Simulating and Constraining Dark Neutrino Sectors

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The Outline

1. **Heavy Neutral Leptons**
2. **Transition Magnetic Moments**
    - MINERvA
3. **Dark photons and HNLs**
    - T2K near detector

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1. Heavy Neutral Leptons

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Type-I seesaw:

$$\mathscr{L} \supset -y^{\nu} \left(\overline{L}\tilde{H}\right) N - \frac{M_N}{2} \overline{N^c} N + \text{h.c.}$$

$$M_\nu \sim M_D M_N^{-1} M_D^T$$

(3x3) (3x?) (?x?) (?x3)

We know nothing about M_N:

- How many states?
- Does it carry new symmetries?
- New dynamics?

The seesaw mechanism

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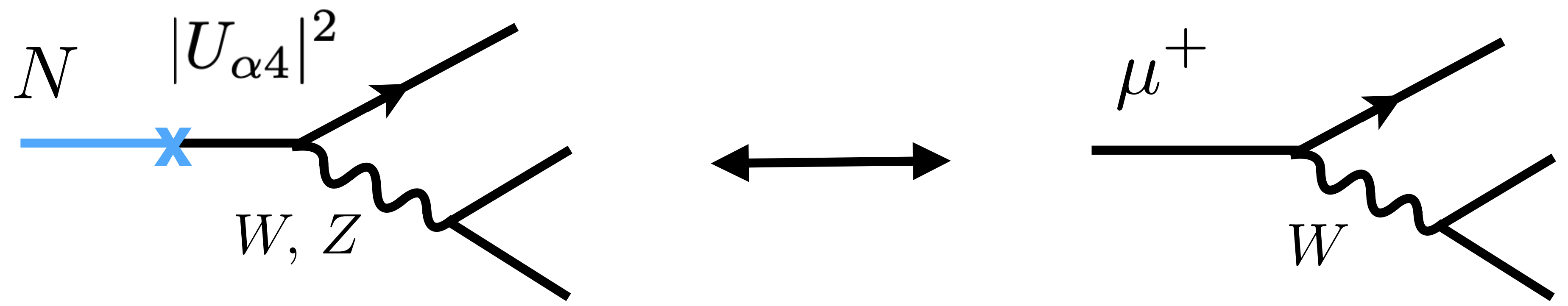
$$M_\nu \sim M_D M_N^{-1} M_D^T$$

(3x3) (3x?) (?x?) (?x3)

Phenomenology in minimal scenarios:

Typically, long-lived particles. $\frac{c\tau_\mu}{c\tau_N} \sim |U_{\alpha 4}|^2 \left(\frac{m_N}{m_\mu}\right)^5$



Production and decay proceed via **"weaker-than-weak"** interactions.

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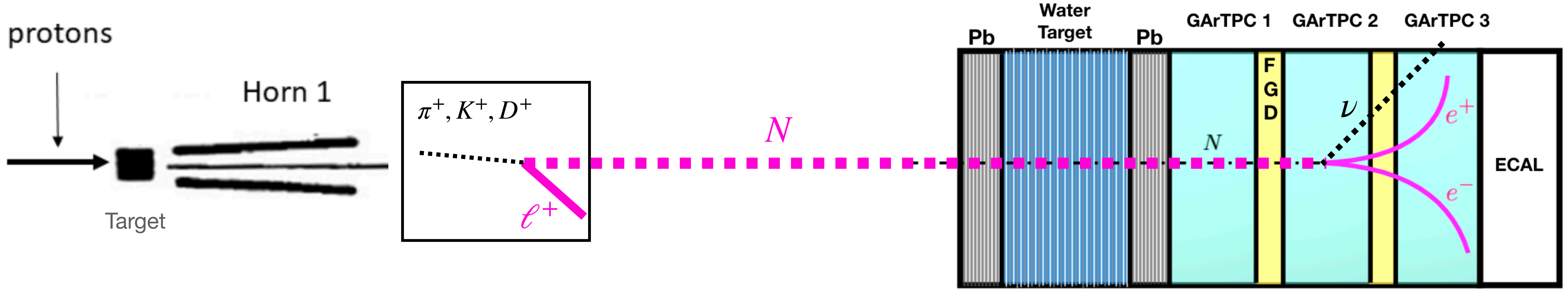
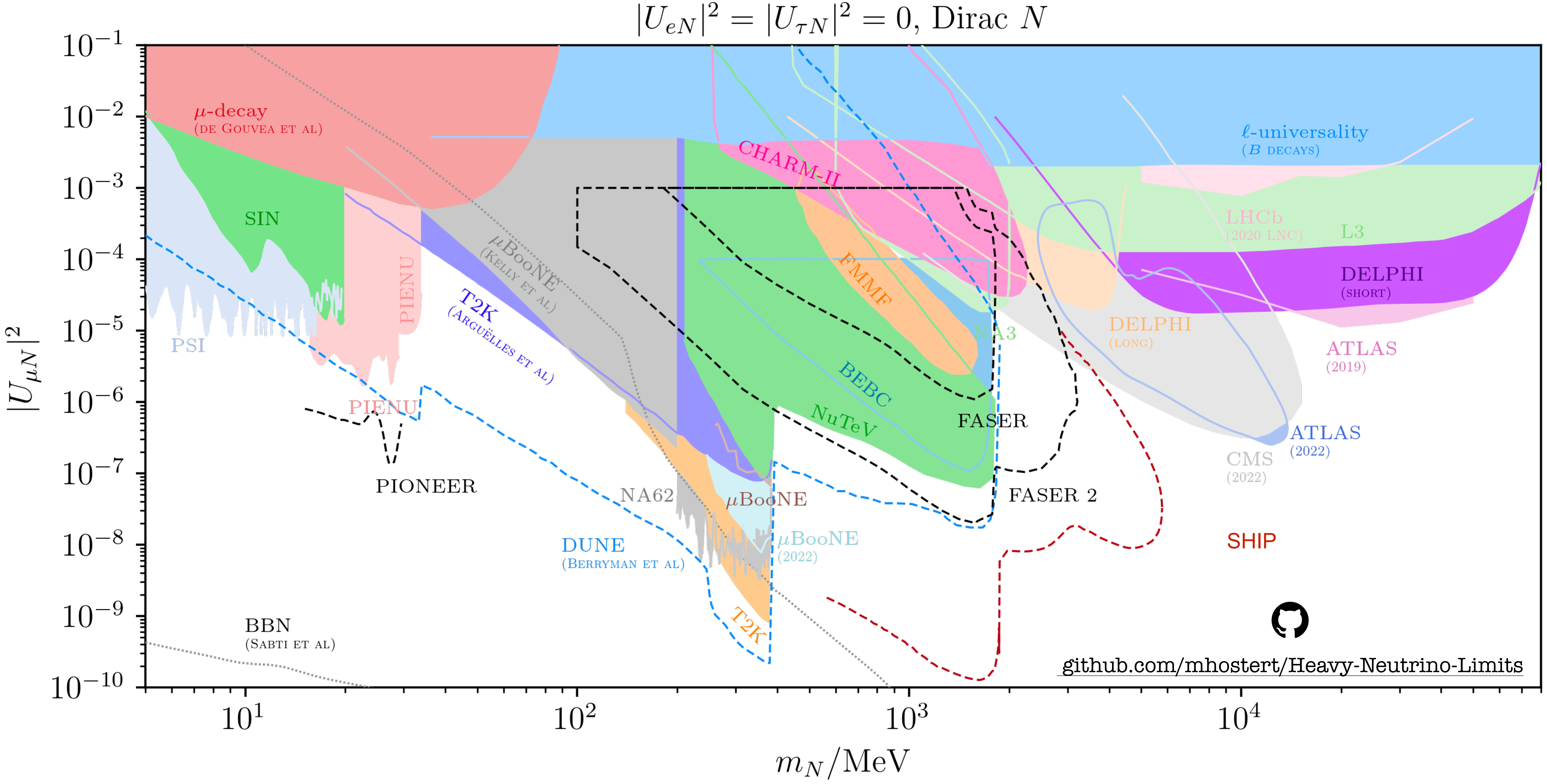
- New dynamics?



ND280 @T2K

Limits on heavy neutrinos



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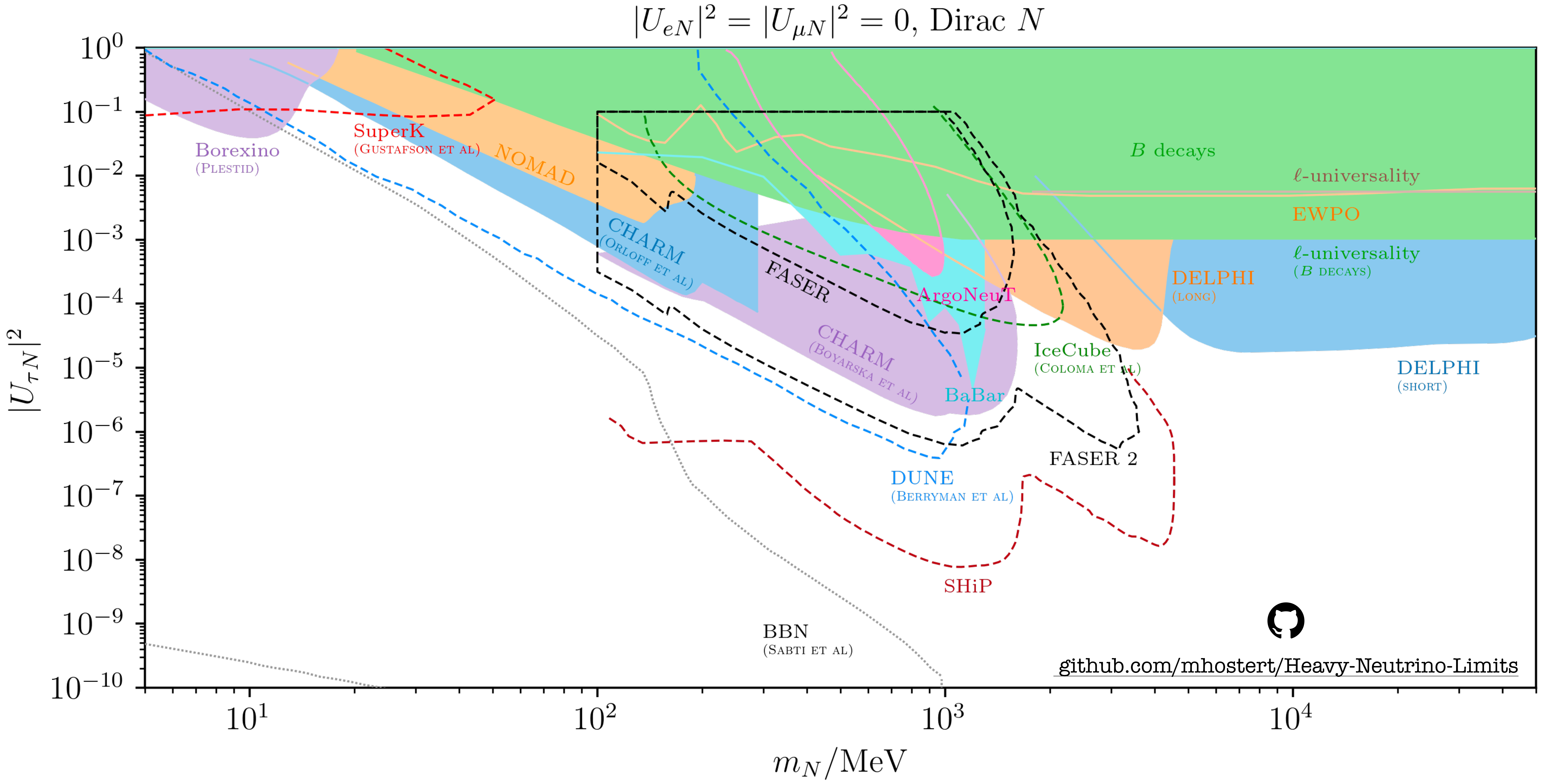
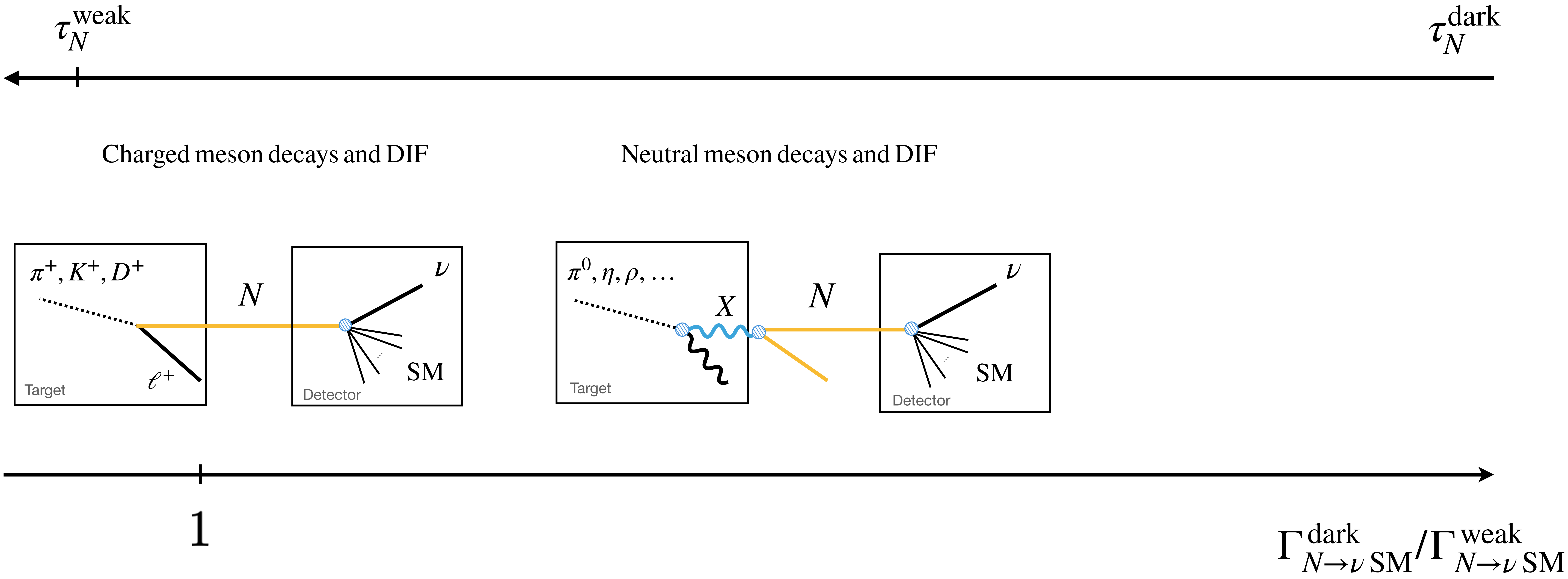


DARK SECTOR (DS)
$\overline{N^c}NS + \overline{N}\not{X}N$
May feel new secret forces…
$\overline{L}\widetilde{H}N$
Neutrino portal
$\frac{1}{\Lambda}\overline{\nu_\alpha}\sigma_{\mu\nu}F^{\mu\nu}N_R$
$\mathscr{L}_{\mathrm{SM}}$
$X_{\mu\nu}F^{\mu\nu}$
These can “leak” back to the SM.
Lifetimes would be much shorter.
Interactions can be comparable to Weak rates.
$|H|^2|S|^2$


$\tau_N^{\rm weak}$
$\tau_N^{\rm dark}$
Charged meson decays and DIF
π^+, K^+, D^+
N
ν
ℓ^+
SM
Target
Detector
1
$\Gamma^{\rm dark}_{N\to\nu\,\rm SM}/\Gamma^{\rm weak}_{N\to\nu\,\rm SM}$

Dark decay channels of HNLs



- Faster decays.
- CC branching ratios may be small, e.g., no $K^+ \to \mu^+\mu^+\pi^-$ even w/ large LNV.
- Missing energy.

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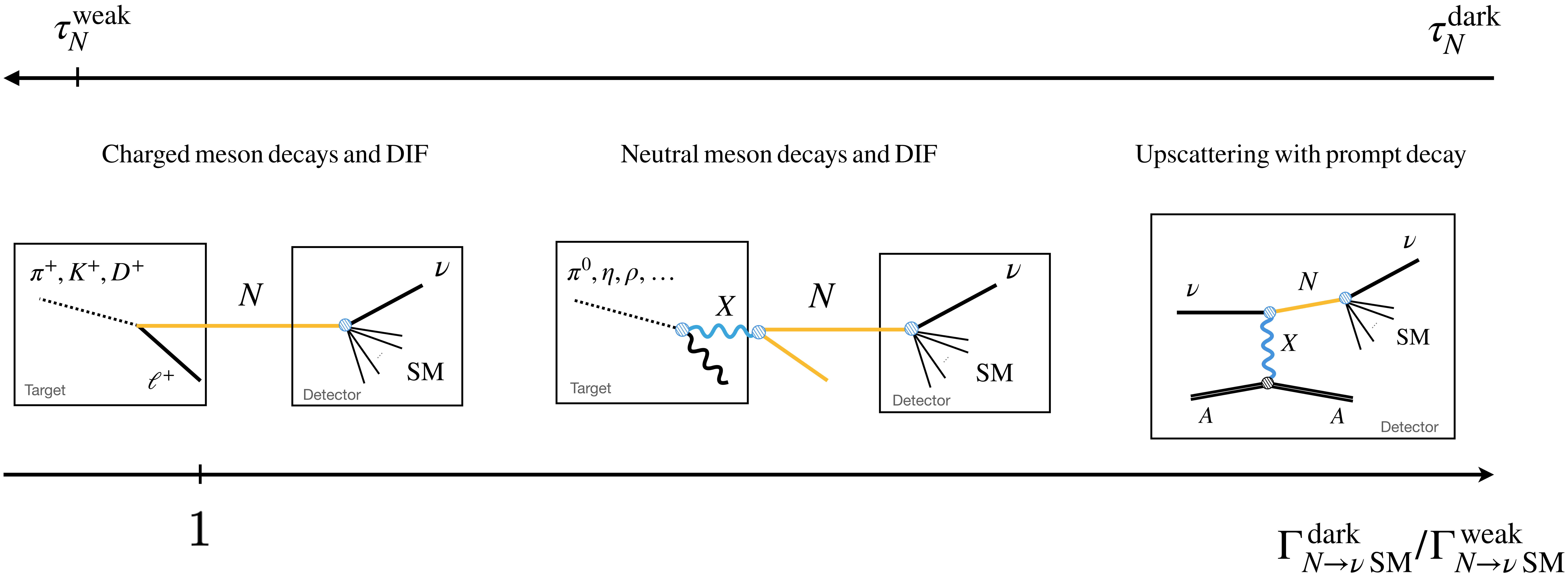

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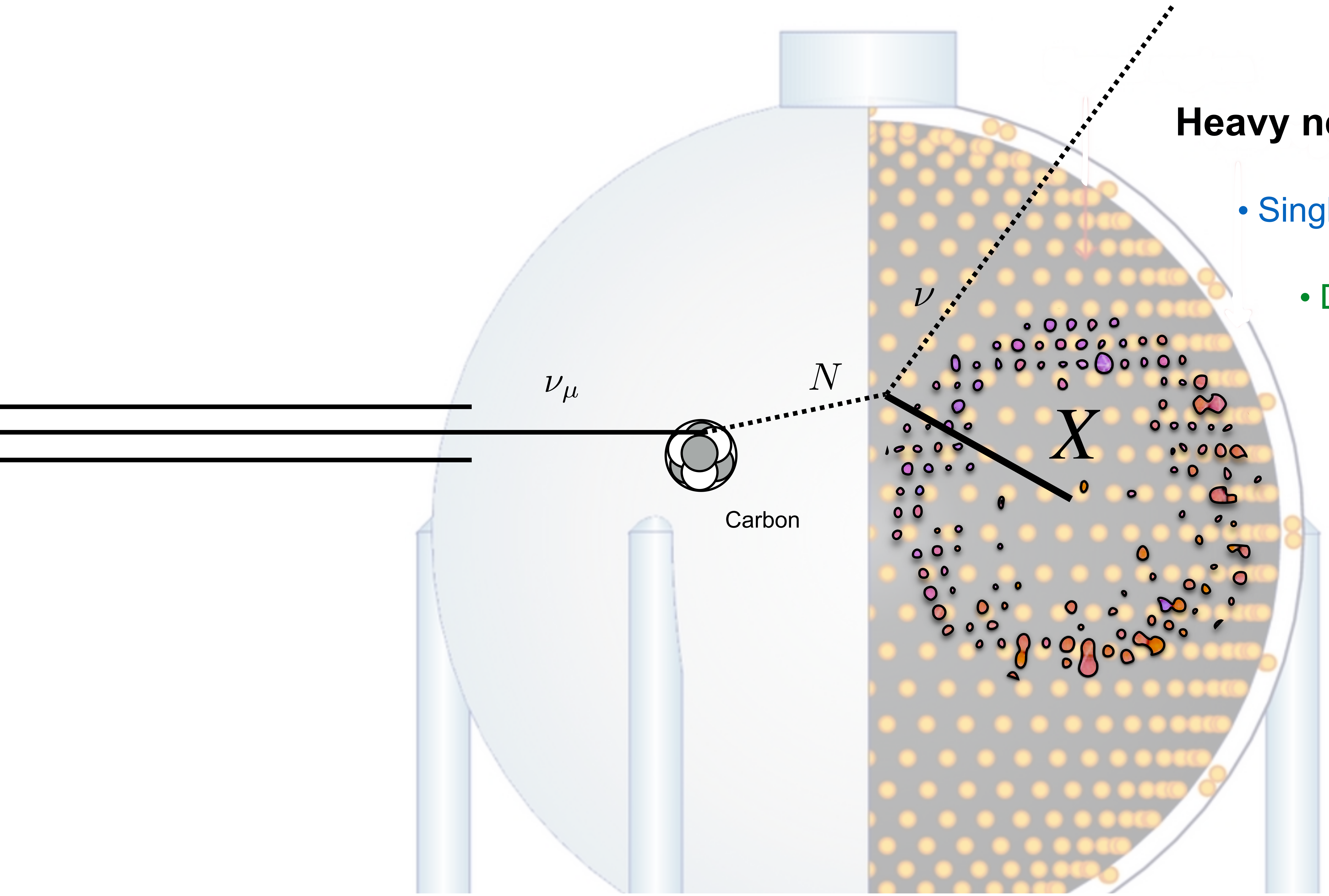
The MiniBooNE Low-Energy Excess
Particle production inside the detector



Heavy neutrino decays:

- Single photons via transition magnetic moment ($X = \gamma$)
- Di-leptons from dark photons or scalars ($X = e^+e^-$)
- Di-photons from dark scalars ($X = \gamma\gamma$)

NF02 White Paper: arXiv:2203.07323

Table of explanations of the short-baseline anomalies

Explored already

To be tested

These mostly involve production of new particles in the detector.

Category	Model	Signature	Anomalies: LSND	MiniBooNE	Reactors	Sources	References
Flavor transitions Secs. 3.1.1-3.1.3, 3.1.5	(3+1) oscillations	oscillations	✓	✓	✓	✓	Reviews and global fits [93, 103, 105, 106]
	(3+1) w/ invisible sterile decay	oscillations w/ ν_4 invisible decay	✓	✓	✓	✓	[151, 155]
	(3+1) w/ sterile decay	$\nu_4 \to \phi \nu_e$	✓	✓	✓	✓	[159–162, 270]
Matter effects Secs. 3.1.4, 3.1.7	(3+1) w/ anomalous matter effects	$\nu_\mu \to \nu_e$ via matter effects	✓	✓	✗	✗	[143, 147, 271–273]
	(3+1) w/ quasi-sterile neutrinos	$\nu_\mu \to \nu_e$ w/ resonant ν_s matter effects	✓	✓	✓	✓	[148]
Flavor violation Sec. 3.1.6	Lepton-flavor-violating μ decays	$\mu^+ \to e^+ \nu_\alpha \overline{\nu_e}$	✓	✗	✗	✗	[174, 175, 274]
	neutrino-flavor-changing bremsstrahlung	$\nu_\mu A \to e \phi A$	✓	✓	✗	✗	[275]
Decays in flight Sec. 3.2.3	Transition magnetic mom., heavy ν decay	$N \to \nu\gamma$	✗	✓	✗	✗	[207]
	Dark sector heavy neutrino decay	$N \to \nu(X \to e^+e^-)$ or $N \to \nu(X \to \gamma\gamma)$	✗	✓	✗	✗	[208]
Neutrino Scattering Secs. 3.2.1, 3.2.2	neutrino-induced upscattering	$\nu A \to N A$, $N \to \nu e^+ e^-$ or $N \to \nu\gamma\gamma$	✓	✓	✗	✗	[205, 206, 209–216]
	neutrino dipole upscattering	$\nu A \to N A$, $N \to \nu\gamma$	✓	✓	✗	✗	[40, 185, 187, 188, 190, 193, 233, 276]
Dark Matter Scattering Sec. 3.2.4	dark particle-induced upscattering	γ or e^+e^-	✗	✓	✗	✗	[217]
	dark particle-induced inverse Primakoff	γ	✓	✓	✗	✗	[217]

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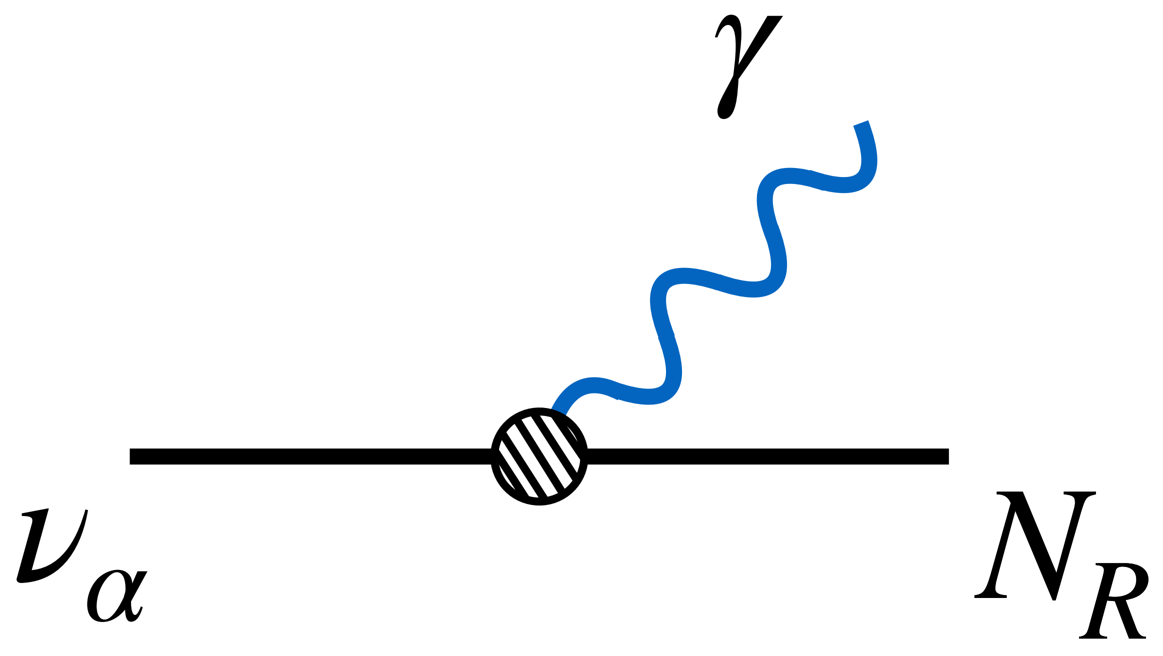
Transition magnetic moment
The model

Dimension-5 operator

$$\mathscr{L} \supset \frac{1}{\Lambda^2}\overline{L}\tilde{H}\sigma^{\mu\nu}N_R\left(C_B^\alpha\, B_{\mu\nu} + C_W^\alpha\, W^a_{\mu\nu}\sigma_a\right) \xrightarrow{\text{EWSB}} \mathscr{L} \supset d_{\alpha N}\,\overline{\nu_\alpha}\sigma_{\mu\nu}F^{\mu\nu}N_R$$



Transition magnetic moment == Dipole portal

Transition magnetic moment
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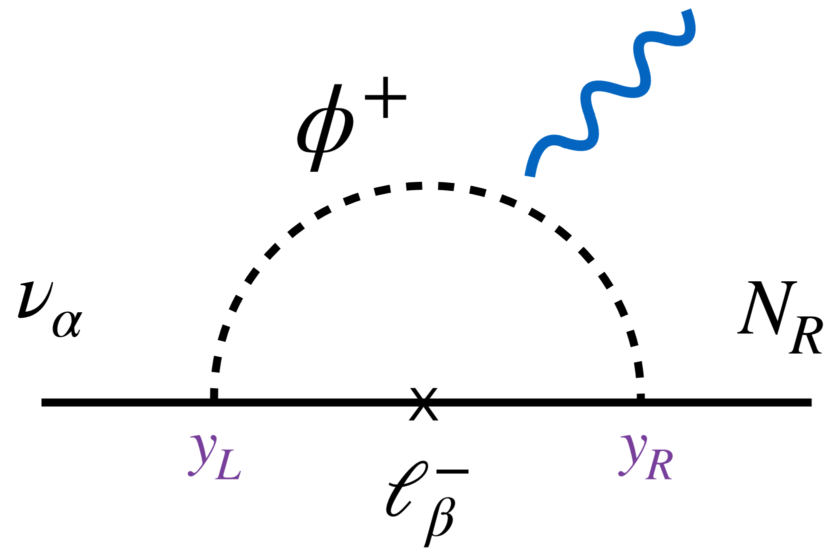
Points to keep in mind:



$$d_{\alpha N} \sim \frac{e\,y_L y_R}{16\pi^2}\frac{m_{\ell_\beta}}{m_\phi^2}$$

$$m_D \sim \frac{y_L y_R}{16\pi^2}m_{\ell_\beta} \longrightarrow U_{\alpha N} \sim \frac{m_D}{M_N}$$

1) Large transition magnetic moments generically lead to large Dirac masses.

One has to do extra work to avoid mixing between ν_α and HNLs.

Can decouple the two with Horizontal symmetries, Voloshin, M. B., Sov. J. Nucl. Phys. 48, 512 (1988).

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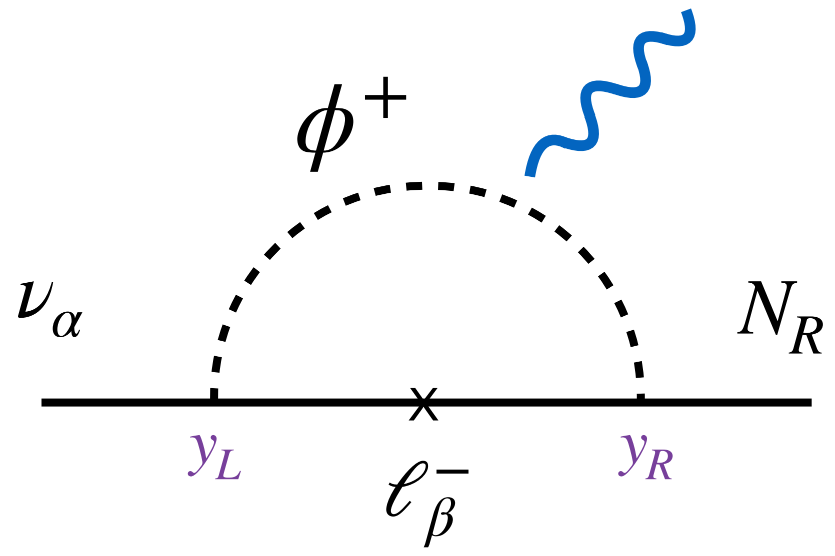

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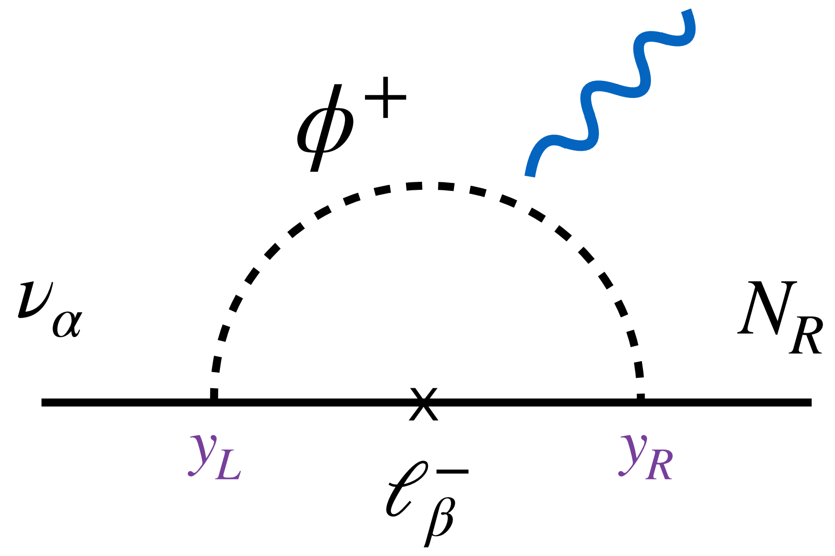

$$d_{\alpha N} \sim \frac{e\,y_L y_R}{16\pi^2}\frac{m_{\ell_\beta}}{m_\phi^2} \longrightarrow d_{\mu N} \sim 1\,\mathrm{PeV}^{-1} \longrightarrow m_\phi \sim \mathcal{O}(100\,\mathrm{GeV})$$

For, e.g., $\ell_\beta = \tau$

$$m_D \sim \frac{y_L y_R}{16\pi^2}m_{\ell_\beta} \longrightarrow U_{\alpha N} \sim \frac{m_D}{M_N} \longrightarrow 0$$

2) For values of interest, probably need some heavy particle inside the loop. May be τ or something else completely.

See also *Brdar et al 2007.15563* for an interesting leptoquark model with b-quarks in the loop.

Transition magnetic moment
The model

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Dimension-5 operator

Points to keep in mind:

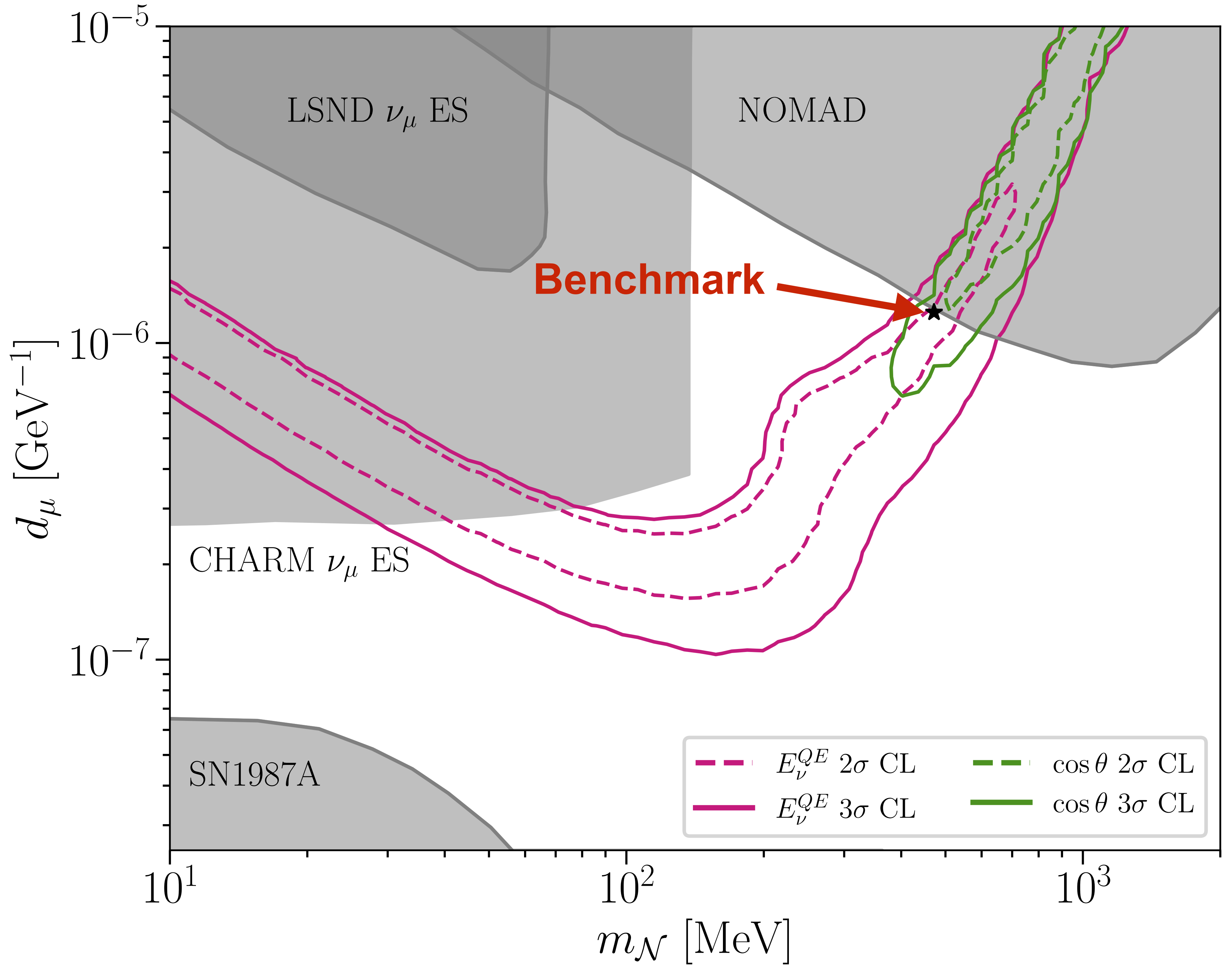
For **flavor-blind** and **flavor-conserving** ($\alpha = \beta$) new physics, we expect:

$$\frac{d_{eN}}{m_e} \simeq \frac{d_{\mu N}}{m_\mu} \simeq \frac{d_{\tau N}}{m_\tau}$$

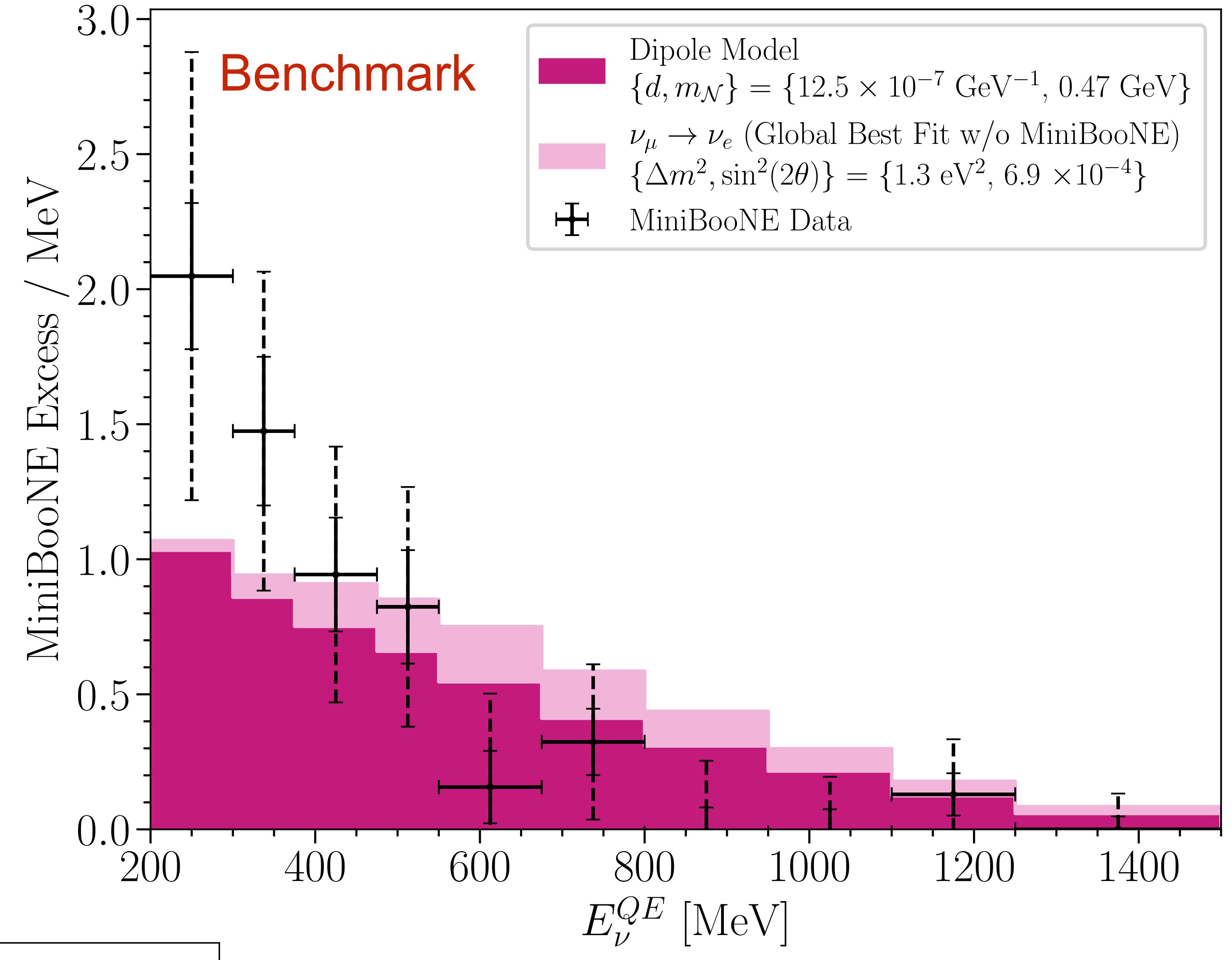
3) τ flavor seems like an interesting possibility to consider.

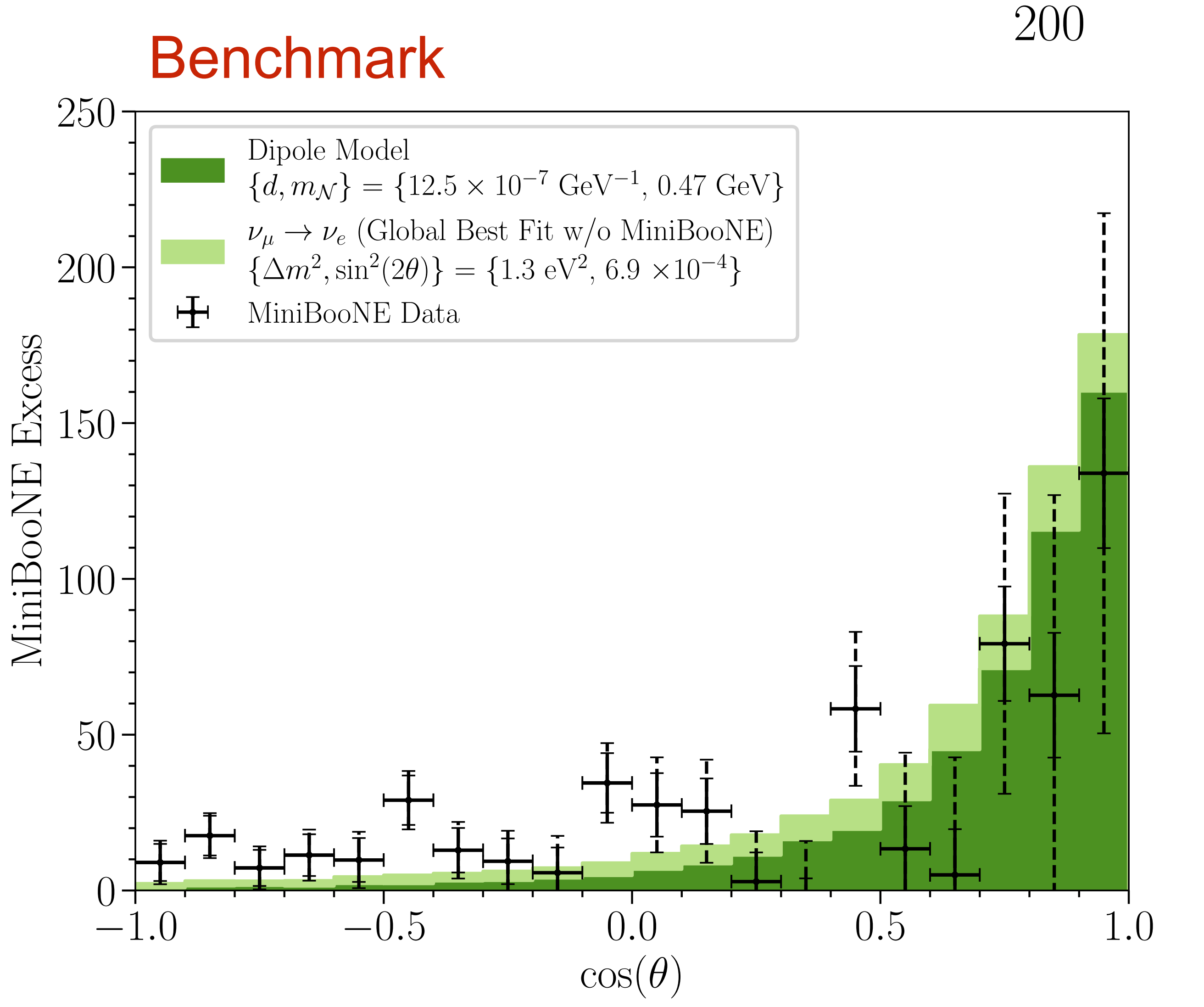
Transition magnetic moment
MiniBooNE region of interest

N. Kamp, M. Hostert, A. Schneider, S. Vergani, C. A. Argüelles, J. M. Conrad, M. H. Shaevitz, and M. Uchida, arXiv:2206.07100



We also added eV-sterile oscillations on top of the dipole using the global best-fit point from Vergani et al.





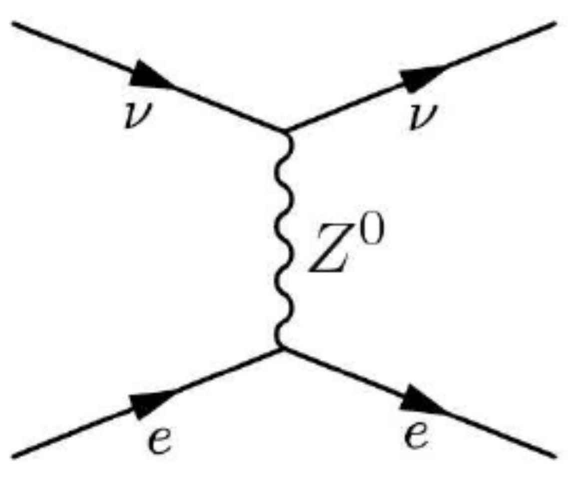
Performed a fit to the MiniBooNE low-energy excess.

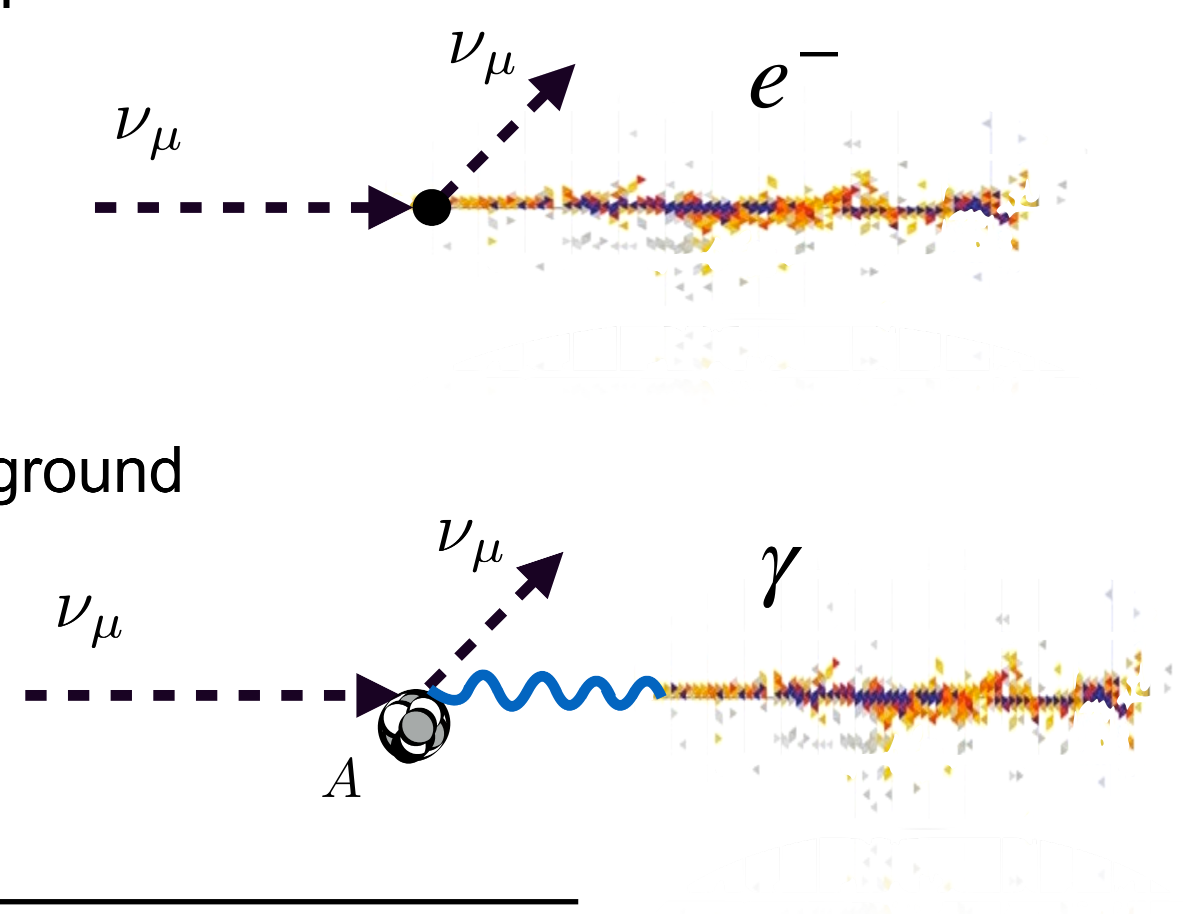
Updates previous fit in Vergani et al arXiv:2105.06470 with a detector simulation in **LeptonInjector** and coherent upscattering cross-sections from **DarkNews** with improved nuclear form factors (see later).

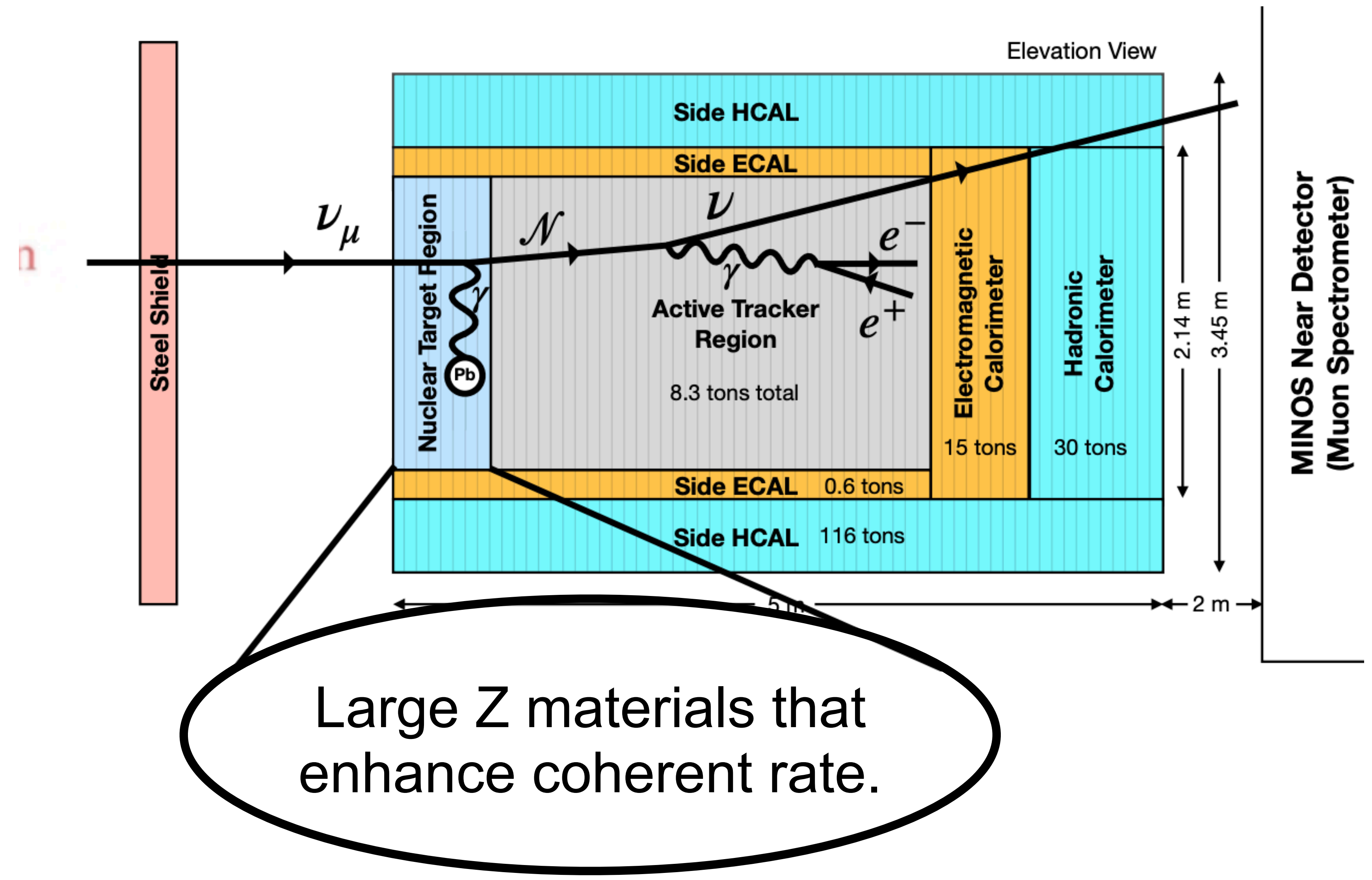
Angular and energy spectrum fits overlap only at the largest m_N values.

Transition magnetic moment
MINERvA limits from $\nu - e$ scattering measurement

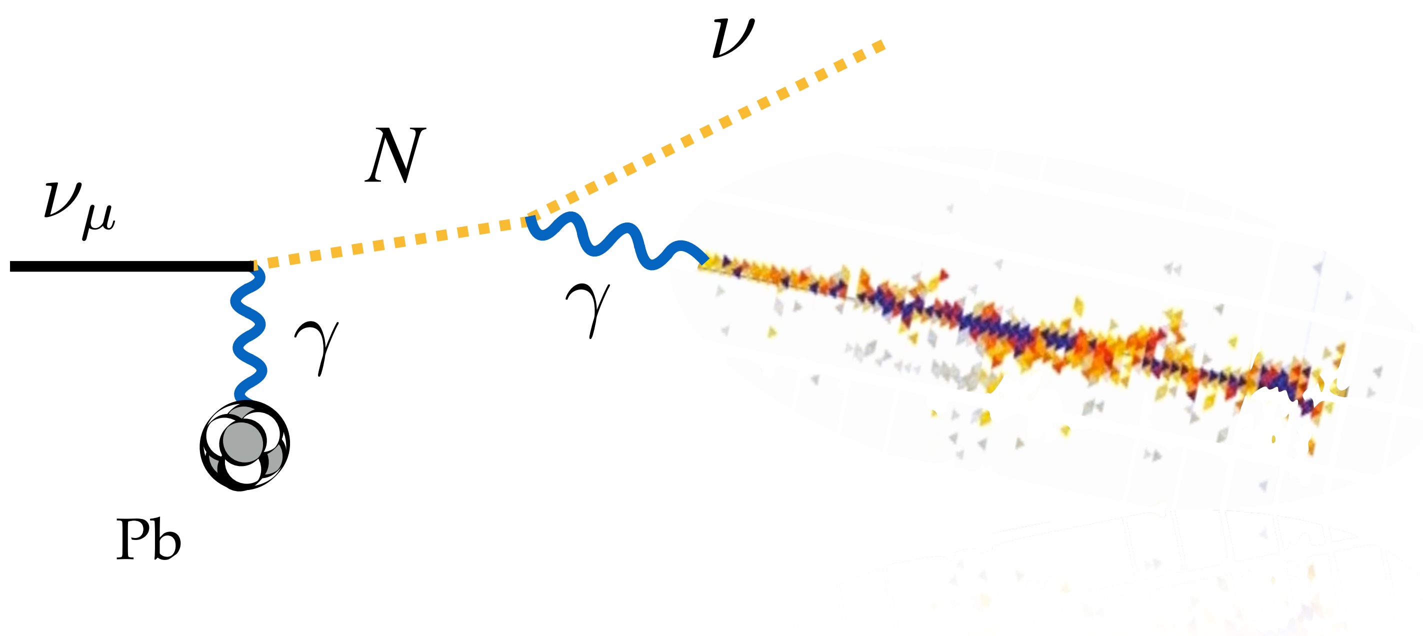
Neutrino-electron scattering

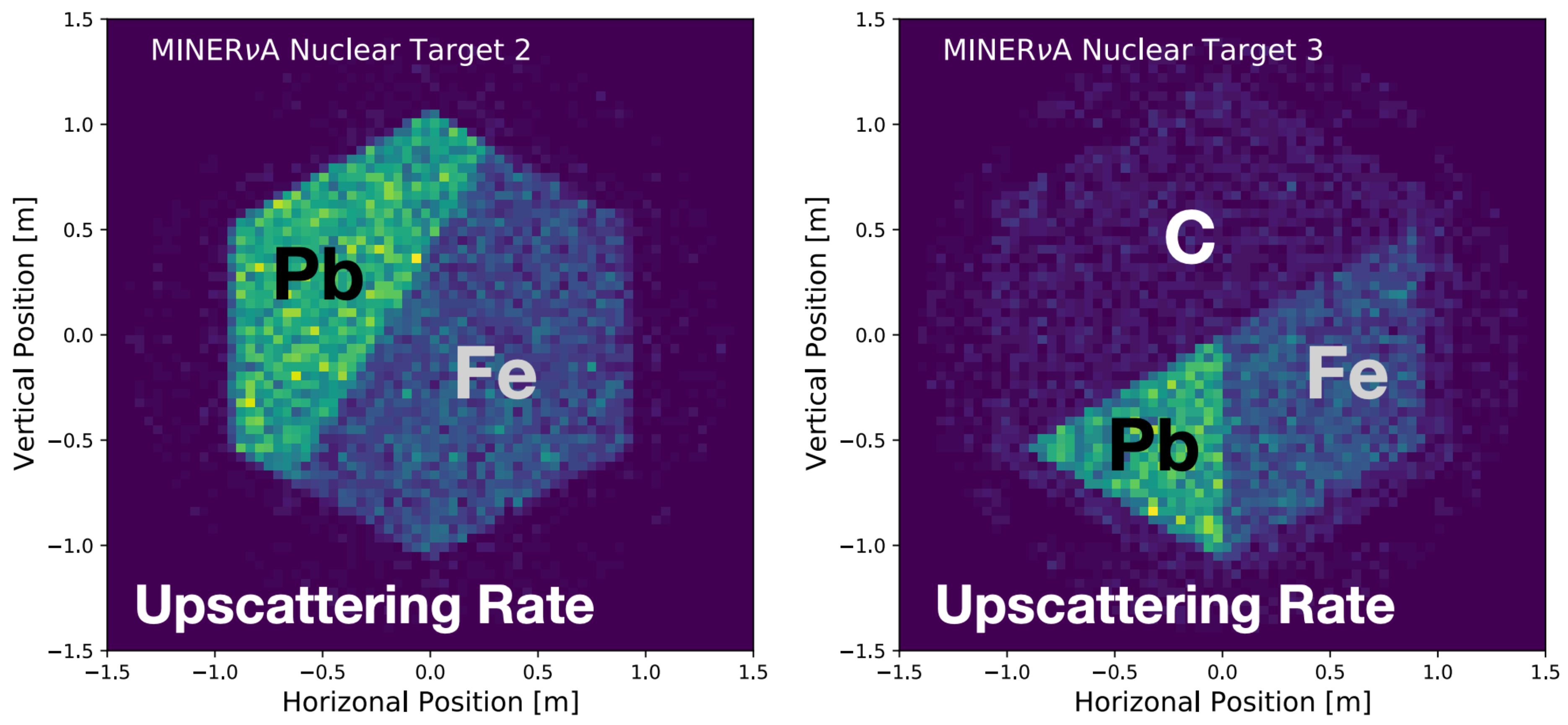






Neutrino-nucleus coherent scattering and HNL decay

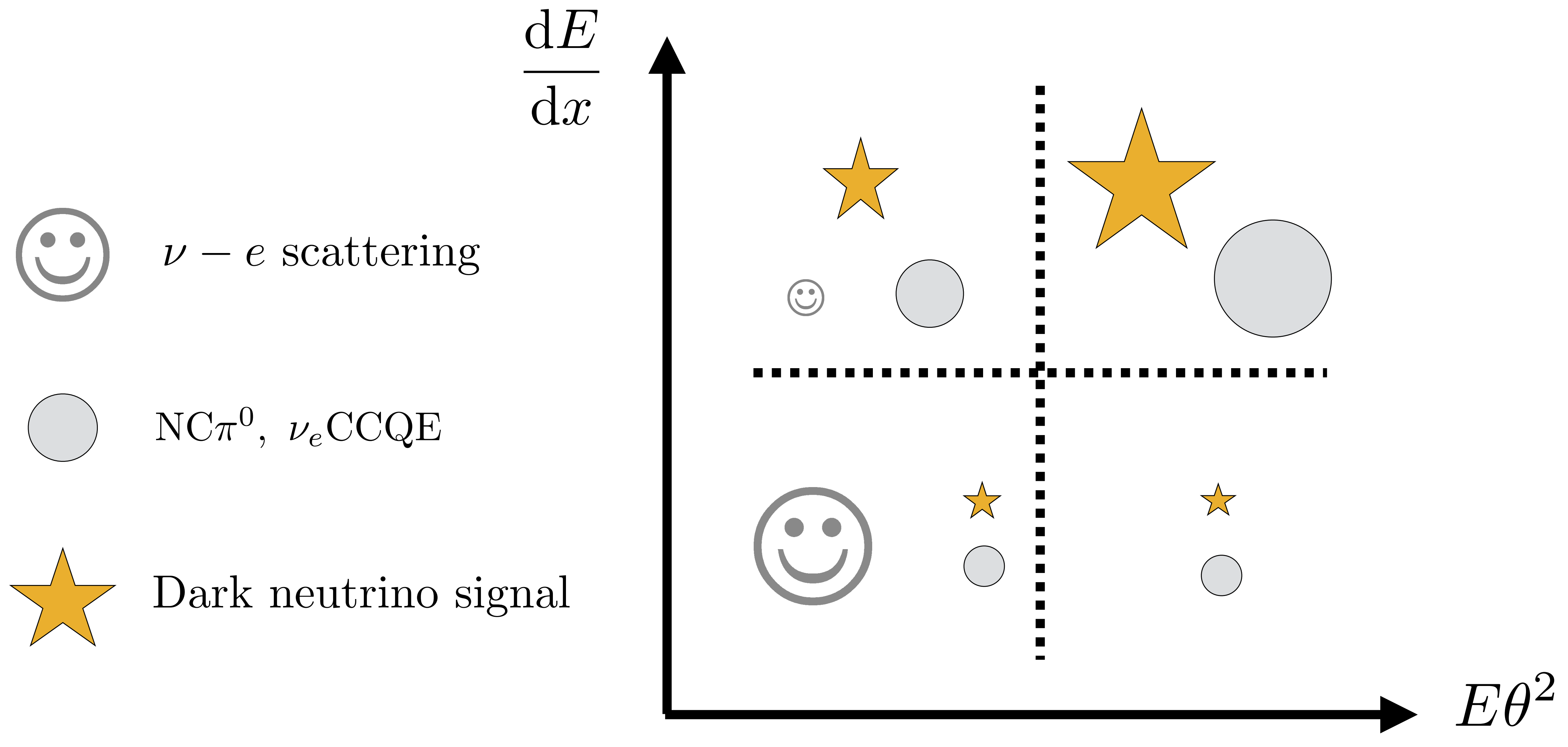




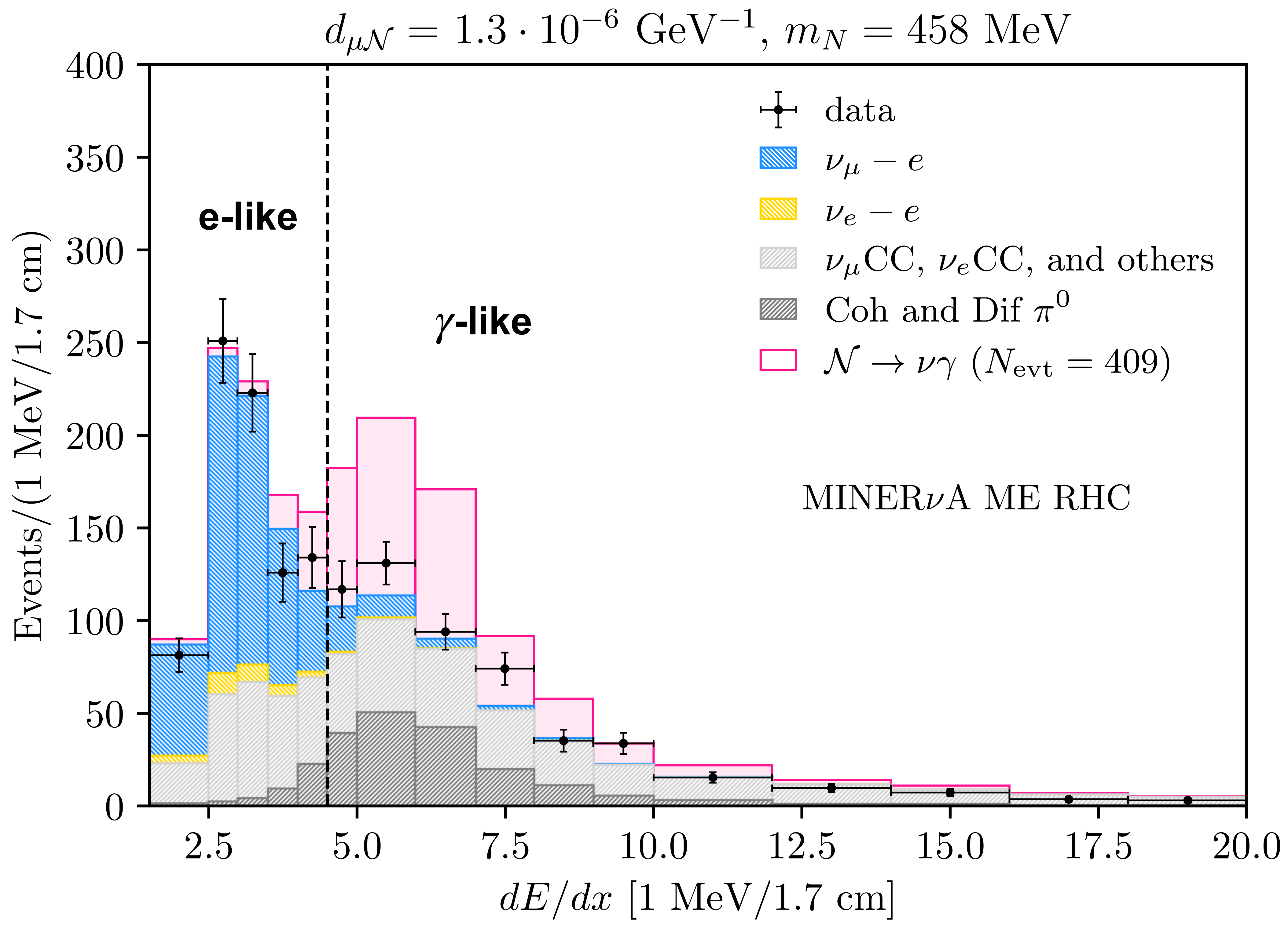
Transition magnetic moment

MINERvA limits from $\nu - e$ scattering measurement

N. Kamp, M. Hostert, A. Schneider, S. Vergani, C. A. Argüelles, J. M. Conrad, M. H. Shaevitz, and M. Uchida, arXiv:2206.07100



Using photon-like sample of the **MINERvA** antineutrino-electron scattering analysis.



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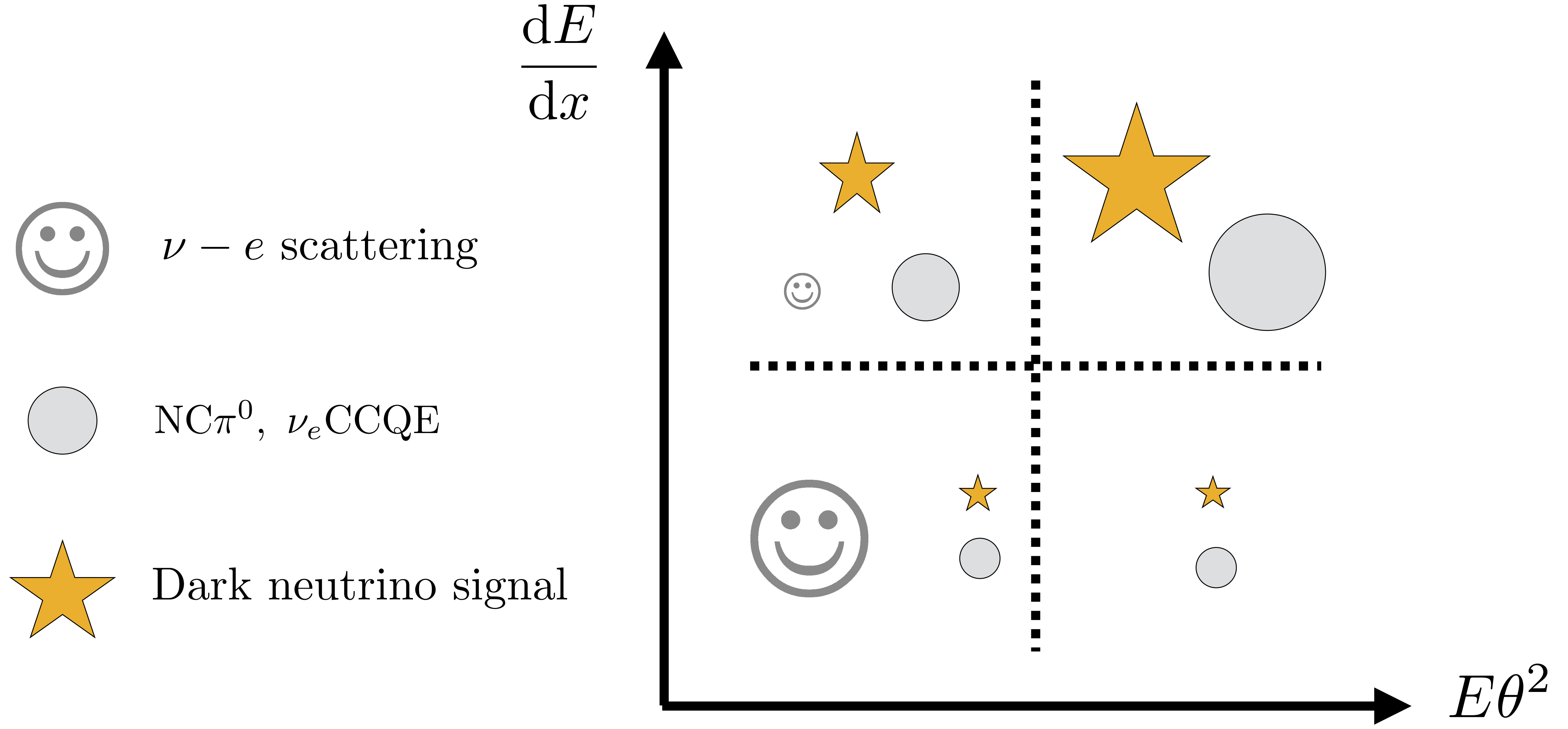
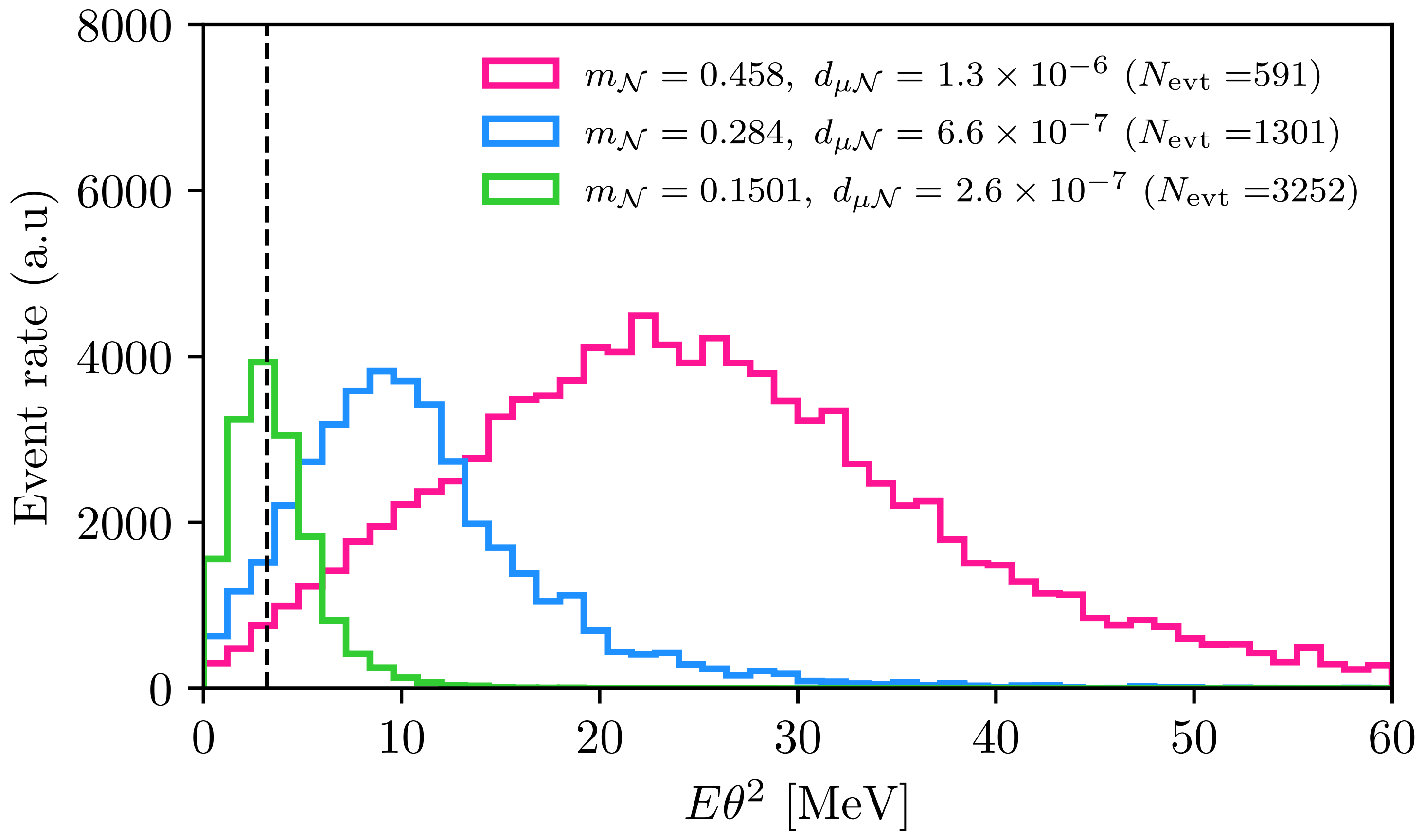




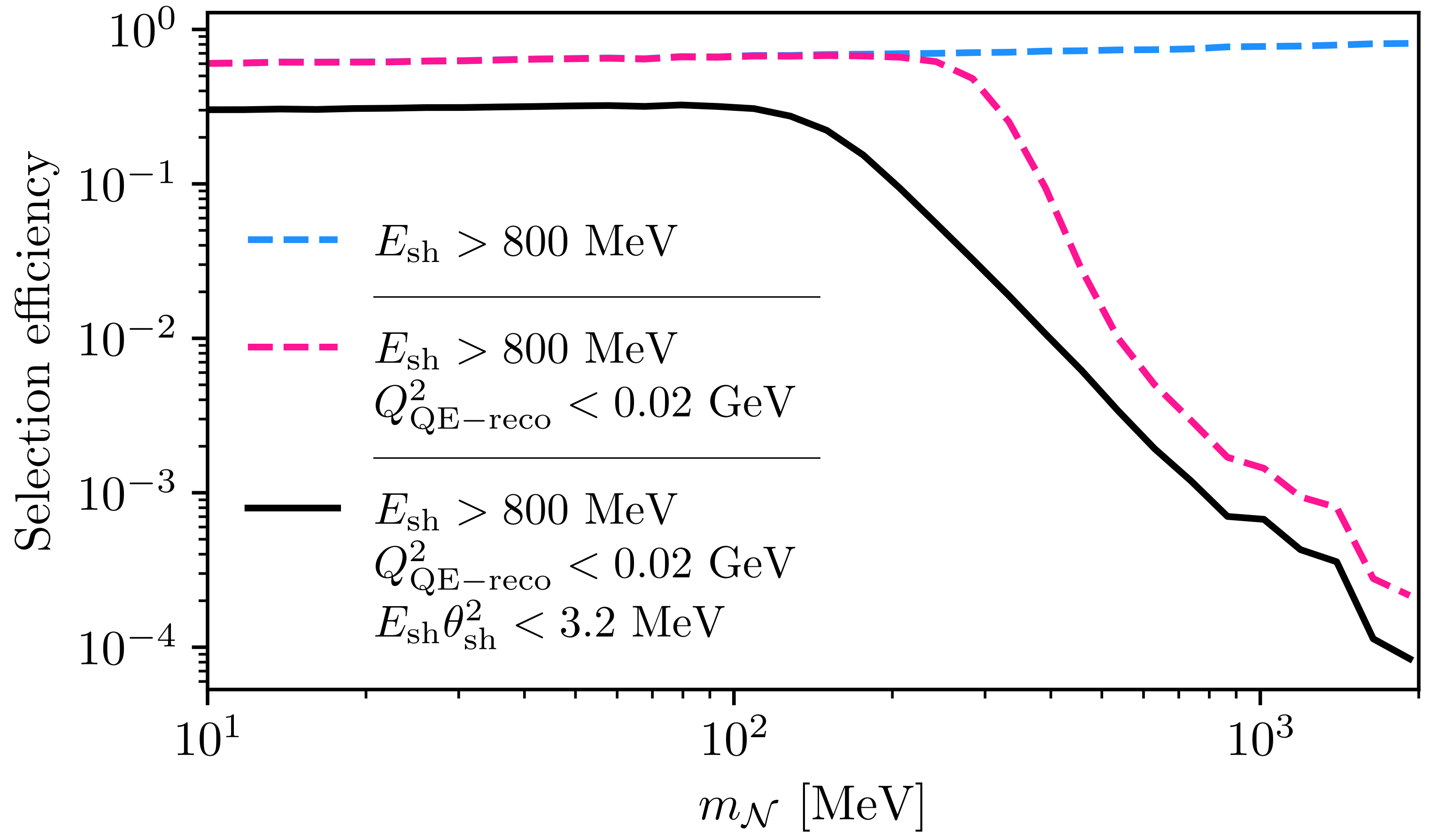
MINERvA uses the fact that

$$E\theta^2 < 2m_e$$

for $\nu - e$ scattering.

This hurts us badly,

but there are a huge number of N that decay inside the volume of the analysis.



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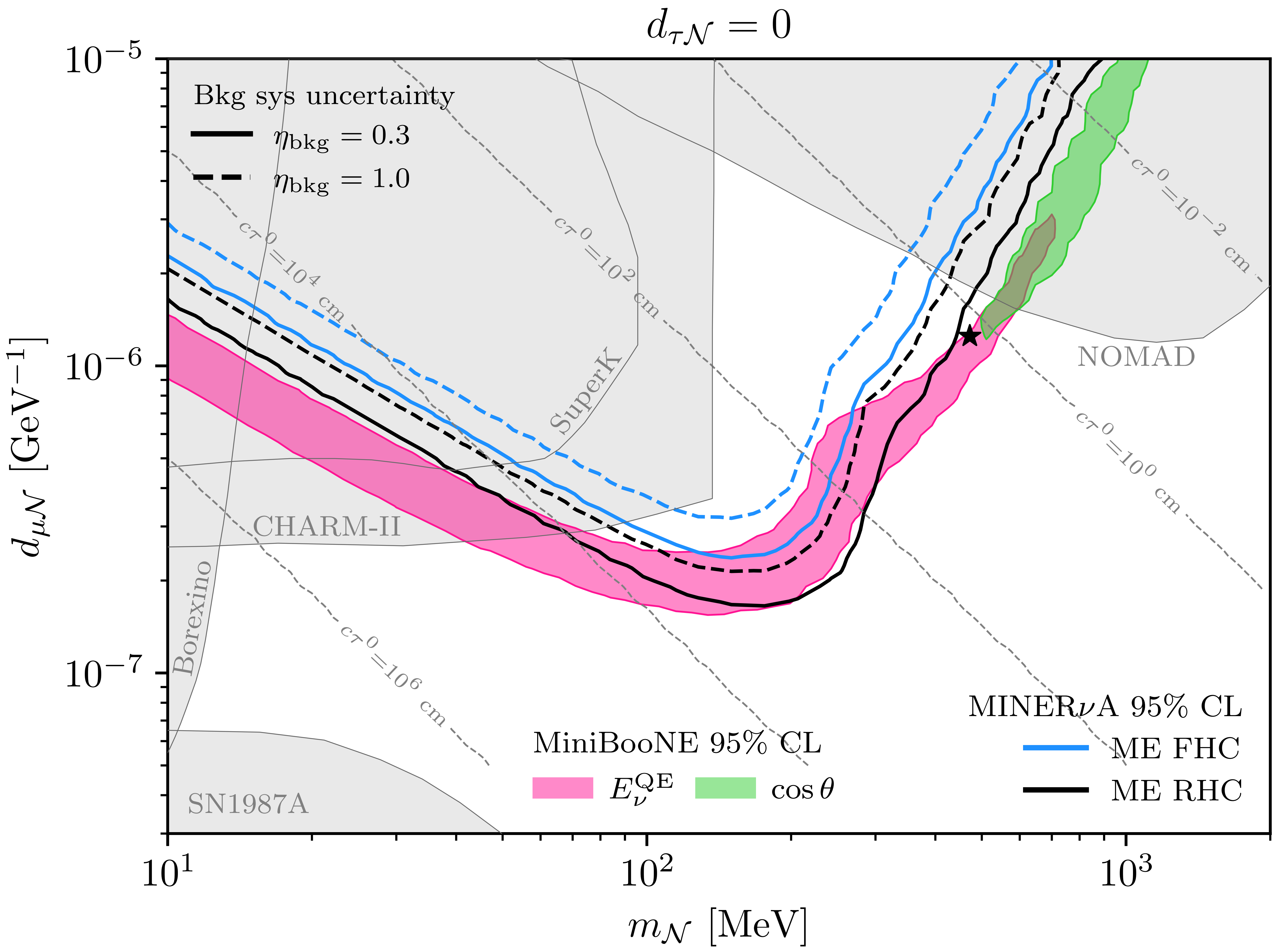

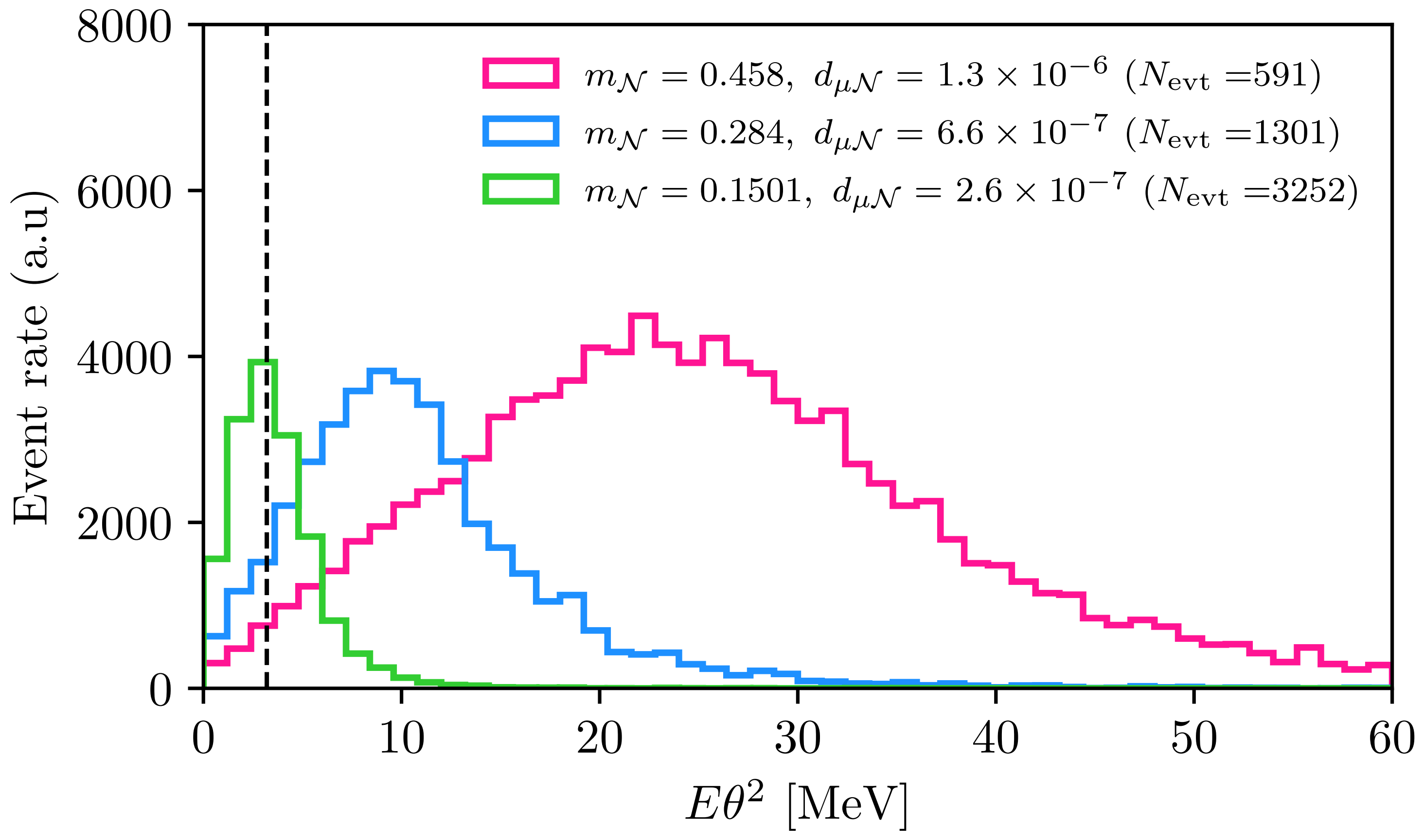

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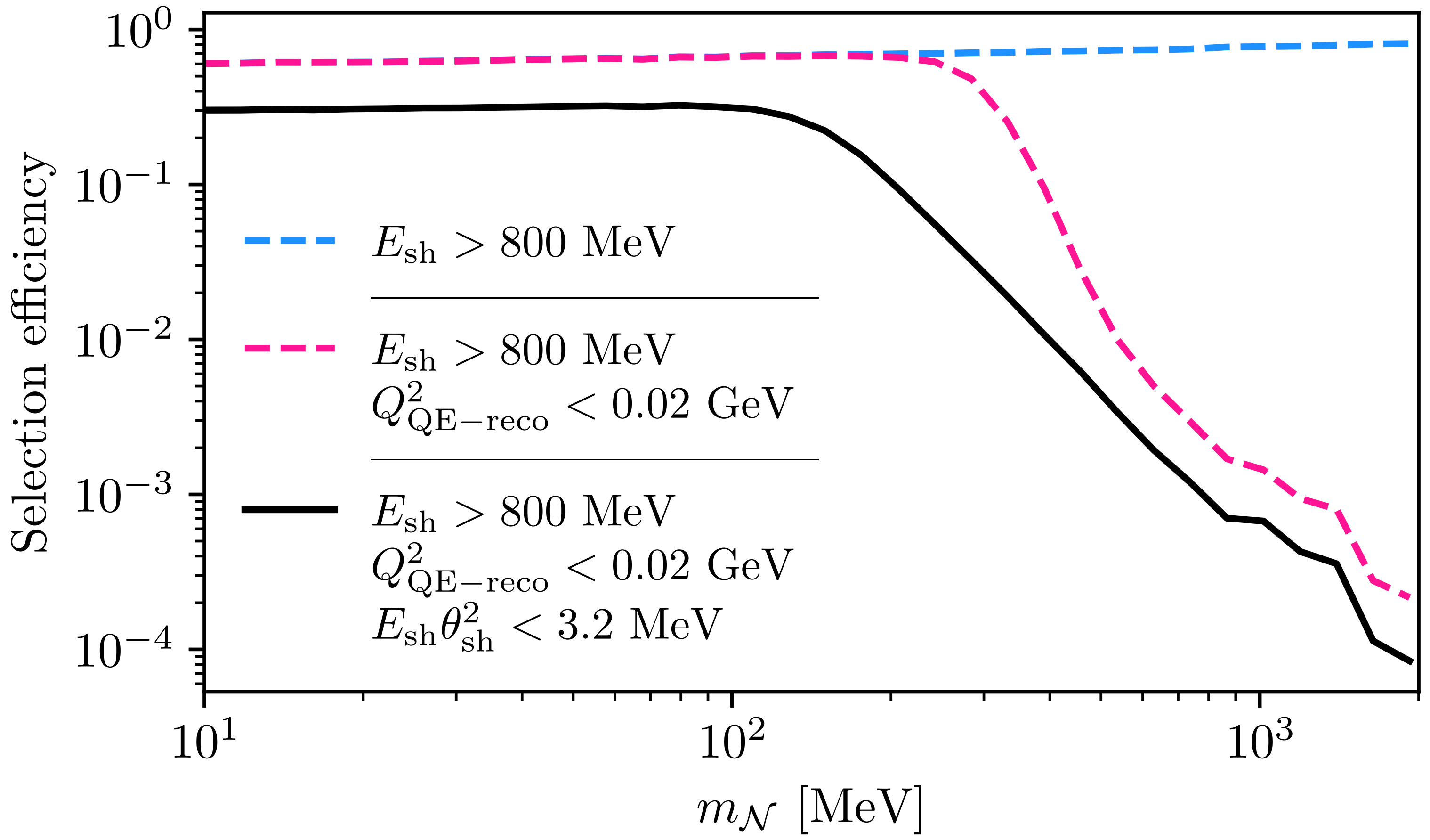

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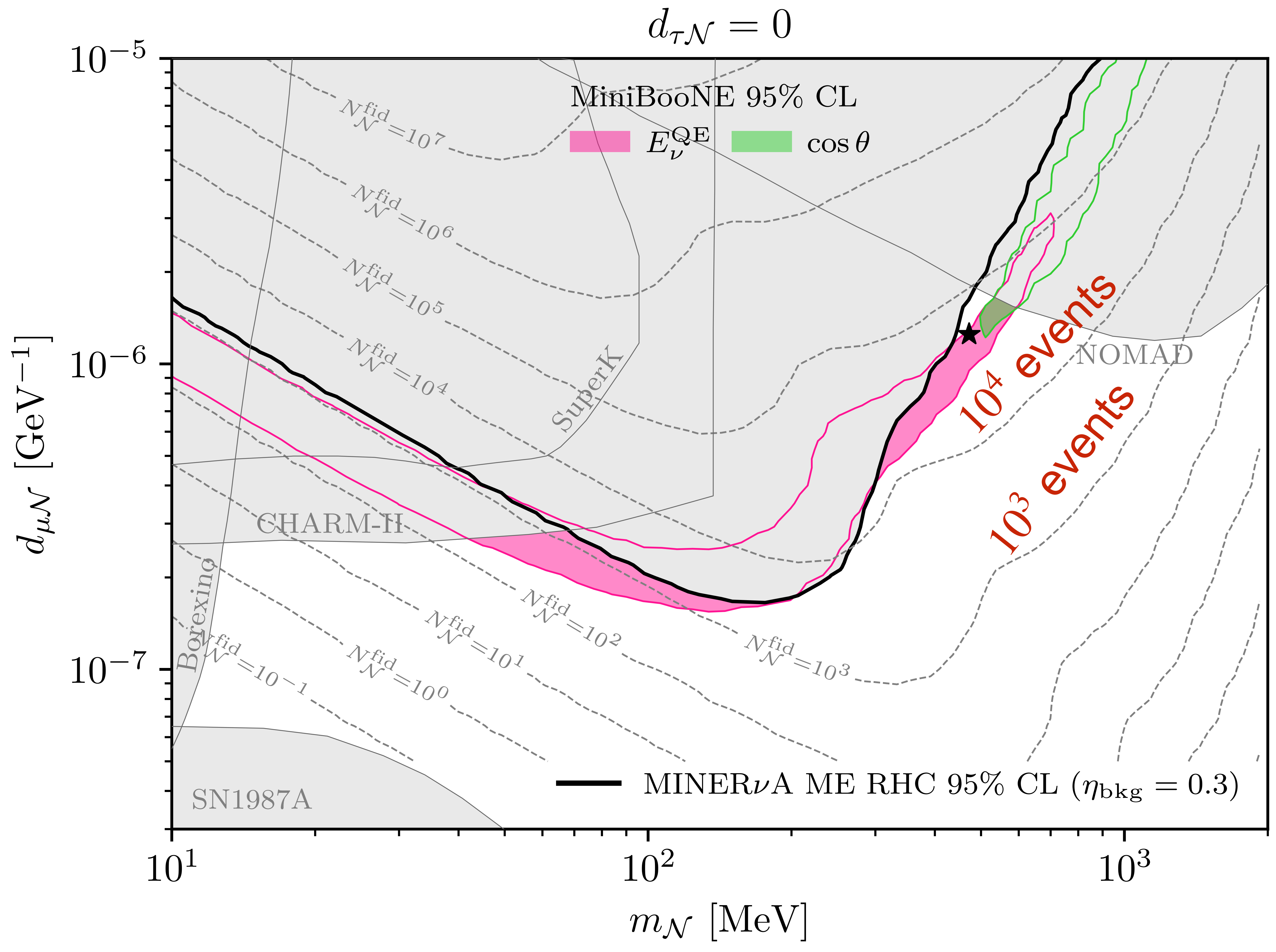

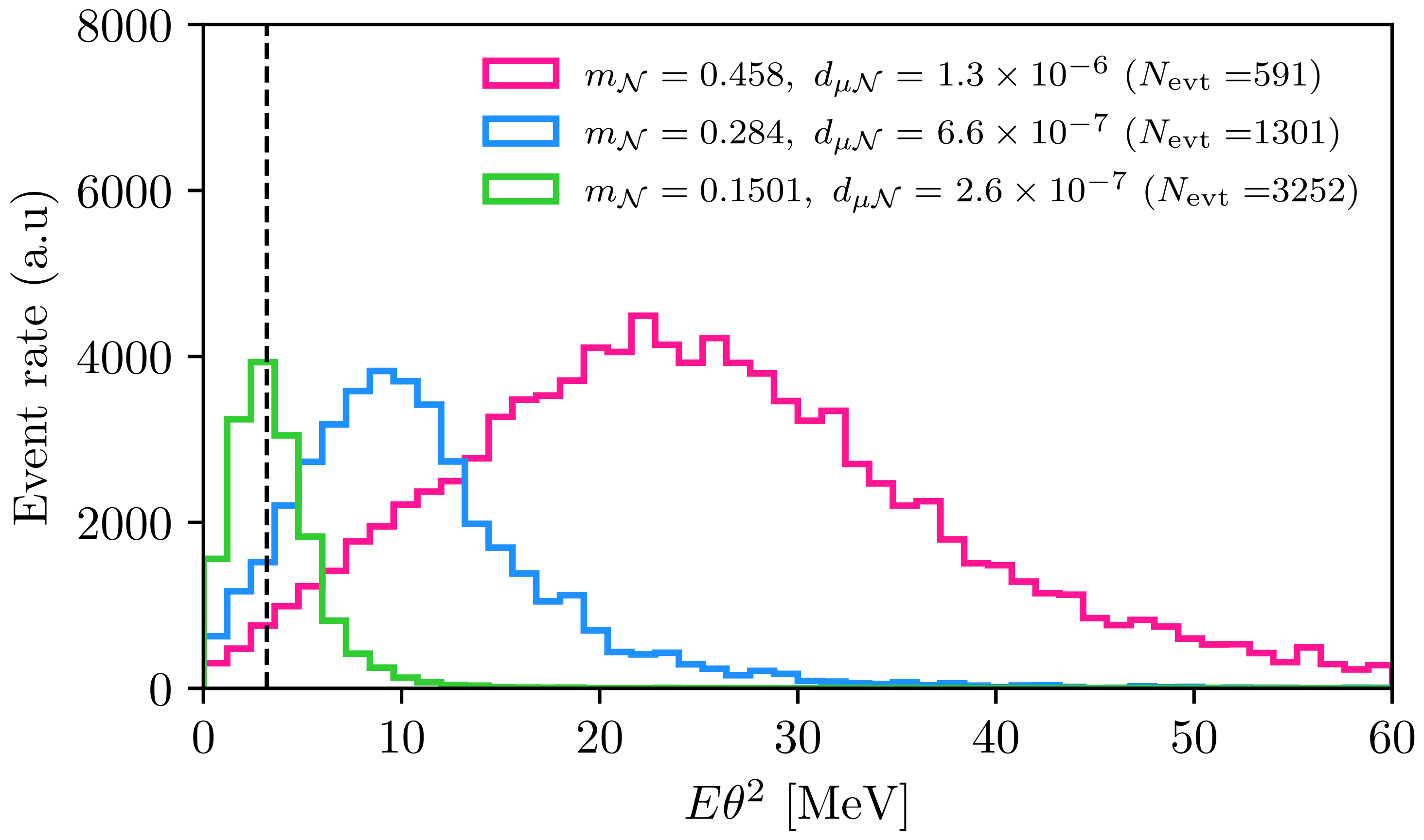

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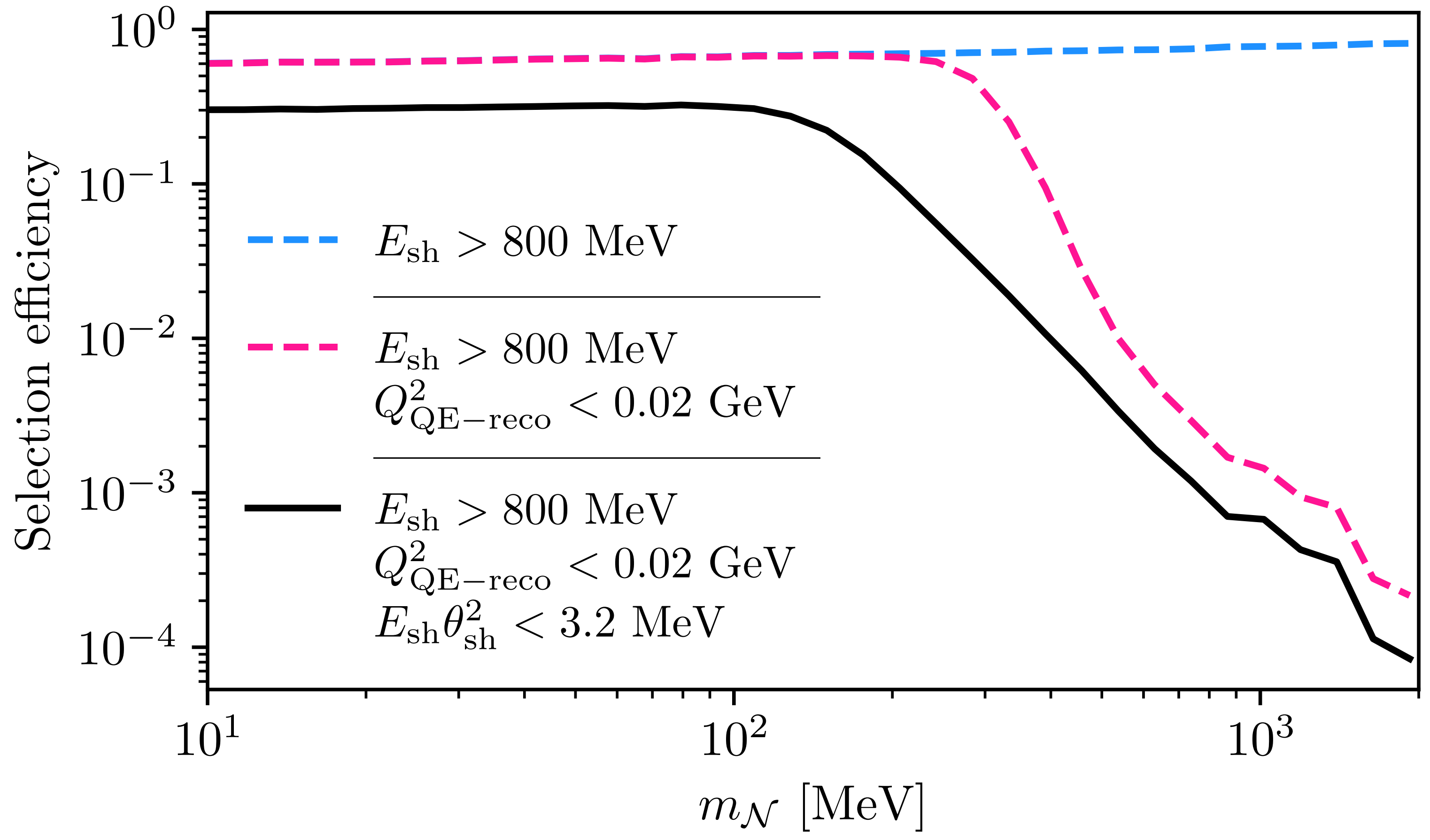

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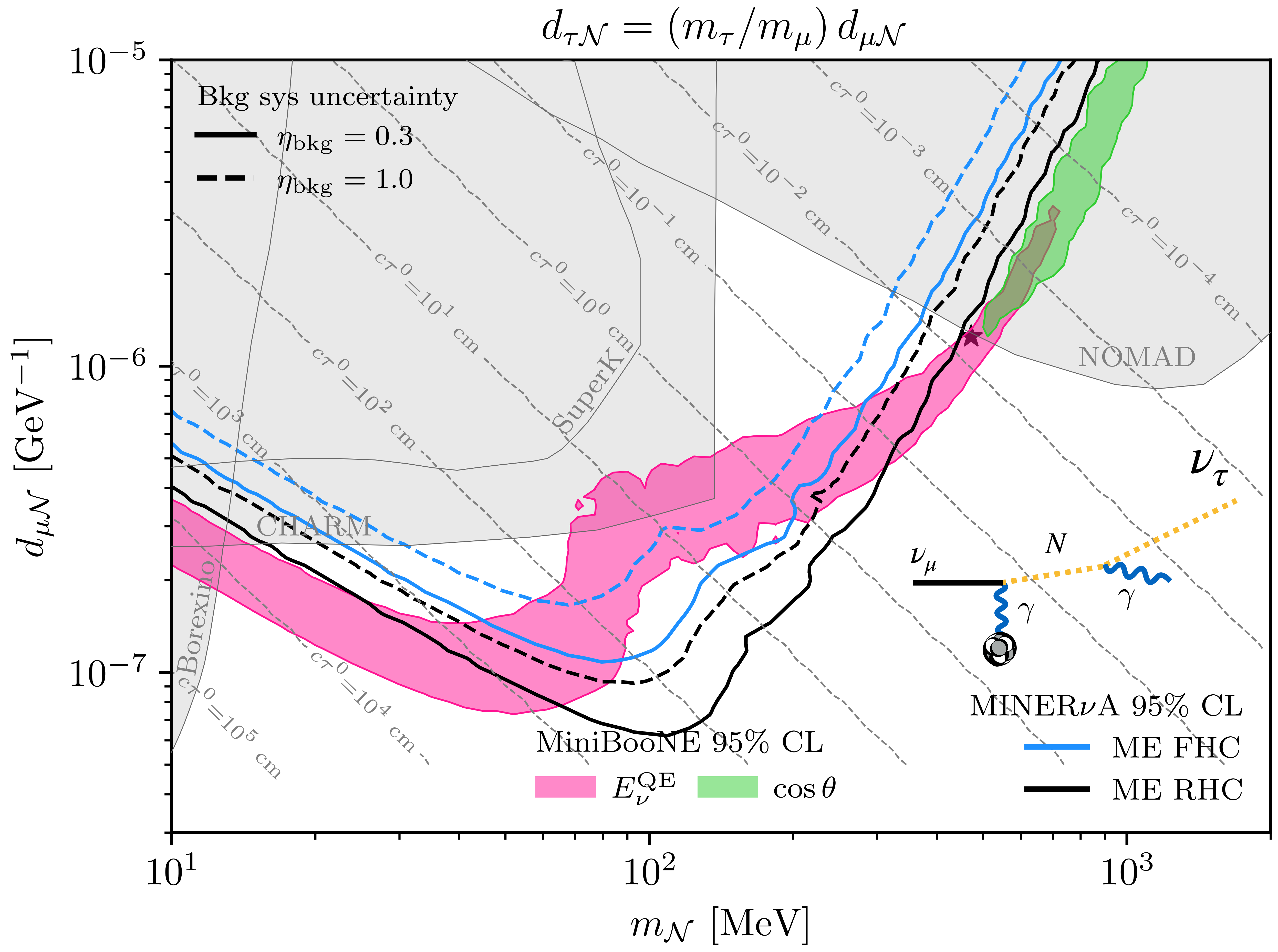

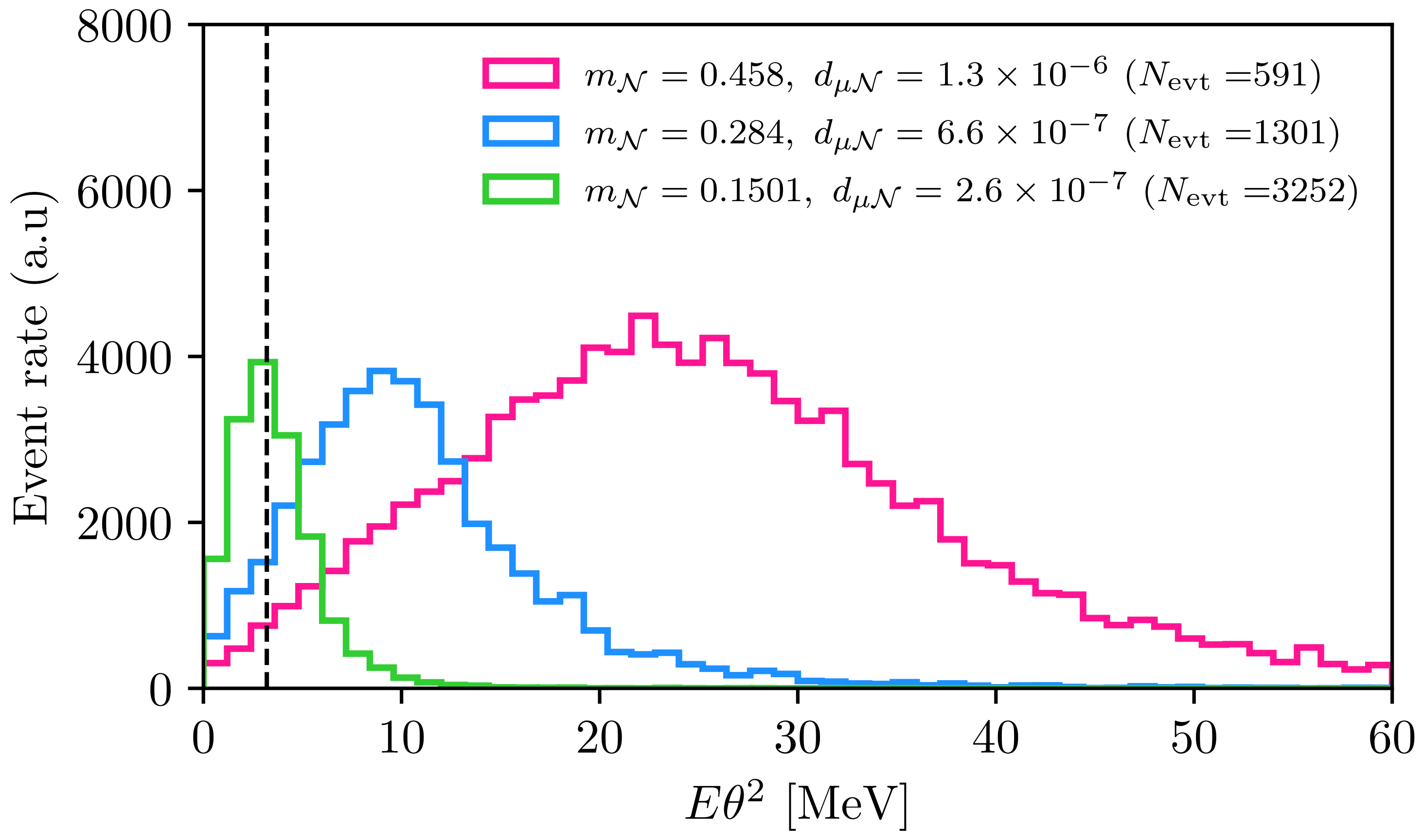

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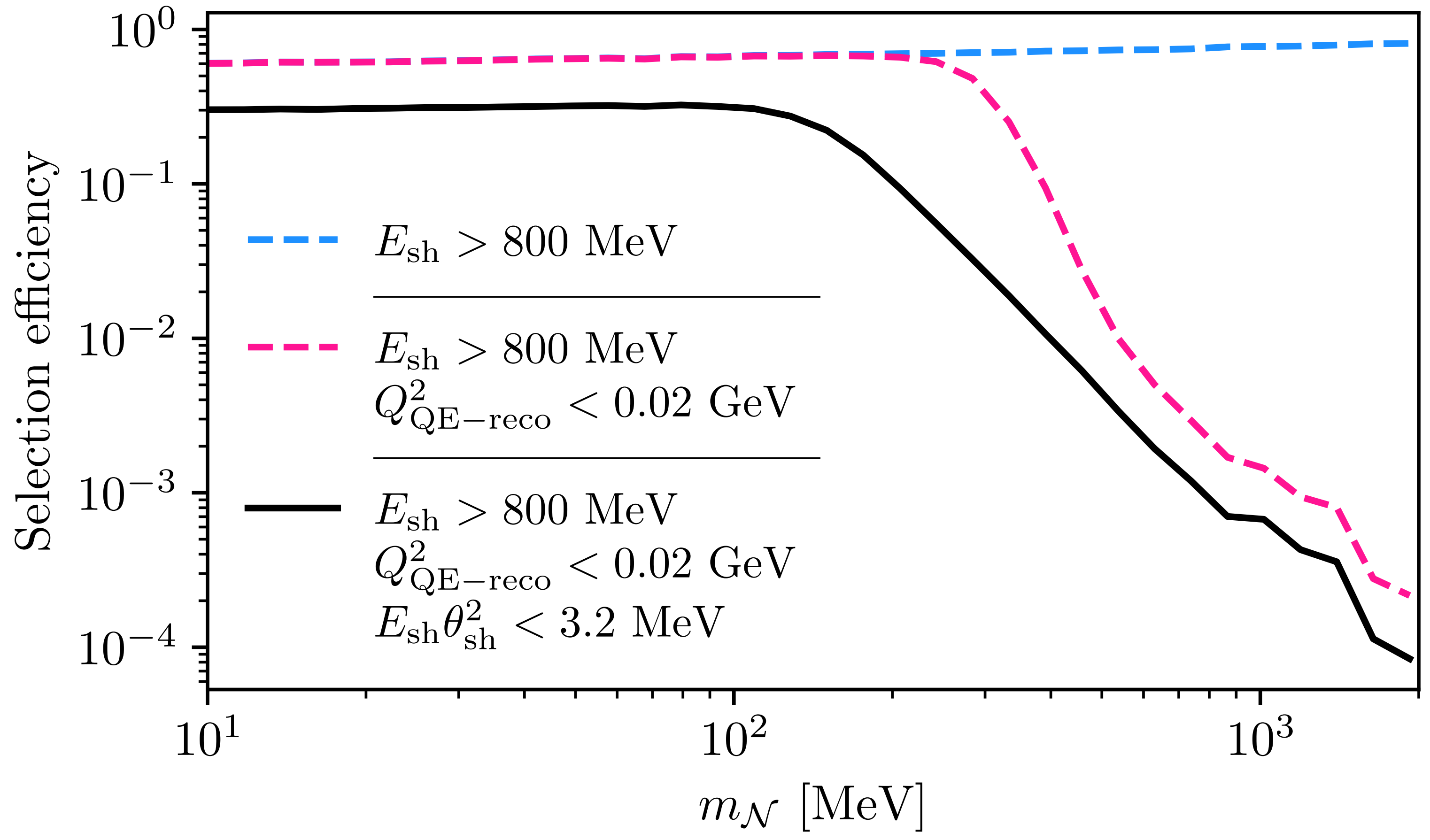

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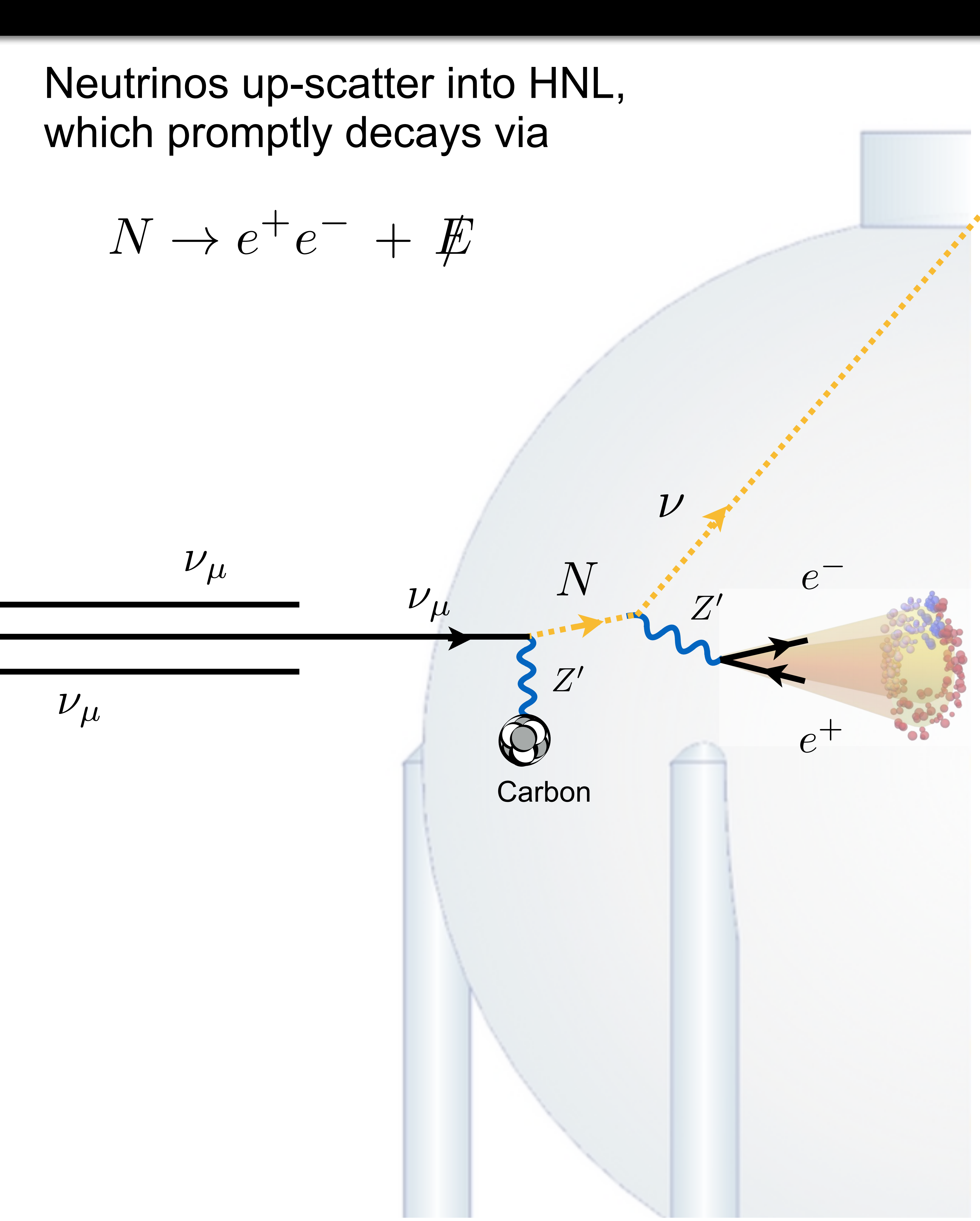
Dark neutrinos
Heavy neutrinos interacting via the dark photon

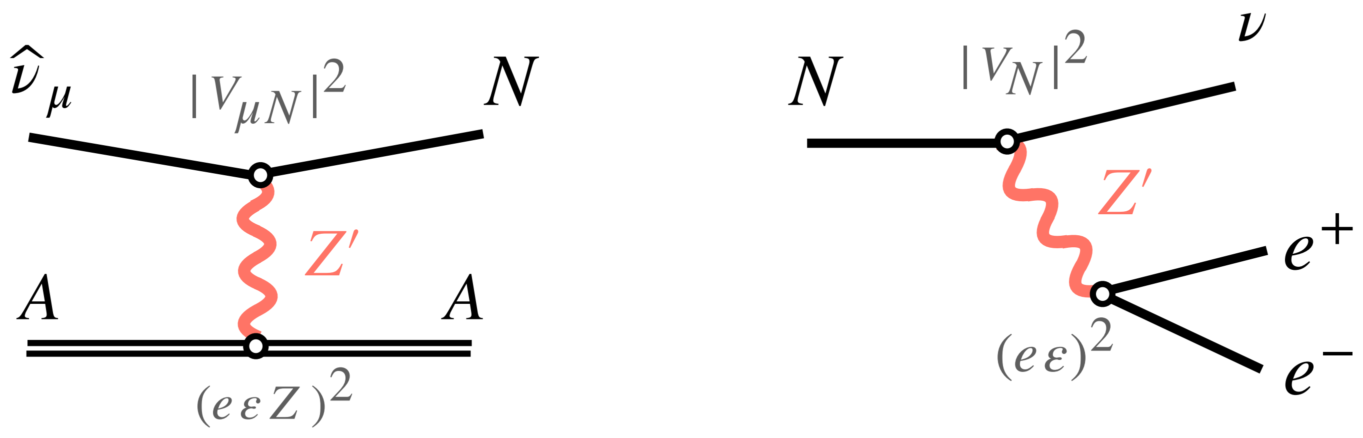
P. Ballett, MH, S. Pascoli [arxiv:1903.07589]
A. Abdullahi, MH, S. Pascoli, [arXiv:2007.11813]
E. Bertuzzo et al., [arXiv:1807.09877]
C. Argüelles et al, [arXiv:1812.08768]
P. Ballett et al, [arxiv:1808.02915]

Neutrinos up-scatter into HNL, which promptly decays via

$$N \to e^+ e^- + \not{E}$$



$$\mathscr{L} \supset \mathscr{L}_{\nu\text{-mass}} + \frac{m_{Z'}^2}{2} Z'^\mu Z'_\mu + Z'_\mu \left(e\epsilon\, J^\mu_{\rm EM} + \sum_{i,j}^{n+3} V_{ij}\, \overline{\nu_i}\gamma^\mu \nu_j \right)$$



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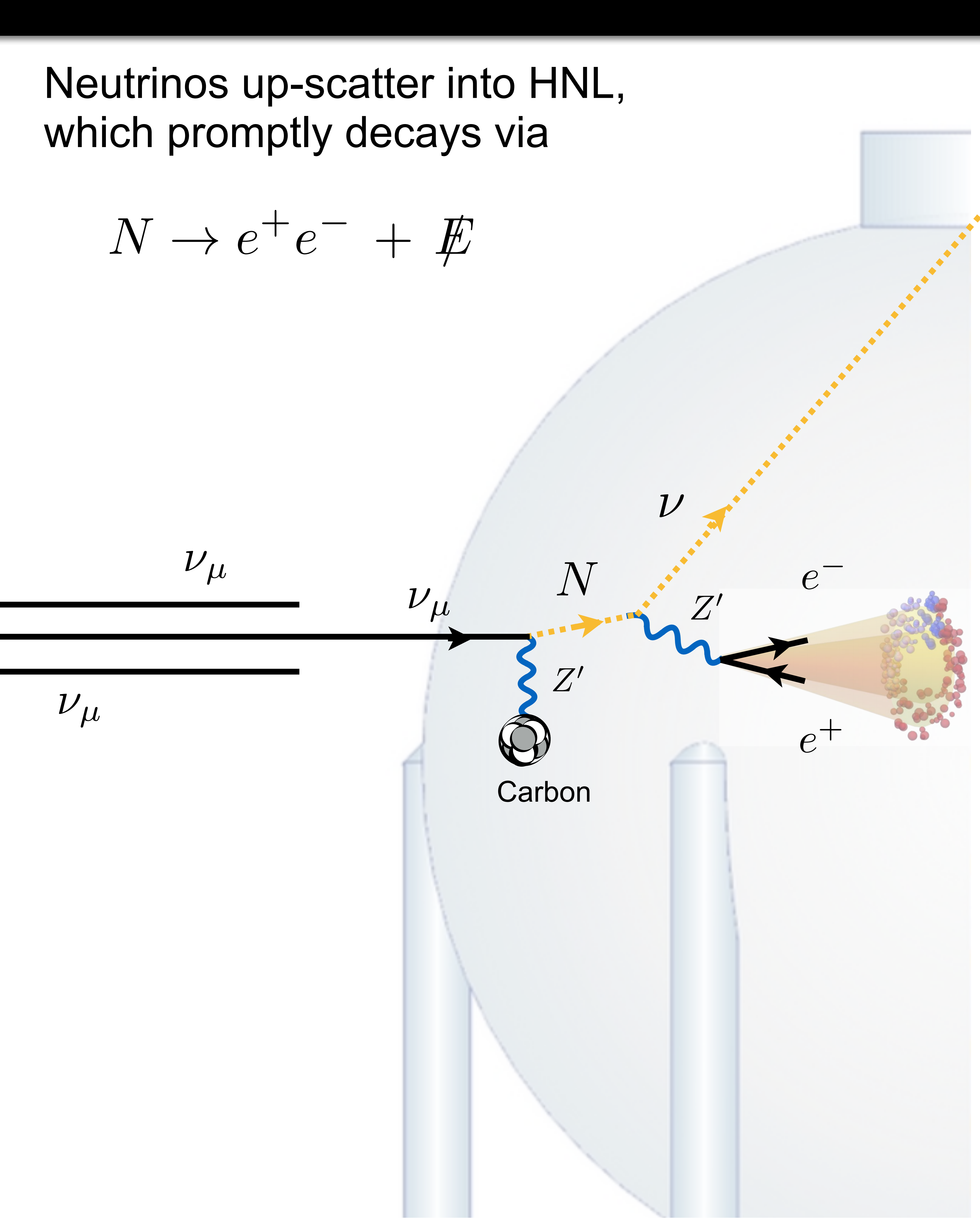
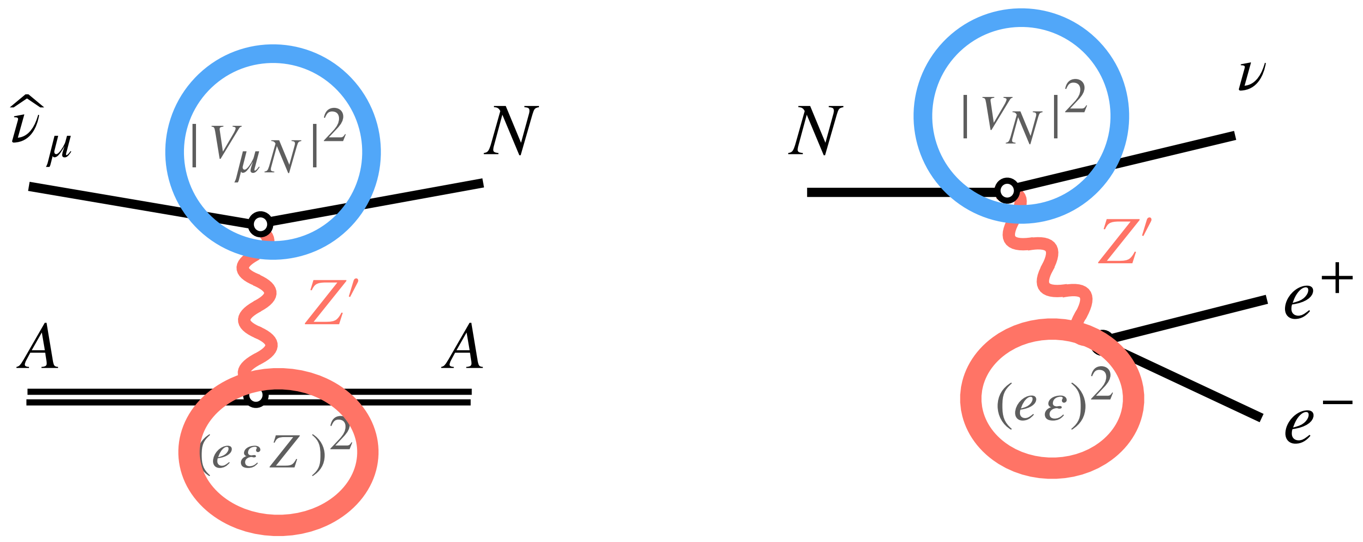
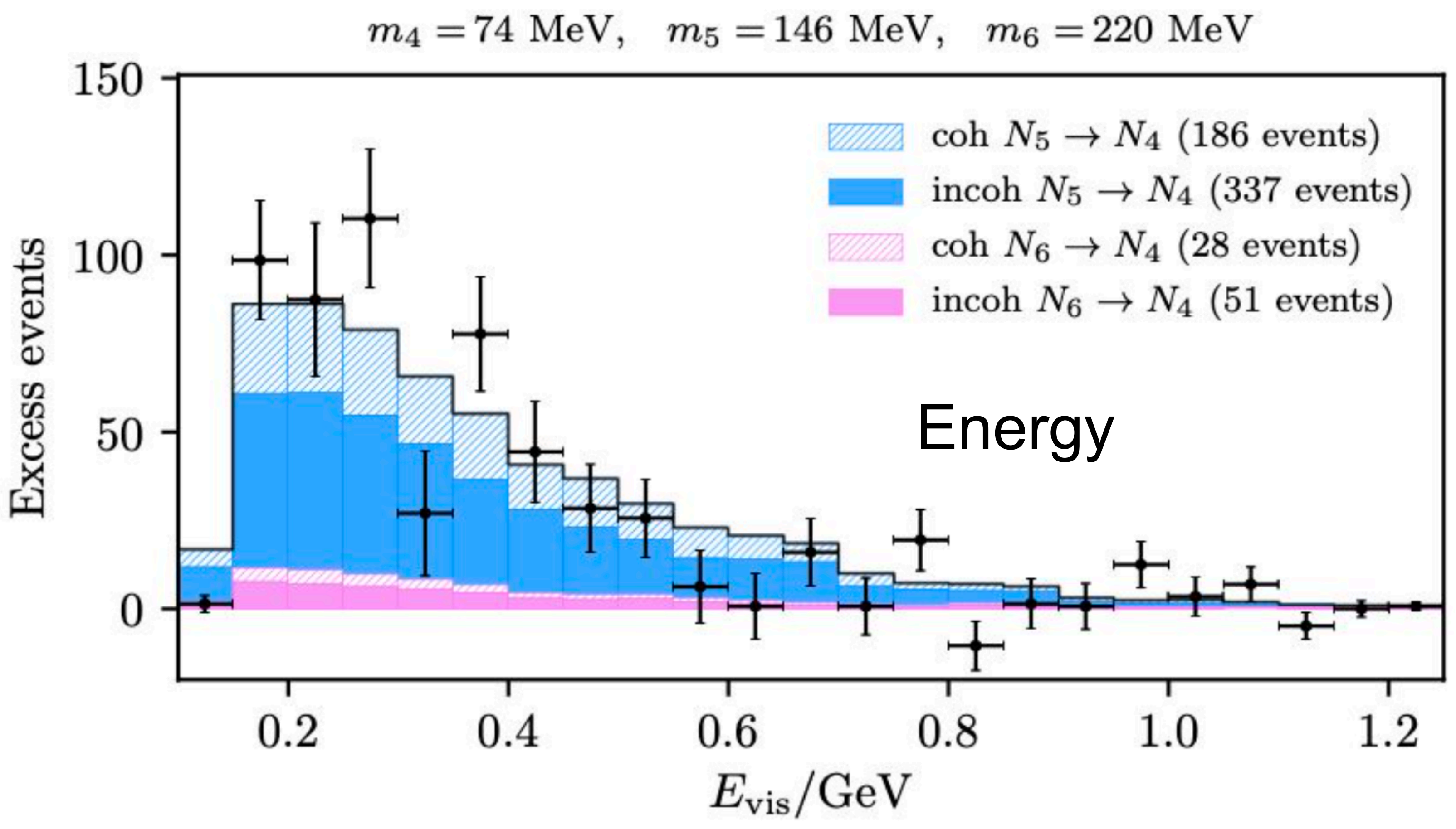
Neutrinos up-scatter into HNL, which promptly decays via

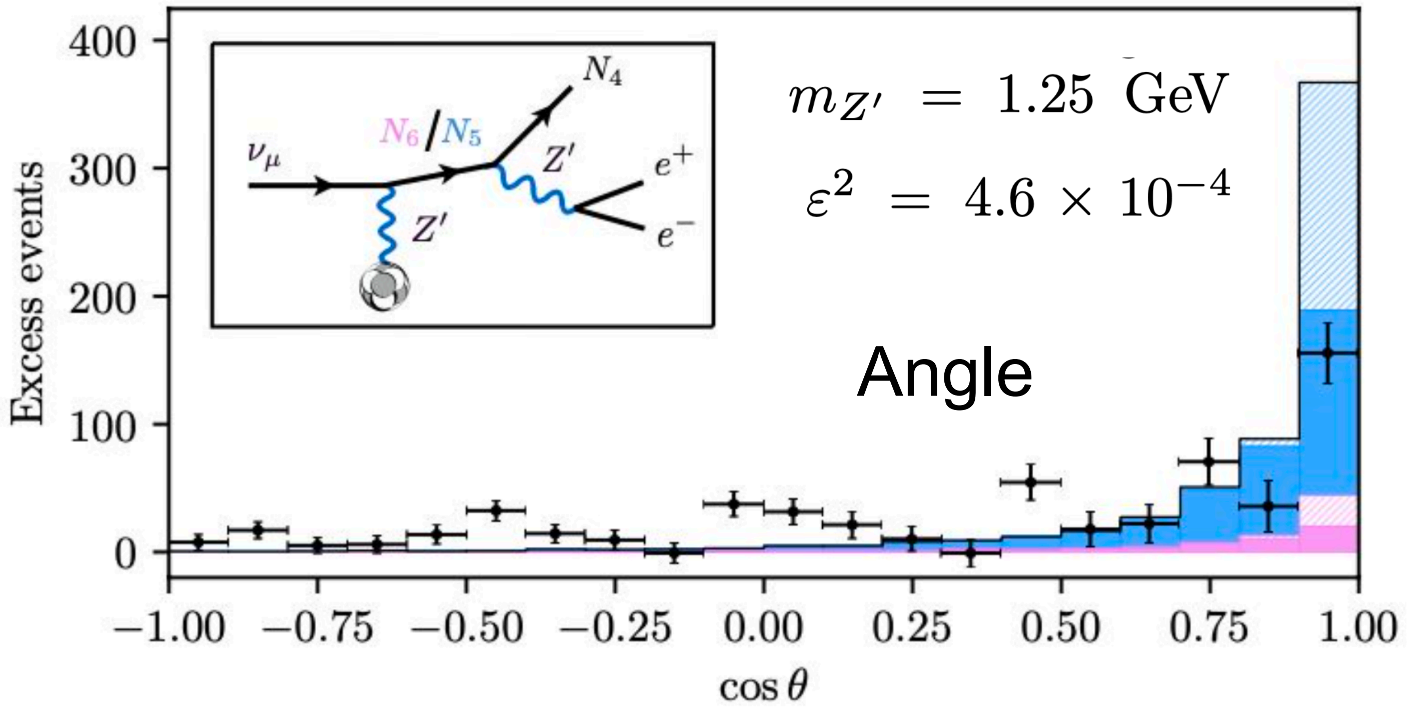
$$N \to e^+ e^- + \not{E}$$



$$\mathscr{L} \supset \mathscr{L}_{\nu\text{-mass}} + \frac{m_{Z'}^2}{2} Z'^\mu Z'_\mu + Z'_\mu \left(e\epsilon J^\mu_{\rm EM} + \sum_{i,j}^{n+3} V_{ij} \overline{\nu_i} \gamma^\mu \nu_j \right)$$

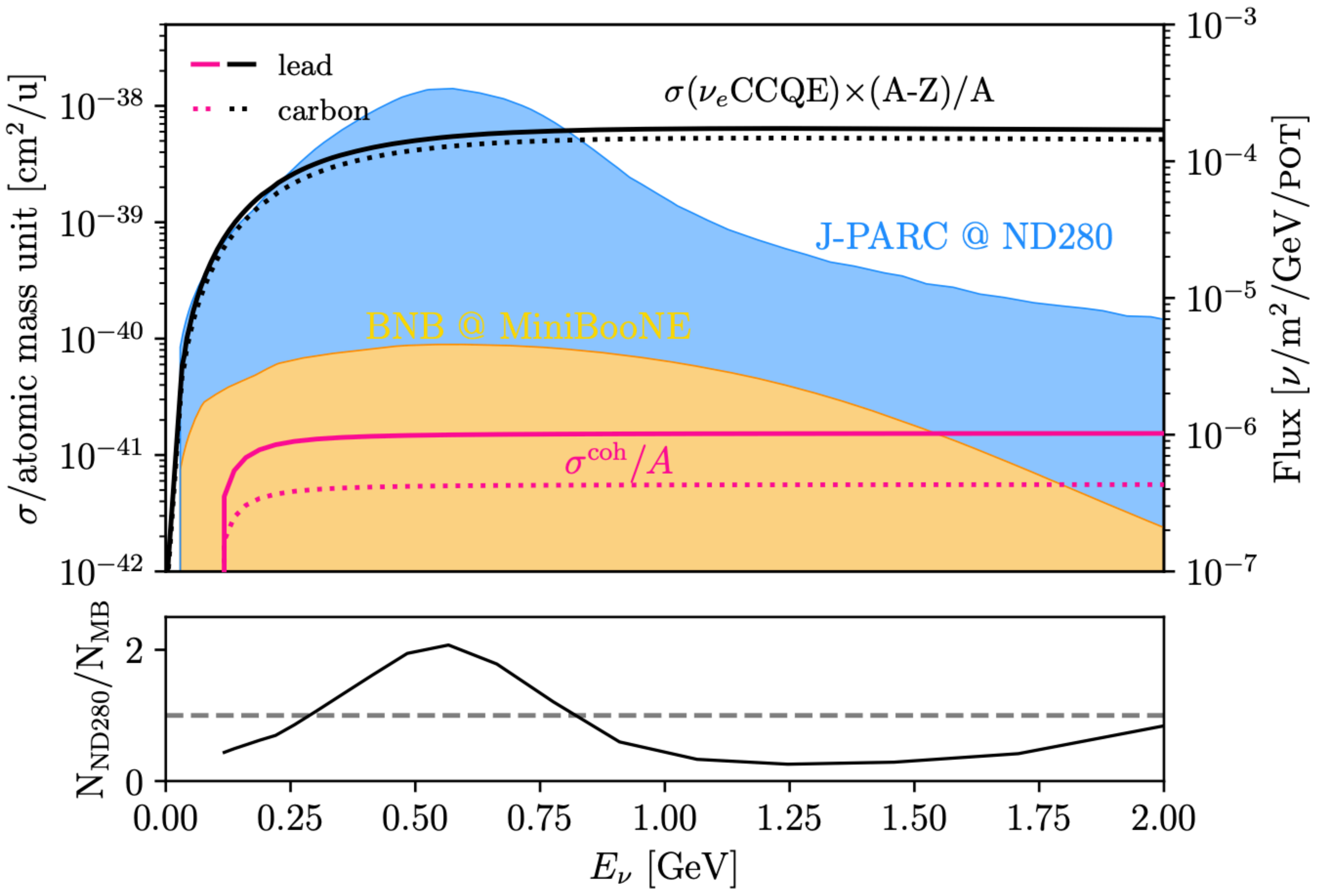






Dark Neutrino Sectors
Upscattering at the T2K near detector

C. Arguelles, MH, N. Foppiani, arXiv:2205.12273



J-PARC beam is more intense and peaks in a similar energy range to the Booster Beam.

Ratio of upscattering events in T2K similar to that in MiniBooNE. Should see hundreds of HNLs or more.

Dark Neutrino Sectors
Upscattering at the T2K near detector

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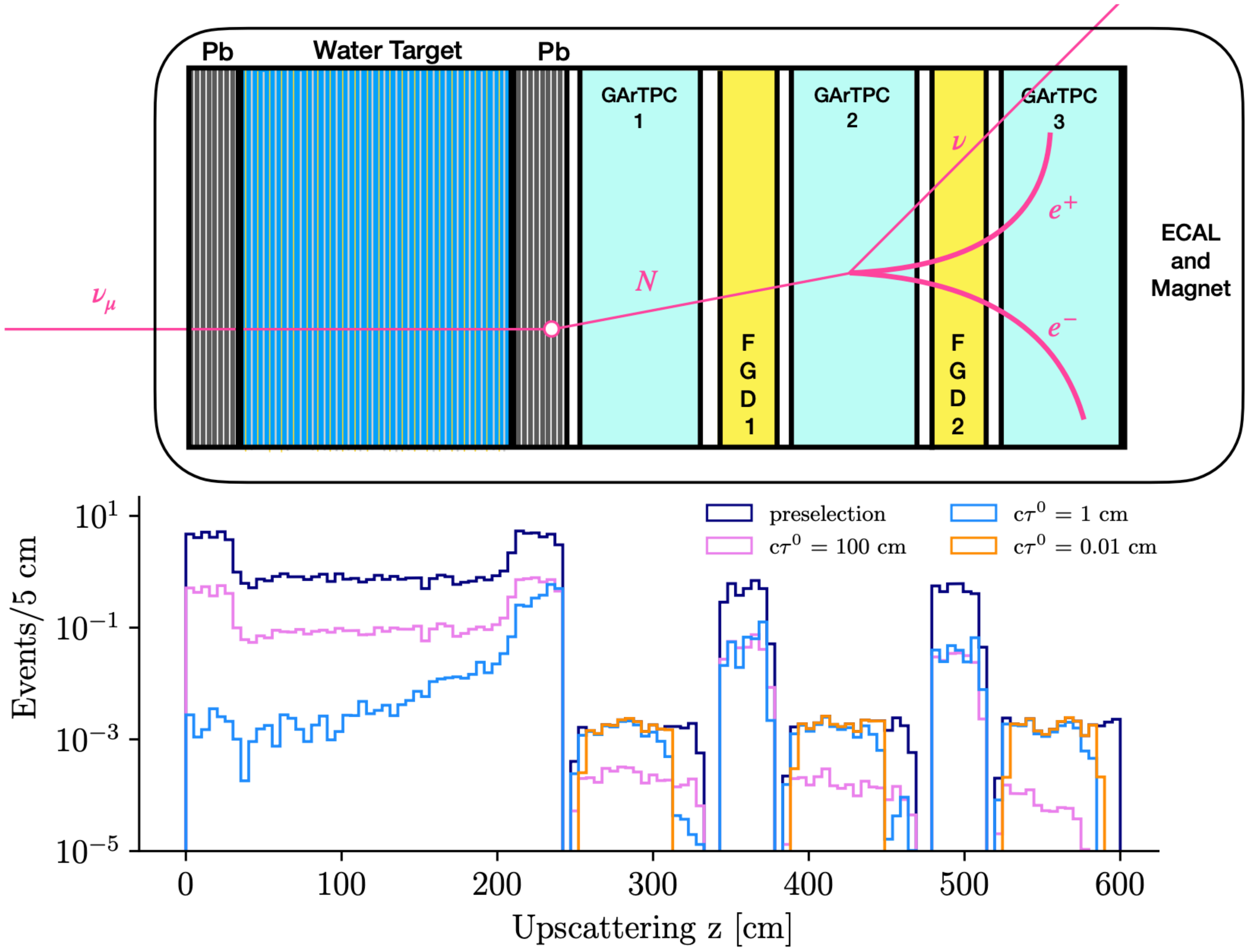


Benefit of this detector:

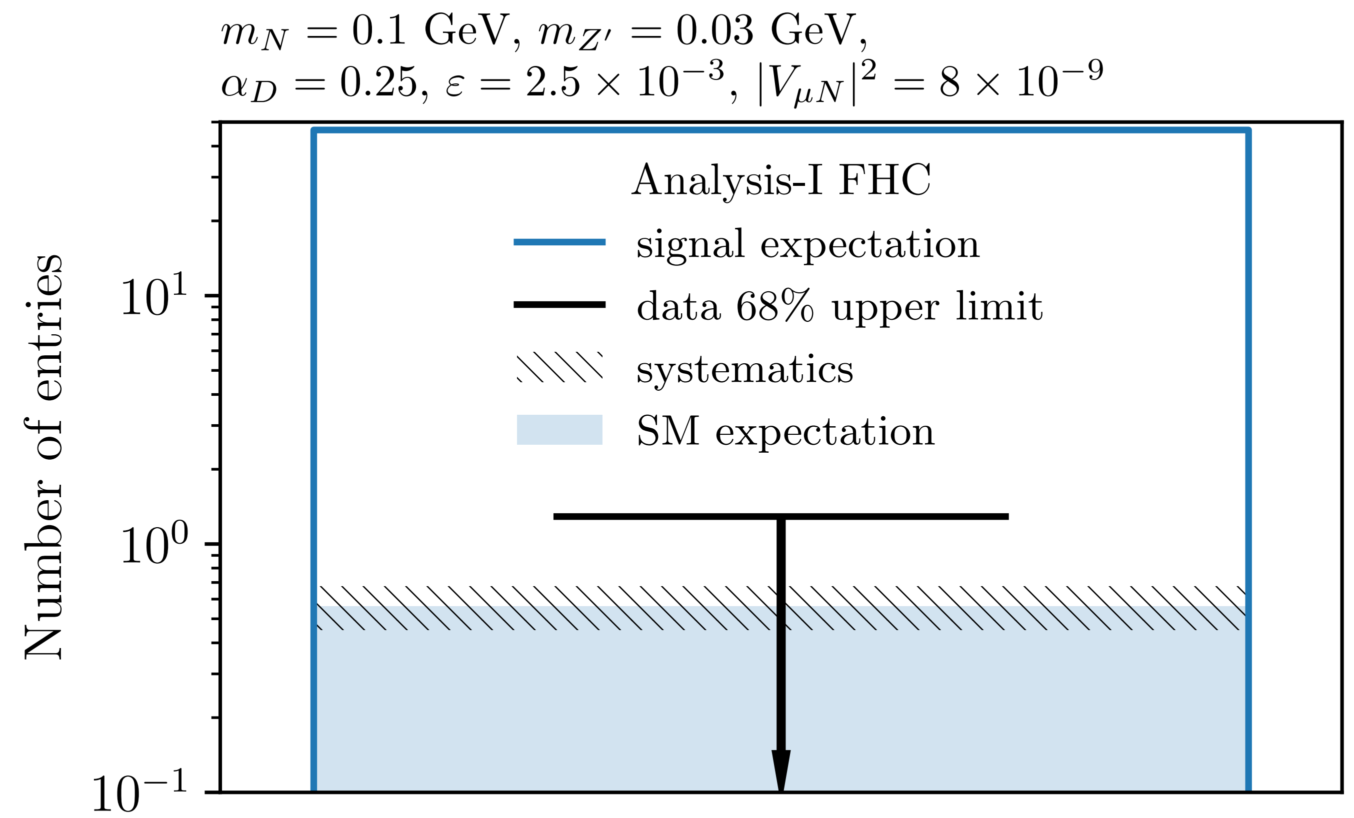
Heavy **lead** plates

+ Gaseous Argon modules

+ Magnetic field to separate e^+e^-

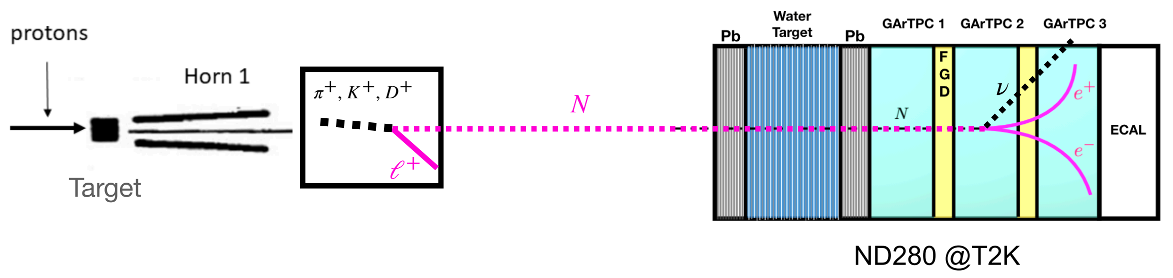
Dark Neutrino Sectors
Upscattering at the T2K near detector

Dataset I — The T2K search for the decay in flight of HNLs

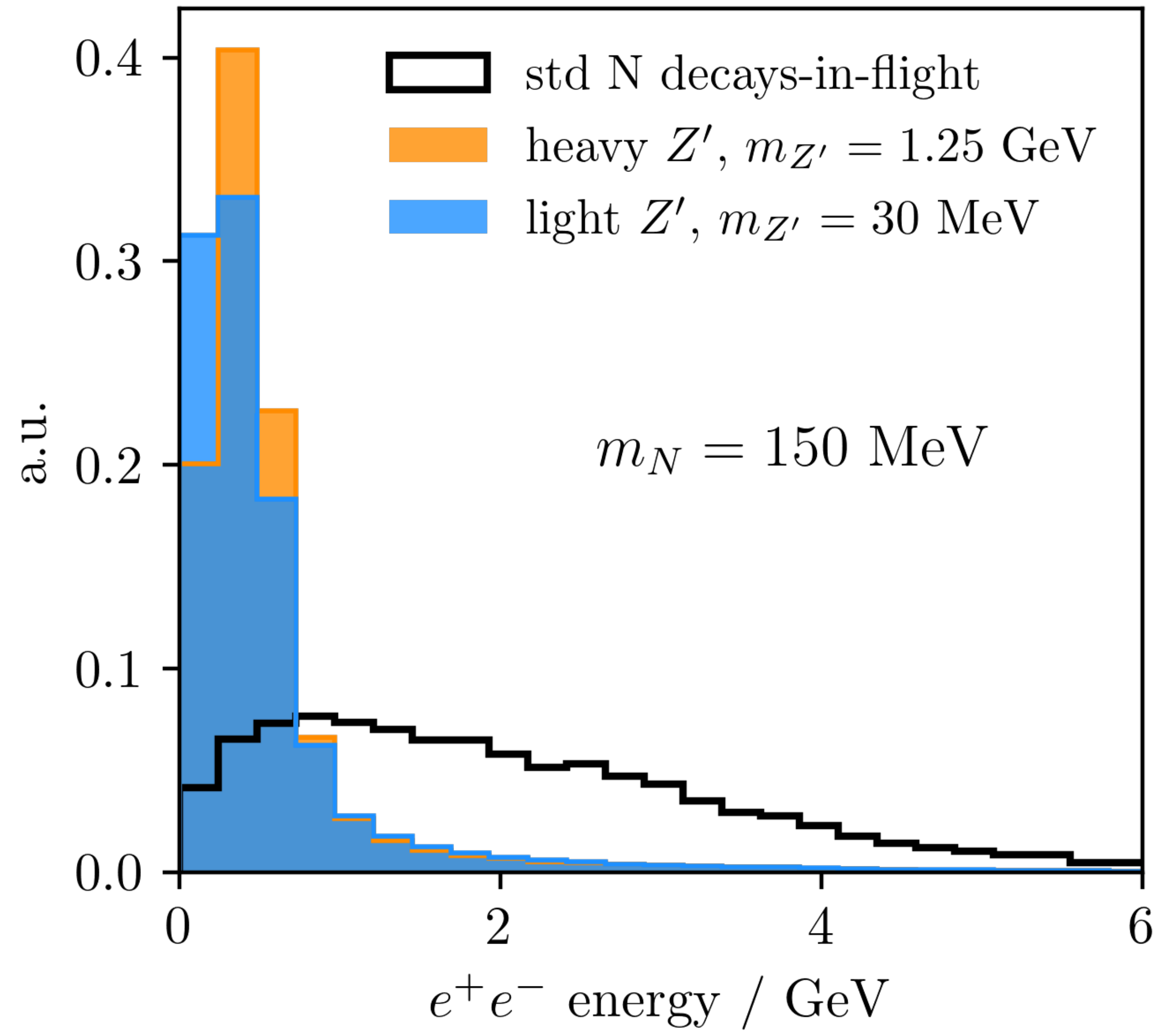


Single bin. No events in the data.
Background-free search.

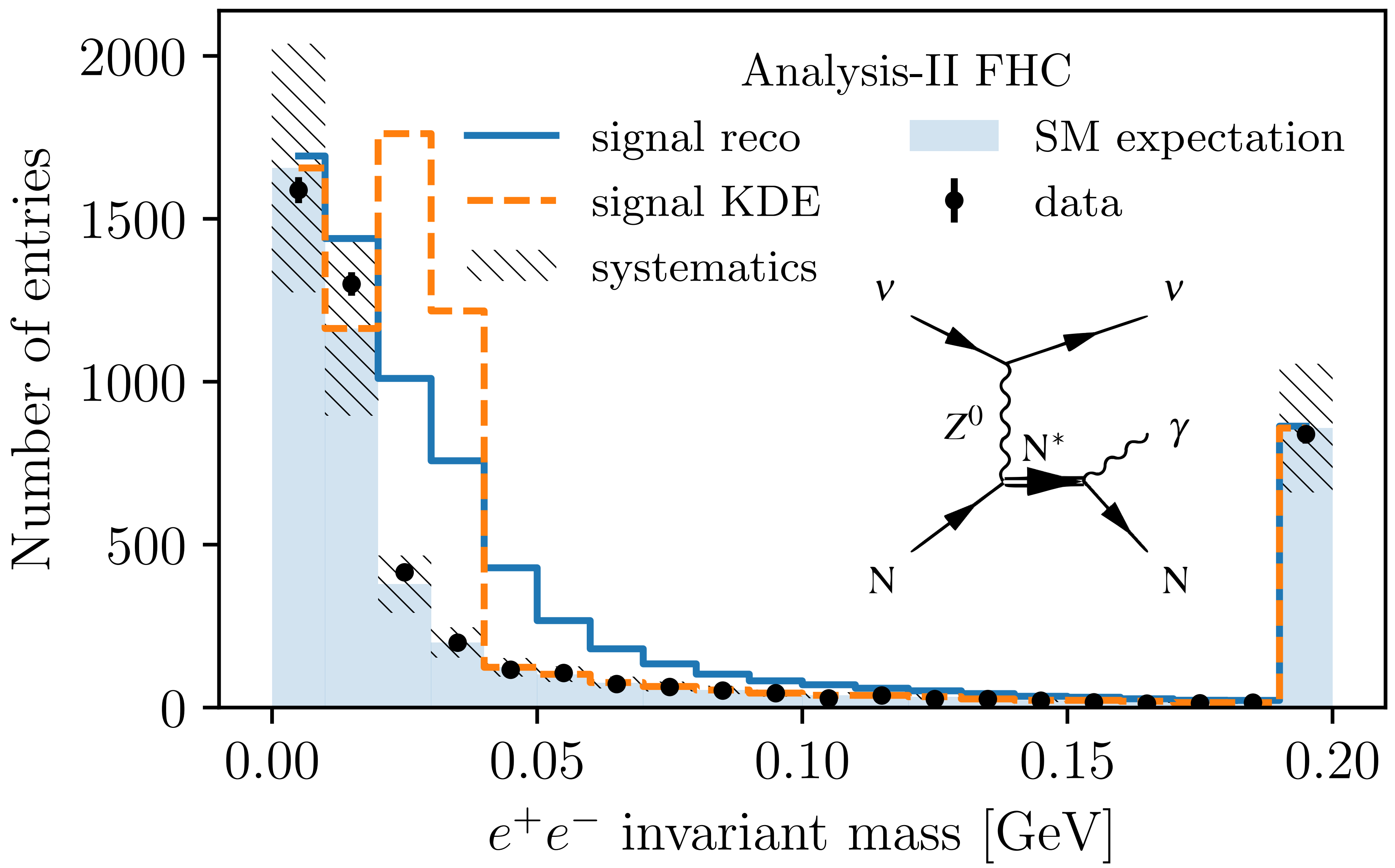
The search focused on the decay in flight of HNLs (solid black)



Our signal is a little different, mostly in energy (colors).



Dataset II — The T2K search for single photons



New physics gets smeared out on e+e- invariant mass.

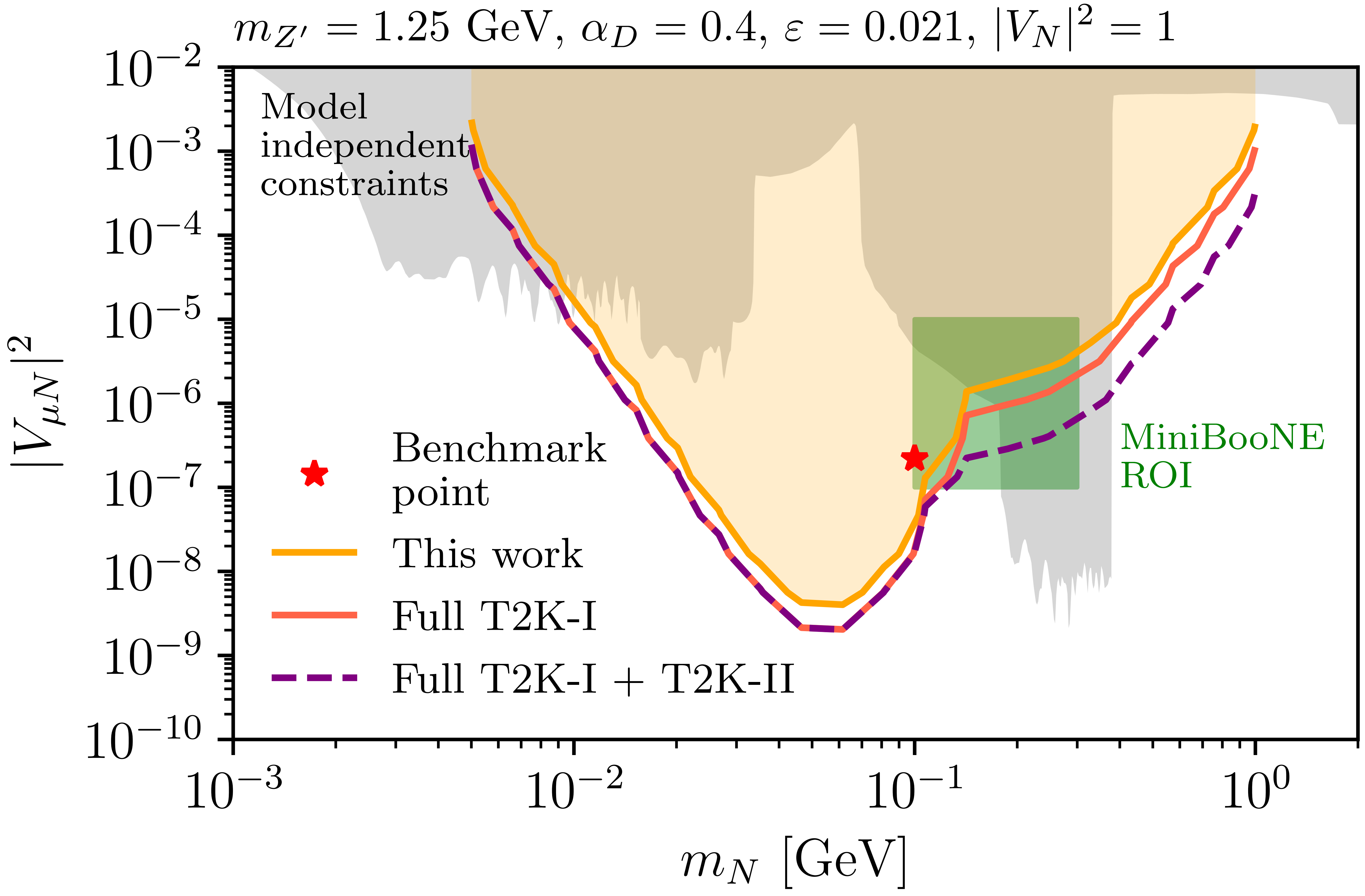
Backgrounds and smaller target mass means this dataset is less sensitive the Dataset I.

Dark Neutrino Sectors
Upscattering at the T2K near detector

T2K Collaboration, Phys. Rev. D 100, 052006 (2019)

See also, Vedran Brdar et al, arXiv:2007.14411

C. Arguelles, MH, N. Foppiani, arXiv:2205.12273



Unfortunately, no MiniBooNE fit is available (but coming soon!)

Set leading limits in parameter space.

Conclusions:

e+e- MiniBooNE explanations with

$$c\tau_N^0/m_N > 1\,\mathrm{cm/GeV}$$

are in tension with T2K data.

DarkNews-Generator

A. Abdullahi, J. Hoefken, MH, D. Massaro, S. Pascoli, arXiv:2207.04137

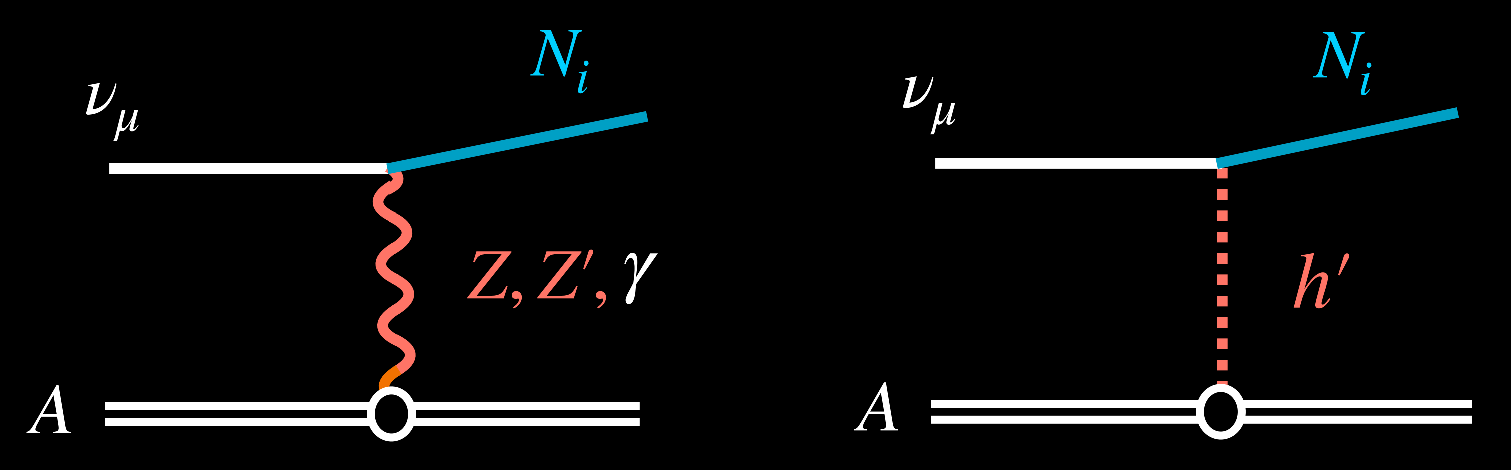
`DarkNews` is a fast MC generator for new physics in neutrino-nucleus scattering.
Including vector, scalar, and dipole mediators. Models with up to 3 HNLs.

`pip install DarkNews`

Modeling several processes for GeV-scale accelerator experiments:

Scattering:

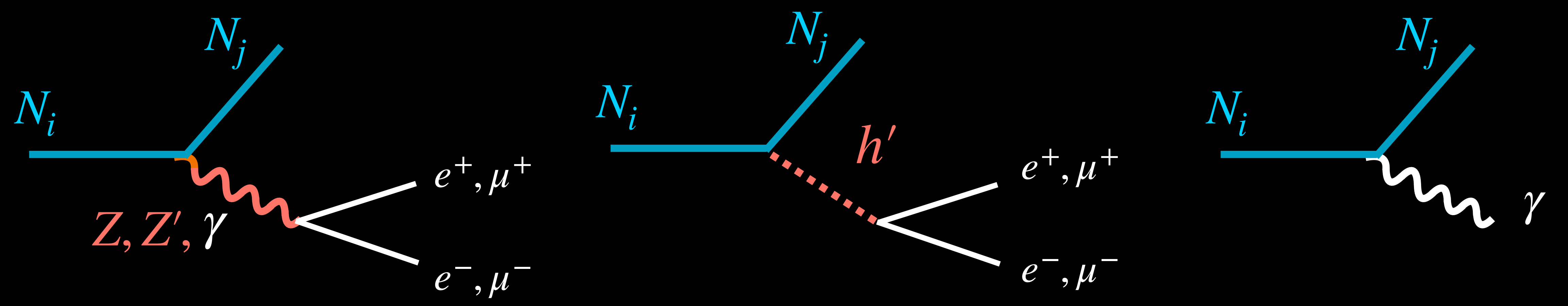
$\nu A \to N A$
(Coherent & QE peak)



Helicity conserving or flipping $\nu \to N$

HNL decay:

$N \to \nu \ell^+ \ell^-$
or
$N \to \nu\gamma$



N may be Majorana or Dirac, with either helicity states.

Conclusions:

The existence of heavy neutral leptons could open a door into dark sectors.

Neutrino experiments are probing new forces that are much weaker-than-Weak

The MiniBooNE puzzle remains unsolved.

New-physics ideas with light particles are on the market. **They are all testable.**

Transition magnetic moment:

Not dead yet. MINERvA could show more slices of their data which will probe all parameter space.

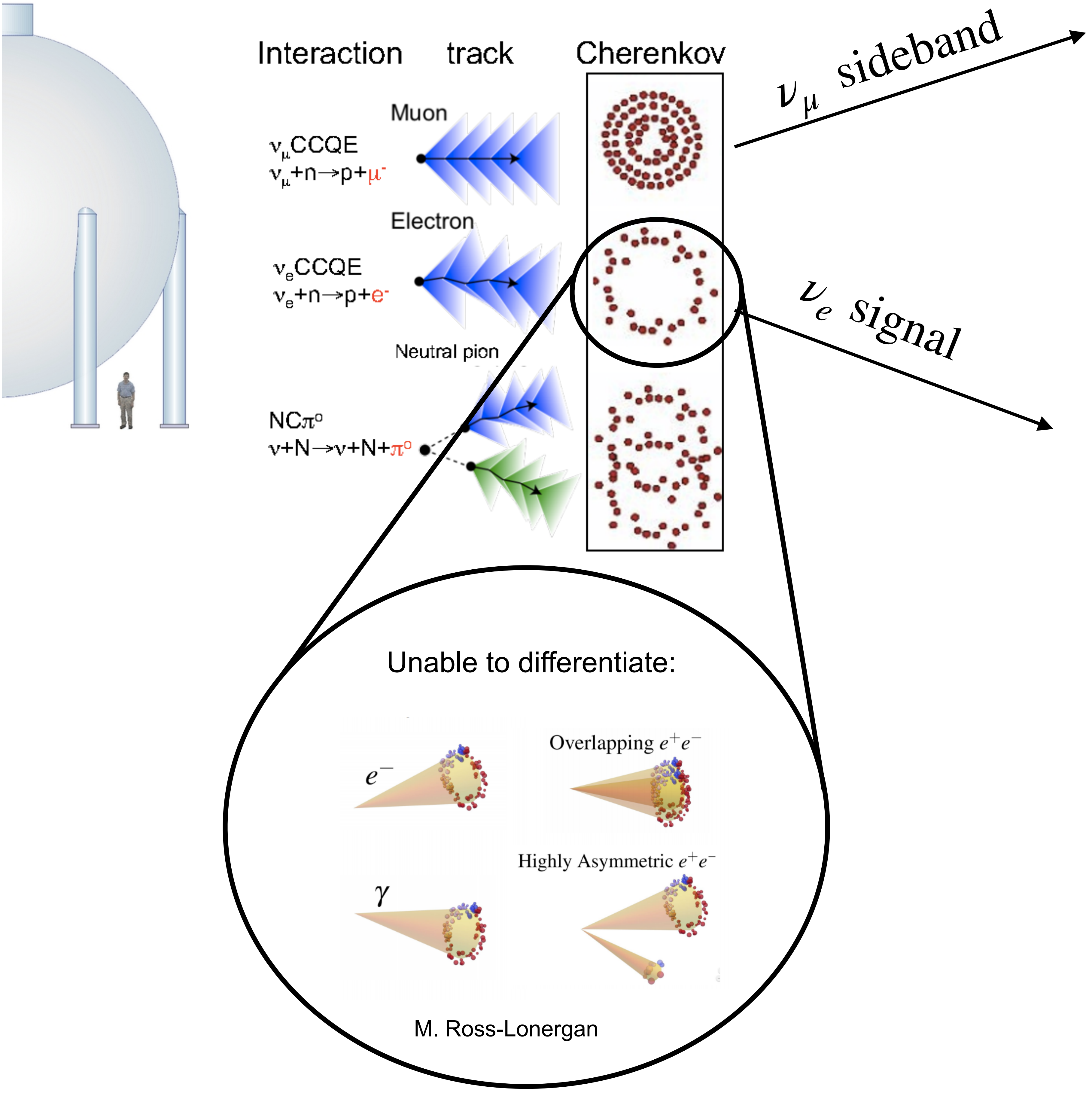
Dark Neutrino Sectors:

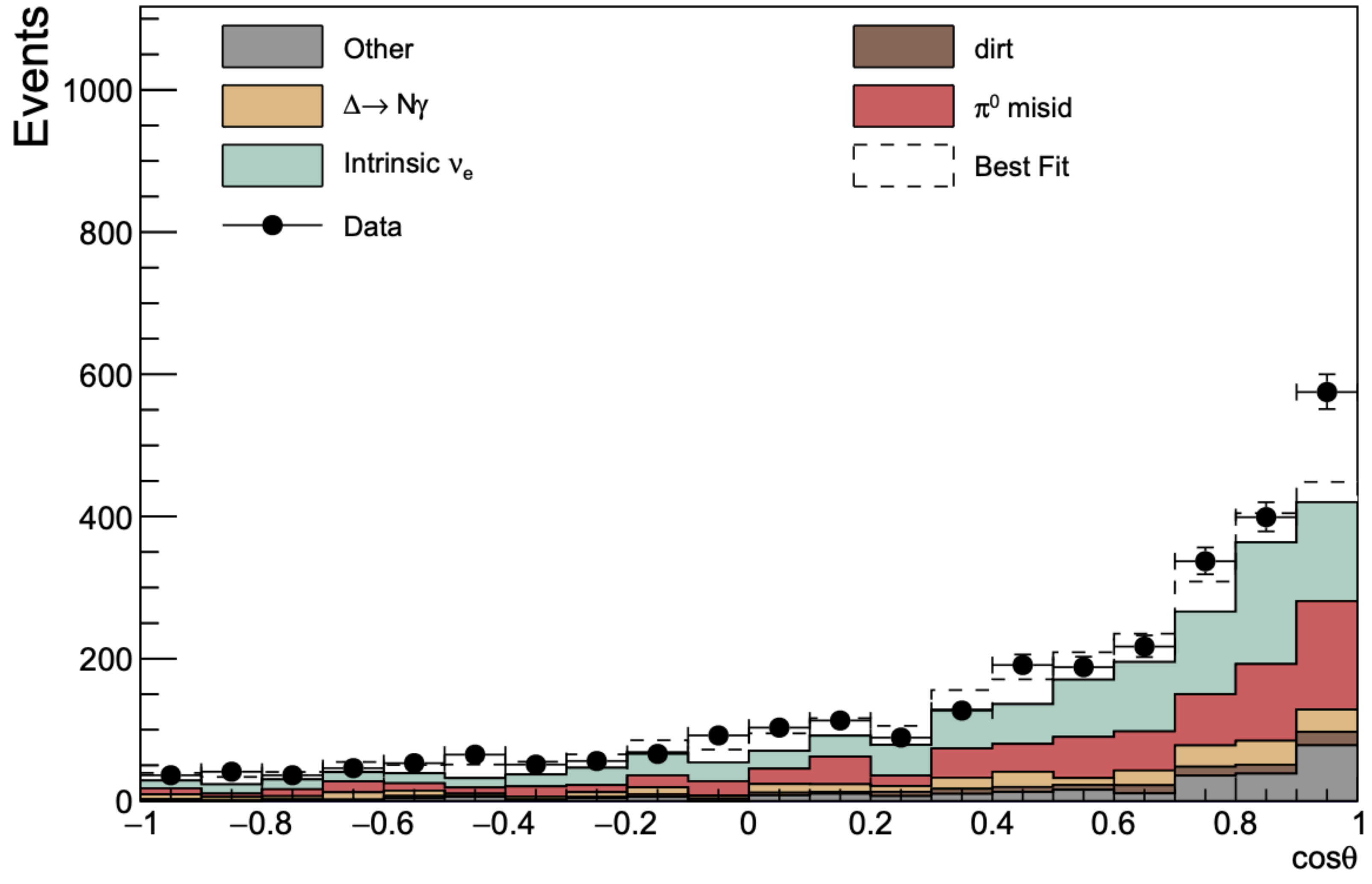
New limits from T2K were studied in detail. Not MiniBooNE fit to compare to, but naively, all explanations without prompt decays are likely excluded.

The MiniBooNE excess

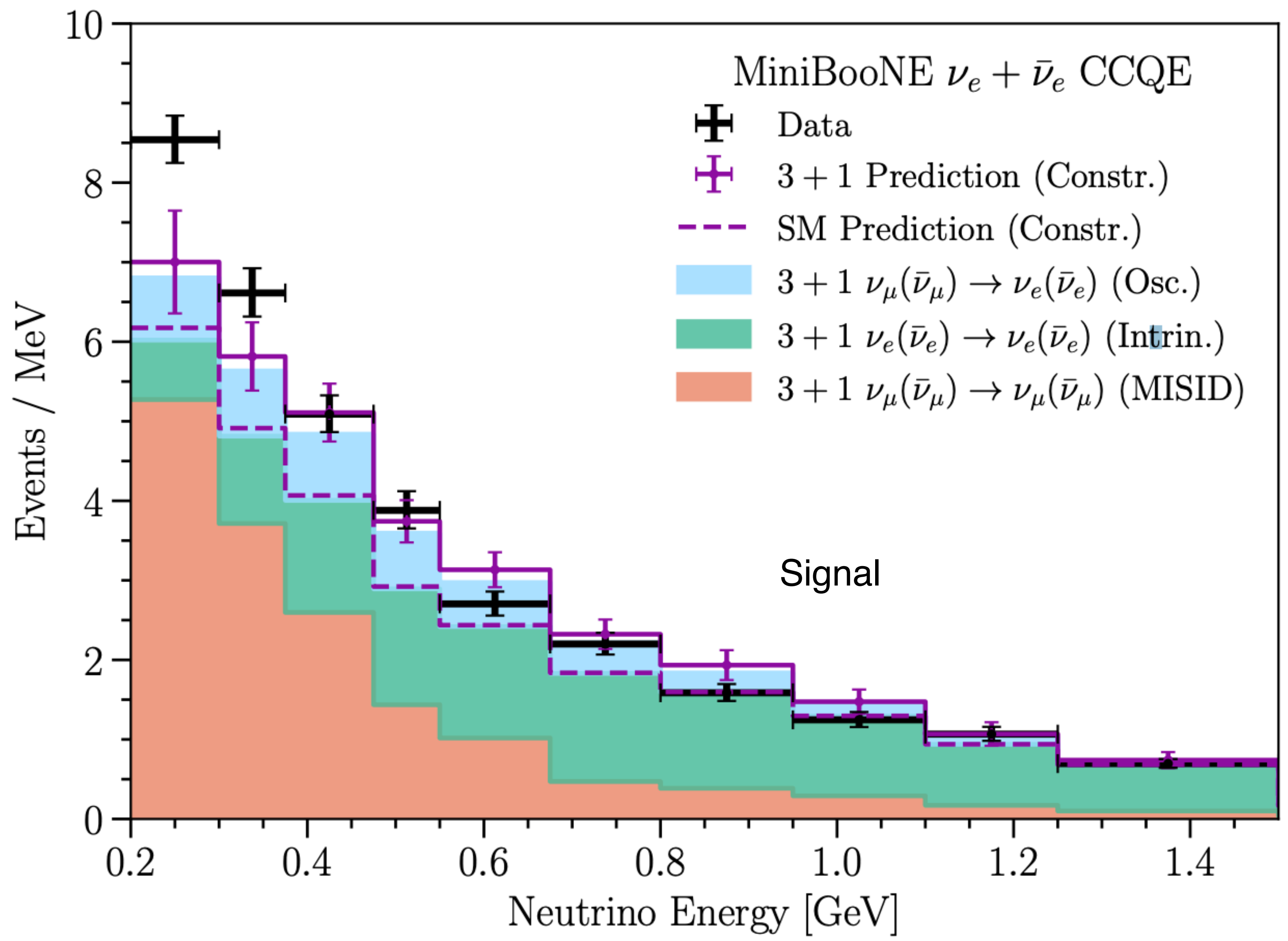
Latest MiniBooNE results:

MiniBooNE coll., Phys. Rev. D 103, 052002 (2021)

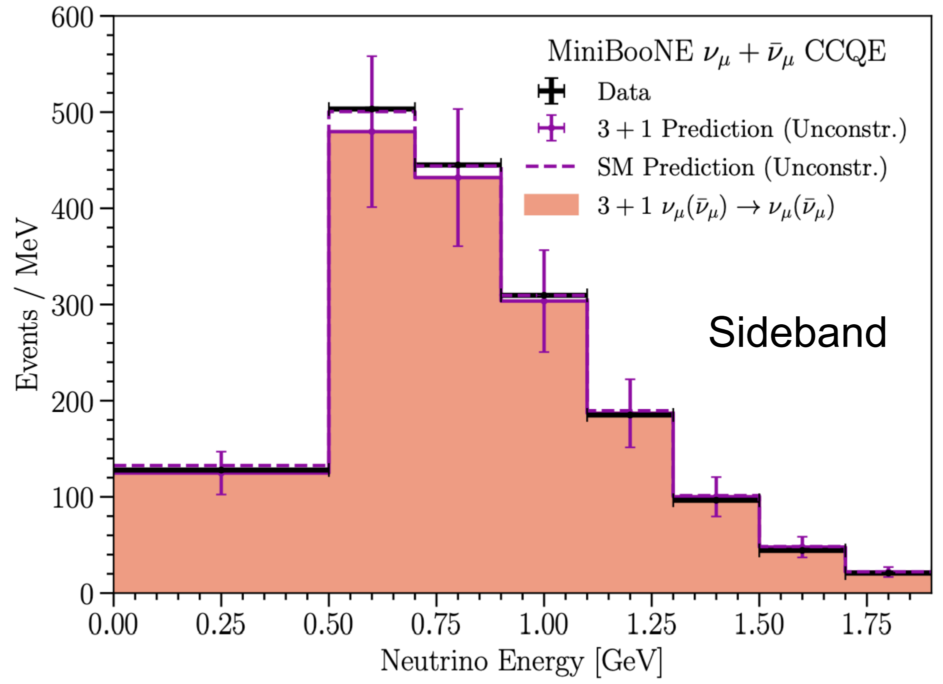




MiniBooNE coll., arXiv:2201.01724



MiniBooNE coll., arXiv:2201.01724



638 ± 52(stat.) ± 122.2(sys.)

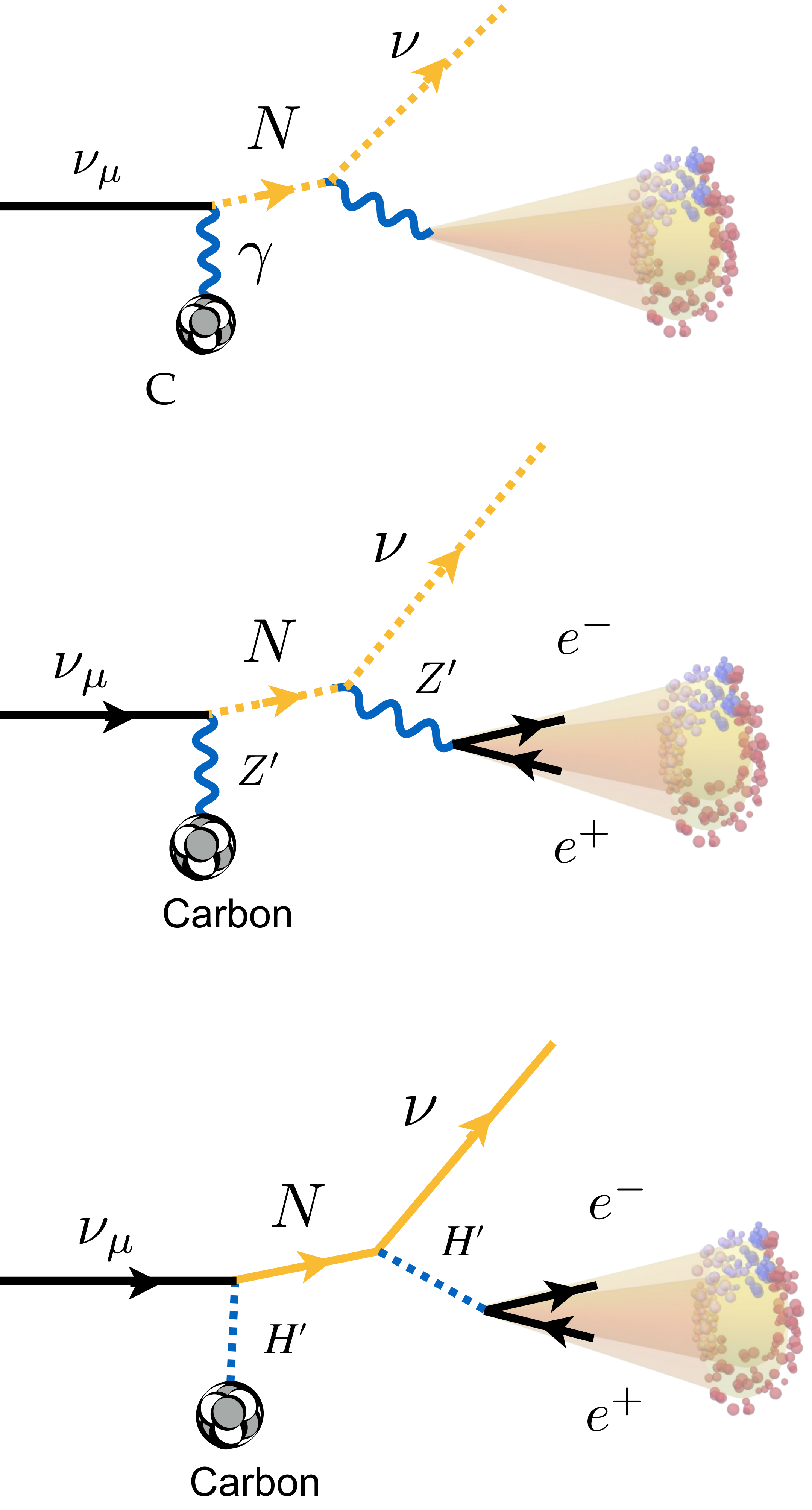
4.8σ significance

MiniBooNE is a very “inclusive” experiment:

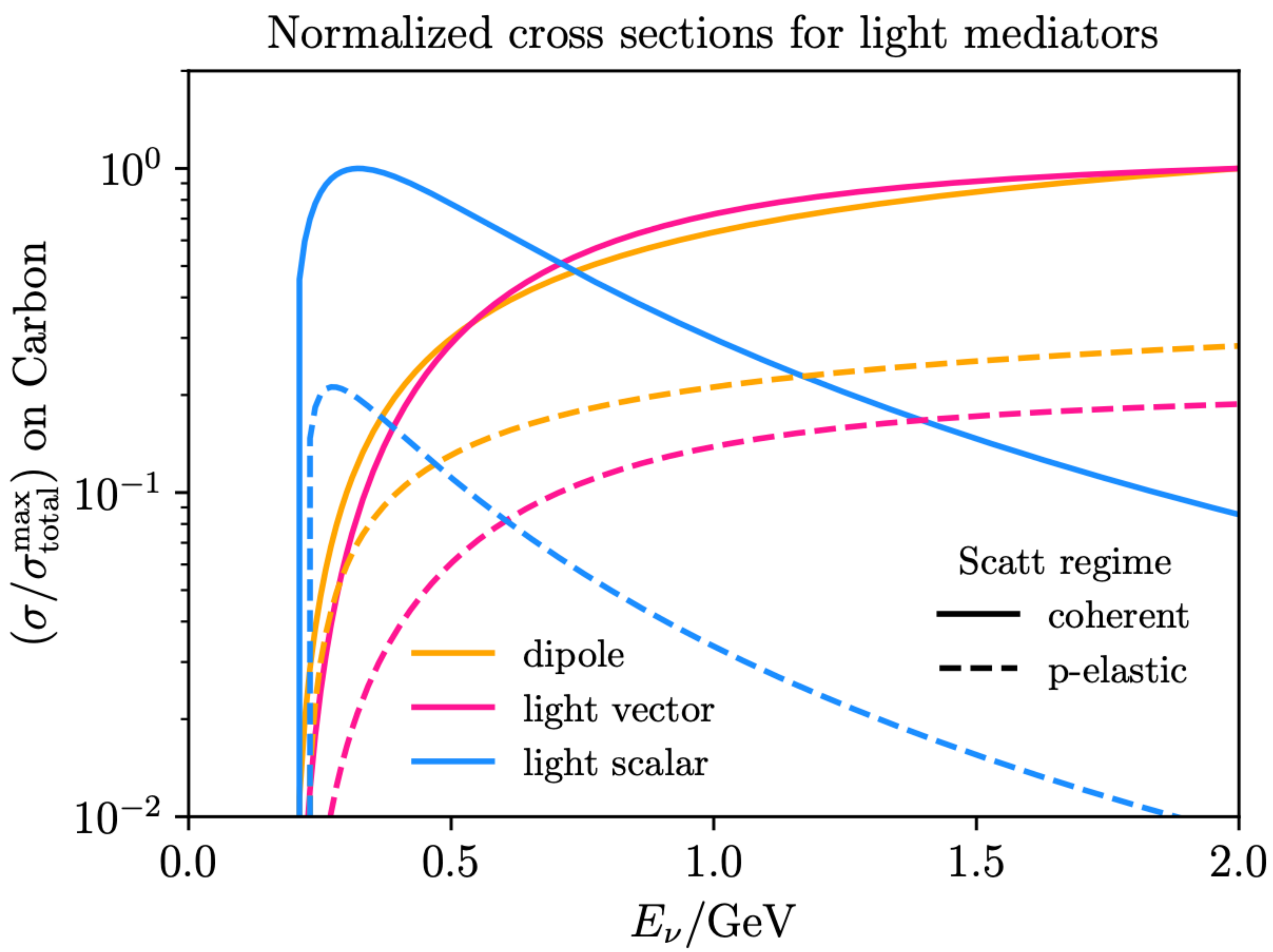
Neutrino scattering signatures
Complementary probes

P. Ballett, MH, S. Pascoli [arxiv:1903.07589]
A. Abdullahi, MH, S. Pascoli, [arXiv:2007.11813]
E. Bertuzzo et al., [arXiv:1807.09877]
C. Argüelles et al, [arXiv:1812.08768]
P. Ballett et al, [arxiv:1808.02915]

B. Dutta et al, [arxiv:2006.01319]
A. Datta et al, [arXiv:2005.08920]
B. Dutta et al, [arxiv:2006.01319]
W. Abdallah et al, arXiv:2202.09373



Upscattering cross sections in different models:

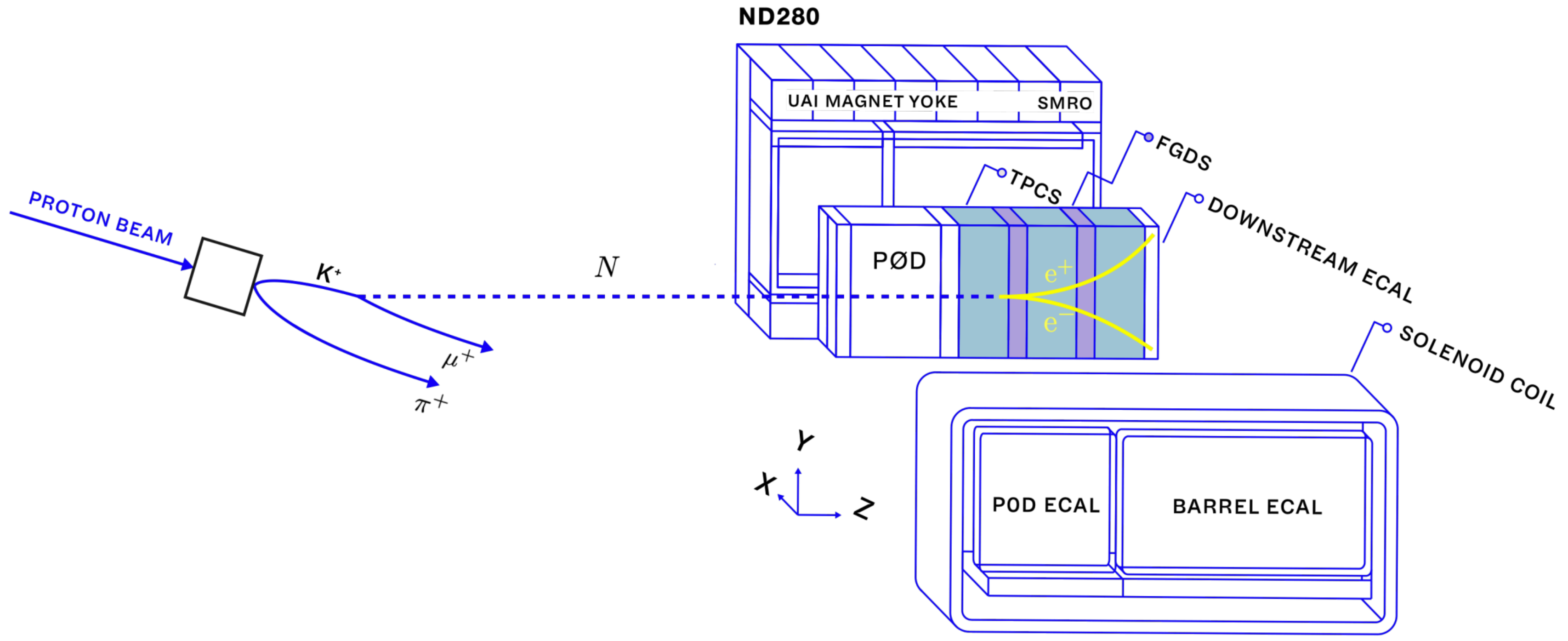


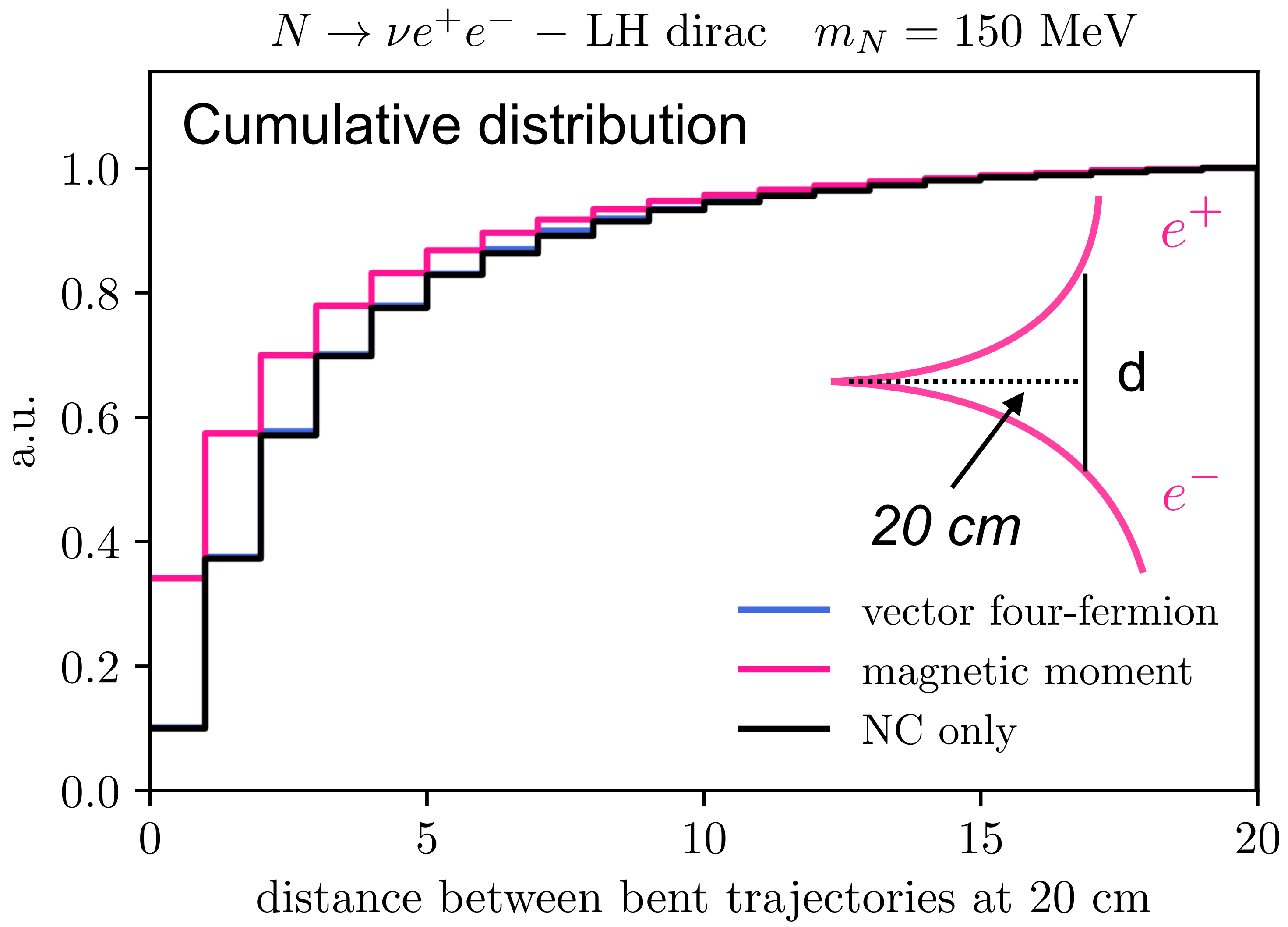
Not all neutrino experiments would see the same physics. Importance of complementarity.

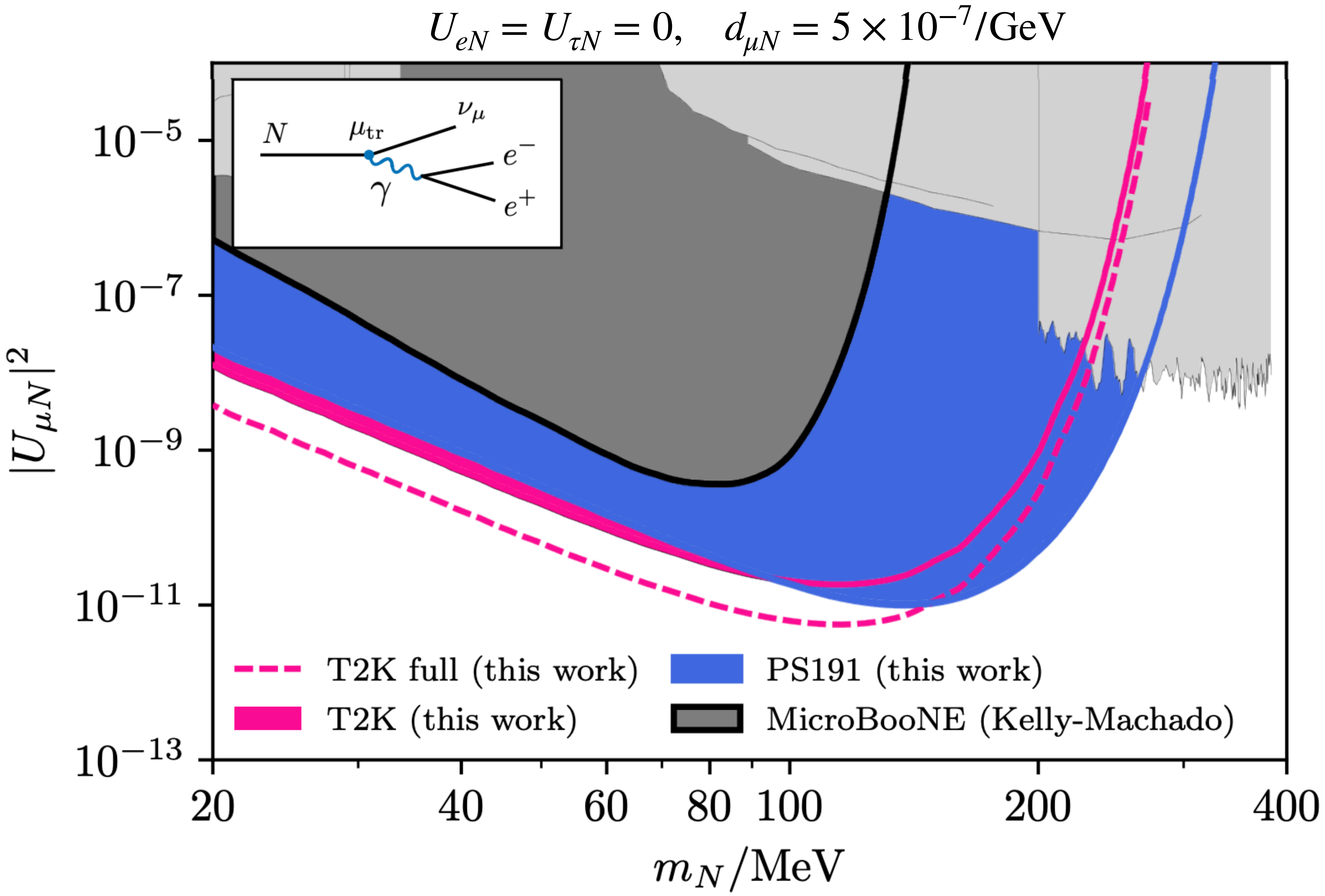
Transition magnetic moment — Parenthesis.

Decay-in-flight signatures due to mass mixing (@ T2K)

C. Argüelles, N. Foppiani, MH arxiv:2109.03831





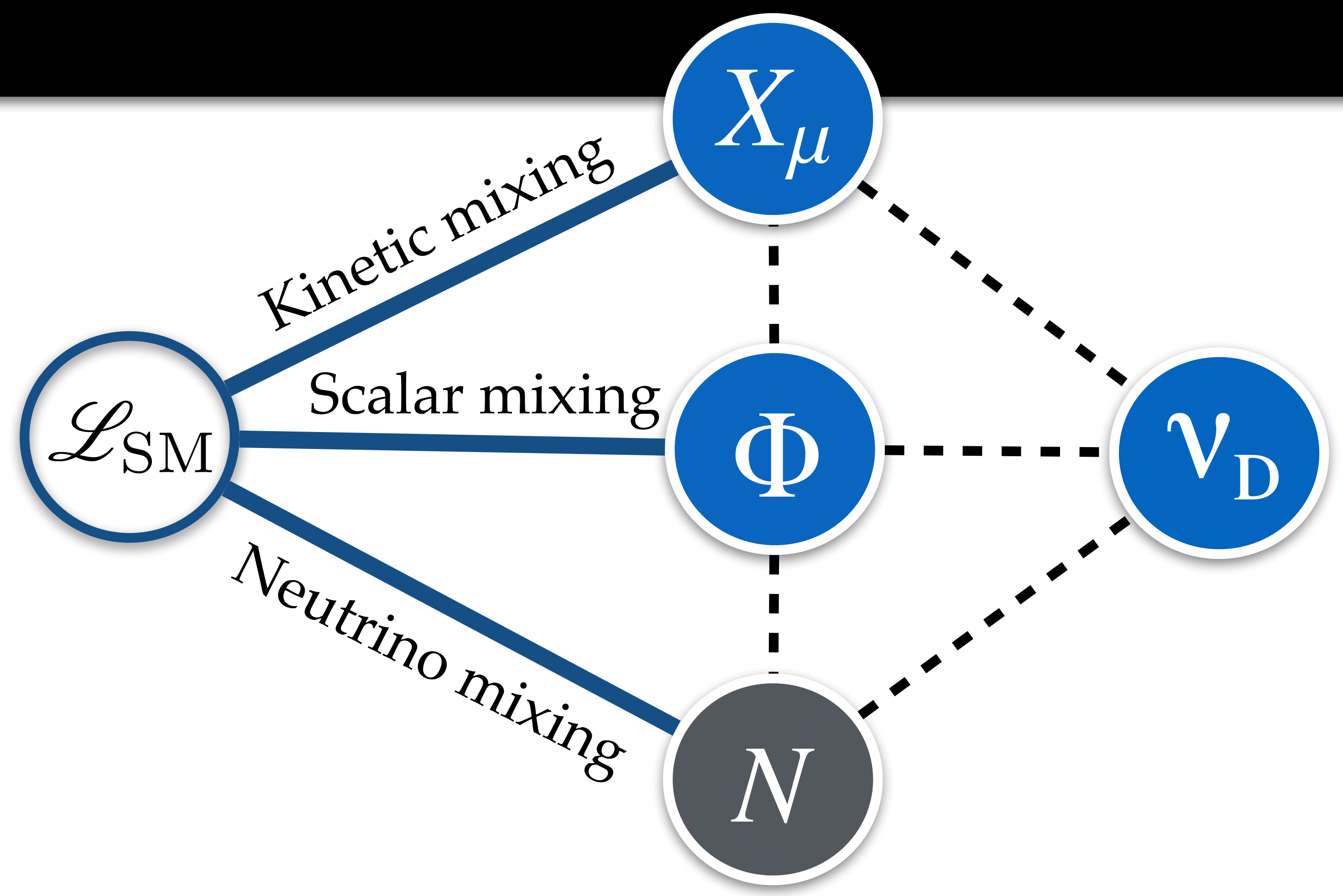


The limits on the mixing are very strong.

If m_D is non-zero, it better be as small as $\mathcal{O}(10\,\text{eV})$ scale.

Dark Neutrino Sectors
A model

A. Abdullahi, MH, S. Pascoli
arXiv:2007.11813



1) A minimal renormalizable model:

	$SU(2)_L$	$U(1)_Y$	$U(1)_X$
ν_N	**1**	0	0
ν_{D_L}	**1**	0	Q
ν_{D_R}	**1**	0	Q
Φ	**1**	0	Q

$$\begin{pmatrix} 0 & M_D & 0 \\ M_D^T & M_N & \Lambda \\ 0 & \Lambda^T & \mathcal{M}_X \end{pmatrix} \begin{pmatrix} \nu_\alpha^c \\ \nu_N^c \\ \nu_D^c \end{pmatrix}$$

Heavy neutrinos charged under a dark U(1)' symmetry, broken at the GeV

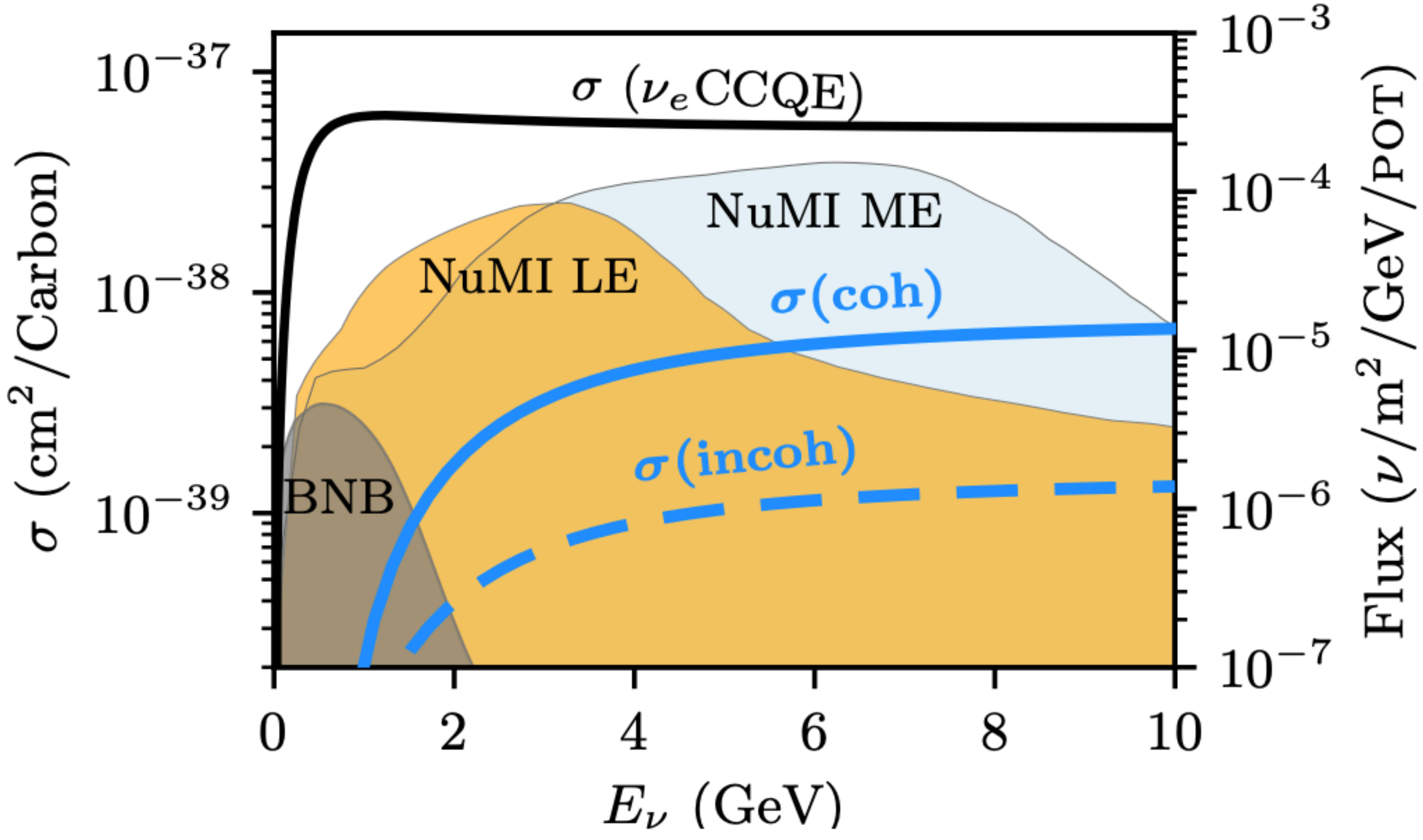
$$\mathcal{L} \supset \mathcal{L}_{\rm SM} - \frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{\sin\chi}{2} X_{\mu\nu} B^{\mu\nu} + (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi) - \lambda_{\Phi H} |H|^2 |\Phi|^2$$
$$+ \overline{\widehat{\nu}_N} i \partial\!\!\!/ \widehat{\nu}_N + \overline{\widehat{\nu}_D} i D\!\!\!\!/_X \widehat{\nu}_D - \left[(\overline{L}\widetilde{H}) Y \widehat{\nu}_N^c + \frac{1}{2} \overline{\widehat{\nu}_N} M_N \widehat{\nu}_N^c + \overline{\widehat{\nu}_N} \left(Y_L \widehat{\nu}_{D_L}^c \Phi + Y_R \widehat{\nu}_{D_R} \Phi^* \right) + \overline{\widehat{\nu}_D} M_X \widehat{\nu}_D + \text{h.c.} \right],$$

See also B. Batell et al, JHEP 1608 (2016) 052, Bertuzzo et al, PLB 791 (2019) 210-214 + others

Transition magnetic moment

MINERvA limits from $\nu - e$ scattering measurement

C. Arguelles, MH, Y. Tsai, PRL123.261801



MINERvA was located in the NuMI beam — larger energy and more neutrinos, but no dedicated search.

Nuclear Form Factors