Lake- and Surface-Based Detectors for Forward Neutrino Physics
+ a brief Update on IceCube's Upgrade

Albrecht Karle
University of Wisconsin-Madison

Based on 2501.08278

Many slides taken from N. Kamp's presentation at TeVPA

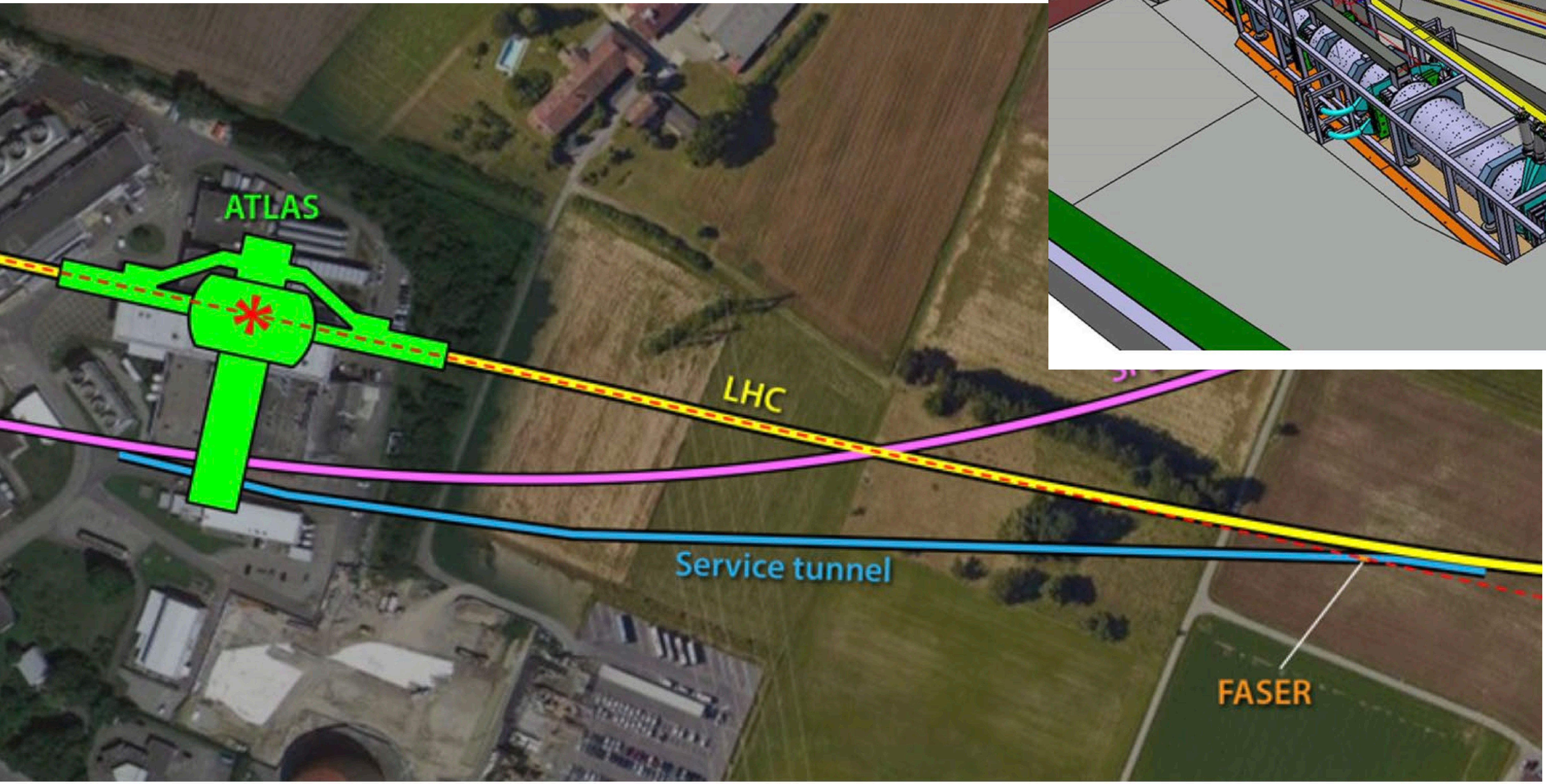

N. Kamp


C. Argüelles

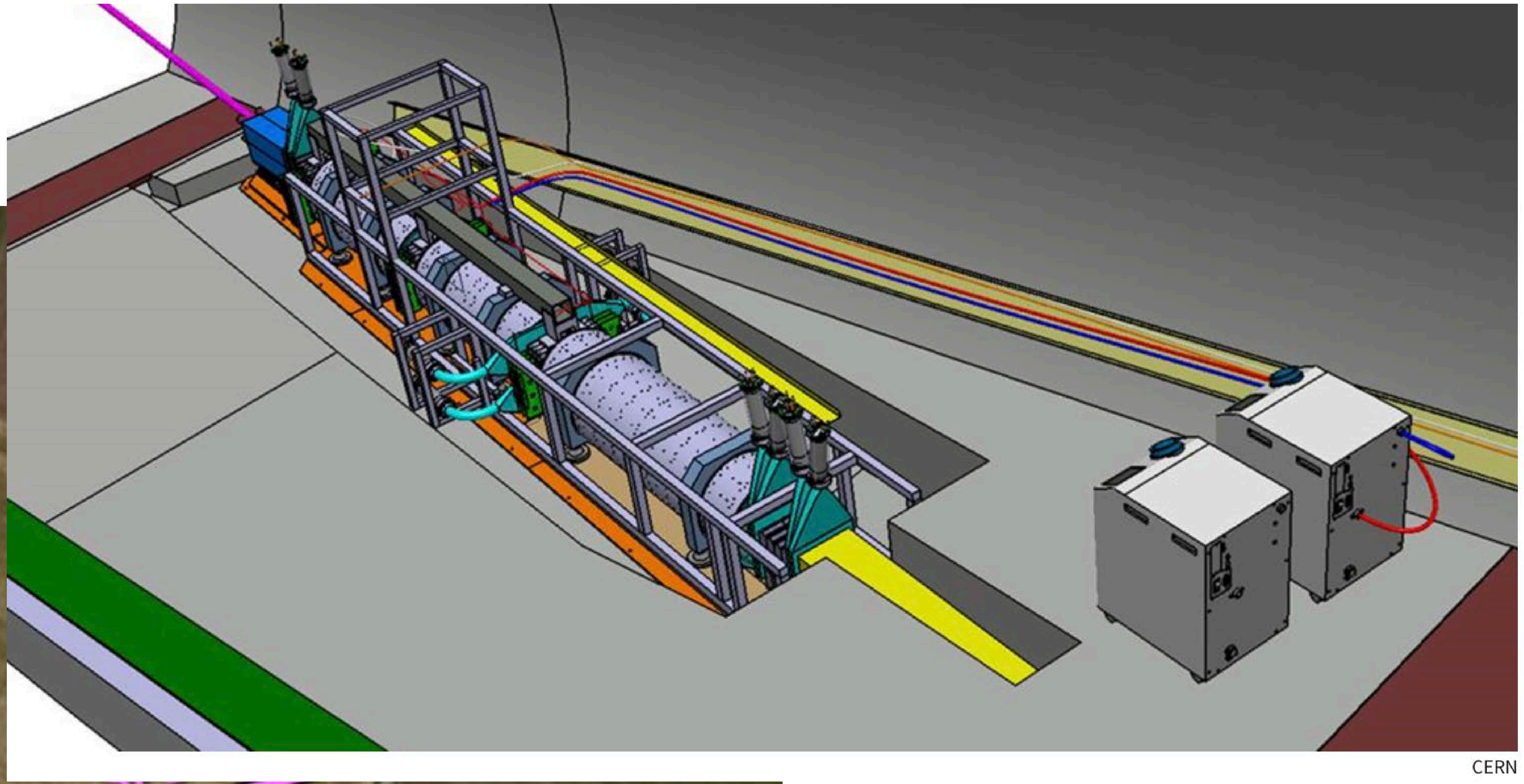

J. Thomas


T. Yuan

FASER: Neutrino Physics at the LHC



Google Earth, imagery (c)2023 Maxar Technologies, map data (c)2023; CERN; adapted by APS/Alan Stonebrake



CERN

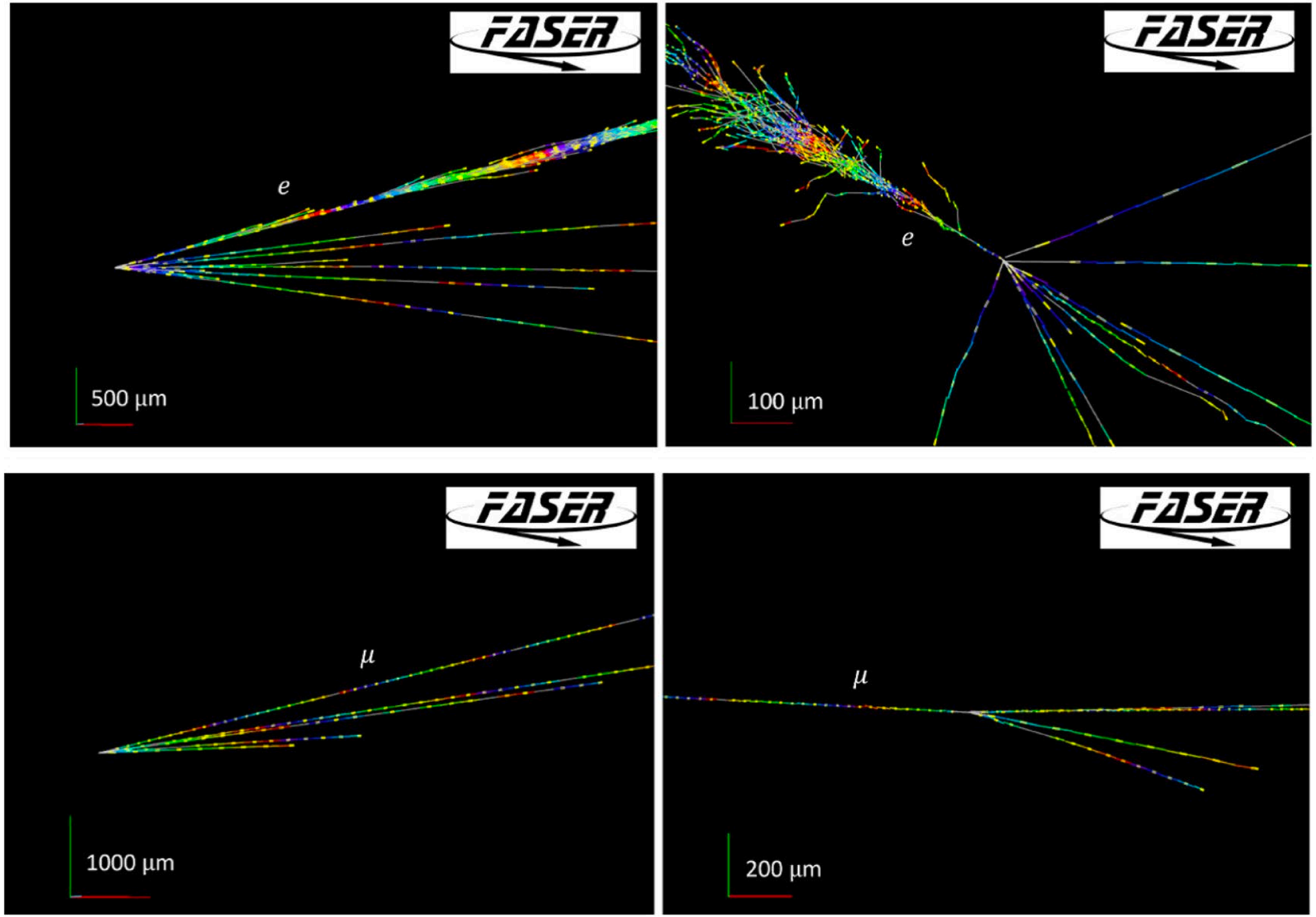
FASER: Neutrino Physics at the LHC

Recorded cc interactions:

Top: electron neutrino

Bottom: Muon neutrino

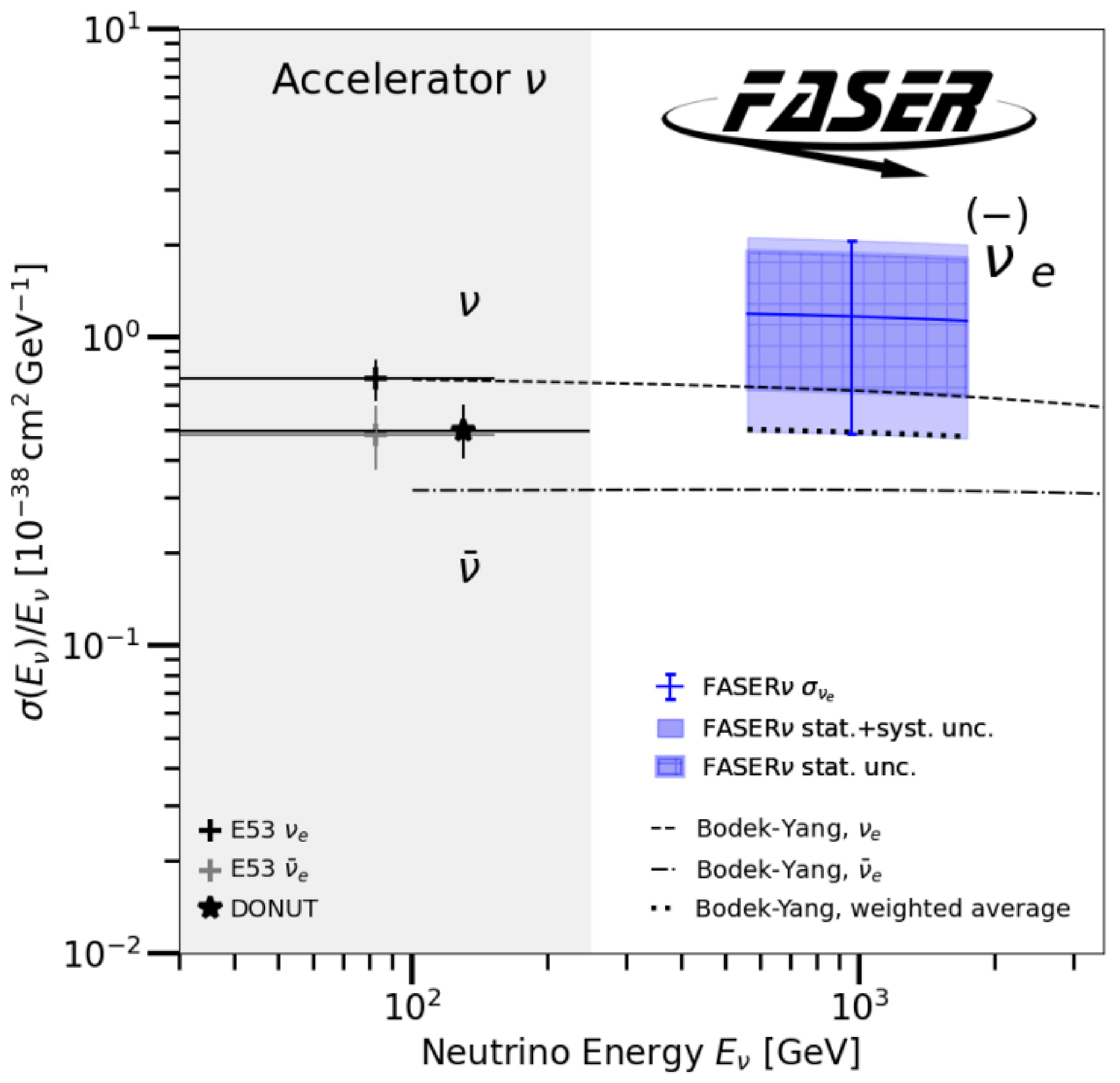
Left: beam direction along the horizontal axis. Right: beam axis perpendicular to the screen.

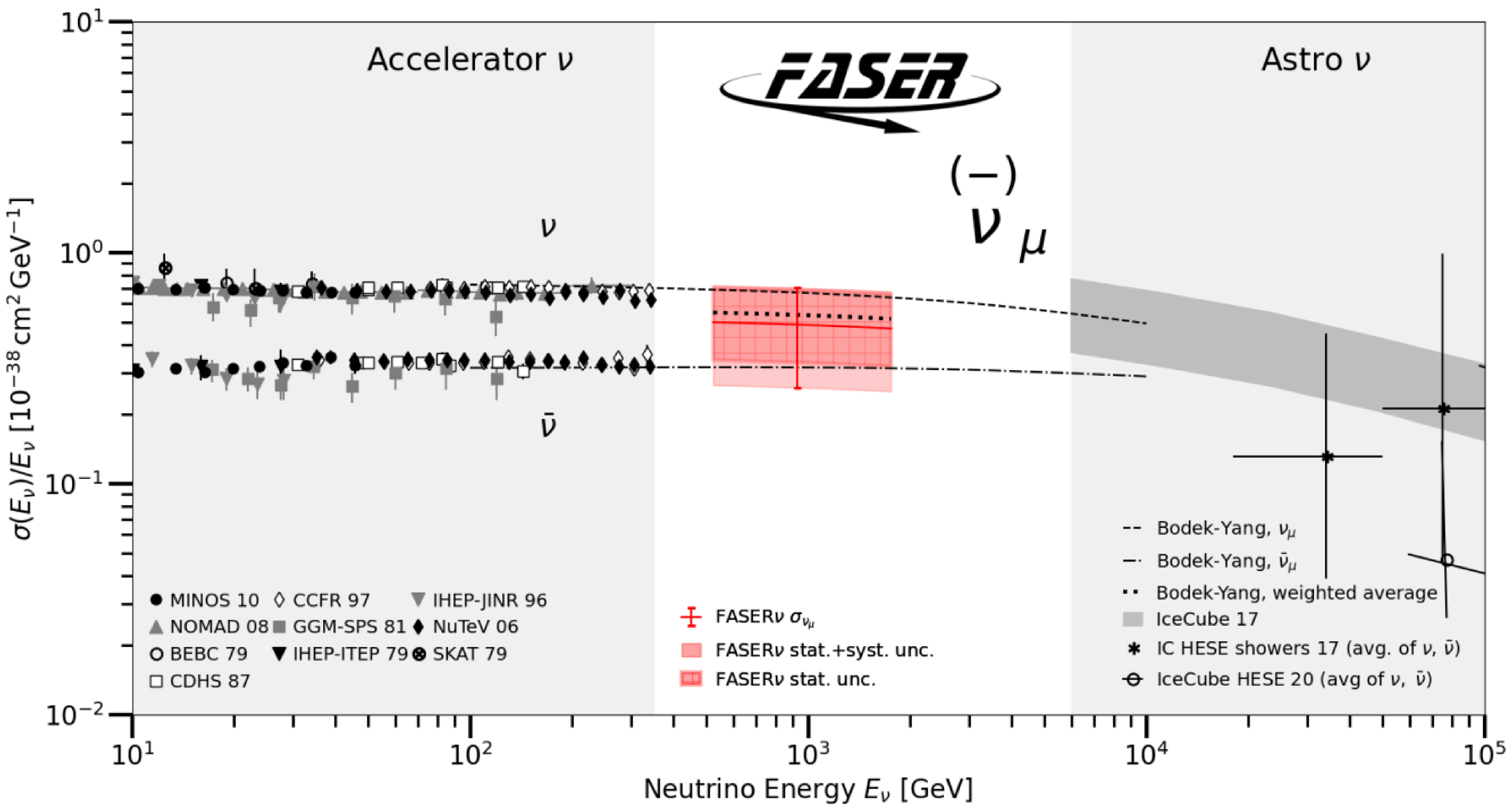


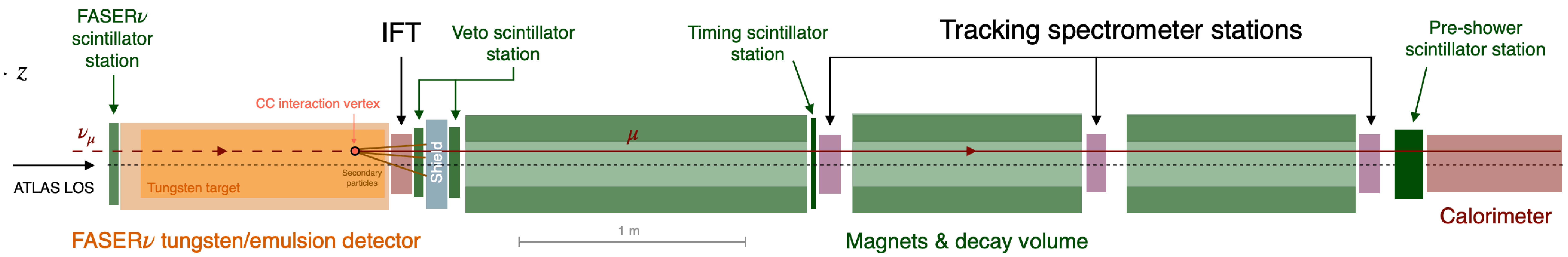
FASER: Neutrino Physics at the LHC

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

Cross section measurement







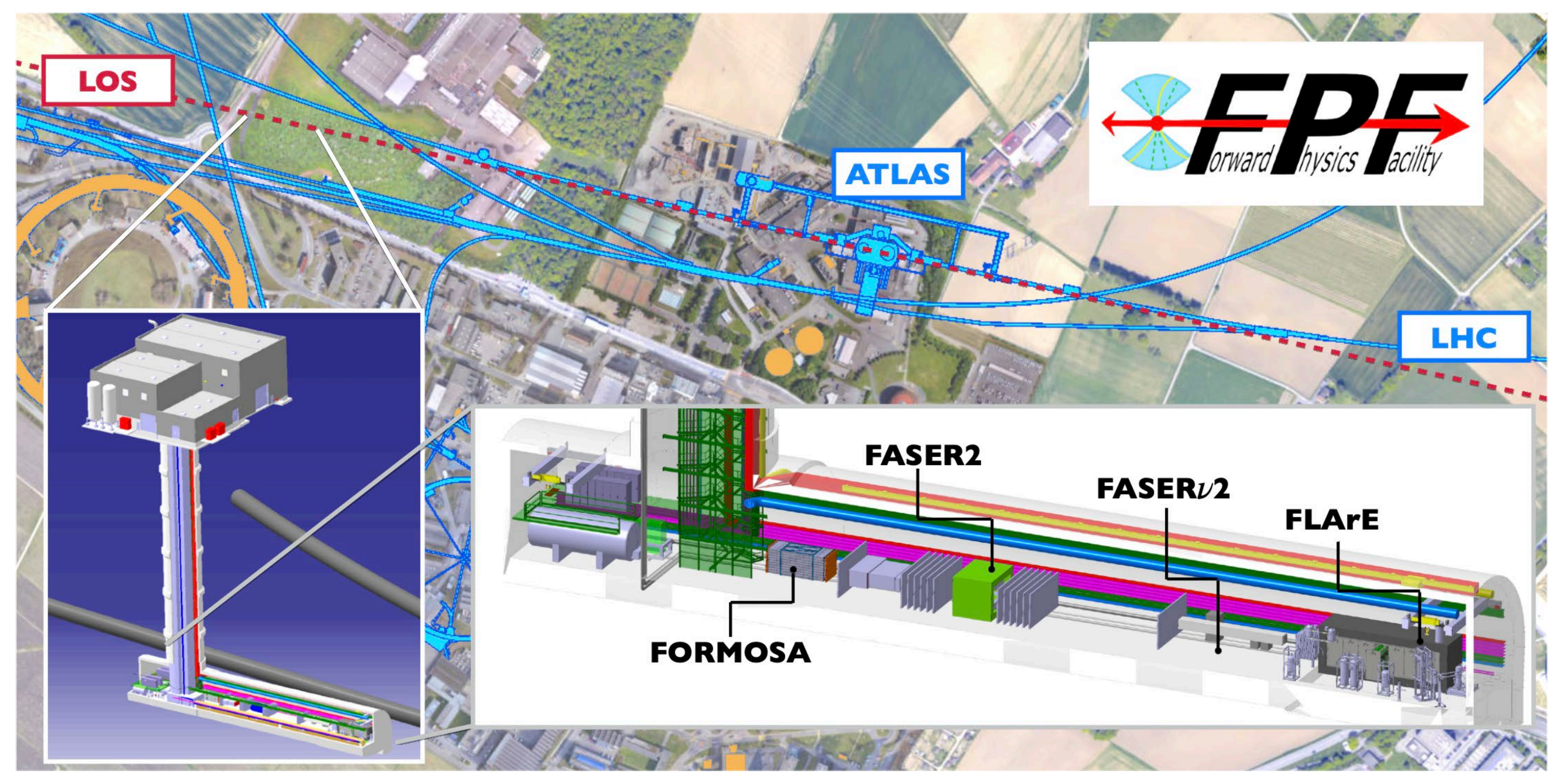
FASER Collab. 2023

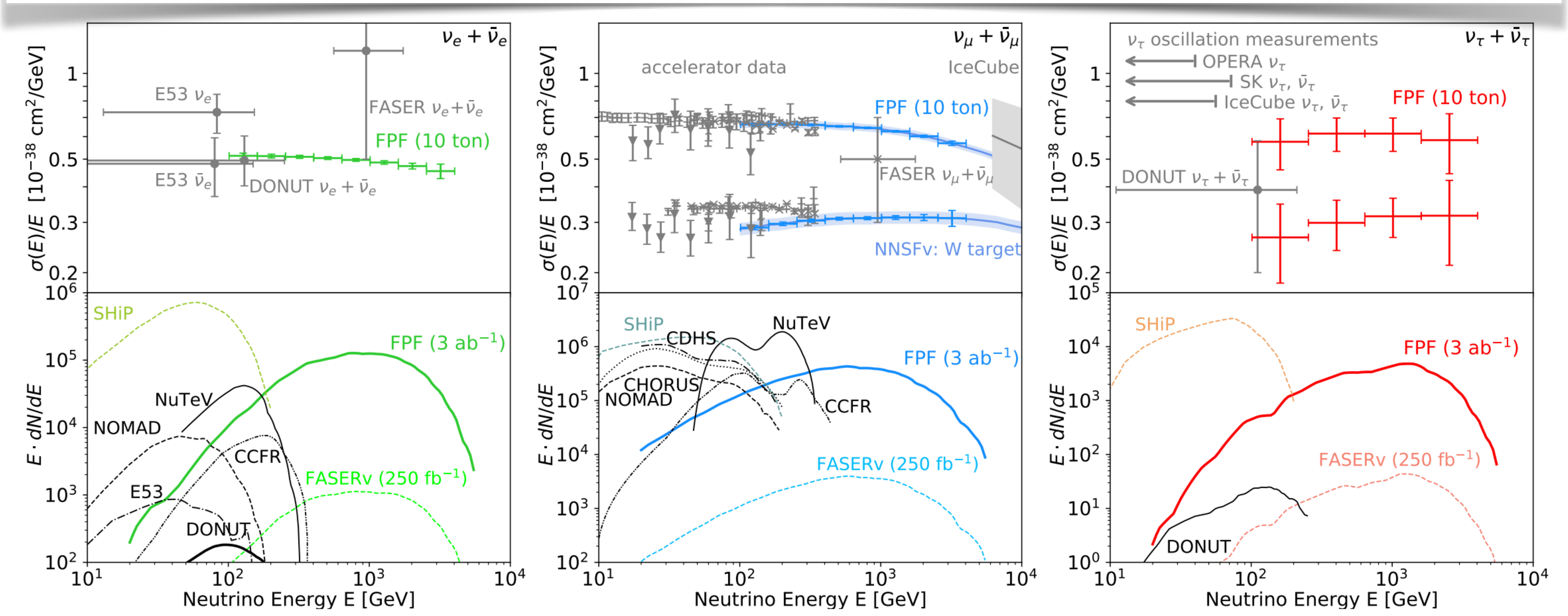
FASER Collab. 2024

The Path Forward

- The Forward Physics Facility (FPF) is a proposed cavern ~700m from the ATLAS IP
- Would house four new experiments during the HL-LHC, significantly expanding the forward neutrino program at the LHC

FPF 2024

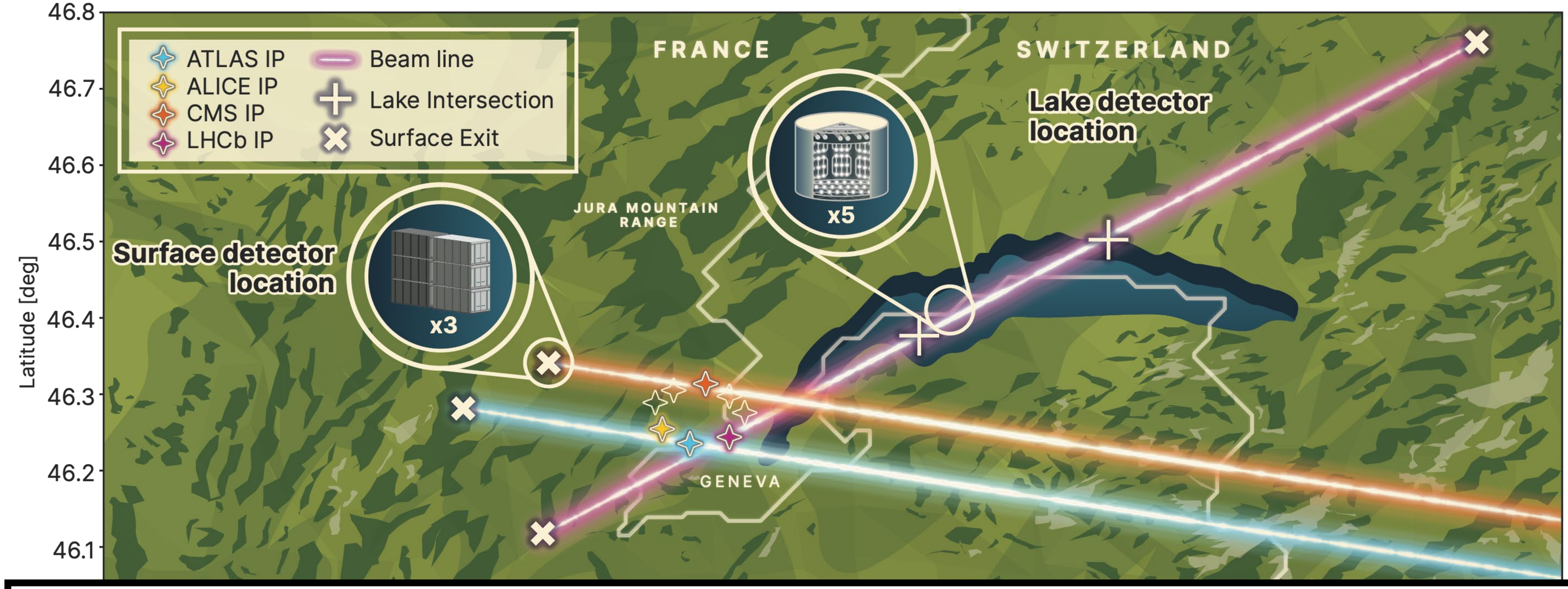




Are there more forward neutrino options for the HL-LHC?

Let’s take a closer look at the neutrino beams - where do they come out?

LHC's Neutrino beams:
They emerge at multiple locations and one passes through Lake Geneva



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

[arXiv:2501.08278](https://arxiv.org/abs/2501.08278)

Lake- and Surface-Based Detectors for Forward Neutrino Physics

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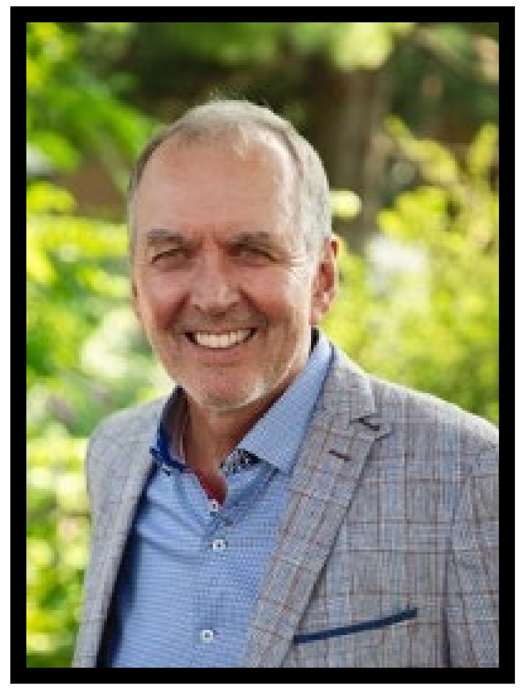
[3] *Department of Physics and Astronomy, University College London, London, WC1E 6BT, UK*

(Dated: January 14, 2025)

J. Thomas



A. Karle

C. Argüelles

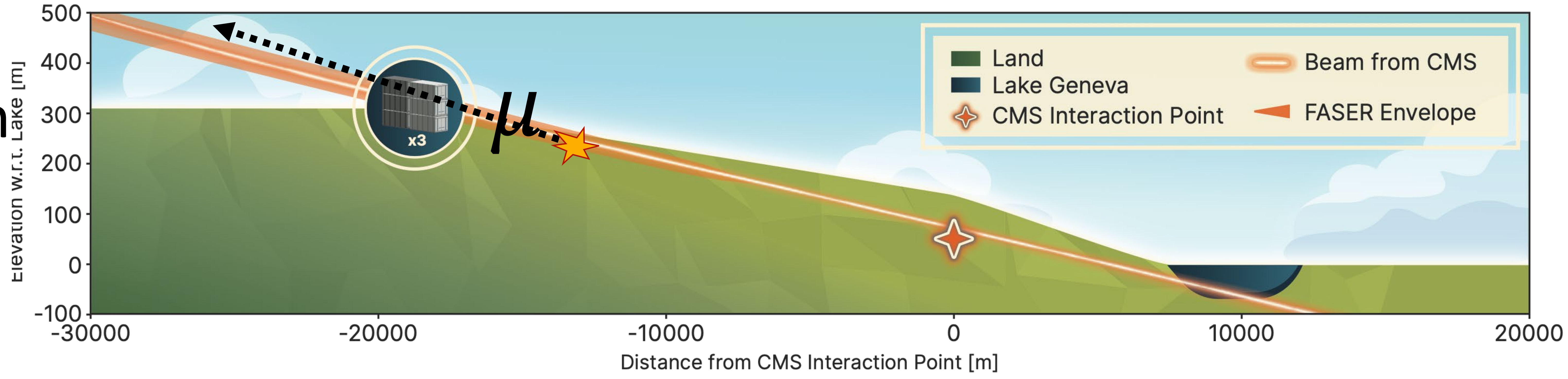
T. Yuan

Distance from CMS Interaction Point [m]

Distance from LHCb Interaction Point [m]

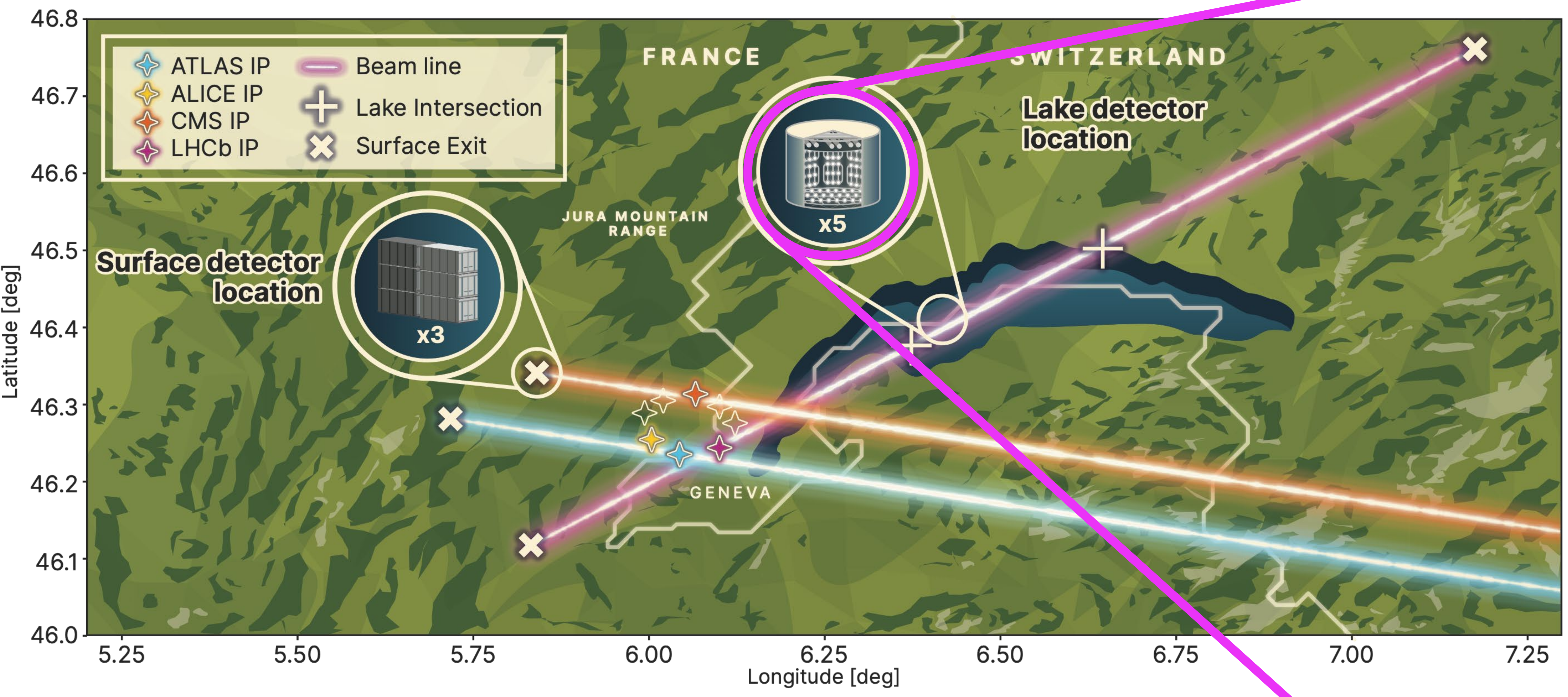
SINE: Surface-based Integrated Neutrino Experiment

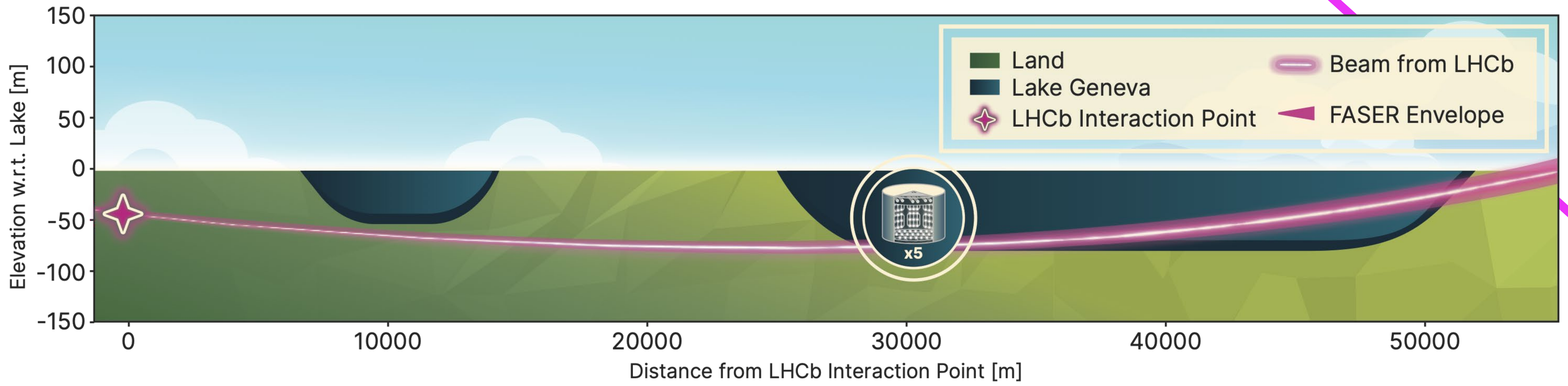
Signal definition: up-going muons from neutrino interactions in bedrock

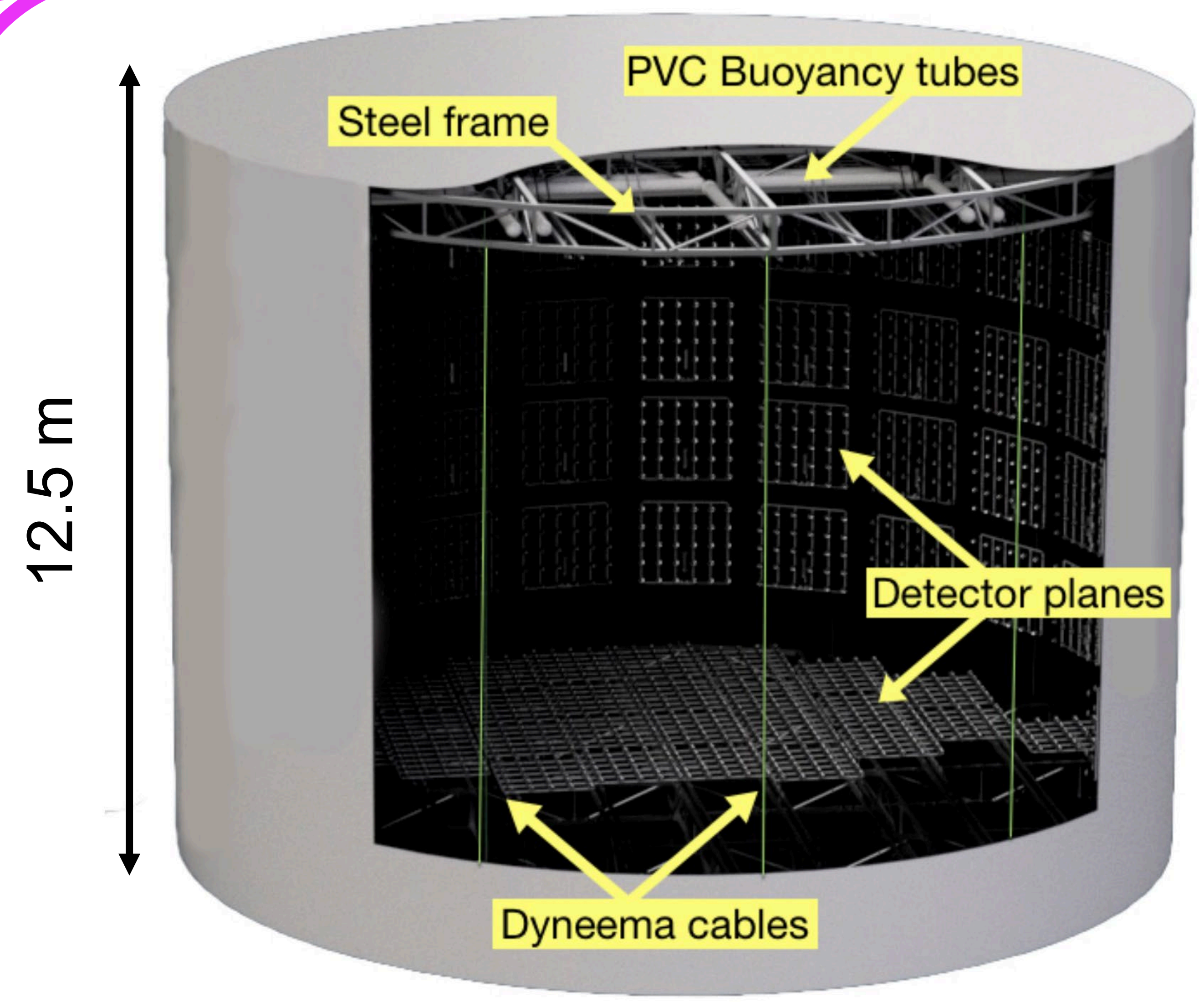


NK+ 2025

UNDINE: UNDerwater Integrated Neutrino Experiment







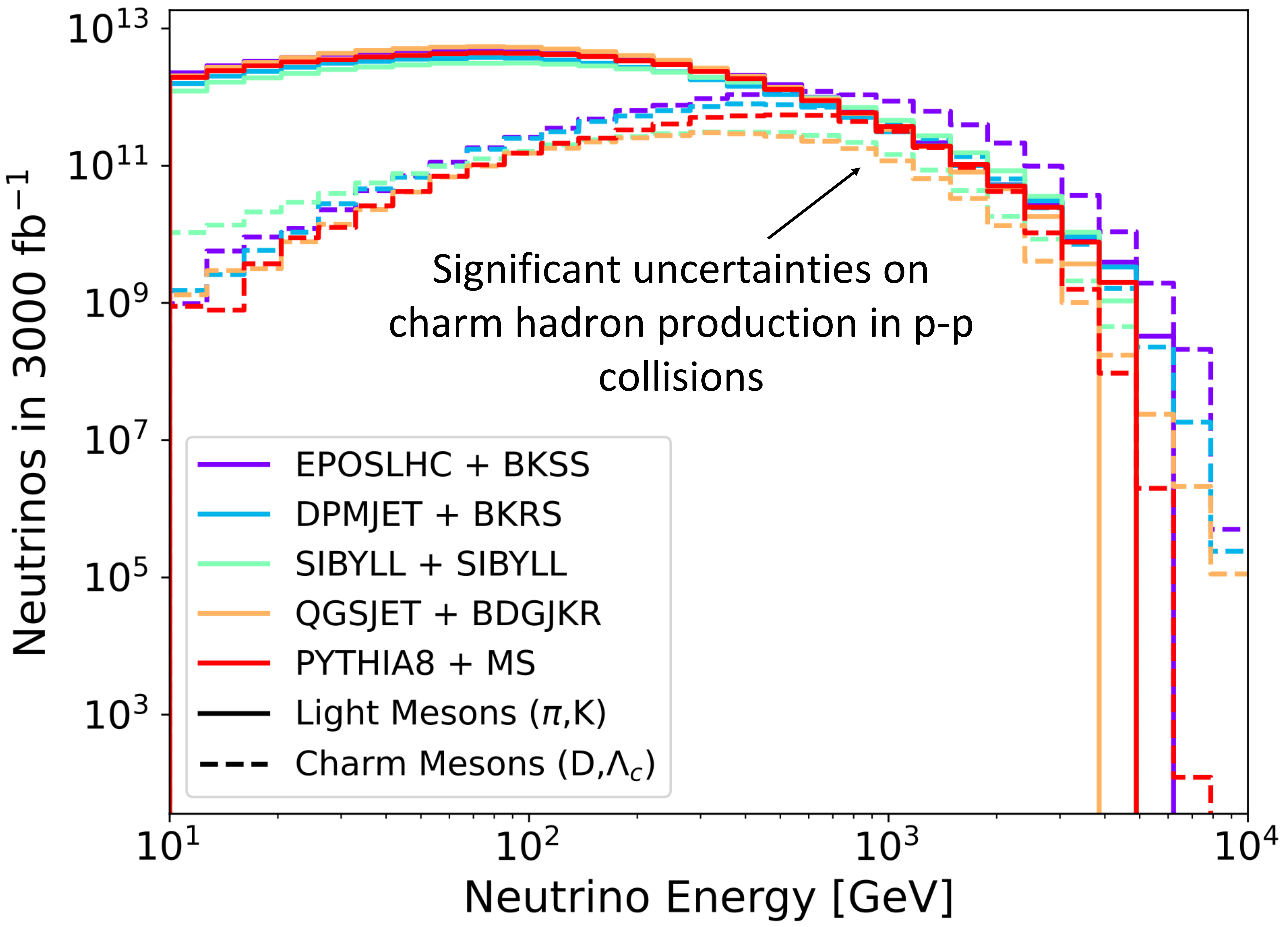
D. Delgado

CHIPS Collab. 2024

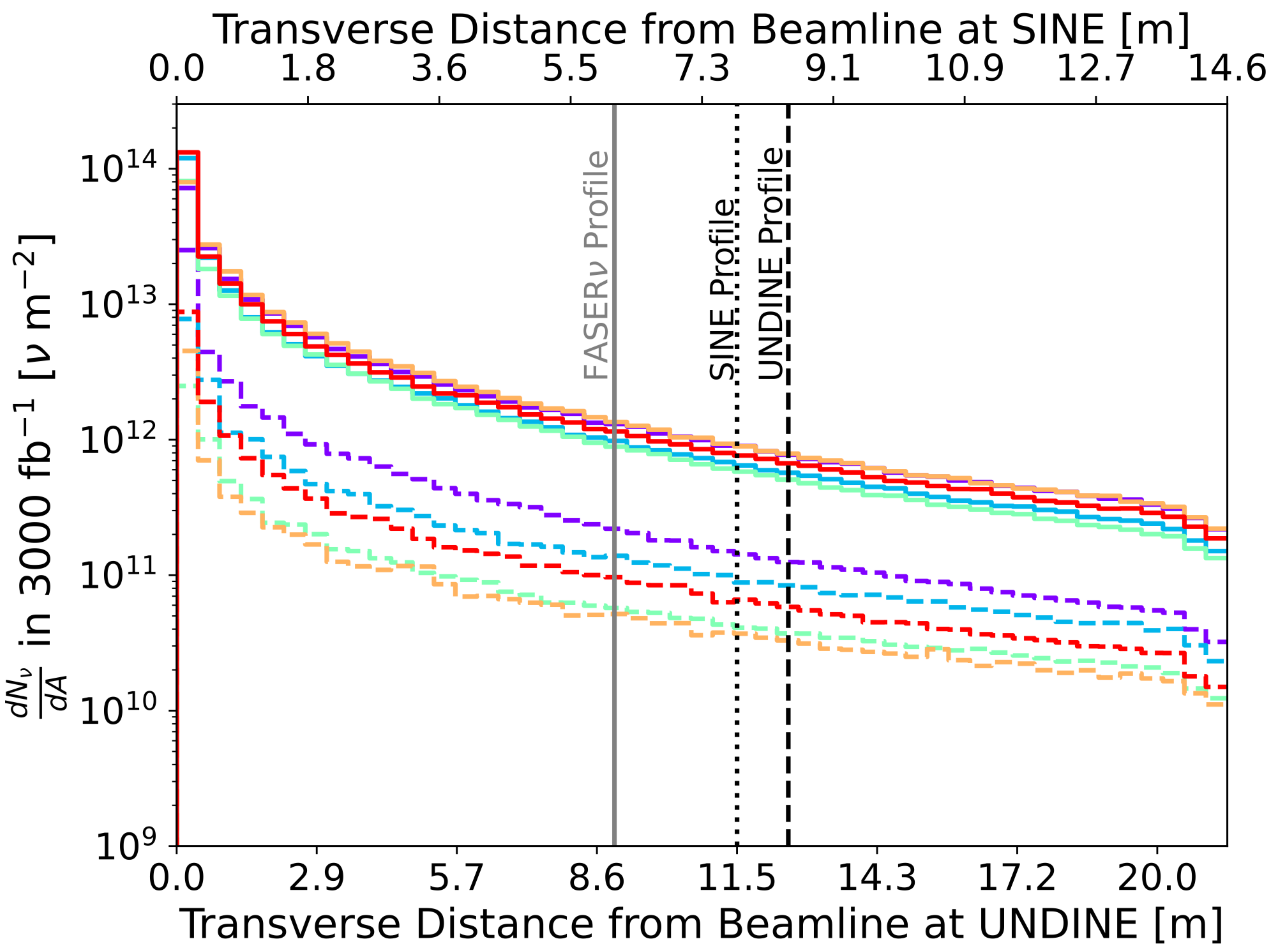
NK+ 2025

LHC Forward Neutrino Flux

We use github.com/makelat/forward-nu-flux-fit for simulated forward neutrino flux samples



(18 km from interaction point)



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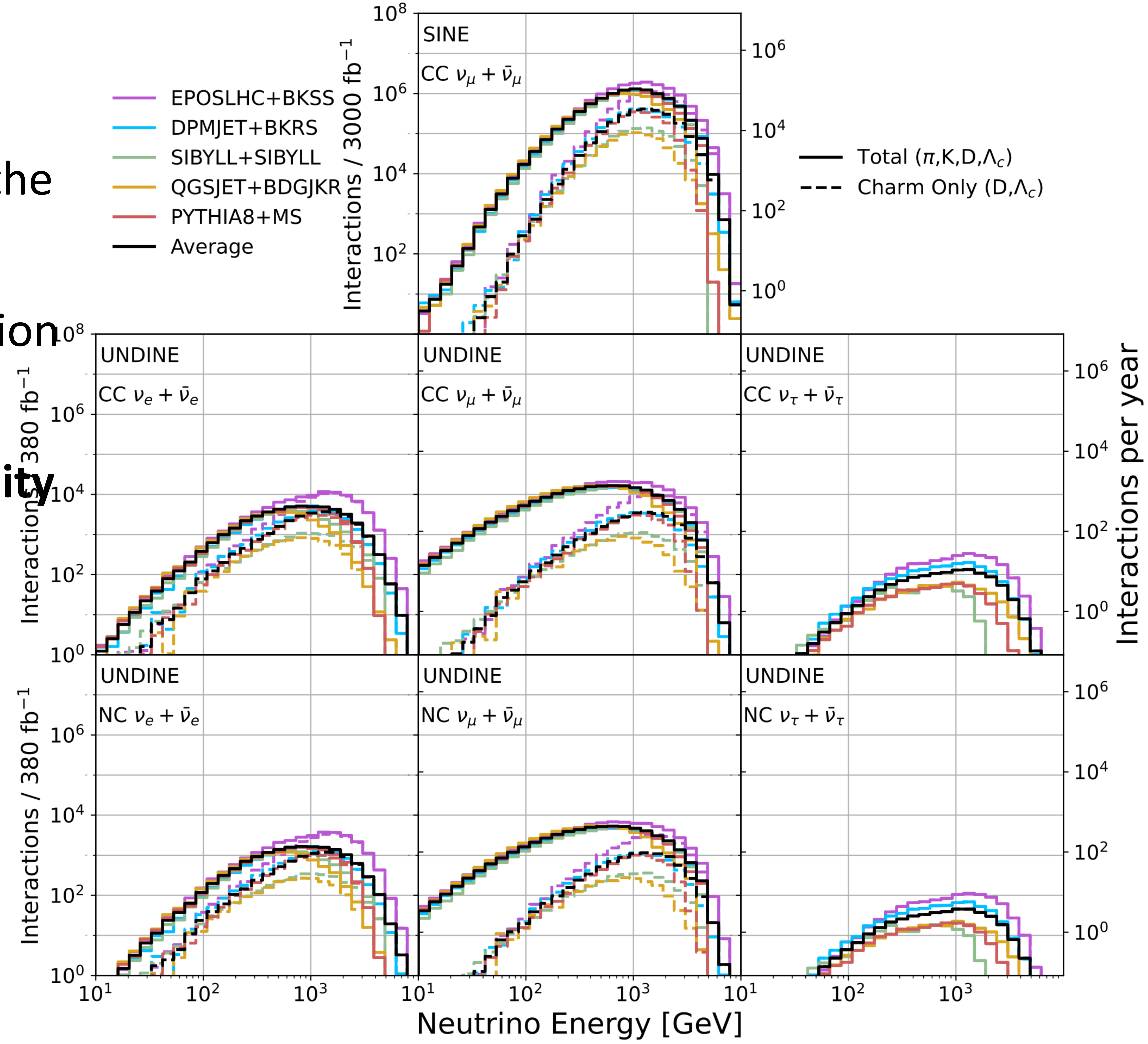
Event Rates

- We simulate DIS neutrino interactions along the LHCb and CMS beam using SIREN [1]
- Cherenkov detectors enable flavor identification in UNDINE

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

Dataset	**Total**	$\pi,\ K$	$D,\ \Lambda_c$
SINE (CC $\nu_\mu + \bar{\nu}_\mu$)	$10^{6.98}$	$10^{6.84}$	$10^{6.40}$
UNDINE (CC $\nu_e + \bar{\nu}_e$)	$10^{4.68}$	$10^{4.32}$	$10^{4.42}$
UNDINE (CC $\nu_\mu + \bar{\nu}_\mu$)	$10^{5.27}$	$10^{5.20}$	$10^{4.41}$
UNDINE (CC $\nu_\tau + \bar{\nu}_\tau$)	$10^{3.07}$	0	$10^{3.07}$
UNDINE (NC $\nu_\alpha + \bar{\nu}_\alpha$)	$10^{4.87}$	$10^{4.76}$	$10^{4.24}$



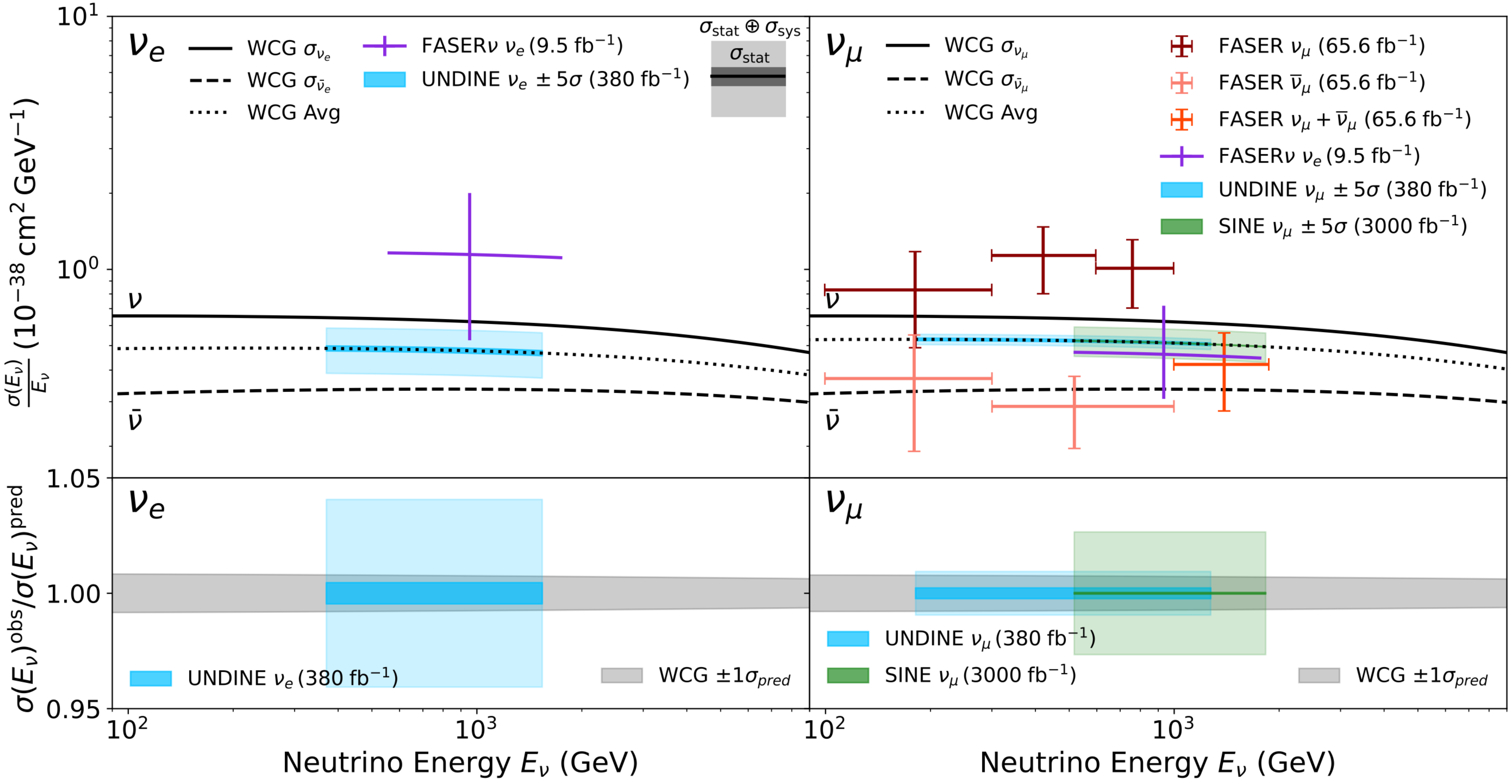
[1] A. Schneider, NK, A. Wen. 2024

NK+ 2025

What can we do with ~a million collider neutrinos?

Neutrino Cross Sections

- FASER recently reported first measurements of the total neutrino cross section at TeV energies [1,2]
- SINE and UNDINE can make complimentary measurements
- **Few-percent-level uncertainties with full dataset**
  - Comparable to theoretical uncertainty [3]



[1] FASER Collab. 2024 [2] FASER Collab. 2024 [3] Weigel+ 2024

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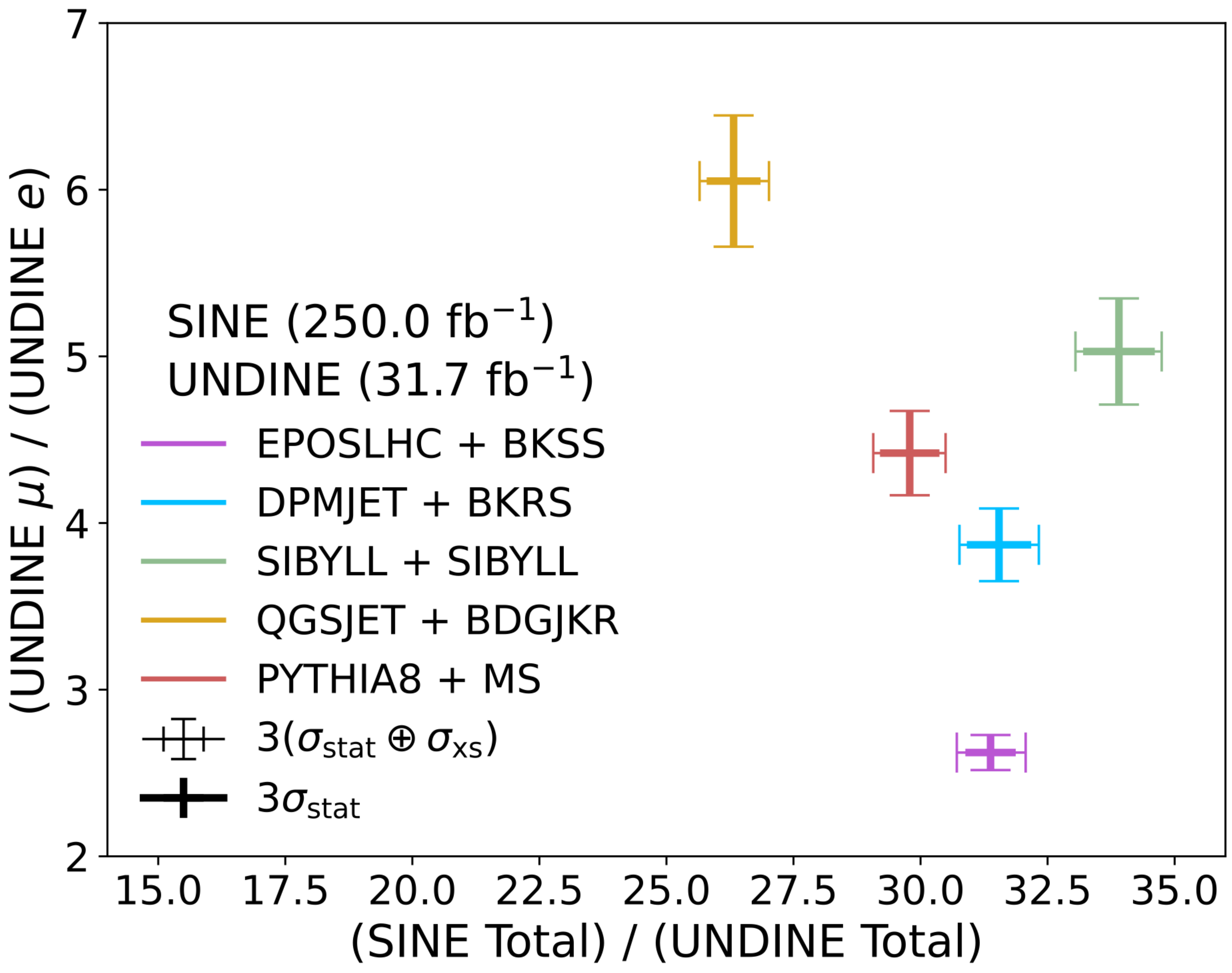
Forward Charm Production in p-p Collisions

- 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]**



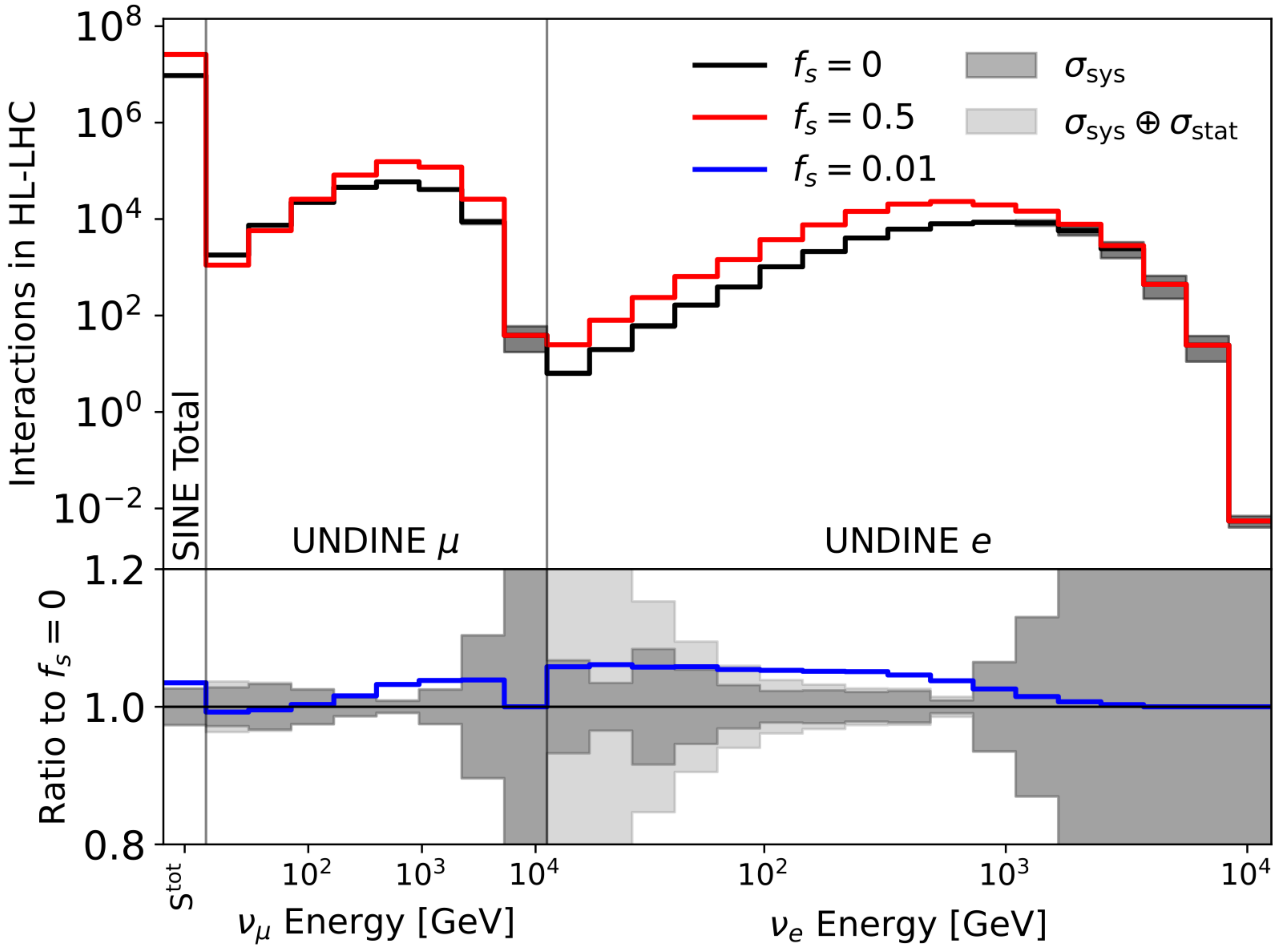
NK+ 2025

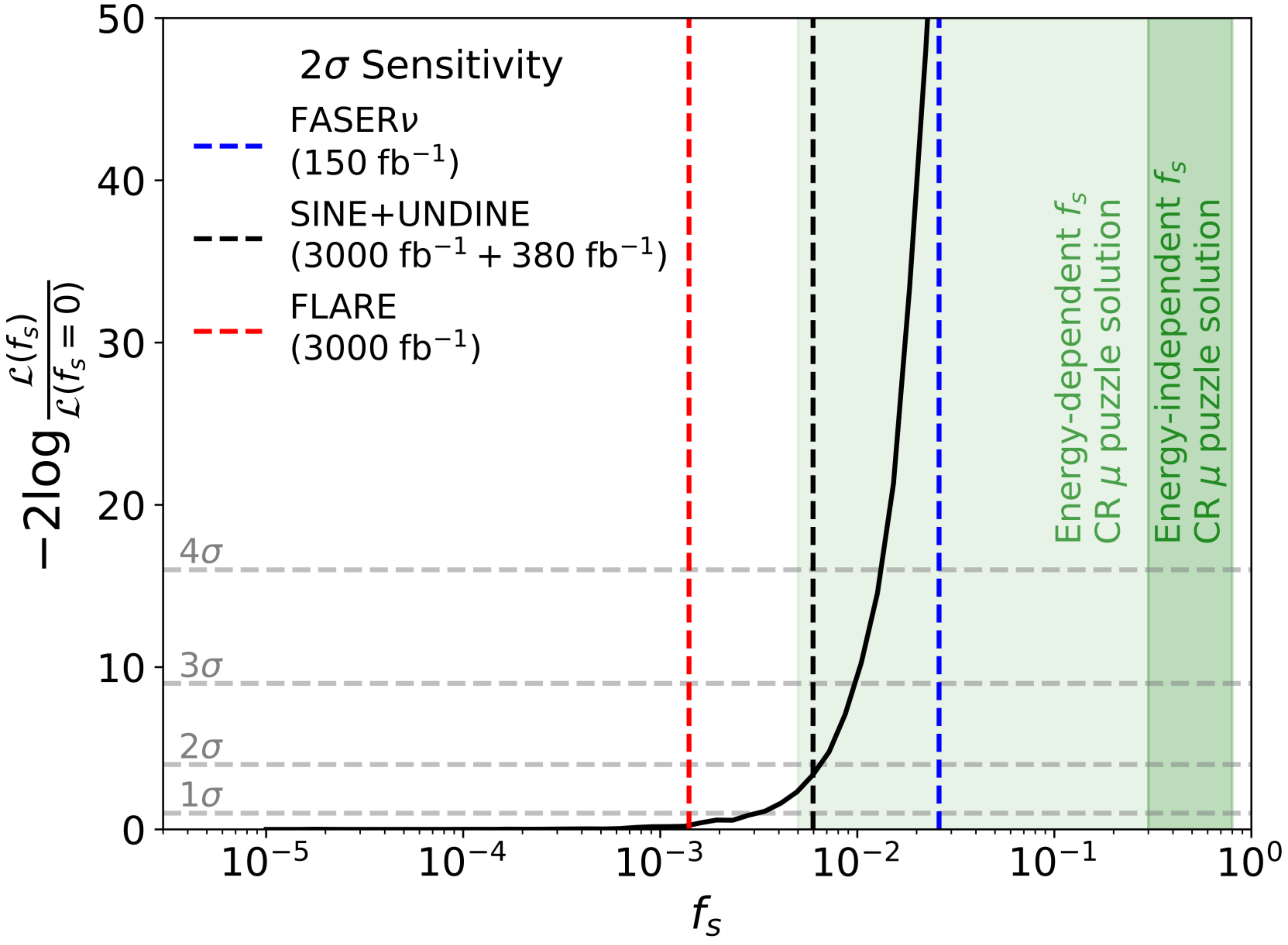
[1] Maciula+ 2022 [2] Jeong+ 2023

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 [1,2]
- SINE and UNDINE have complementary sensitivity to future FPF experiments [3]





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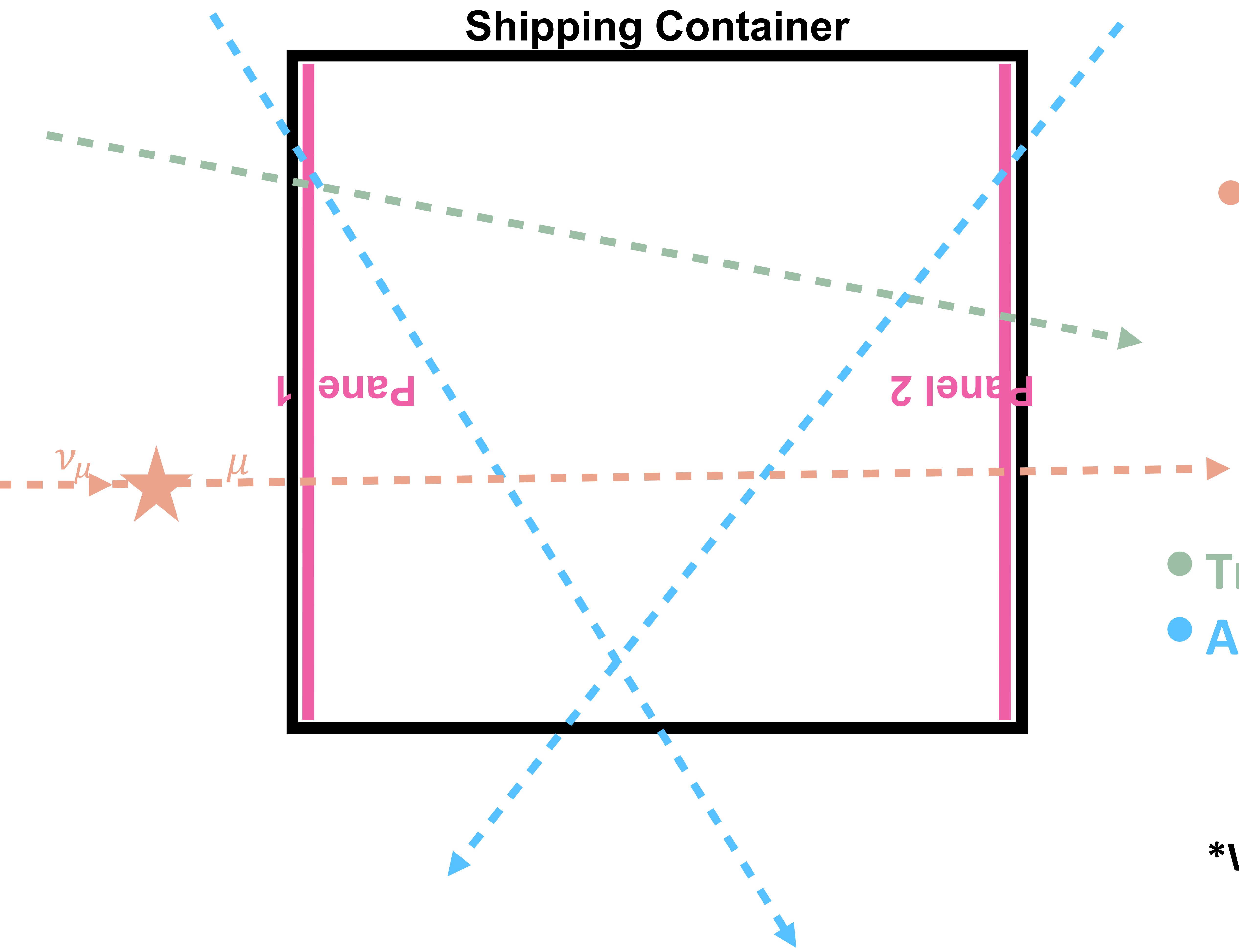
Can we separate the neutrino signal from cosmic backgrounds in SINE?

SINE Cosmic Backgrounds



Signal

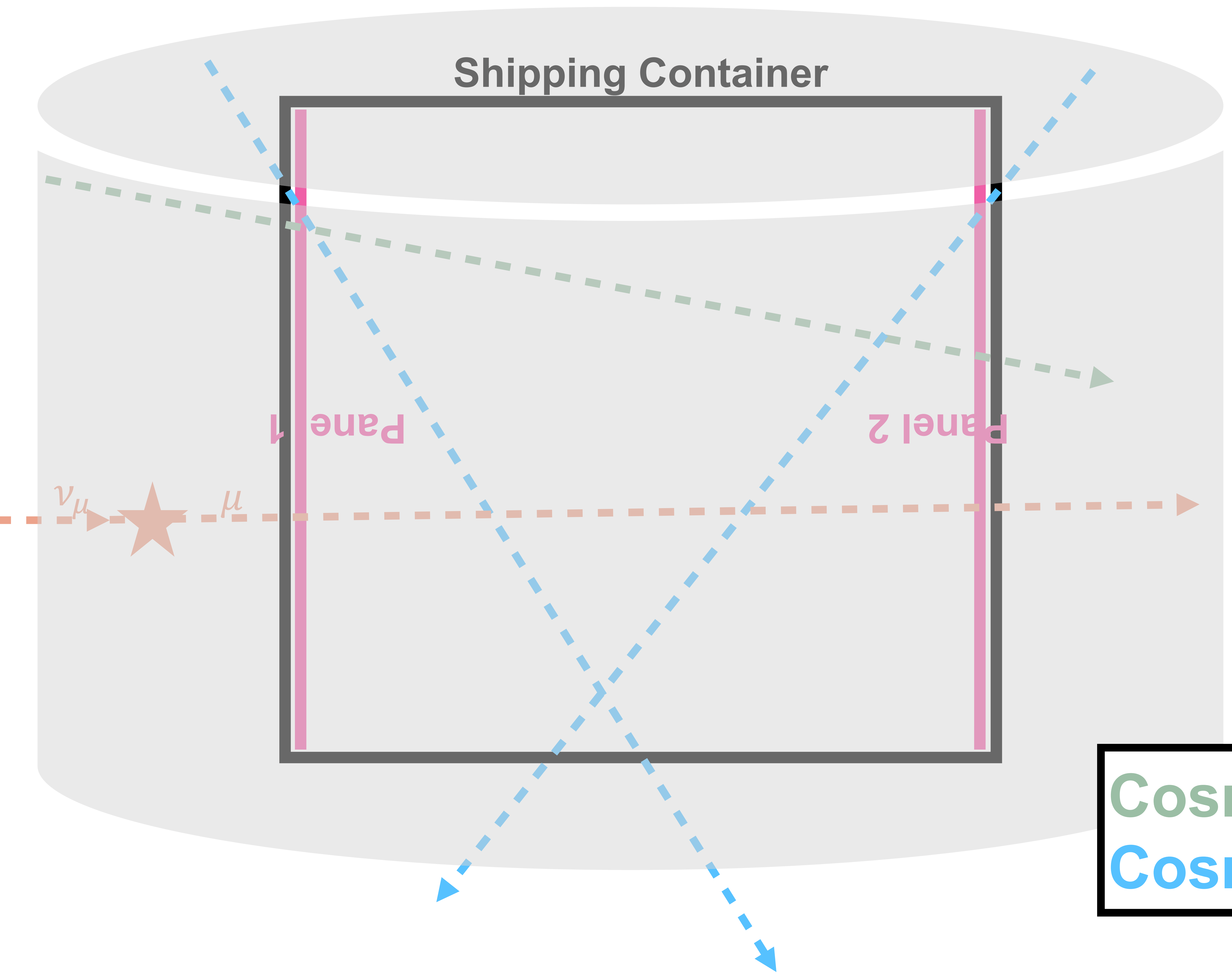
- True coincidence from a ν-induced muon
  ~11 mHz per surface detector during HL-LHC

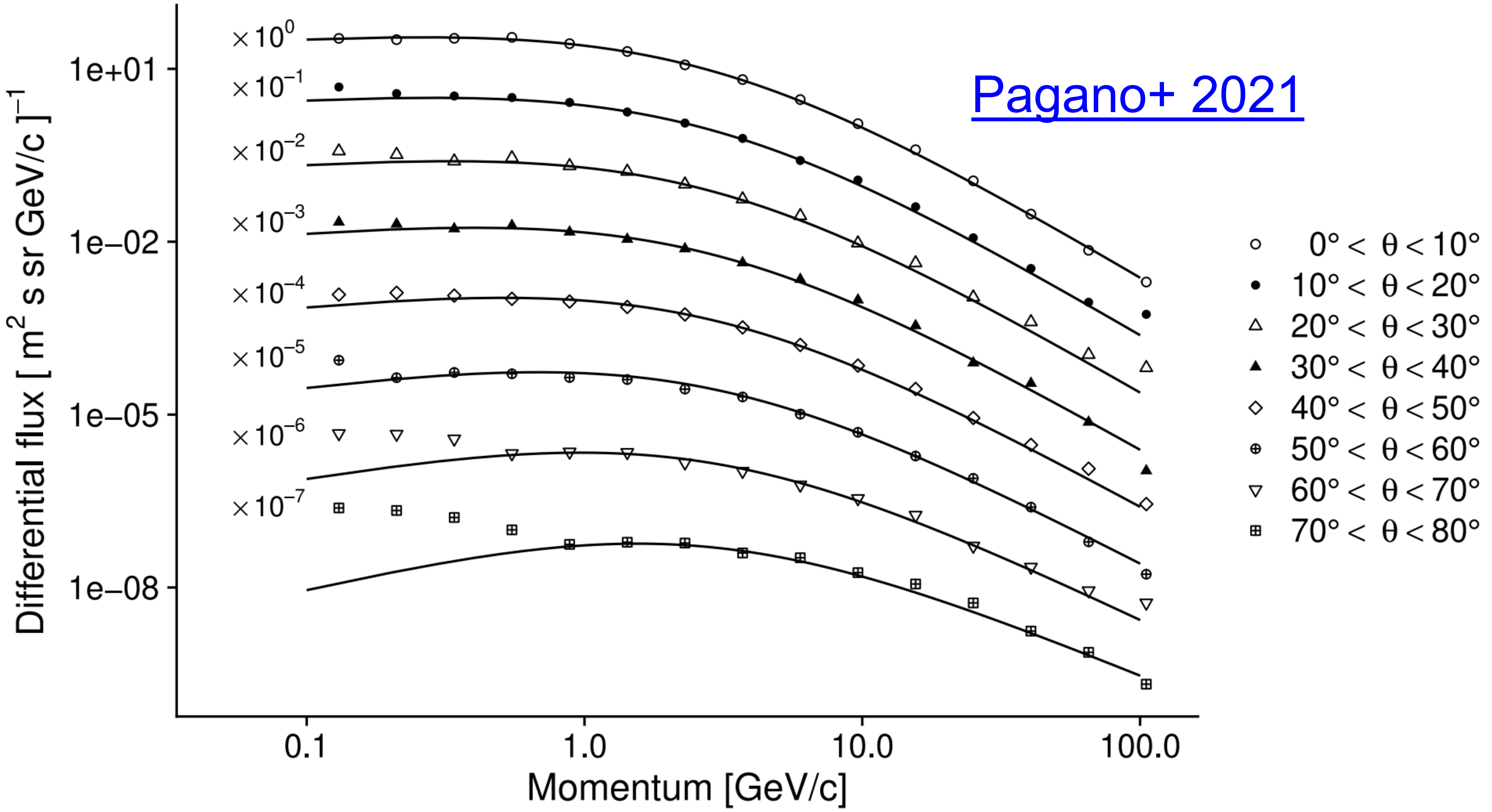
Background

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

*Water overburden reduces cosmic backgrounds in lake detector

SINE Cosmic Backgrounds



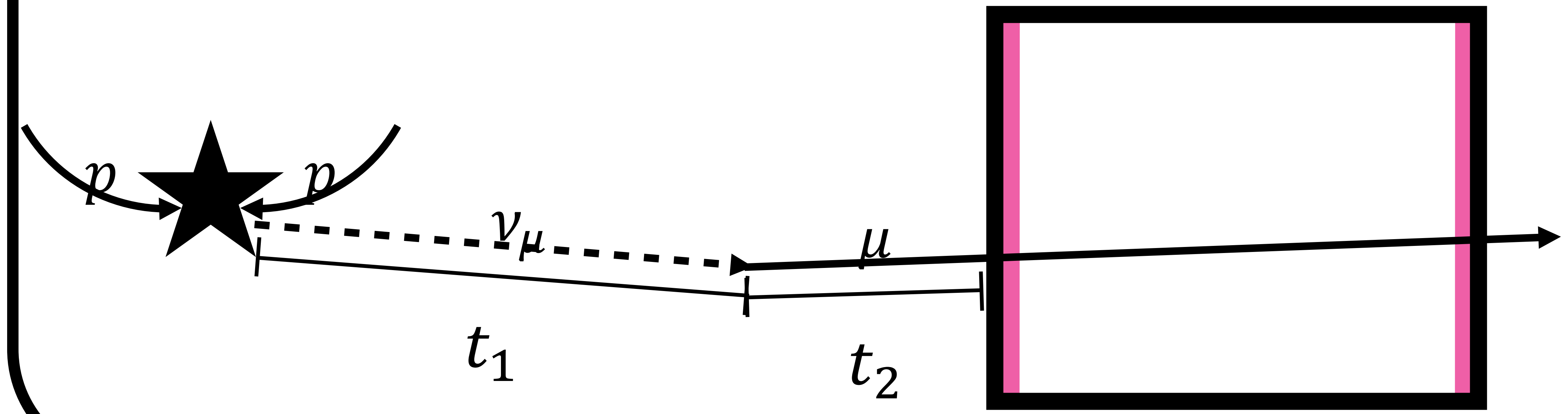


We use EcoMug to generate cosmic muons in a cylinder surrounding one of the shipping containers

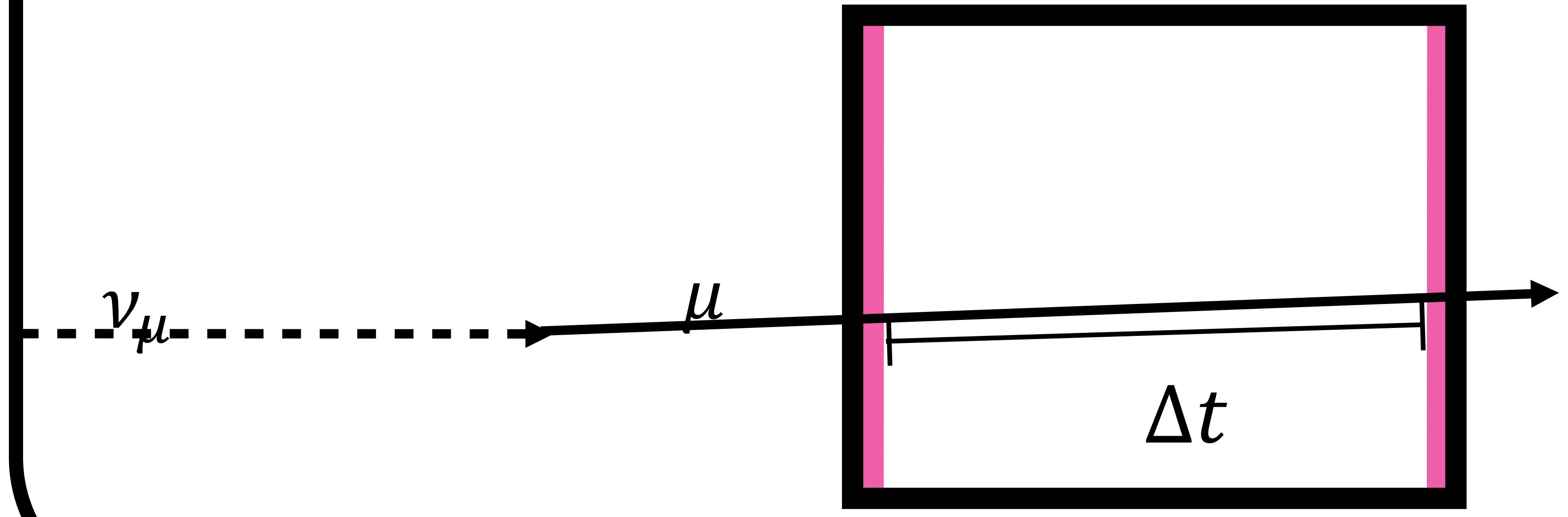
Cosmic muon true coincidence rate: 1.67 kHz
Cosmic muon single panel rate: 1.62 kHz

Four Strategies for Background Rejection

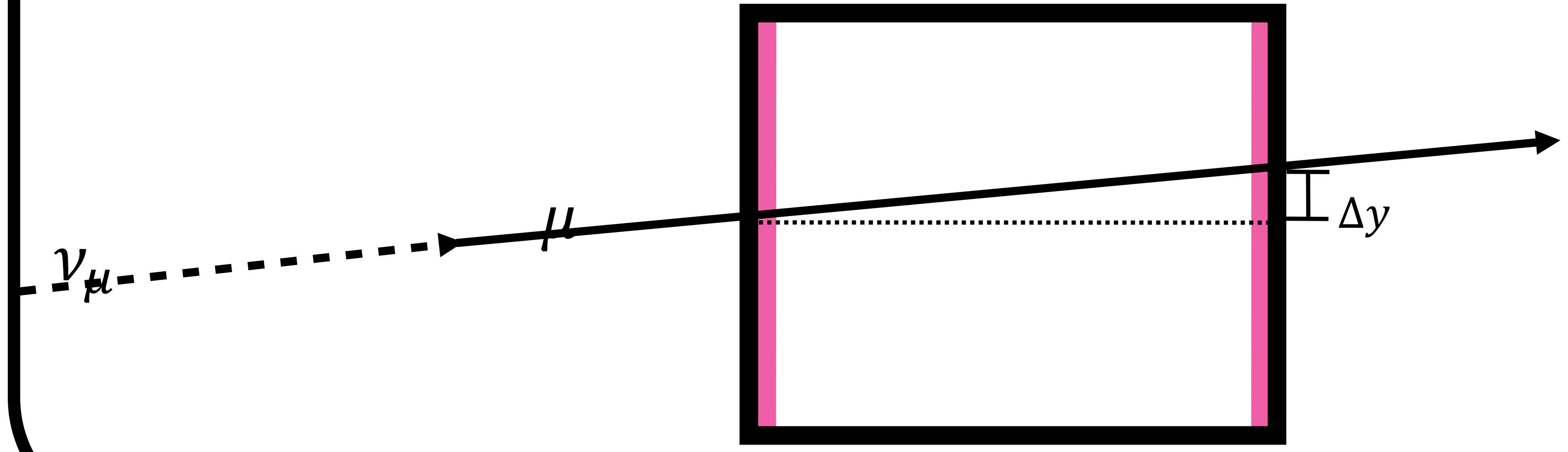
1. Timing with respect to proton collision



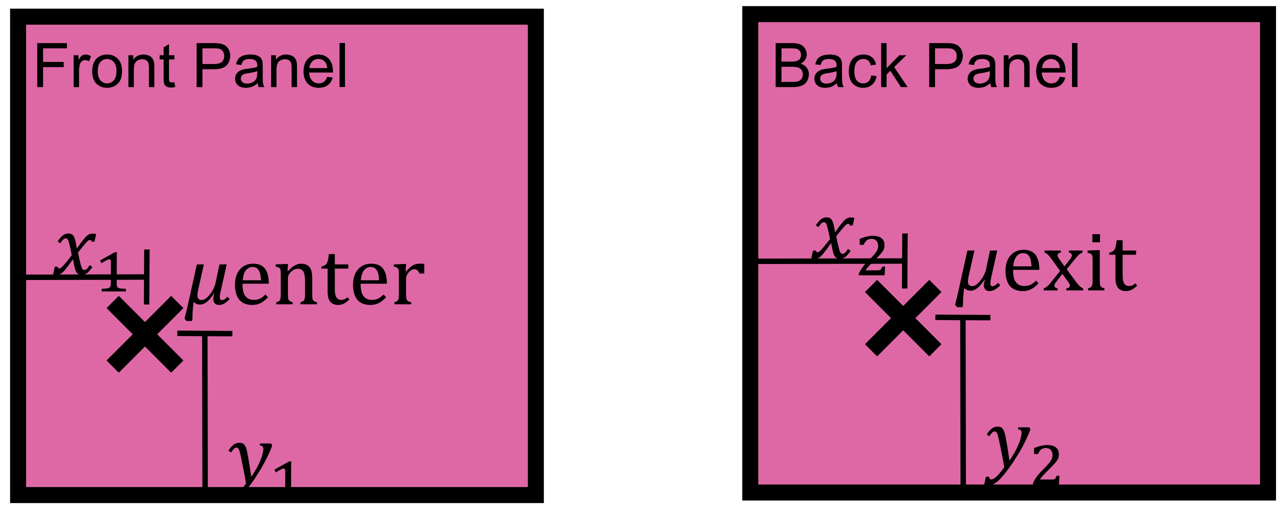
2. Time difference between scintillator panels



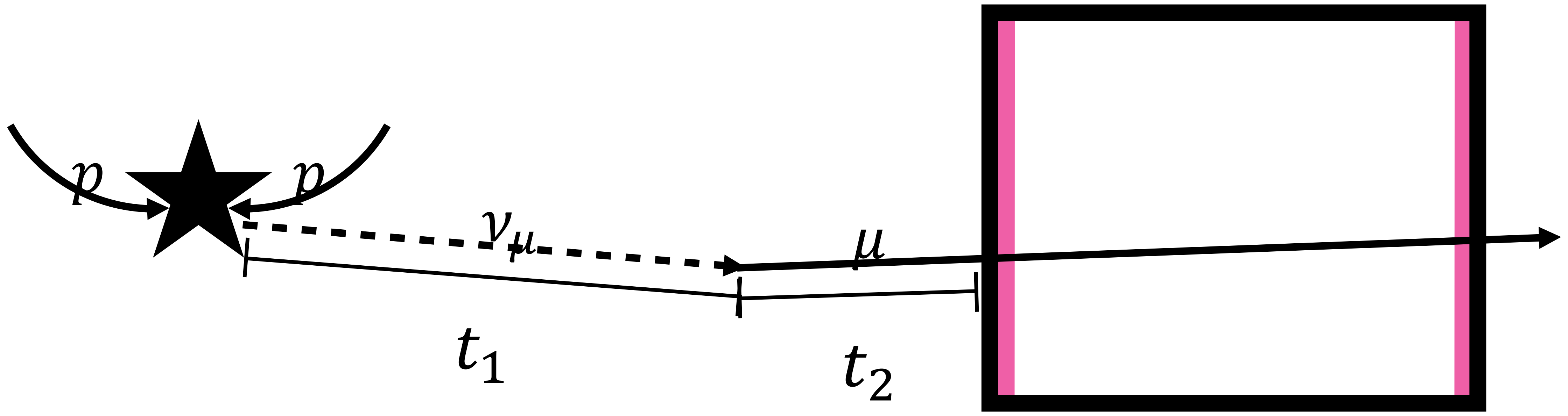
3a. Up-going spatial information



3b. Two-dimensional spatial information

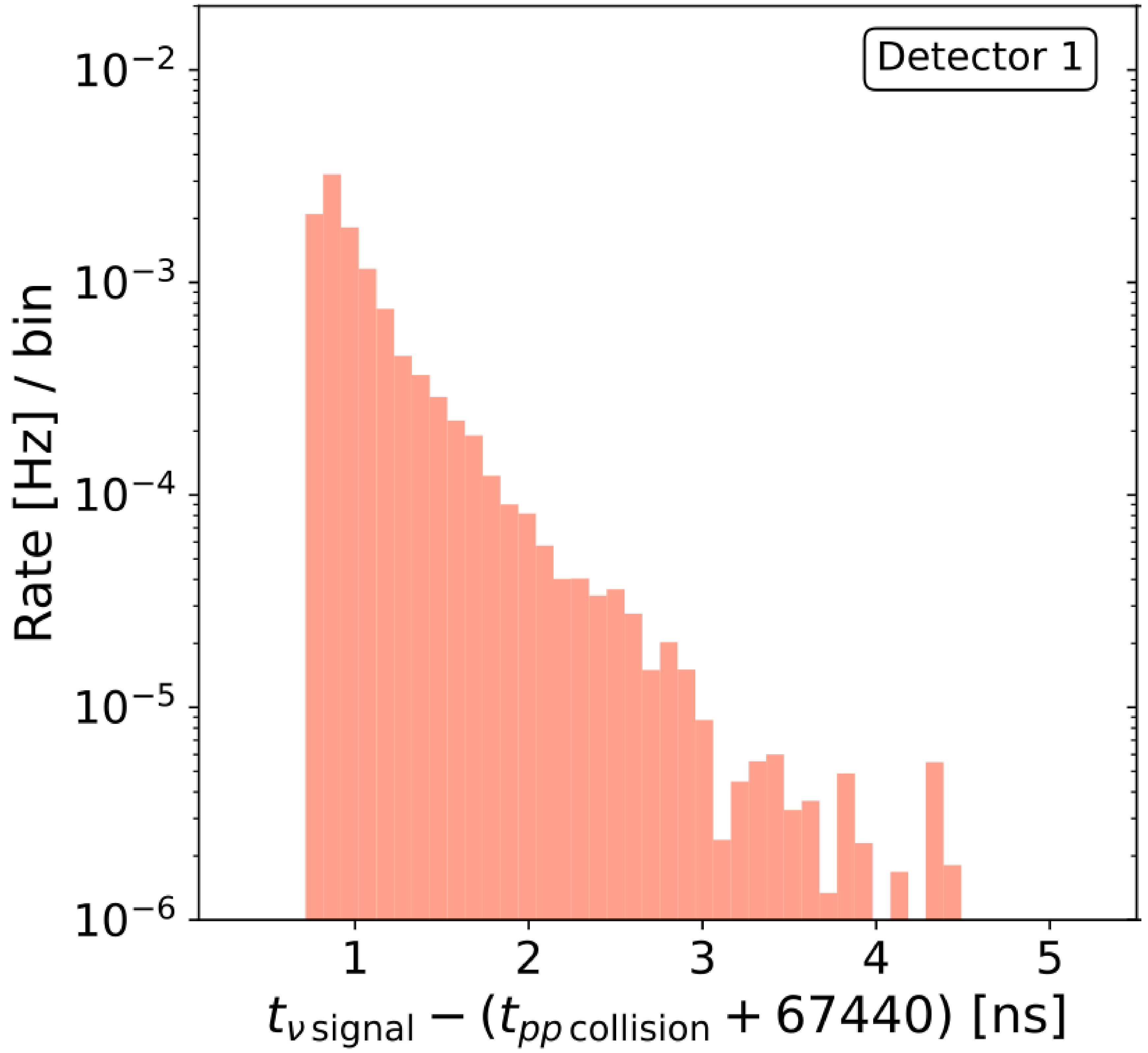


1. Timing with respect to proton collision



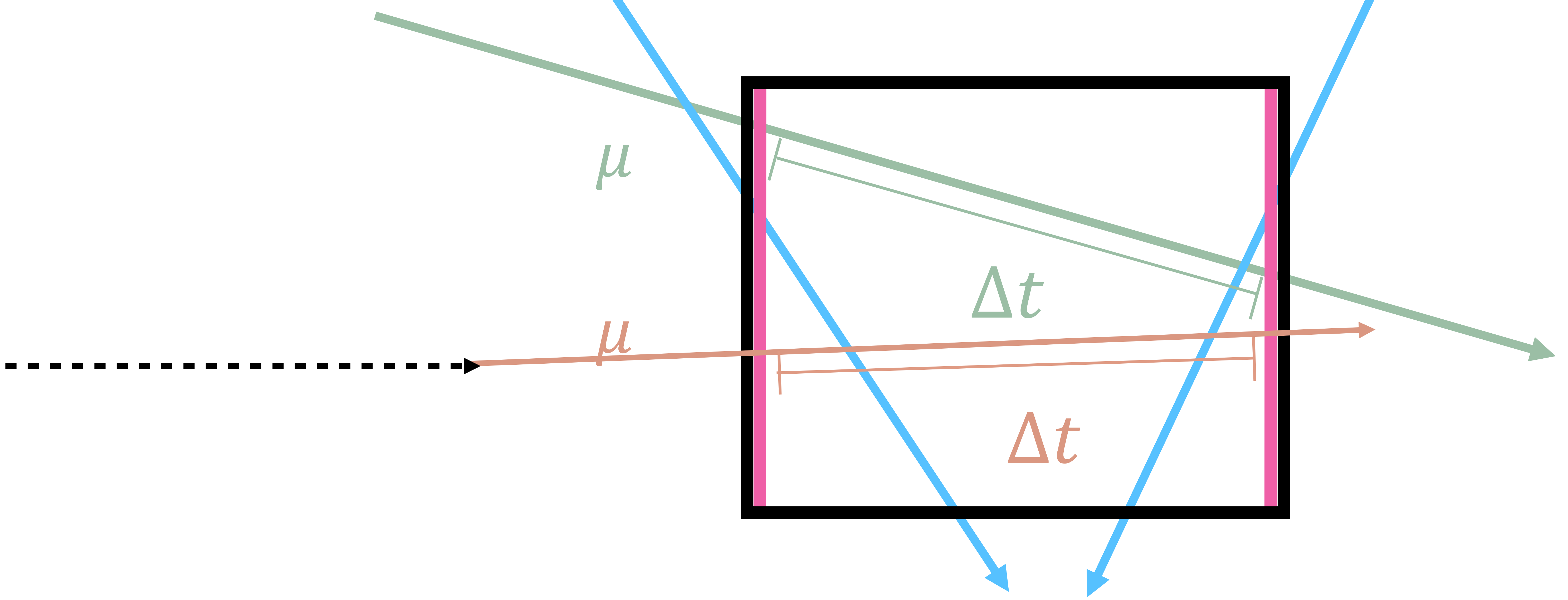
- The LHC has an inherent duty factor of 78.9%
- Within each 25 ns bunch, >99% of neutrino signal events arrive within a 2.5 ns window

Effective duty factor: 7.9%

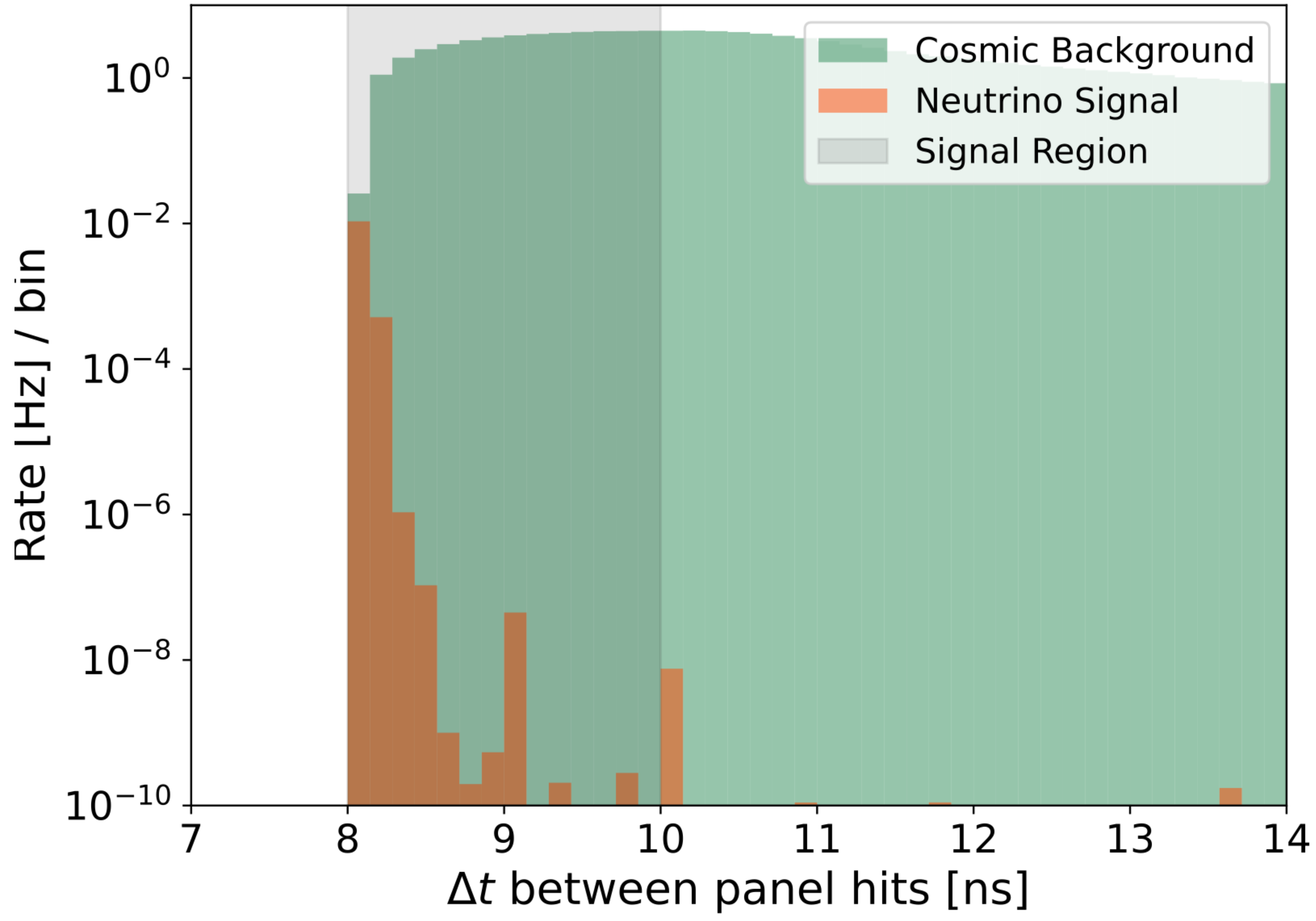


ν-induced muon rate: 11 mHz
Cosmic muon true coincidence rate: 132 Hz
Cosmic muon single panel rate: 128 Hz

2. Time difference between scintillator panels



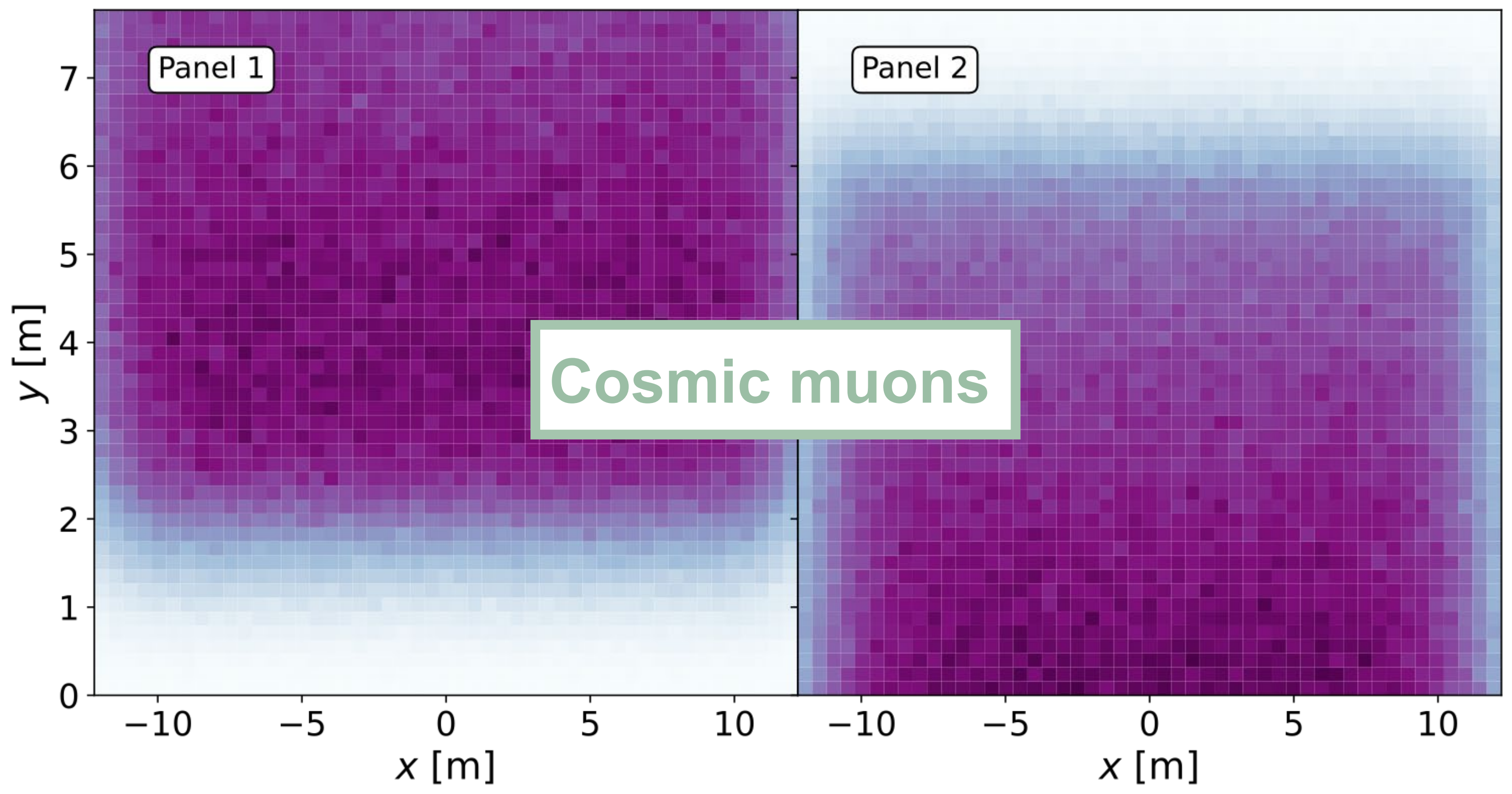
- Neutrino-induced muons tend to travel transverse to the scintillator plane, while cosmic muons pass through at larger angles on average
- **Strategy: only keep events any events for which $\mathbf{8 < \Delta t/ns < 10}$**

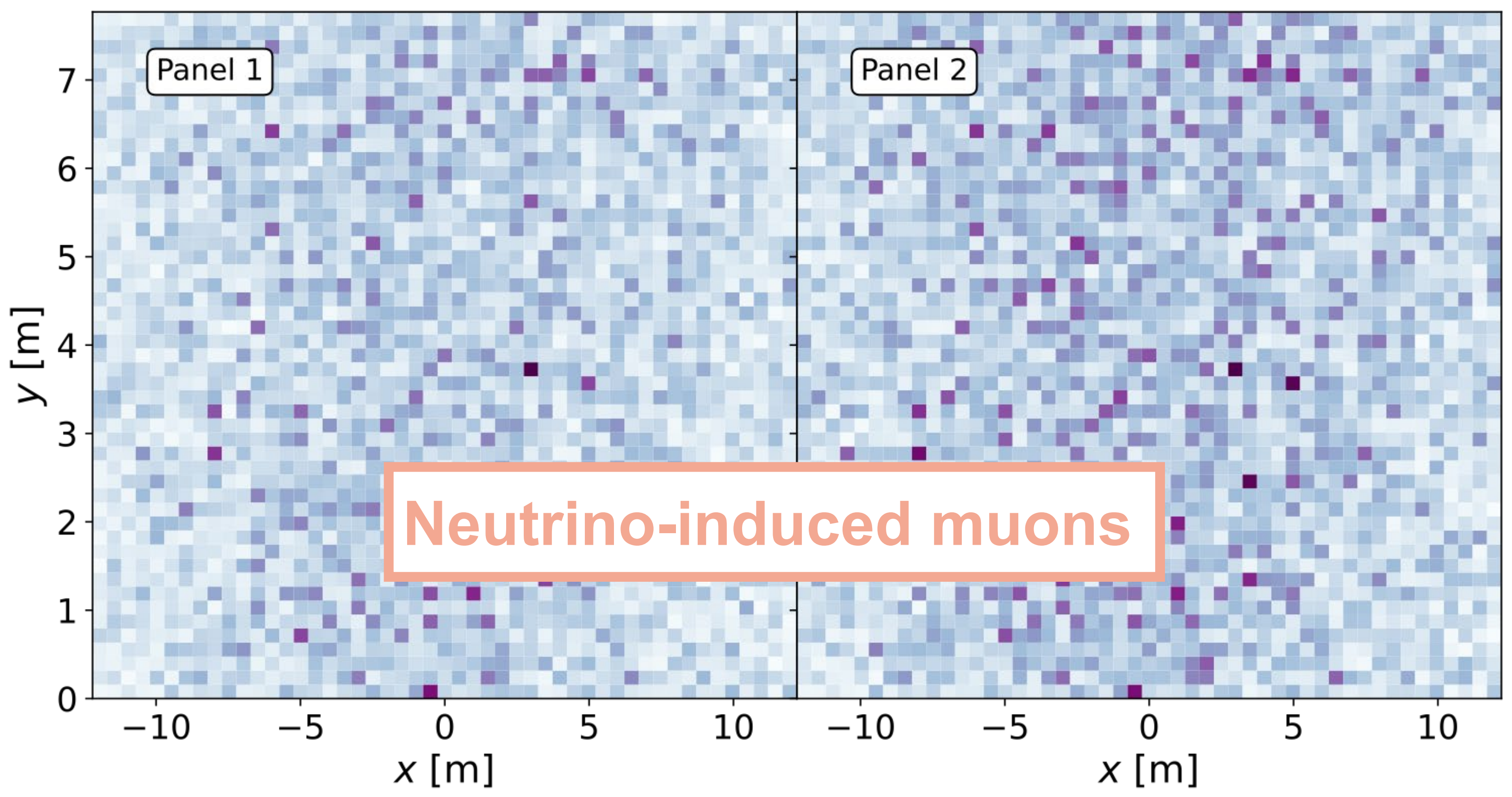


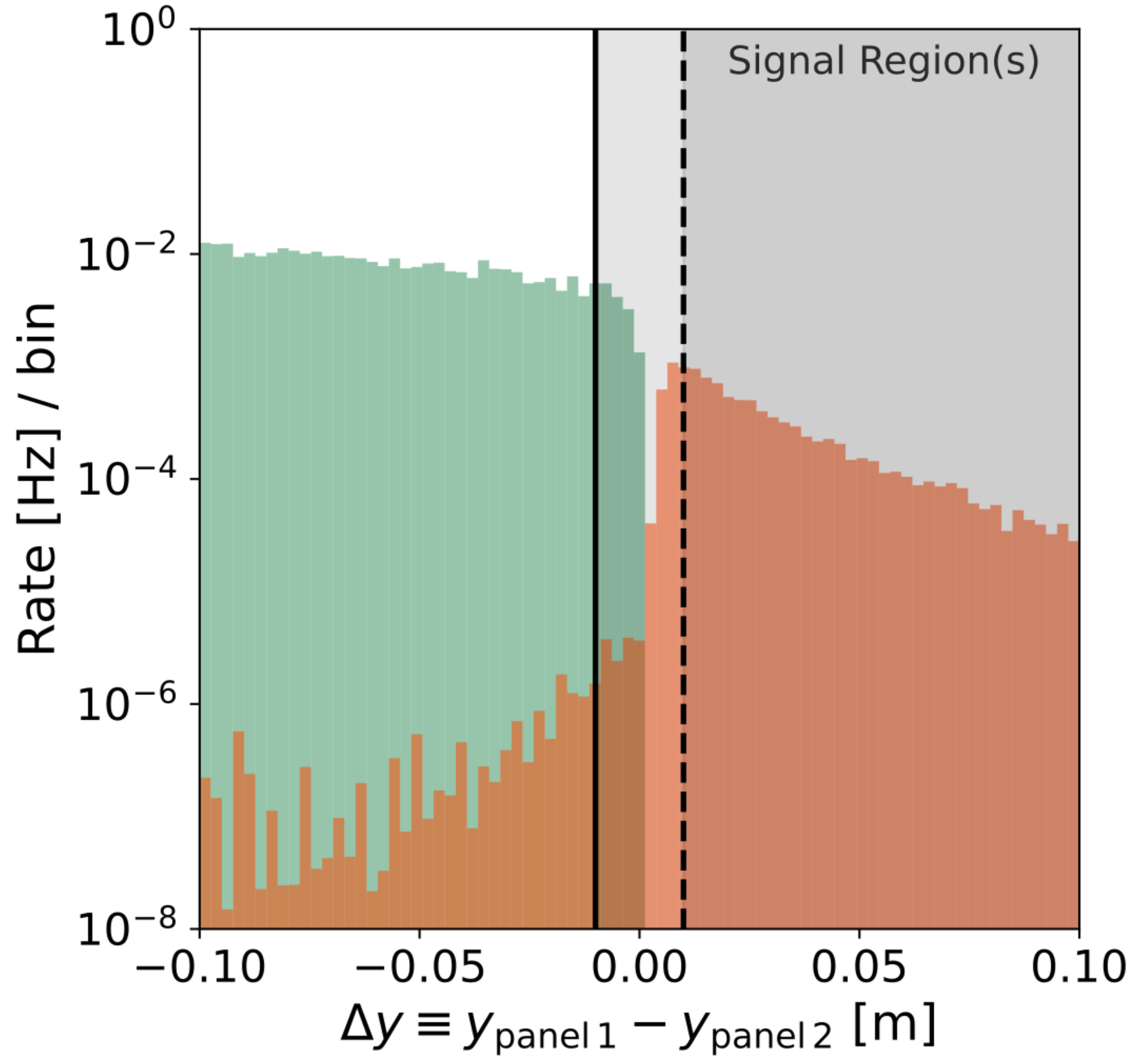
ν-induced muon rate: 11 mHz
Cosmic muon true coincidence rate: 45 Hz
Cosmic muon accidental coincidence rate: 128 Hz $\times$ (1.62 kHz $\times$ 2 ns) = 0.4 mHz

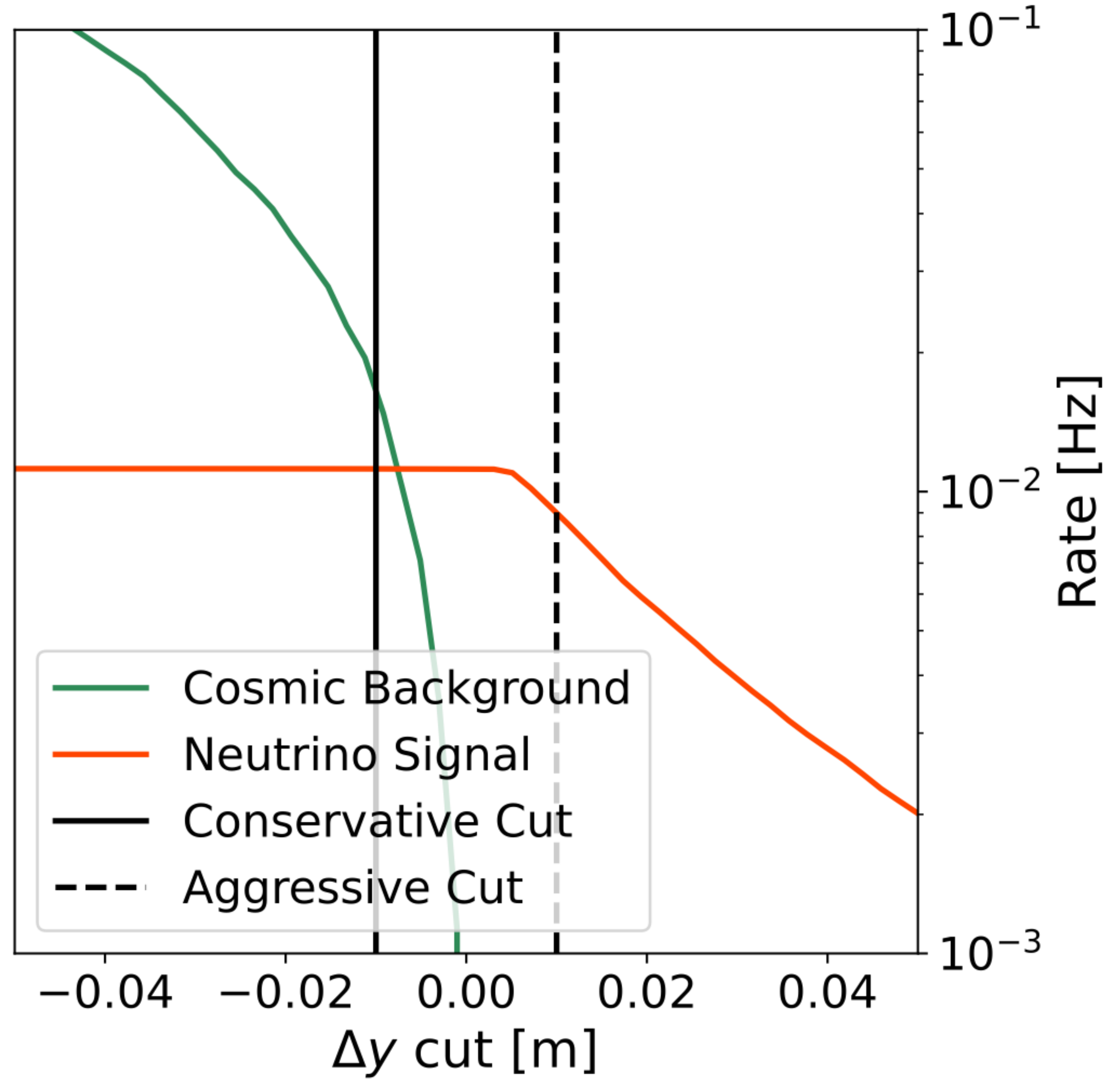
3a. Up-going spatial information

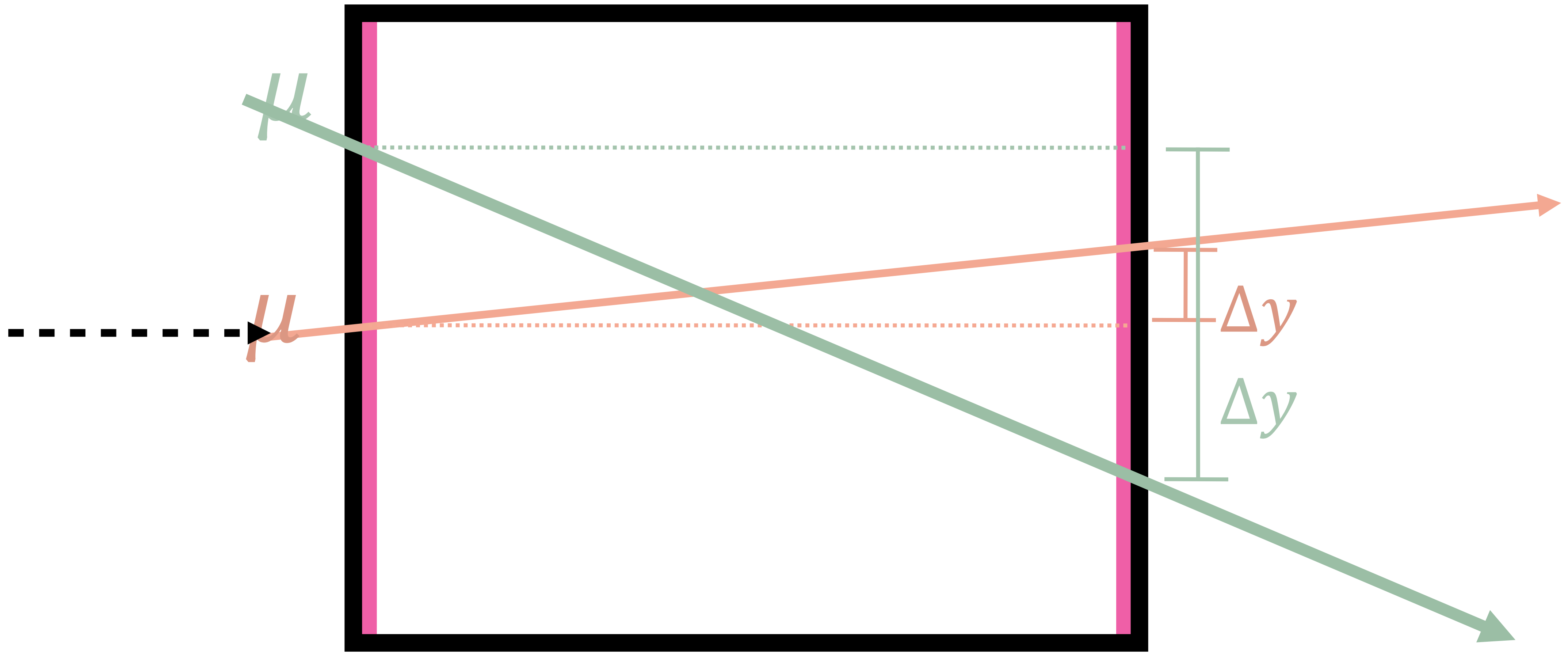
- Neutrino-induced (cosmic) muons tend to travel upward (downward)
- **Strategy: only keep events for which Δy > -1 cm**
- A more aggressive cut is possible but will reduce signal efficiency







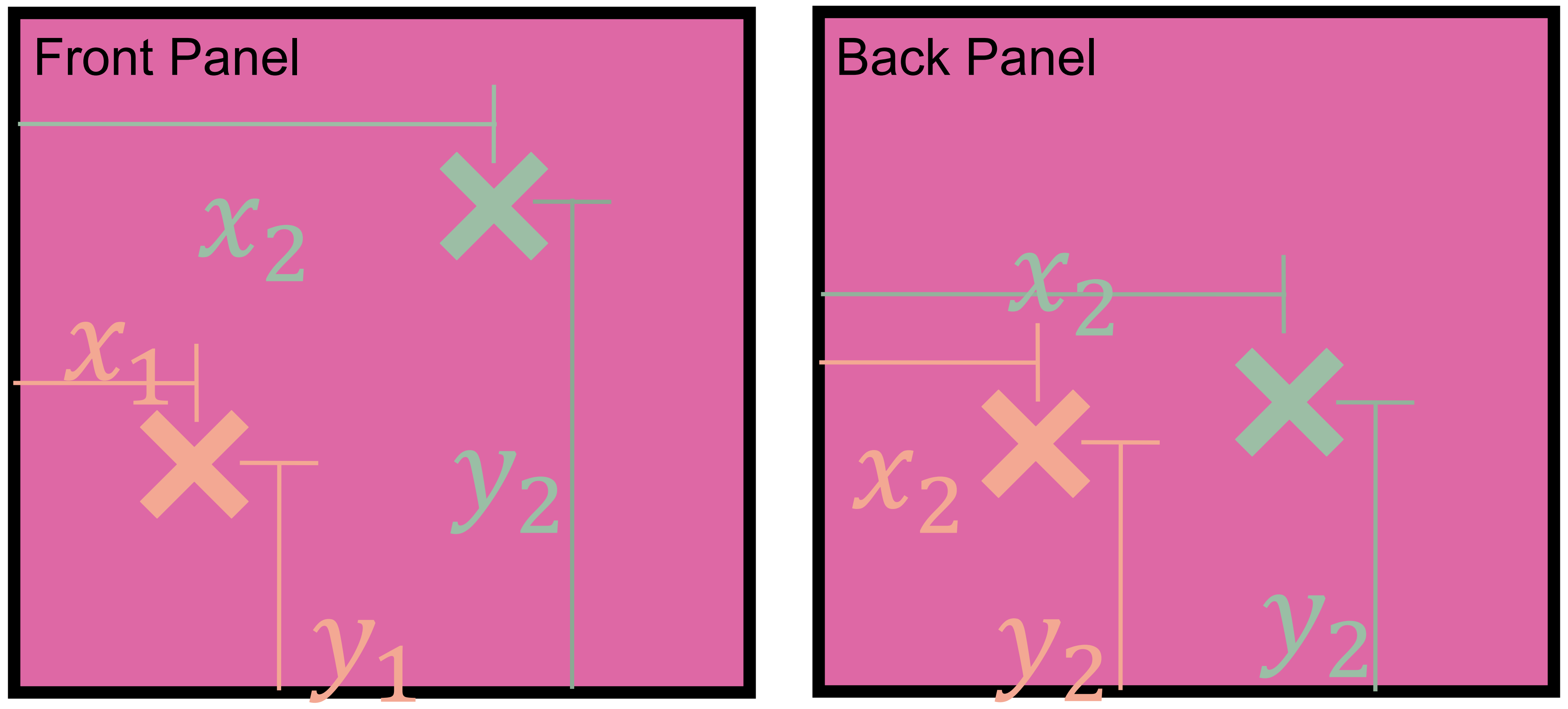




ν-induced muon rate: 11 mHz

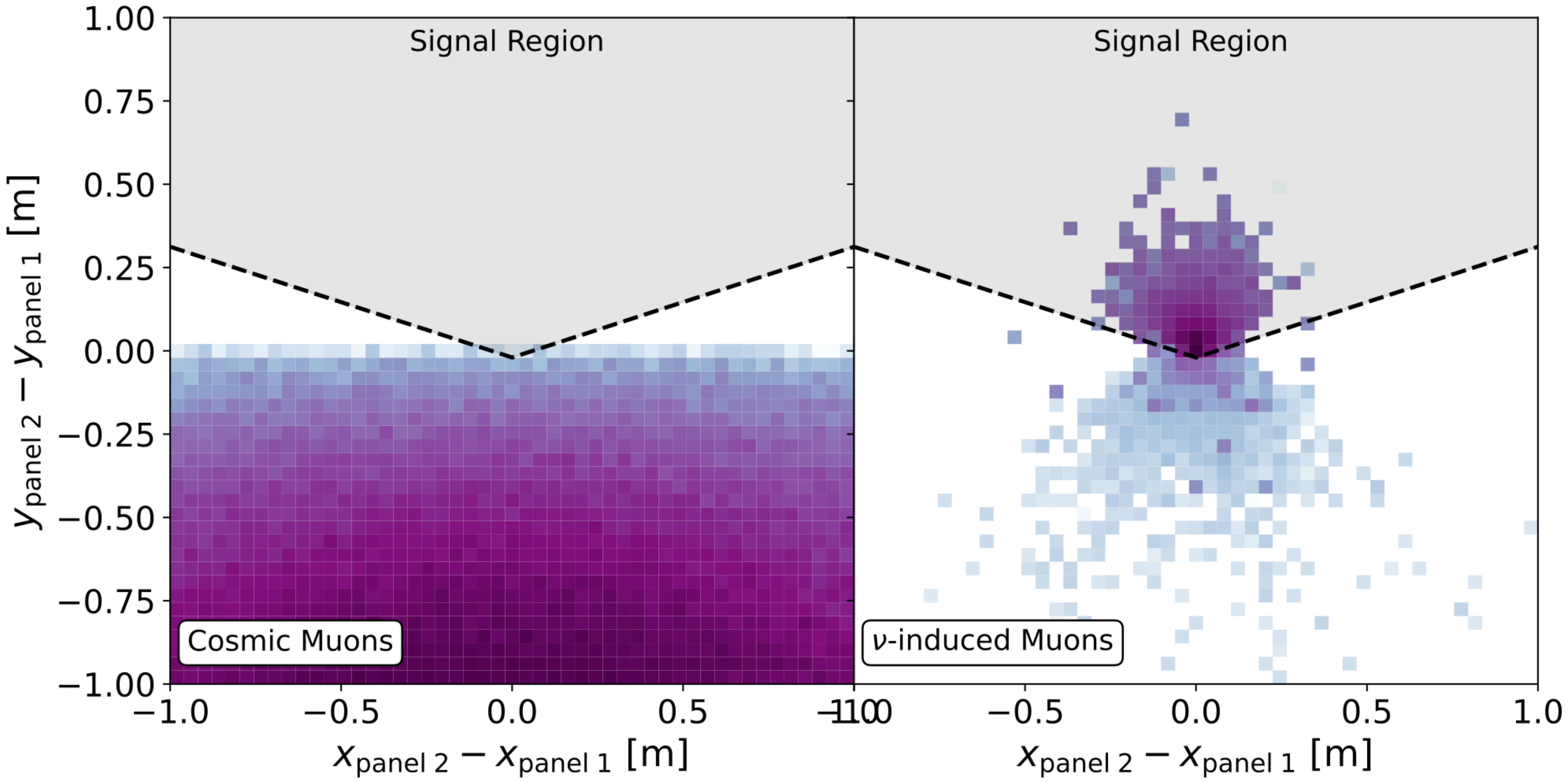
Cosmic muon true coincidence rate: 17 mHz

3b. Two-dimensional spatial information



- The neutrino beam is a point source!

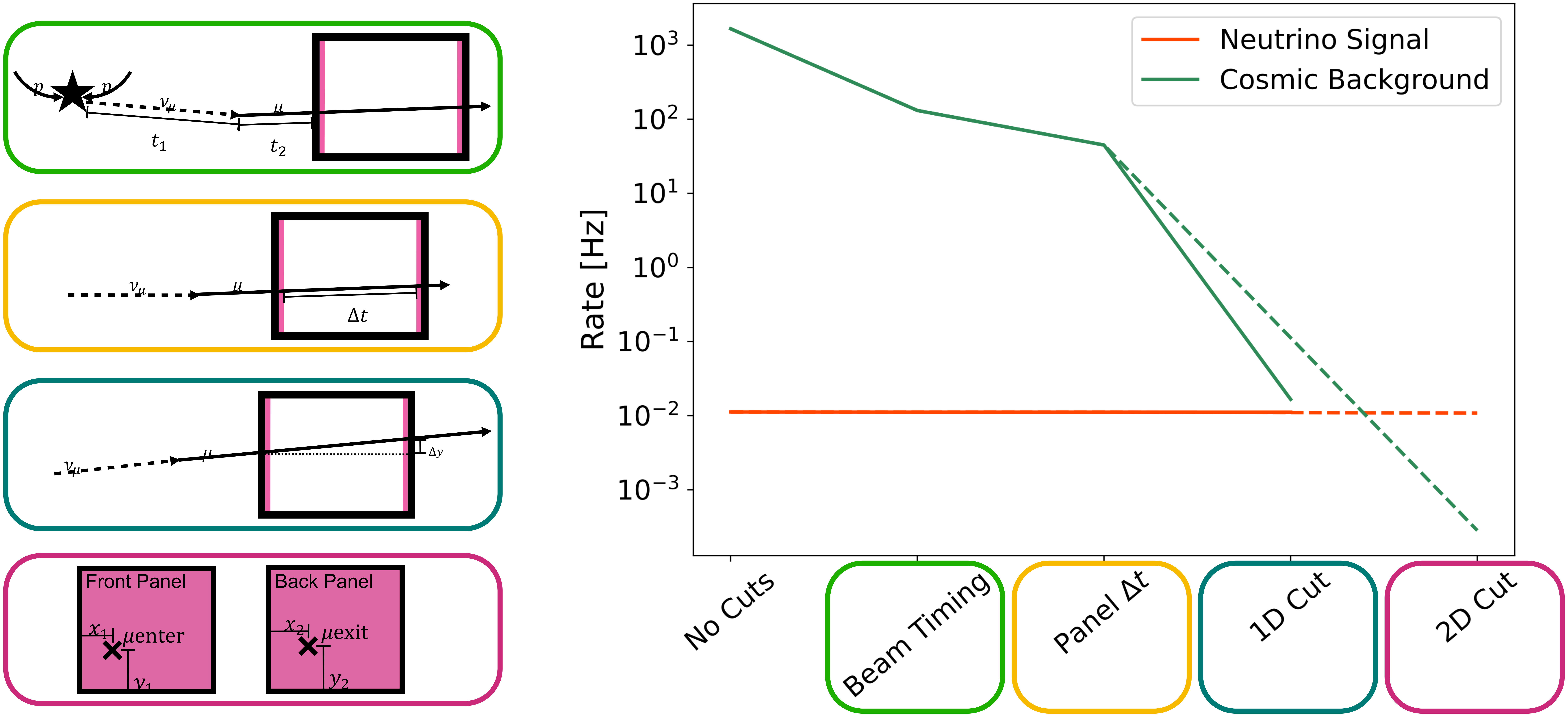
- **Strategy: make a triangle-based cut on Δx and Δy**



ν-induced muon rate: 11 mHz

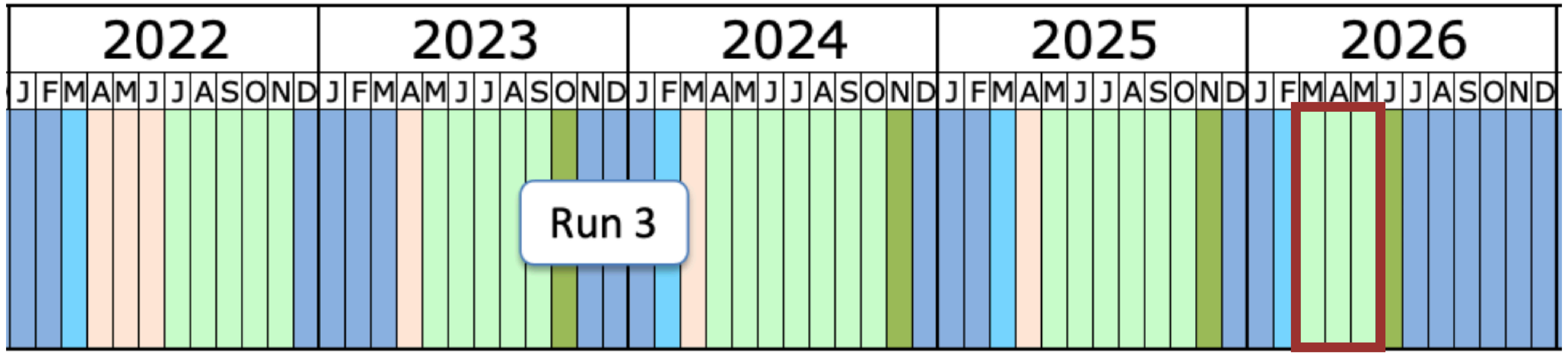
Cosmic muon true coincidence rate: ~0.3 mHz

SINE Background Summary



Prototype SINE Detector

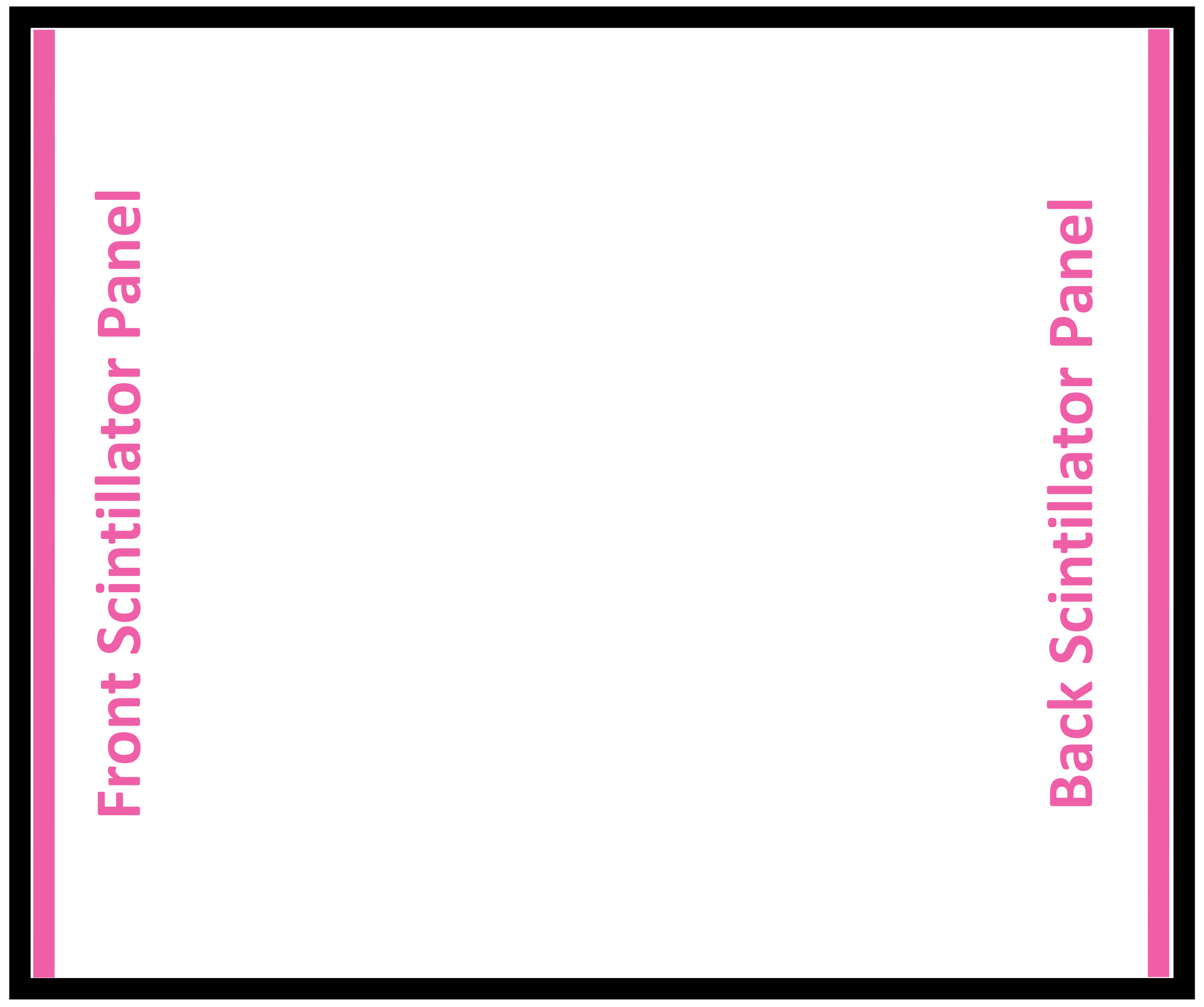
lhc-commissioning.web.cern.ch/schedule/LHC-long-term.htm



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

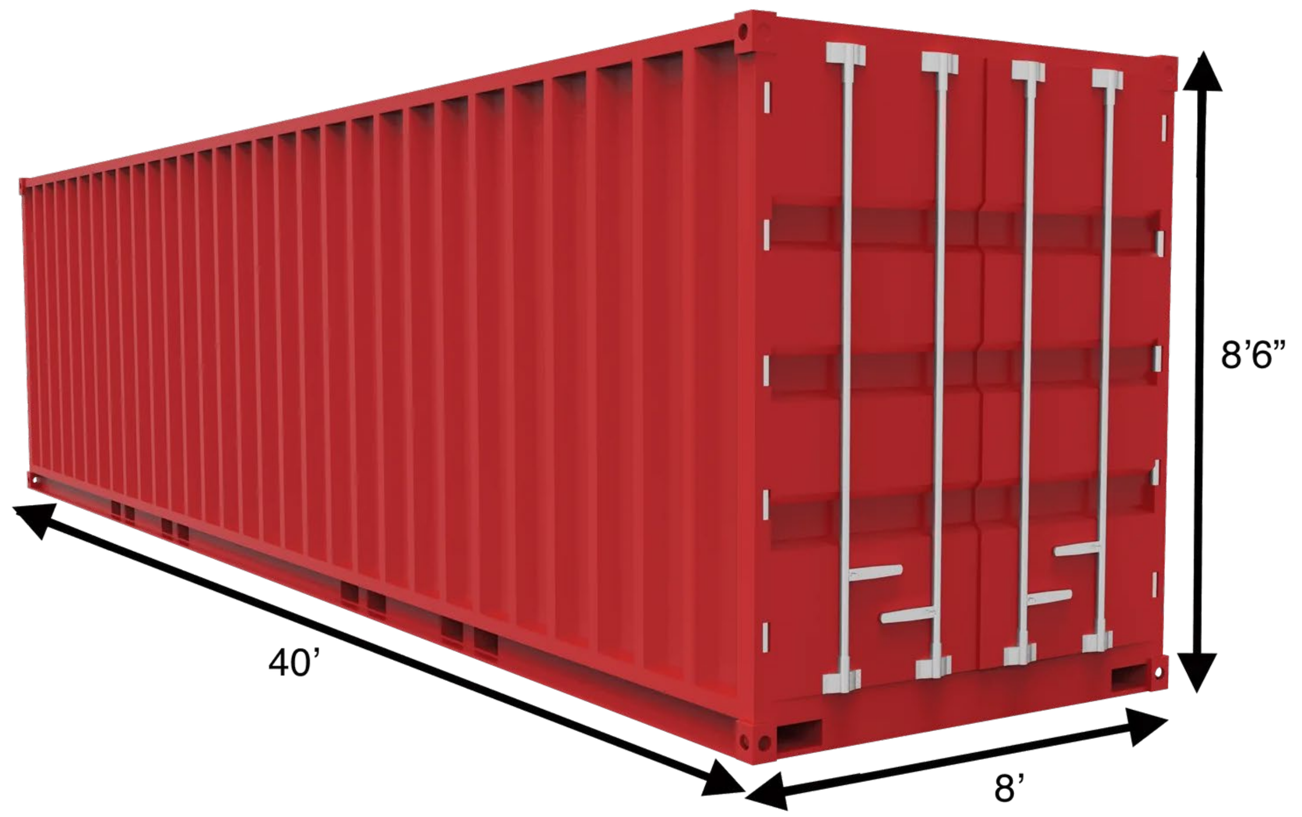
What can we do here with one shipping crate detector?

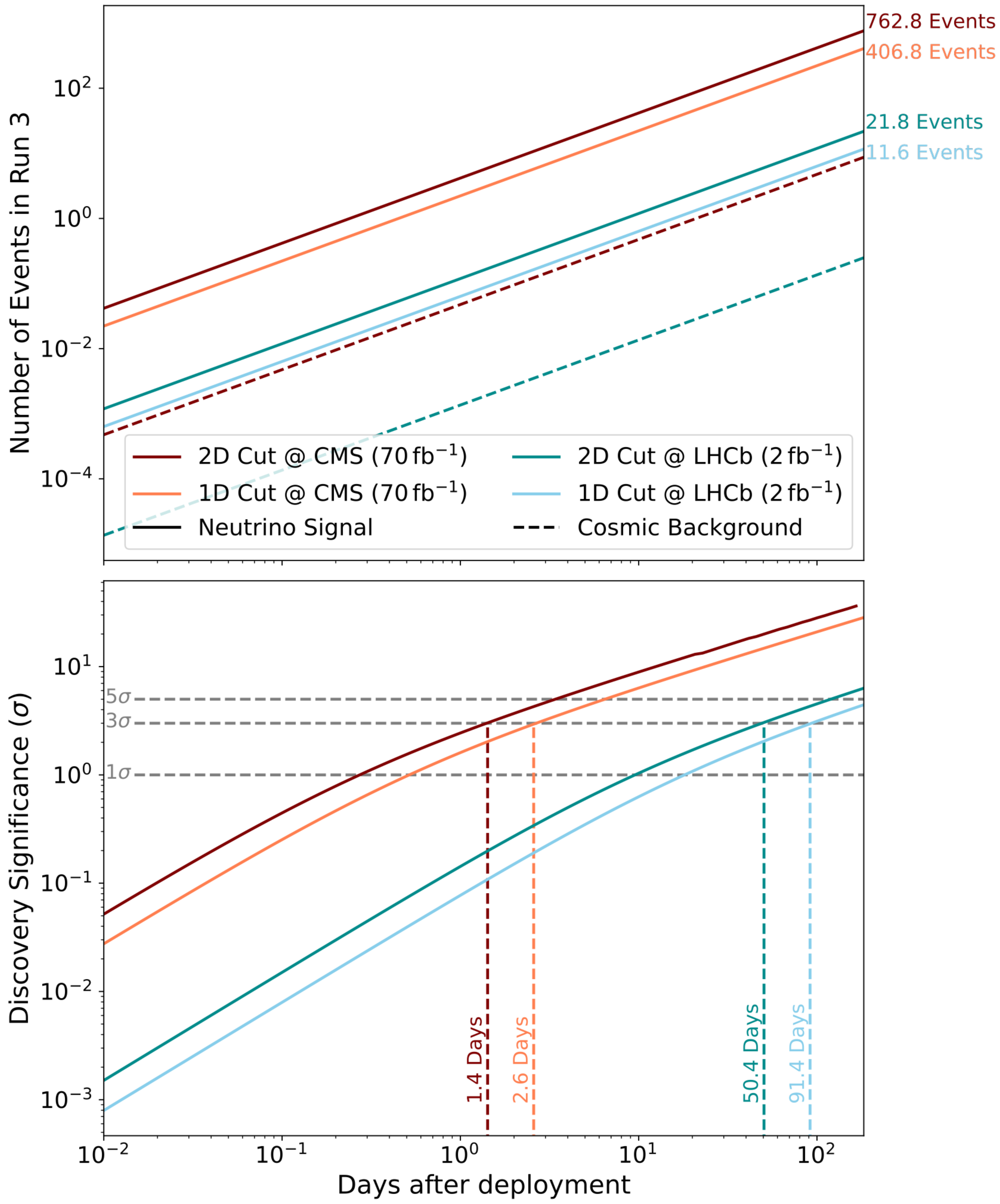
Shipping Container



Prototype SINE Detector

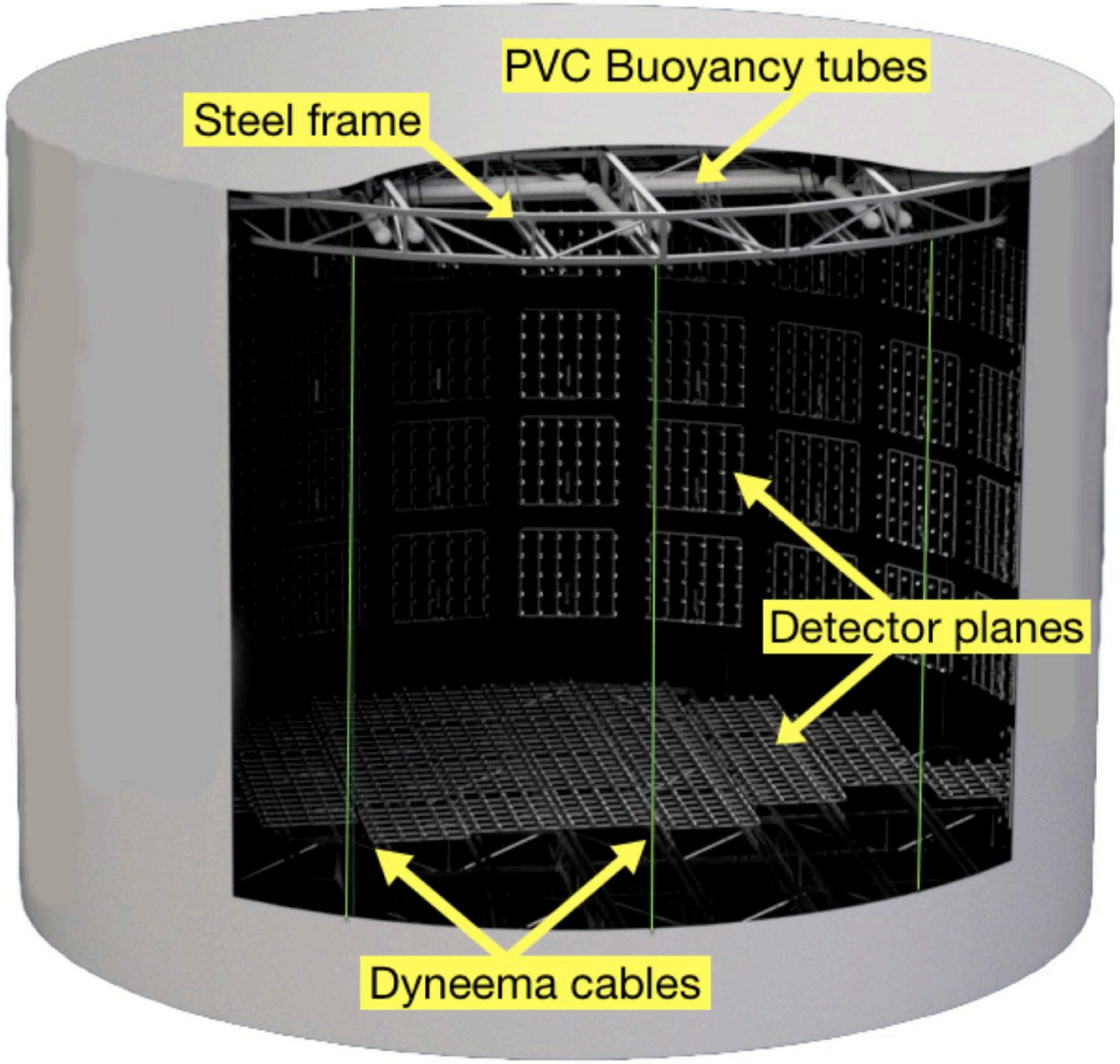
Detect 10 to 20 events above background in 100 days.



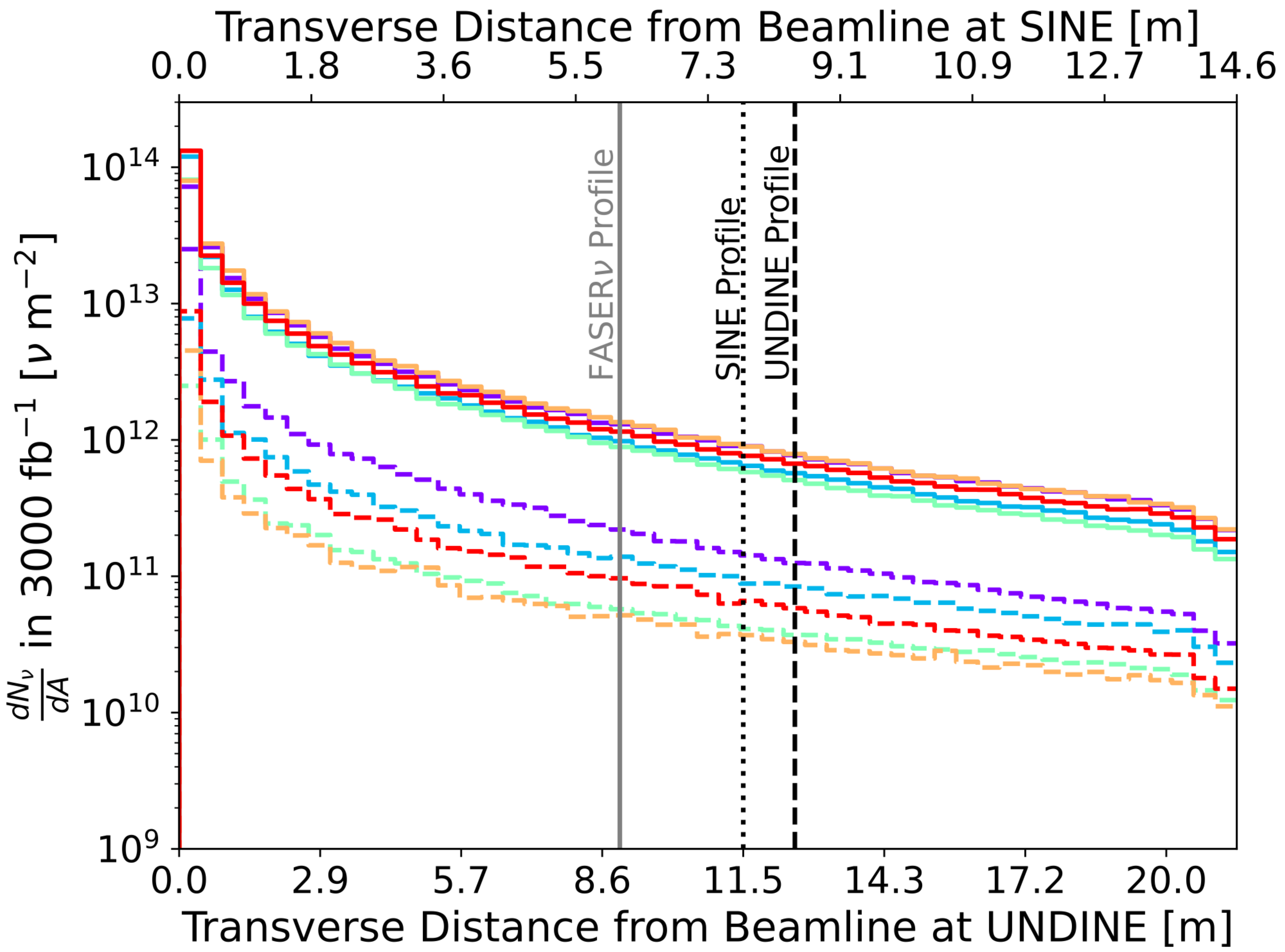


UNDINE design

Starting point: CHIPS



(18 km from interaction point)



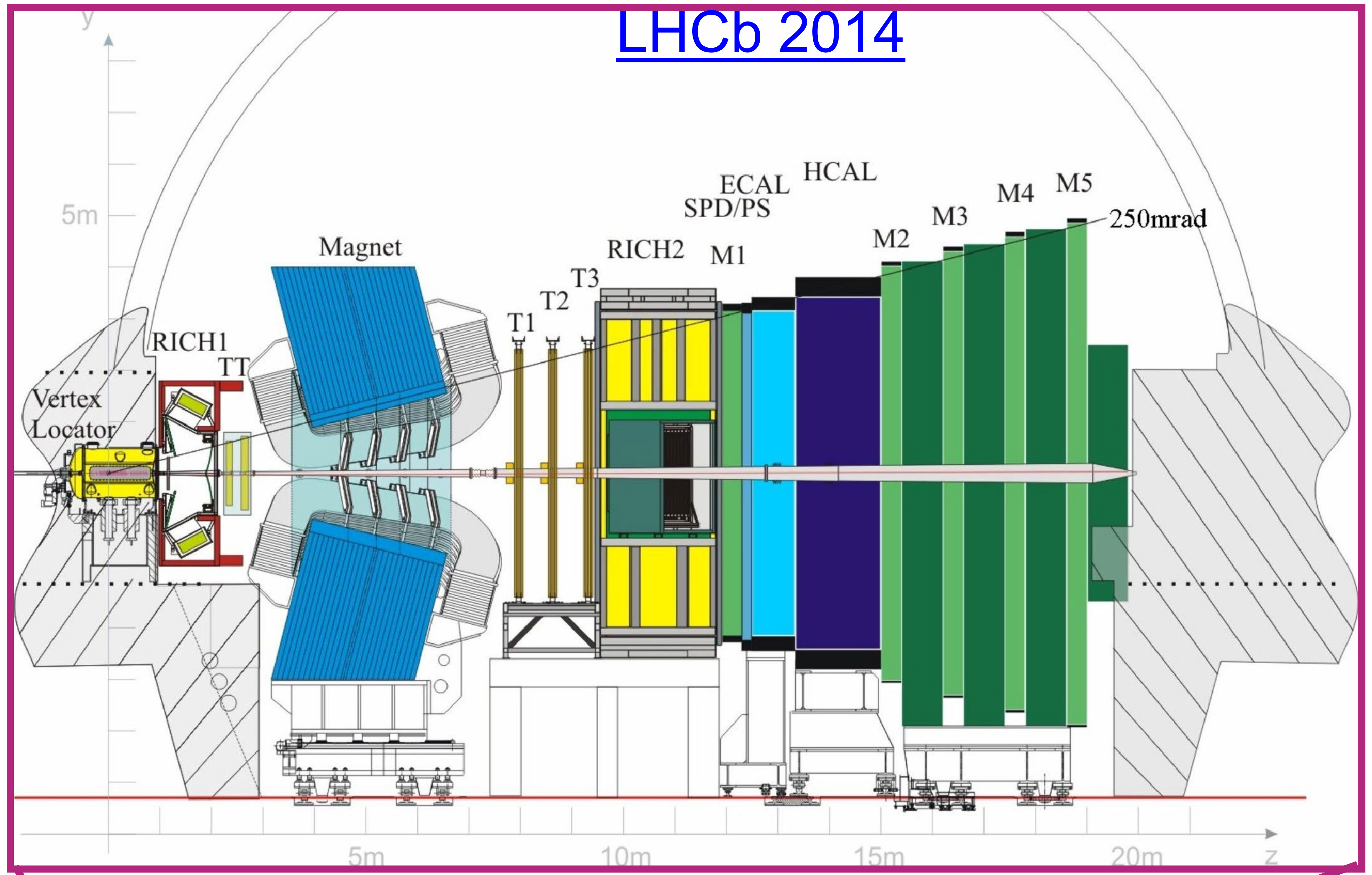
The “CHIPS” Neutrino detector design.

https://arxiv.org/pdf/2401.11728

CHIPS was designed for the NuMi beam.
LHC neutrinos are of much higher energy, and the beam is much narrower, only a few m.
—>
simpler design,
smaller scale,
smaller photdetectors.

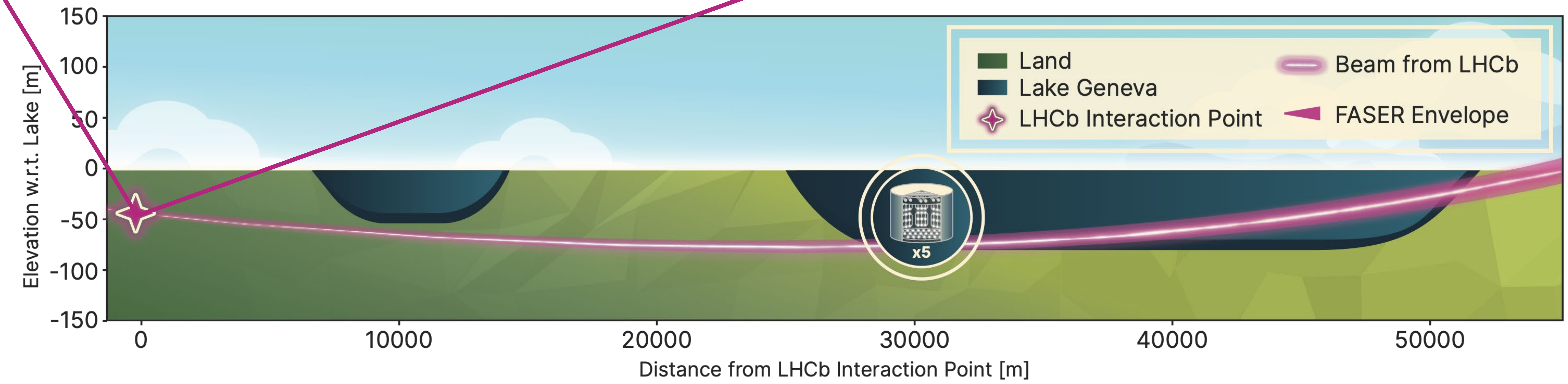
Are there synergies between SINE/UNDINE and LHCb?

SINE/UNDINE-LHCb Synergy



How do these experiments complement one another?

- Potential for indirect synergy: SINE and UNDINE can make a strong measurement of forward D Meson production
- Potential for direct synergy: charm and beauty-tagged neutrinos with UNDINE@LHCb



Summary

SINE and UNDINE are lake- and surface-based collider neutrino detectors that can observe millions of neutrinos during the HL-LHC

Cost-effective complements to the FPF

Sensitive to neutrino cross sections, forward charm production, and strangeness enhancement

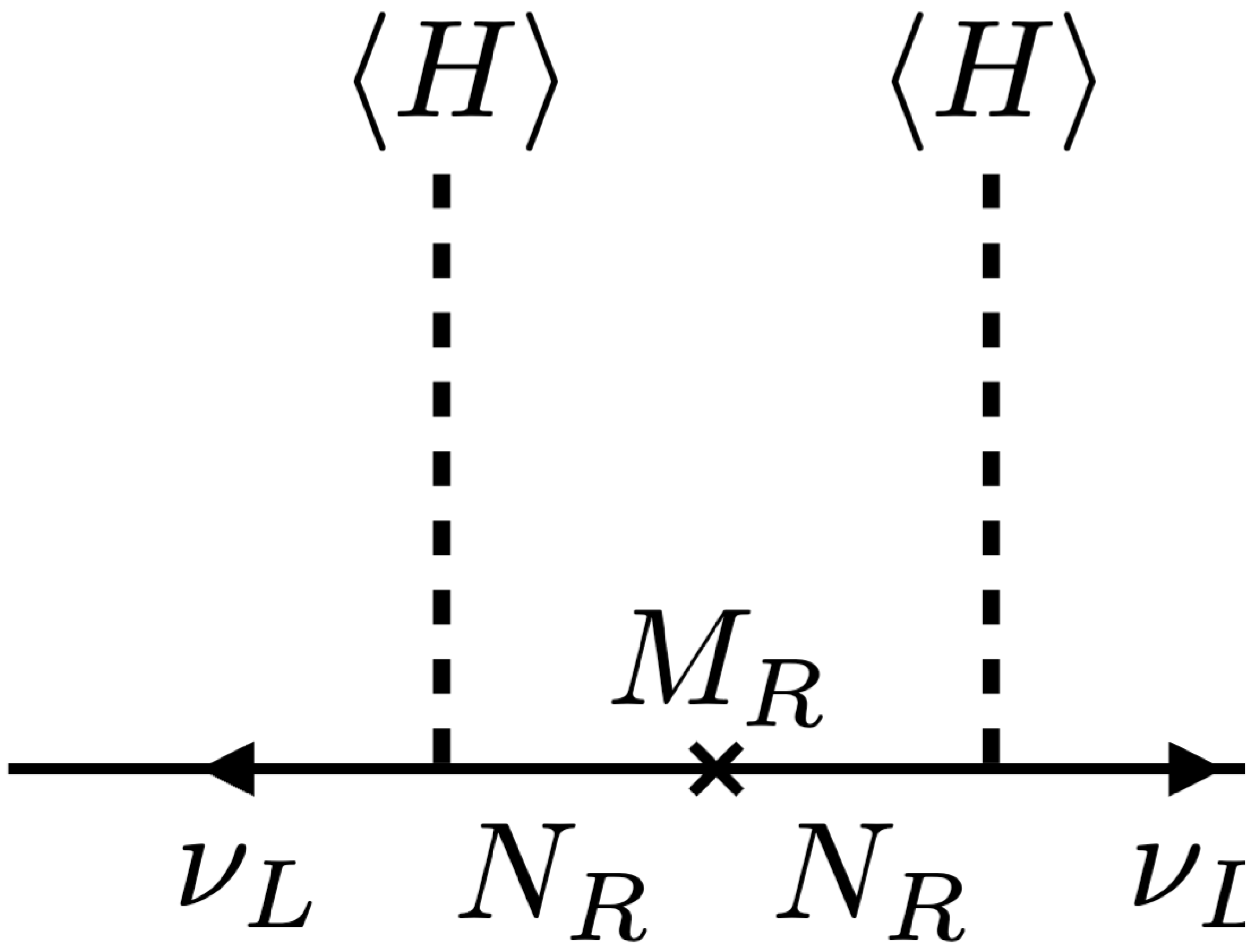
N. Kamp is currently investigating sensitivity to BSM scenarios, including HNLs. Possibility for synergies between LHCb and UNDINE, including beauty-tagged neutrinos

Thank you!

HNLs in SINE and UNDINE

- **Mass-mixed heavy neutral lepton (HNLs):** minimal extension of the Standard Model
- Famously appear in the See-saw mechanism for neutrino mass generation
- Each neutrino flavor state α couples to the HNL by a small mixing $U_{\alpha 4}$

Can we look for them in SINE and UNDINE?



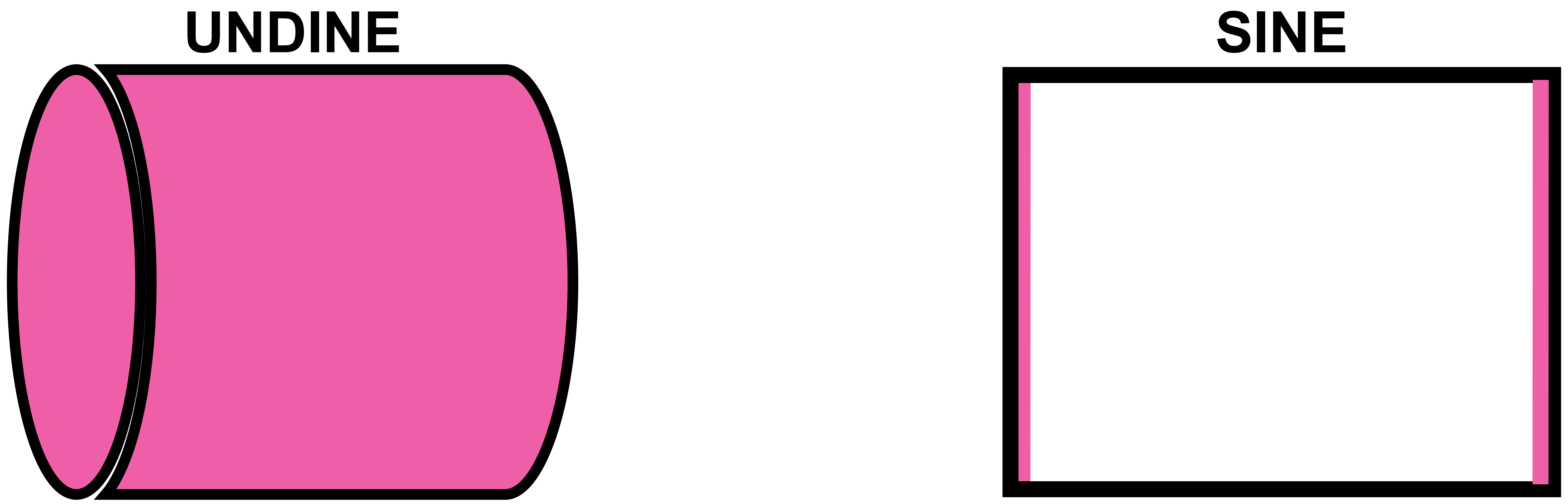
See-saw type I

$$\mathcal{L} = \mathcal{L}_{SM} + i\bar{N}_I\gamma^\mu\partial_\mu N_I - F_{\alpha I}\bar{L}_\alpha\tilde{\Phi}N_I - \frac{M_{IJ}}{2}\bar{N}_I^c N_J + h.c.,$$

Abudllahi+ 2022

HNLs in SINE and UNDINE

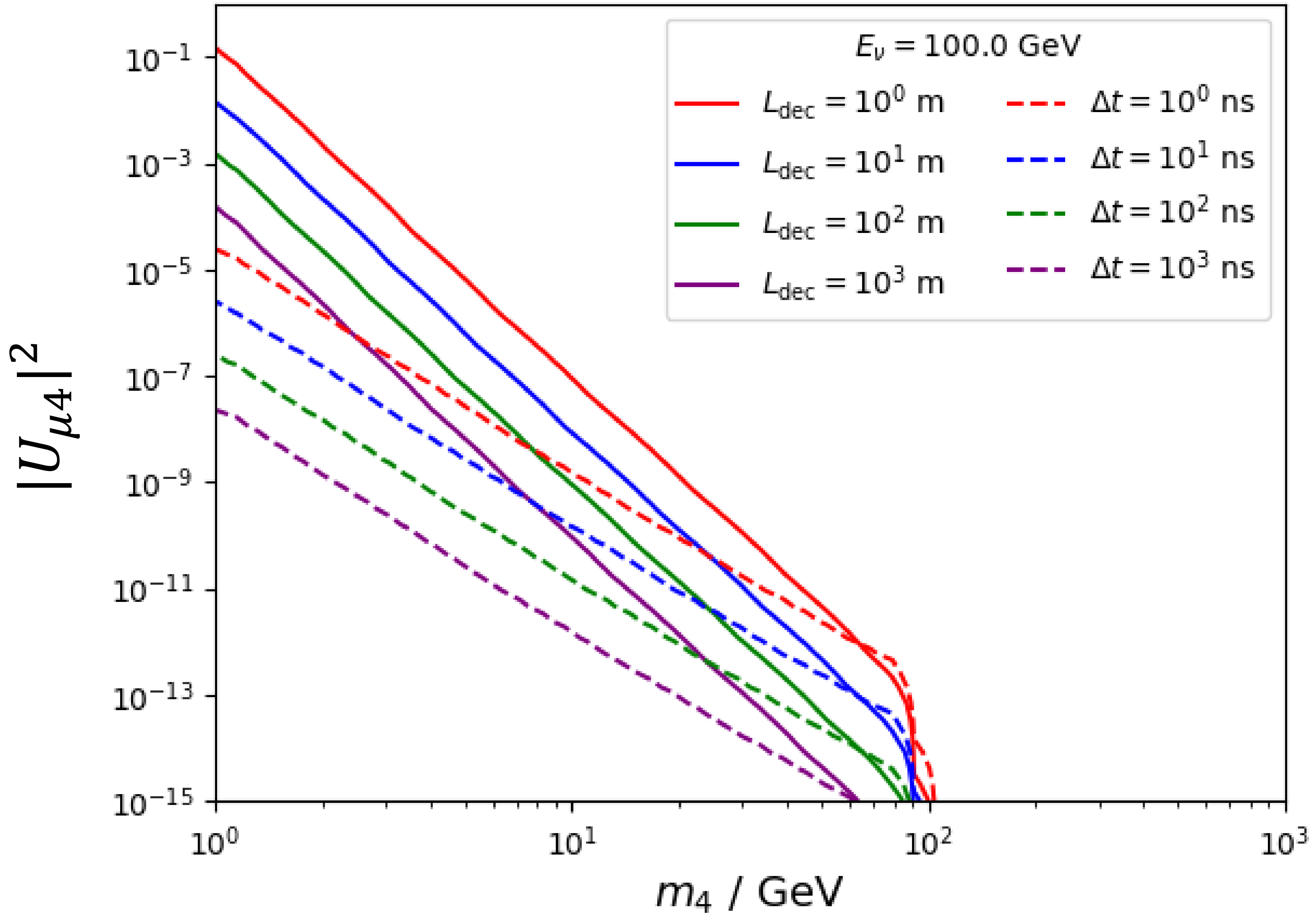
- Two ideas to look for mass-mixed HNLs in SINE and UNDINE



HNLs in SINE and UNDINE

- Two ideas to look for mass-mixed HNLs in SINE and UNDINE

  1. $m_{\mathcal{N}} \lesssim 10\text{GeV}$: Delayed muons with respect to the beam trigger from HNL time-of-flight

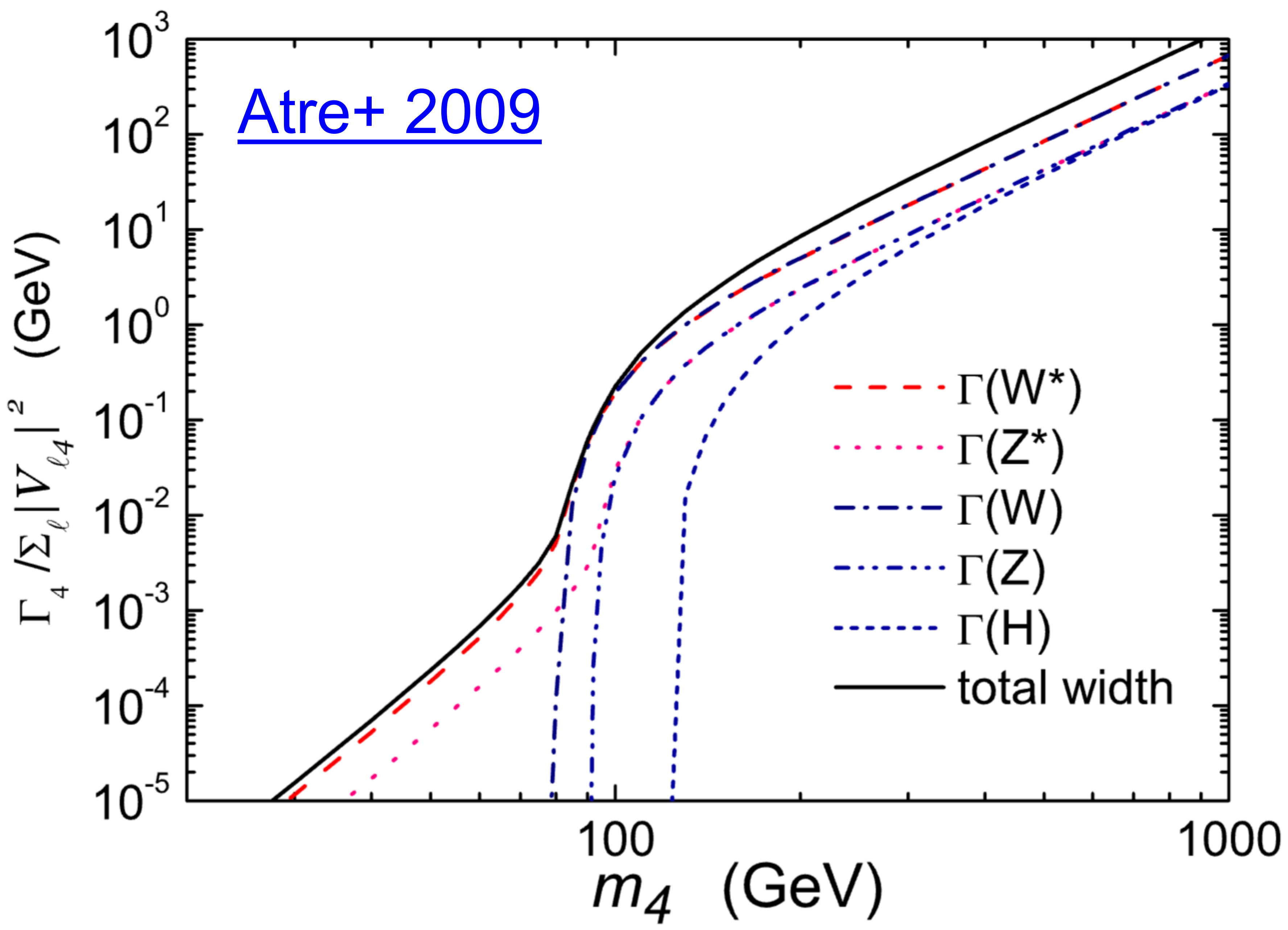


HNLs in SINE and UNDINE

- Two ideas to look for mass-mixed HNLs in SINE and UNDINE

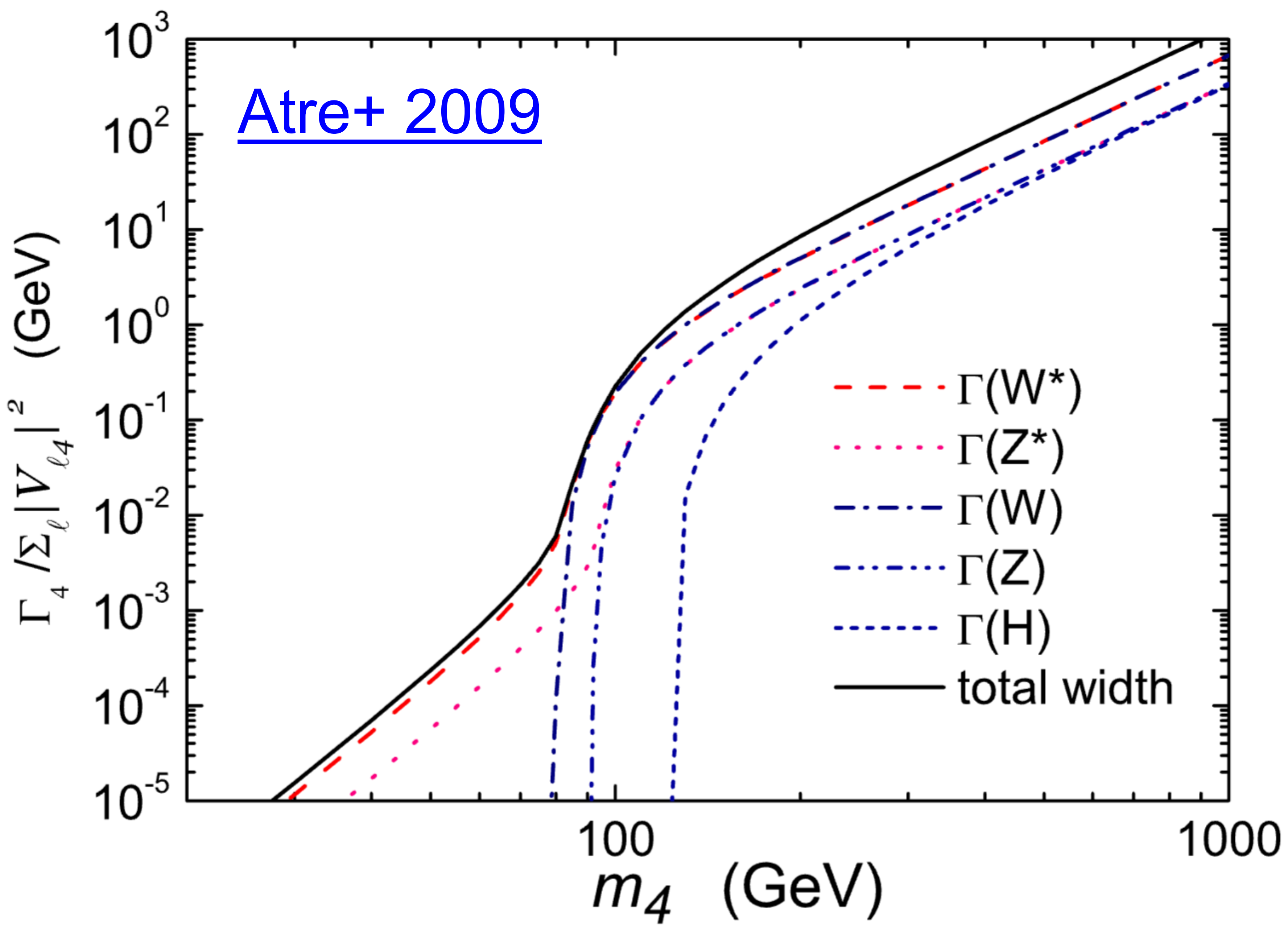
  1. $m_{\mathcal{N}} \lesssim 10\mathrm{GeV}$: Delayed muons with respect to the beam trigger from HNL time-of-flight

  2. $m_{\mathcal{N}} > 10\mathrm{GeV}$: Di-muons from $\mathcal{N} \to \mu(W^{(\star)} \to \mu\nu_\mu)$ or $\mathcal{N} \to \nu(Z^{(\star)} \to \mu\mu)$



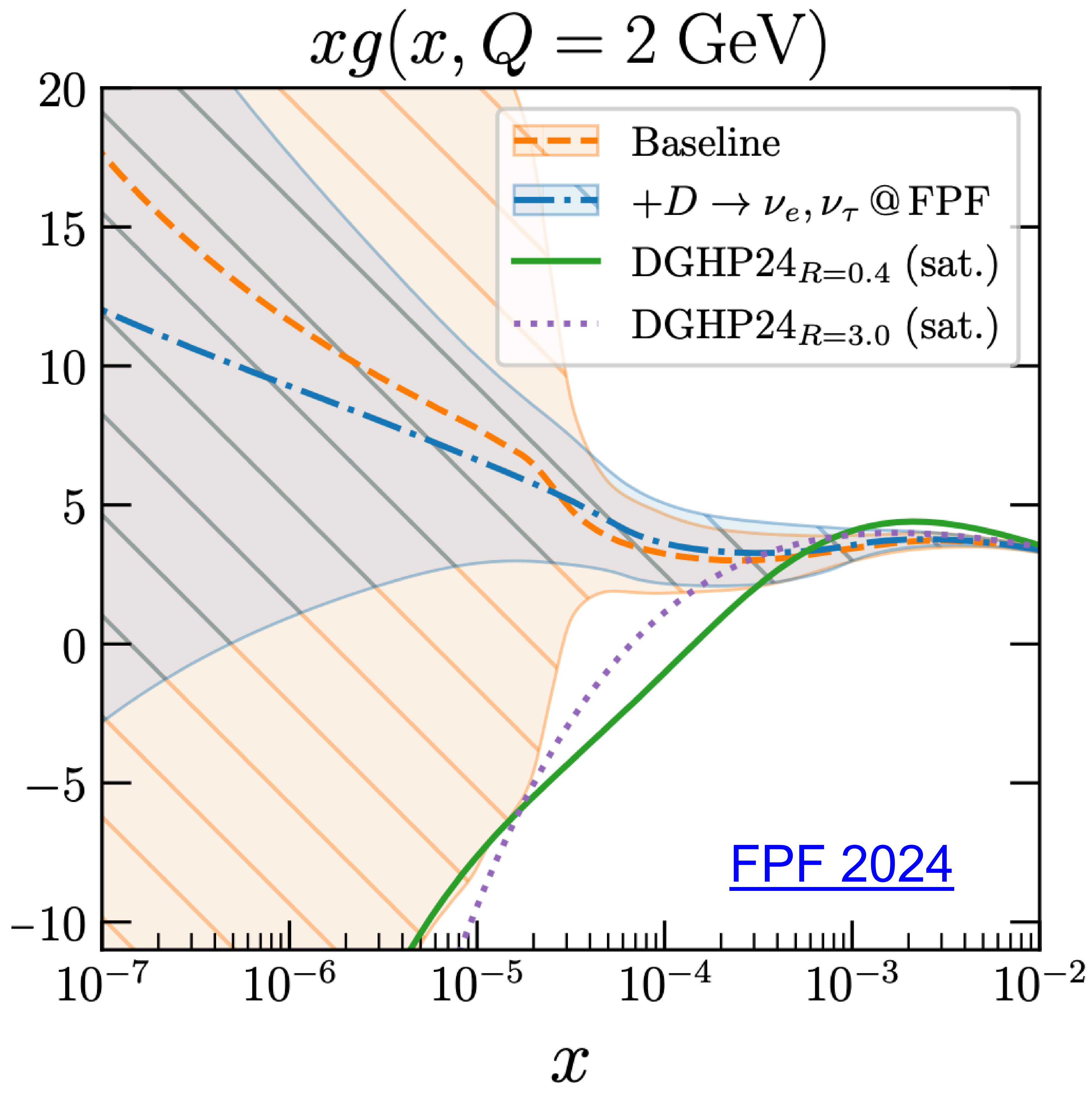
HNLs in SINE and UNDINE

- Two ideas to look for mass-mixed HNLs in SINE and UNDINE
  1. $m_{\mathcal{N}} \lesssim 10\mathrm{GeV}$: Delayed muons with respect to the beam trigger from HNL time-of-flight
  2. $m_{\mathcal{N}} > 10\mathrm{GeV}$: Di-muons from $\mathcal{N} \to \mu(W^{(\star)} \to \mu\nu_\mu)$ or $\mathcal{N} \to \nu(Z^{(\star)} \to \mu\mu)$ **Sensitivity studies in progress**



SINE/UNDINE-LHCb Synergy: Gluon PDFs

- Forward D-meson measurements at LHCb constrain the gluon pdf down to $x \sim 10^{-5}$
- Forward neutrino measurements can push constraints down to $x \sim 10^{-7}$
- **Potential for <u>indirect</u> synergy: SINE and UNDINE can make a strong measurement of forward D production**
  - Impact on small x PDF uncertainties under investigation, following [Cruz-Martinez+ 2023]

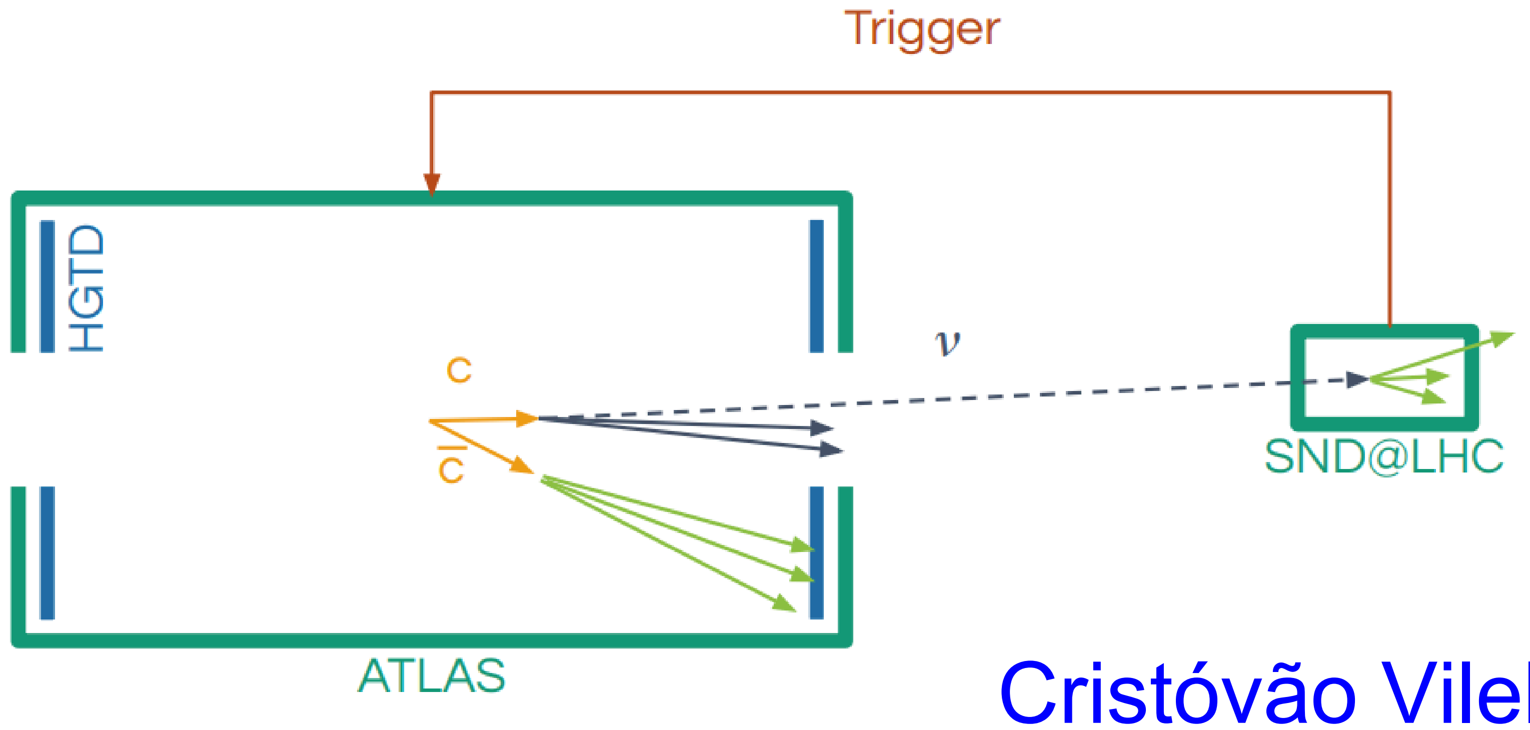


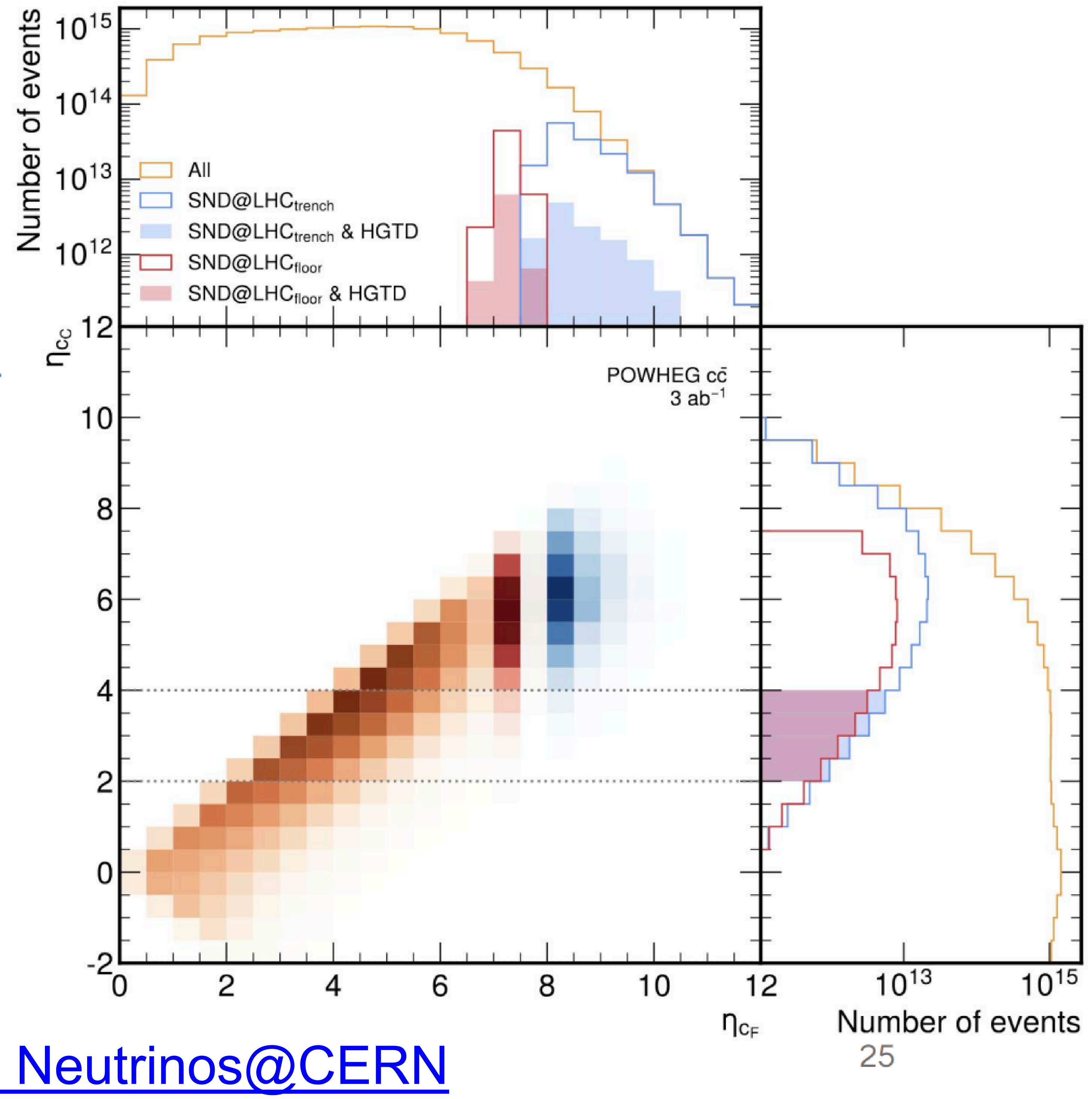
UNDINE-LHCb Synergy: Tagged Neutrinos

- SND@ATLAS expects to observe ~500 charm-tagged neutrinos throughout the HL-LHC
- **Potential for <u>direct</u> synergy: charm and beauty-tagged neutrinos with UNDINE@LHCb**

Prospects for charm-tagged neutrinos

- A sizeable fraction of the interacting neutrinos originate in open charm production.
- In around 10% of these events, the associated charm quark is emitted within the acceptance of ATLAS: over 500 events expected.
- A charm-tagged neutrino sample would allow for clean flavour ratio measurements.
- Requires fast timing detectors to resolve the pile-up, and sending a trigger signal to ATLAS.



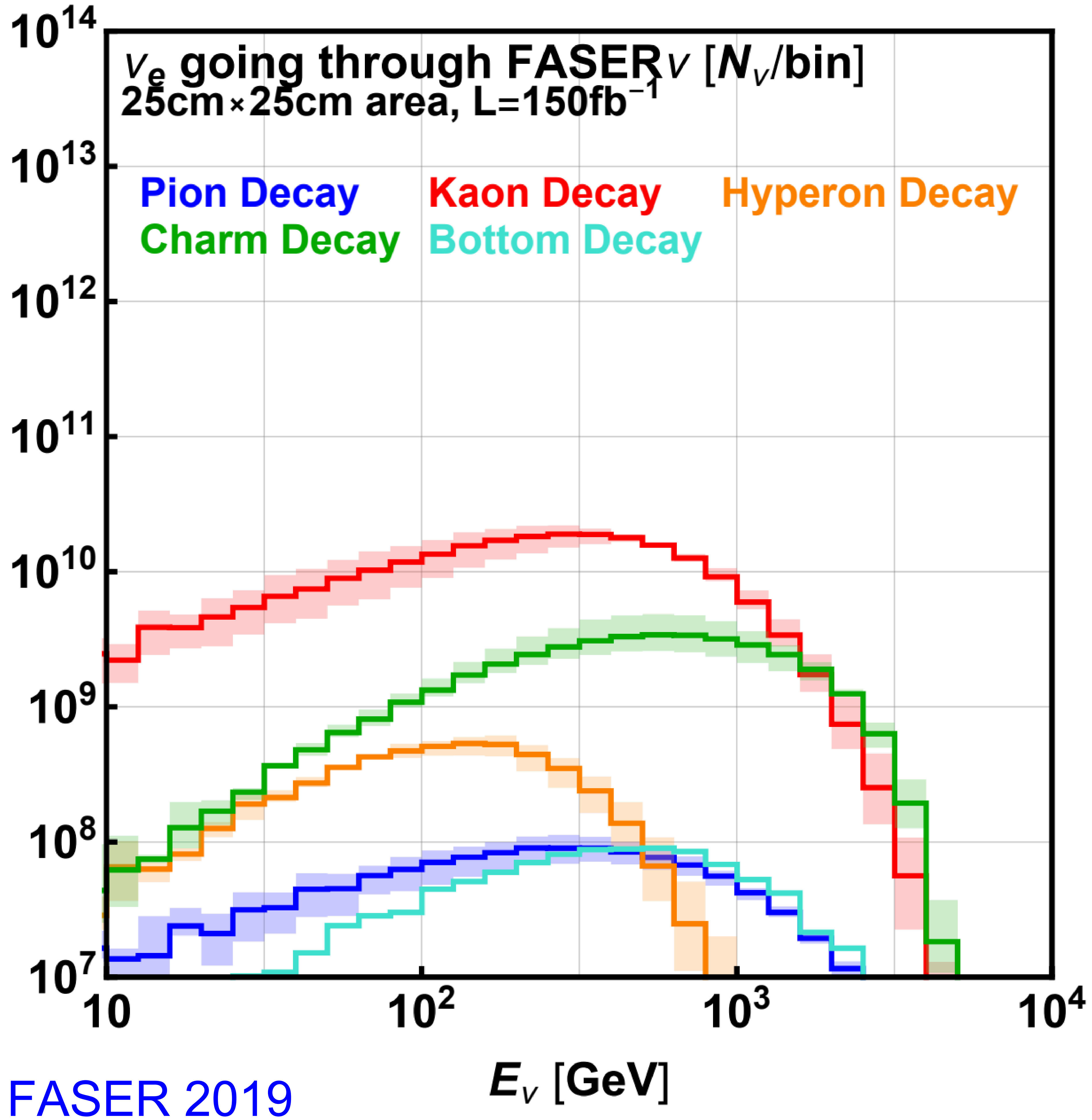


[Cristóvão Vilela, Neutrinos@CERN](#)

UNDINE-LHCb Synergy: Tagged Neutrinos

- LHCb reaches higher pseudorapidites than ATLAS:
  $\gtrsim$ **2000 charm-tagged electron neutrinos**
- The ν_e flux from beauty decays is ~1% of that from kaon or charm decays
  $\gtrsim$ **20 beauty-tagged electron neutrinos**
- Potentially useful for lepton flavor universality tests

Dataset	**Total**	$\pi,\ K$	$D,\ \Lambda_c$
SINE (CC $\nu_\mu + \bar{\nu}_\mu$)	$10^{6.98}$	$10^{6.84}$	$10^{6.40}$
UNDINE (CC $\nu_e + \bar{\nu}_e$)	$10^{4.68}$	$10^{4.32}$	$10^{4.42}$
UNDINE (CC $\nu_\mu + \bar{\nu}_\mu$)	$10^{5.27}$	$10^{5.20}$	$10^{4.41}$
UNDINE (CC $\nu_\tau + \bar{\nu}_\tau$)	$10^{3.07}$	0	$10^{3.07}$
UNDINE (NC $\nu_\alpha + \bar{\nu}_\alpha$)	$10^{4.87}$	$10^{4.76}$	$10^{4.24}$



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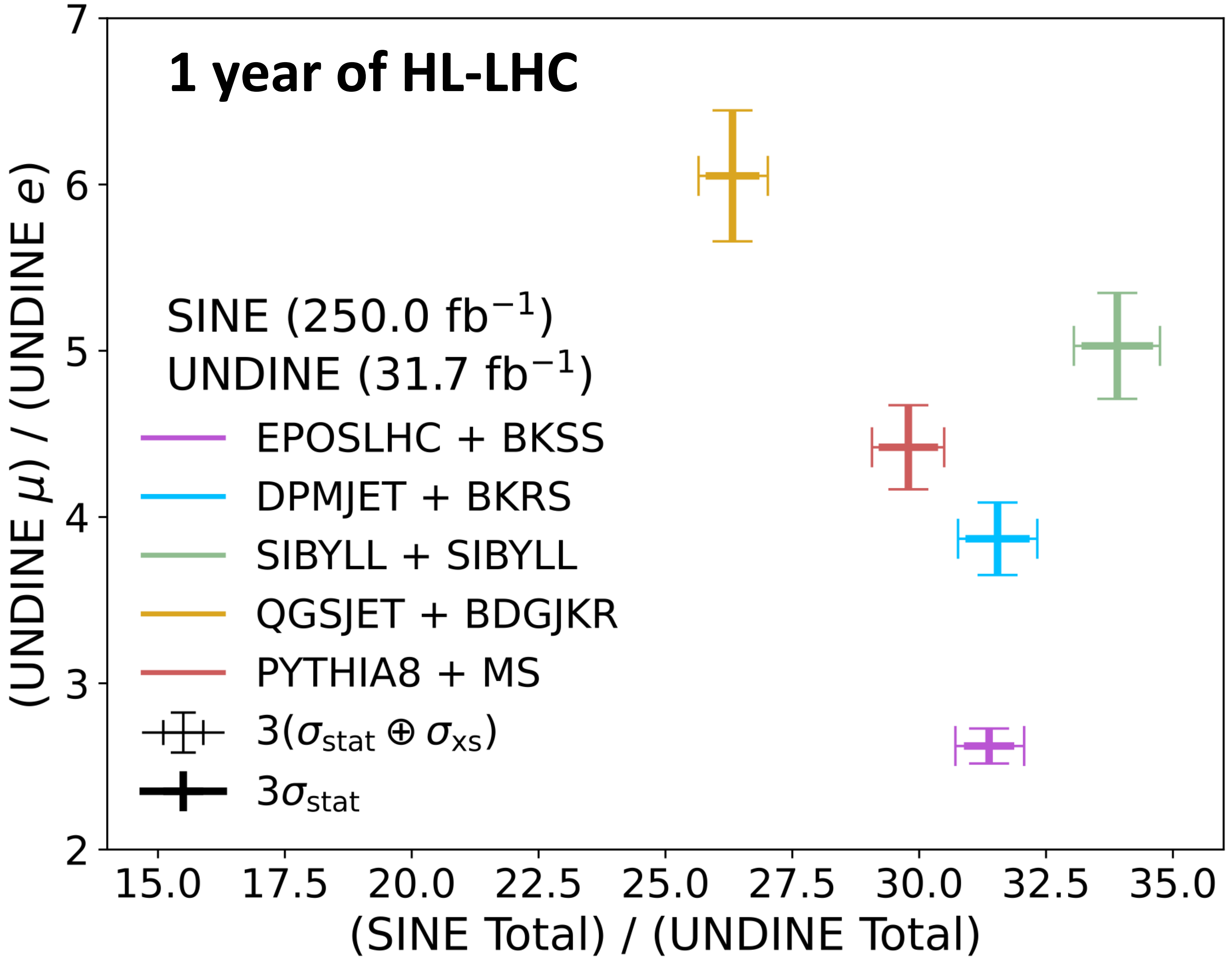
What if UNDINE can't separate electrons and hadrons?



Most pessimistic UNDINE reconstruction

No ν_e CC v.s. ν_α NC separation in UNDINE