SIREN (Sampling and Injection for Rare EveNts)

A Toolkit for Standard and Non-Standard Neutrino Physics

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Neutrino-Nucleus Interactions in the Standard Model and Beyond

MITP | 20 May 2025

Altkönig Viewpoint

Harvard-Neutrino / SIREN

A. Schneider, NK, A. Wen. 2024

A. Schneider

A. Wen

the David & Lucile Packard FOUNDATION

NSF

Outline

1. Overview of SIREN
2. Using SIREN for…
   - BSM physics with accelerator neutrinos
   - SM physics with collider neutrinos
   - SM + BSM physics with neutrino telescopes

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- Full detector simulations to estimate signal rates are **computationally expensive**
- Home-brewed detector simulations must make **simplifying approximations**
- **But sometimes, detector geometry details are important!**

When Detector Geometry Matters: An Example

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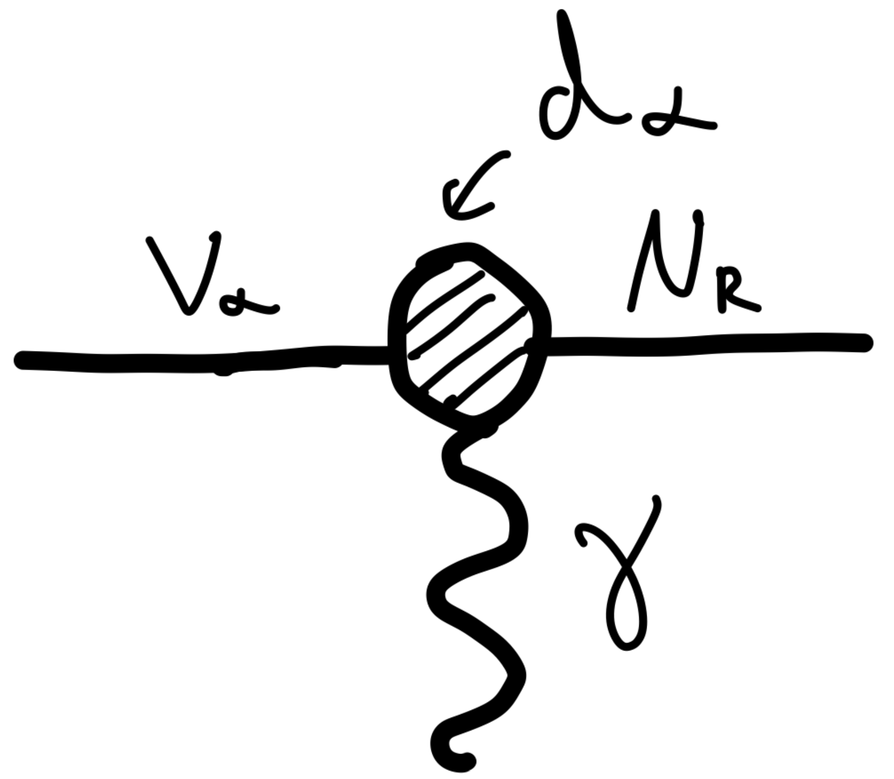
Dipole-Portal HNL

Heavy neutral lepton (HNL) with an effective transition magnetic moment

Parameters

- M_N : HNL mass
- $d_{\alpha N}$: effective dipole moment



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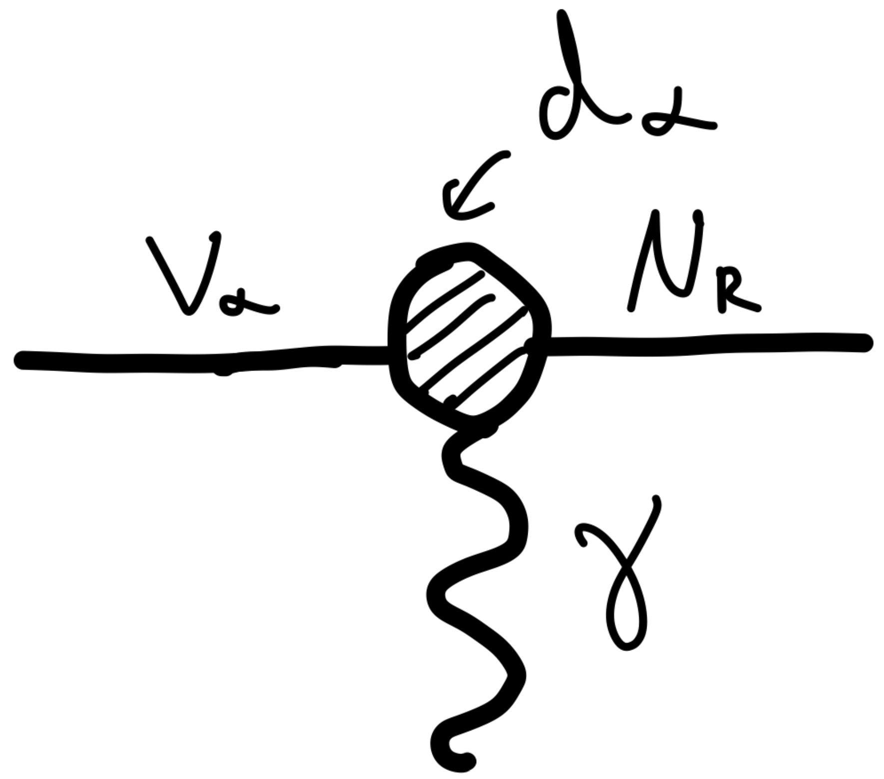
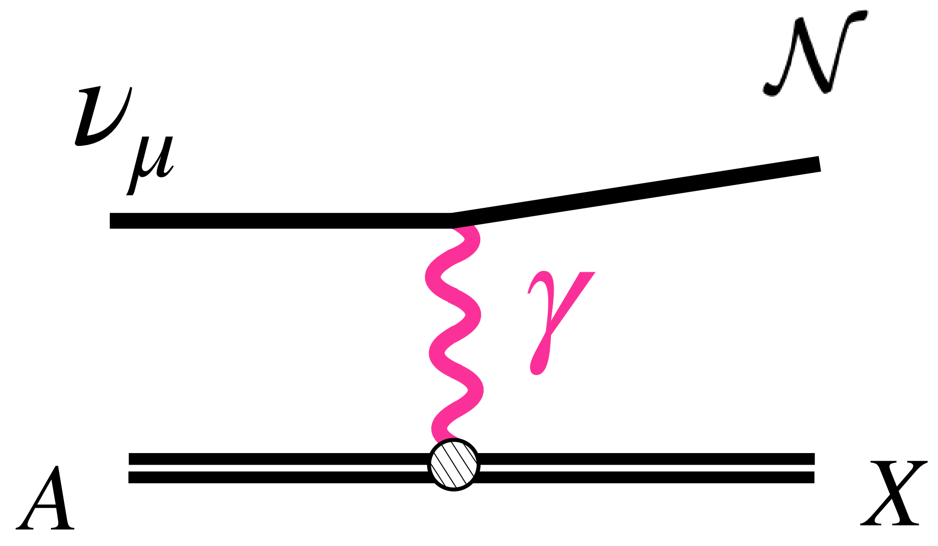
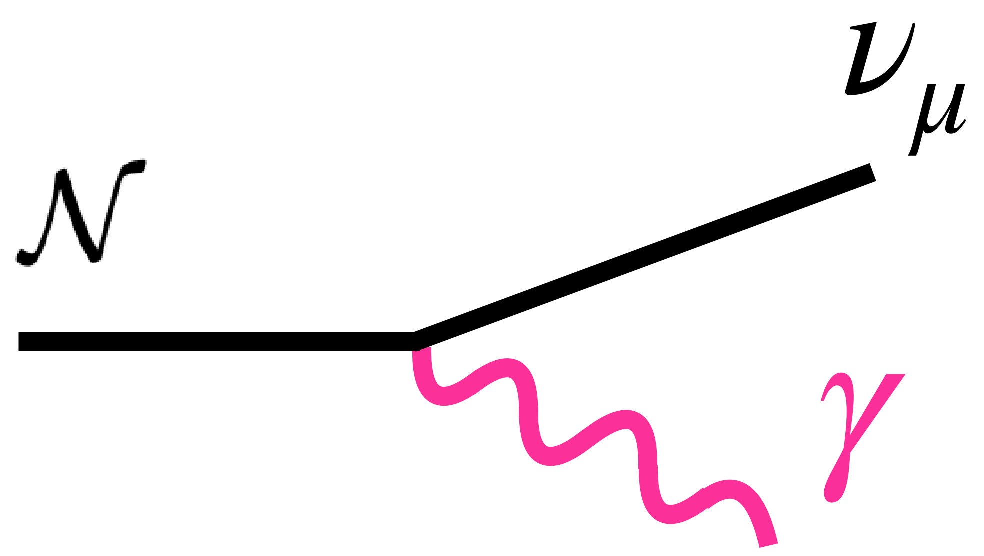


Production



Detection



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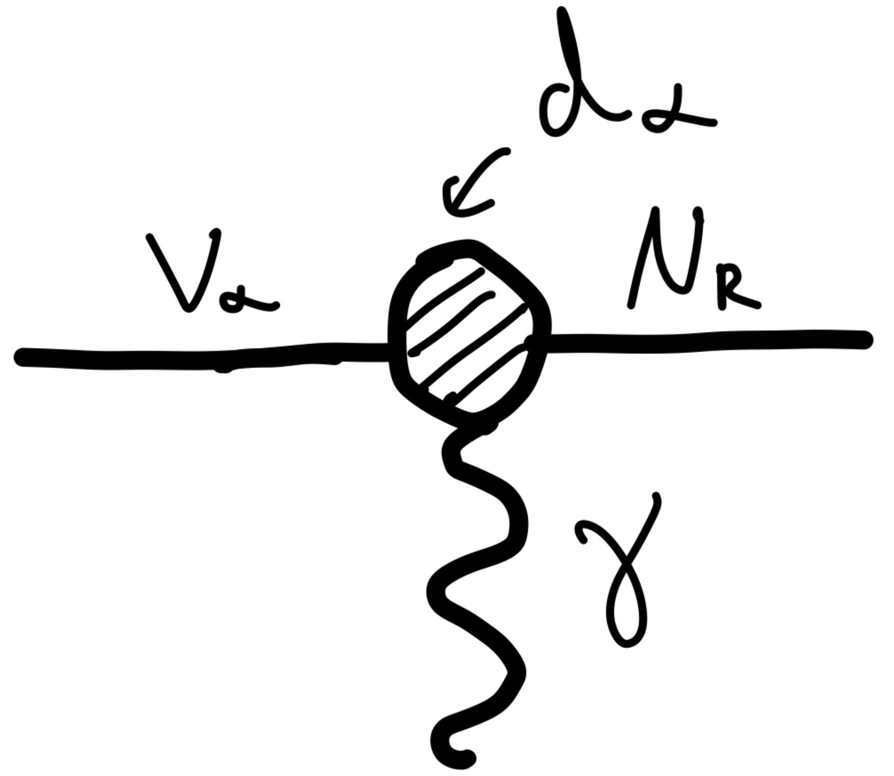

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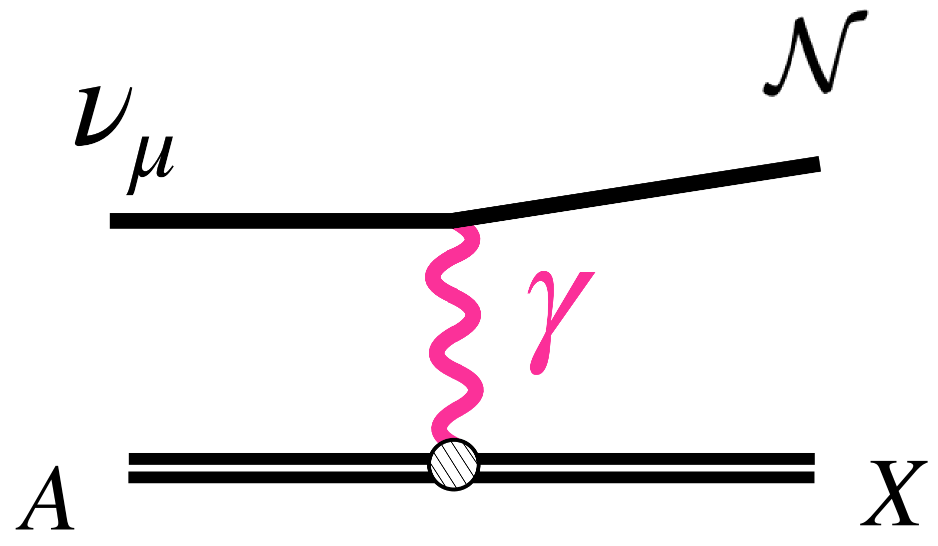

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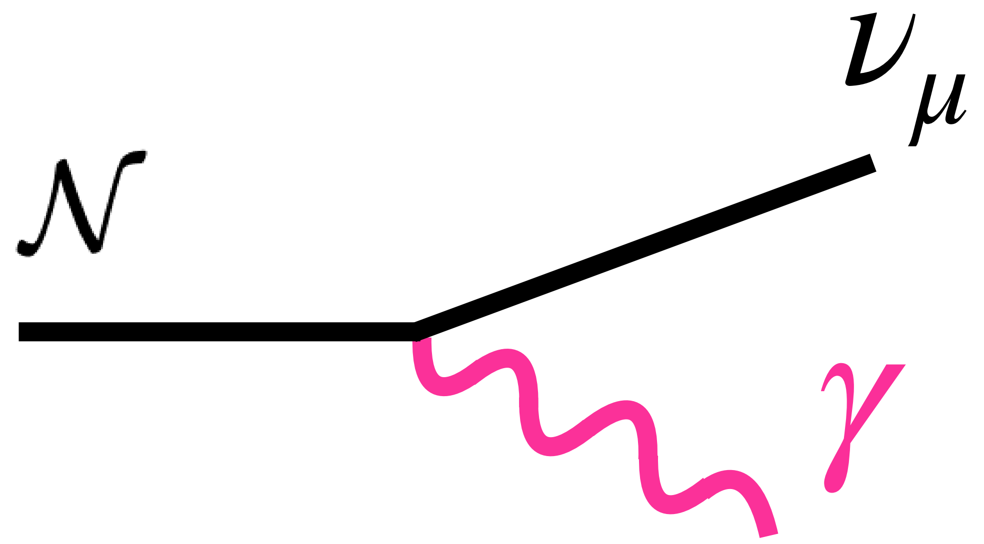
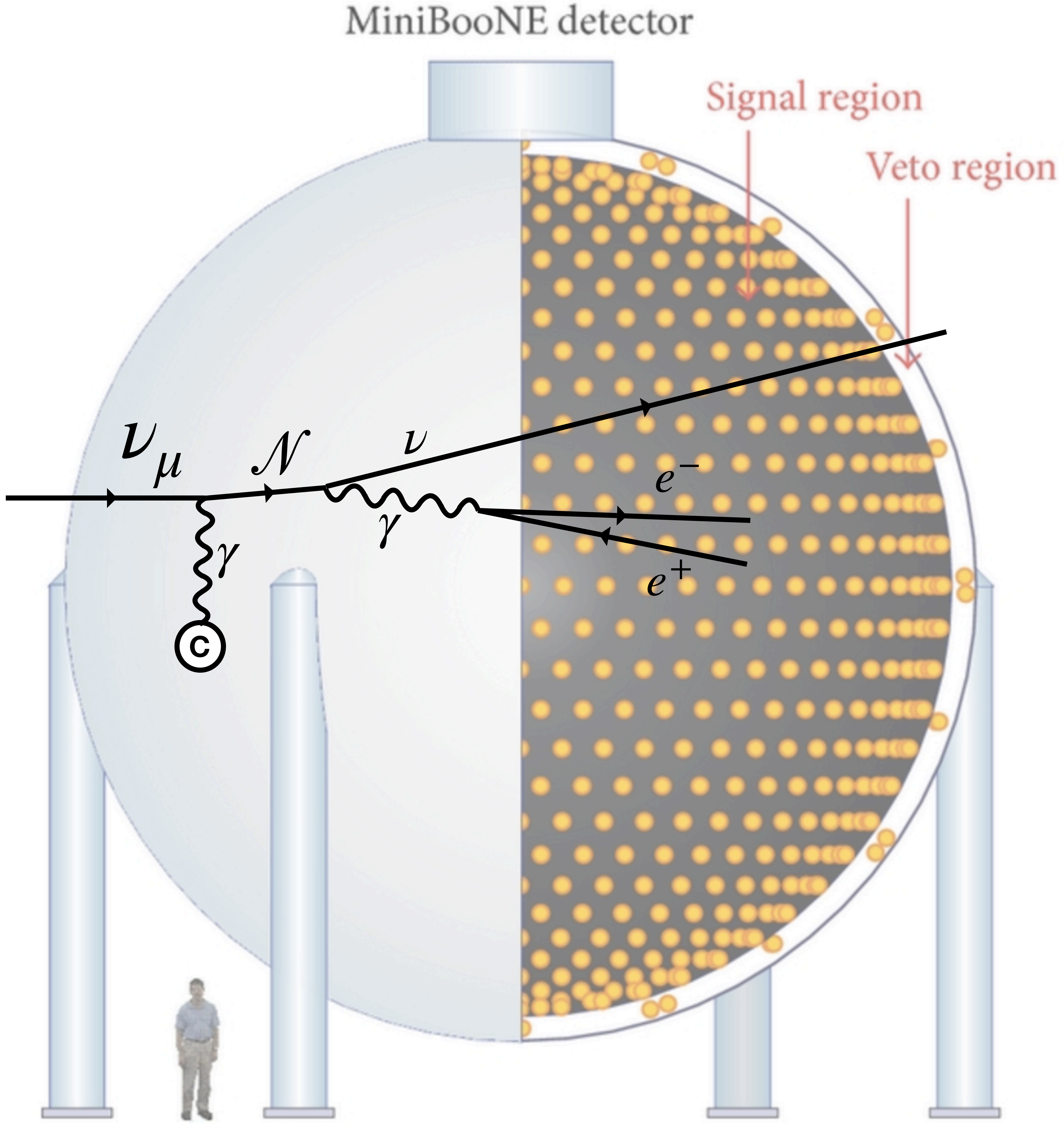


Simple detector geometry: MiniBooNE



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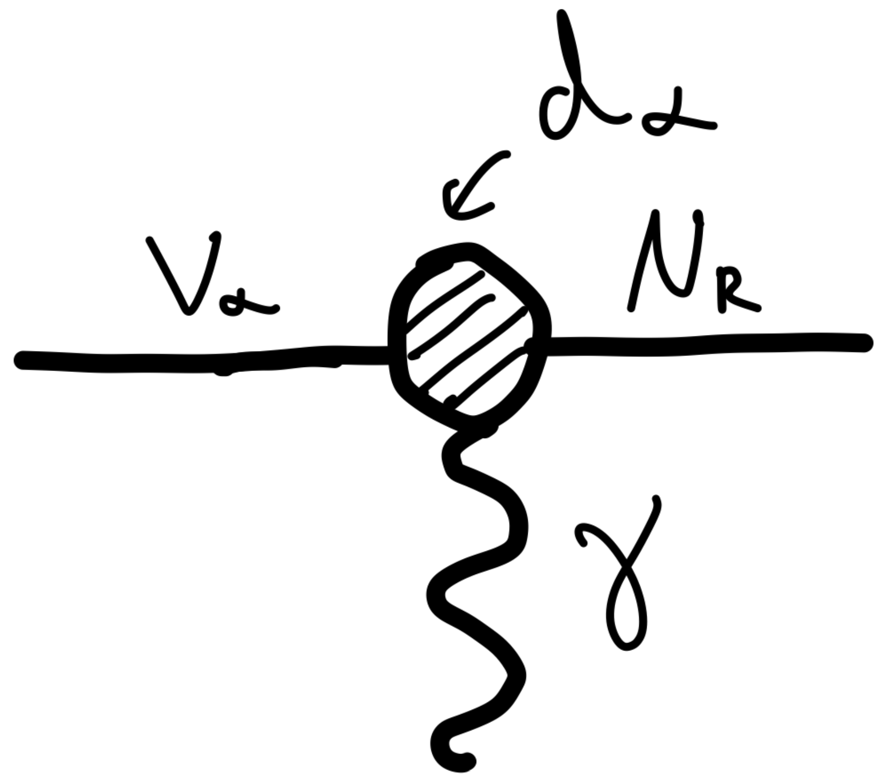

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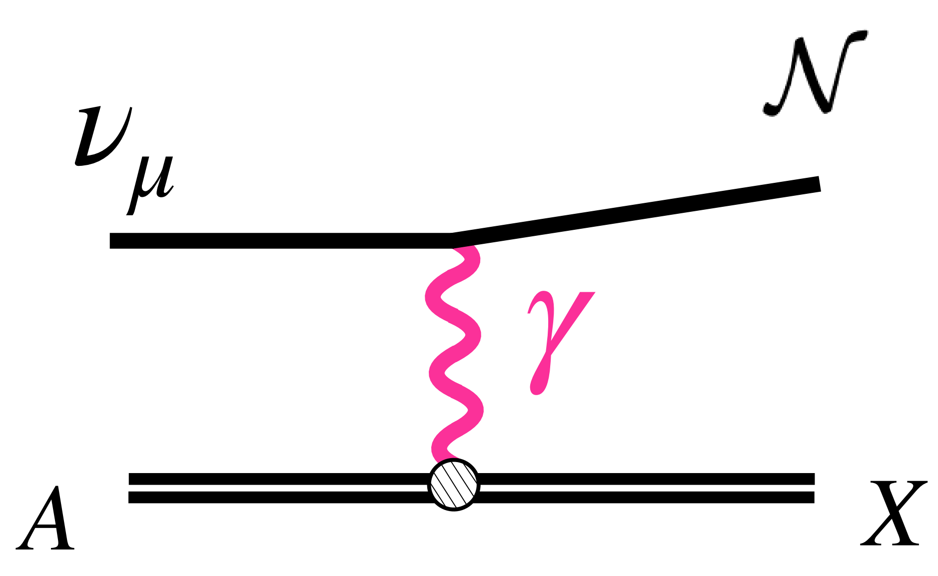

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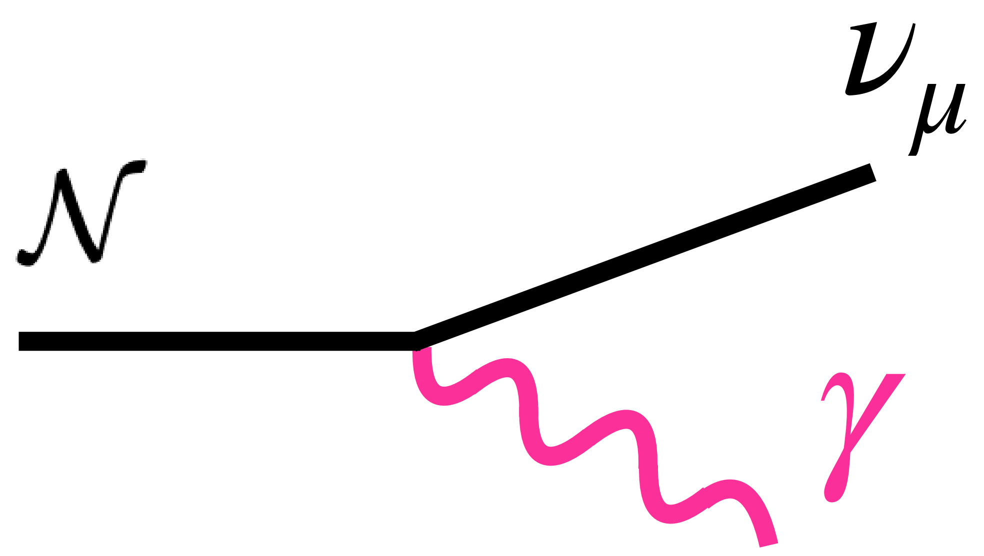
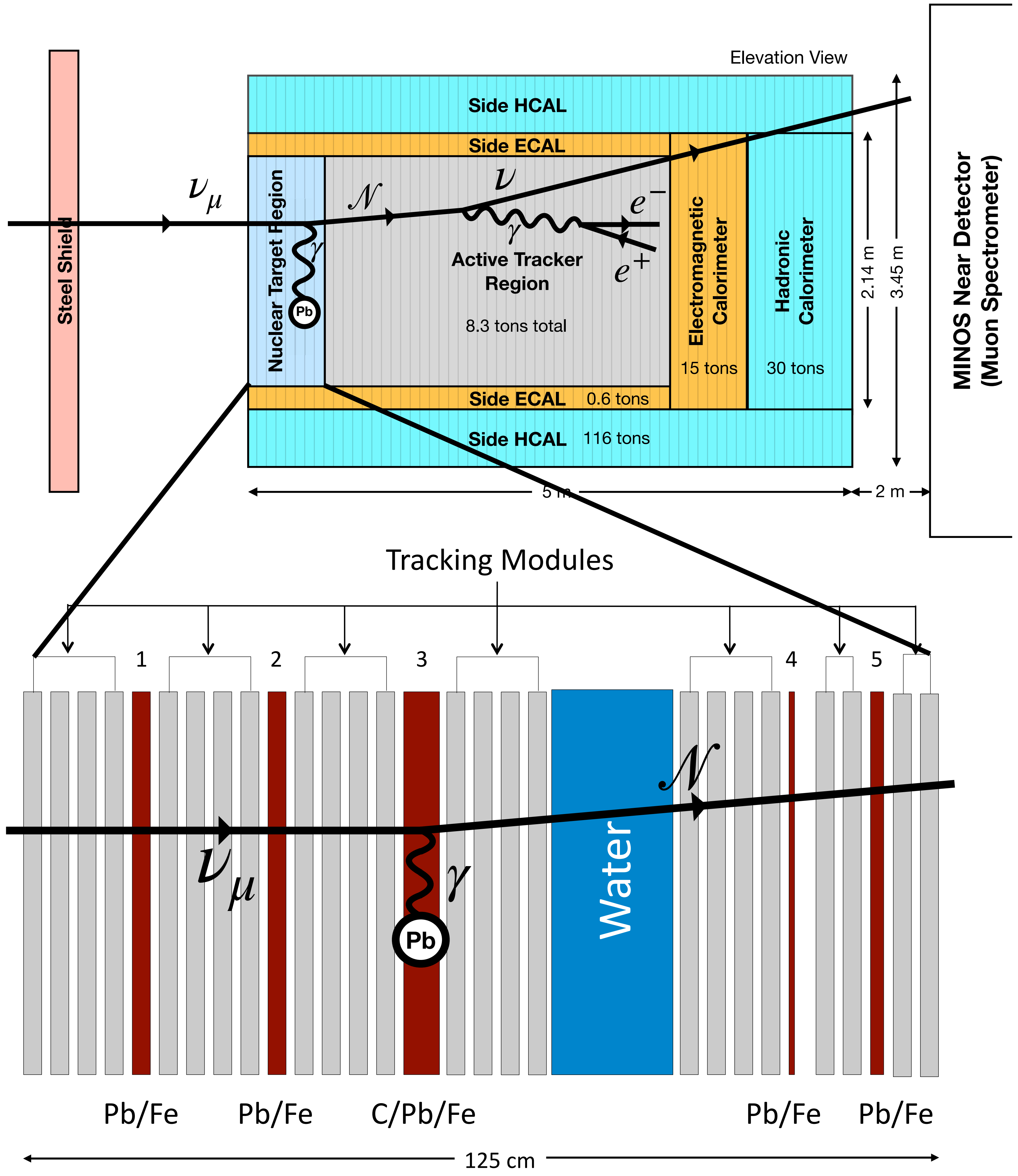
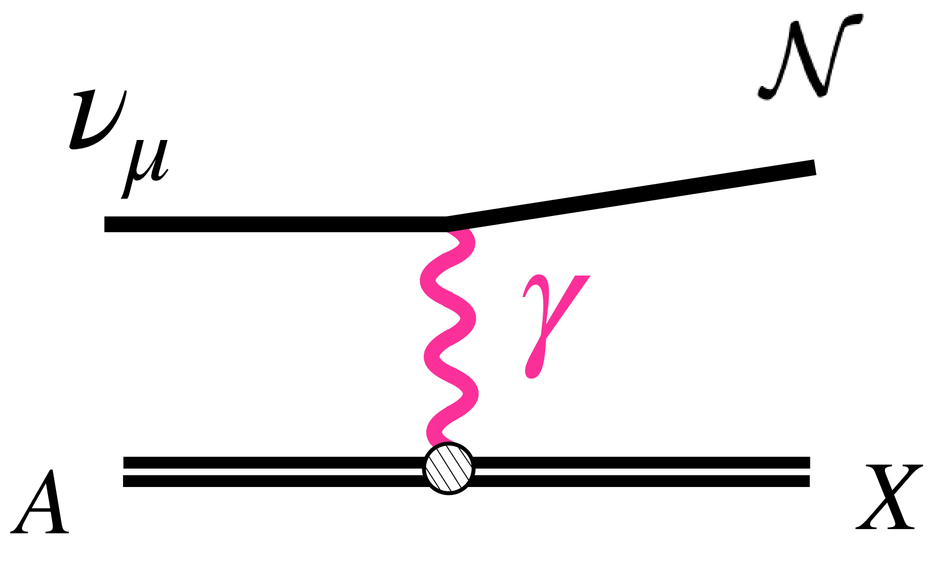


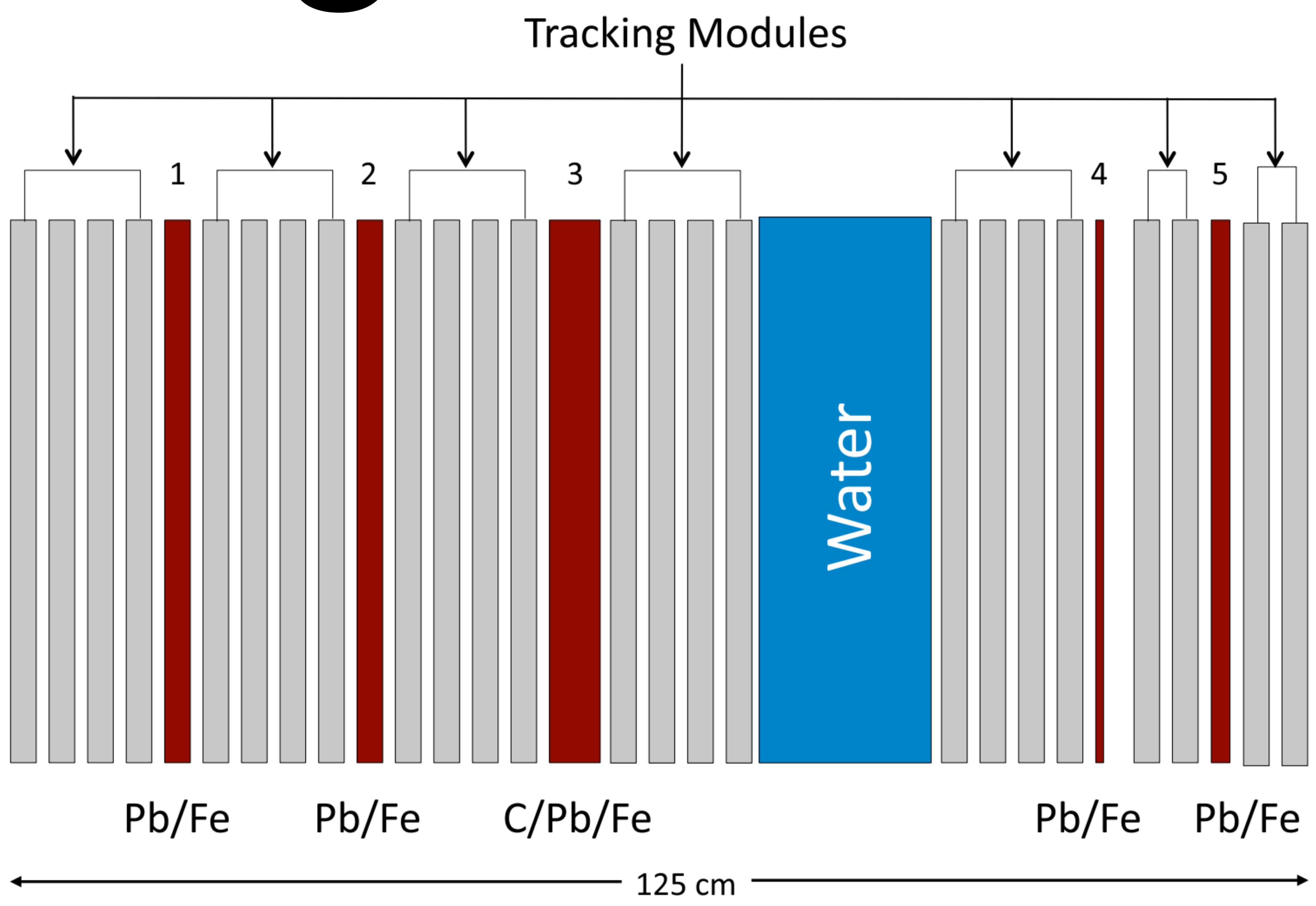
Complex detector geometry: MINERvA



Modeling the MINERvA Detector



$$\sigma^{\mathrm{coh}}_{\nu A \to \mathcal{N} A} \propto Z^2$$



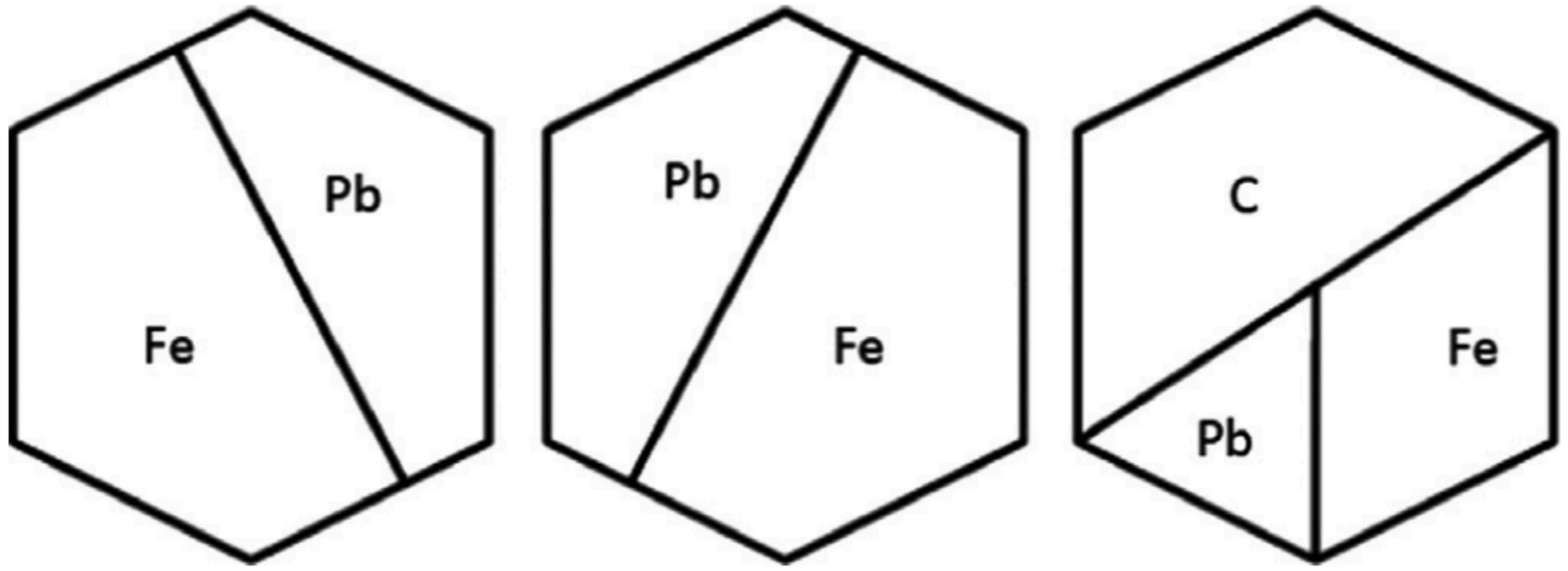


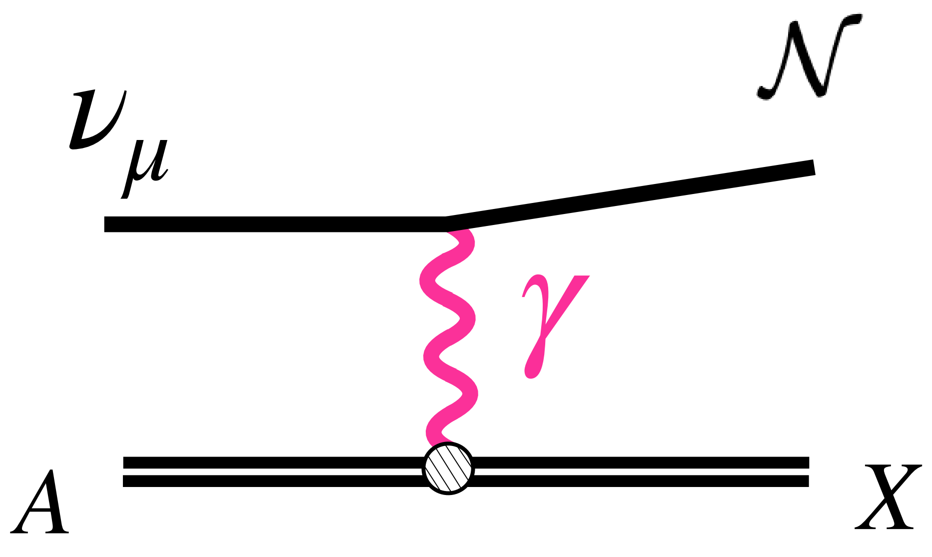
Fig. 3. Orientation of the nuclear targets looking downstream. Targets 1 and 5 have the leftmost orientation, target 2 has the middle orientation, and target 3 the rightmost orientation.

The production cross section has a Z^2 coherent enhancement

Detailed modeling of the nuclear targets is essential!

This was the original motivation behind SIREN

Modeling the MINERvA Detector



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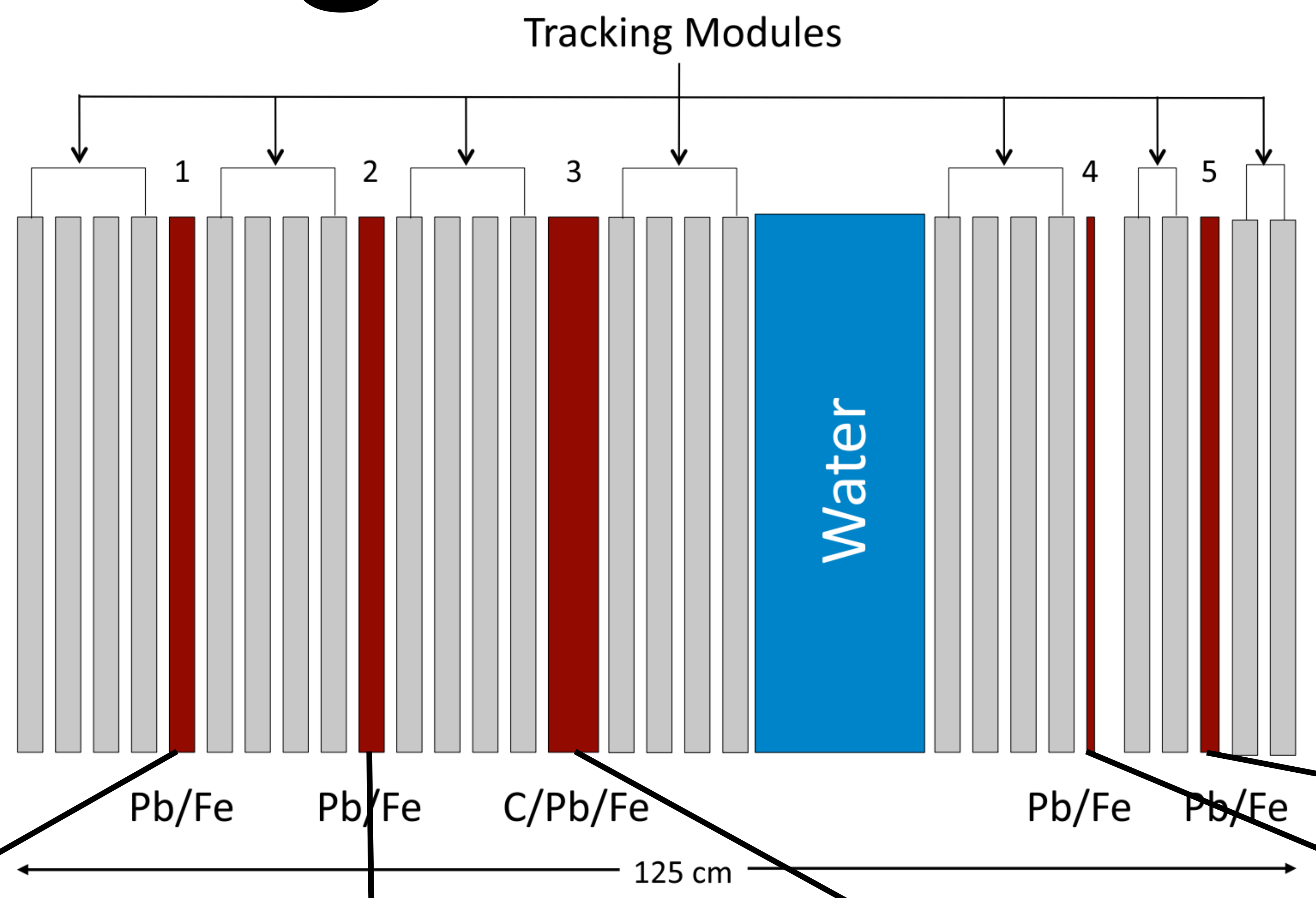

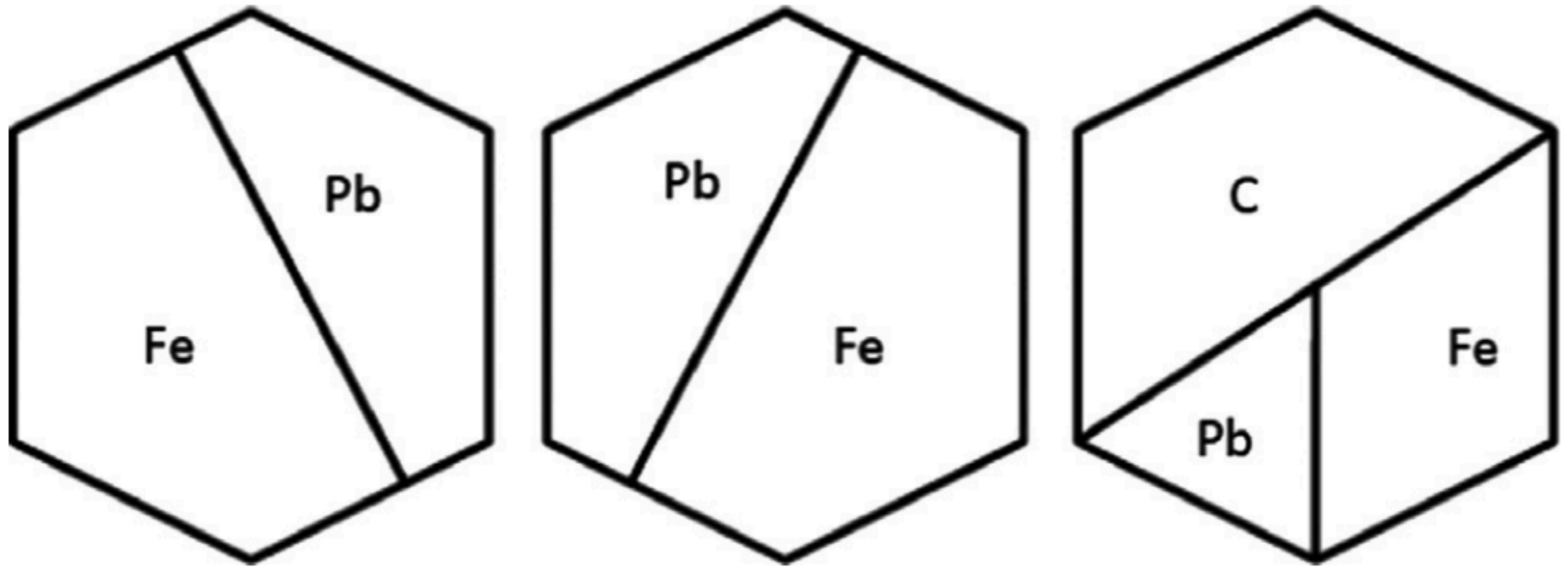

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Introducing SIREN

Harvard-Neutrino / SIREN

A. Schneider, NK, A. Wen. 2024

- Open-source simulation toolkit for modeling rare interactions
- Three main features:

1. **Extensible interaction service:** Support for arbitrary interaction trees of scattering $(2 \to n)$ and decay $(1 \to n)$ processes
2. **Extensible detector service:** Support for complicated detector geometries based on 3D volumes with arbitrary atomic compositions and density profiles
3. **Computational efficiency:** Fast methods for injection and (re-)weighting make SIREN suitable for large simulation campaigns

1: Extensible interaction service

Cross section and decay models are defined by specifying:

- The possible initial and final states
- The total and differential cross section or decay width
- A method for determining final state kinematics

Cross Section Models

- Neutrino DIS: $\nu A \to (\nu, \ell)X$
- Elastic scattering: $\nu e \to \nu e$
- HNL production off nuclei*: $(\nu A \to \mathcal{N} A)$
- HNL DIS production: $\nu A \to \mathcal{N} X$
- Charm production: $\nu A \to (\nu, \ell)DX$

Decay Models

- HNL single photon: $\mathcal{N} \to \nu\gamma$
- HNL dilepton*: $\mathcal{N} \to \nu\ell^+\ell^-$
- HNL hadronic: $\mathcal{N} \to (\nu, \ell)X$
- D semi-leptonic: e.g. $D \to \nu\mu K$
- D hadronic: e.g. $D \to K\pi\pi$

Available in first release

Under development

*Uses internal interface to DarkNews [Abdullahi+ 2022]

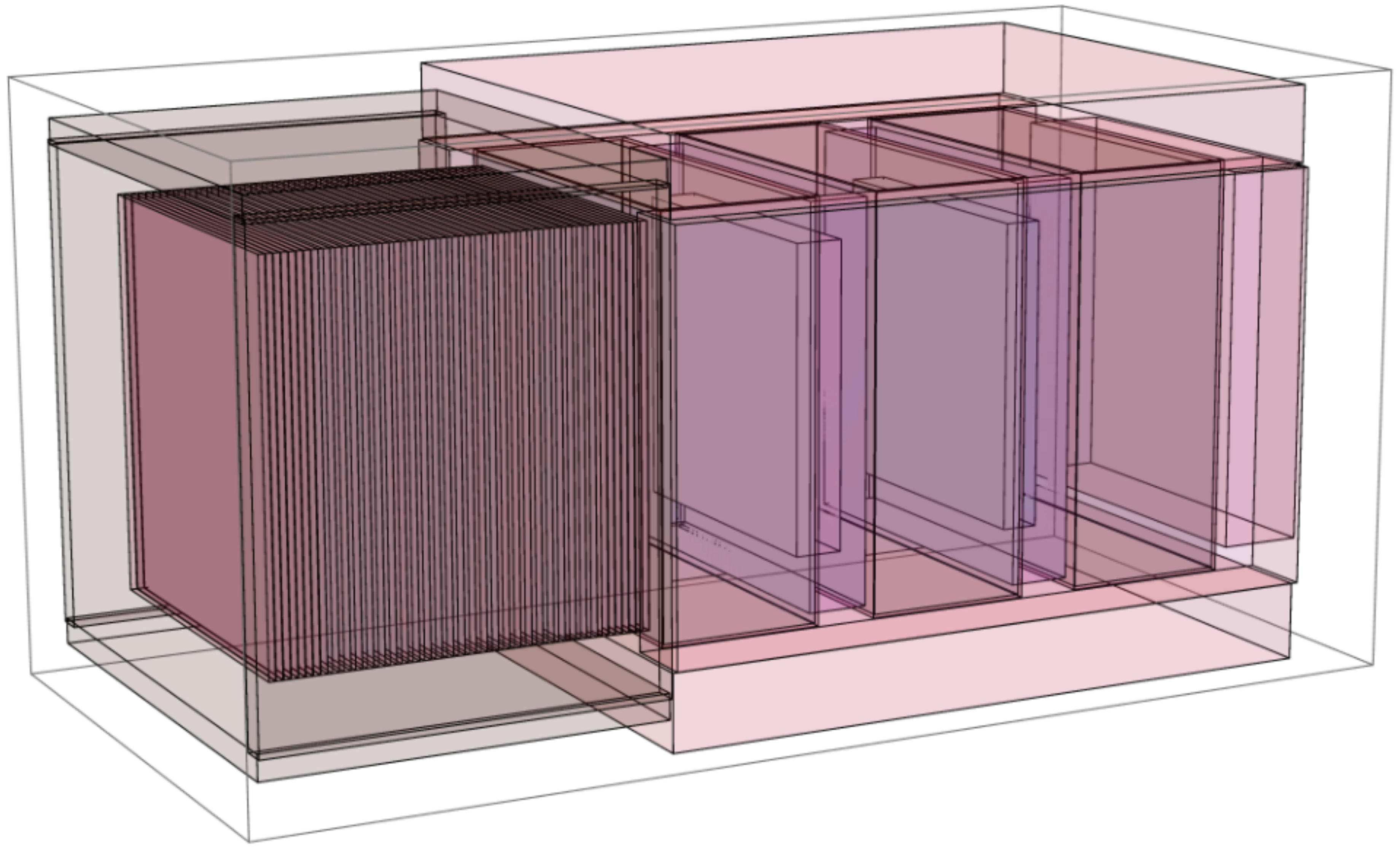
2: Extensible detector service

A detector model is defined through a plain text file specifying:

- A set of three-dimensional objects
- The atomic composition and density profile of each object
- A special 3D object representing the fiducial volume (optional)

Detector Models in SIREN

- **Available in first release:** IceCube, DUNE, ATLAS, HyperK, MiniBooNE, MINERvA, CCM
- **Implemented, available on main branch:** ND280, ND280+

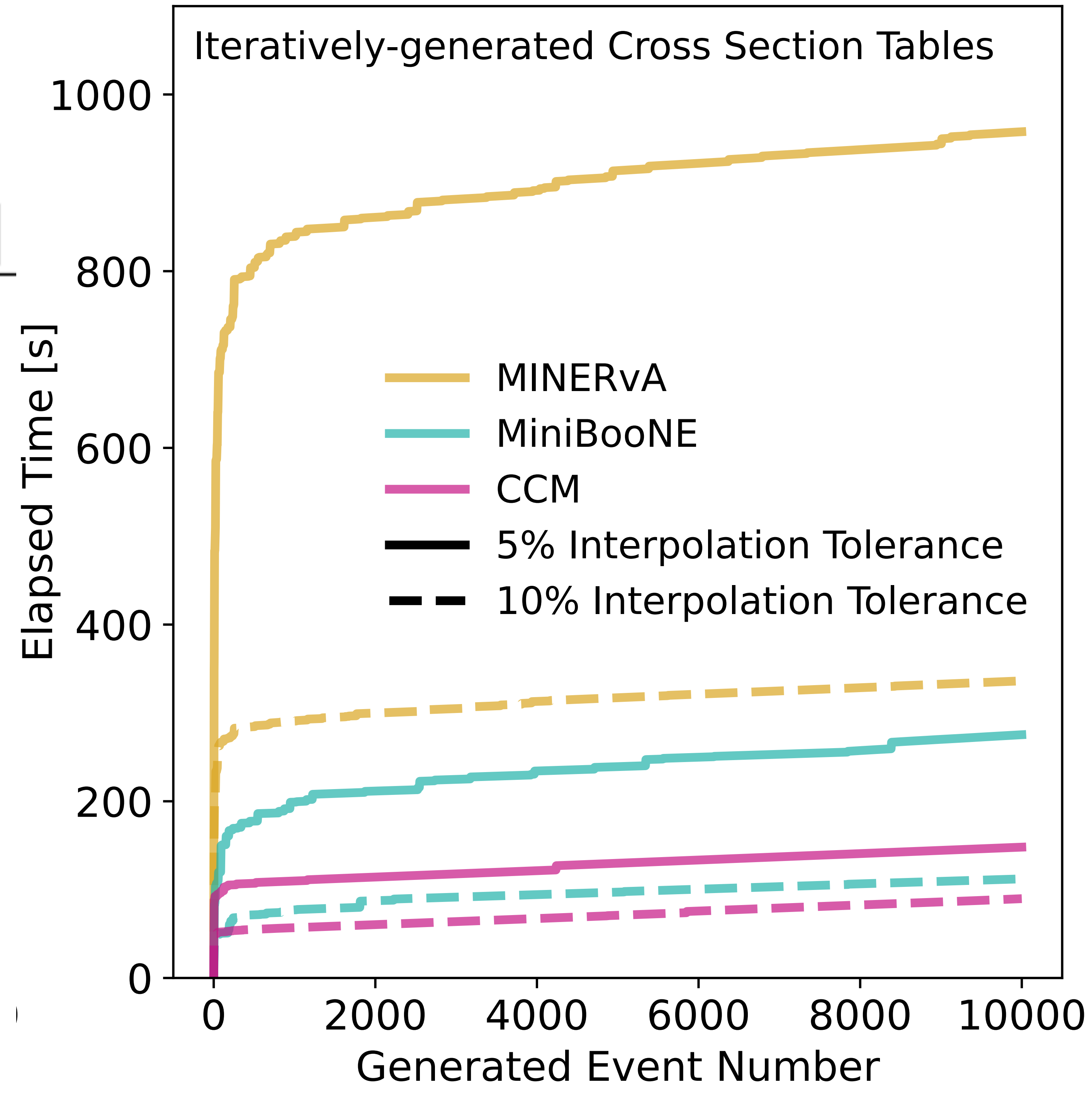


ND280 in SIREN, implemented by M. S. Liu

3: Computational Efficiency

- SIREN can generate/compute weights for $\mathcal{O}(10^3 - 10^5)$ events per second, depending on the interaction and detector models
- Events can be easily re-weighted to different flux, cross section, and/or detector models

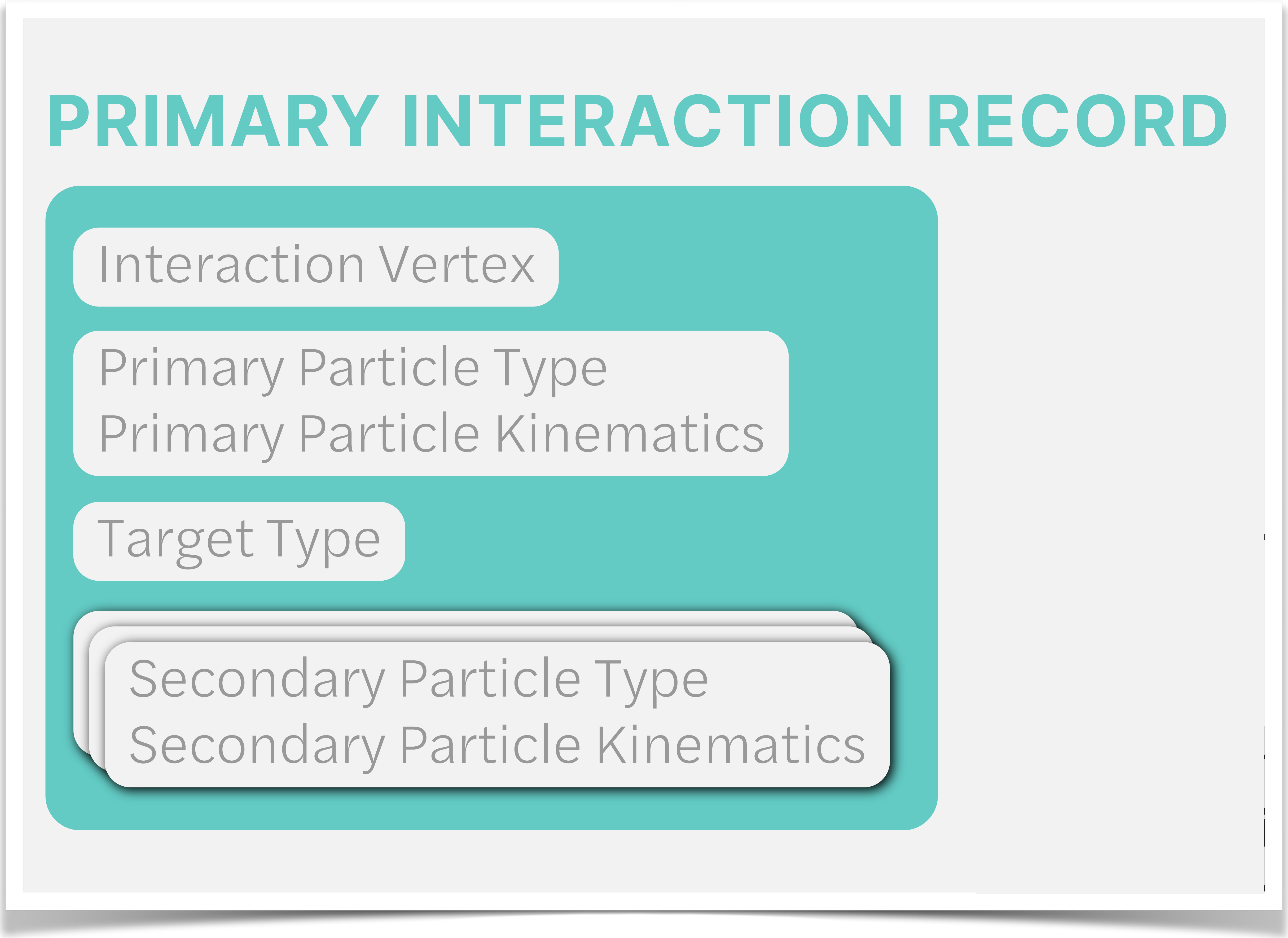
Simulation case	Generation time per event [s]	Weight calculation time per event [s]
ν_μ DIS in IceCube	$7.37^{+1.24}_{-1.31} \times 10^{-5}$	$12.83^{+1.45}_{-3.36} \times 10^{-5}$
ν_μ DIS in DUNE	$5.63^{+0.98}_{-0.76} \times 10^{-5}$	$8.63^{+1.41}_{-1.93} \times 10^{-5}$
ν_μ DIS in ATLAS	$3.74^{+0.14}_{-0.10} \times 10^{-5}$	$6.58^{+0.21}_{-0.29} \times 10^{-5}$
Dipole-portal HNLs in MiniBooNE	$2.97^{+0.04}_{-0.07} \times 10^{-3}$	$2.07^{+0.03}_{-0.25} \times 10^{-3}$
Dipole-portal HNLs in MINERνA	$4.72^{+5.93}_{-1.12} \times 10^{-3}$	$4.00^{+1.91}_{-0.42} \times 10^{-3}$
Dipole-portal HNLs in CCM	$3.83^{+0.05}_{-0.07} \times 10^{-3}$	$4.25^{+0.08}_{-0.13} \times 10^{-3}$

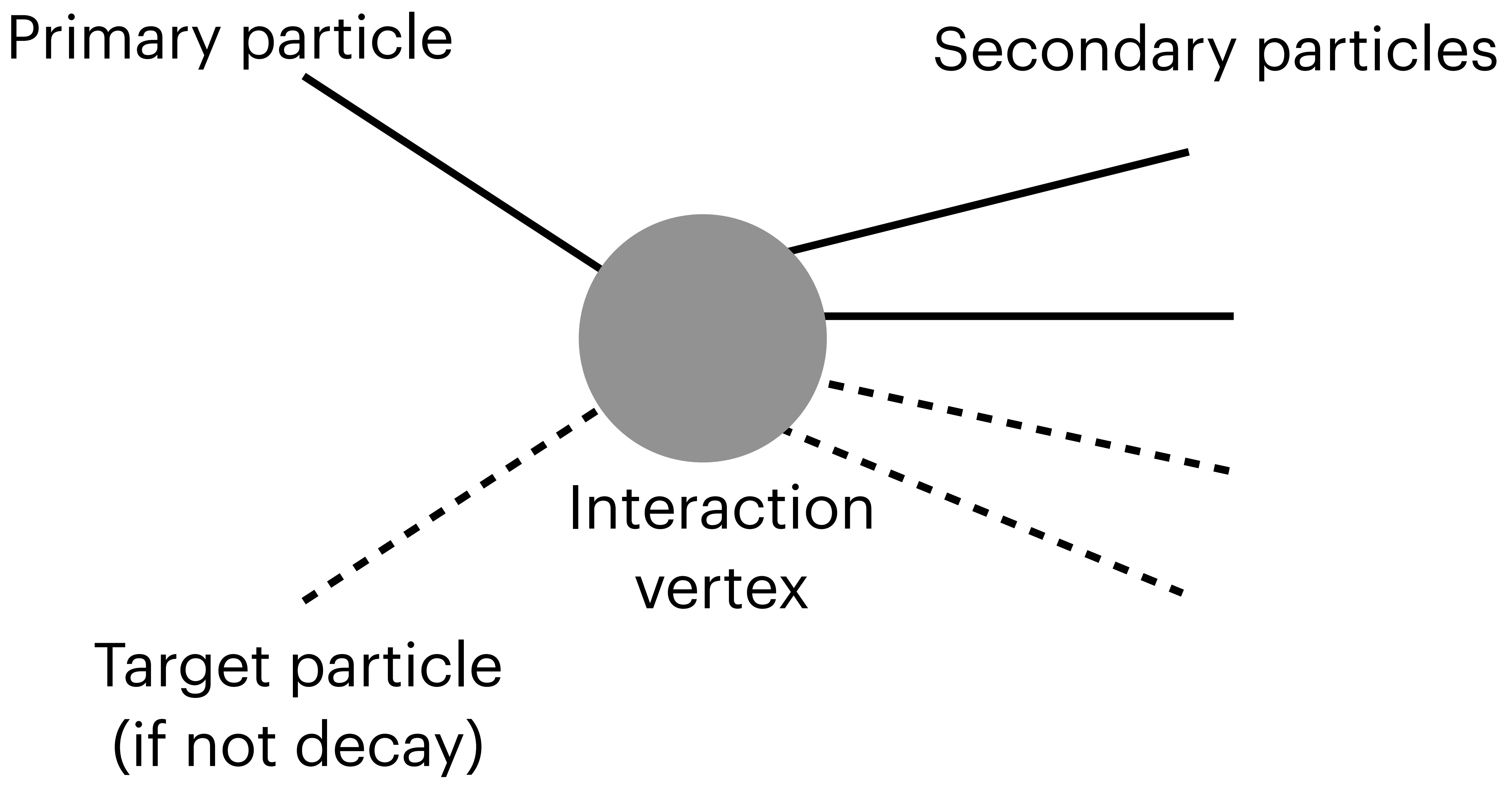


How does it work?

Interaction Record

The “fundamental unit” of SIREN





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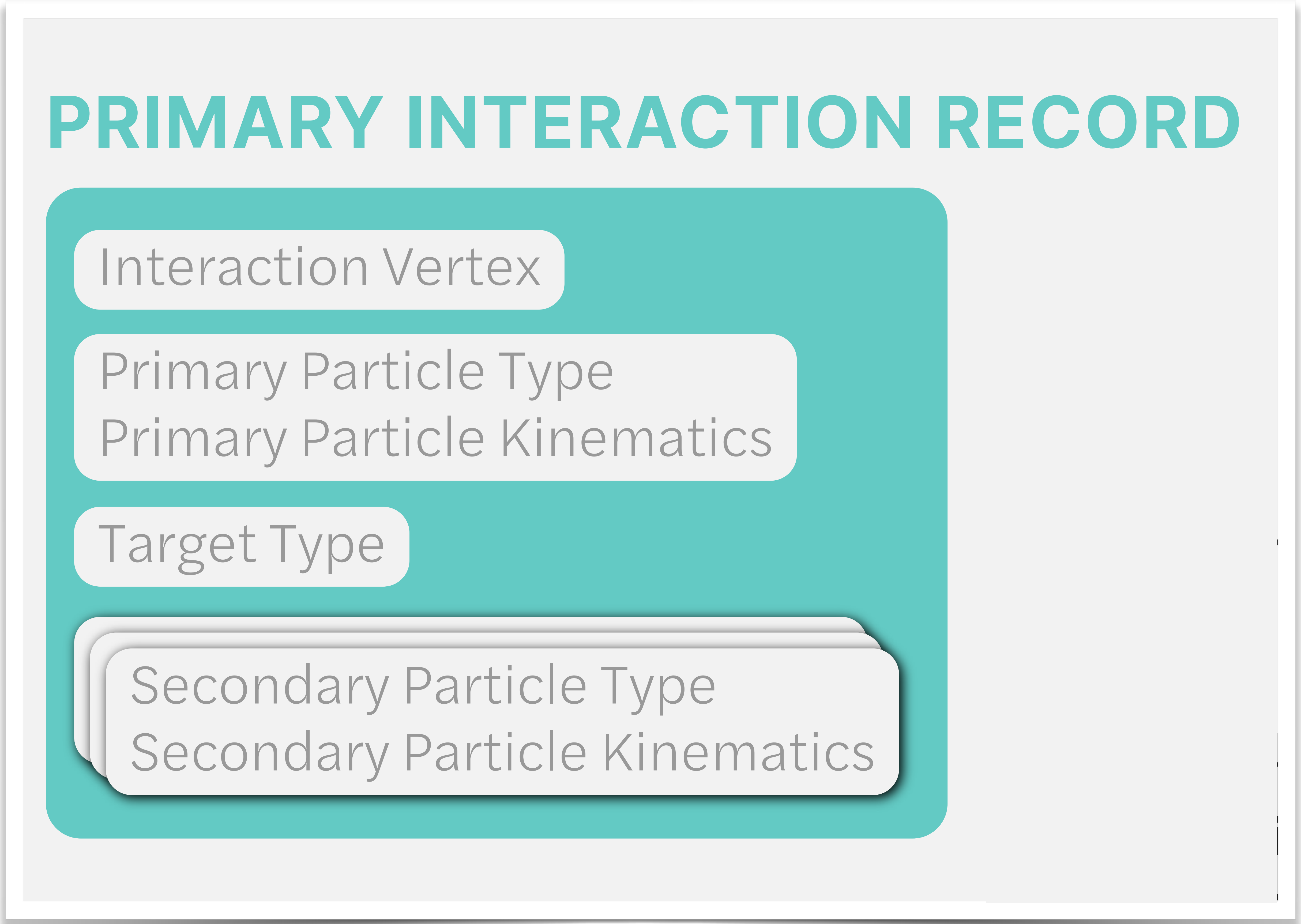
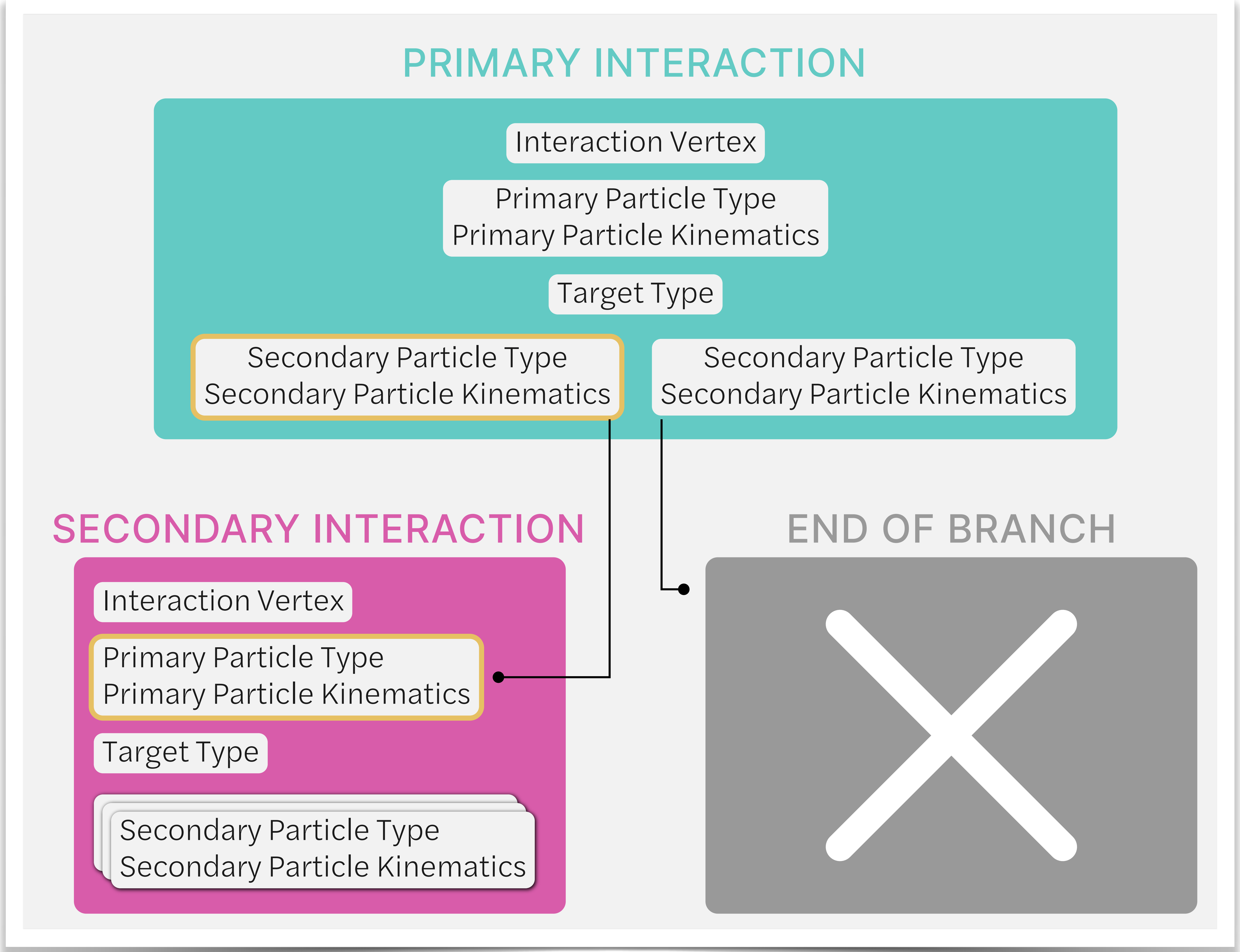


Interaction Tree

A tree of interaction records




PRIMARY INTERACTION RECORD
Interaction Vertex
Primary Particle Type
Primary Particle Kinematics
Target Type
Secondary Particle Type
Secondary Particle Kinematics
PrimaryEnergyDistribution()
PrimaryDirectionDistribution()
VertexPositionDistribution()
...
SampleCrossSection()
SECONDARY INTERACTION RECORD
SecondaryPositionDistribution()
...
SampleCrossSection()
BEDROCK
PRIMARY INTERACTION
SECONDARY INTERACTION
Illustration from J. Parin
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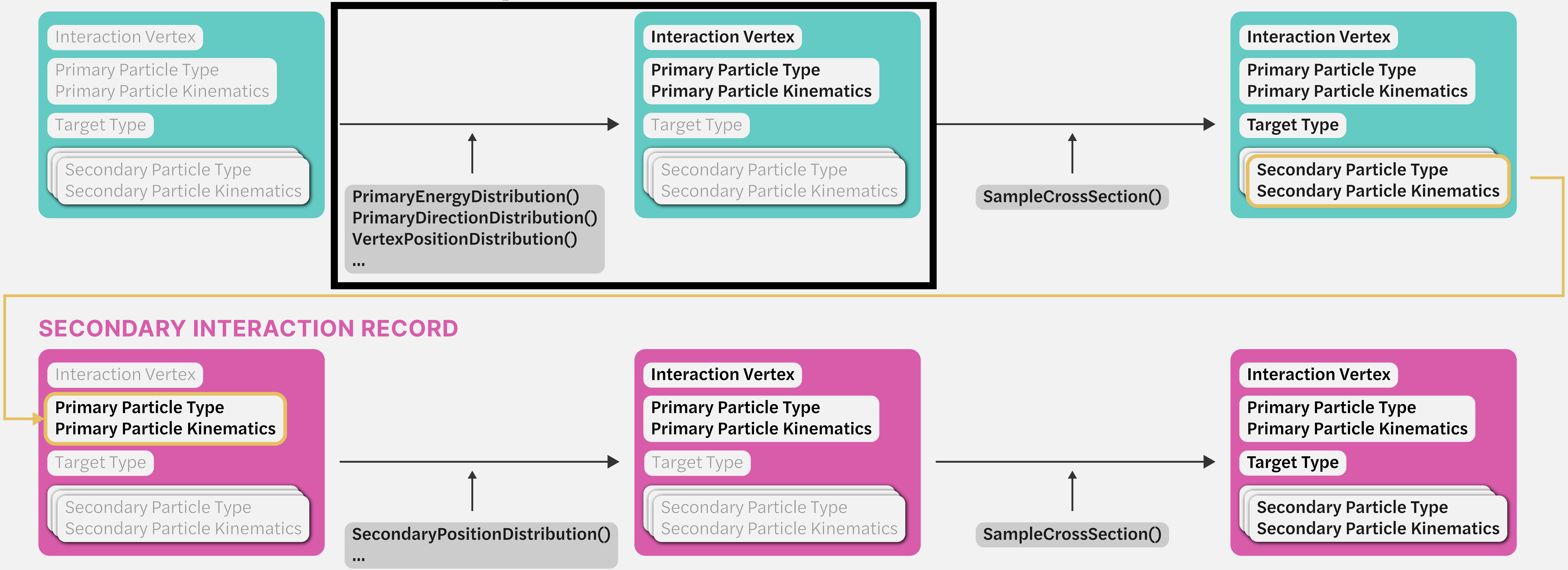
MINERAL OIL (CH_2)

Sample the flux & interaction location

PRIMARY INTERACTION RECORD



Sample the primary cross section/decay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Interaction Vertex
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PrimaryEnergyDistribution()
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Interaction Vertex
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SampleCrossSection()
Interaction Vertex
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Secondary Particle Kinematics
Identify a relevant secondary interaction
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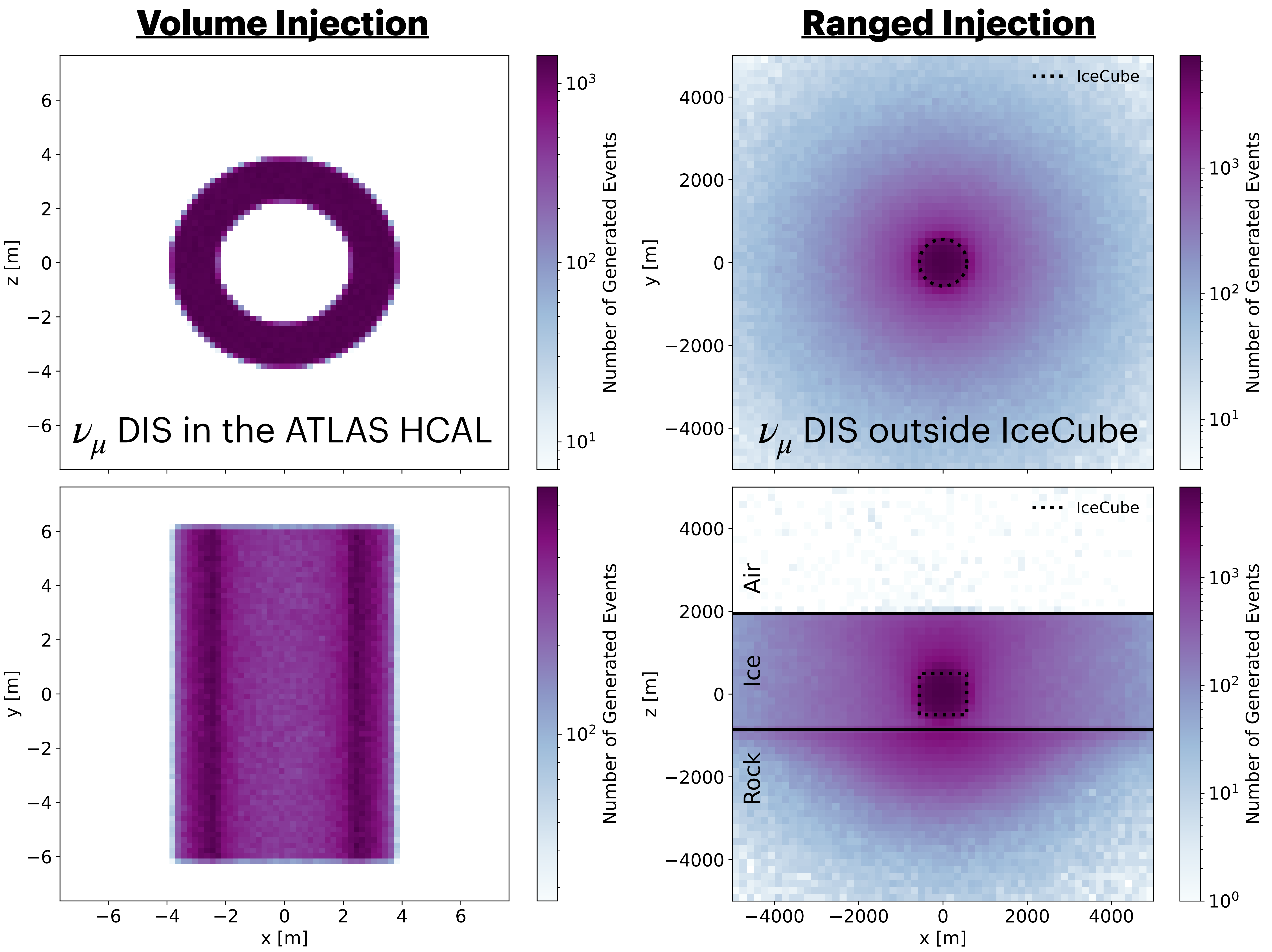
Two Vertex Injection Strategies

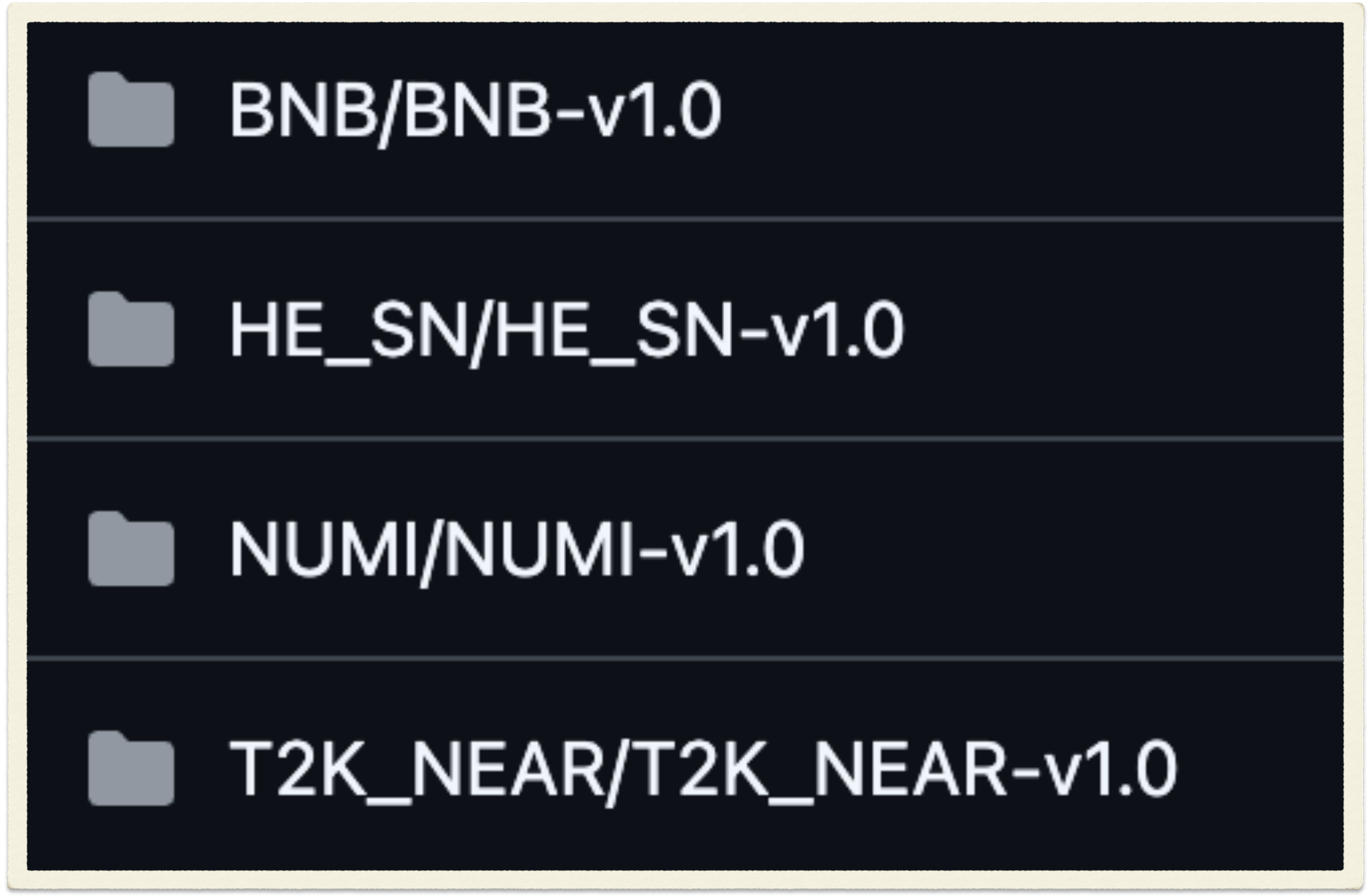
- **Volume Injection:** distribute events uniformly throughout the fiducial volume
- **Ranged Injection:** inject events up to a specified distance outside of the detector
  - This is appropriate when interactions outside the detector are important, e.g. high-energy muons outside of IceCube or dipole-portal HNLs outside of MINERvA



Sampling the Neutrino Flux

- Sampling the neutrino flux amounts to sampling an energy and a direction
- Many combinations possible, but some typical choices:
  - **For a beam:** tabulated 1D energy distribution + mono-directional
  - **For astrophysical neutrinos:** power-law energy distribution + isotropic direction
  - **For atmospheric neutrinos:** tabulated 2D energy-direction distribution

Energy Distributions in SIREN

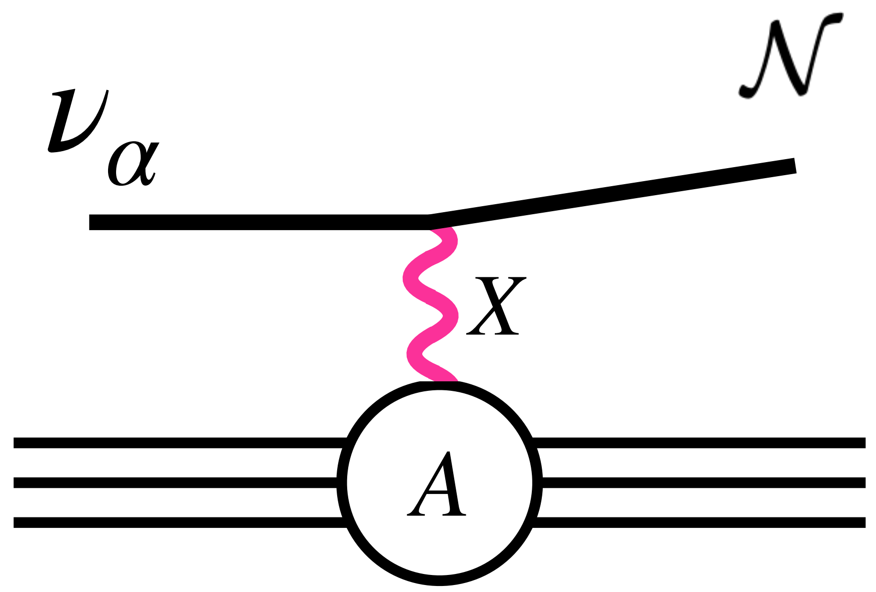


Heavy Neutral Leptons in SIREN: Production

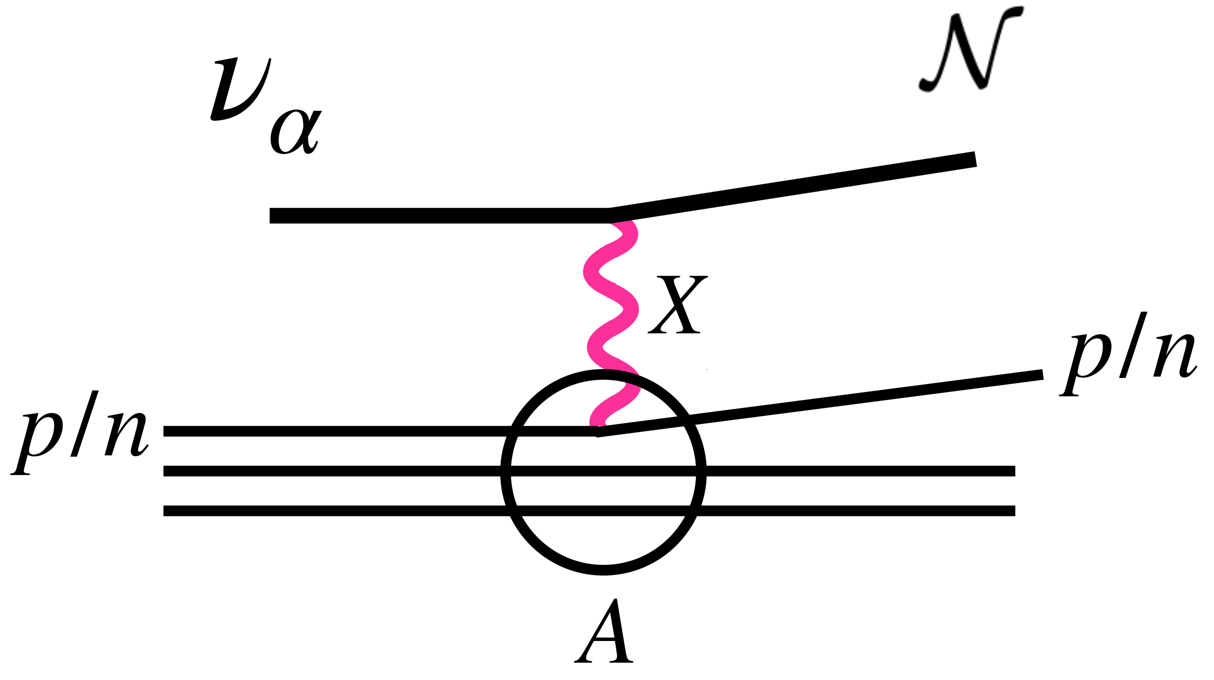
HNLs are the first BSM physics scenario implemented in SIREN

We currently support HNL production via **upscattering**

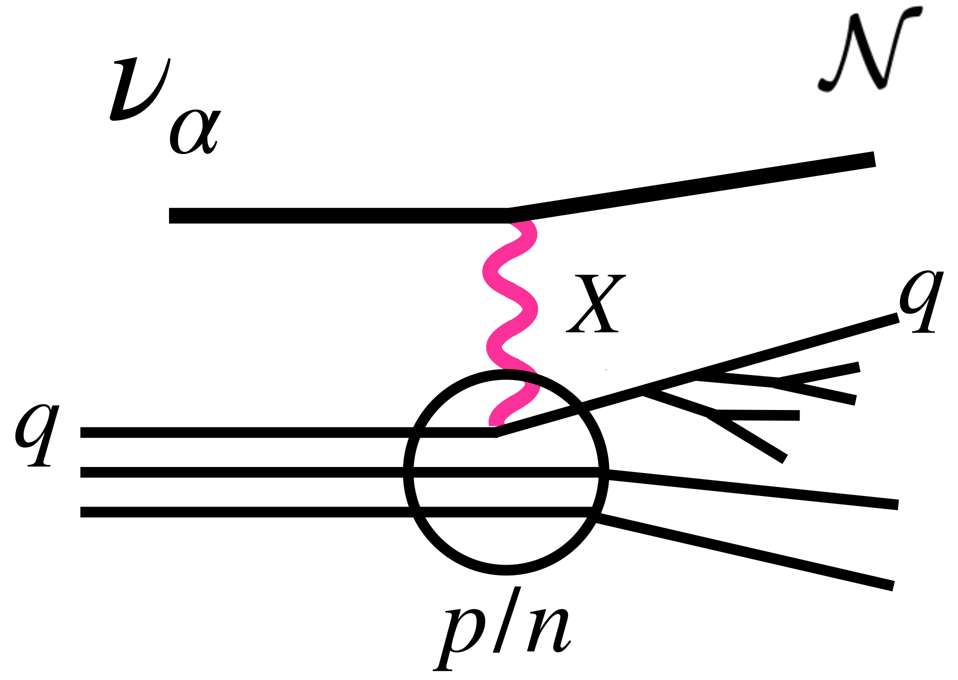
$0 < Q^2/\mathrm{GeV}^2 \lesssim 0.5$



$0.5 \lesssim Q^2/\mathrm{GeV}^2 \lesssim 2$



$2 \lesssim Q^2/\mathrm{GeV}^2$

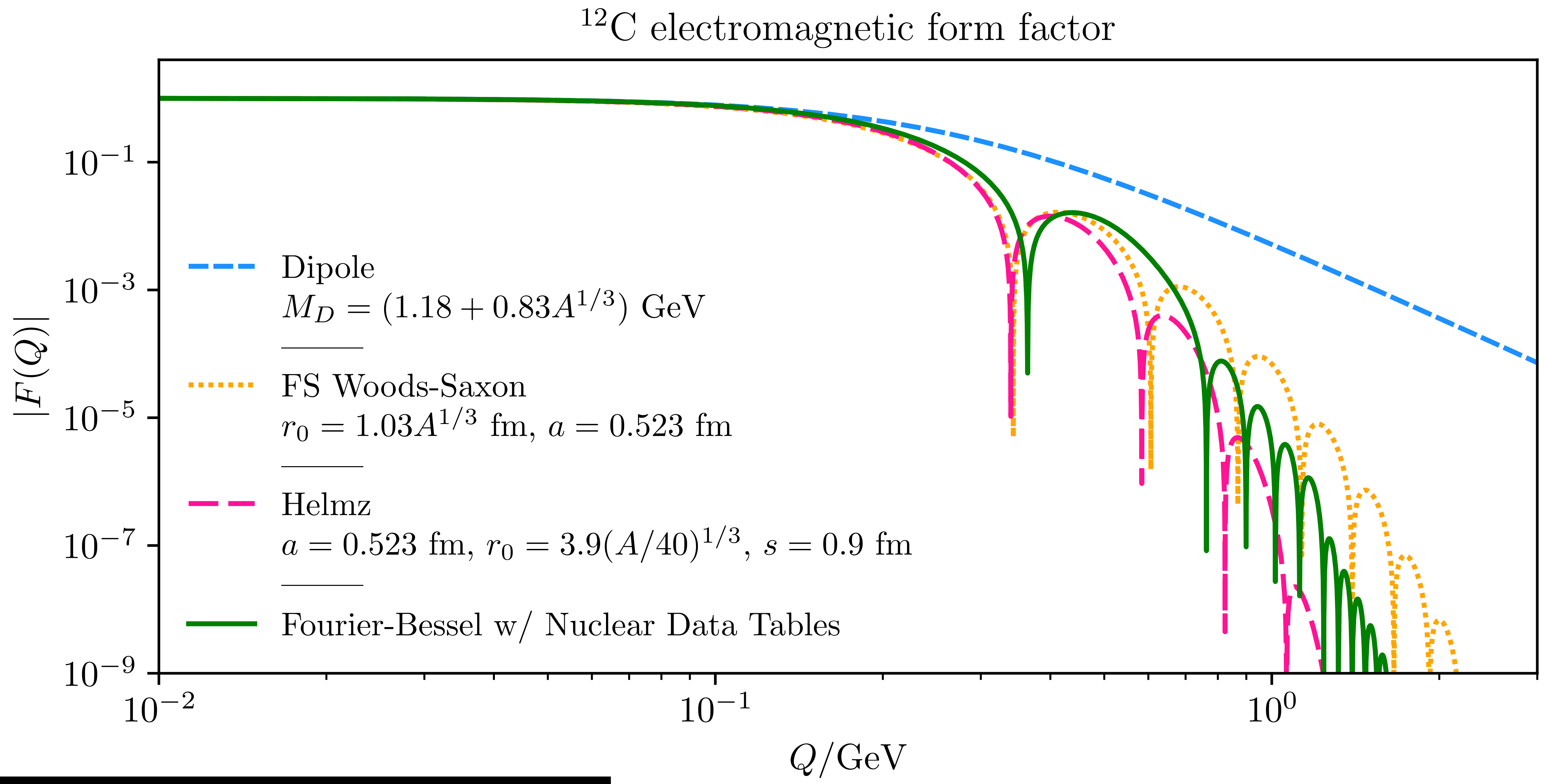


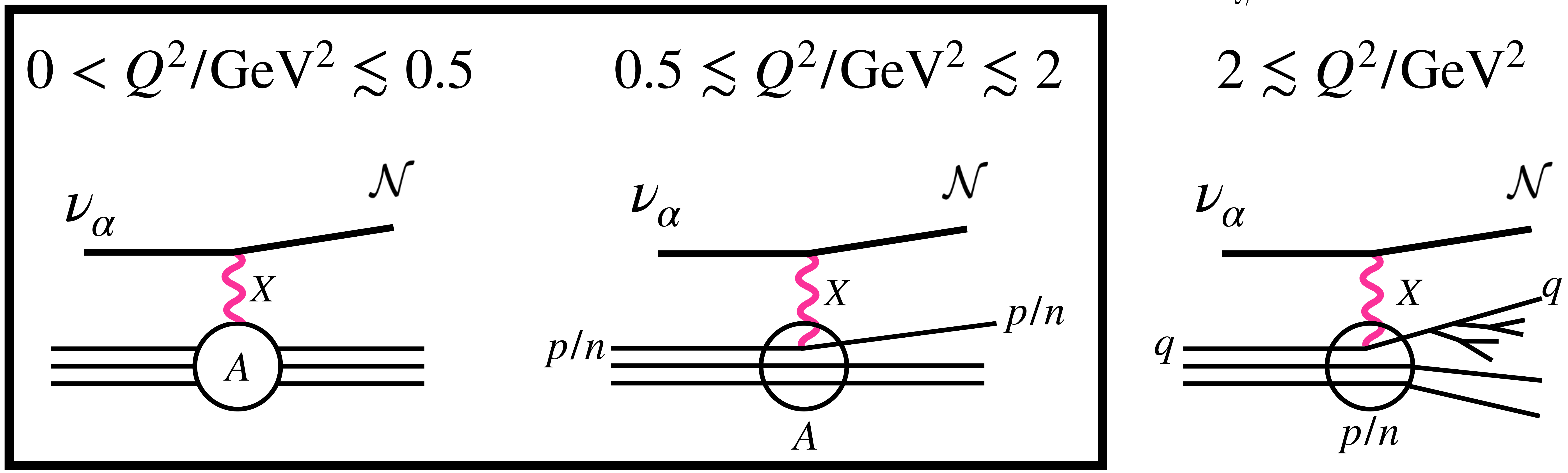
Heavy Neutral Leptons in SIREN: Production

Handled by a custom interface to DarkNews for $X \in \{Z, \gamma, Z', h'\}$

mhostert / DarkNews-generator

Abdullahi+ 2022



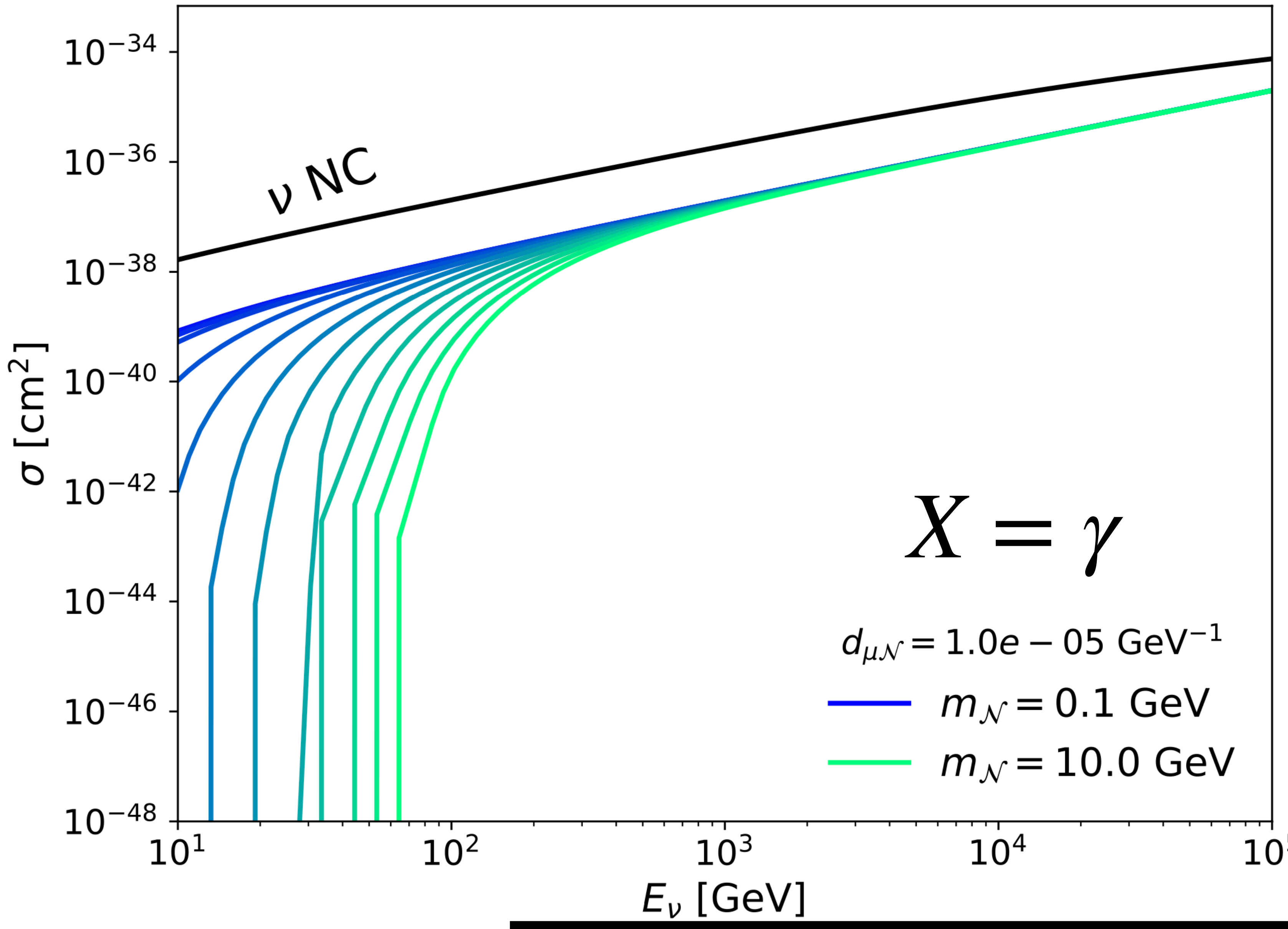


Heavy Neutral Leptons in SIREN: Production

Handled by splines of σ and $\frac{d^2\sigma}{dxdy}$ for

$X = Z$ (following Cooper-Sarkar+ 2011)

$X = \gamma$ (following Coloma+ 2017)



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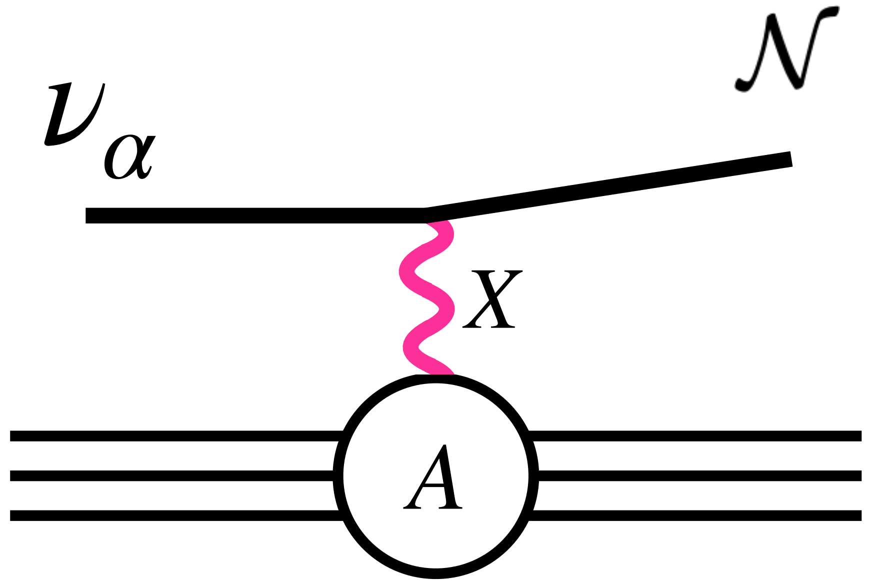

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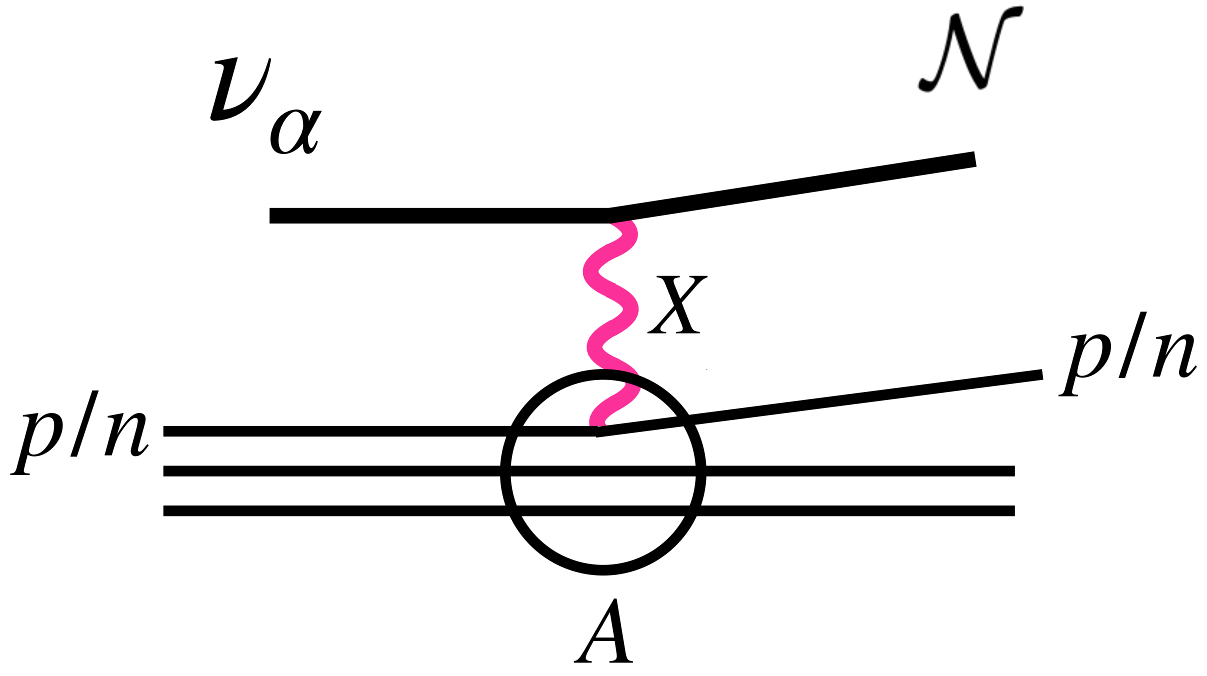
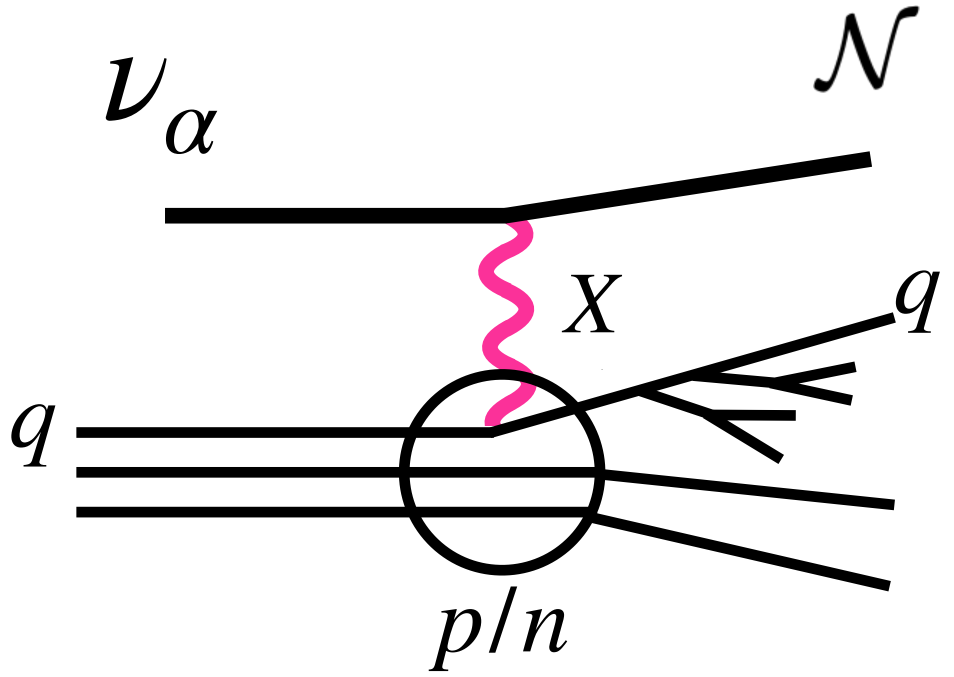
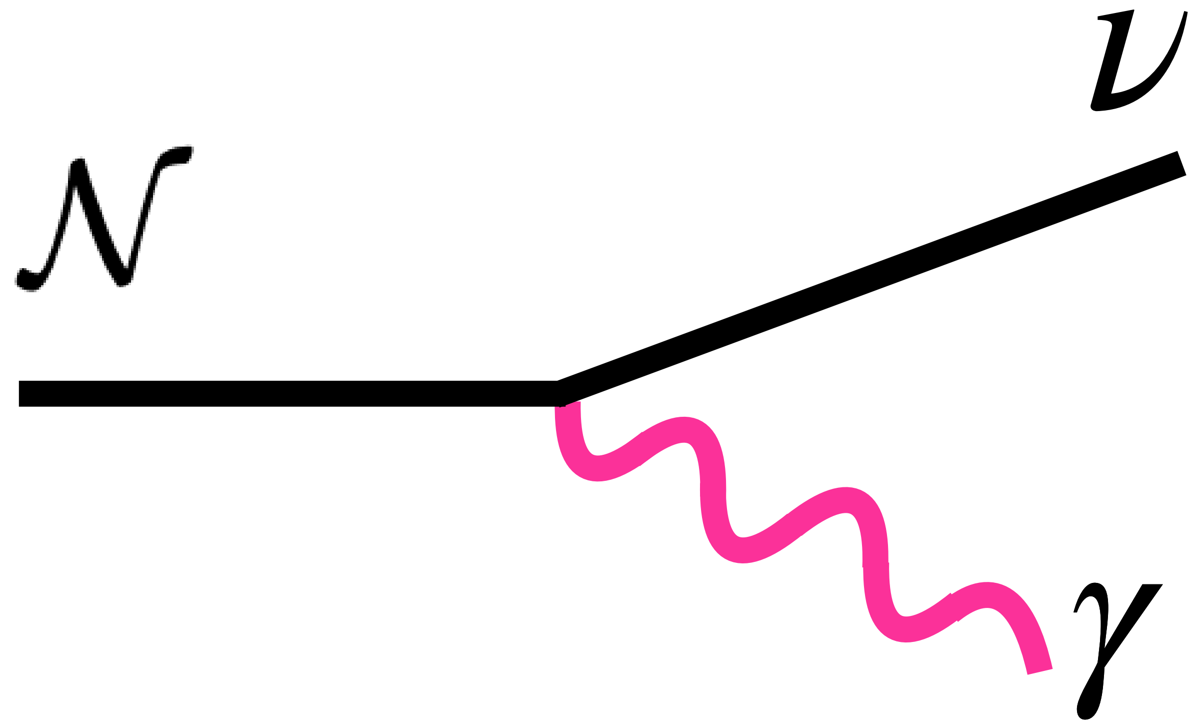


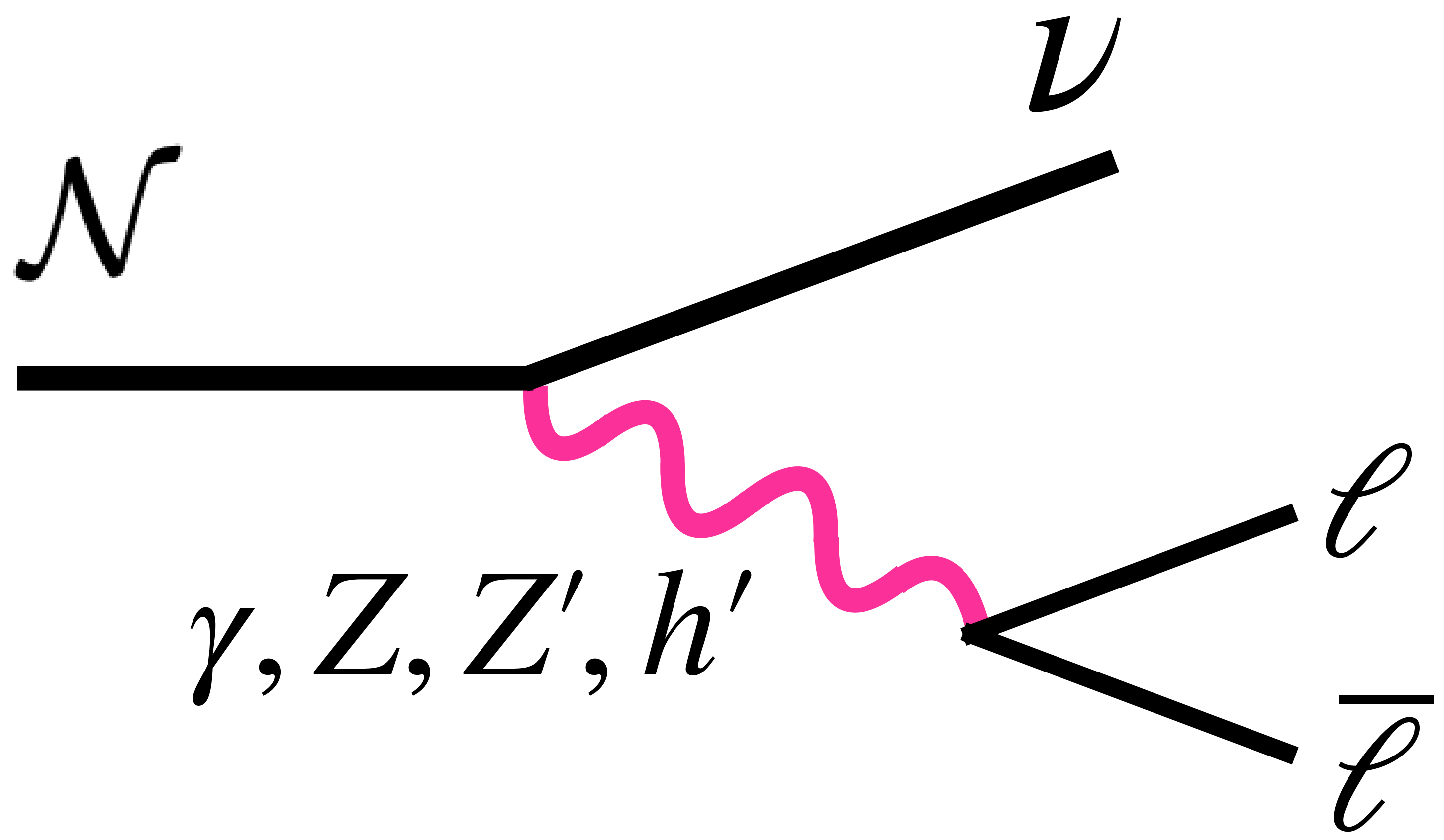
$\boxed{2 \lesssim Q^2/\mathrm{GeV}^2}$



Heavy Neutral Leptons in SIREN: Decay

The SIREN-DarkNews interface handles HNL decays via dipole, vector, and scalar portals, as well as Z-mediated di-lepton decays





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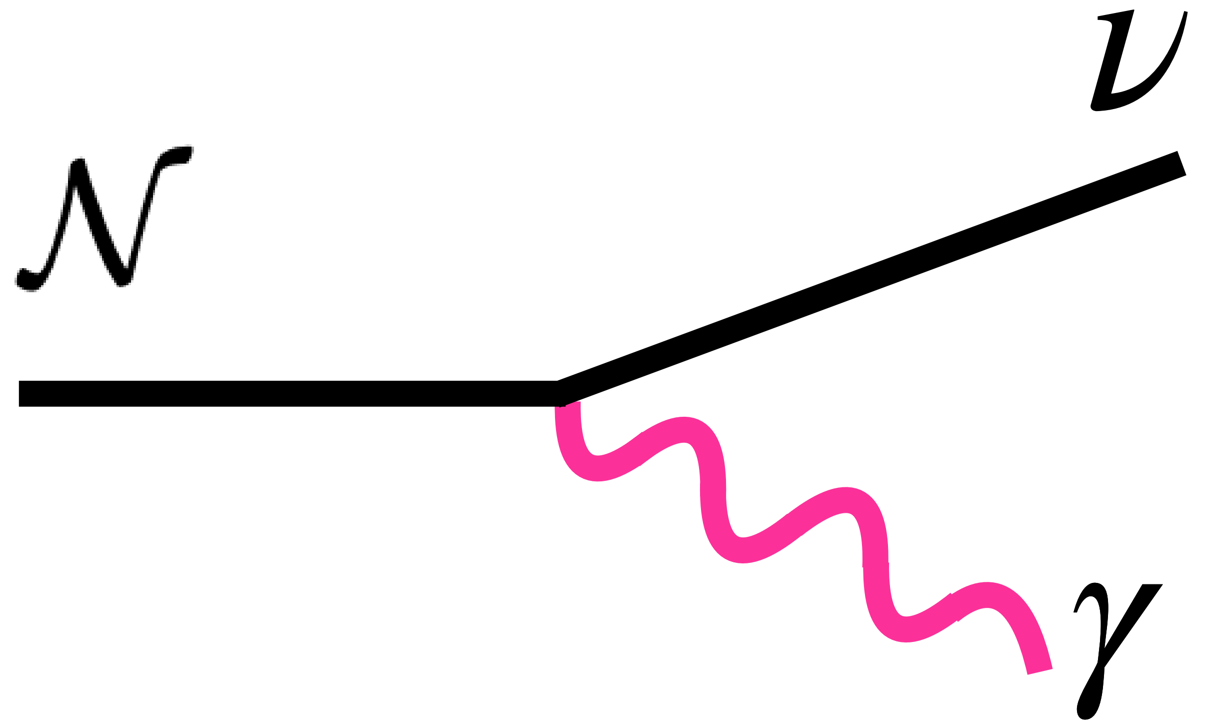
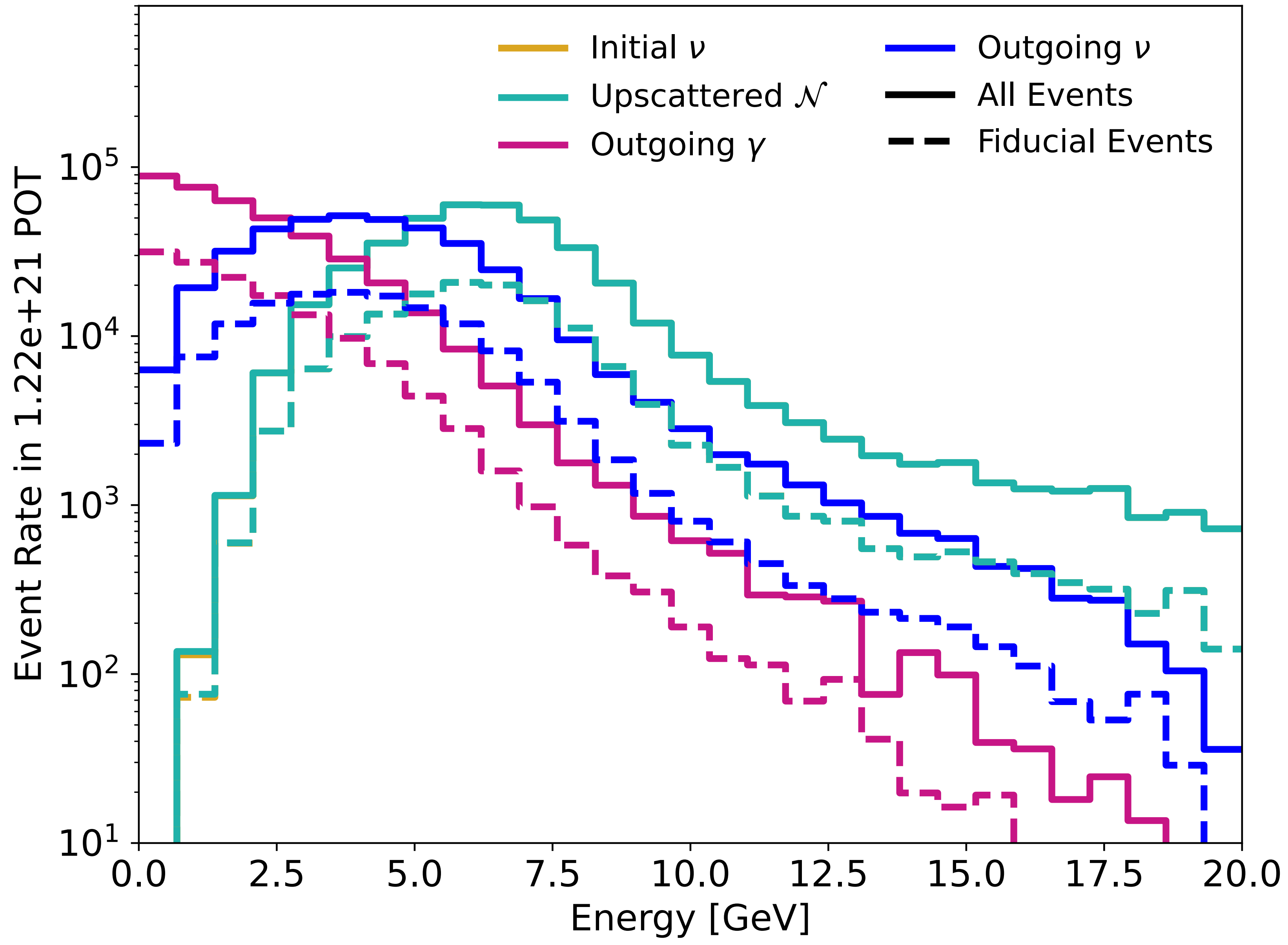
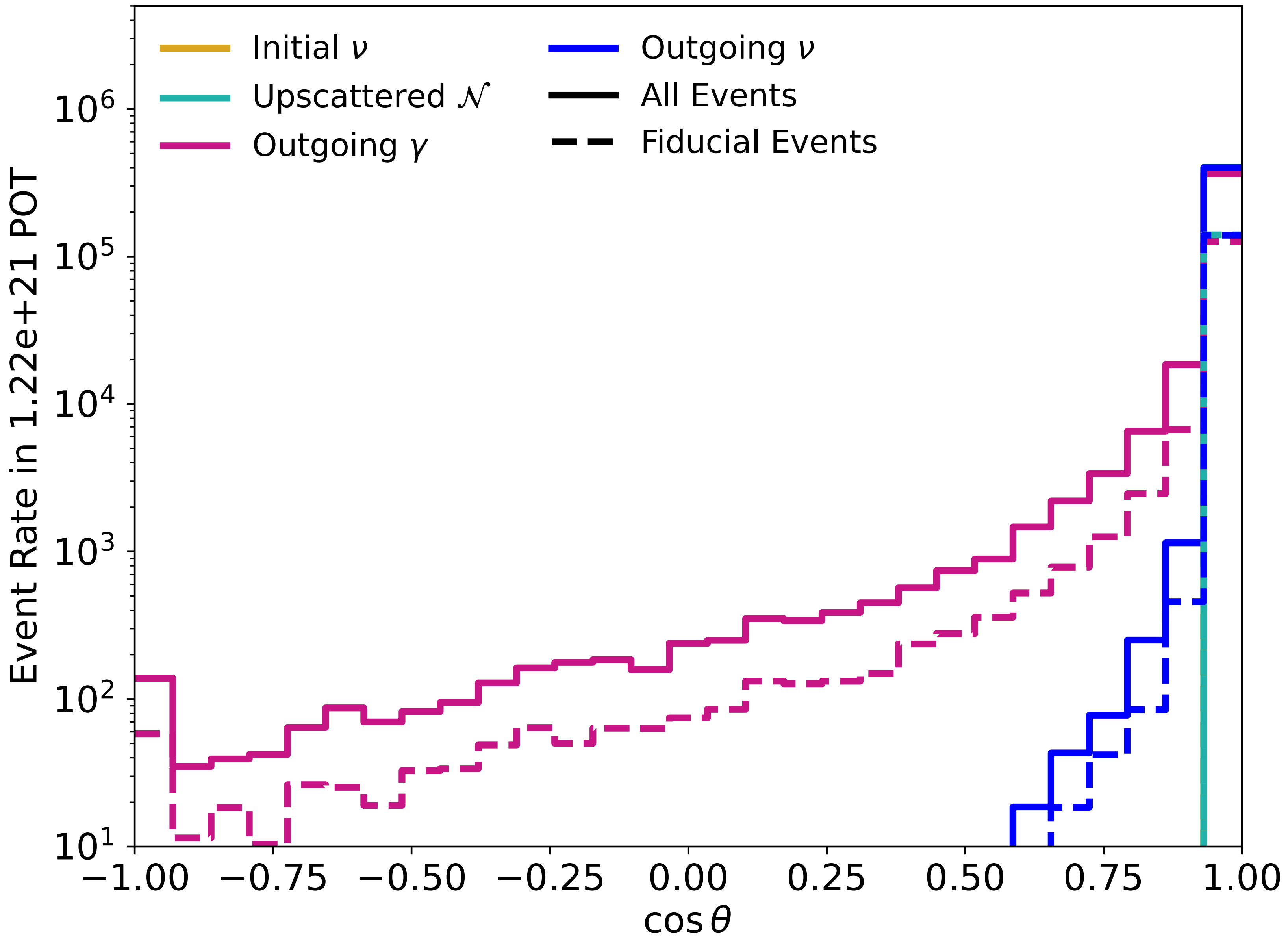
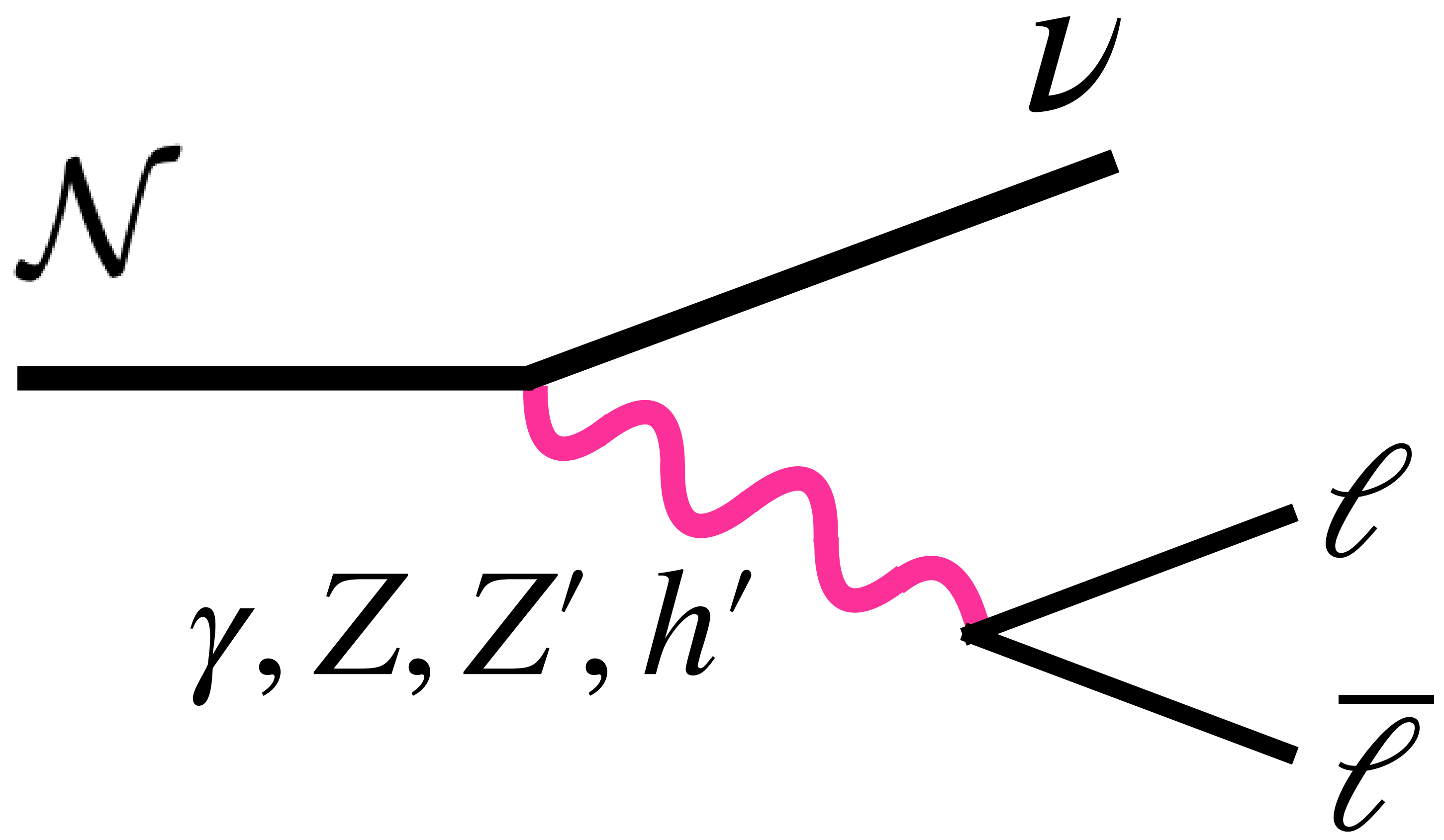


Example: Dipole-portal HNL interactions in MINERvA

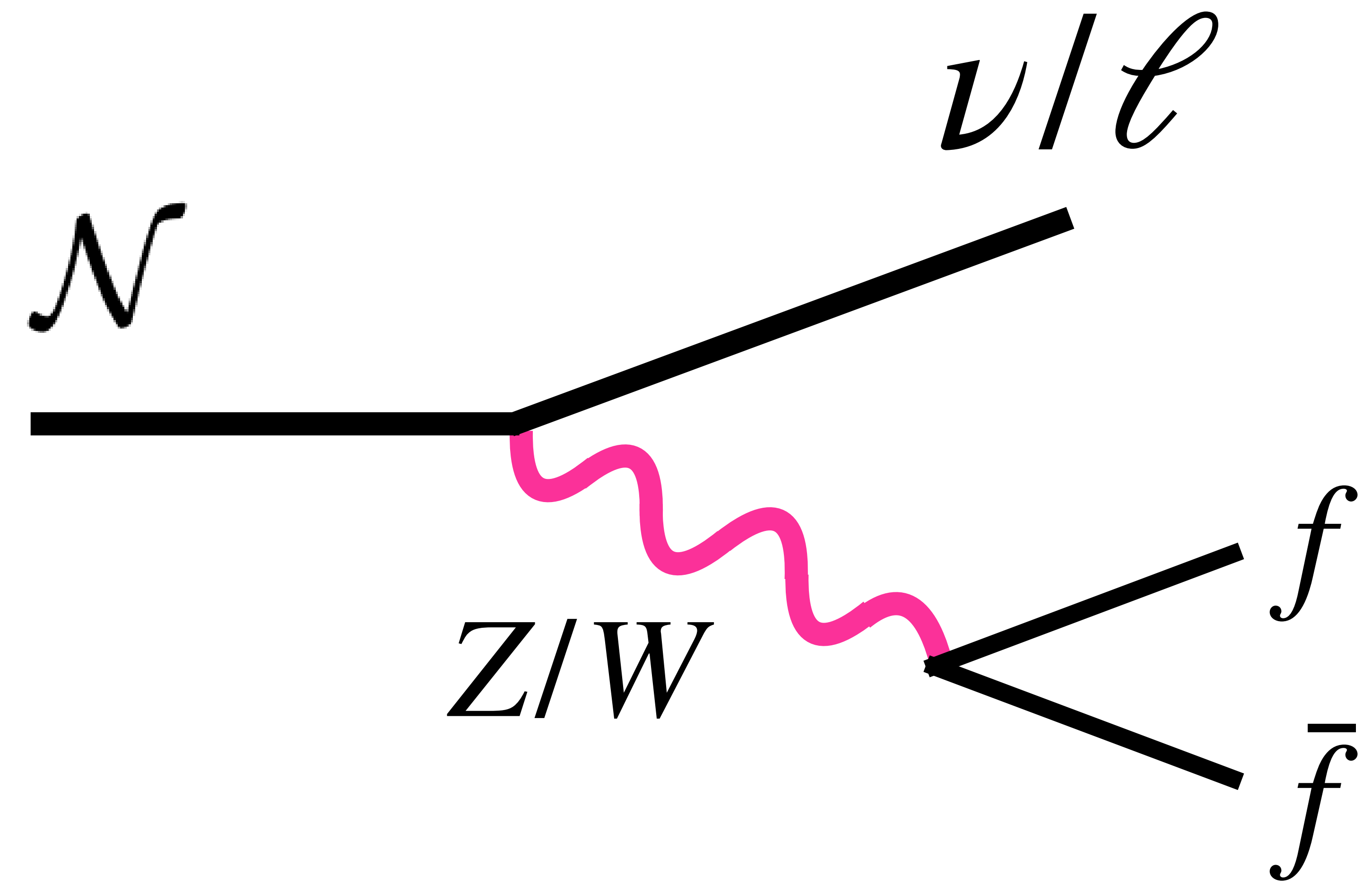




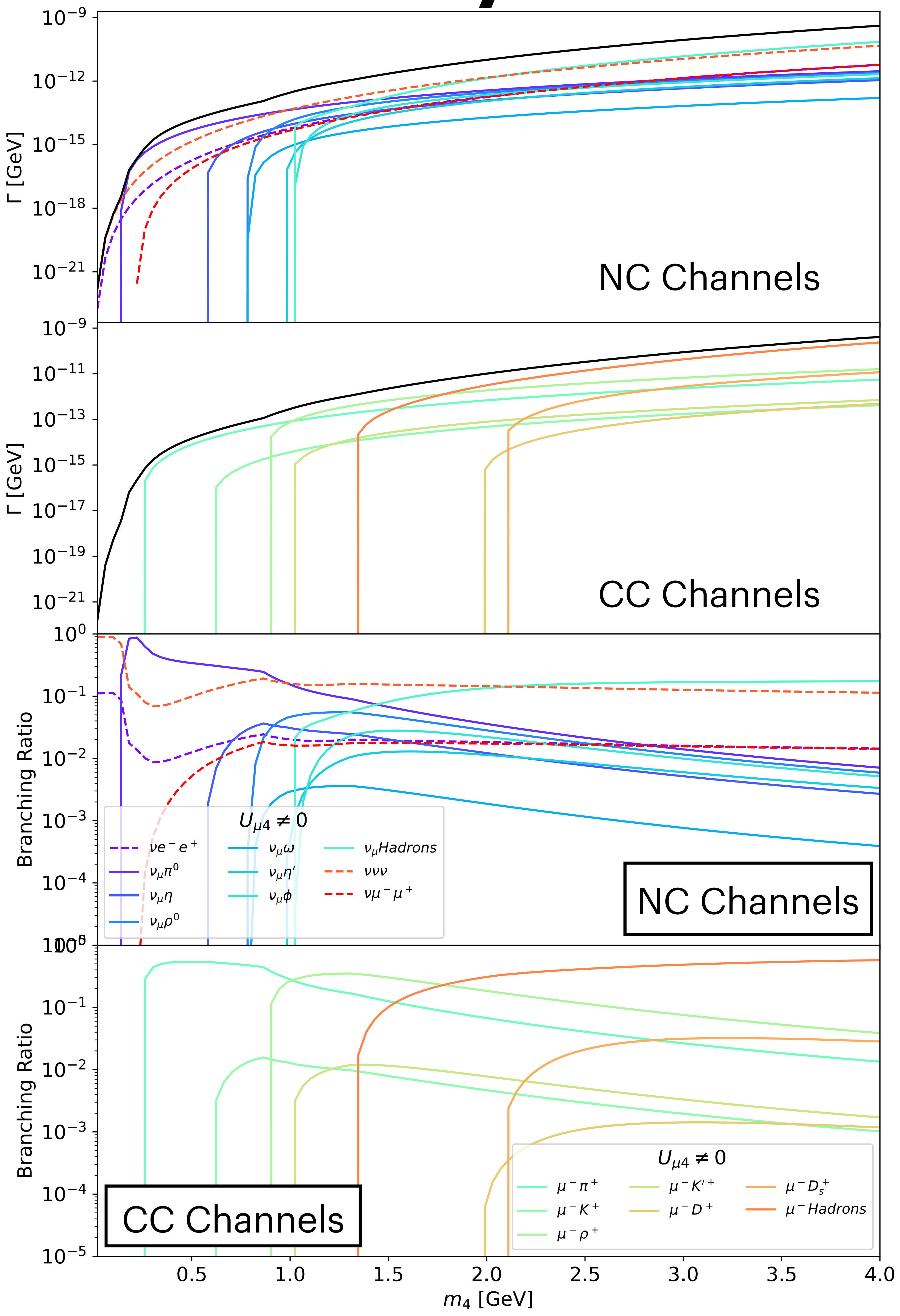


Heavy Neutral Leptons in SIREN: Decay

Native SIREN class in development to handle all decay modes of mass-mixed HNLs



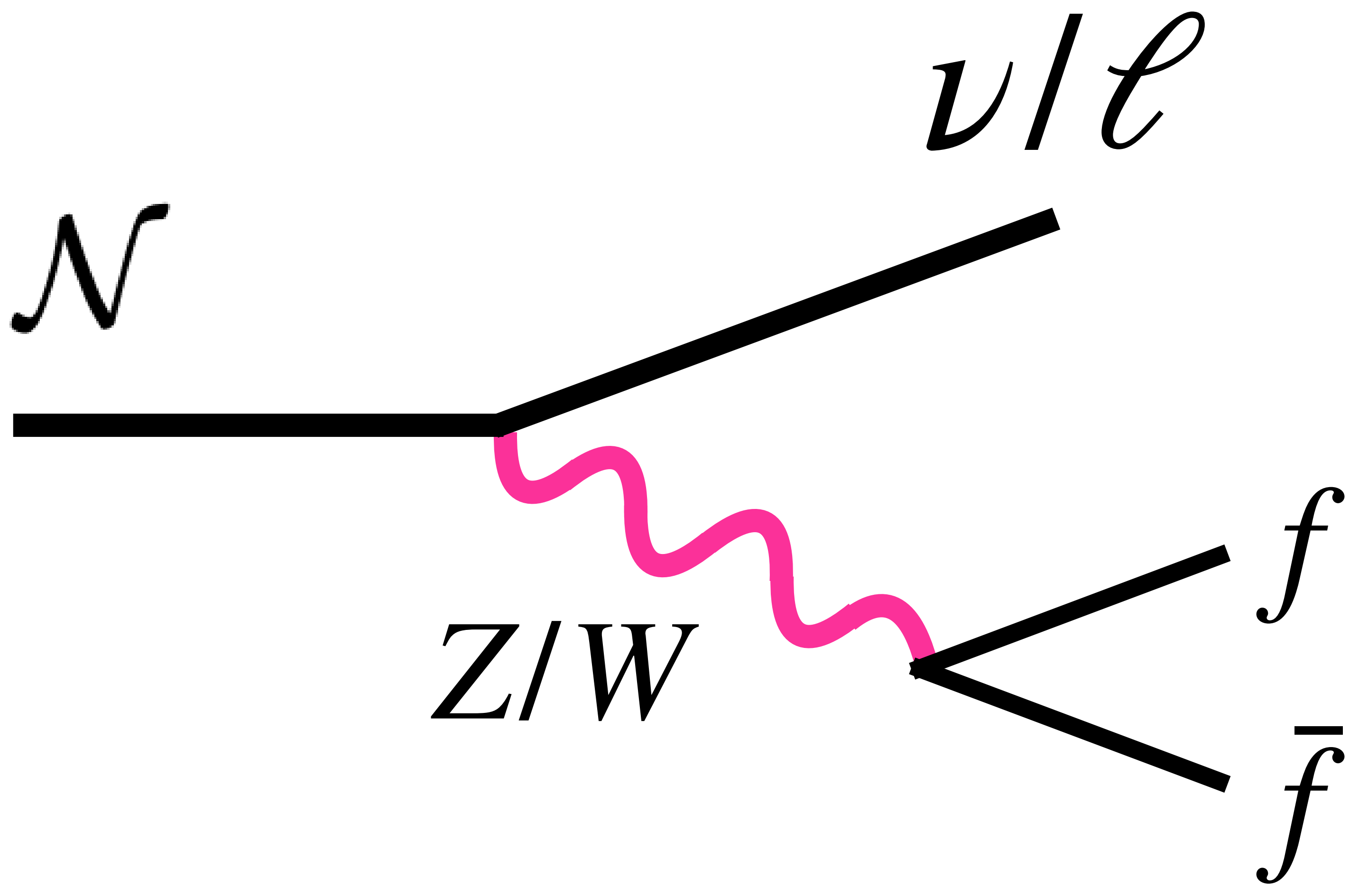
Heavy Neutral Leptons in SIREN: Decay



Native SIREN class in development to handle all decay modes of mass-mixed HNLs

$$m_{\mathcal{N}} < m_W$$

Follows Coloma+ 2020, Ballett+ 2019



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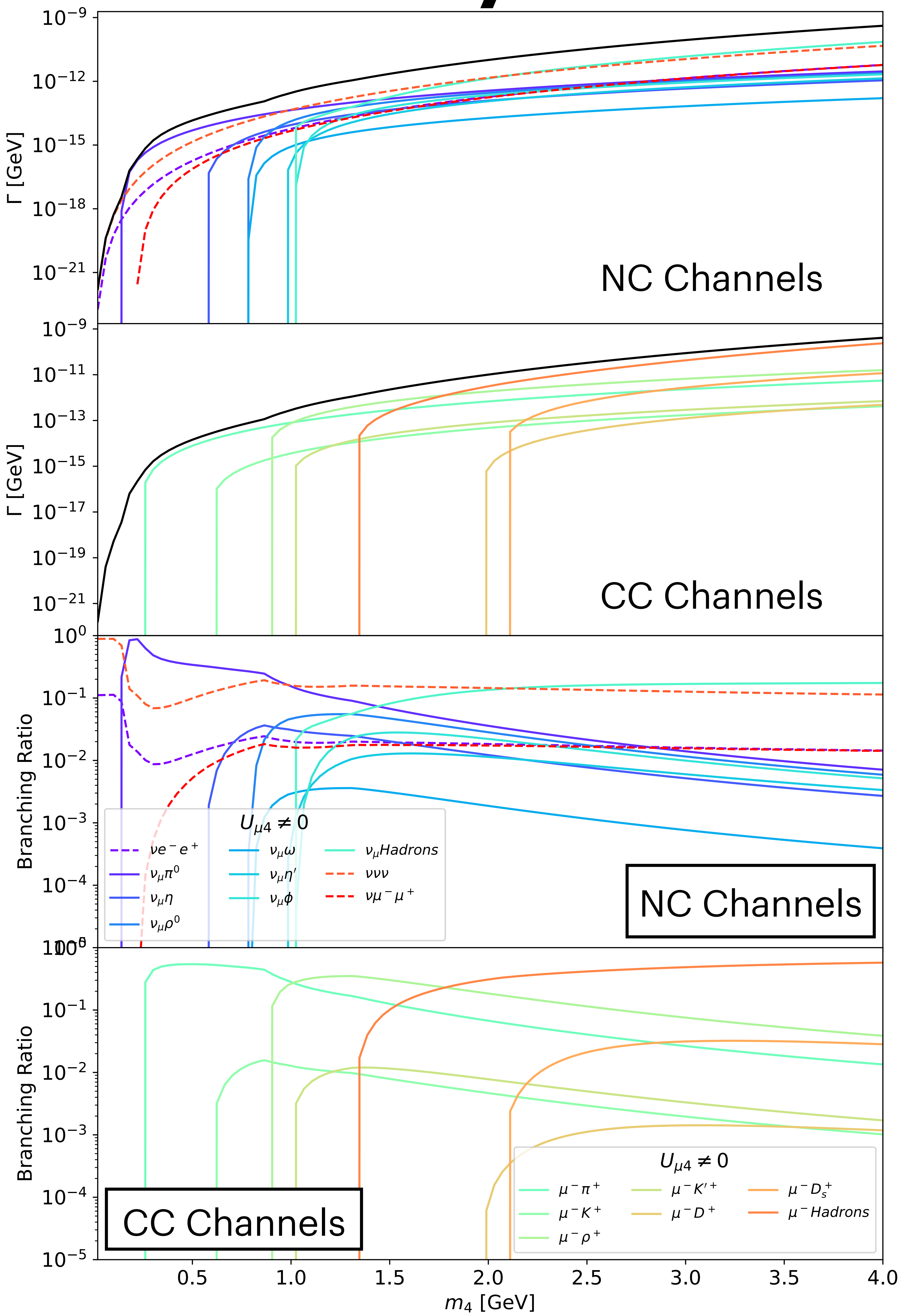

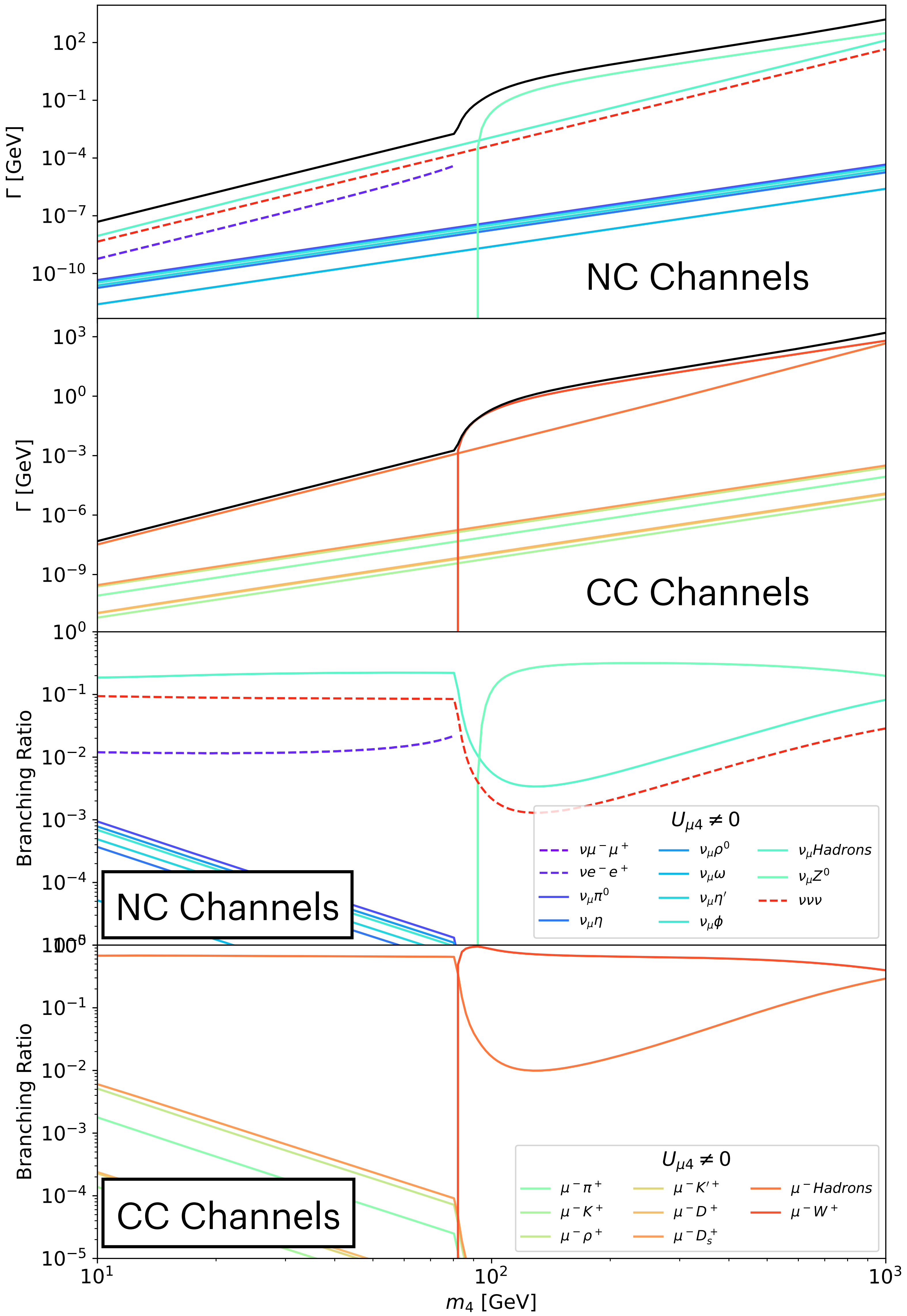

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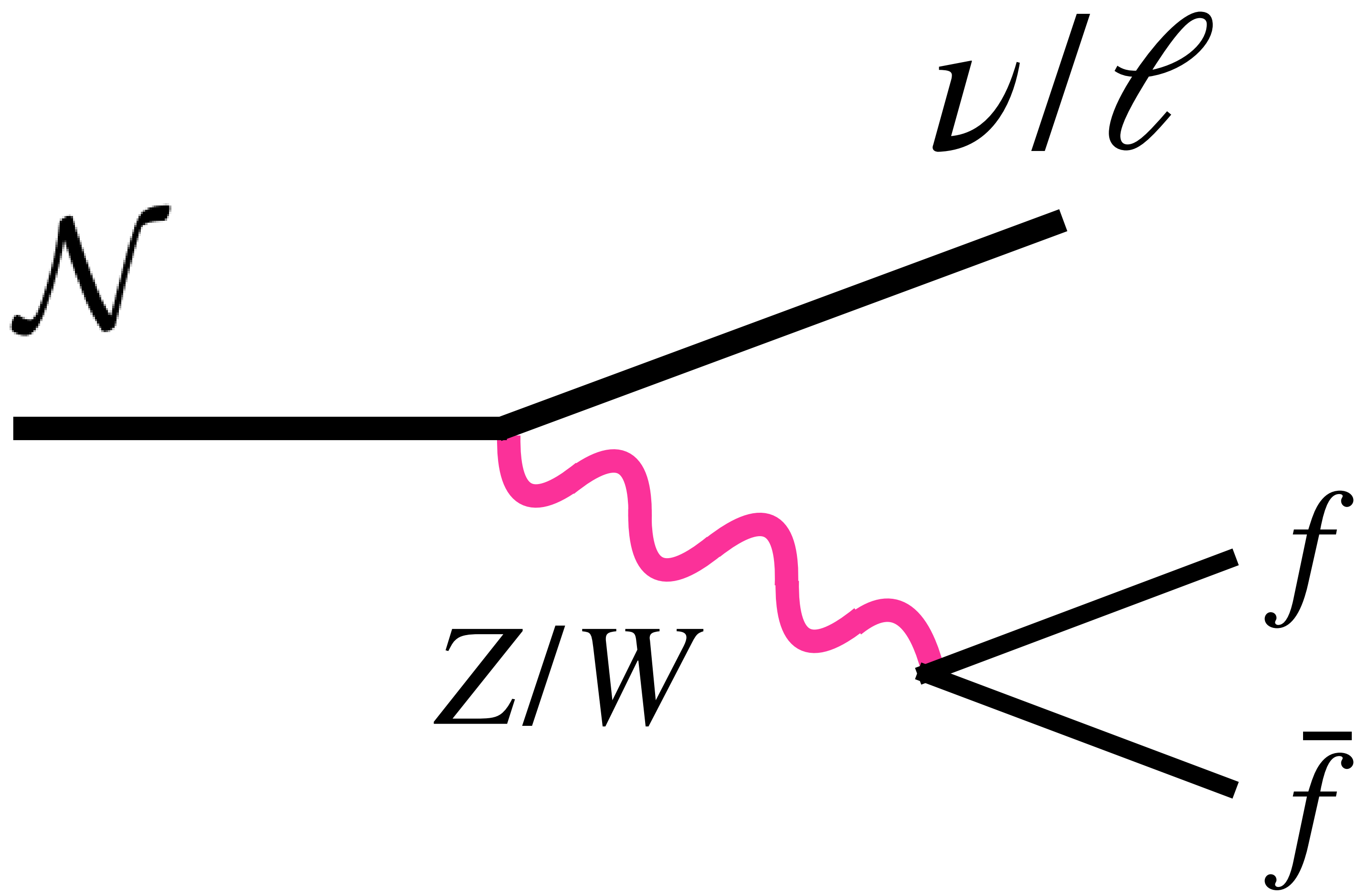
$m_{\mathcal{N}} > m_W$ Follows Atre+ 2009



That’s all fine and dandy,
but can we actually use it?

Outline

1. Overview of SIREN
2. Using SIREN for…
   - BSM physics with accelerator neutrinos
   - SM physics with collider neutrinos
   - SM + BSM physics with neutrino telescopes

BSM physics with accelerator neutrinos

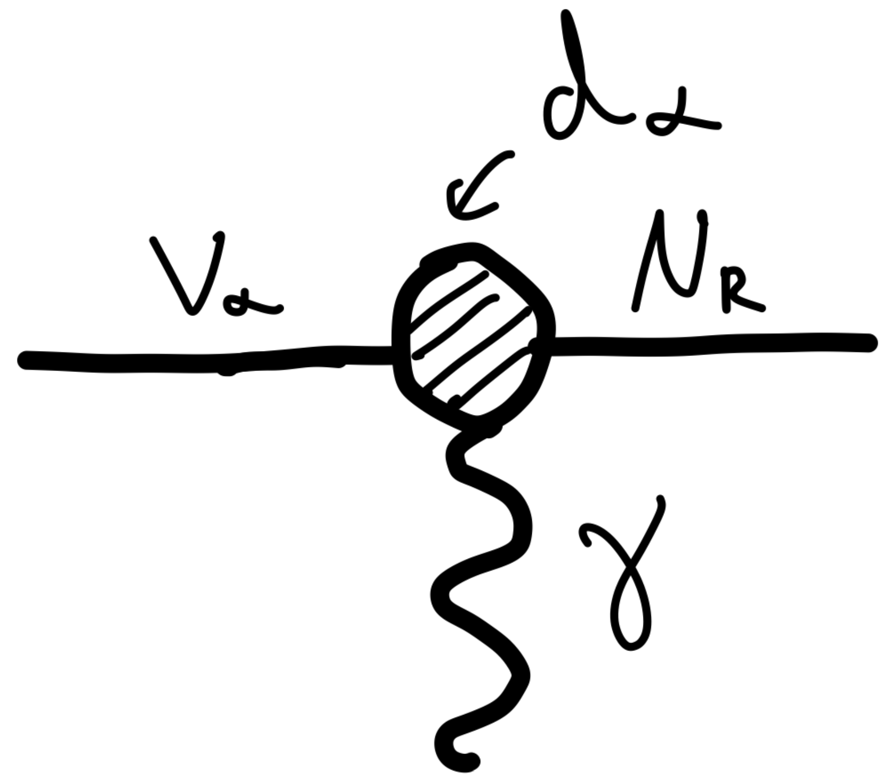
- We've used SIREN to explore dipole-portal HNLs in a variety of accelerator neutrino experiments:
  - MiniBooNE (NK, Hostert, Schneider+ 2022)
  - MINERvA (NK, Hostert, Schneider+ 2022)
  - Coherent-CAPTAIN-Mills (NK Thesis 2023)
  - ND280 & ND280+ (M.S. Liu, NK, Argüelles 2024)

Dipole-Portal HNL

Heavy neutral lepton (HNL) with an effective transition magnetic moment

Parameters

- M_N : HNL mass
- $d_{\alpha N}$: effective dipole moment



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I’ll touch on these three

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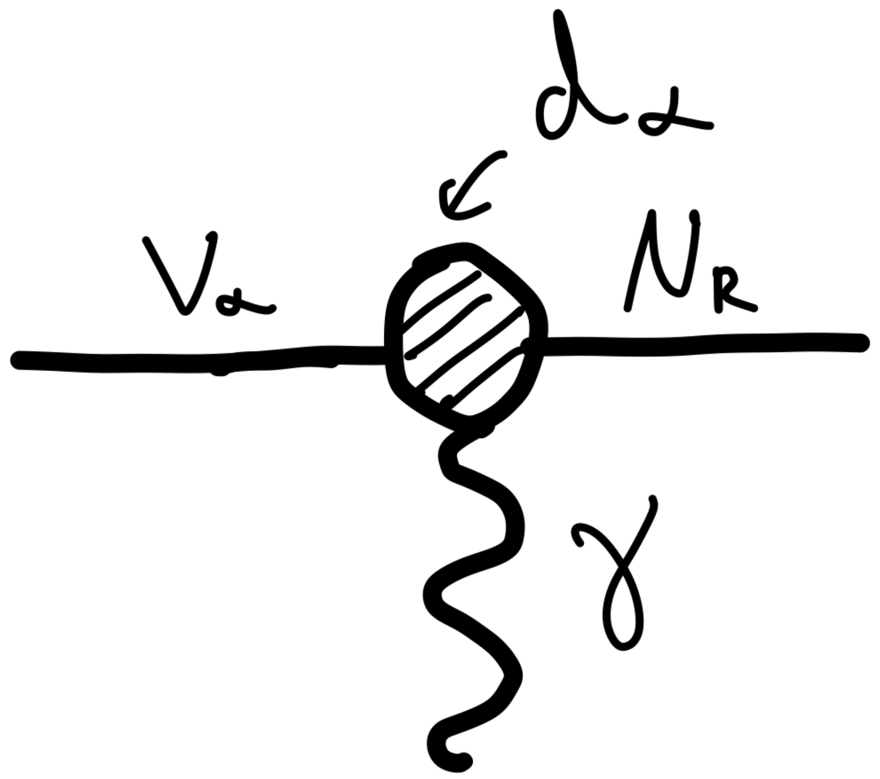
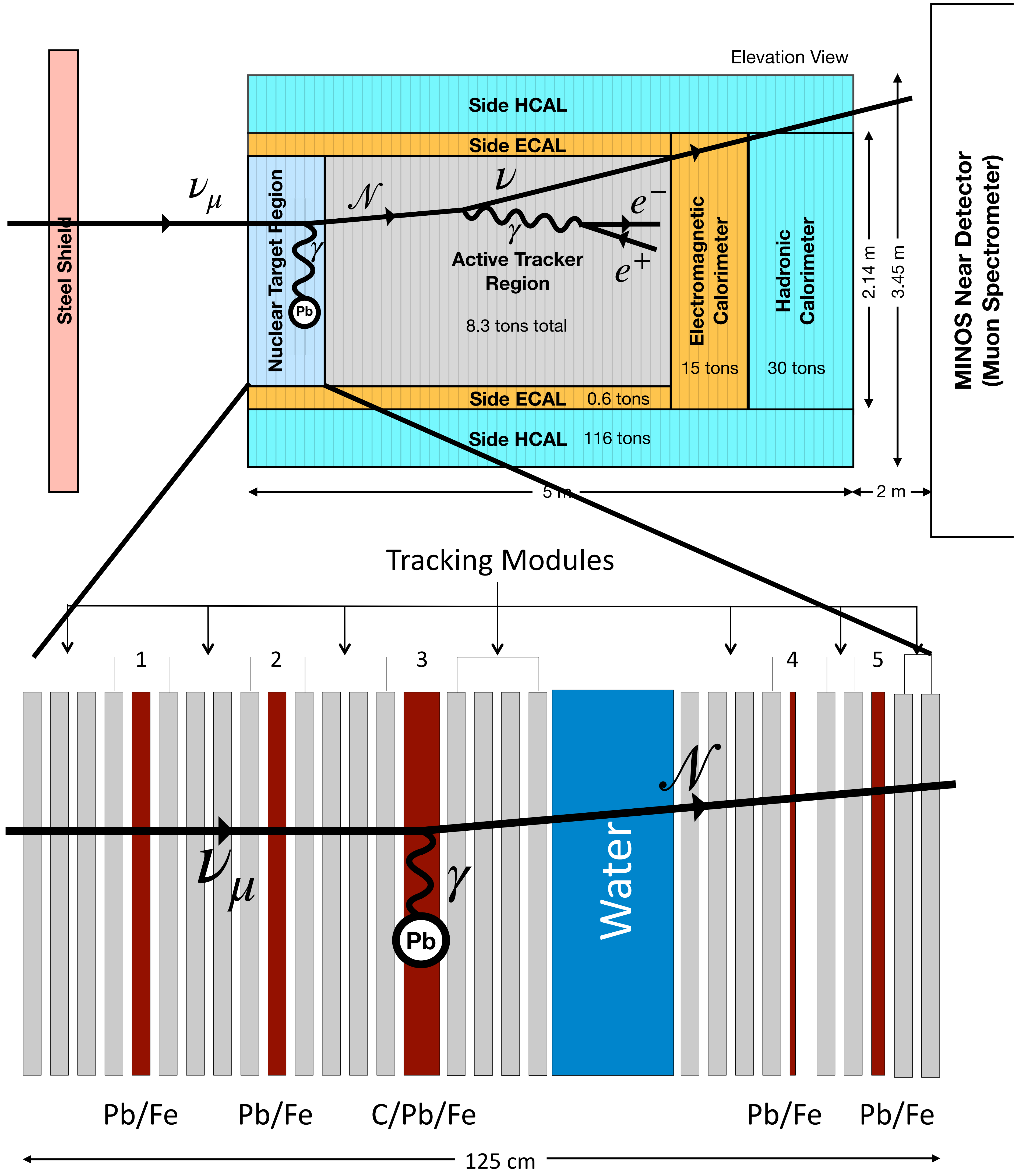


SIREN for Dipole-Portal HNLs @ MINERvA

SIREN enables an accurate calculation of the HNL production rate

NK, Hostert, Schneider+ 2022

SIREN for Dipole-Portal HNLs @ MINERvA



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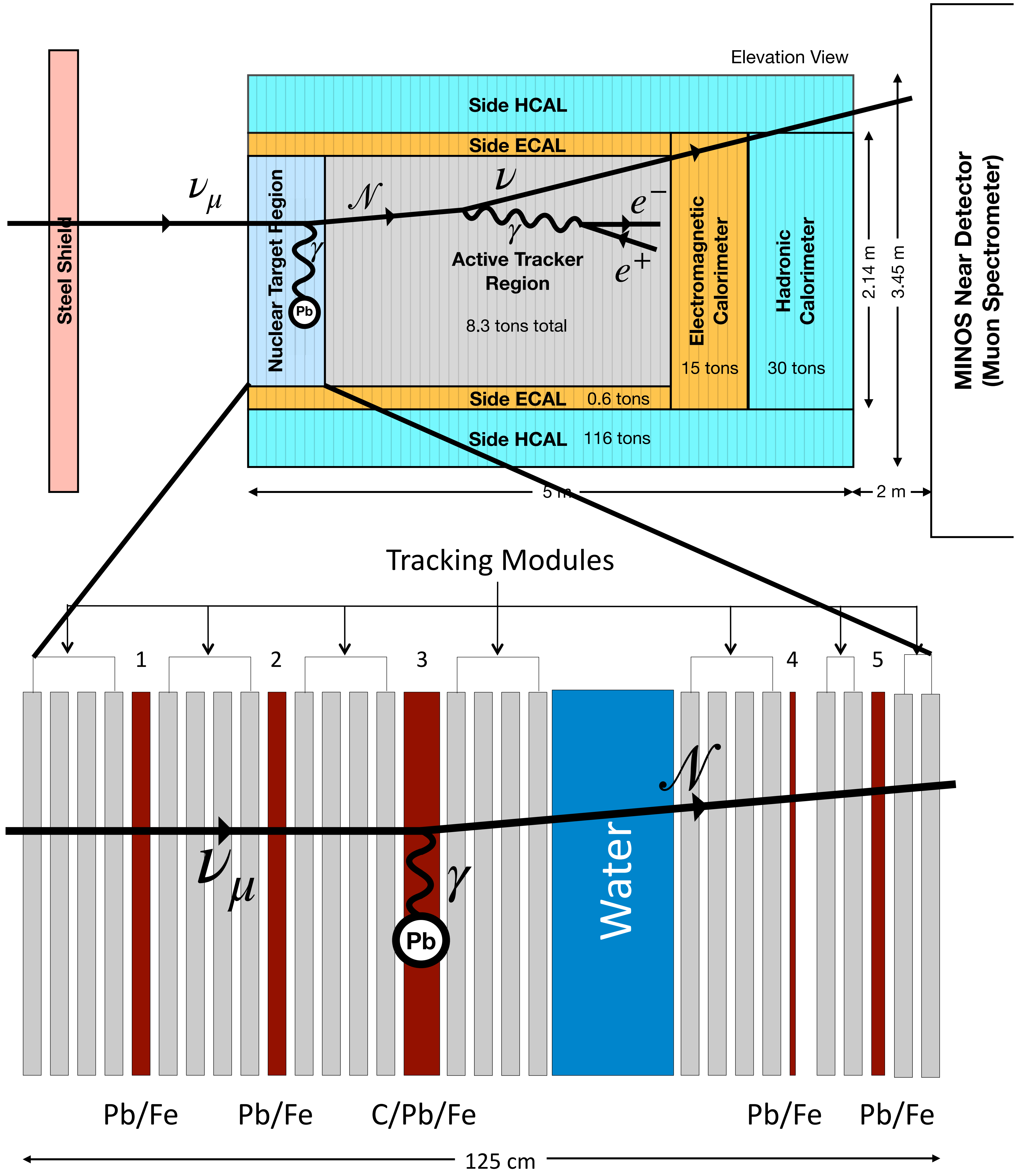

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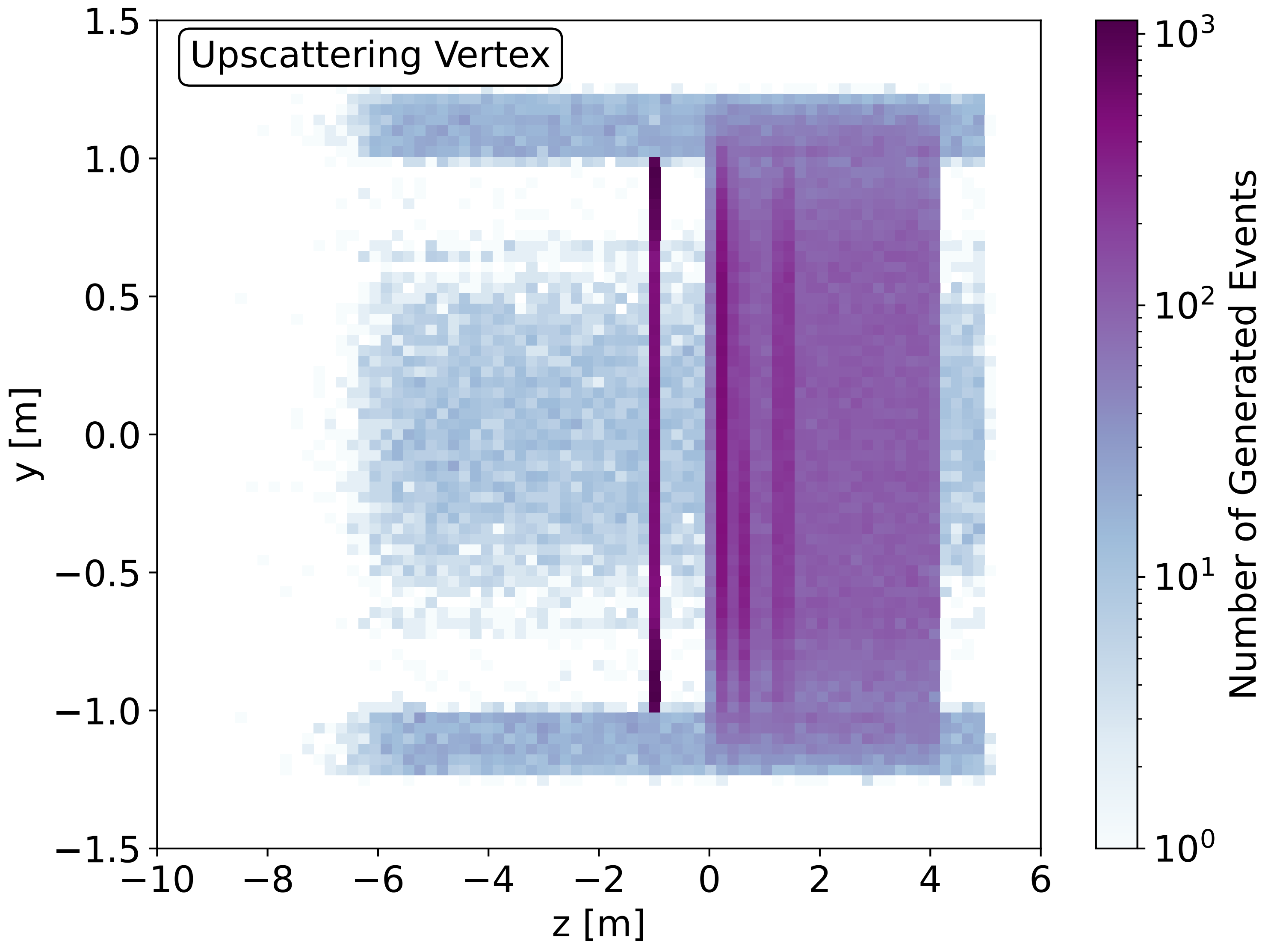

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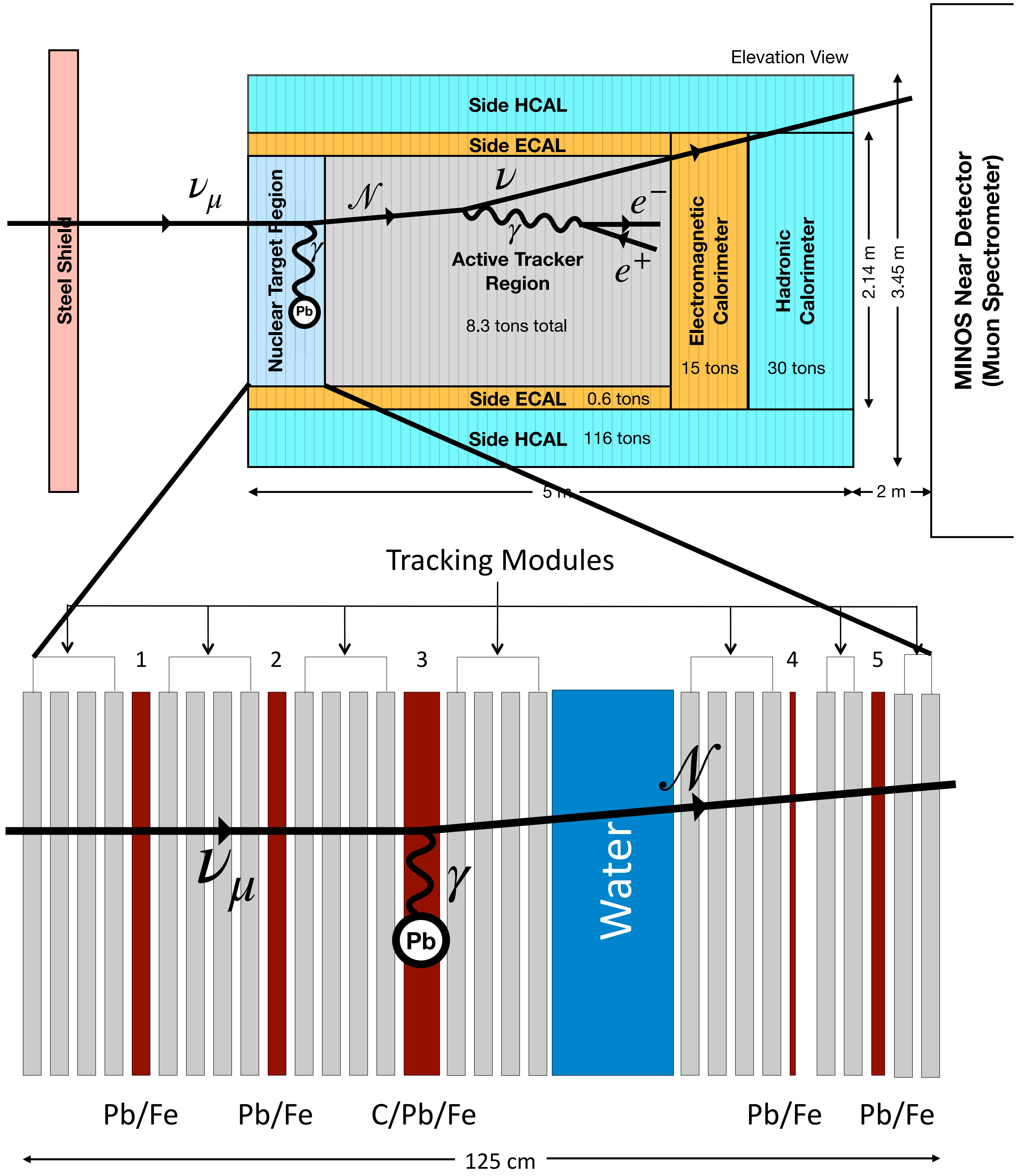

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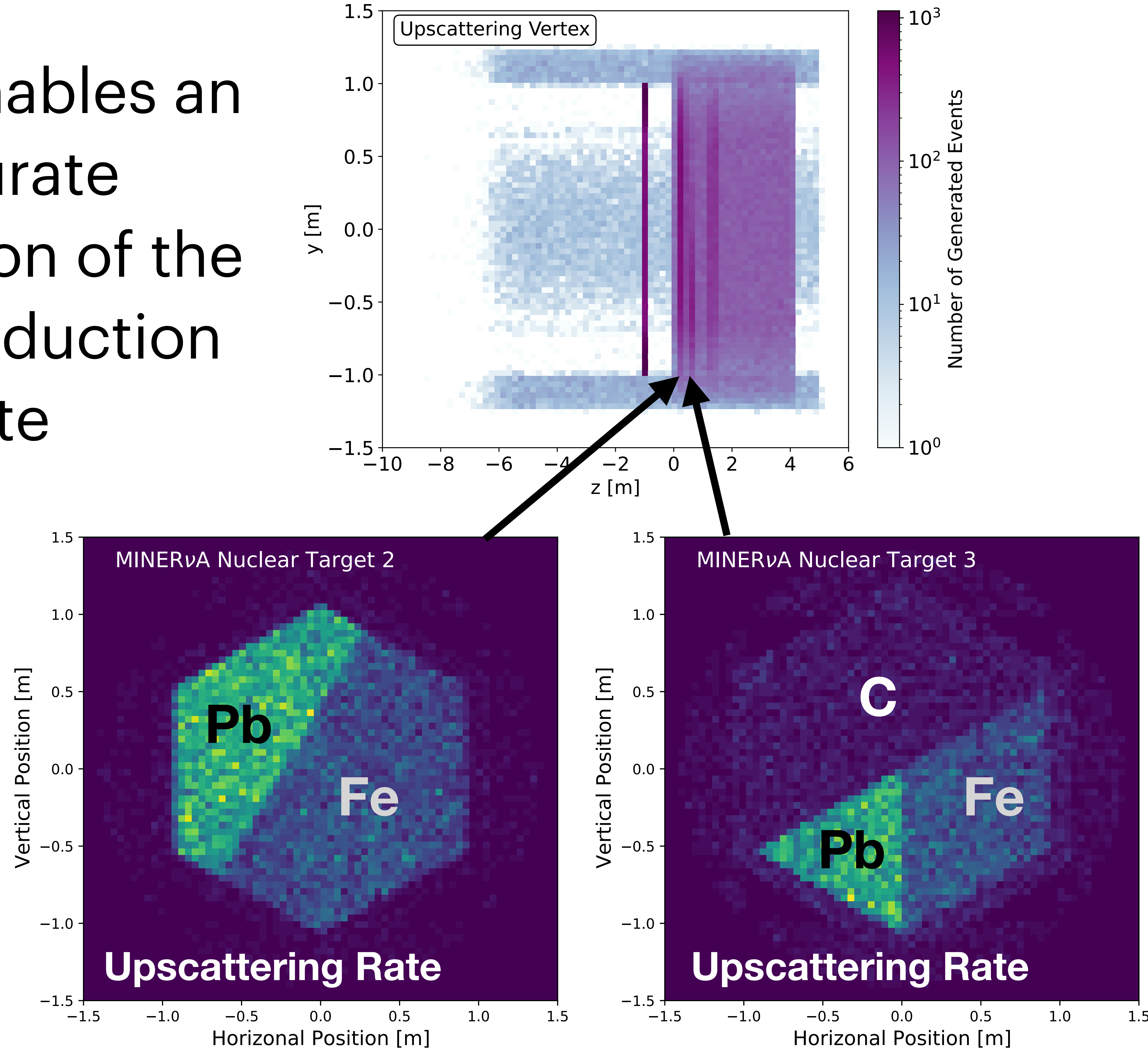

NK, Hostert, Schneider+ 2022

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SIREN further enables an accurate evaluation of kinematic cuts from the MINERvA elastic scattering analysis

NK, Hostert, Schneider+ 2022

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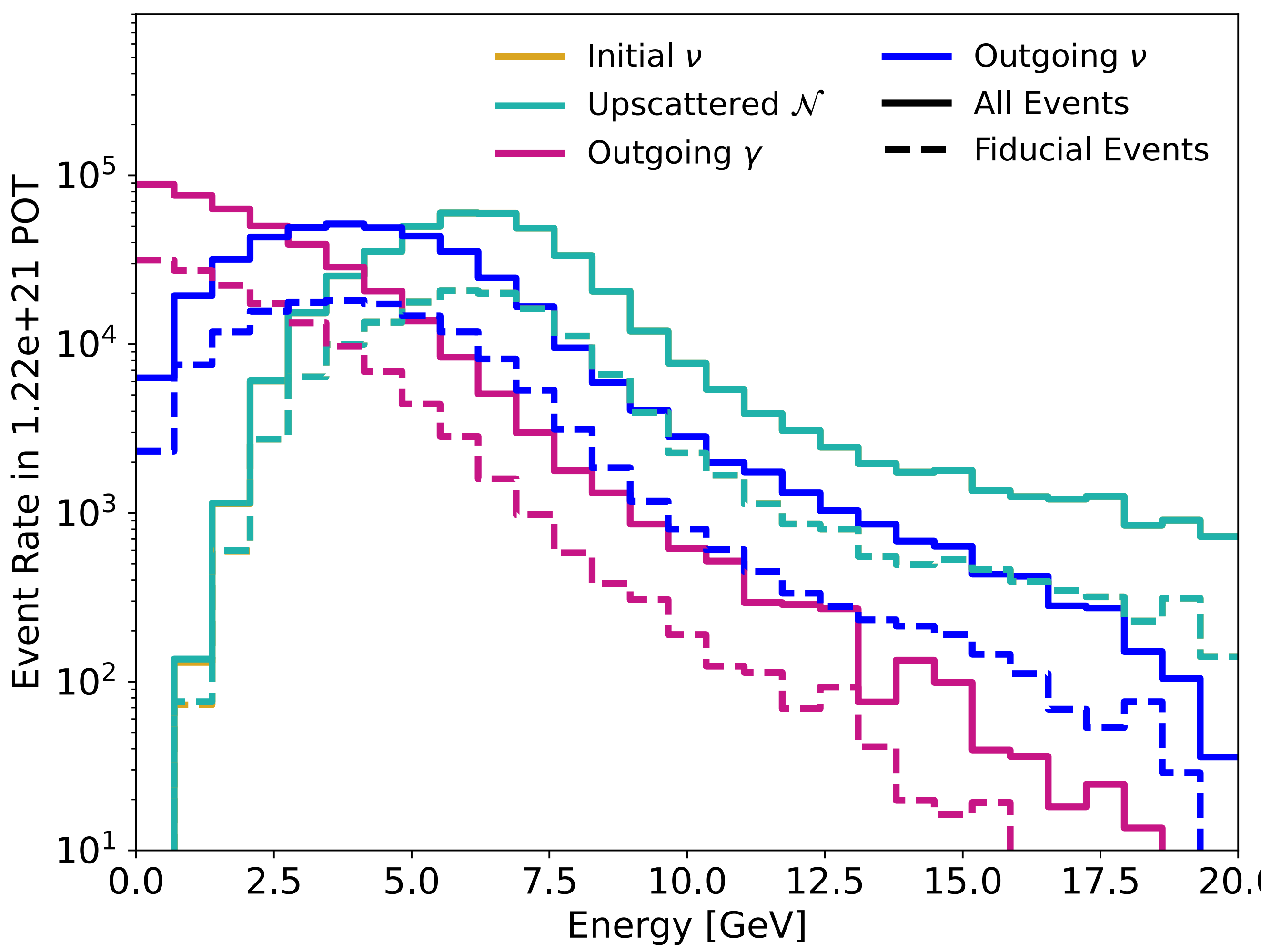

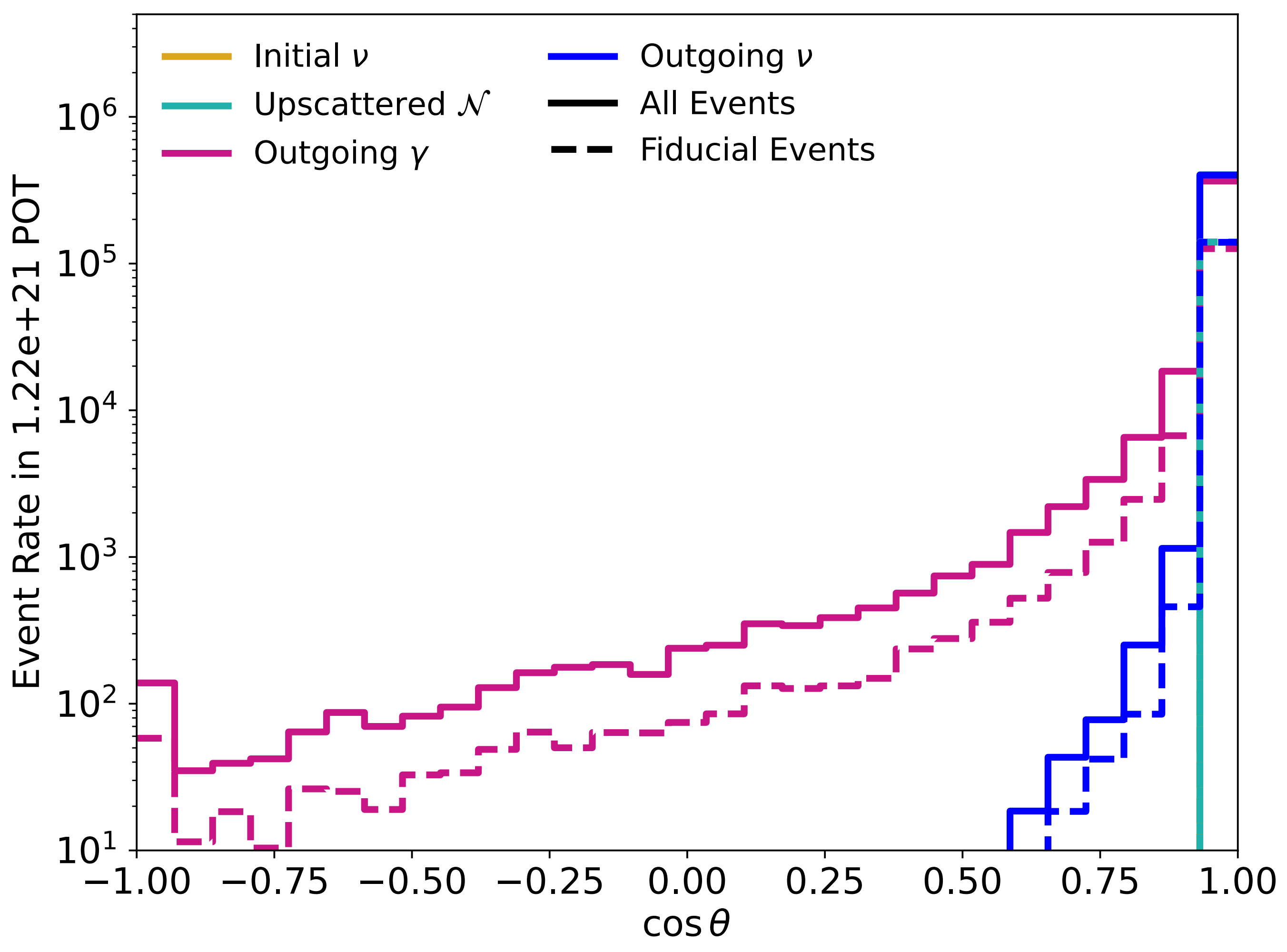

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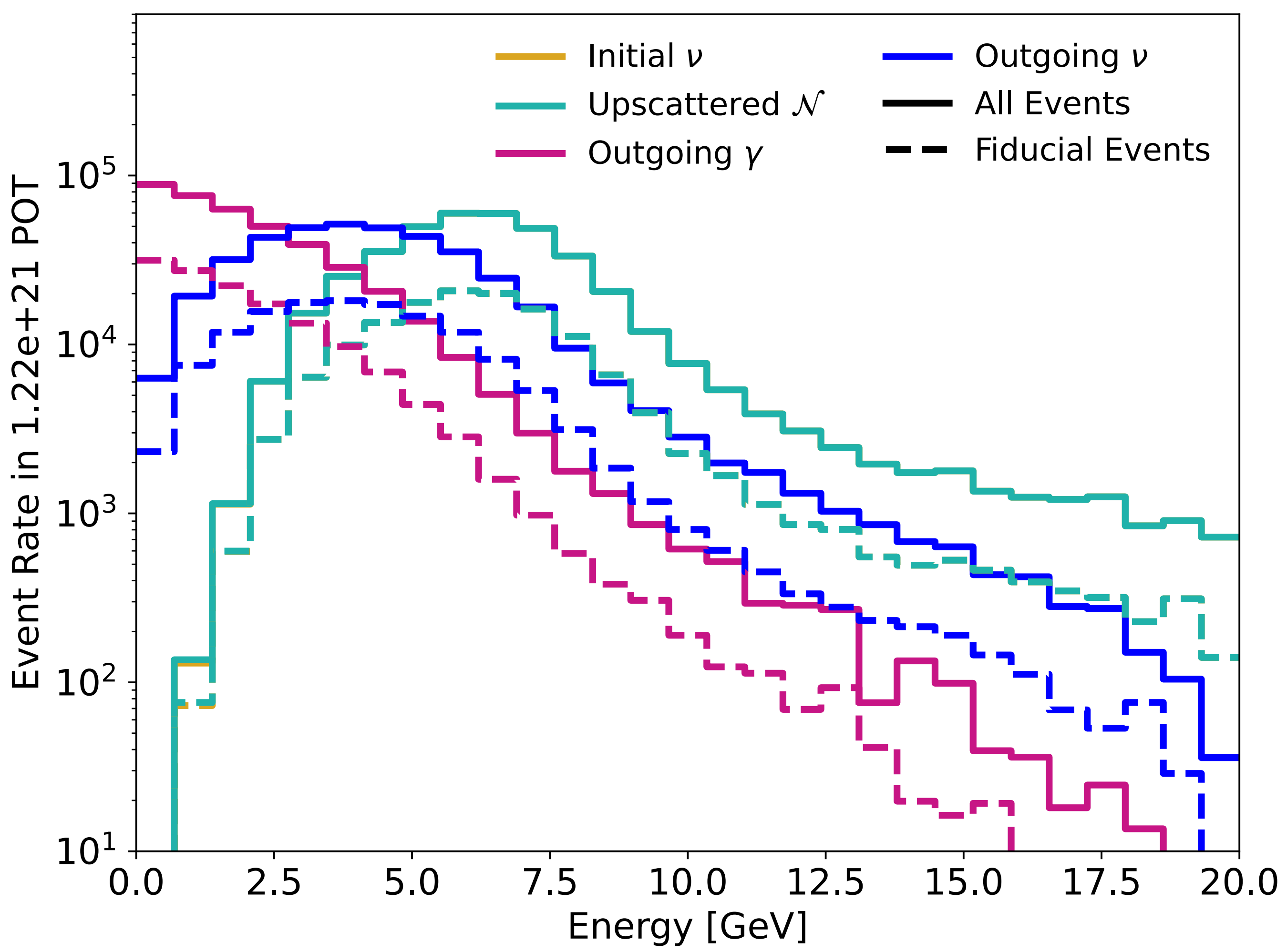

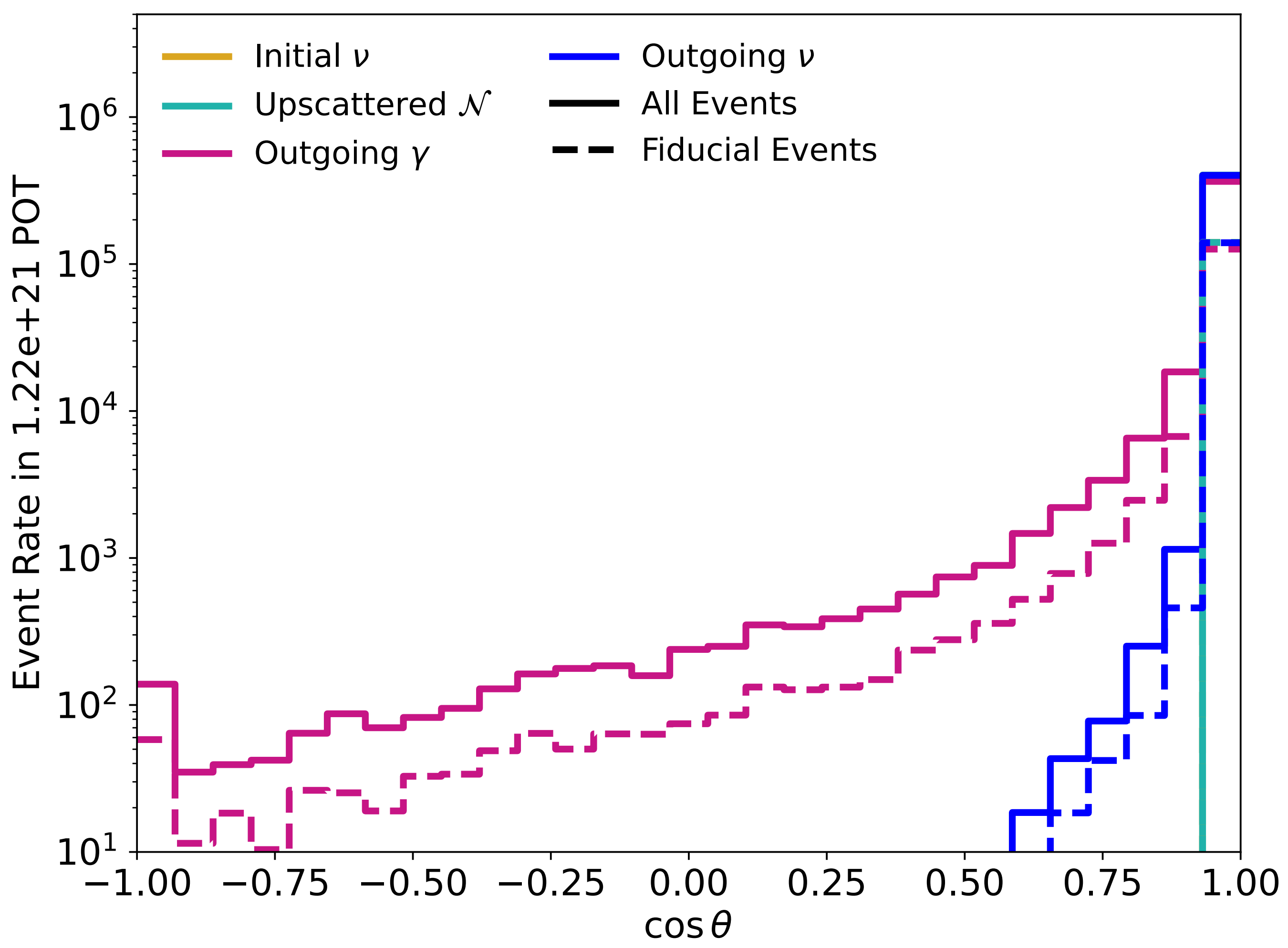

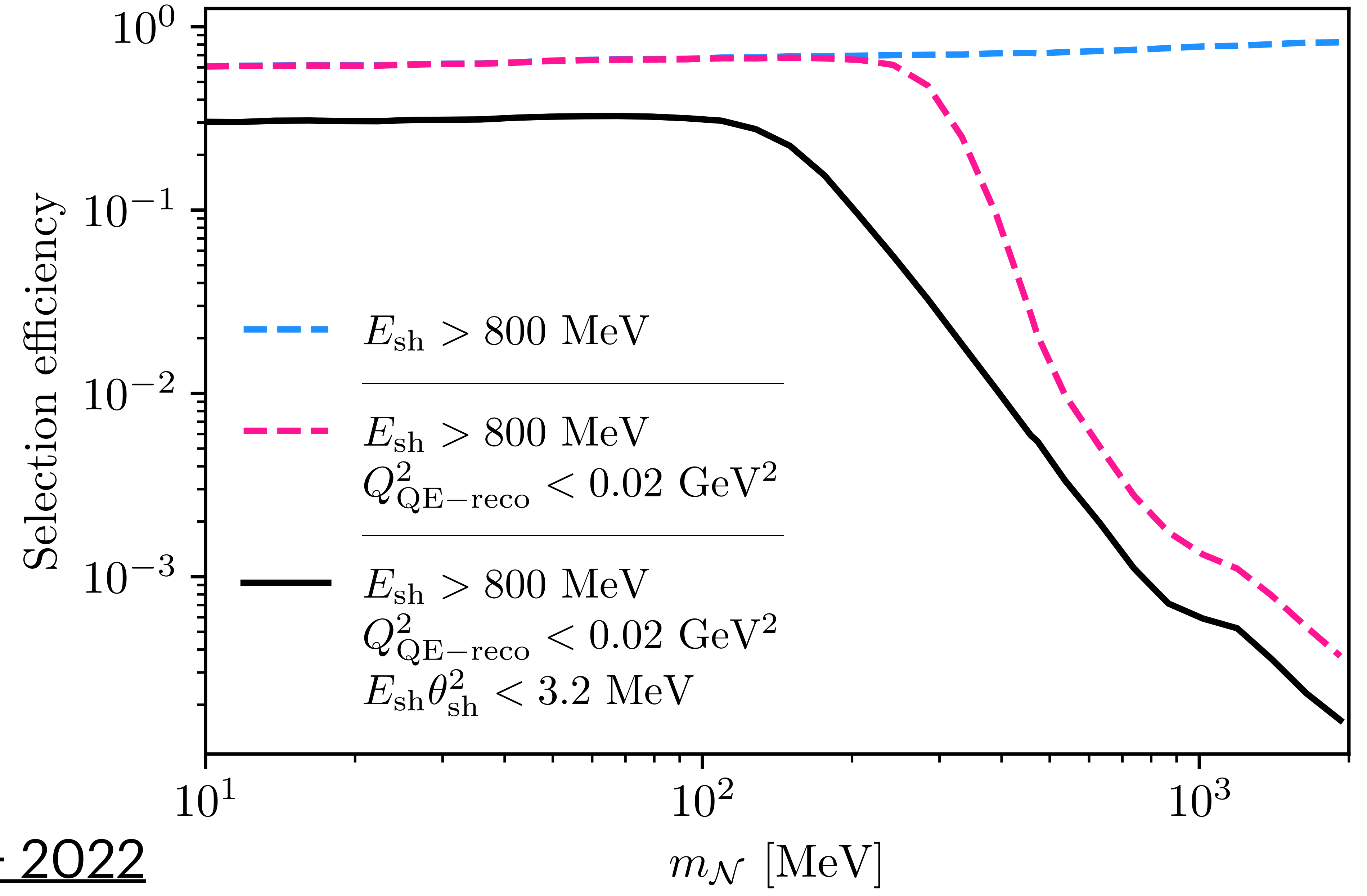

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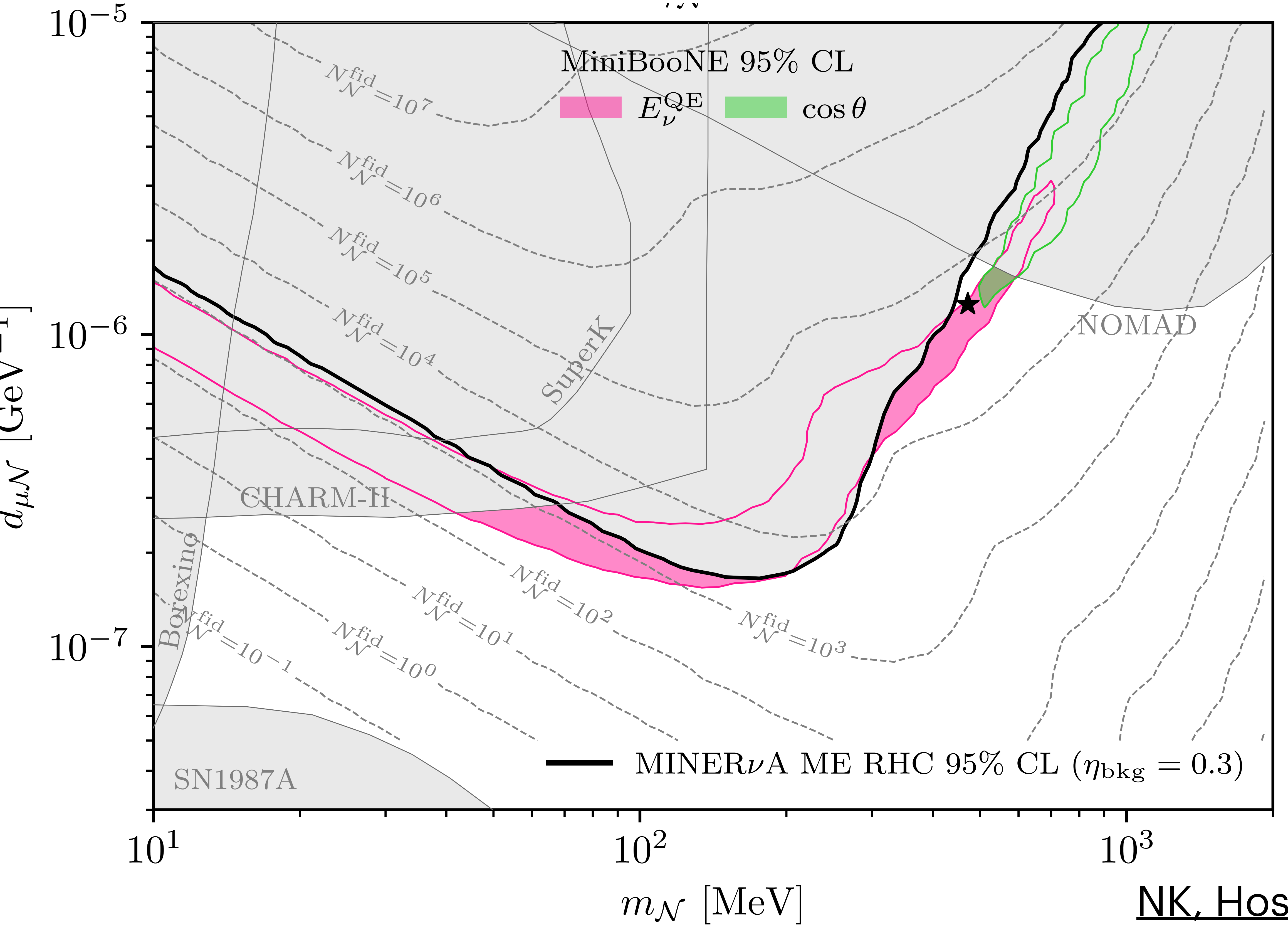
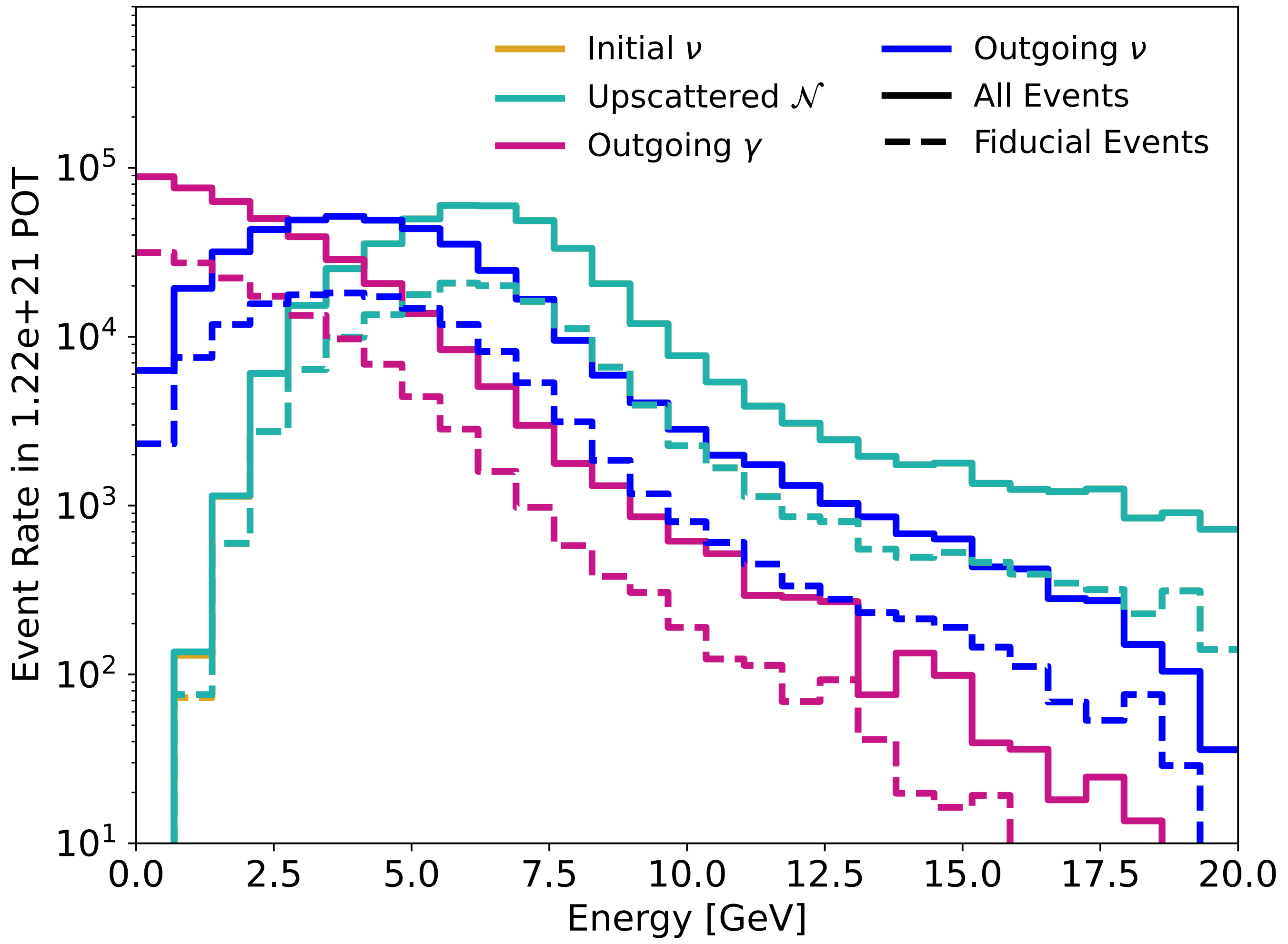
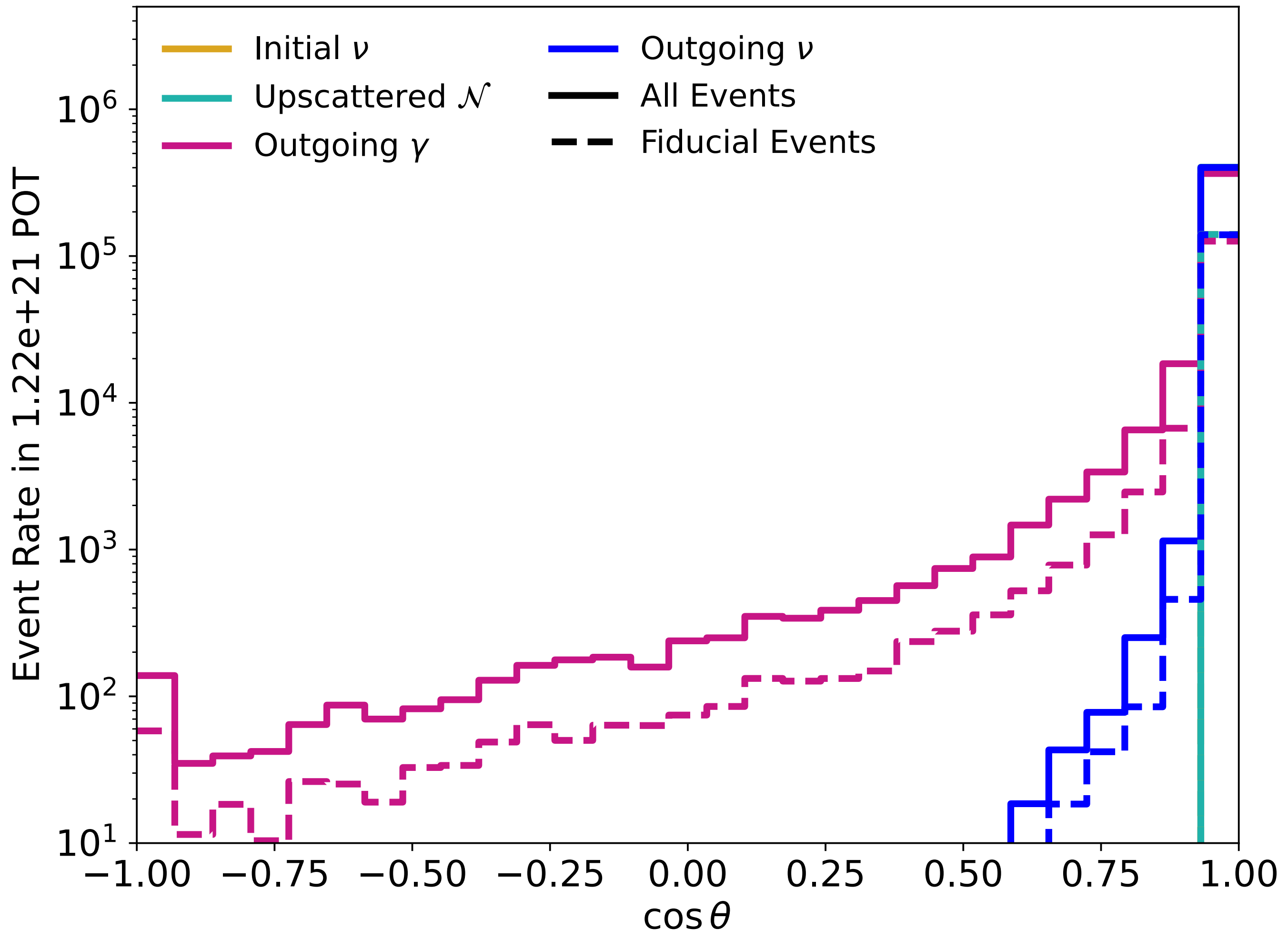
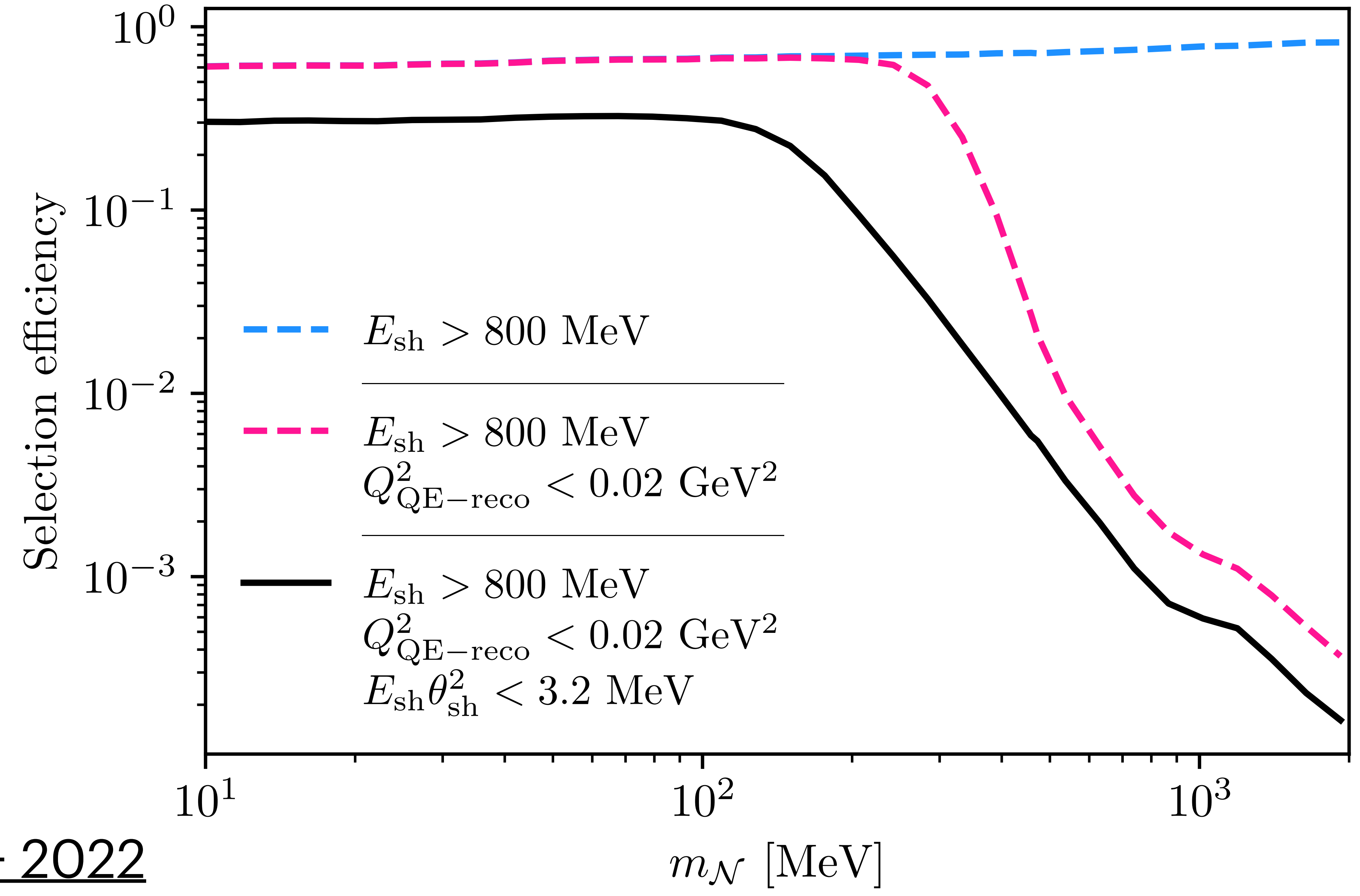




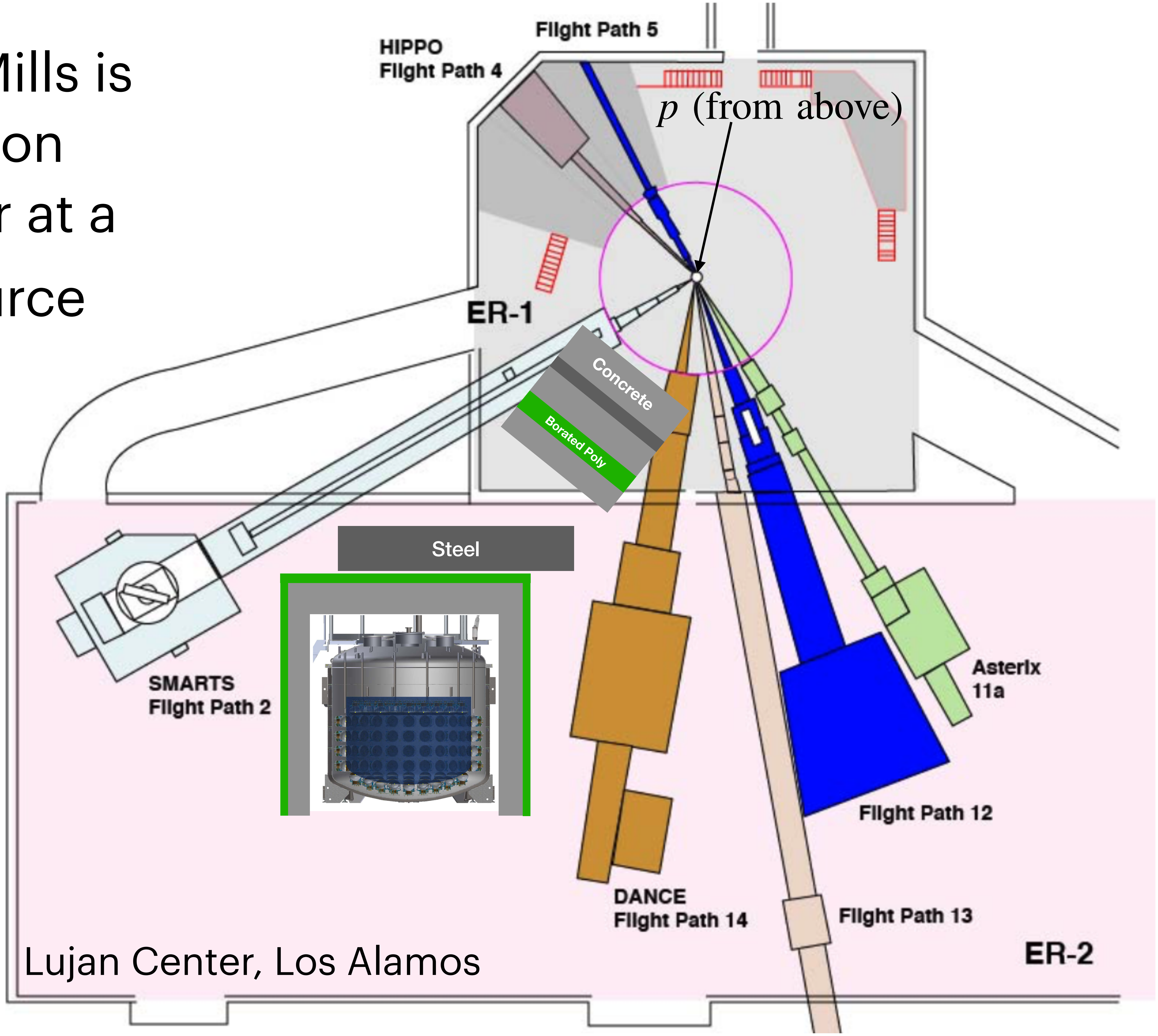




NK, Hostert, Schneider+ 2022

SIREN for Dipole-Portal HNLs @ CCM

Coherent CAPTAIN-Mills is a 10-ton liquid argon scintillation detector at a π decay-at-rest source



Neutrinos can upscatter to HNLs in surrounding shielding!

NK Thesis 2023

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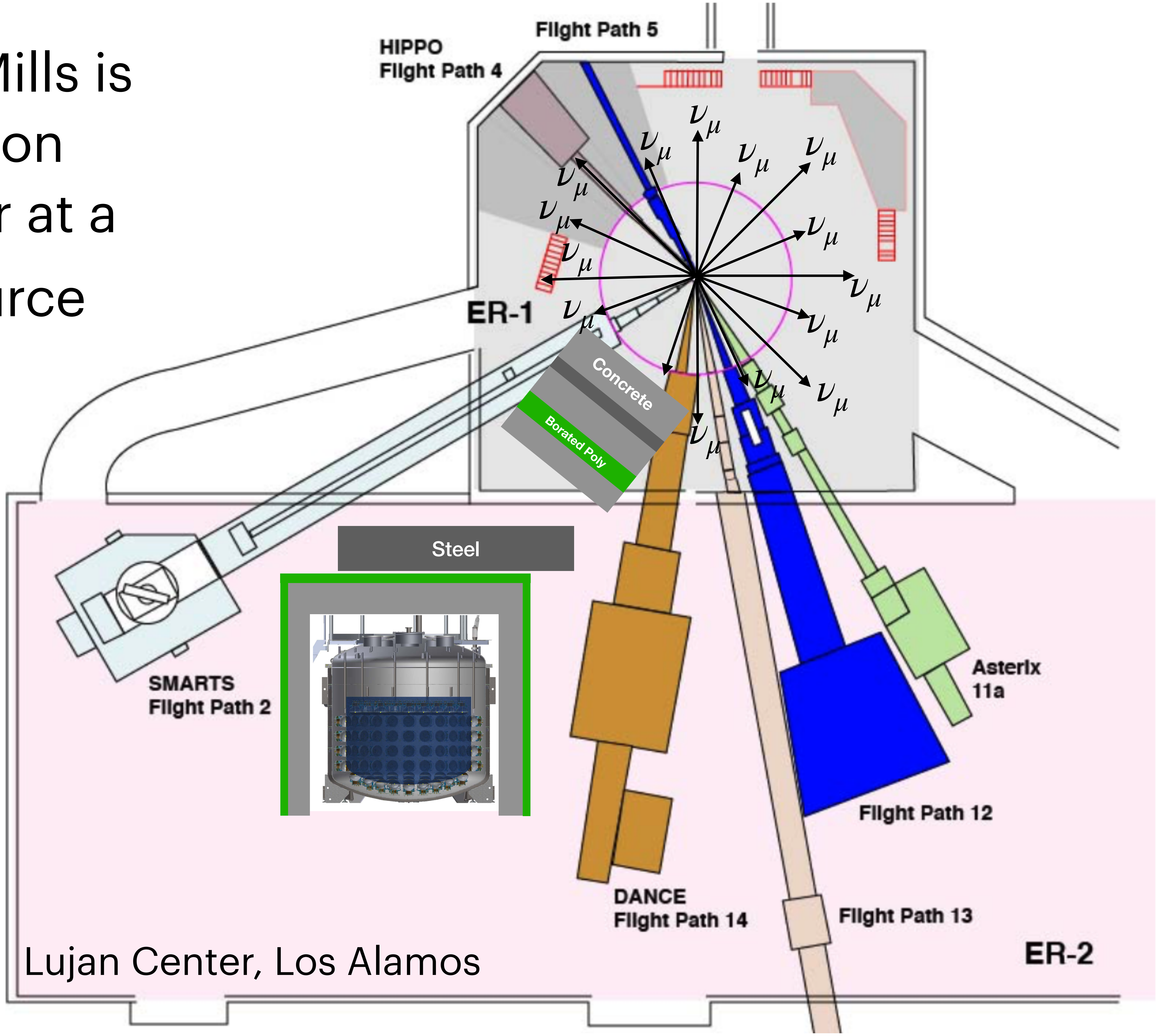

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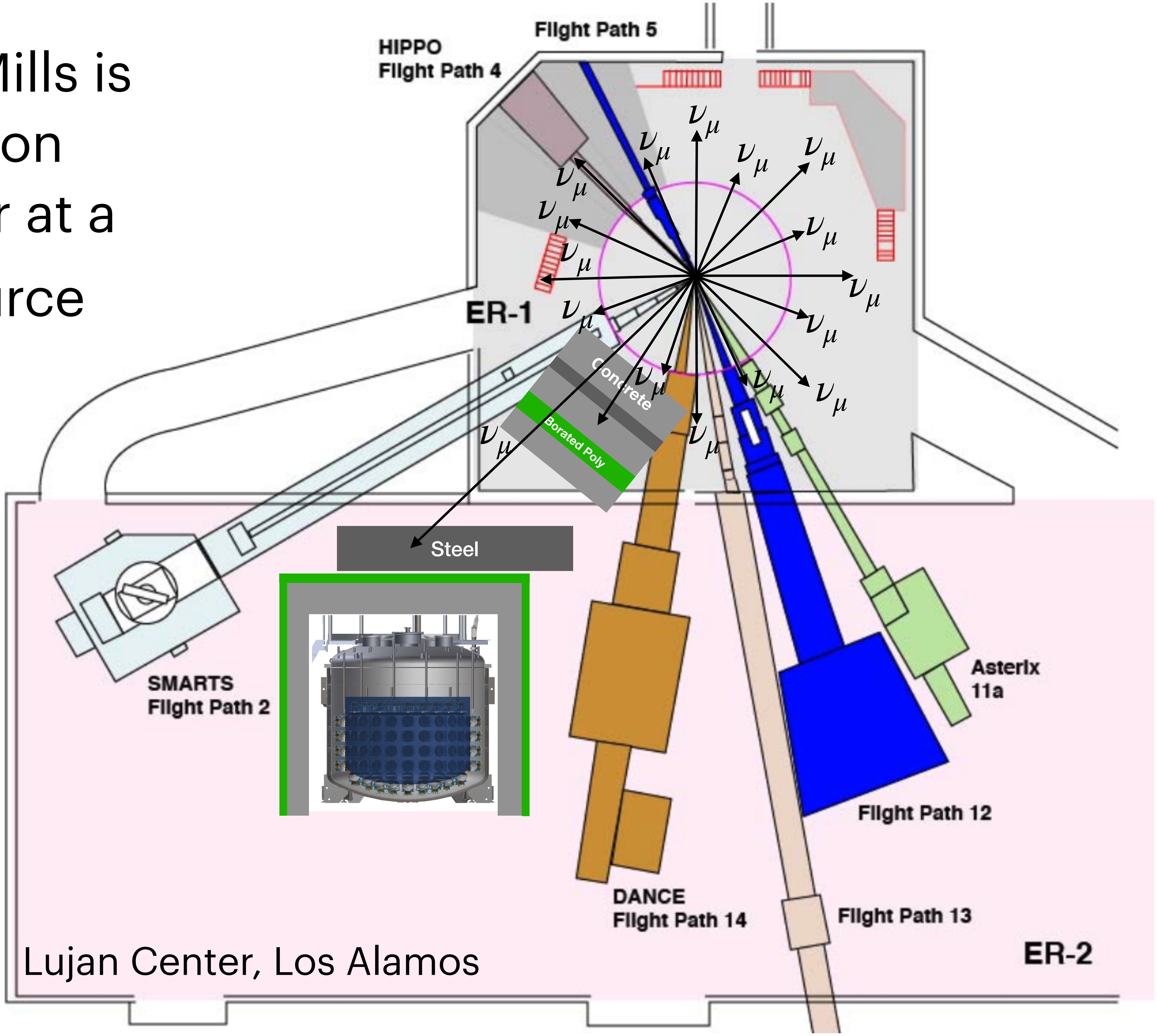

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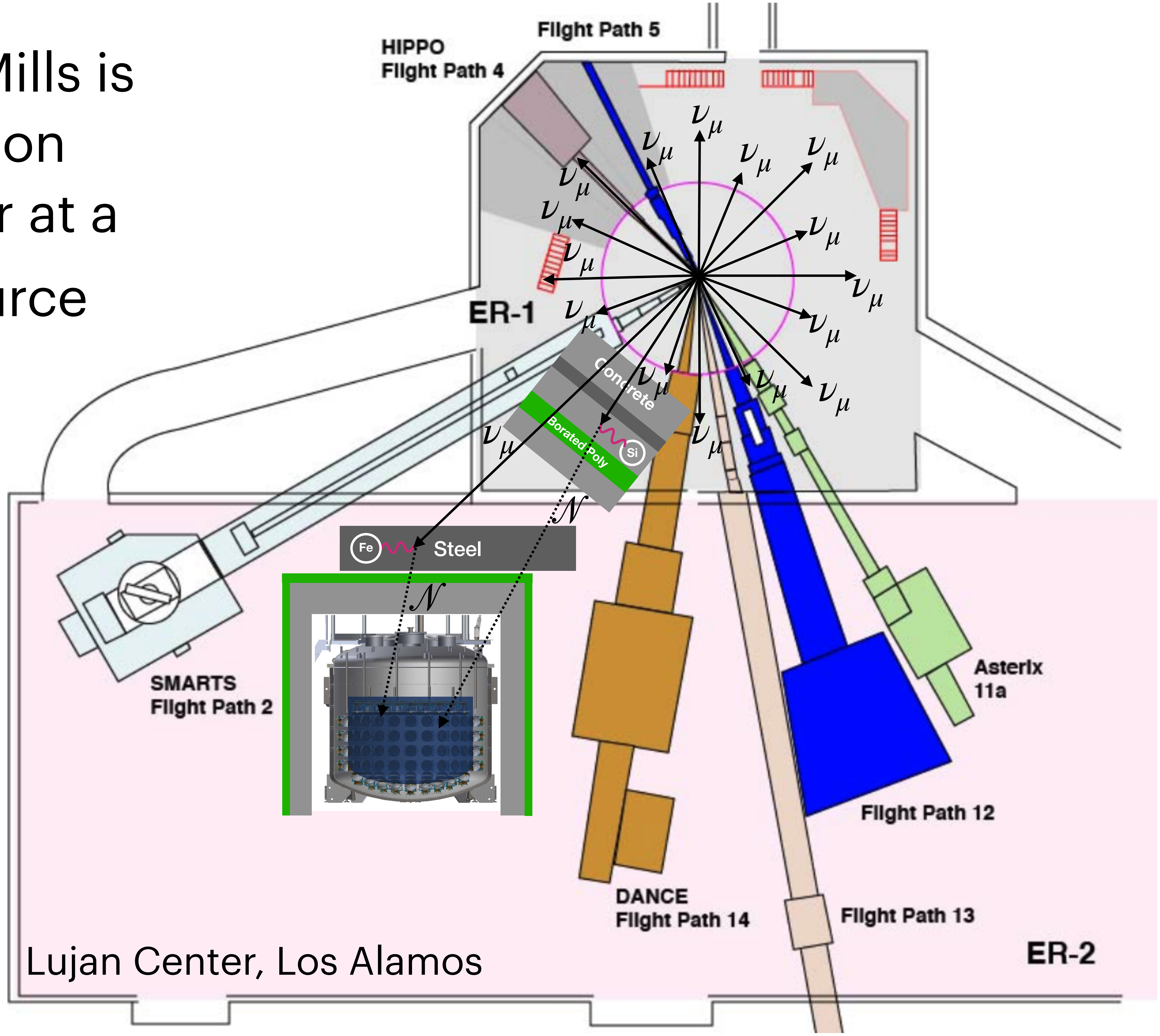

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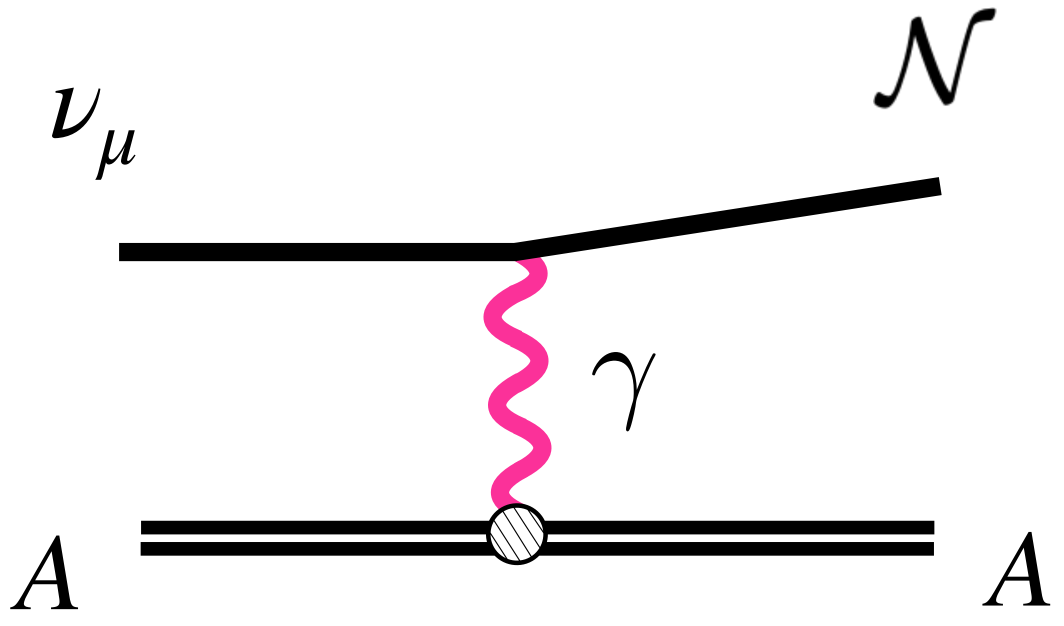

NK Thesis 2023

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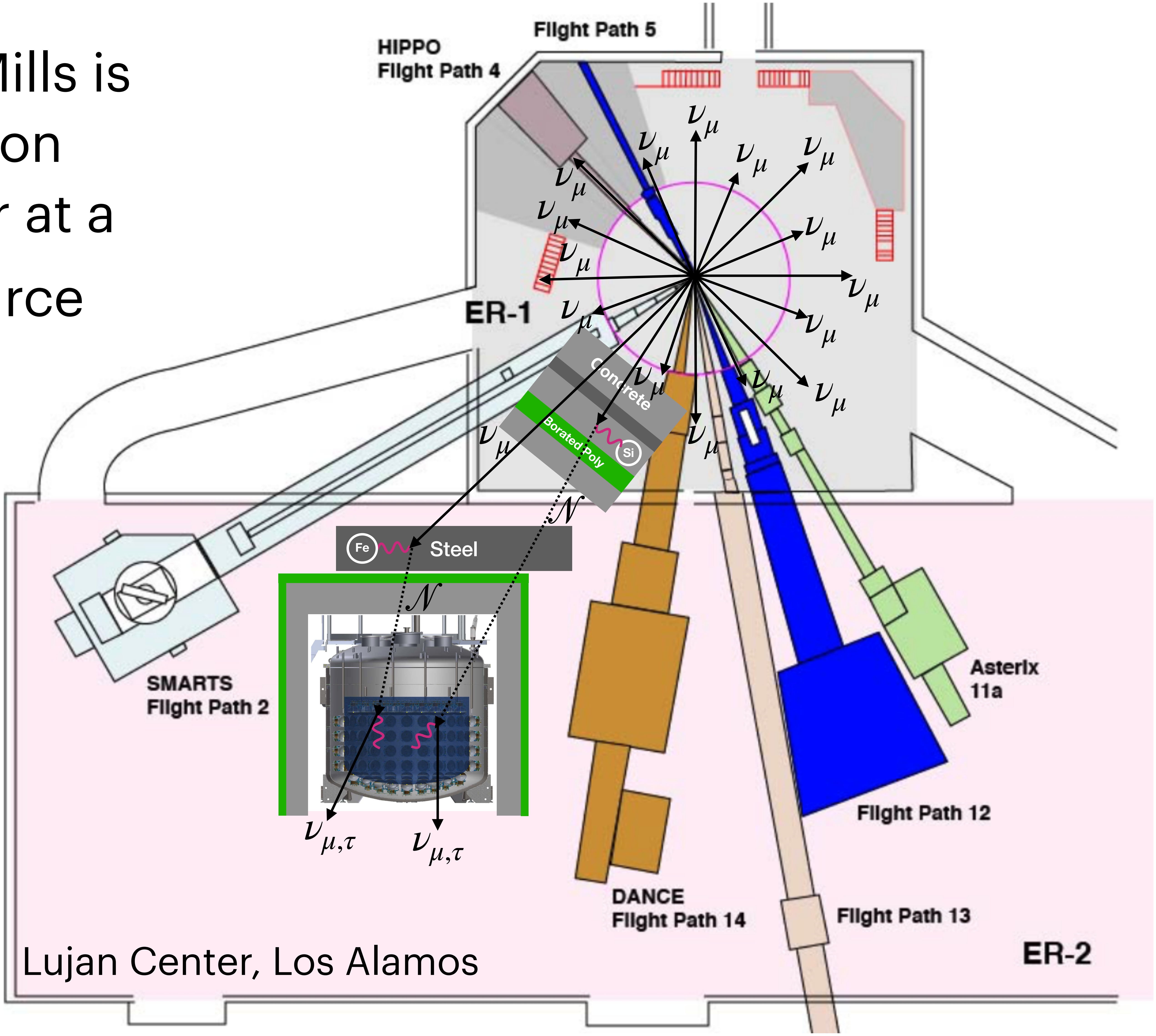

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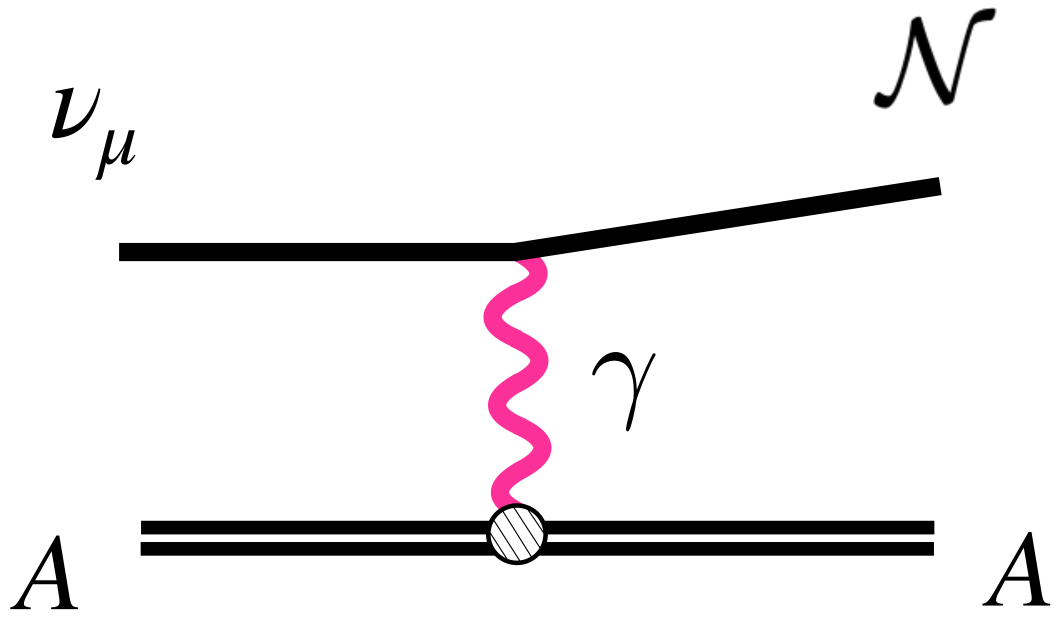
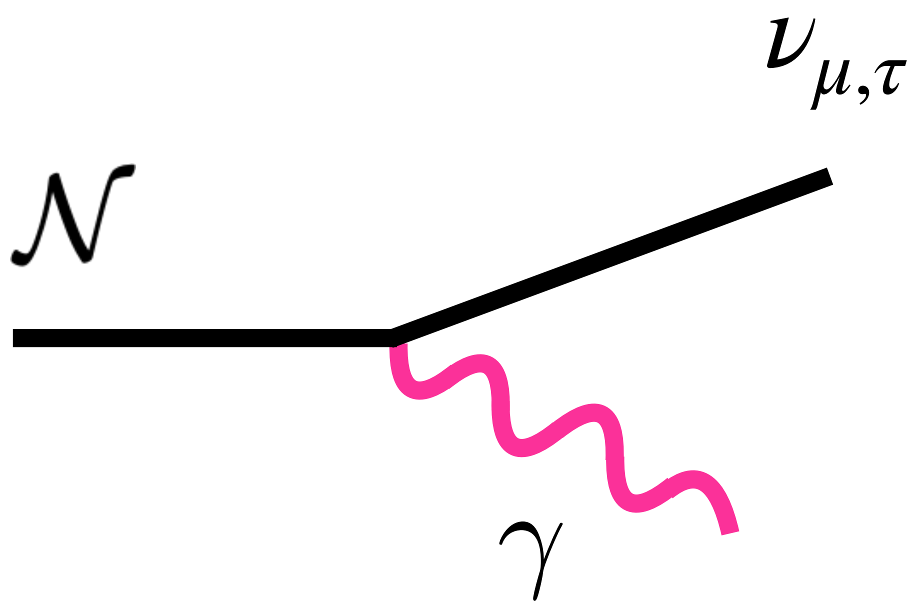
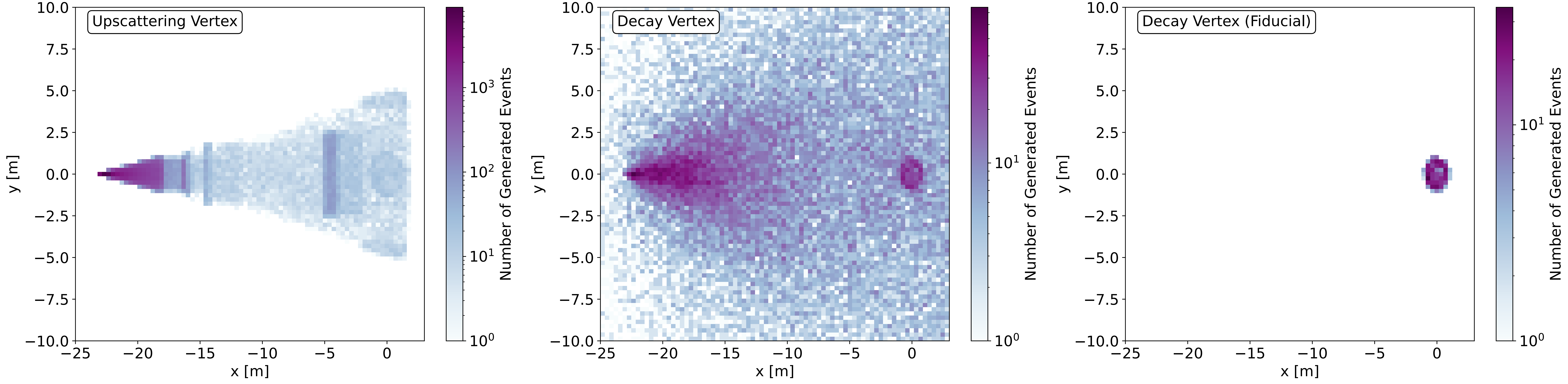




NK Thesis 2023

SIREN for Dipole-Portal HNLs @ CCM

SIREN makes it easy to account for HNL production in all surrounding shielding!



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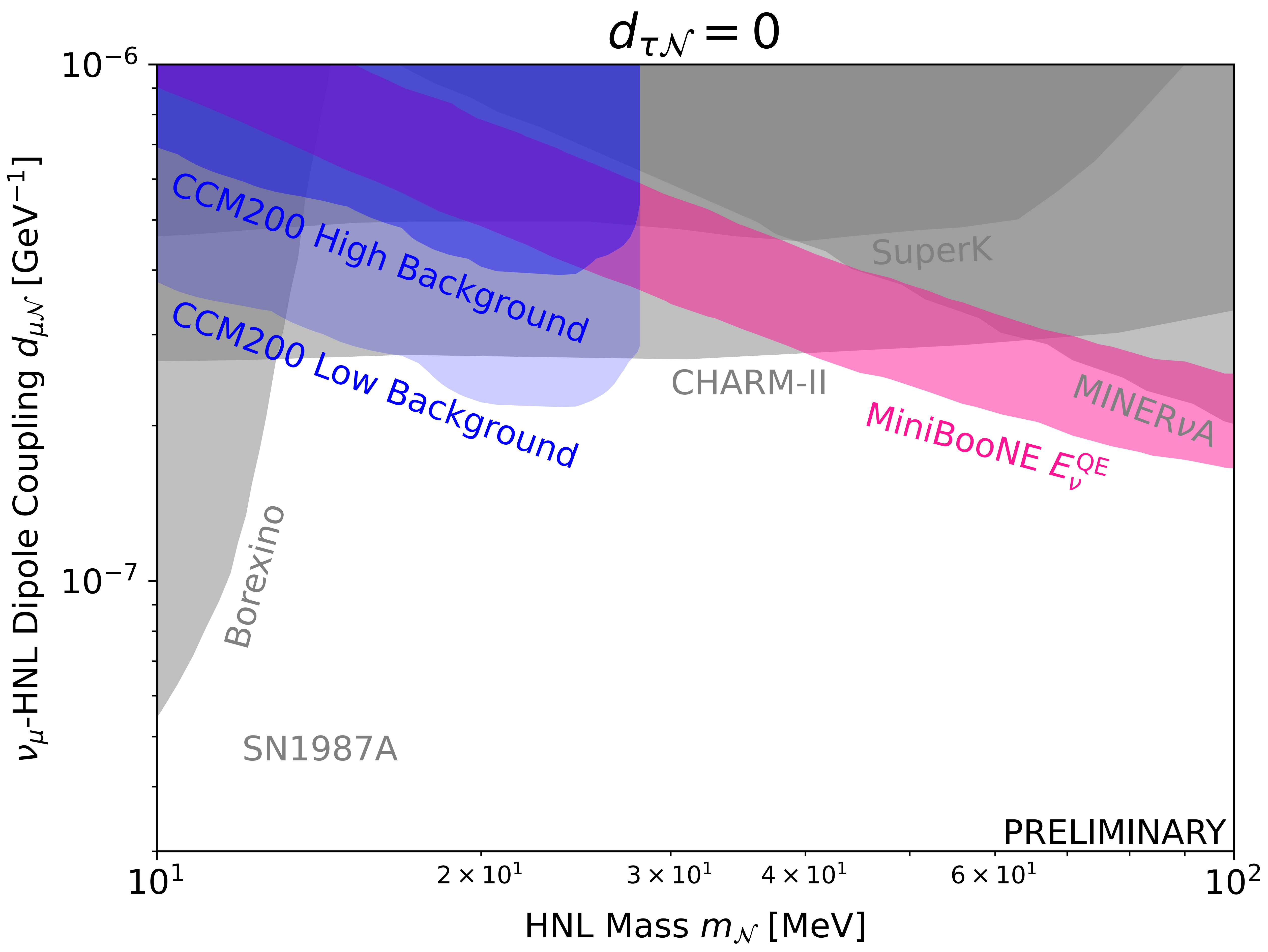
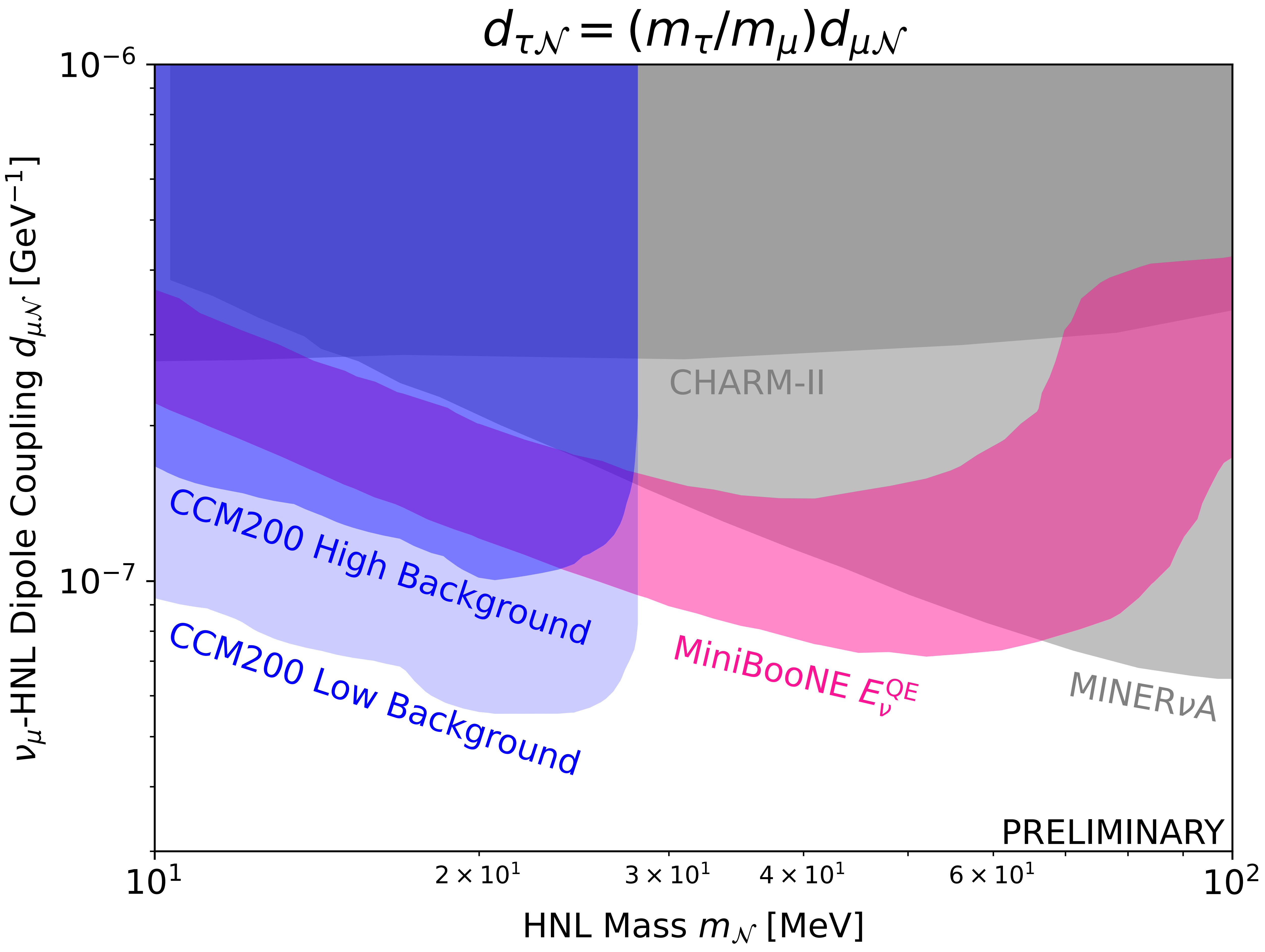
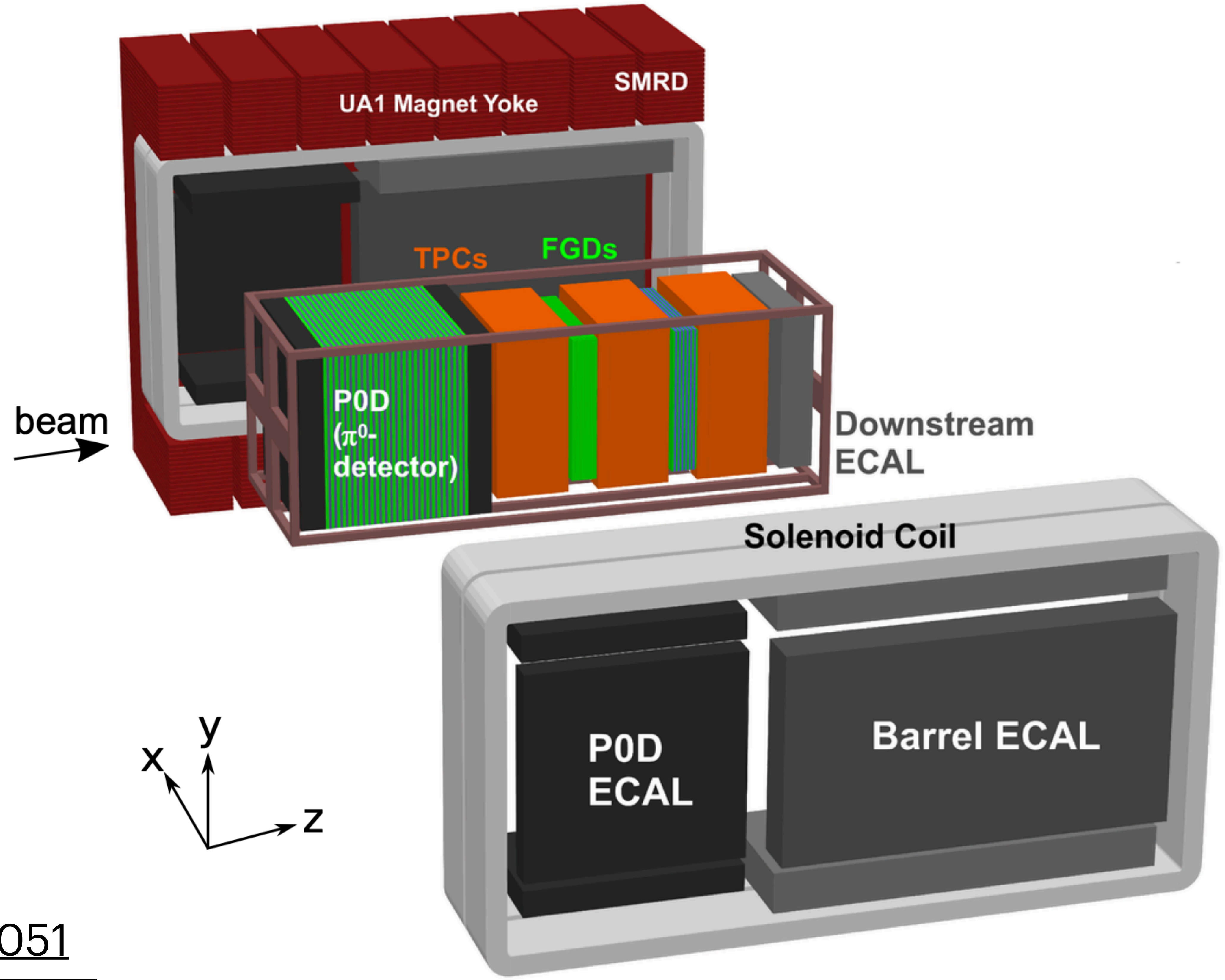




NK Thesis 2023

SIREN for Dipole-Portal HNLs @ 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 used SIREN to repurpose their results and 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

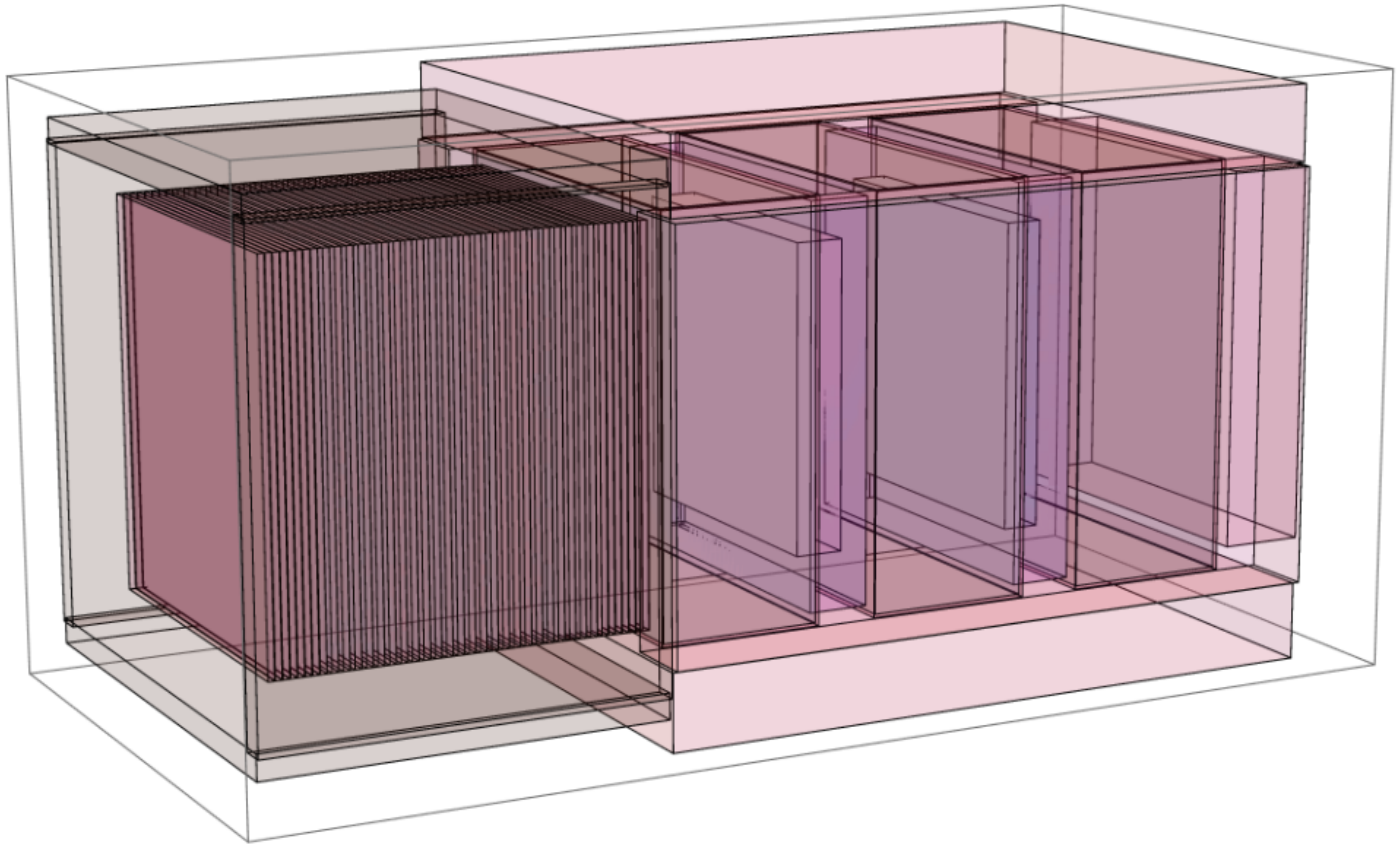
[1] T2K 2019

M. Lamoureux thesis

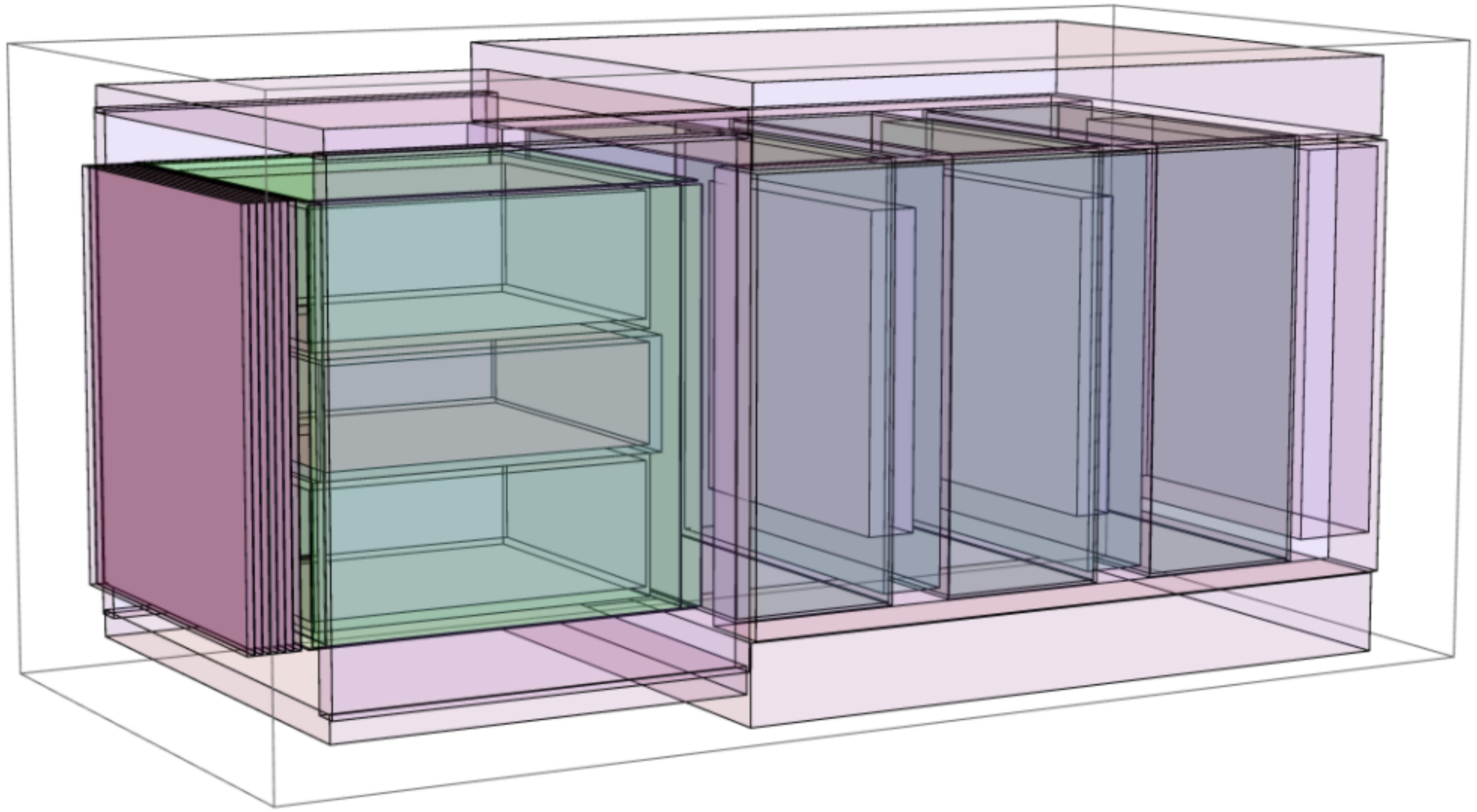
SIREN for Dipole-Portal HNLs @ ND280(+)

3D rendering of our SIREN-based implementation of ND280 and its upgrade

<u>ND280</u>



<u>ND280+</u>



M-S Liu, NK, C. Argüelles 2024

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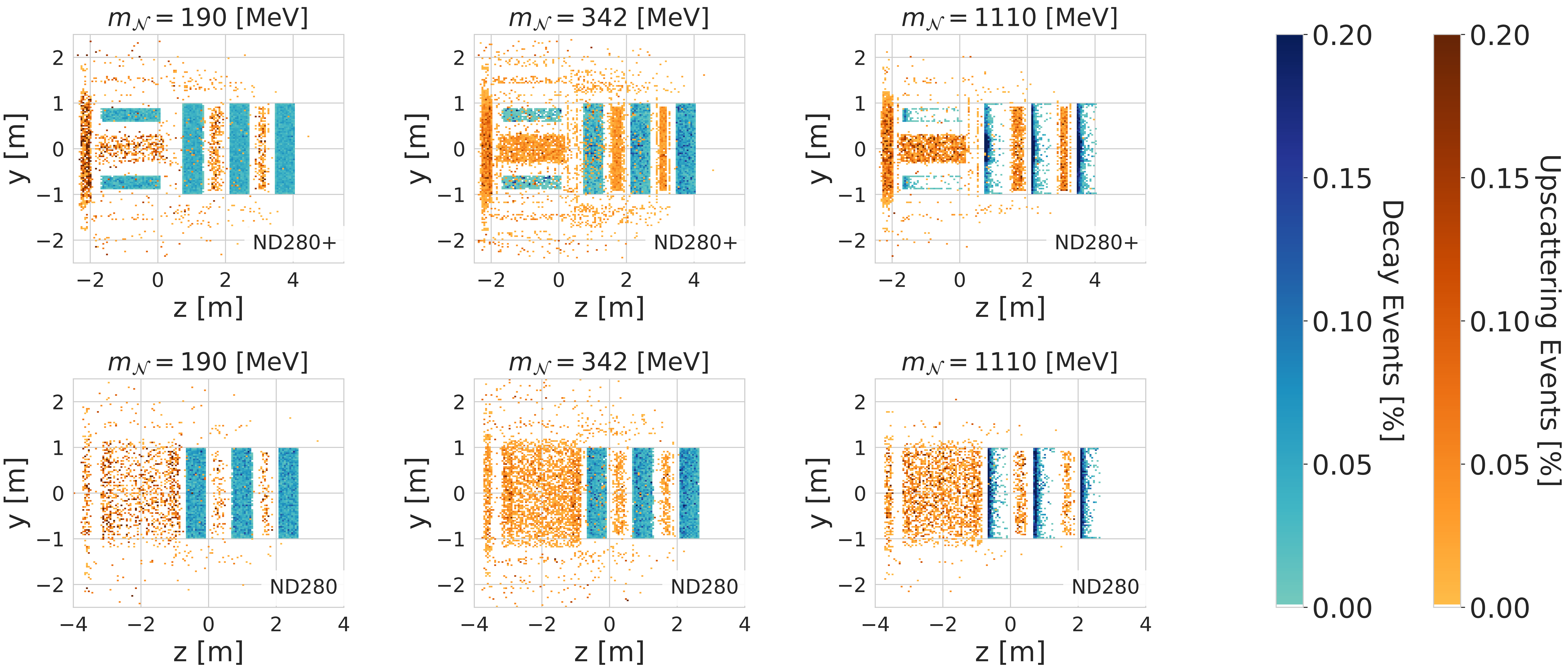

$$\Gamma_{\mathcal{N}\to\nu\gamma} \propto m_{\mathcal{N}}^3$$

M-S Liu, NK, C. Argüelles 2024

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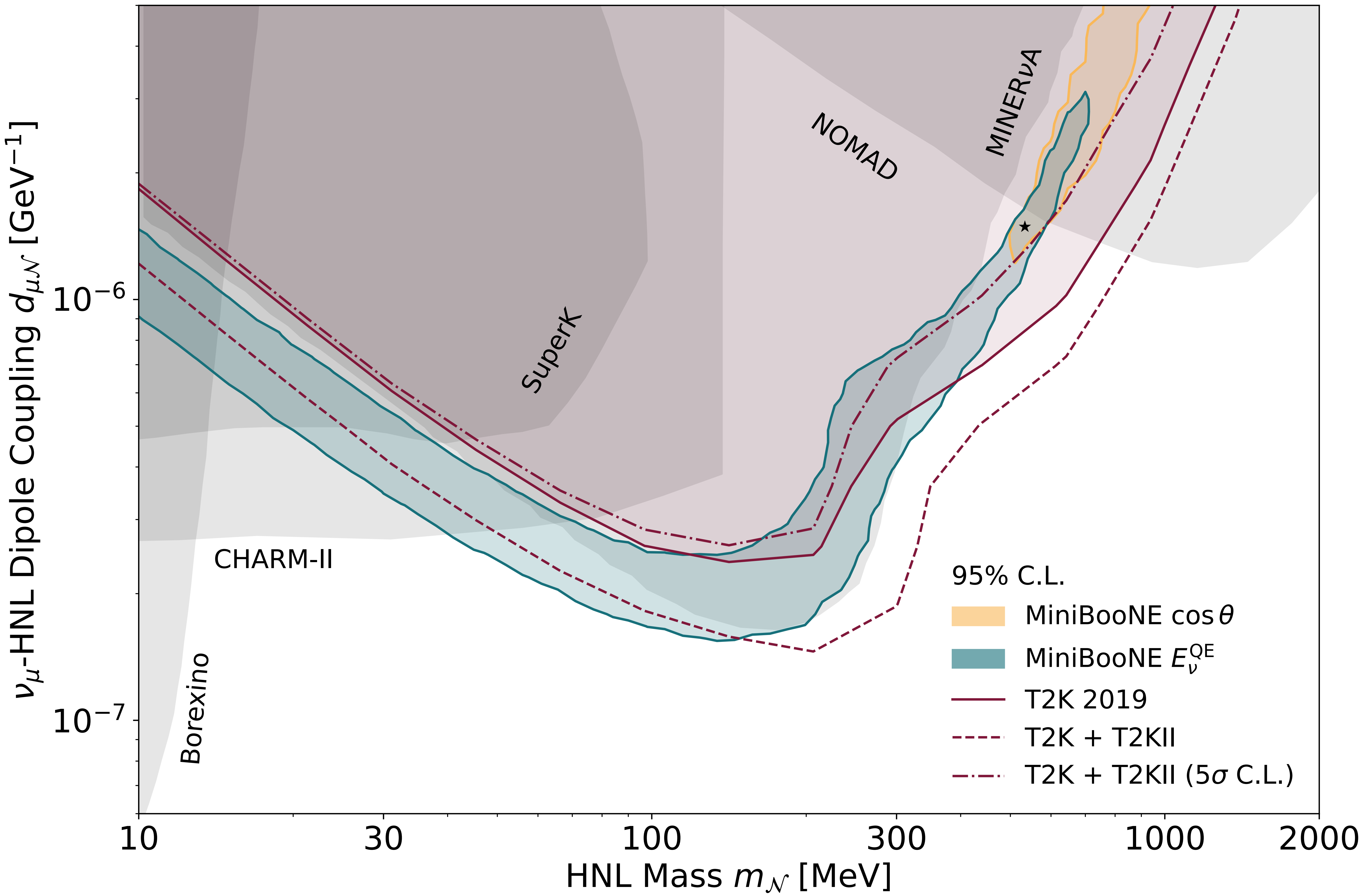

The 2019 T2K search observes zero e^+e^- pairs in the ND280 gas TPCs, constraining the region of parameter space preferred by MiniBooNE

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

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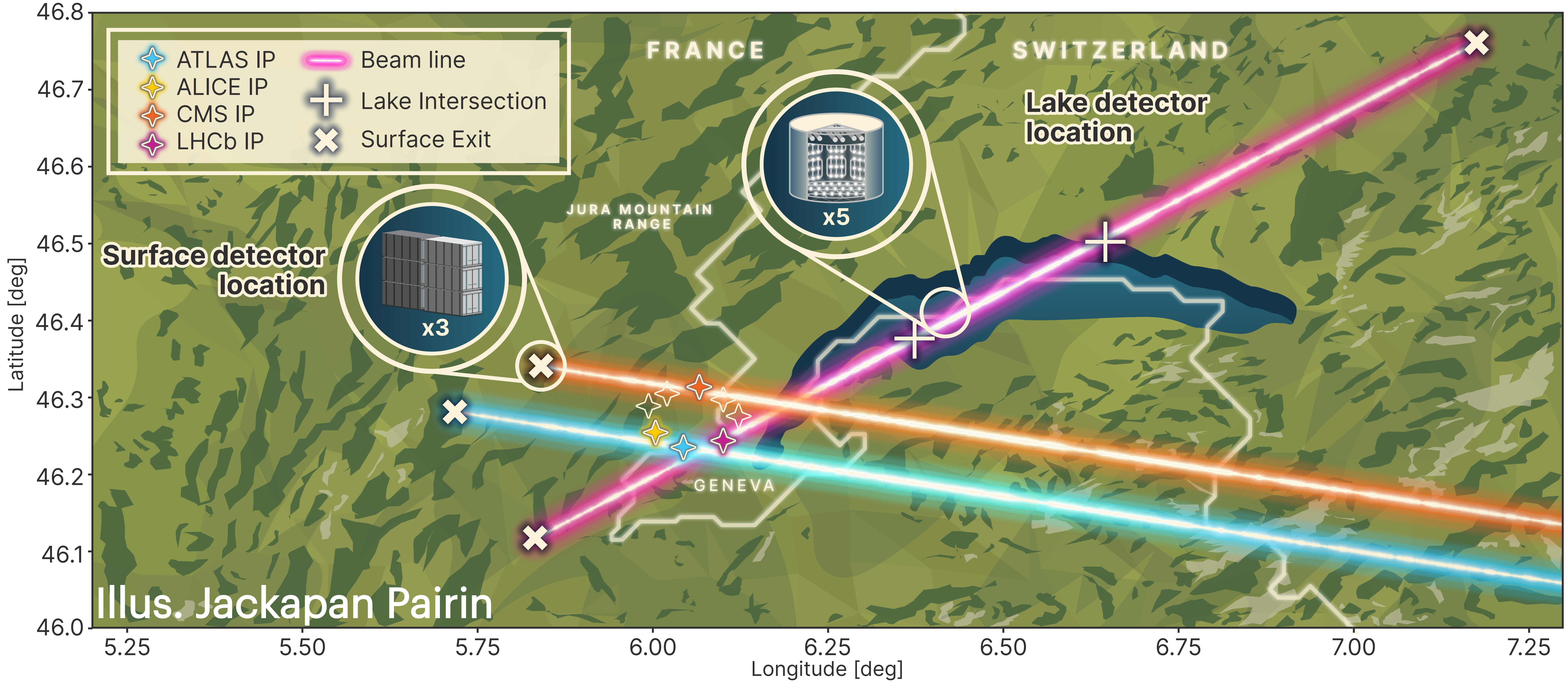
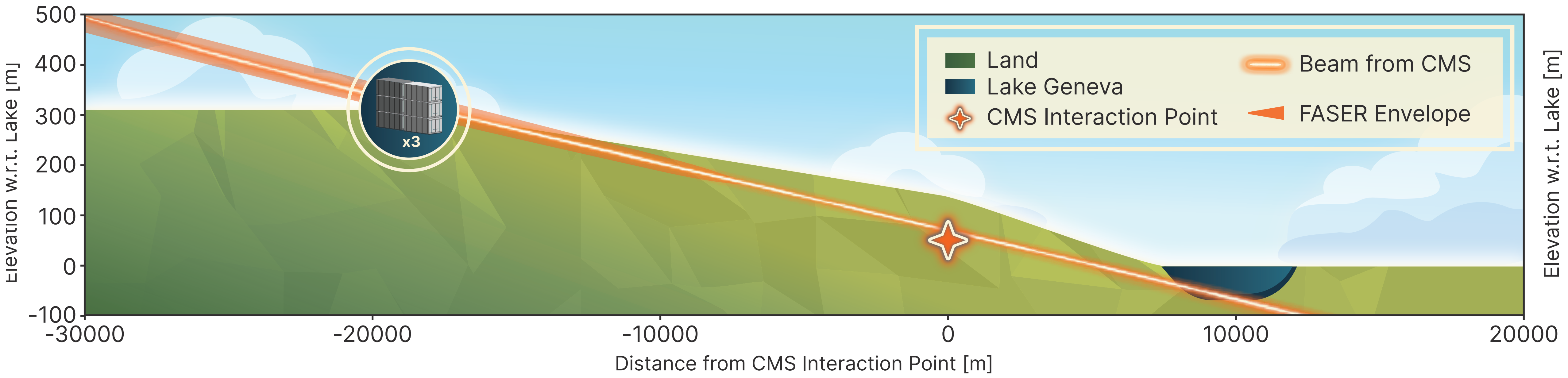
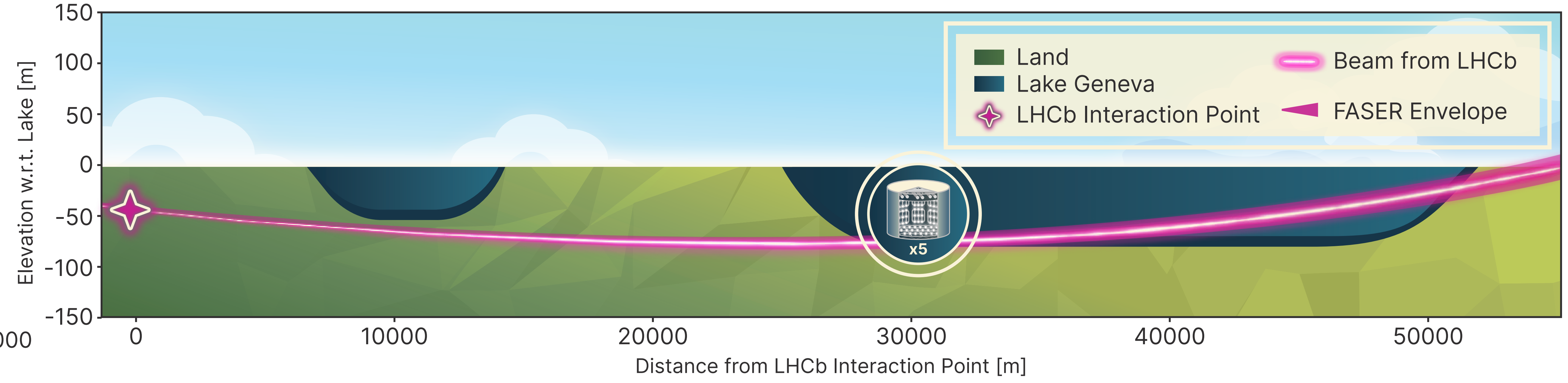
LHC Neutrinos pass through Lake Geneva



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

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





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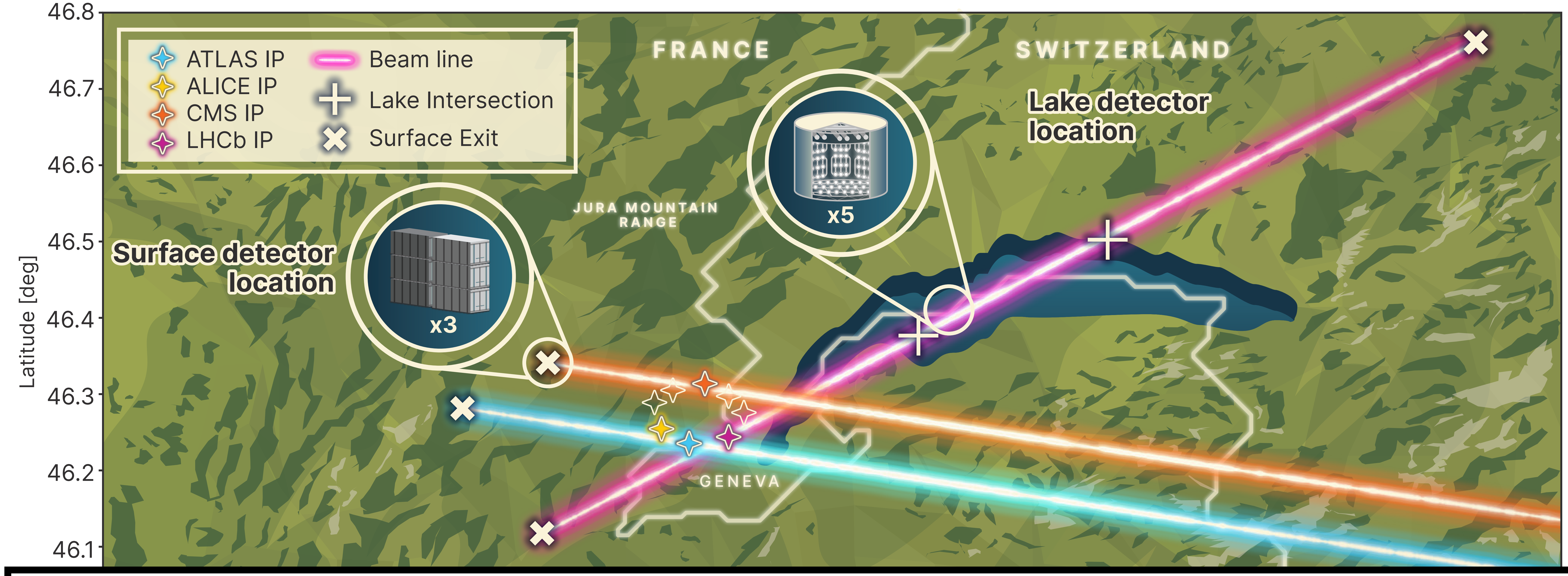

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Thanks to Benjamin Weyer and

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

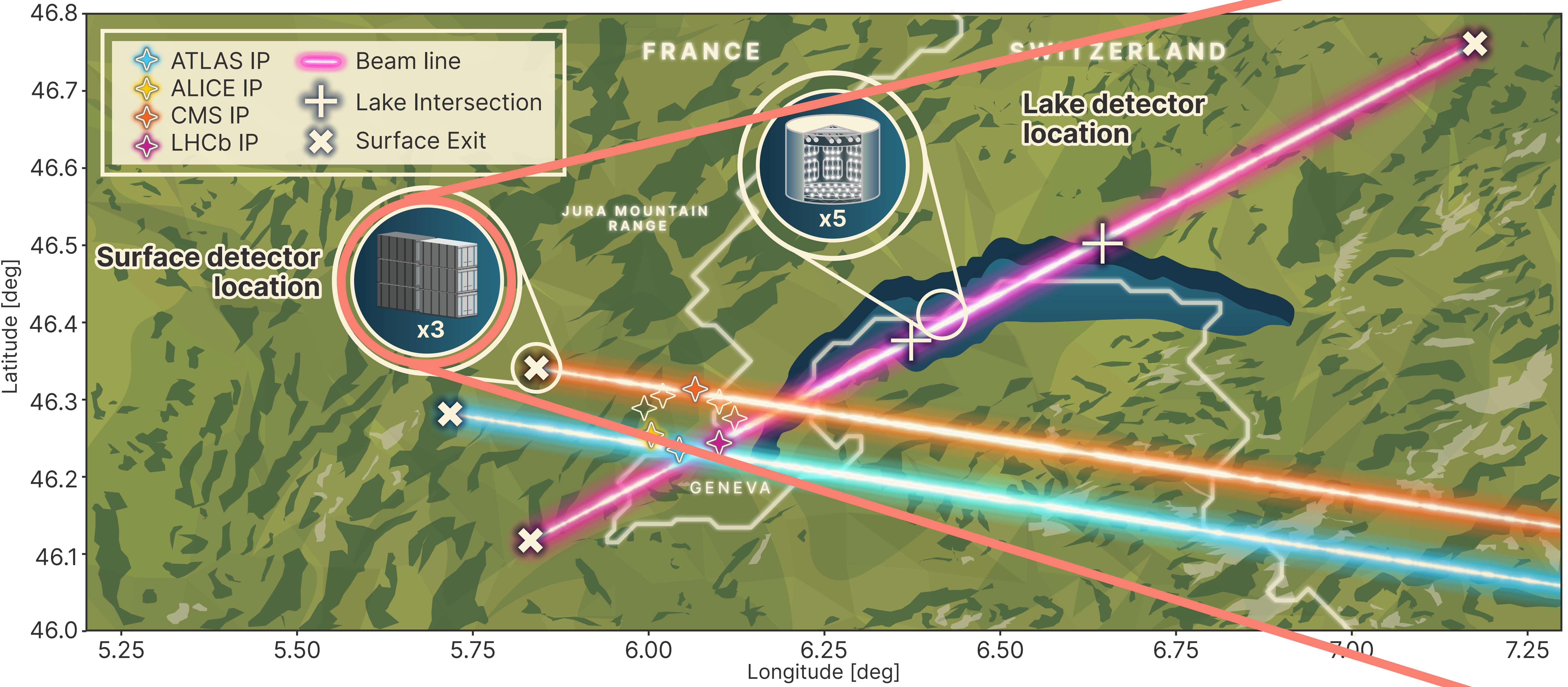
C. Argüelles

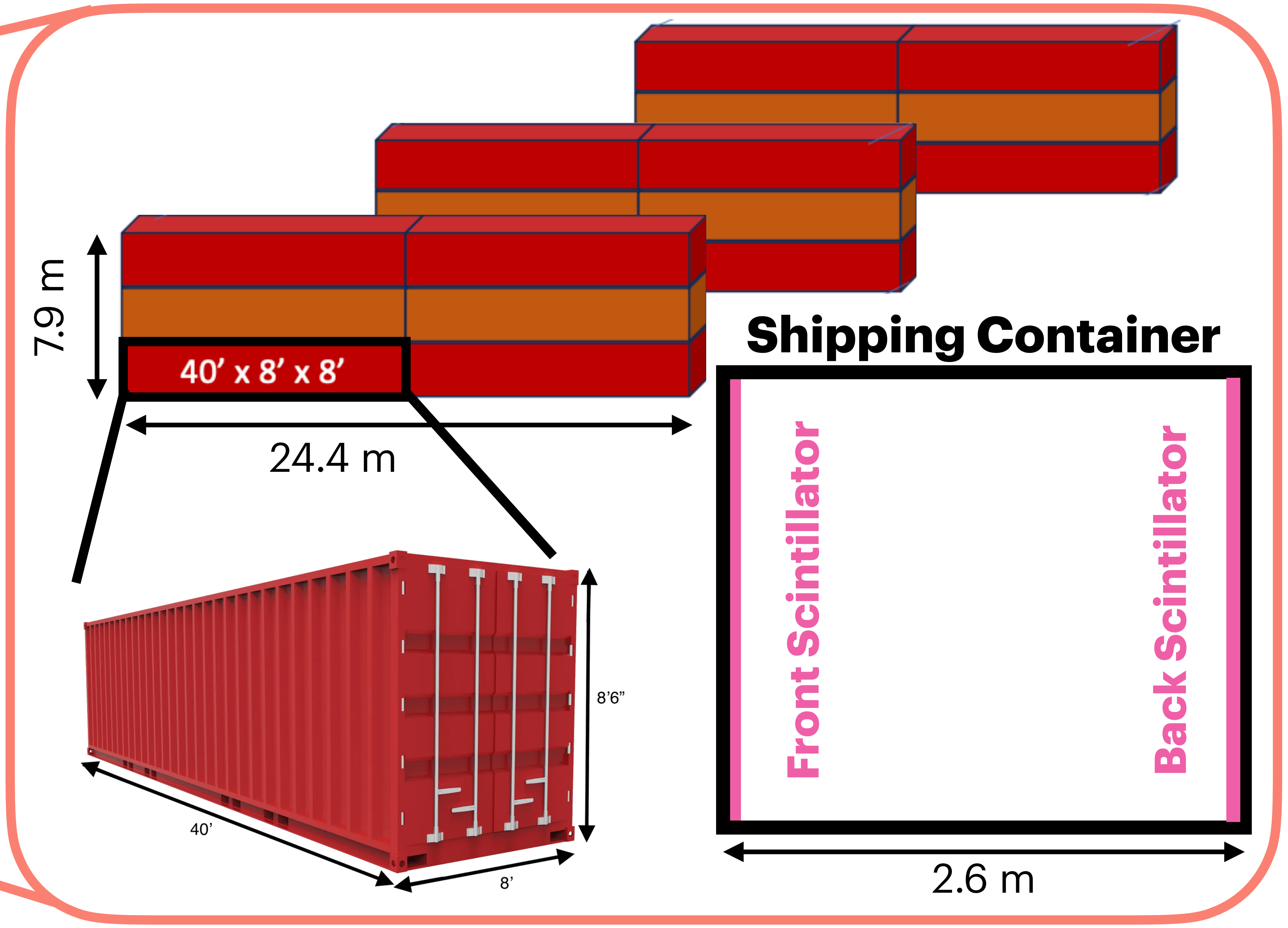
T. Yuan

Distance from CMS Interaction Point [m]

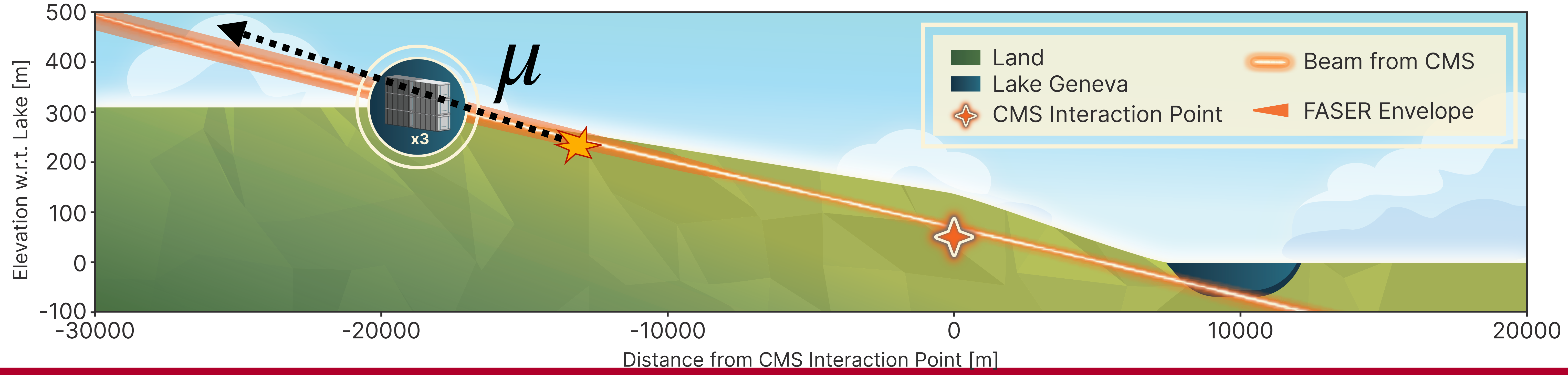
Distance from LHCb Interaction Point [m]

SINE: Surface-based Integrated Neutrino Experiment



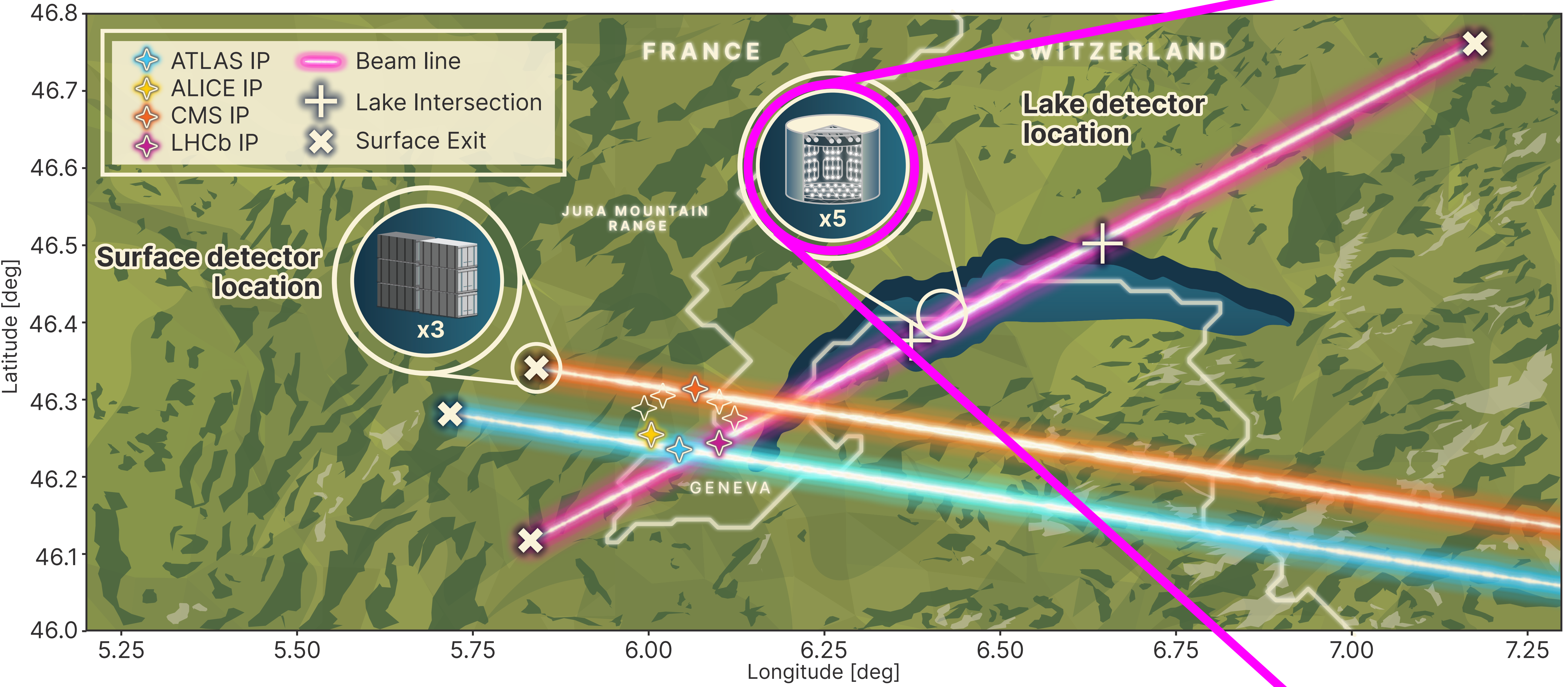


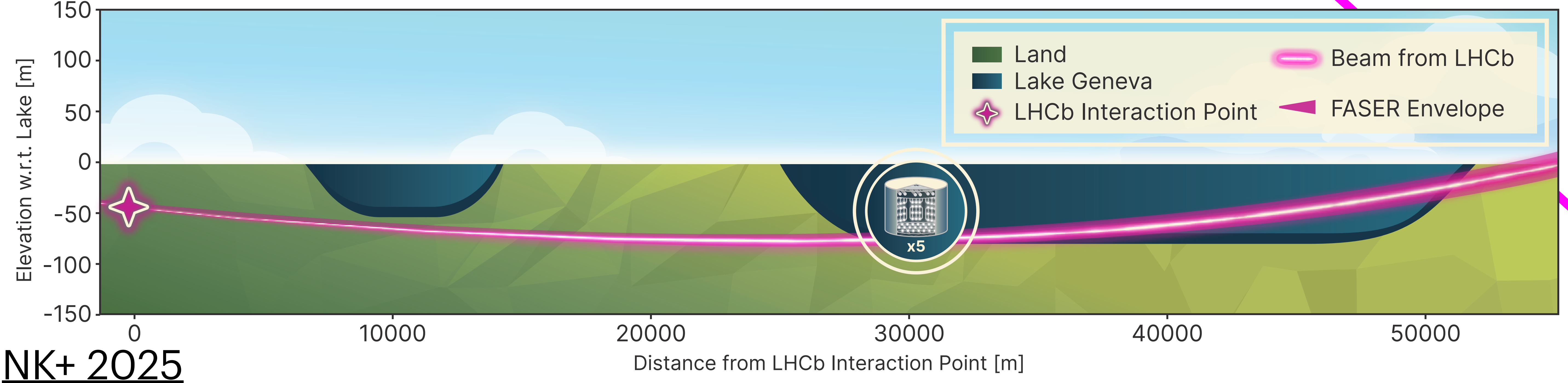
Signal definition: up-going muons from neutrino interactions in bedrock



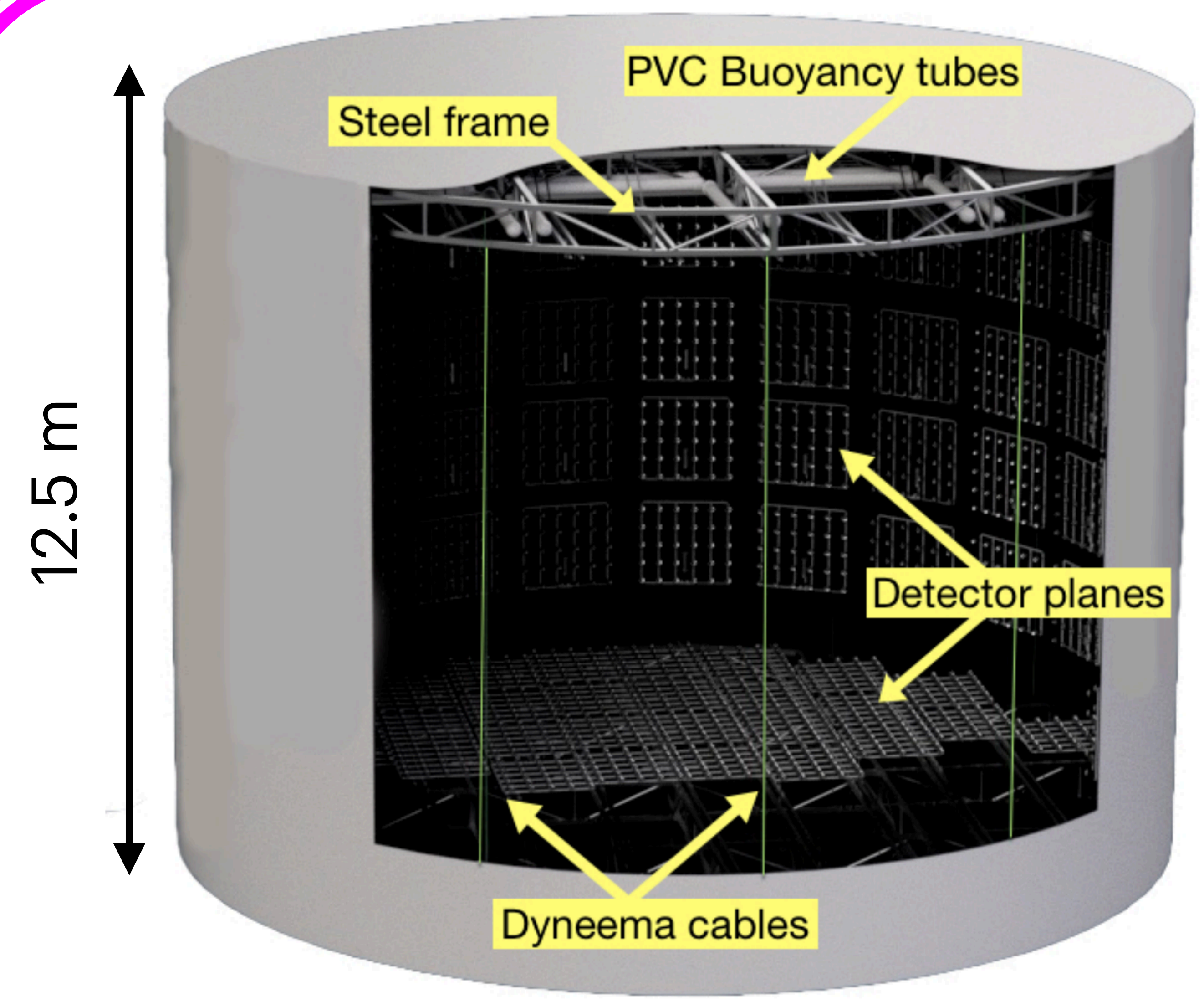
NK+ 2025

UNDINE: UNDerwater Integrated Neutrino Experiment





NK+ 2025



D. Delgado

CHIPS Collab. 2024

NK+ 2025

What does SIREN allow us to study?

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1. Event rates using flux predictions from multiple hadronic models and modern DIS cross sections [1]

[1] Weigel, Garcia-Soto, Conrad 2024

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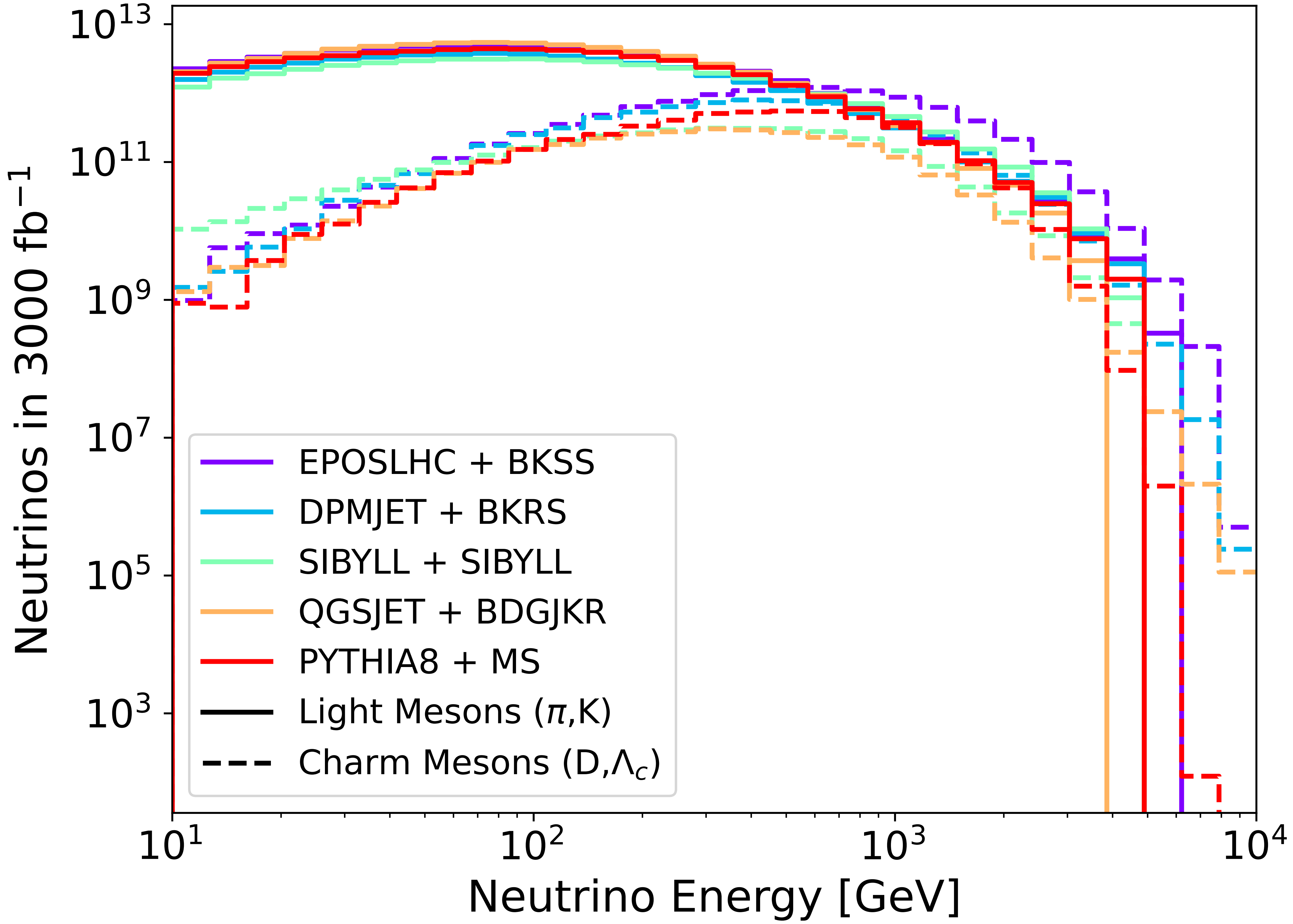
github.com/makelat/forward-nu-flux-fit



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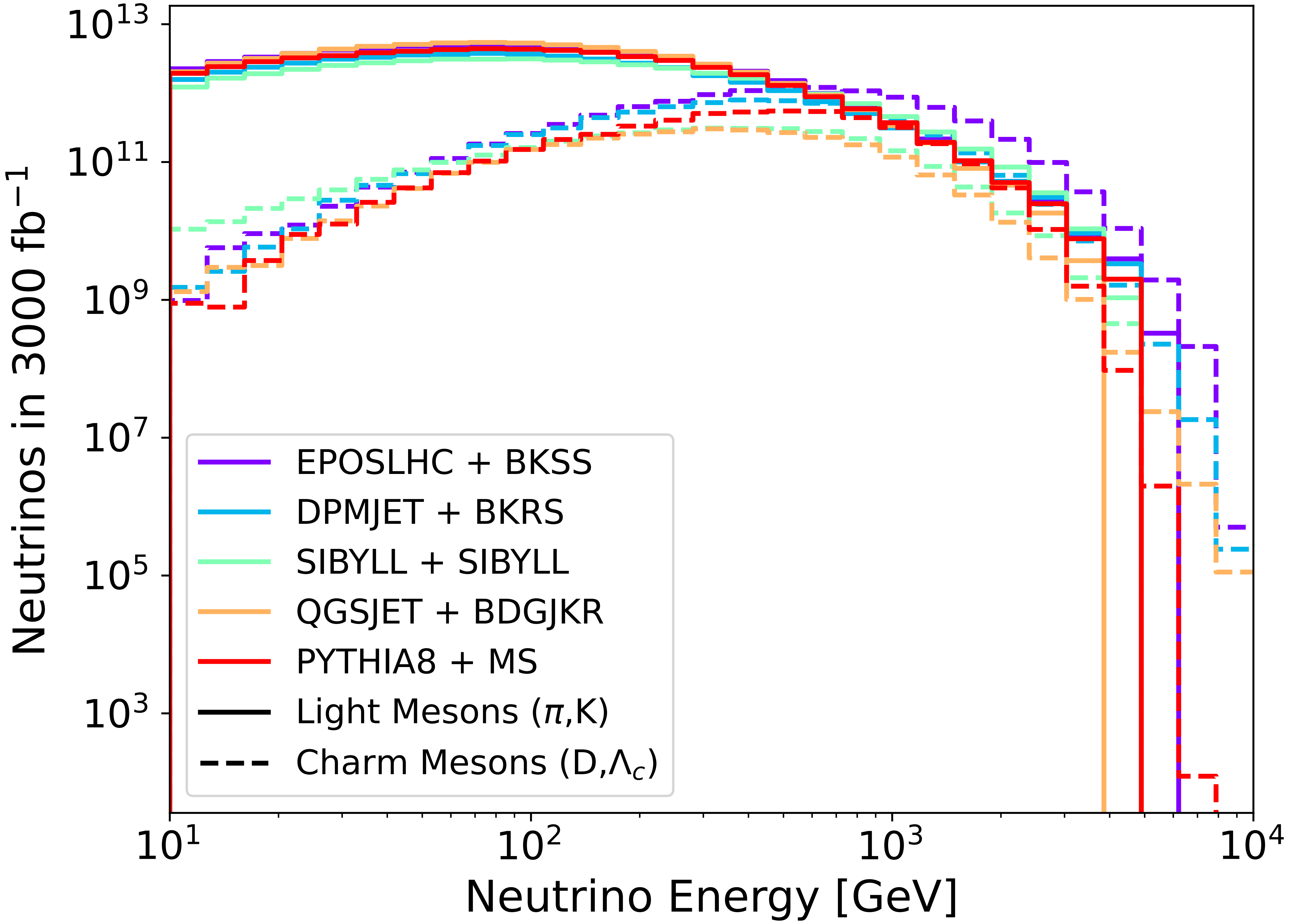

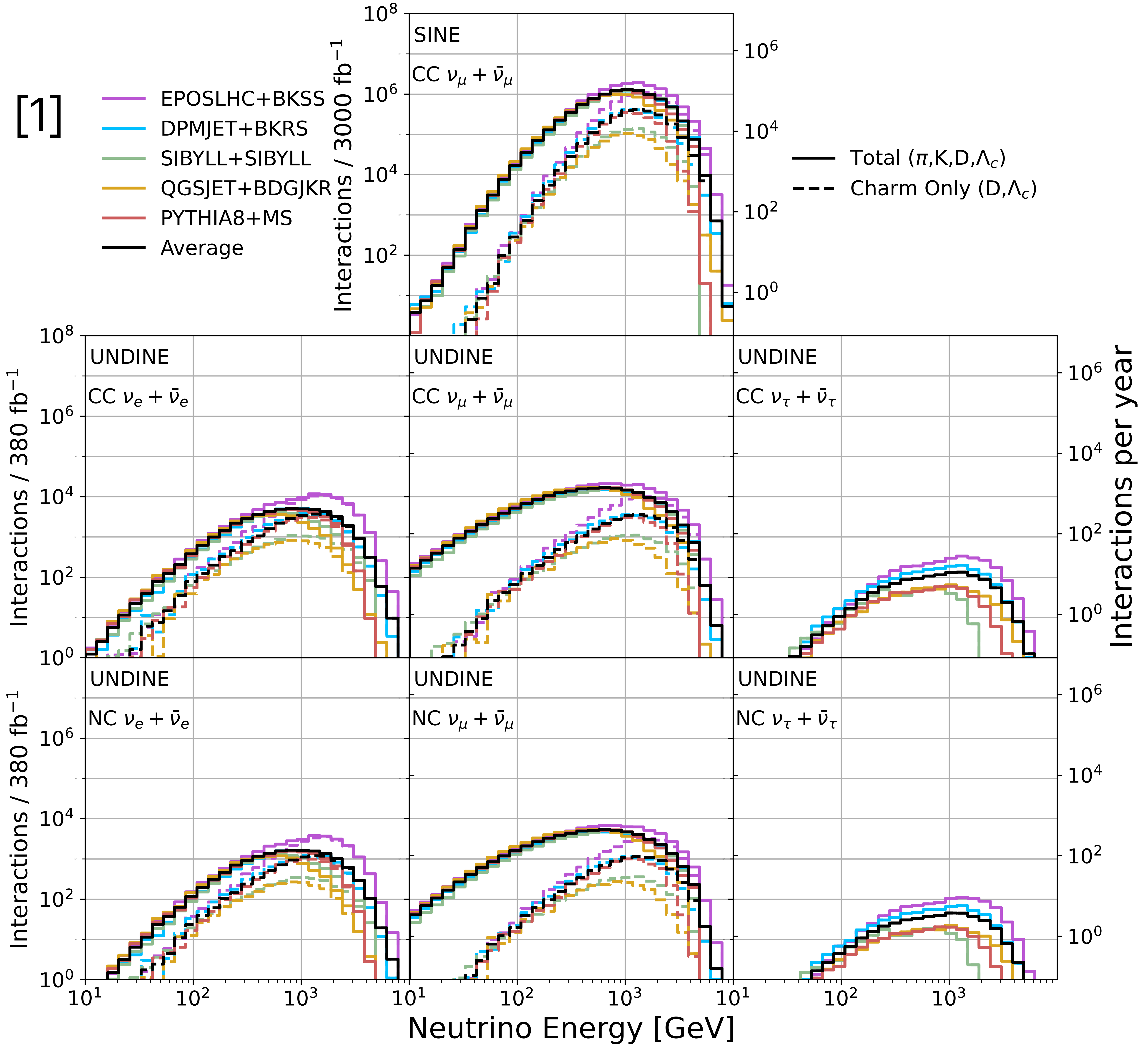

[1] Weigel, Garcia-Soto, Conrad 2024

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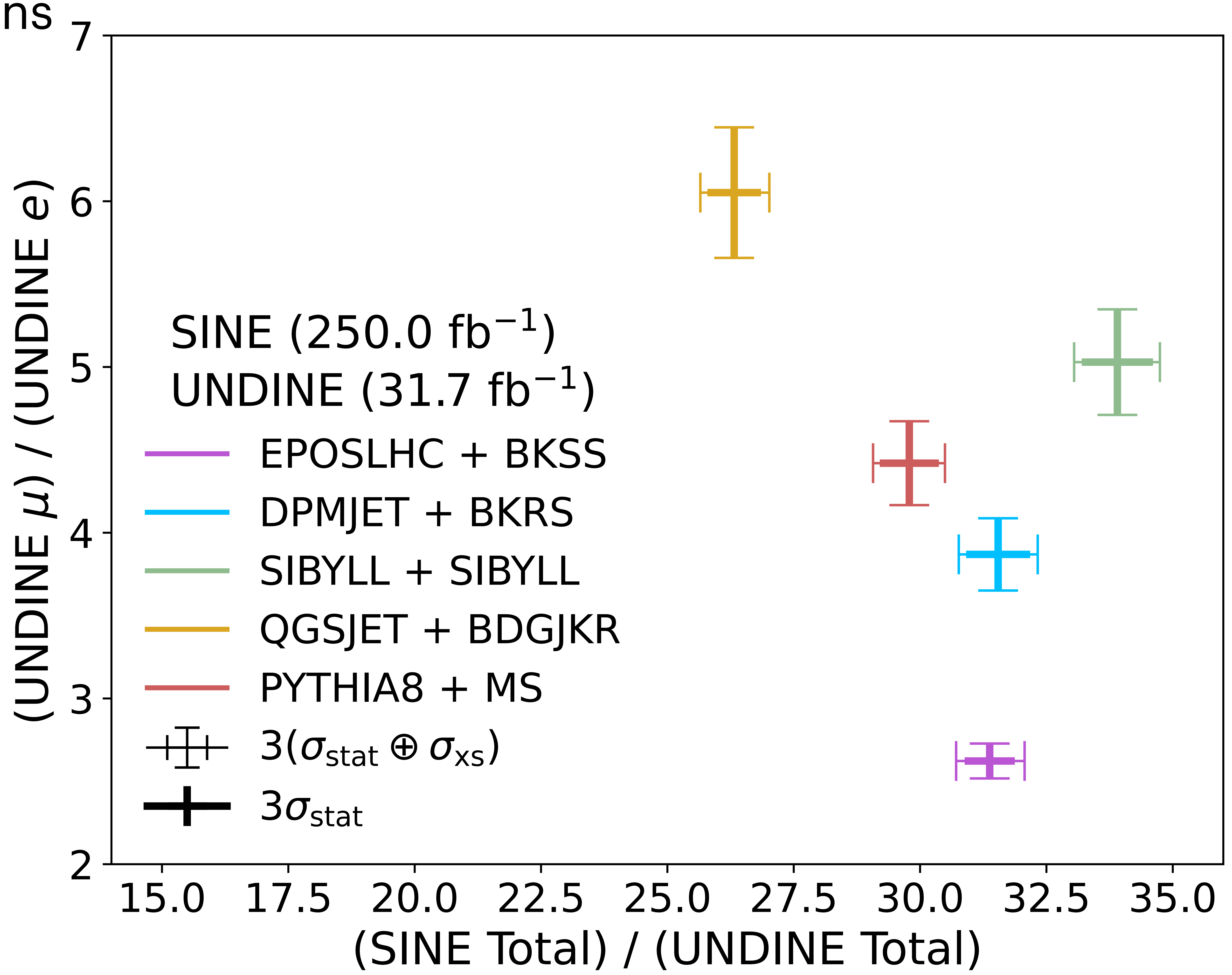

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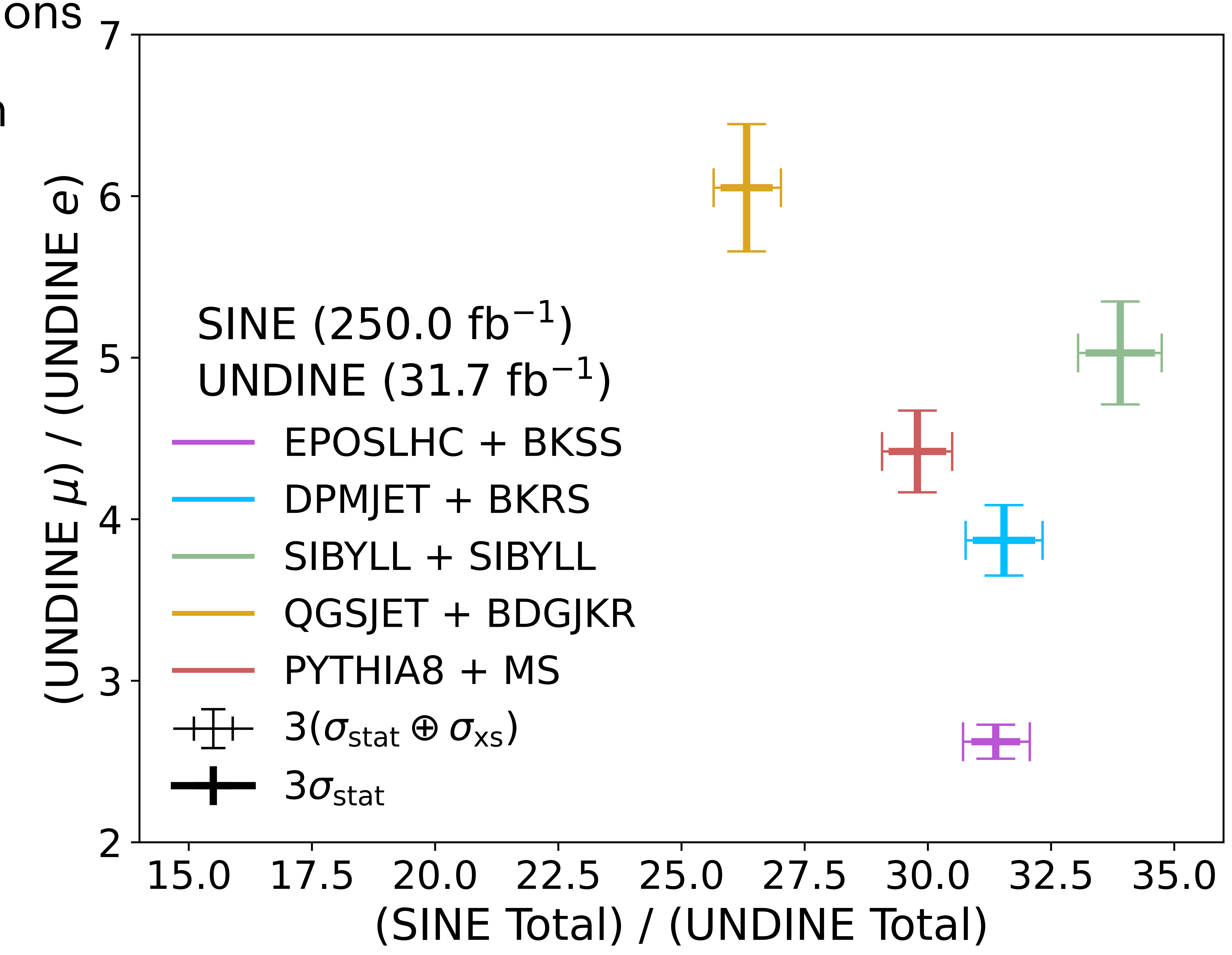

Important implications for the intrinsic charm content of the proton (Maciula+ 2022)and the prompt atmospheric neutrino flux (Jeong+ 2023)

What does SIREN allow us to study?

1. Event rates using flux predictions from multiple hadronic models and modern DIS cross sections
2. The ability of SINE and UNDINE to distinguish between forward charm production models
3. Strategies to separate cosmic muon backgrounds from neutrino-induced muons in SINE

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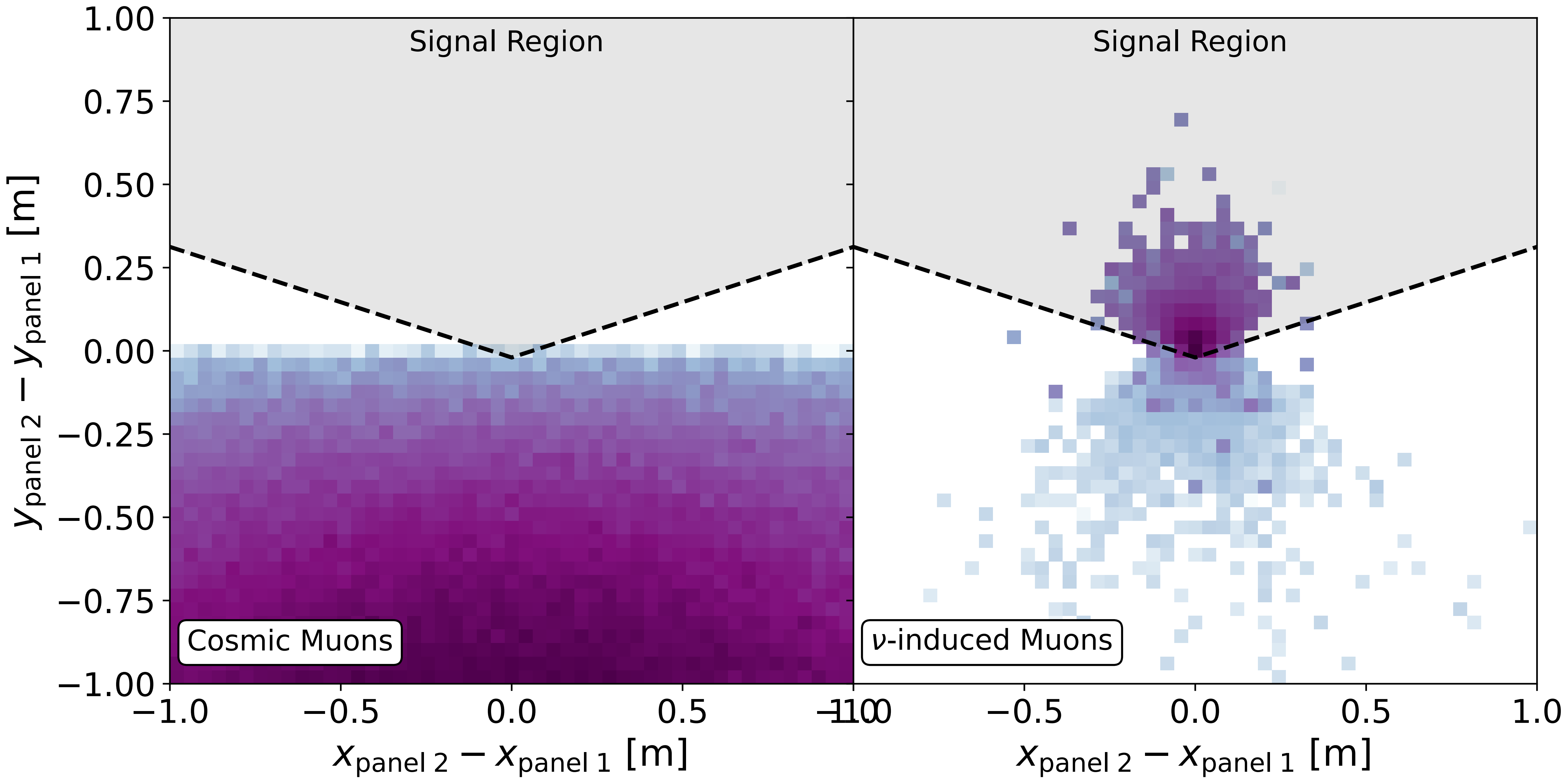

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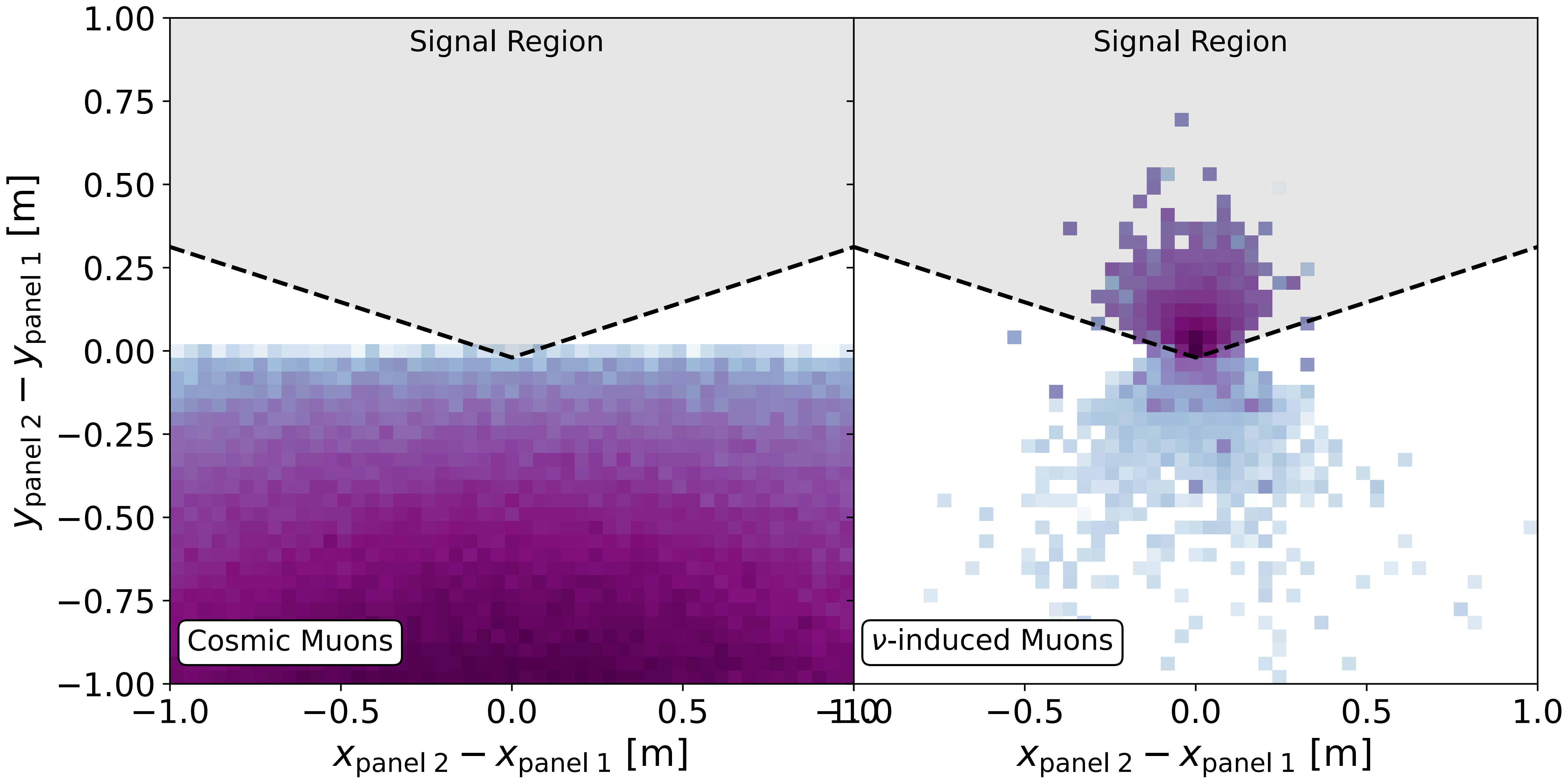

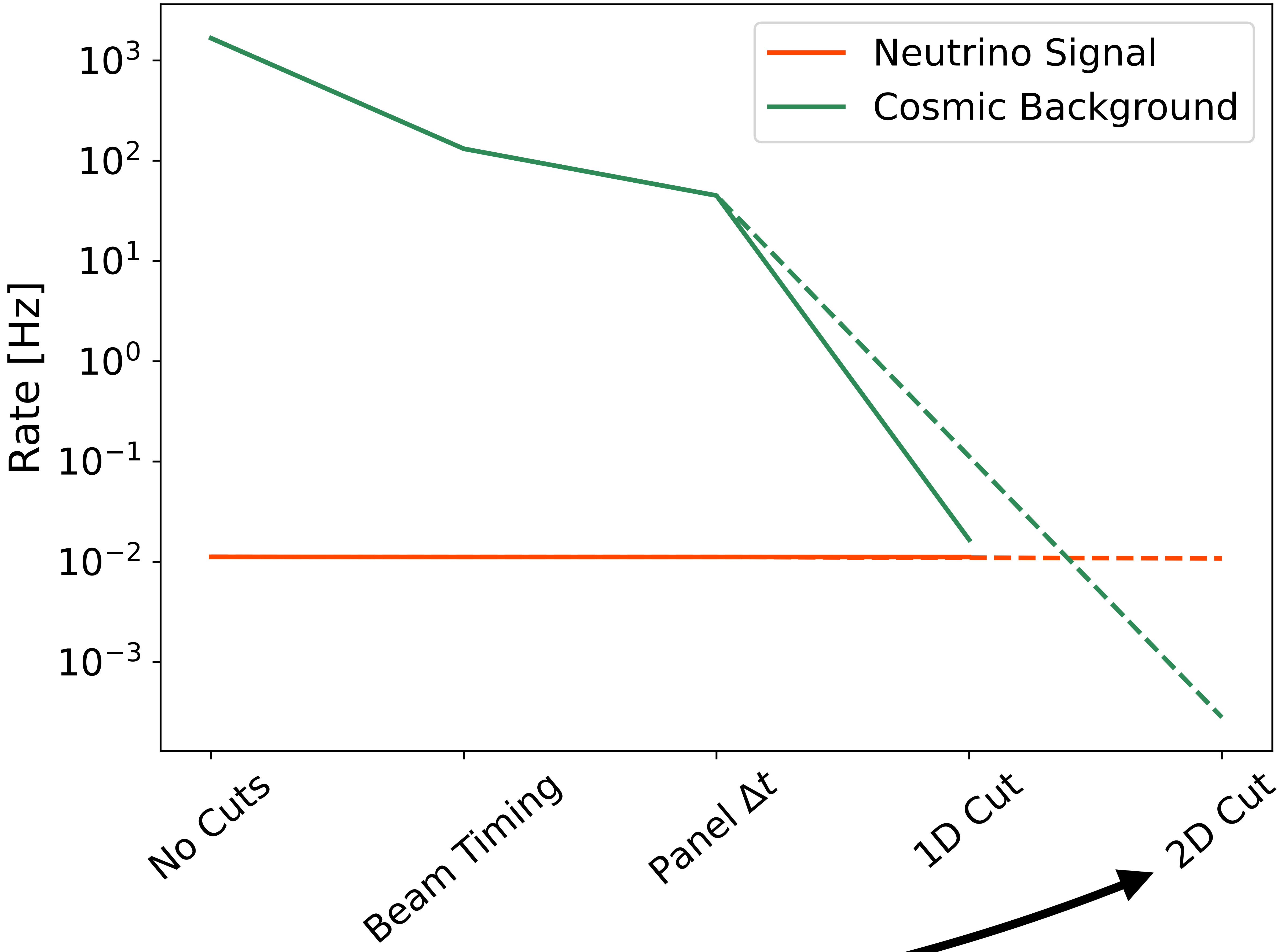

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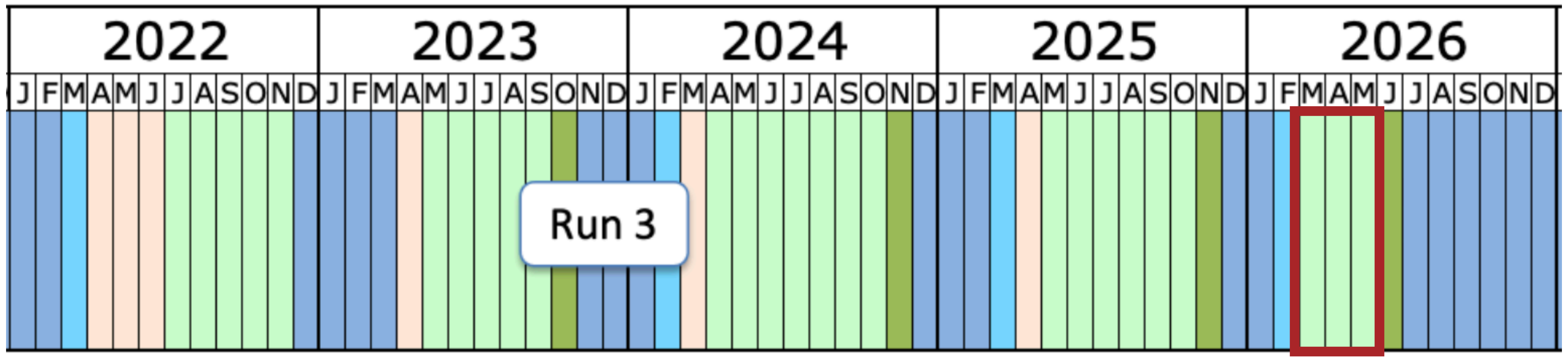

LHC-long-term

Prototype deployment target

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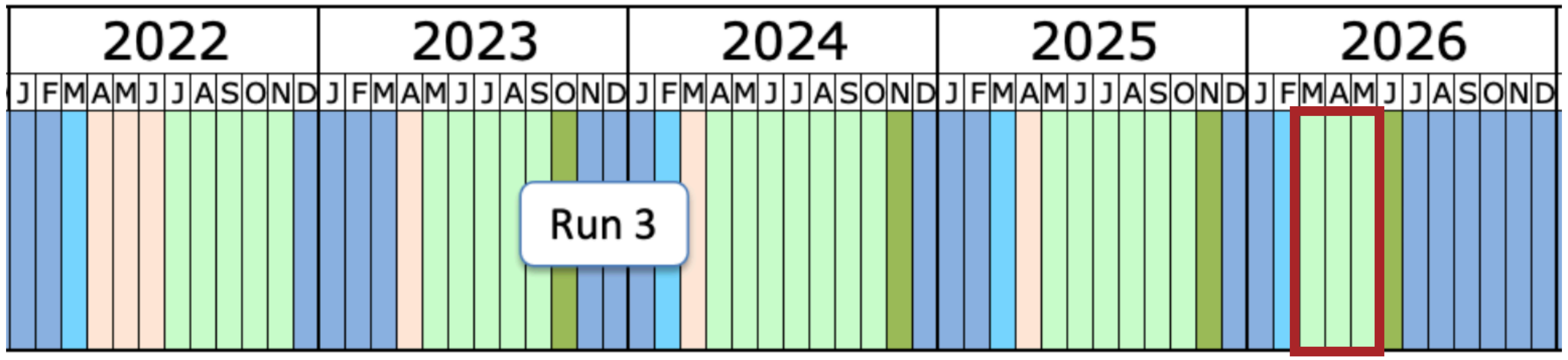

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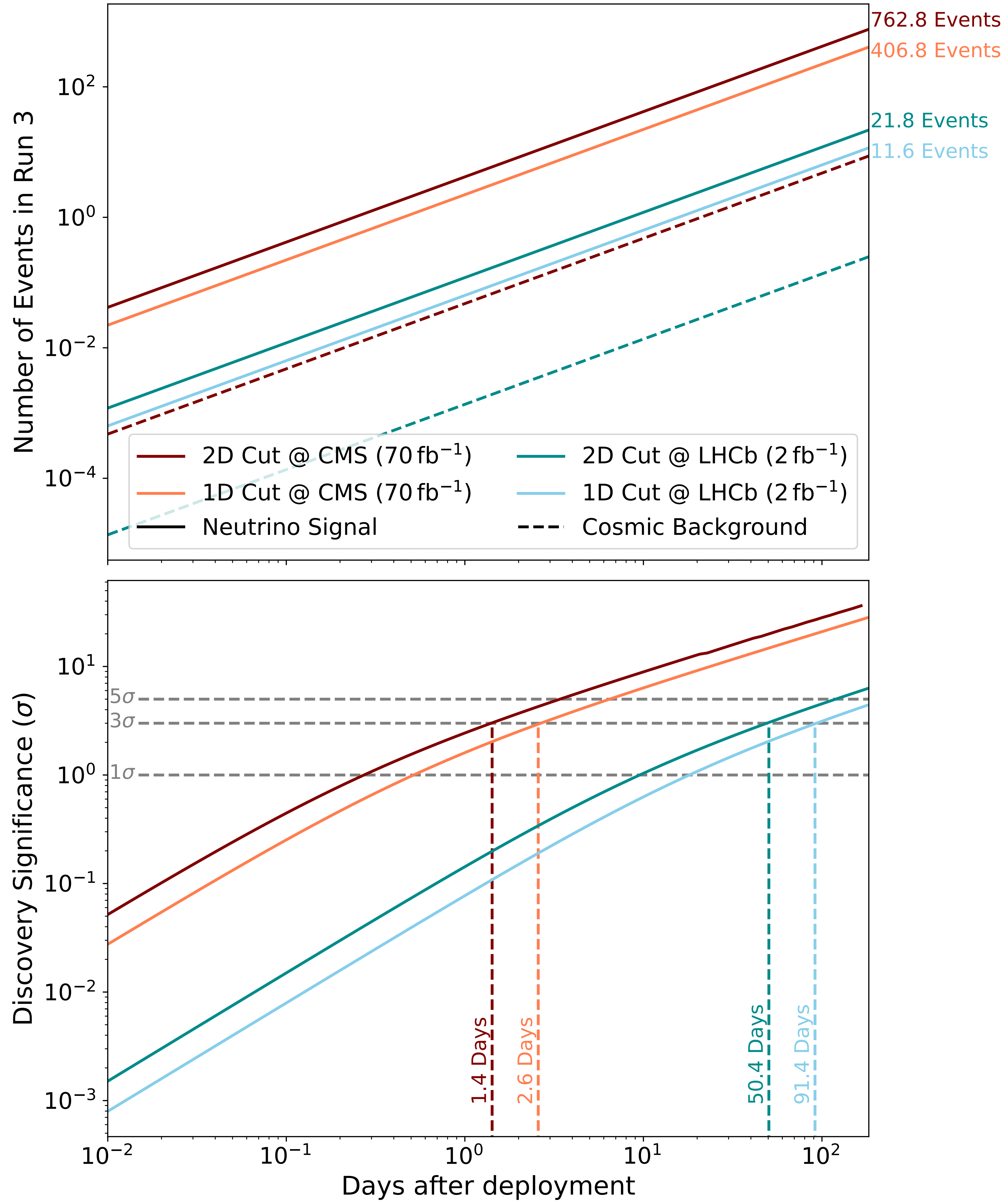

Outline

1. Overview of SIREN
2. Using SIREN for…
   - BSM physics with accelerator neutrinos
   - SM physics with collider neutrinos
   - SM + BSM physics with neutrino telescopes

Charm Production in Neutrino DIS

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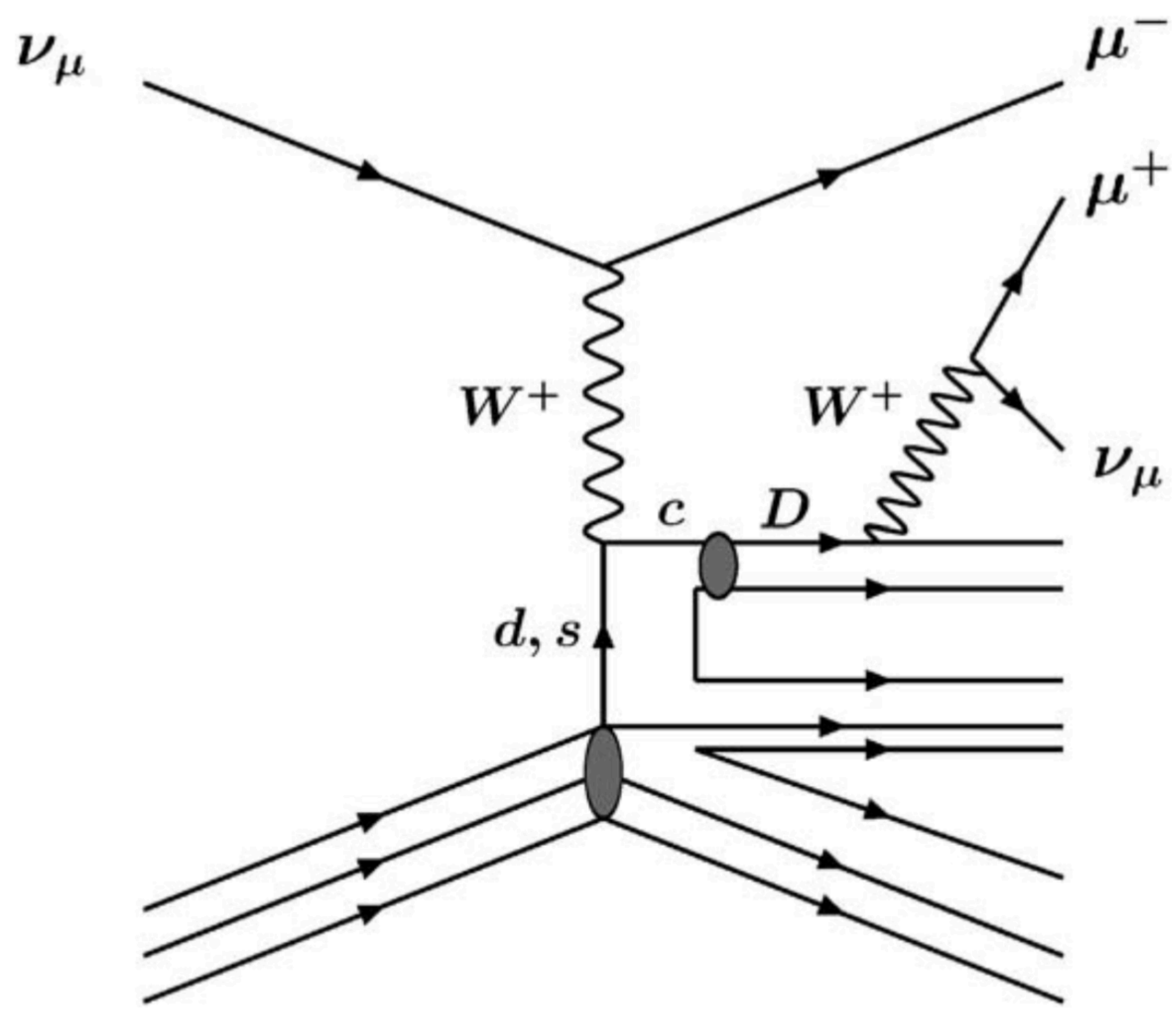

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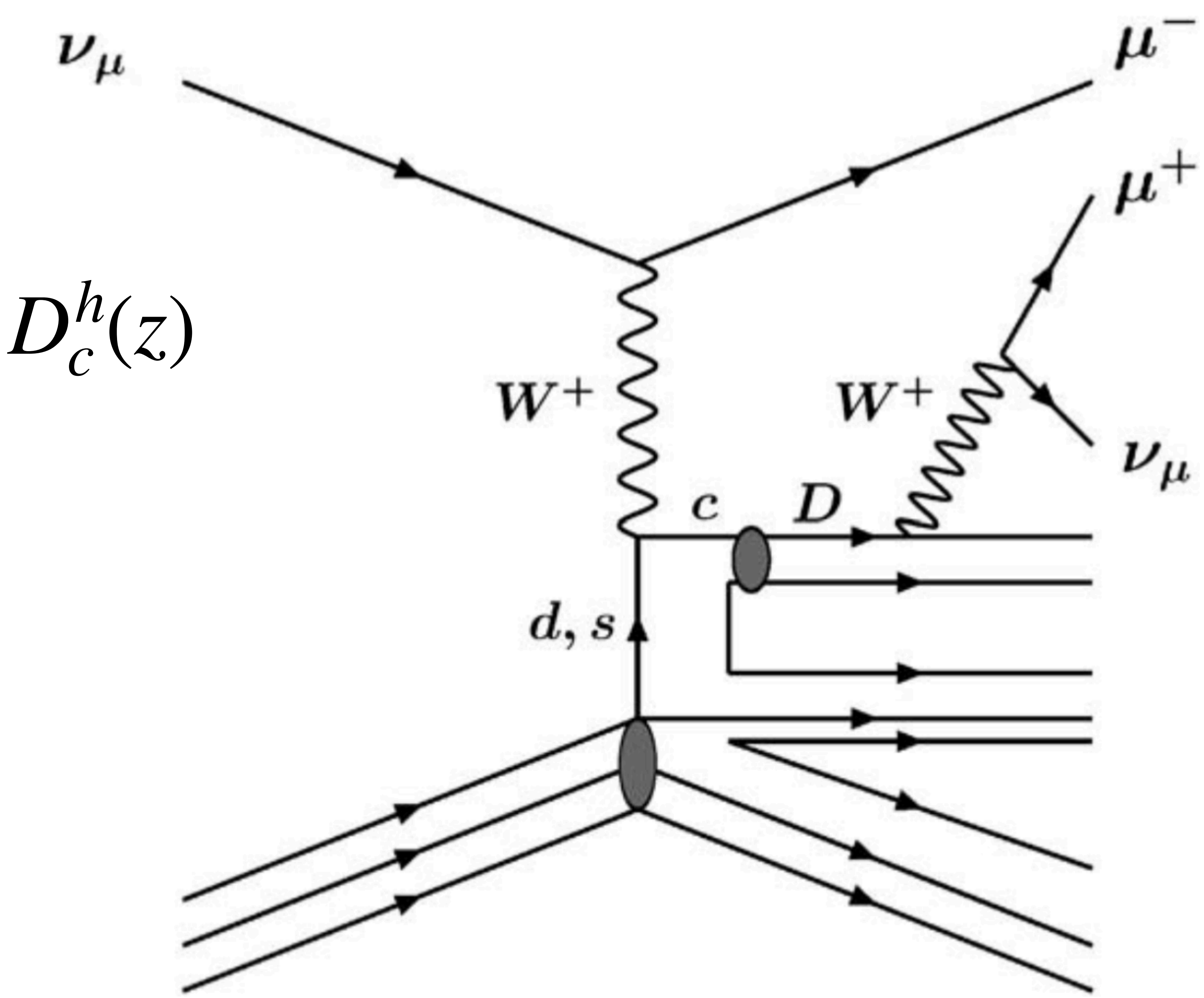

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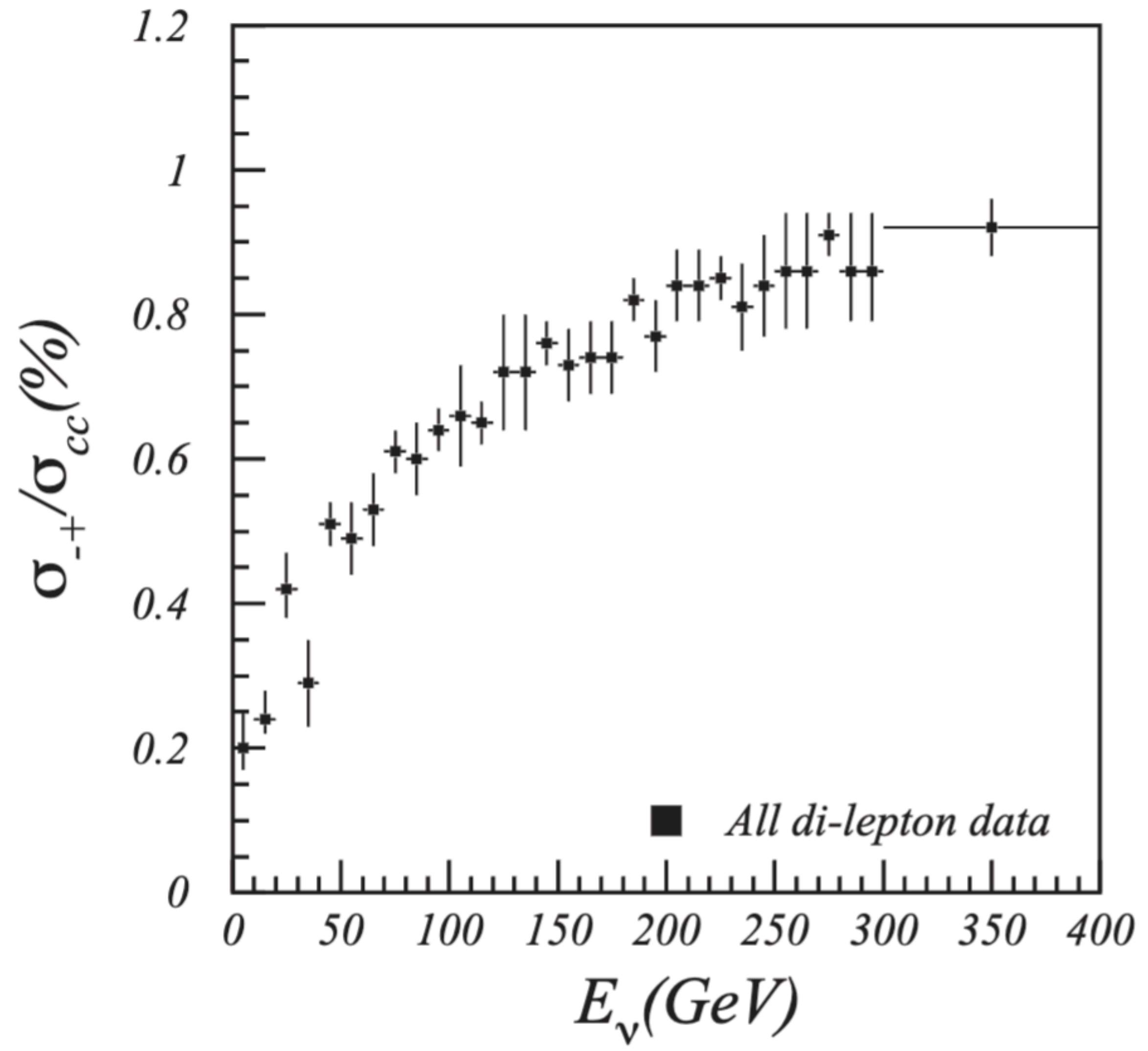
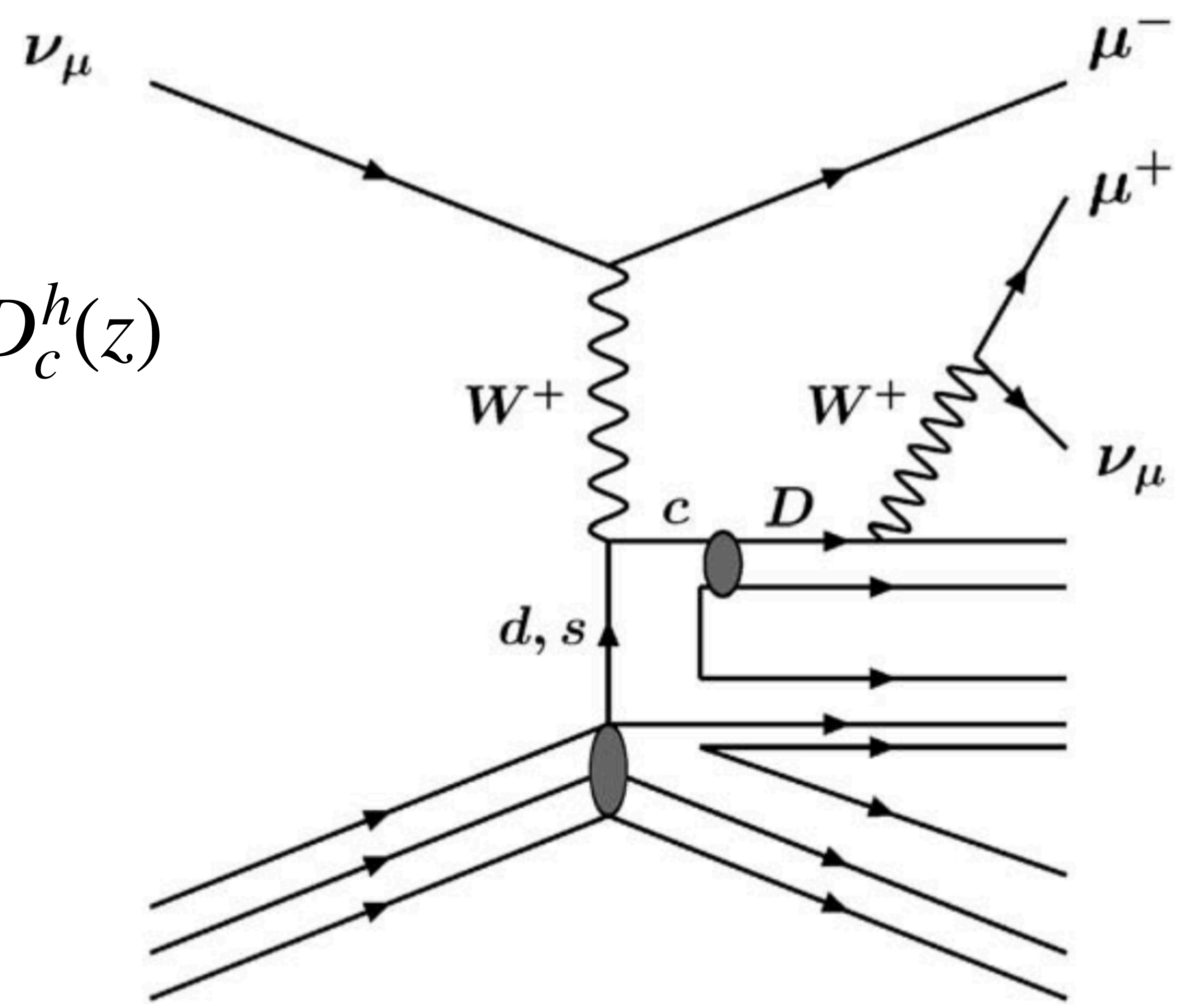
- Cross sections measured extensively by experiments such as CDHS, CCFR, CHORUS, NuTeV (see De Lellis+ 2004 and references therein)





Charm Production in IceCube

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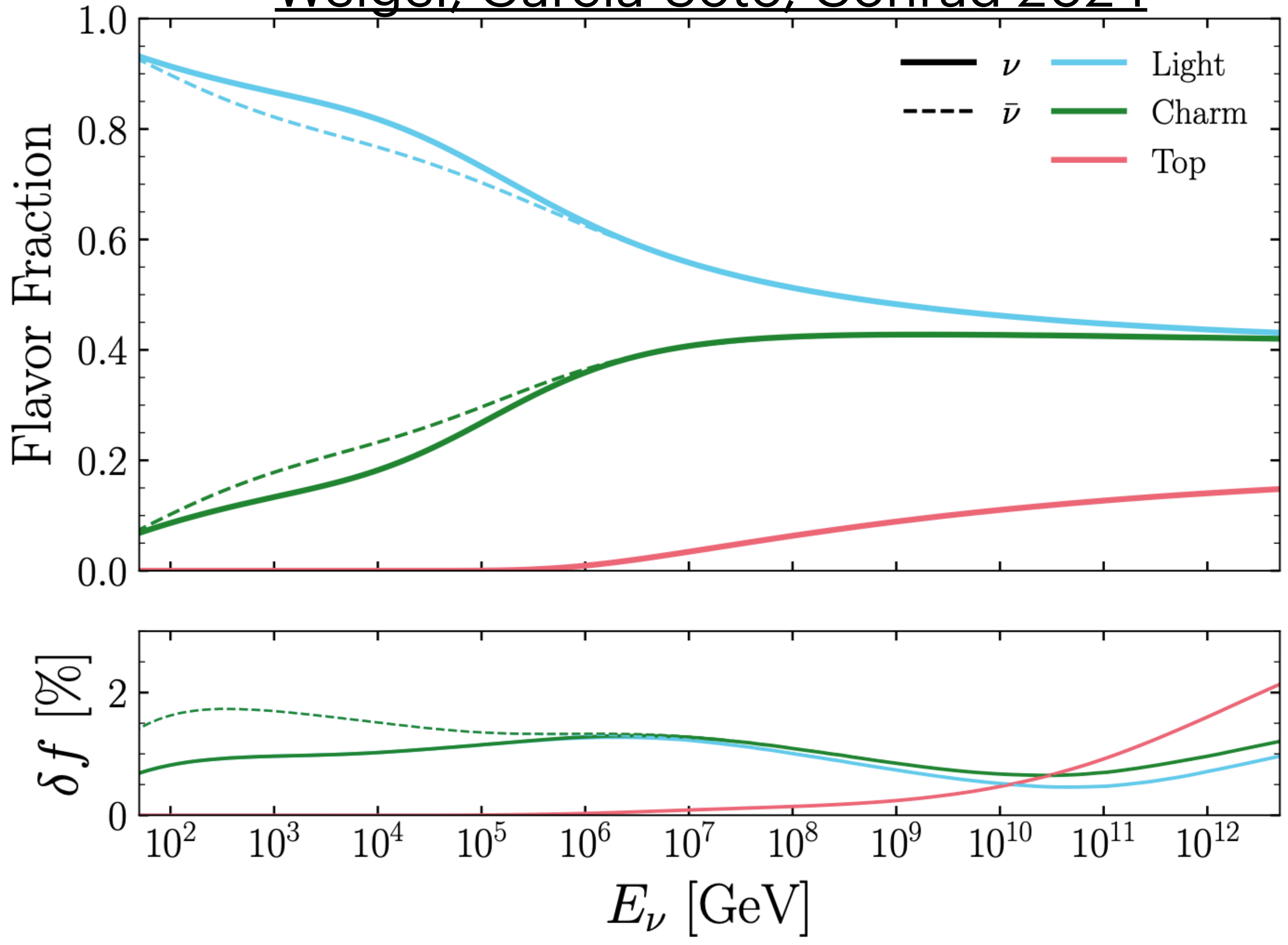
Weigel, Garcia-Soto, Conrad 2024

- Large fraction of the DIS cross section comes from charm, especially at higher energies



Charm Production in IceCube

- Large fraction of the DIS cross section comes from charm, especially at higher energies
- D mesons and τ leptons have a similar lifetime

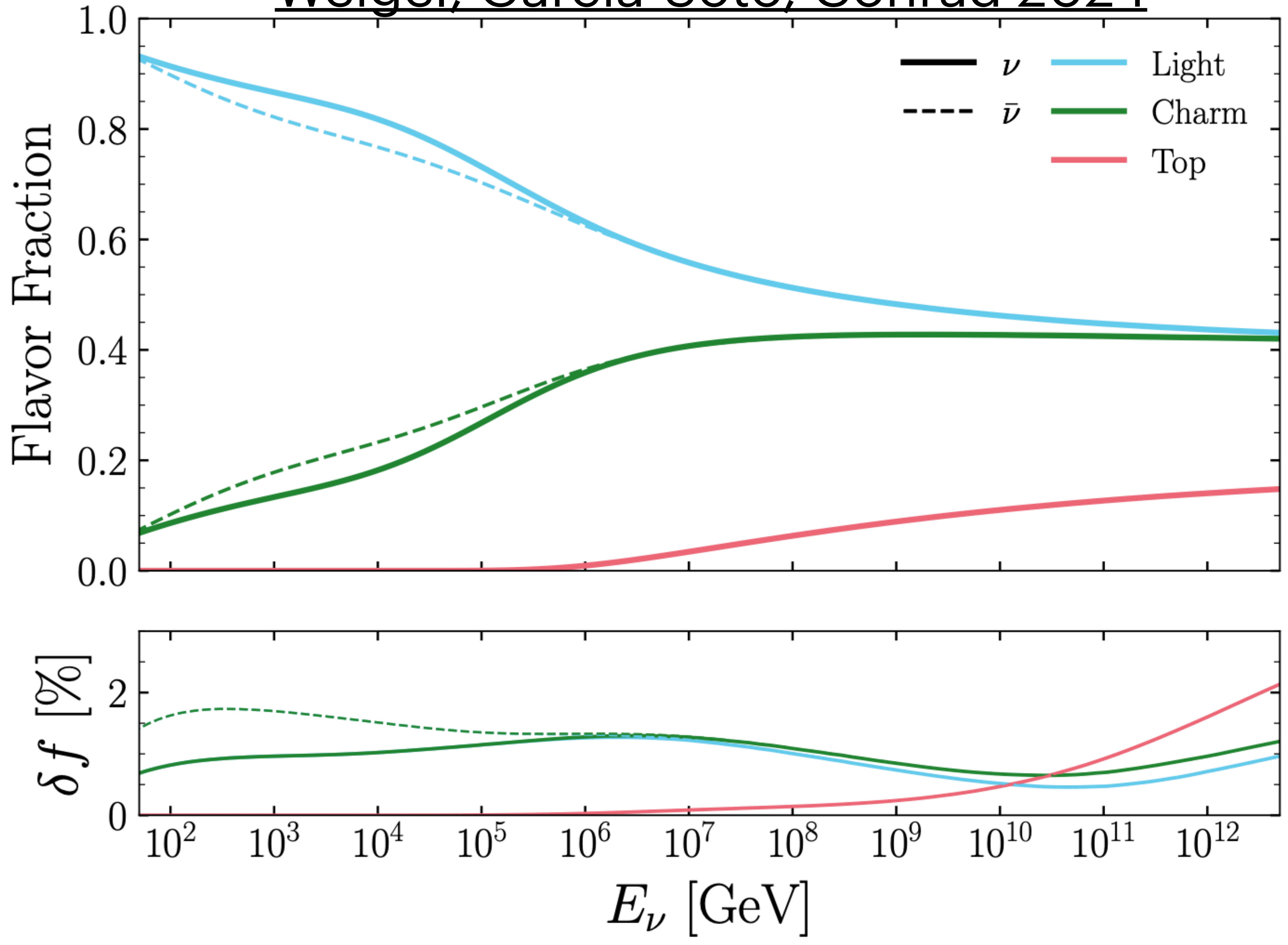
$\boxed{D^{\pm}}$ $\quad I(J^P) = \frac{1}{2}(0^-)$

Mass $m = 1869.66 \pm 0.05$ MeV
Mean life $\tau = (1033 \pm 5) \times 10^{-15}$ s
$c\tau = 309.8\ \mu$m

τ MEAN LIFE

VALUE (10^{-15} s)	*EVTS*
290.3 ± 0.5	**OUR AVERAGE**

Weigel, Garcia-Soto, Conrad 2024



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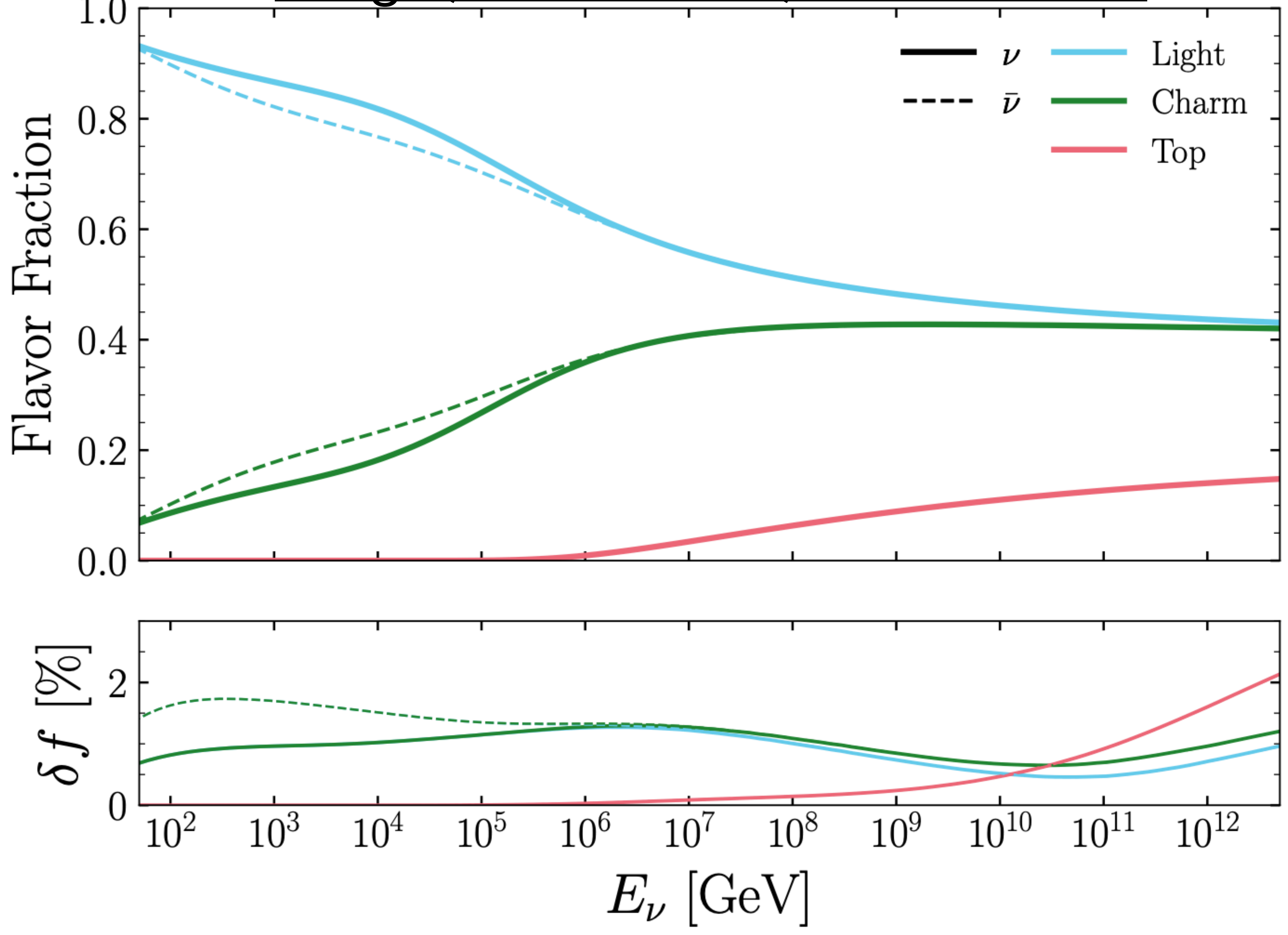

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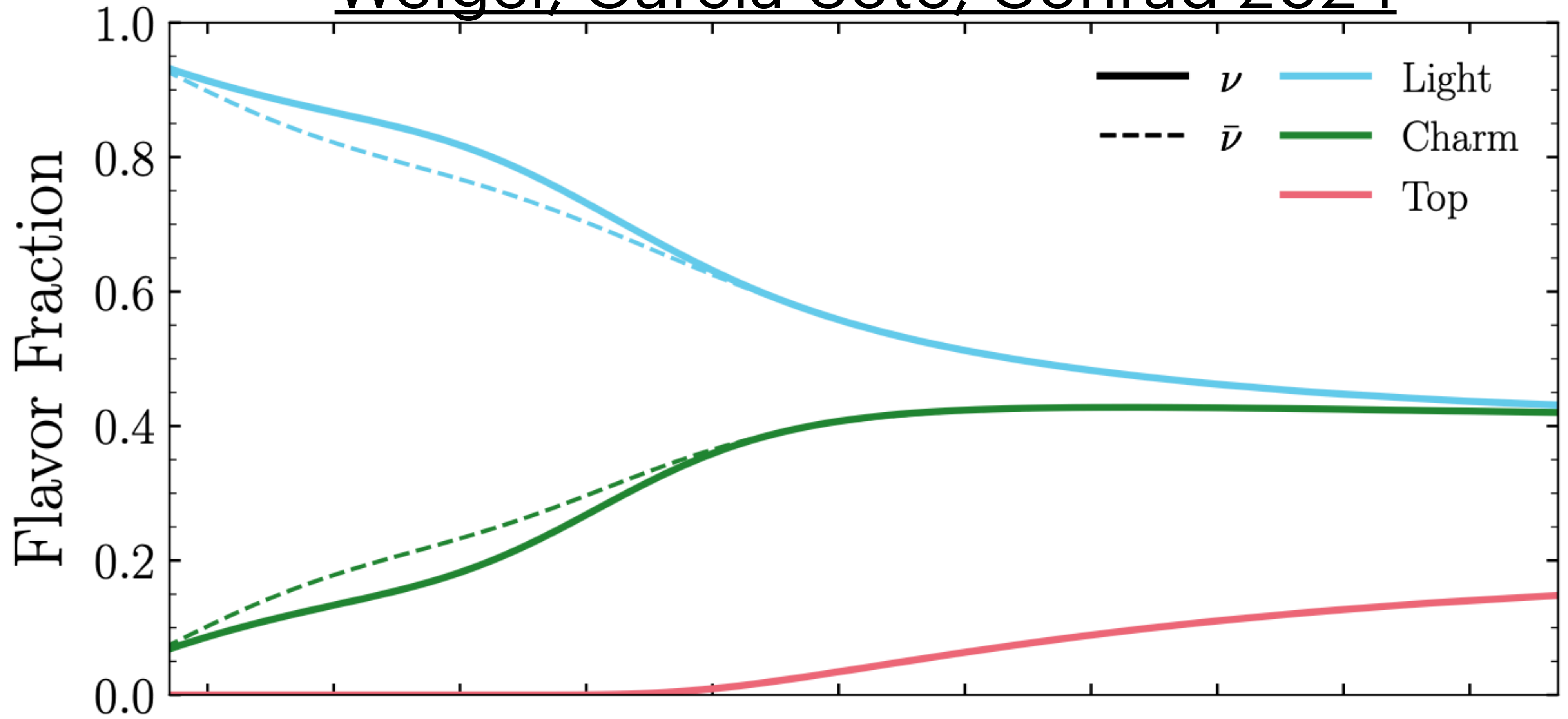
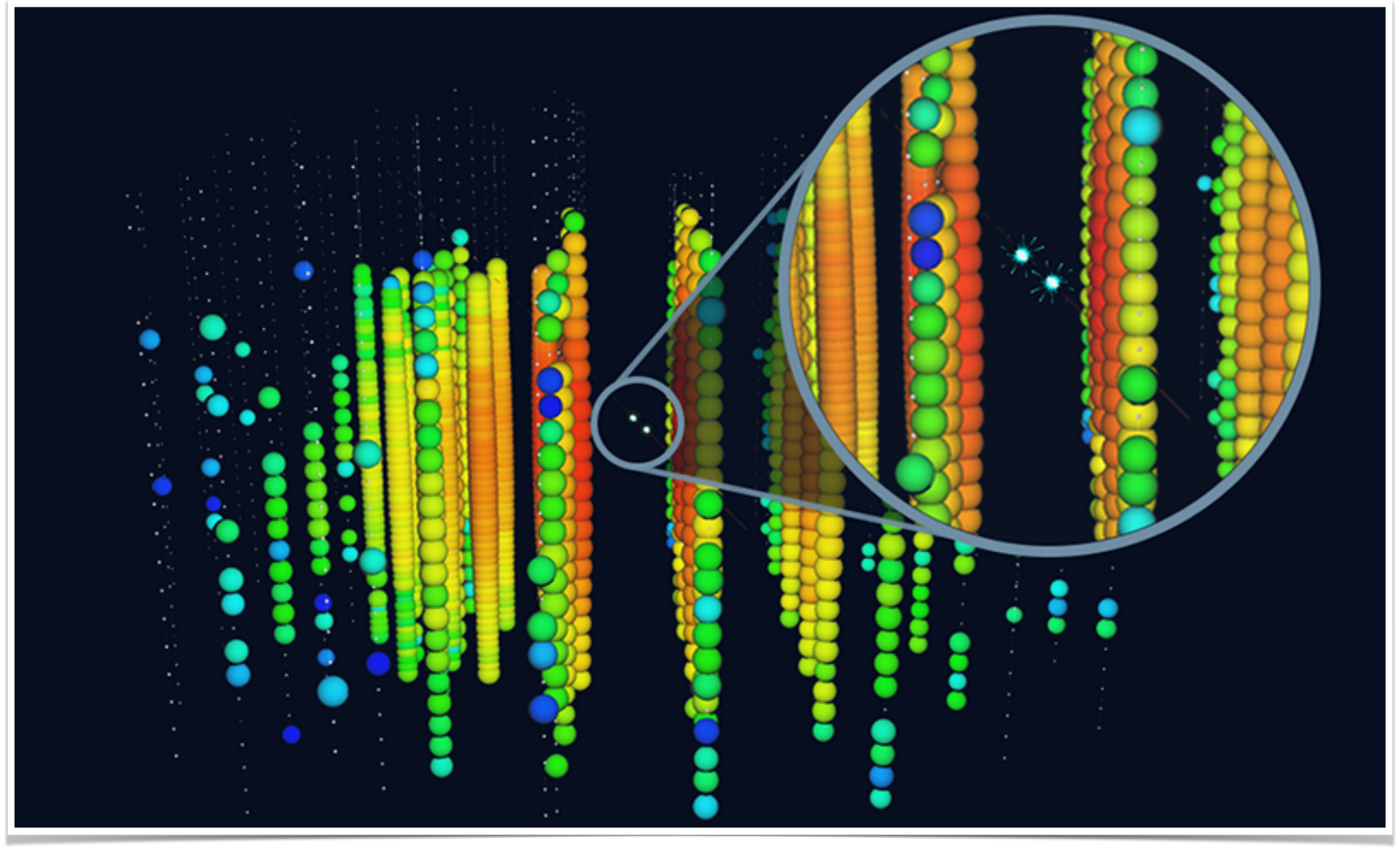
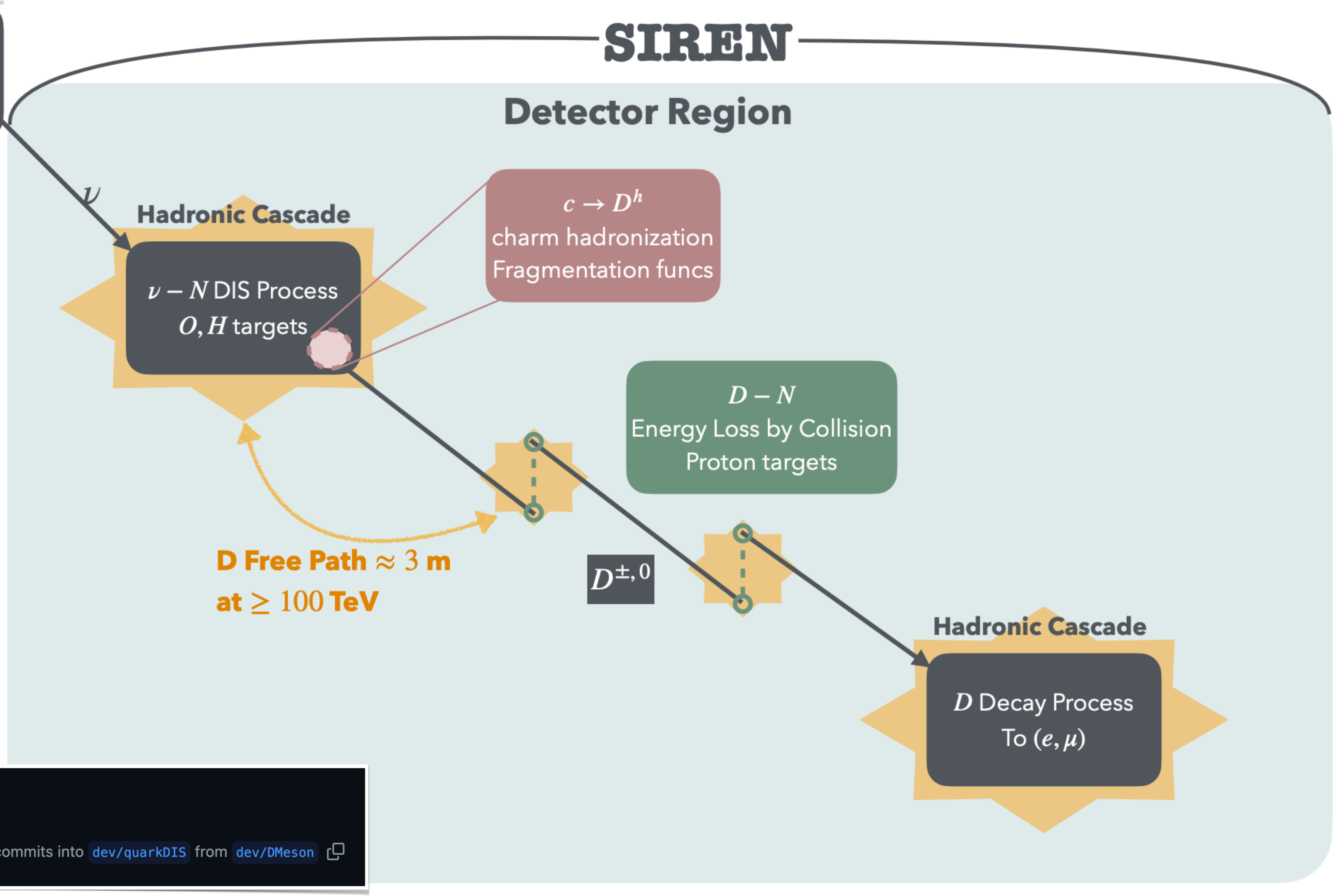
PRL: Seven Astrophysical Tau Neutrinos Unmasked

Weigel, Garcia-Soto, Conrad 2024







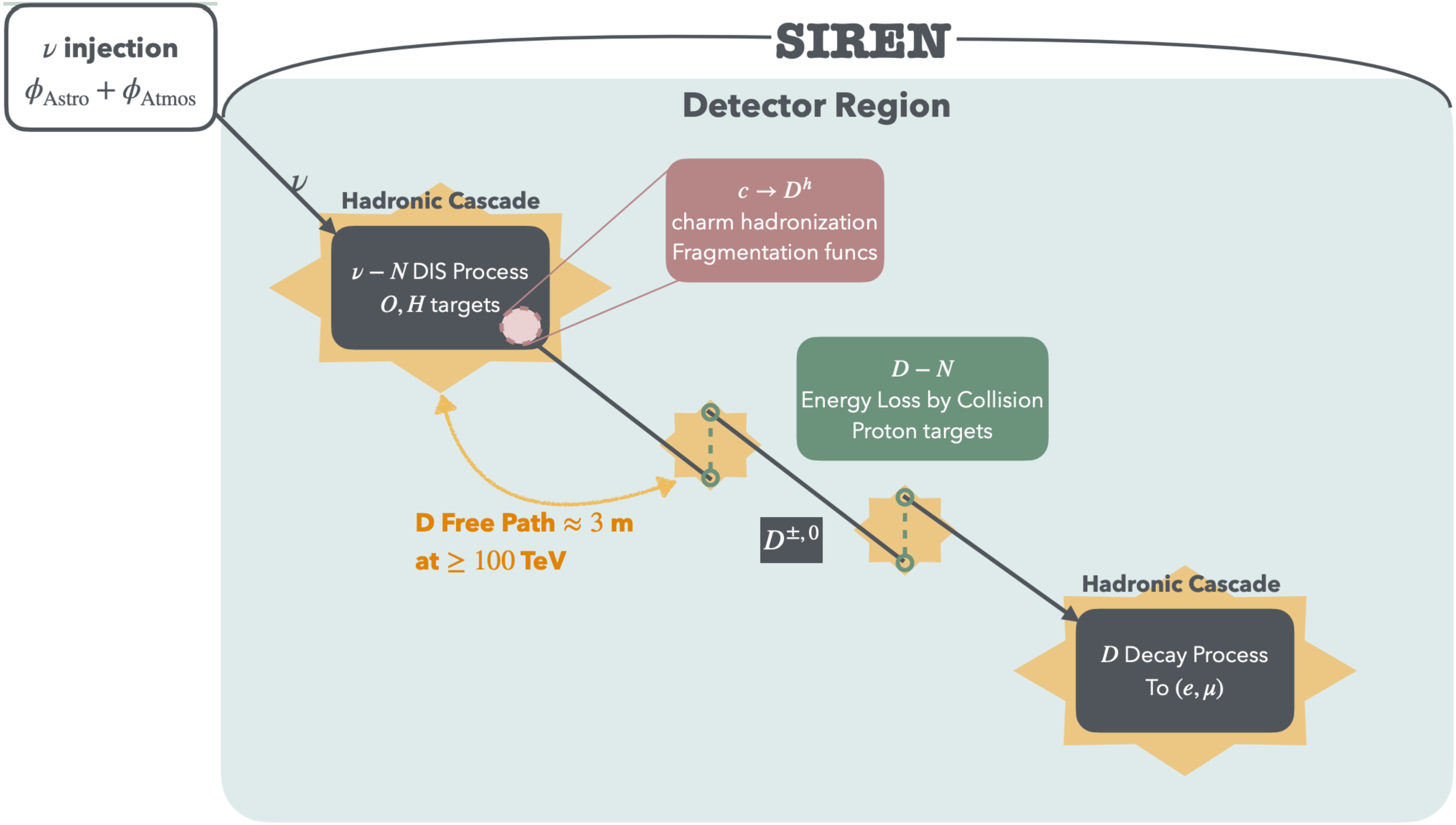
Fully-implemented in SIREN!

M. Jin

Dev/d meson #1

Open MiaochenJin wants to merge 15 commits into `dev/quarkDIS` from `dev/DMeson`

Charm Production in SIREN



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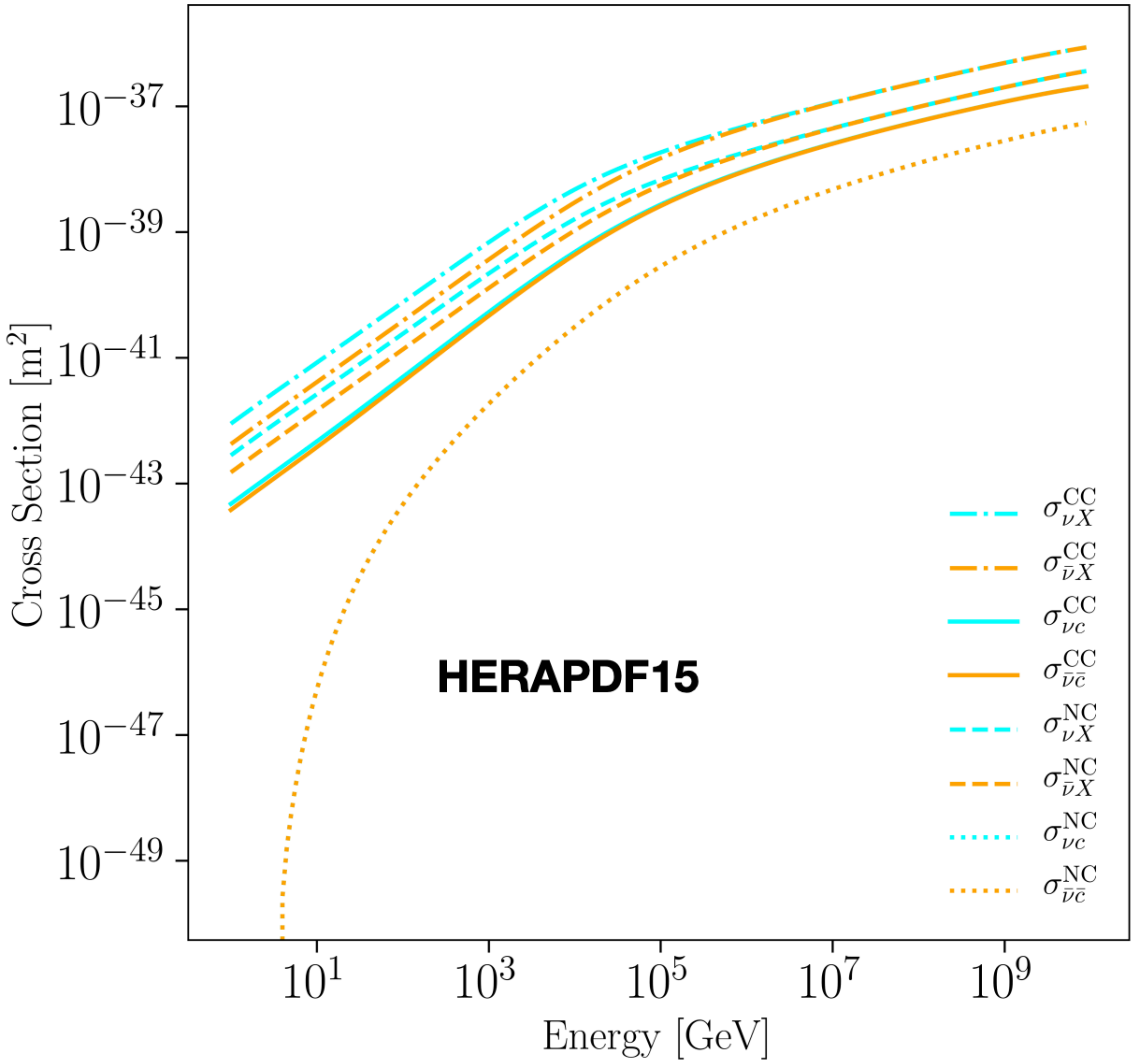
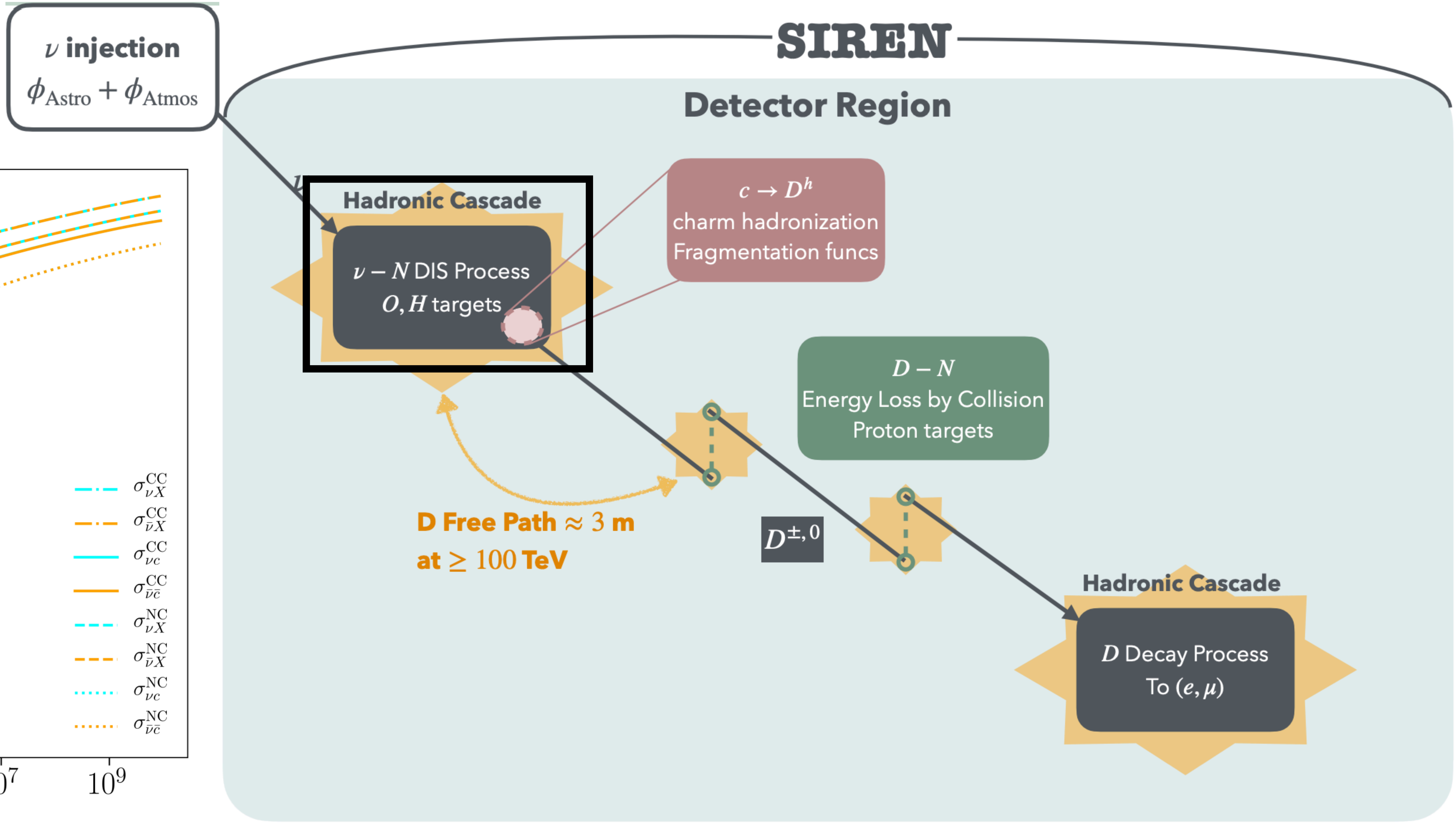
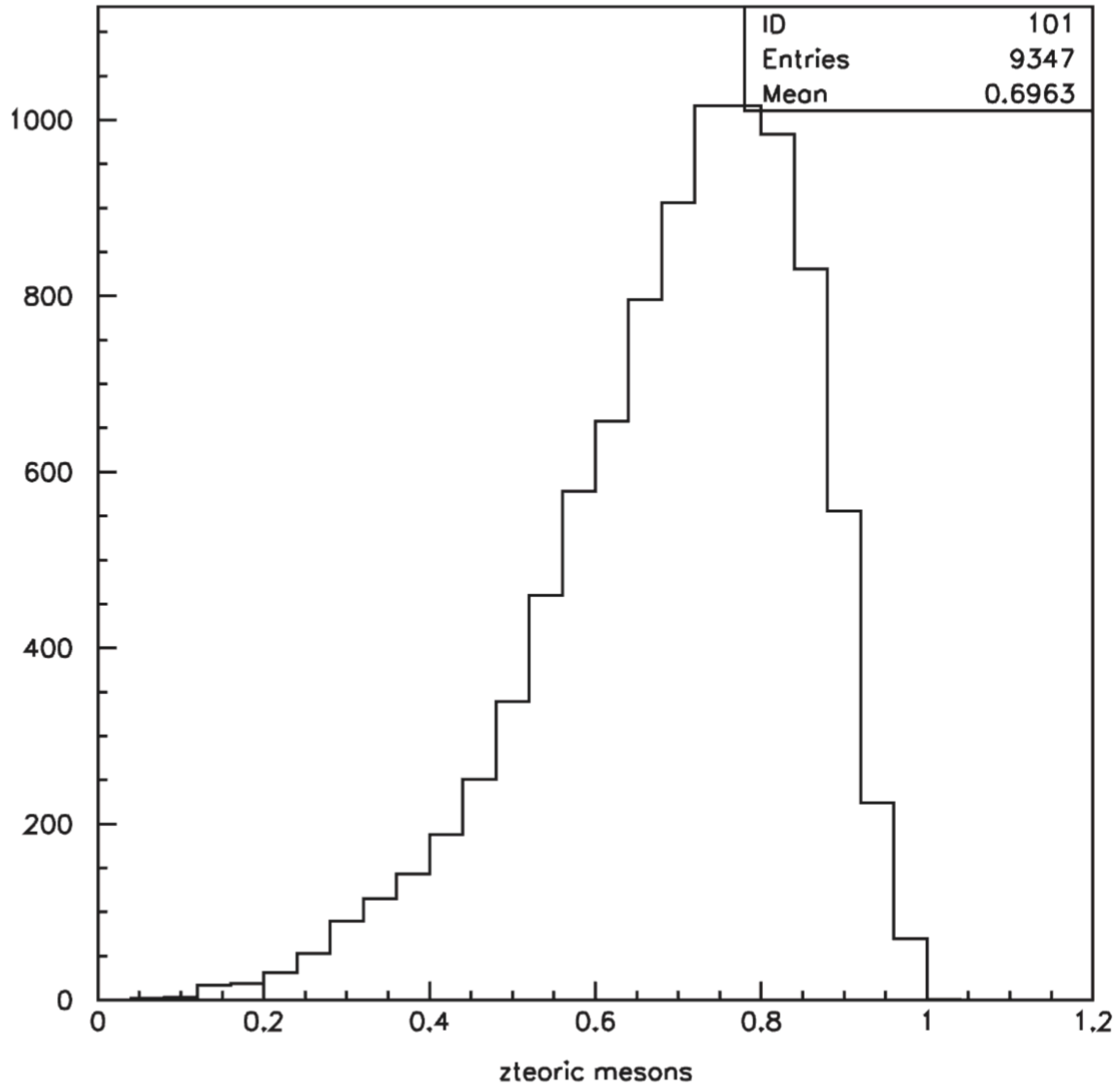




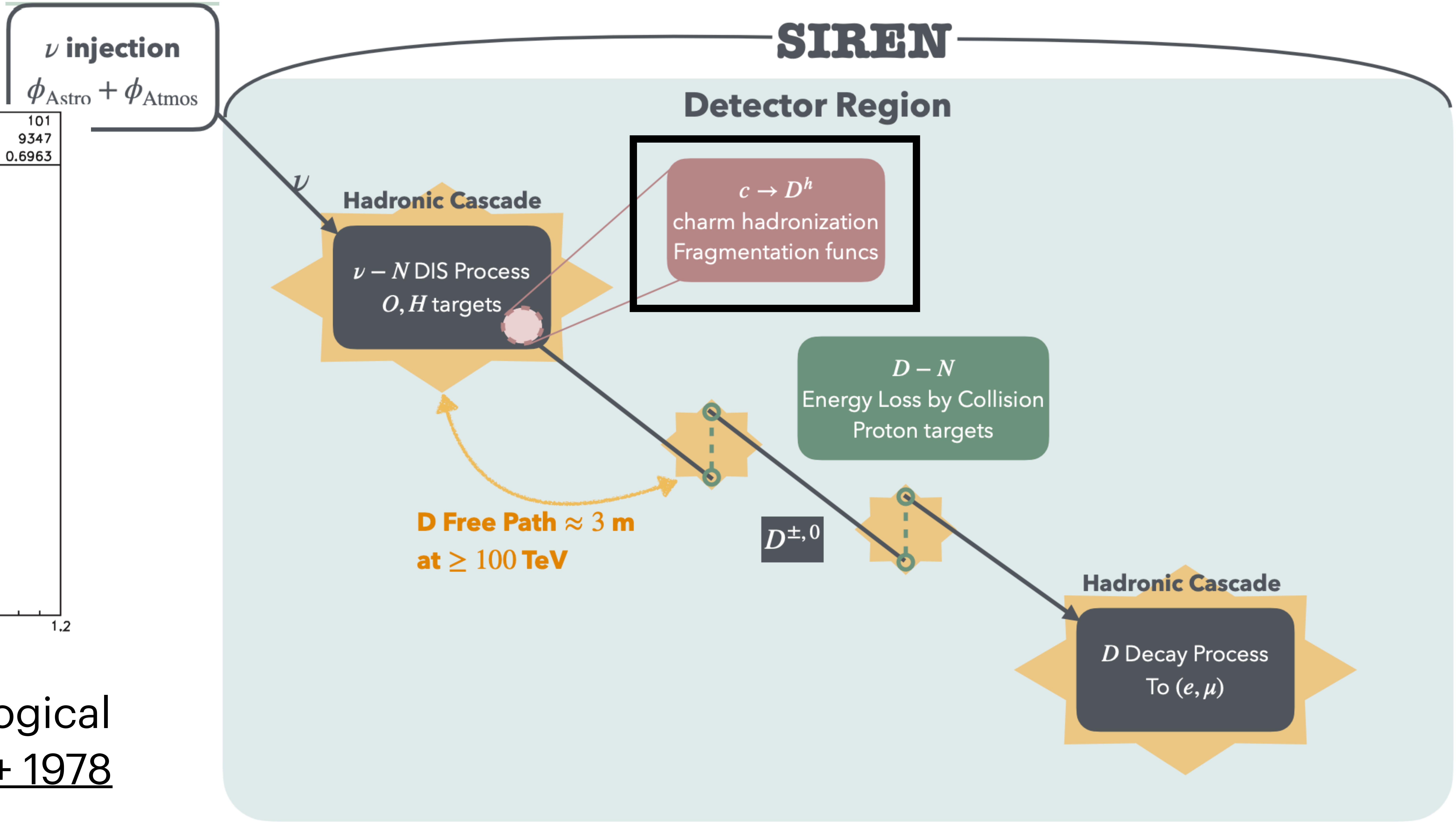
Charm Production in SIREN

De Lellis+ 2004



Choose a phenomenological form, e.g. Kartvelishvili+ 1978

$$D(z) \propto z^{\alpha}(1-z)$$



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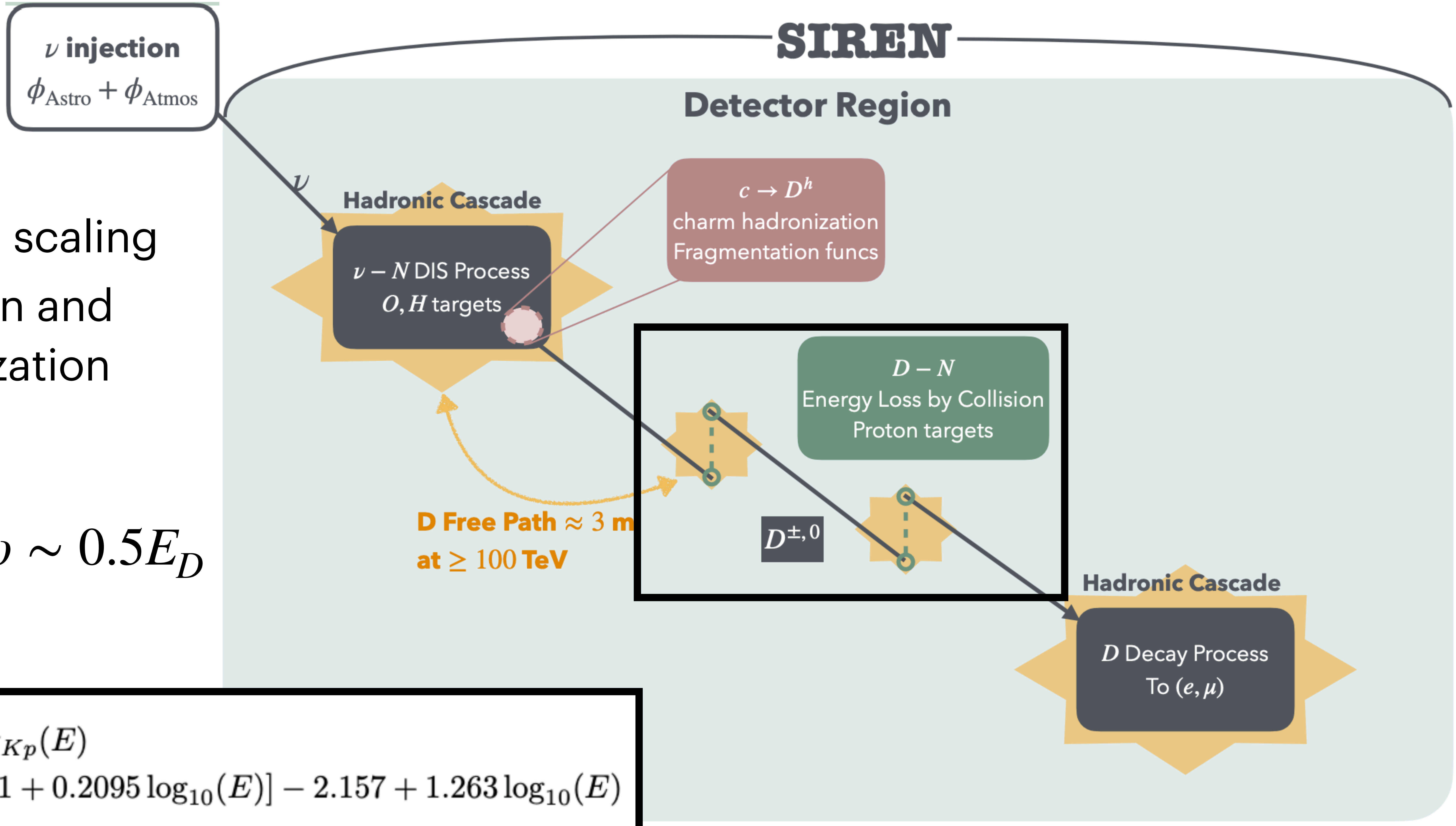


Not well known! Rely on scaling of $K - N$ cross section and CORSIKA parameterization

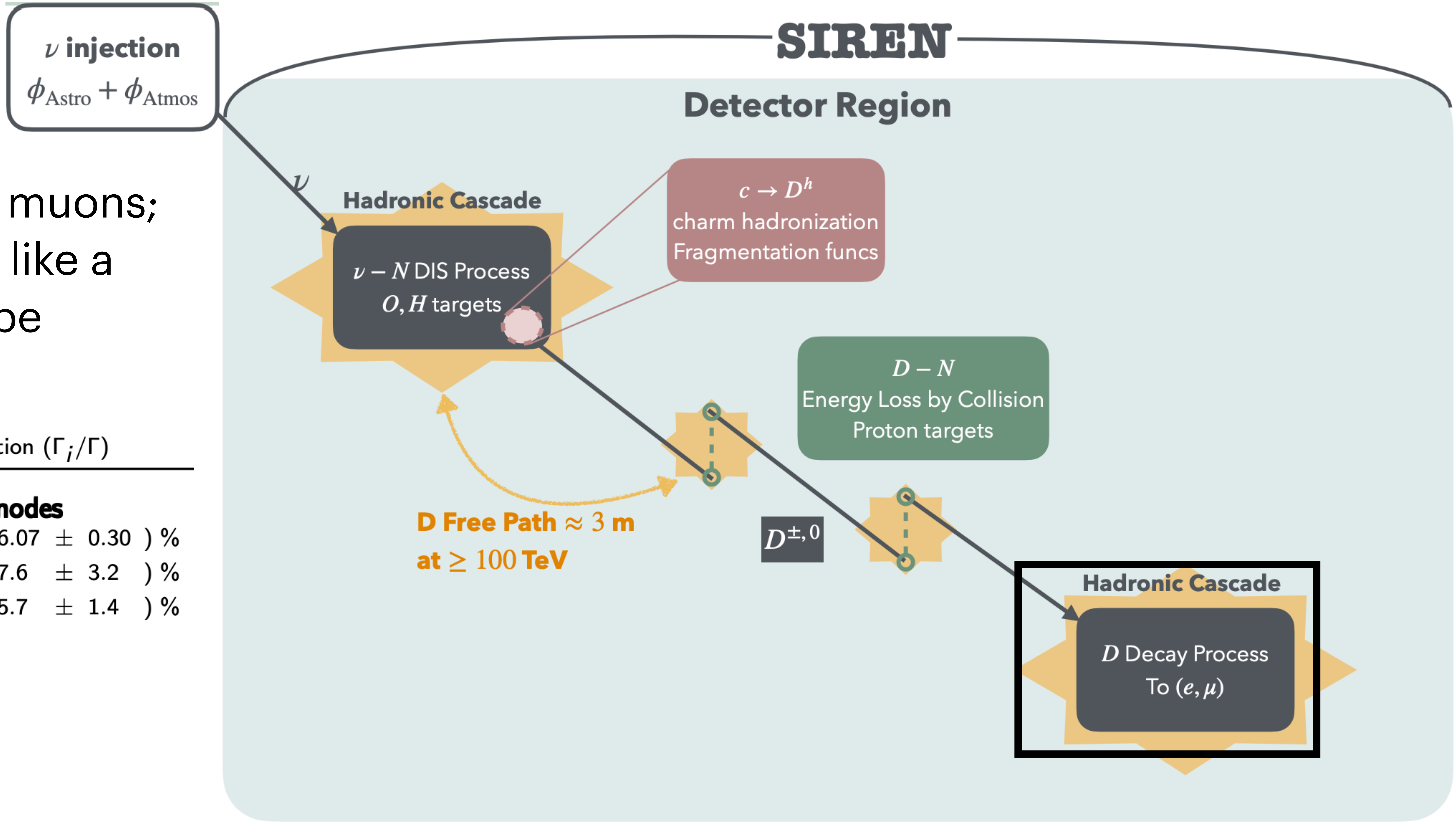
Typical energy transfer $\omega \sim 0.5 E_D$

$$\sigma_{Dp}(E) = \begin{cases} E < 1\ \text{PeV} & 0.87549\sigma_{Kp}(E) \\ E \geq 1\ \text{PeV} & \exp\left[1.891 + 0.2095\log_{10}(E)\right] - 2.157 + 1.263\log_{10}(E) \end{cases}$$

Charm Production in SIREN

~17% branching ratio to muons; everything else looks like a cascade in IceCube

D^+ DECAY MODES	Fraction (Γ_i/Γ)
Inclusive modes	
e^+ semileptonic	(16.07 ± 0.30) %
μ^+ anything	(17.6 ± 3.2) %
K^- anything	(25.7 ± 1.4) %



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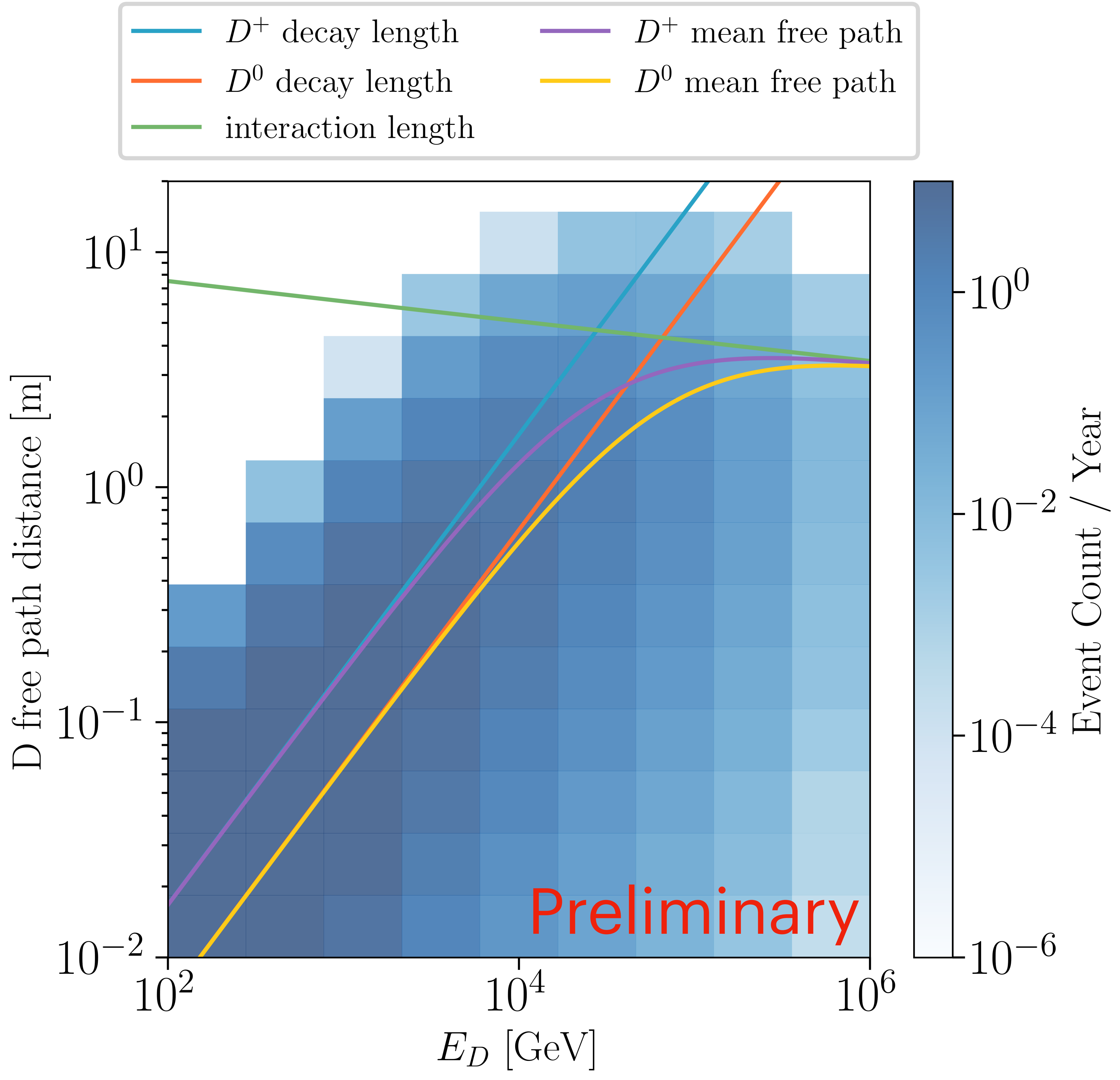

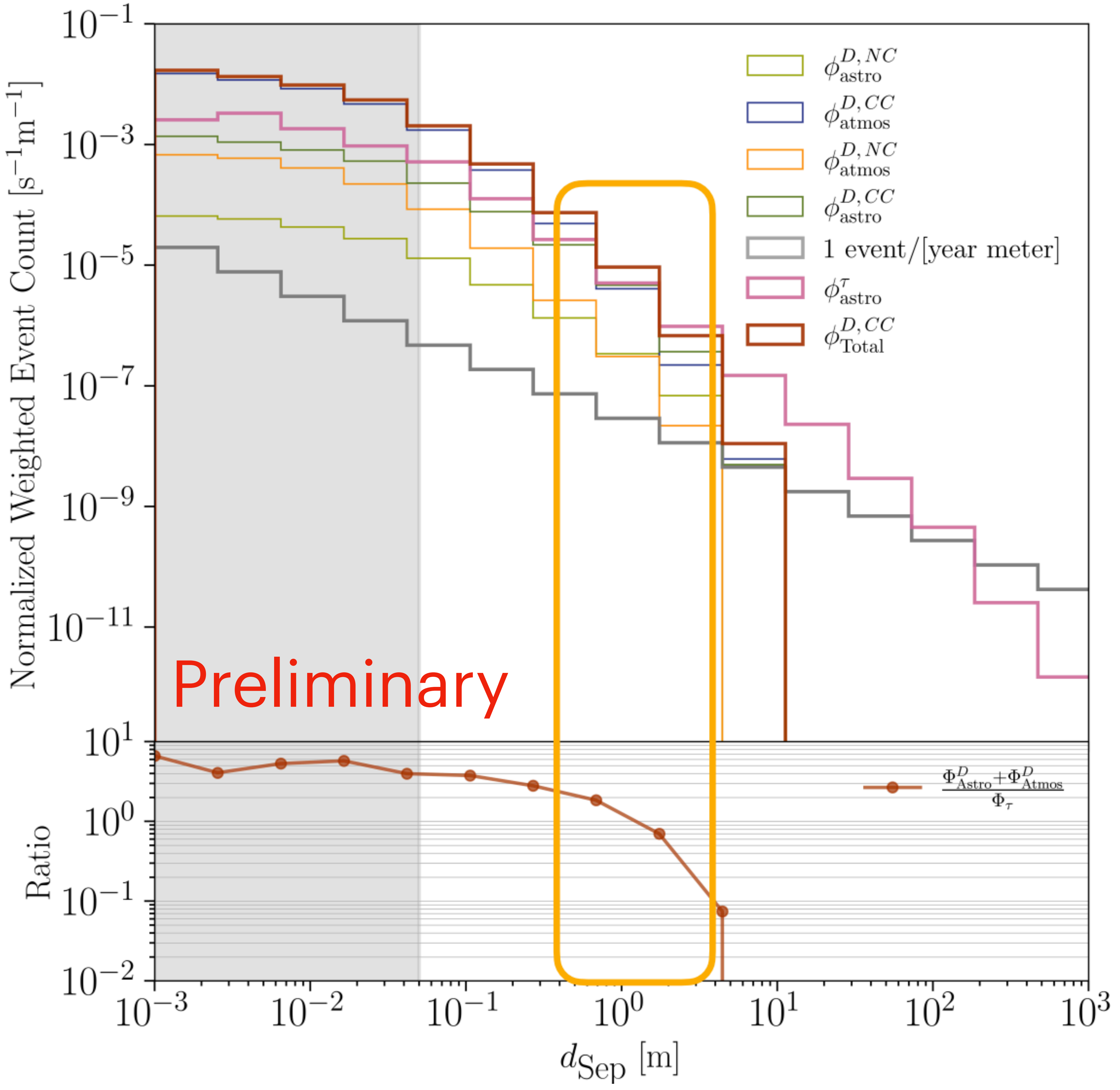

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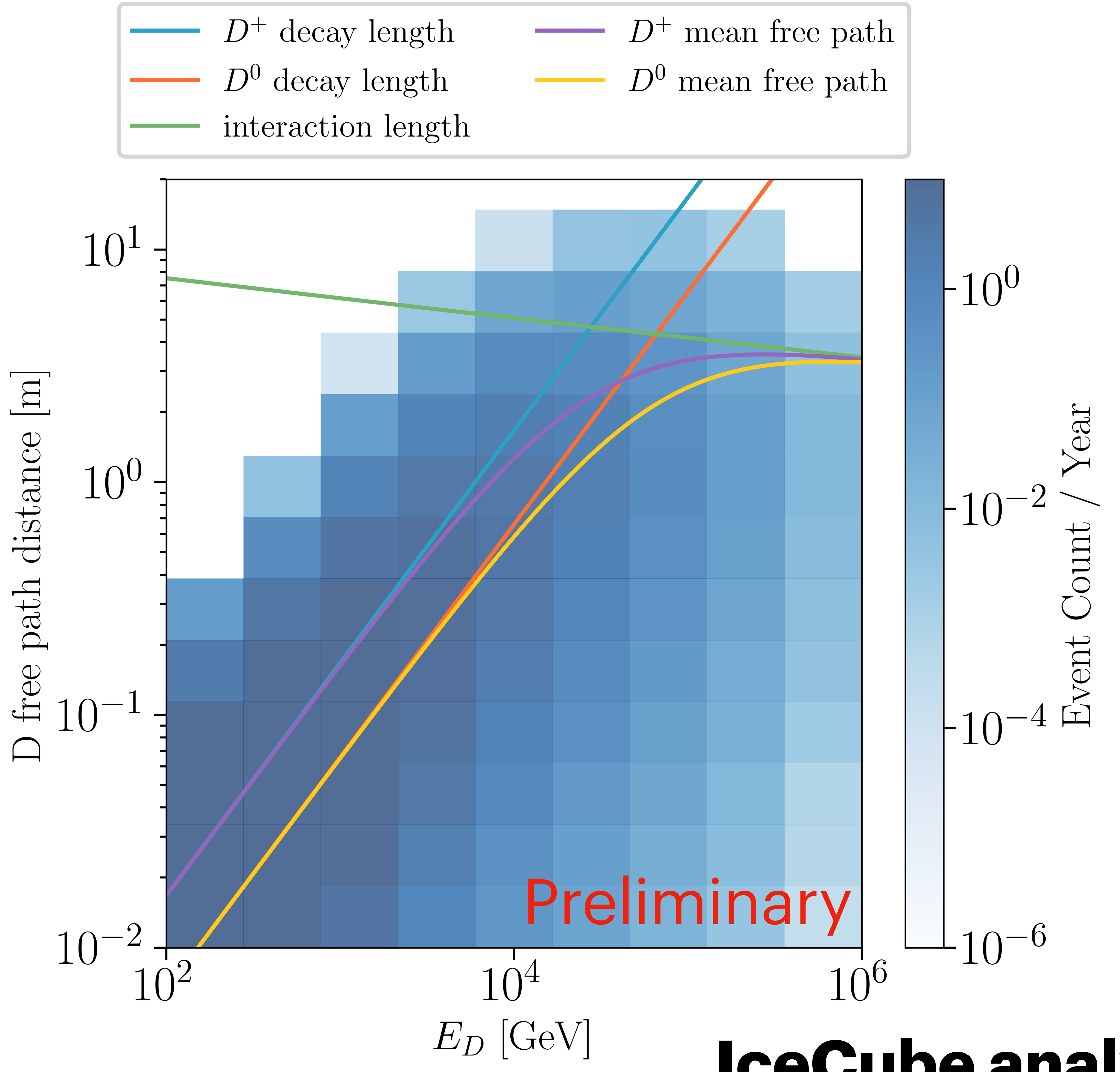
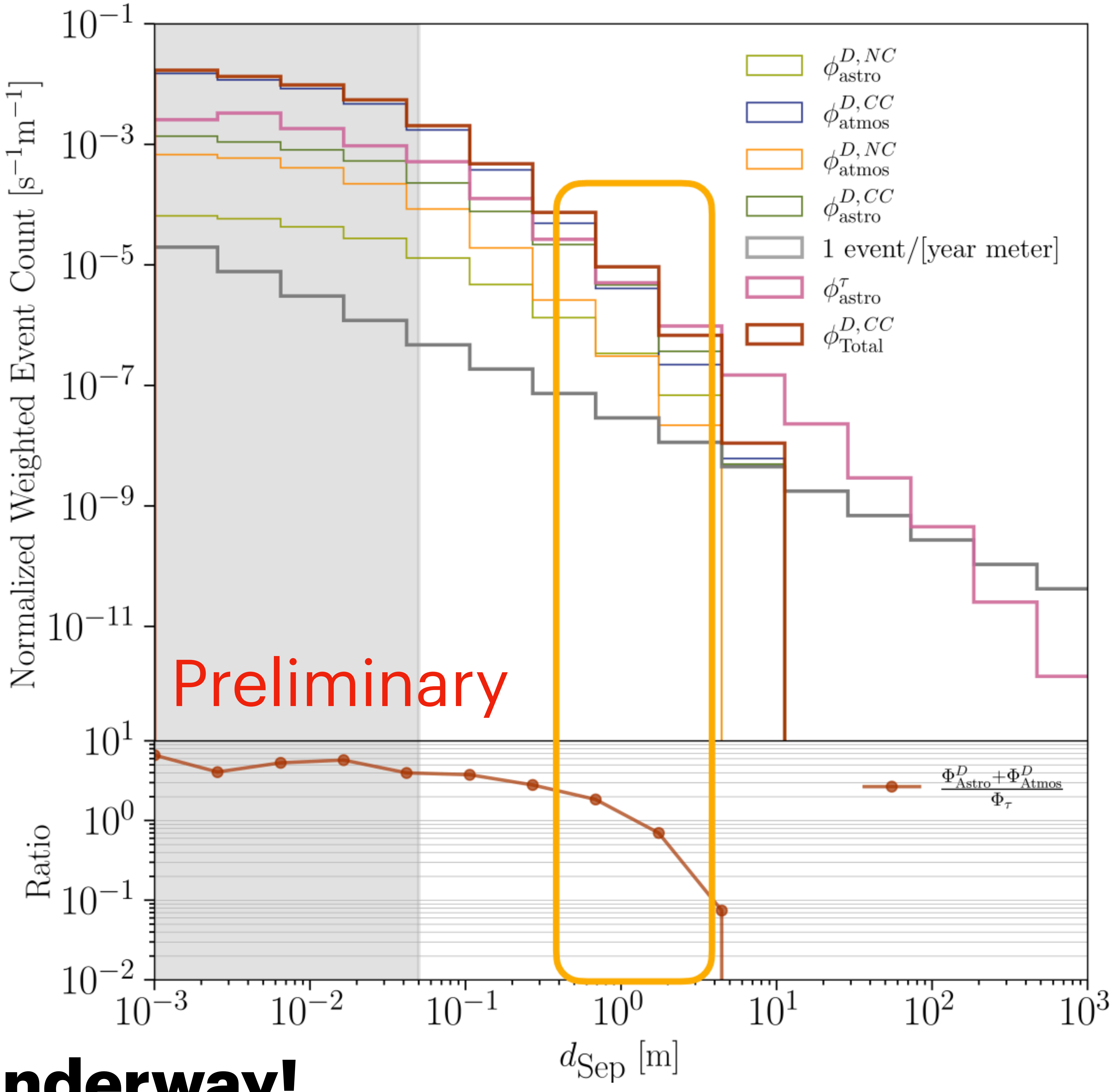


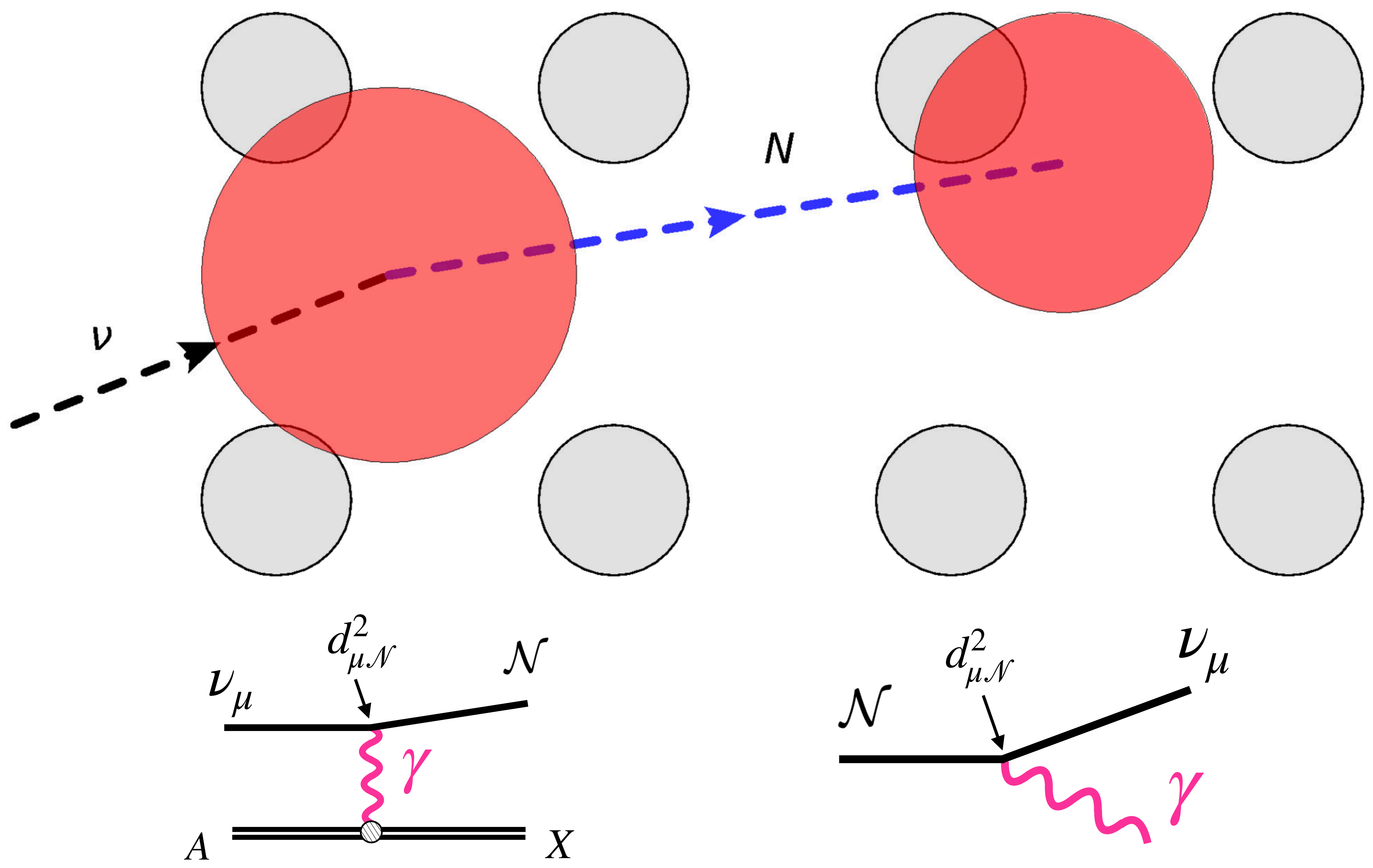


IceCube analysis underway!

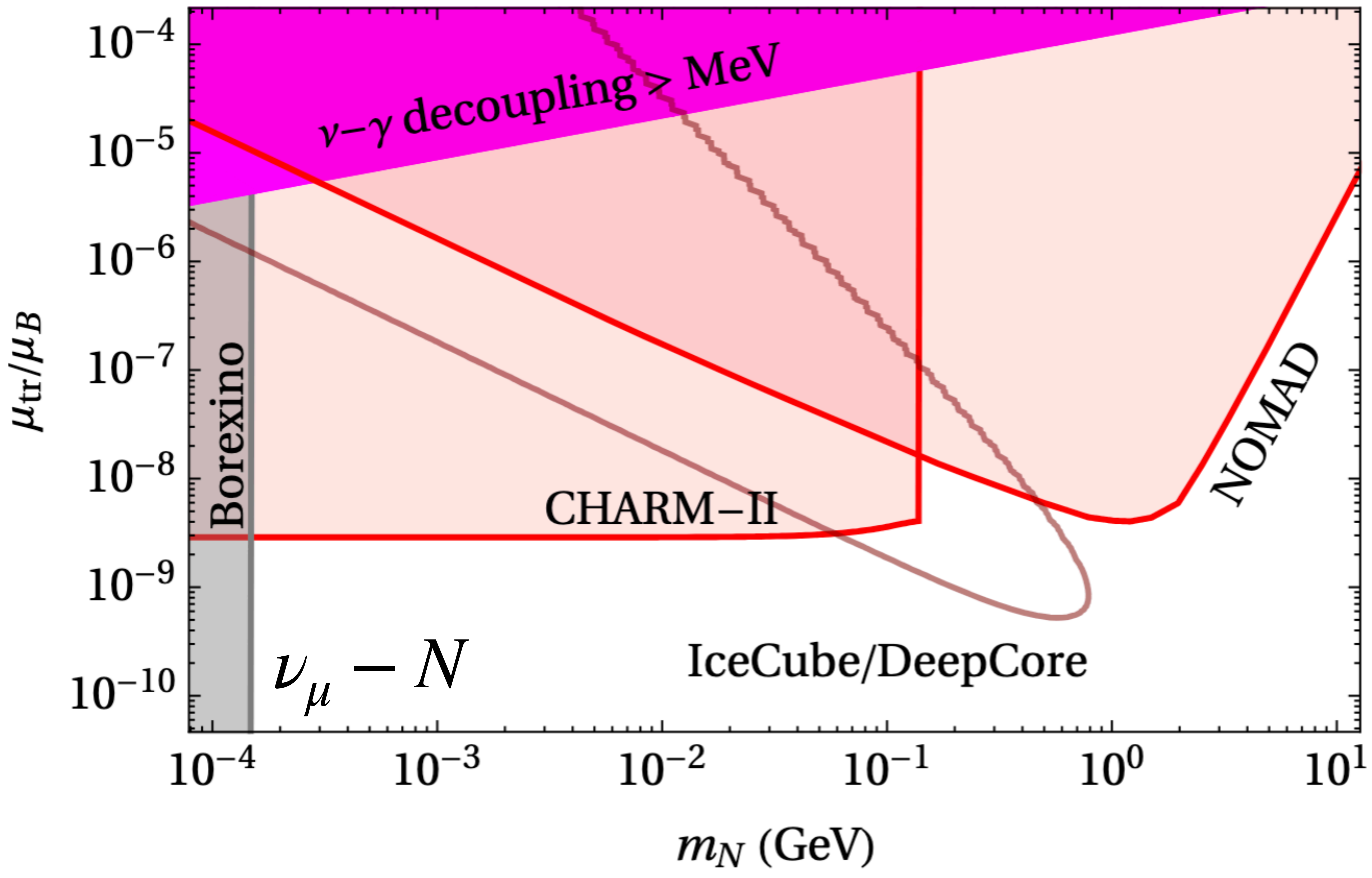
Dipole-Portal HNLs @ IceCube

BSM source of separated cascades!

We consider HNL production from atmospheric $\nu_\mu + \bar{\nu}_\mu$ flux

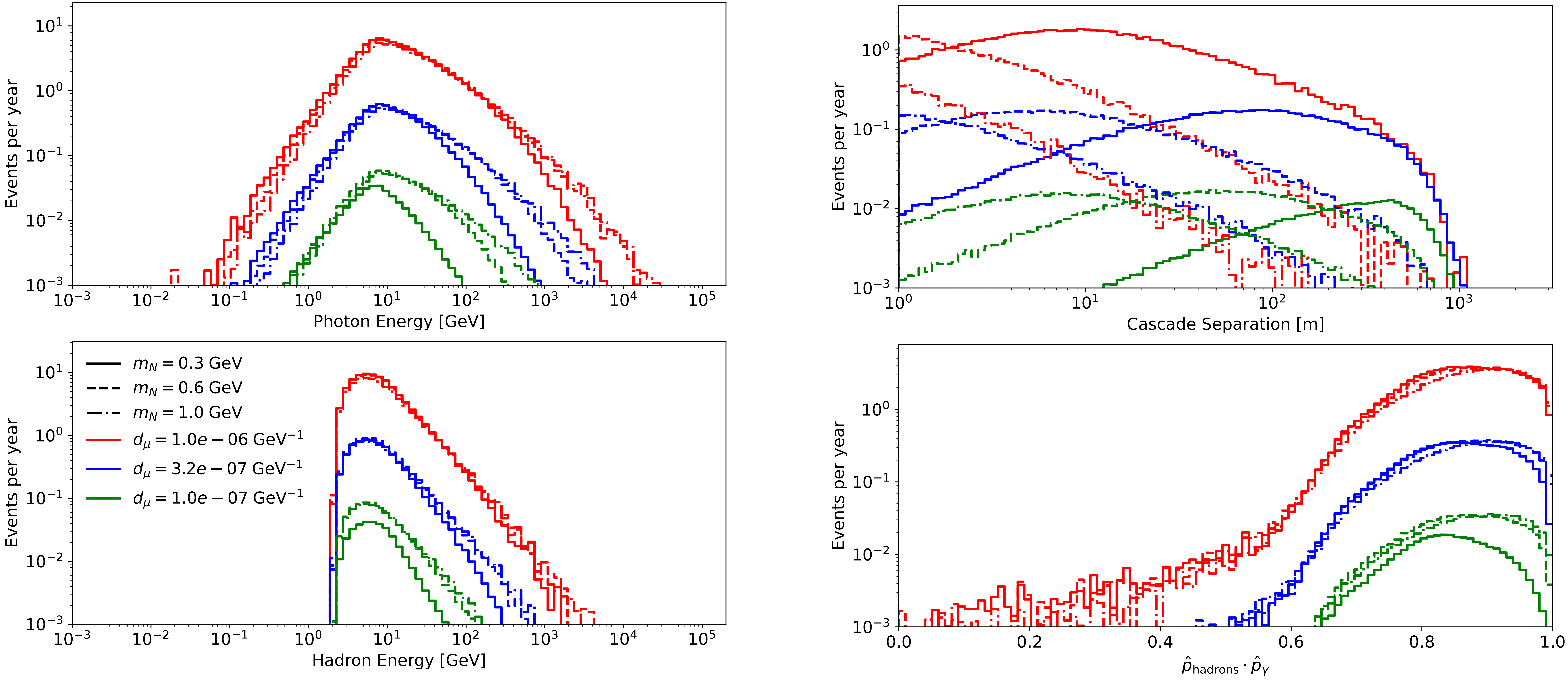


Coloma+ 2017



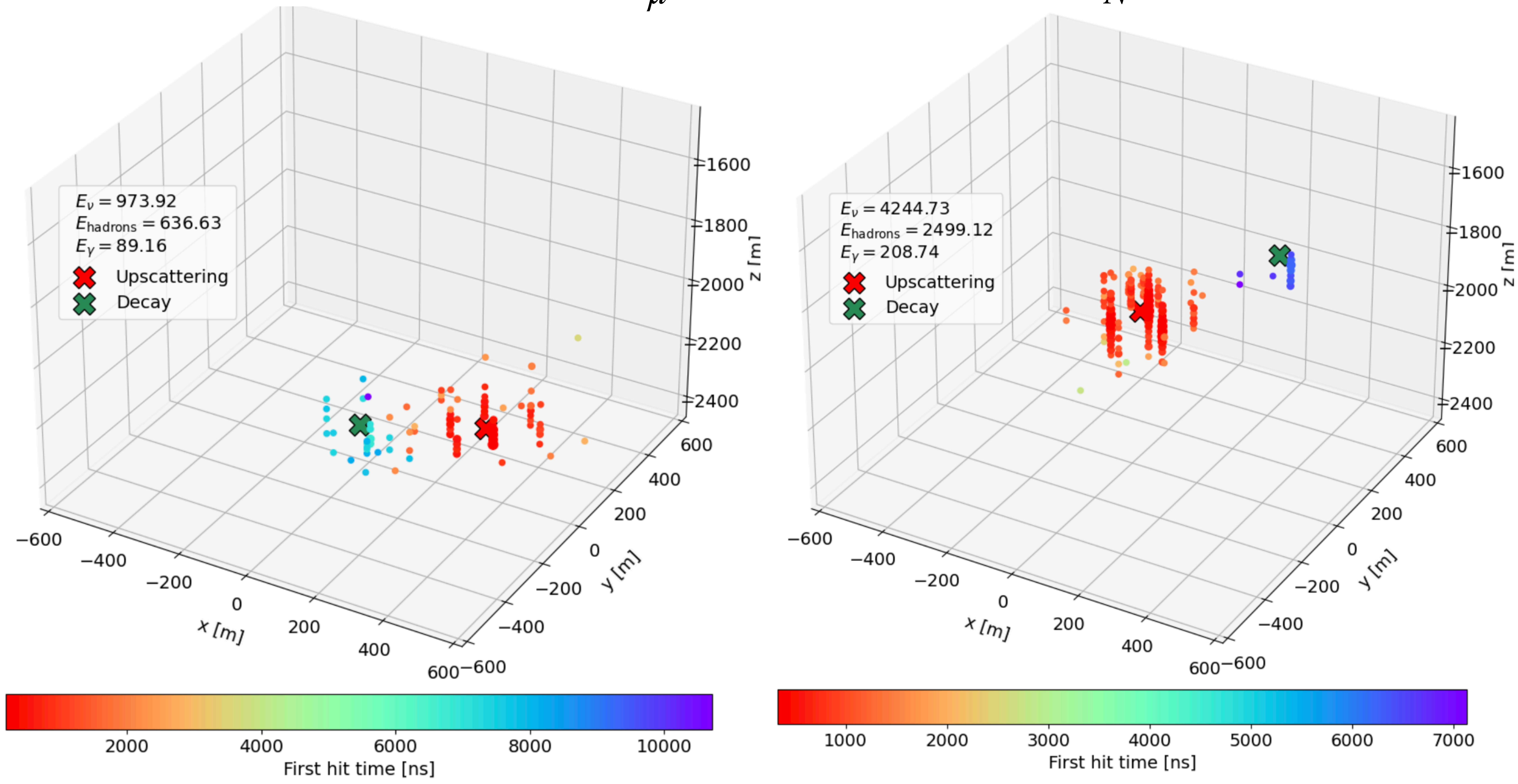
Dipole-Portal HNLs in SIREN

$$10 \leq E_\nu/\mathrm{GeV} \leq 10^5$$



Dipole-Portal HNLs in SIREN

$$d_\mu = 10^{-7}\ \mathrm{GeV}^{-1} \qquad m_N = 0.6\ \mathrm{GeV}$$



Photon propagation with Prometheus (Lazar+ 2023)

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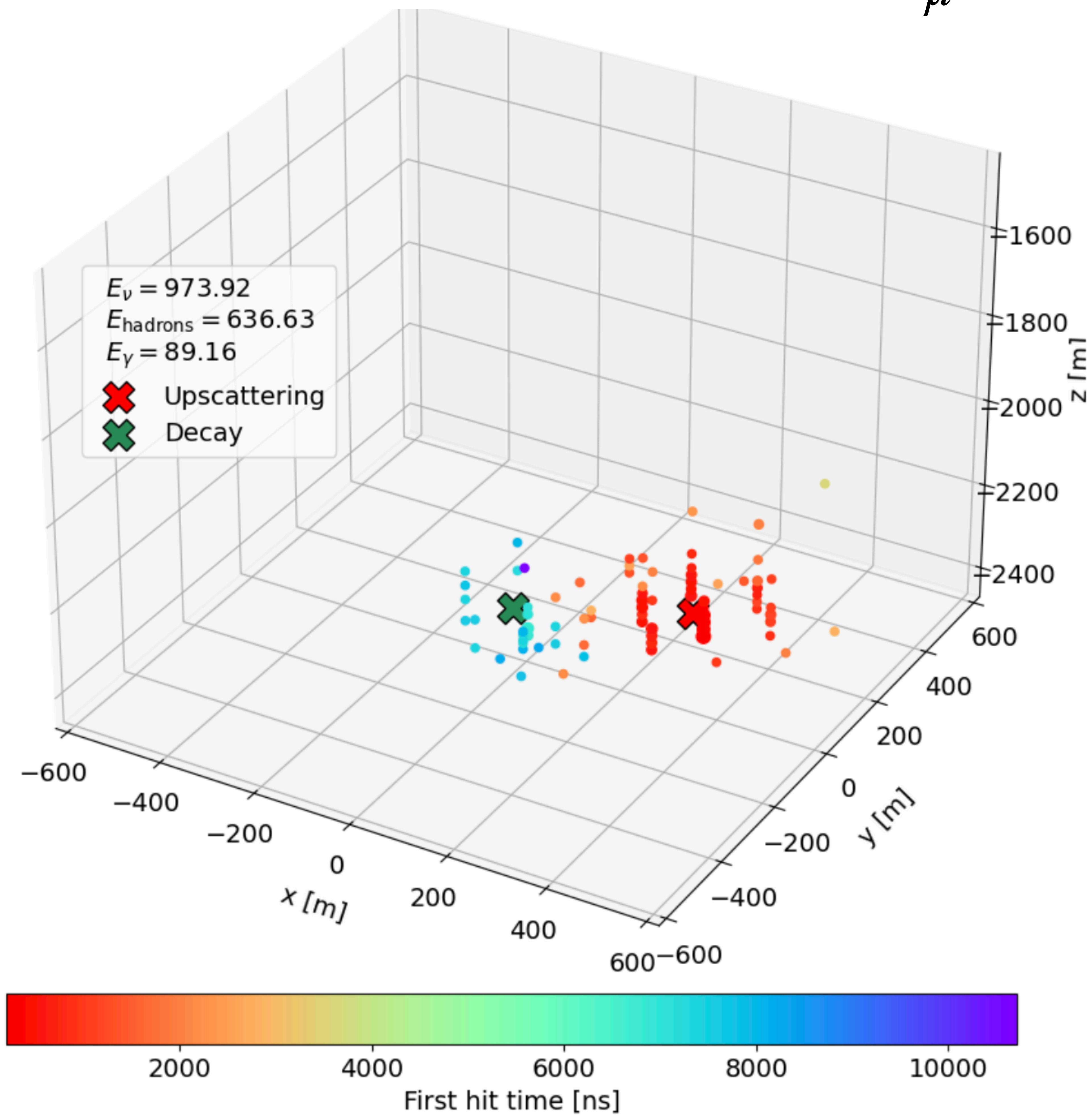

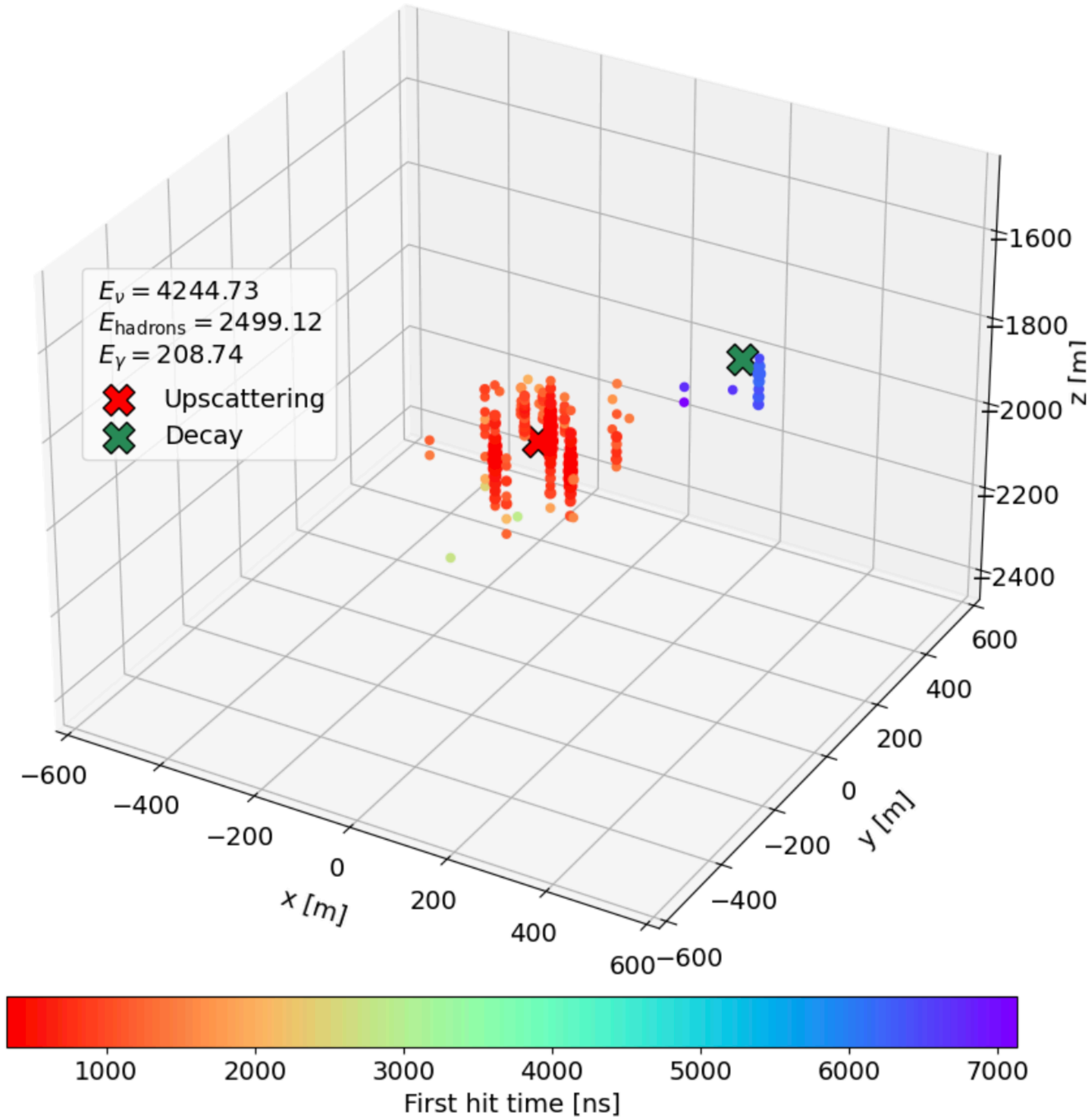

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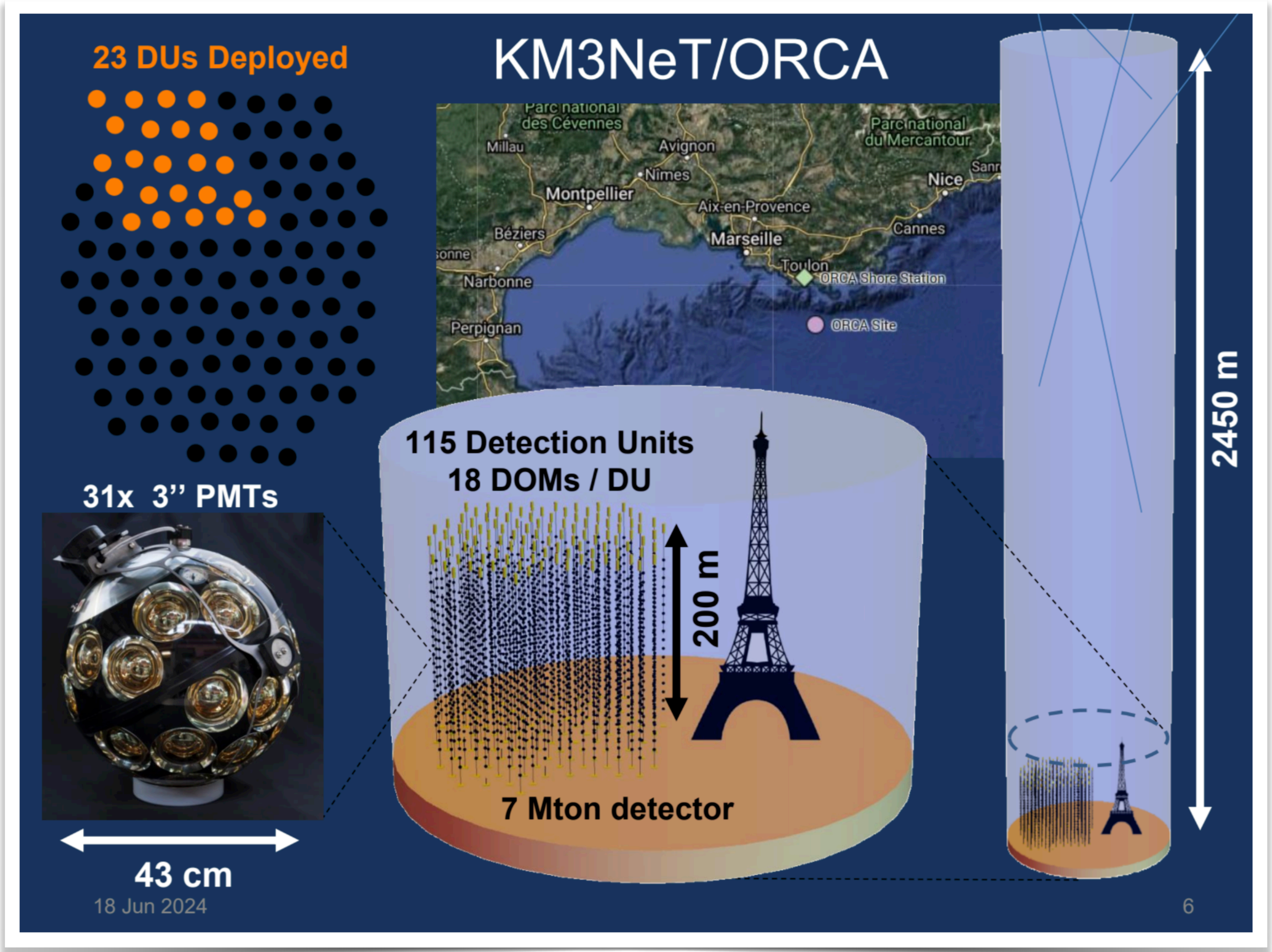
Dipole-Portal HNLs in ORCA

- SIREN is also being used to simulate double cascades from dipole-portal HNLs in ORCA
- Preliminary reconstruction efforts with full detector look promising

J. Prado

A. García Soto

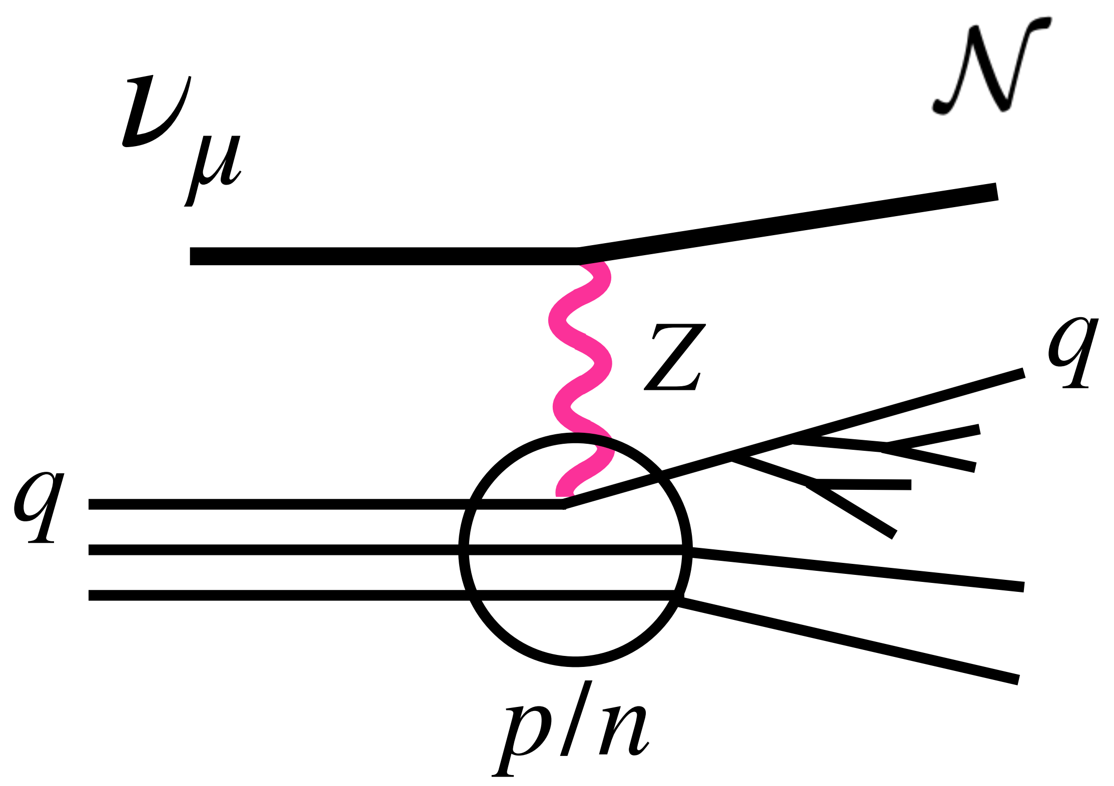


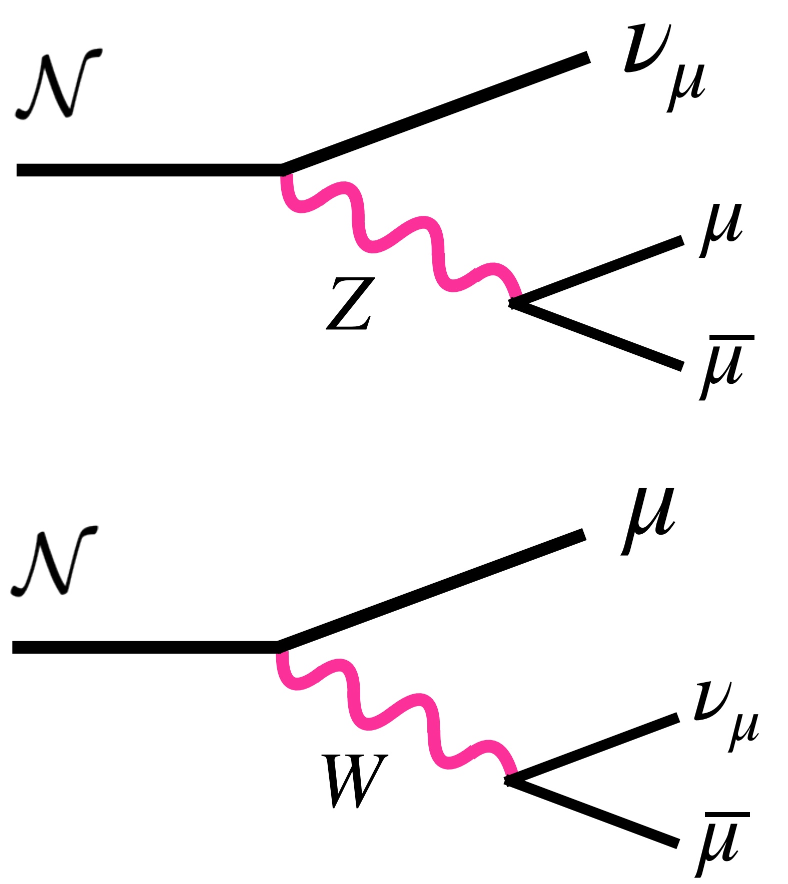
Joao Coelho, Neutrino 2024

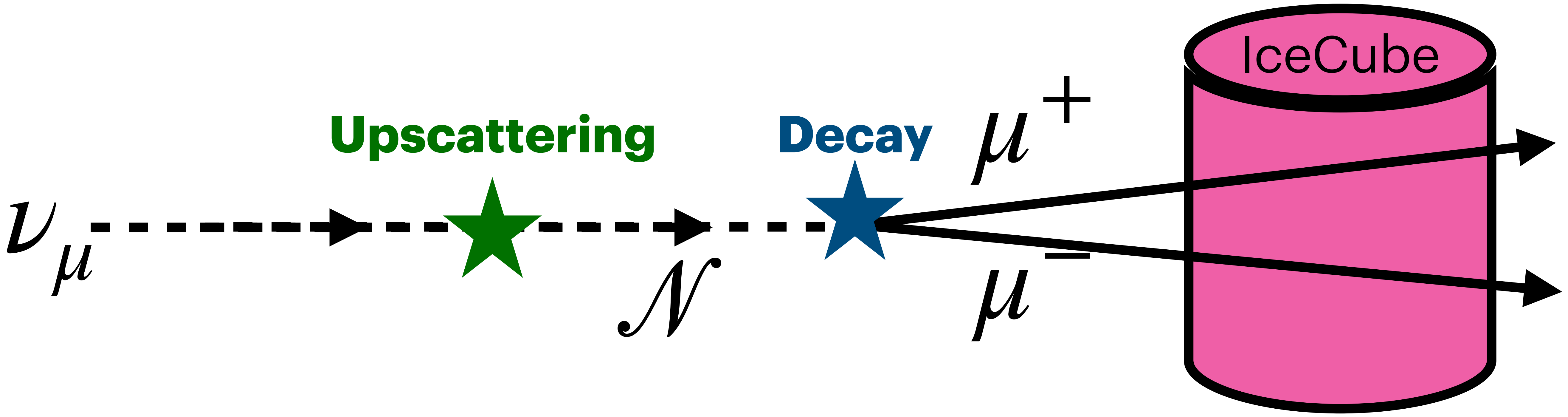
Mass-Mixed HNLs in IceCube

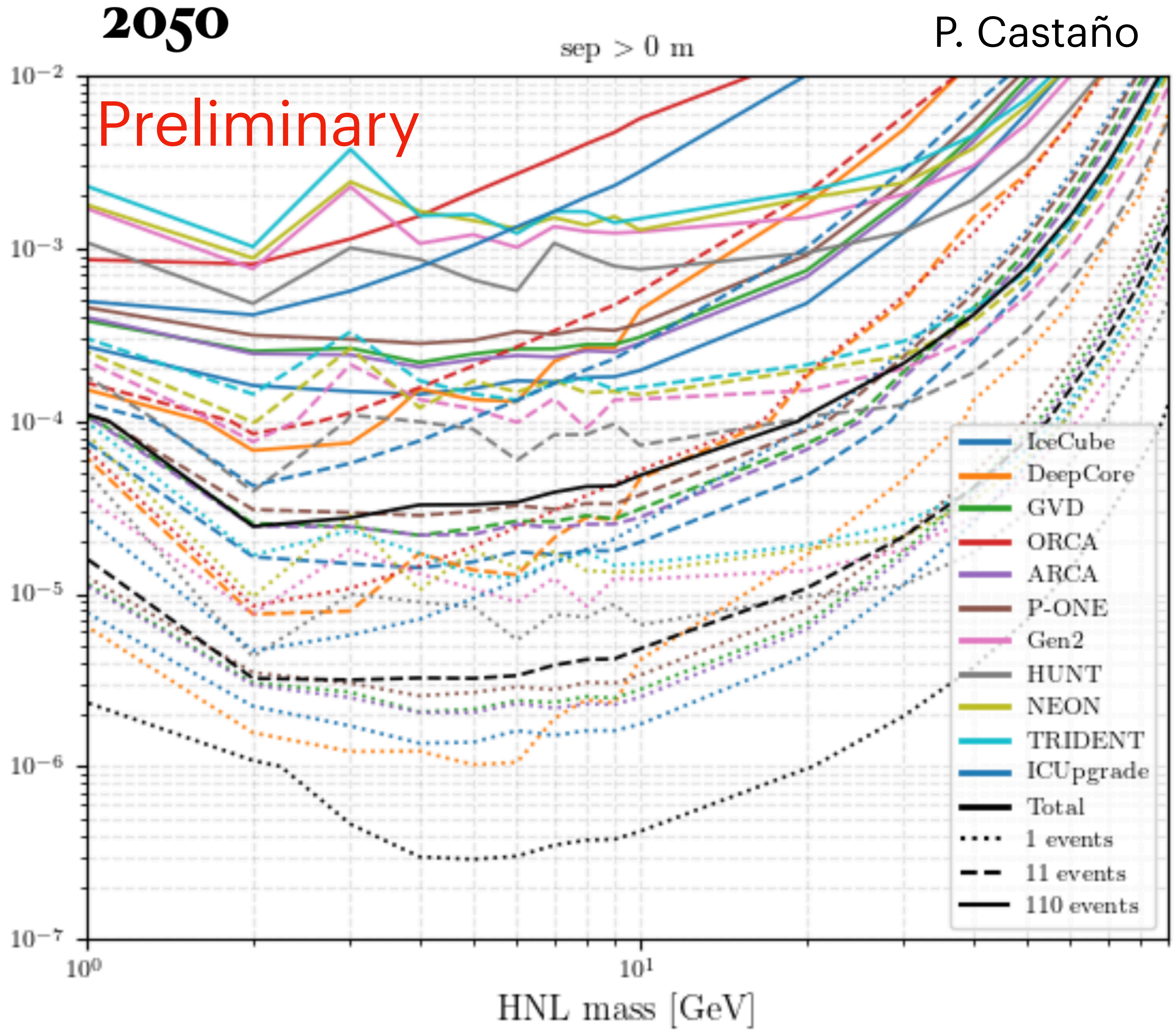
P. Castaño

We're also exploring HNL searches with di-muons at existing and future neutrino telescopes









Conclusion

- SIREN is an open-source simulation tool for neutrino physics
- We've used it to study:
  - Dipole-portal HNLs with accelerator neutrinos
  - New detectors for collider neutrinos
  - Charm-production and HNL signatures in neutrino telescopes

pip install siren

A. Schneider, NK, A. Wen. 2024

Next Steps for SIREN

- Support for standard geometry files like GDML (Chytracek+ 2006)
  - Thanks to S. Dolan and K. Mahn for coordinating public release of the official ND280 detector geometry
- Integration with more neutrino cross section models, including MARLEY (Gardiner 2021) and ACHILLES (Isaacson+ 2023)
- **If you have a favorite neutrino-portal model that has non-trivial dependence on detector geometry, let us know!**

pip install siren

A. Schneider, NK, A. Wen. 2024

Thanks