Heavy Neutrinos in Ice, Rock, Water, and Plastic

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Université catholique de Louvain | CP3 Seminar
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Conwaybreen Glacier, Svalbard

The *Big* Picture

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Progress in neutrino physics is driven by **experimental anomalies**

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Novel detectors and unique signatures are essential to resolve anomalies

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This talk: a new perspective on an old anomaly

A Brief History of Neutrino Anomalies

Experimental Anomaly **Theoretical Resolution** **Experimental Validation**

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Continuous electron energy spectrum in beta decays

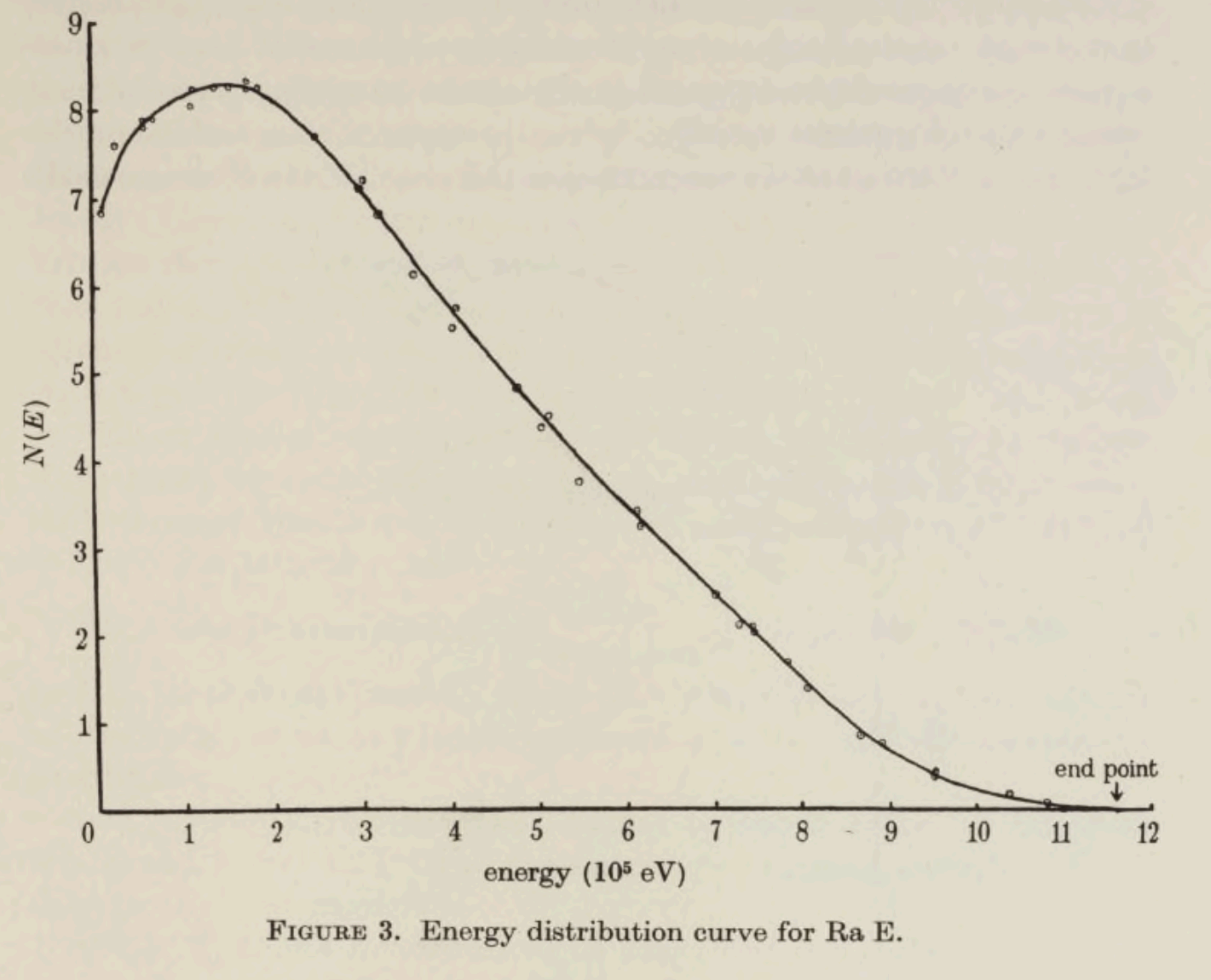

FIGURE 3. Energy distribution curve for Ra E.

Neary 1940

A Brief History of Neutrino Anomalies

Experimental Anomaly

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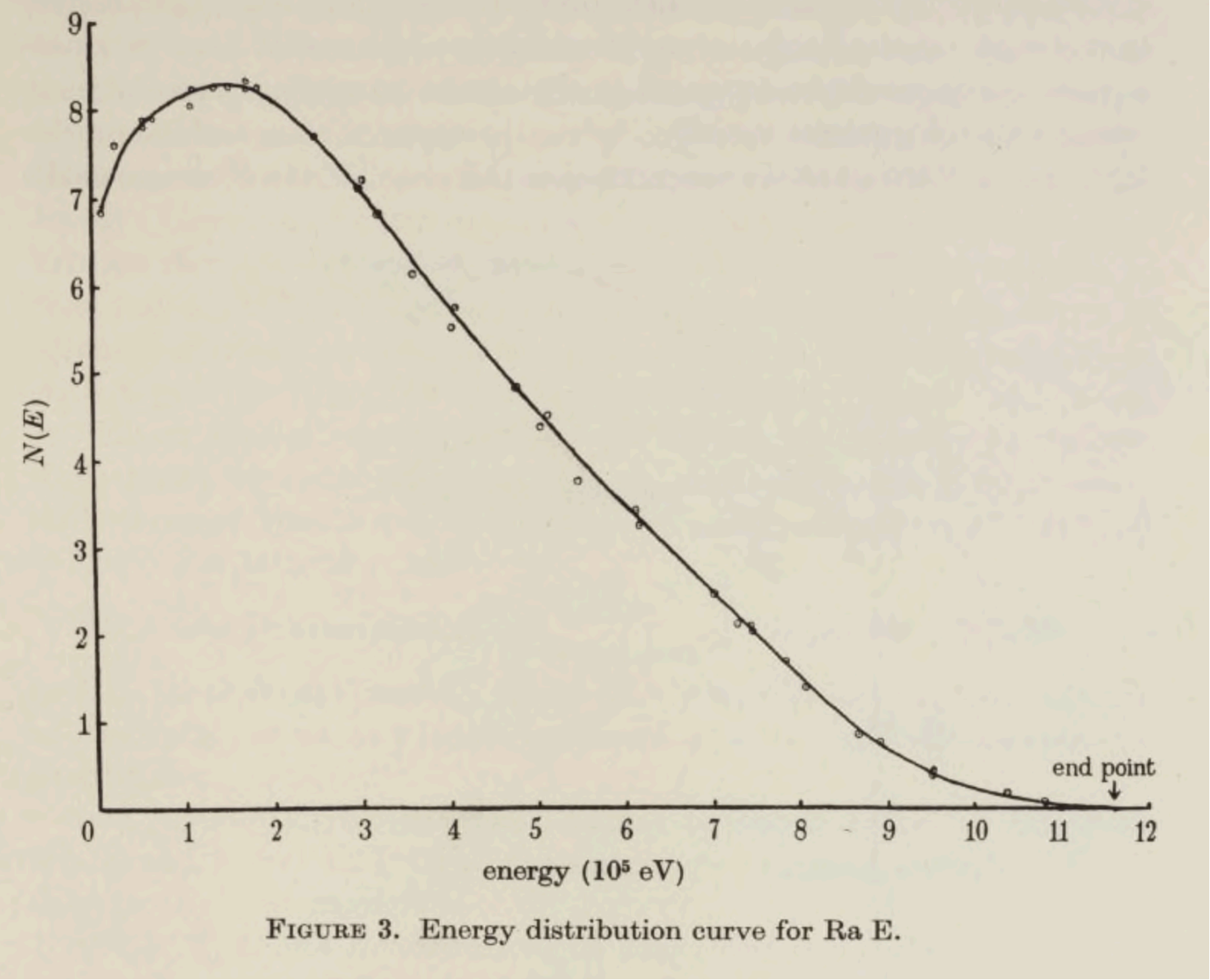

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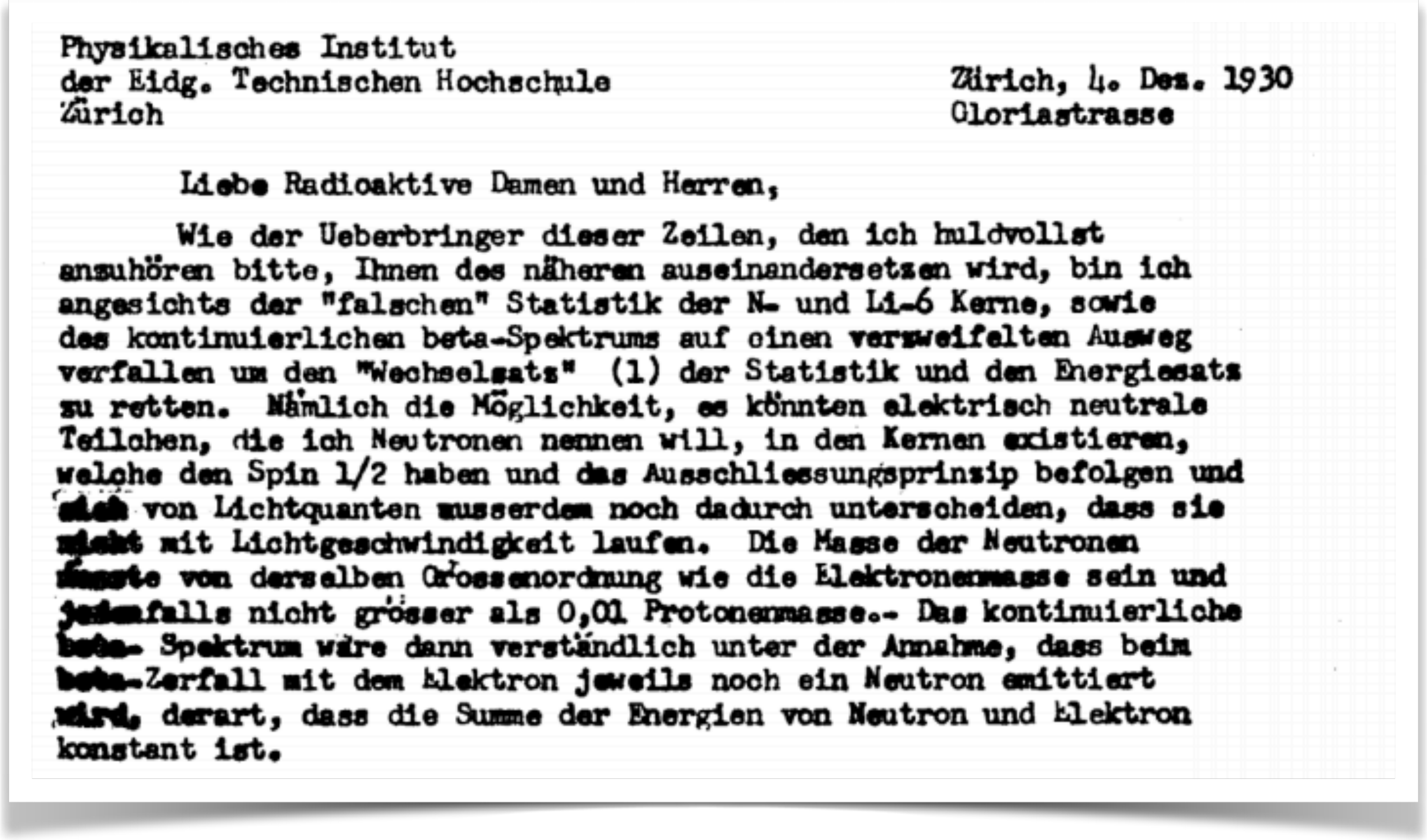
Neary 1940

Theoretical Resolution

A new neutral particle



Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Des. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

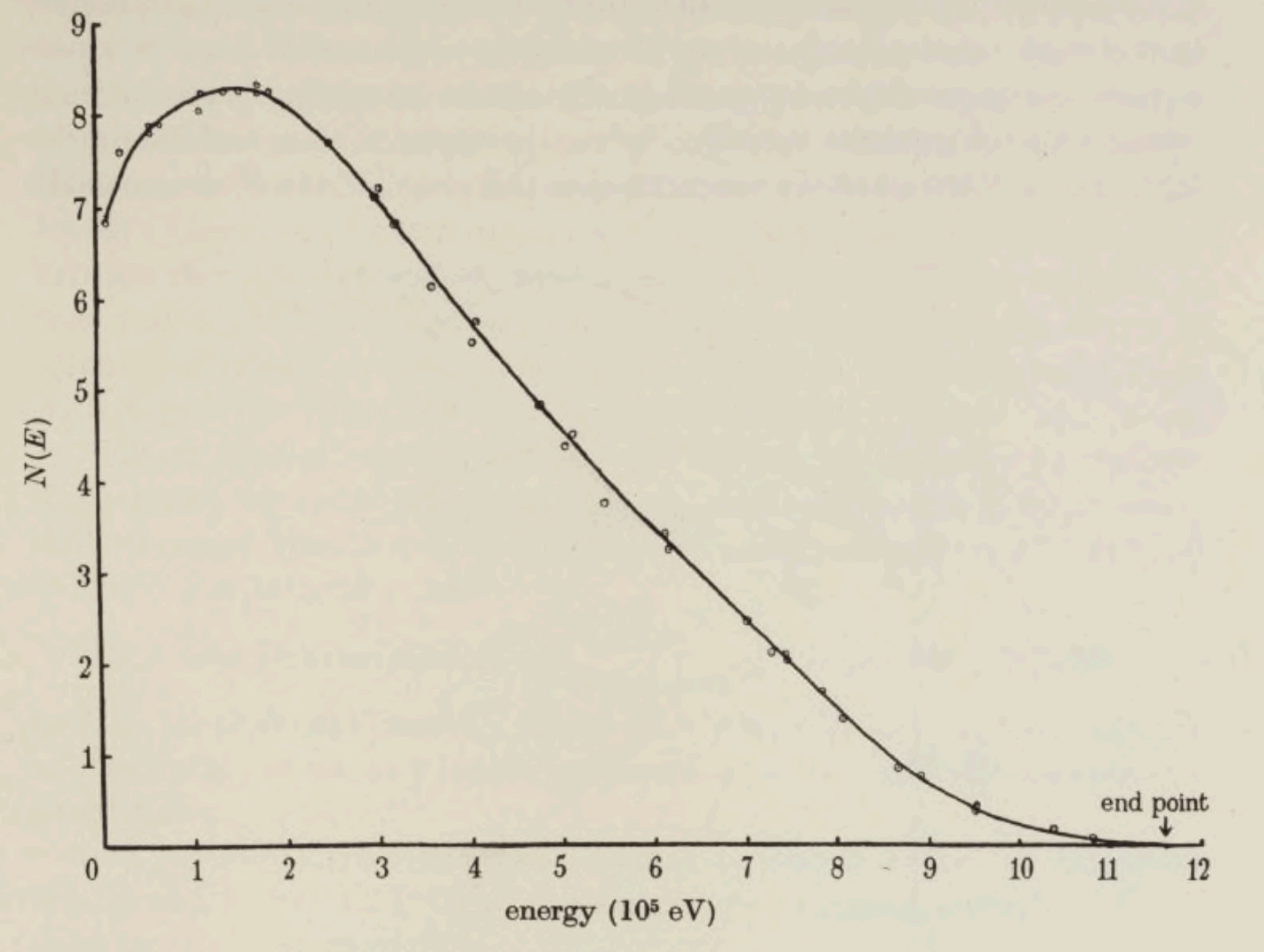
Wie der Ueberbringer dieser Zeilen, den ich huldvollst ansuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Pauli 1930

Experimental Validation

A Brief History of Neutrino Anomalies

Experimental Anomaly	**Theoretical Resolution**	**Experimental Validation**
Continuous electron energy spectrum in beta decays	A new neutral particle	Detection of a neutrino from a nuclear reactor



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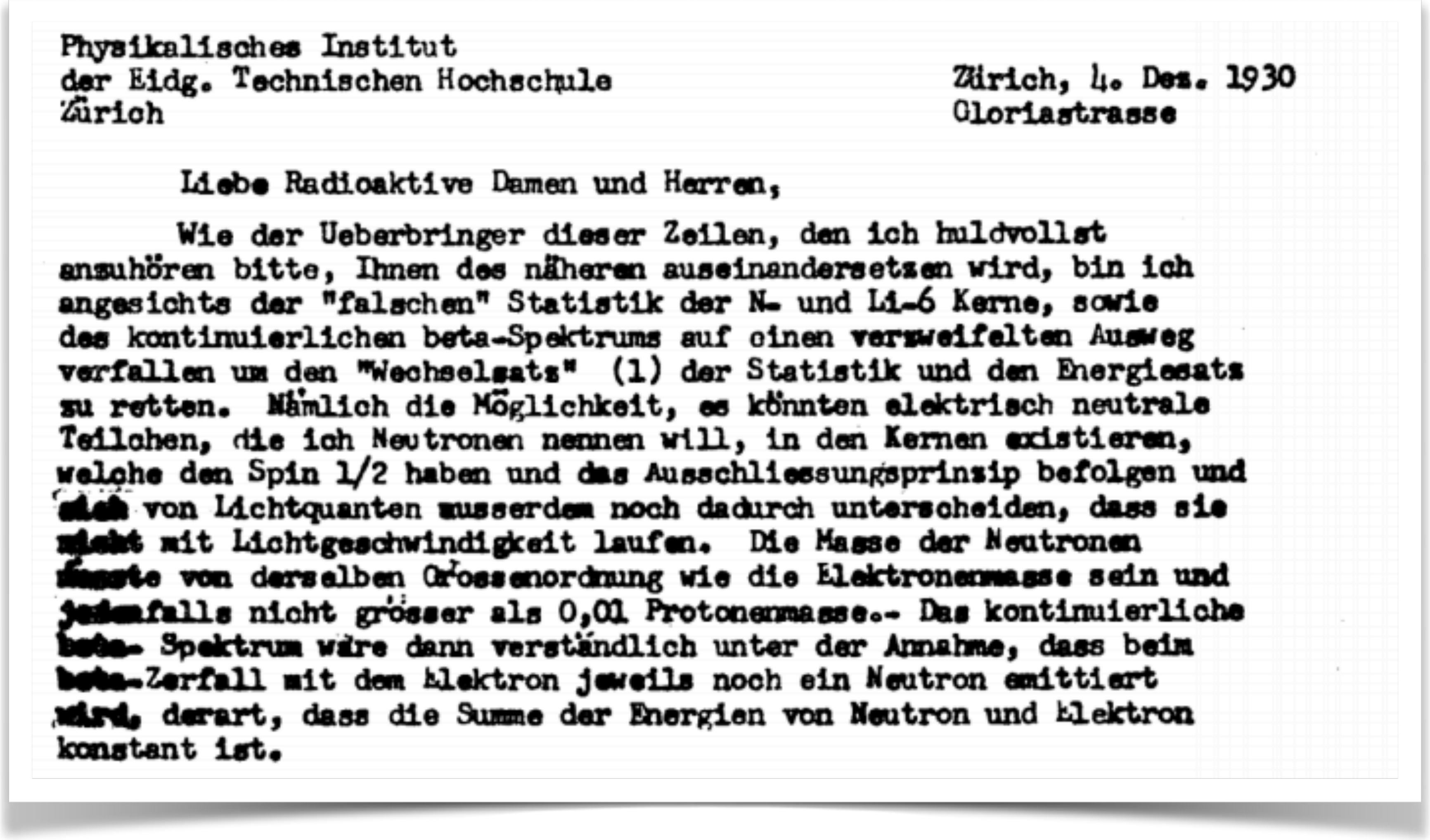

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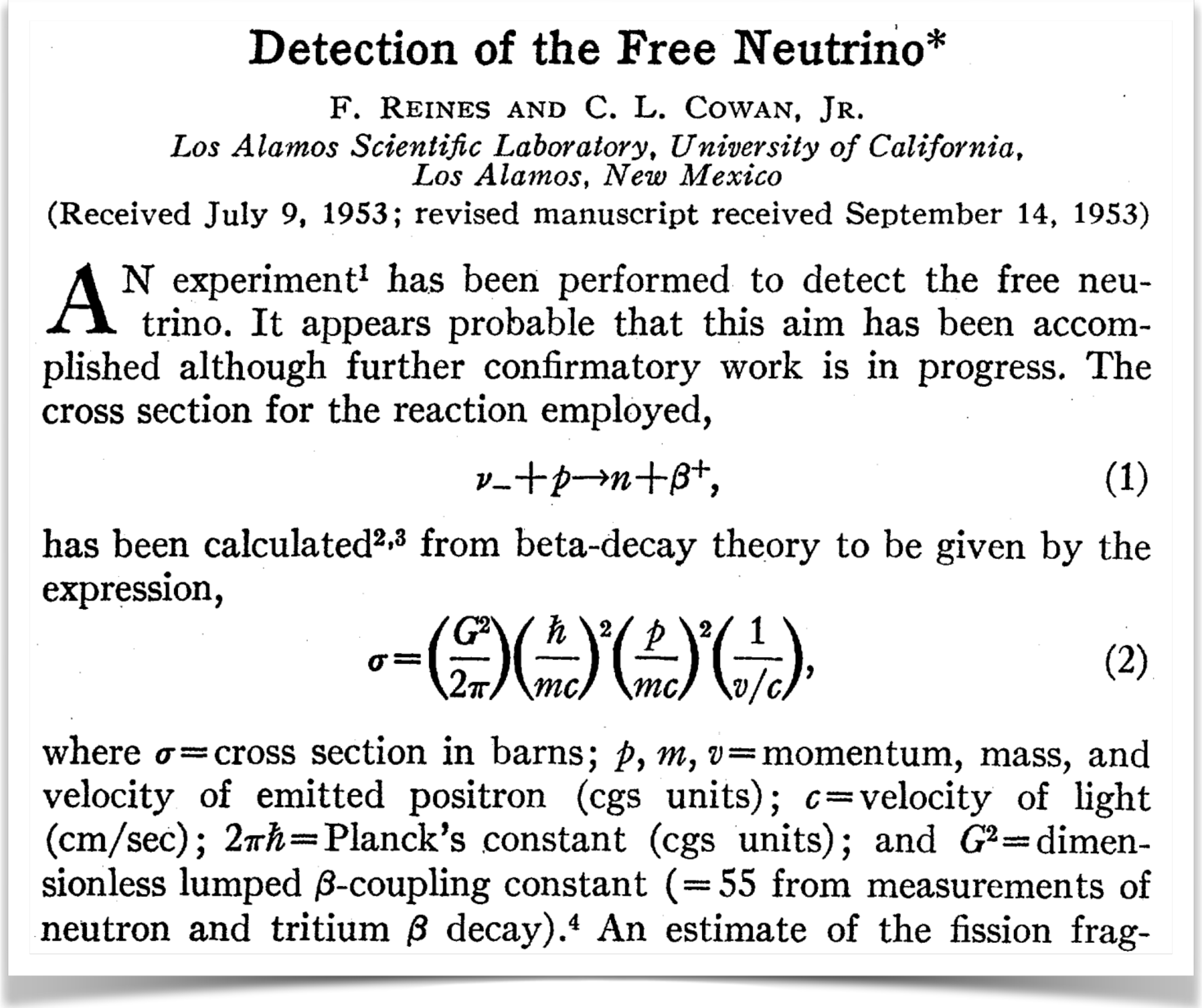

Detection of the Free Neutrino*

F. REINES AND C. L. COWAN, JR.
Los Alamos Scientific Laboratory, University of California,
Los Alamos, New Mexico
(Received July 9, 1953; revised manuscript received September 14, 1953)

AN experiment[1] has been performed to detect the free neutrino. It appears probable that this aim has been accomplished although further confirmatory work is in progress. The cross section for the reaction employed,

$$\nu_- + p \rightarrow n + \beta^+, \quad (1)$$

has been calculated[2,3] from beta-decay theory to be given by the expression,

$$\sigma = \left(\frac{G^2}{2\pi}\right)\left(\frac{\hbar}{mc}\right)^2\left(\frac{p}{mc}\right)^2\left(\frac{1}{v/c}\right), \quad (2)$$

where σ = cross section in barns; p, m, v = momentum, mass, and velocity of emitted positron (cgs units); c = velocity of light (cm/sec); $2\pi\hbar$ = Planck's constant (cgs units); and G^2 = dimensionless lumped β-coupling constant (=55 from measurements of neutron and tritium β decay).[4] An estimate of the fission frag-

Reines, Cowan 1953

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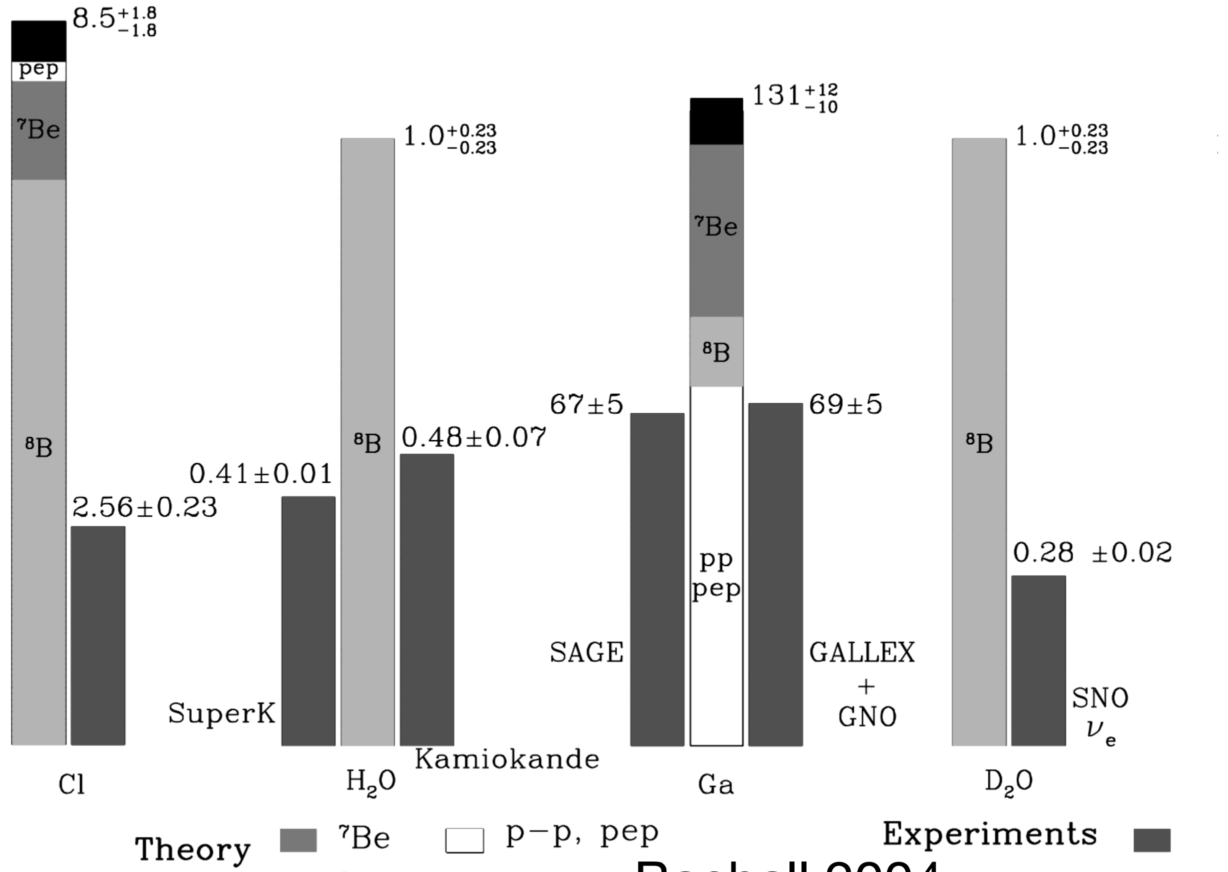
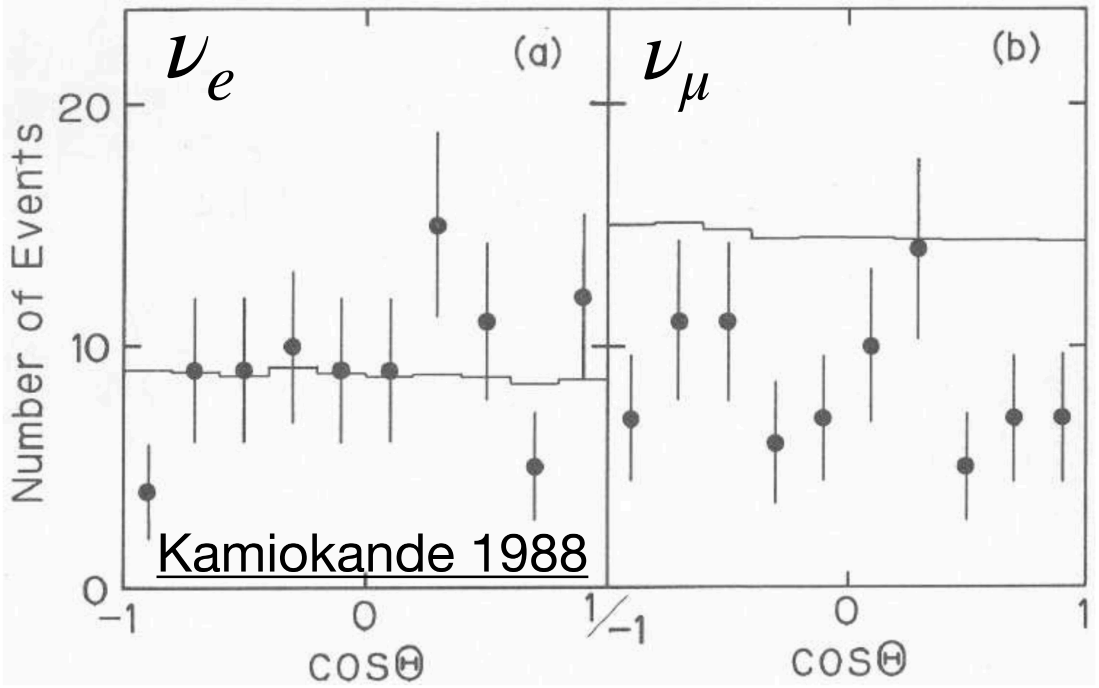
Observed deficits of solar and atmospheric neutrinos



Bachall 2004



Kamiokande 1988

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Experimental Anomaly

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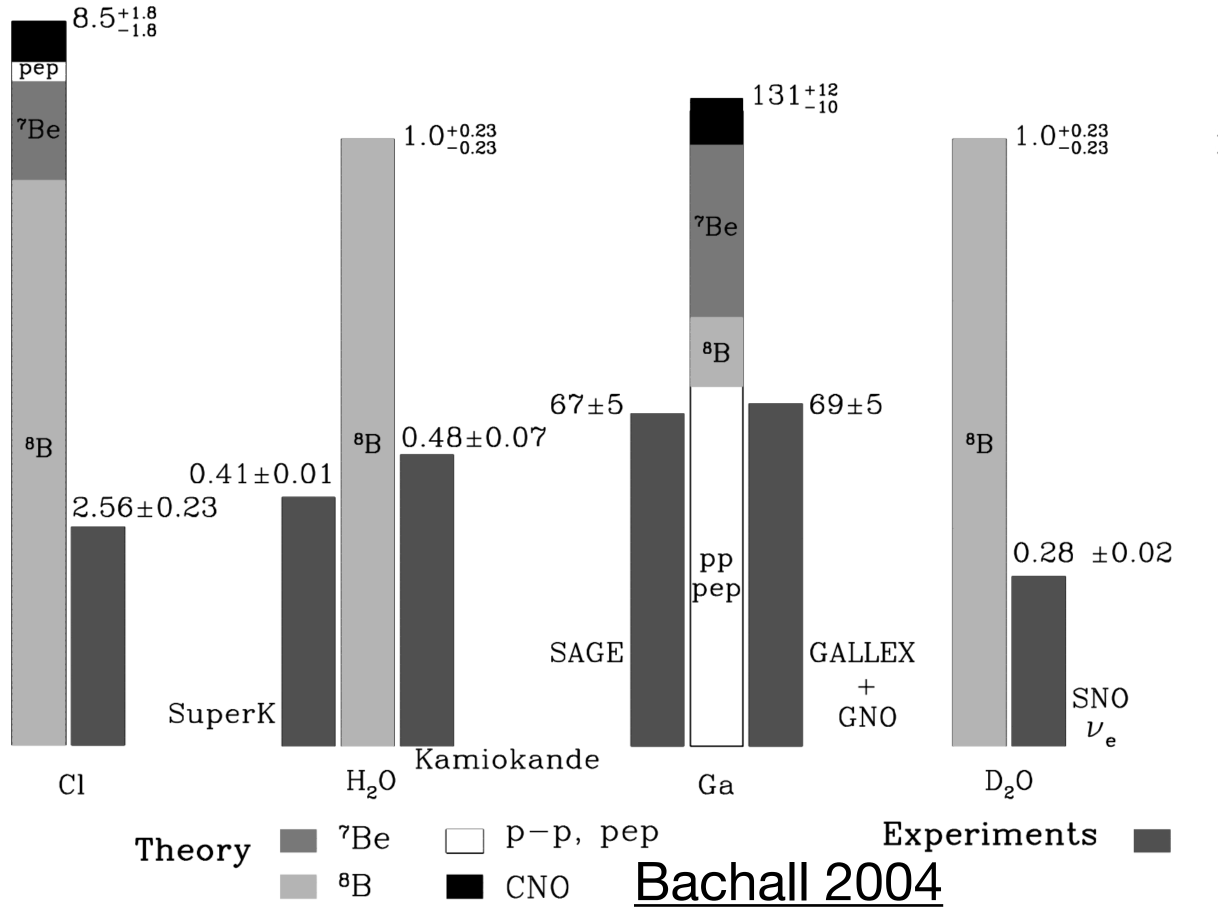

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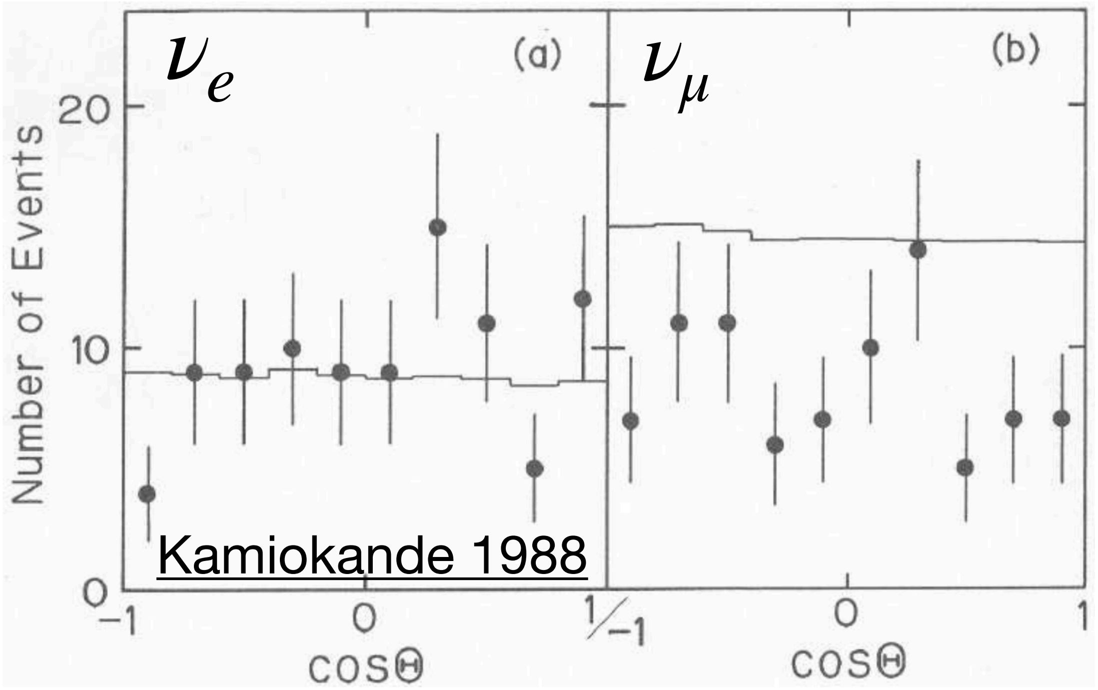

Kamiokande 1988

Theoretical Resolution

Oscillations* from mixing between mass and flavor states

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$$P(\nu_\alpha \to \nu_\beta) \approx \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

*and matter effects

Experimental Validation

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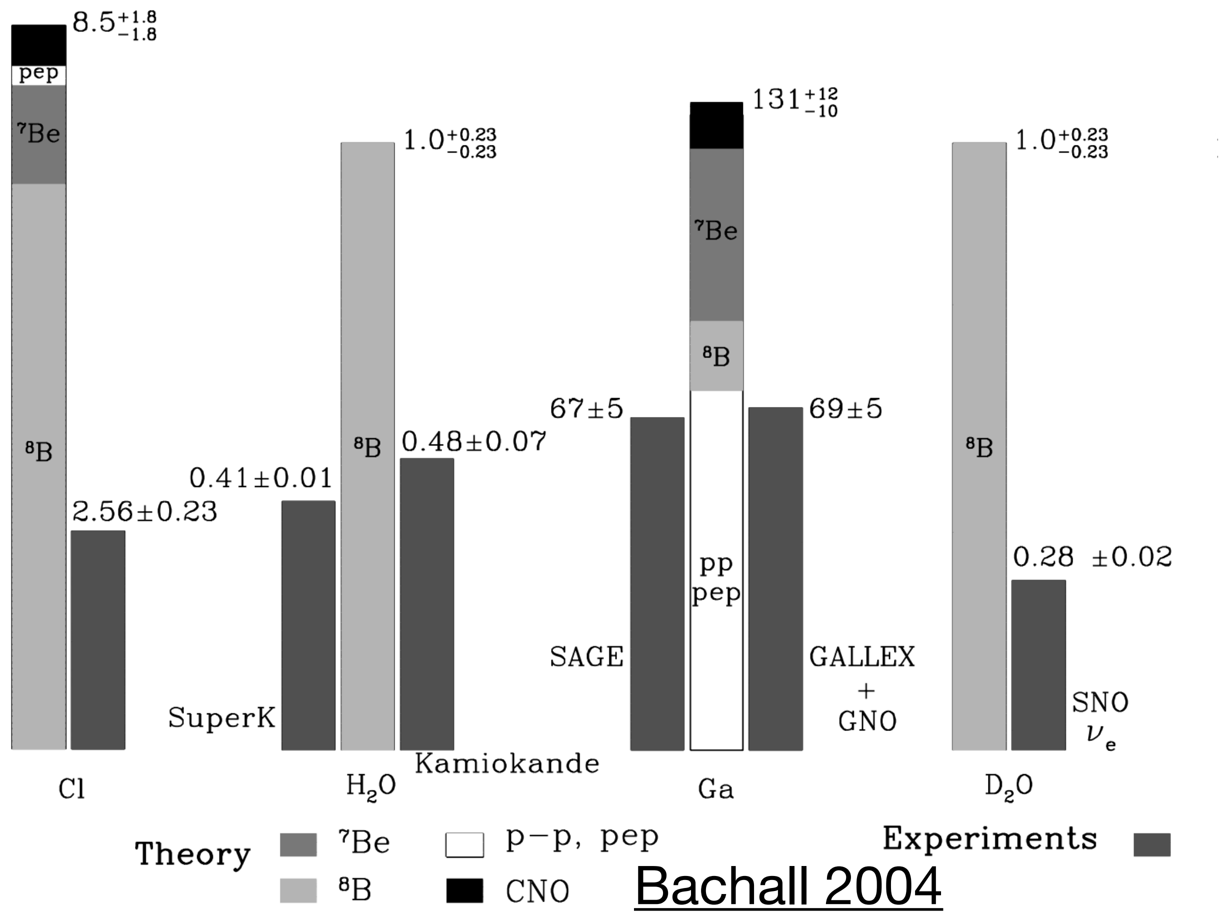

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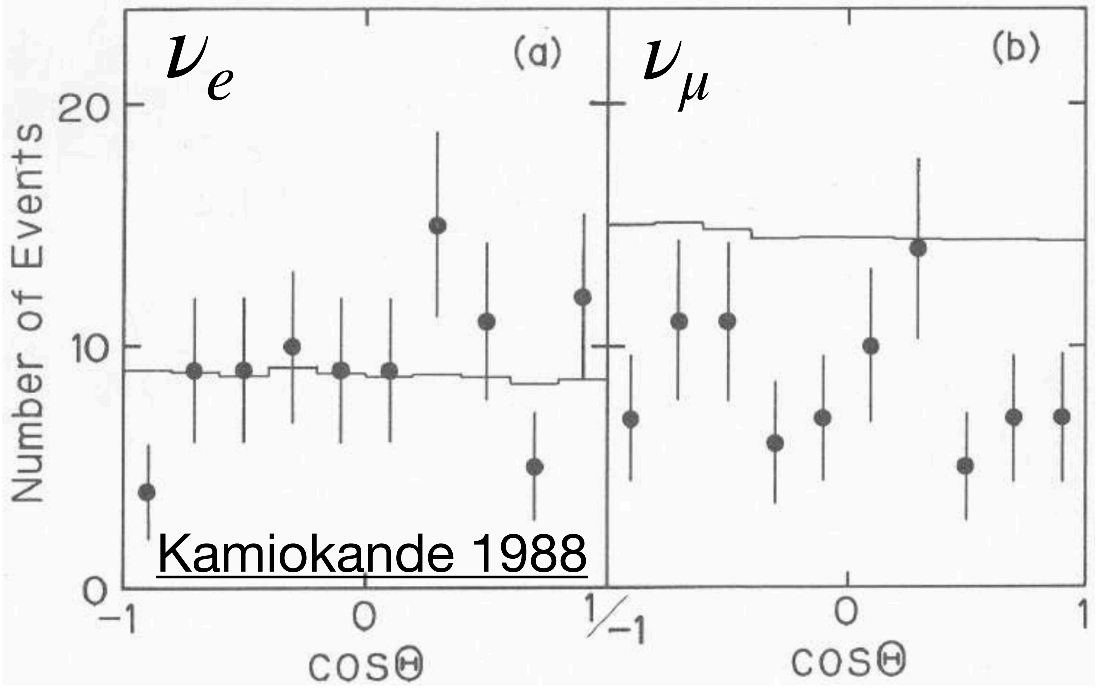

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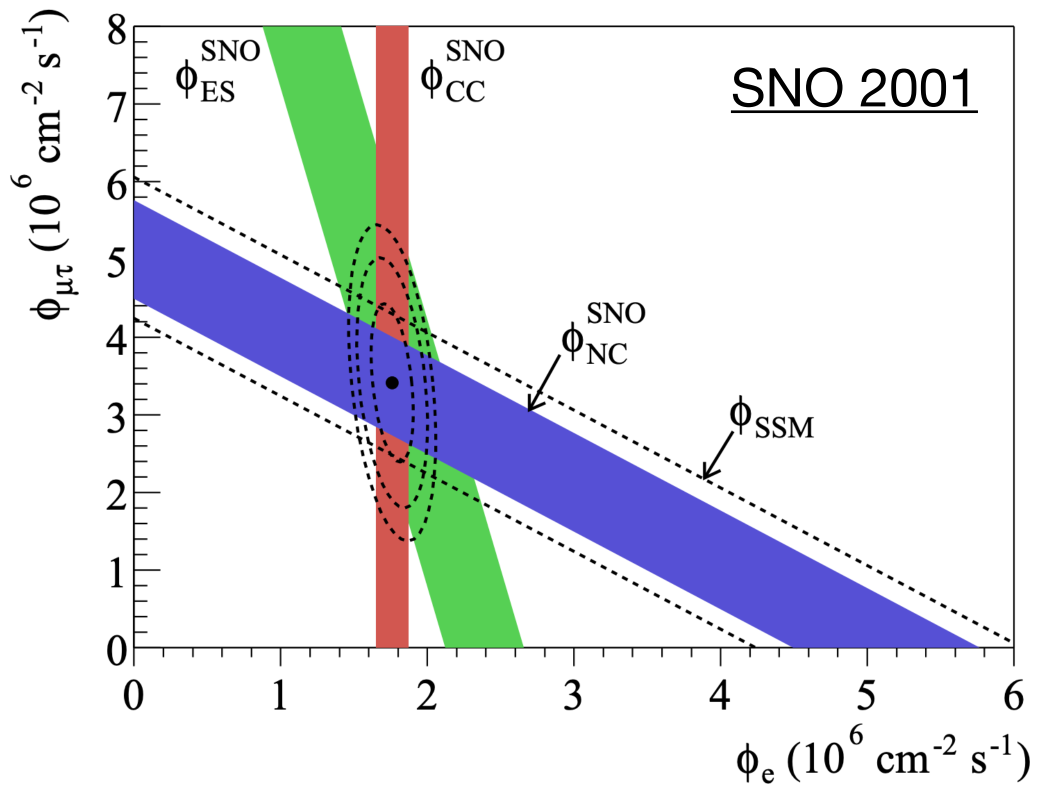
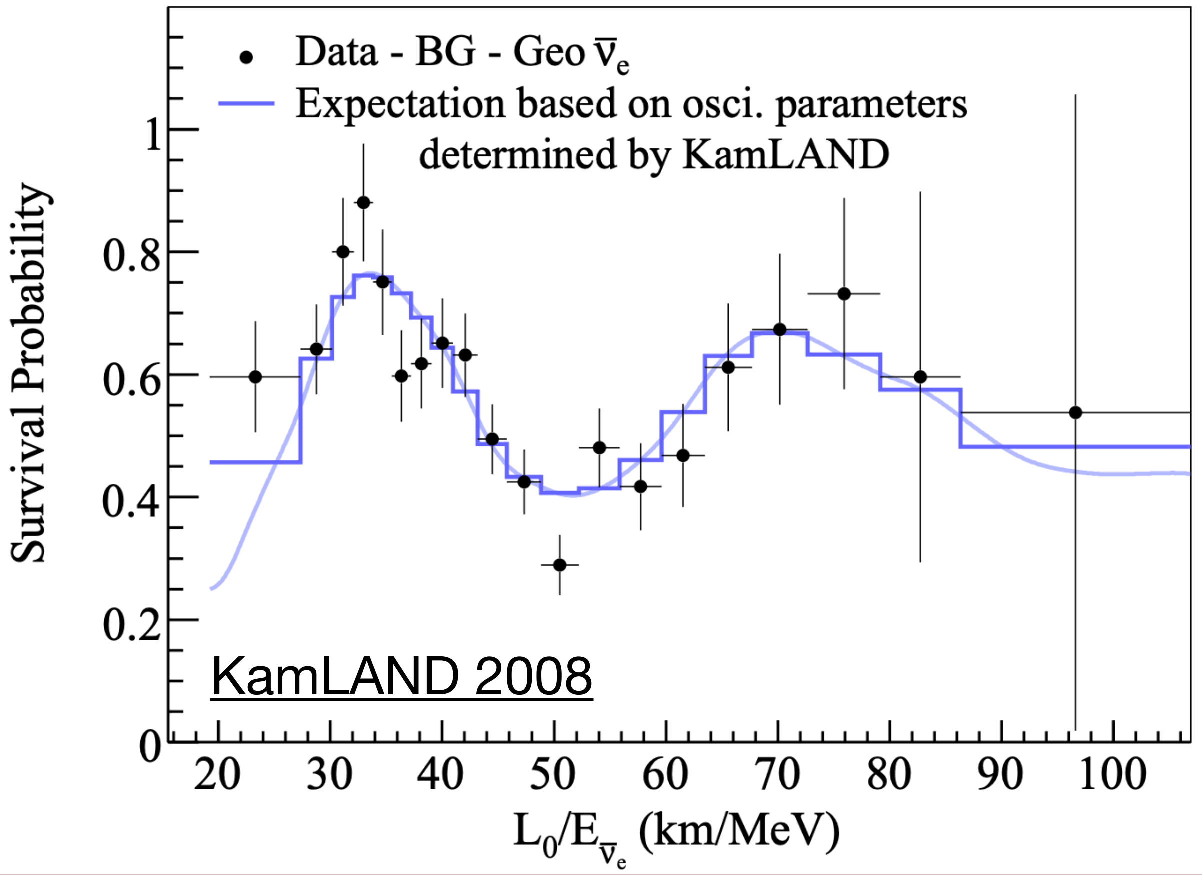
Experimental Validation

New measurements of solar, atmospheric, and reactor neutrinos



SNO 2001



KamLAND 2008

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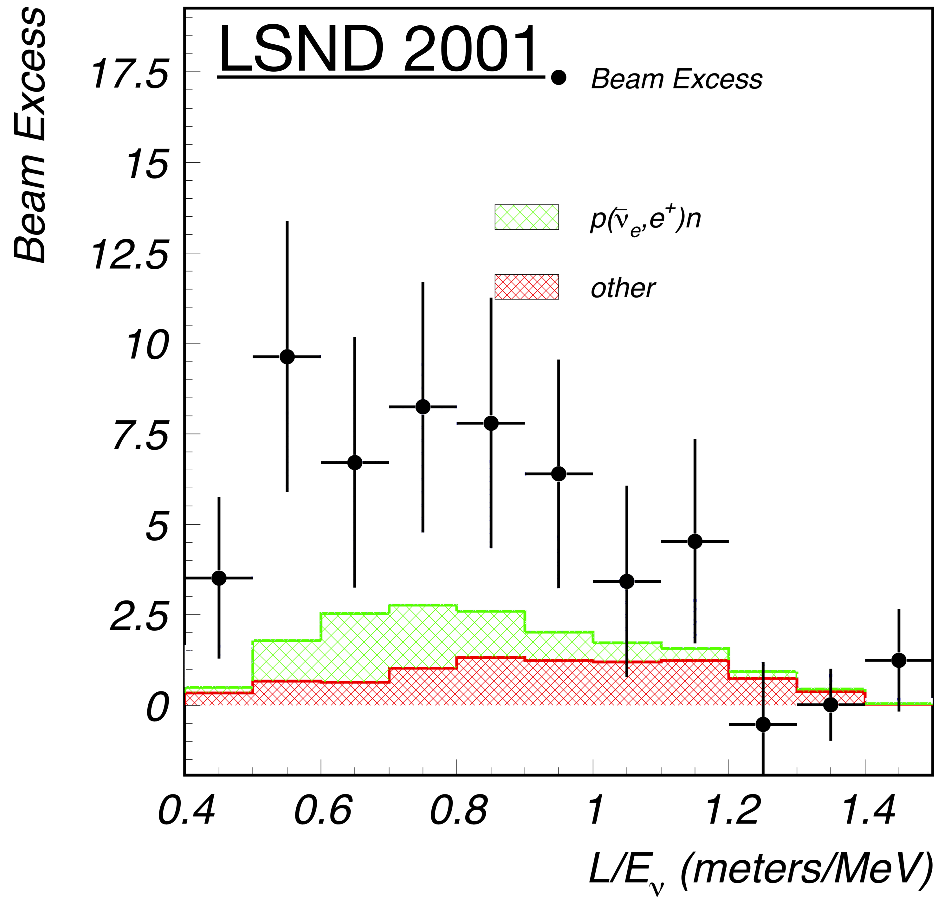
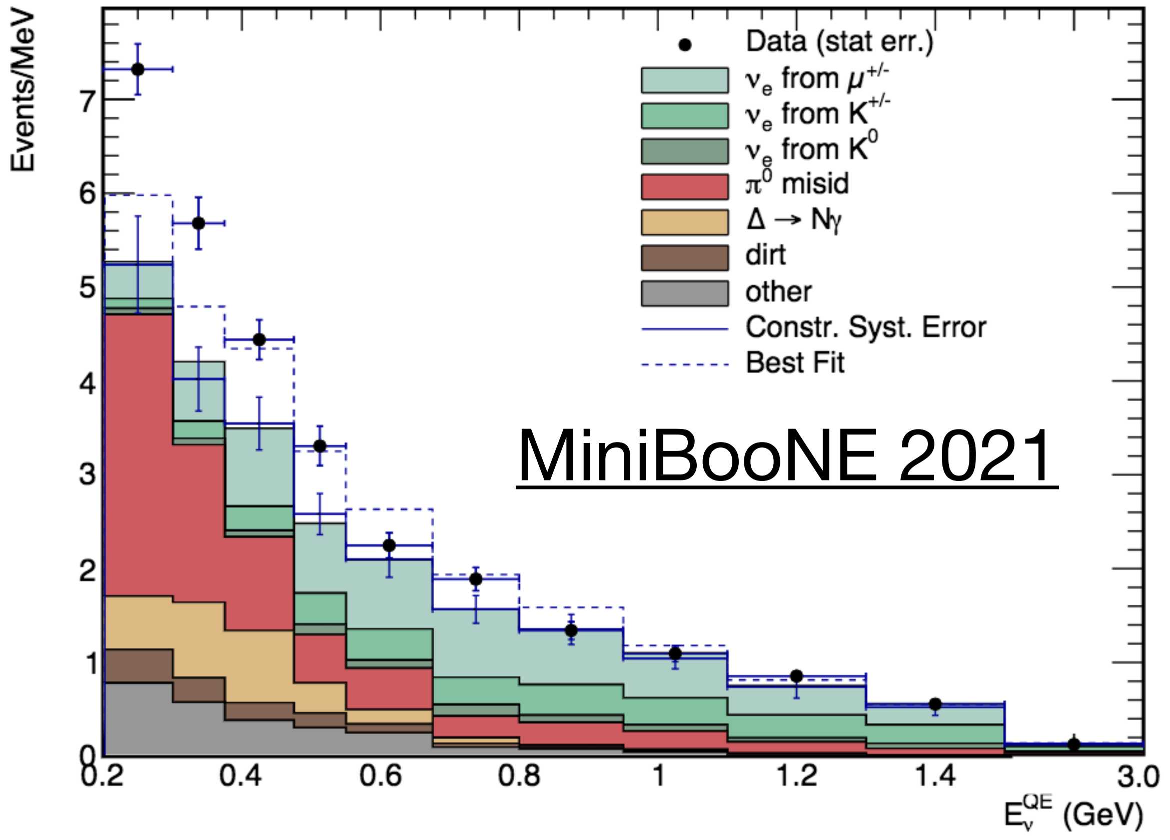
Experimental Anomaly

Excesses of ν_e and $\bar{\nu}_e$ events in short baseline neutrino experiments





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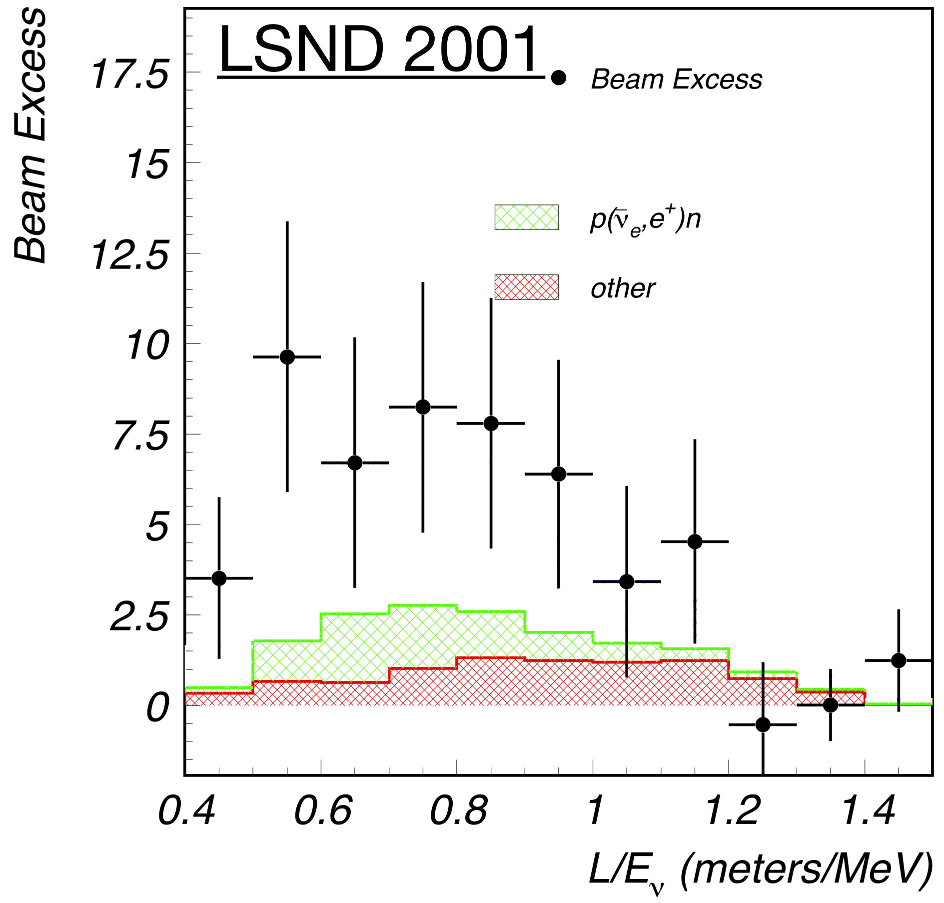

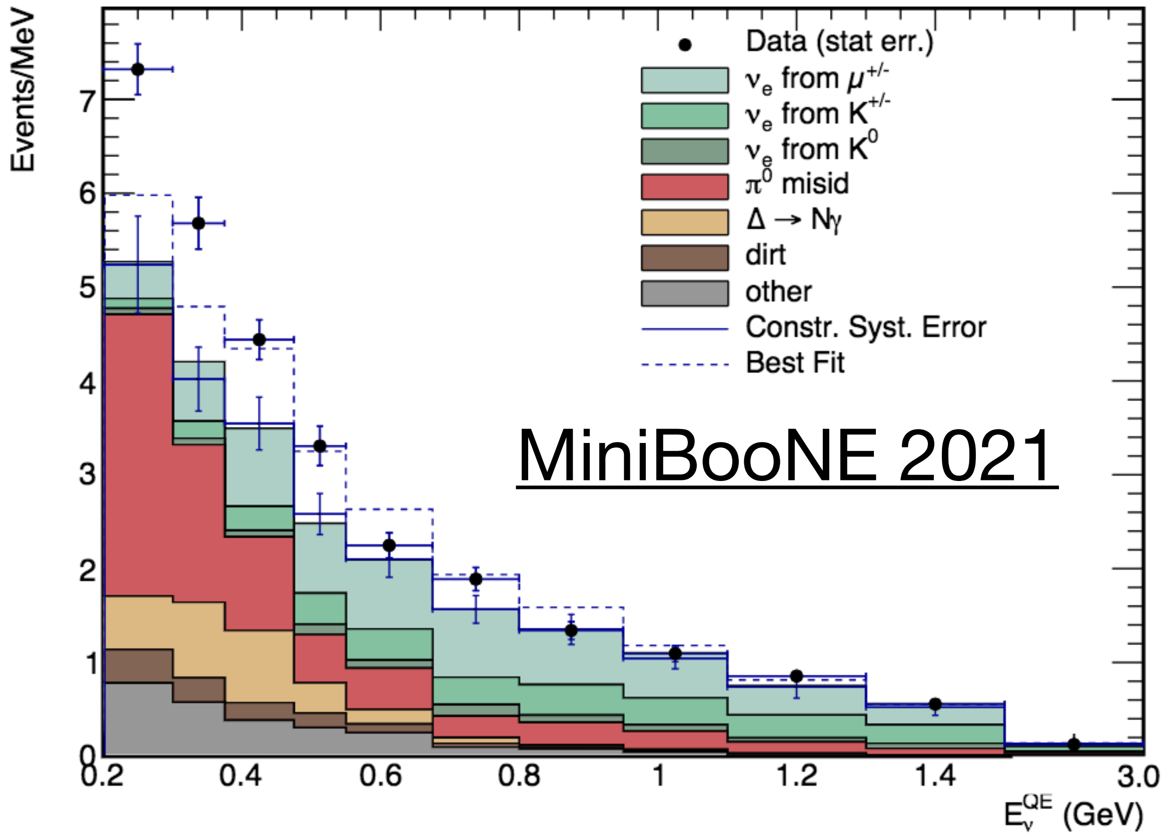

Theoretical Resolution

Unresolved!

Unknown systematic uncertainties?

eV-scale sterile neutrinos?

GeV-scale heavy neutrinos?

Experimental Validation

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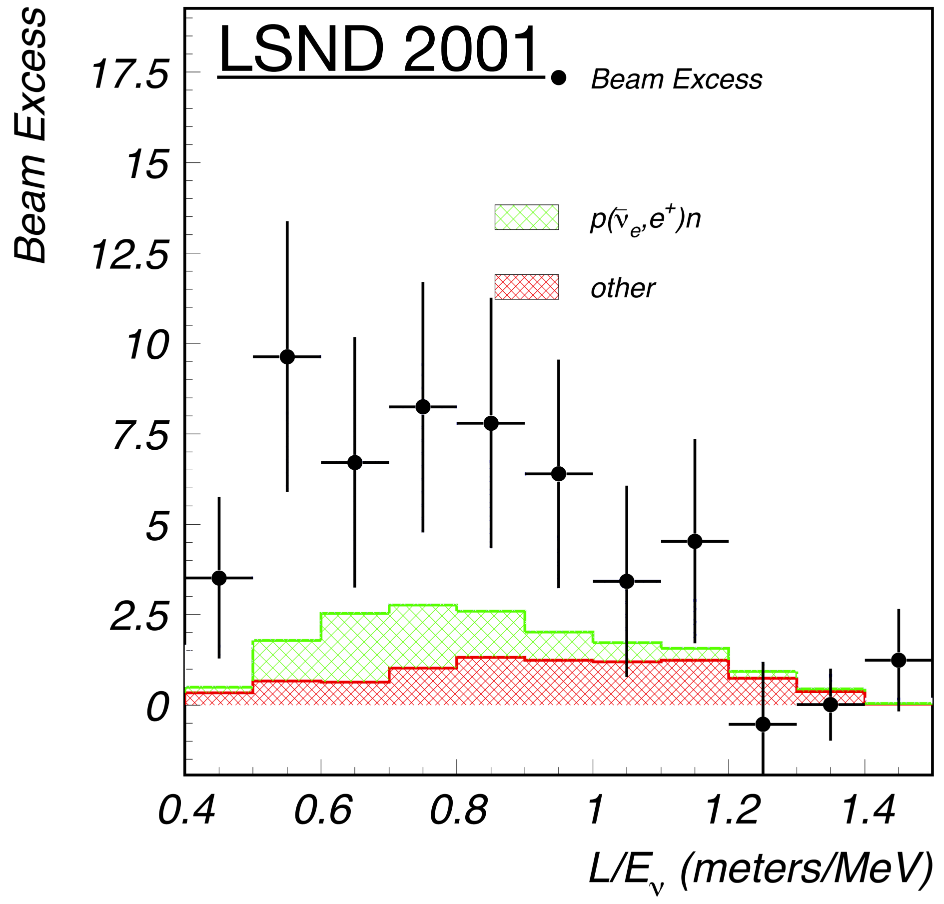

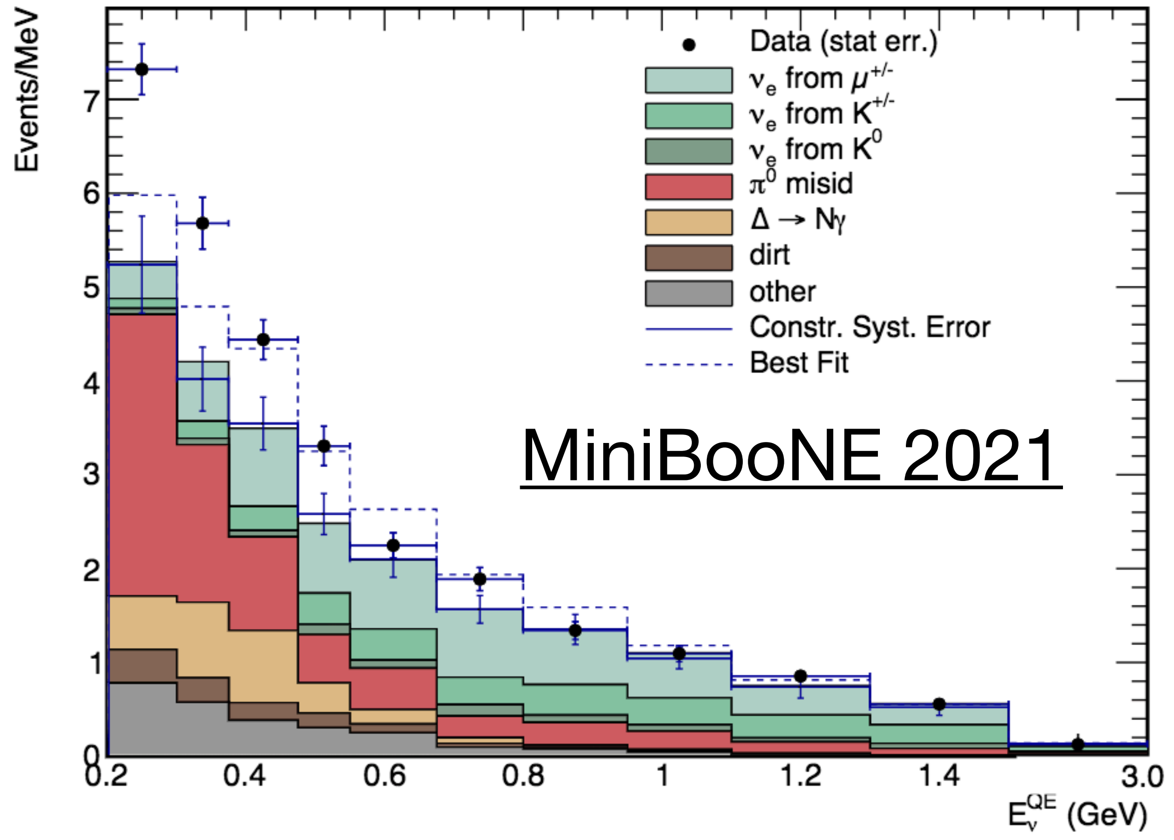

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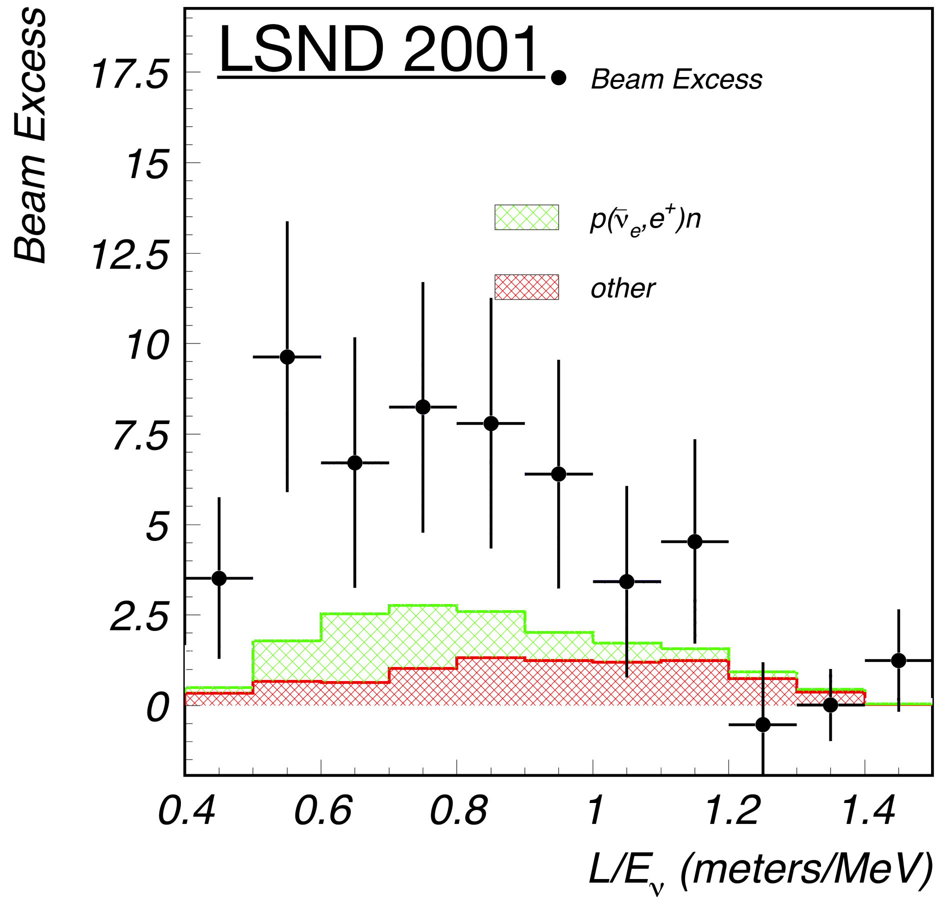

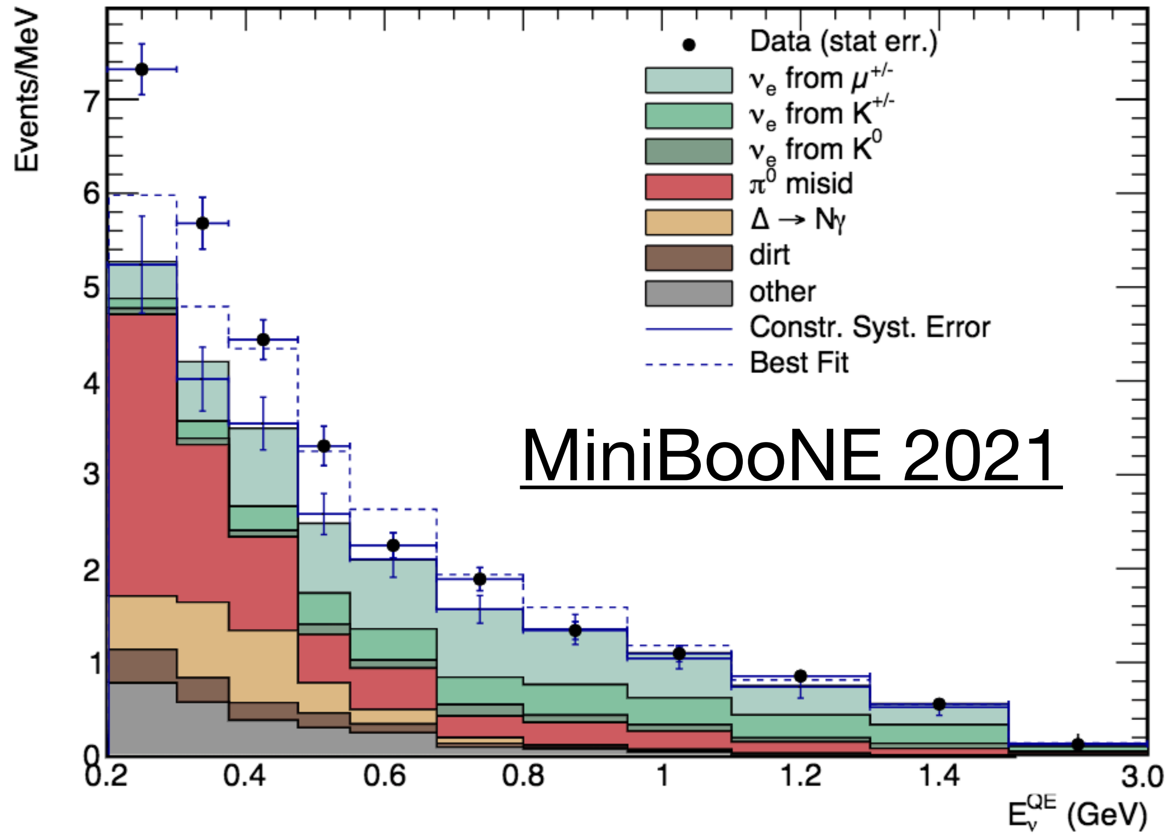

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This talk!

Experimental Validation

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Outline

1. **MiniBooNE:** A long-standing neutrino anomaly
2. **Heavy neutrinos in plastic:** constraints on a promising MiniBooNE solution
3. **Heavy neutrinos in ice and water:** searches at neutrino telescopes
4. **Heavy neutrinos (and more) in water and rock**: new detectors for collider neutrinos

Ice

Rock

Water

Plastic

Outline

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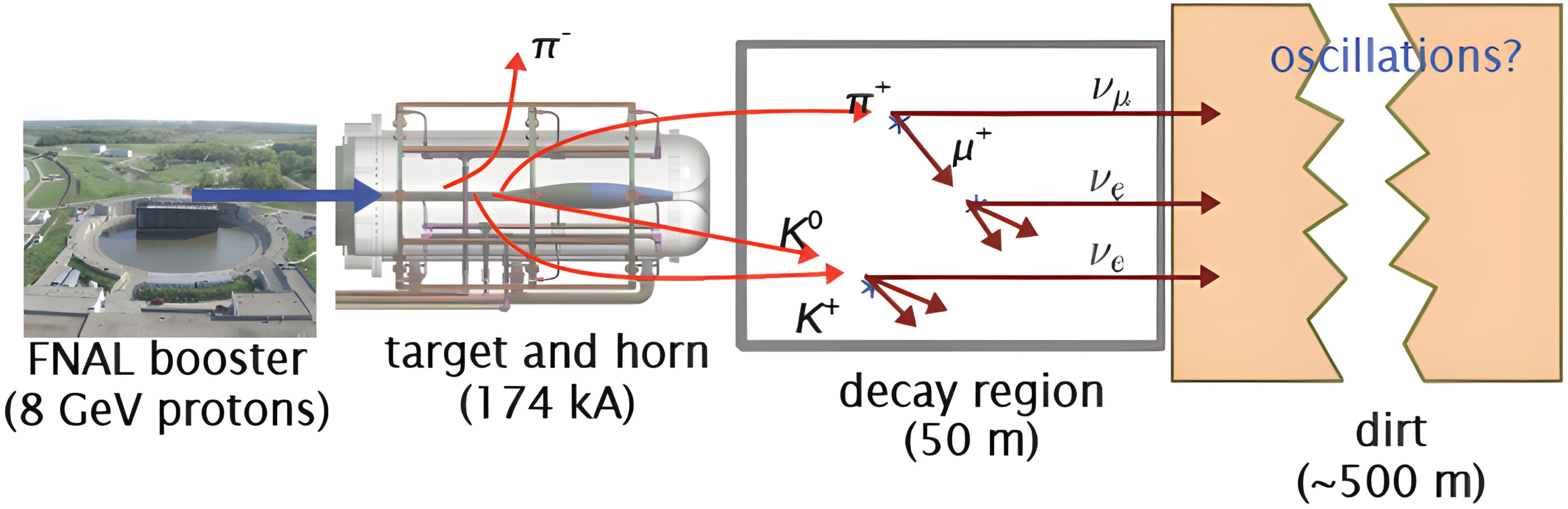
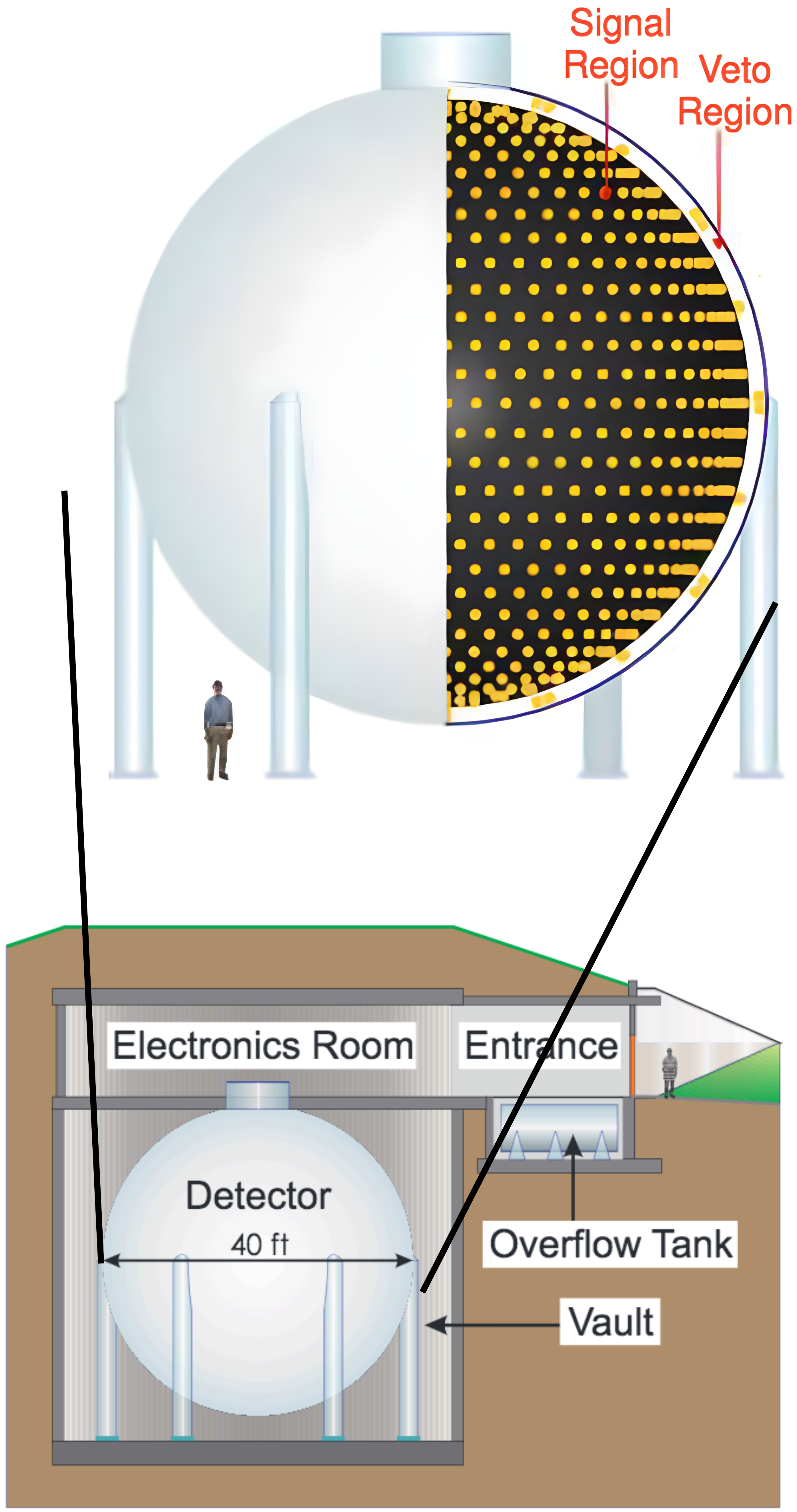
4. **Heavy neutrinos (and more) in water and rock:** new detectors for collider neutrinos

The MiniBooNE Experiment

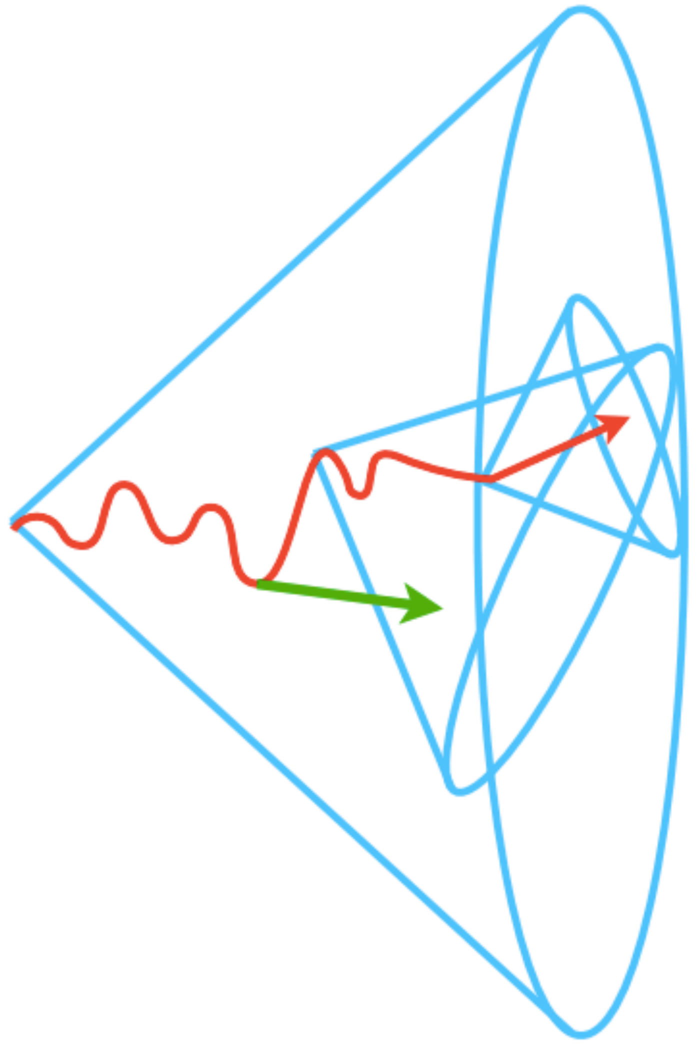
- 800-ton $\mathrm{CH_2}$ Cherenkov detector
- Situated along Fermilab's Booster Neutrino Beam
  - ~540 m from the beryllium target
- Observes mostly ν_μ and $\bar{\nu}_\mu$ from charged pion decays

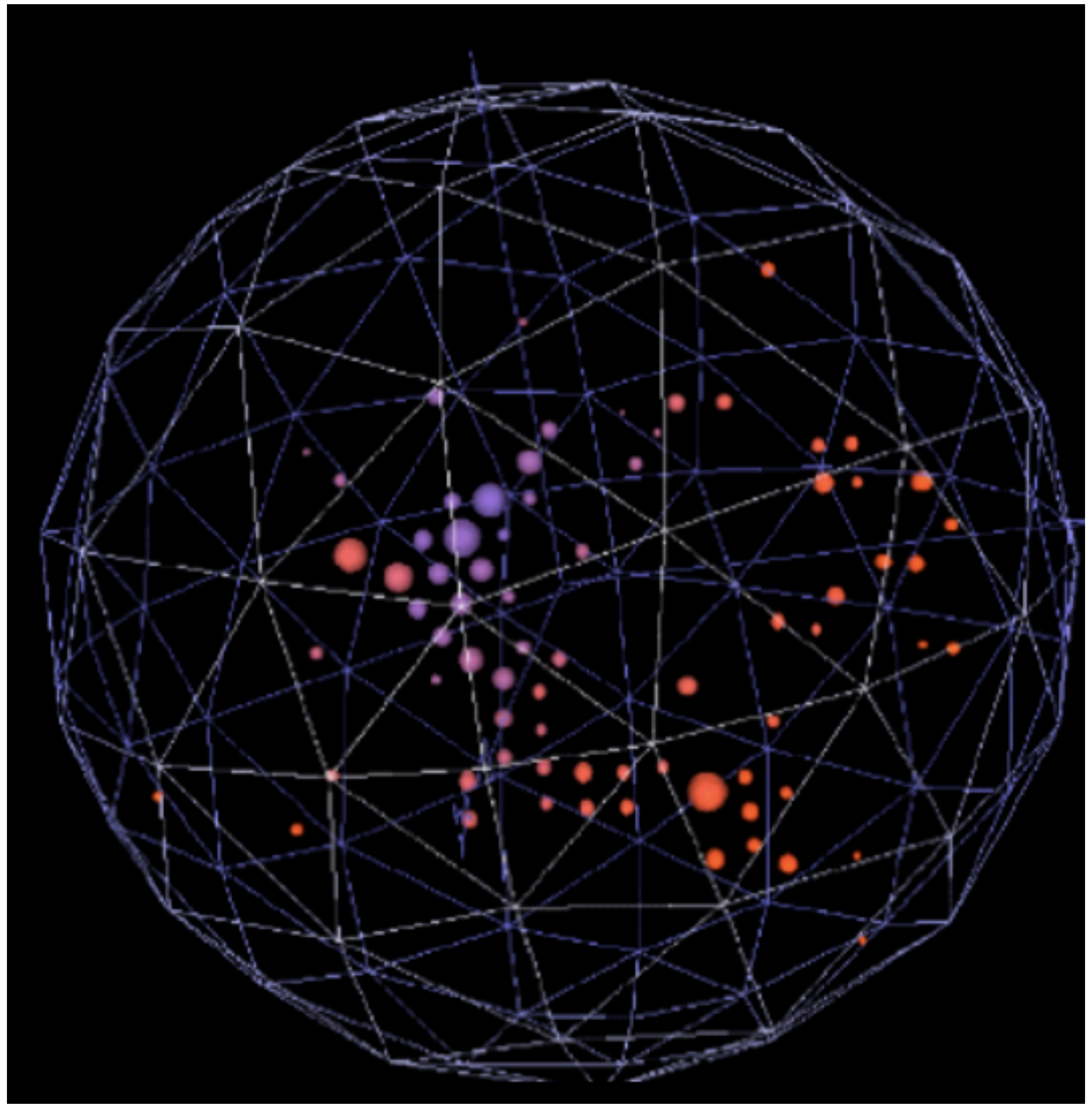




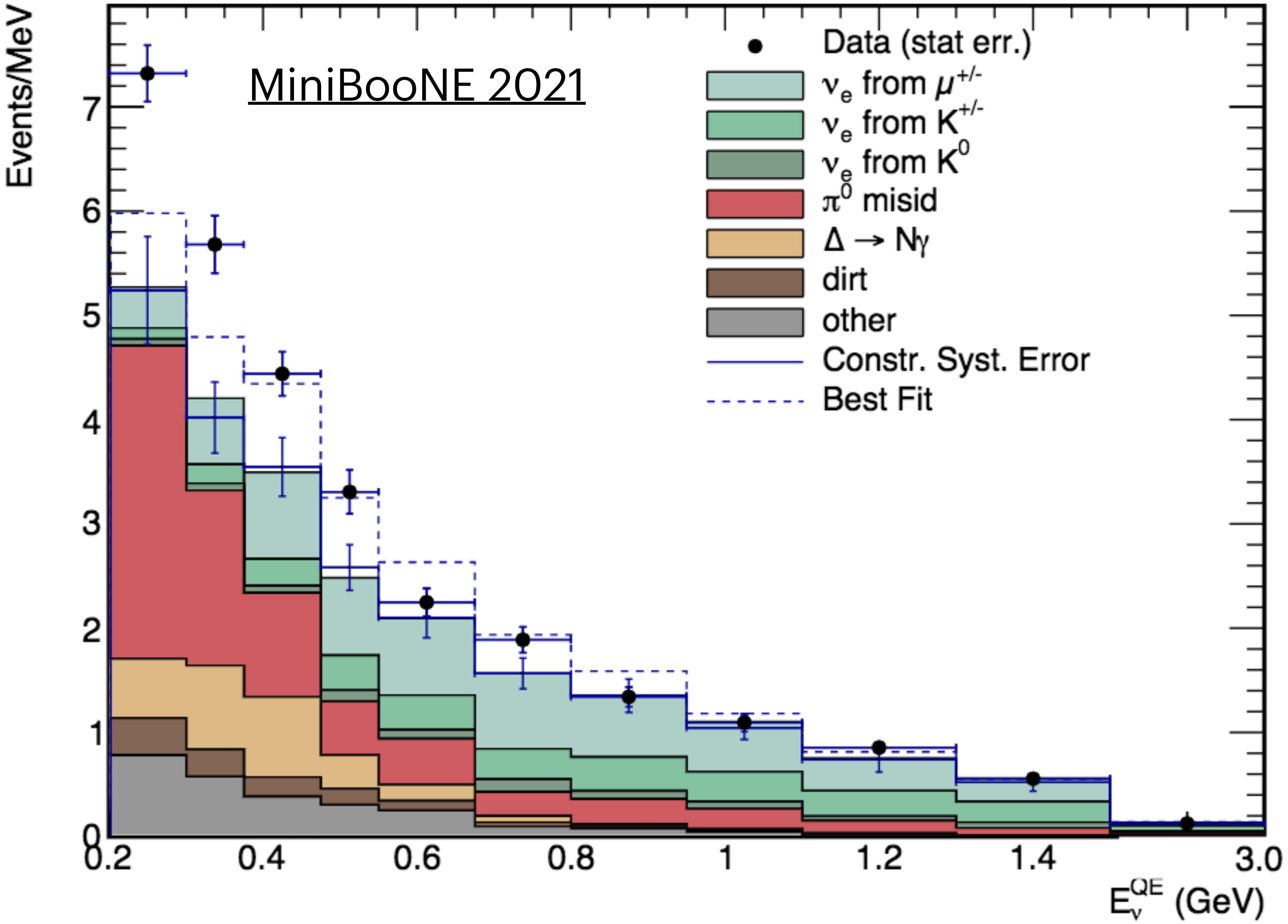
The MiniBooNE Anomaly

Electrons:
“fuzzy” rings from multiple scattering





4.8σ excess of electron-like events

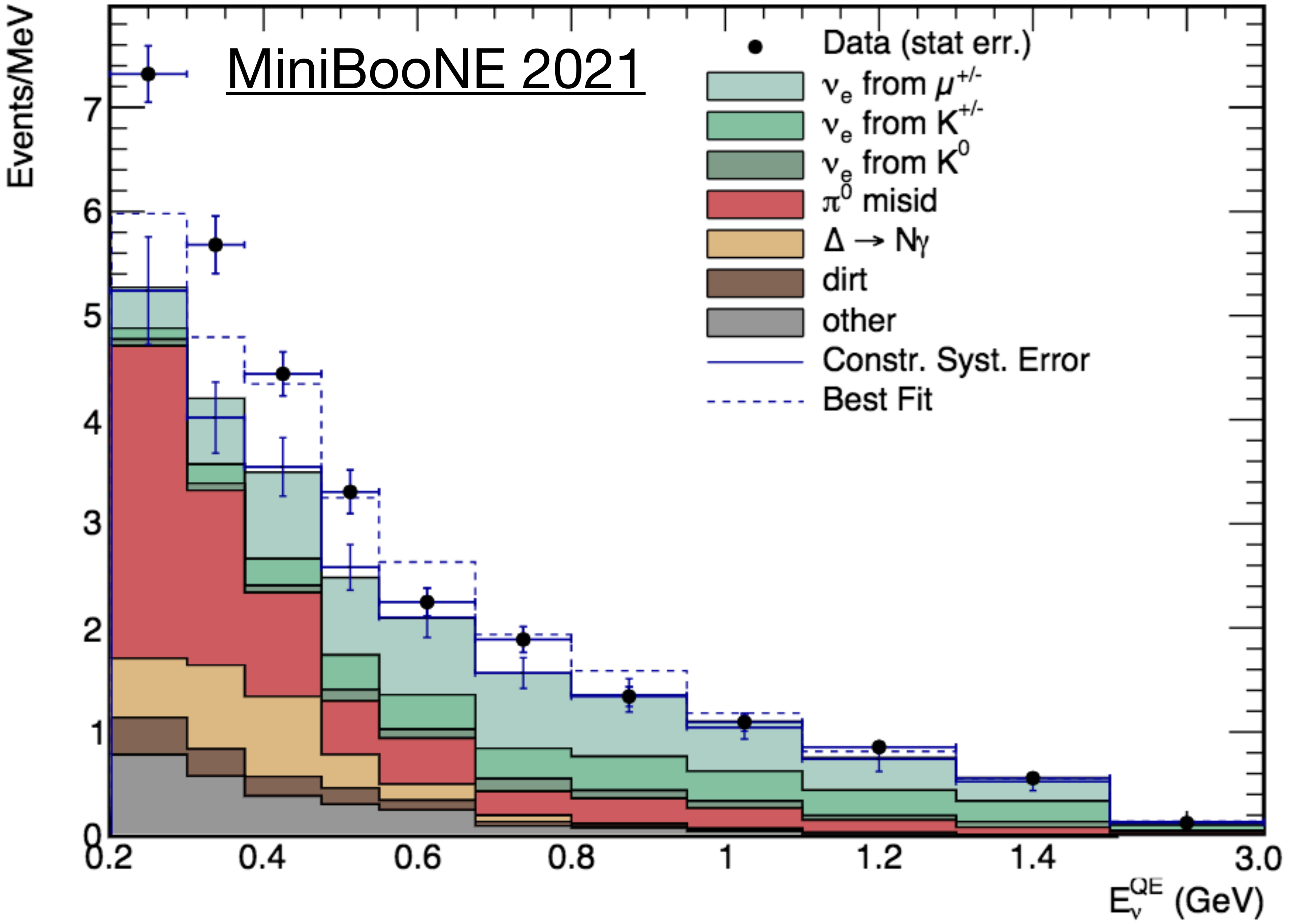


What could it be?

Cherenkov limitations:

- Electrons/photons indistinguishable
- No hadronic information

The excess could be…



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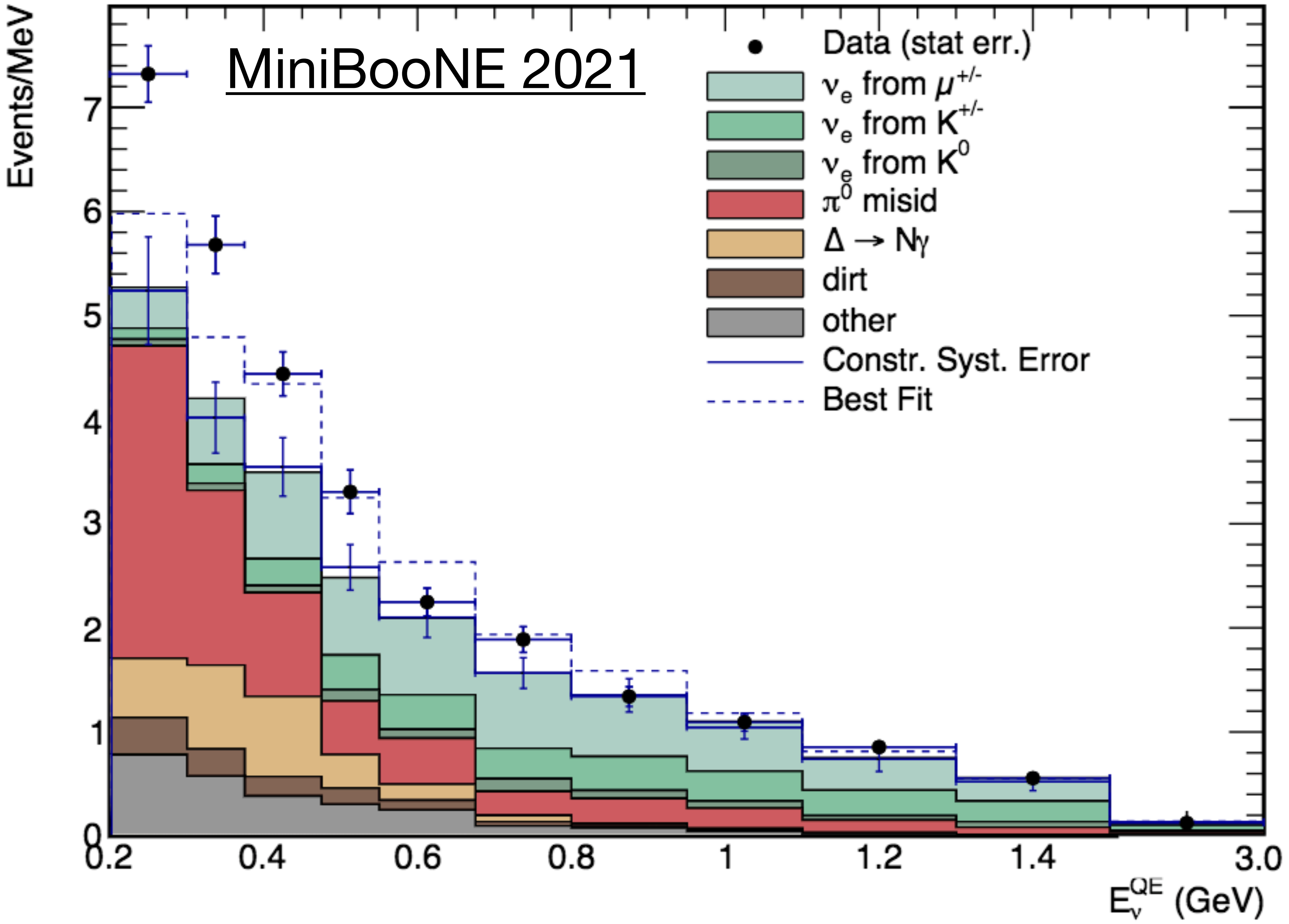

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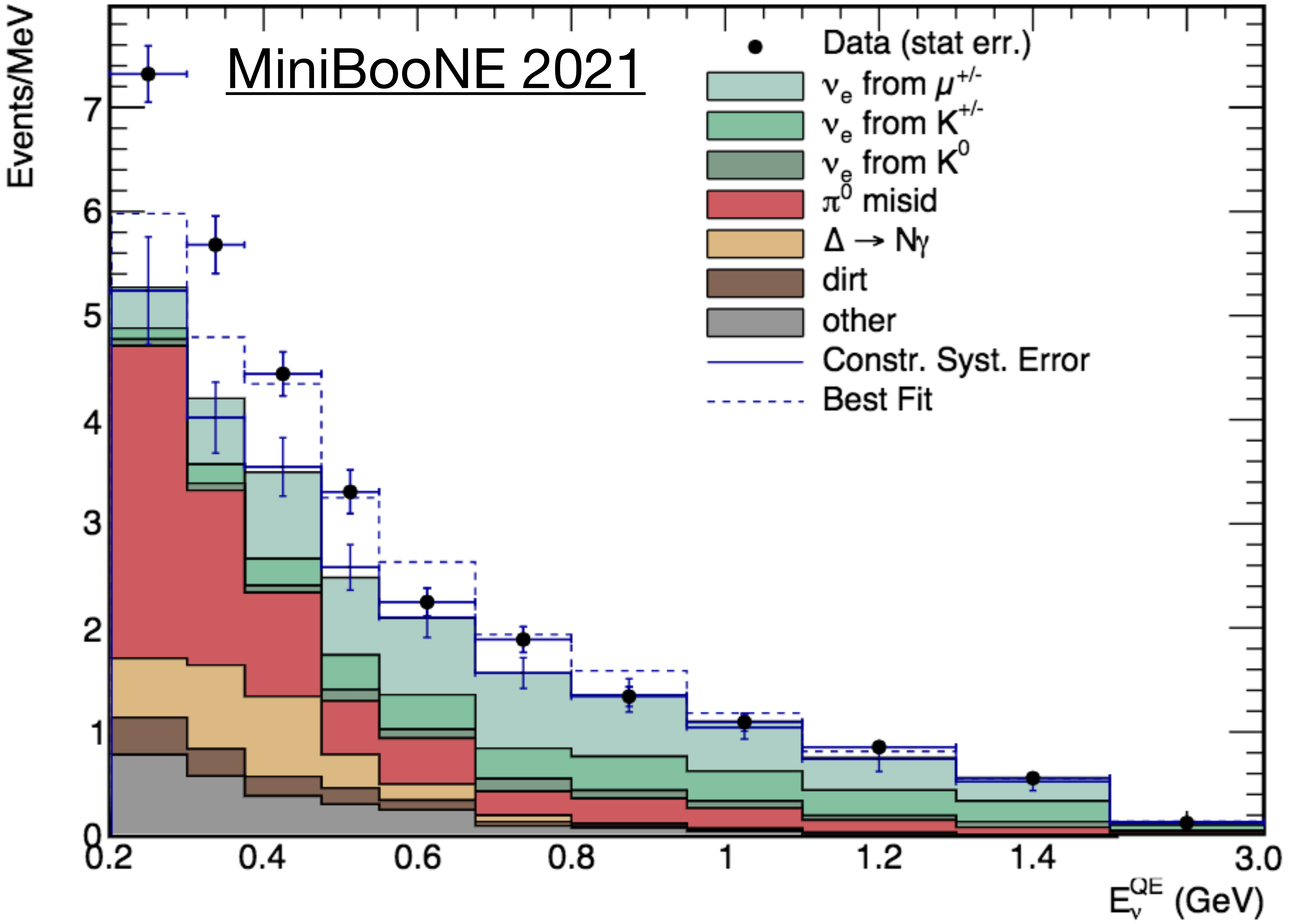

Recall $P(\nu_\mu \rightarrow \nu_e) \propto \sin^2(\Delta m^2 L/4E)$

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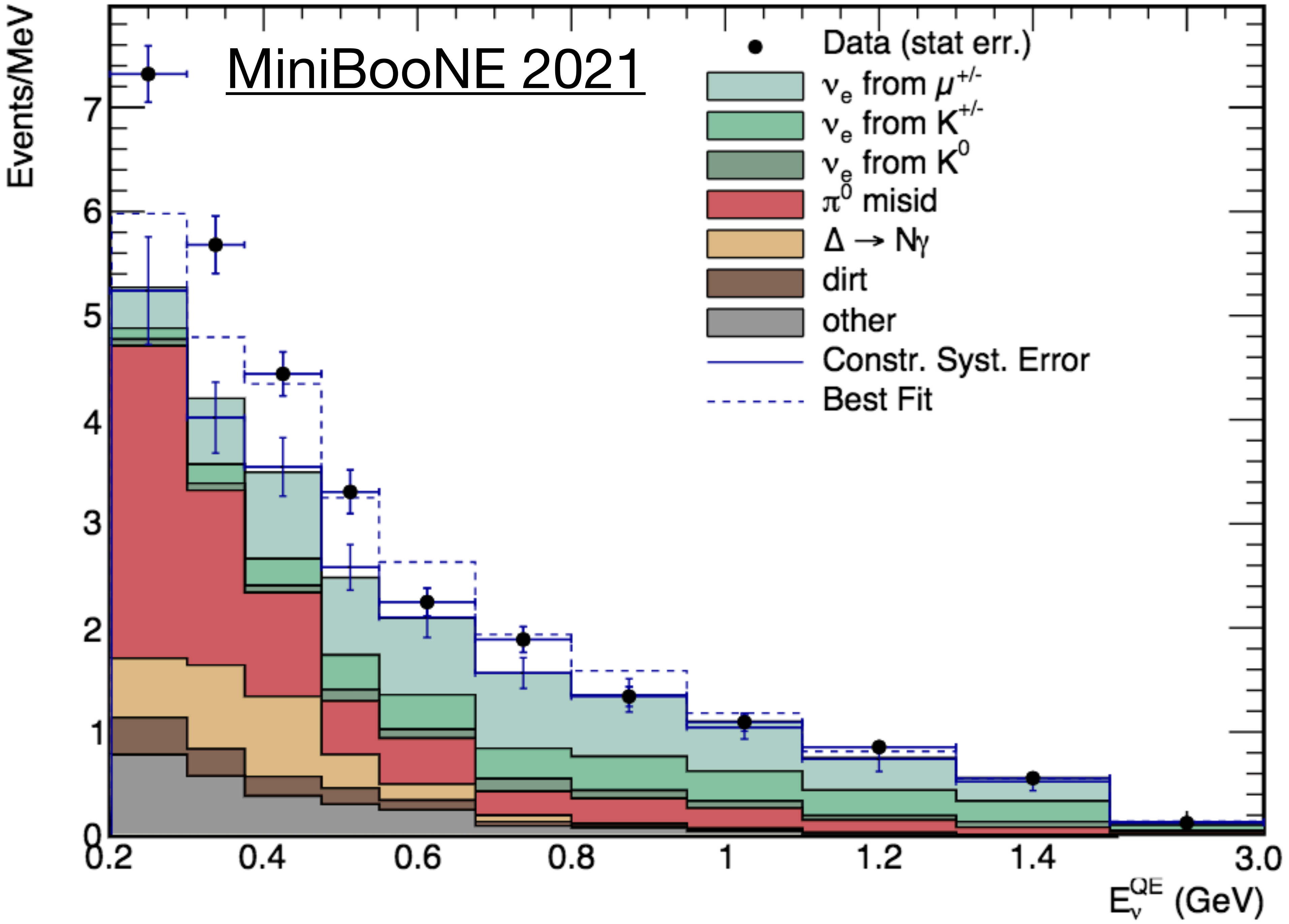

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$$\Delta m^2_{23} \sim 2 \times 10^{-3}\,\mathrm{eV}^2,\ E_\nu \sim 500\,\mathrm{MeV} \implies L_{\mathrm{osc}} \sim 200\,\mathrm{km}$$

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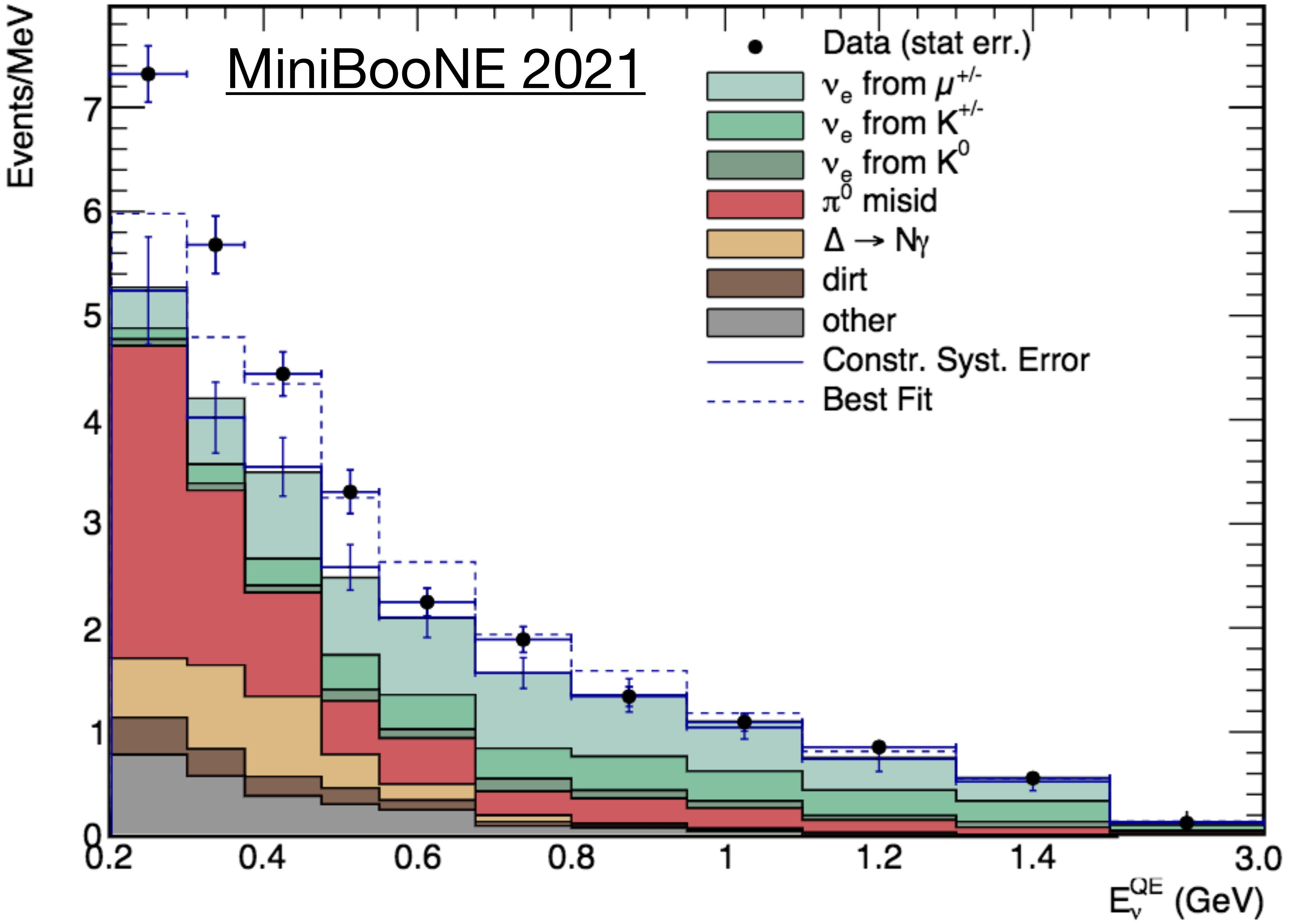

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$L_{\mathrm{MB}} \sim 500\,\mathrm{m}$, much too short for $\nu_\mu \to \nu_e$ oscillations via Δm^2_{23}!

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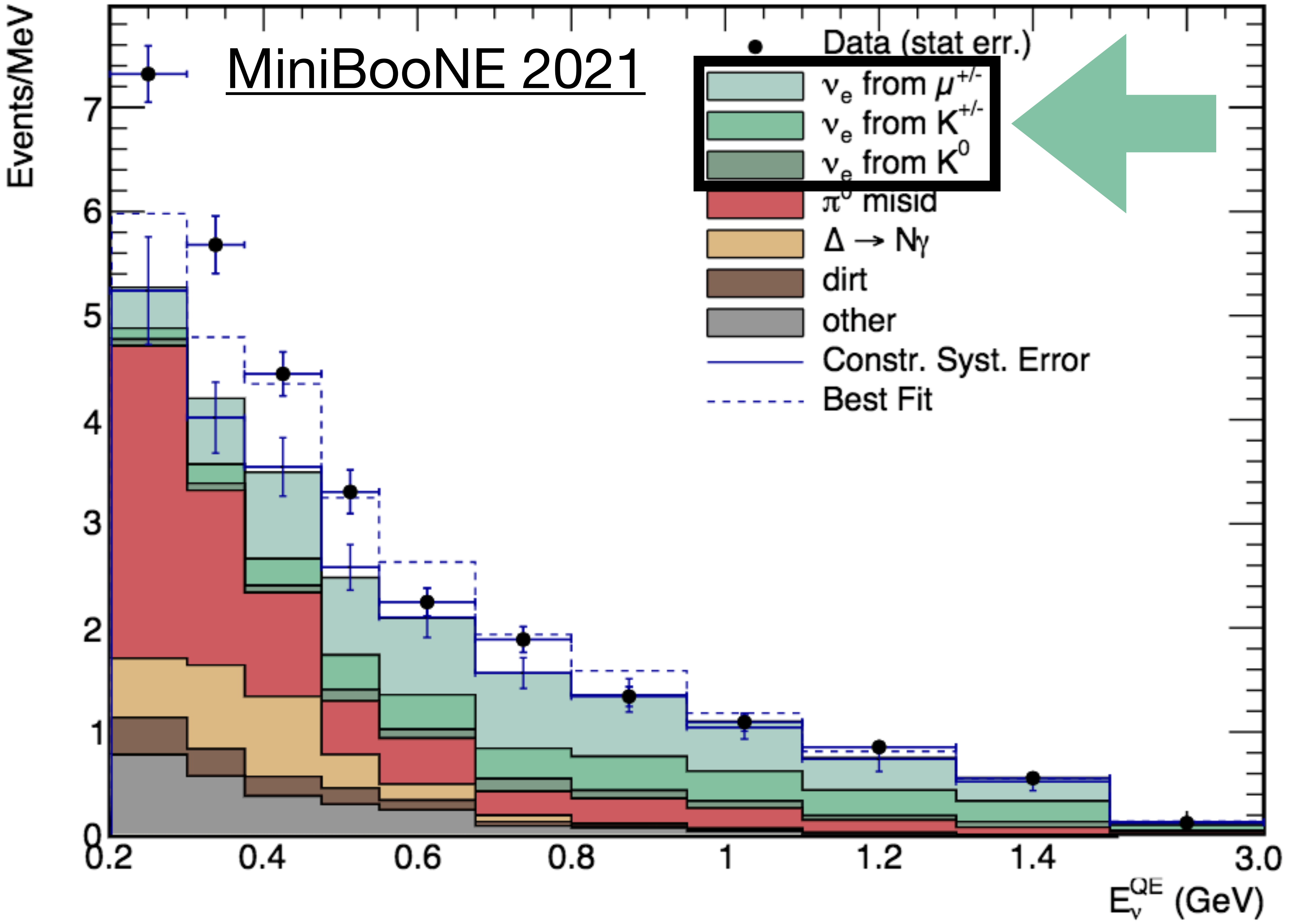
What about extra intrinsic electron neutrinos in the BNB?



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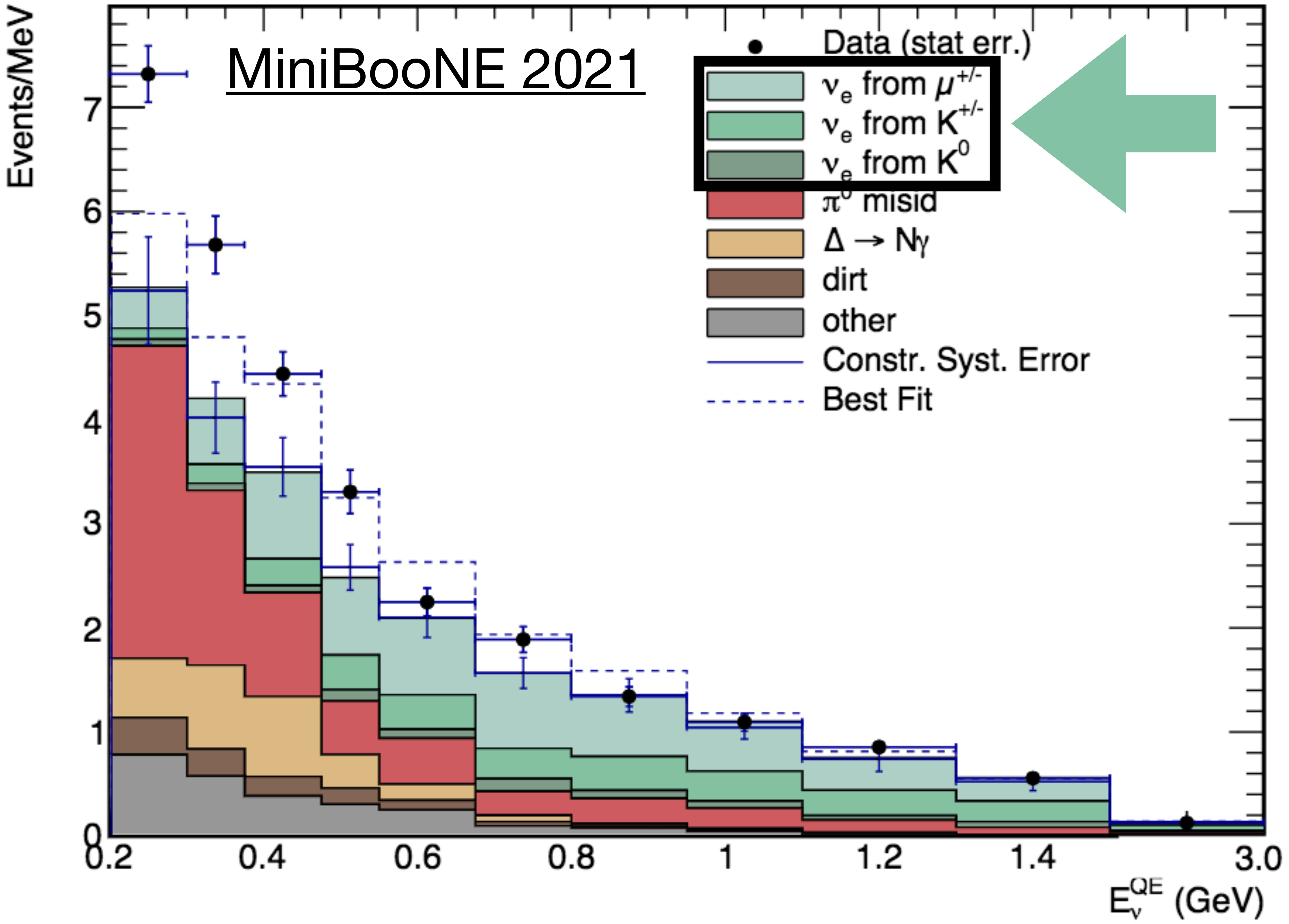
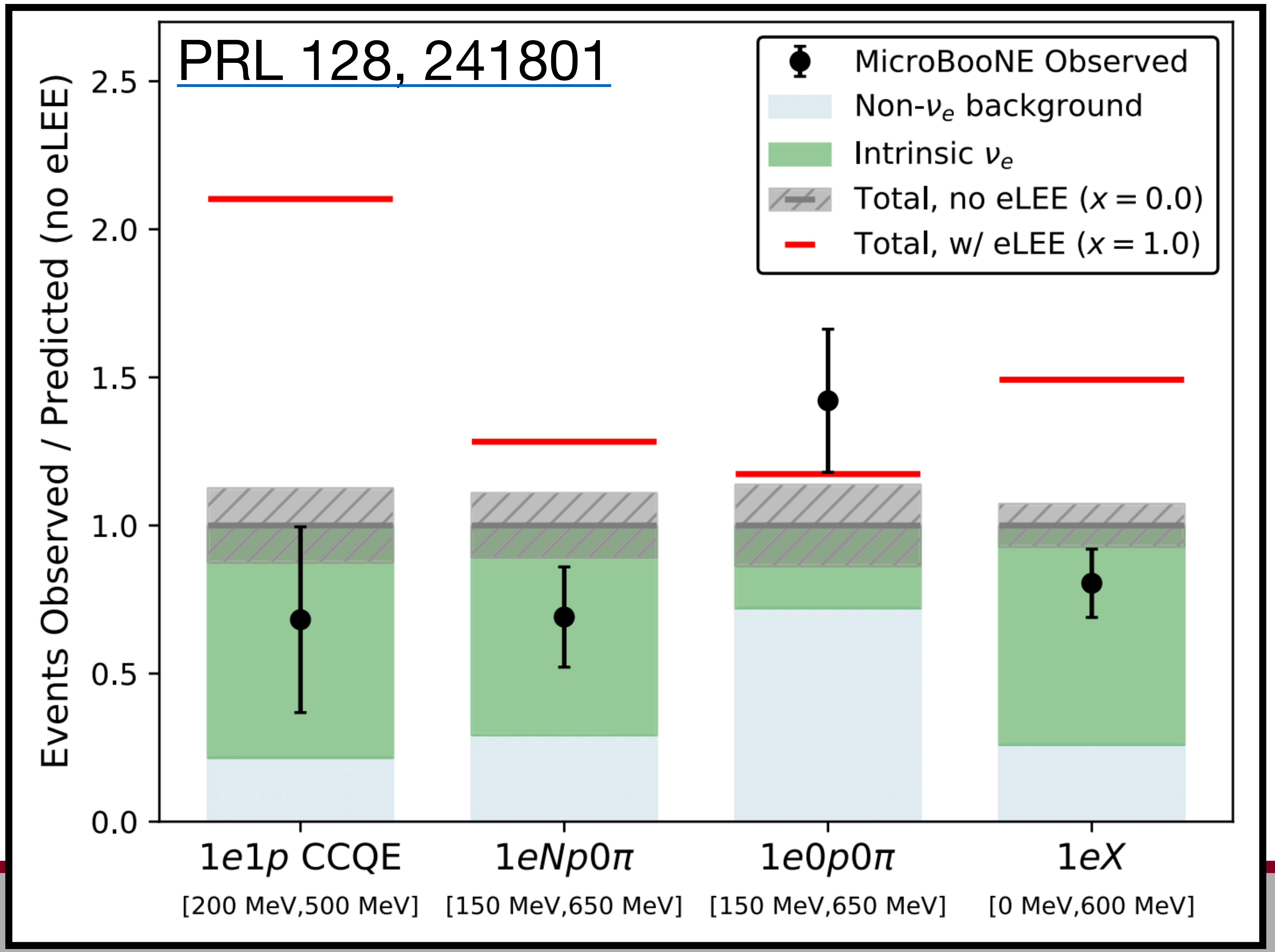
MicroBooNE data disfavor this hypothesis at the 3σ confidence level





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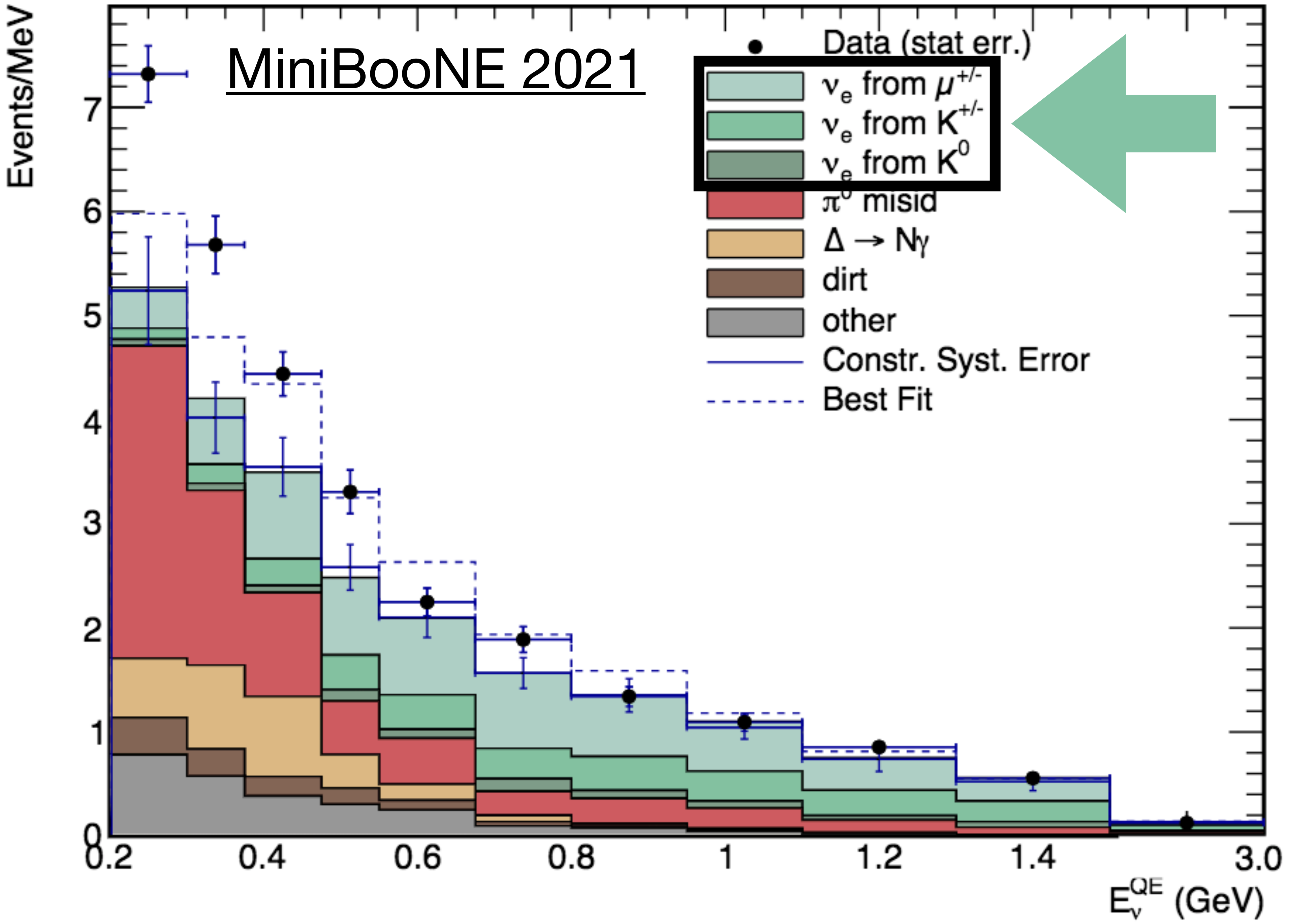

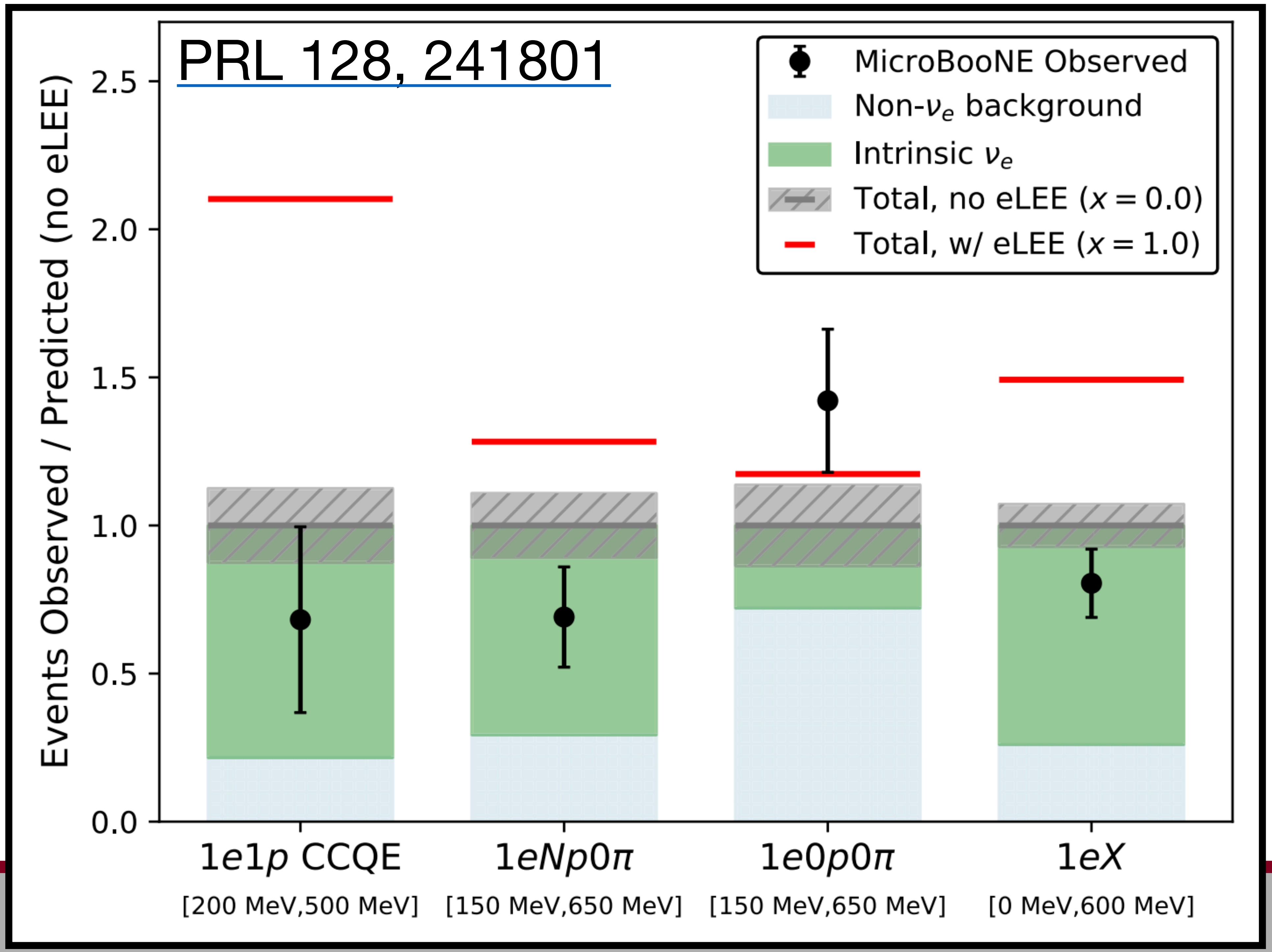

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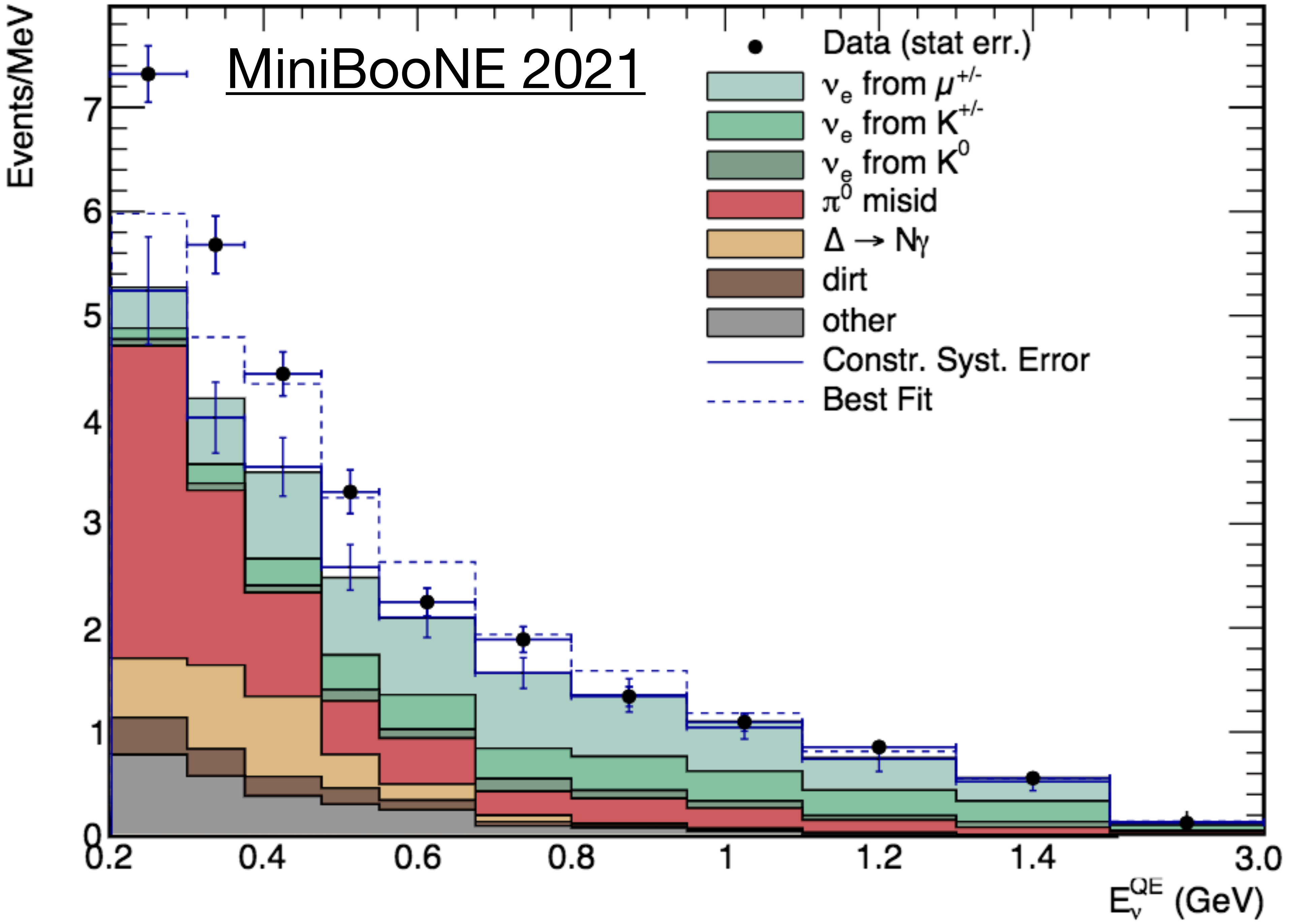
1. True electron neutrinos?✘
2. Mis-modeled photon background?



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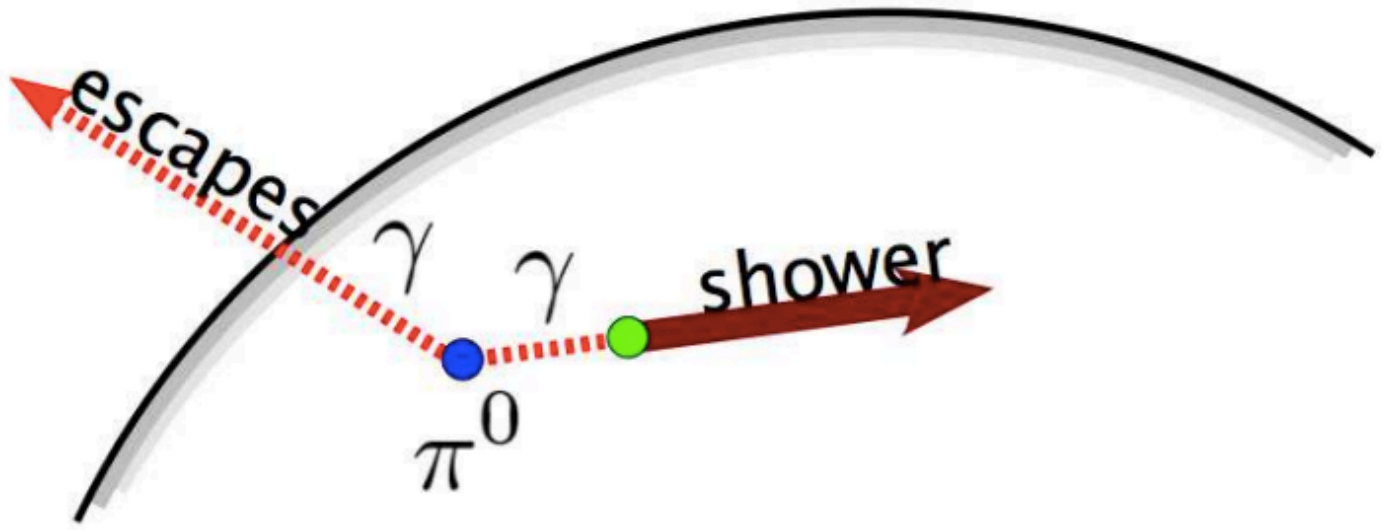
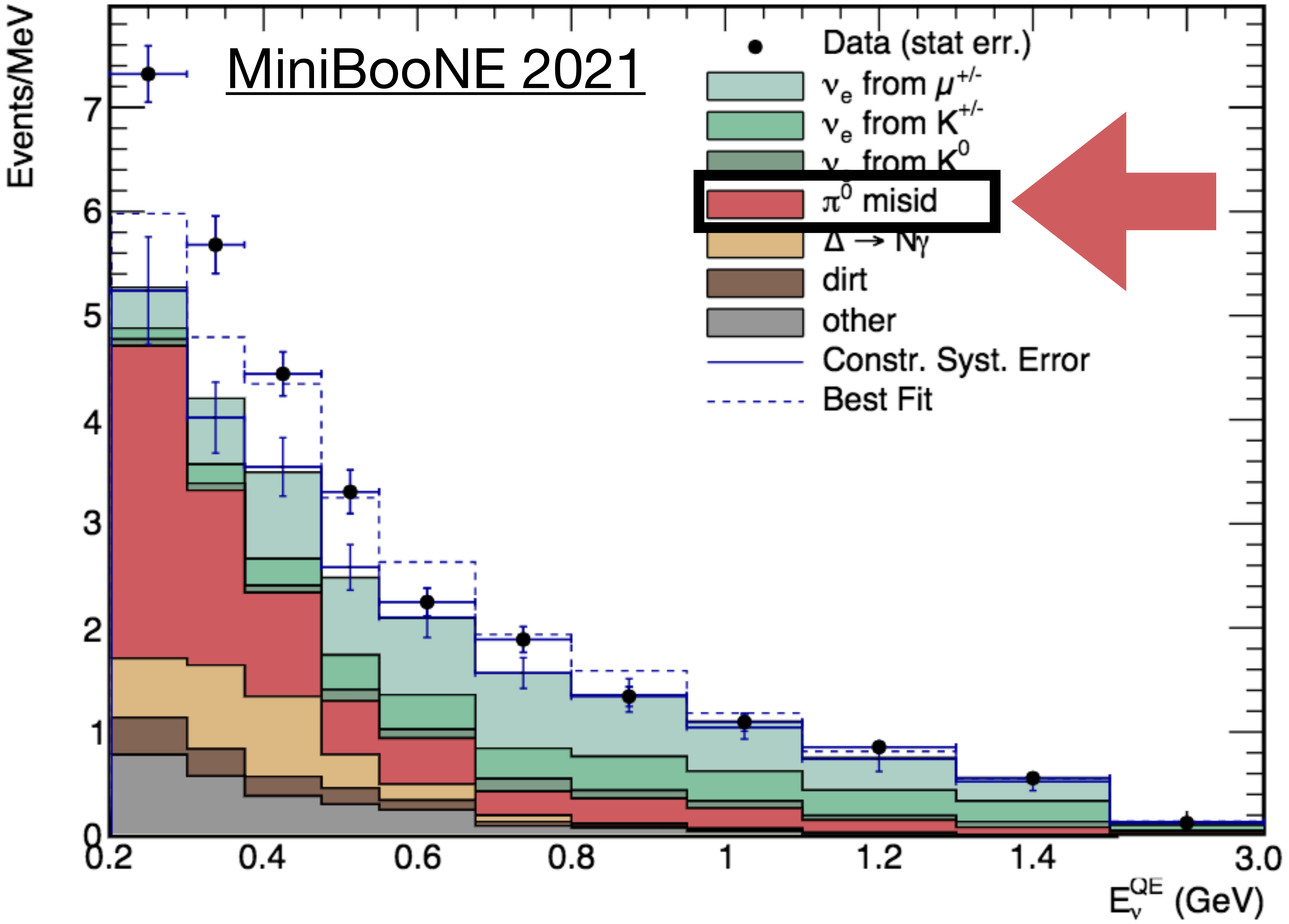
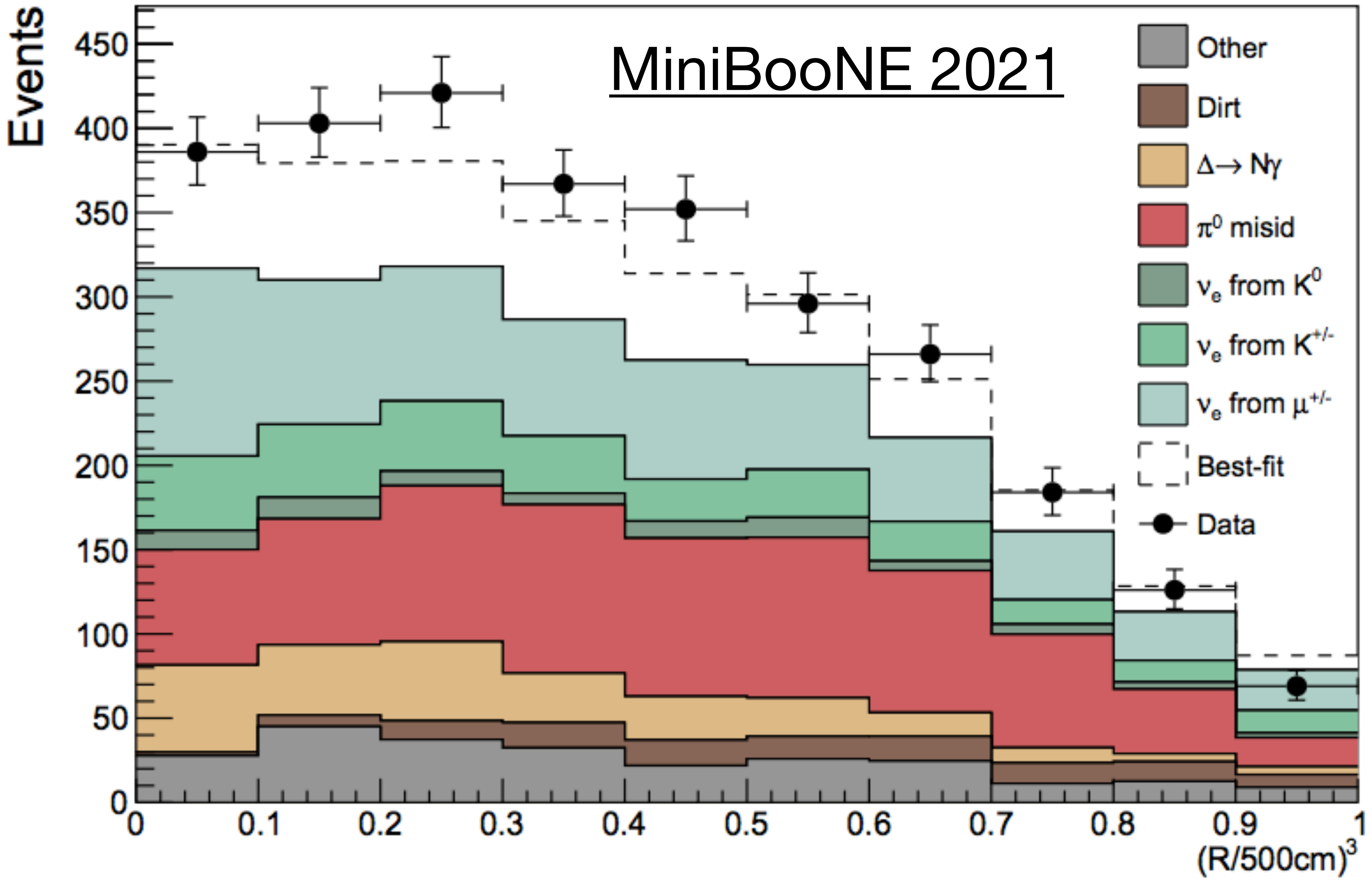
π^0 misidentification background constrained in-situ <u>and</u> disfavored by the radial distribution



Example of a π⁰ mis-ID





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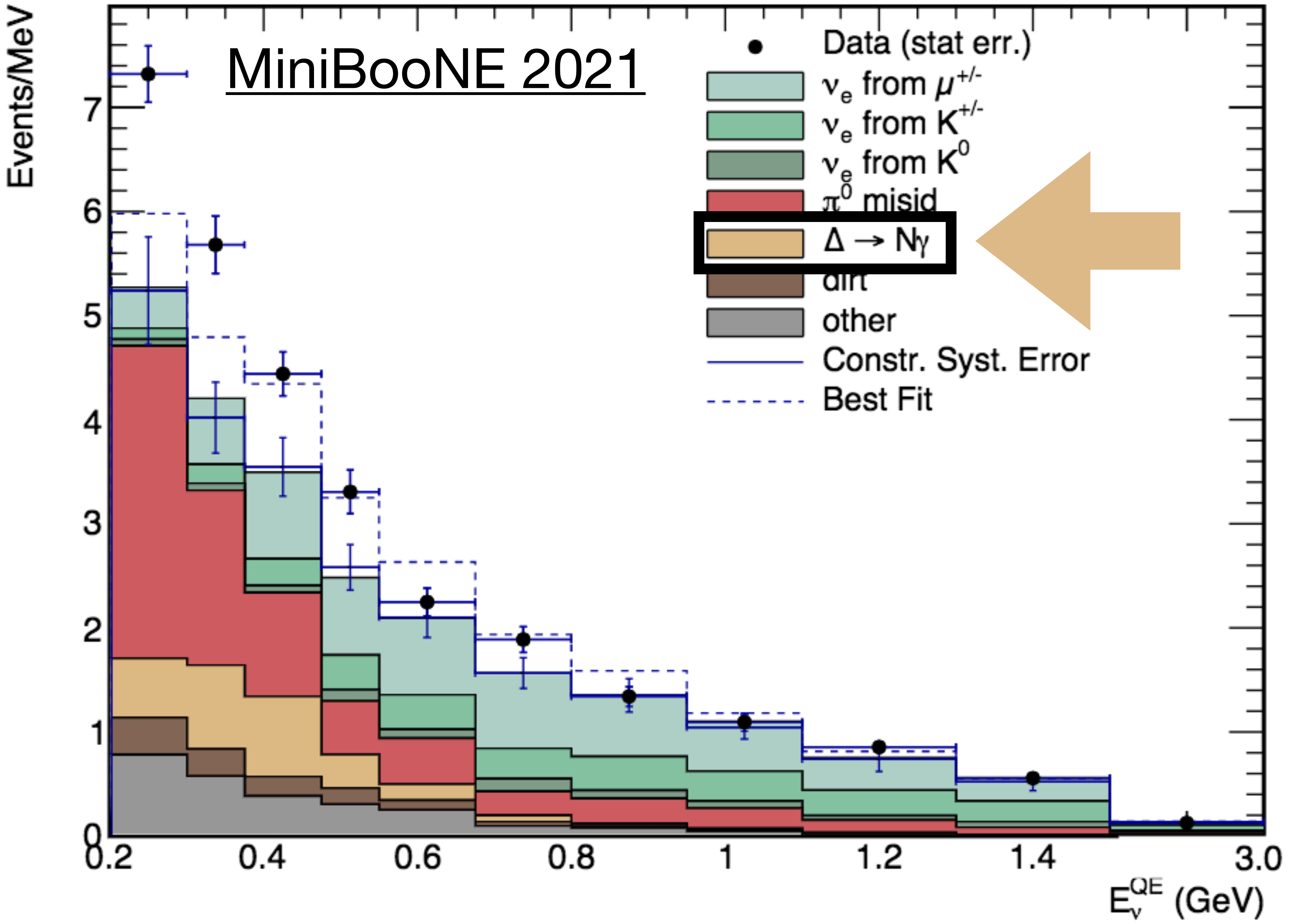
Rare Δ decays to single photons are <u>not</u> constrained in situ by MiniBooNE



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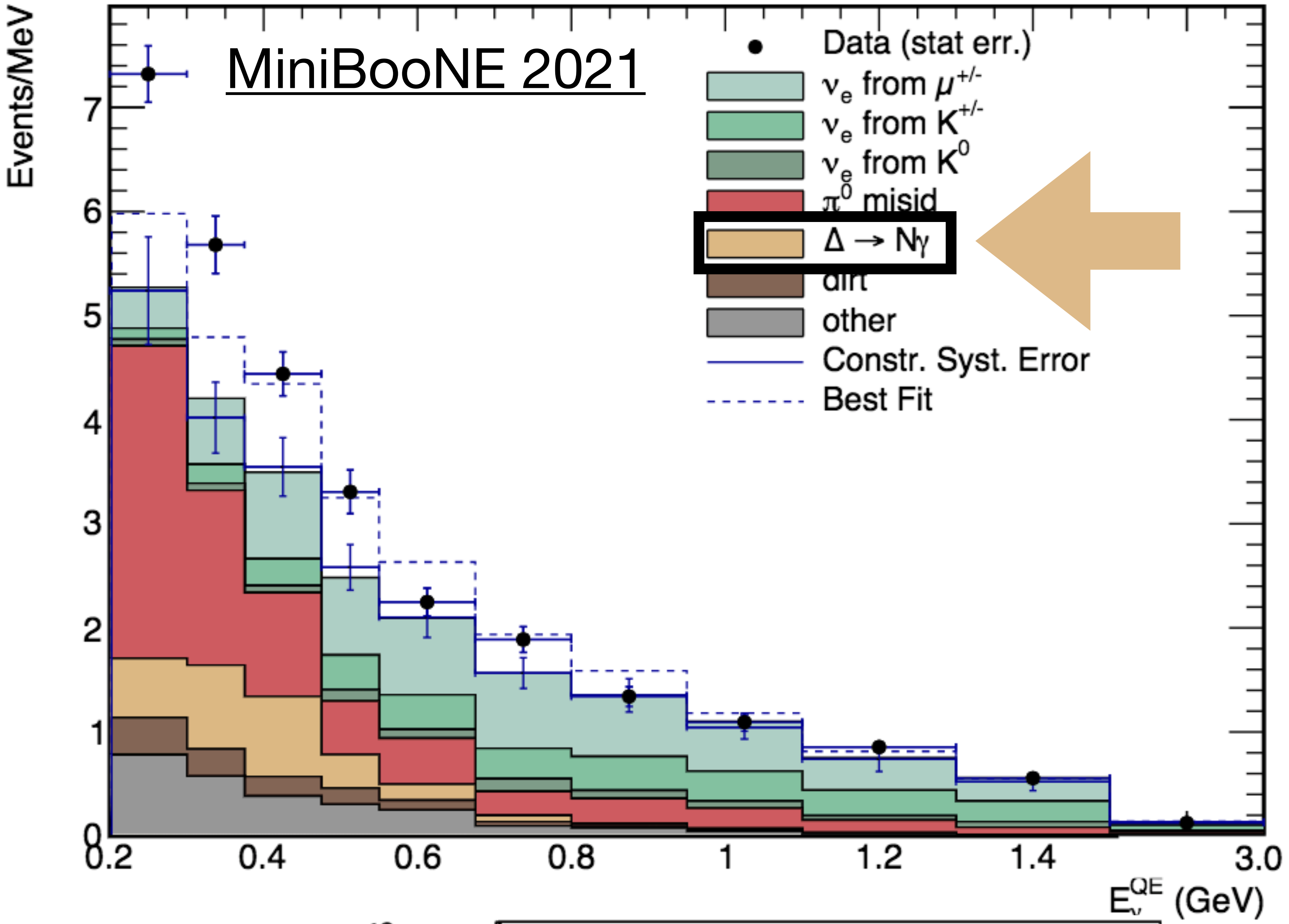
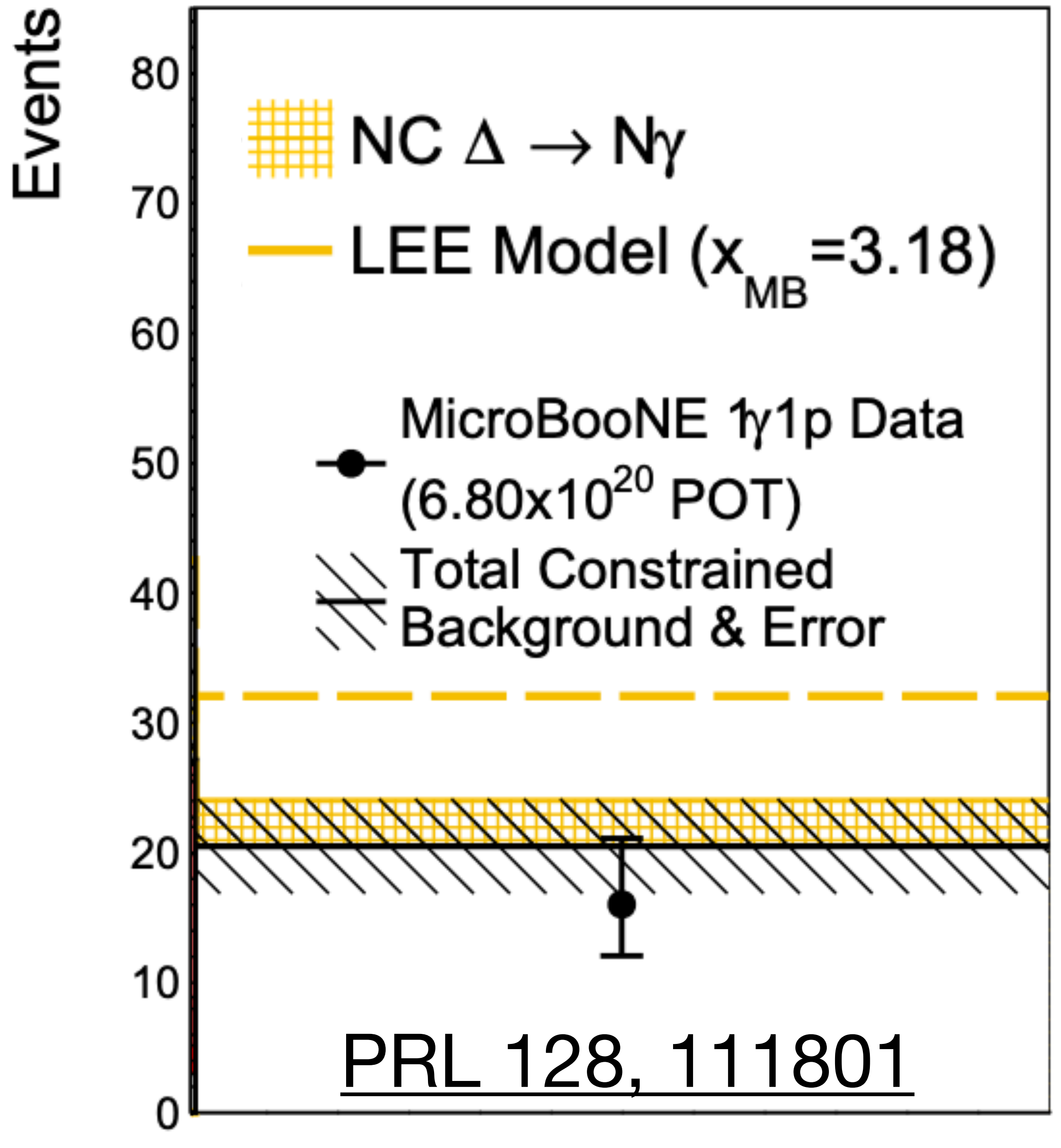
Rare Δ decays to single photons are not constrained in situ by MiniBooNE

MicroBooNE data also disfavor a MiniBooNE-like excess of $\Delta \rightarrow N\gamma$ events at the 95% confidence level


MiniBooNE 2021


PRL 128, 111801

What could it be?

Cherenkov limitations:

- Electrons/photons indistinguishable
- No hadronic information

The excess could be…

1. True electron neutrinos? ✗
2. Mis-modeled photon background? ✗

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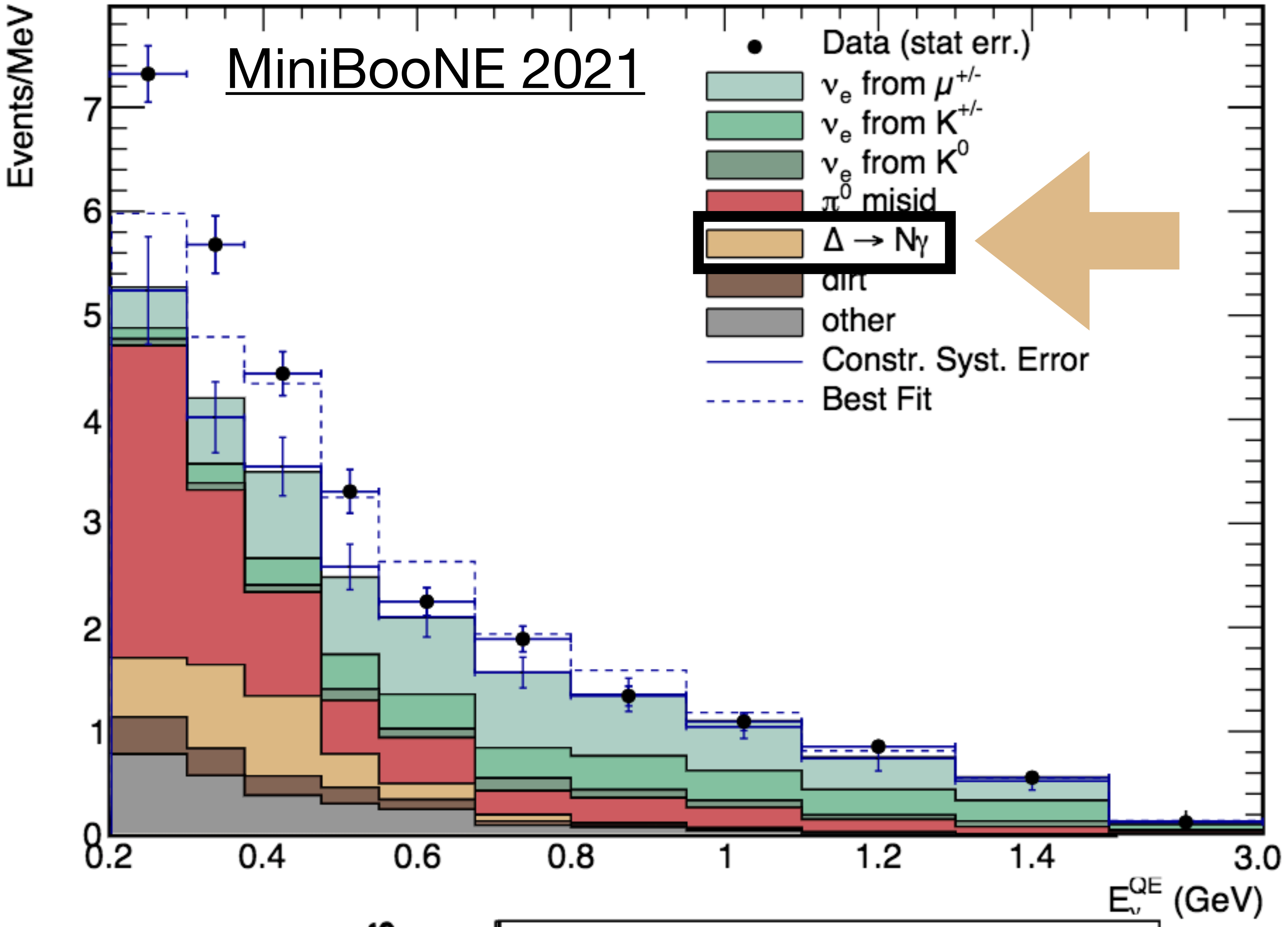

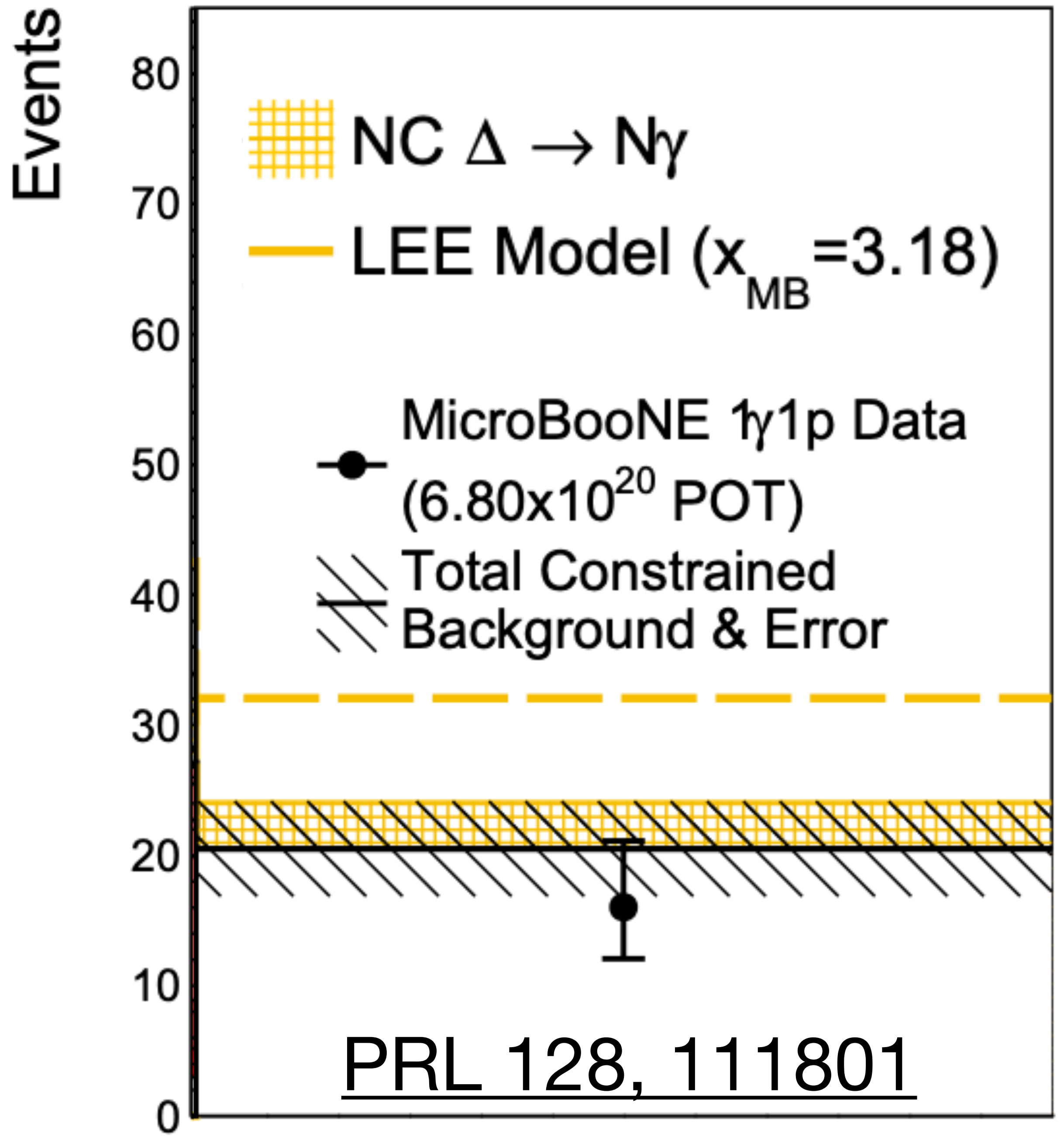

PRL 128, 111801

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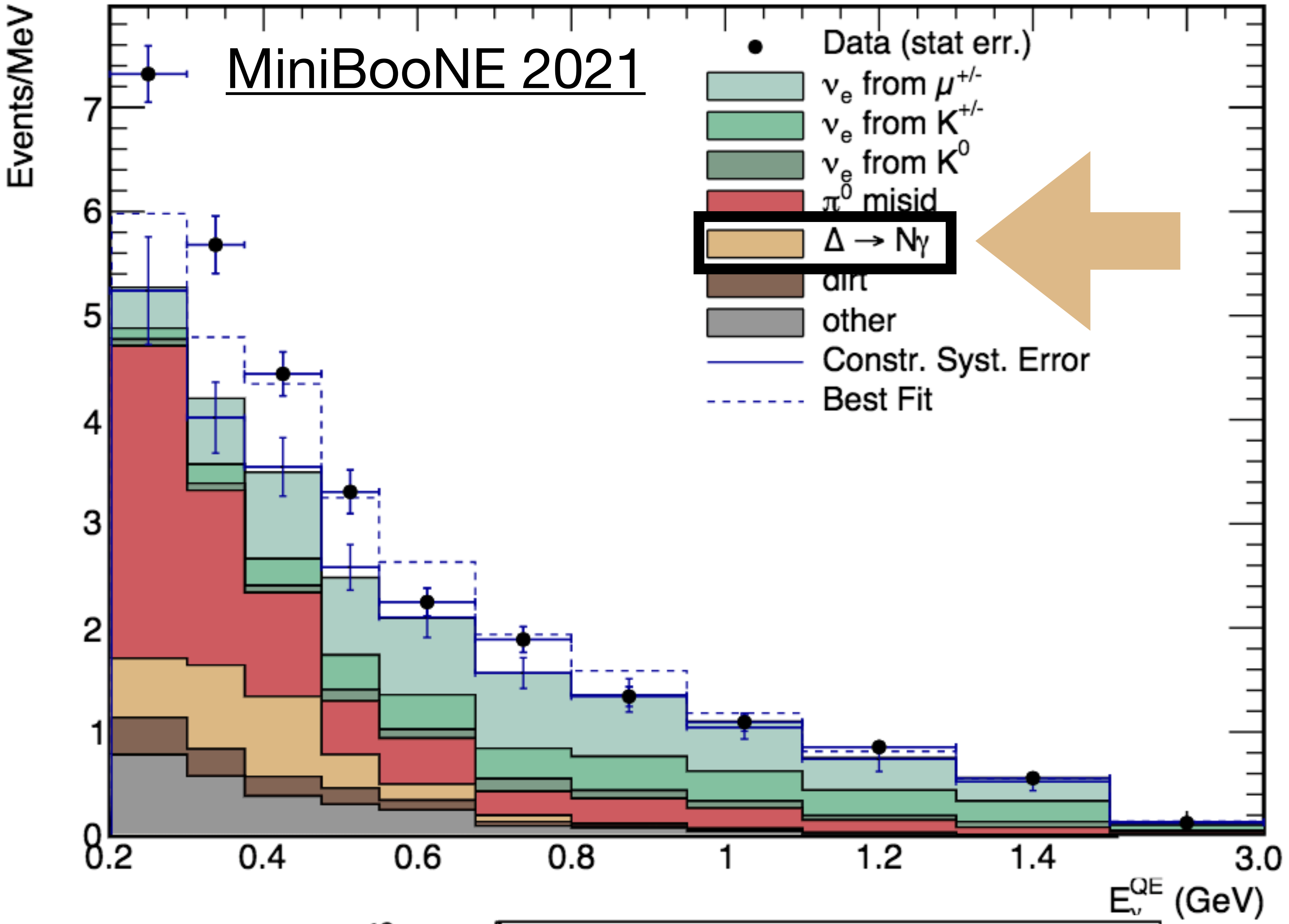
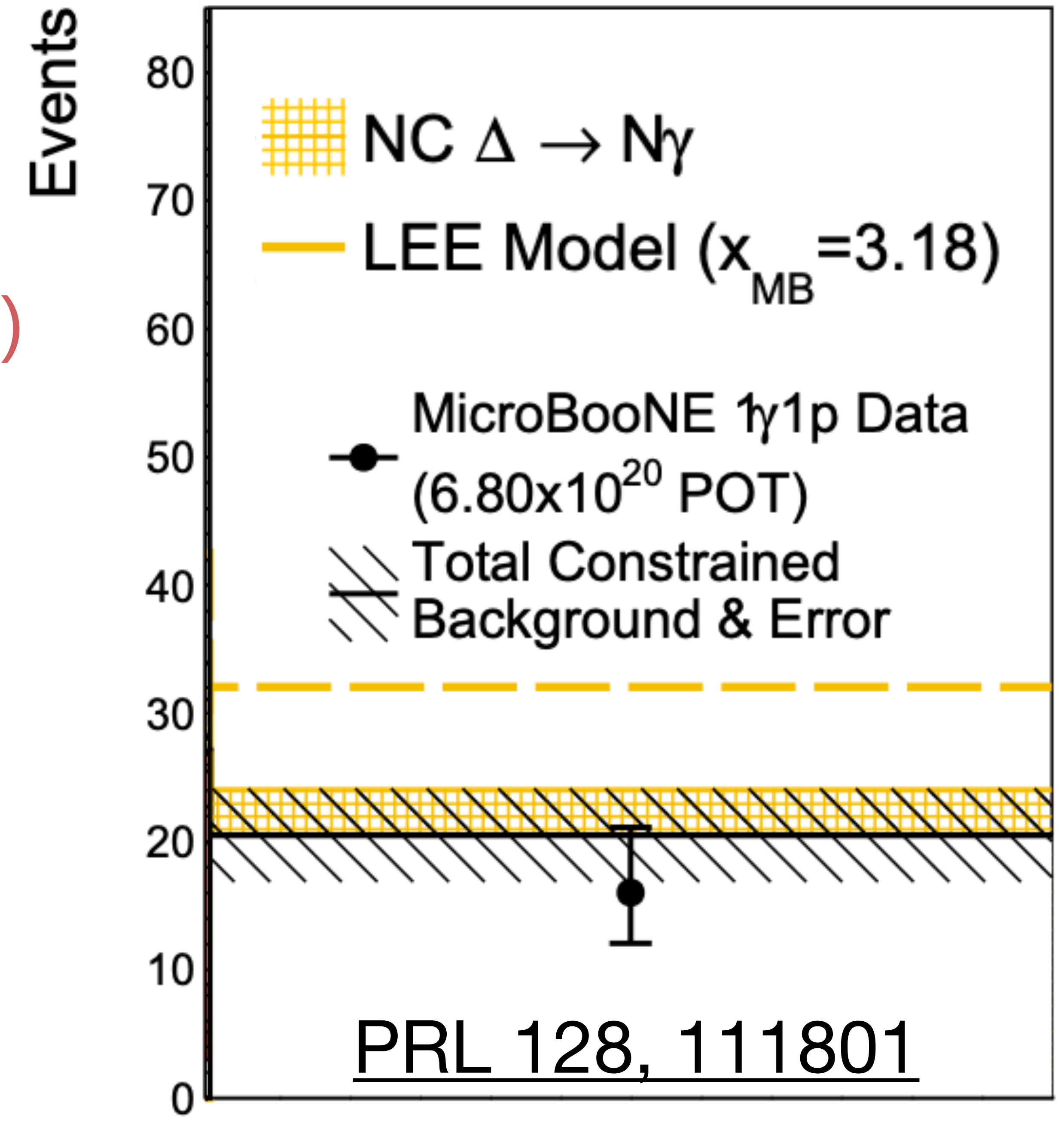

MiniBooNE 2021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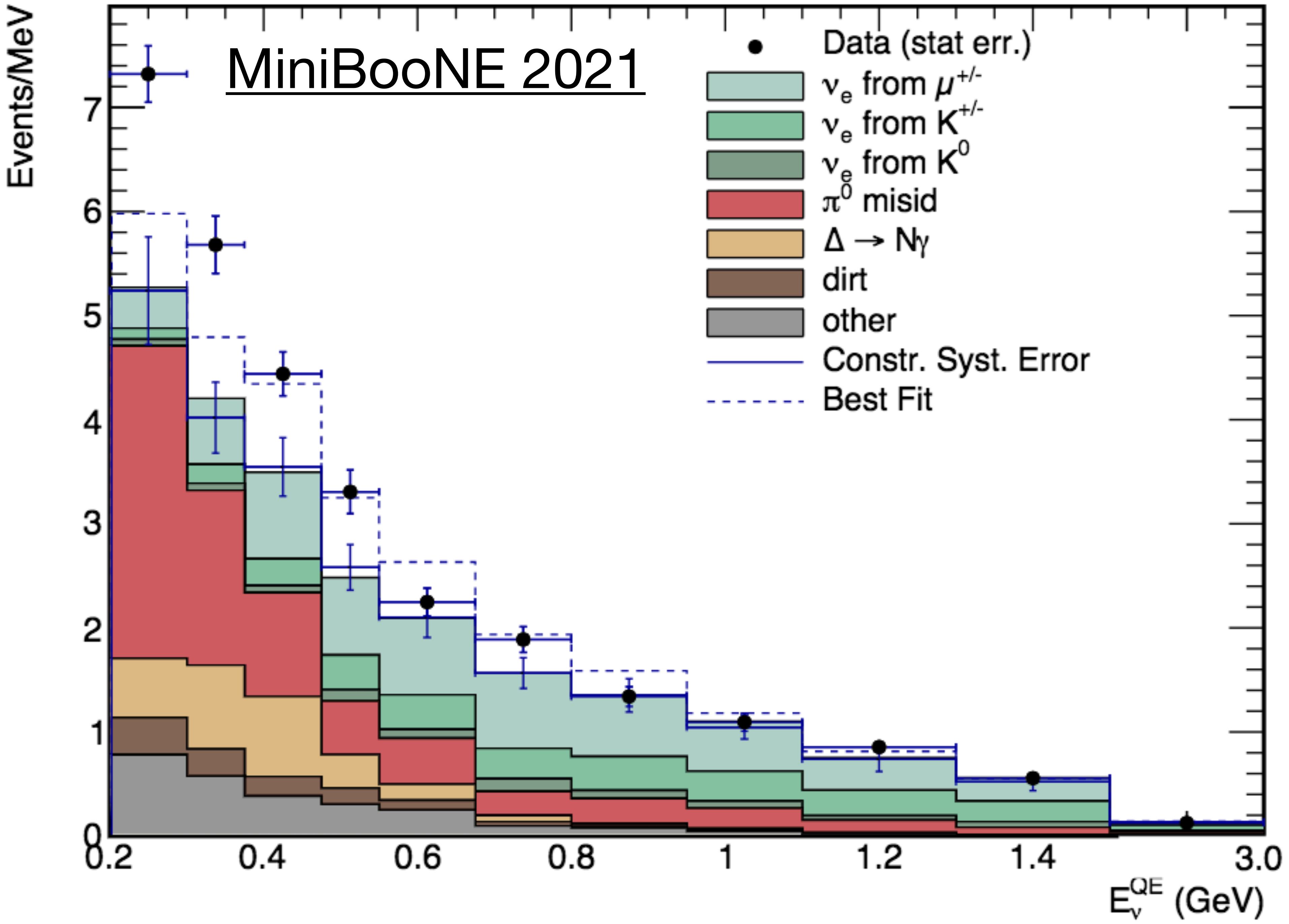

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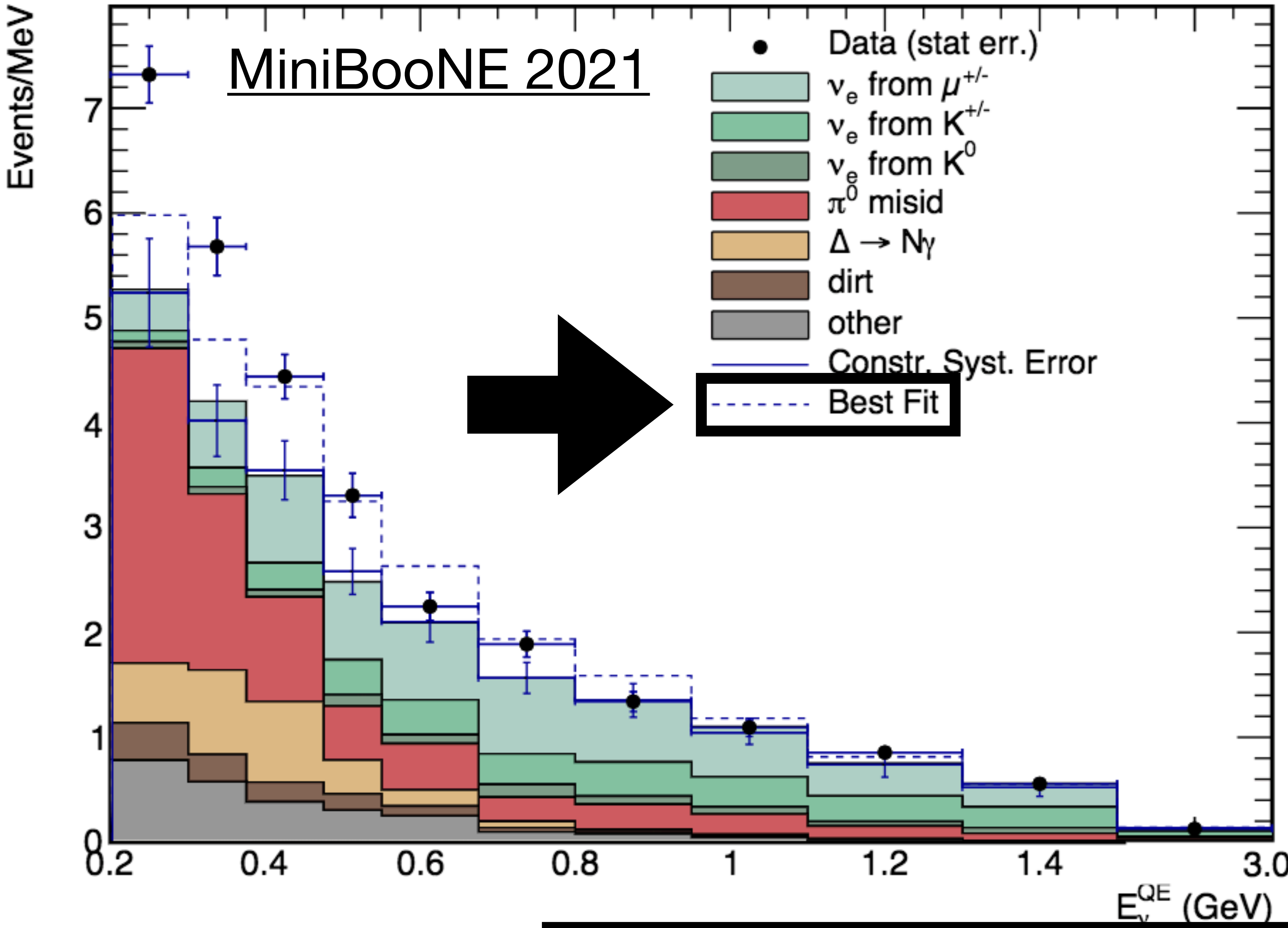
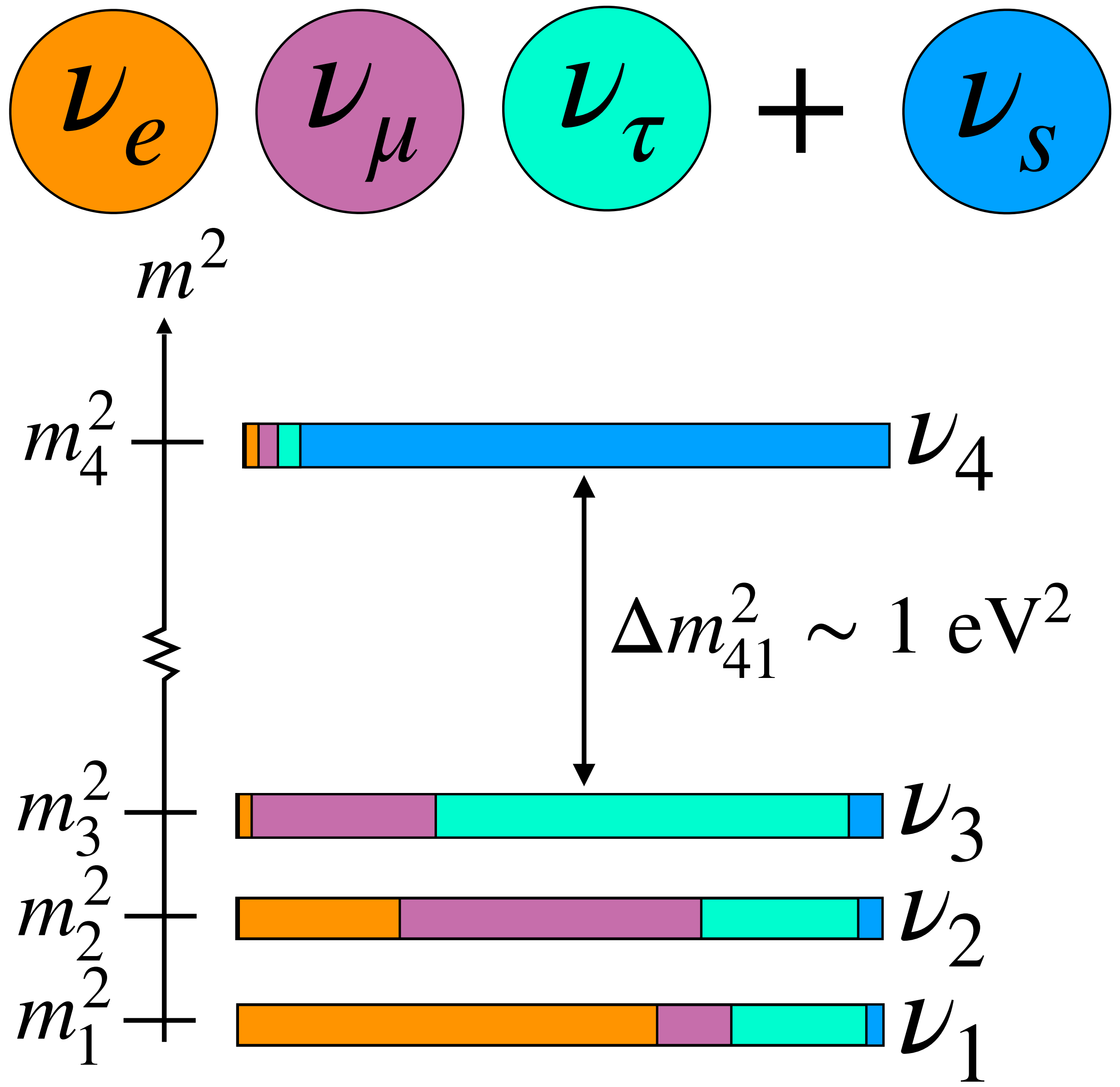
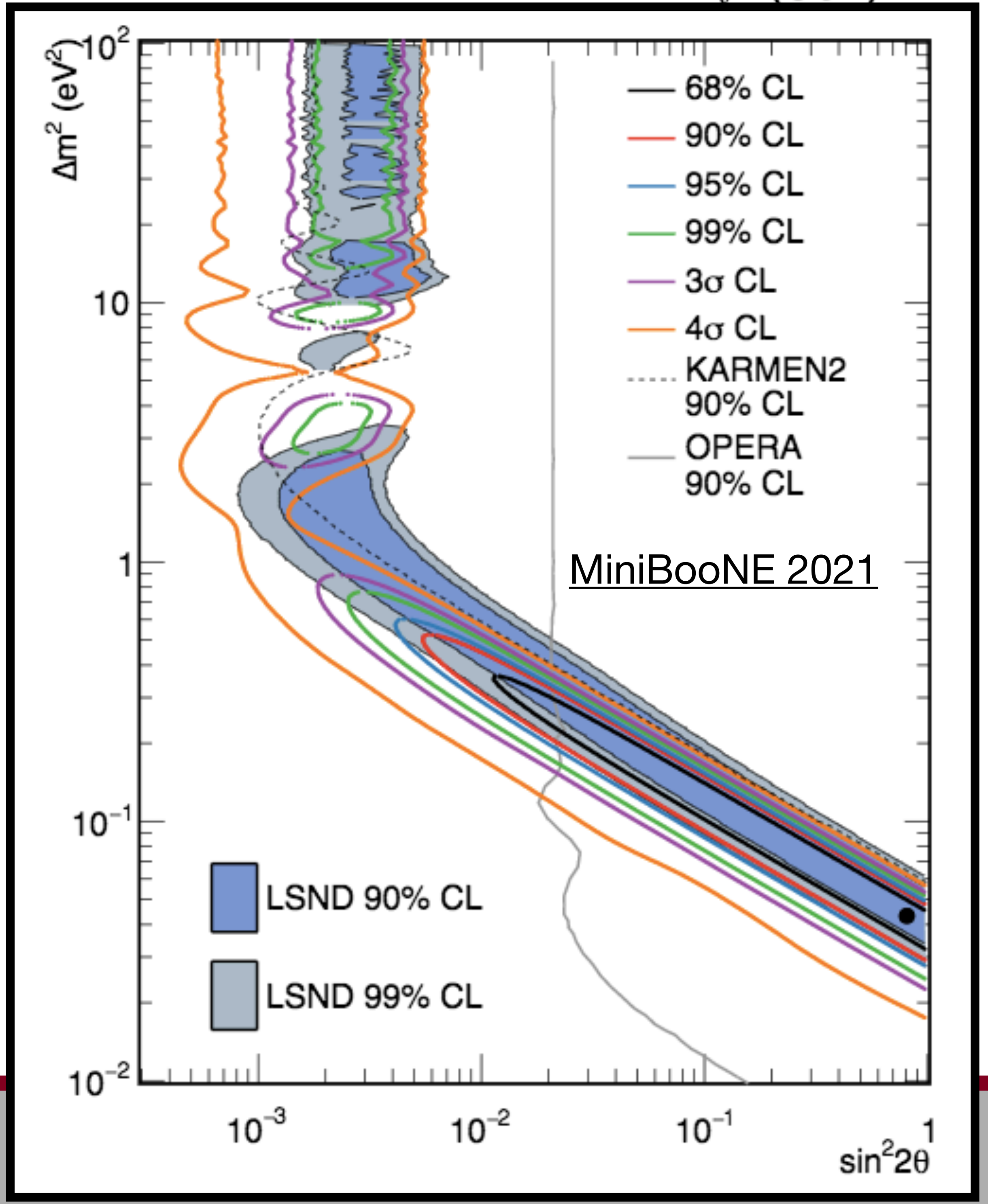
An eV-scale sterile neutrino can induce

$\nu_\mu \to \nu_e$ oscillations at short baselines







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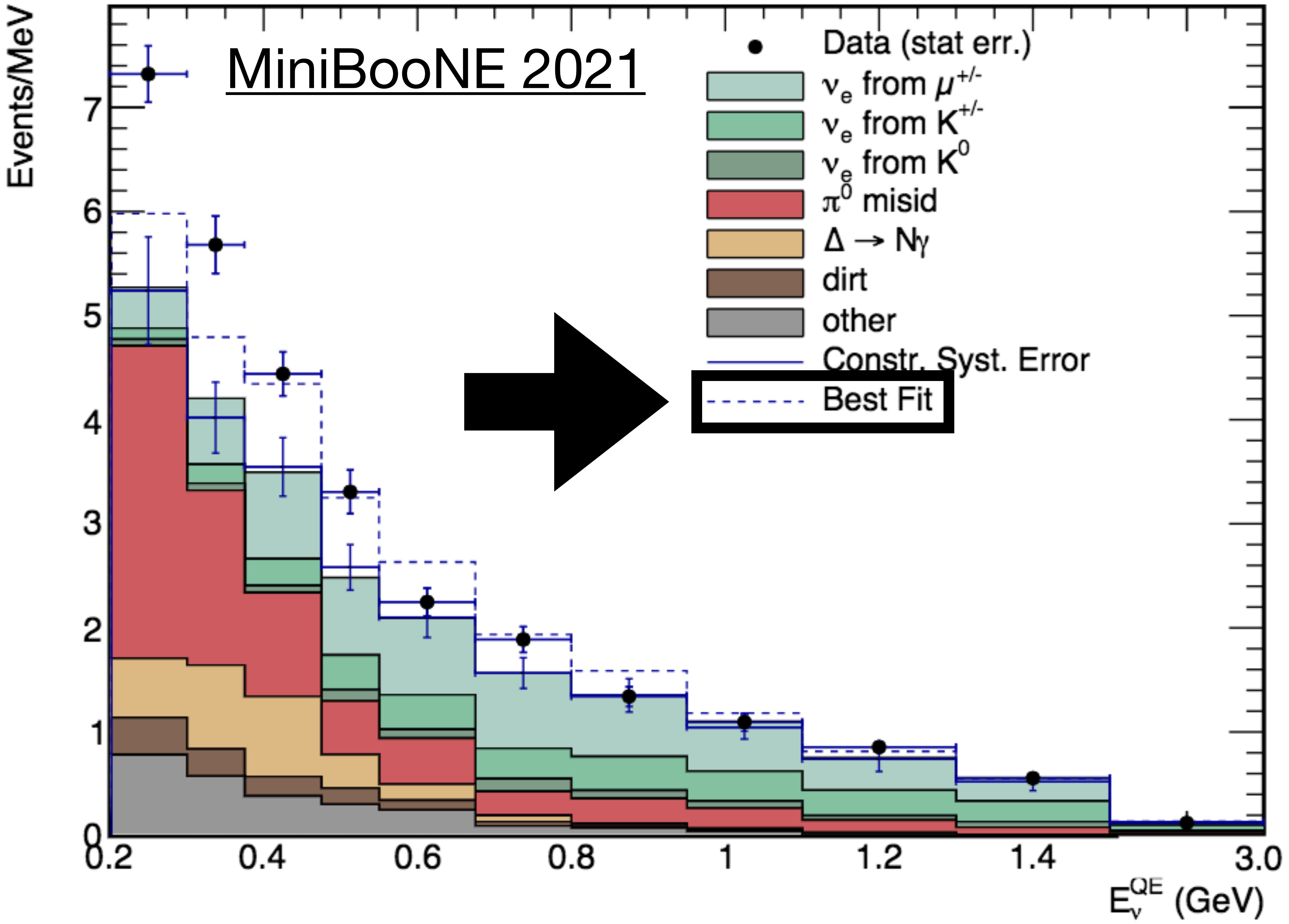
So why haven’t we declared victory?



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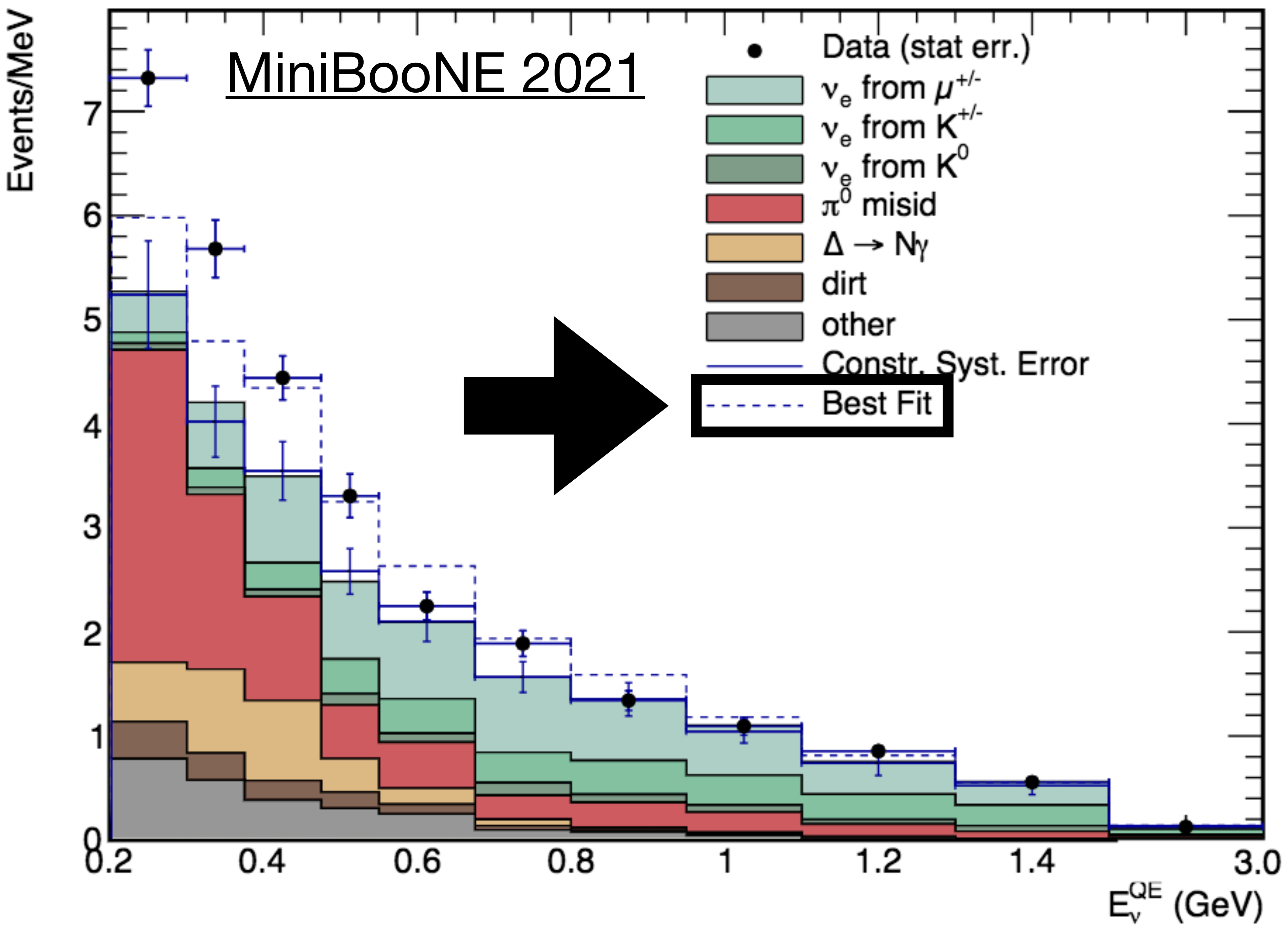
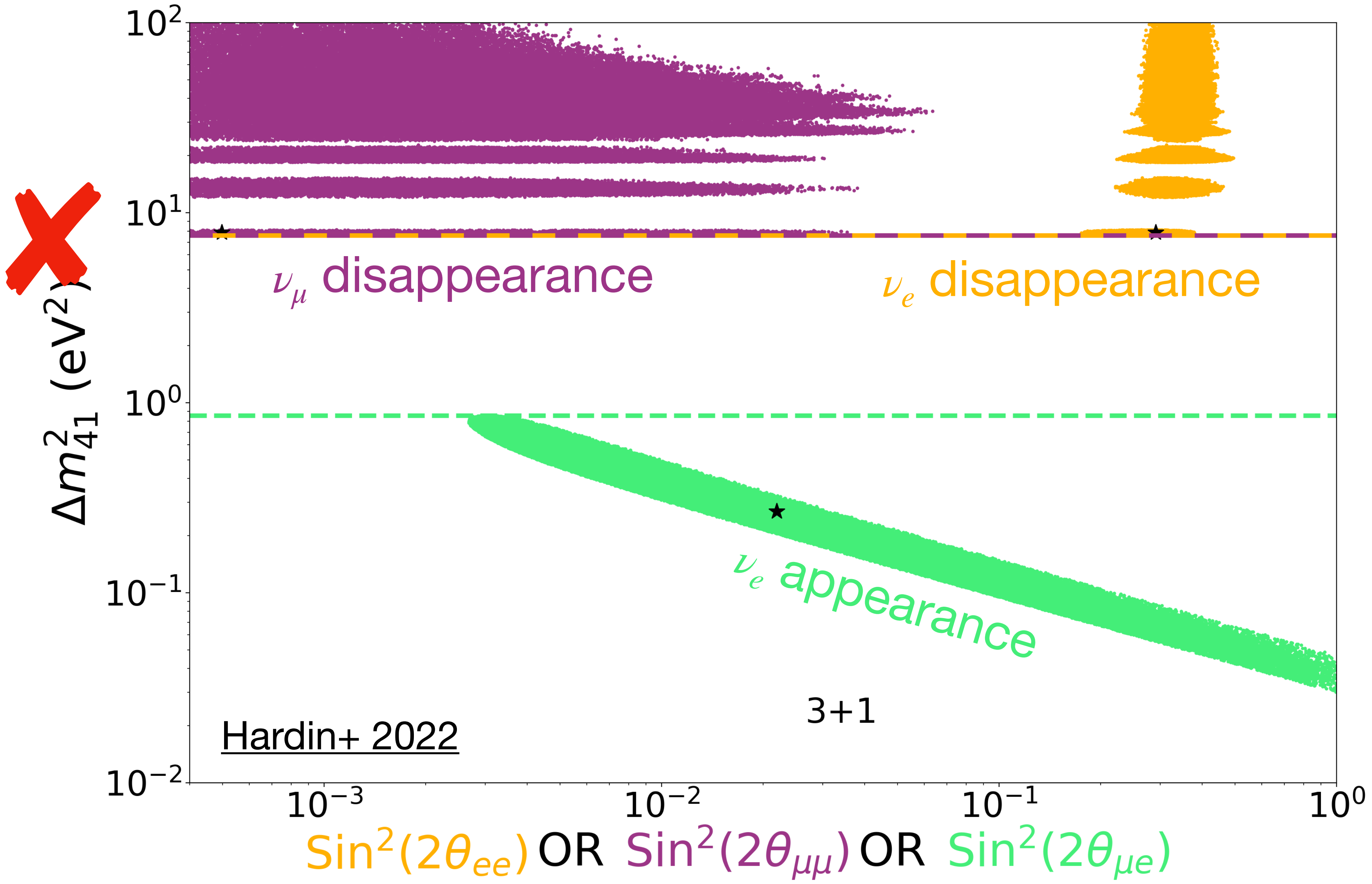
So why haven't we declared victory?

Significant internal tension in sterile neutrino global fits





No positive evidence for ν_μ disappearance, up to a persistent ~2σ hint from IceCube PRL 133, 201804 (2024)

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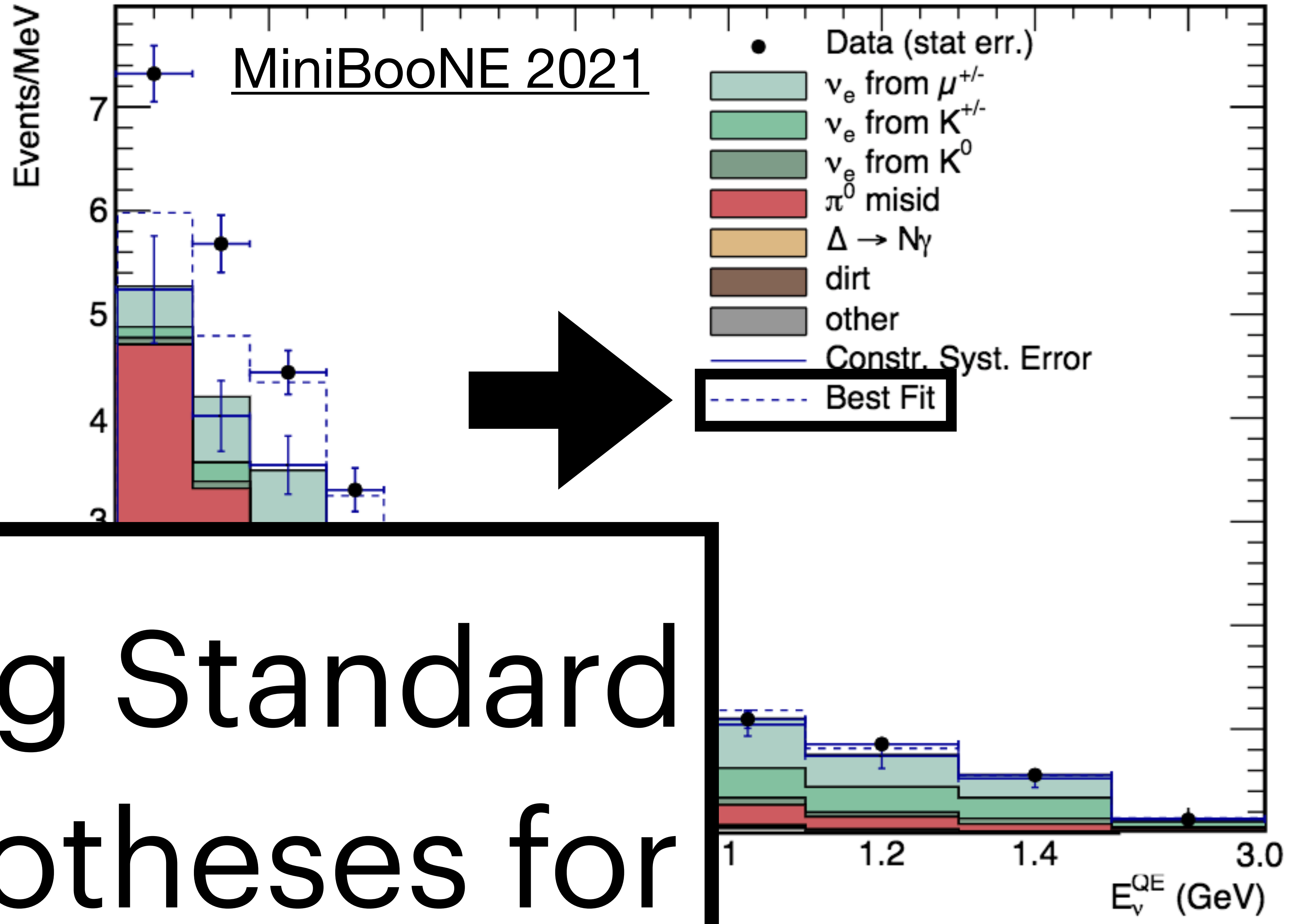
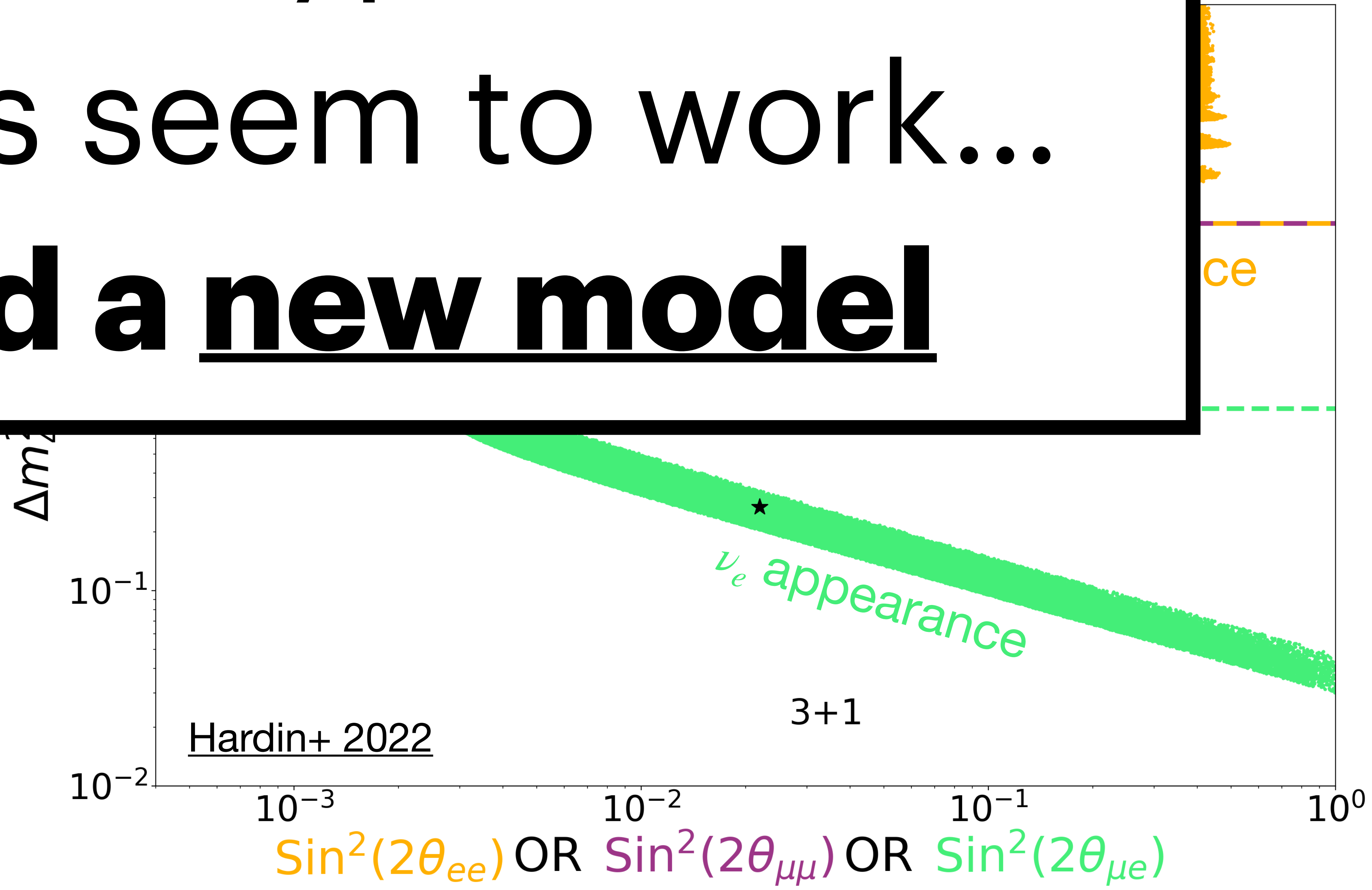
So why haven't we declared victory?

Significant internal tension in sterile neutrino global fits

None of our leading Standard Model or BSM hypotheses for the excess seem to work…

We need a <u>new model</u>





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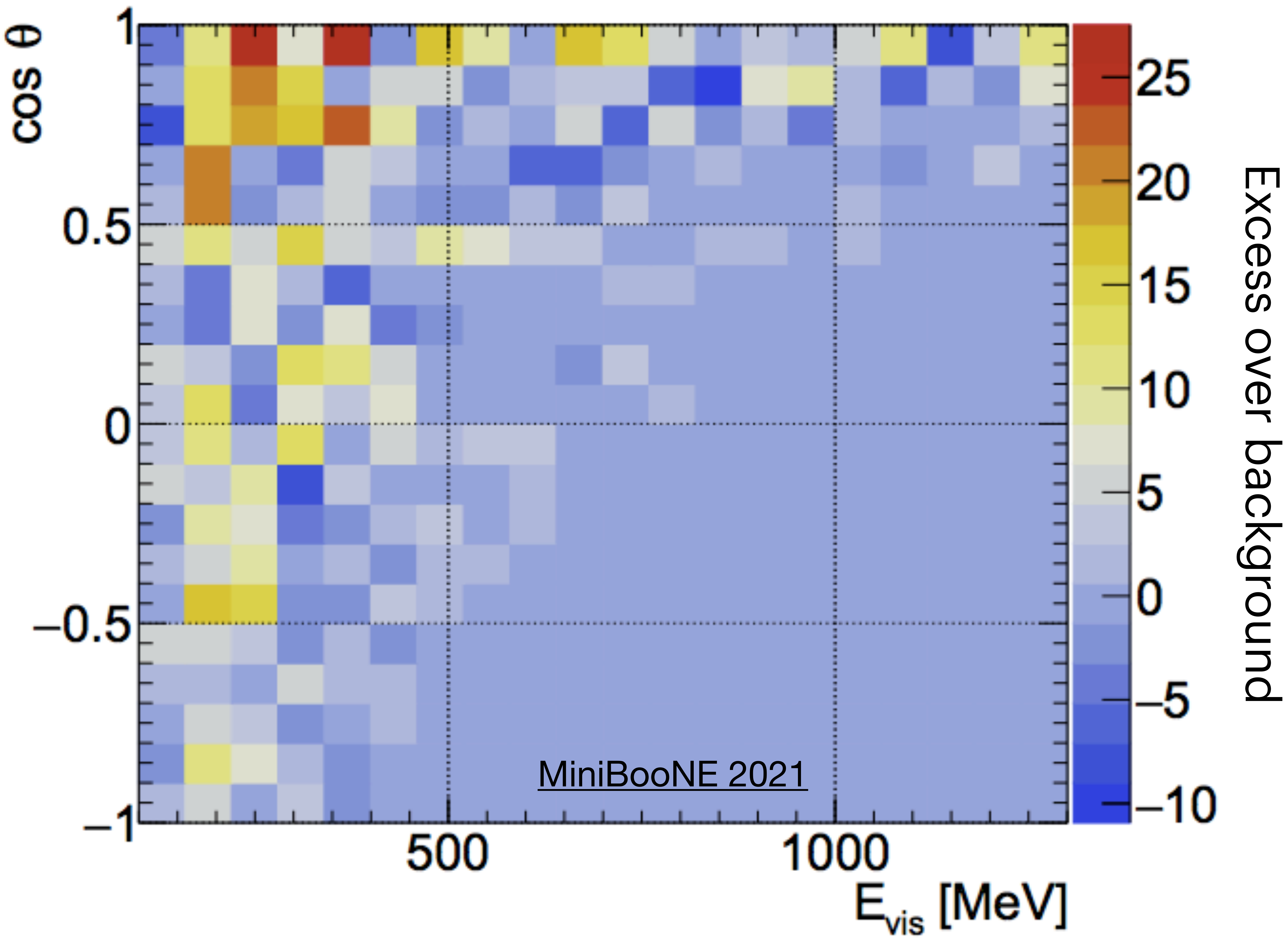
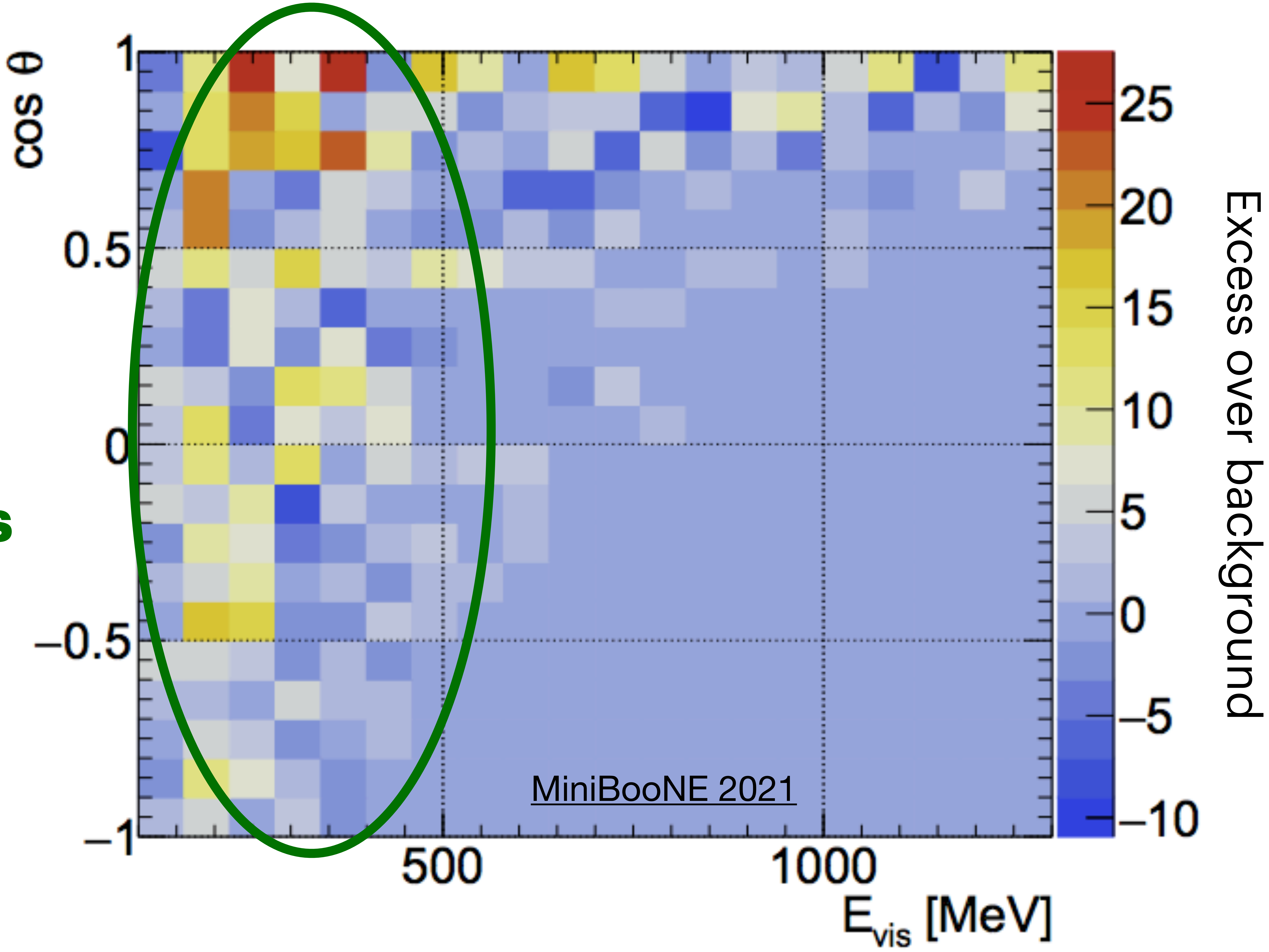
A hint for a two component solution



MiniBooNE 2021

A hint for a two component solution

A broad angle component at lower energies



MiniBooNE 2021

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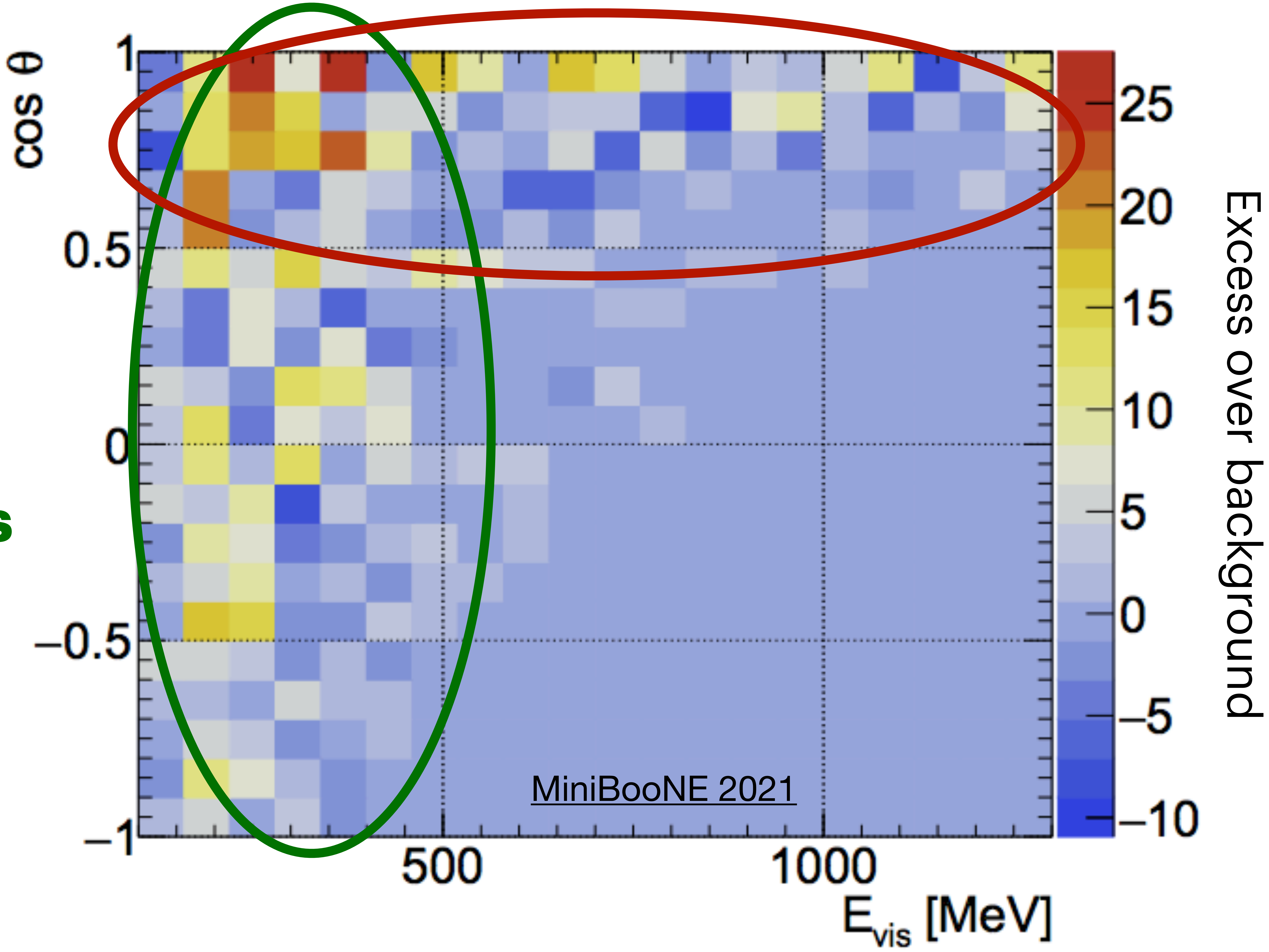


MiniBooNE 2021

A forward component that extends to higher energies

Outline

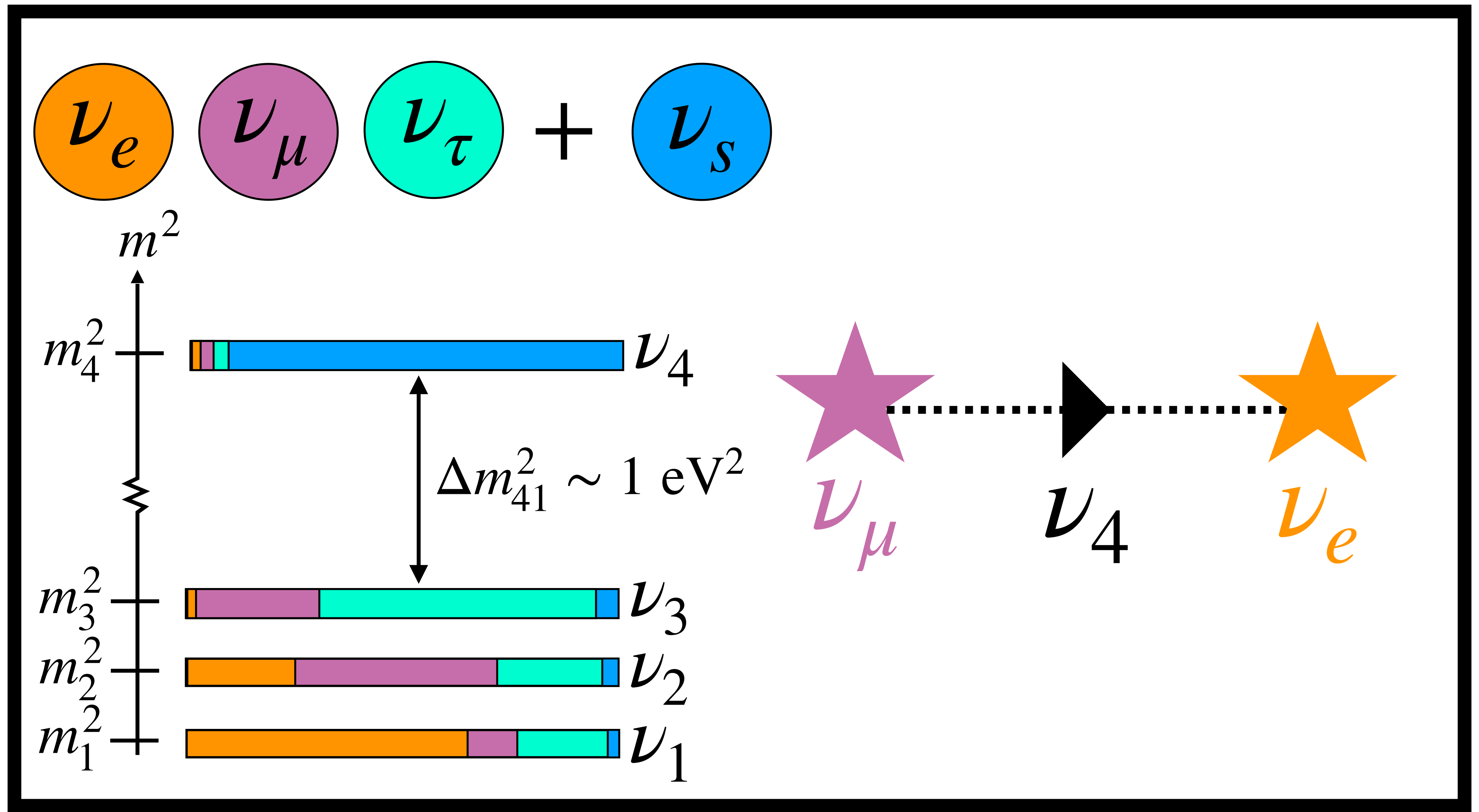
1. **MiniBooNE:** A long-standing neutrino anomaly
2. **Heavy neutrinos in plastic:** constraints on a promising MiniBooNE solution
3. **Heavy neutrinos in ice and water:** searches at neutrino telescopes
4. **Heavy neutrinos (and more) in water and rock:** new detectors for collider neutrinos

Can we find a two component solution for MiniBooNE?

[1] Hardin+ 2211.02610 [2] Vergani, NK+ PRD 104, 095005 [3] NK+ PRD 107, 055009

Can we find a two component solution for MiniBooNE?

(1) An eV-scale sterile neutrino



Subdominant contribution to the MiniBooNE excess while still explaining other short baseline neutrino anomalies [1,2]

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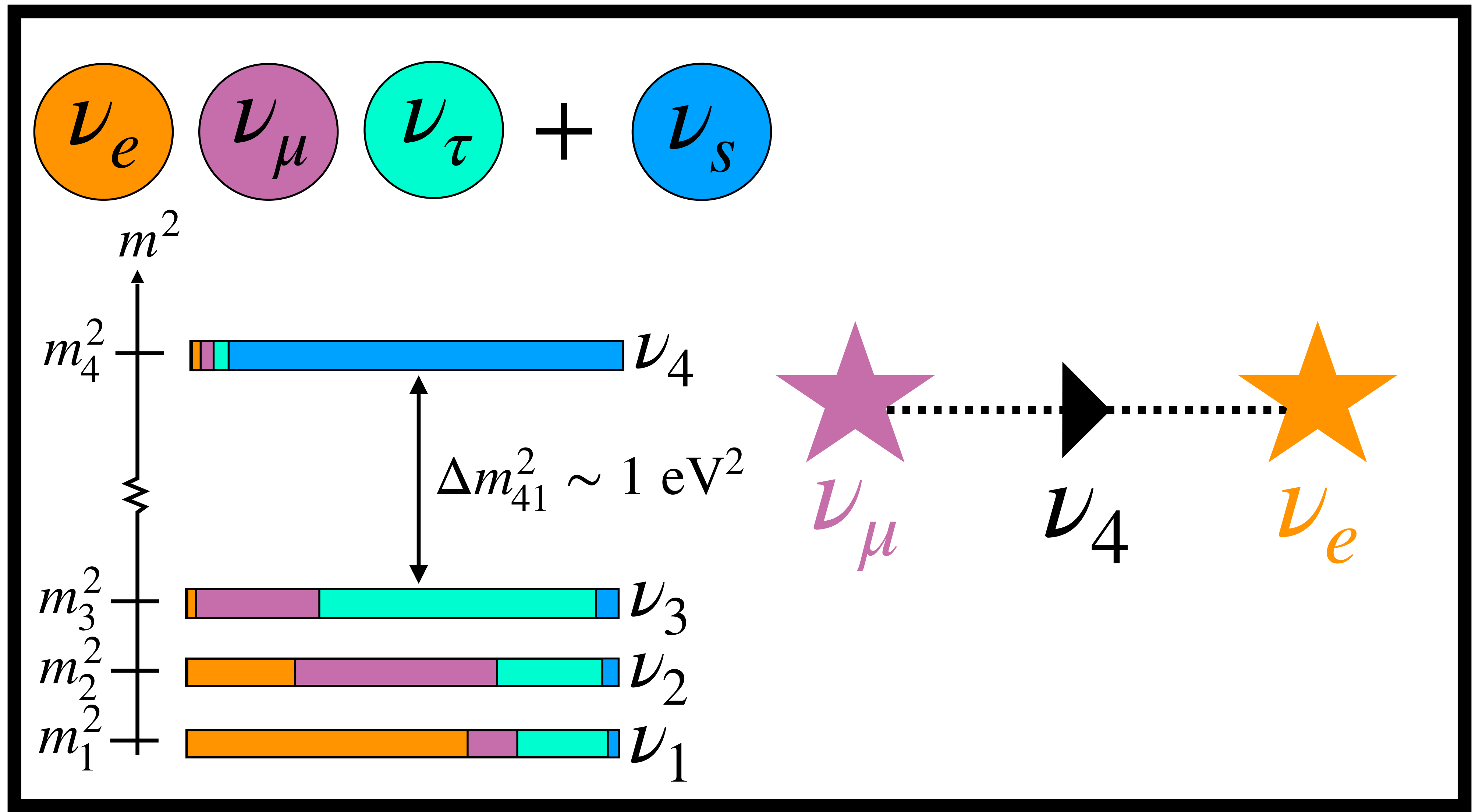

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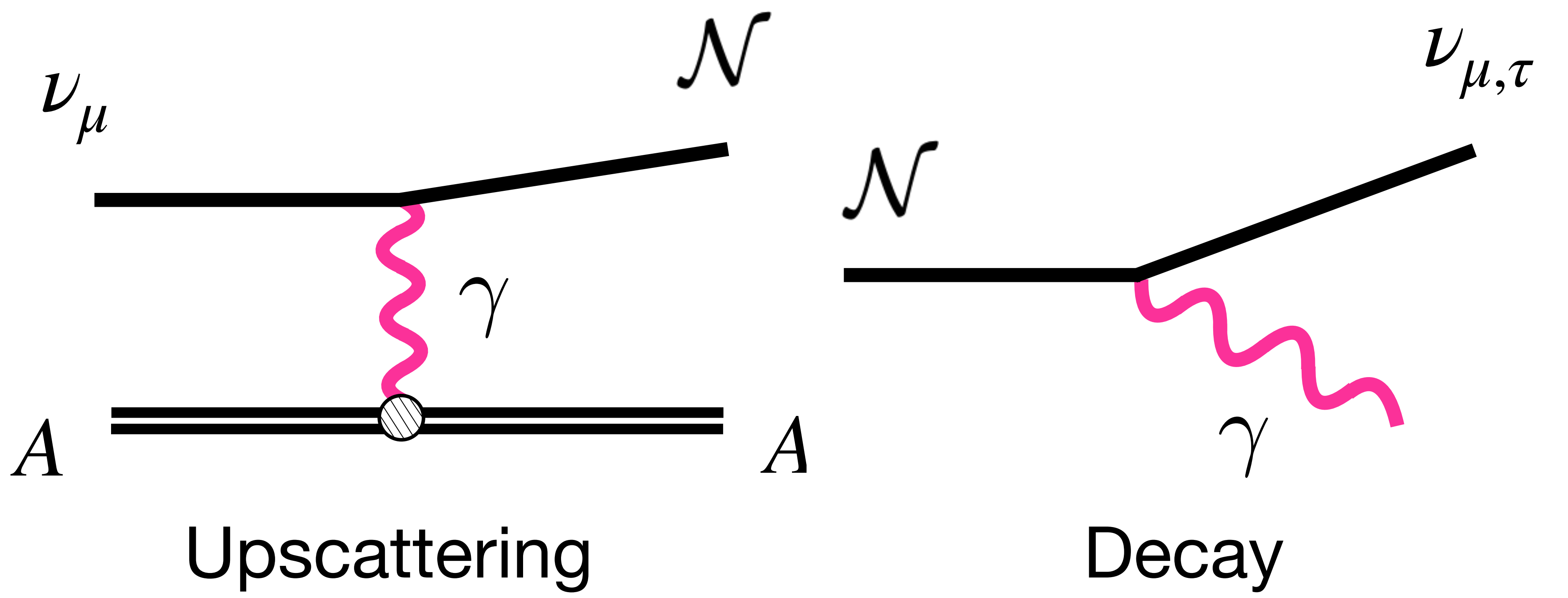
$\oplus$

(2) A dipole-portal heavy neutral lepton (HNL)

$$\mathscr{L}_{\text{eff}} \supset d_{\alpha\mathcal{N}}\overline{\nu_\alpha}\sigma_{\mu\nu}F^{\mu\nu}\mathcal{N}_R + \mathrm{h.c.}$$



These new interactions explain the bulk of the MiniBooNE excess, relieving tension in sterile neutrino global fits ($4.8\sigma \rightarrow 2.3\sigma$) [2,3]

[1] Hardin+ 2211.02610 [2] Vergani, NK+ PRD 104, 095005 [3] NK+ PRD 107, 055009

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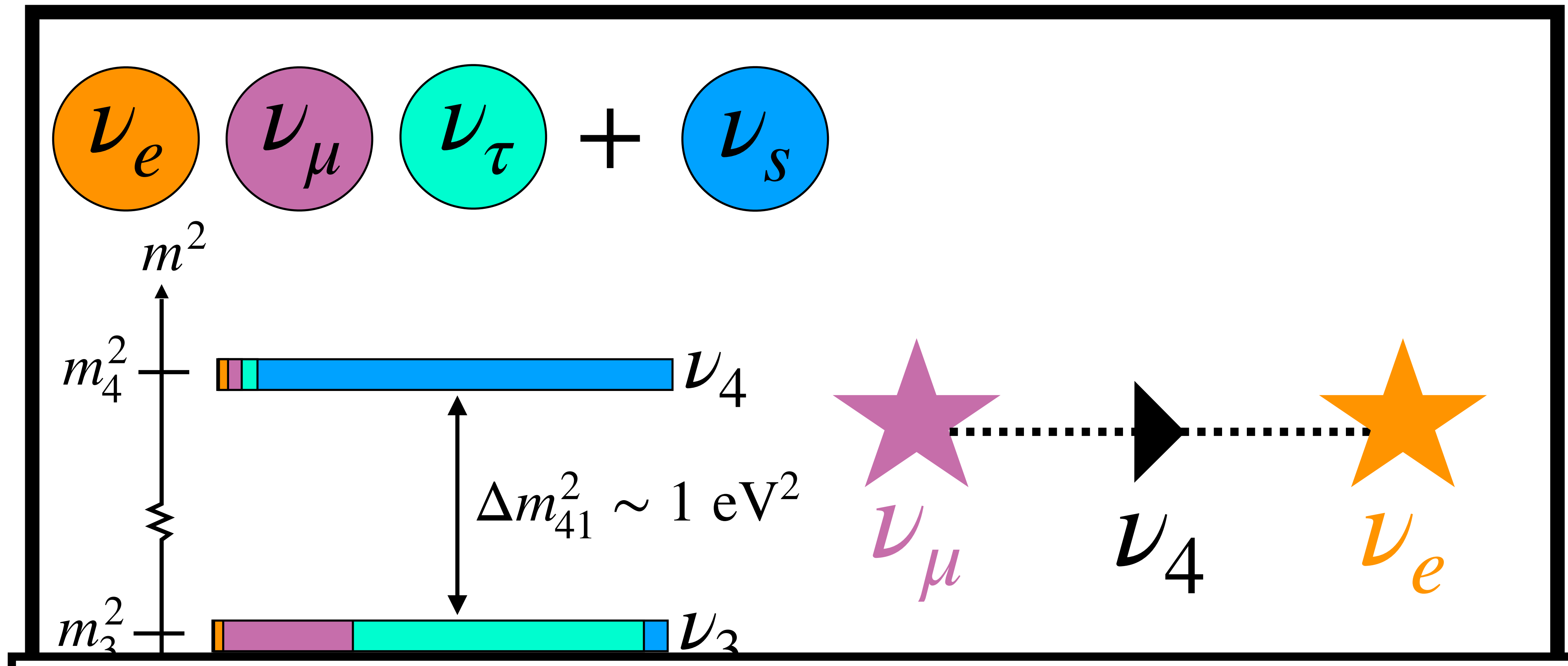

Explaining the MiniBooNE excess through a mixed model of neutrino oscillation and decay

S. Vergani, N. W. Kamp, A. Diaz, C. A. Argüelles, J. M. Conrad, M. H. Shaevitz, and M. A. Uchida
Phys. Rev. D **104**, 095005 – Published 8 November 2021

Dipole-coupled heavy-neutral-lepton explanations of the MiniBooNE excess including constraints from MINERvA data

N. W. Kamp, M. Hostert, A. Schneider, S. Vergani, C. A. Argüelles, J. M. Conrad, M. H. Shaevitz, and M. A. Uchida
Phys. Rev. D **107**, 055009 – Published 9 March 2023

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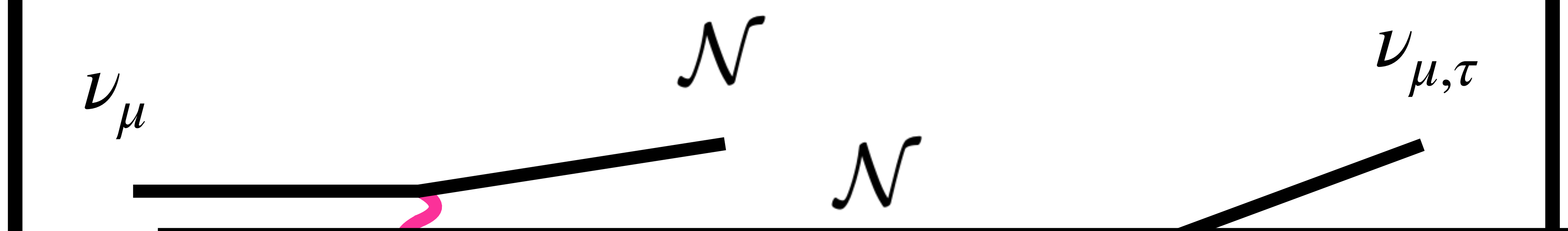

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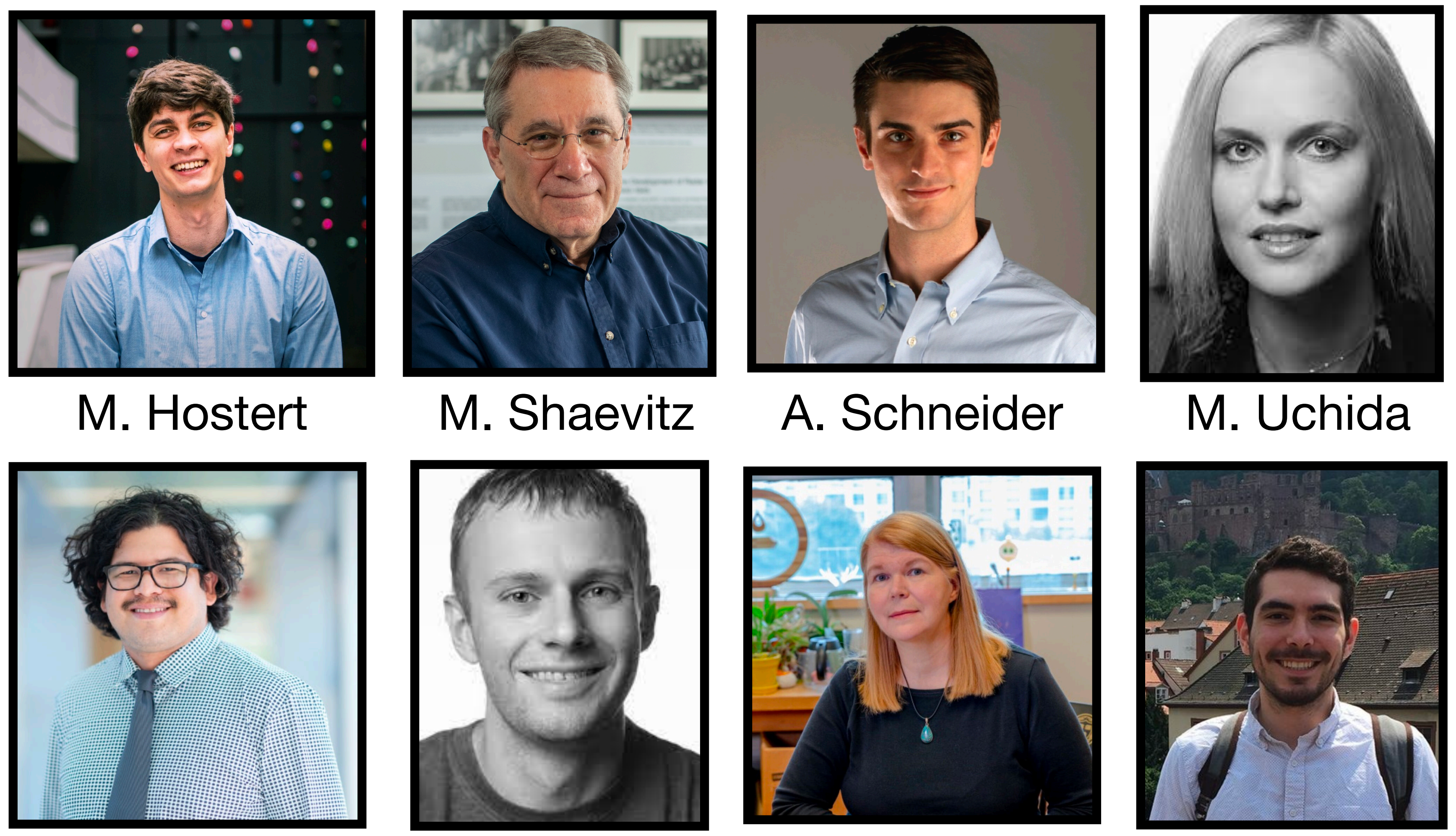
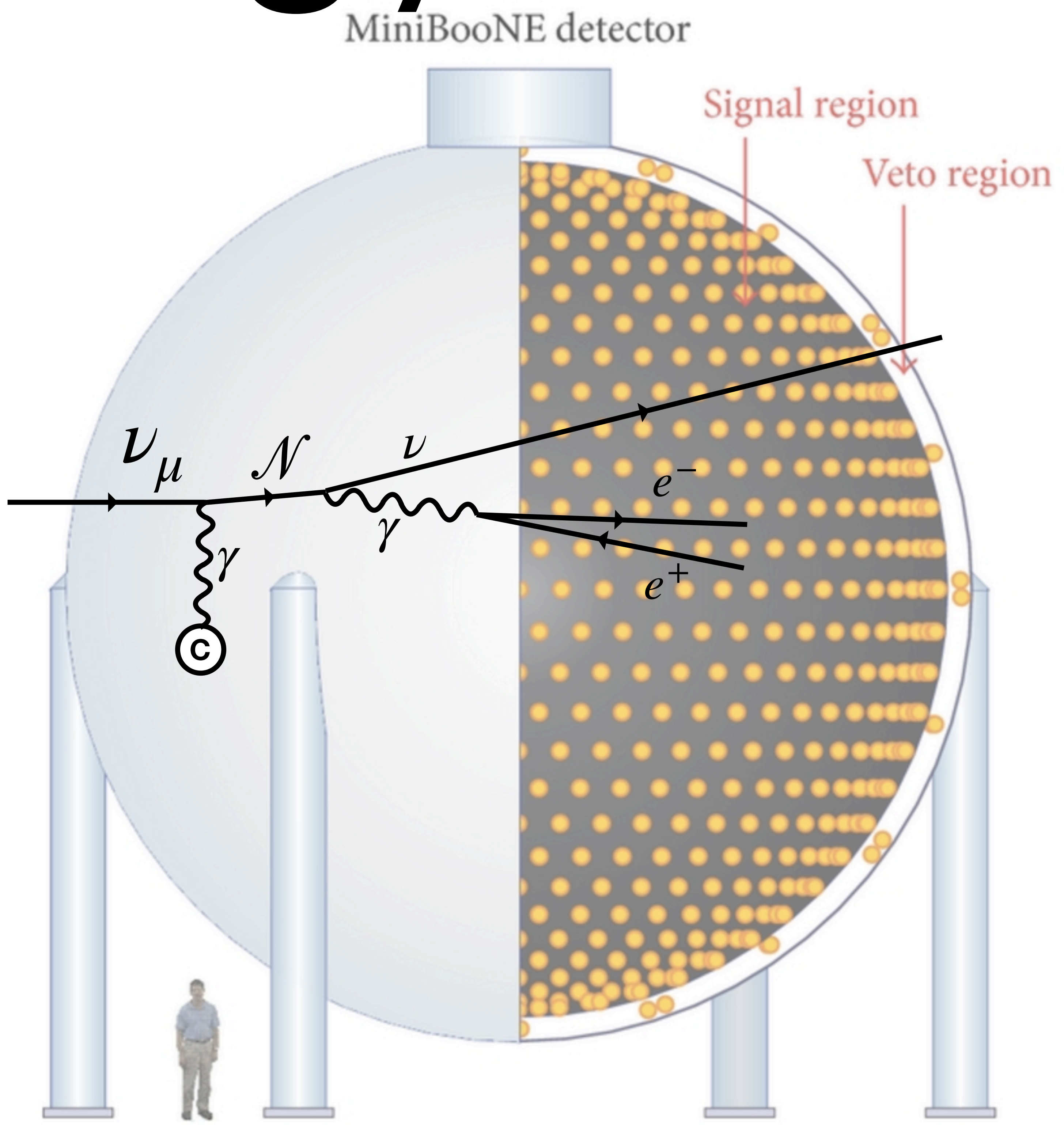


M. Hostert M. Shaevitz A. Schneider M. Uchida
C. Argüelles S. Vergani J. Conrad A. Diaz

[1] Hardin+ 2211.02610 [2] Vergani, NK+ PRD 104, 095005 [3] NK+ PRD 107, 055009

Mixed Model Fit Strategy

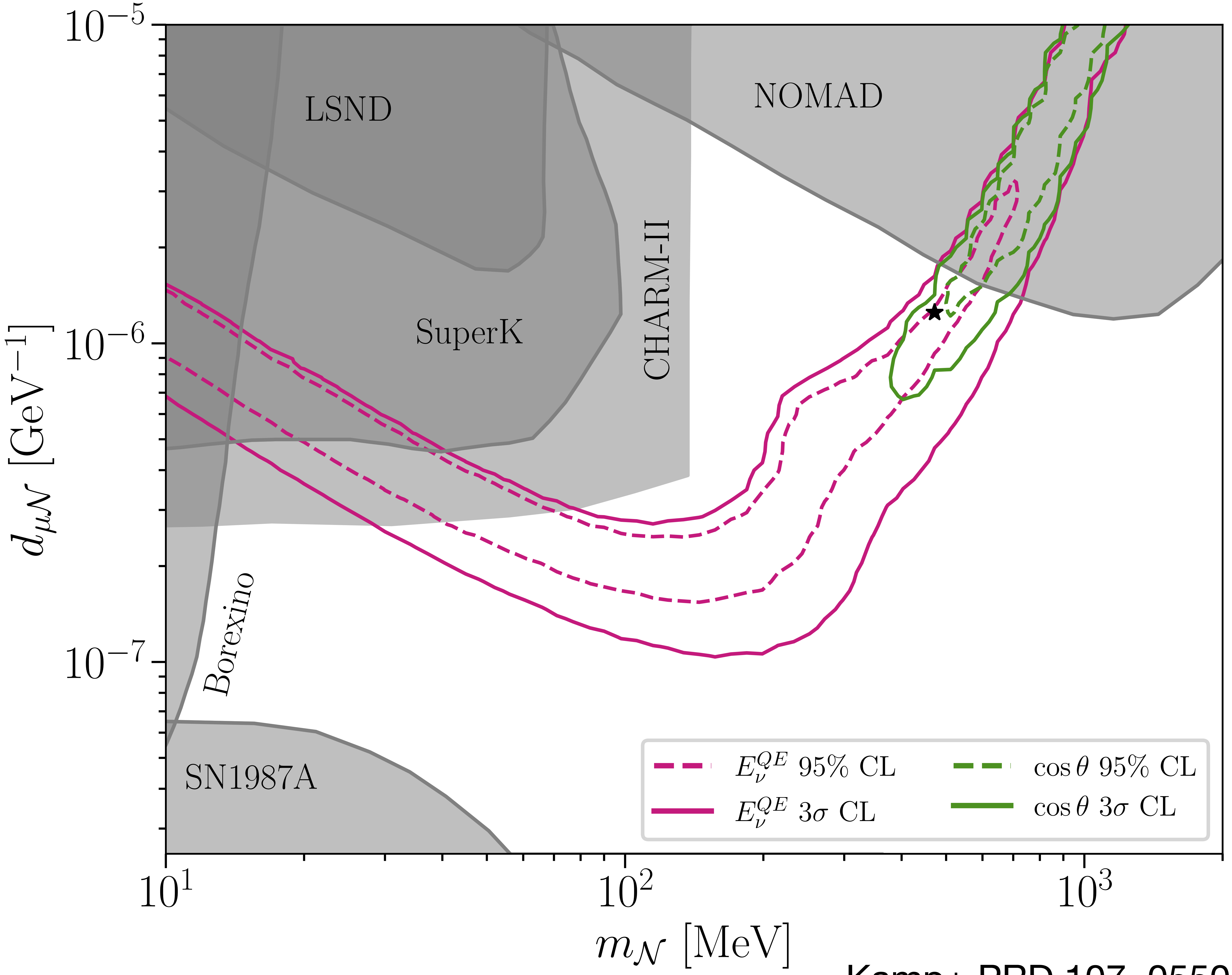
1. Perform a global sterile neutrino fit without MiniBooNE to fix the sterile neutrino parameters [1]
2. Simulate HNL upscattering and decay in MiniBooNE using the open source SIREN simulation package [2]
3. Fit the remaining excess for the preferred HNL mass and dipole coupling



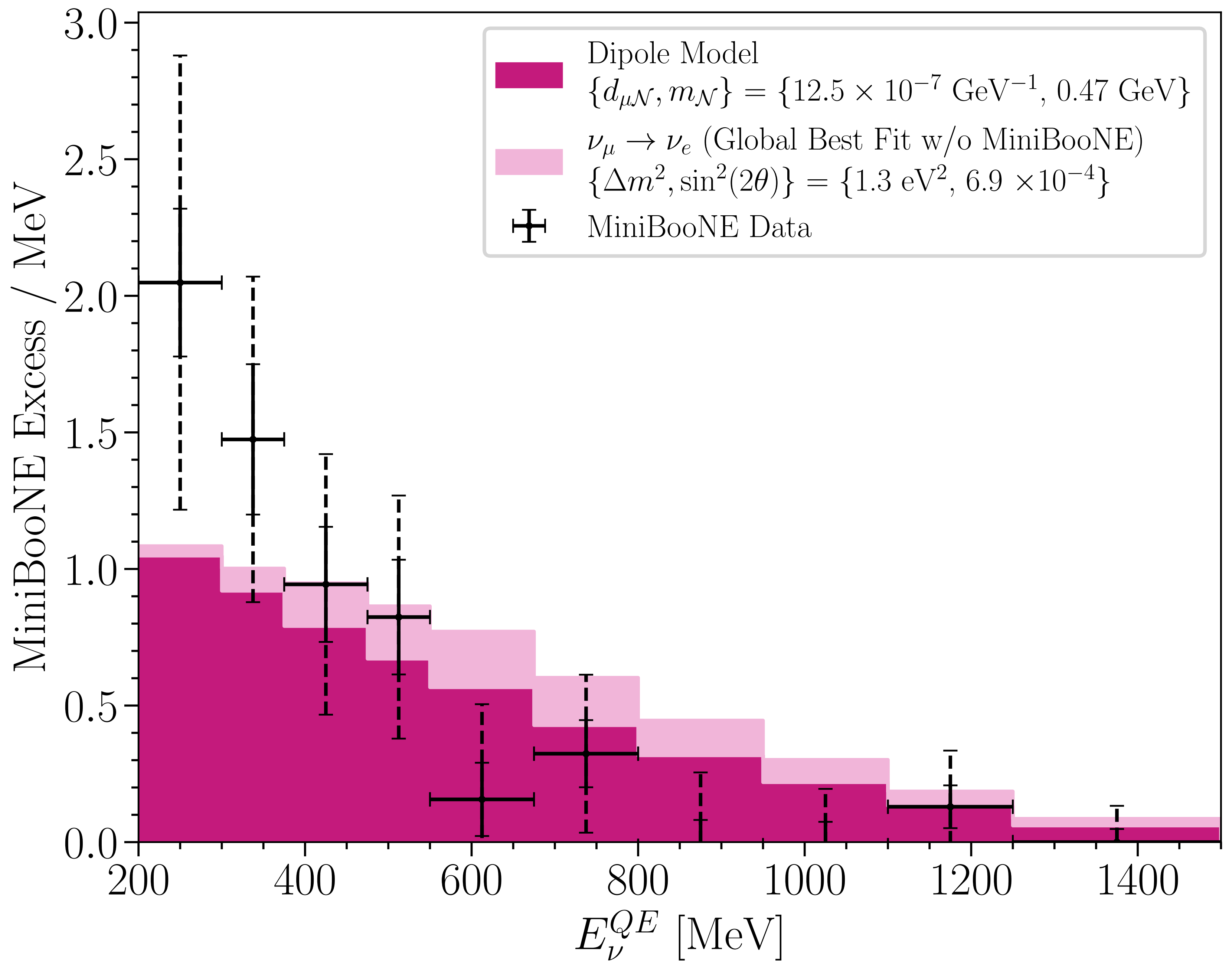
[1] Vergani, NK+ PRD 104, 095005 [2] A. Schneider, NK, A. Wen. 2024

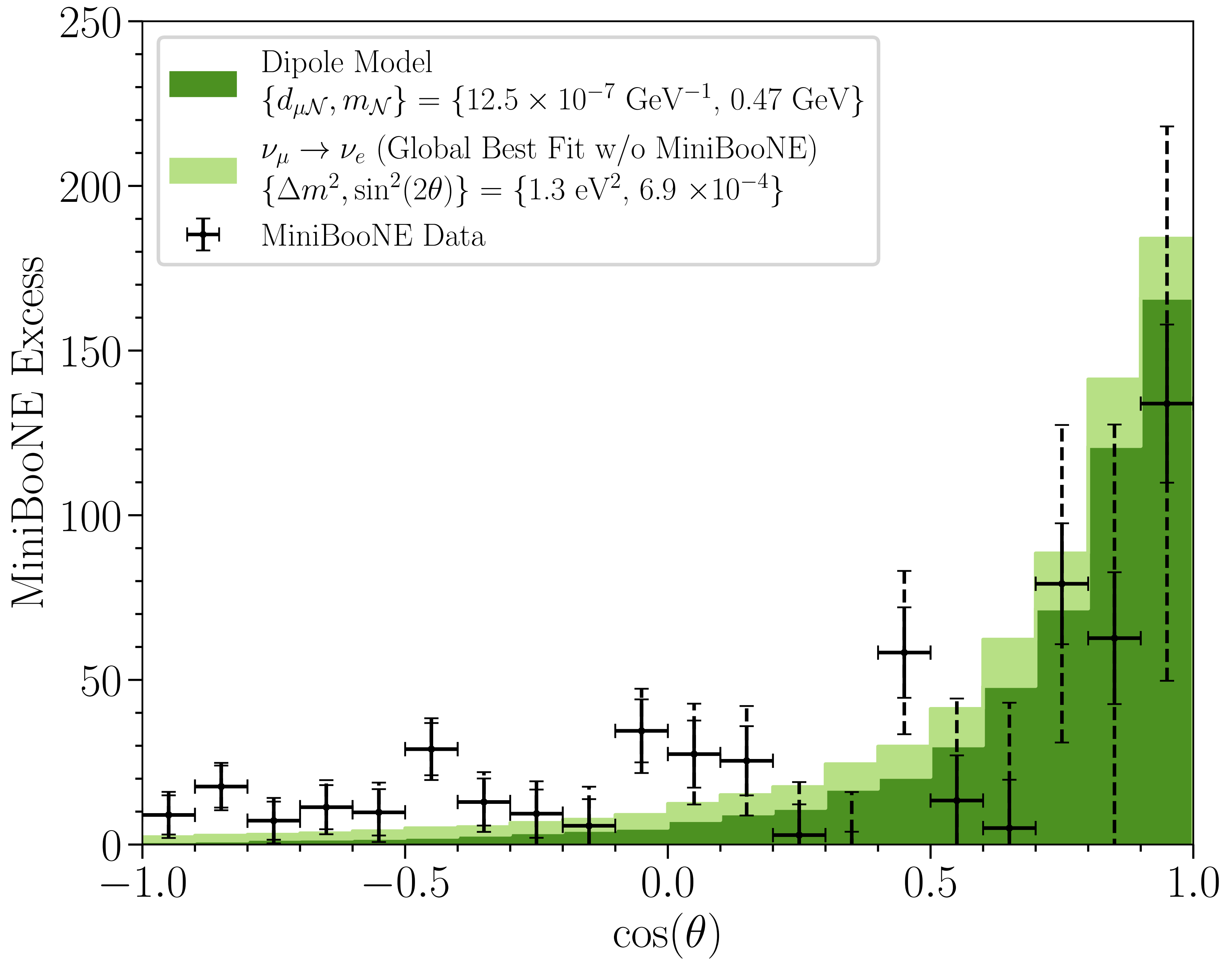
Illustration from J. Pairin

Dipole-portal HNLs @ MiniBooNE



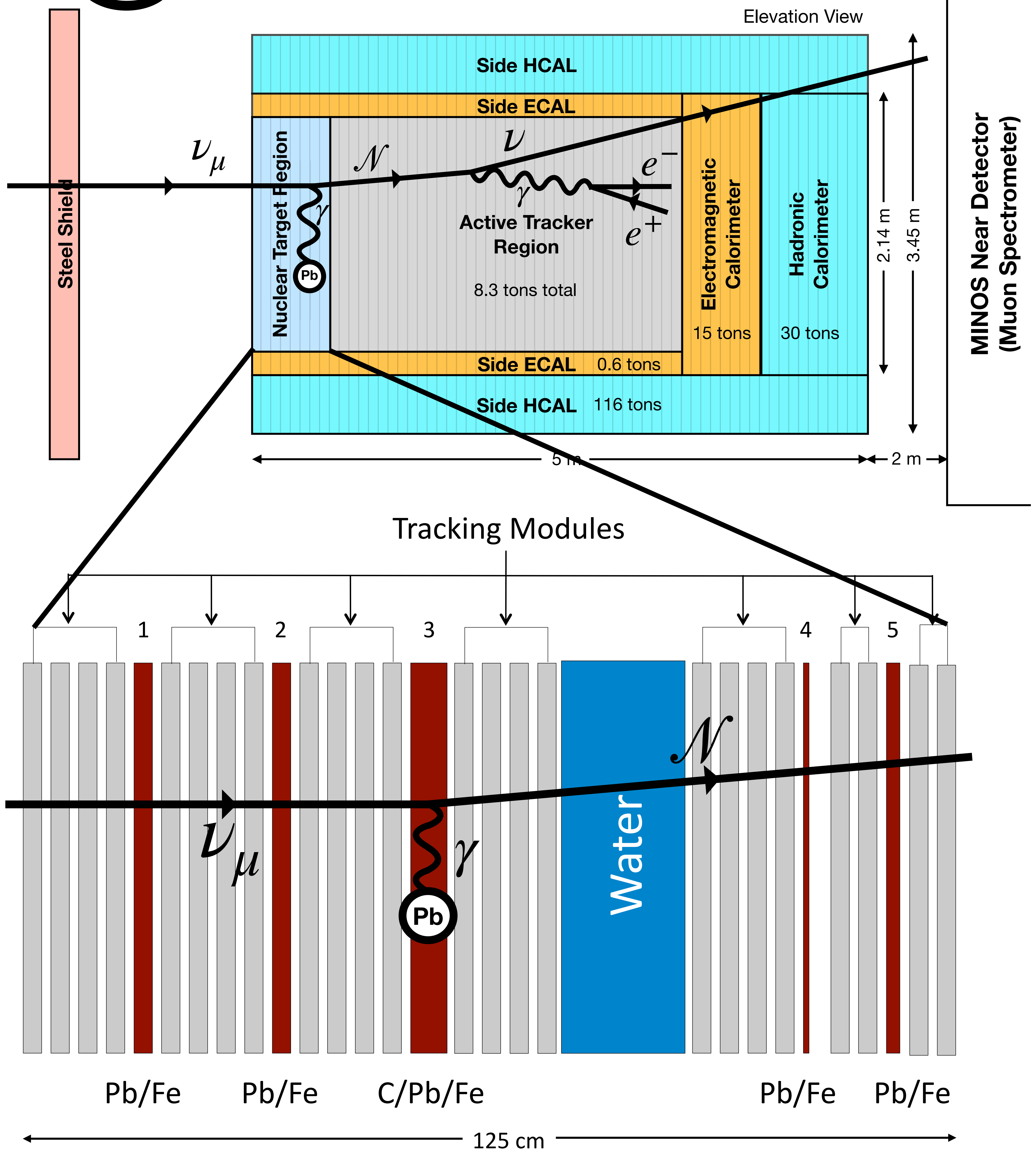
Kamp+ PRD 107, 055009

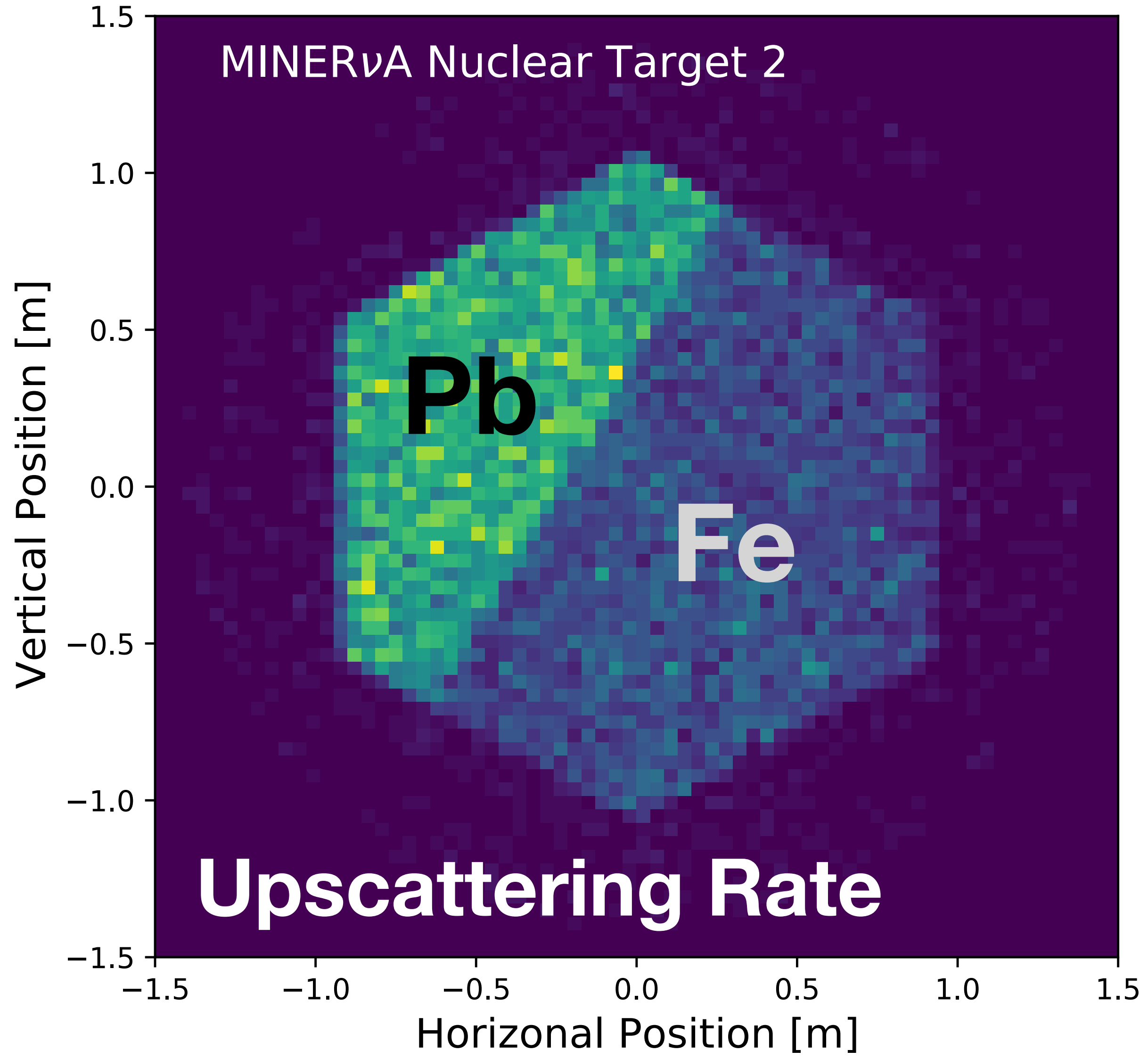


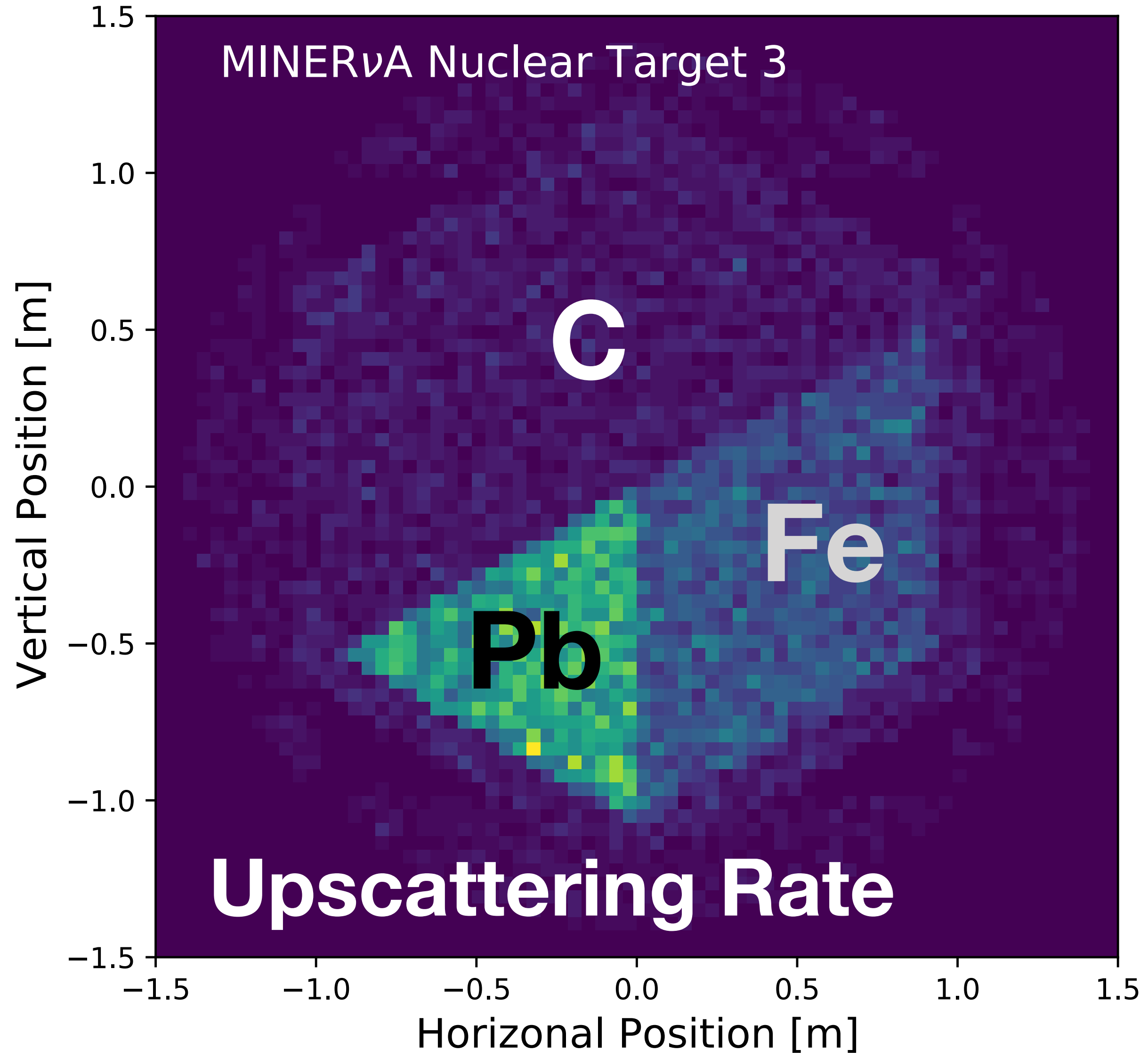


HNLs in Plastic @ MINERvA

- Single showers from dipole-portal HNL decays would show up in MINERvA neutrino-electron elastic scattering measurements [1]
- We simulate upscattering and decay in a realistic MINERvA detector using SIREN





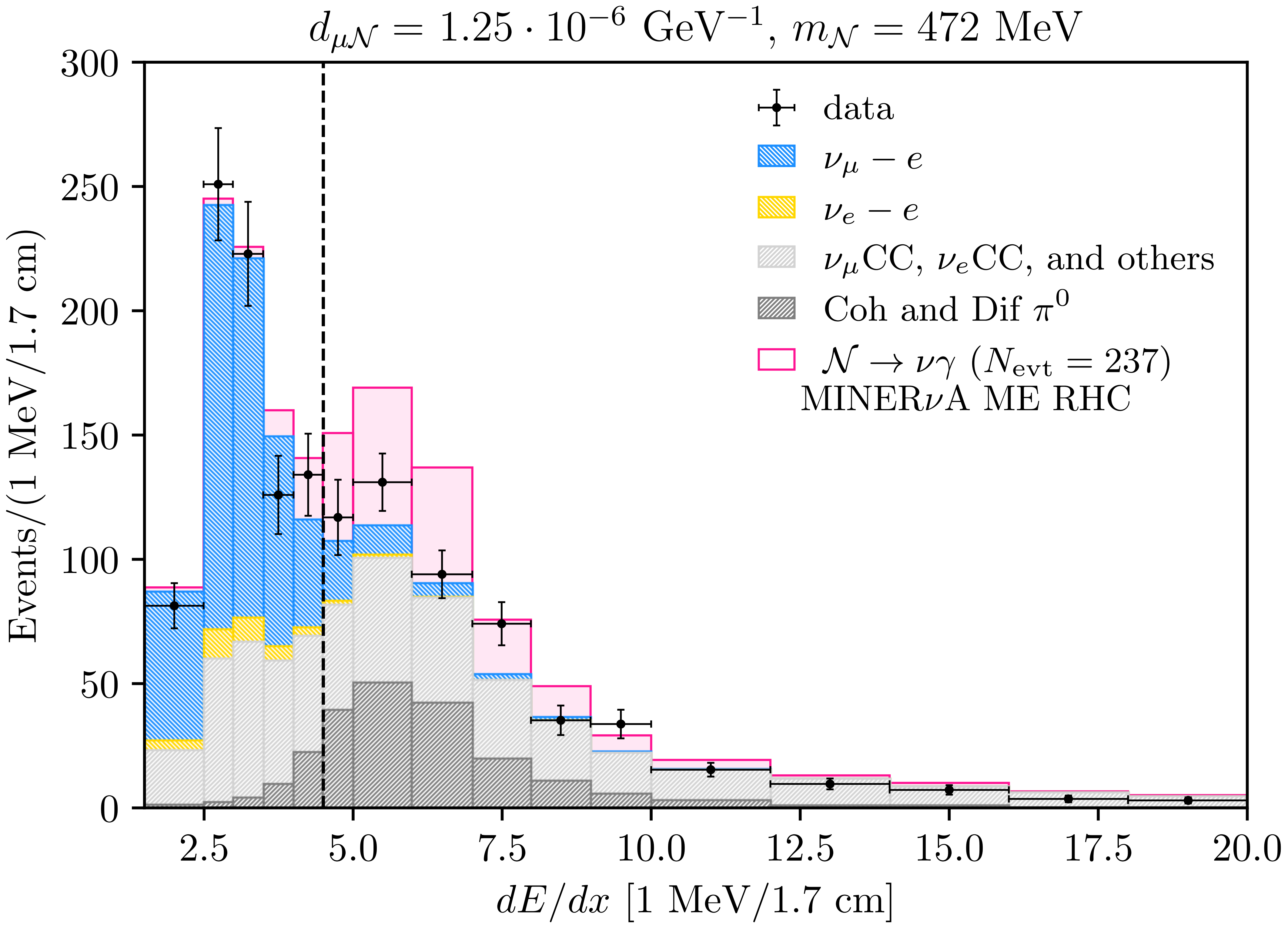


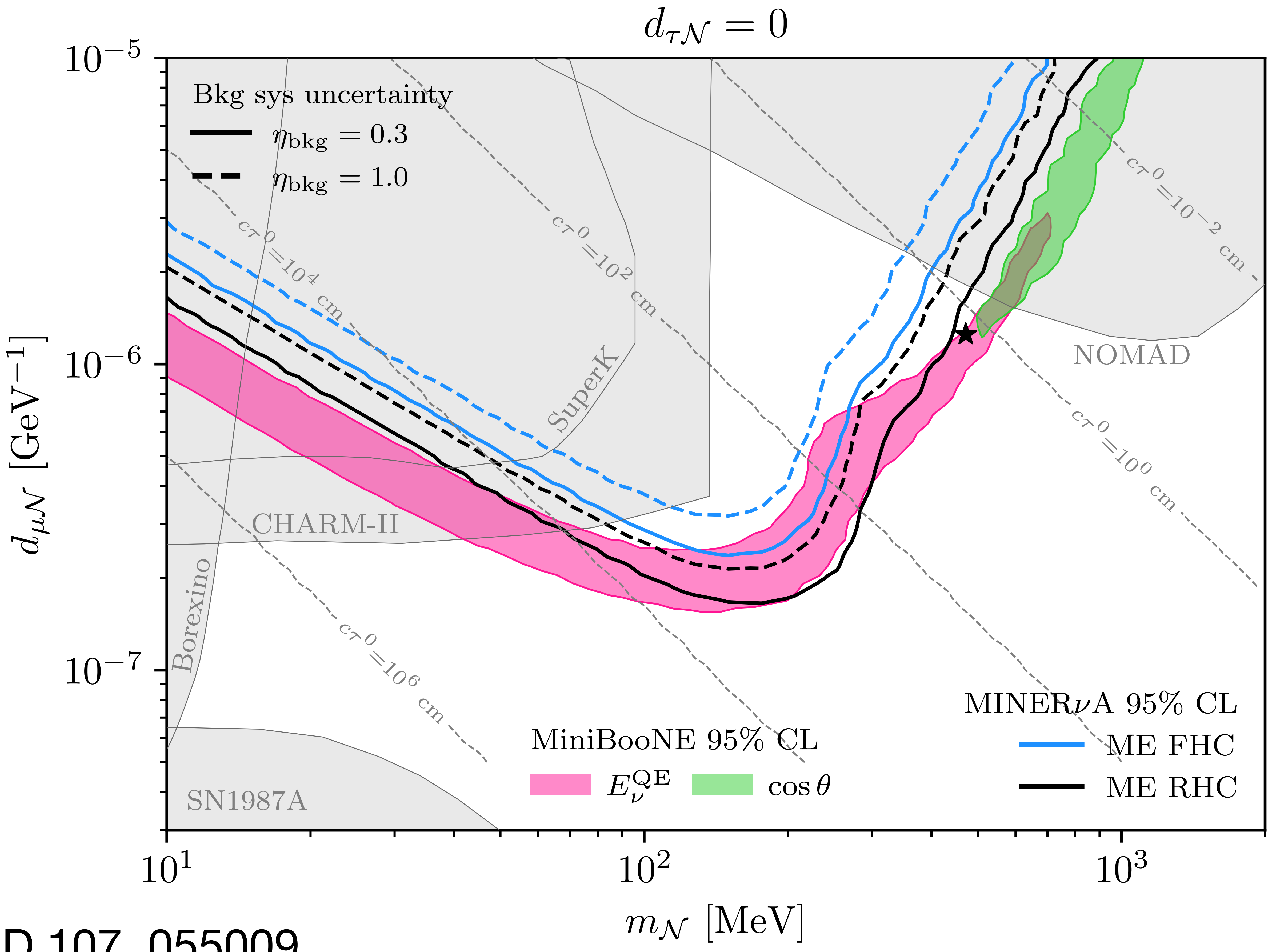
[1] MINERvA 2019

Kamp+ PRD 107, 055009

HNLs in Plastic @ MINERvA

- We use the high dE/dx sideband region to set constraints on dipole-portal HNLs
- Most stringent MINERvA constraints do not rule out the MiniBooNE-preferred region at the 95% CL





Kamp+ PRD 107, 055009

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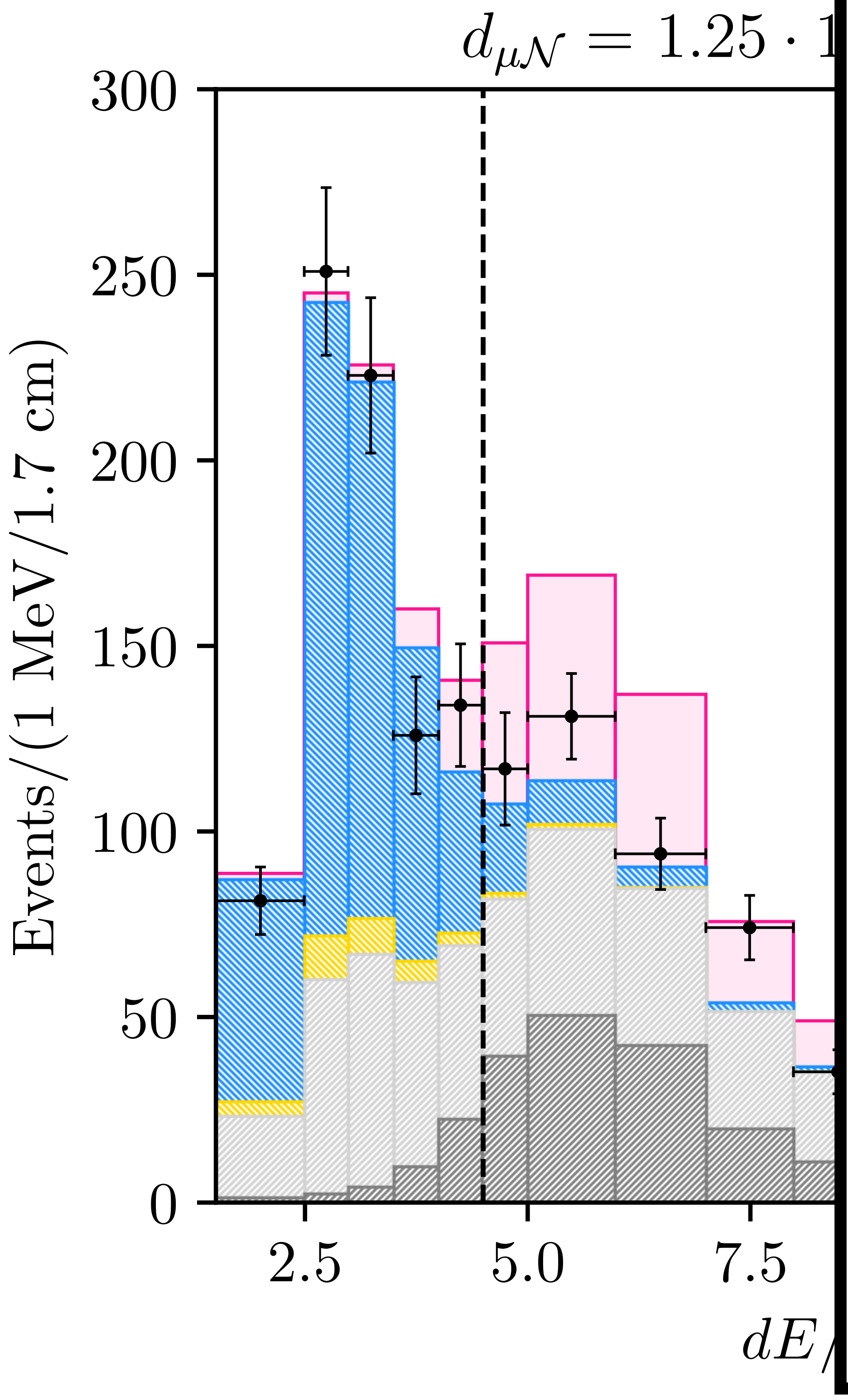
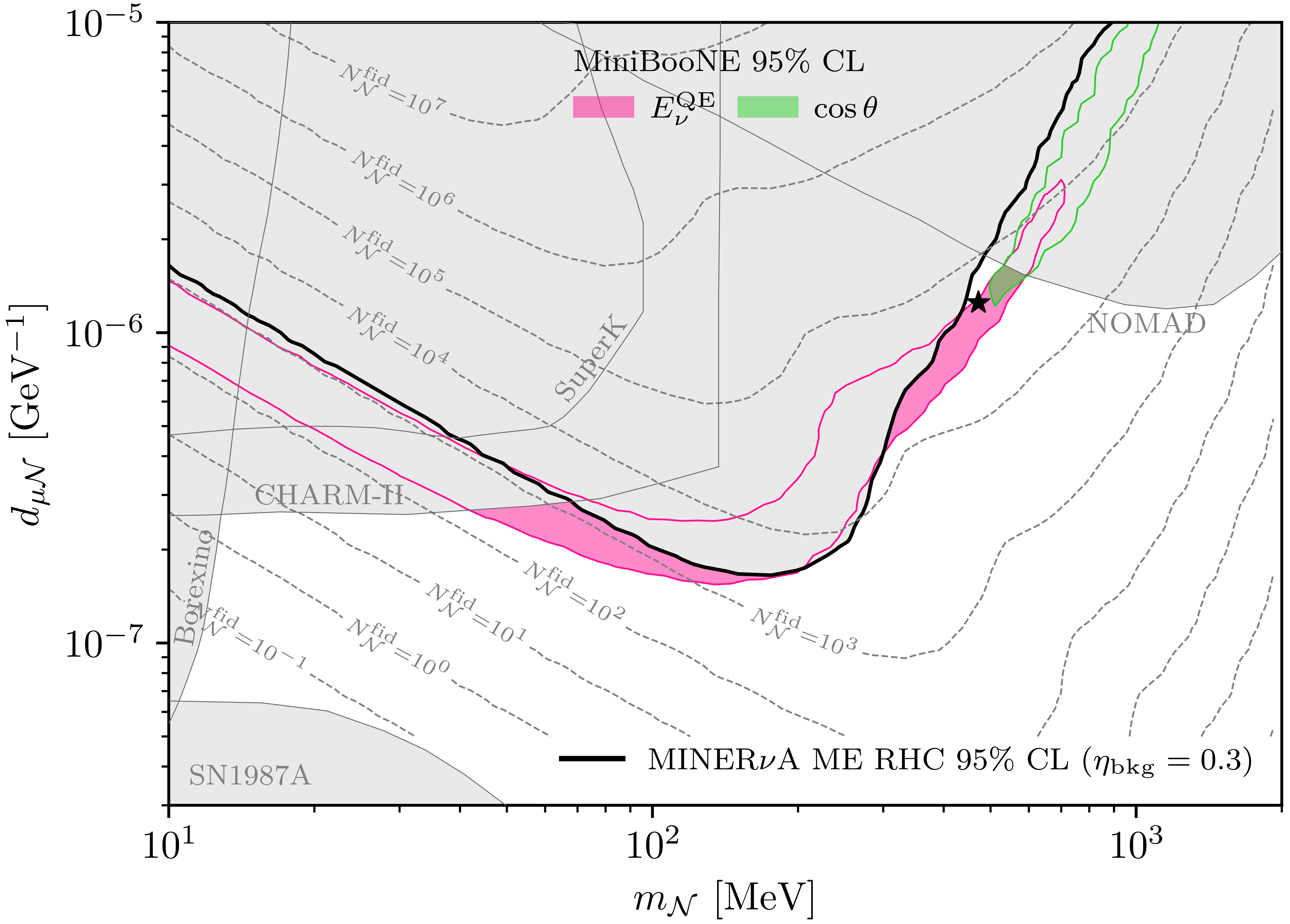
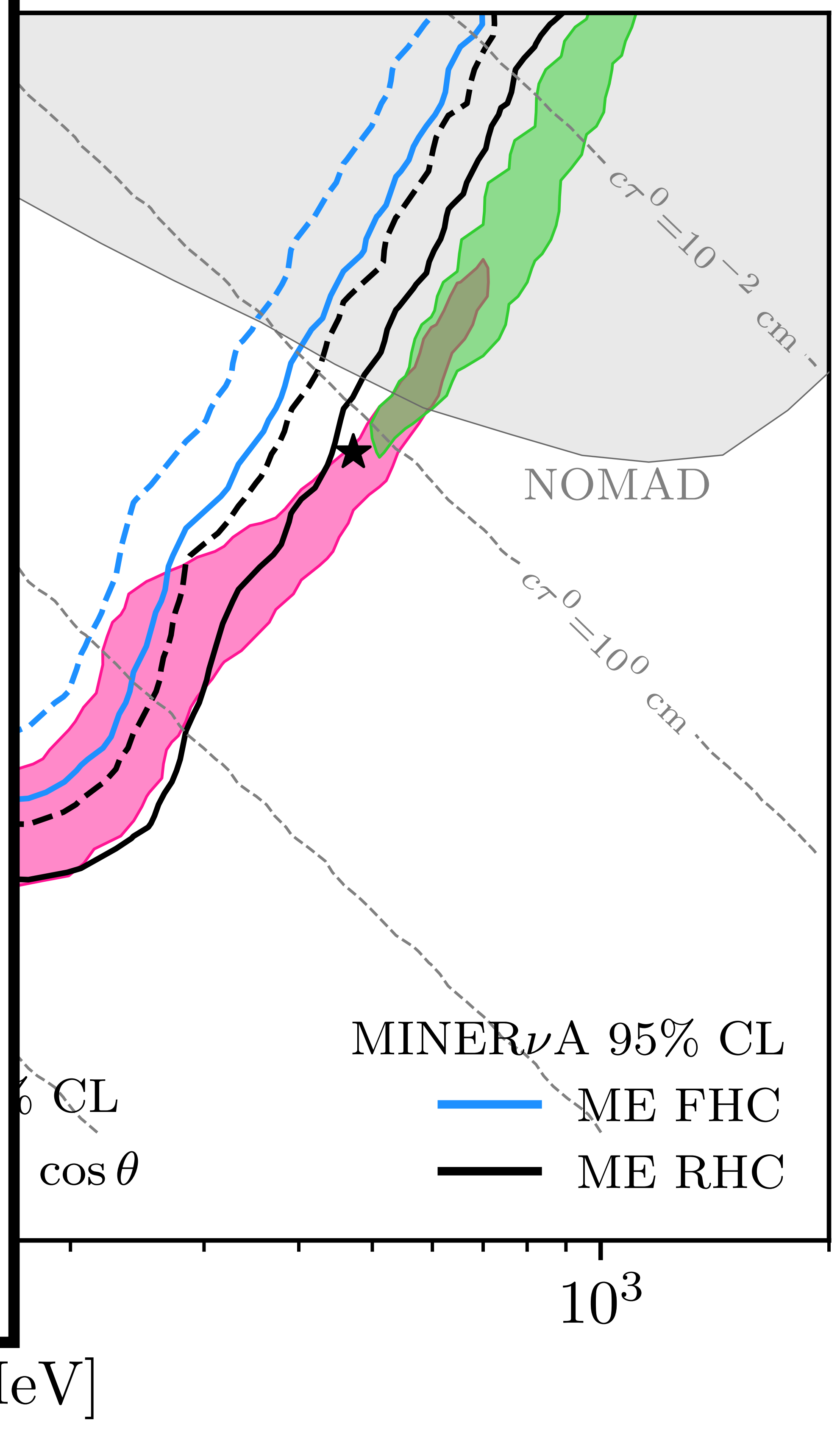




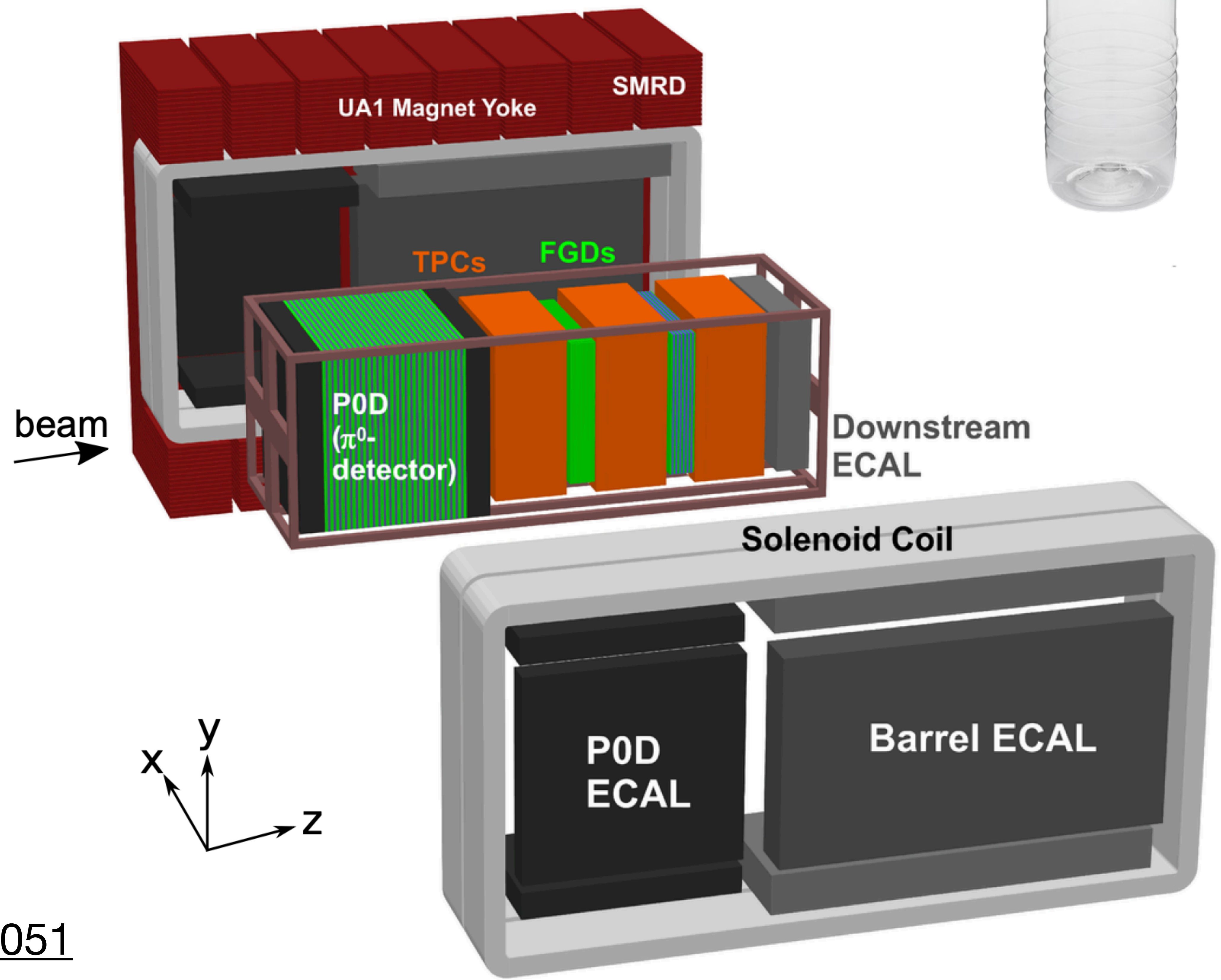
A dedicated MINERvA analysis would be able to make a strong statement here!



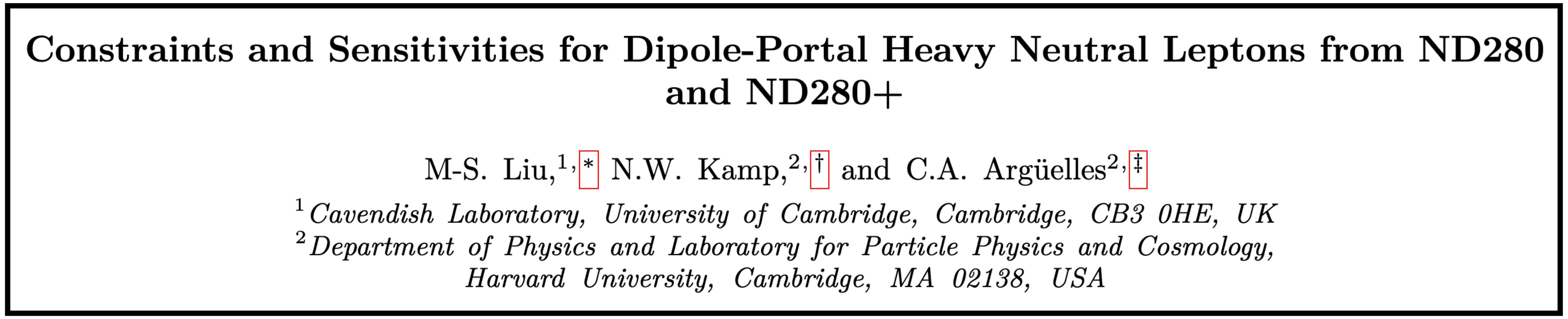
Kamp+ PRD 107, 055009

HNLs in Plastic @ ND280(+)

- ND280's gaseous time projection chambers (TPCs) have low single shower backgrounds
- T2K leveraged this to search for e^+e^- pairs from mass-mixed HNL decays [1]
- **We repurpose their results to set constraints on dipole-portal HNLs**



arXiv:2412.15051



Constraints and Sensitivities for Dipole-Portal Heavy Neutral Leptons from ND280 and ND280+

M-S. Liu,[1,*] N.W. Kamp,[2,†] and C.A. Argüelles[2,‡]
[1] *Cavendish Laboratory, University of Cambridge, Cambridge, CB3 0HE, UK*
[2] *Department of Physics and Laboratory for Particle Physics and Cosmology,*
Harvard University, Cambridge, MA 02138, USA

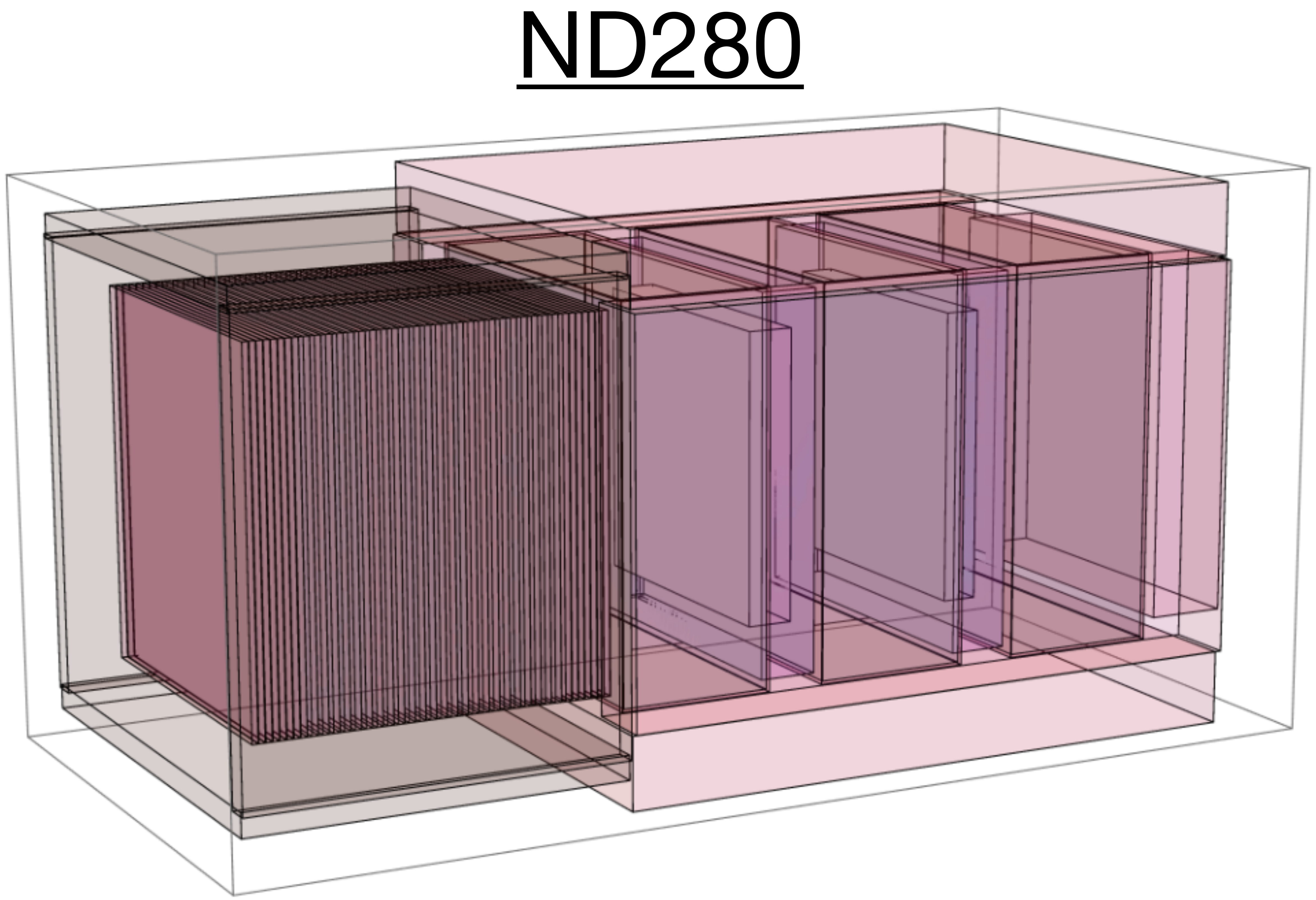
M-S. Liu

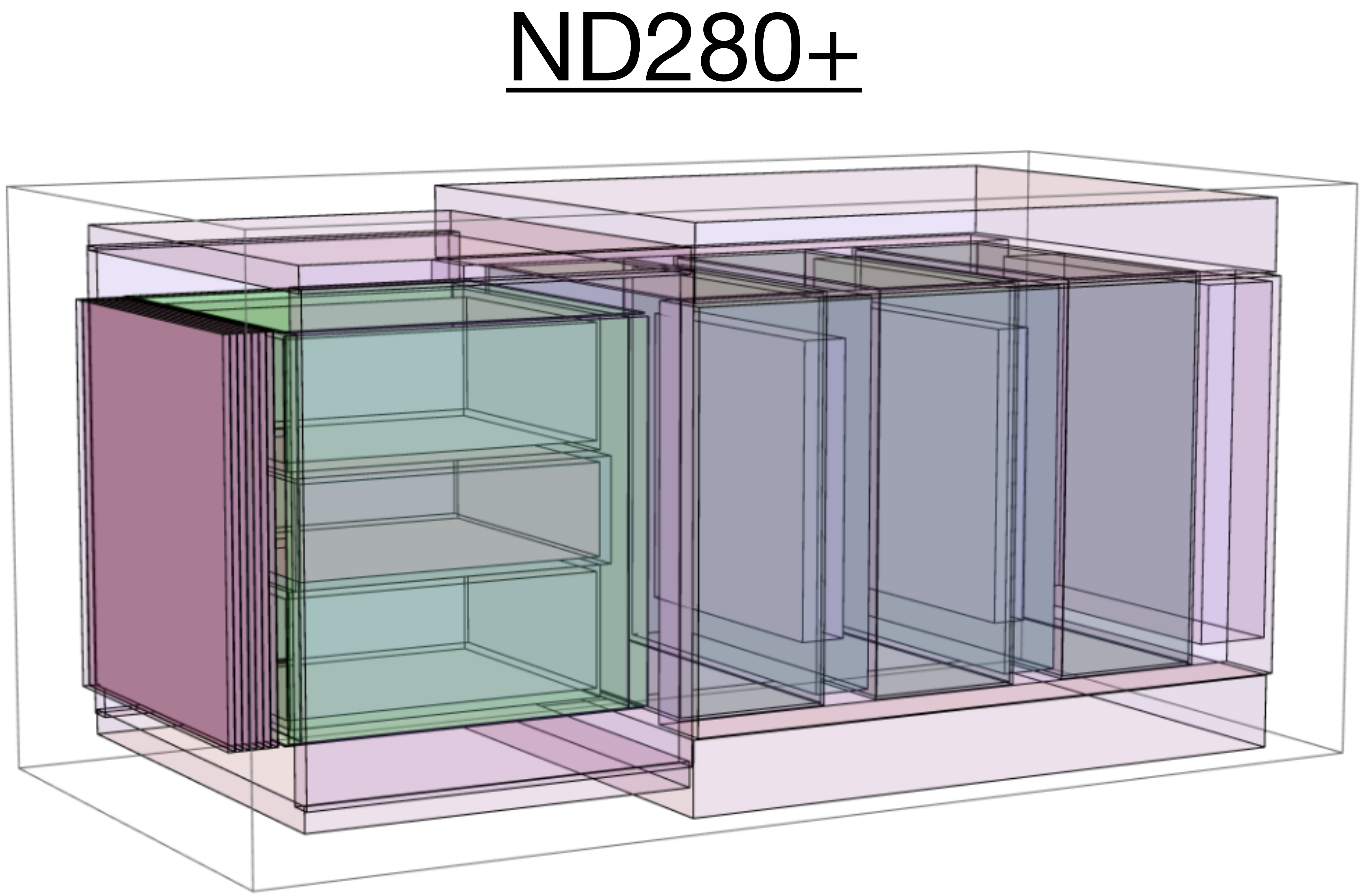
[1] T2K 2019

M. Lamoureux thesis

HNLs in Plastic @ ND280(+)

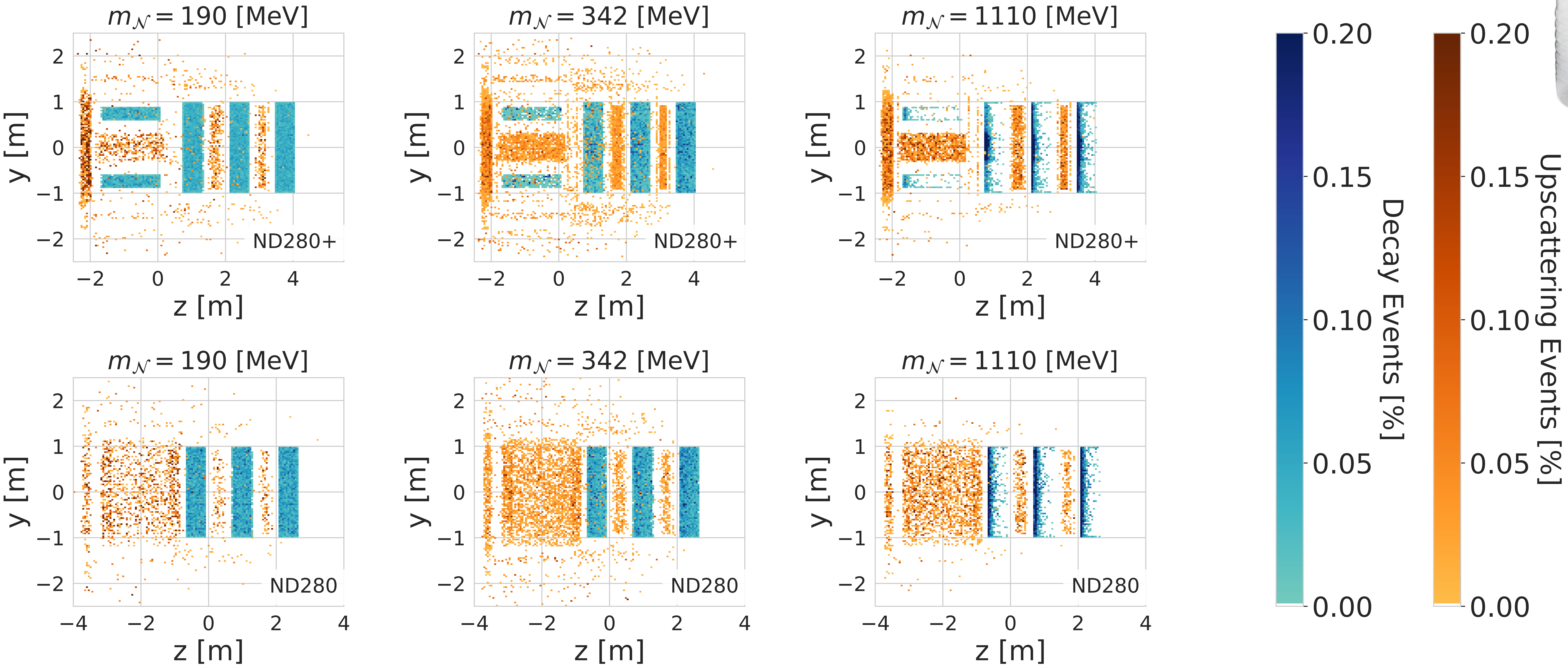
3D rendering of our SIREN-based implementation of the nominal and upgraded ND280 detector





M-S Liu, NK, C. Argüelles 2024

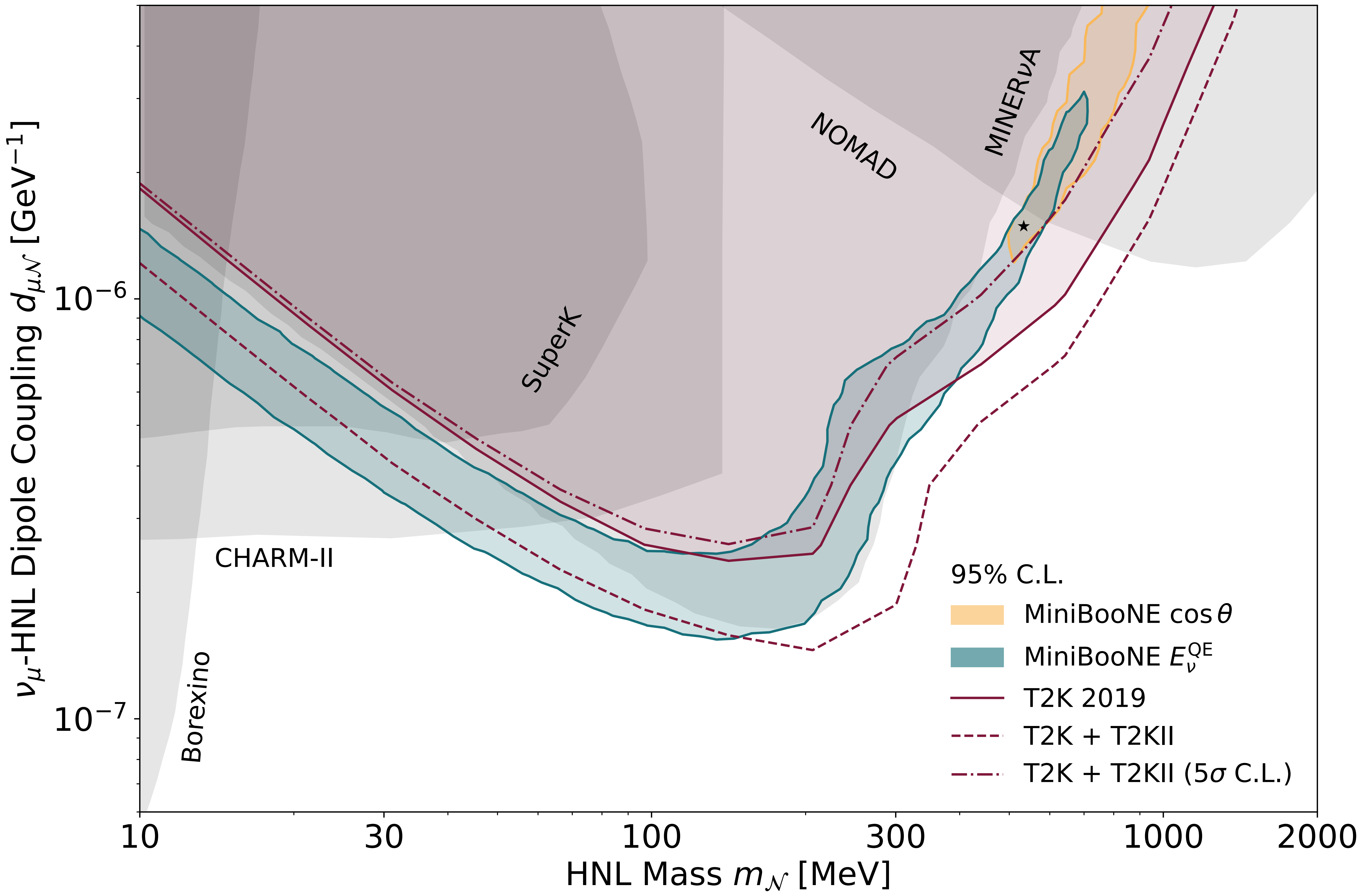
HNLs in Plastic @ ND280(+)



$$\Gamma_{\mathcal{N}\to\nu\gamma} \propto m_{\mathcal{N}}^{3}$$

M-S Liu, NK, C. Argüelles 2024

HNLs in Plastic @ ND280(+)



The 2019 T2K search observes zero e^+e^- pairs in the ND280 gas TPCs, constraining the region of parameter space preferred by MiniBooNE

The addition of three years of ND280 upgrade data will further improve the sensitivity

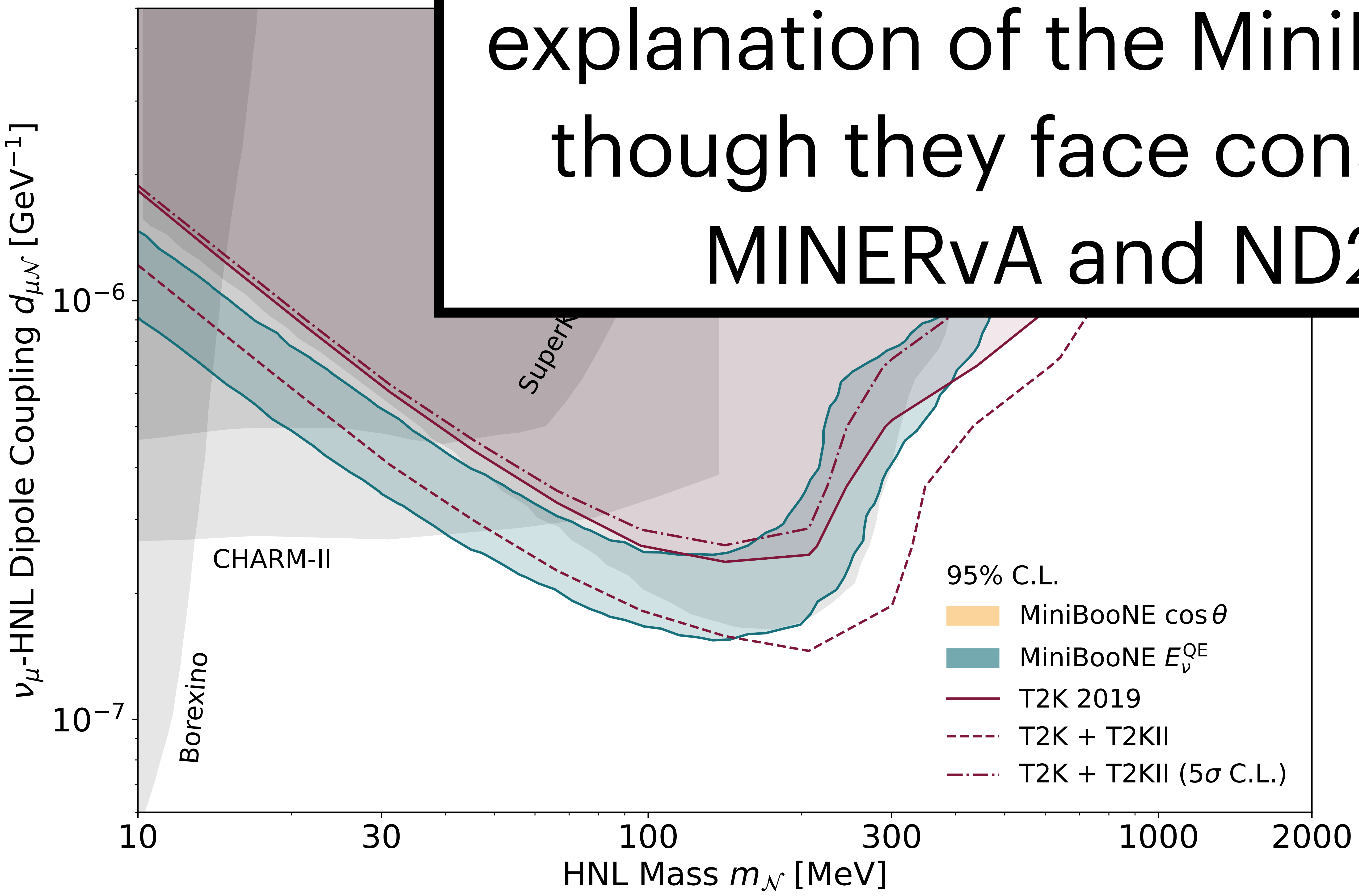
Caveat: these constraints assume the same efficiency for tagging mass-mixed and dipole-portal HNL decays

M-S Liu, NK, C. Argüelles 2024

H +)

Takeaway:

Dipole-portal HNLs are a promising explanation of the MiniBooNE excess, though they face constraints from MINERvA and ND280 data



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M-S Liu, NK, C. Argüelles 2024

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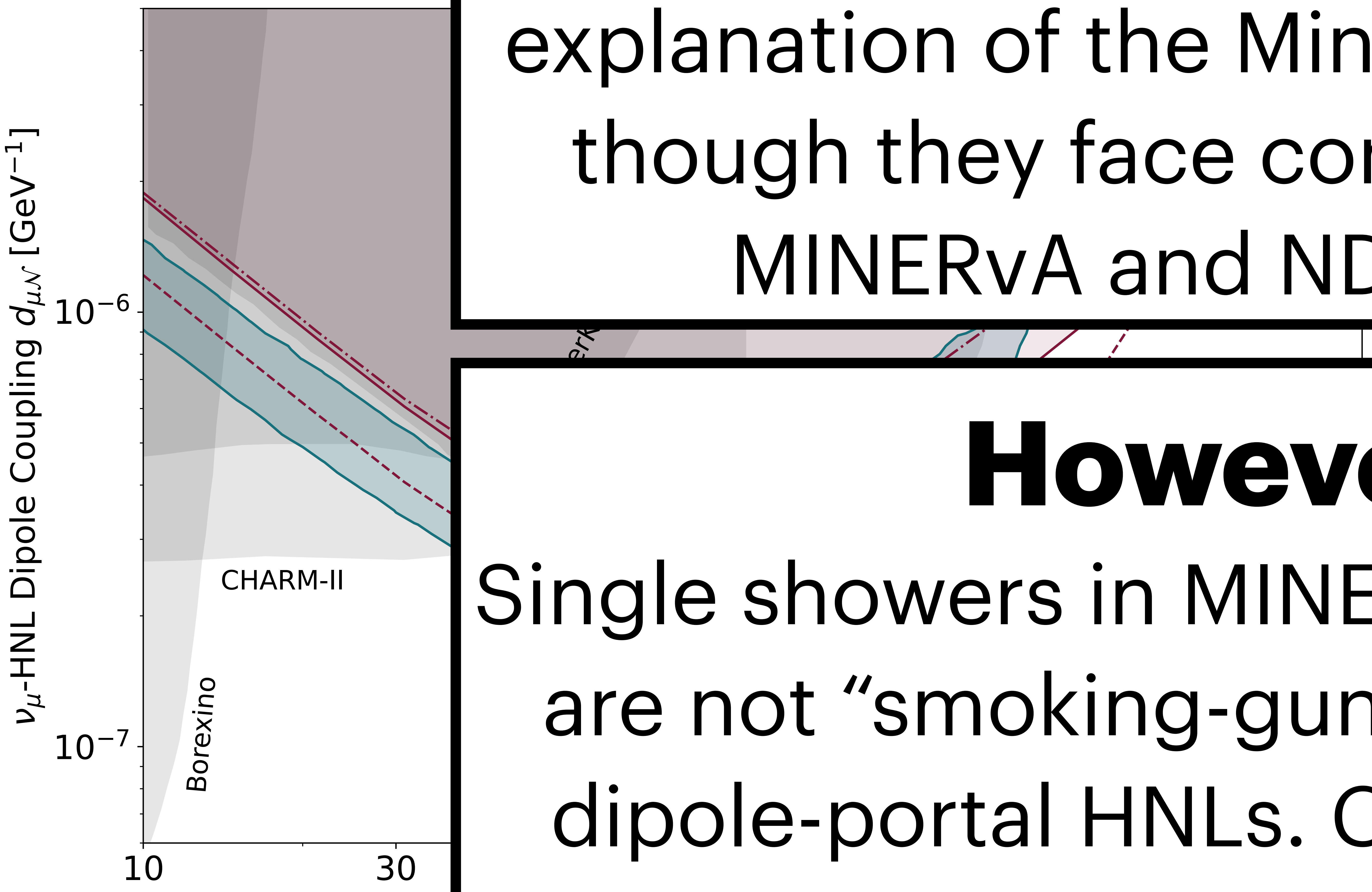

Takeaway:

Dipole-portal HNLs are a promising explanation of the MiniBooNE excess, though they face constraints from MINERvA and ND280 data

However:

Single showers in MINERvA and ND280 are not “smoking-gun” evidence for dipole-portal HNLs. Can we make a more compelling search elsewhere?

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M-S Liu, NK, C. Argüelles 2024

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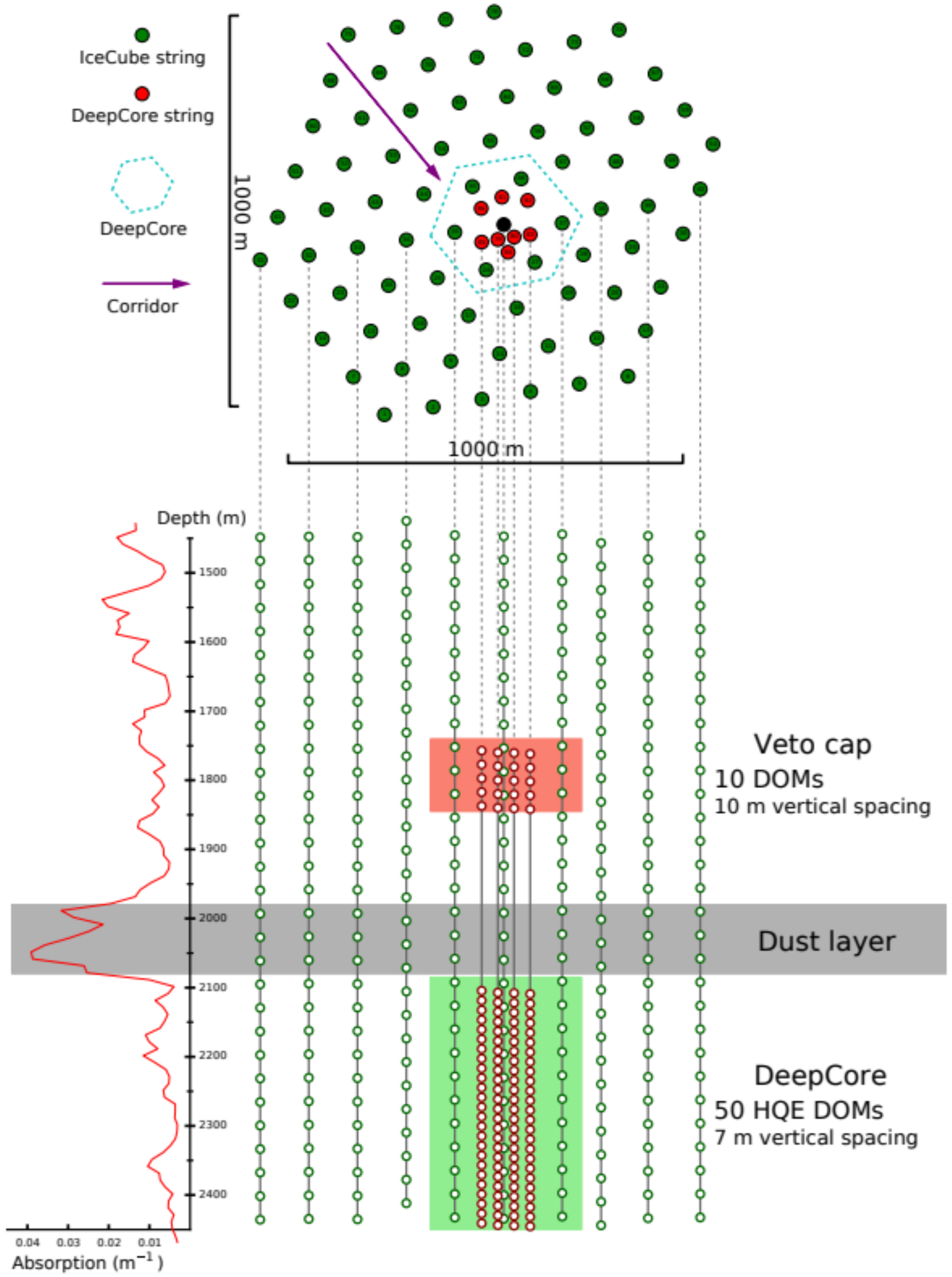
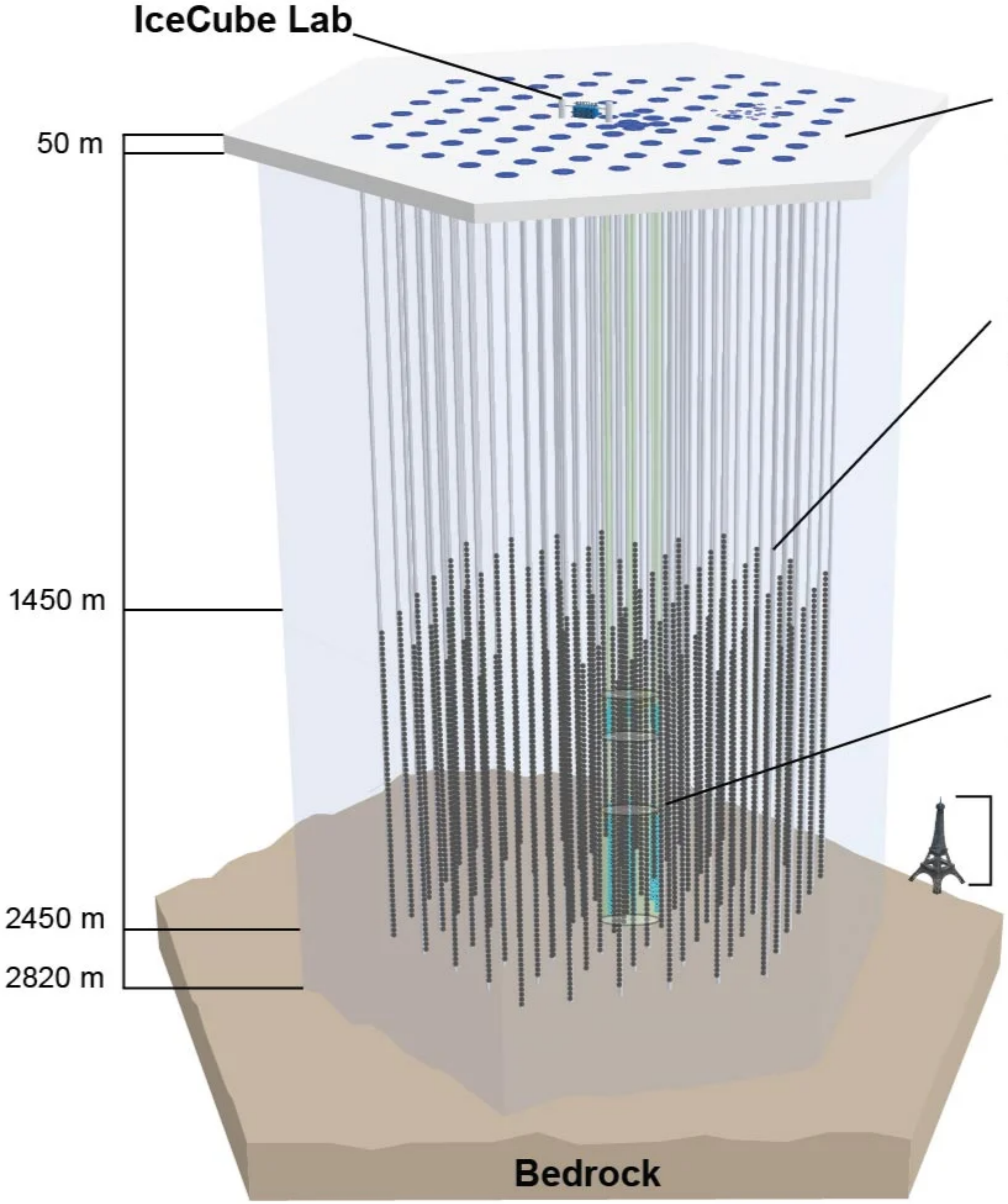
2. **Heavy neutrinos in plastic:** constraints on a promising MiniBooNE solution
3. **Heavy neutrinos in ice and water:** searches at neutrino telescopes
4. **Heavy neutrinos (and more) in water and rock:** new detectors for collider neutrinos

The IceCube Detector



Veto cap
10 DOMs
10 m vertical spacing

DeepCore
50 HQE DOMs
7 m vertical spacing



IceTop
81 stations
324 optical sensors

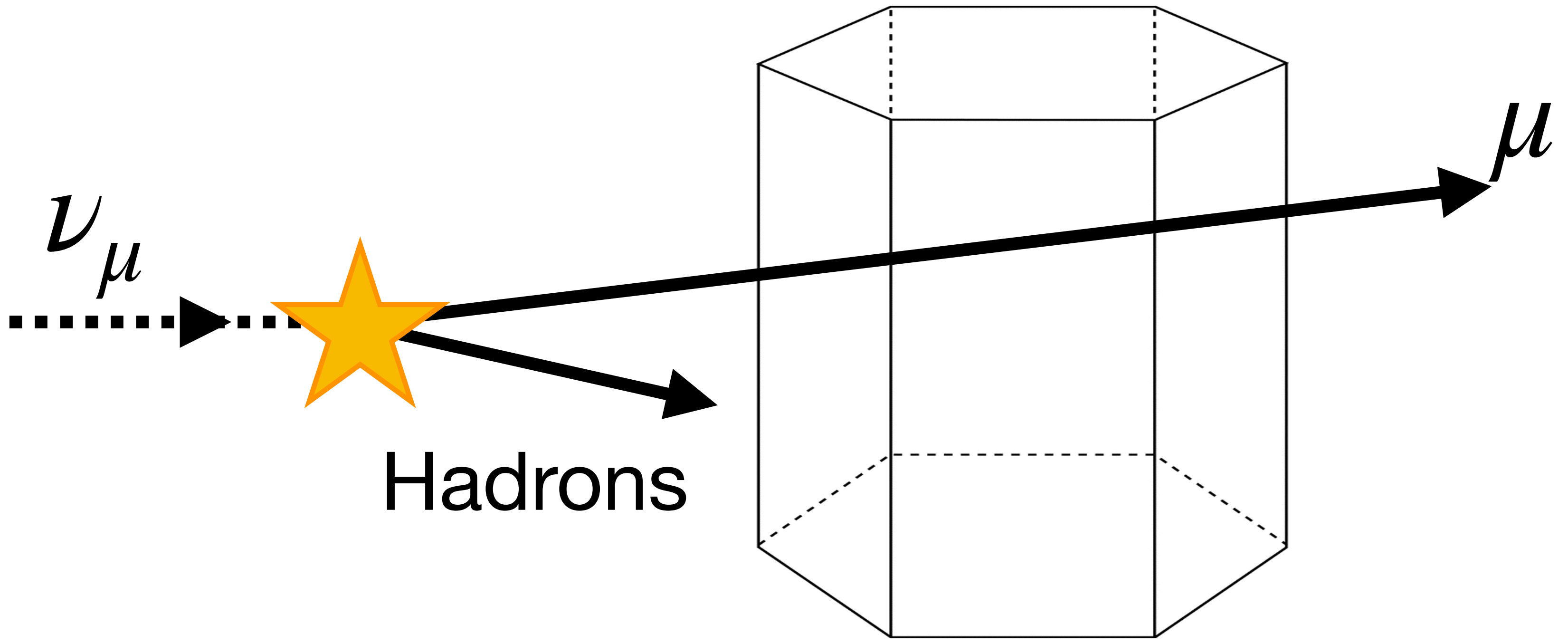
IceCube Array
86 strings including 8 DeepCore strings
5160 optical sensors

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

Eiffel Tower
324 m

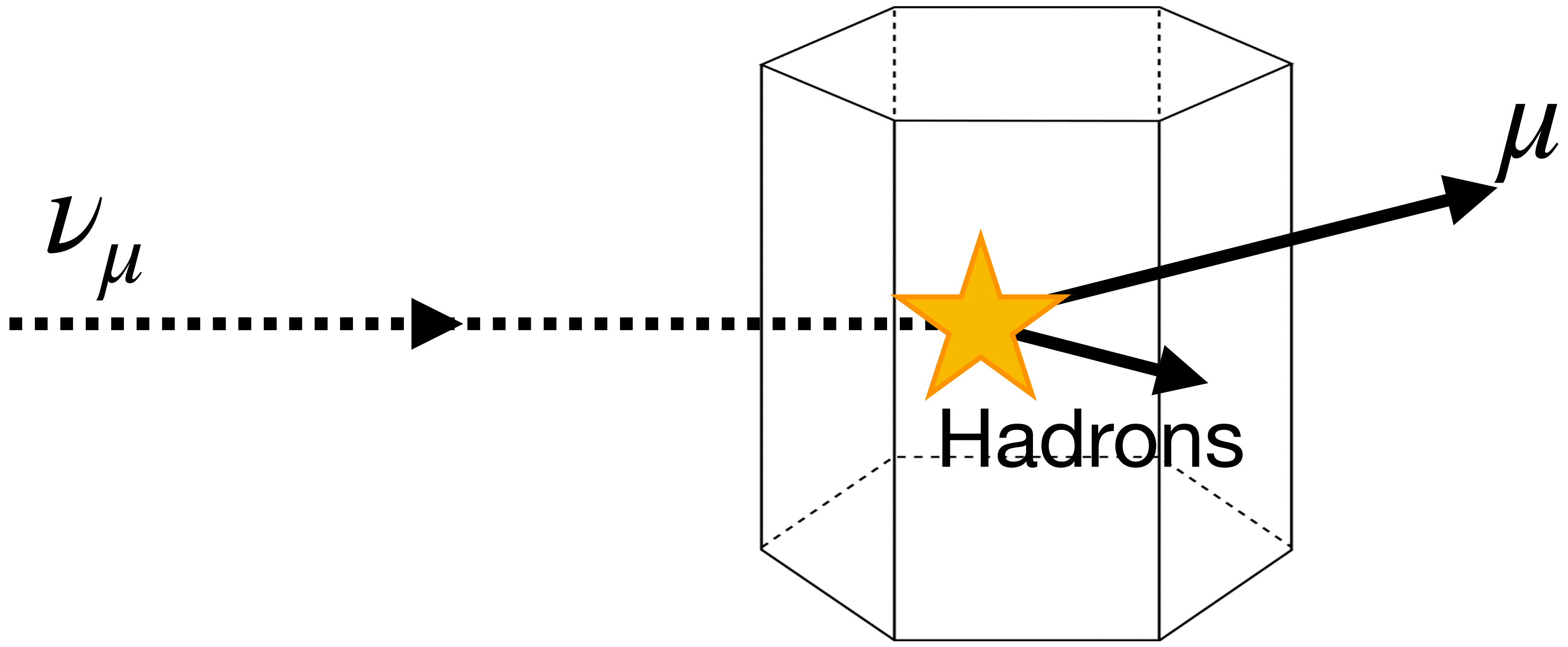
Quanta 2023

IceCube Event Categories



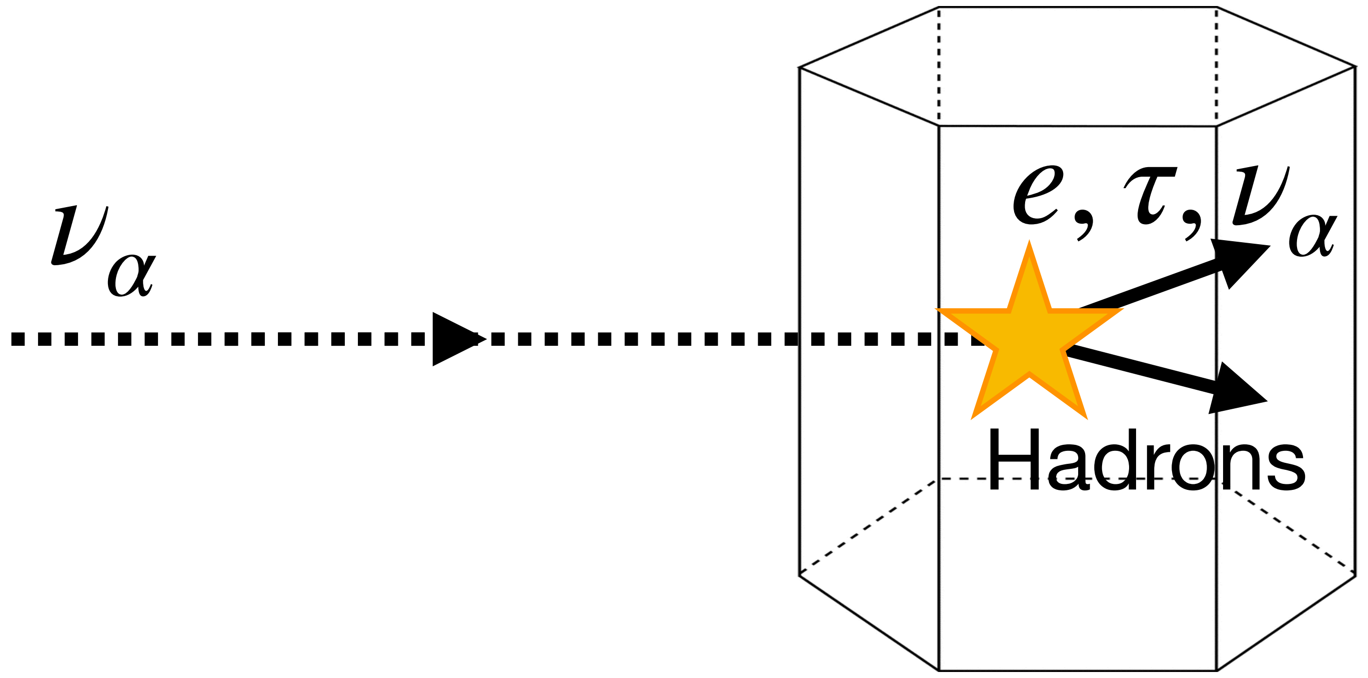
<u>"Through-going track"</u>

ν_μ charged-current DIS outside the active volume



<u>"Starting track"</u>

ν_μ charged-current DIS inside the active volume

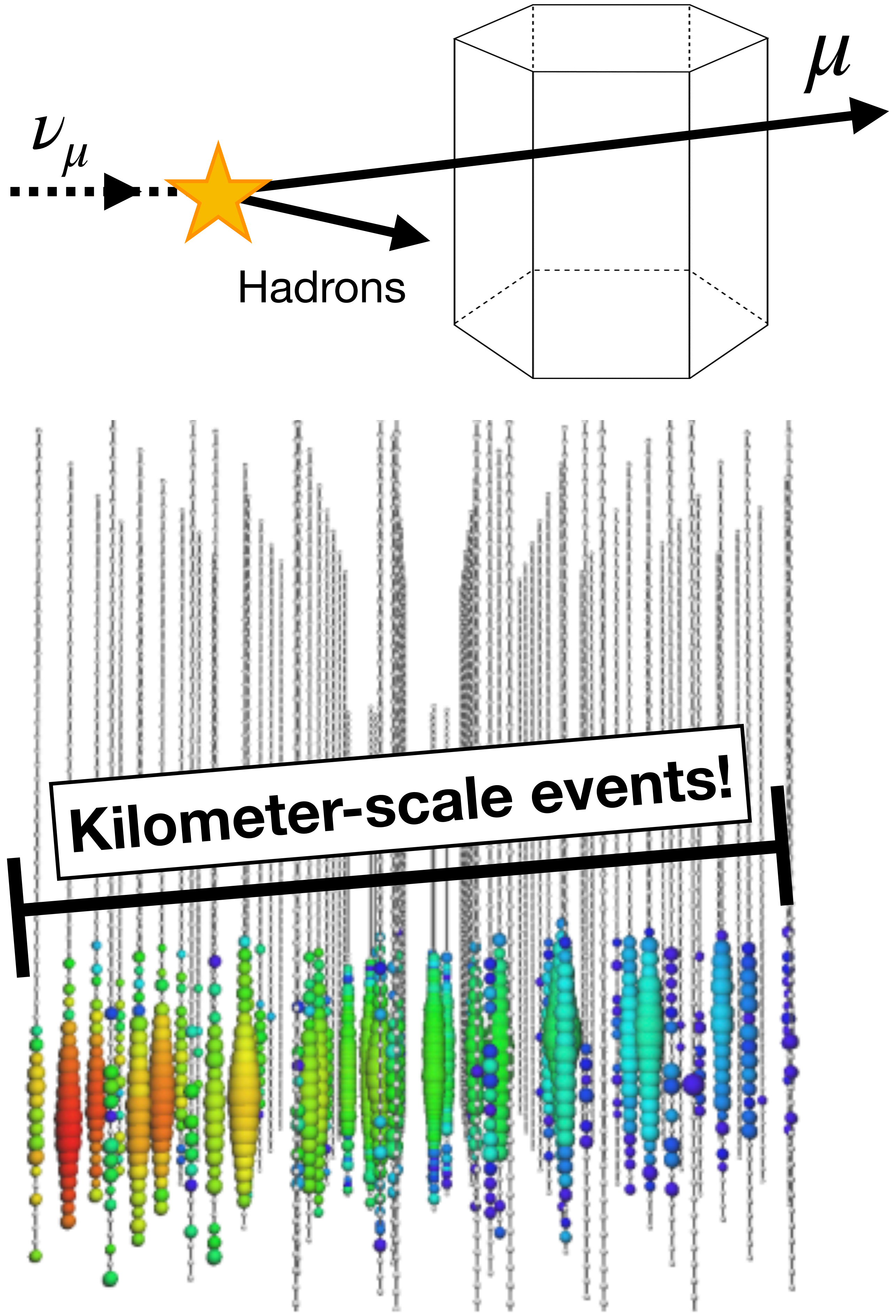


<u>"Cascade"</u>

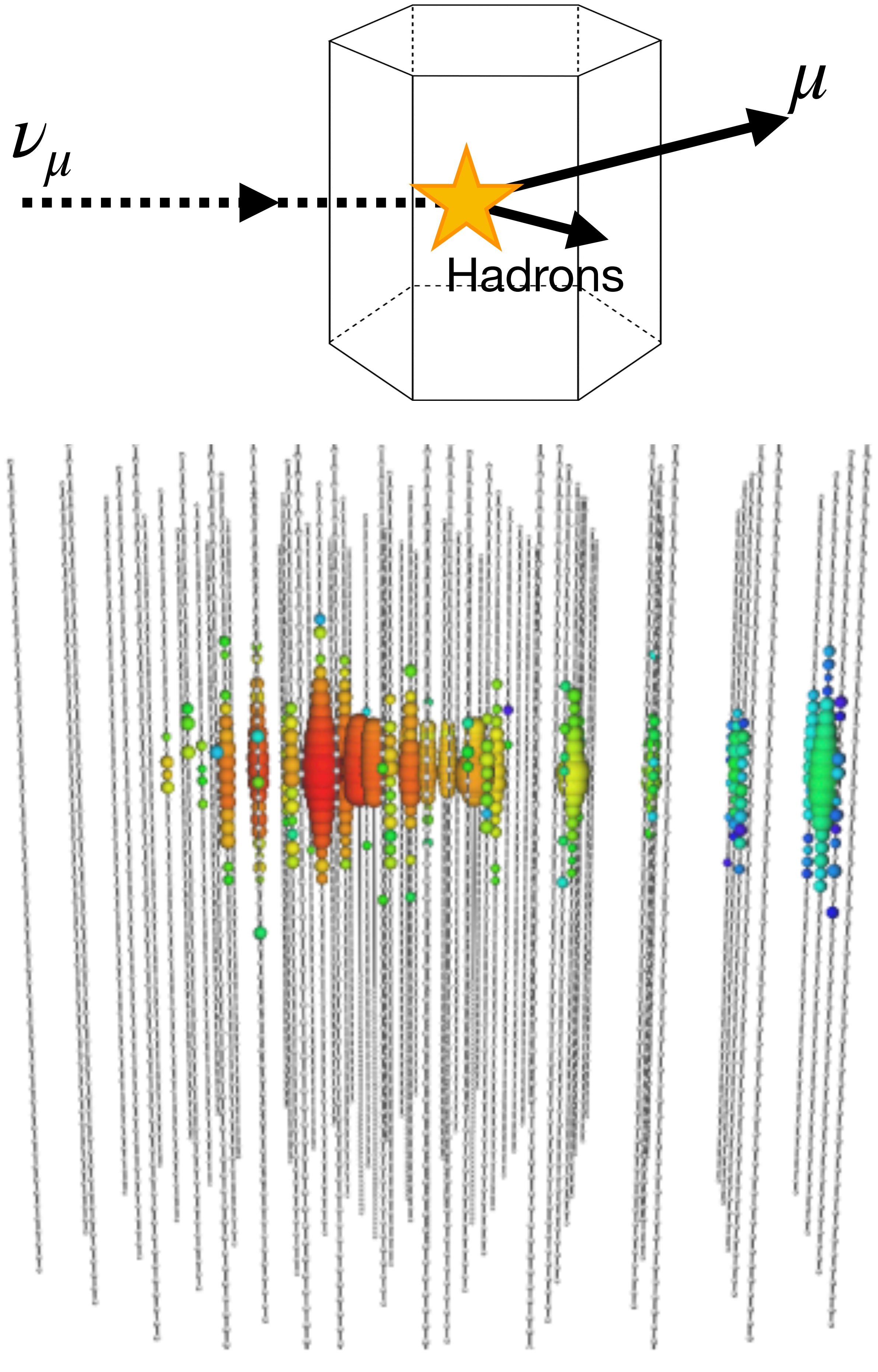
$\nu_{e,\tau}$ charged-current DIS or ν_α neutral-current DIS inside the active volume

IceCube Event Categories

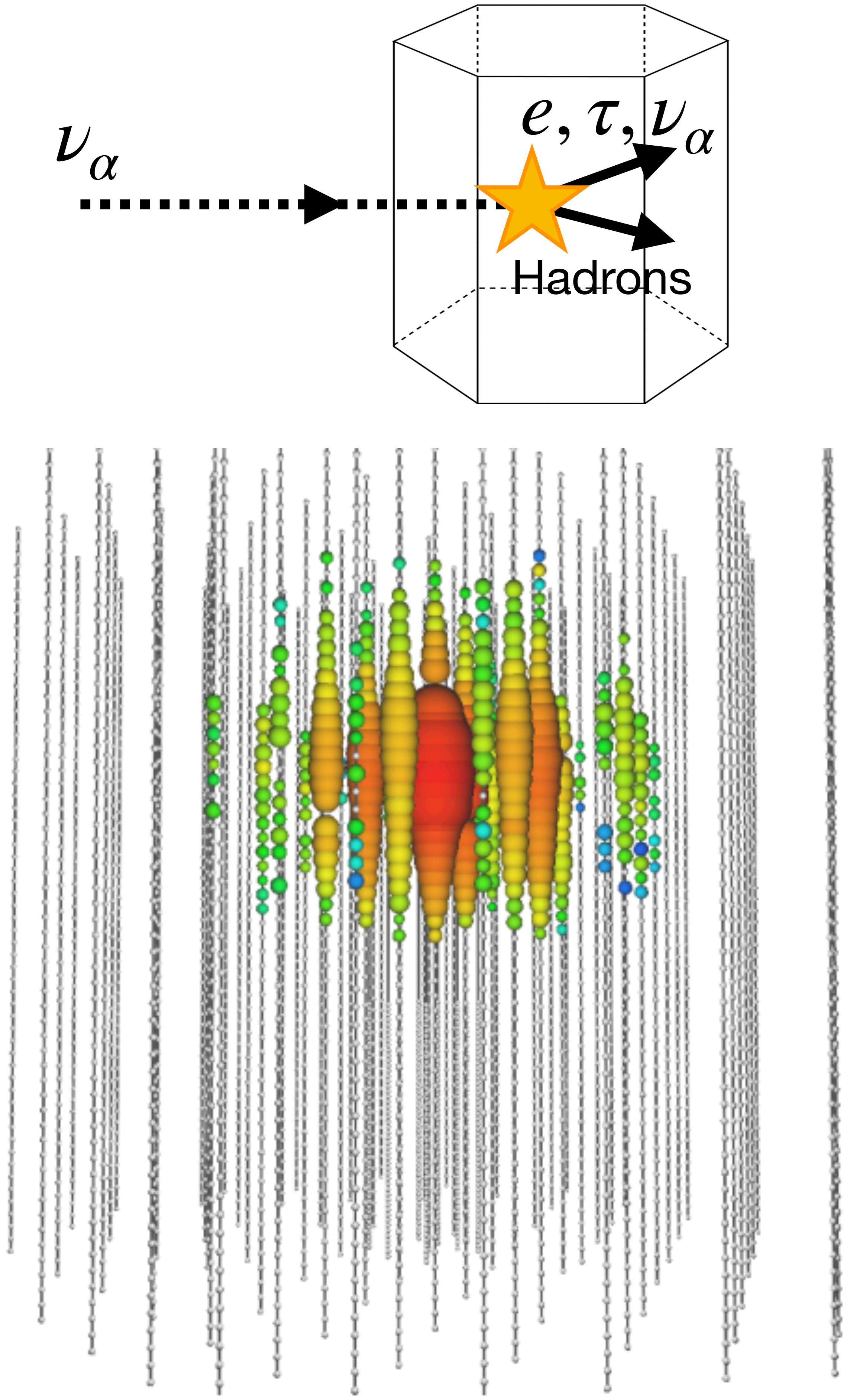
Through-going track



Starting track



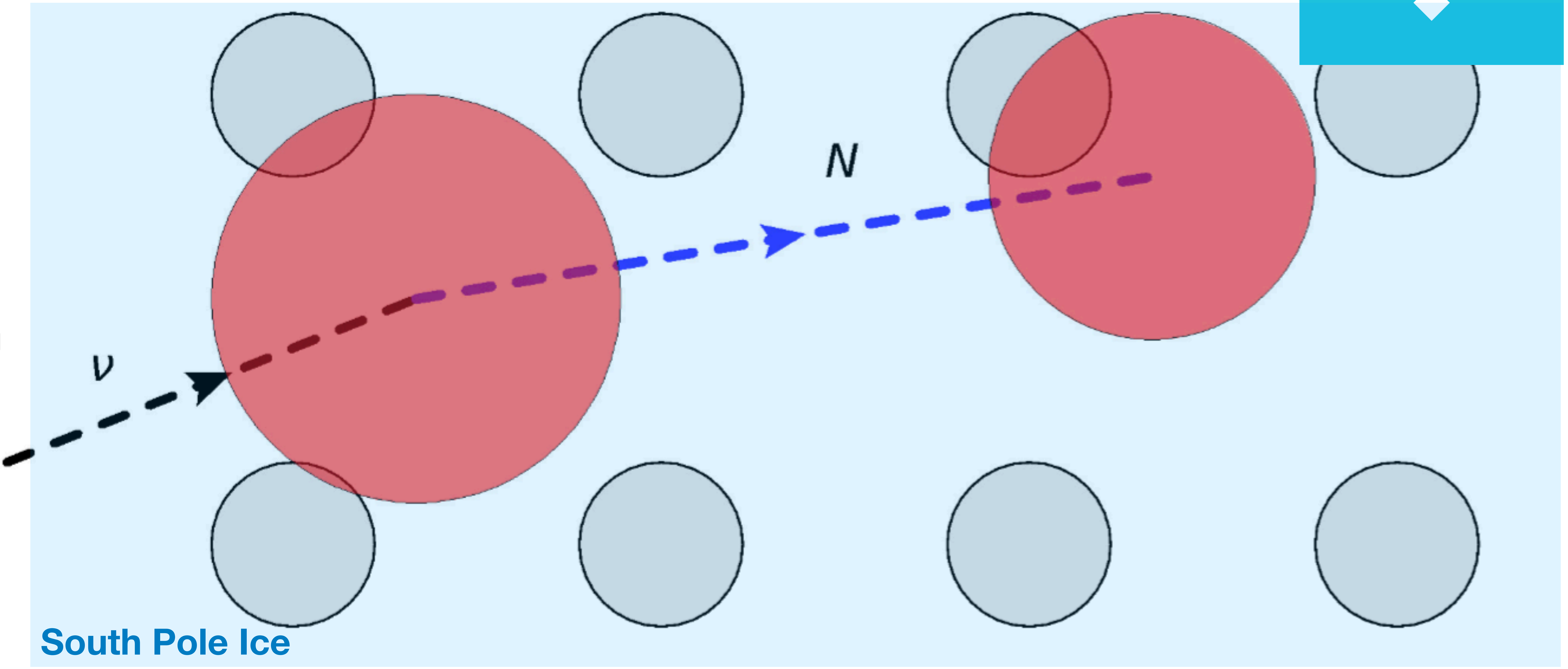
Cascade

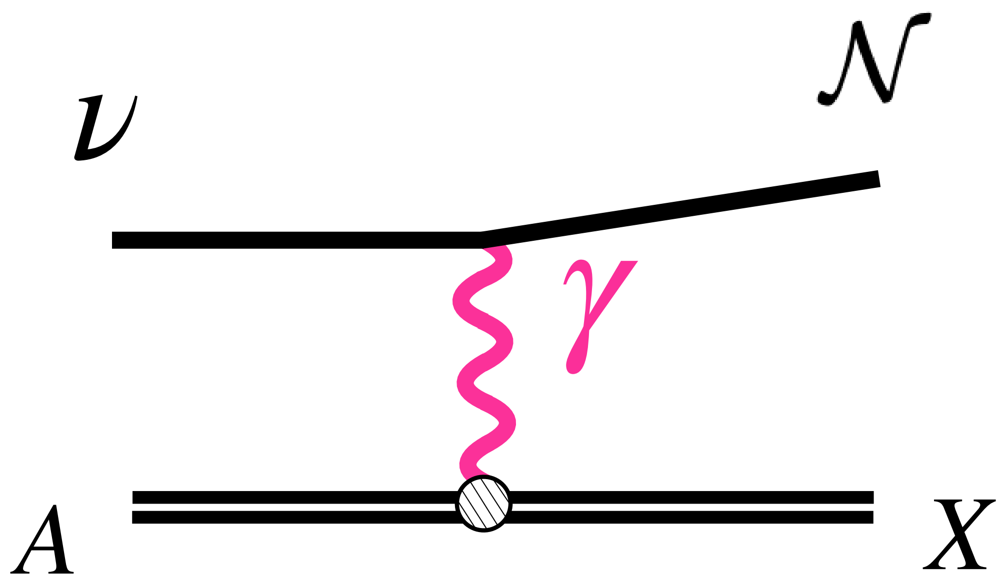


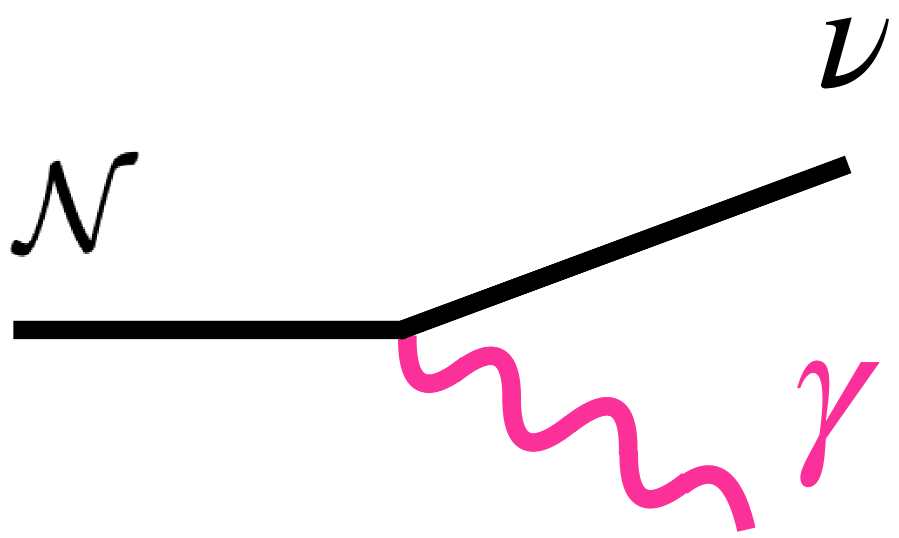
Earliest photons 🟥🟨🟩🟦🟪 Latest photons

HNLs in Ice @ IceCube

- We look for two isolated cascades from the HNL upscattering and decay
- **This is a smoking gun signature of dipole-portal HNLs!**
- First proposed in Coloma+ (2017)

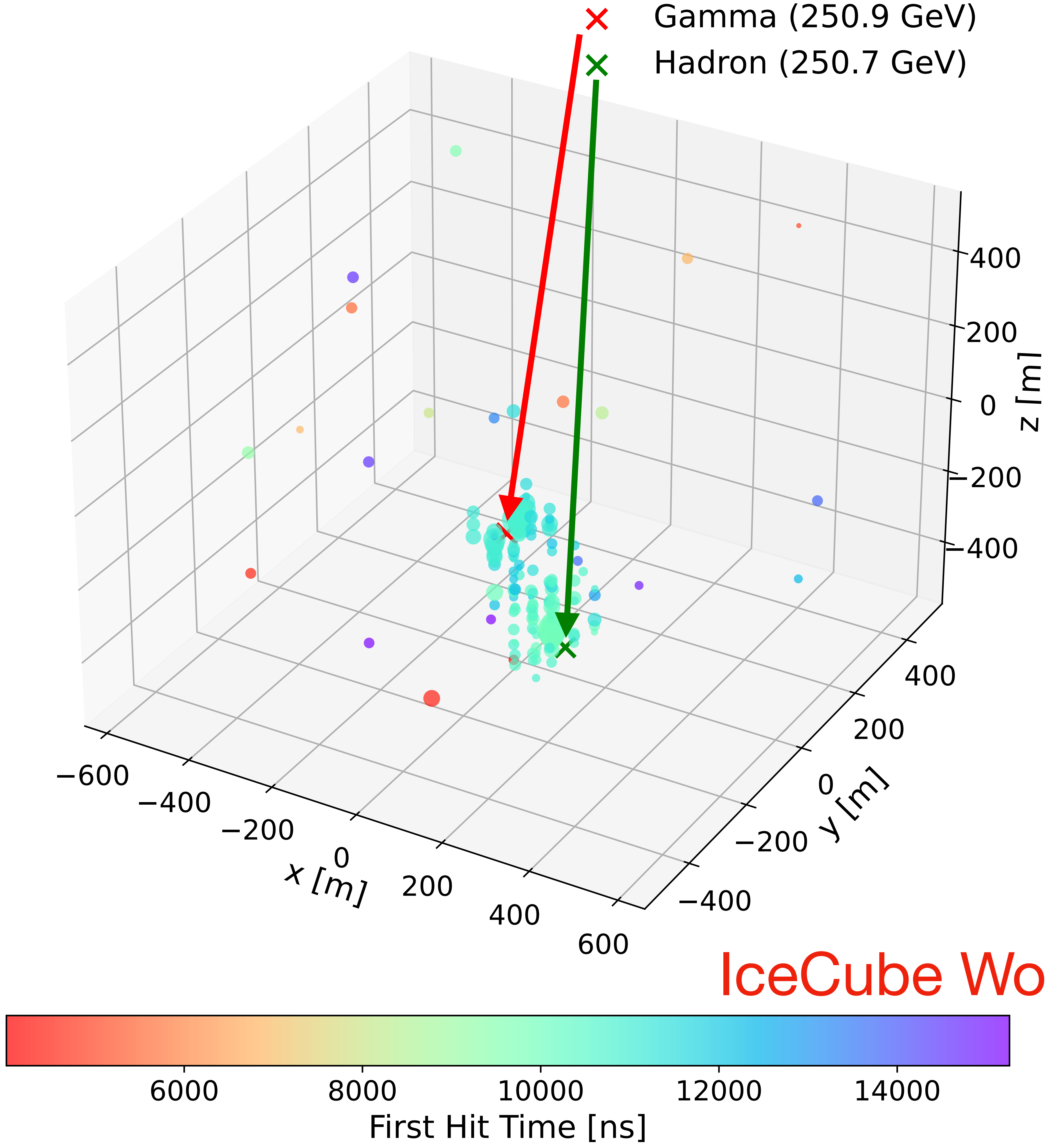


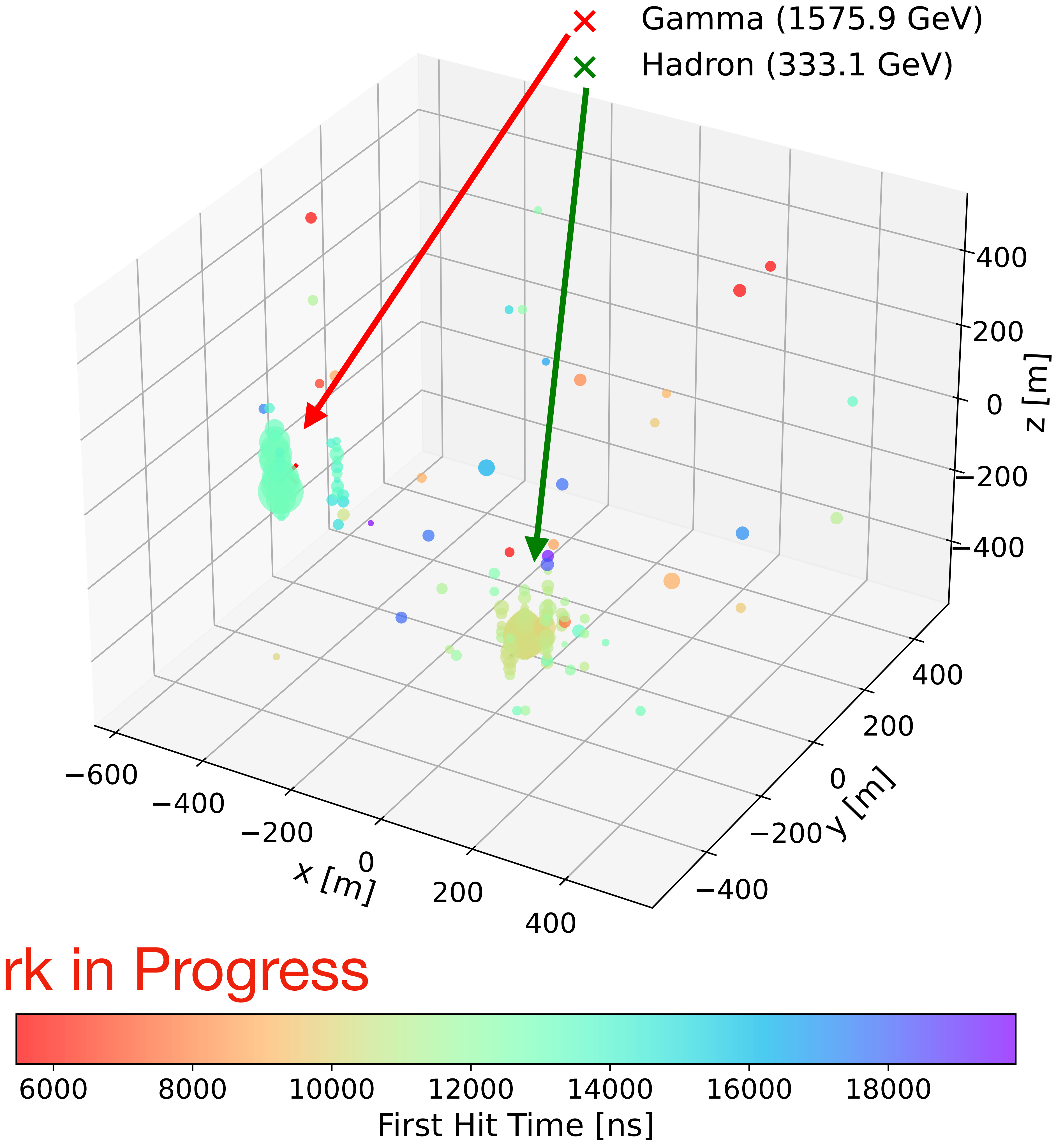




HNLs in Ice @ IceCube

- Upscattering and decay of HNLs simulated using SIREN
- Photon propagation and detector response simulated using internal IceCube software

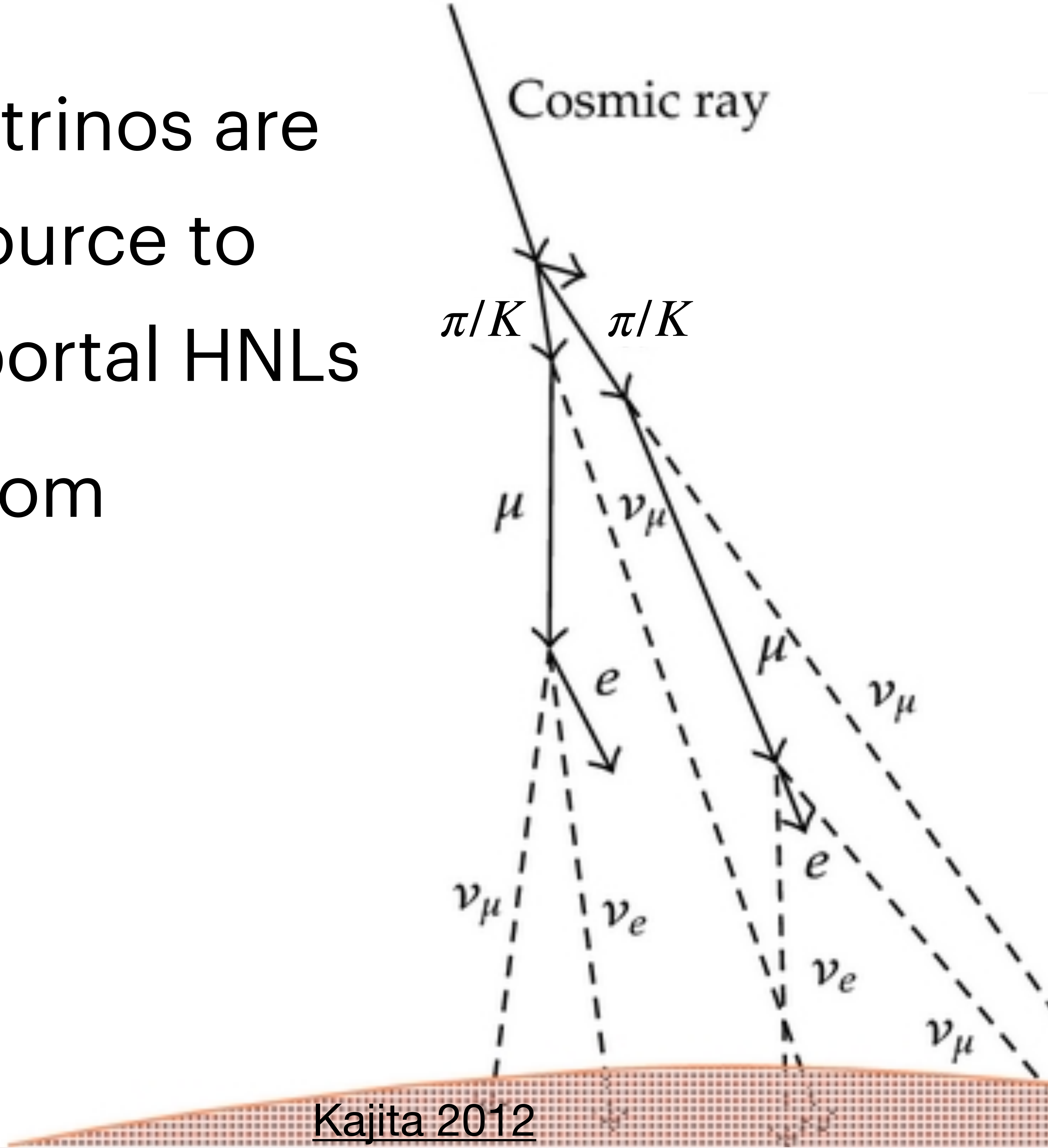




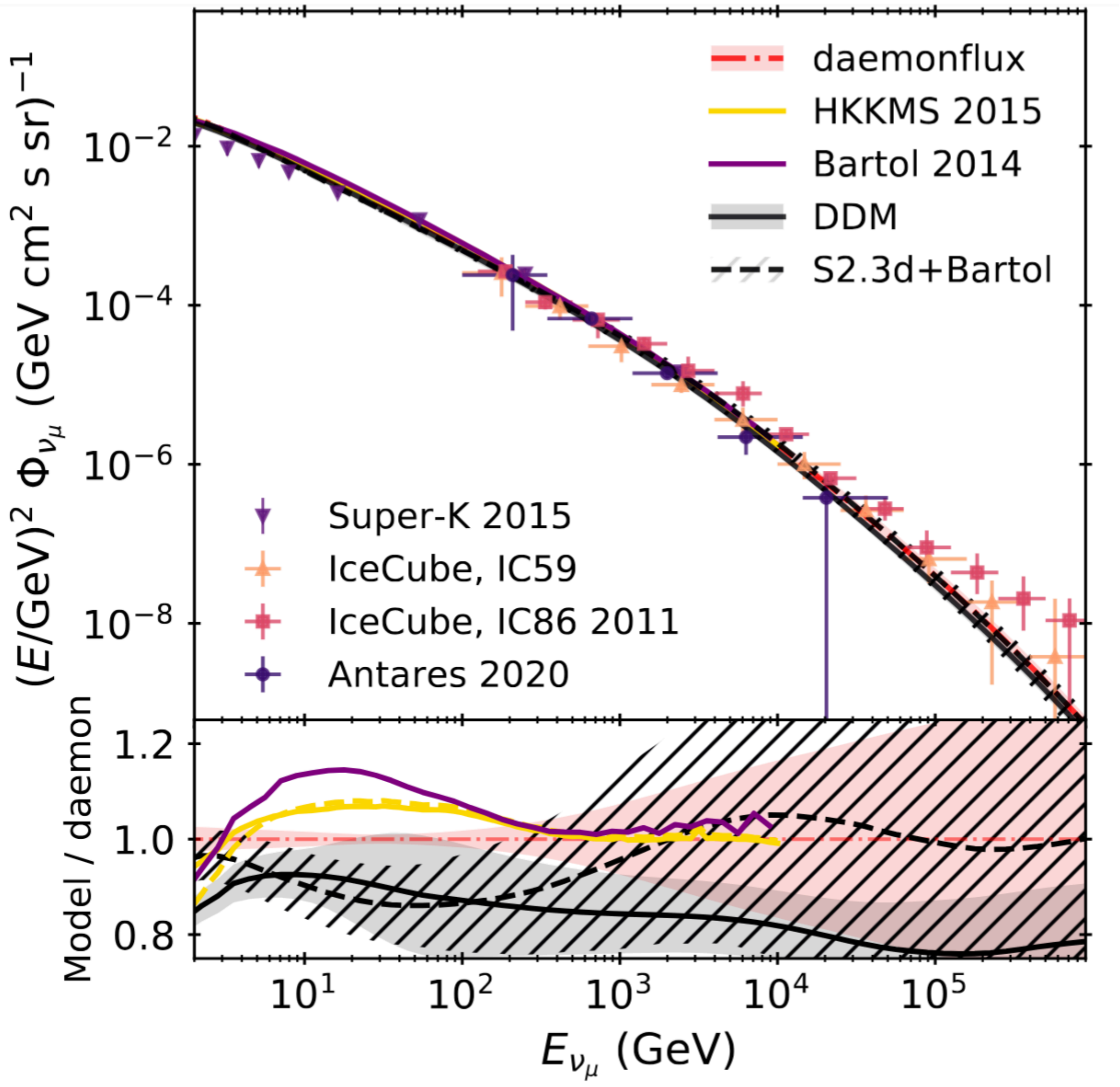
IceCube Work in Progress

Atmospheric Neutrino Flux

- Atmospheric neutrinos are our main $\nu_\mu/\overline{\nu}_\mu$ source to produce dipole-portal HNLs
- Flux prediction from DAEMONFLUX [1]

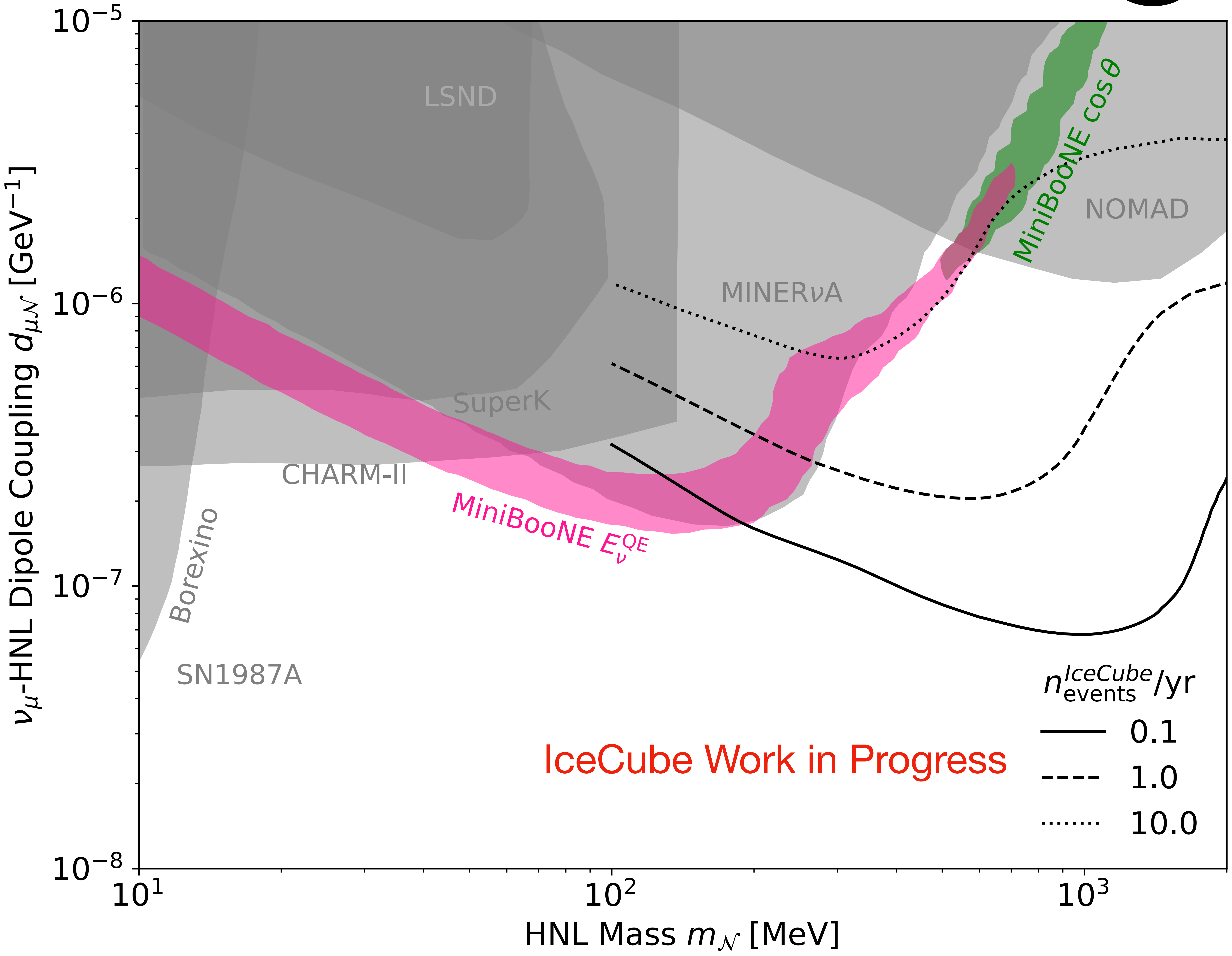


Kajita 2012



[1] Yañez+ 2023

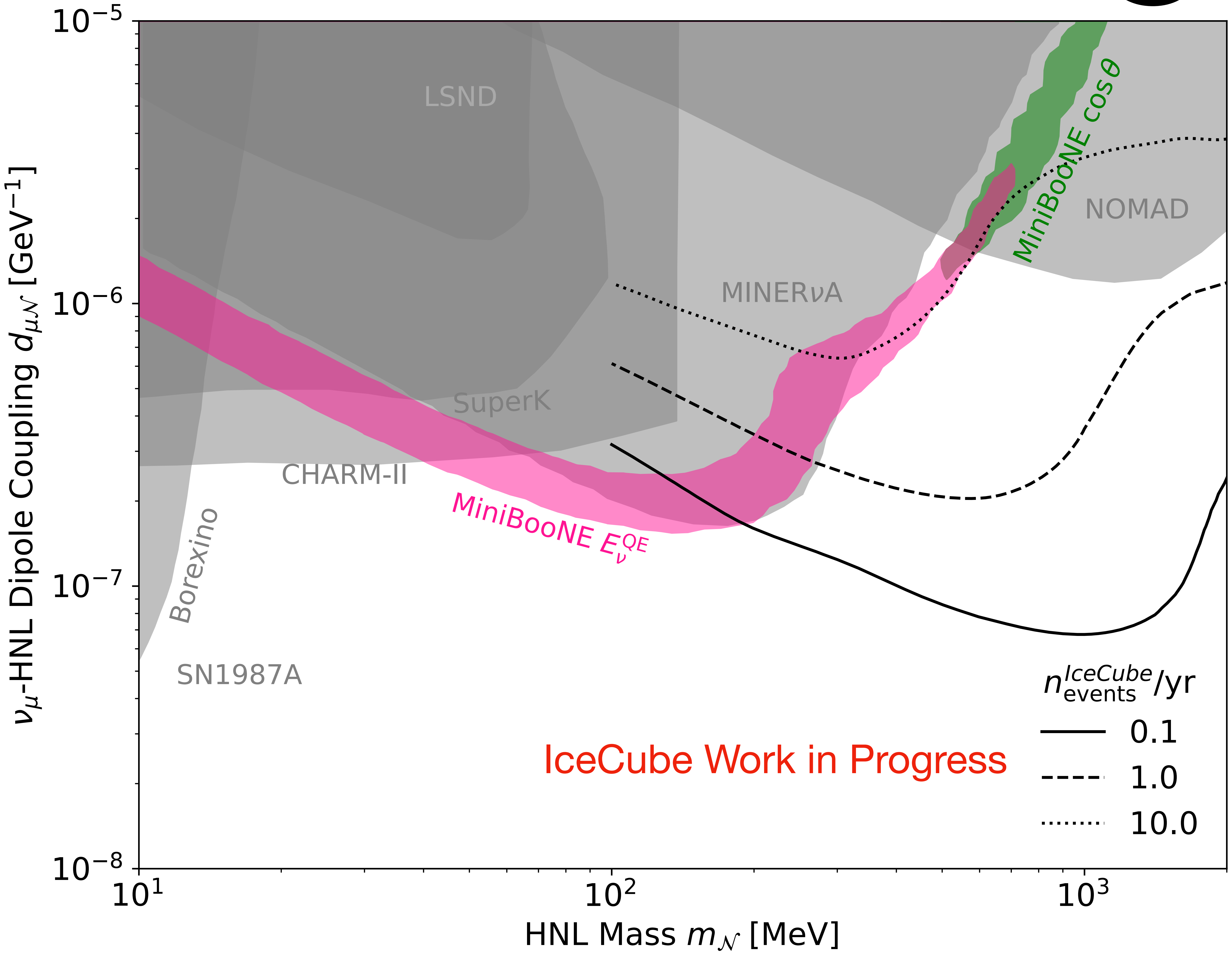
HNLs in Ice @ IceCube



Number of double cascade from dipole-portal HNLs per year:

1. Passing IceCube's data filtration system
2. With cascade separation > 5 m

HNLs in Ice @ IceCube



Number of double cascade from dipole-portal HNLs per year:

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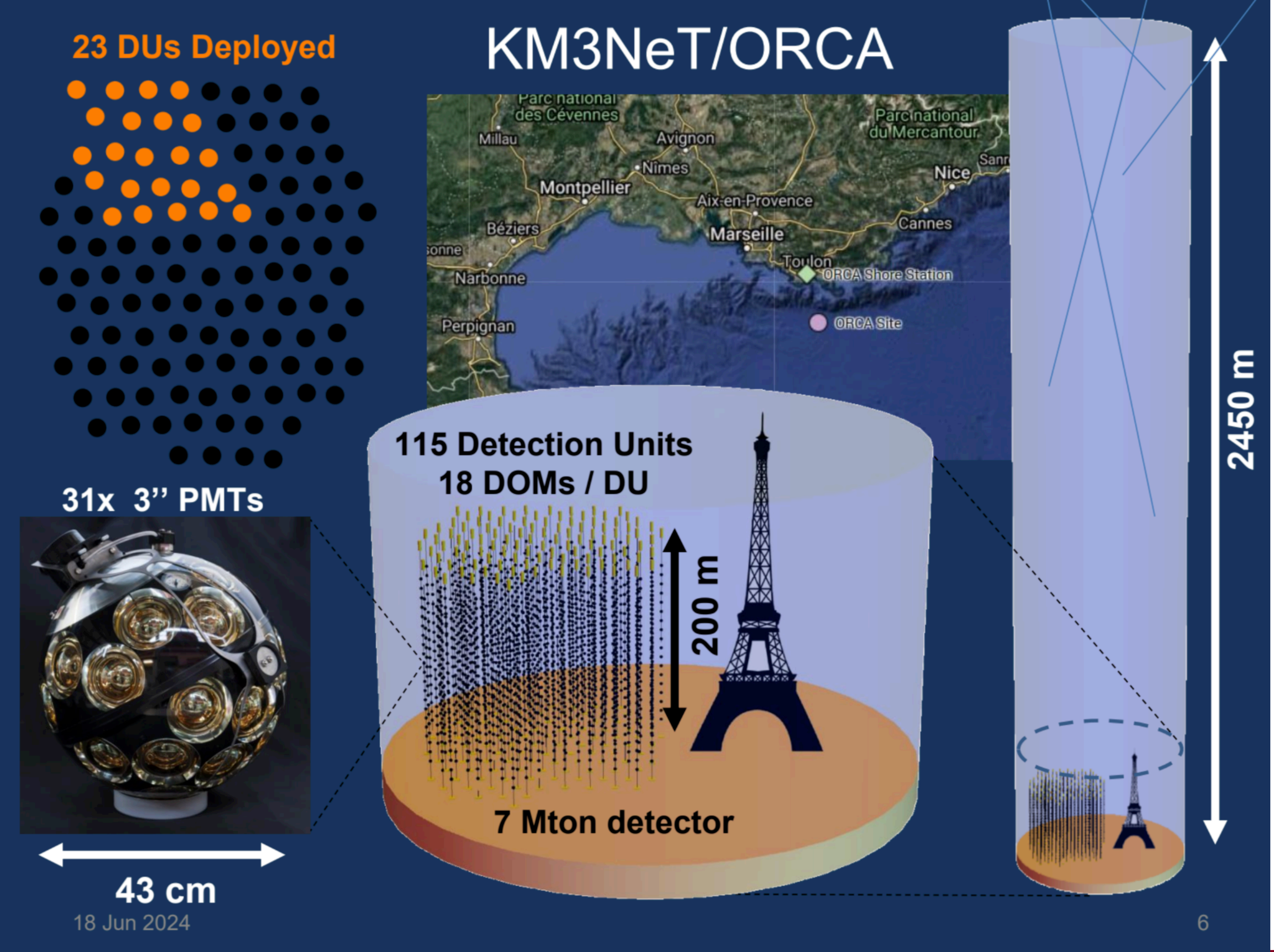
2. With cascade separation > 5 m

Background studies in progress



KM3NeT/ORCA

23 DUs Deployed

31x 3” PMTs

43 cm

115 Detection Units
18 DOMs / DU

200 m

7 Mton detector

2450 m

18 Jun 2024

6

We can also search for HNLs in KM3NeT

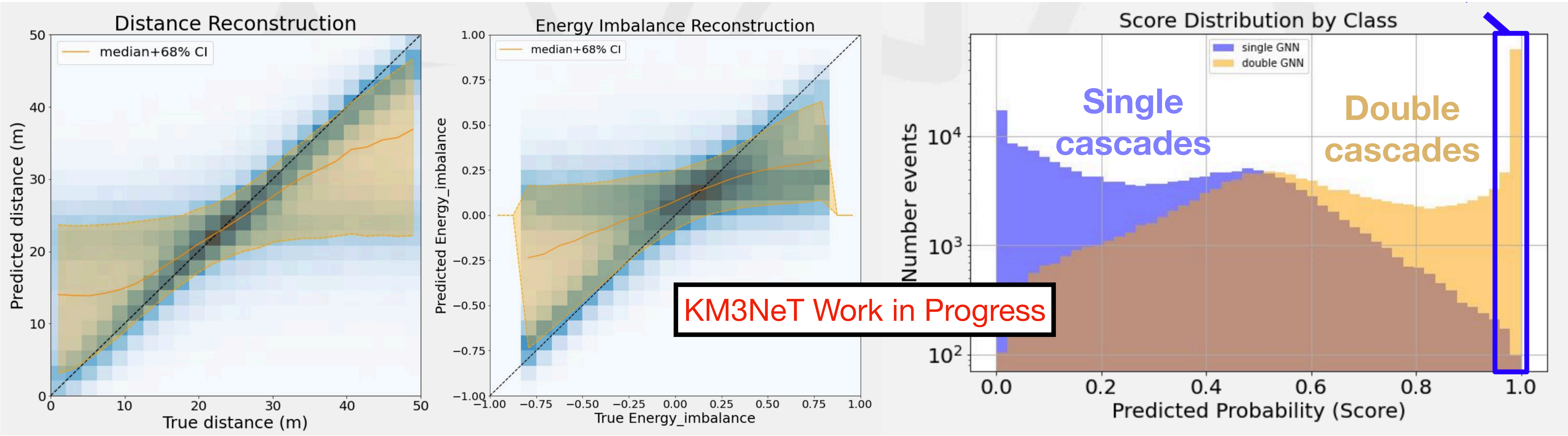
The longer photon scattering length of water v.s. ice is advantageous for event reconstruction

Reproduced from
Joao Coelho, Neutrino 2024

HNLs in Water @ KM3NeT

- We begin with a SIREN-based simulation of dipole-portal HNL double cascades in ORCA
- Graph neural networks appear to have strong separation capability between double cascade signals and single cascade backgrounds

Sensitivity studies underway



KM3NeT Work in Progress

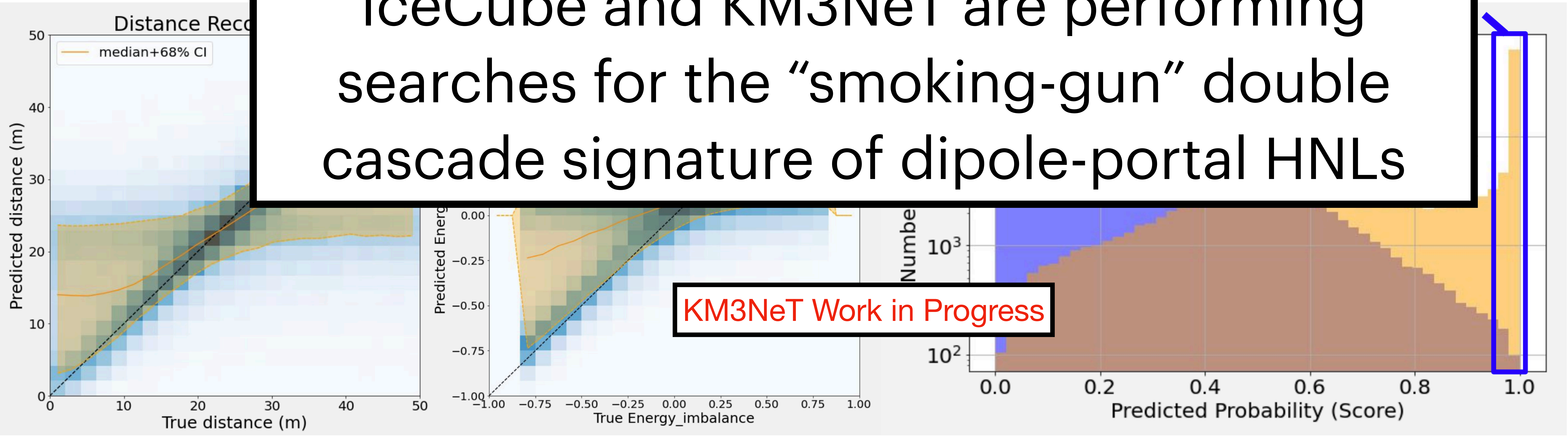
J. Prado

HNLs in Water @ KM3NeT

- We begin with a SIREN-based simulation of dipole-portal HNL double cascades in ORCA

Takeaway:

IceCube and KM3NeT are performing searches for the “smoking-gun” double cascade signature of dipole-portal HNLs



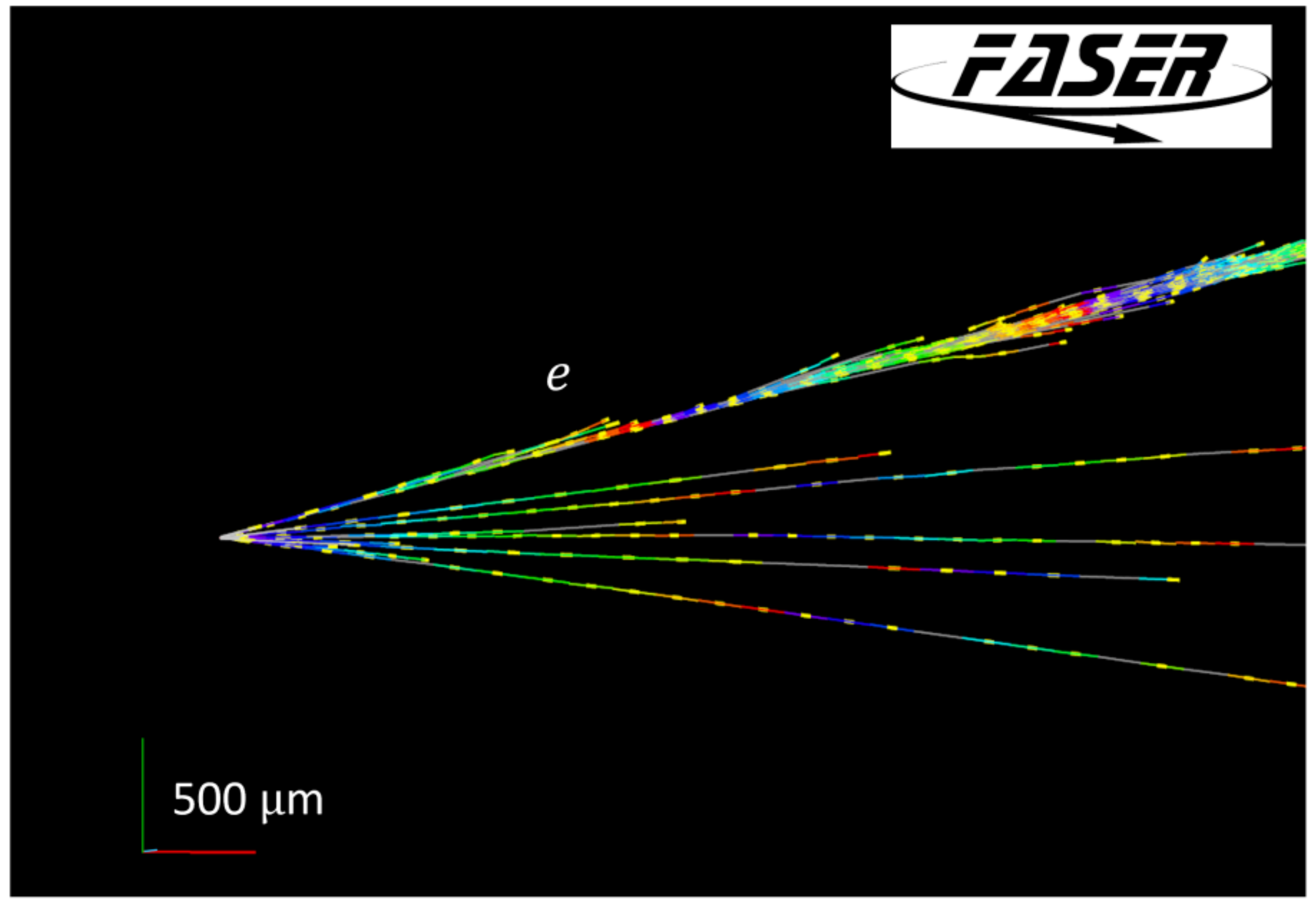
KM3NeT Work in Progress

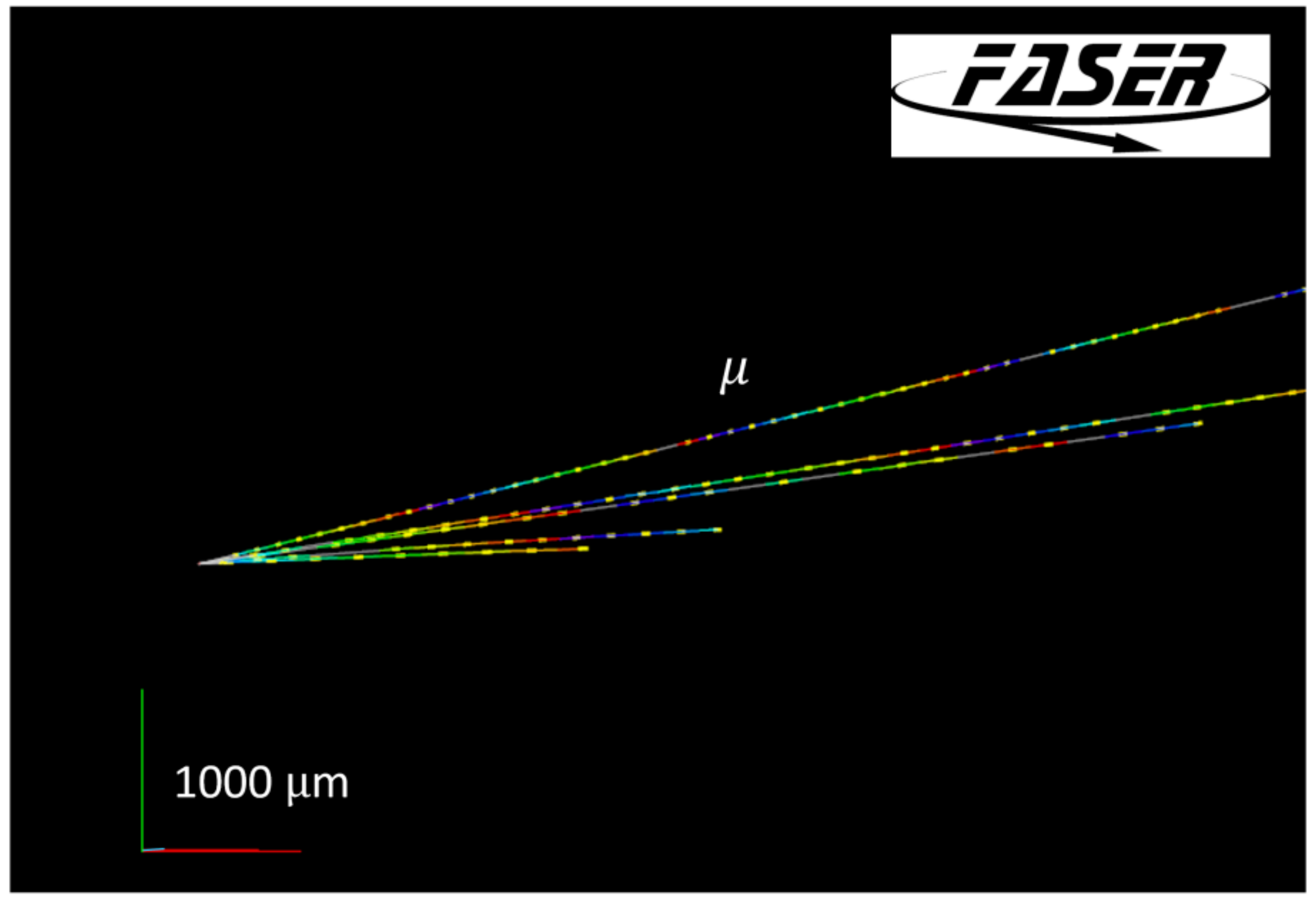
J. Prado

Outline

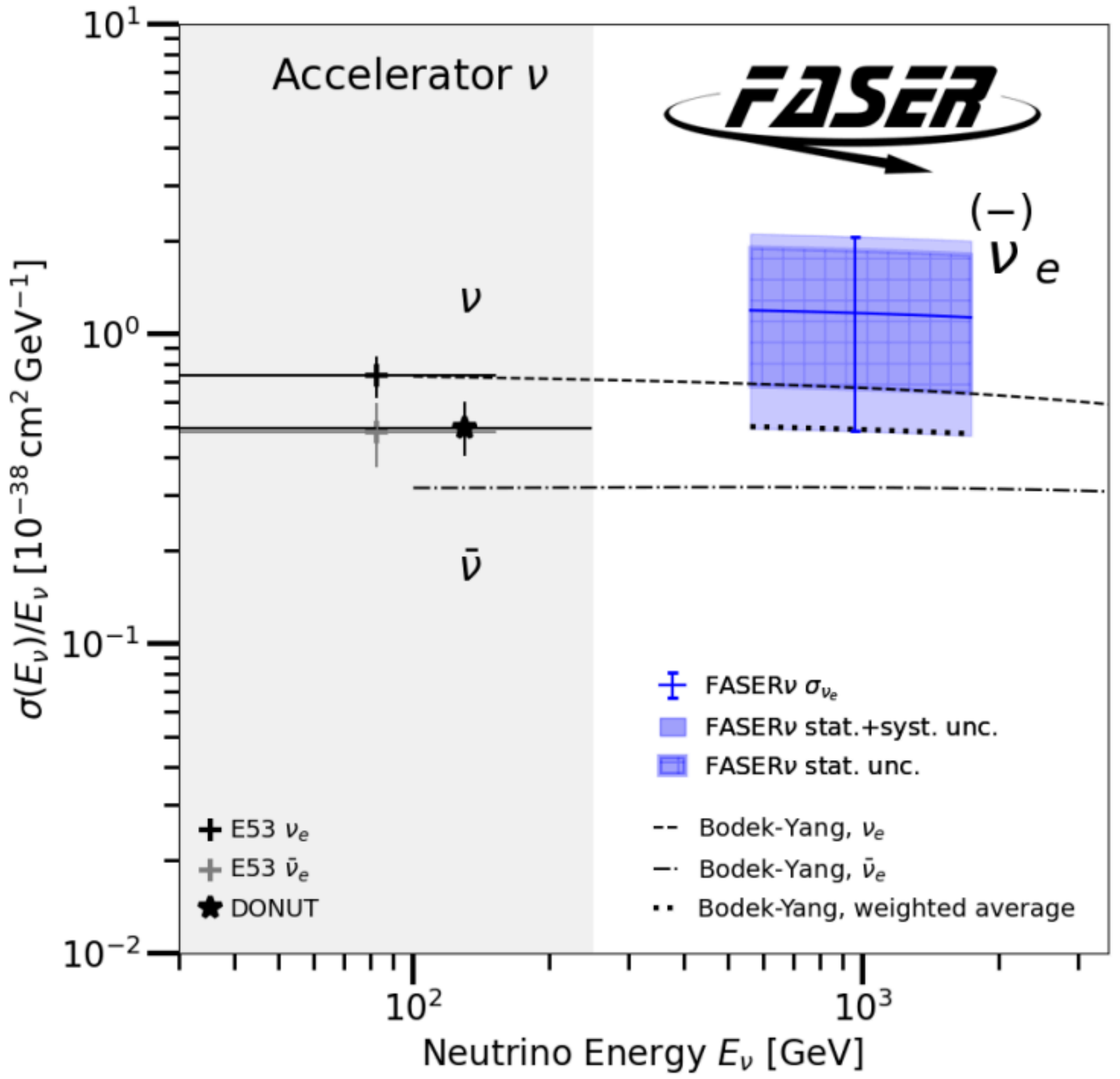
1. **MiniBooNE:** A long-standing neutrino anomaly
2. **Heavy neutrinos in plastic:** constraints on a promising MiniBooNE solution
3. **Heavy neutrinos in ice and water:** searches at neutrino telescopes
4. **Heavy neutrinos (and more) in water and rock**: new detectors for collider neutrinos

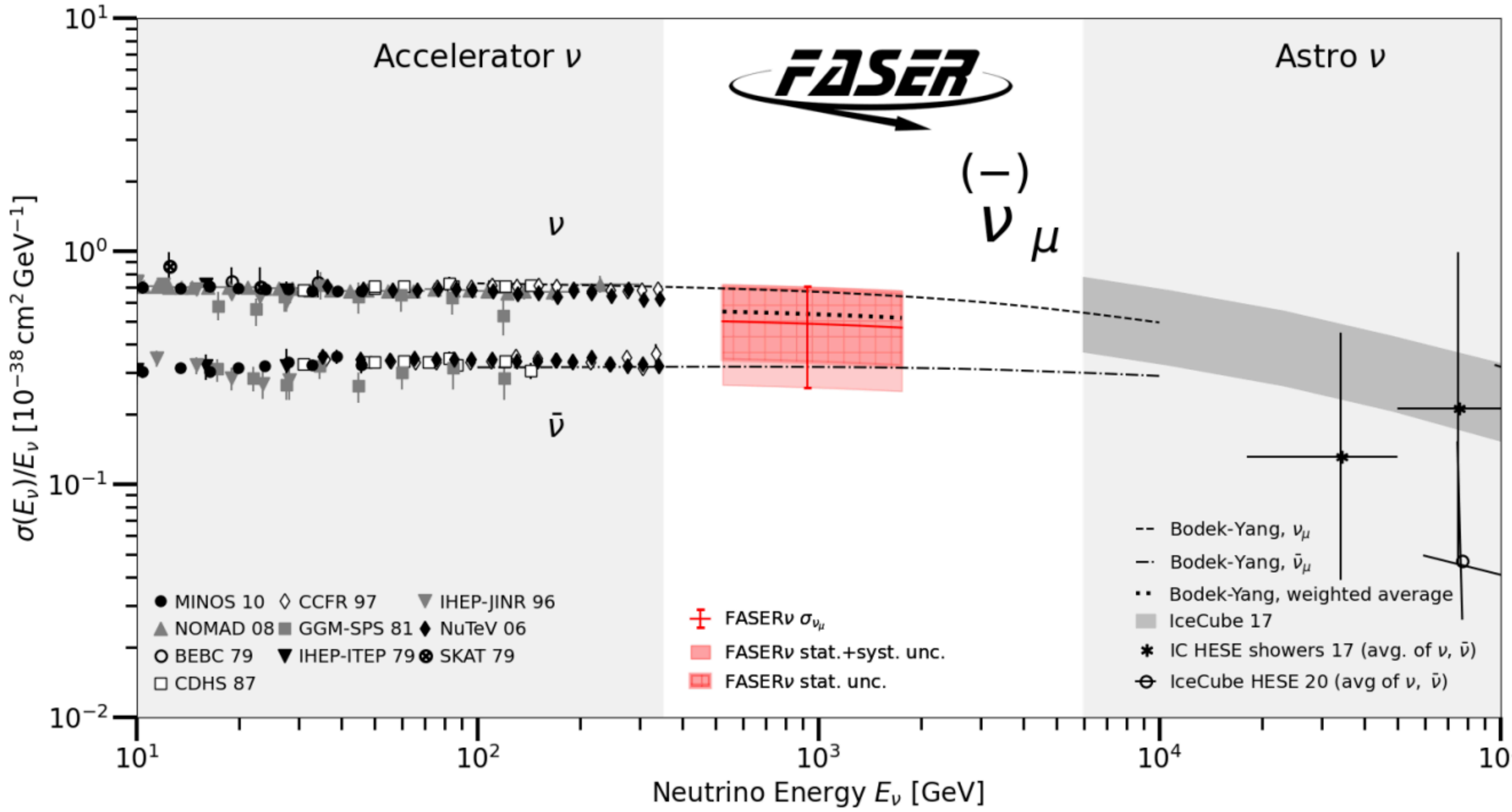
The Dawn of Collider Neutrino Physics

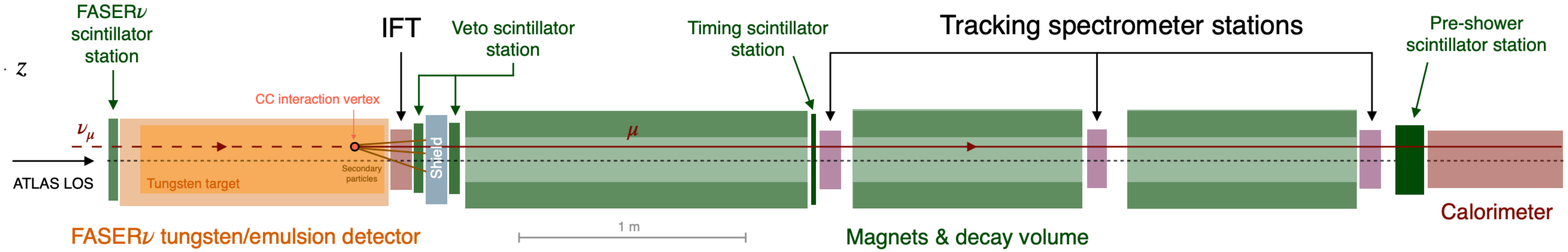




Unique sensitivity to TeV neutrinos and long-lived particles produced in the forward direction at the LHC



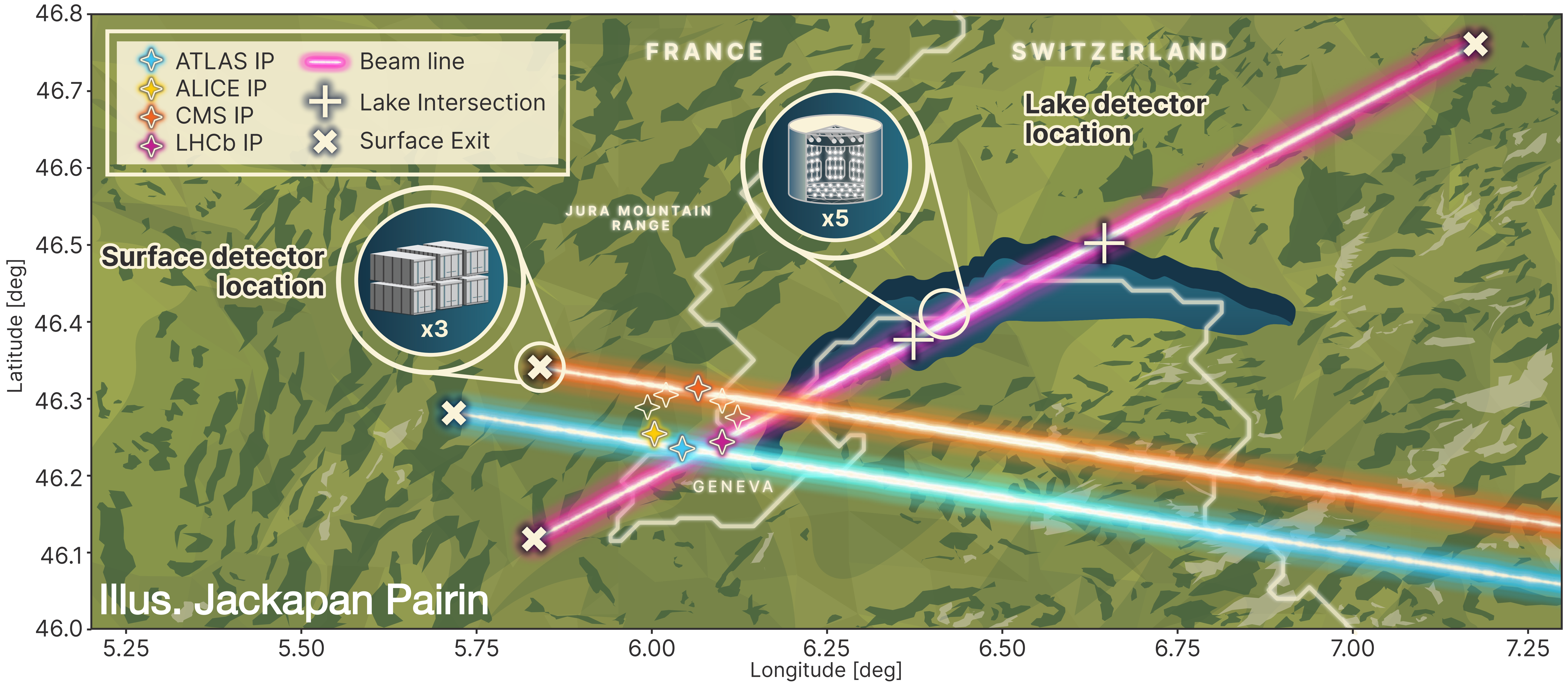




FASER Collab. 2023

FASER Collab. 2024

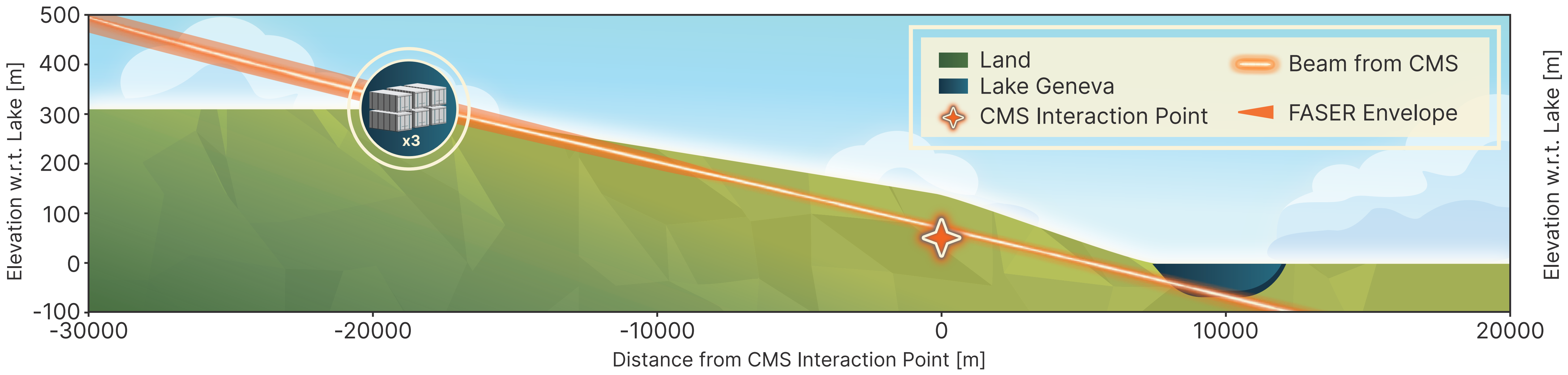
LHC Neutrinos pass through Lake Geneva

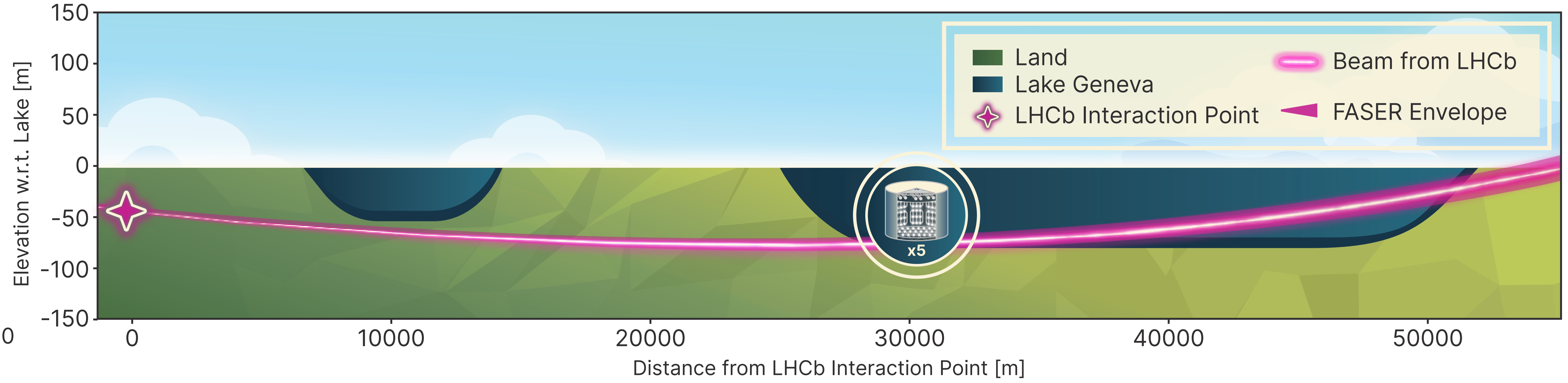


Illus. Jackapan Pairin

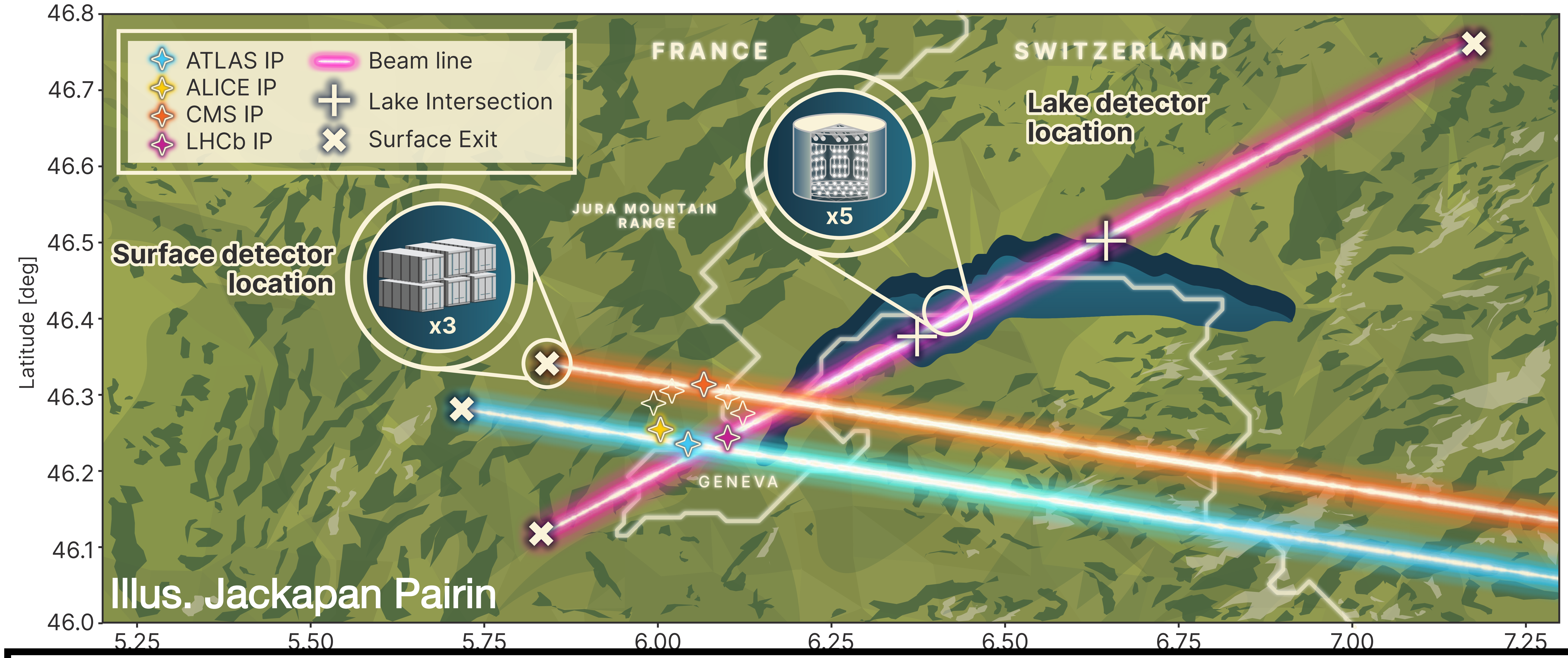
This enables the construction of large-scale lake-and-surface-based detectors that evade muon backgrounds from the p-p collision

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





LHC Neutrinos pass through Lake Geneva



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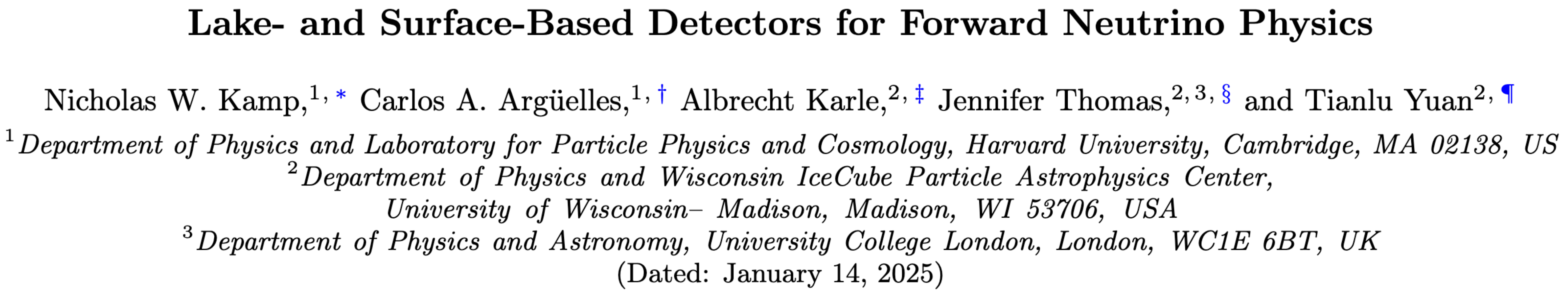
arXiv:2501.08278



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)

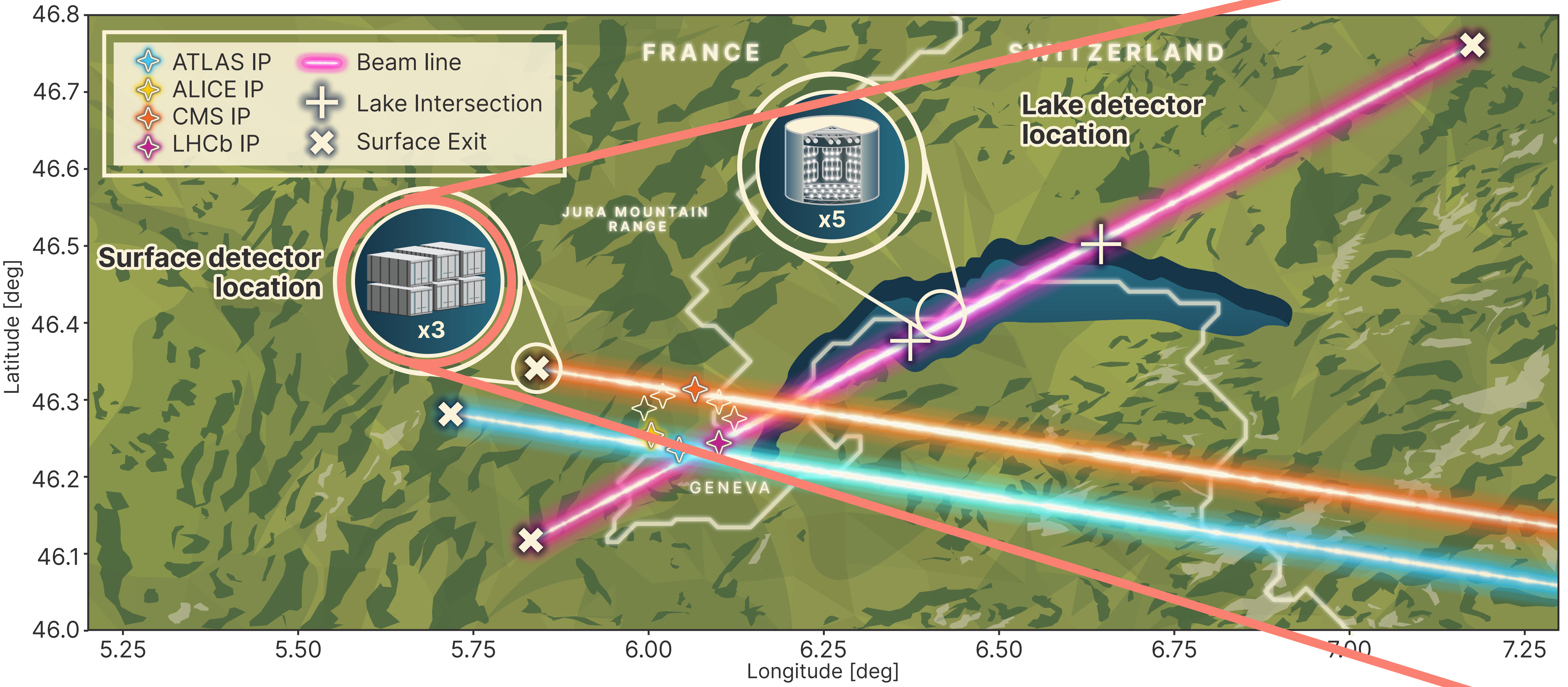
J. Thomas

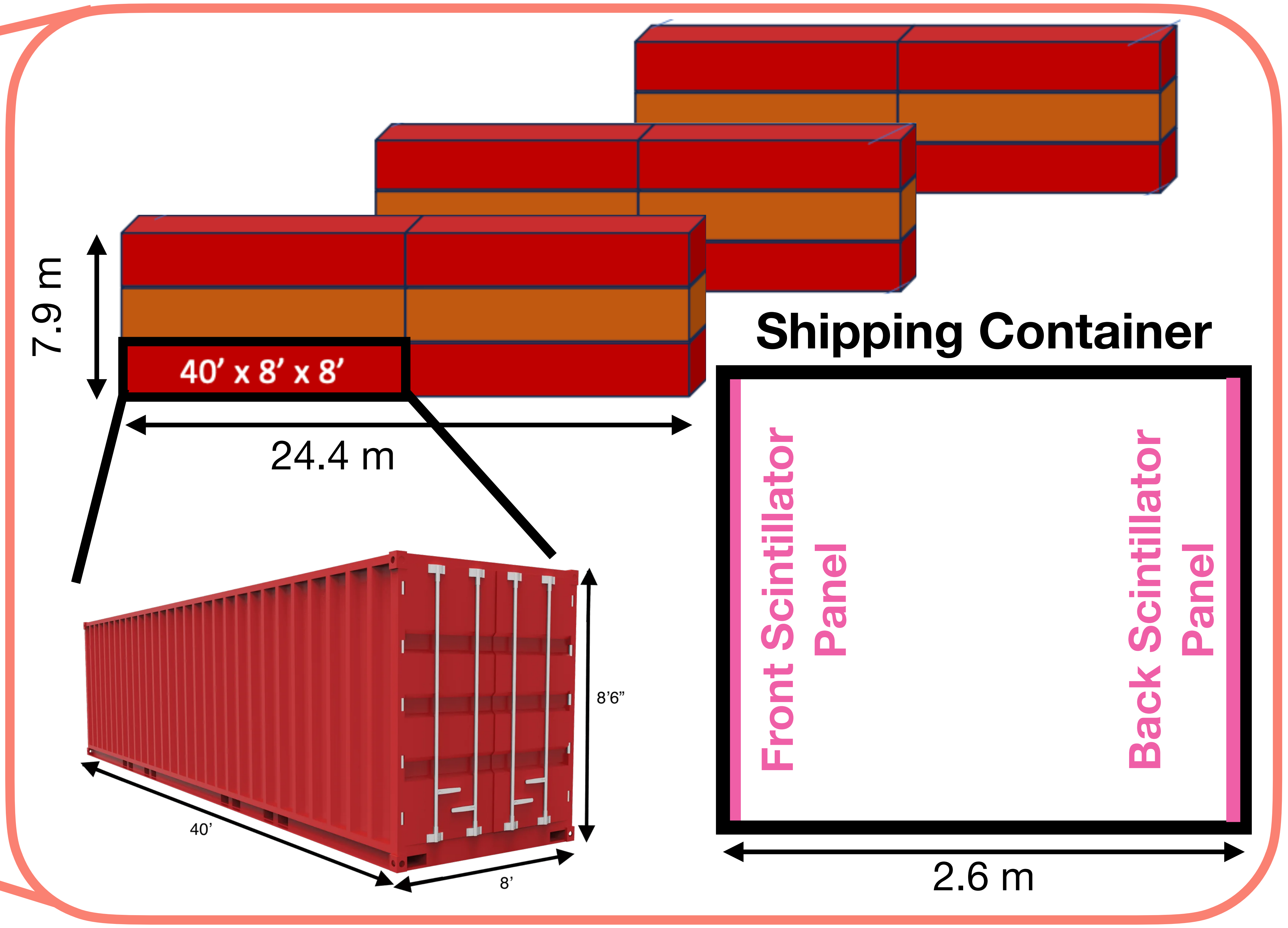
A. Karle

C. Argüelles

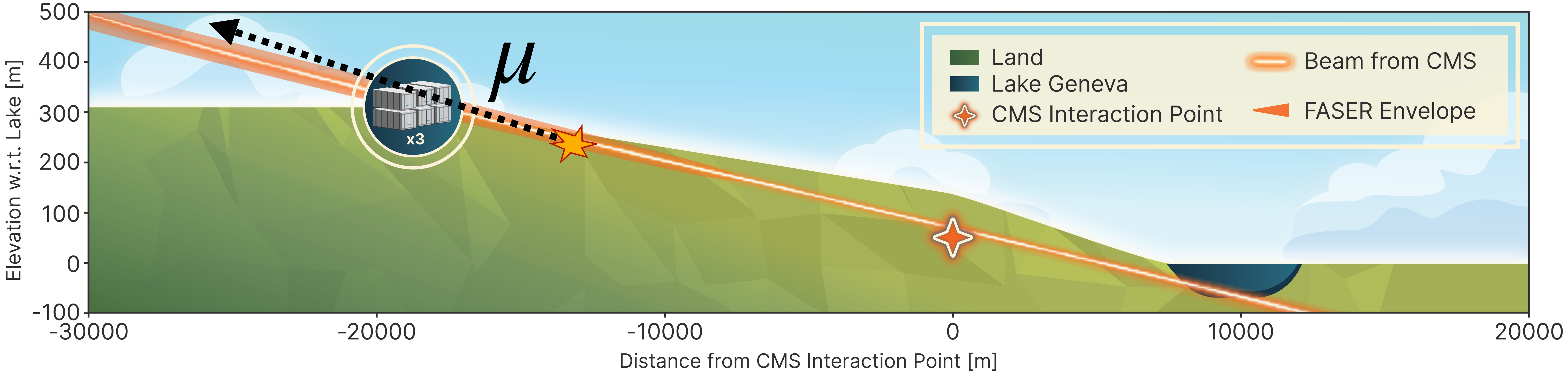
T. Yuan

SINE: Surface-based Integrated Neutrino Experiment





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



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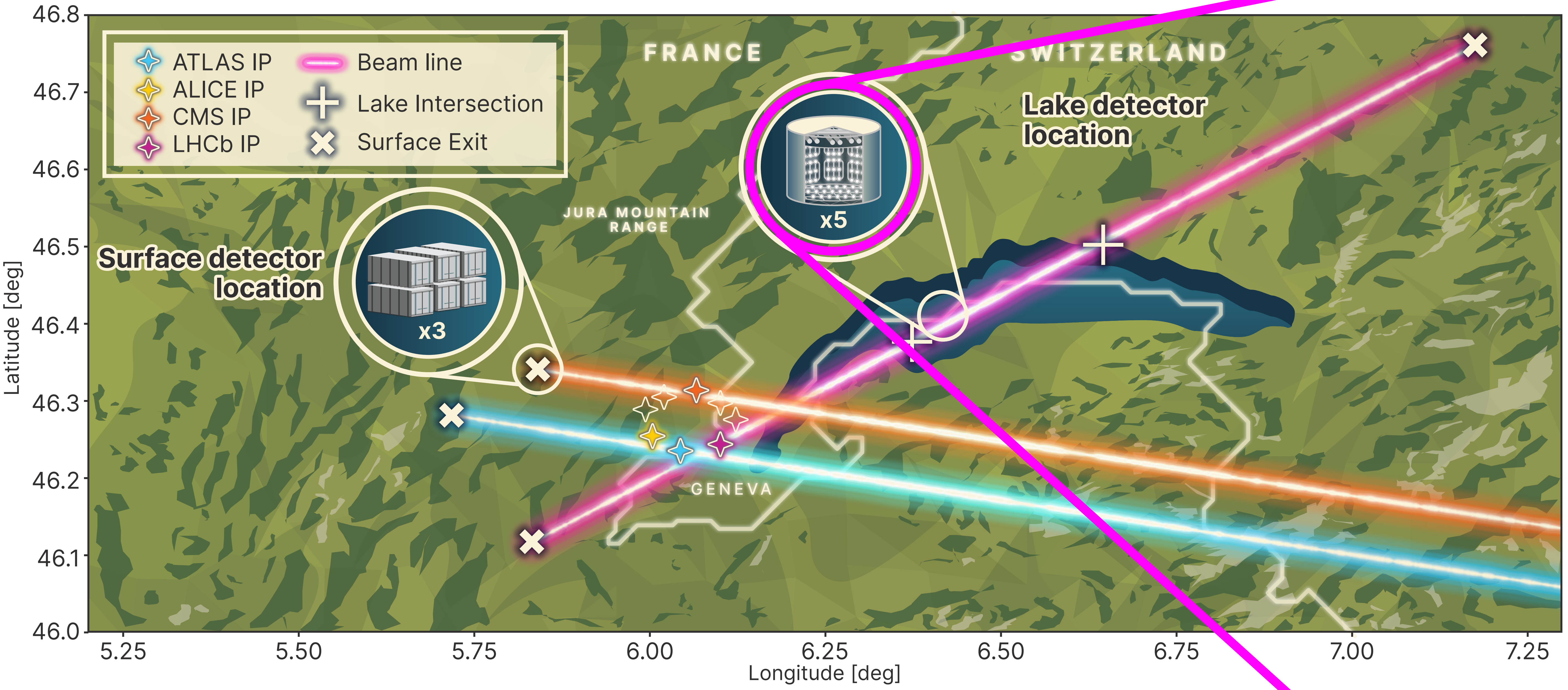
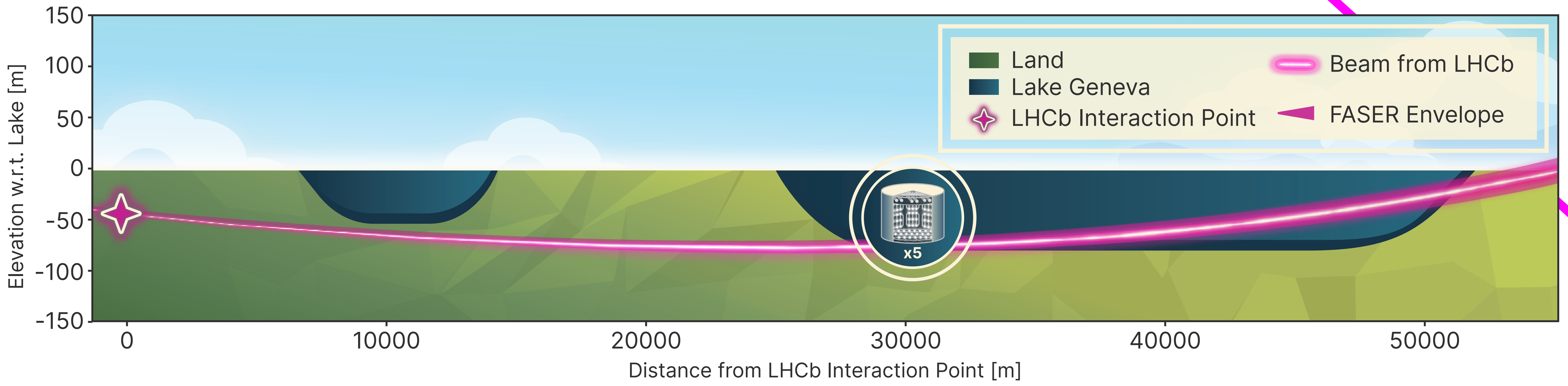
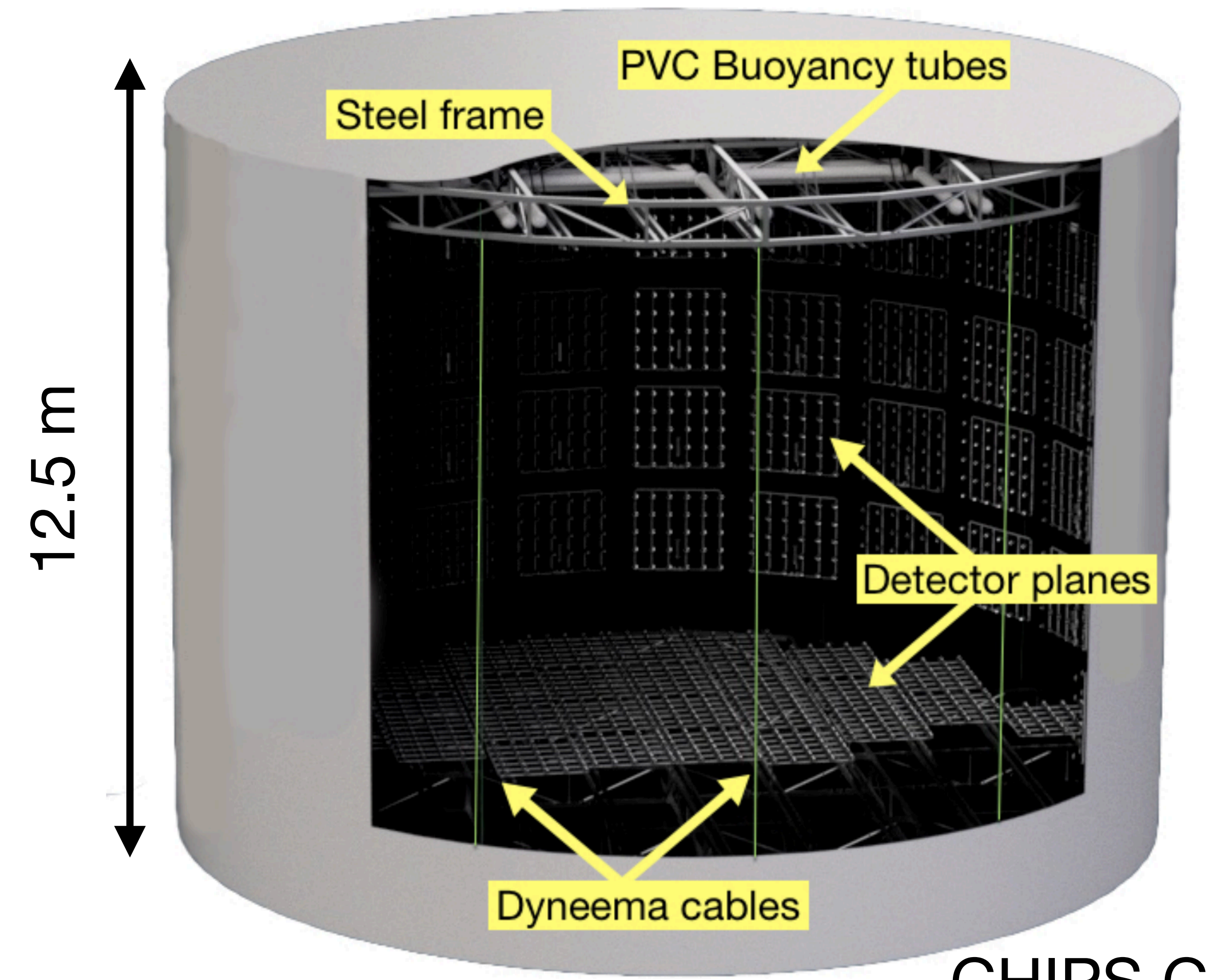
UNDINE: UNDerwater Integrated Neutrino Experiment







CHIPS Collab. 2024

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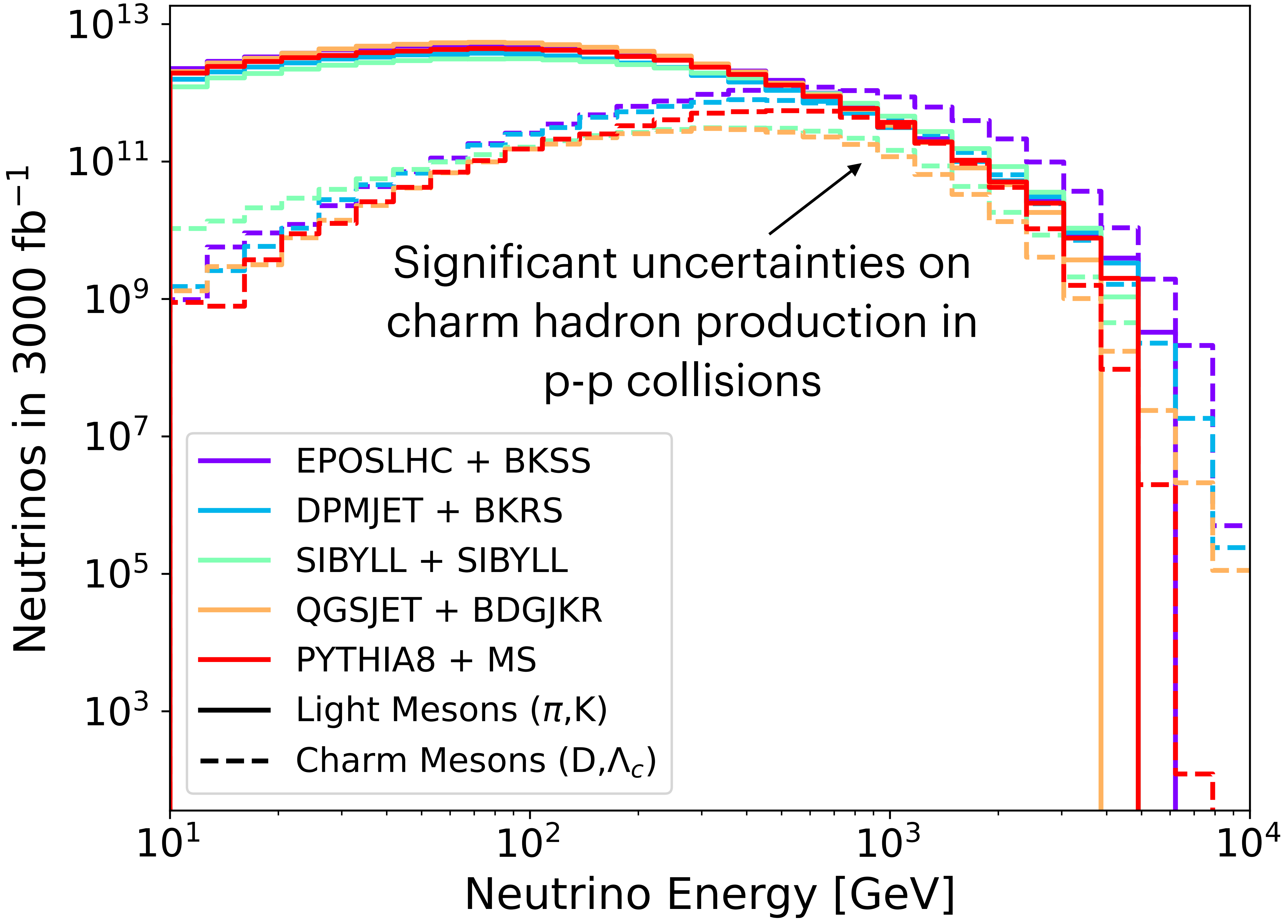
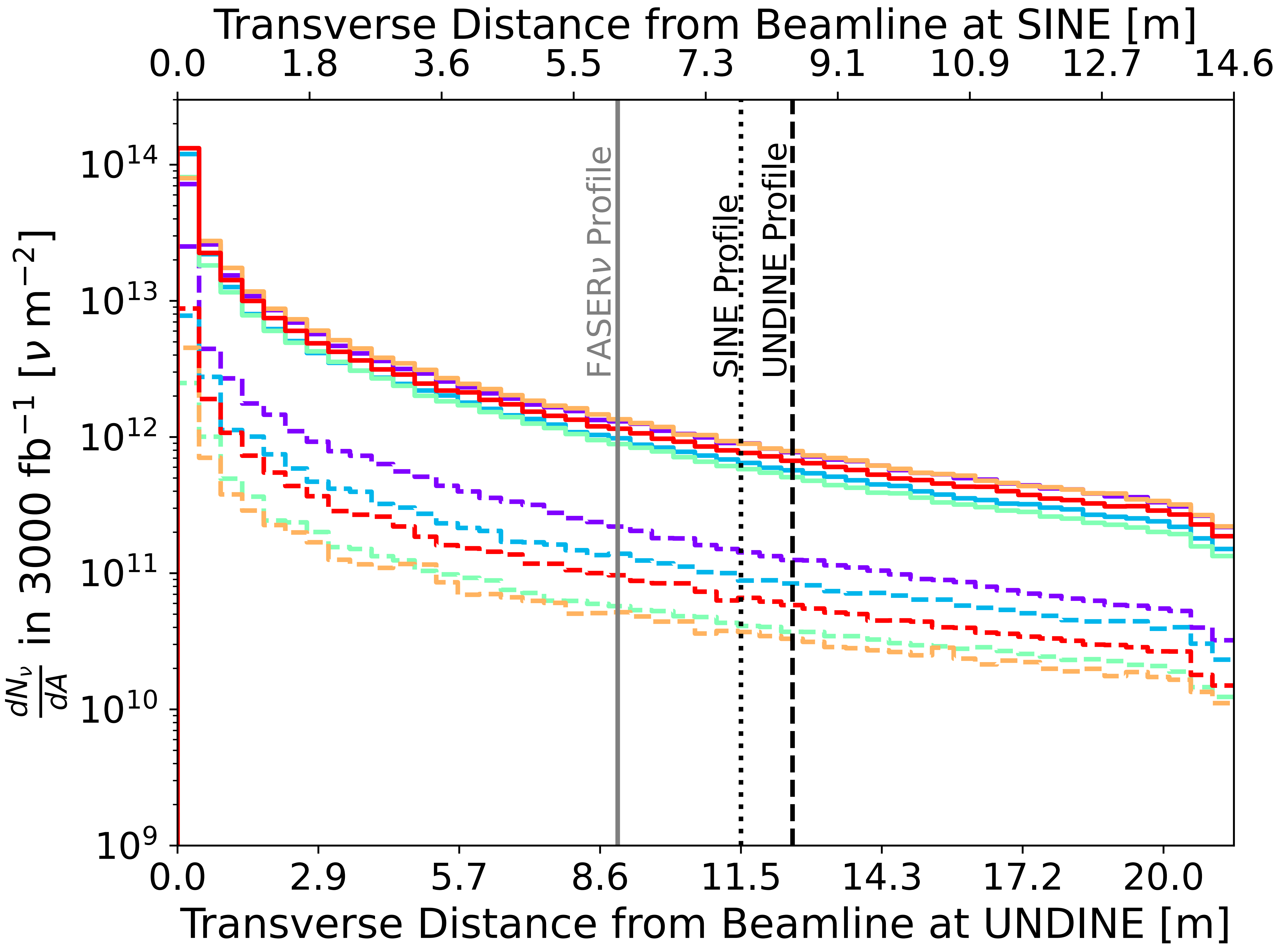
LHC Forward Neutrino Flux

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


Significant uncertainties on charm hadron production in p-p collisions



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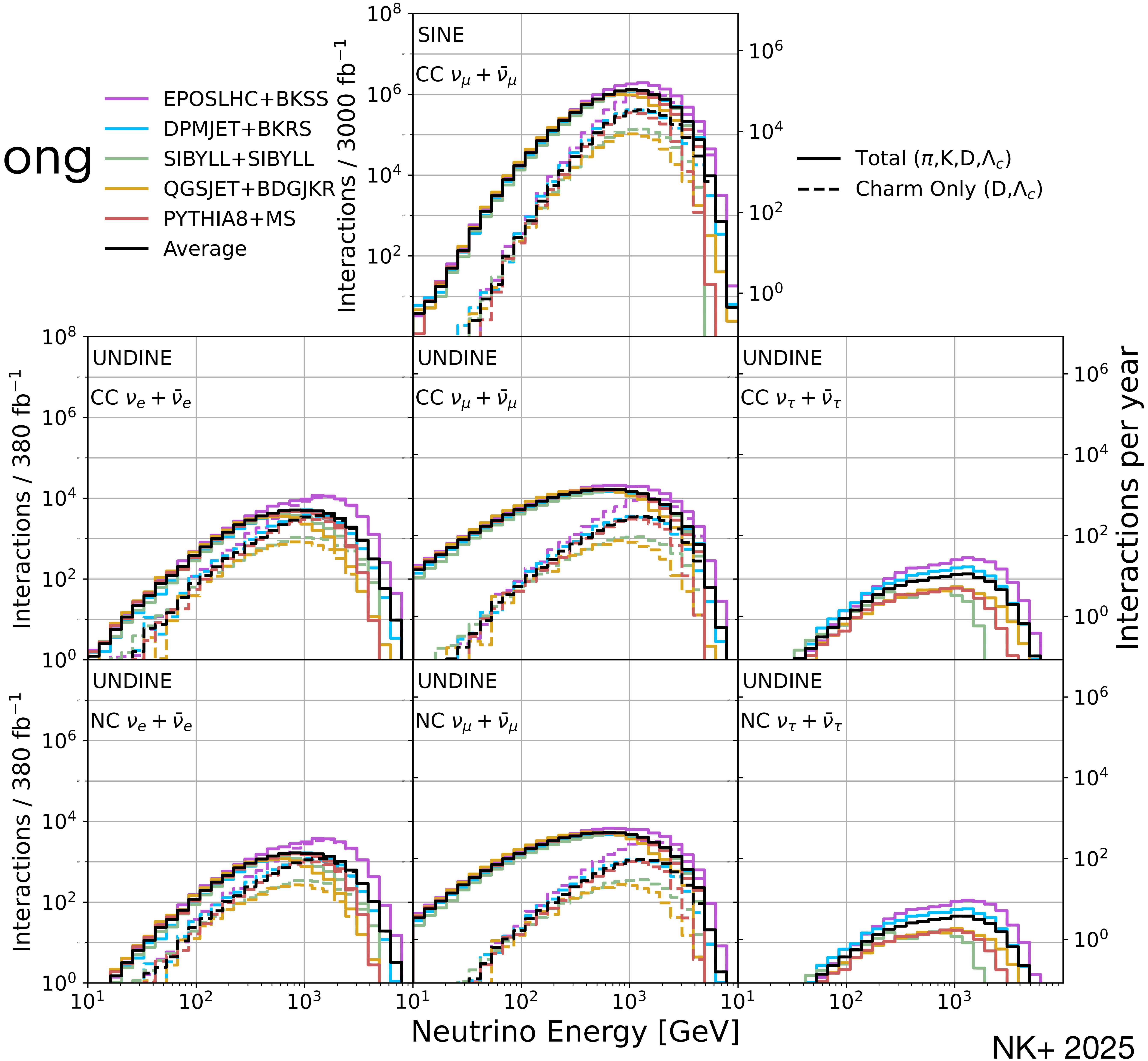
Event Rates

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

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

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 $\nu_\alpha + \bar{\nu}_\alpha$)	$10^{4.87}$	$10^{4.76}$	$10^{4.24}$



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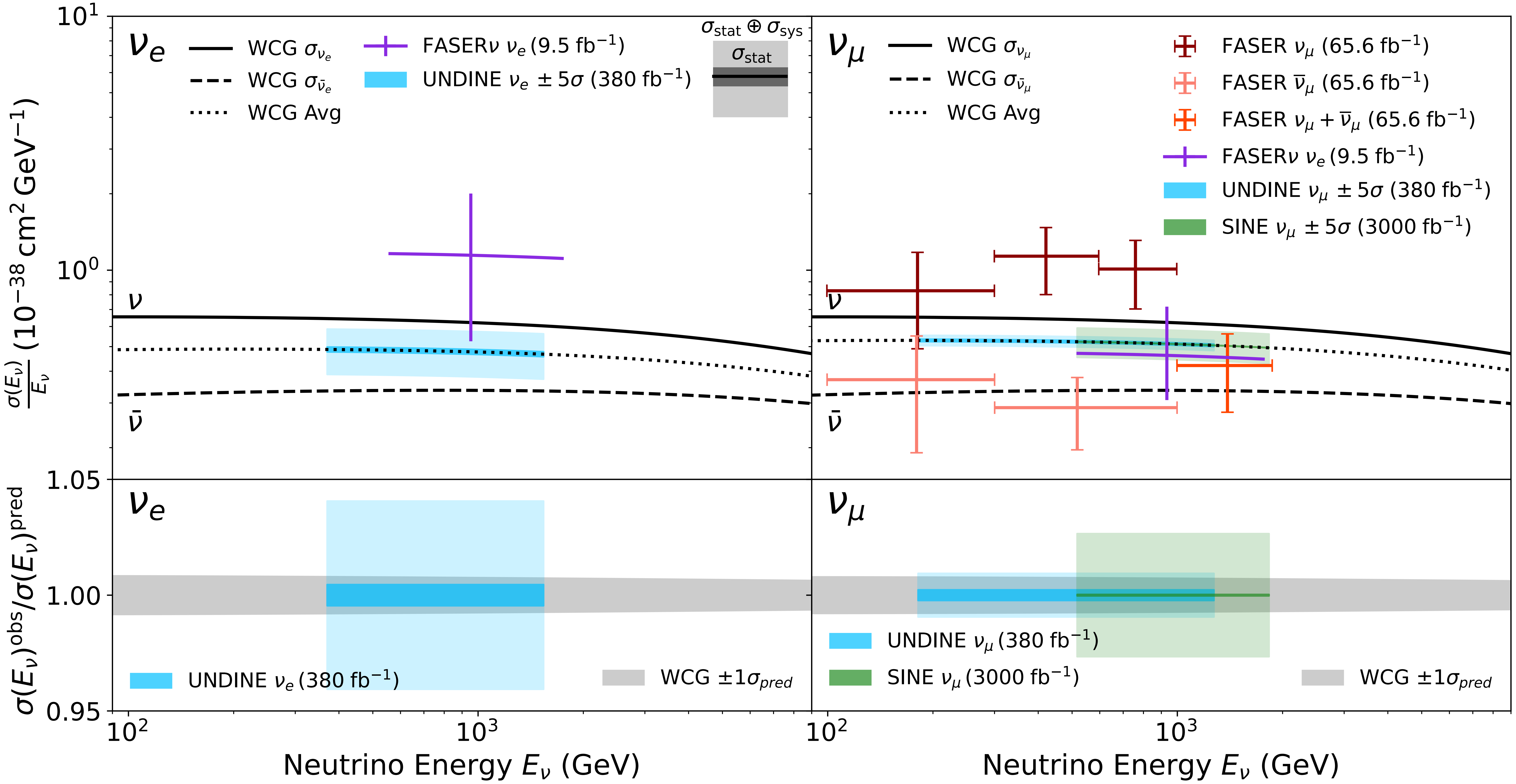
What can we do with ~a million collider neutrinos?

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]



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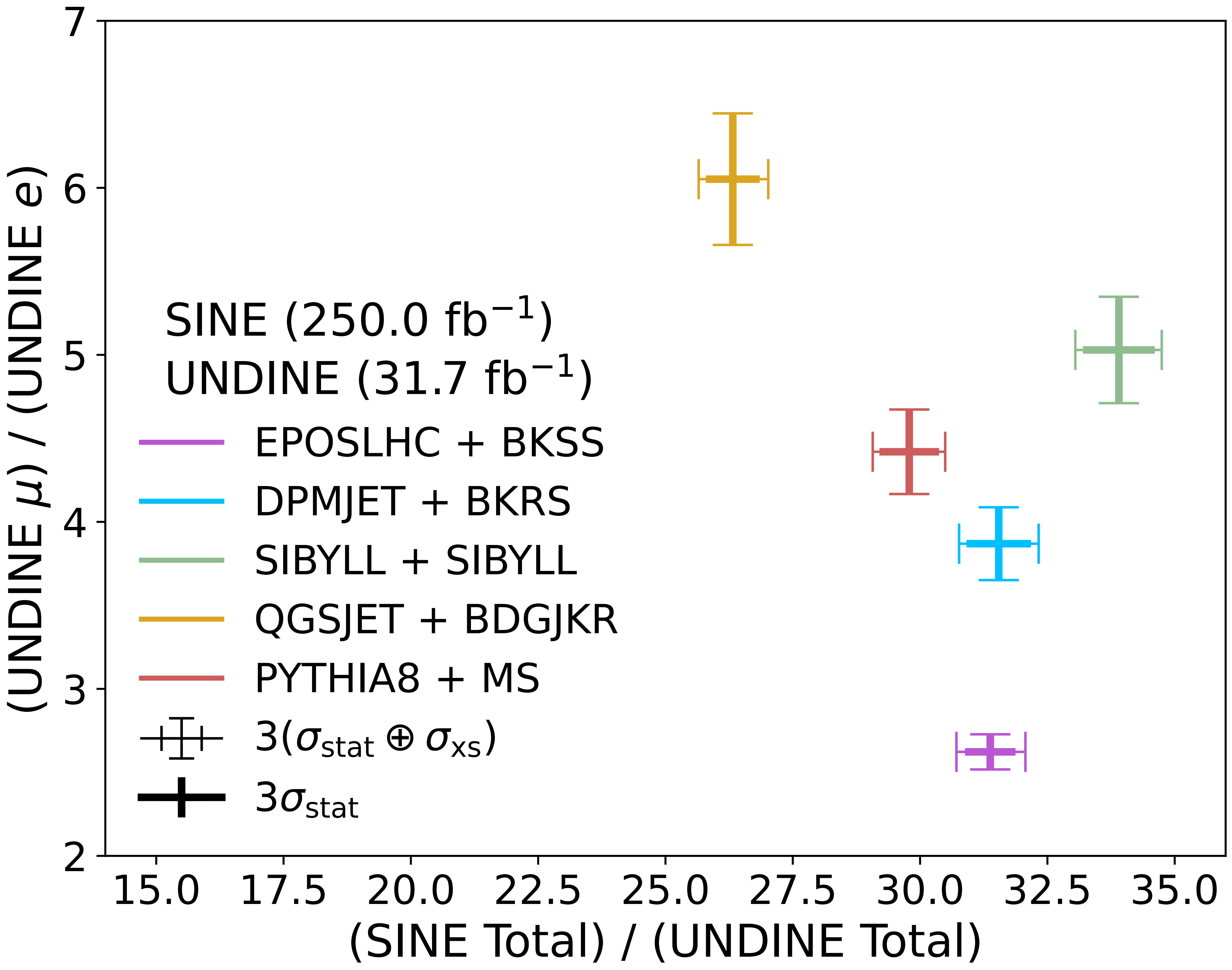
[1] FASER Collab. 2024 [2] FASER Collab. 2024 [3] Weigel+ 2024

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]**



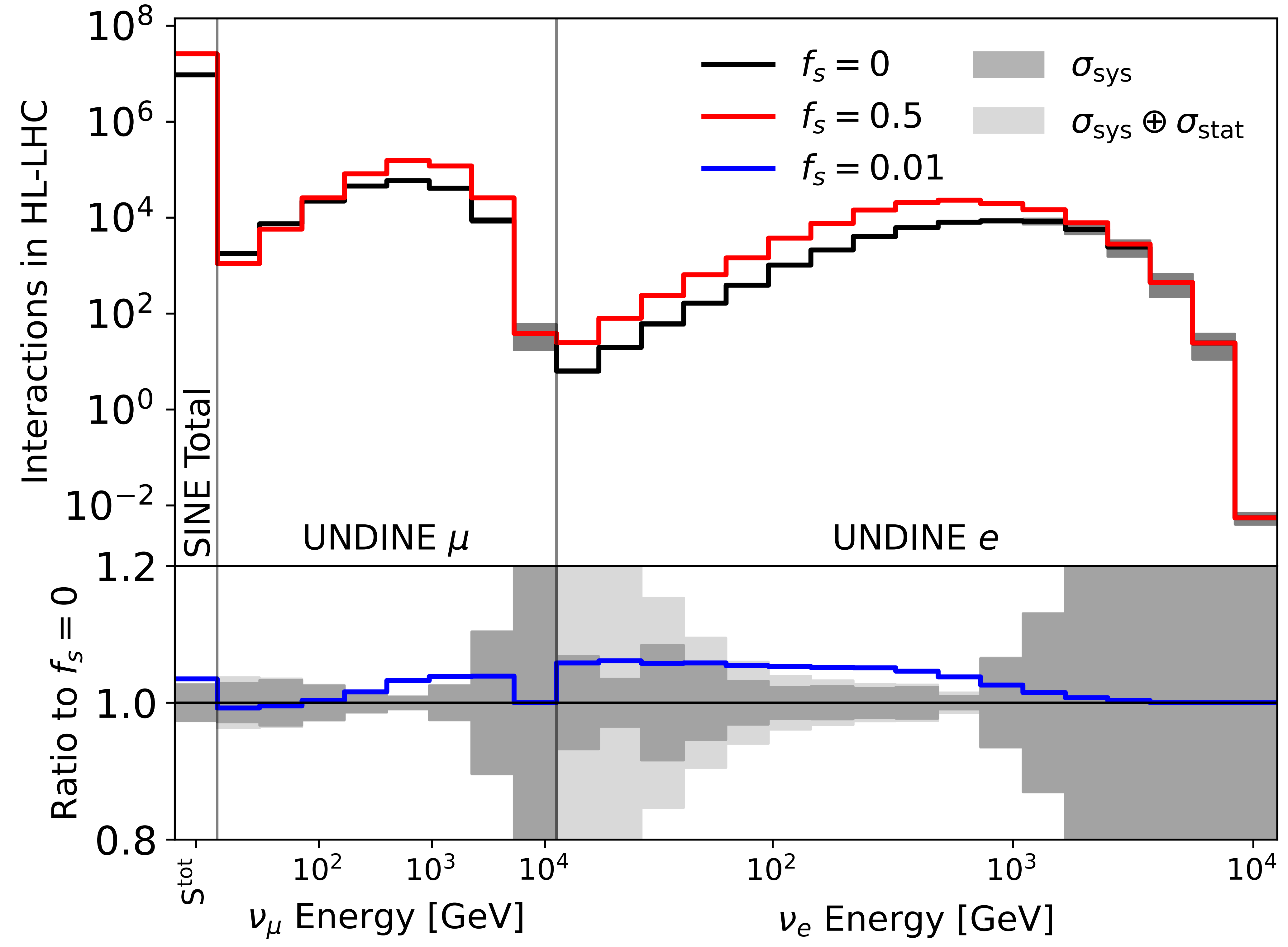
[1] Maciula+ 2022 [2] Jeong+ 2023

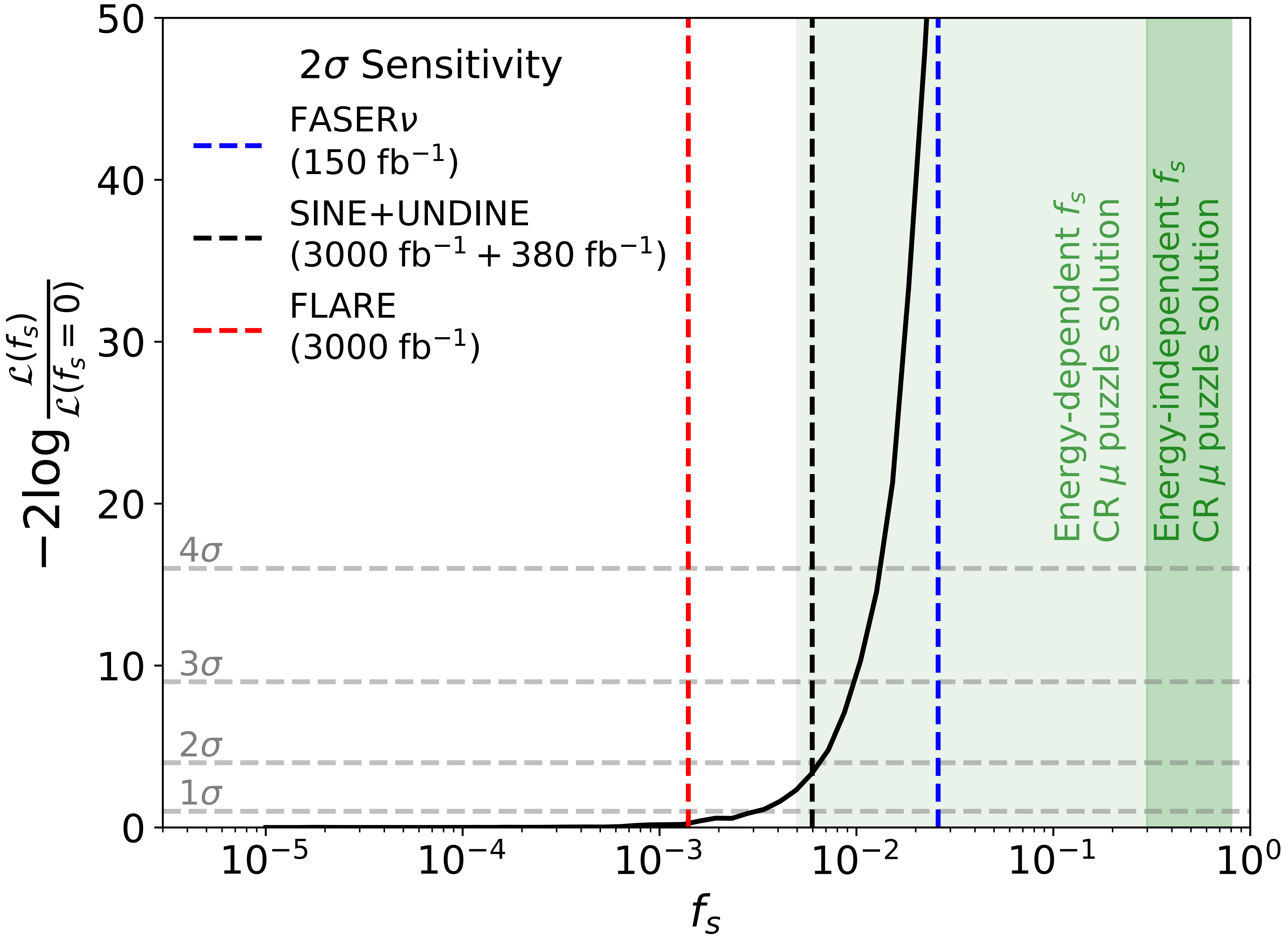
NK+ 2025

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 complementary sensitivity to future FPF experiments [3]



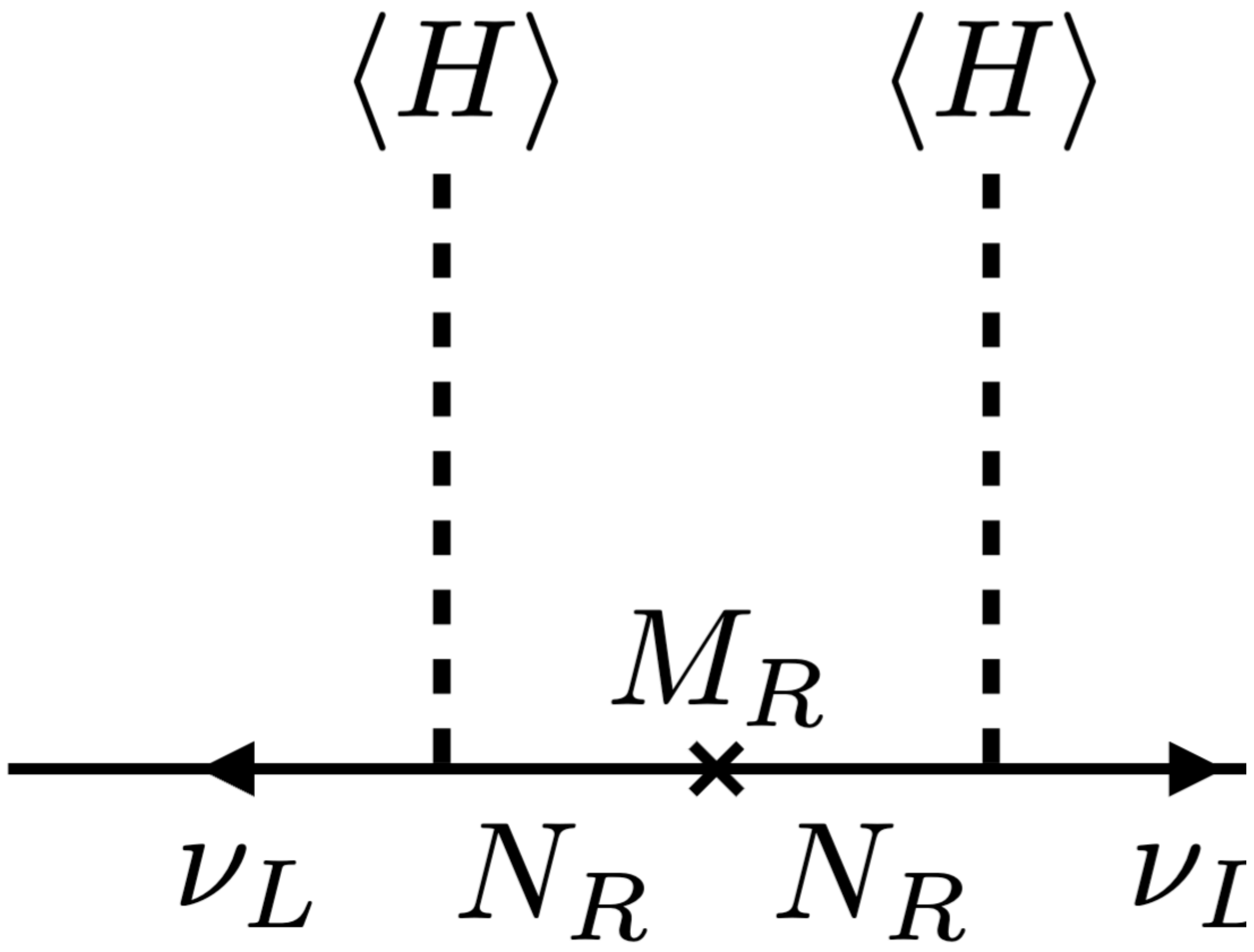


NK+ 2025

HNLs in Rock and Water

- **Mass-mixed HNLs:** minimal extension of the Standard Model with HNLs
- 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?



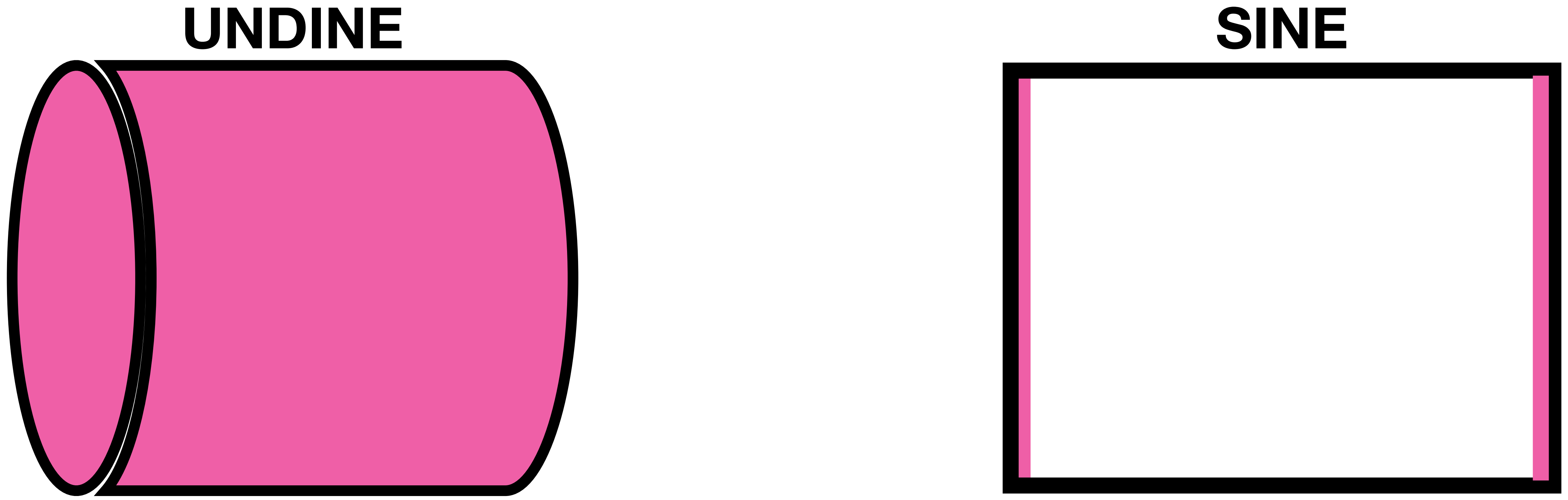
See-saw type I

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

Abudllahi+ 2022

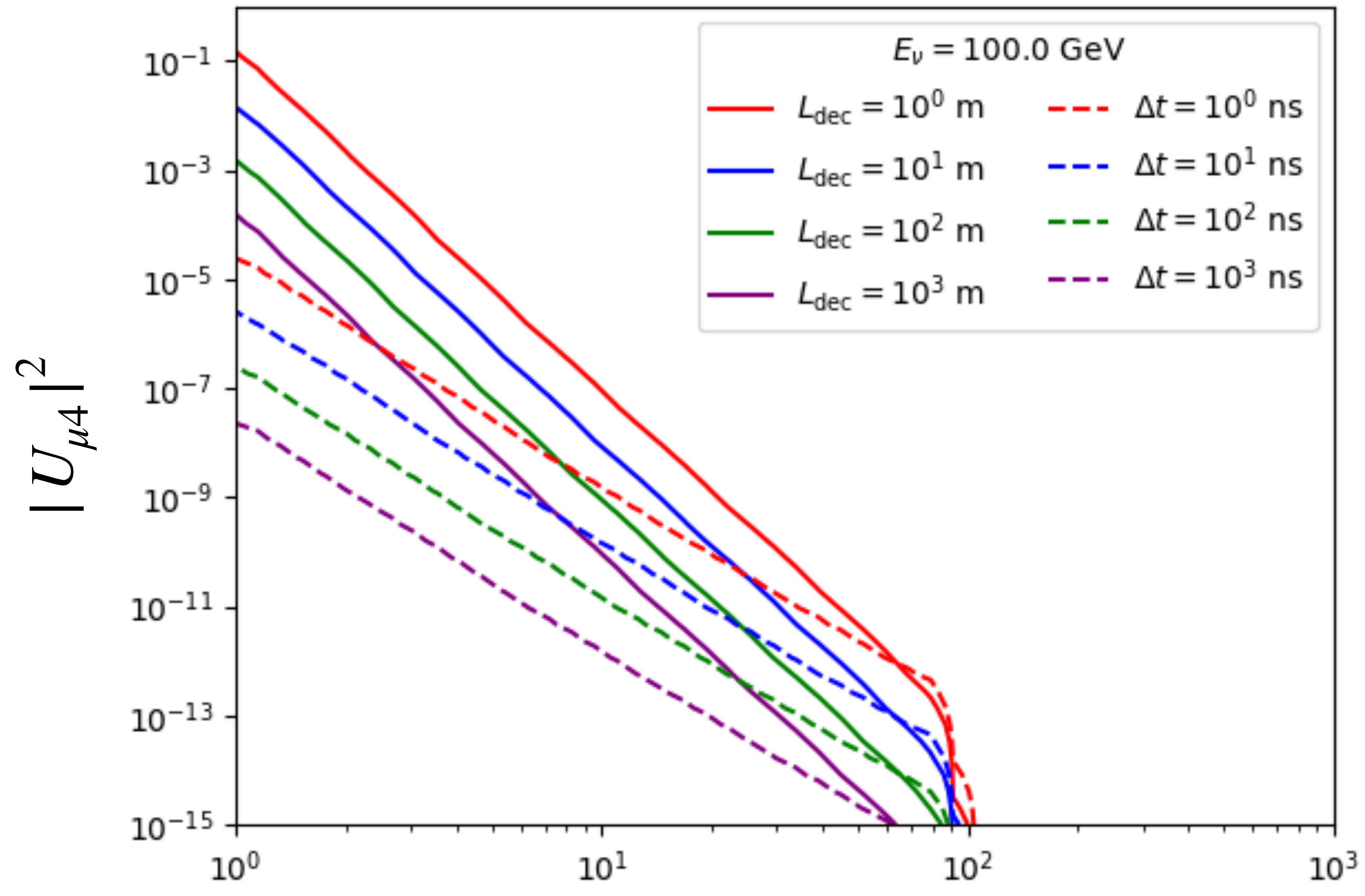
HNLs in Rock and Water

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



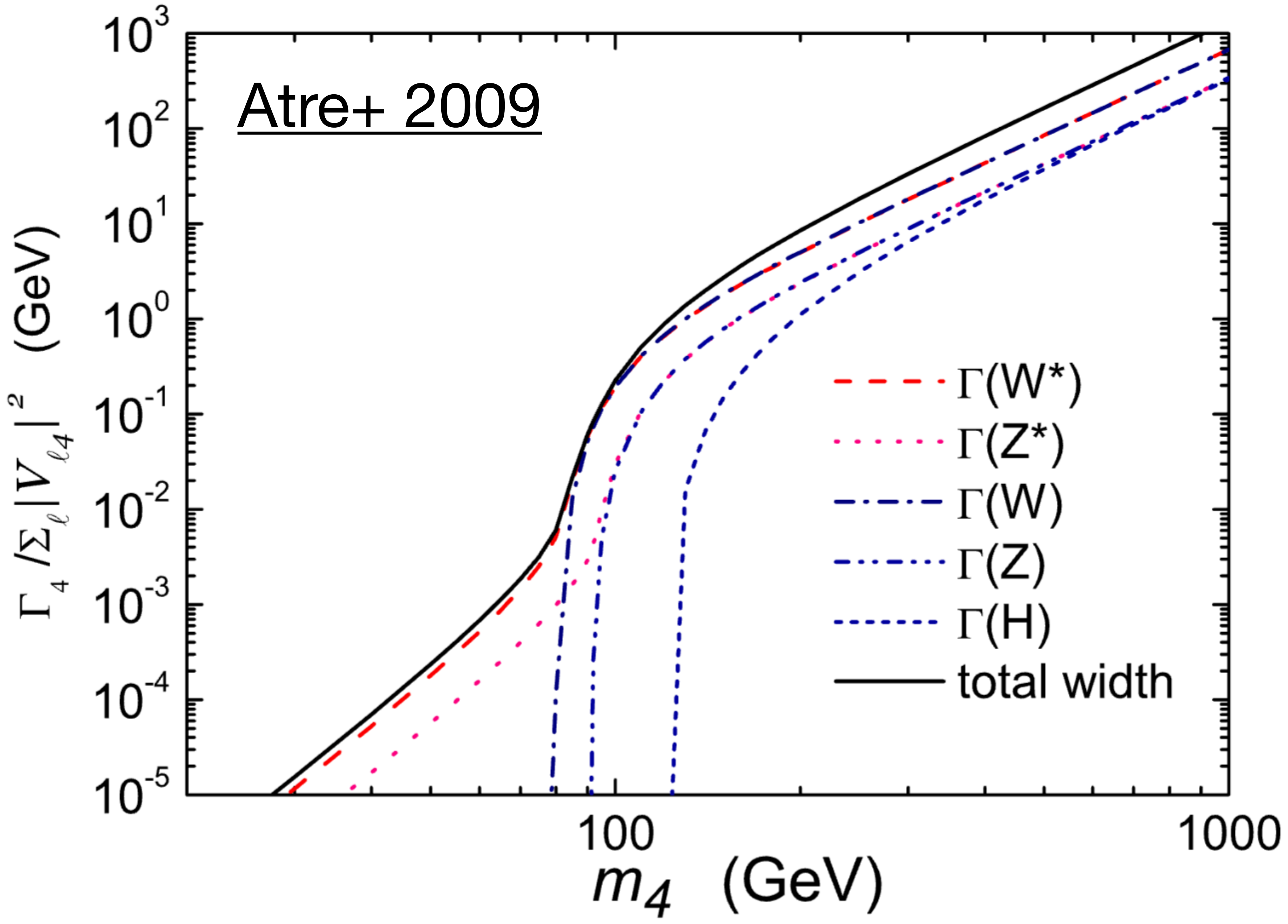
HNLs in Rock and Water

- 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



HNLs in Rock and Water

- 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 Rock and Water

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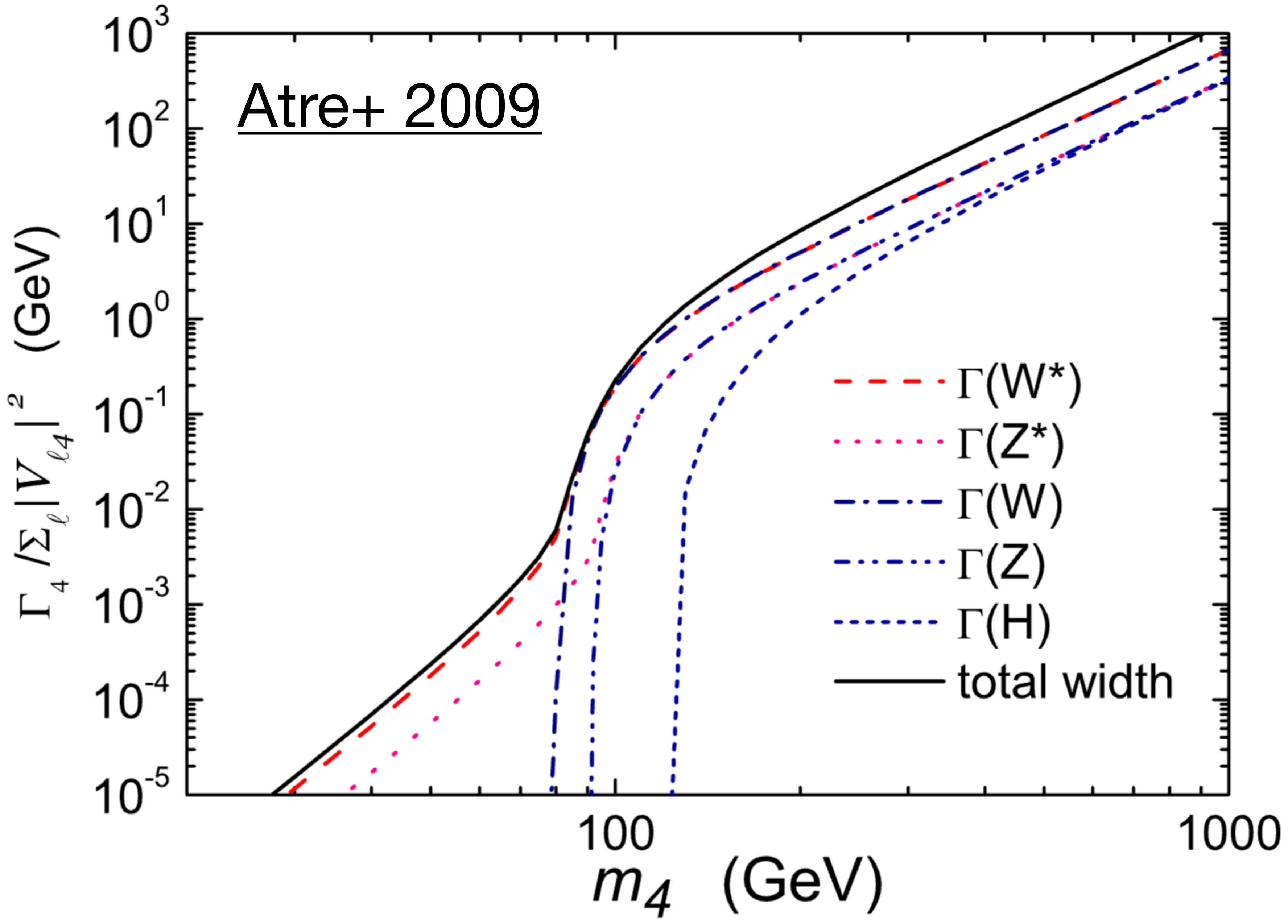
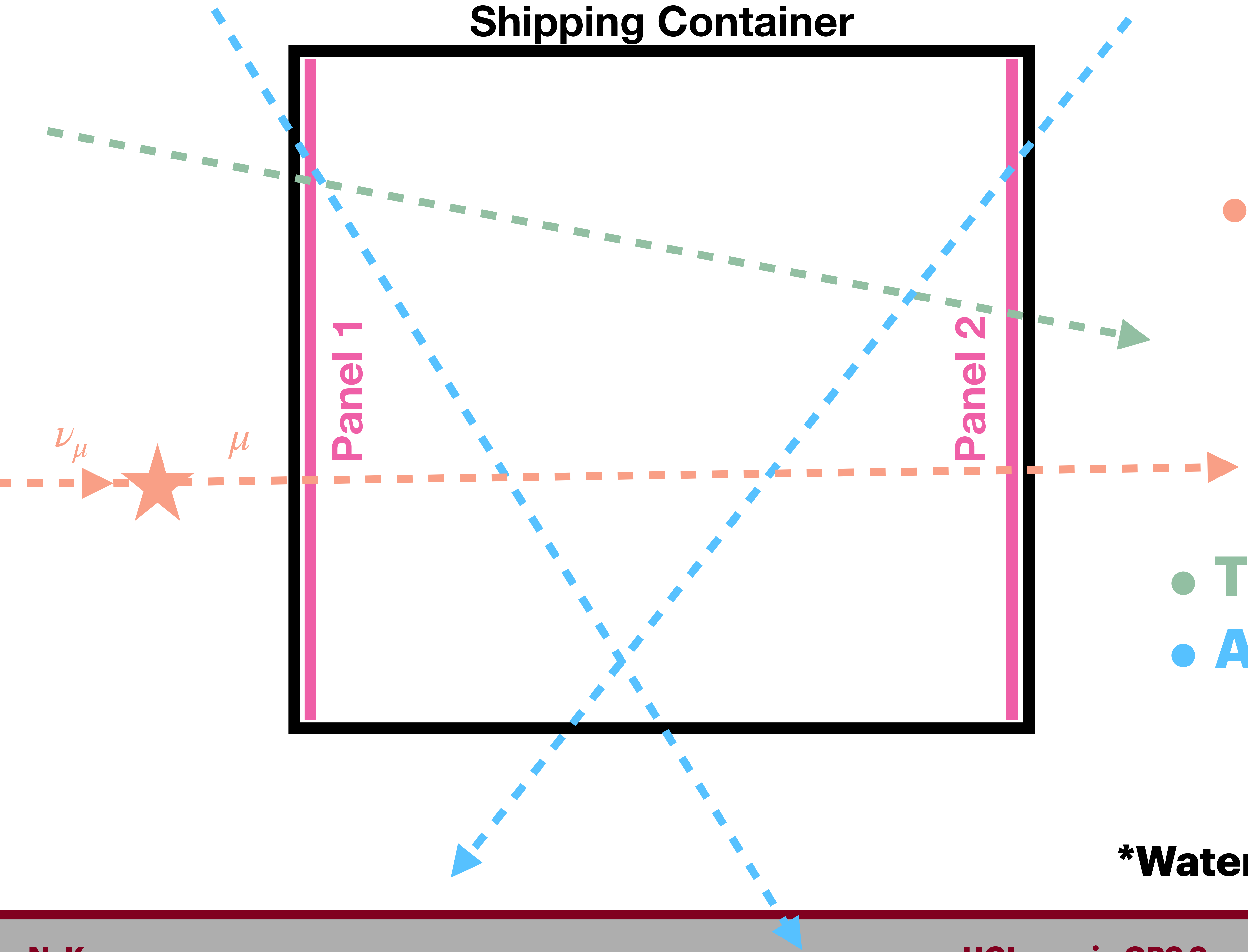
     Sensitivity studies in progress



Surface Detector Background



Signal

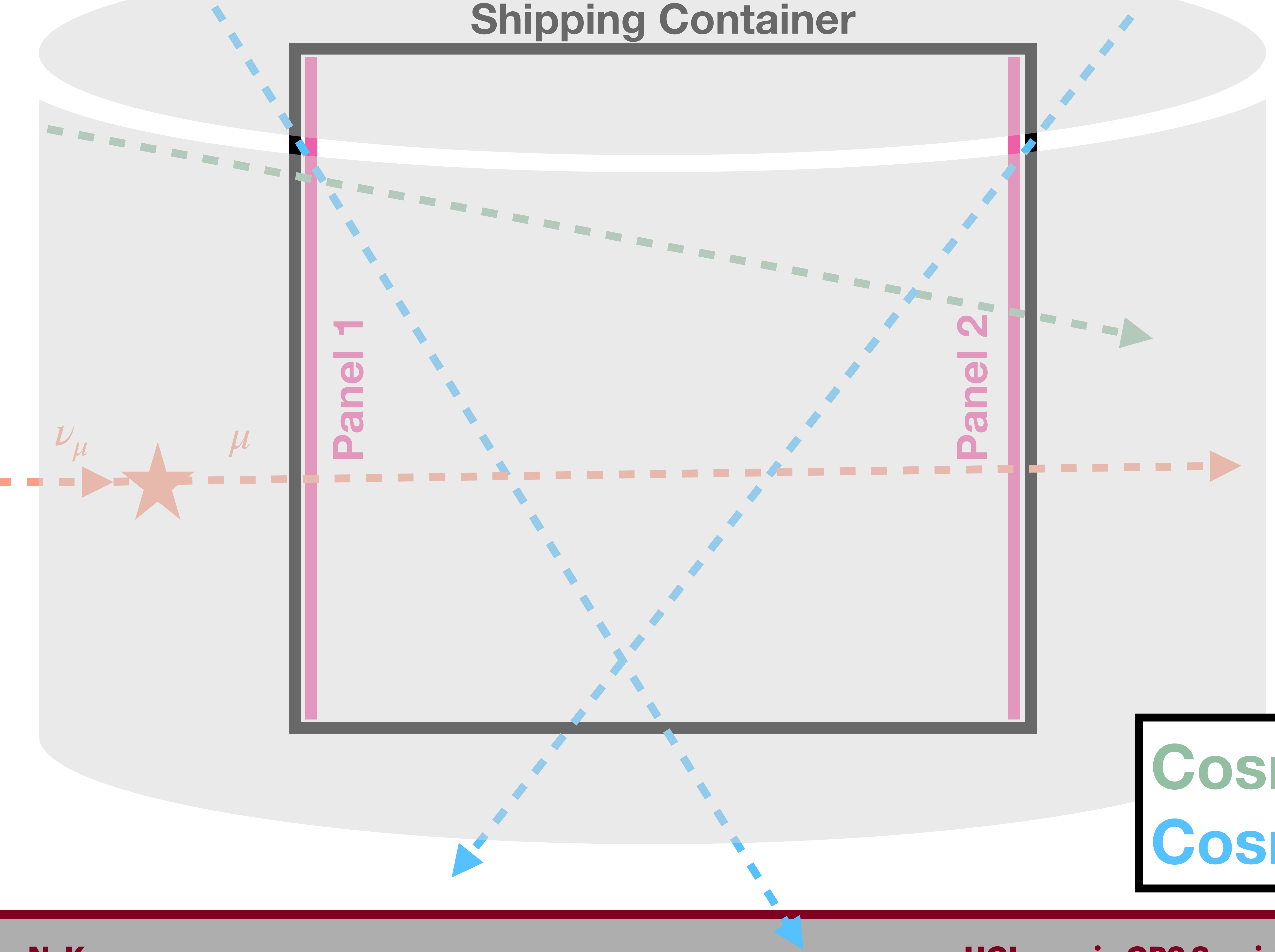
- True coincidence from a ν-induced muon ~11 mHz per surface detector during HL-LHC

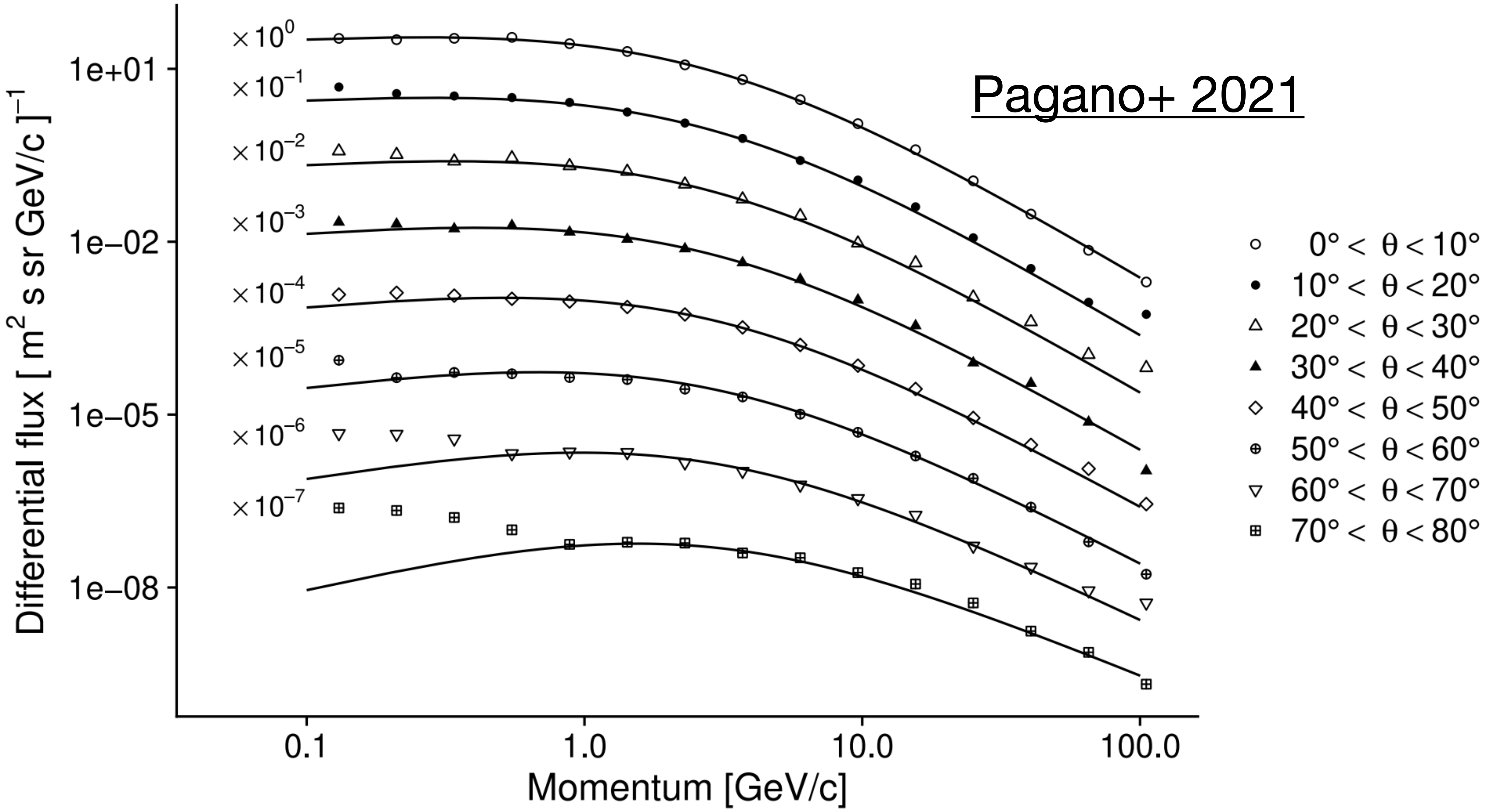
Background

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

***Water overburden reduces cosmic backgrounds in lake detector**

Surface Detector Background





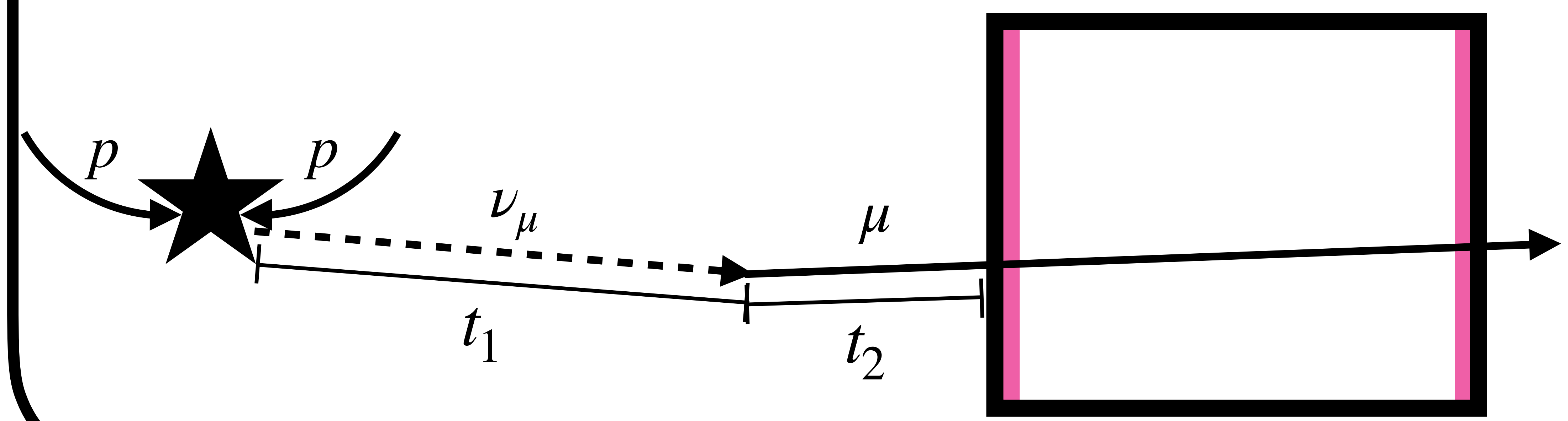
We use EcoMug to generate cosmic muons in a cylinder surrounding one of the shipping containers

Cosmic muon true coincidence rate: 1.67 kHz

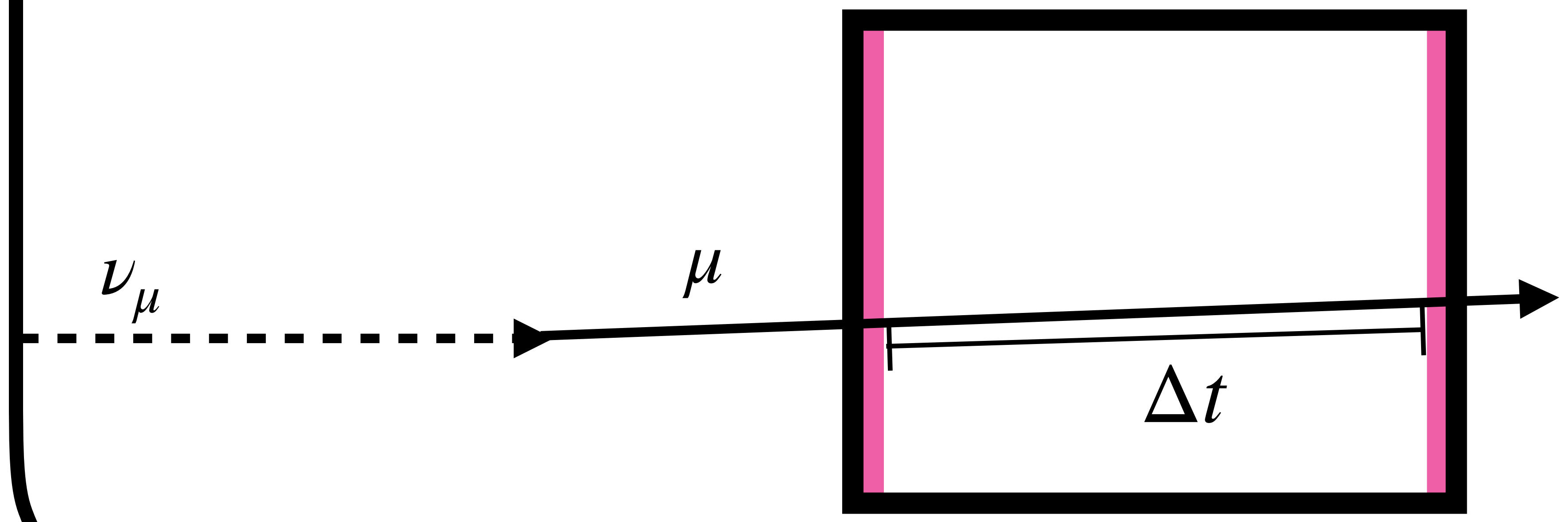
Cosmic muon single panel rate: 1.62 kHz

Four Strategies for Background Rejection

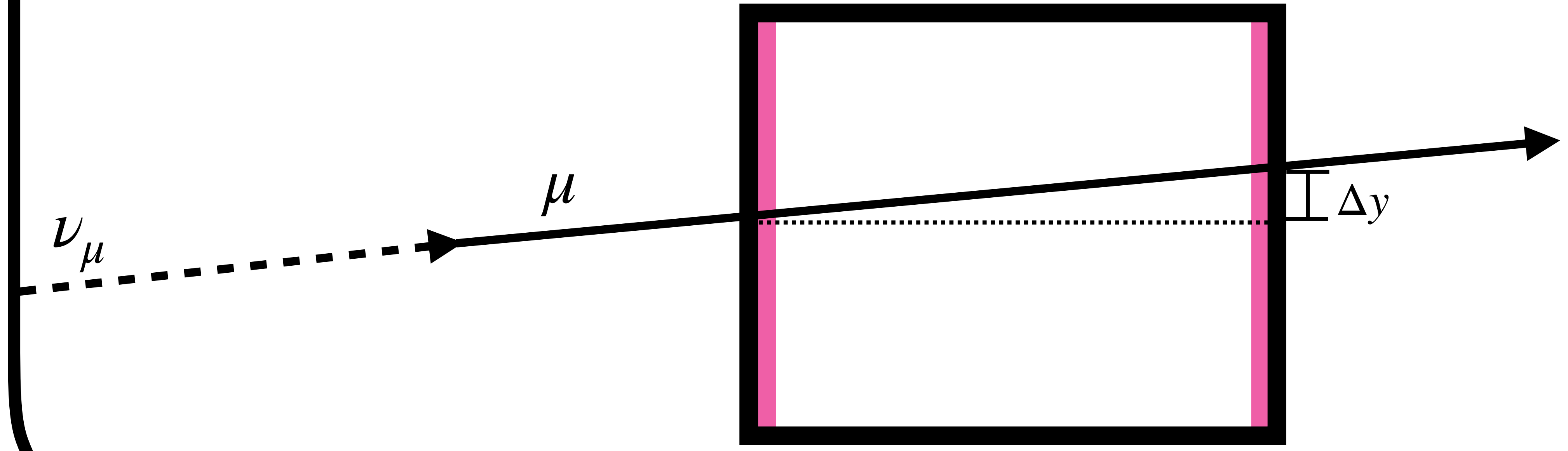
1. Timing with respect to proton collision



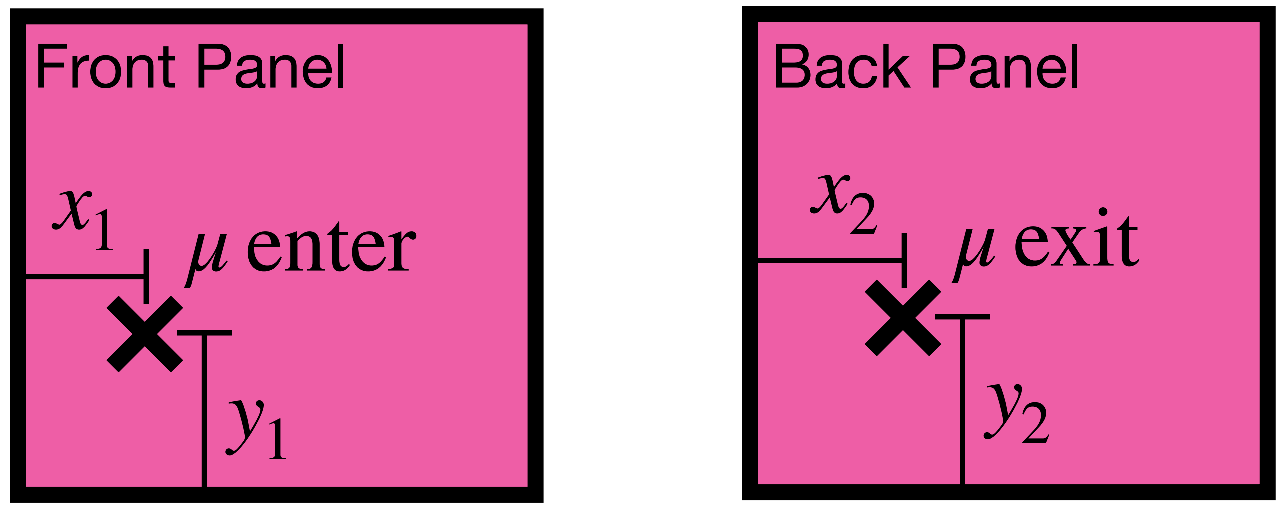
2. Time difference between scintillator panels



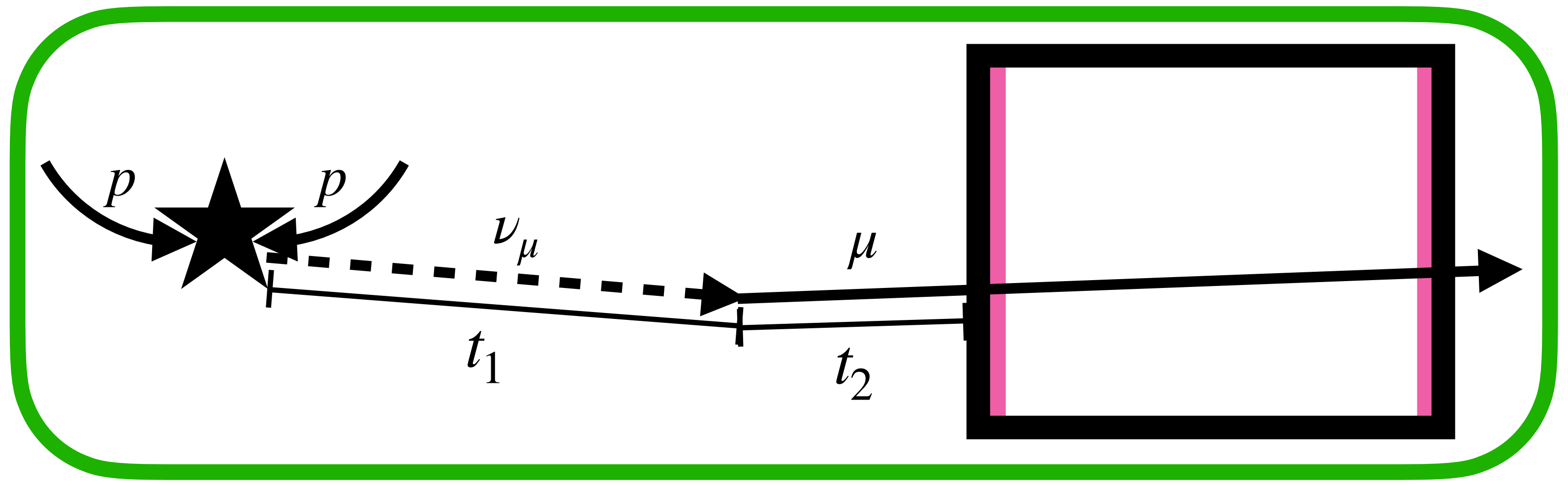
3a. Up-going spatial information

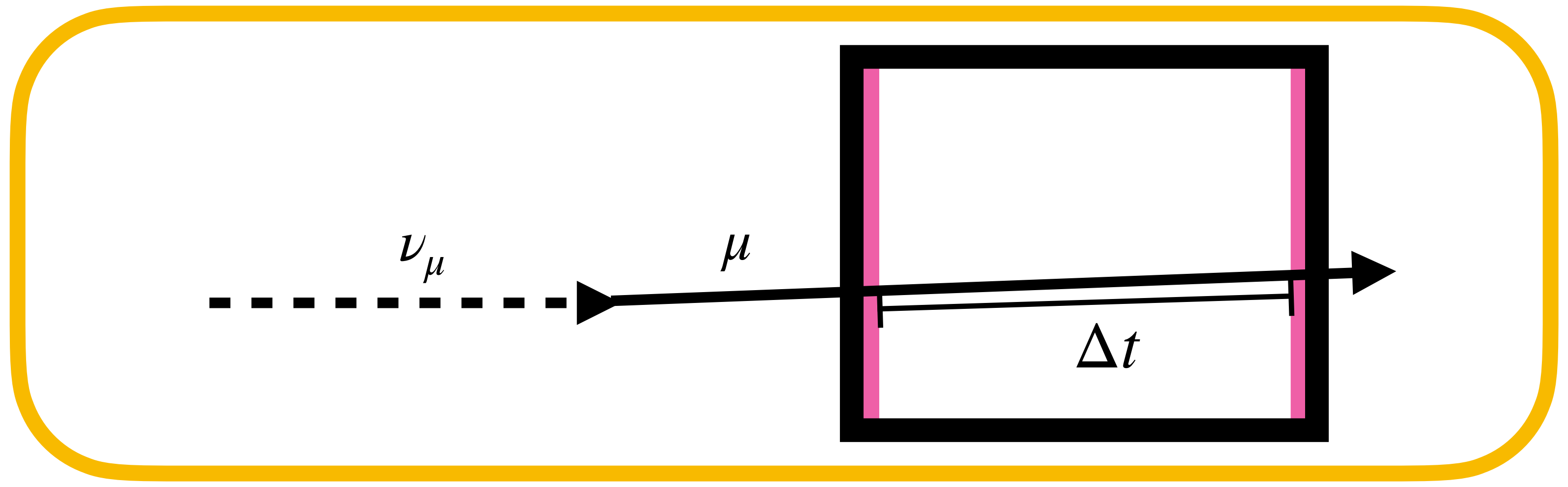


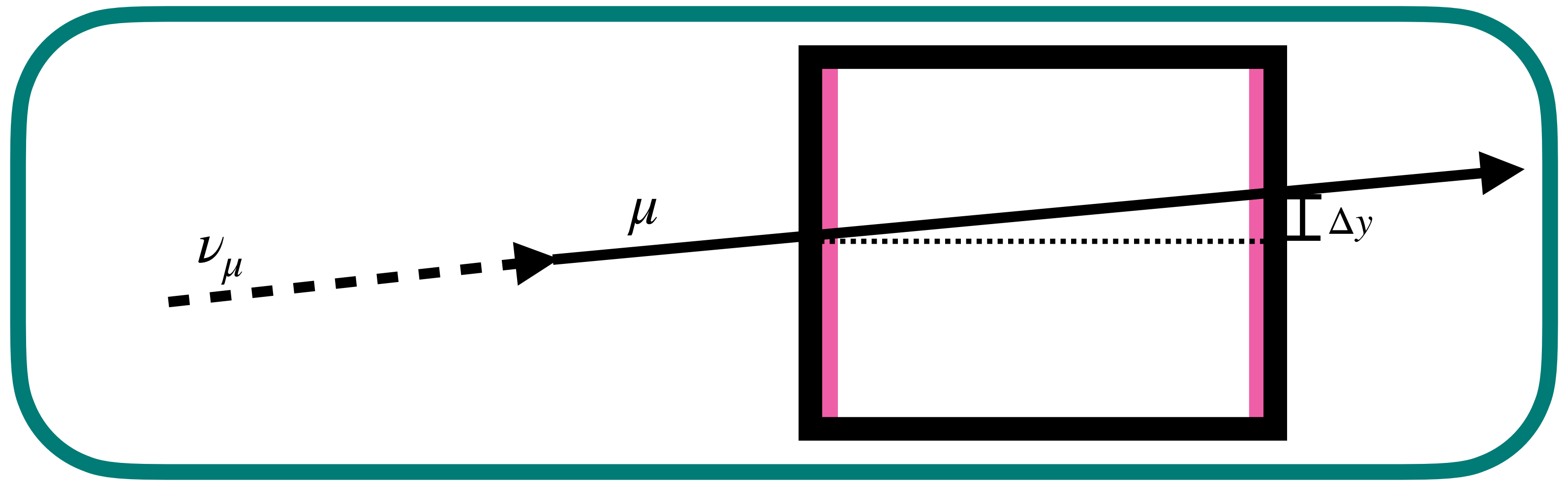
3b. Two-dimensional spatial information

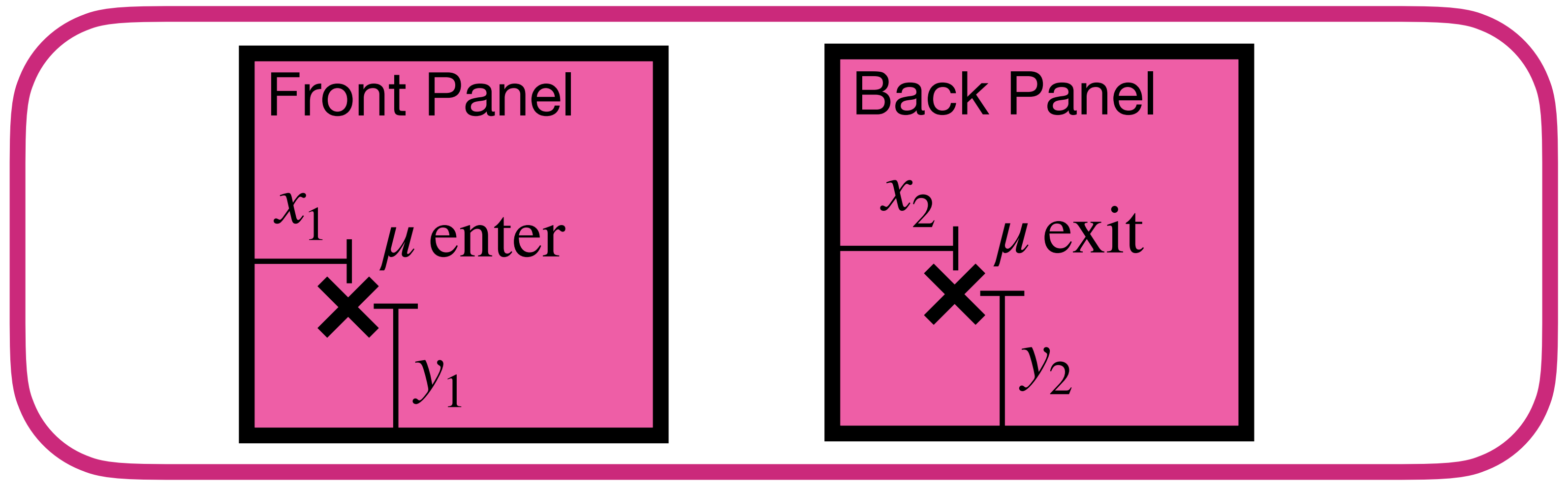


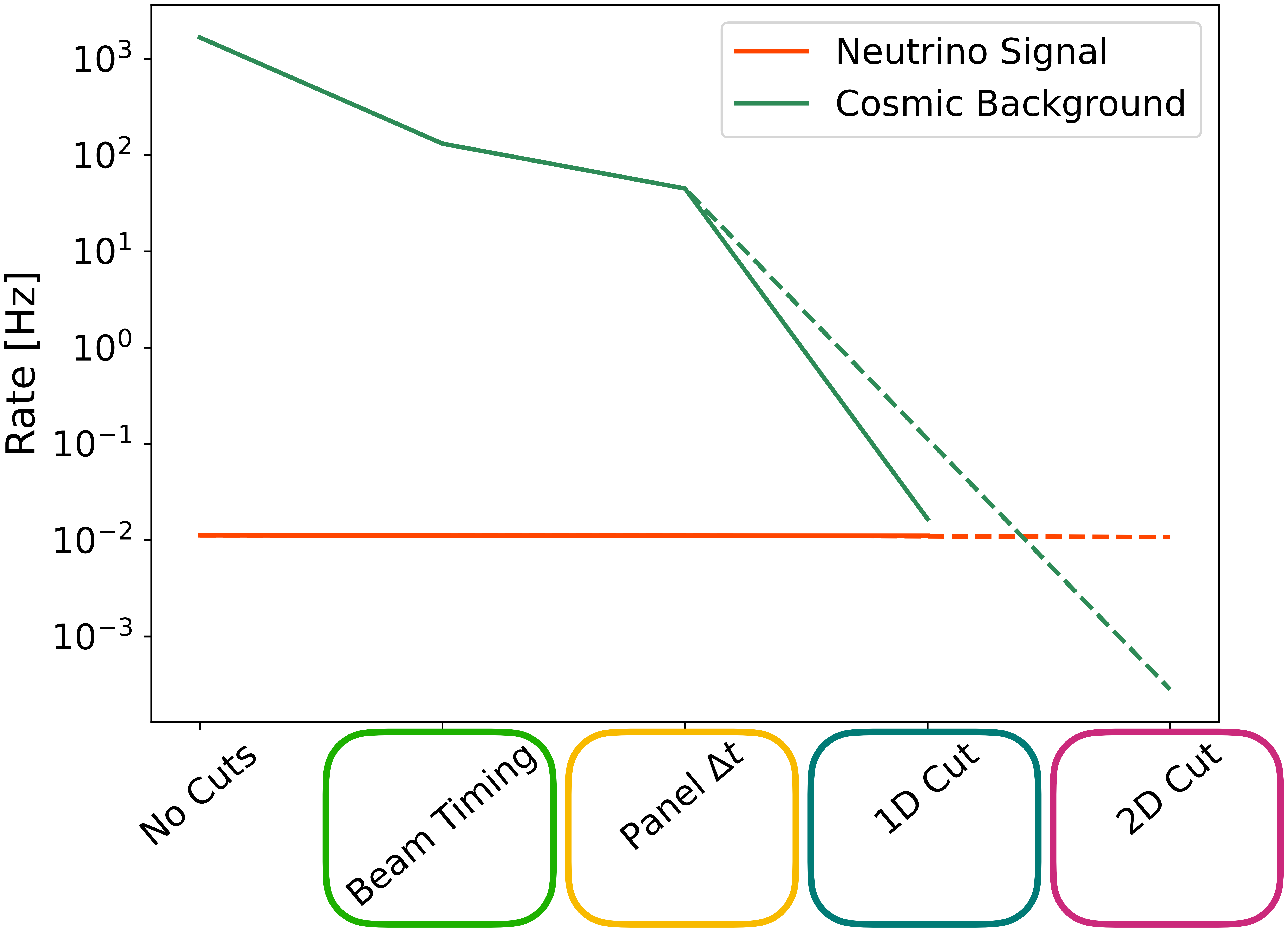
Surface Background Summary





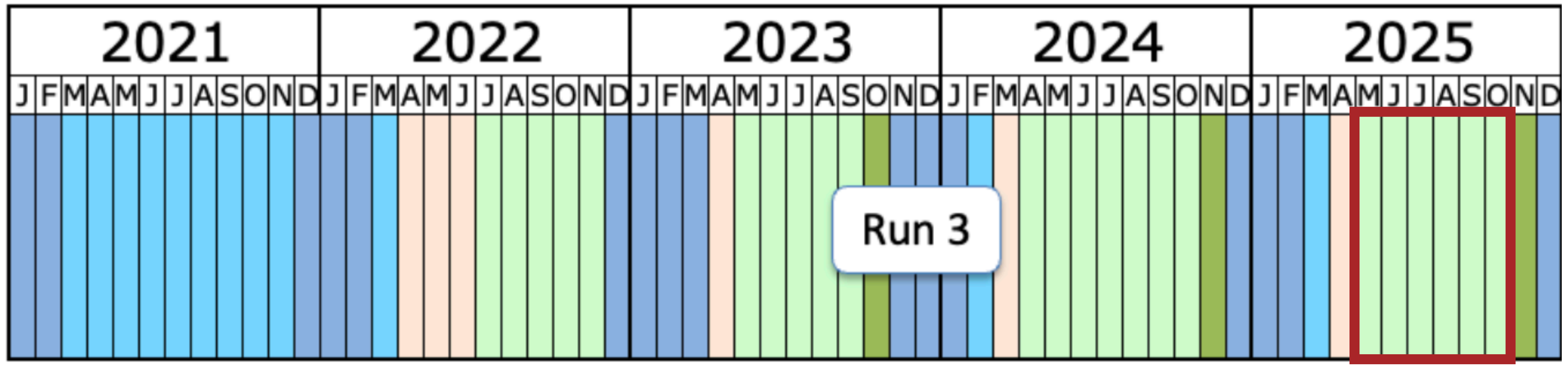






Prototype Surface Detector

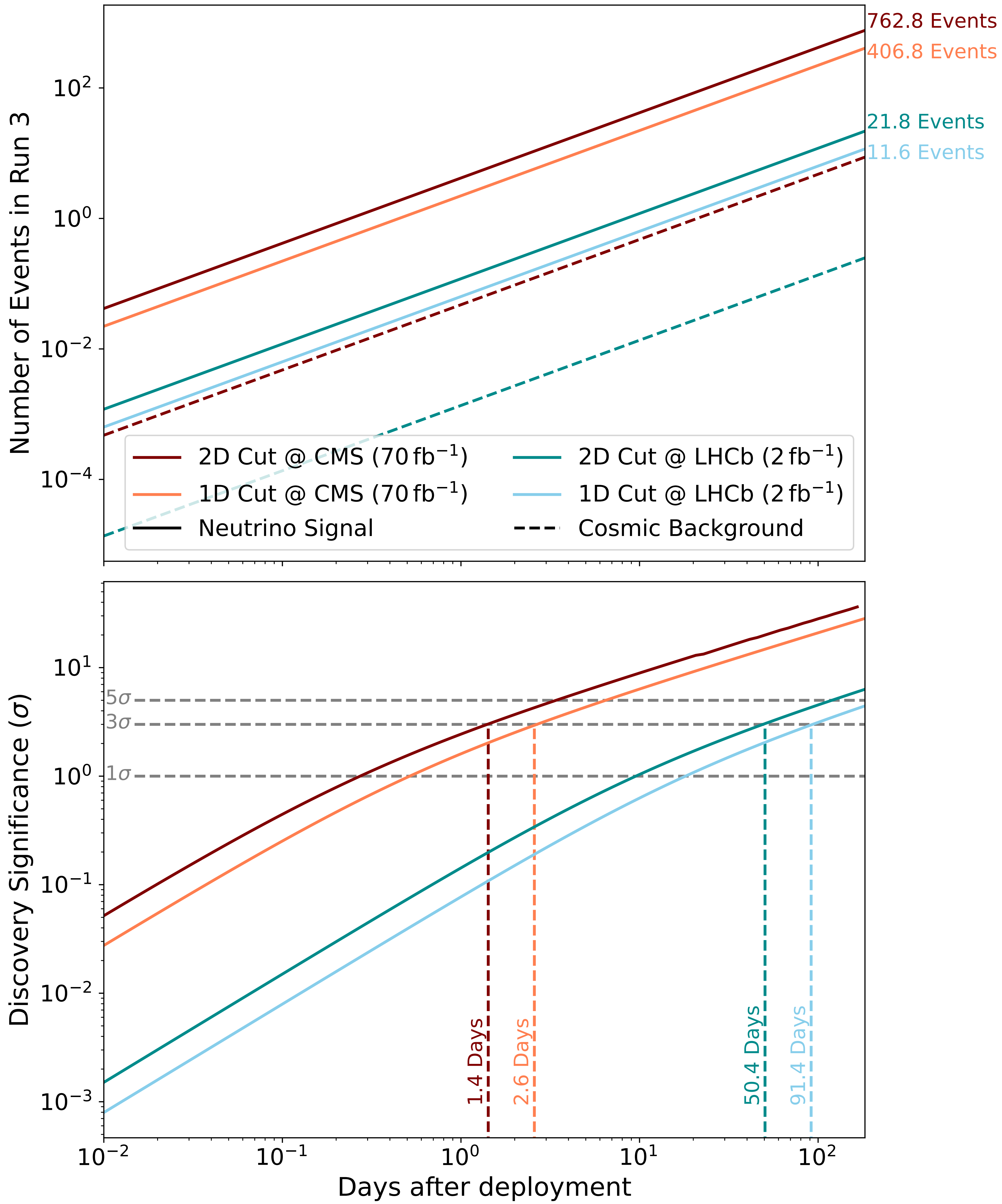
lhc-commissioning.web.cern.ch/schedule/LHC-long-term.htm



🟦 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



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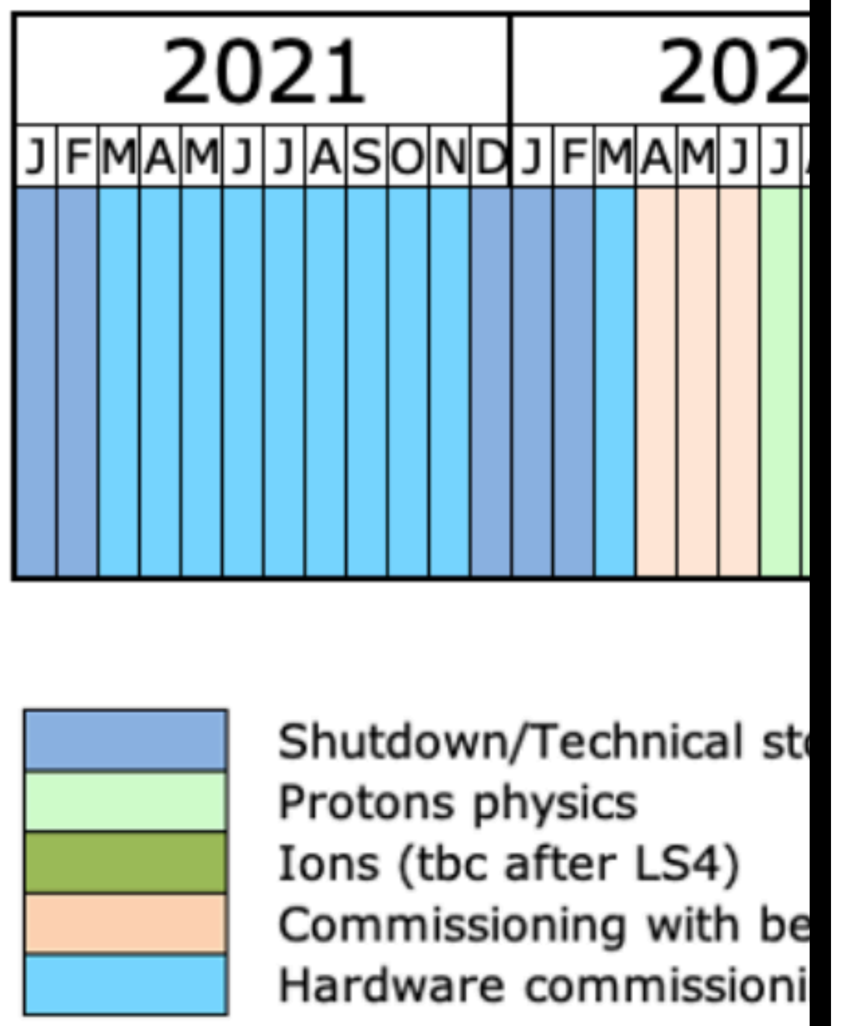
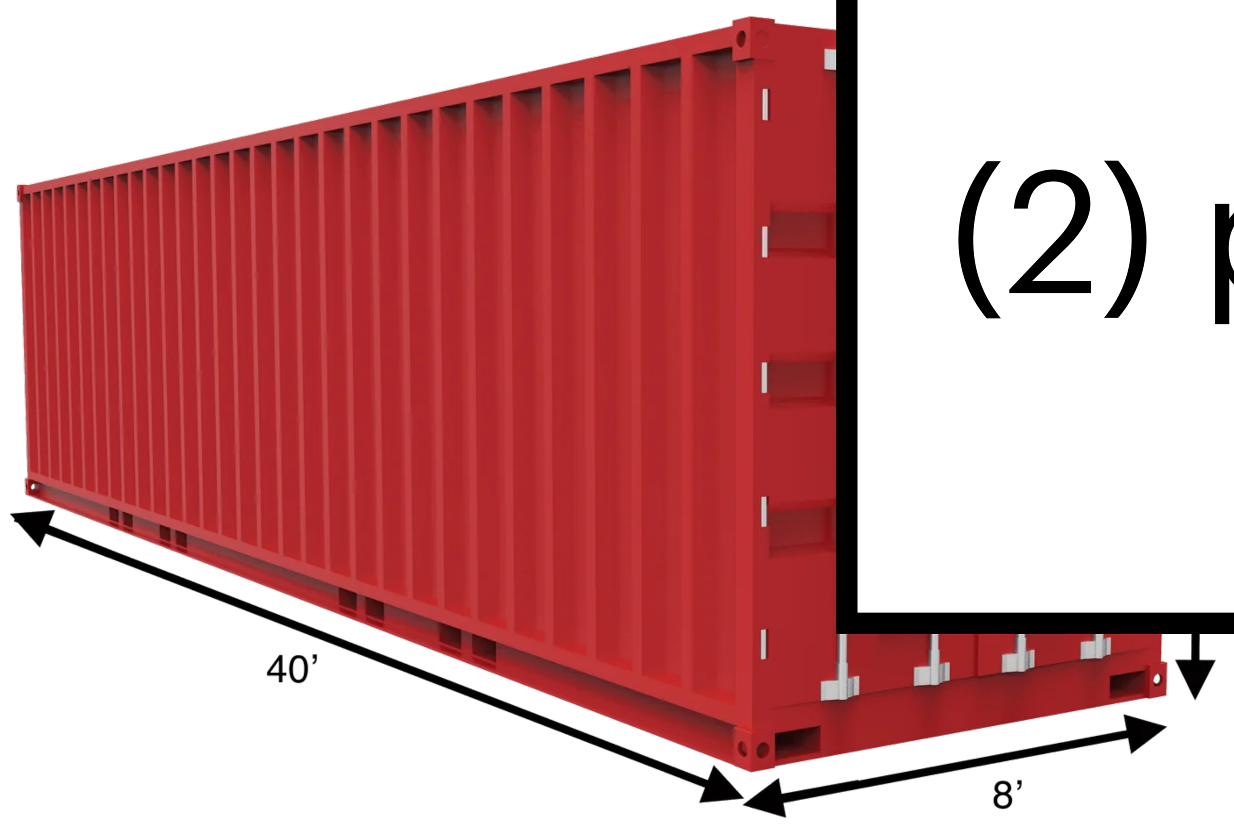
lhc-commissioning.web.cern.ch/schedule/LHC-long-term.htm



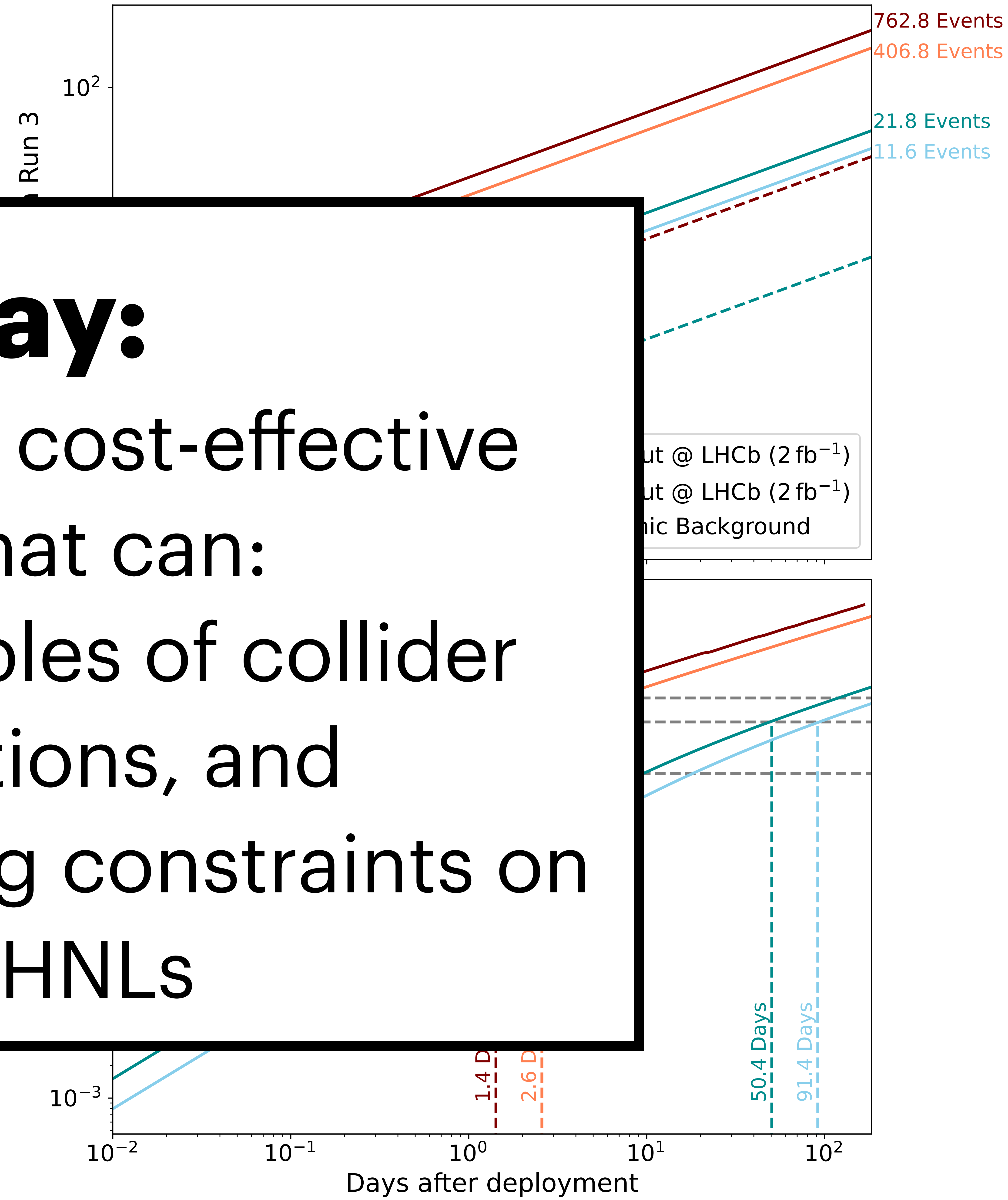


Takeaway:

SINE and UNDINE are cost-effective experiments that can:

(1) collect large samples of collider neutrino interactions, and

(2) potentially set strong constraints on mass-mixed HNLs



Conclusion

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SINE and UNDINE can collect large samples of collider neutrino interactions, constraining Standard Model neutrino physics and potentially HNLs

Thank you!

Backups