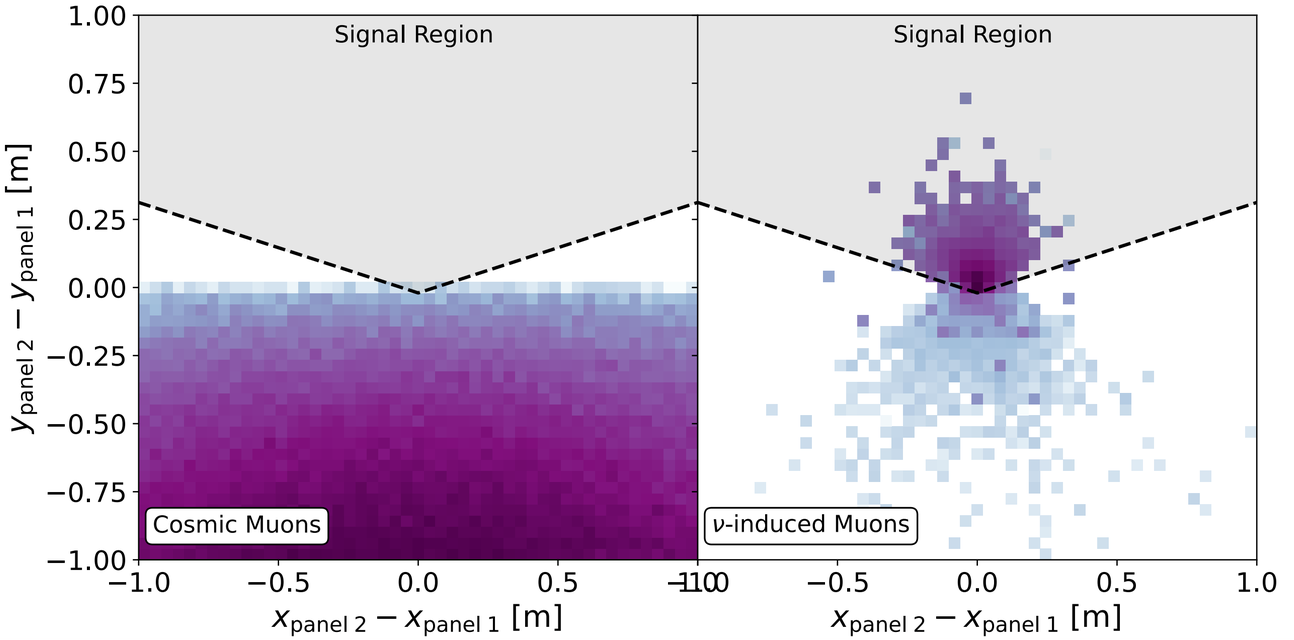
- Neutrino-induced muons also don't tend to deviate in the horizontal direction
- **Strategy: make a triangle-based cut on Δx and Δy**







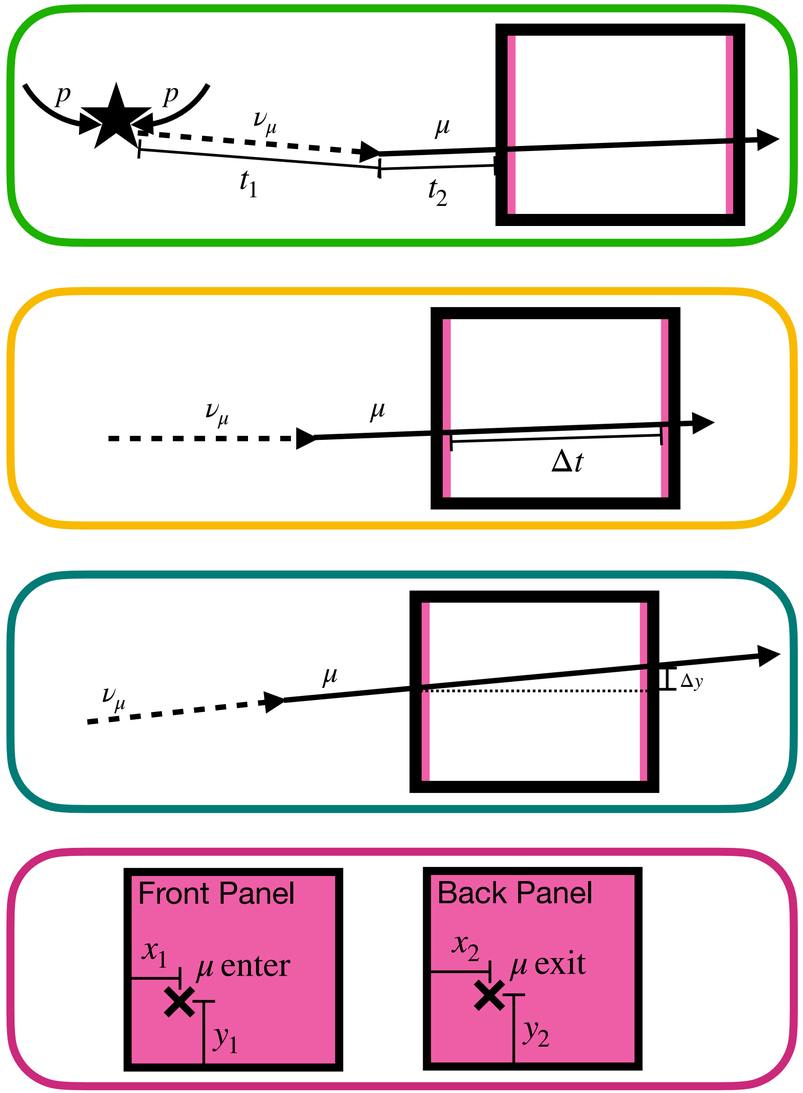


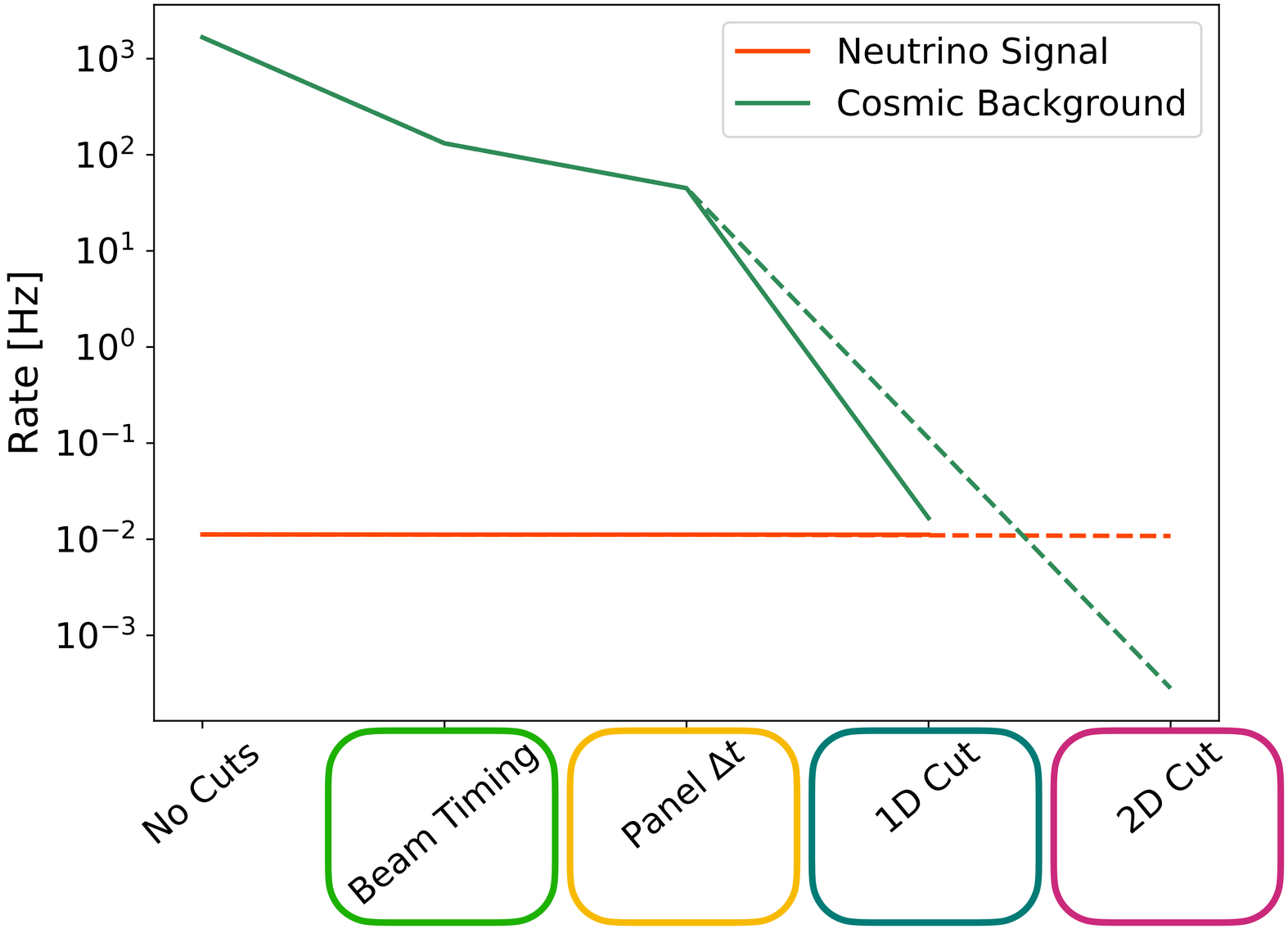


ν-induced muon rate: 11 mHz

Cosmic muon true coincidence rate: ~0.3 mHz

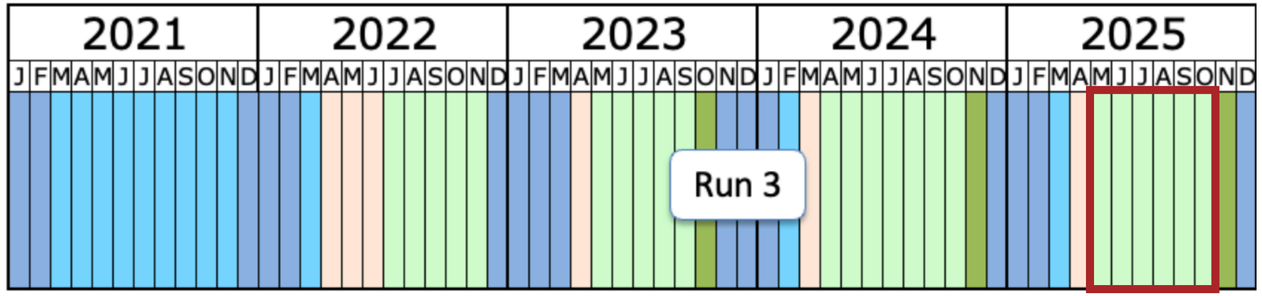
Surface Background Summary





Prototype Surface Detector

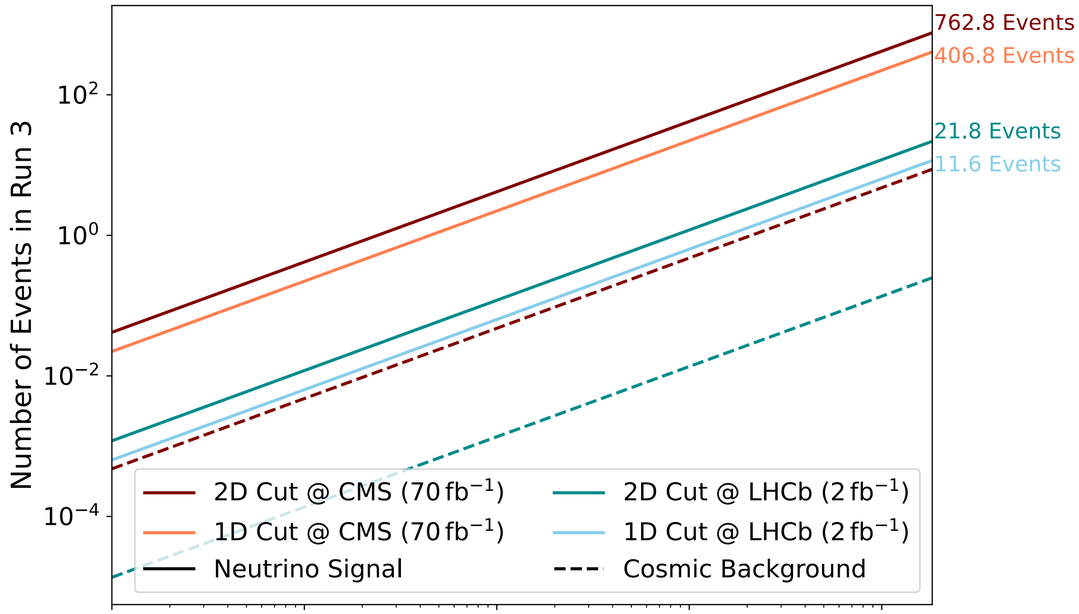
lhc-commissioning.web.cern.ch/schedule/LHC-long-term.htm

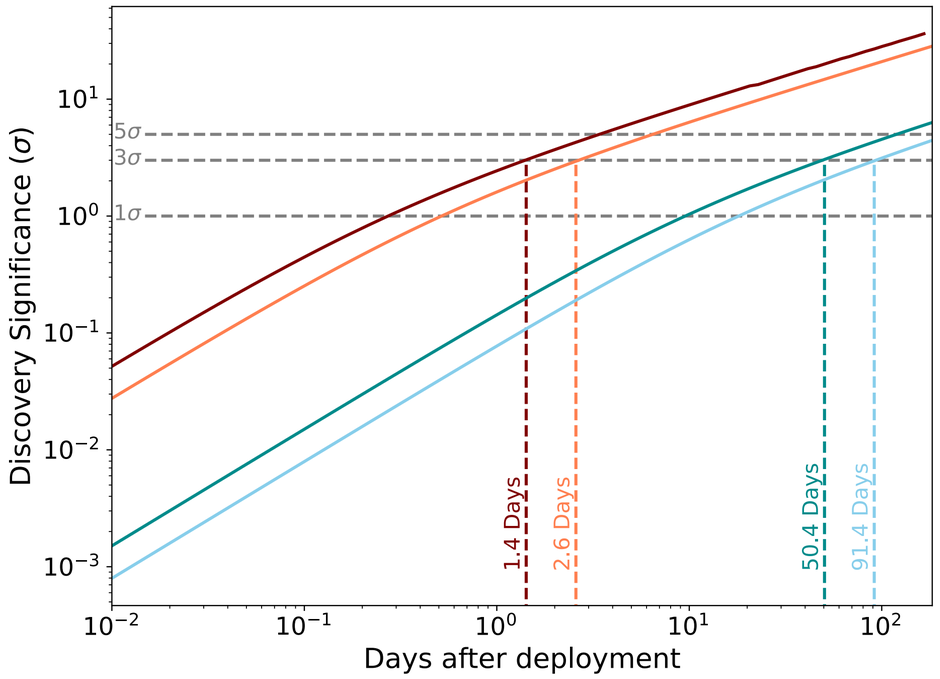


Shutdown/Technical stop
Protons physics
Ions (tbc after LS4)
Commissioning with beam
Hardware commissioning

What can we do here with one shipping crate detector?

Shipping Container





Takeaways

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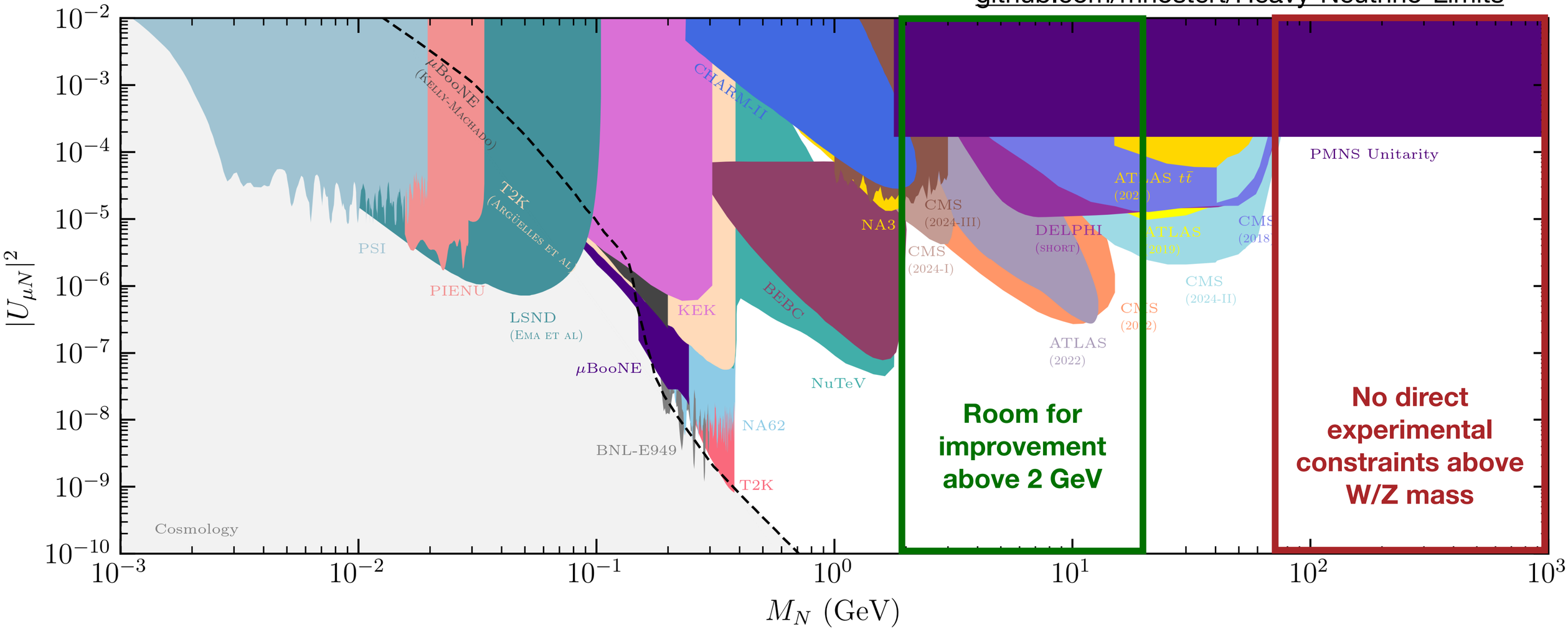
A prototype SINE detector can be deployed at the end of LHC Run 3

Backups

Heavy Neutral Leptons

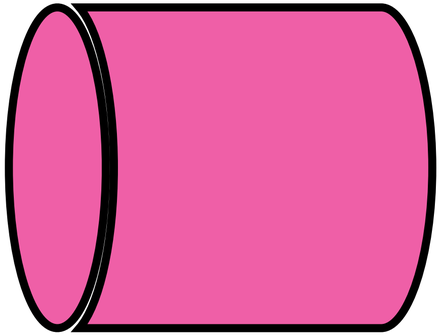
github.com/mhostert/Heavy-Neutrino-Limits



Heavy Neutral Lepton Searches

- Two ideas to look for HNLs in our proposed detectors

Lake Detector



Surface Detector

Heavy Neutral Lepton Searches

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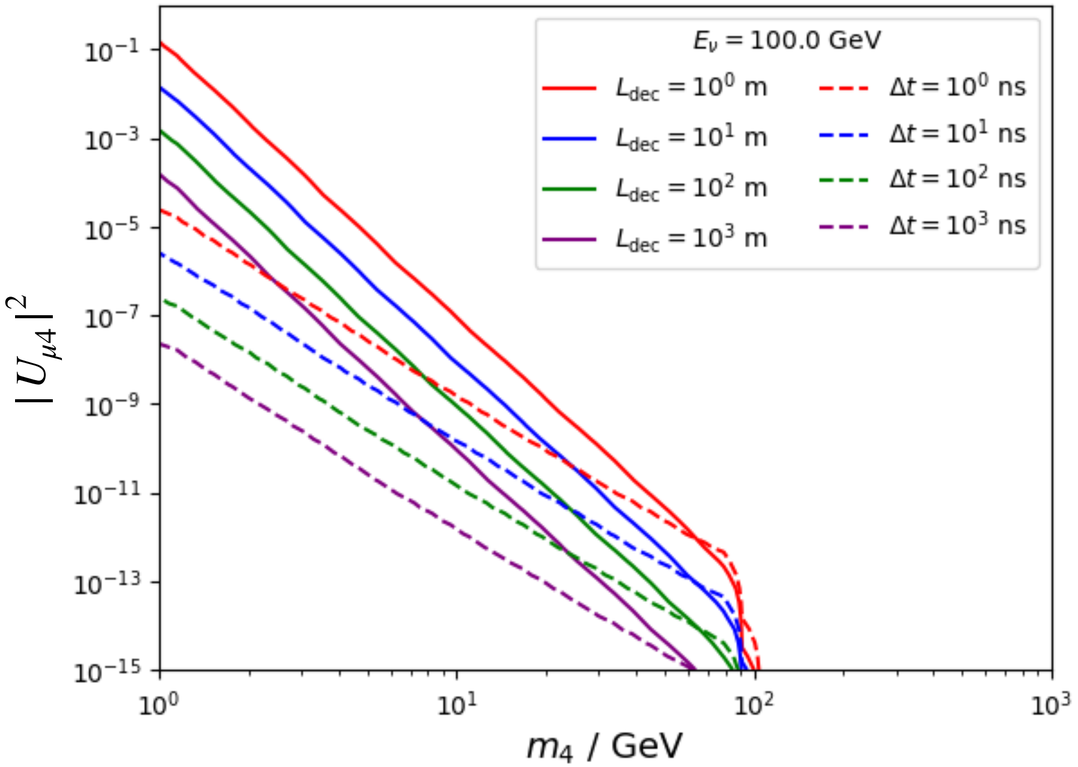
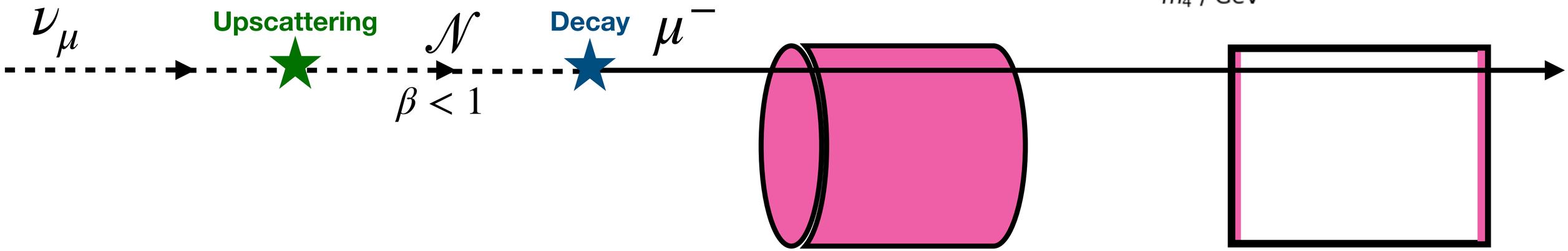
  1. **GeV-scale:** Delayed muons with respect to the beam trigger from HNL time-of-flight





Heavy Neutral Lepton Searches

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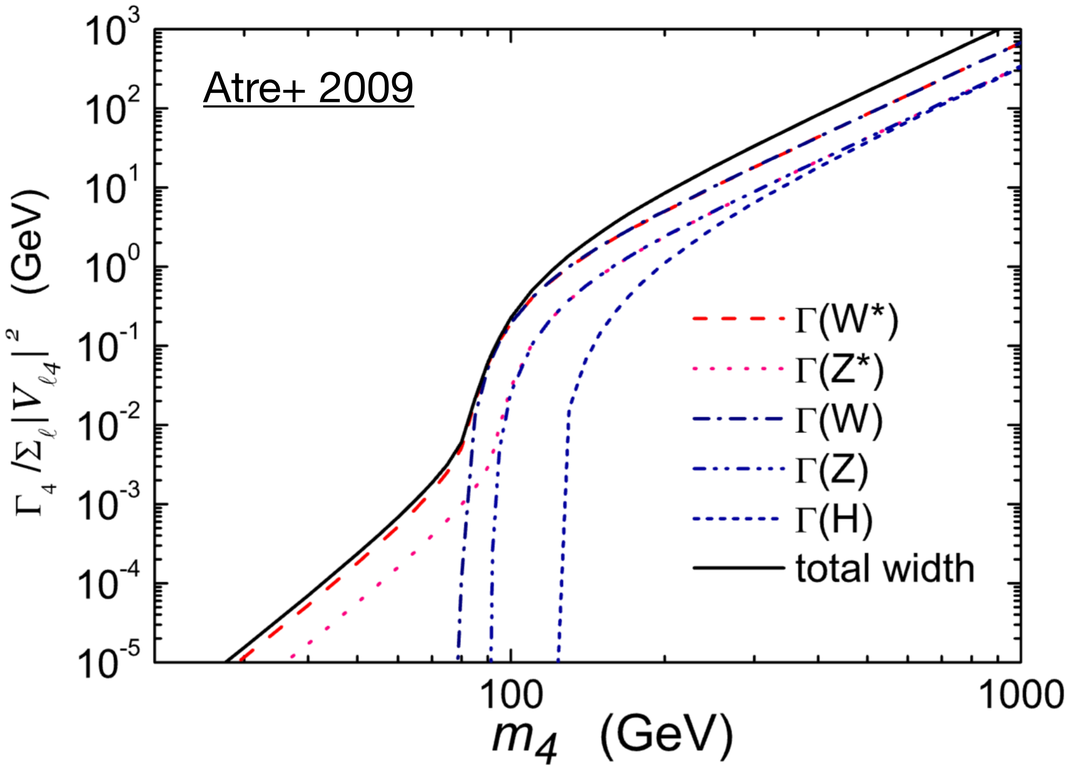
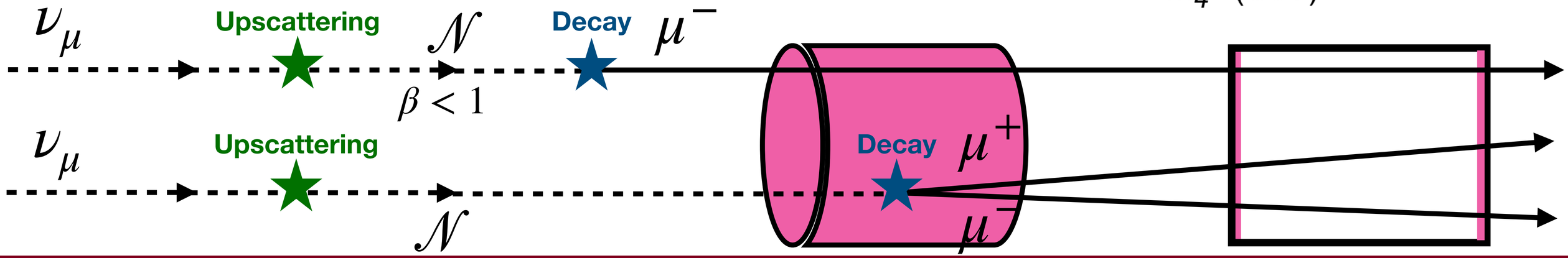
  2. **TeV-scale:** Di-muons from $\mathcal{N} \to \mu(W \to \mu\nu_\mu)$ or $\mathcal{N} \to \nu(Z \to \mu\mu)$





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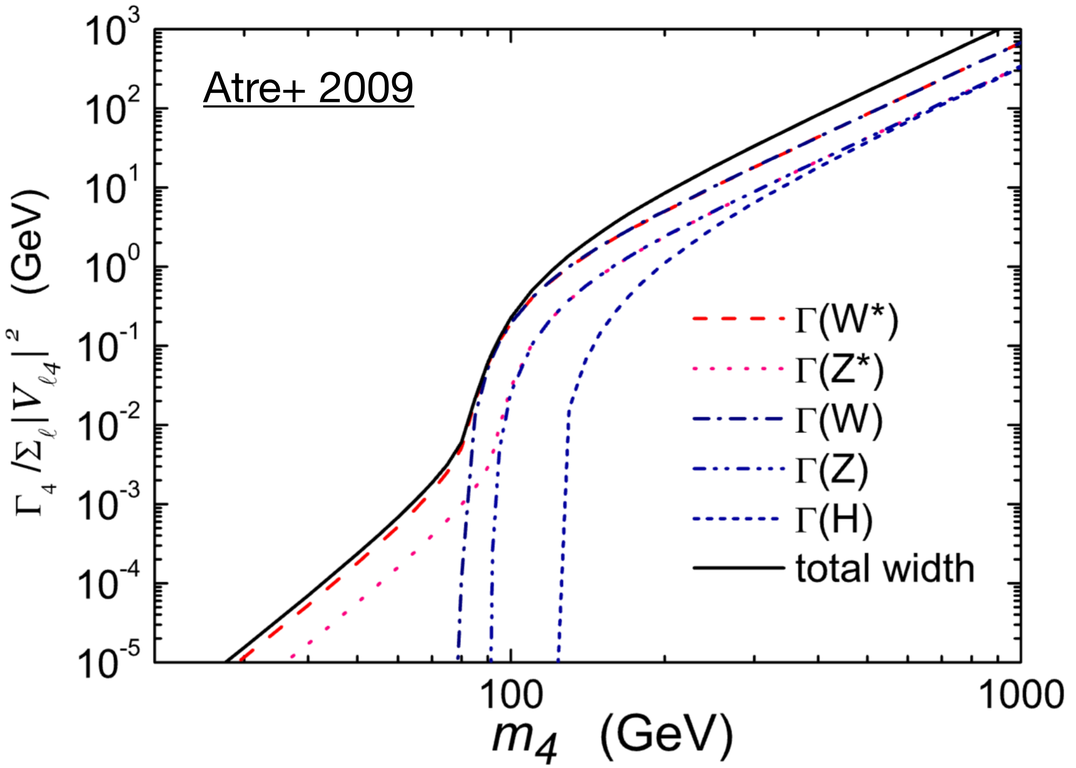
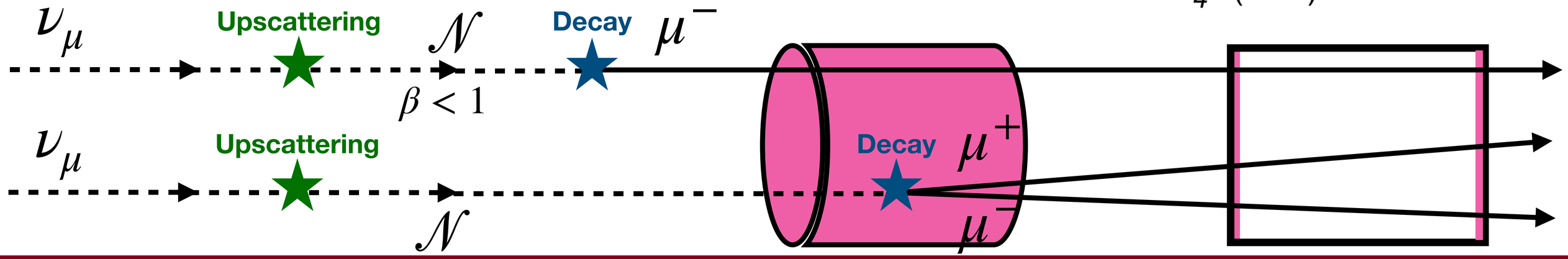


Sensitivity studies in progress



Prototype Sensitivity Details