New Directions for Collider Neutrino Physics

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Sylvan Lake, Custer State Park

Outline: Three New Directions for Collider Neutrinos

1. Lake- and surface-based detectors for LHC neutrinos
2. The “Neutrino Kaleidoscope": pairing muon colliders and neutrino telescopes
3. Searching for heavy neutrinos with a muon beam

Outline: Three New Directions for Collider Neutrinos

1. **Lake- and surface-based detectors for LHC neutrinos**
2. The “Neutrino Kaleidoscope": pairing muon colliders and neutrino telescopes
3. Searching for heavy neutrinos with a muon beam

arXiv:2501.08278

Lake- and Surface-Based Detectors for Forward Neutrino Physics

Nicholas W. Kamp,[1,*] Carlos A. Argüelles,[1,†] Albrecht Karle,[2,‡] Jennifer Thomas,[2,3,§] and Tianlu Yuan[2,¶]

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[2] *Department of Physics and Wisconsin IceCube Particle Astrophysics Center, University of Wisconsin– Madison, Madison, WI 53706, USA*
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(Dated: January 14, 2025)

See also related independent work: Ariga+ 2501.0614

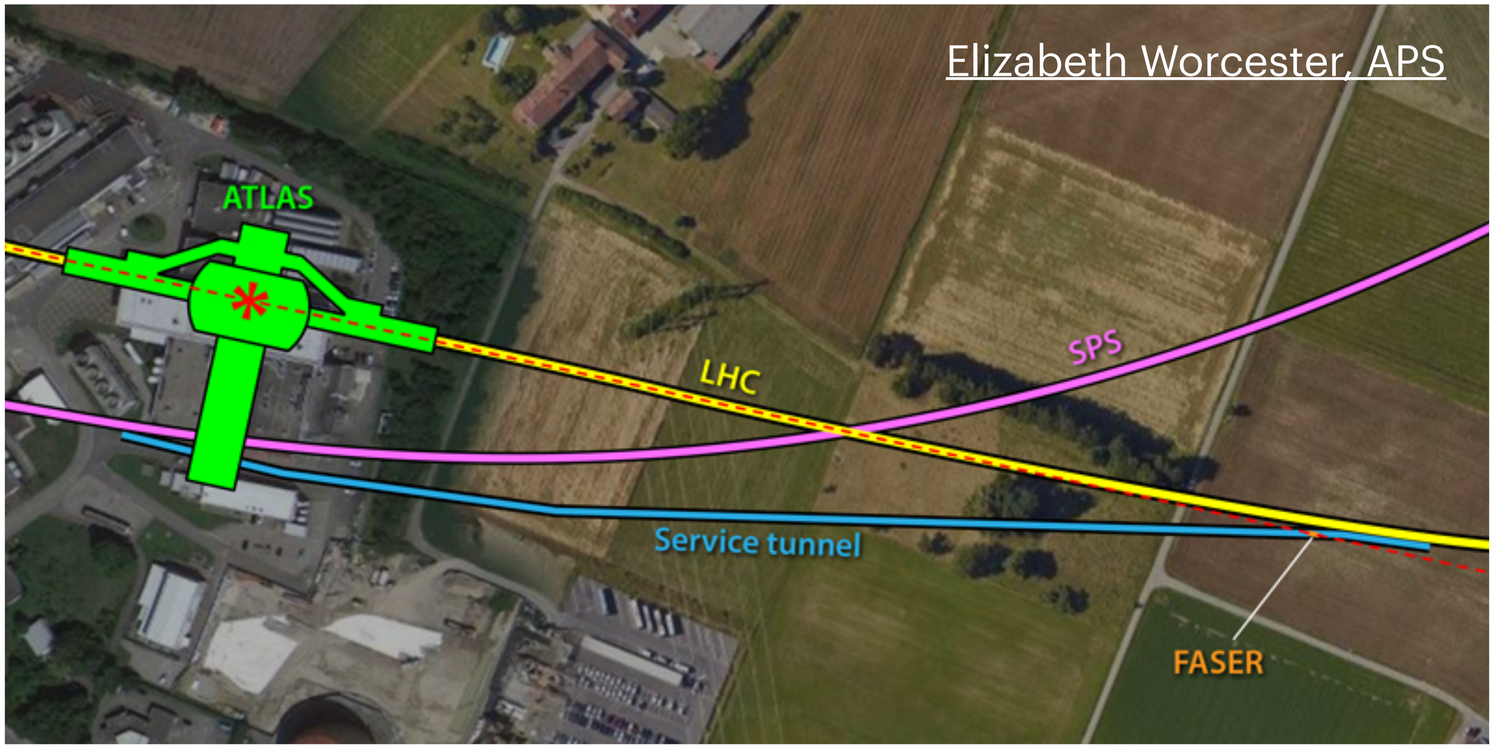
J. Thomas

A. Karle

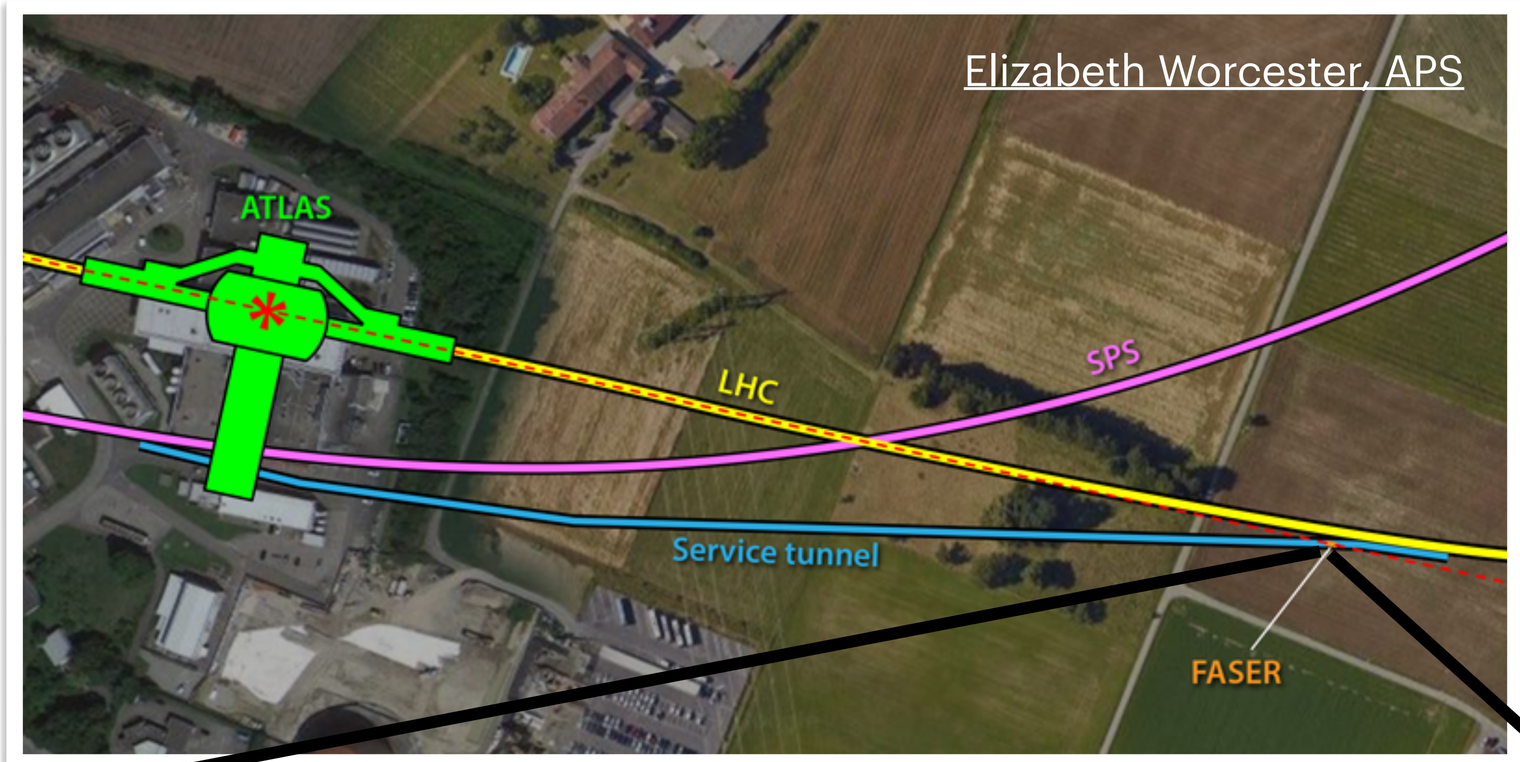
C. Argüelles

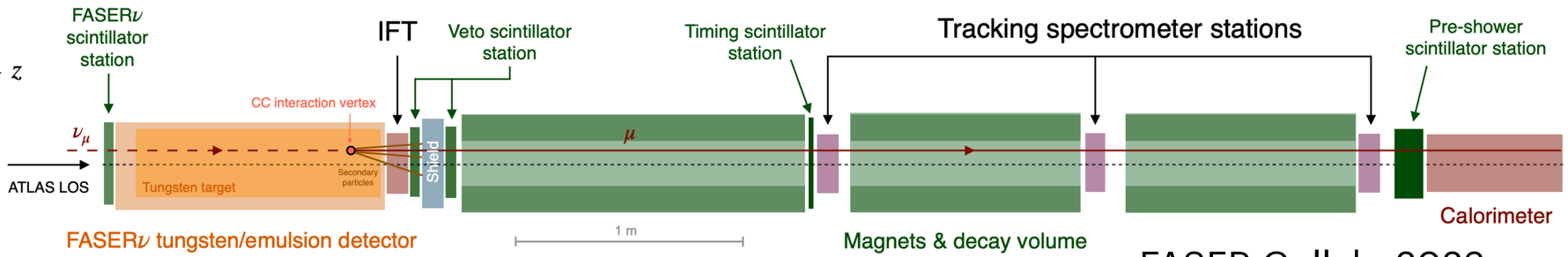
T. Yuan

The Dawn of Collider Neutrino Physics



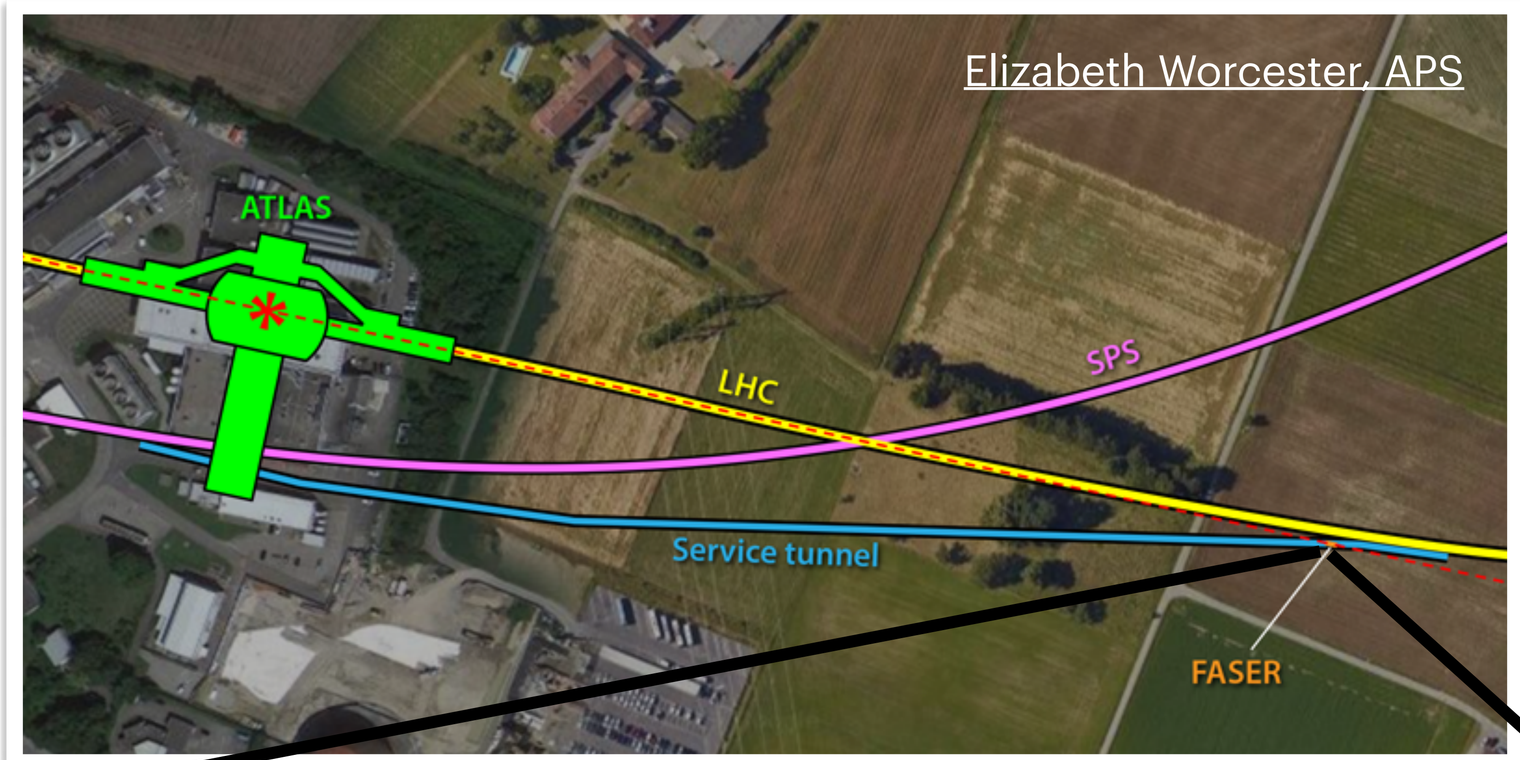
The Dawn of Collider Neutrino Physics

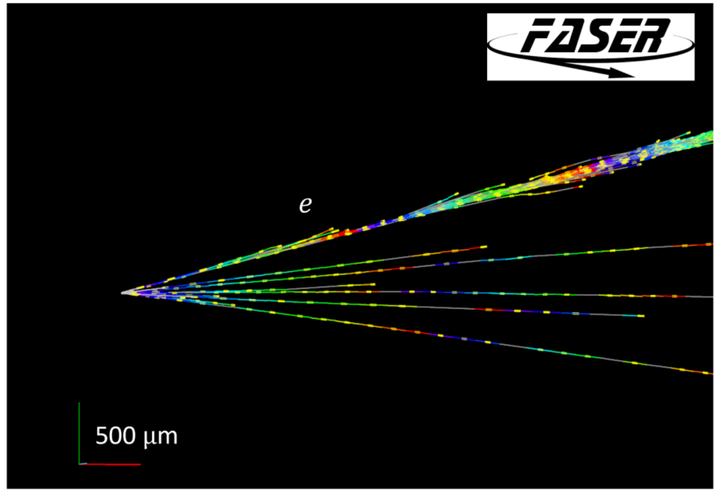


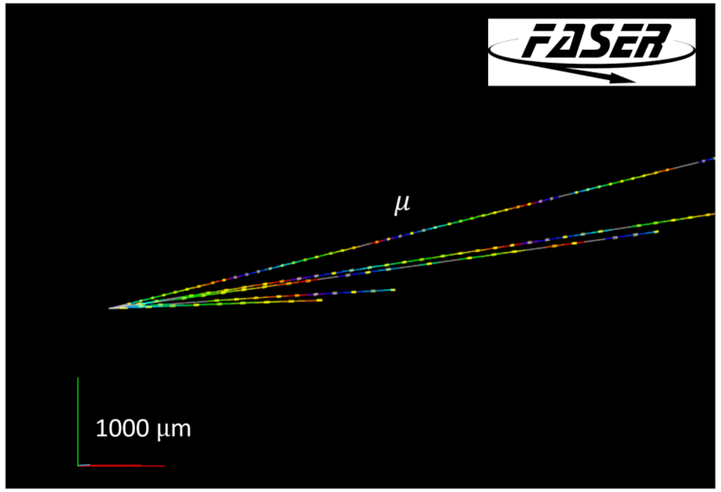


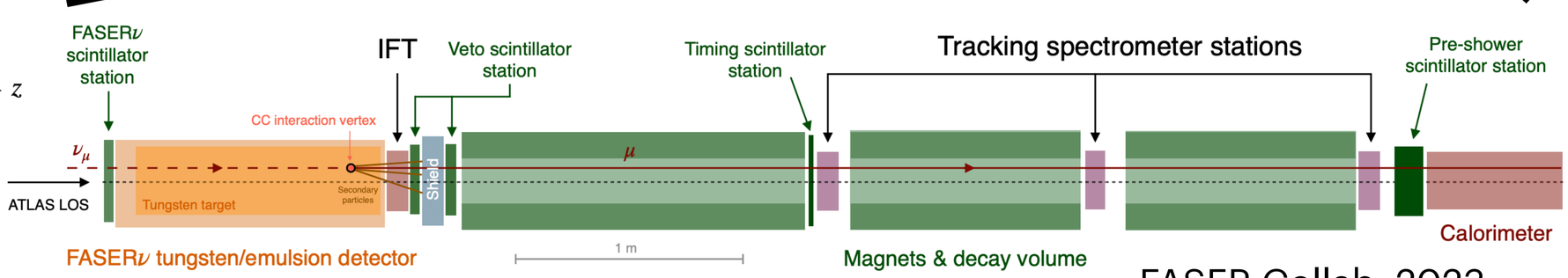
FASER Collab. 2023

The Dawn of Collider Neutrino Physics



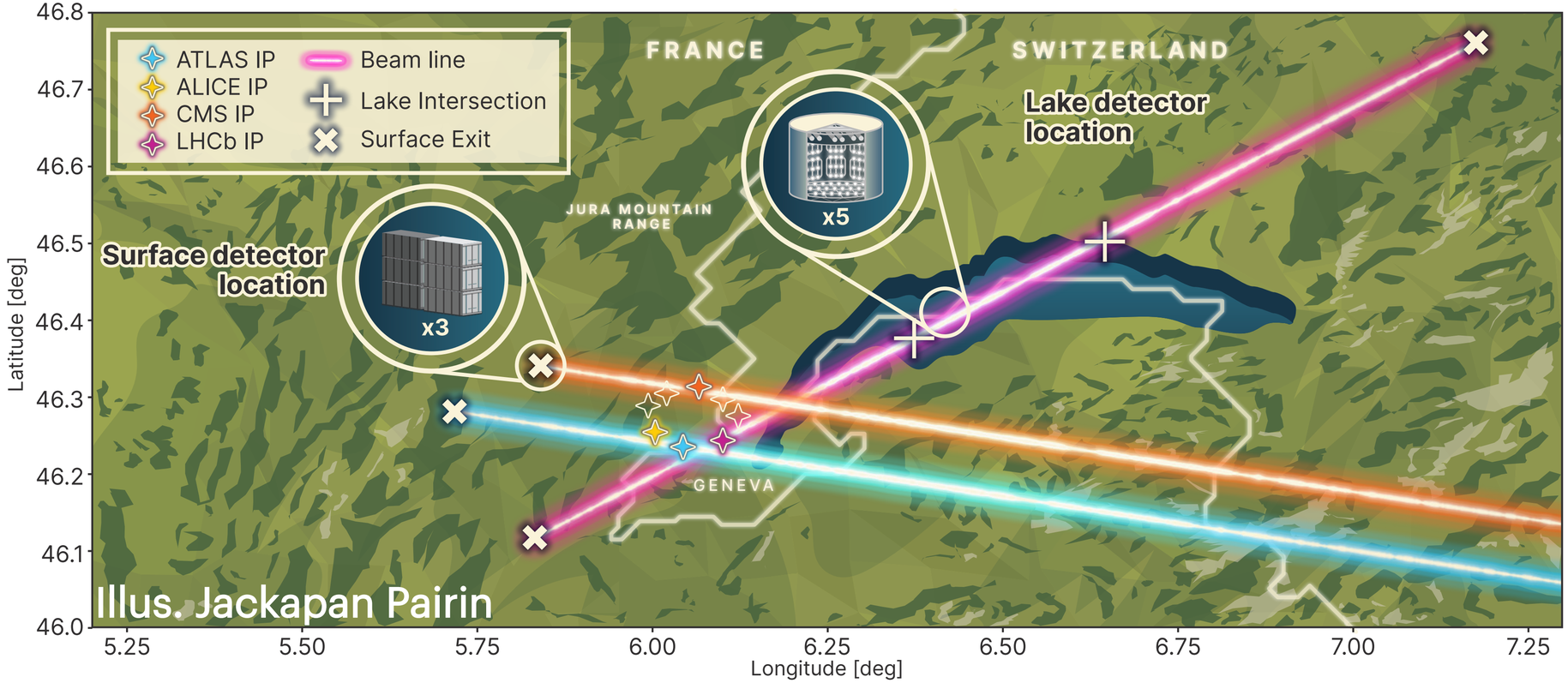


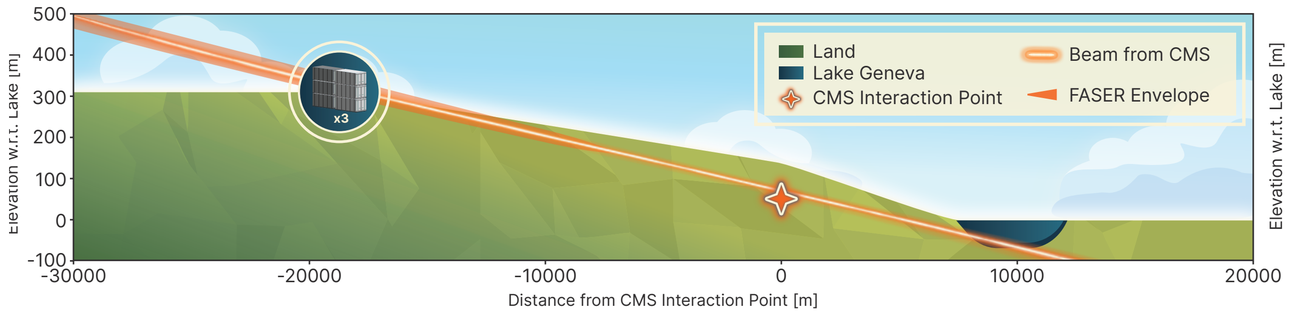


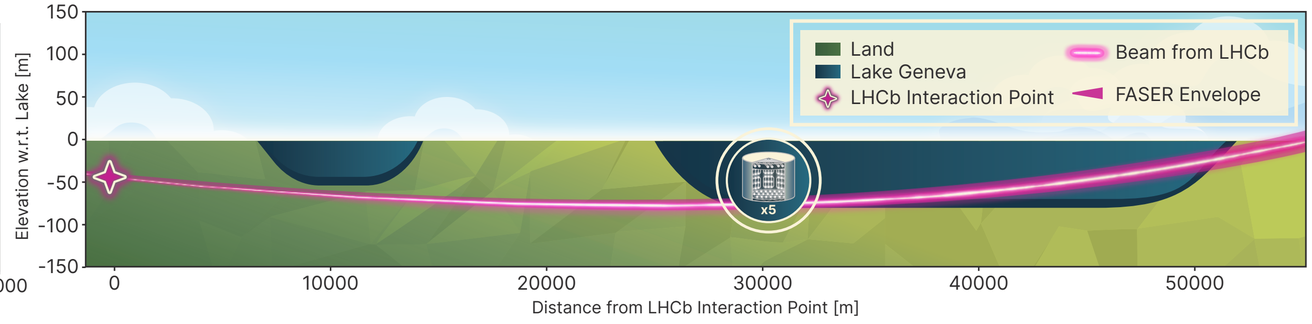


FASER Collab. 2023

LHC Neutrinos pass through Lake Geneva







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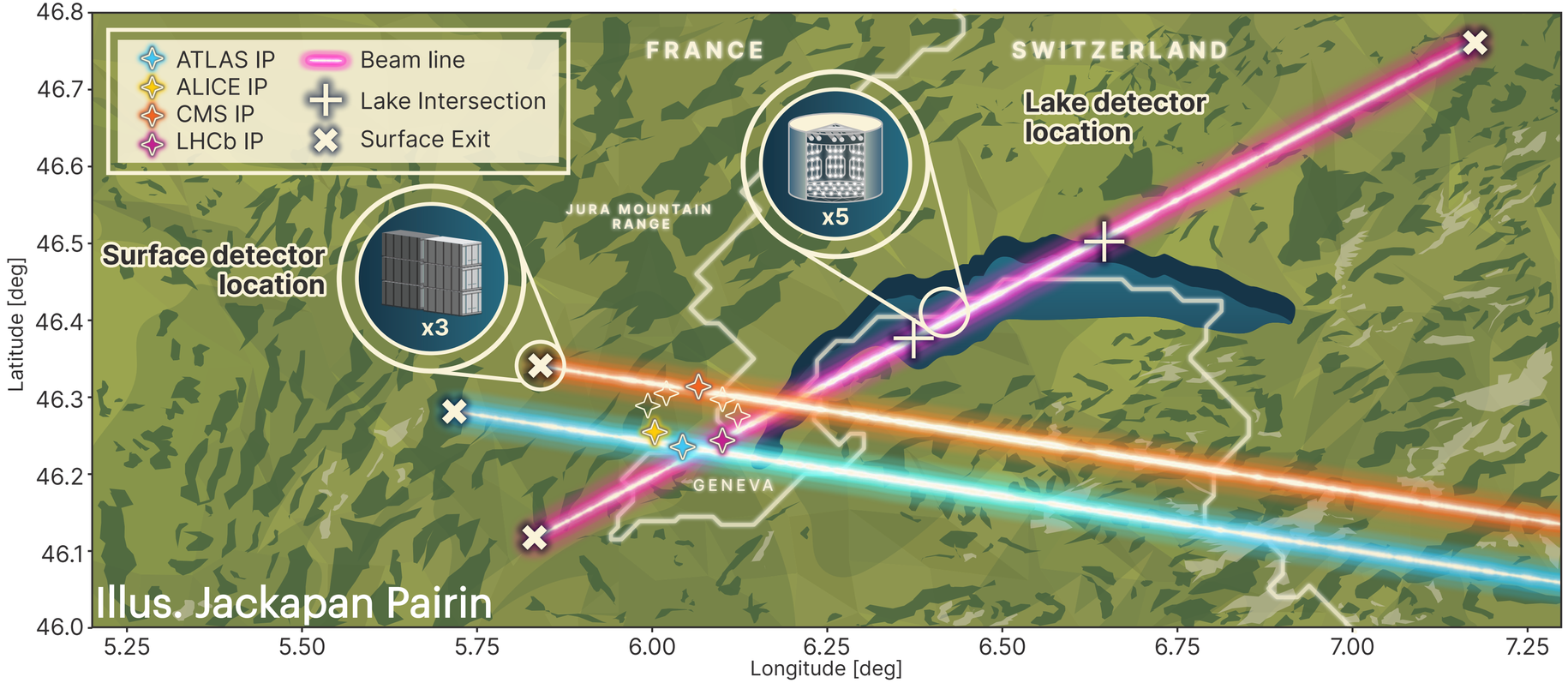
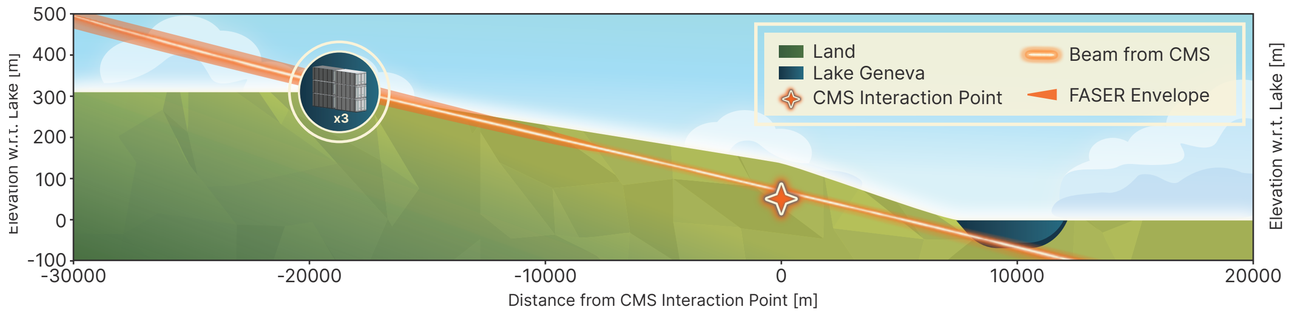
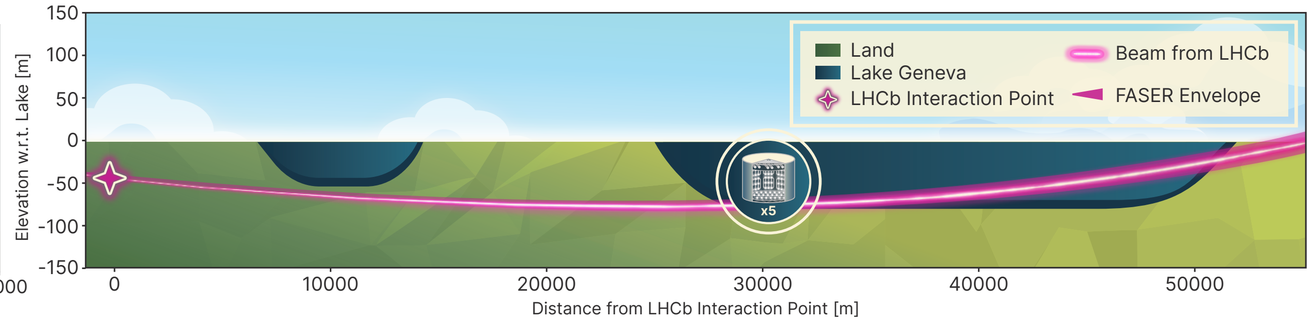
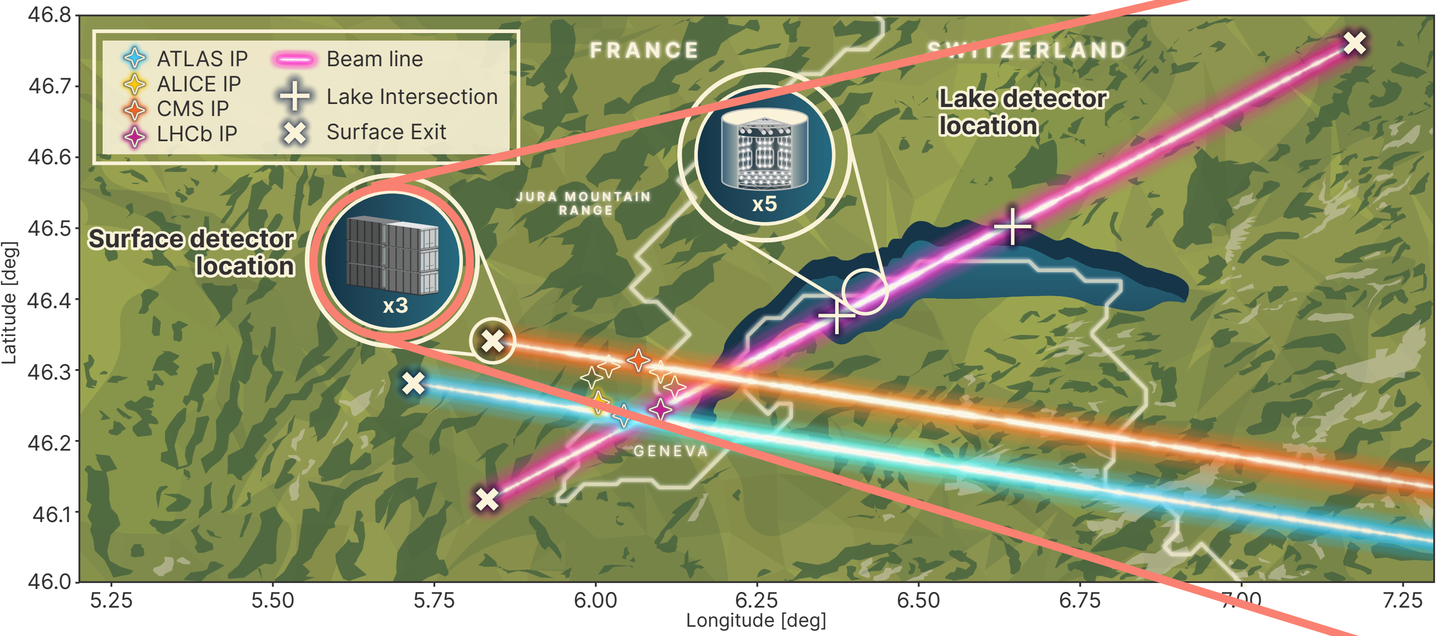


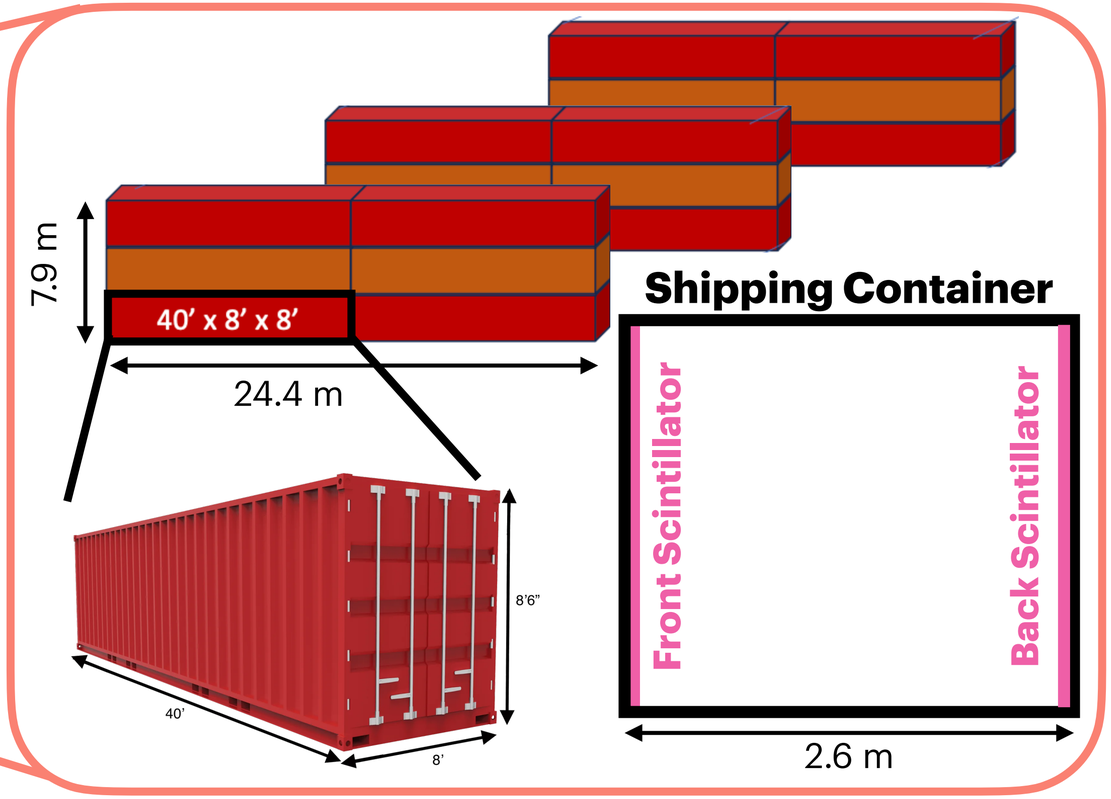
This enables the construction of large-scale natural detectors



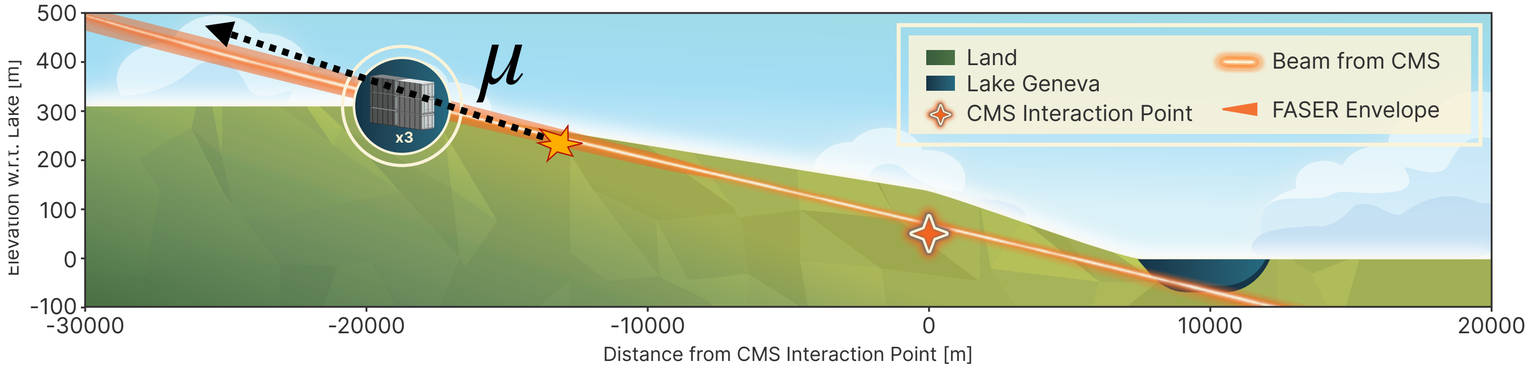


SINE: Surface-based Integrated Neutrino Experiment

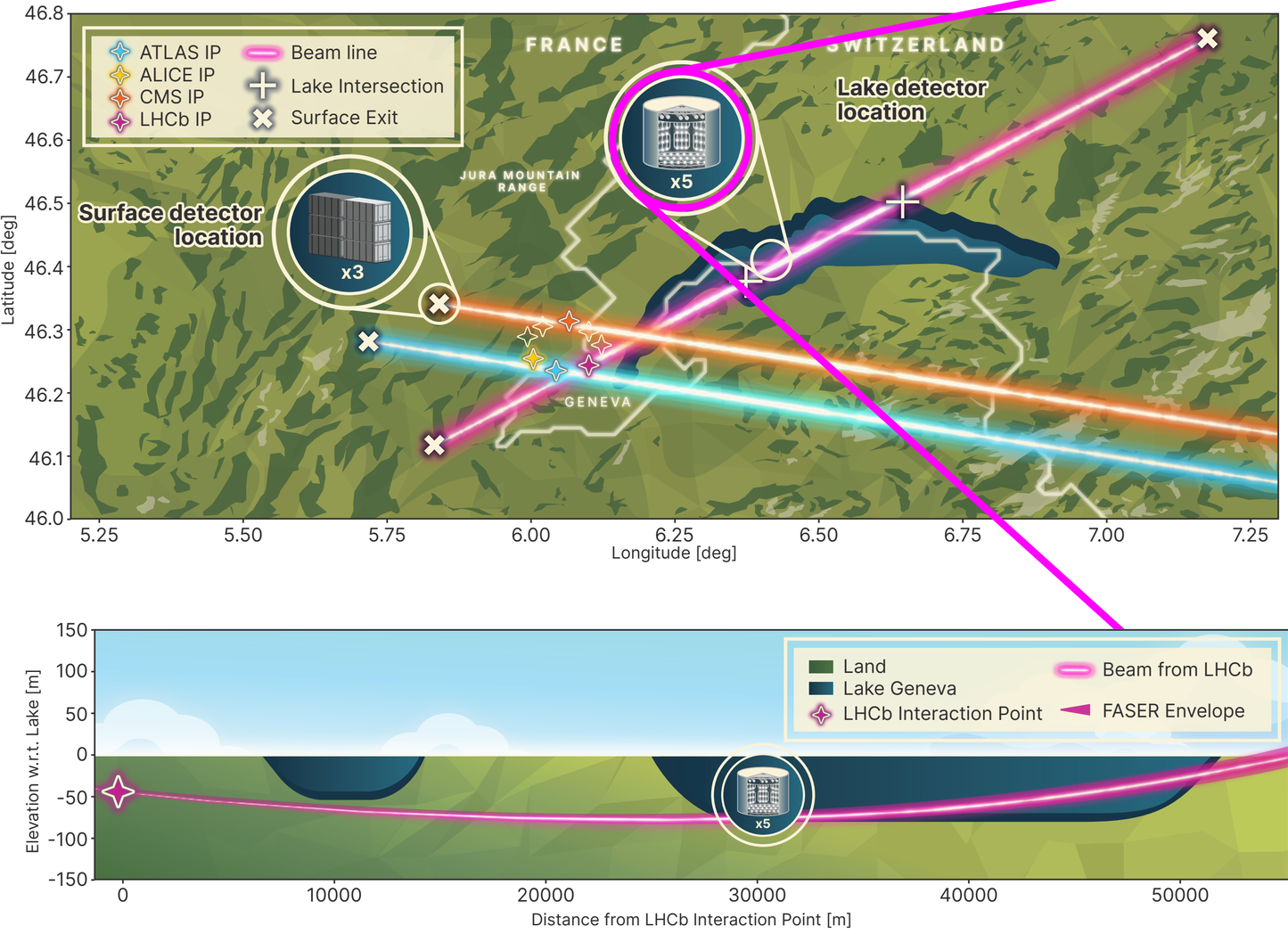


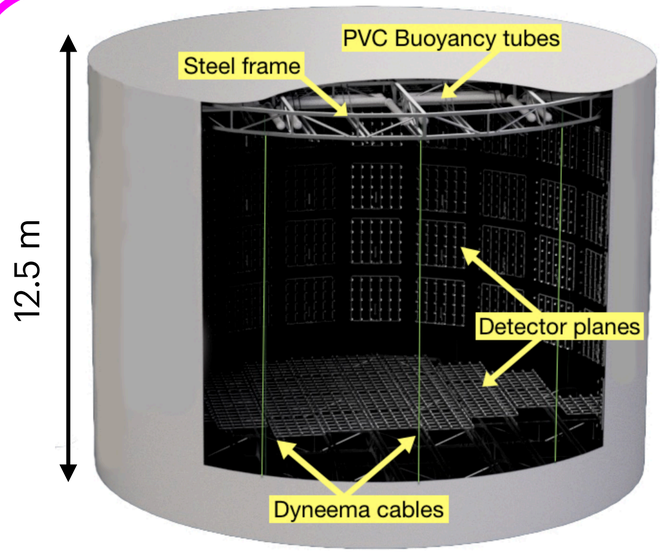


Signal definition: up-going muons from neutrino interactions in bedrock



UNDINE: UNDerwater Integrated Neutrino Experiment





D. Delgado

CHIPS Collab. 2024

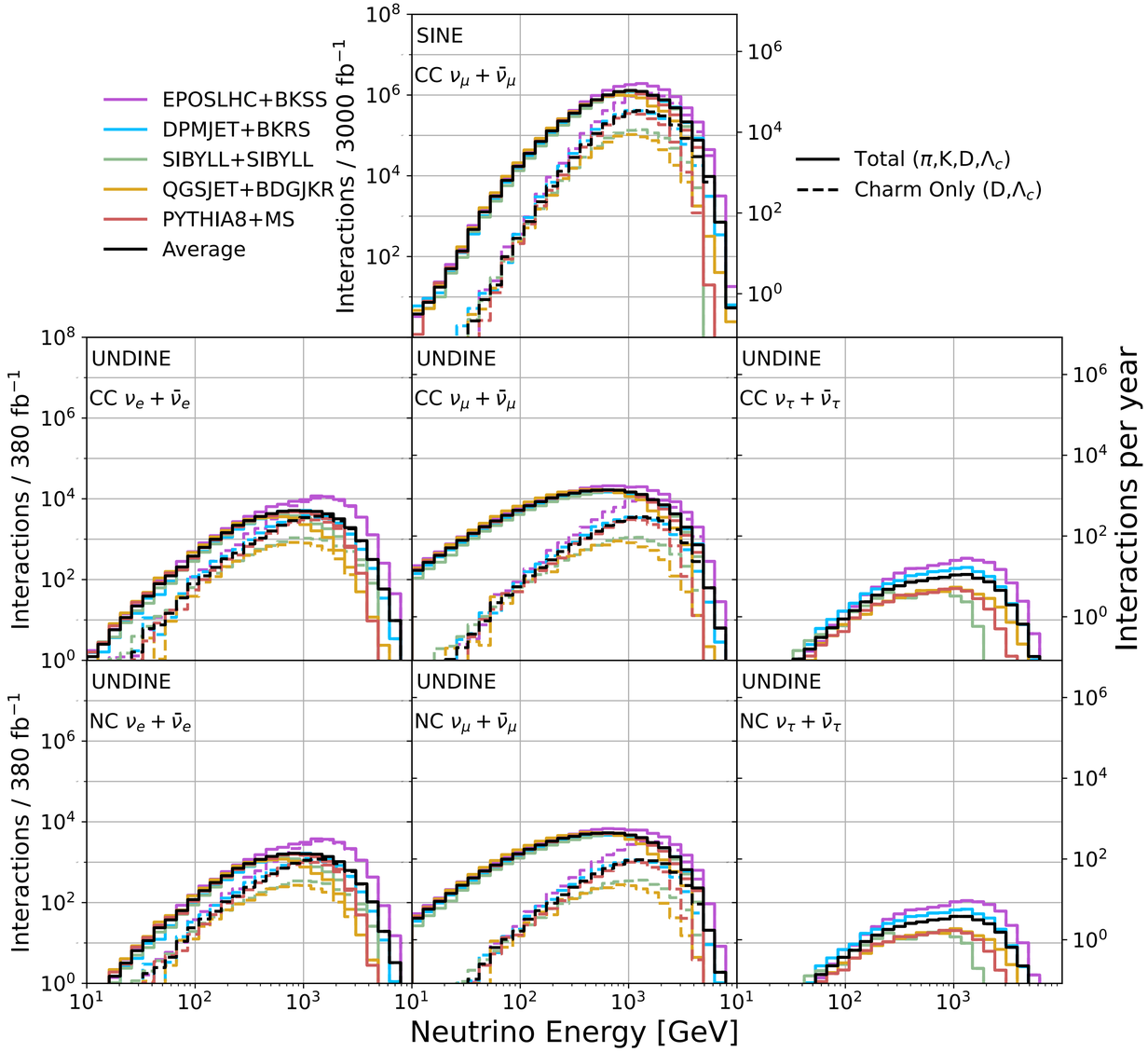
HL-LHC Event Rates

$\mathcal{O}(10\mathrm{M})$ ν_μ interactions in SINE

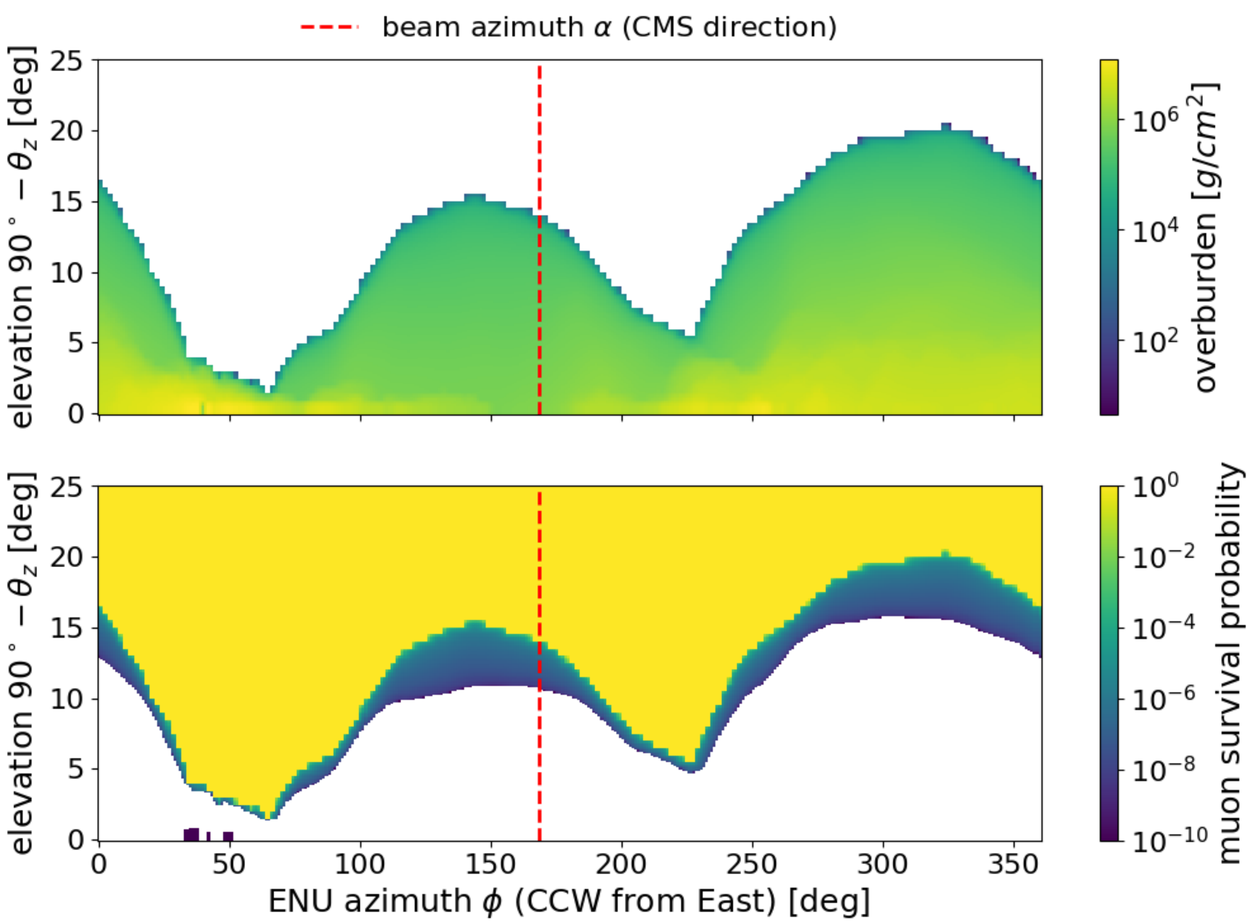
$\mathcal{O}(100\mathrm{k})$ all-flavor neutrino interactions in UNDINE

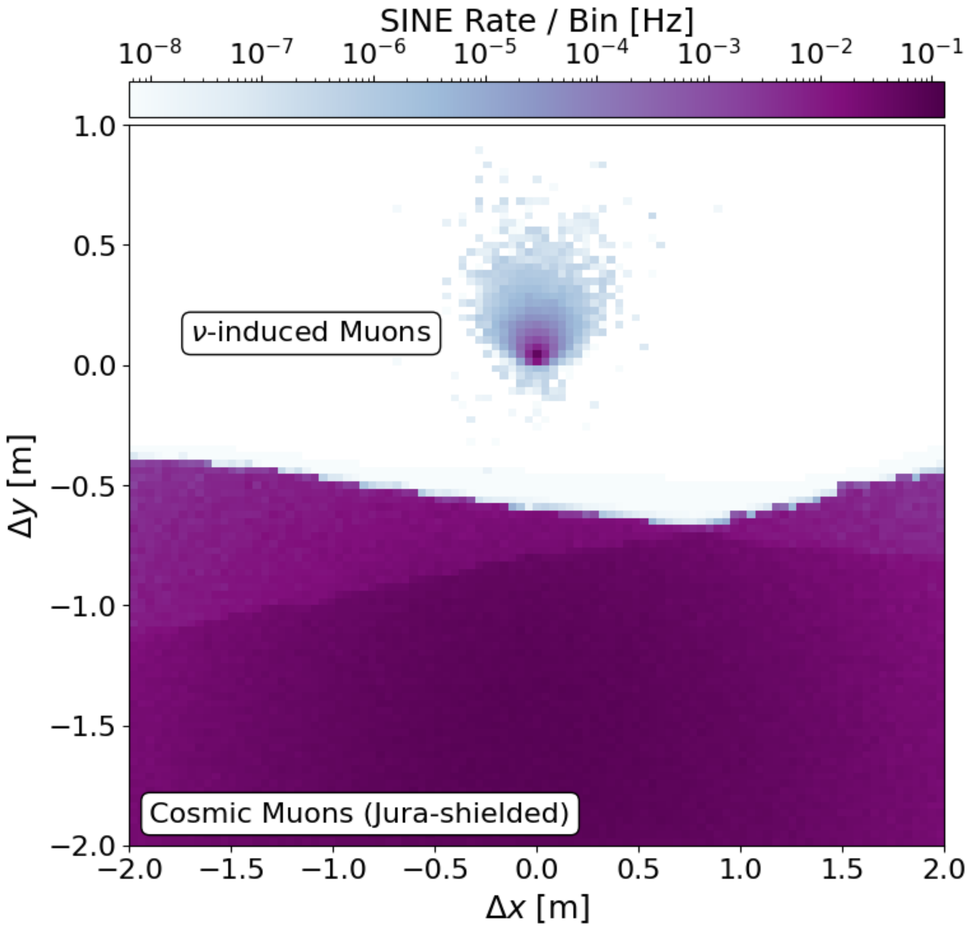
Cost-effective opportunity to collect **large collider neutrino datasets**

Dataset	**Total**	π, K	D, Λ_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 $\nu_\alpha + \bar{\nu}_\alpha$)	$10^{4.87}$	$10^{4.76}$	$10^{4.24}$



Jura Mountains Shield the Vast Majority of Atmospheric Muon Backgrounds in SINE

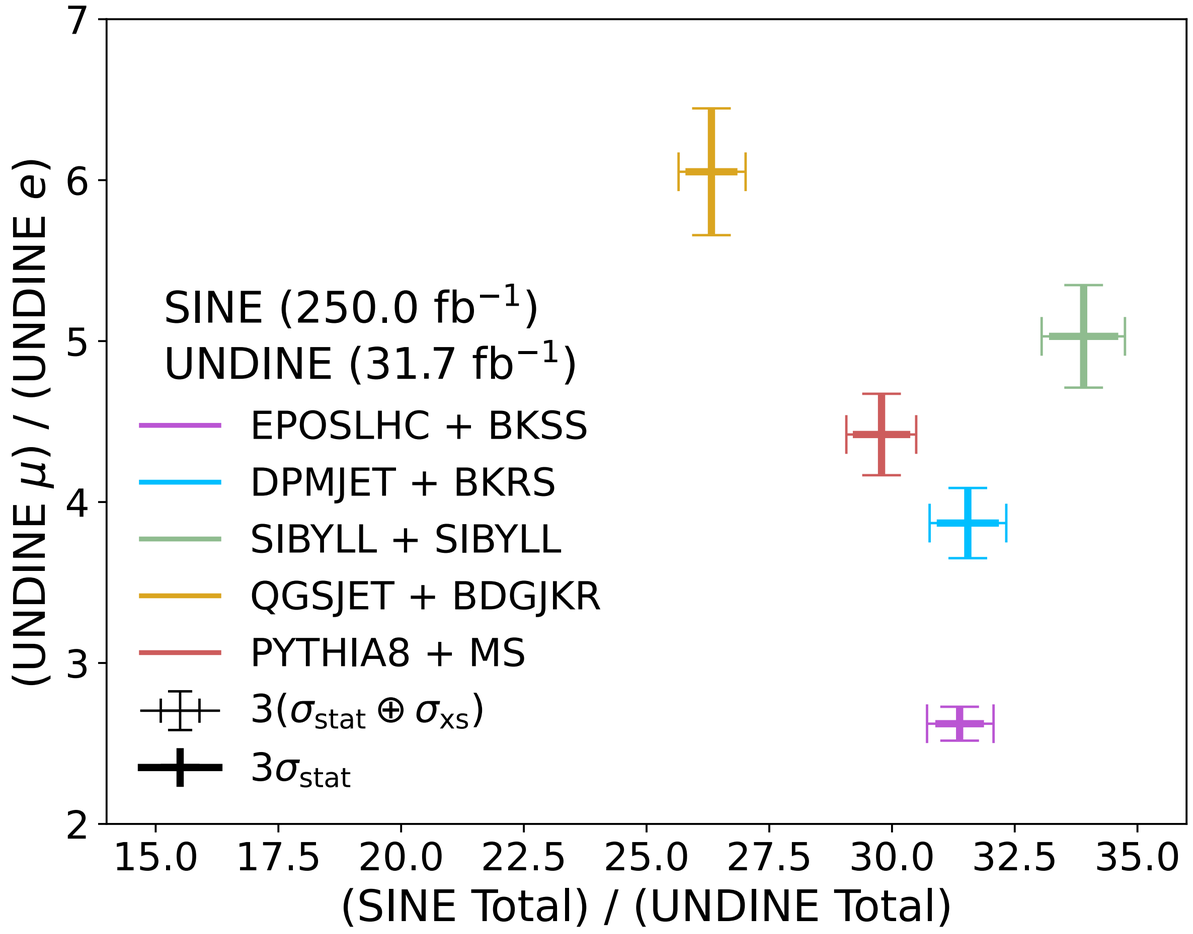




What can we do with ~a million collider neutrinos?

Forward Charm Production in p-p Collisions

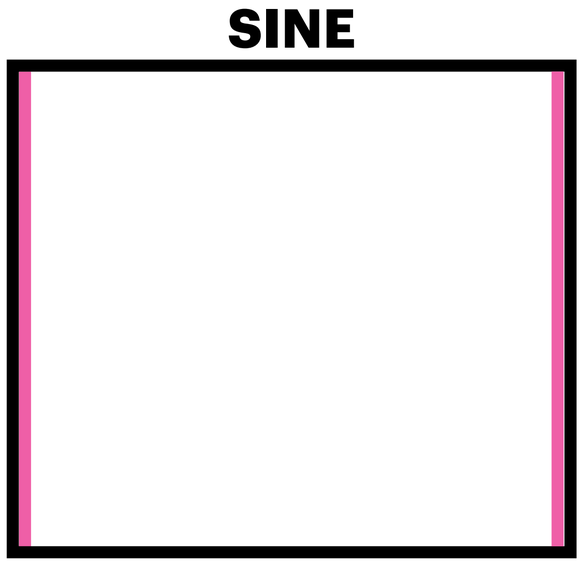
- Increasing forward charm production rates corresponds to...
  1. **More high-energy muon neutrinos**
  2. **More electron and tau neutrinos**
- Ratio measurements can distinguish between charm production models
- Important implications for **intrinsic charm content of the proton [1]** and the **prompt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



[1] Maciula+ 2022 [2] Jeong+ 2023 See also Hallsie Reno's talk from Monday

Heavy Neutral Leptons with SINE

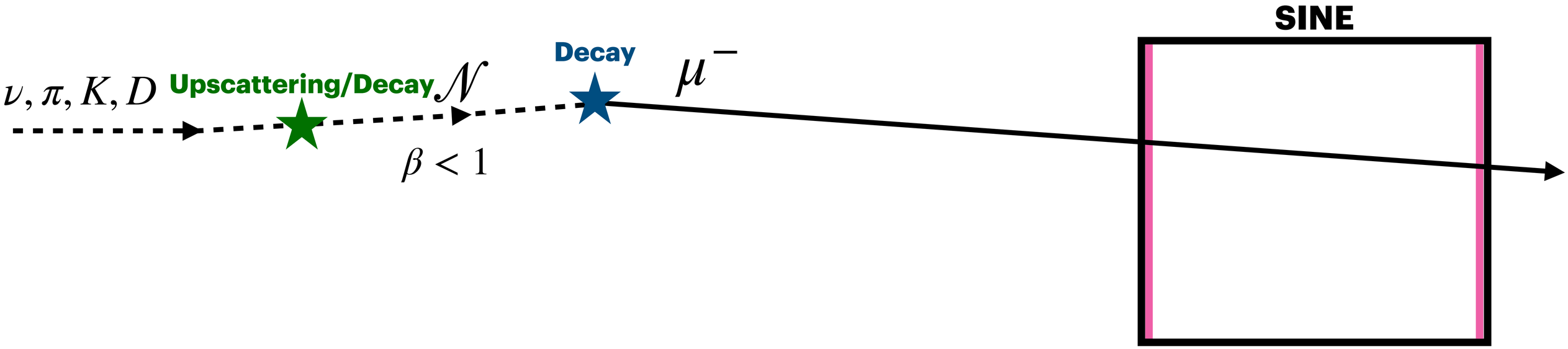
Three signatures:



Heavy Neutral Leptons with SINE

Three signatures:

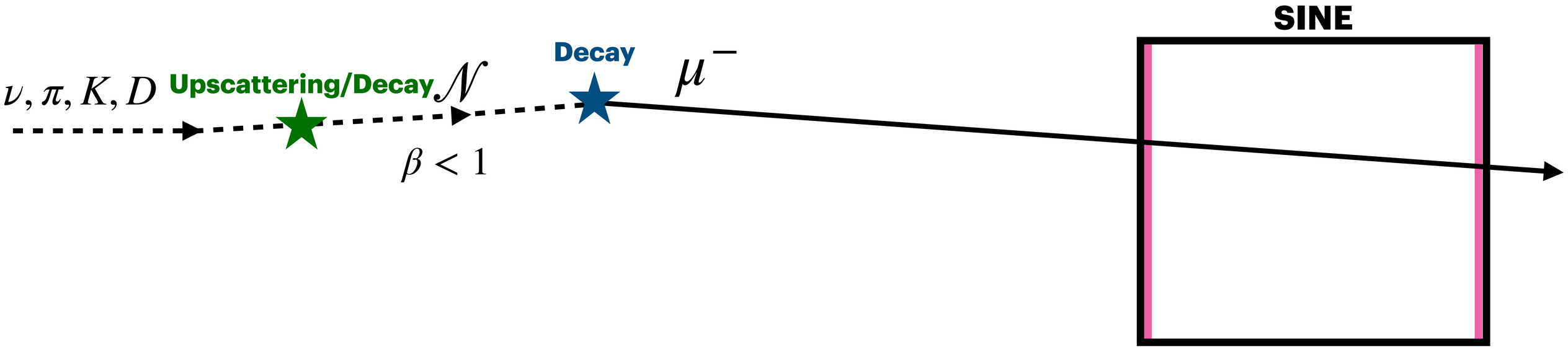
1. Delayed muons with respect to the beam trigger



Heavy Neutral Leptons with SINE

Three signatures:

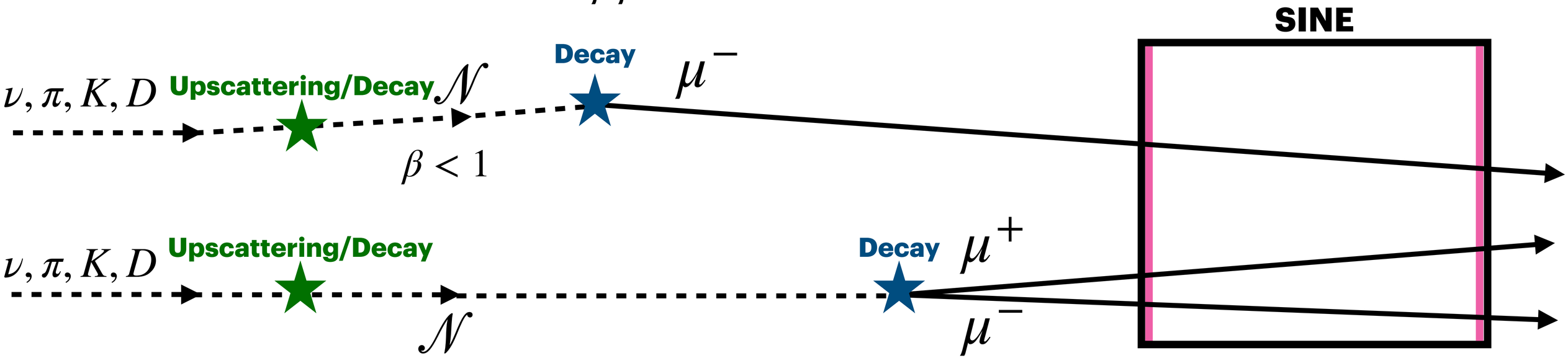
1. Delayed muons with respect to the beam trigger
2. Muons with large transverse displacement between panels



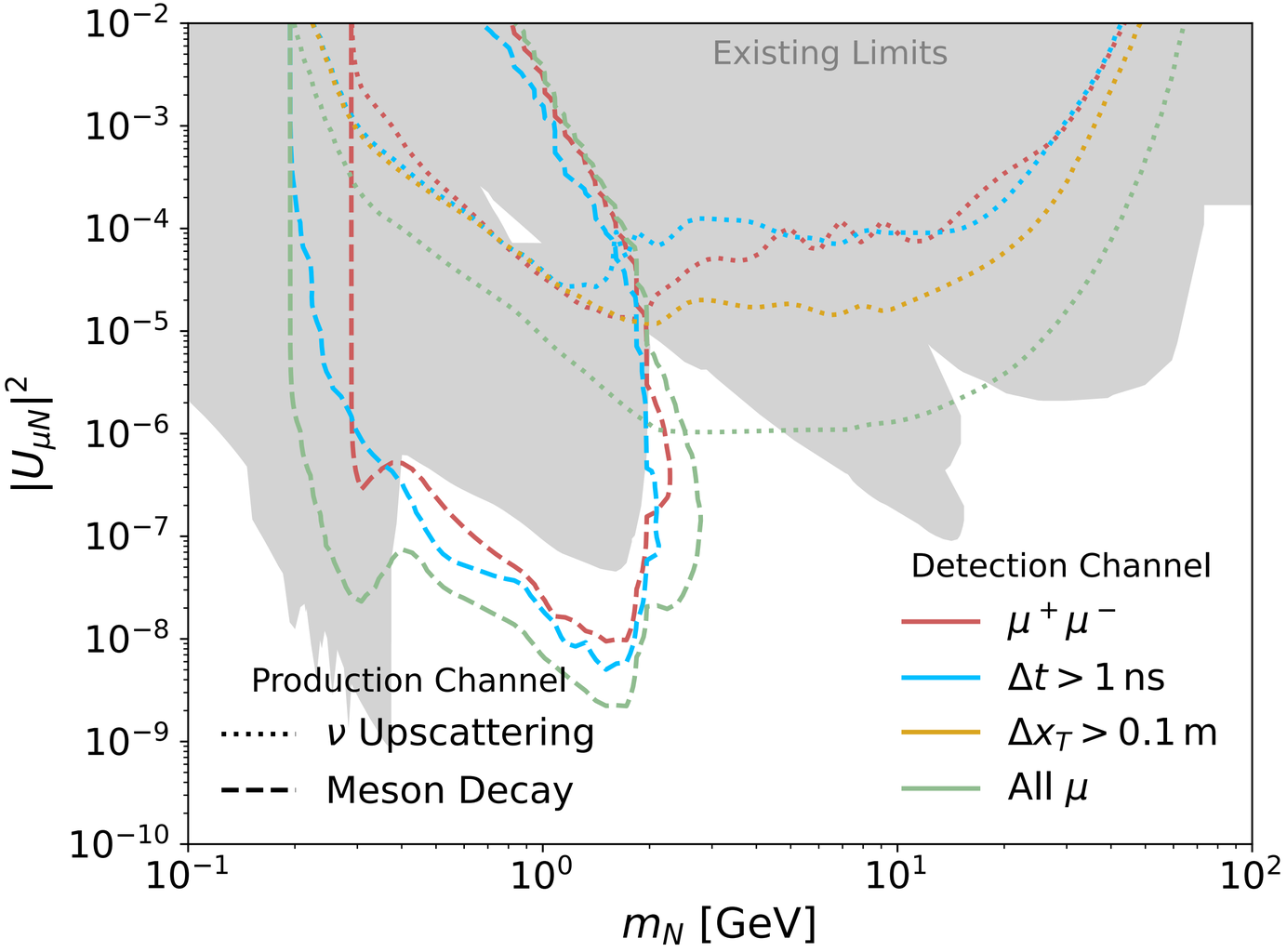
Heavy Neutral Leptons with SINE

Three signatures:

1. Delayed muons with respect to the beam trigger
2. Muons with large transverse displacement between panels
3. Di-muons from $\mathcal{N} \rightarrow \nu\mu\mu$



Heavy Neutral Leptons with SINE



Combination of upscattering and decay production channels covers broader range of HNL masses

Outline: Three New Directions for Collider Neutrinos

1. Lake- and surface-based detectors for LHC neutrinos
2. **The “Neutrino Kaleidoscope": pairing muon colliders and neutrino telescopes**
3. Searching for heavy neutrinos with a muon beam

arXiv:2508.09249

The Neutrino Kaleidoscope: Searches for Non-Standard Neutrino Oscillations at Neutrino Telescopes with a TeV Muon Accelerator Source

Nicholas W. Kamp[1] and Gray Putnam[2]

[1] *Department of Physics and Laboratory for Particle Physics & Cosmology, Harvard University*
[2] *Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*

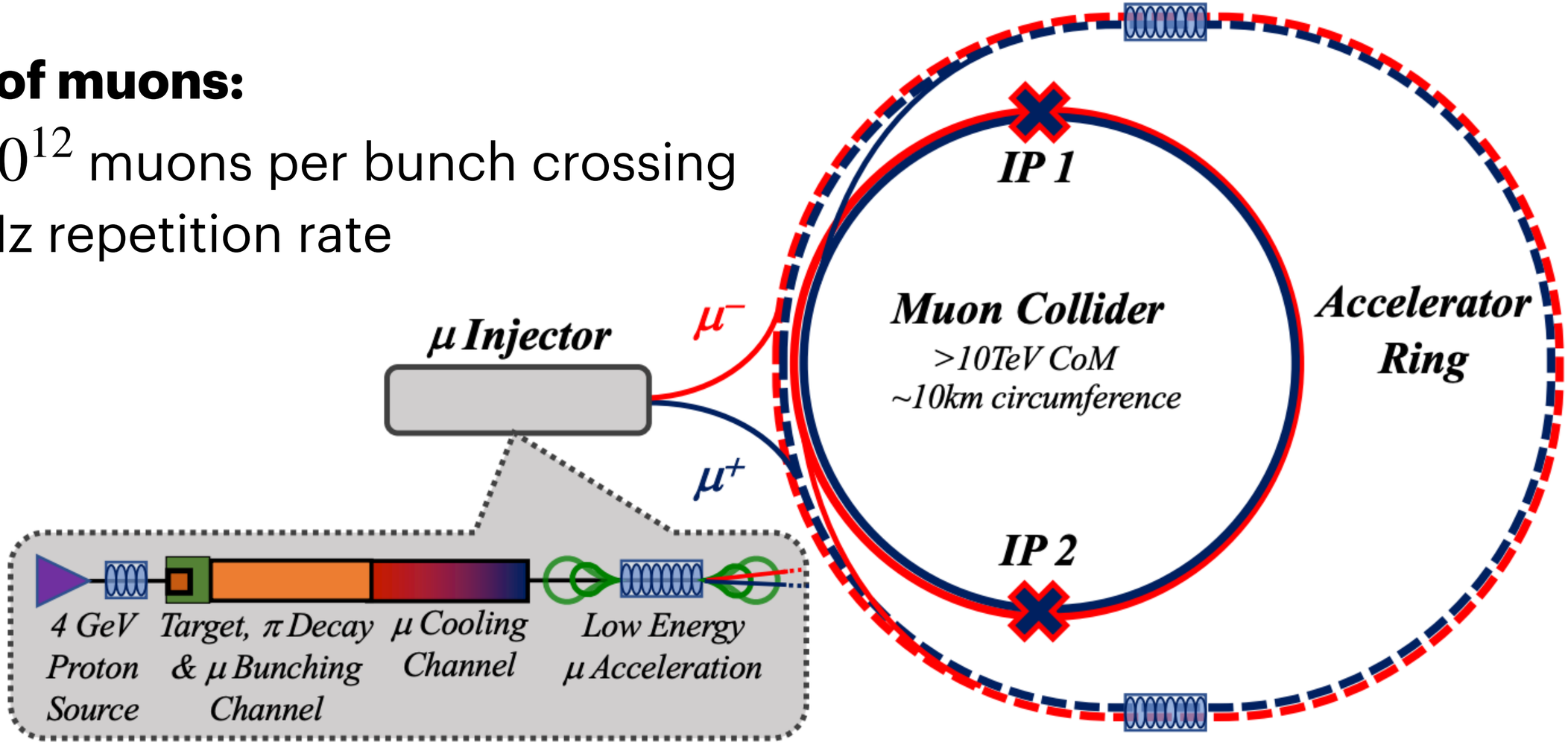
G. Putnam

A “Typical” Muon Collider

Lots of muons:

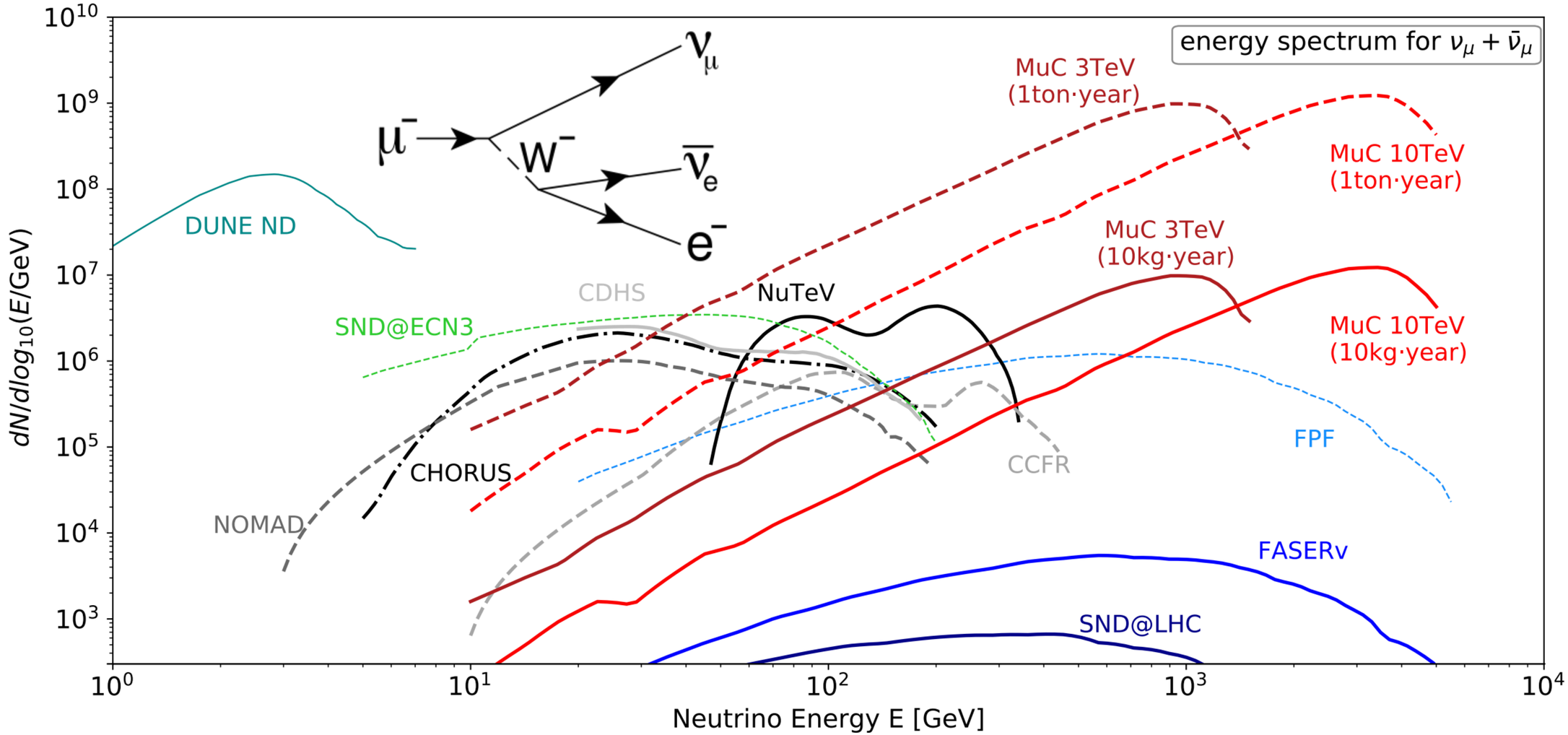
2×10^{12} muons per bunch crossing

@ 5 Hz repetition rate



Interim report for the International Muon Collider Collaboration, 2024

Muon Decay → Free* Neutrino Beam



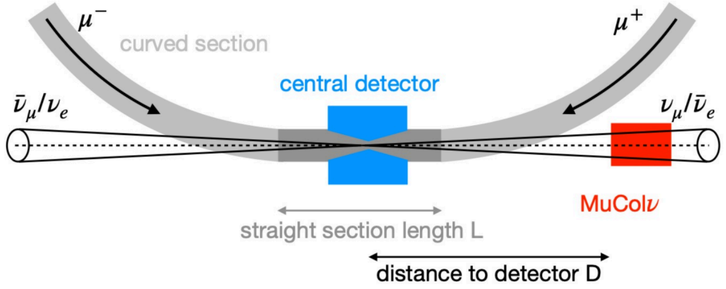
Interim report for the International Muon Collider Collaboration, 2024

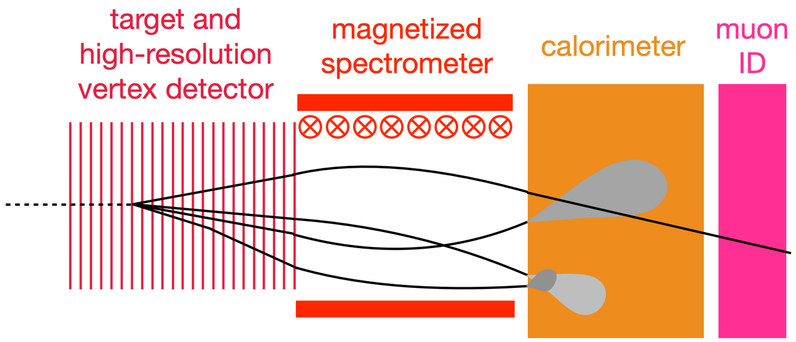
*after you build a multi-billion $ muon beam

Proposed Neutrino Detectors @ a Muon Collider

A "general purpose" forward detector

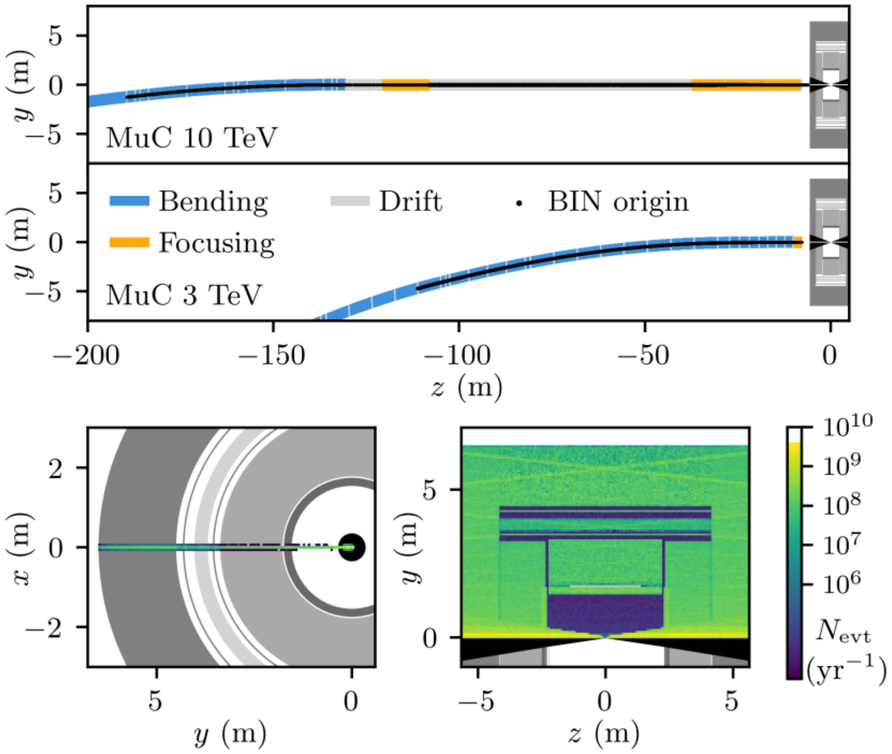
Kling+ 2025 Bigi+ 2001





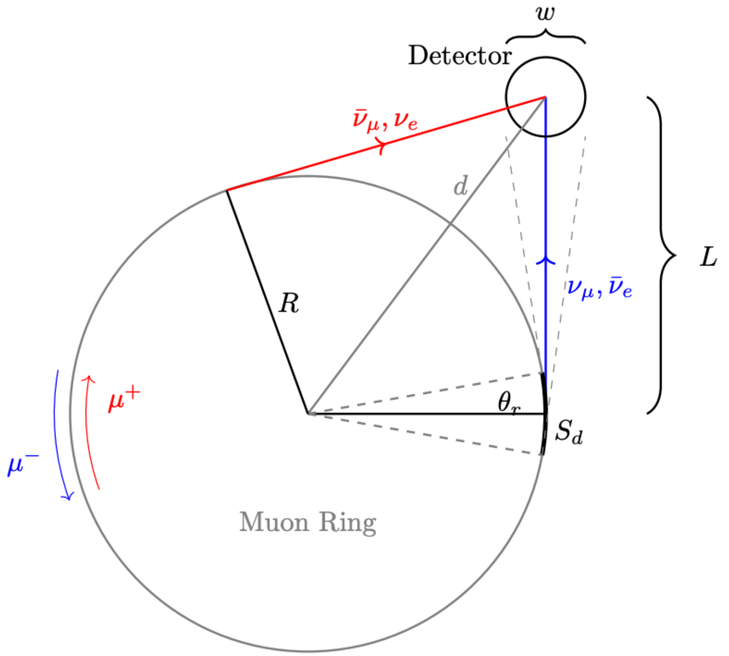
The "neutrino slice" at the interaction point

Bojorquez-Lopez+ 2024



A "hockey-puck" detector measuring both beams

de Gouvêa+ 2025



Rich physics program: cross sections, QCD, electroweak observables, and more

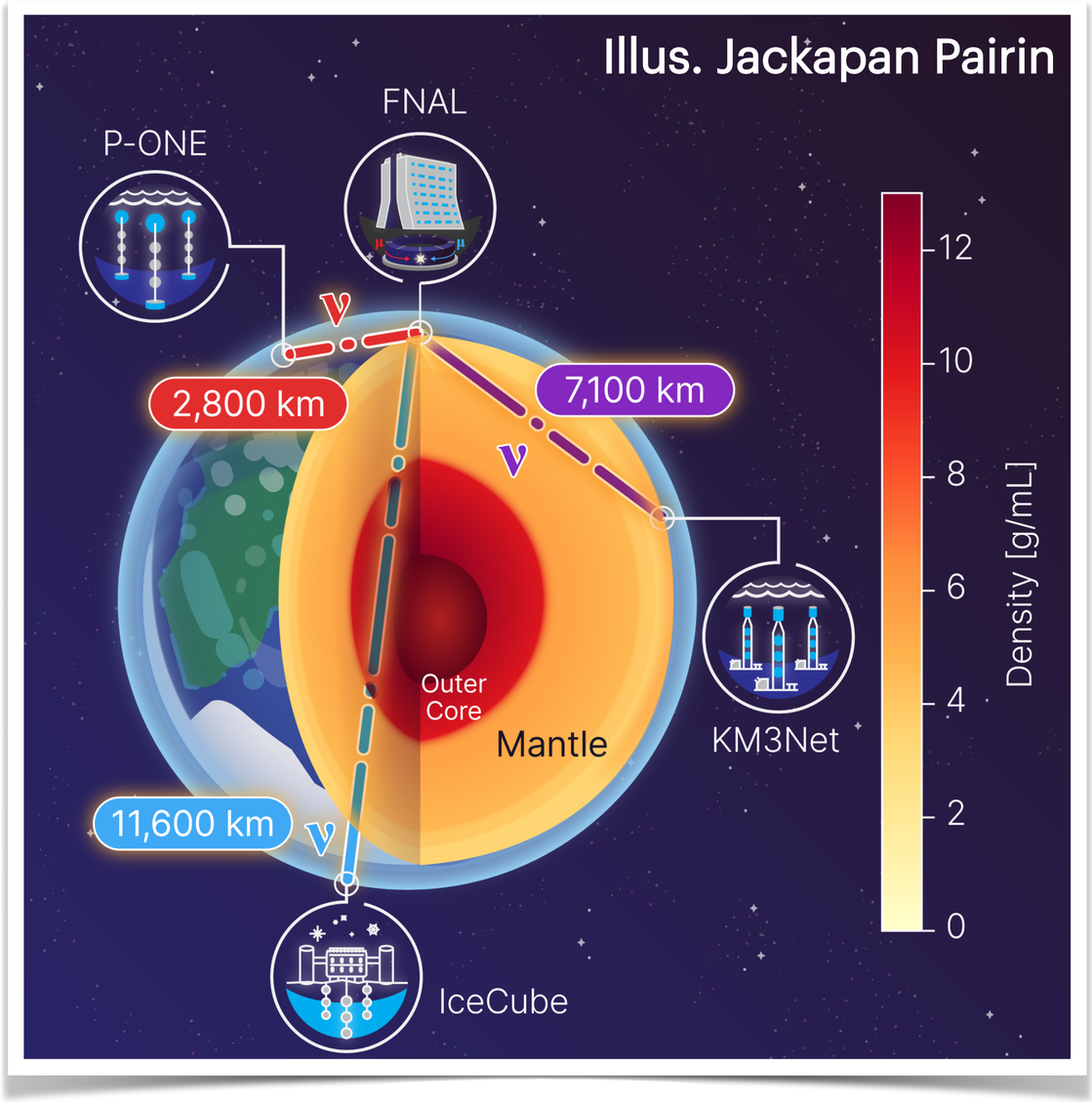
See Zahra Tabrizi's talk last Friday

Introducing the “Neutrino Kaleidoscope”

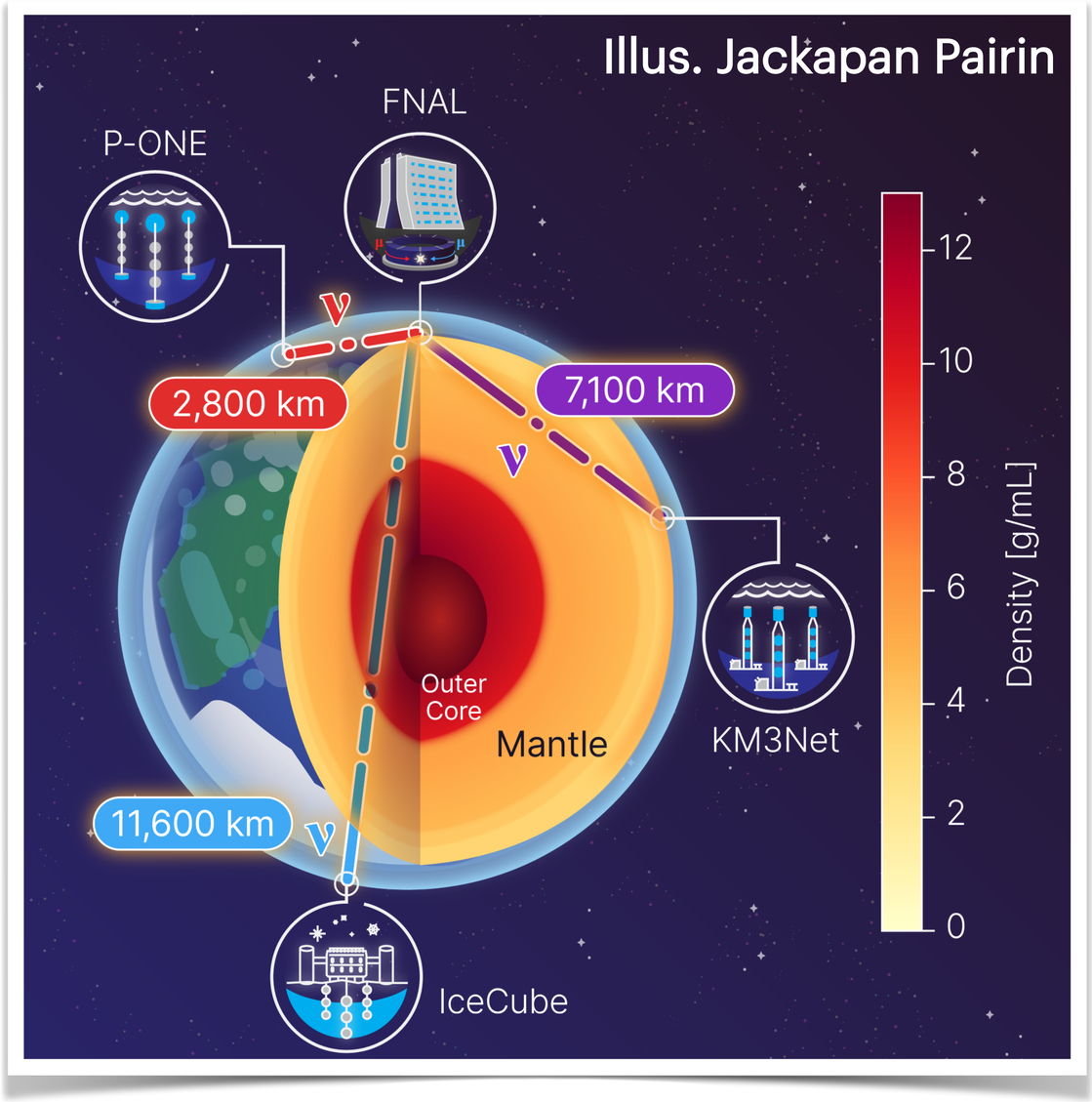
Introducing the “Neutrino Kaleidoscope”

Or, if you will, “collide-o-scope”

Introducing the “Neutrino Kaleidoscope”

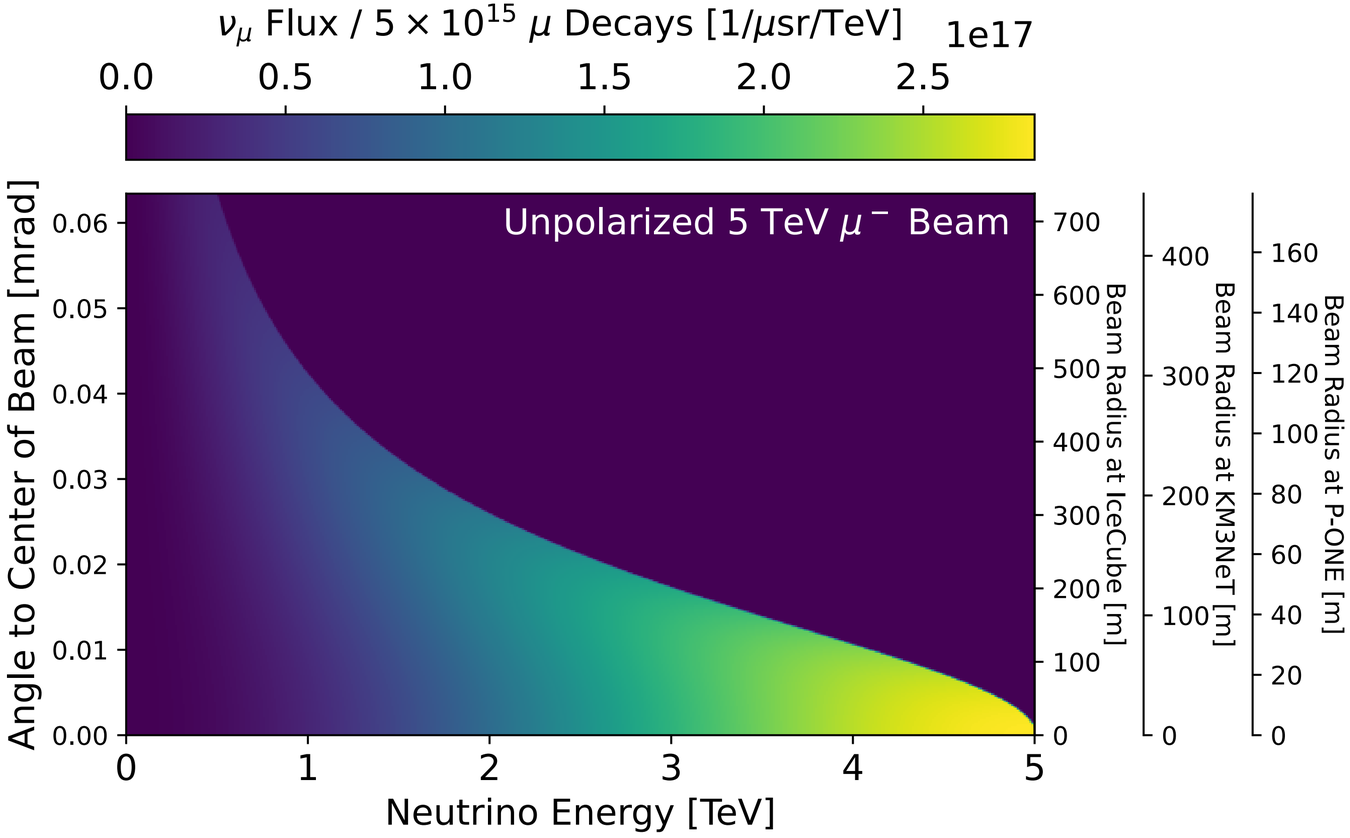


Introducing the “Neutrino Kaleidoscope”

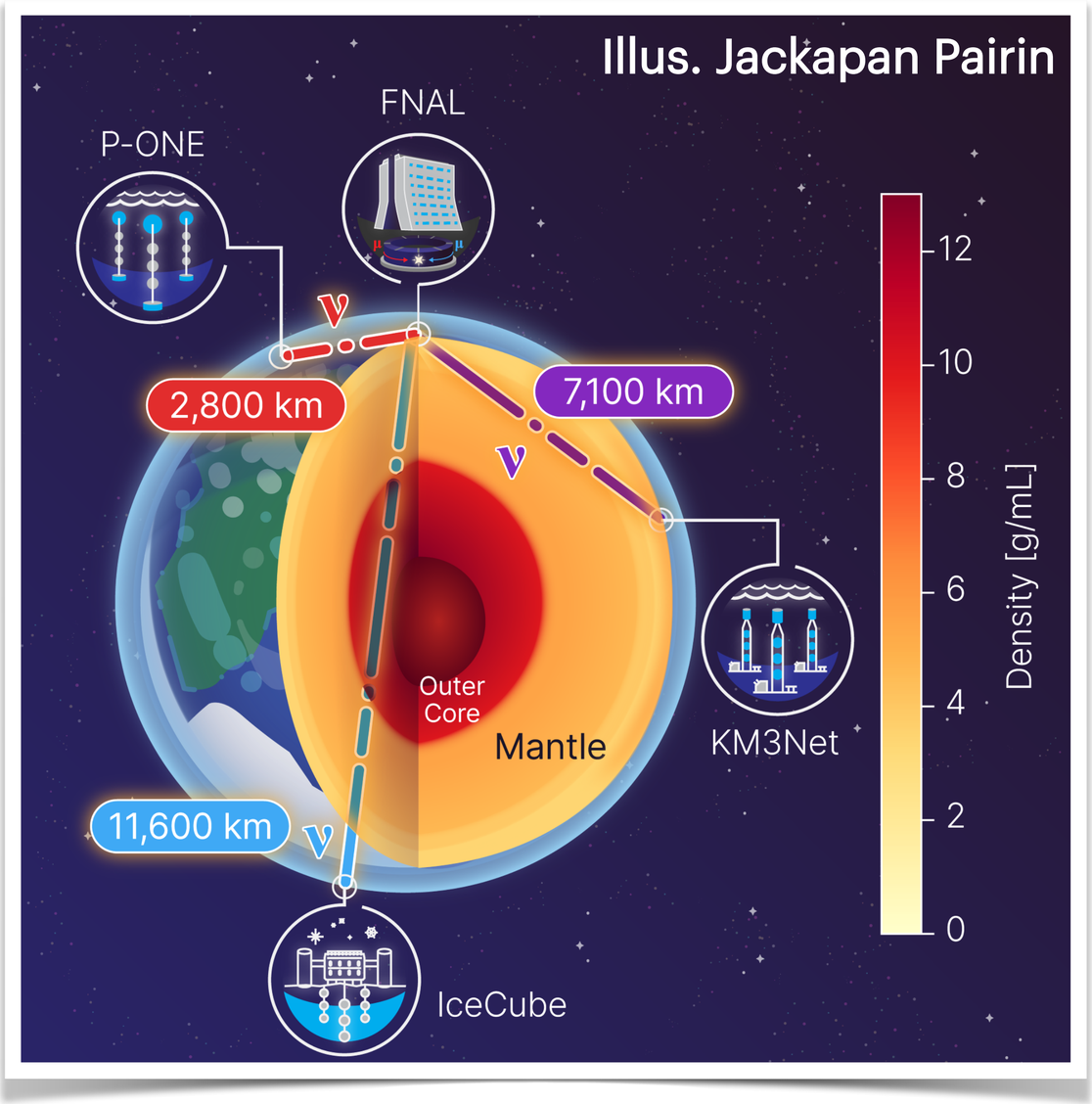


The neutrino beam is collimated to within $\mathcal{O}(100\,\mathrm{m})$ over Earth-diameter distances:

Perfect for Gigaton-scale neutrino telescopes!

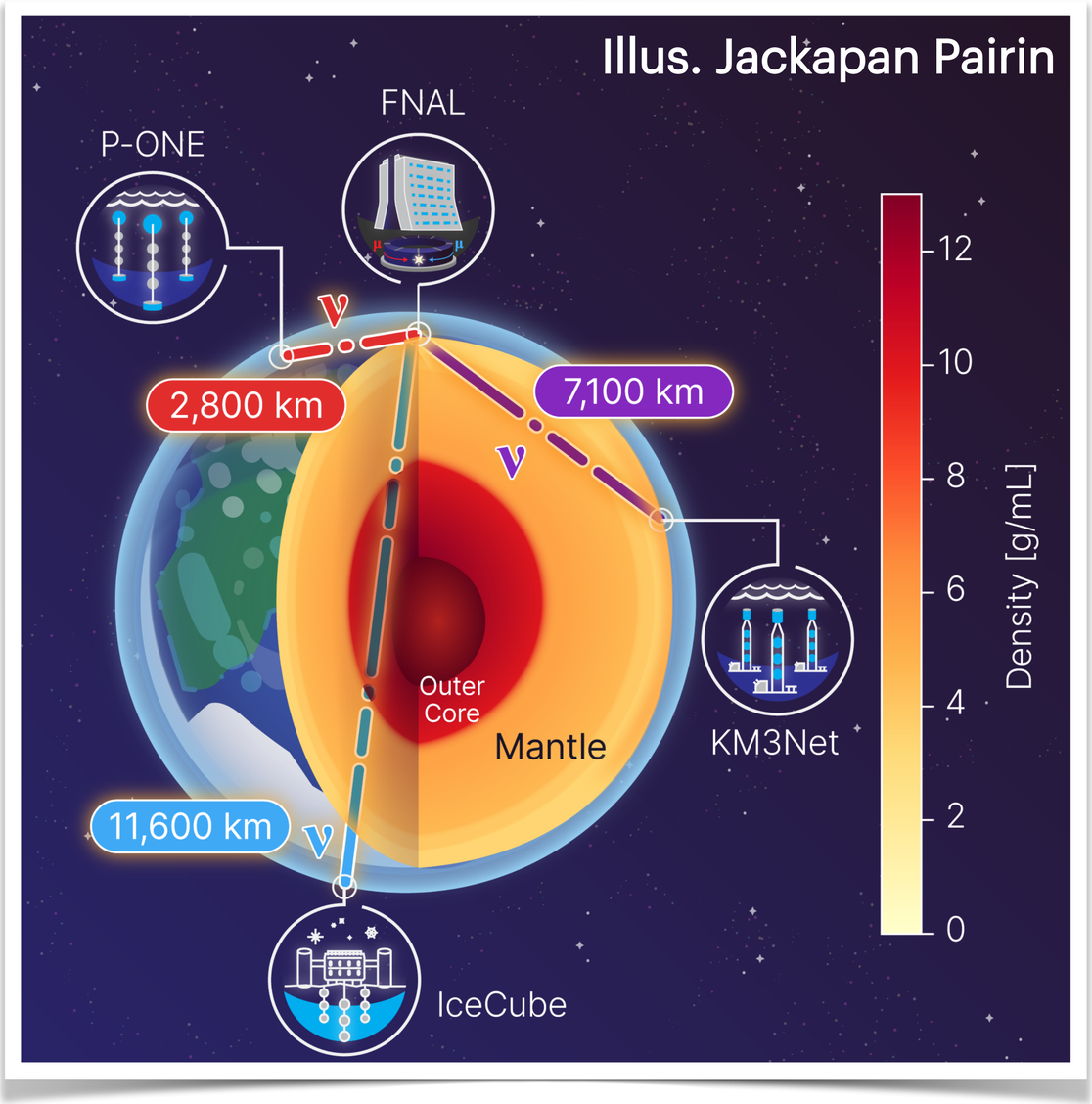


A Beam for Neutrino Telescopes



Two options for pointing:

A Beam for Neutrino Telescopes

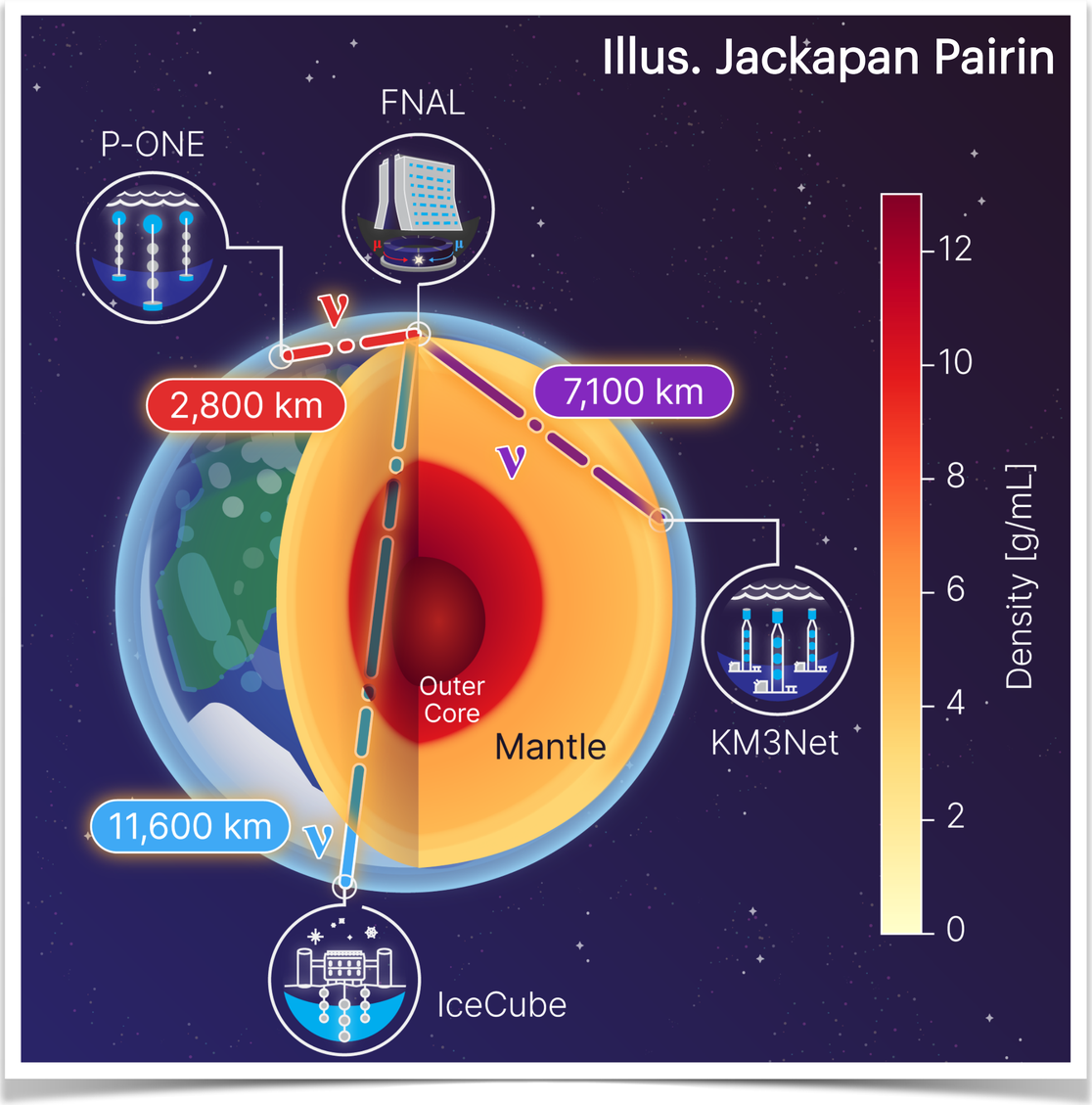


Two options for pointing:

1: Point a straight section of the ring at a telescope

- Typical 30 cm section results in 5×10^{14} muon decays per year
- 100 m straight section near the interaction point results in 8×10^{18} muon decays per year, though larger angular spread
- Likely only possible for FNAL → P-ONE

A Beam for Neutrino Telescopes



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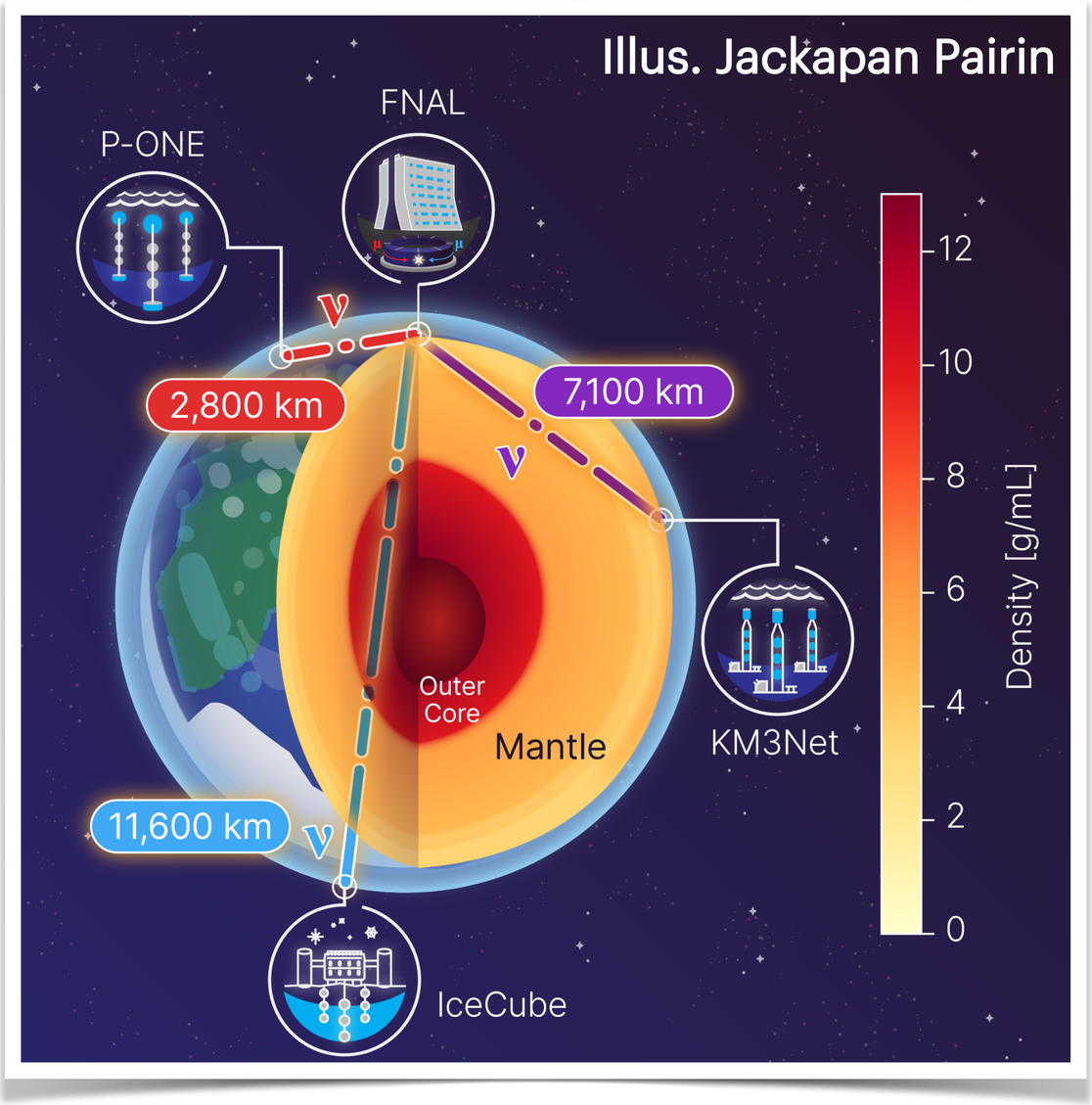
2: Point the beam dump toward a telescope

- 25 m decay tunnel results in 2×10^{14} muon decays per year
- Possible for FNAL → {P-ONE, IceCube, KM3NeT}

A Beam for Neutrino Telescopes



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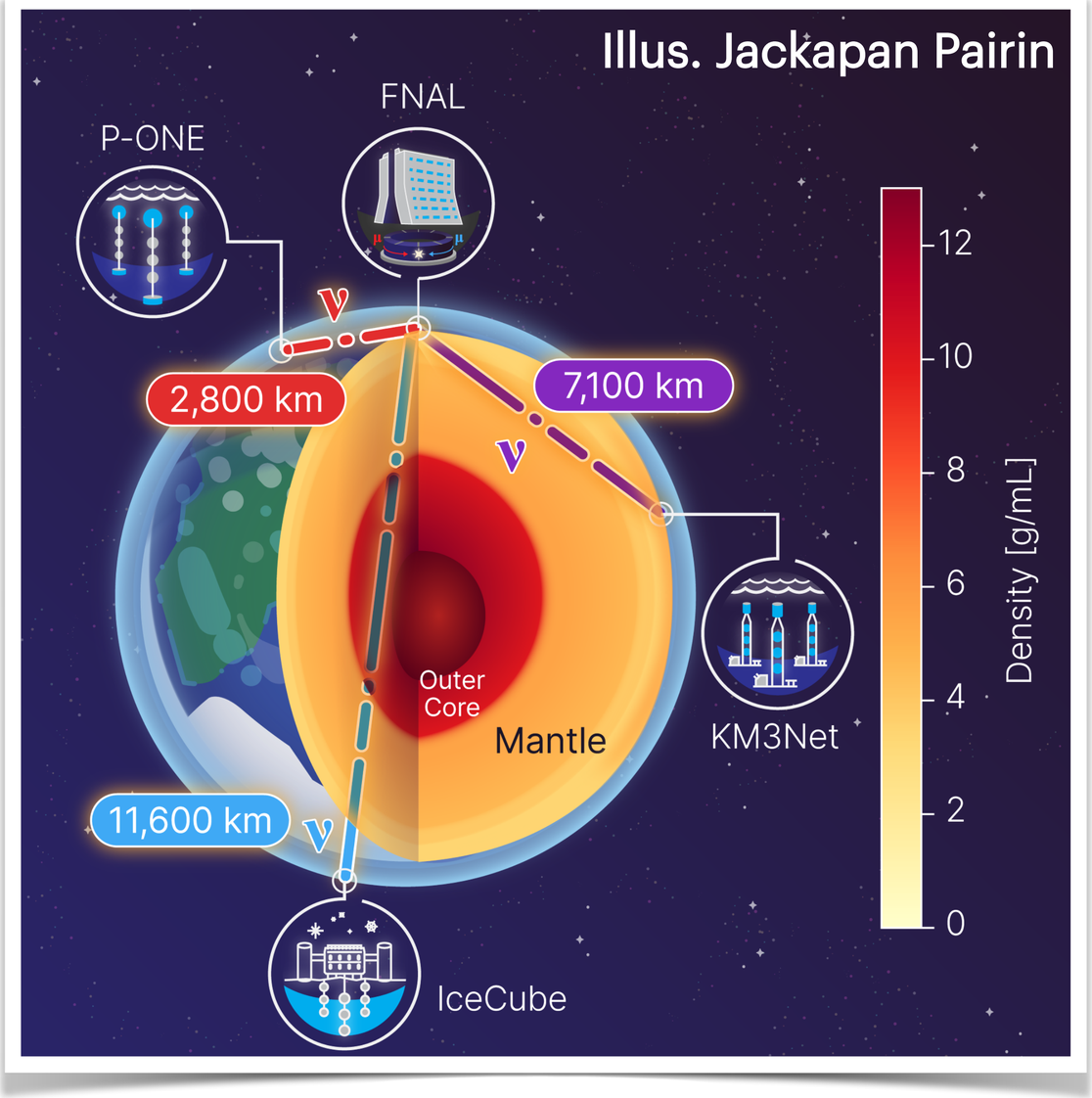

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Between these cases, we expect approximately $10^{8} - 10^{11}$ neutrino interactions per year

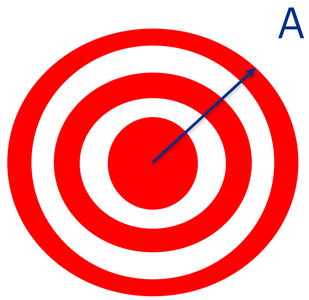
ν Kaleidoscopes for Sterile Neutrinos

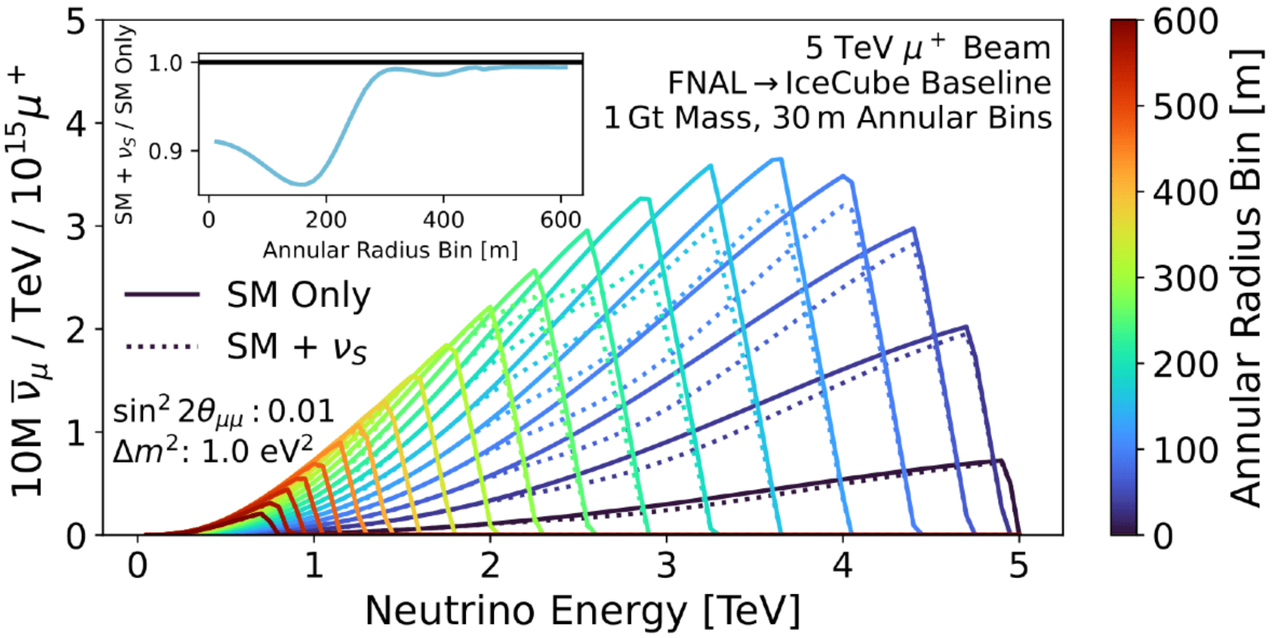
An eV-scale HNL (aka a sterile neutrino) would induce non-standard matter effects as neutrinos propagate through the Earth

$$i\frac{d}{dx}\begin{pmatrix}\nu_\alpha\\ \nu_S\end{pmatrix} = \begin{pmatrix}-\frac{\Delta m^2_{41}}{4E}\cos 2\theta_{\alpha\alpha} \pm_\alpha G_F N_e/\sqrt{2} & \frac{\Delta m^2_{41}}{4E}\sin 2\theta_{\alpha\alpha}\\ \frac{\Delta m^2_{41}}{4E}\sin 2\theta_{\alpha\alpha} & \frac{\Delta m^2_{41}}{4E}\cos 2\theta_{\alpha\alpha}\end{pmatrix}\begin{pmatrix}\nu_\alpha\\ \nu_S\end{pmatrix}$$

$$\pm_\alpha = \begin{cases}+1 & \alpha \in \{e, \bar{\mu}\}\\ -1 & \alpha \in \{\bar{e}, \mu\}\end{cases}$$

This would lead to a distortion in the energy **and** radial distributions in a ν kaleidoscope



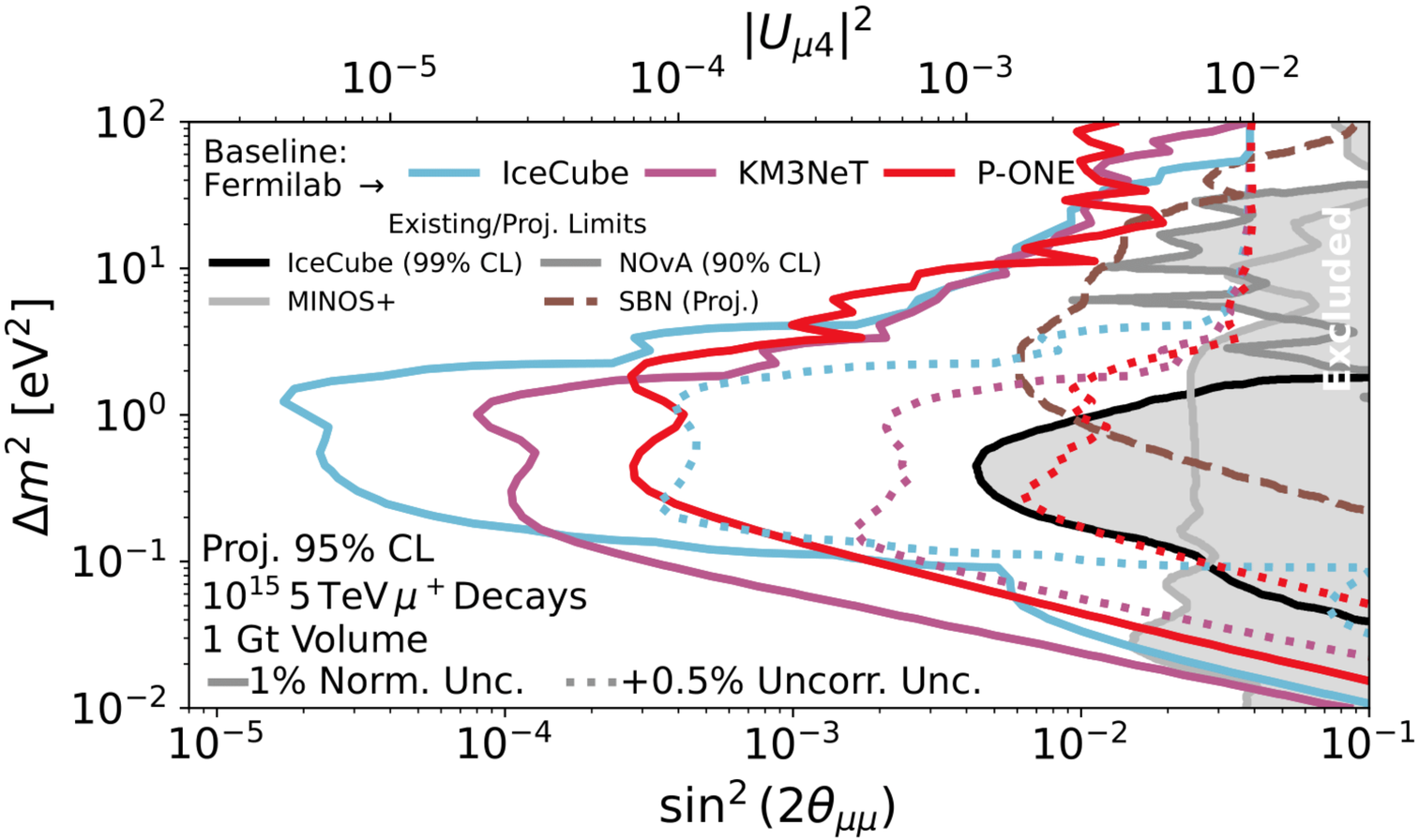


ν Kaleidoscopes for Sterile Neutrinos

We consider muon neutrino disappearance via a sterile neutrino with a “tracks” dataset at each telescope

The sensitivity is computed with the annular radius of the neutrino interaction vertex

The reach goes up to three **orders of magnitude beyond** existing searches!



What about active neutrino oscillations?

Oscillations the $\mu - \tau$ sector are governed by:

$$i\frac{d}{dx}\begin{pmatrix}\nu_\mu \\ \nu_\tau\end{pmatrix} = \left[\frac{\Delta m^2_{31}}{4E}\begin{pmatrix}-\cos 2\theta_{23}\sin 2\theta_{23} \\ \sin 2\theta_{23}\cos 2\theta_{23}\end{pmatrix} + \begin{pmatrix}V_{\mu\mu}V_{\mu\tau} \\ V^*_{\mu\tau}V_{\tau\tau}\end{pmatrix}\right]\begin{pmatrix}\nu_\mu \\ \nu_\tau\end{pmatrix},$$

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In the short baseline regime, $\frac{\Delta m^2_{31}}{4E}L, VL << 1,$

$$P_{\nu_\mu\to\nu_\tau} = L^2\left|\frac{\Delta m^2_{31}}{4E}\sin 2\theta_{23} + V_{\mu\tau}\right|^2 + \mathcal{O}(L^4)\,.$$

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We can look for new physics that produces non-standard oscillations via a nonzero $V_{\mu\tau}$

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Oscillations from Lorentz Violation

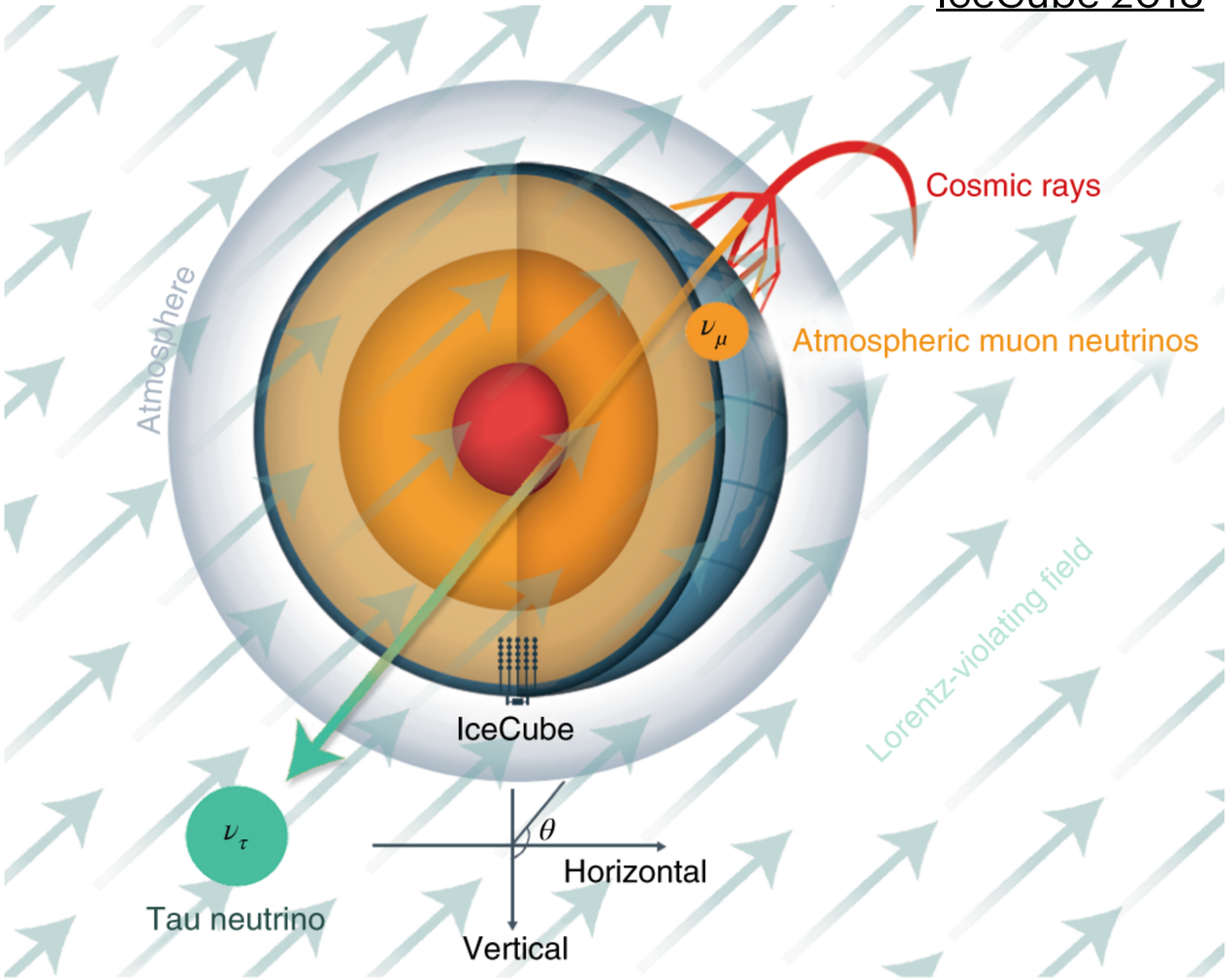
Lorentz violation appears in many theories of quantum gravity [Addazi+ 2021]

Leads to frame-dependent neutrino oscillations described by the Standard Model Extension [Kostelecký+ 2003]

$$V_{\mu\tau} = \frac{1}{E}[(a_L)^{\mu}_{\mu\tau} p_\mu - (c_L)^{\mu\nu}_{\mu\tau} p_\mu p_\nu]$$

$$P_{\nu_\mu \to \nu_\tau} \approx L^2 \left| \frac{\Delta m^2_{31}}{4E} \sin 2\theta_{23} + V_{\mu\tau} \right|^2$$

IceCube 2018



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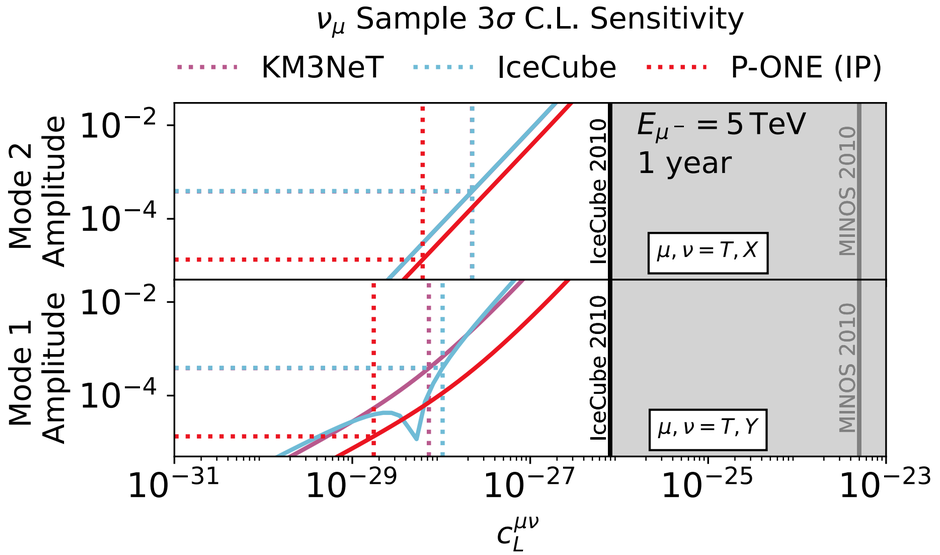
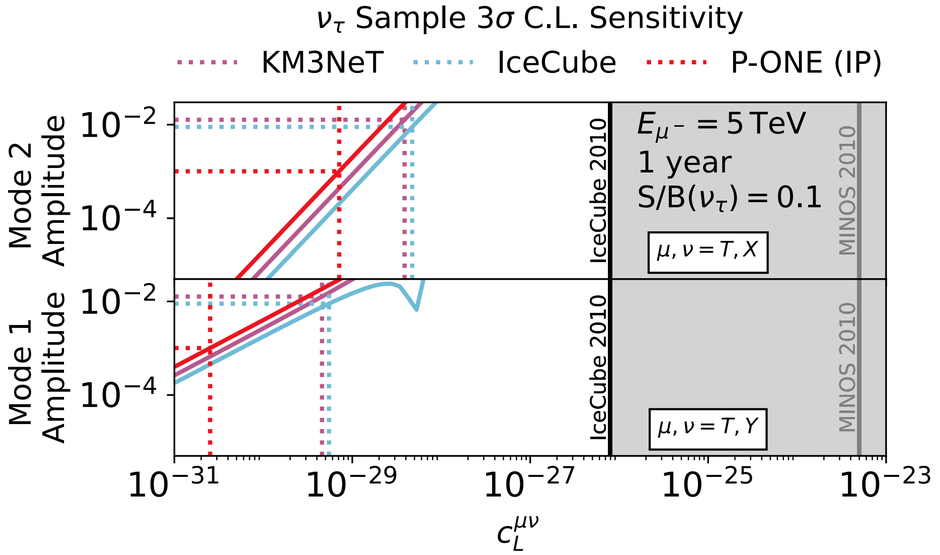
Sidereal variations in ν_μ disappearance:



Sidereal variations in ν_τ disappearance:



Reaching Double Planck Suppression

$$V_{\mu\tau} \sim a_{\mu\tau}^{(3)} - c_{\mu\tau}^{(4)} \cdot p + a_{\mu\tau}^{(5)} \cdot p^2 - c_{\mu\tau}^{(6)} \cdot p^3 + \ldots$$

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Naive power counting suggests Planck-suppressed higher-dimension operators from quantum gravity [Kostelecký+ 2011]

$$a^{(5)} \sim E_P^{-1} \qquad c^{(6)} \sim E_P^{-2} \qquad E_P = 1.22 \times 10^{19}\ \text{GeV}$$

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ν_μ sample, $E_\mu = 5$ TeV	$2.8 \times 10^3 / E_P^2$	$1.2 \times 10^3 / E_P^2$	$5.3 \times 10^2 / E_P^2$
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Sensitivity to $c^{(6)}$ in units of E_P^{-2}

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Sensitivity to $c^{(6)}$ in units of E_P^{-2}

First terrestrial access to double-Planck-suppressed Lorentz violation!

Outline: Three New Directions for Collider Neutrinos

1. Lake- and surface-based detectors for LHC neutrinos
2. The “Neutrino Kaleidoscope": pairing muon colliders and neutrino telescopes
3. **Searching for heavy neutrinos with a muon beam**

arXiv:26XX.XXXX

In collaboration with:

K. Xie

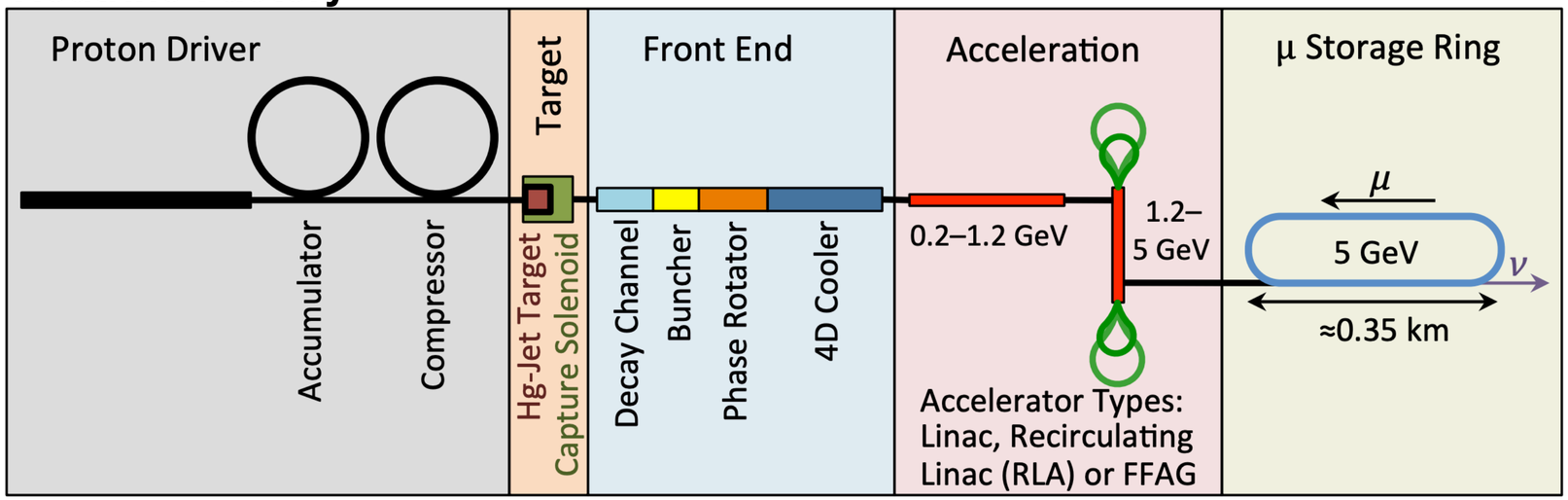
P.-C. Lu

C. Argüelles

G. Herrera

Two possible muon beams

Neutrino Factory

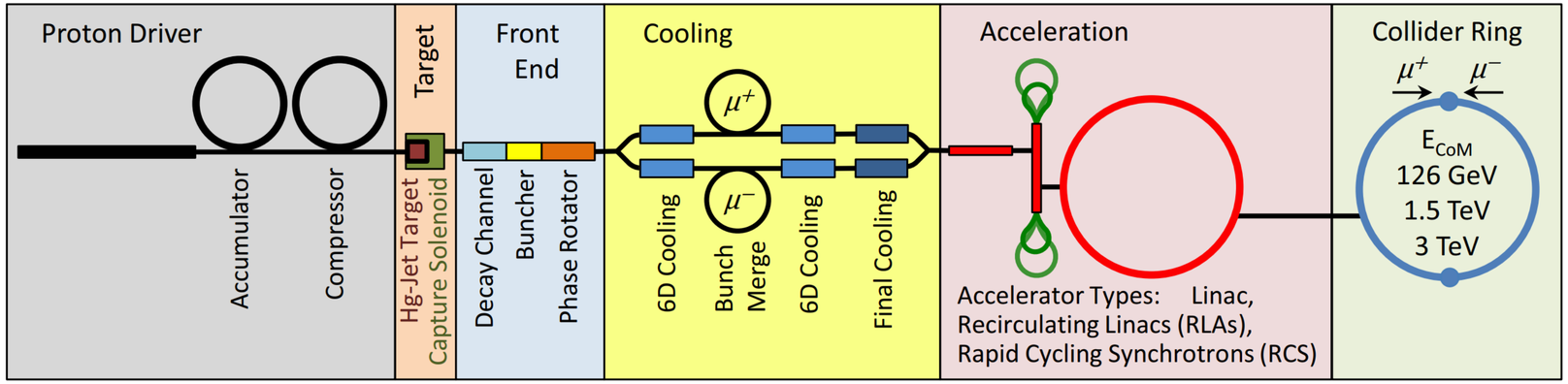


Goal:

$$\mathcal{O}(10^{21}\,\mu/\mathrm{yr})$$

$$E_\mu = \mathcal{O}(10\,\mathrm{GeV})$$

Muon Collider



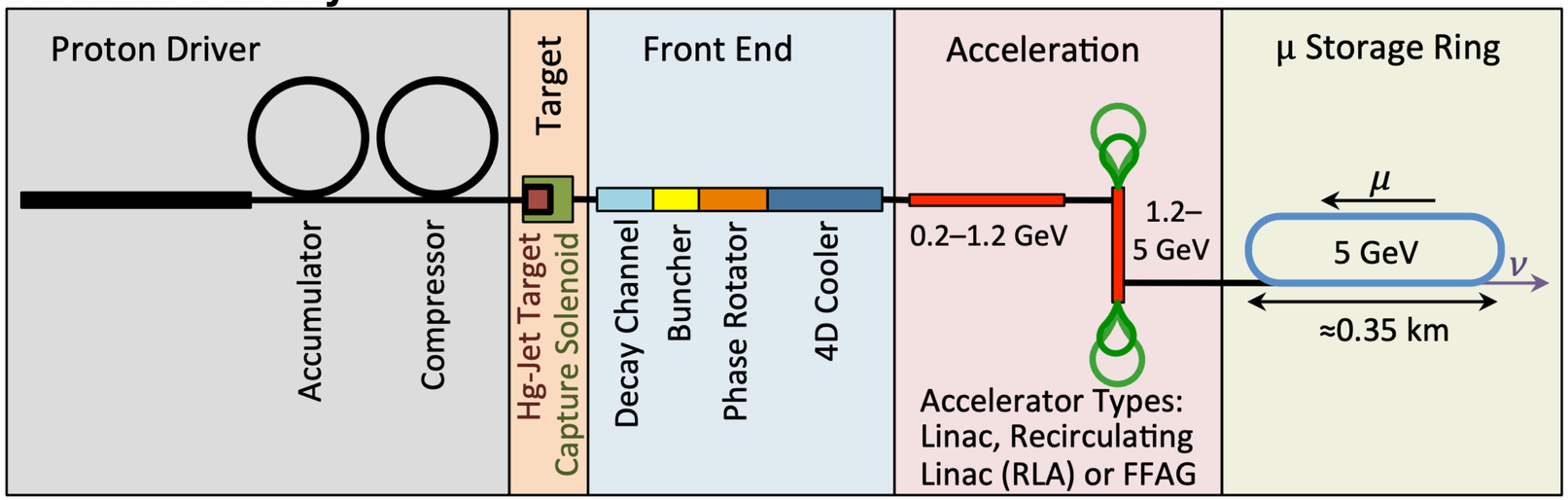
Goal:

$$\mathcal{O}(10^{20-21}\,\mu/\mathrm{yr})$$

$$E_\mu = \mathcal{O}(\mathrm{TeV})$$

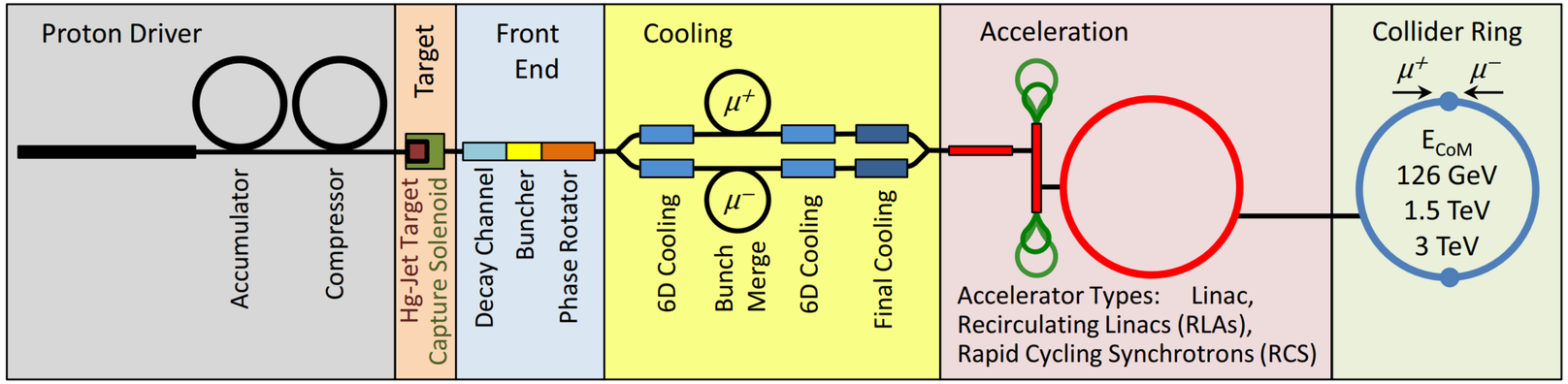
Four possible HNL searches

Neutrino Factory



1. “Heavy neutrino factory”

Muon Collider



2. “Traditional” muon beam dump
3. “Atmospheric” muon beam dump
4. Muon-ion collider

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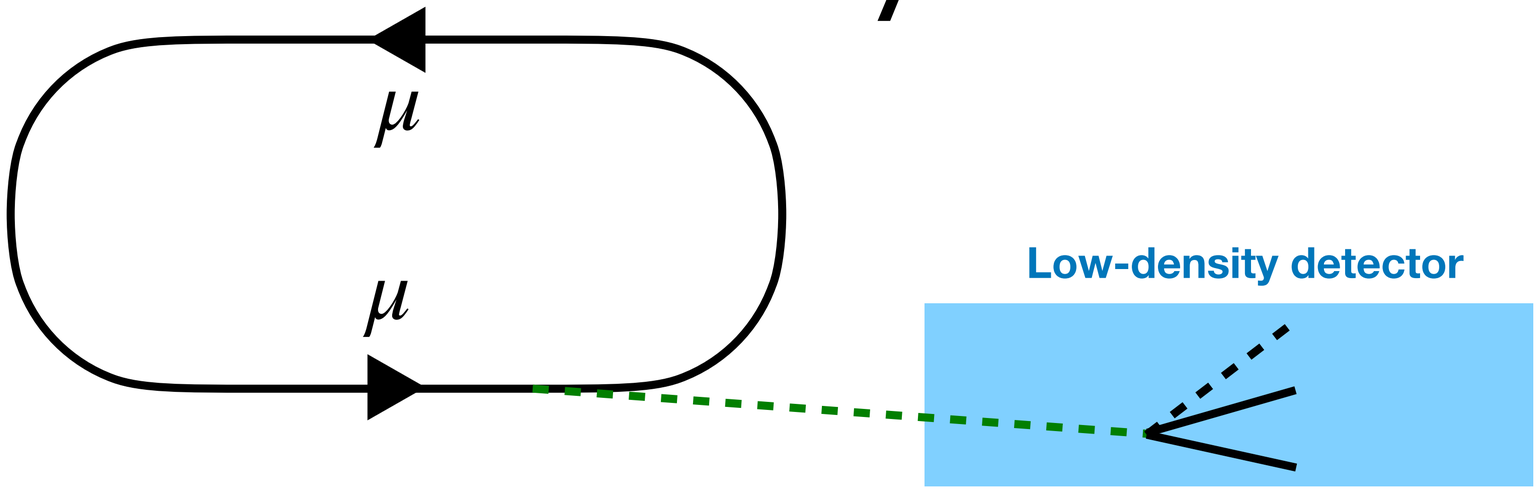

As a baseline, we take:

$L_{\text{det}} = 100\,\text{m}$ $R_{\text{det}} = 5\,\text{m}$

$N_\mu = 10^{22}$ $E_\mu = 25\,\text{GeV}$

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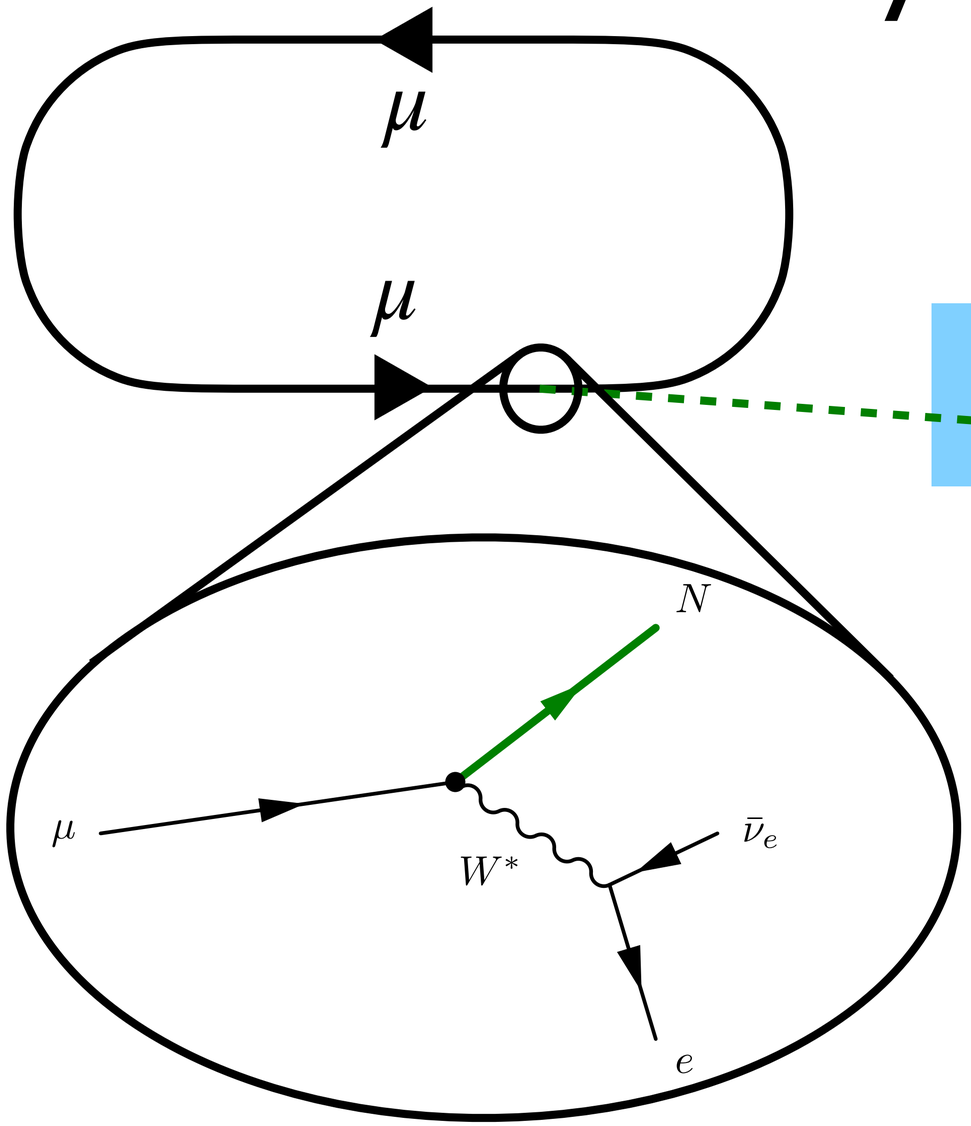
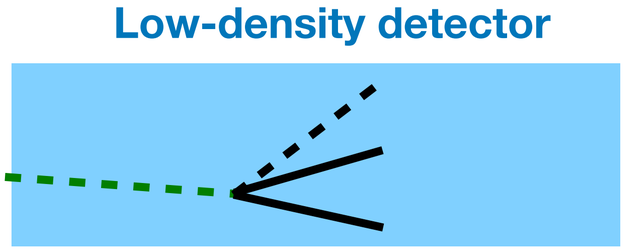


Production via muon decay



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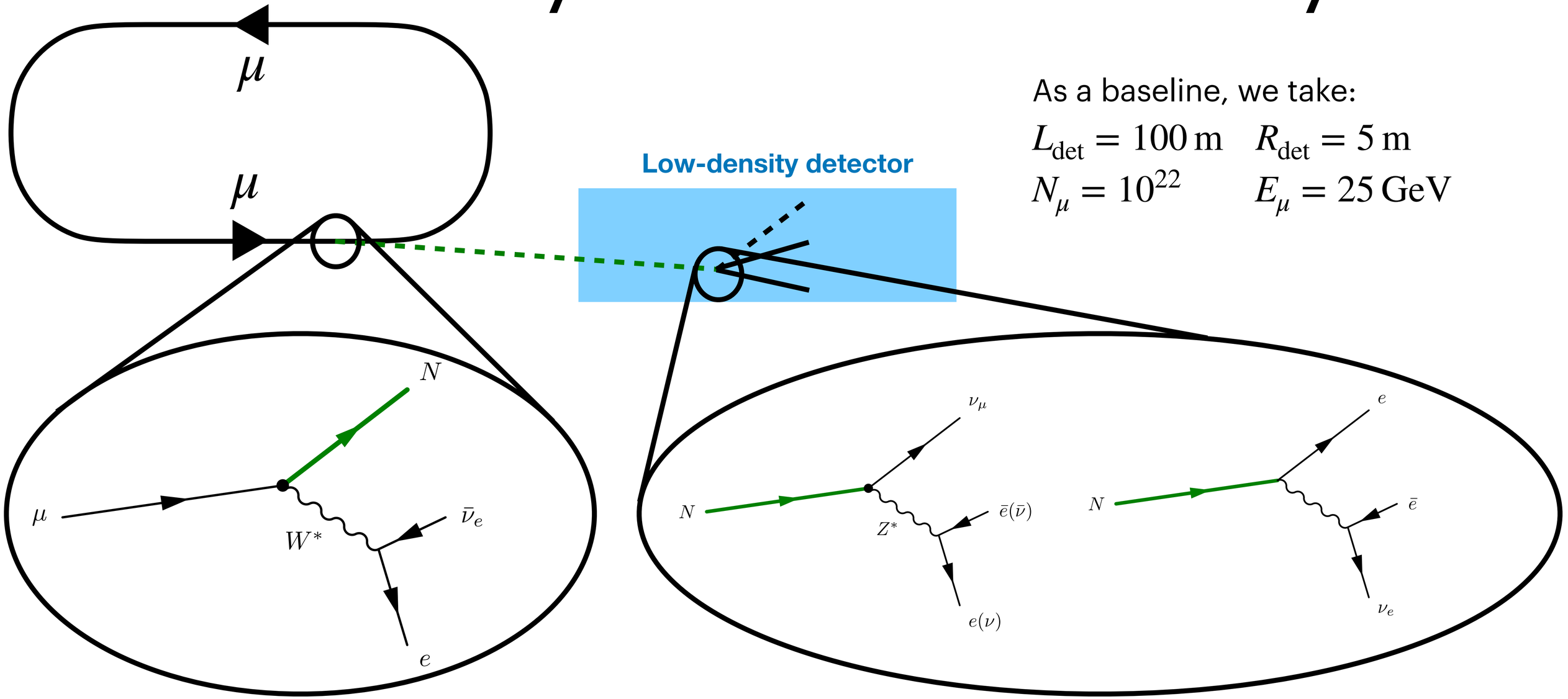

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Production via muon decay

Detection via e^+e^- signature

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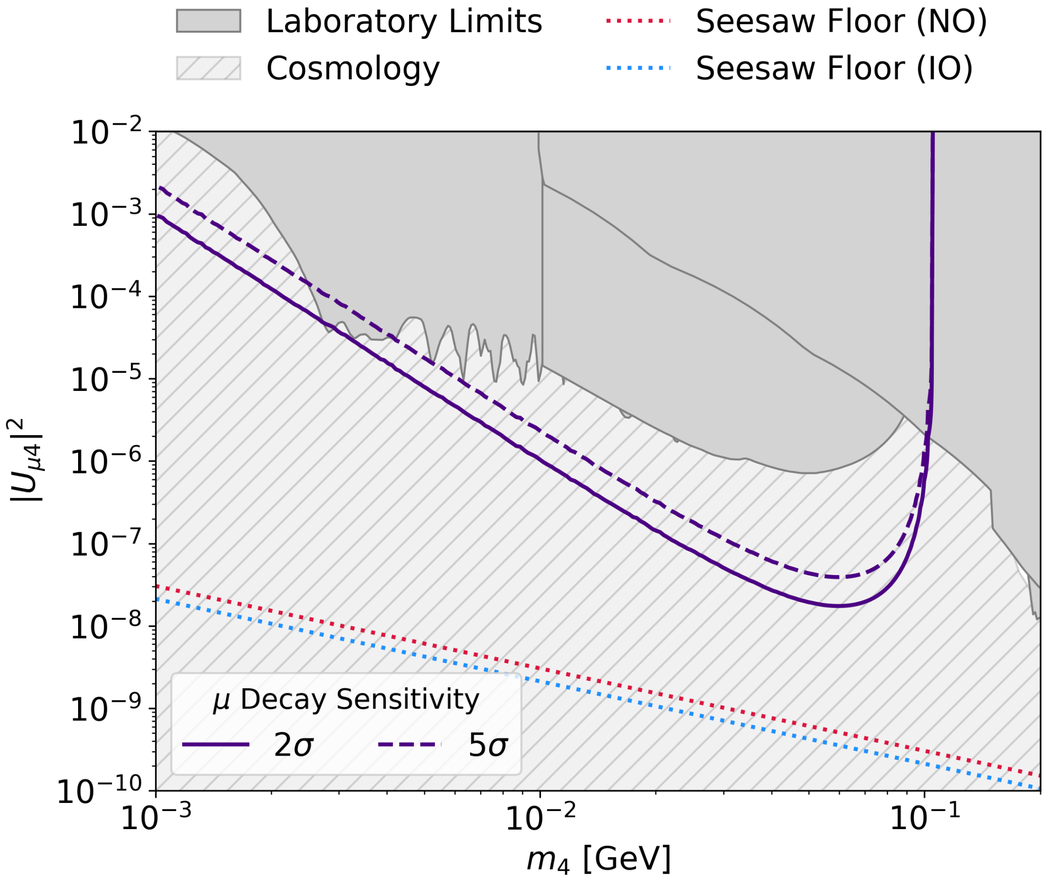

Improved constraints on $|U_{\mu N}|^2$ for $m_N < m_\mu$

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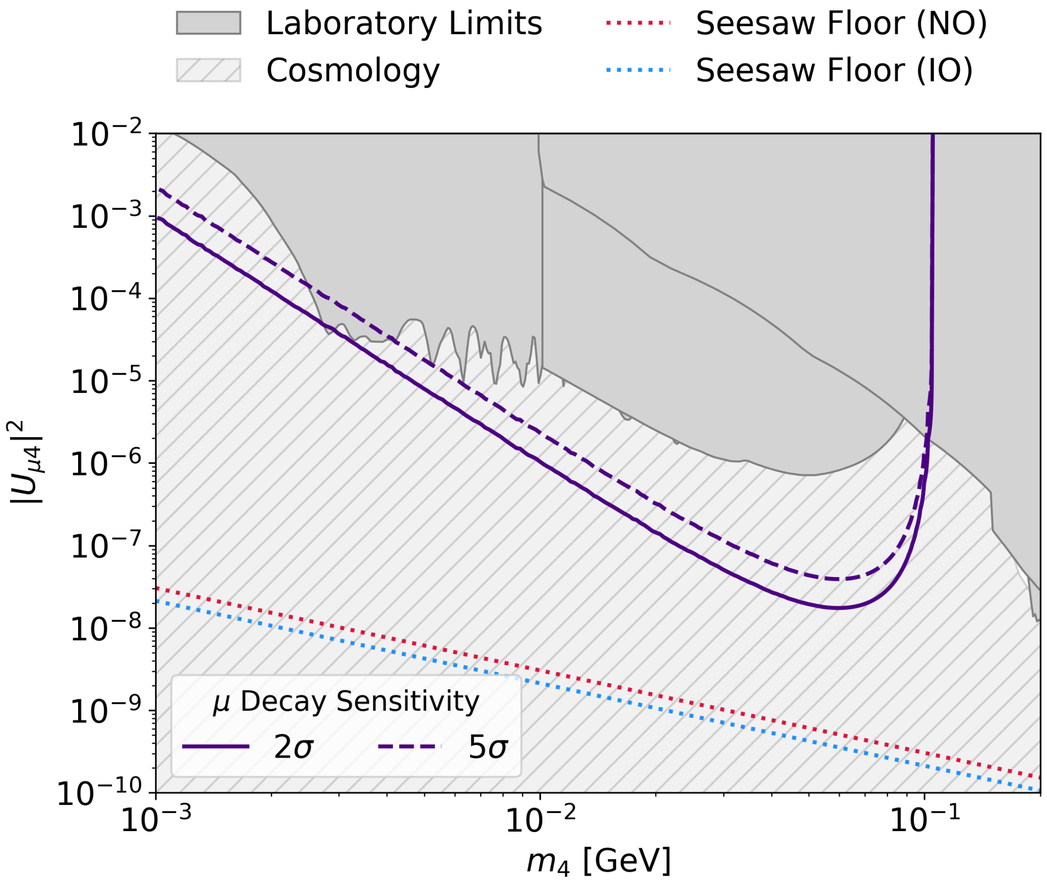

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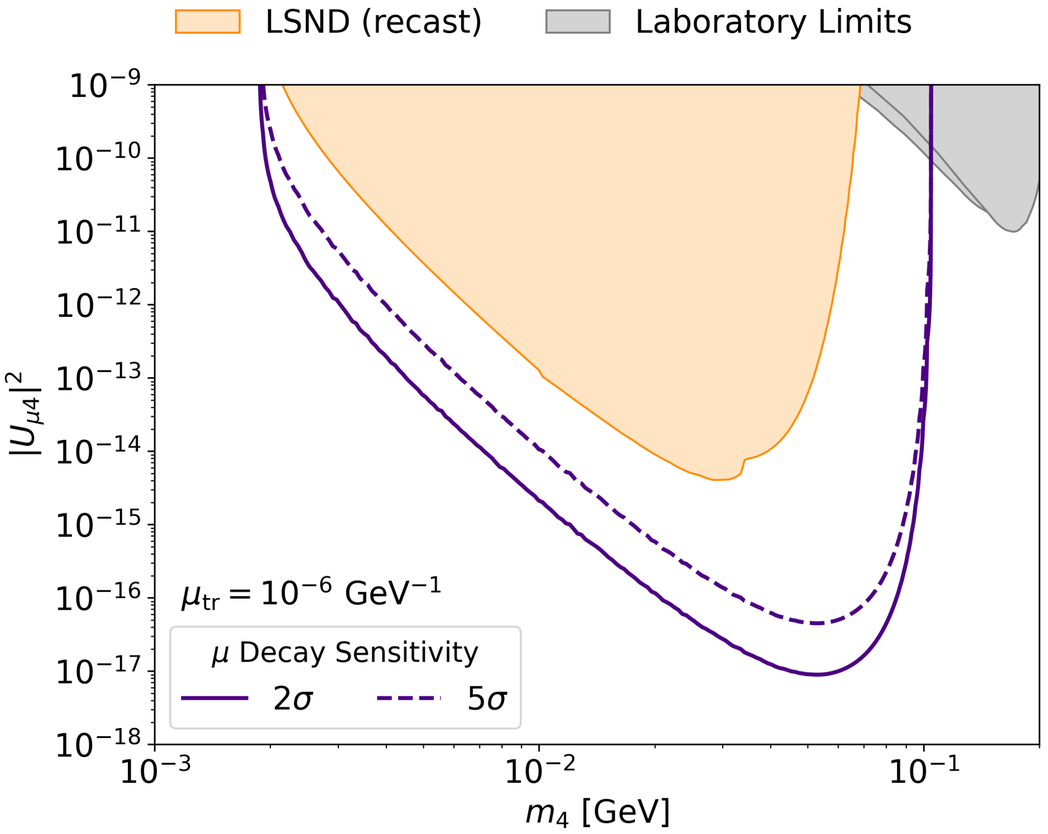
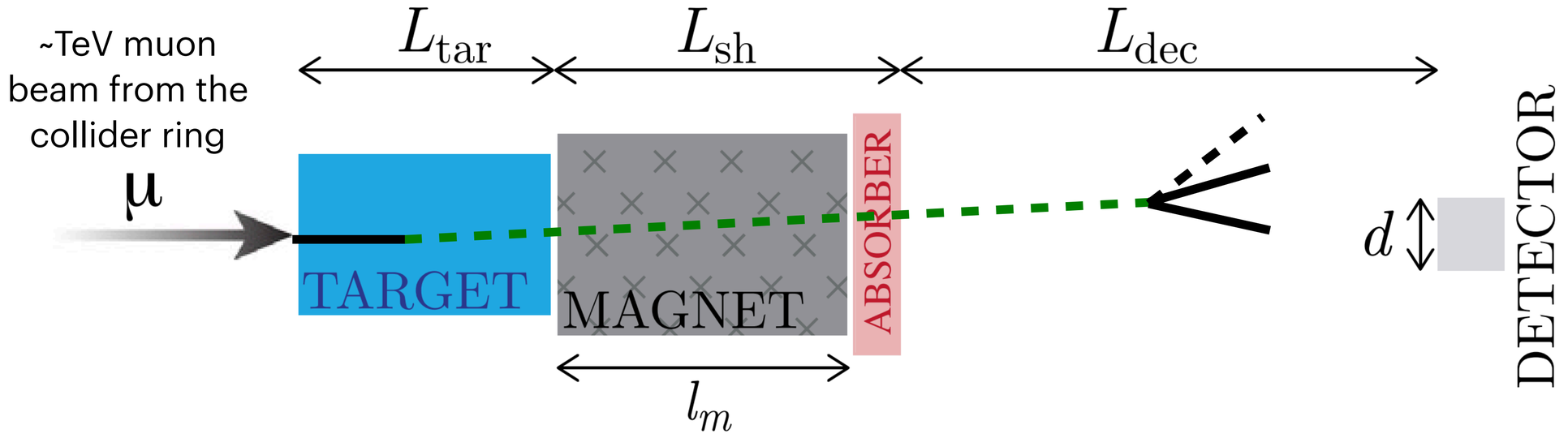


Improvement holds for models evading BBN bounds, e.g. addition of transition magnetic moment

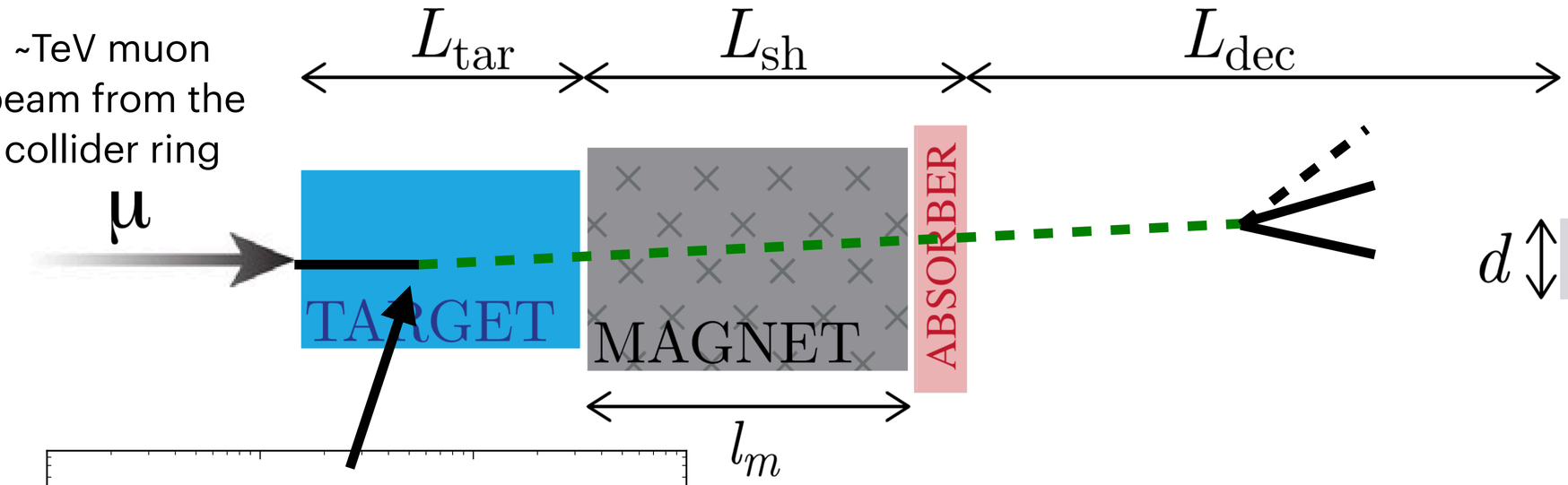
2: “Traditional” Muon Beam Dump

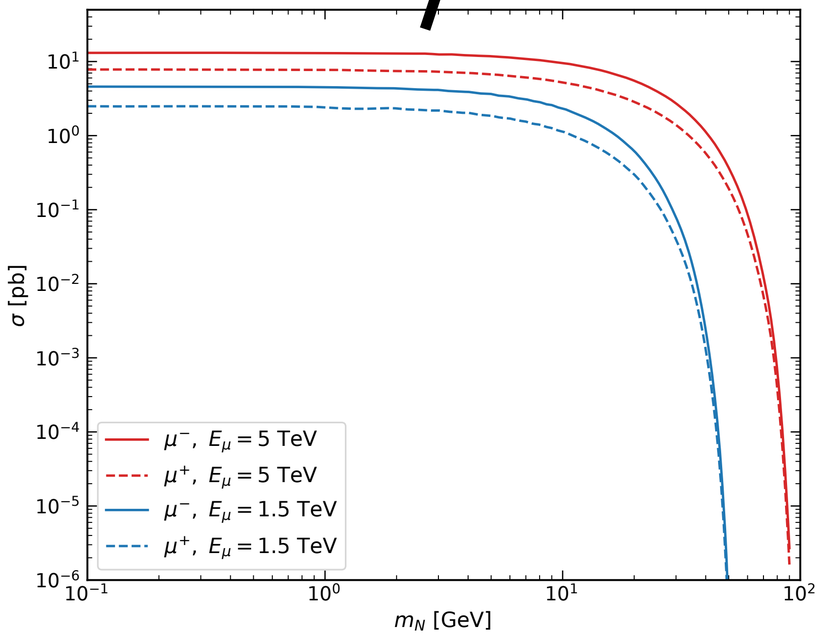


We consider the muon beam dump configuration proposed in Cesarotti+ PRL 2023

2: “Traditional” Muon Beam Dump

~TeV muon beam from the collider ring





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Production via CC scattering $\mu A \to N A$

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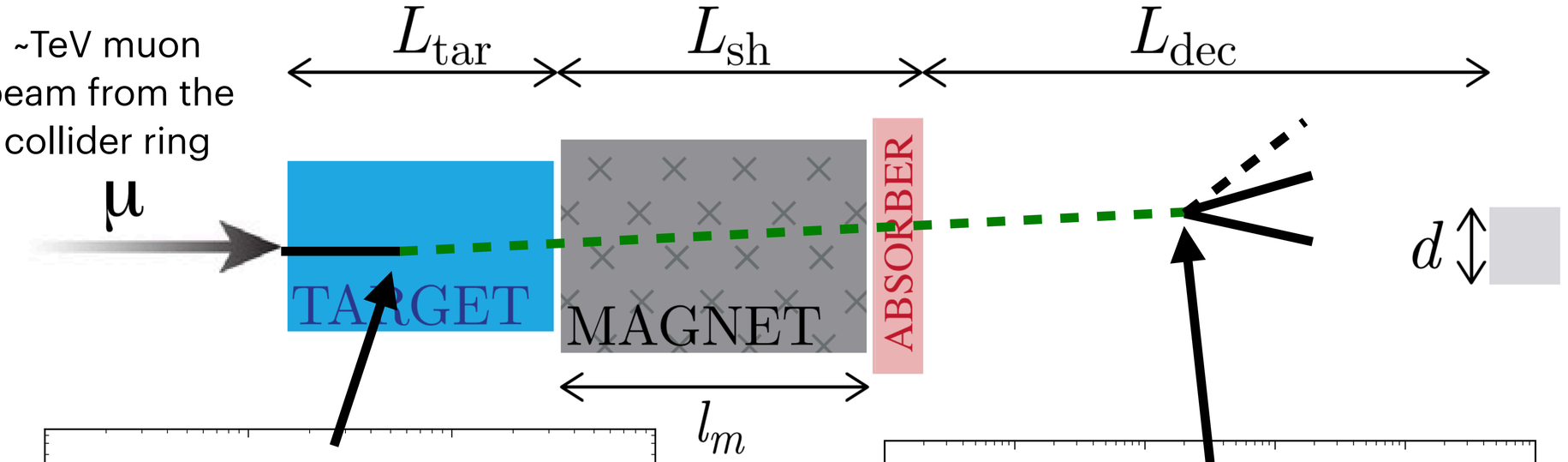

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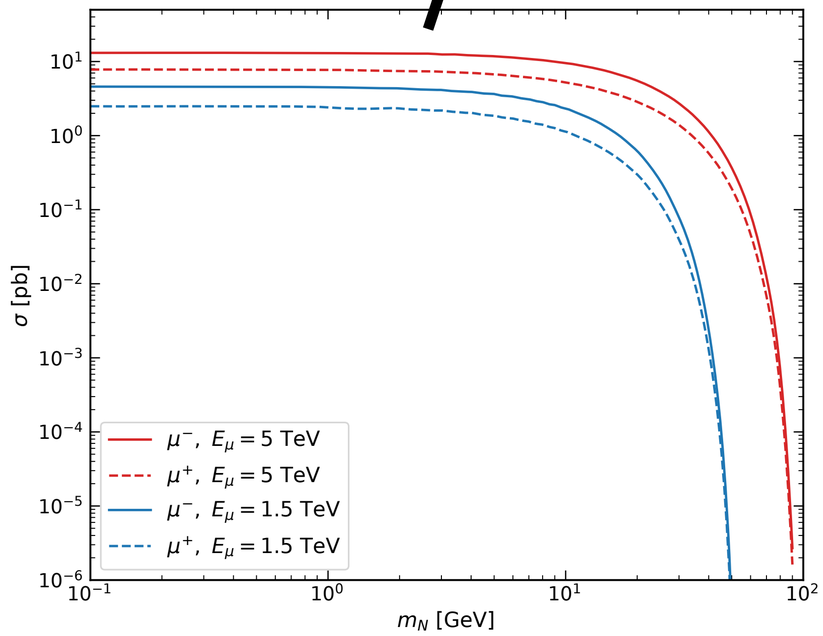

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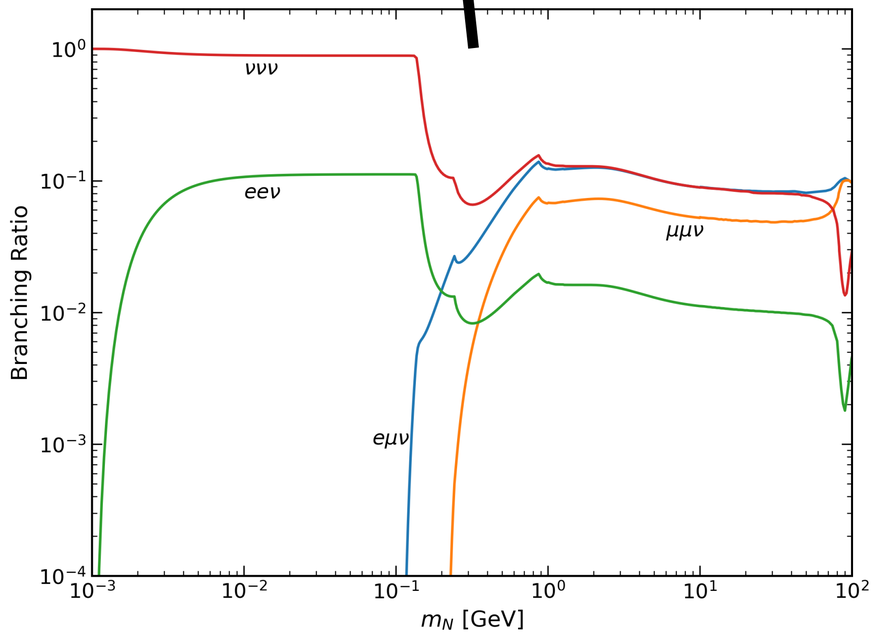
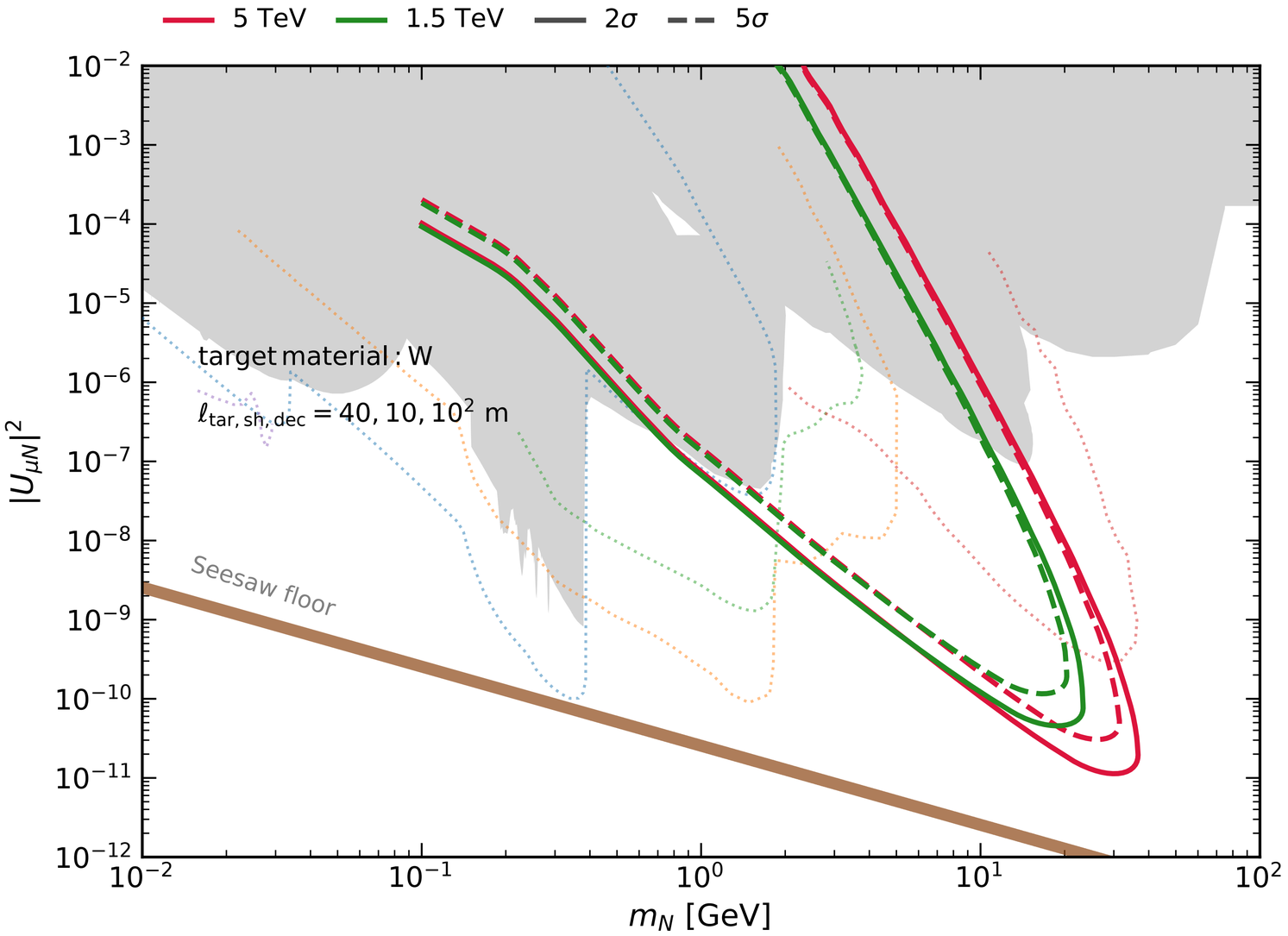


Detection via HNL decays to di-leptons

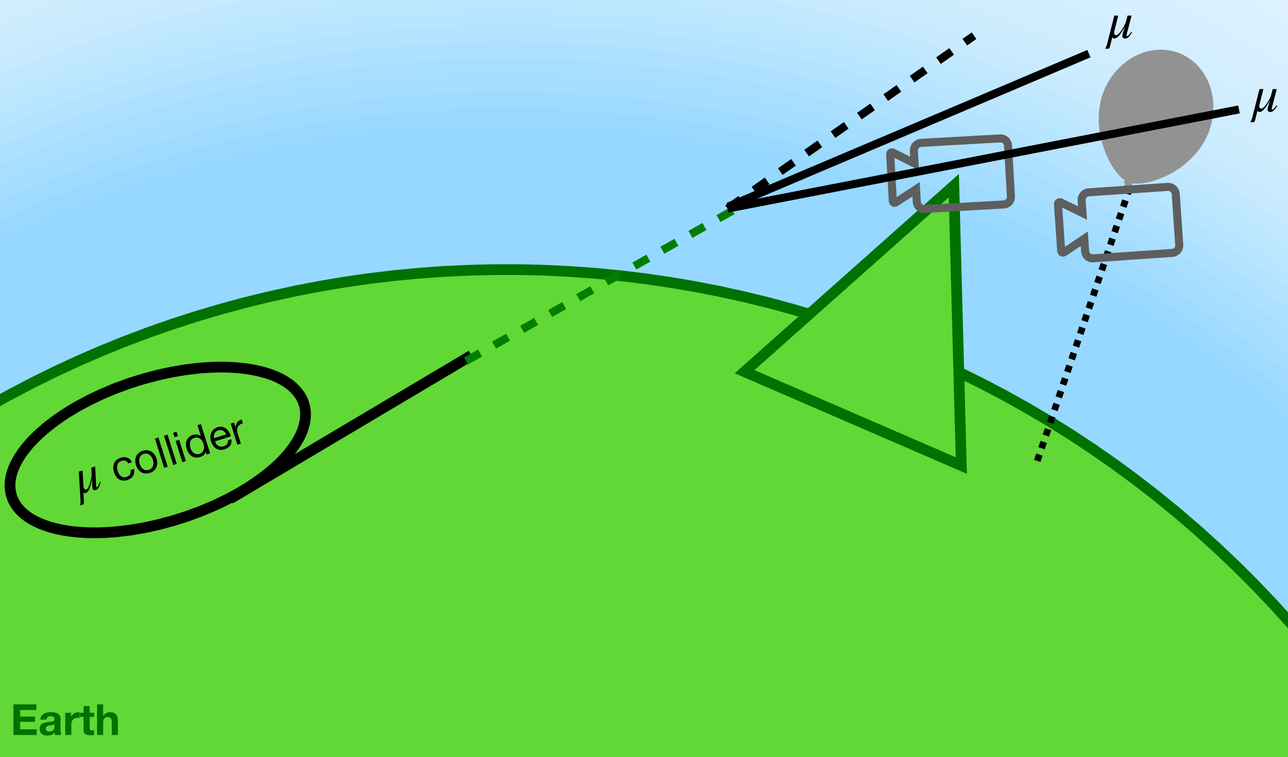
2: “Traditional” Muon Beam Dump

Sensitivity for 10^{22} muon decays (~10 years operation)

Significant improvement over existing constraints (gray region) and next-generation sensitivities (dotted lines)

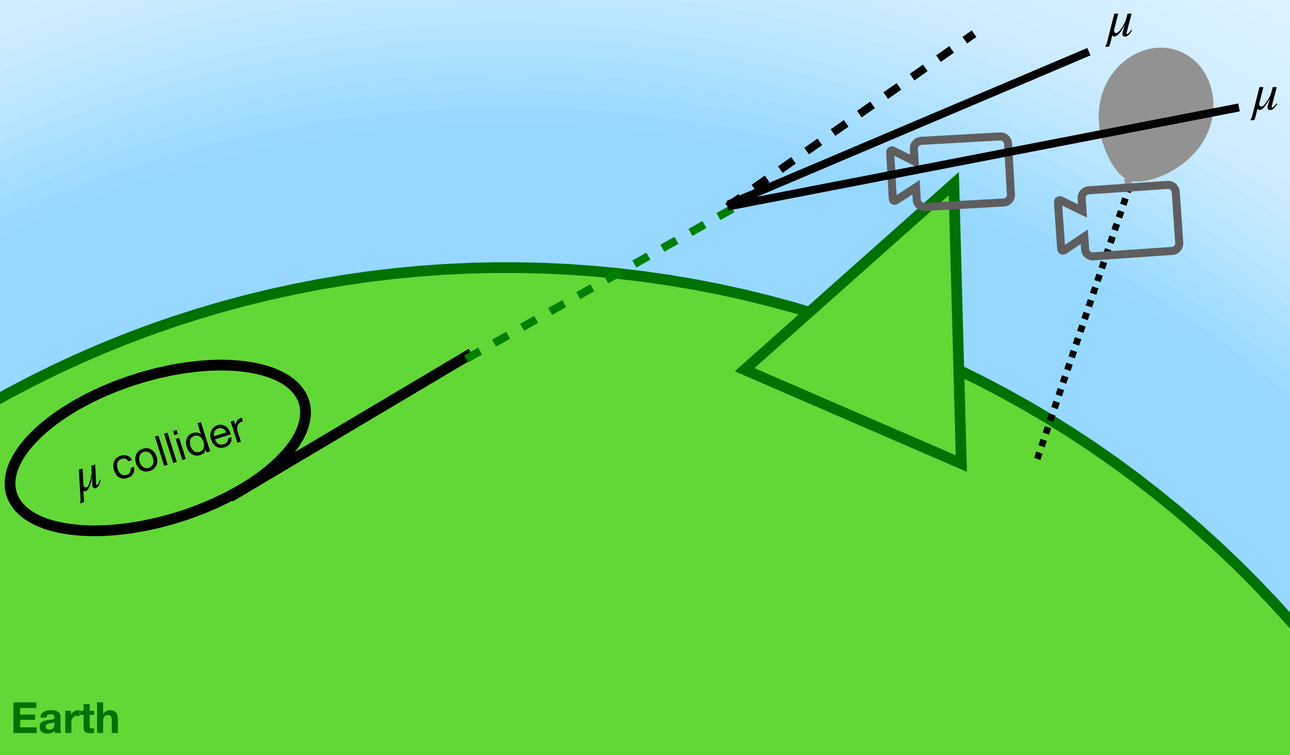


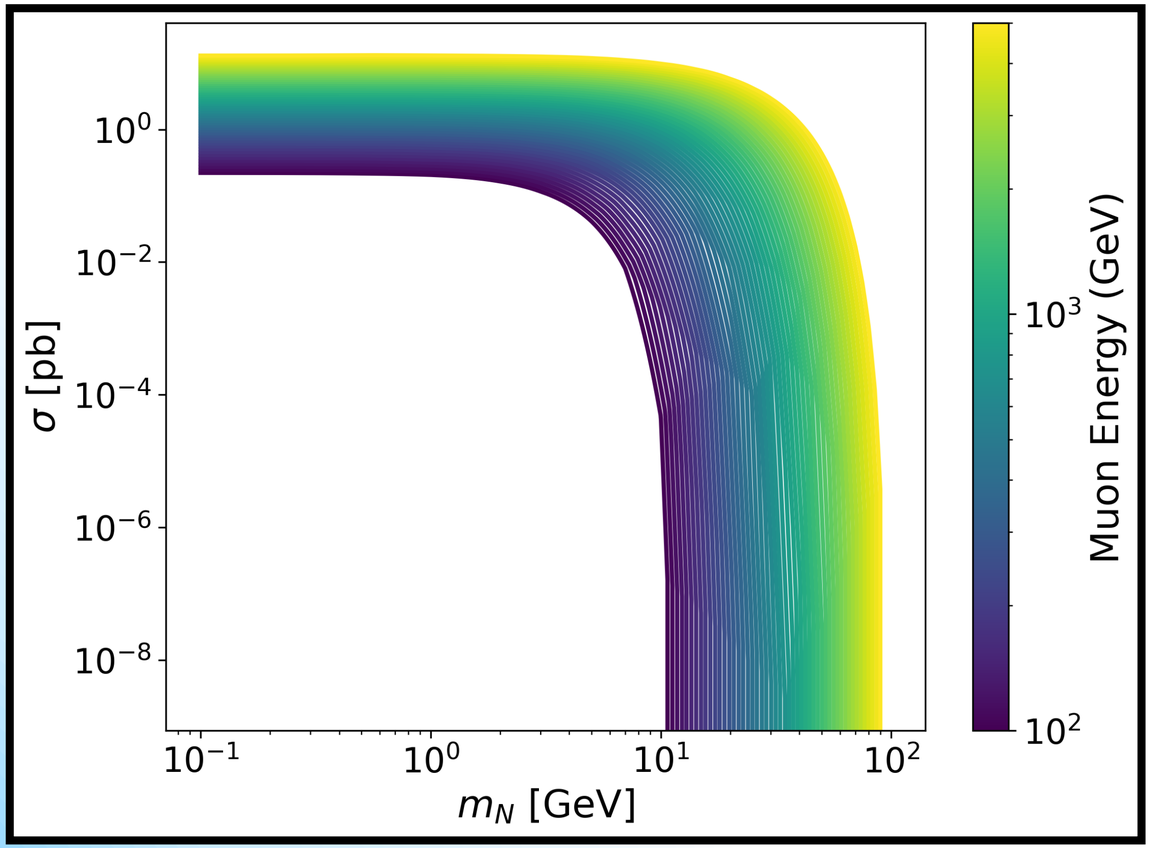
3: “Atmospheric” Muon Beam Dump



3: “Atmospheric” Muon Beam Dump

Production via $\mu A \to NX$ **in the Earth,** accounting for muon energy losses over their ~km range in rock





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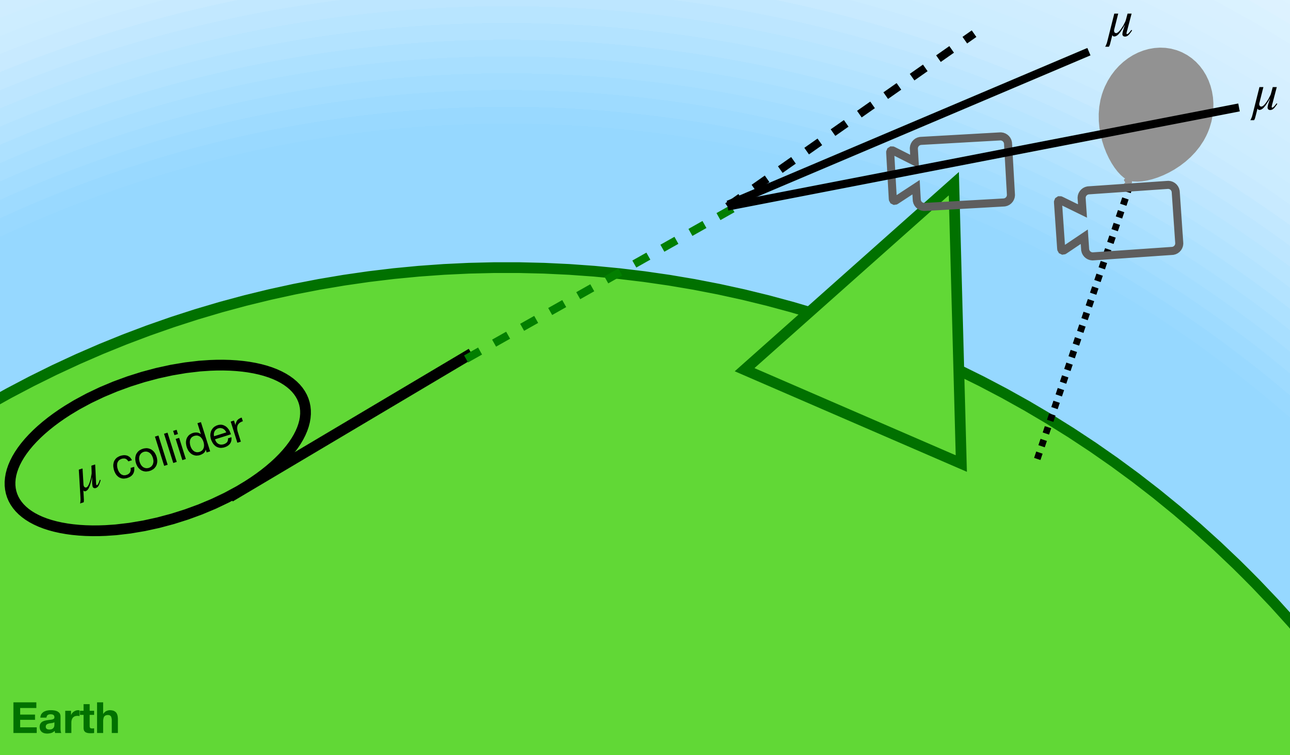
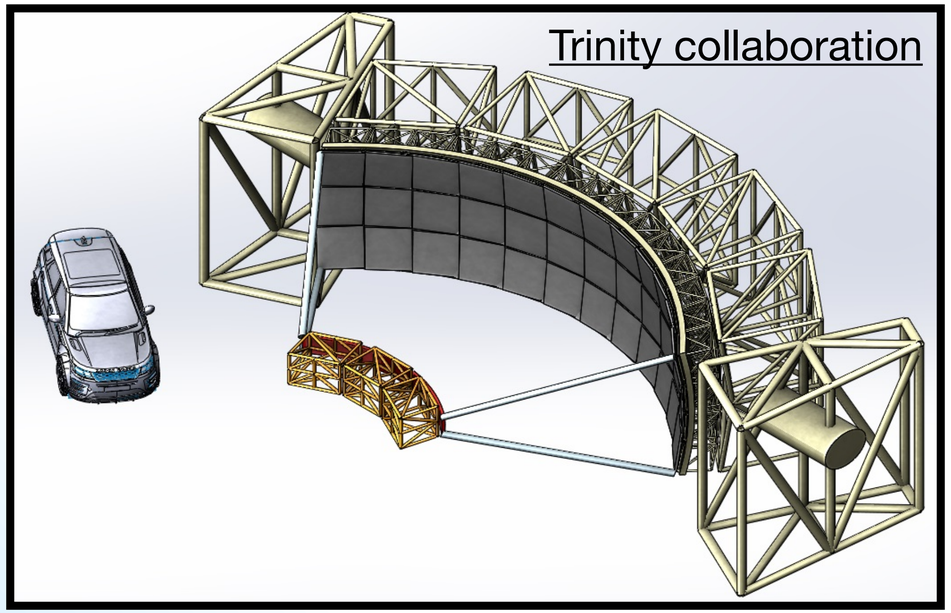
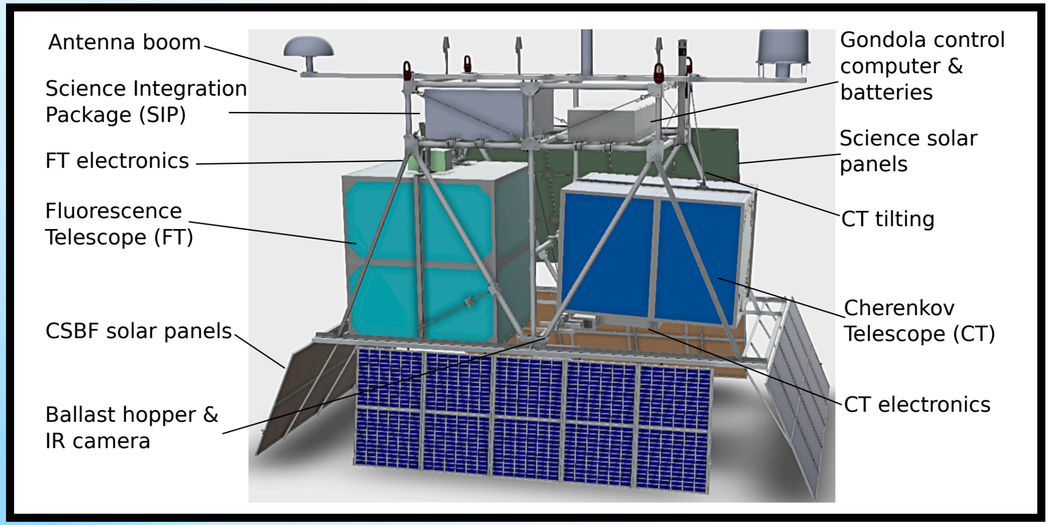
Detection via the Cherenkov light emitted by HNL decay products in atmosphere using **high-altitude air Cherenkov cameras**





EUSO-SPB2 2022



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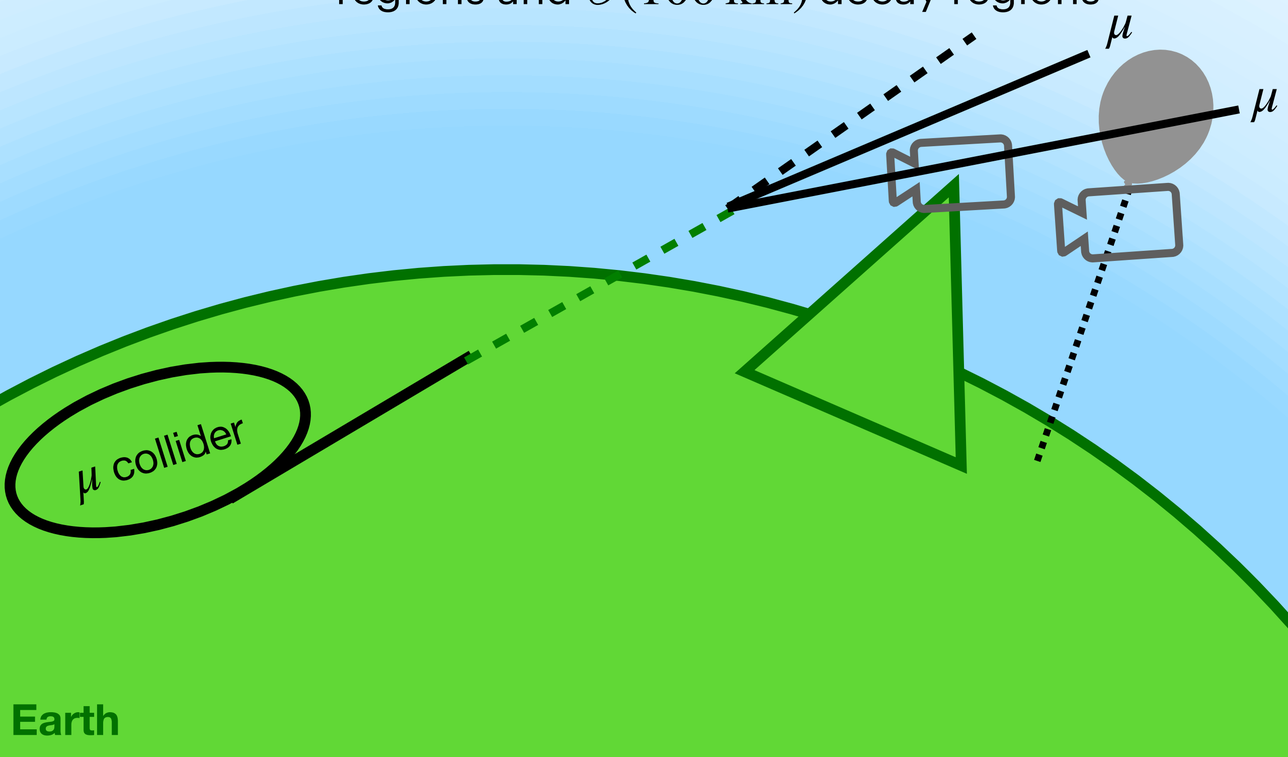
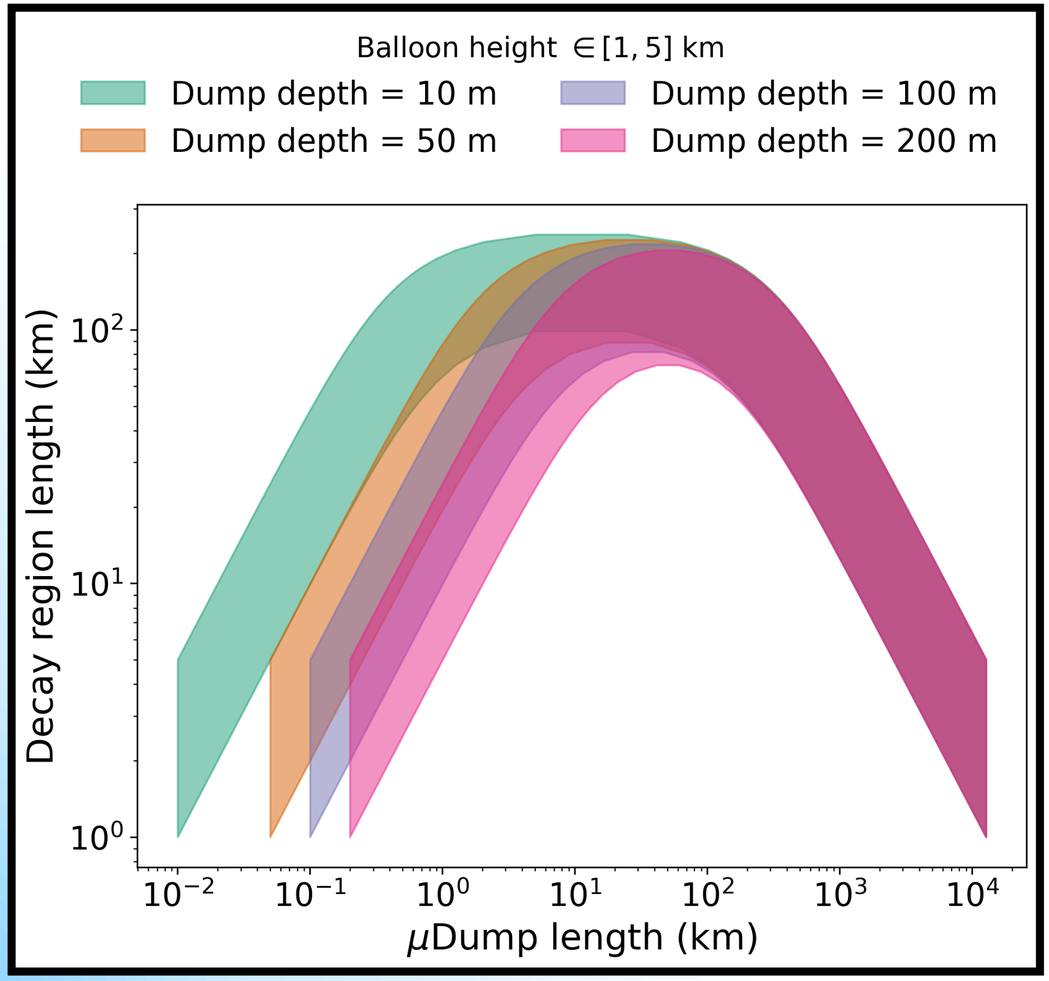
Optimized beam dump: $\mathcal{O}(\mathrm{km})$ target regions and $\mathcal{O}(100\,\mathrm{km})$ decay regions

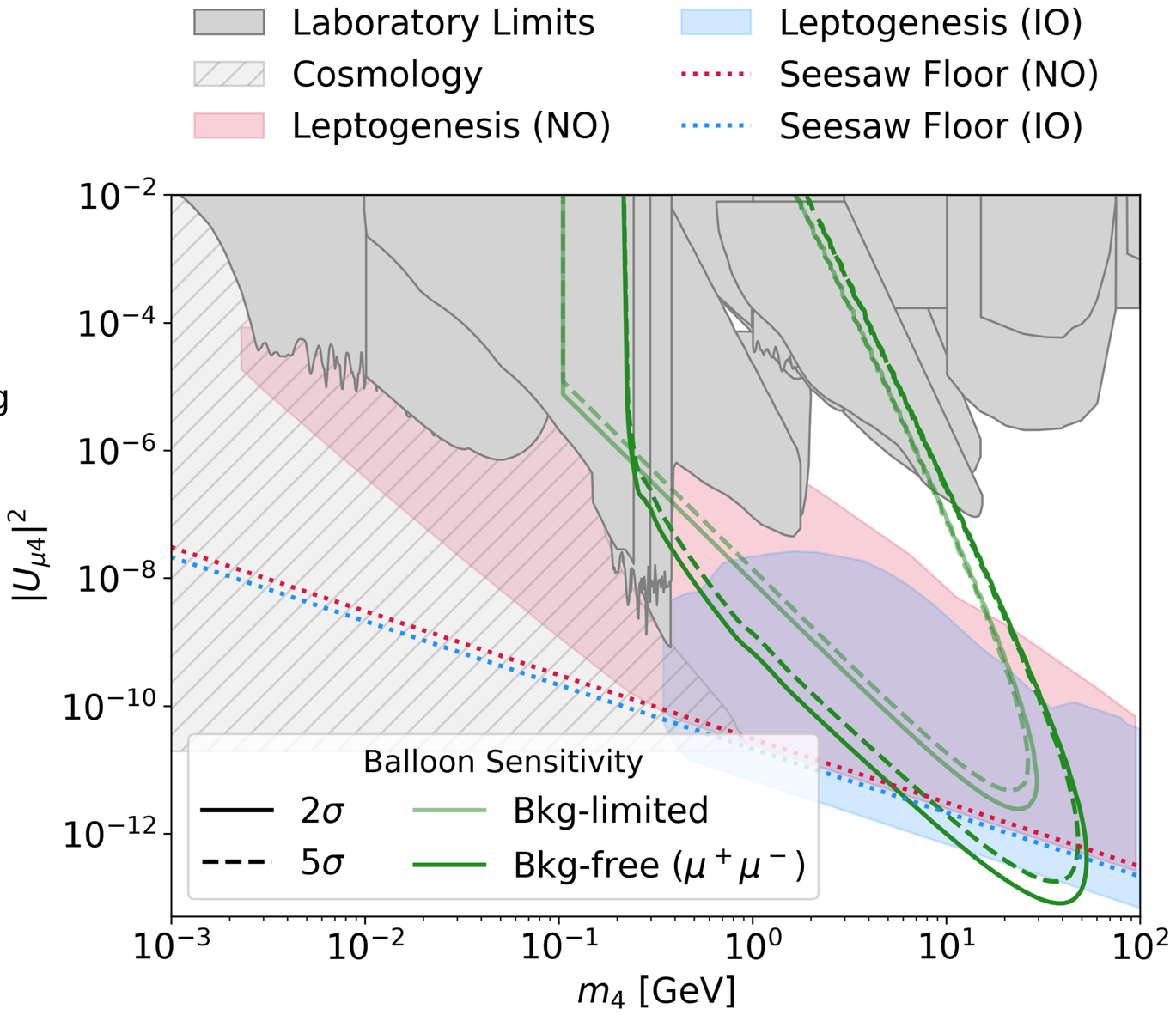




3: “Atmospheric” Muon Beam Dump

Relatively detailed simulation including:

- Energy loss and multiple Coulomb scattering of muons in rock
- Accurate kinematic sampling of HNL production and decay
- Altitude-dependent atmospheric effects, including index of refraction and Rayleigh/Mie scattering
- Cherenkov photon ray tracing
- Air Cherenkov camera trigger threshold of 12 p.e. per pixel [Otte 2018, Trinity 2025]



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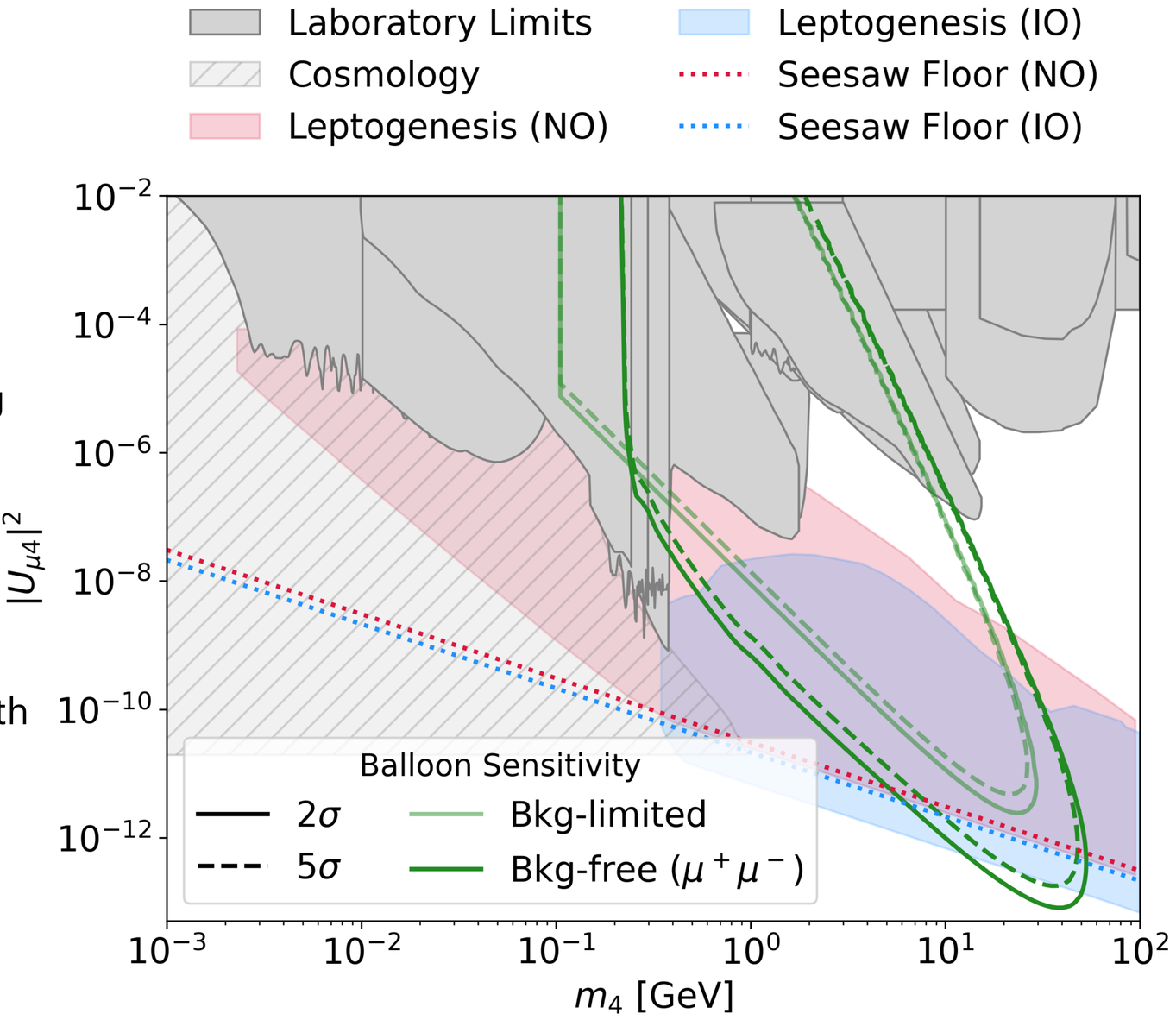
- Air Cherenkov camera trigger threshold of 12 p.e. per pixel [Otte 2018, Trinity 2025]

Strongest case: HNL decays to dimuons in which both muons to pass the trigger condition



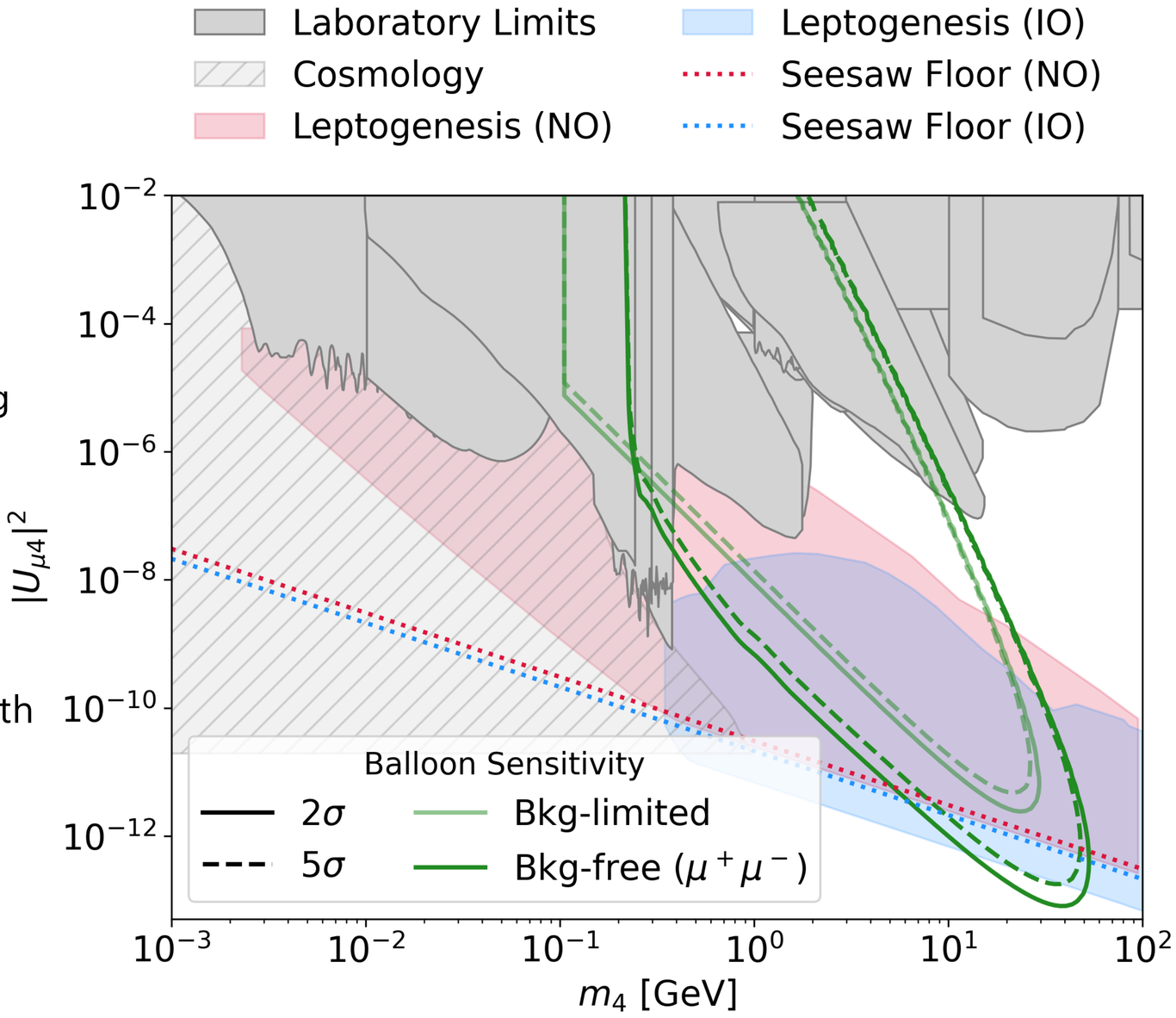
3: “Atmospheric” Muon Beam Dump

Relatively detailed simulation including:

- Energy loss and multiple Coulomb scattering of muons in rock
- Accurate kinematic sampling of HNL production and decay
- Altitude-dependent atmospheric effects, including index of refraction and Rayleigh/Mie scattering
- Cherenkov photon ray tracing
- Air Cherenkov camera trigger threshold of 12 p.e. per pixel [Otte 2018, Trinity 2025]

Strongest case: HNL decays to dimuons in which both muons to pass the trigger condition

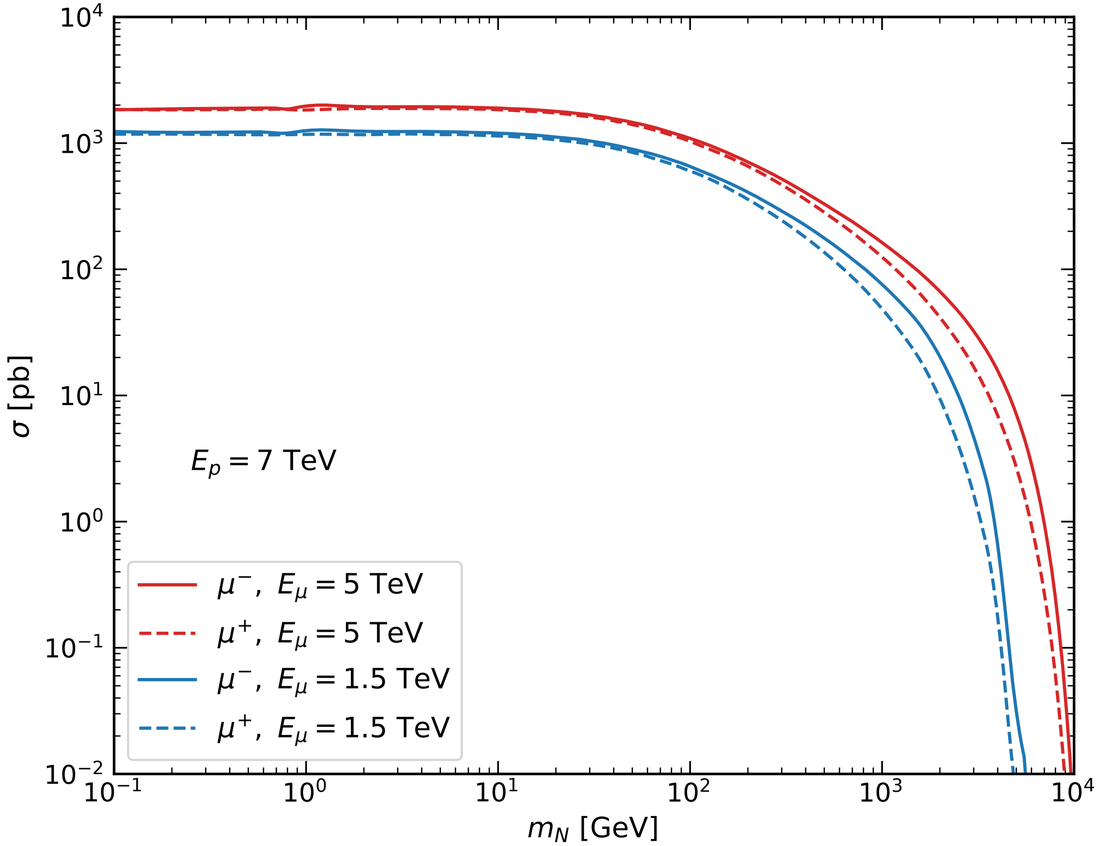
Background-free sensitivity covers large portion of **Leptogenesis-motivated parameter space** [Akmehdov+ 1998] and reaches the **Seesaw floor**



4: Muon-Ion Collider

4: Muon-Ion Collider

Consider HNL production in a μp collider [Acosta+ 2022] via CC interaction $\mu p \to NX$



4: Muon-Ion Collider

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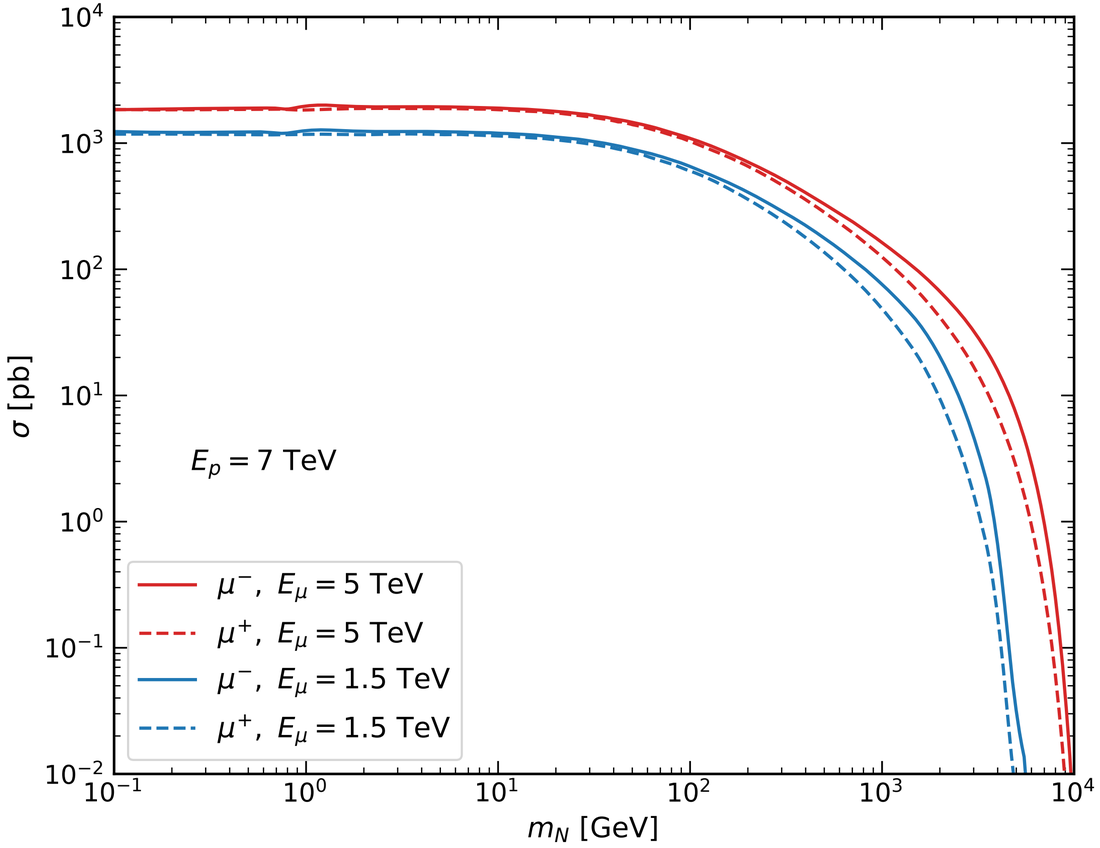
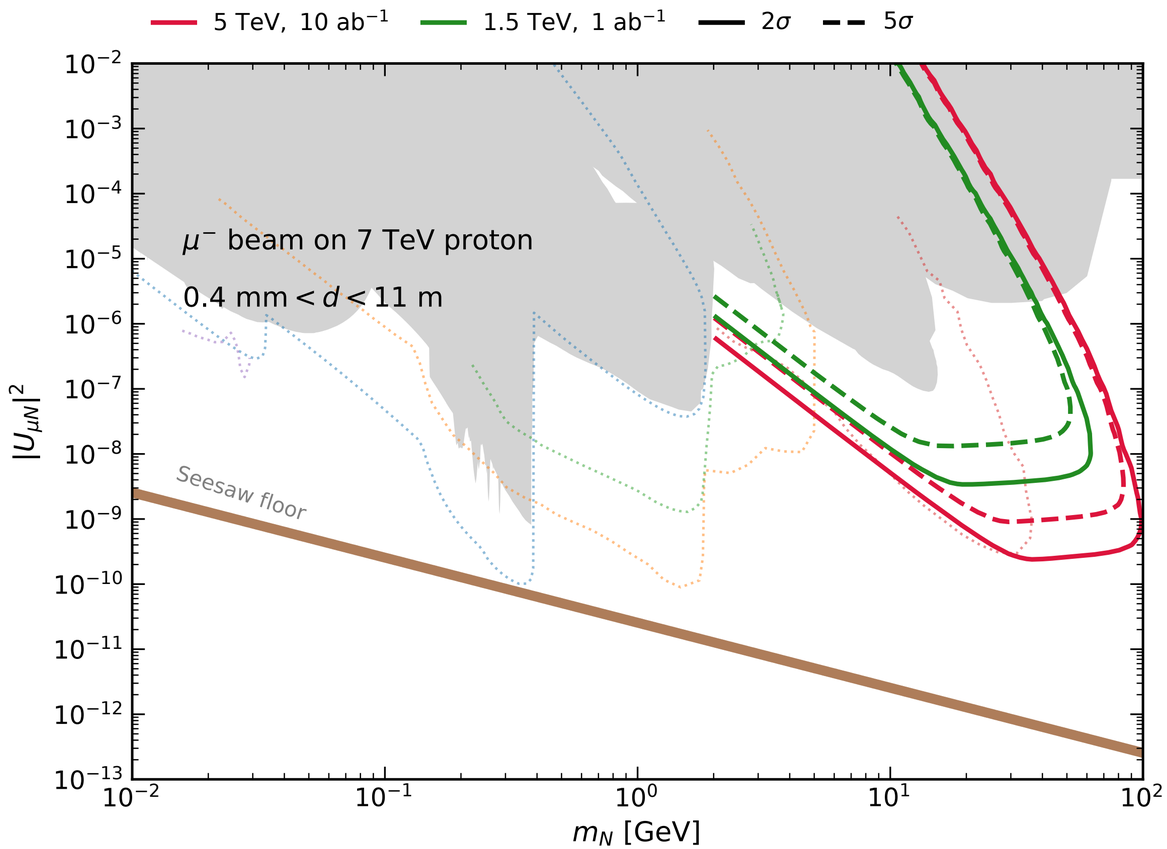
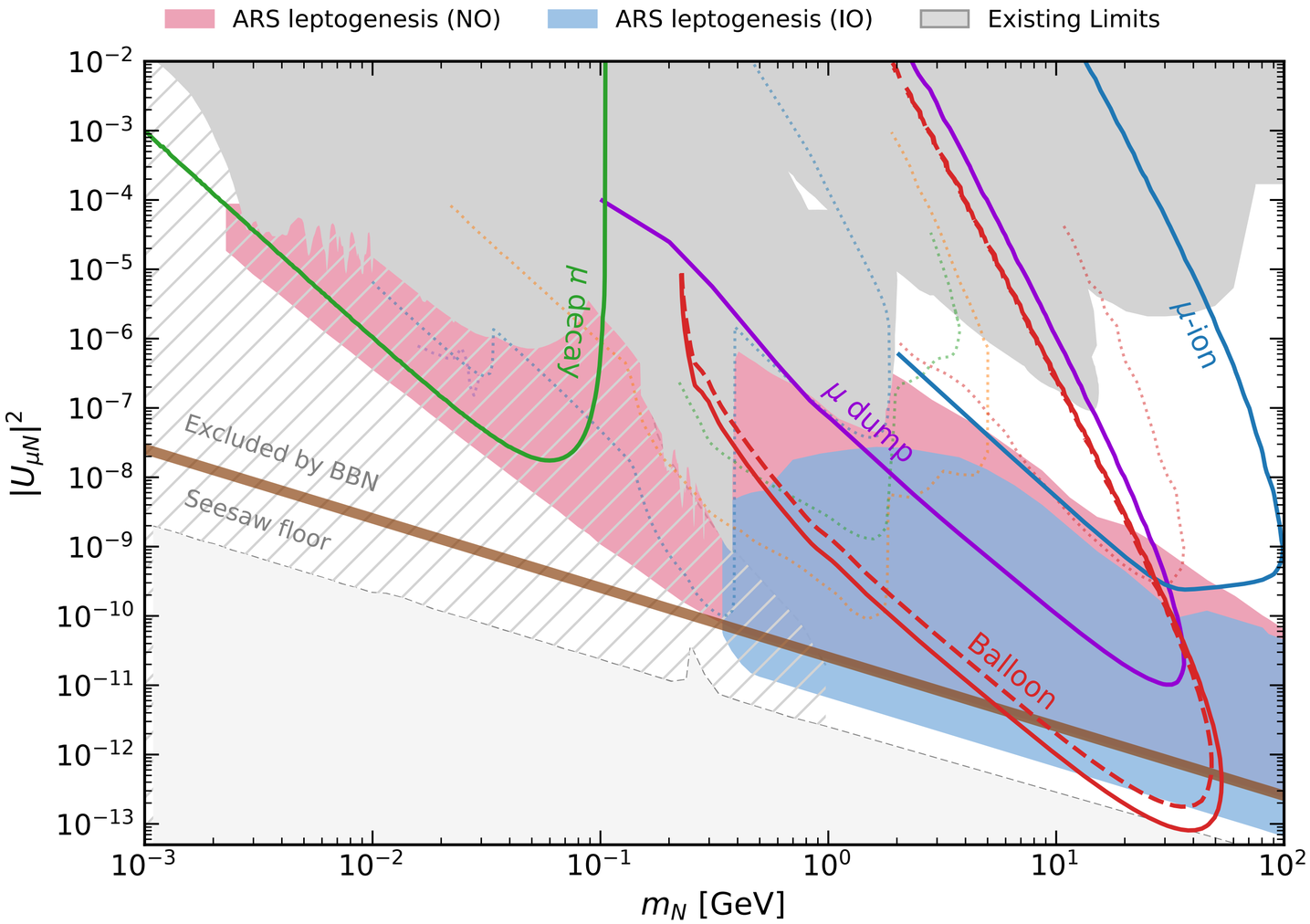


Searches for HNL decays in the detector at the μp interaction point can extend the reach up to $m_N \sim 100\,\mathrm{GeV}$



In combination, the four proposed muon beam HNL searches can cover a large region of parameter space



Summary: Three New Directions for Collider Neutrinos

1. **Lake- and surface-based detectors for LHC neutrinos** NK, Argüelles, Karle, Thomas, Yuan 2501.08278

SINE and UNDINE are cost-effective kiloton-scale LHC neutrino detectors that can constrain **forward charm production** and **heavy neutral leptons**, ...

2. **The "Neutrino Kaleidoscope"** NK, Putnam 2508.09249

Intensity and collimation a muon collider neutrino beam plus gigaton-mass neutrino telescopes → extremely sensitive search for **anomalous neutrino oscillations**, ...

3. **Heavy neutrinos with a muon beam** Argüelles, Herrera, NK, Lu, Xie 26XX.XXXX

HNL searches via muon decay, muon beam dumps, or a muon-ion collider can cover **Leptogenesis-motivated** parameter space and potentially reach the **Seesaw floor**

Thank you!

Backups

Outline: Three New Directions for Collider Neutrinos

1. **Lake- and surface-based detectors for LHC neutrinos**
2. The “Neutrino Kaleidoscope": pairing muon colliders and neutrino telescopes
3. Searching for heavy neutrinos with a muon beam

arXiv:2501.08278

Lake- and Surface-Based Detectors for Forward Neutrino Physics

Nicholas W. Kamp,[1,*] Carlos A. Argüelles,[1,†] Albrecht Karle,[2,‡] Jennifer Thomas,[2,3,§] and Tianlu Yuan[2,¶]

[1] *Department of Physics and Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA 02138, US*
[2] *Department of Physics and Wisconsin IceCube Particle Astrophysics Center, University of Wisconsin– Madison, Madison, WI 53706, USA*
[3] *Department of Physics and Astronomy, University College London, London, WC1E 6BT, UK*

(Dated: January 14, 2025)

See also related independent work: Ariga+ 2501.0614

J. Thomas

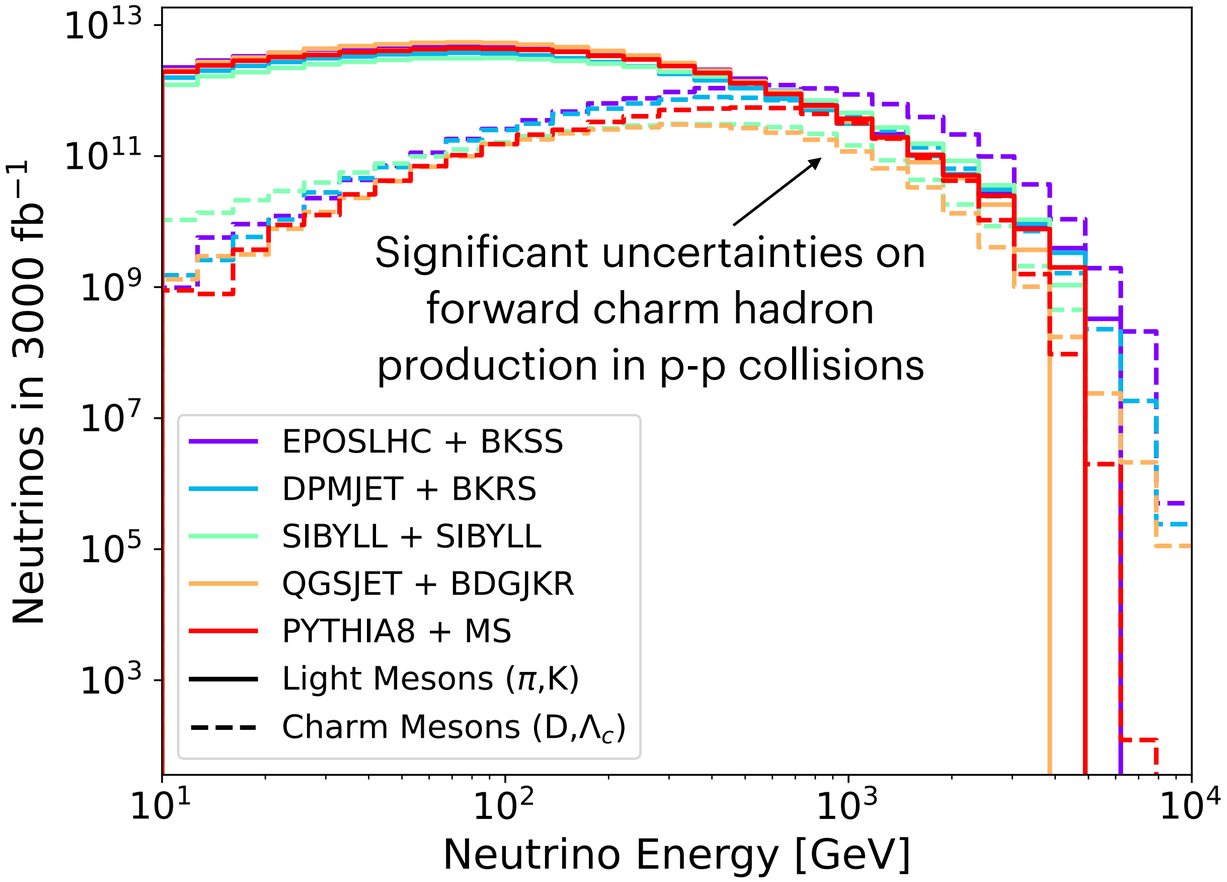
A. Karle

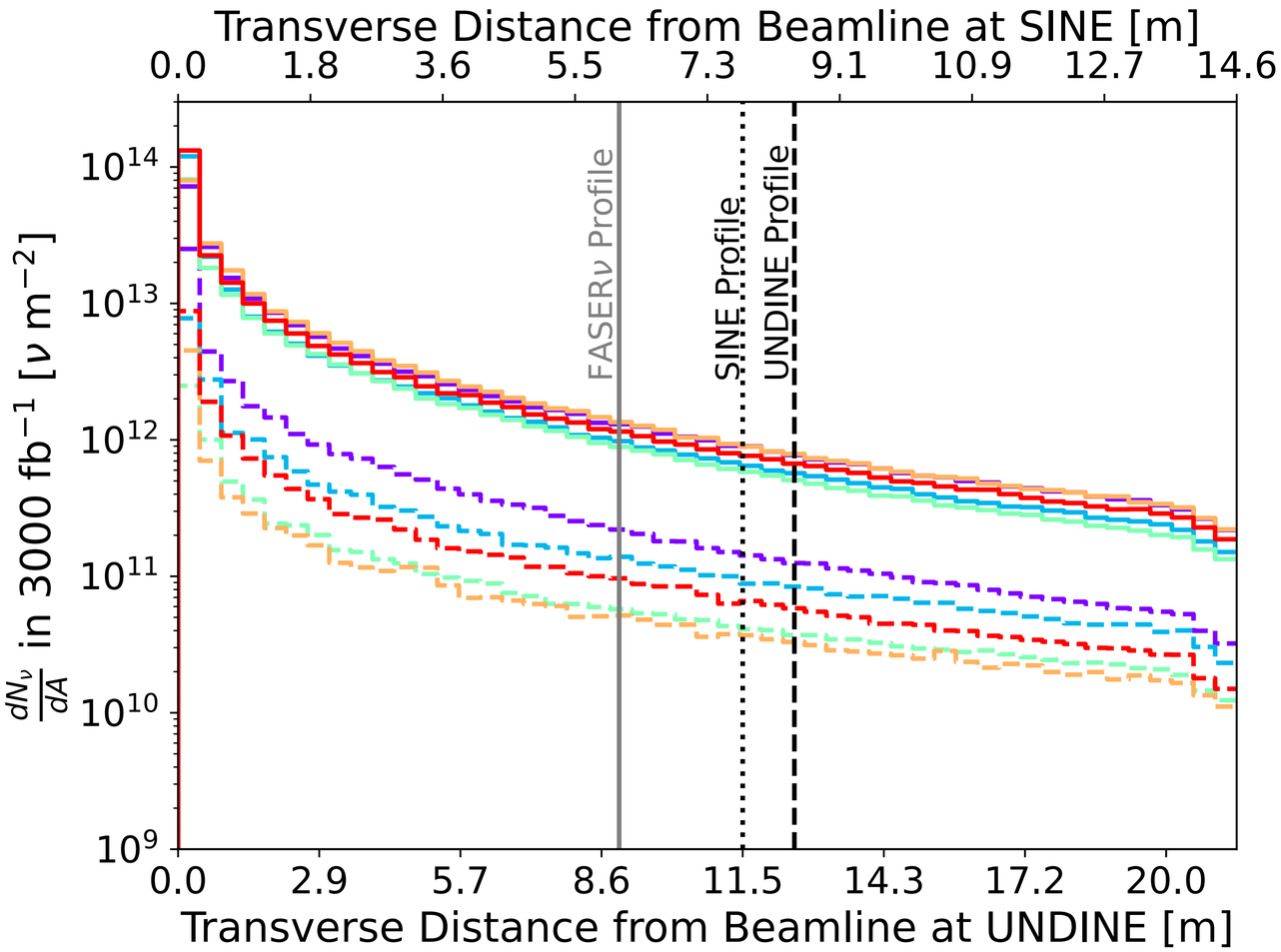
C. Argüelles

T. Yuan

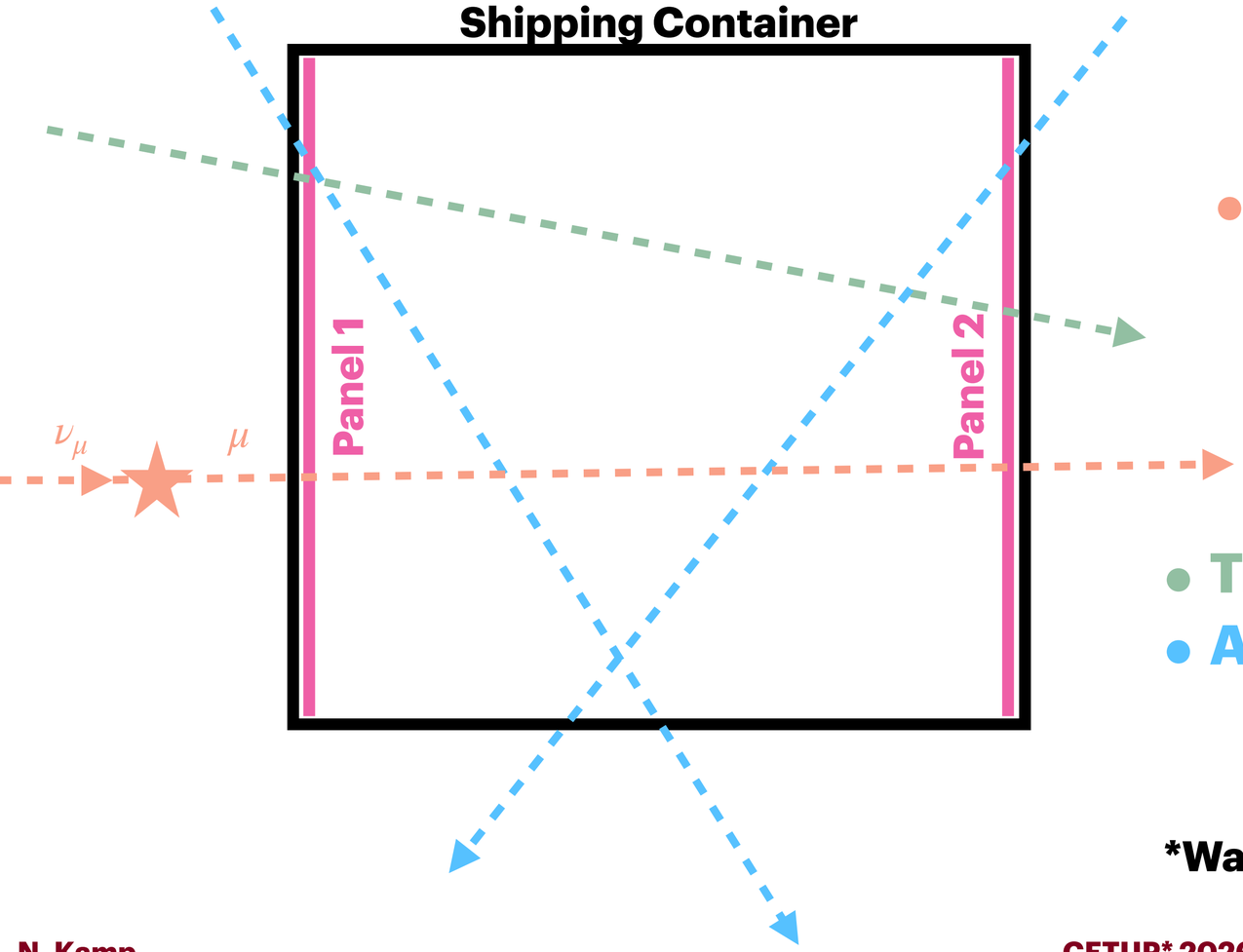
LHC Forward Neutrino Flux

github.com/makelat/forward-nu-flux-fit





What about backgrounds in SINE?



Signal

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

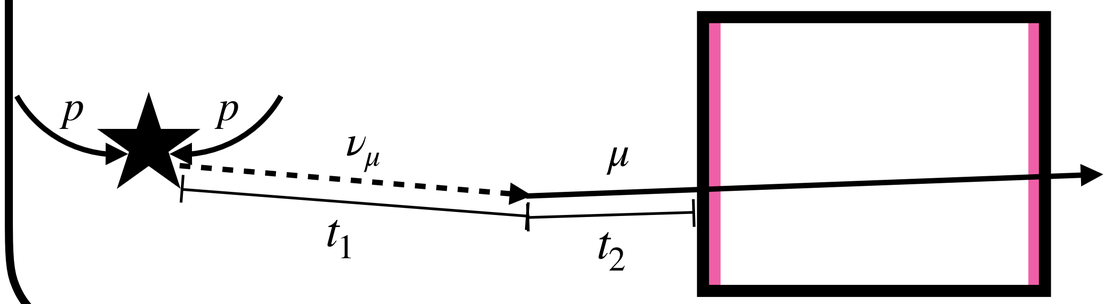
Background

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

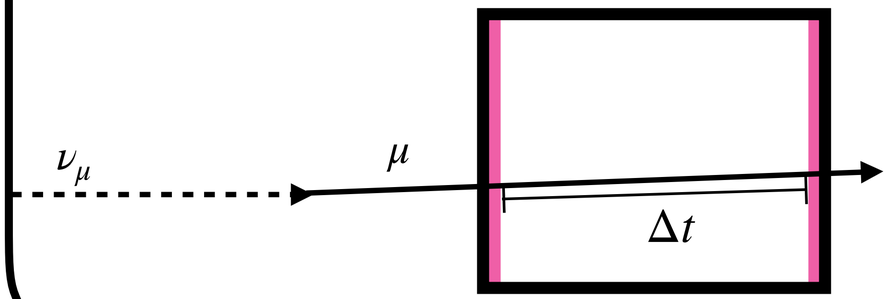
*Water overburden reduces cosmic backgrounds in UNDINE

Timing Cuts

1. Timing with respect to proton collision

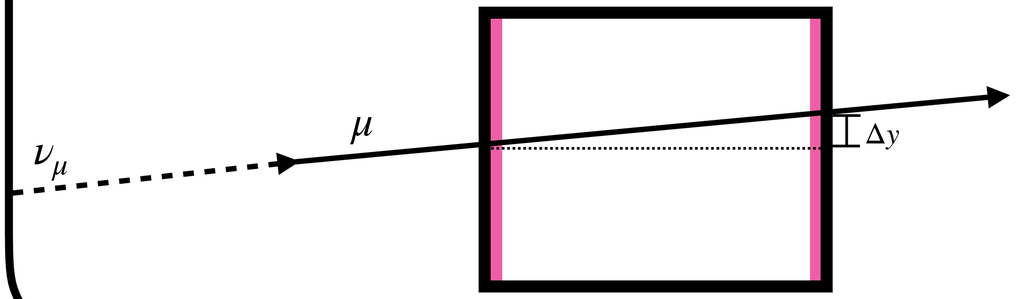


2. Time difference between scintillator panels

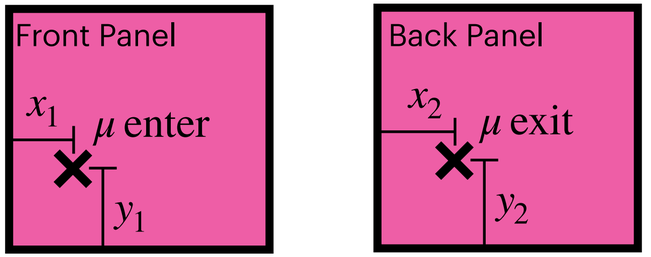


Spatial Cuts

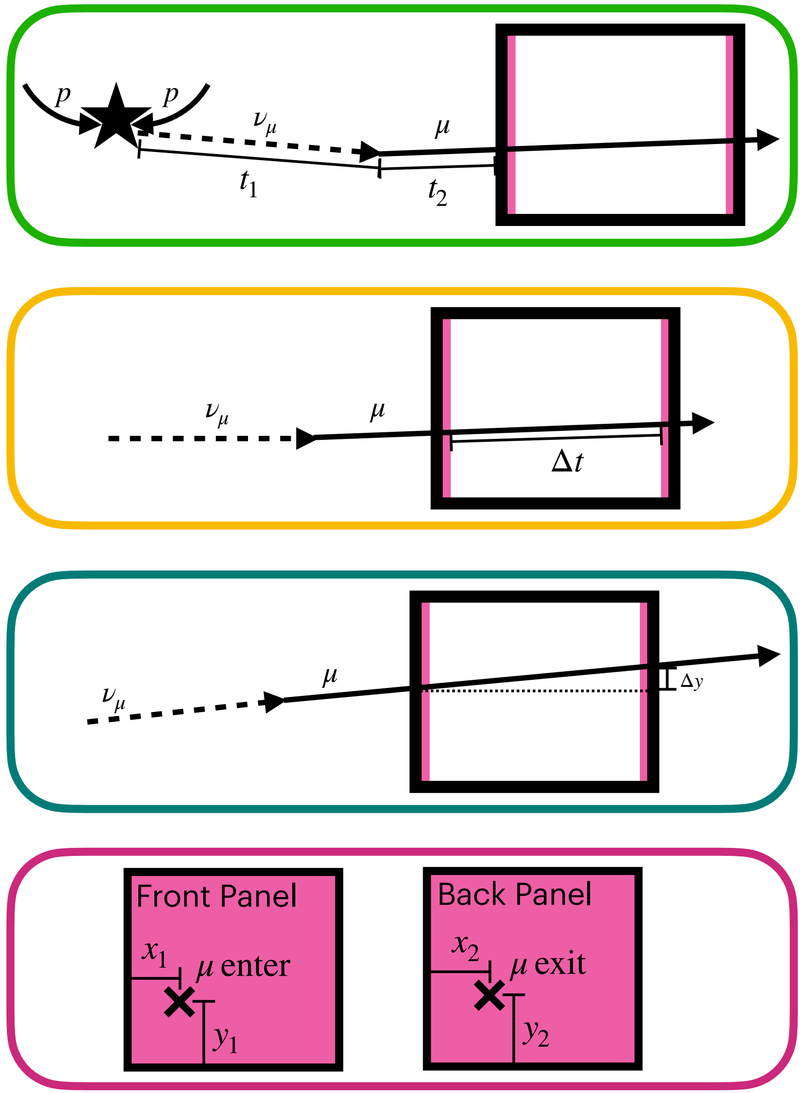
3a. One-dimensional spatial information

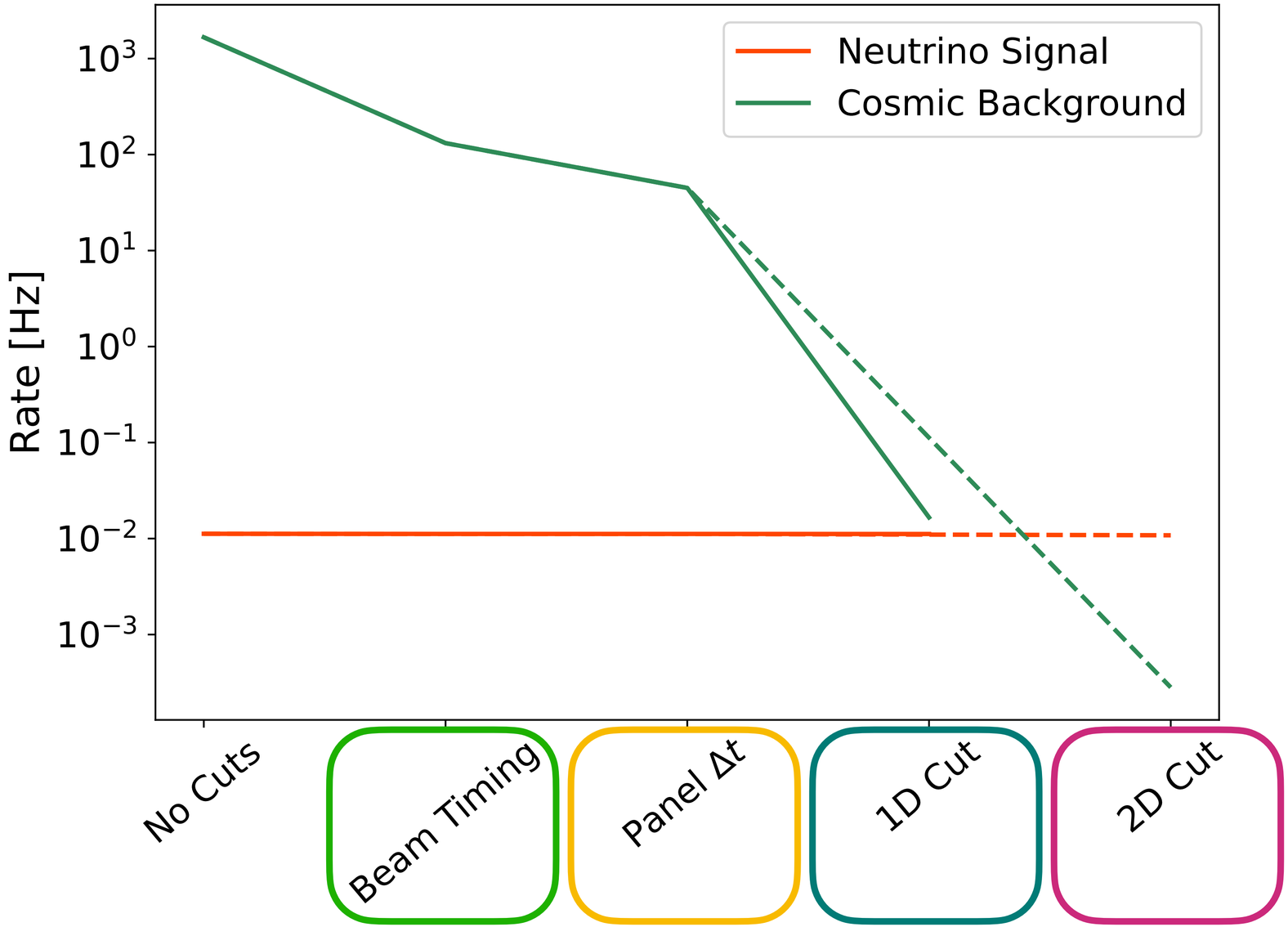


3b. Two-dimensional spatial information



SINE Background Summary





Outline: Three New Directions for Collider Neutrinos

1. Lake- and surface-based detectors for LHC neutrinos
2. **The “Neutrino Kaleidoscope": pairing muon colliders and neutrino telescopes**
3. Searching for heavy neutrinos with a muon beam

arXiv:2508.09249

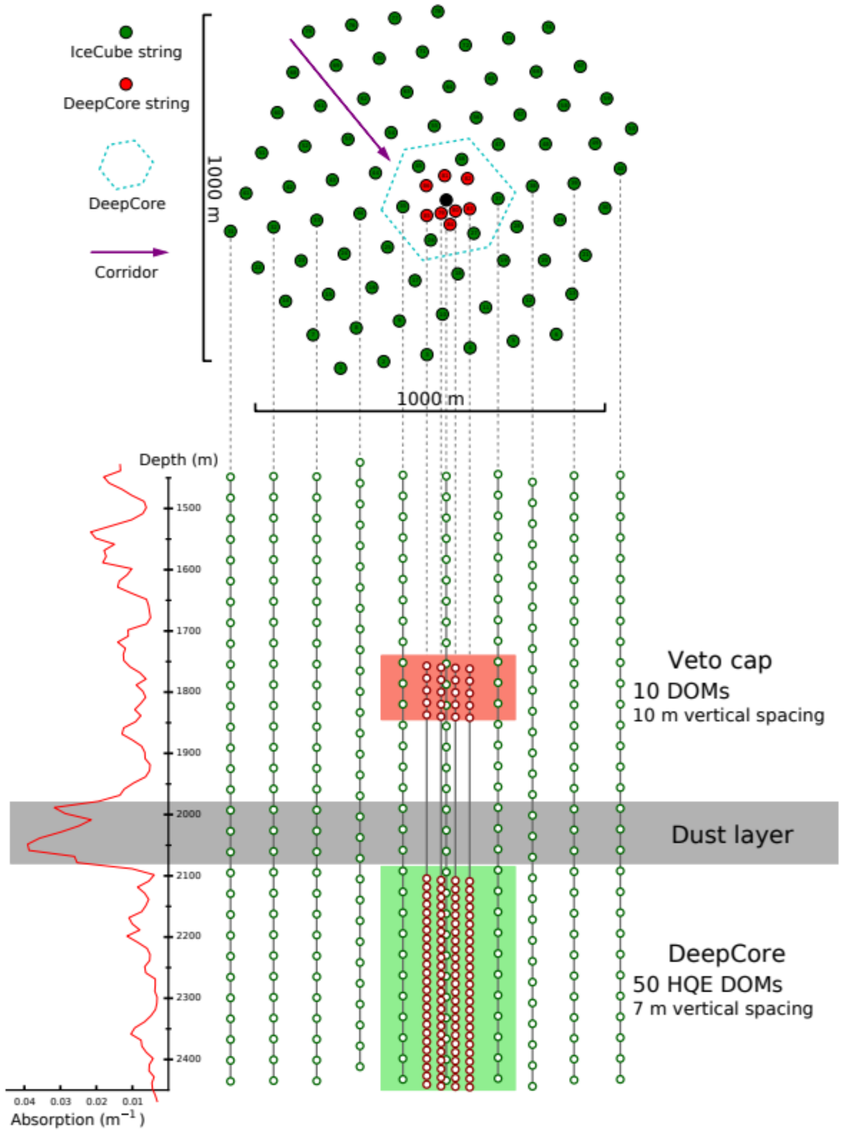
The Neutrino Kaleidoscope: Searches for Non-Standard Neutrino Oscillations at Neutrino Telescopes with a TeV Muon Accelerator Source

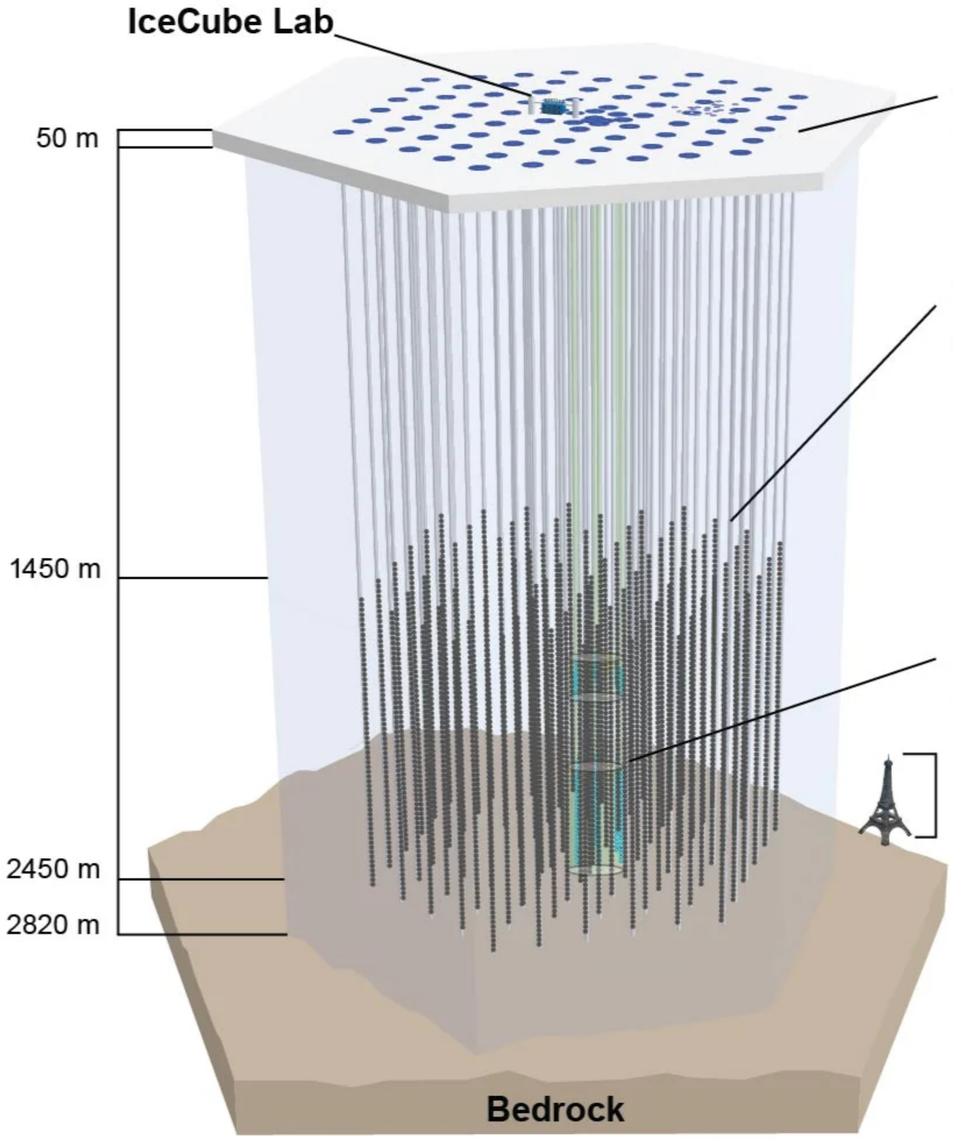
Nicholas W. Kamp[1] and Gray Putnam[2]

[1] *Department of Physics and Laboratory for Particle Physics & Cosmology, Harvard University*
[2] *Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*

G. Putnam

IceCube: an Example Neutrino Telescope





IceTop
81 stations
324 optical sensors

IceCube Array
86 strings including 8 DeepCore strings
5160 optical sensors

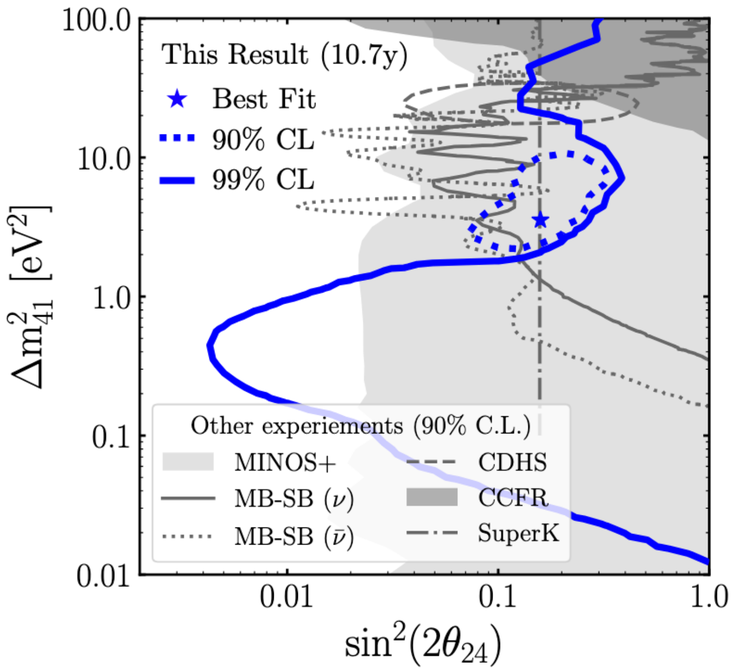
DeepCore
8 strings—spacing optimized for lower energies
480 optical sensors

Eiffel Tower
324 m

Quanta 2023

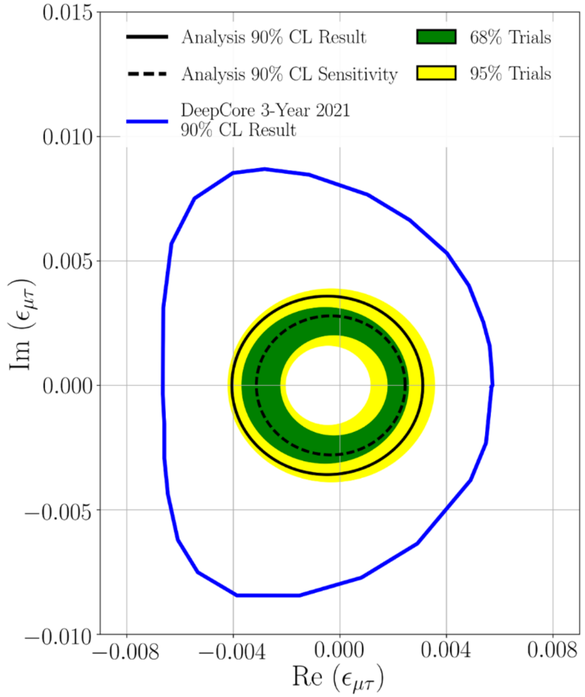
Neutrino Telescopes Search for **Non-Standard** Neutrino Oscillations with TeV Atmospheric Neutrinos

eV-Scale Sterile Neutrinos



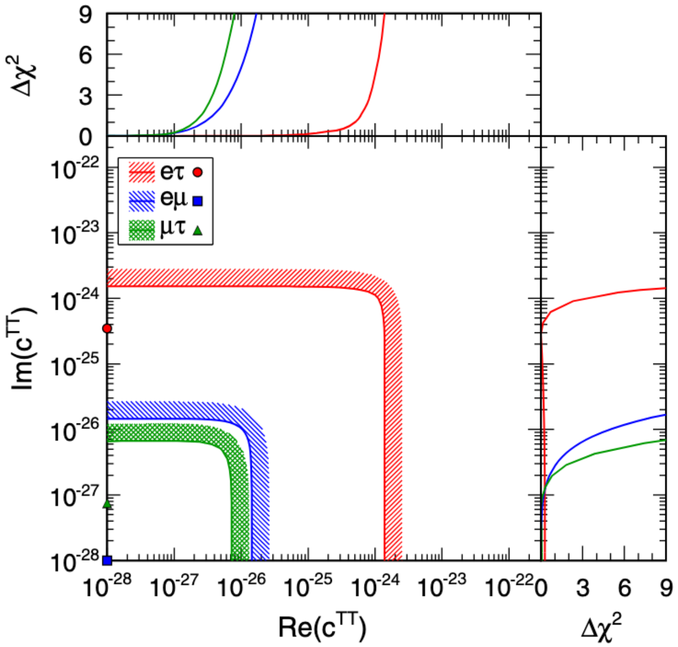
Phys. Rev. Lett. 133, 201804 (2024)

Neutrino-Matter Potential



Phys. Rev. Lett. 129 (2022) 1, 011804

Lorentz Invariance Violation



Phys. Rev. D 91, 052003 (2015)

Oscillations from Lorentz Violation

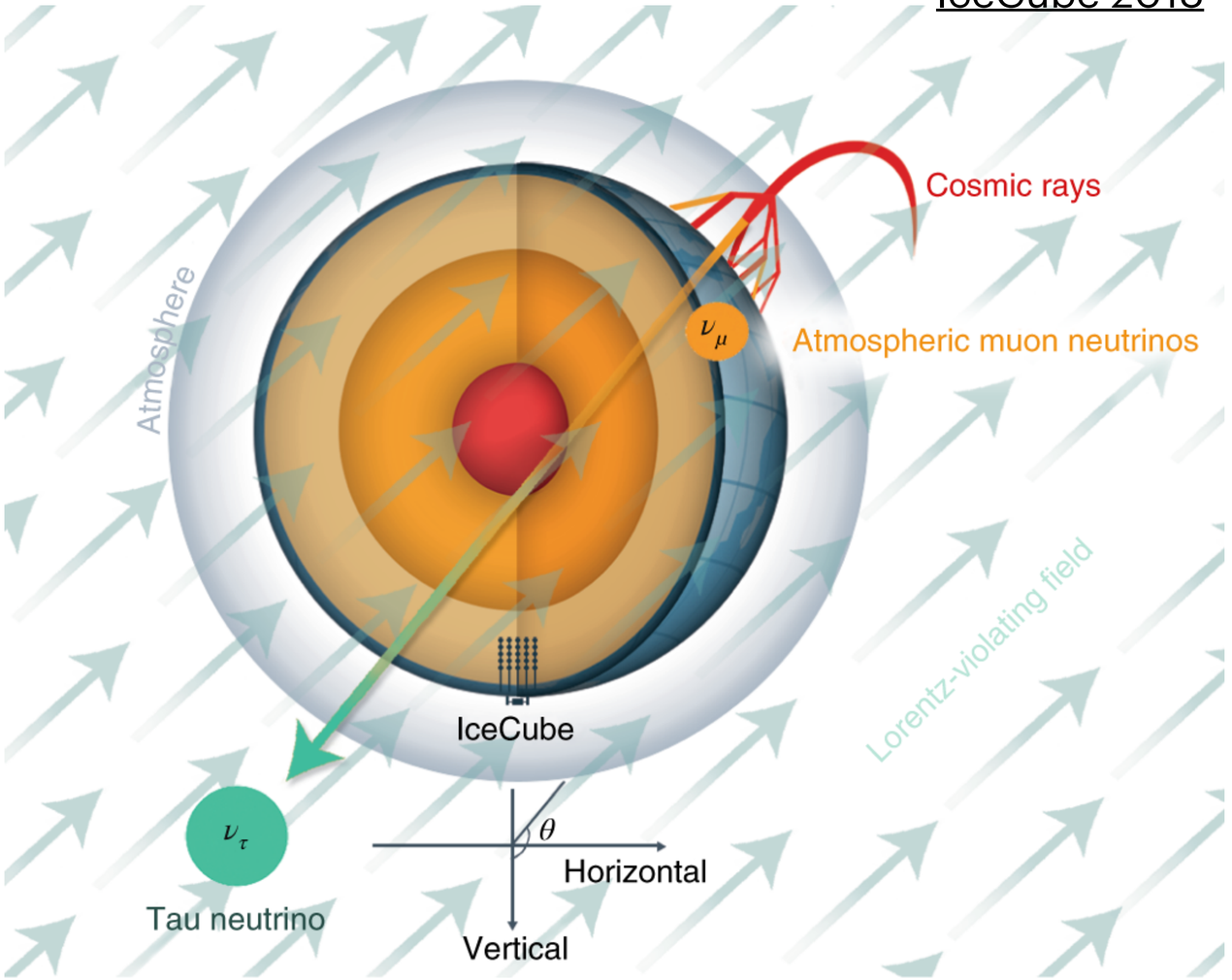
Lorentz violation appears in many theories of quantum gravity [Addazi+ 2021]

Leads to frame-dependent neutrino oscillations described by the Standard Model Extension [Kostelecký+ 2003]

$$V_{\mu\tau} = \frac{1}{E}[(a_L)^{\mu}_{\mu\tau} p_\mu - (c_L)^{\mu\nu}_{\mu\tau} p_\mu p_\nu]$$

$$P_{\nu_\mu \to \nu_\tau} \approx L^2 \left| \frac{\Delta m^2_{31}}{4E} \sin 2\theta_{23} + V_{\mu\tau} \right|^2$$

IceCube 2018



Lorentz Violation in Practice

We look for oscillations at the sidereal frequency: $\omega_\oplus = 2\pi/(23\ \mathrm{h}\ 56\ \mathrm{min})$

$$V_{\mu\tau} = (C)_{\mu\tau} + (A_s)_{\mu\tau}\sin\omega_\oplus T_\oplus + (A_c)_{\mu\tau}\cos\omega_\oplus T_\oplus + (B_s)_{\mu\tau}\sin 2\omega_\oplus T_\oplus + (B_c)_{\mu\tau}\cos 2\omega_\oplus T_\oplus,$$

$$V_{\mu\tau} = \frac{1}{E}[(a_L)^\mu_{\mu\tau} p_\mu - (c_L)^{\mu\nu}_{\mu\tau} p_\mu p_\nu]$$

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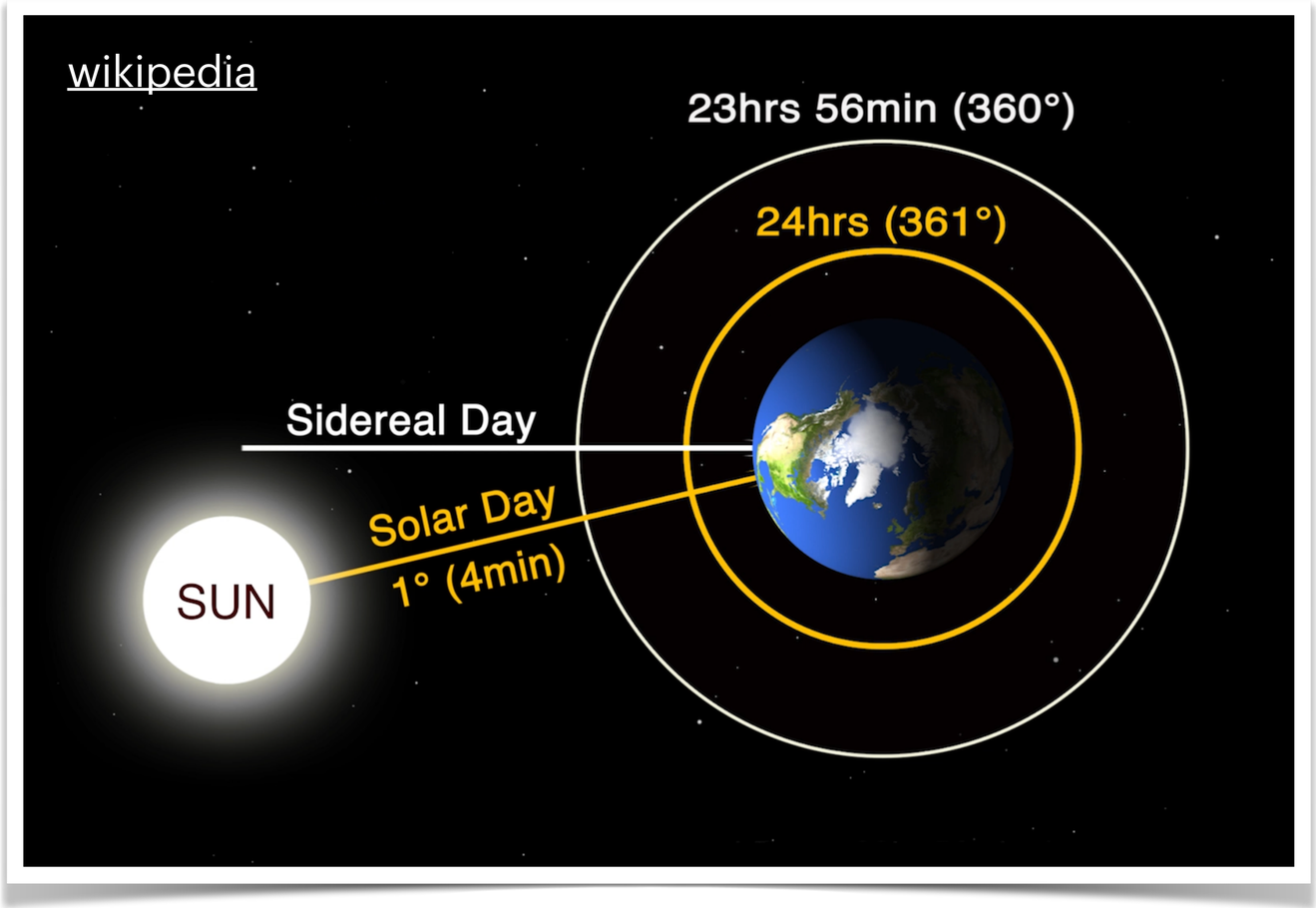

$\{C, A_s, A_c, B_s, B_c\}$ are experiment-dependent linear combinations of a_L^μ, $c_L^{\mu\nu}$

Lorentz Violation in Practice

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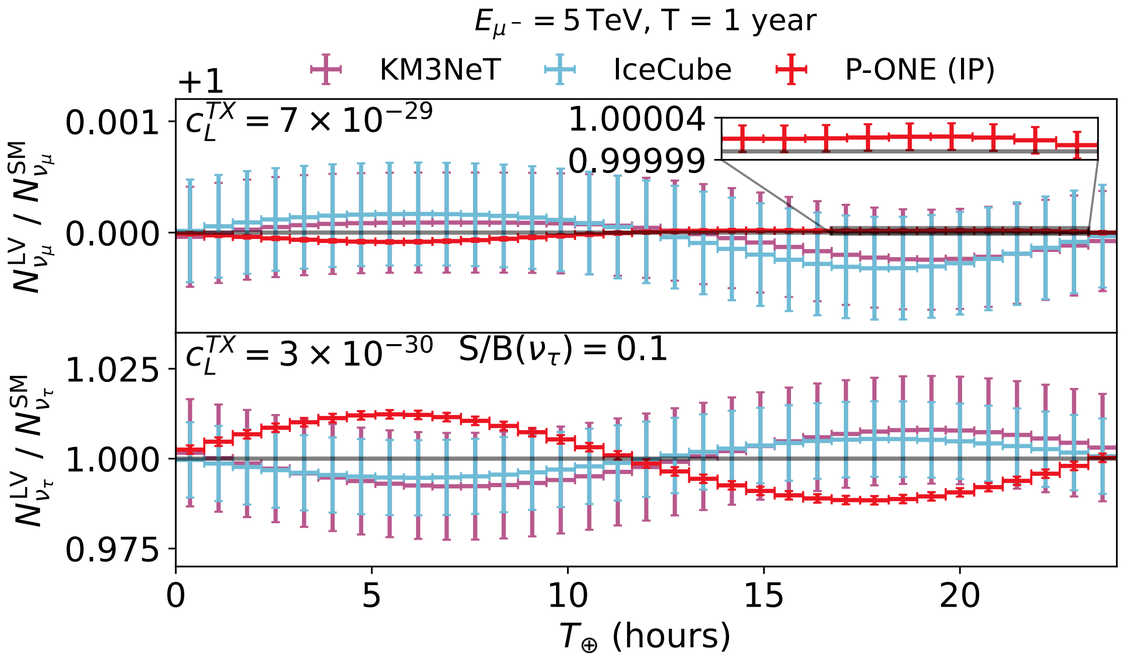
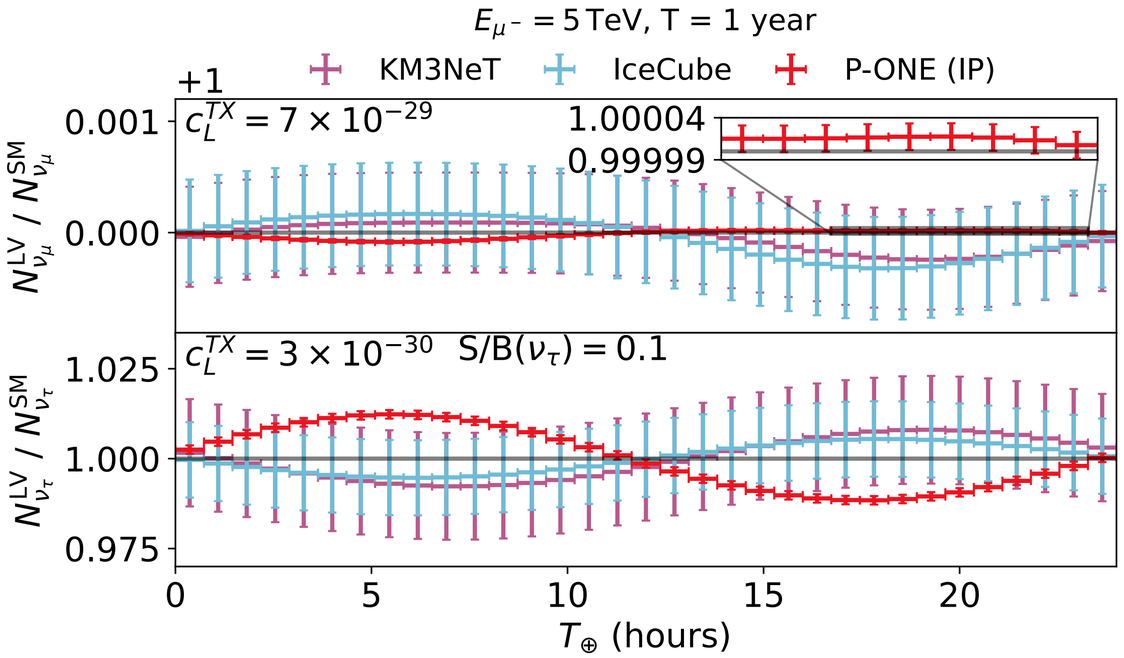
$$P_{\nu_\mu\to\nu_\tau} \approx L^2 \left| \frac{\Delta m^2_{31}}{4E}\sin 2\theta_{23} + V_{\mu\tau} \right|^2$$

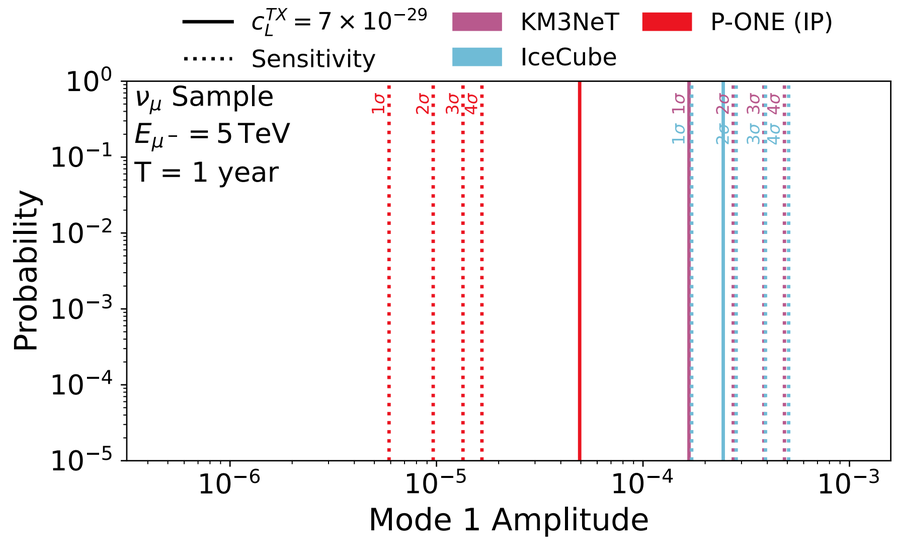
Easy case: ν_μ oscillations in a "tracks" sample

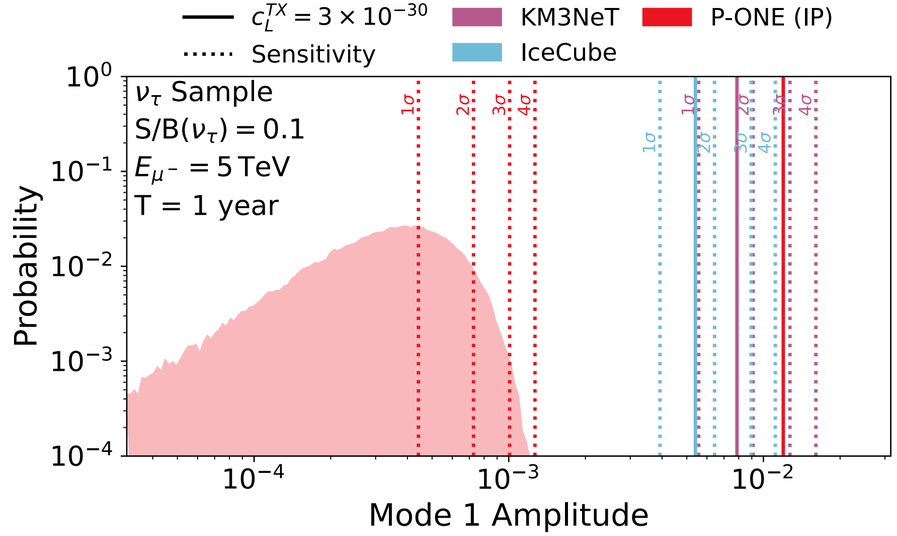


Challenge case: ν_τ oscillations in a ν_τ-enhanced sample with a signal-to-background ratio of 10%

Lorentz Violation in Practice

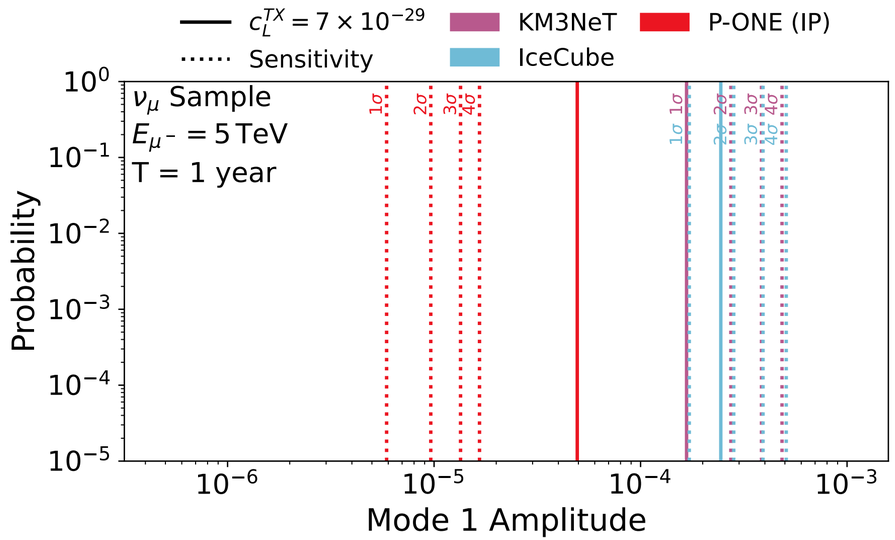


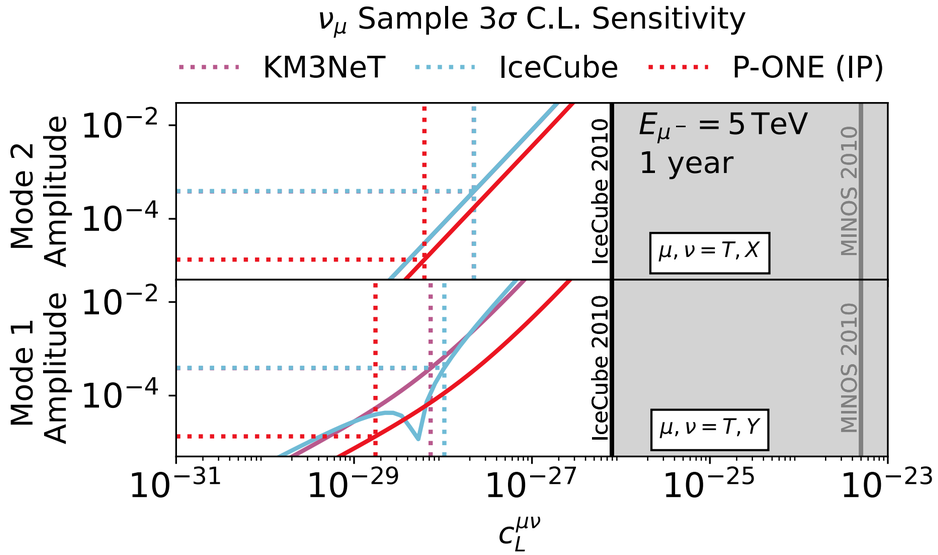


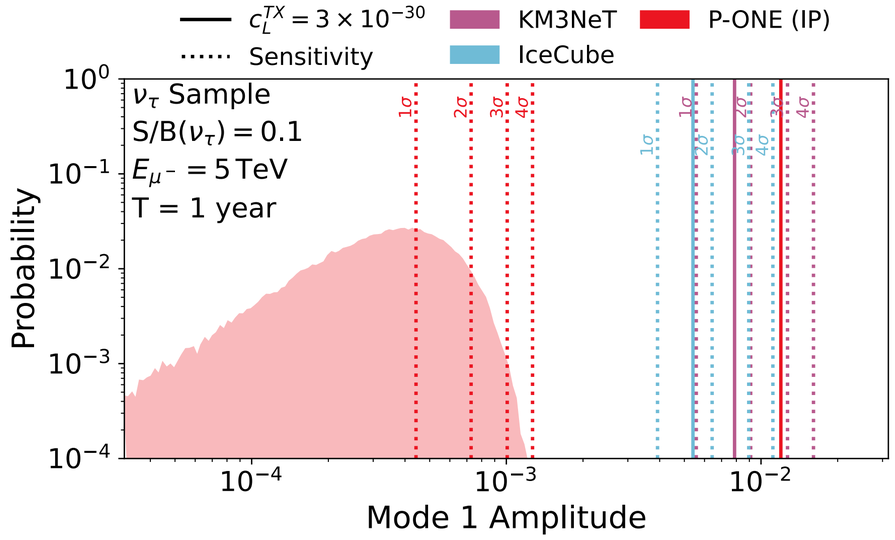


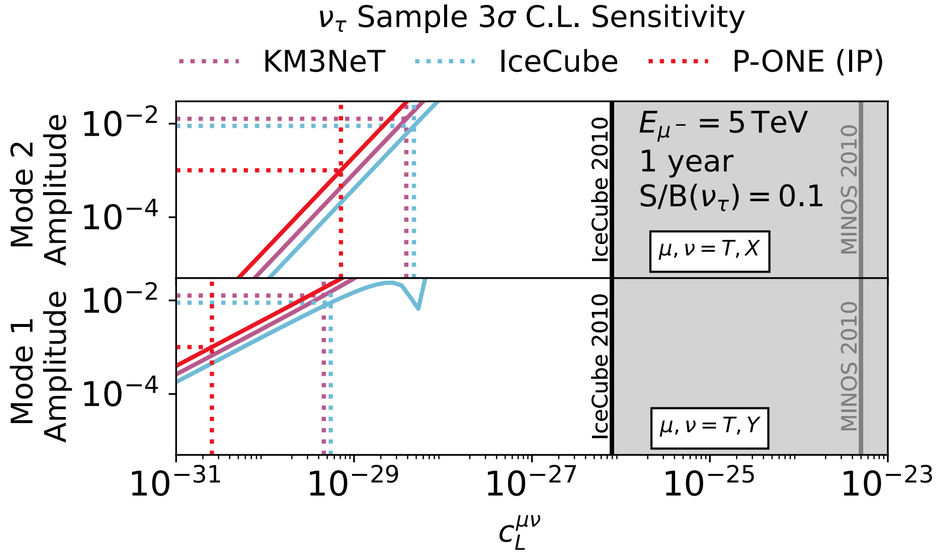
We perform a Fourier analysis on harmonics of the sidereal frequency

Lorentz Violation in Practice

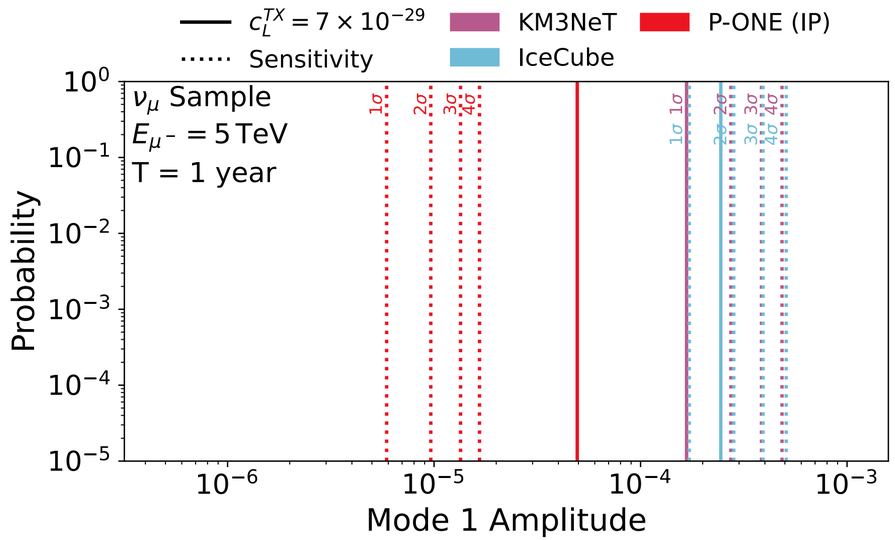


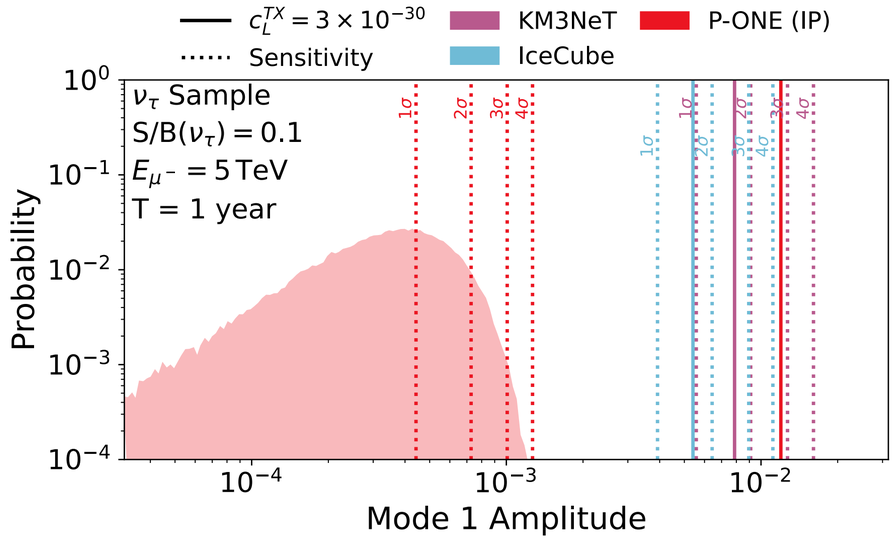




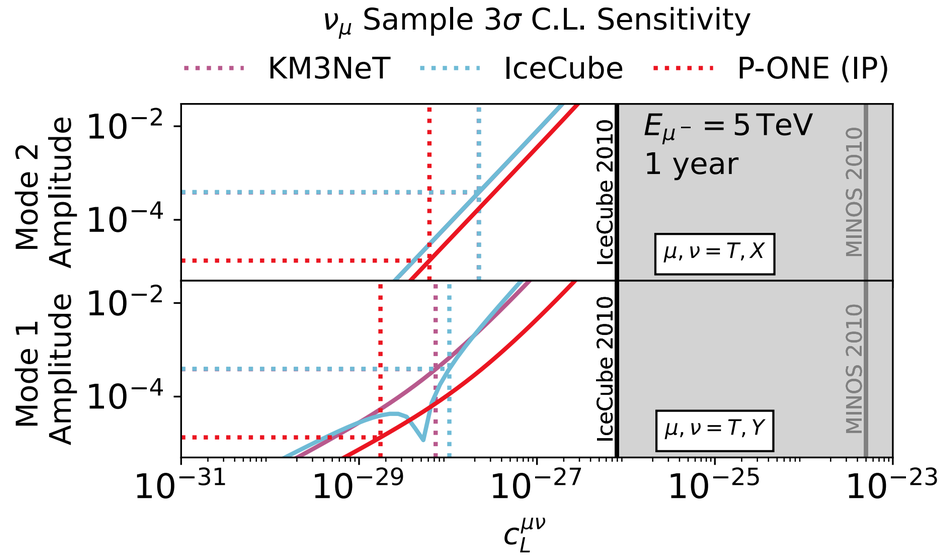


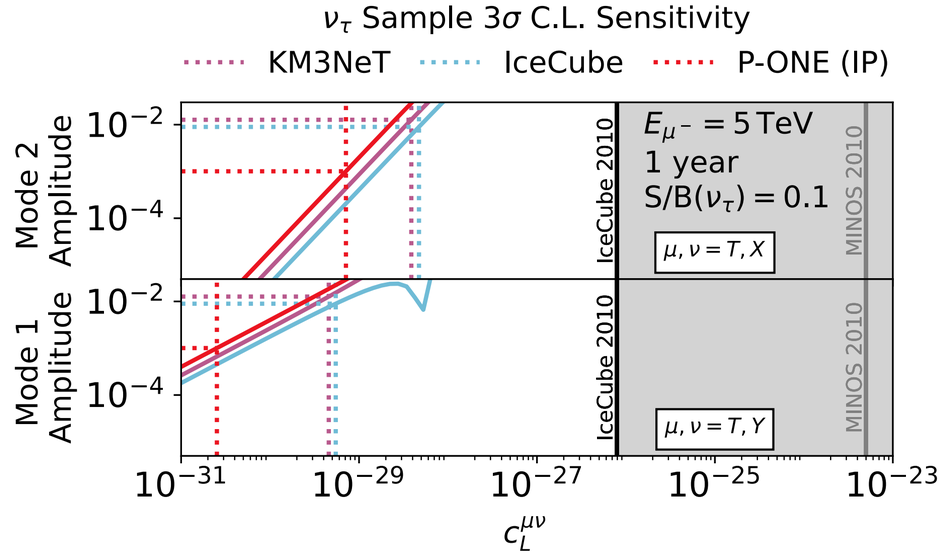
Lorentz Violation in Practice





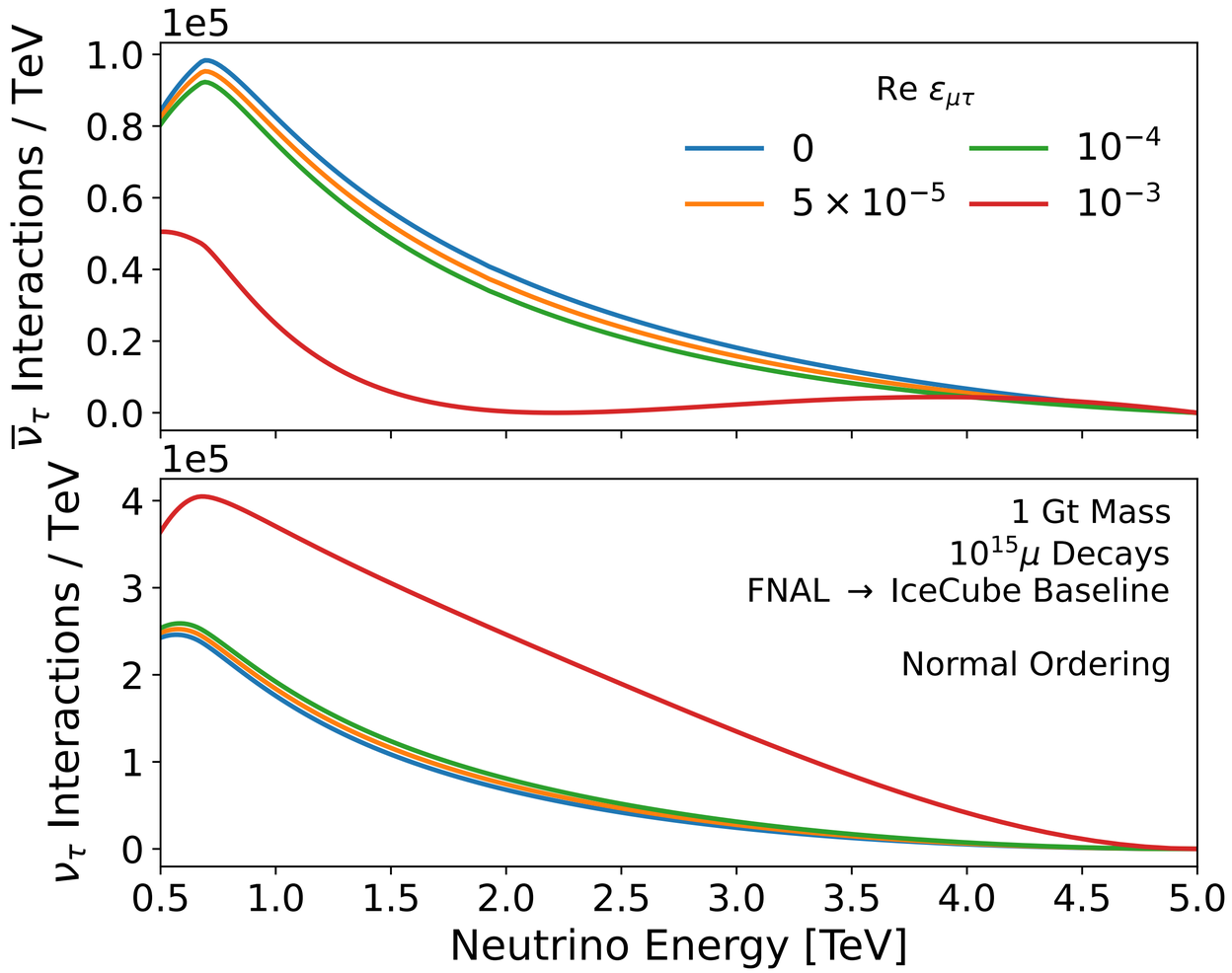
ν kaleidoscopes can improve upon existing constraints by multiple orders of magnitude!



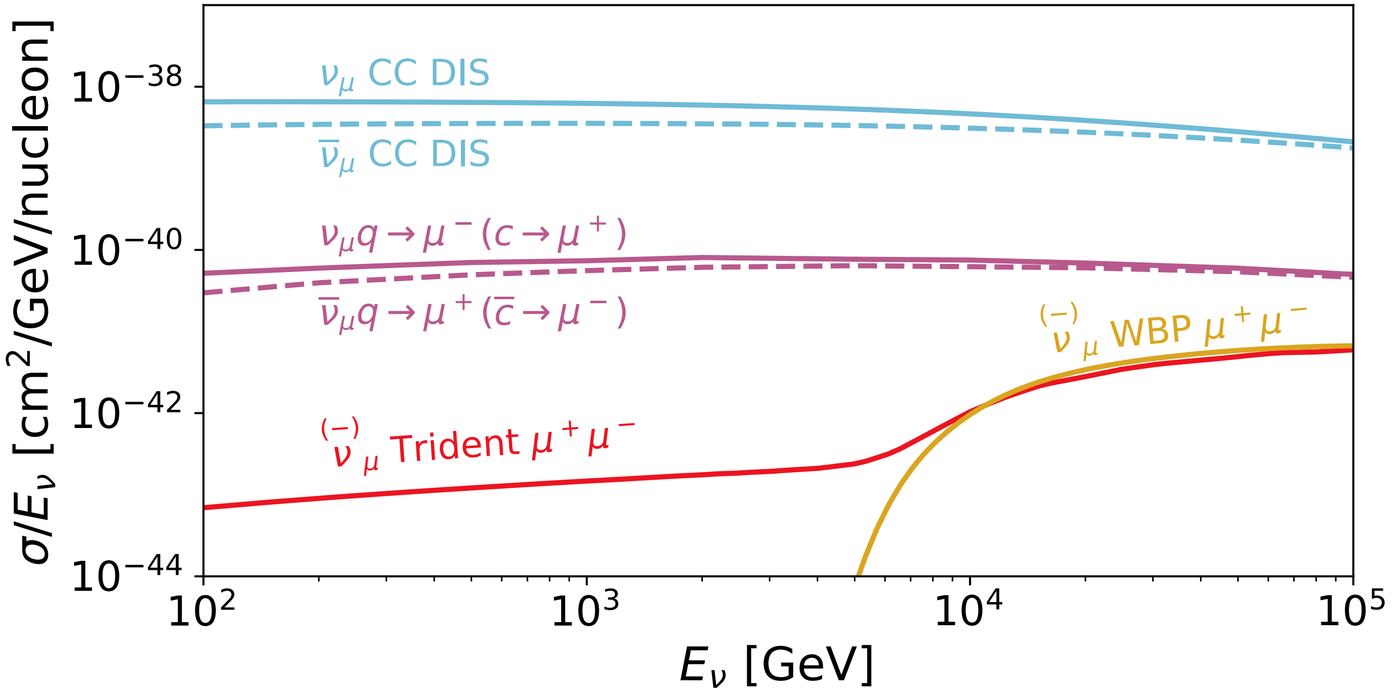


Bonus: Non-Standard Matter Potential

- A small muon-tau (*off diagonal*) matter potential term would have a large impact on the tau neutrino interaction rate
- The effect would be different in direction for tau and anti-tau neutrinos (for a real potential)
- **If we can measure tau neutrinos,** possible strong sensitivity to $\epsilon_{\mu\tau}$



Bonus: Unprecedented Rates of Rare Neutrino Interactions Producing $\mu^+\mu^-$ Pairs



Events per year:

Process	KM3NeT	IceCube	P-ONE (IP)
ν_μ CC DIS	1.7×10^8	1.6×10^8	1.3×10^{11}
$\nu_\mu q \to \mu^-(c \to \mu^+)$	2.2×10^6	2.1×10^6	1.8×10^9
ν_μ Trident $\mu^+\mu^-$	5.2×10^3	5×10^3	4.2×10^6
ν_μ WBP $\mu^+\mu^-$	3.6	3.6	2.8×10^3

See Zhou+ 2021 and S. Sarkar Thesis (2023) for discussions on tagging dimuons in IceCube

Outline: Three New Directions for Collider Neutrinos

1. Lake- and surface-based detectors for LHC neutrinos
2. The “Neutrino Kaleidoscope": pairing muon colliders and neutrino telescopes
3. **Searching for heavy neutrinos with a muon beam**

arXiv:26XX.XXXX

In collaboration with:

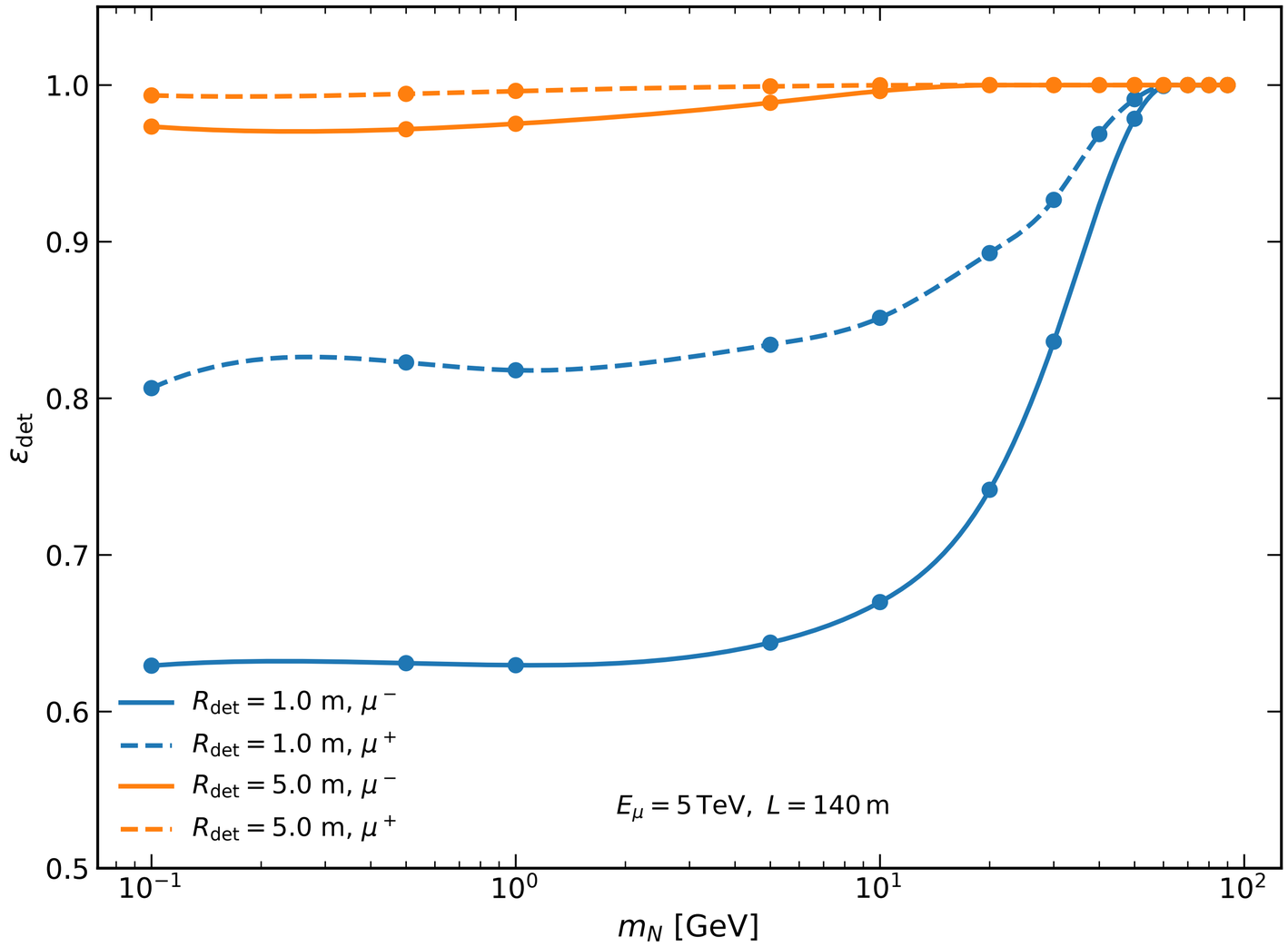
K. Xie

P.-C. Lu

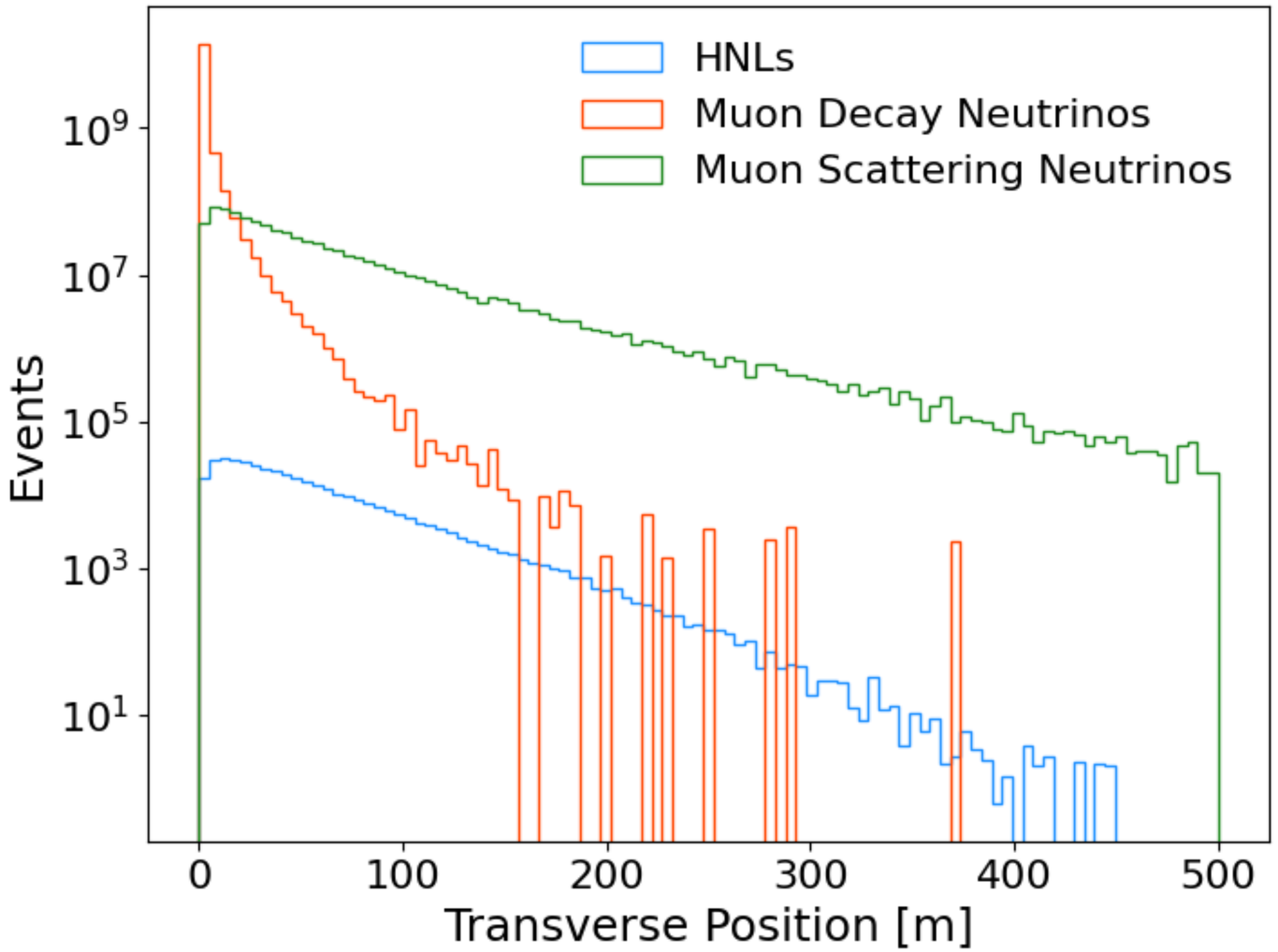
C. Argüelles

G. Herrera

2: “Traditional” Muon Beam Dump



Atmospheric Muon Beam Dump Sensitivity



Muon-Ion Collider Sensitivity