

Neutrinos Experiments and Heavy Neutral Leptons



University of Minnesota

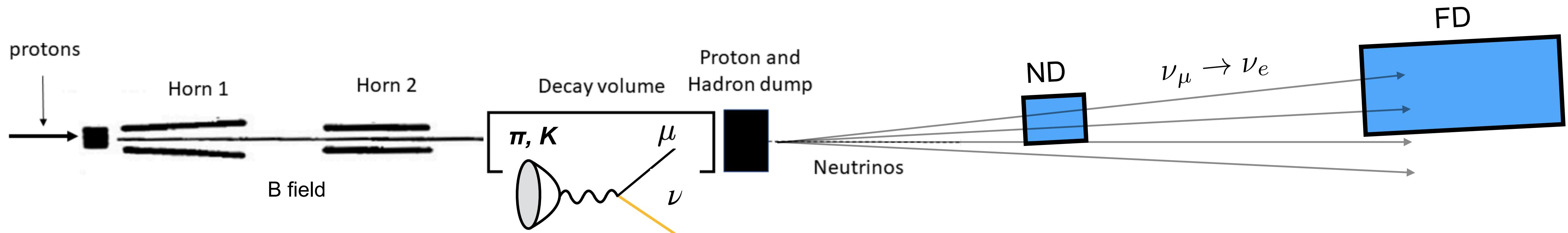
PITT PACC NuTools Workshop, December 14th, 2022

Matheus Hostert

Perimeter Institute
University of Minnesota



Why Neutrino Experiments?

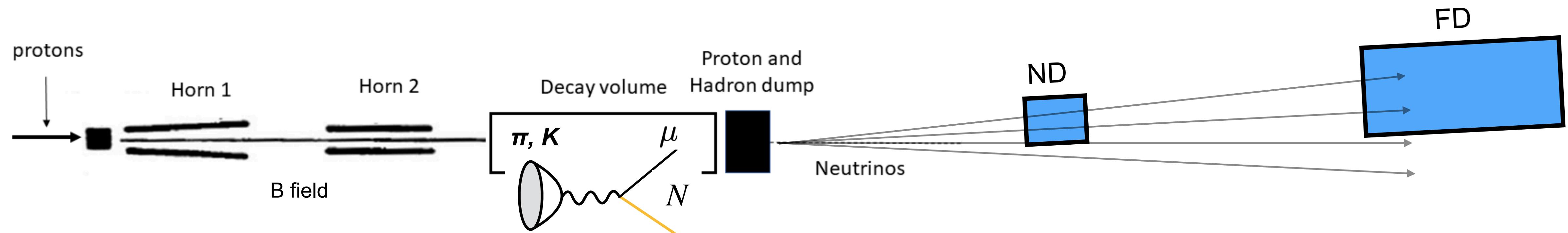


Neutrino experiments are, by construction, sensitive to very rare phenomena.

Very schematically,

$$N \sim (N_{\text{POT}} N_{\text{protons}}) \times \left(\frac{G_F^2 E_\nu m_p}{L^2} \right) > 10^{41}$$

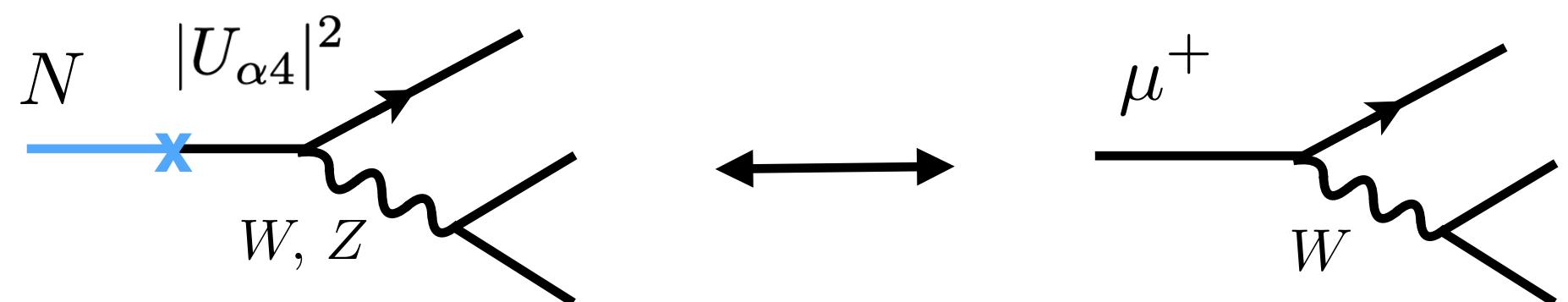
Heavy neutral leptons @ neutrino experiments



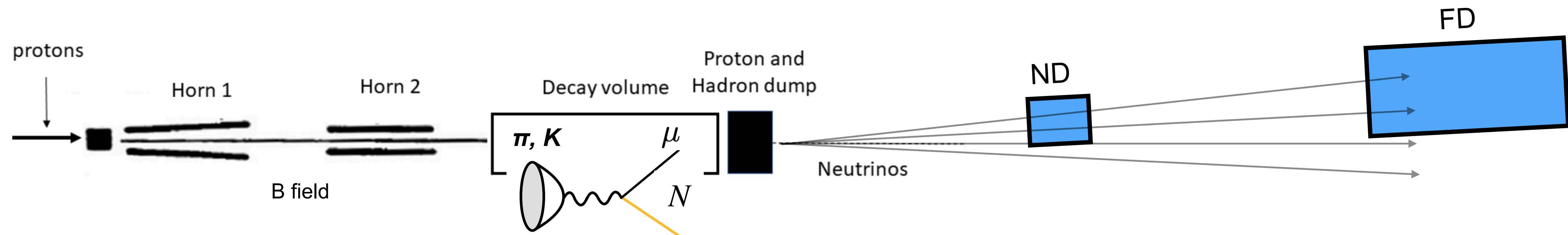
Heavy Neutral Leptons

Typically, long-lived particles.

$$\frac{c\tau_\mu}{c\tau_N} \sim |U_{\alpha 4}|^2 \left(\frac{m_N}{m_\mu}\right)^5$$



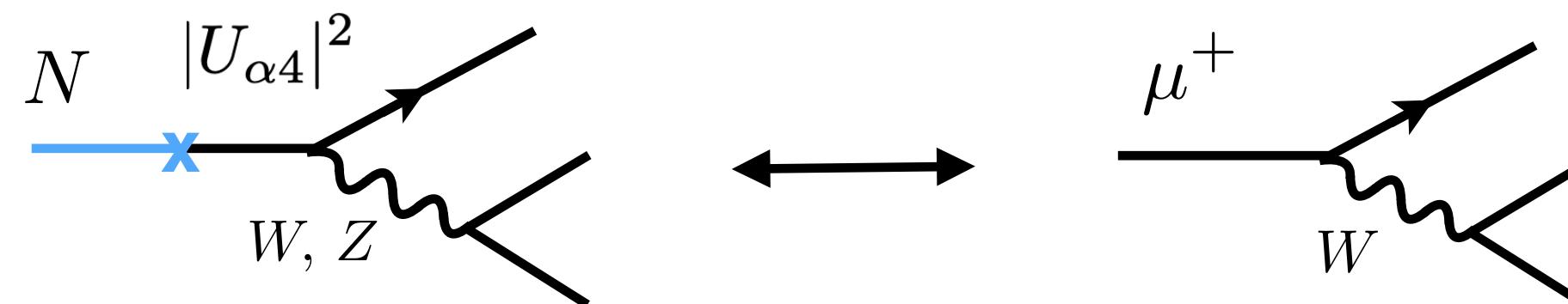
Heavy neutral leptons @ neutrino experiments



Heavy Neutral Leptons

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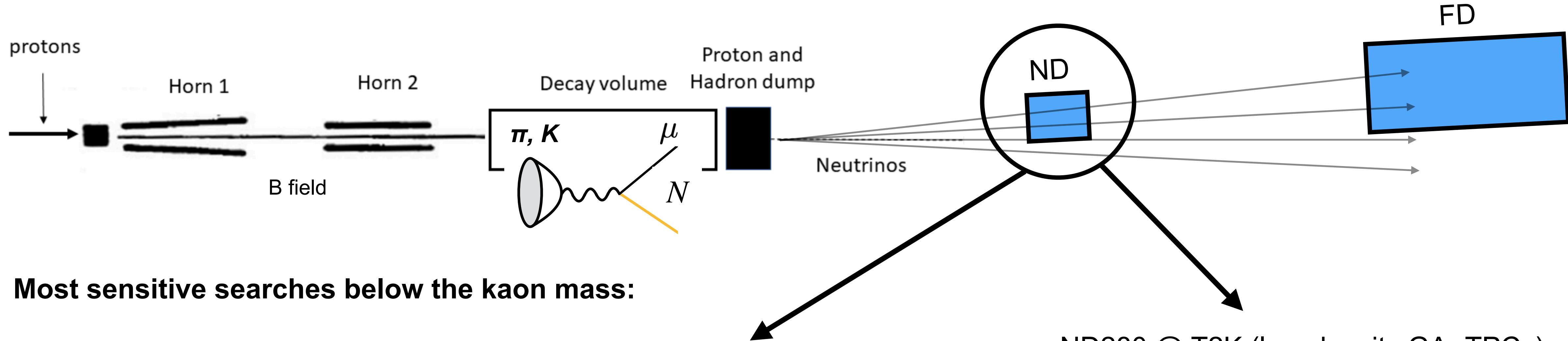
$$N \sim N_{\text{POT}} \times \left(G_F^2 m_N^5 \times V_{\text{det}} \times \frac{1}{L^2} \times \frac{m_N}{E_N} \right) \times |U_{\alpha N}|^4$$

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

Decay-in-flight searches

T2K near detector (ND280)

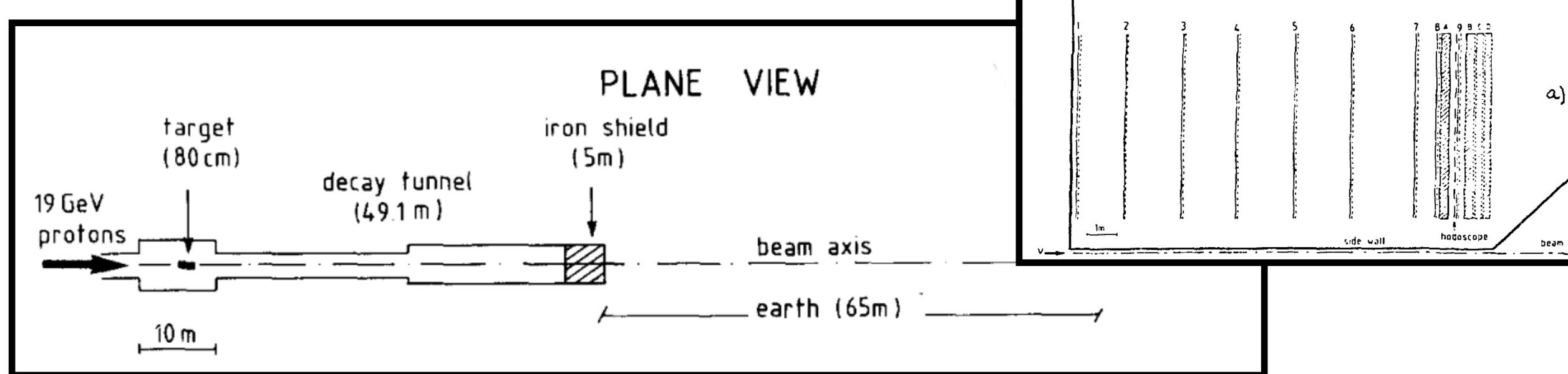
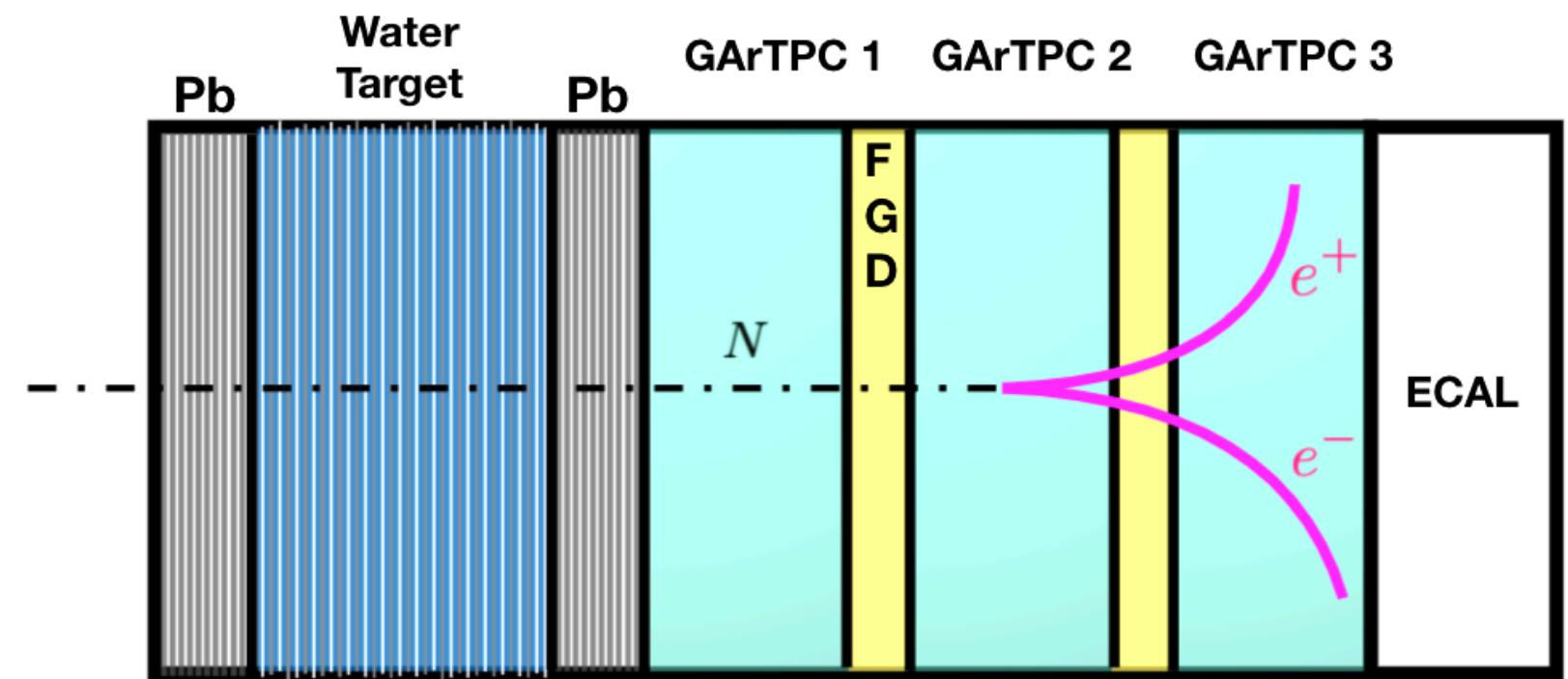
C. Argüelles, N. Foppiani, MH arxiv:2109.03831



Most sensitive searches below the kaon mass:

PS191 (low-density Helium bags)
(1985 — 1 month of data)

ND280 @ T2K (low-density GAr TPCs)

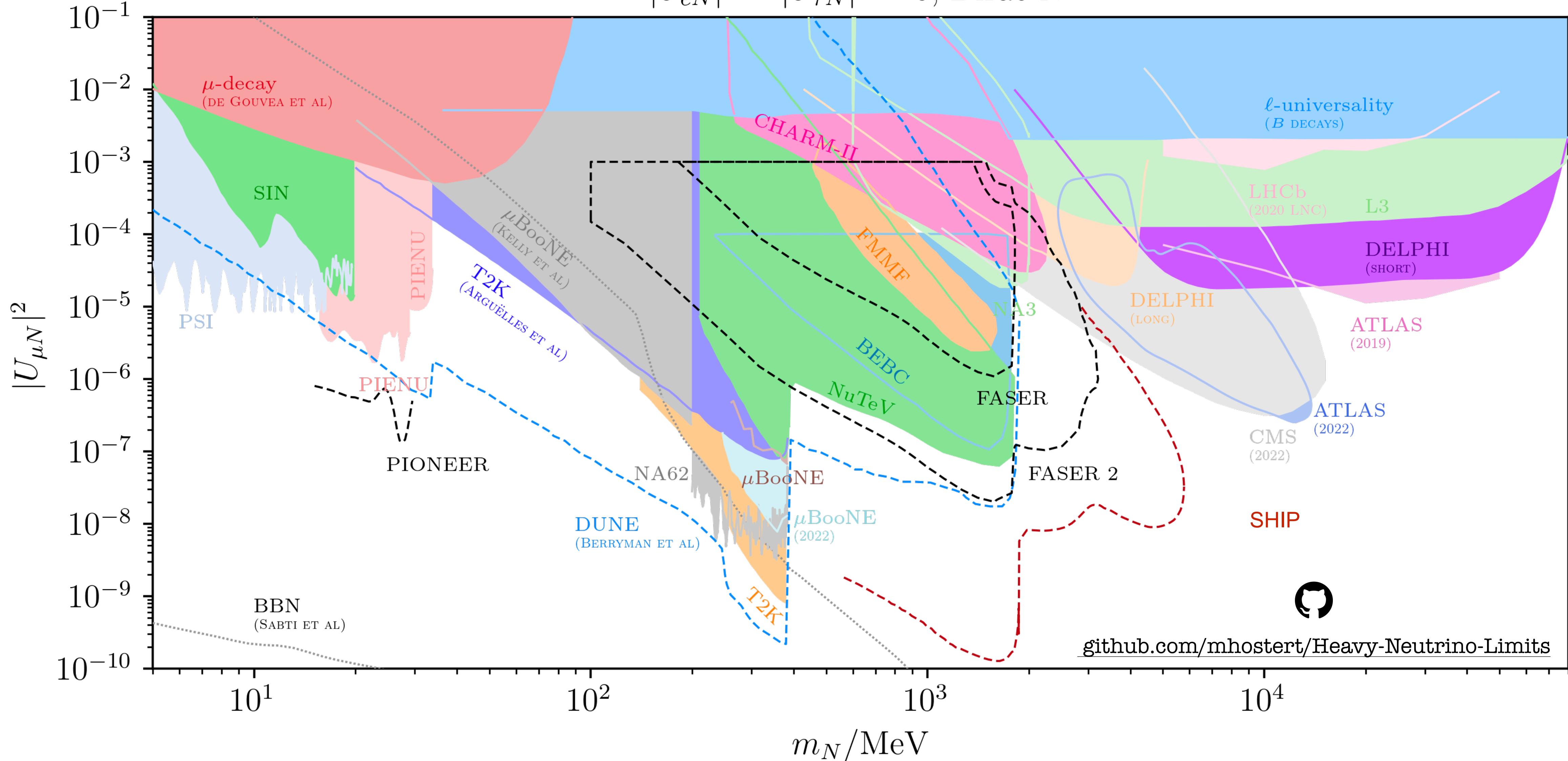


G. Bernardi et al, Phys. Lett. 166B (1986) 479–483

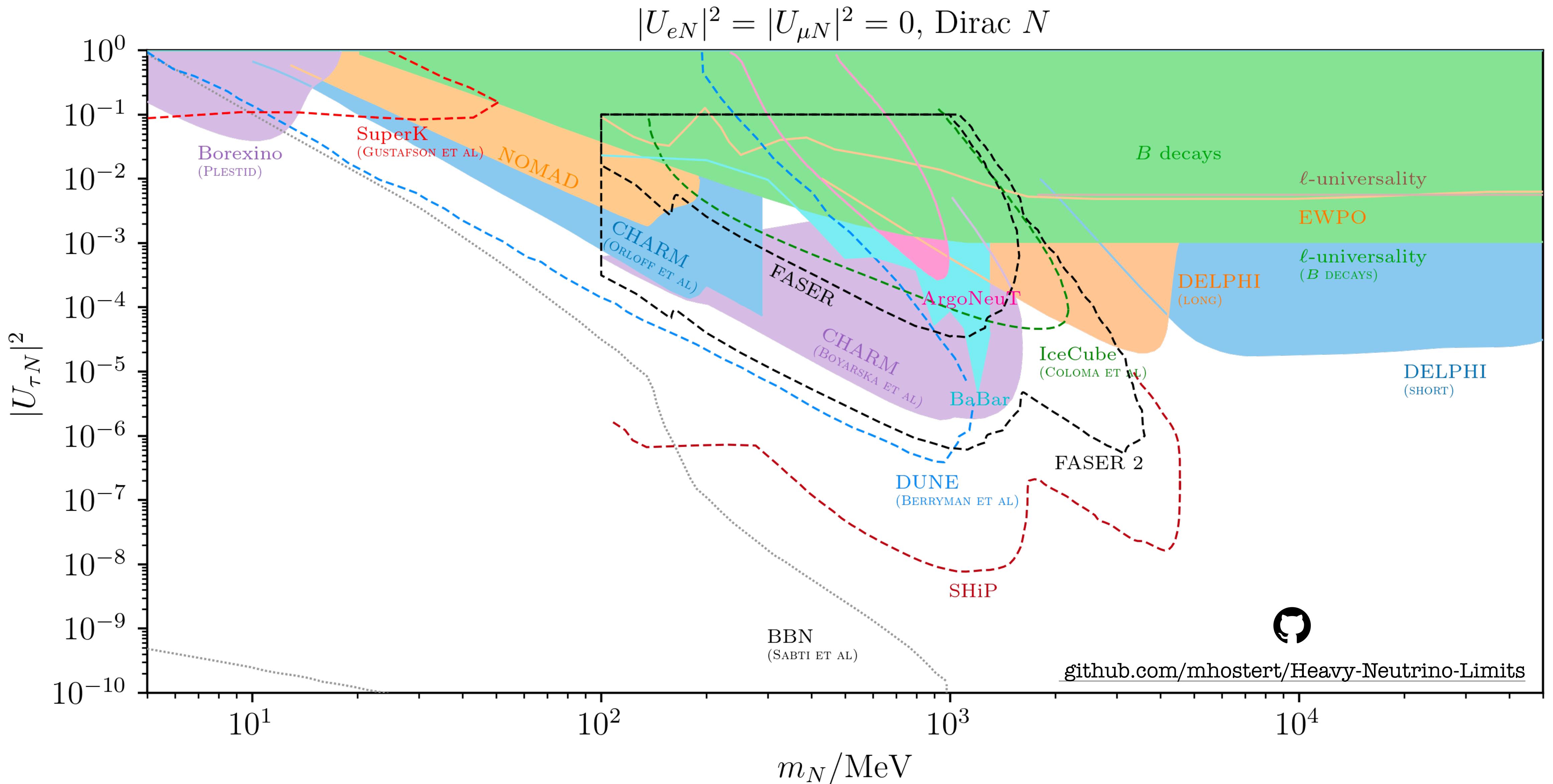
T2K collaboration, PRD 100 (2019) 5, 052006

Limits on heavy neutrinos

$$|U_{eN}|^2 = |U_{\tau N}|^2 = 0, \text{ Dirac } N$$



Limits on heavy neutrinos

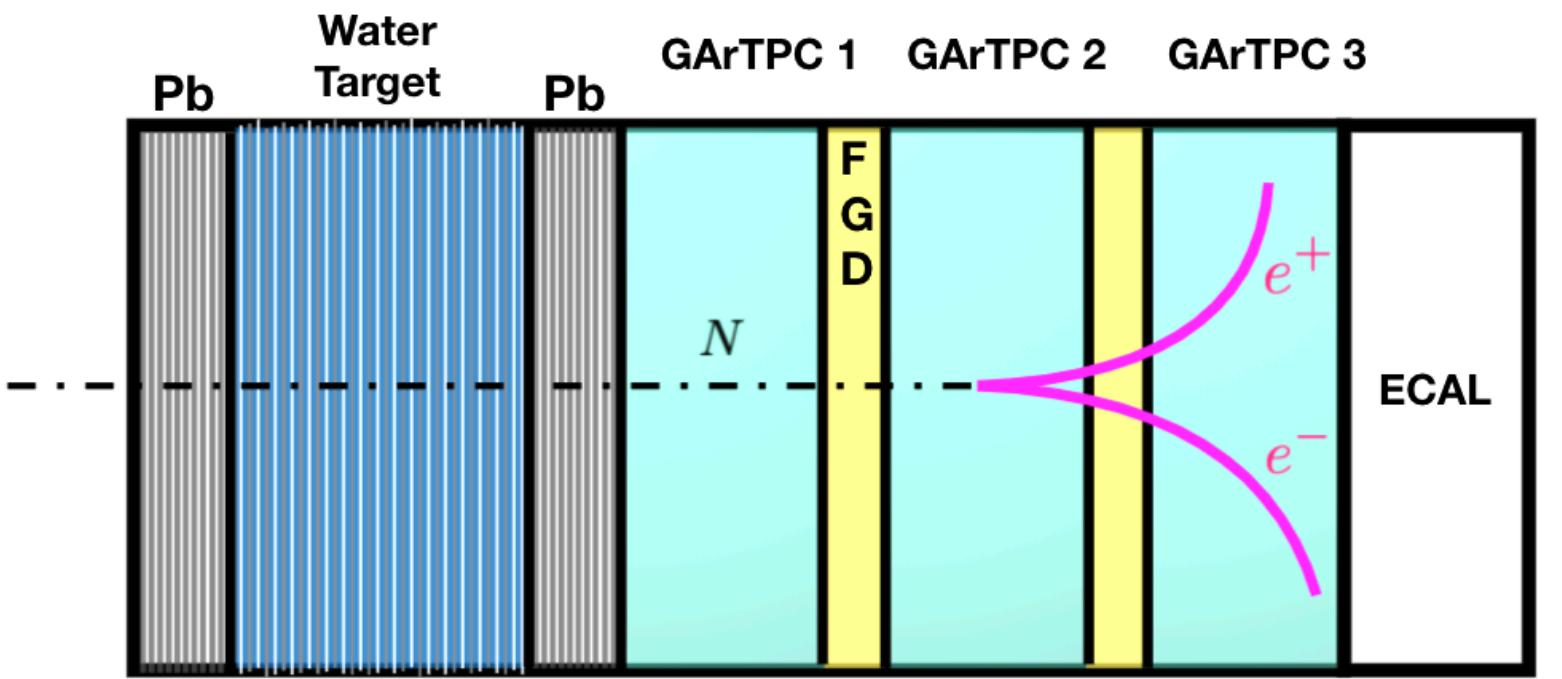


Decay-in-flight searches

T2K near detector (ND280)

T2K collaboration, *PRD* 100 (2019) 5, 052006

C. Argüelles, N. Foppiani, MH [arxiv:2109.03831](https://arxiv.org/abs/2109.03831)



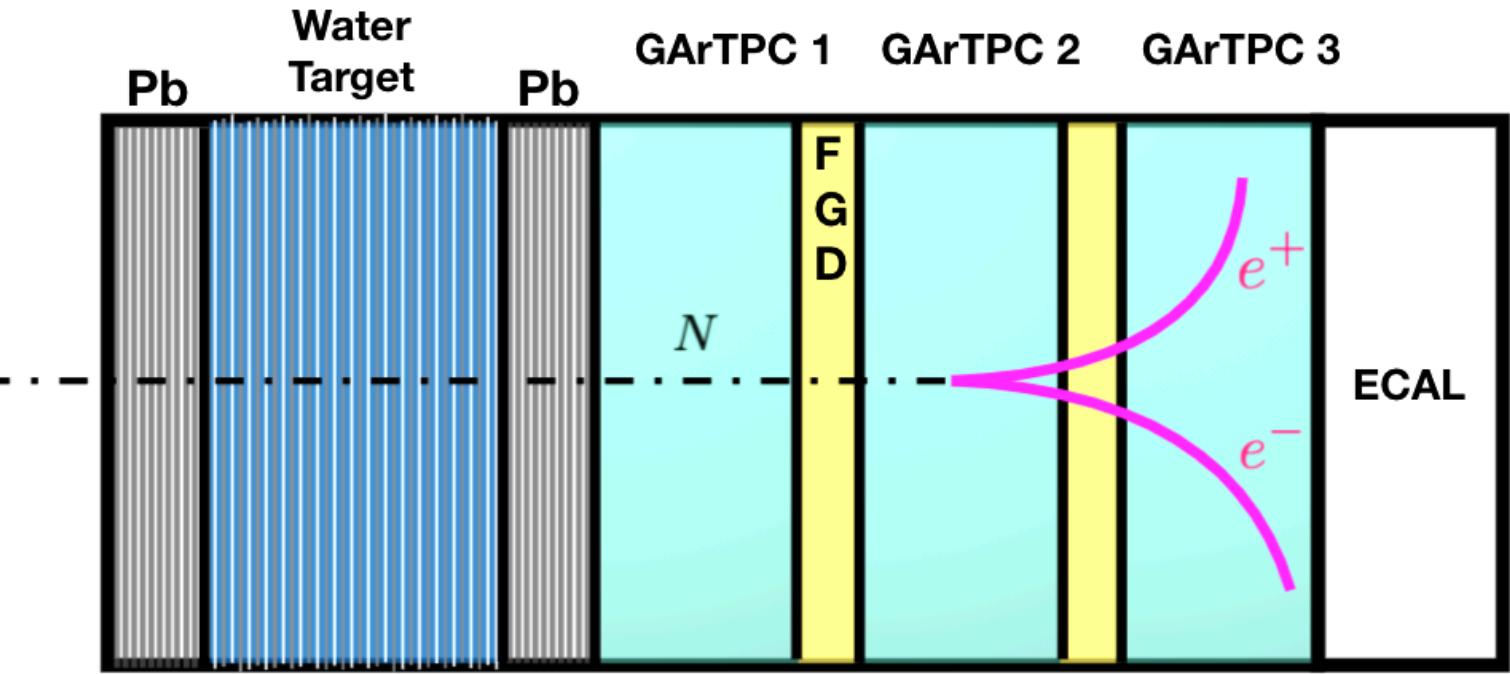
T2K performed a nearly-background-free search in multiple channels, saw no events.

Decay-in-flight searches

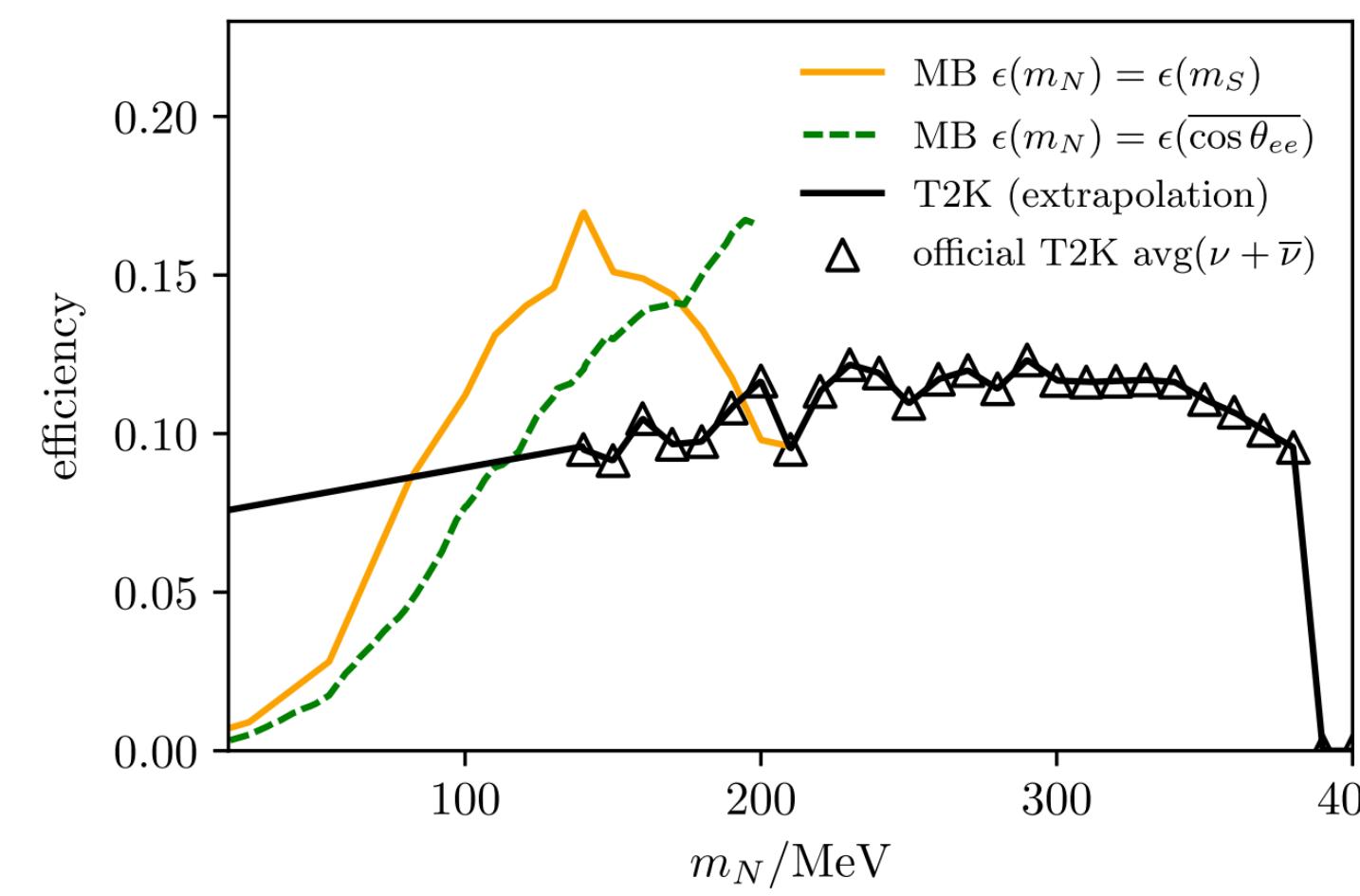
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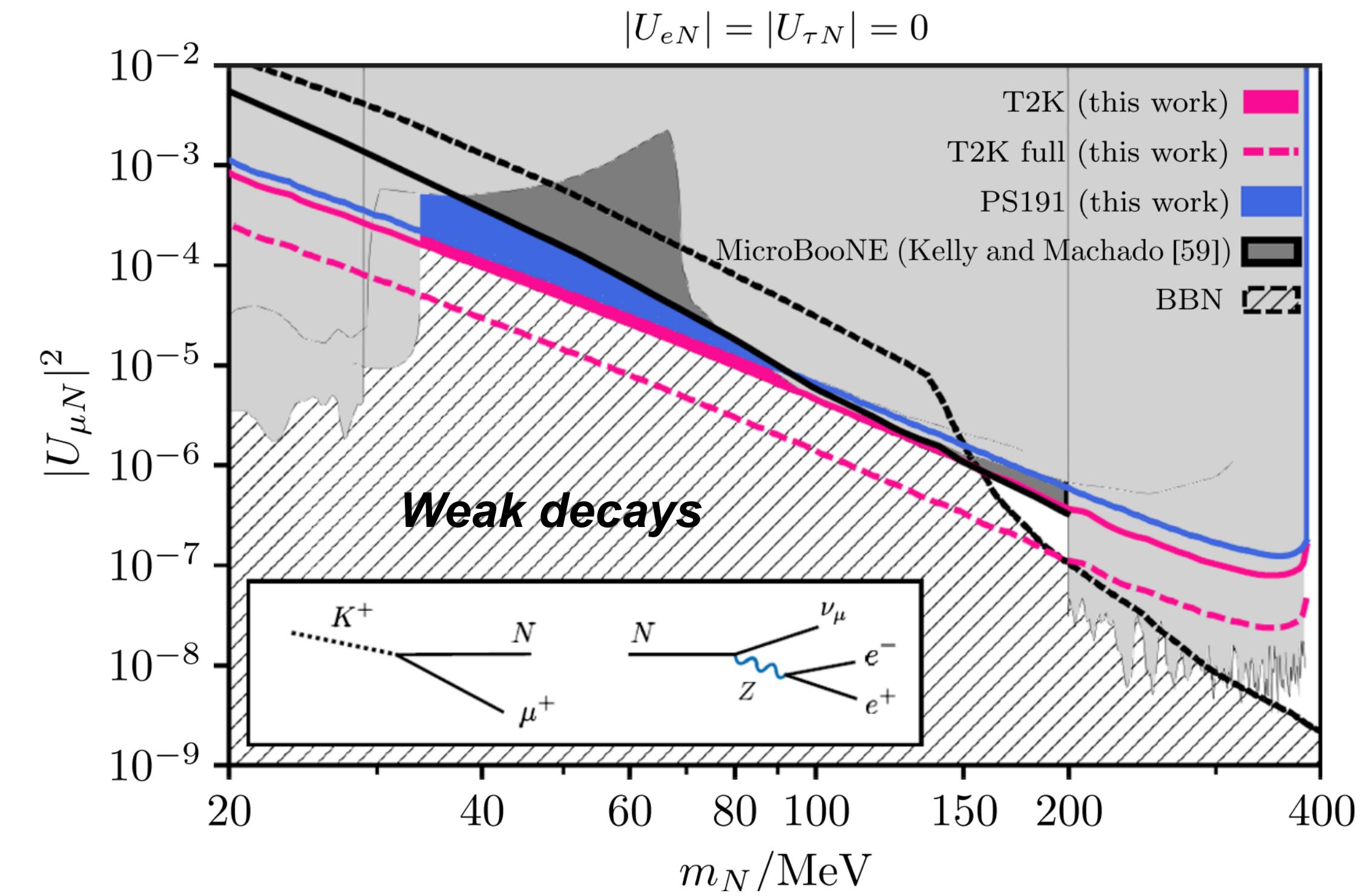


T2K performed a nearly-background-free search in multiple channels, saw no events.



We extended these limits to $M_N < M_\pi$ by extrapolating efficiencies.

Re-evaluated PS-191 limits (~ 7 times weaker than lit), and showed that **T2K provides the leading limits on HNLs decaying to e+e- below the kaon mass***.

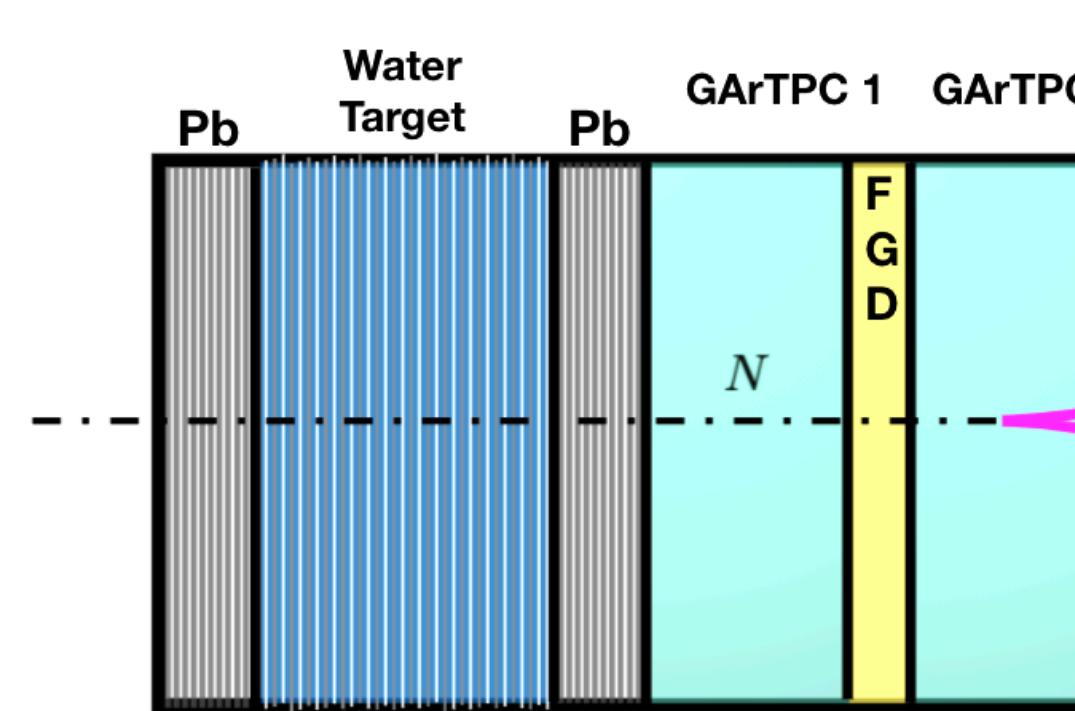


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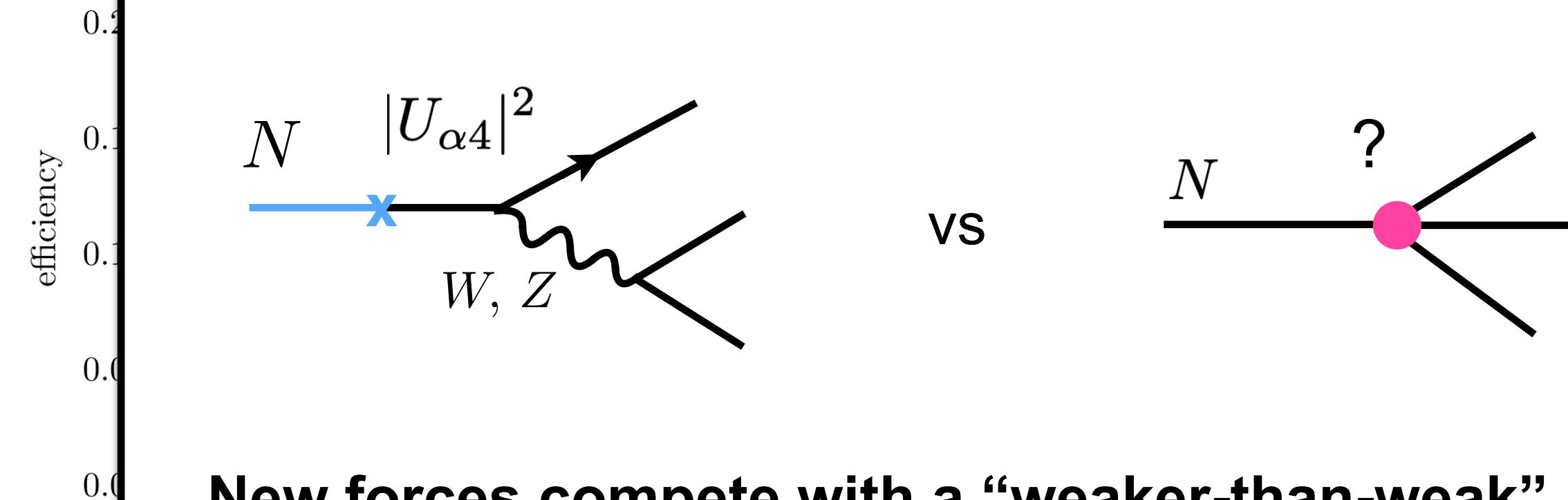
T2K performed a nearly-barrier search in multiple channels,

We extended these limits to $M_N < M_\pi$ by extrapolating efficiencies.

Cosmological constraints from BBN are complementary, and severely constraint HNLs below the kaon mass with

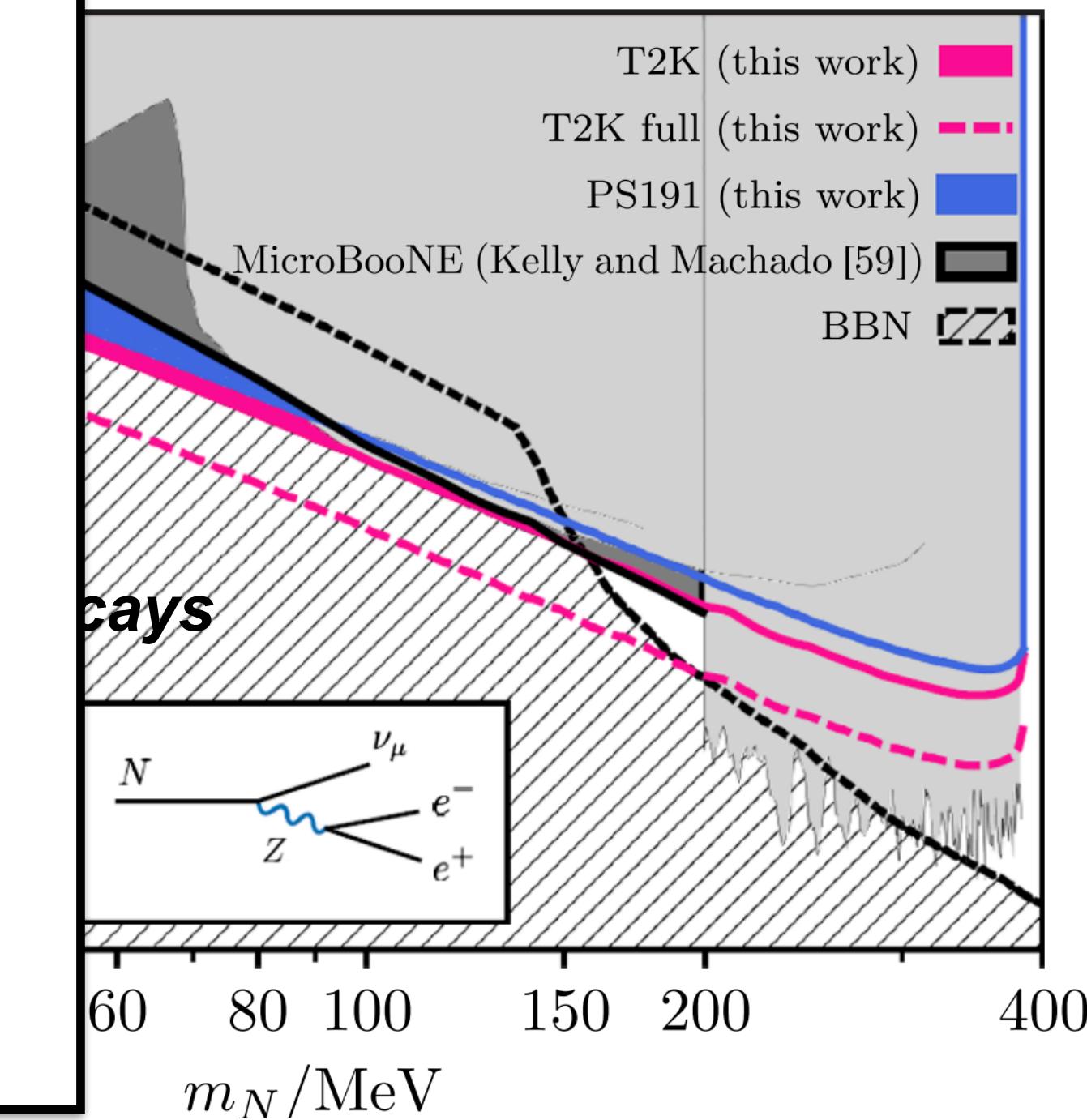
$$c\tau > O(0.1) \text{ s.}$$

But HNLs can be much shorter lived in the presence of new interactions.



limits (~ 7 times weaker than lit),
provides the leading limits on HNLs e- below the kaon mass*.

$$|U_{eN}| = |U_{\tau N}| = 0$$



Decay-in-flight searches

T2K near detector (ND280)

C. Argüelles, N. Foppiani, MH [arxiv:2109.03831](https://arxiv.org/abs/2109.03831)

Event rate proportional to new physics decay rate

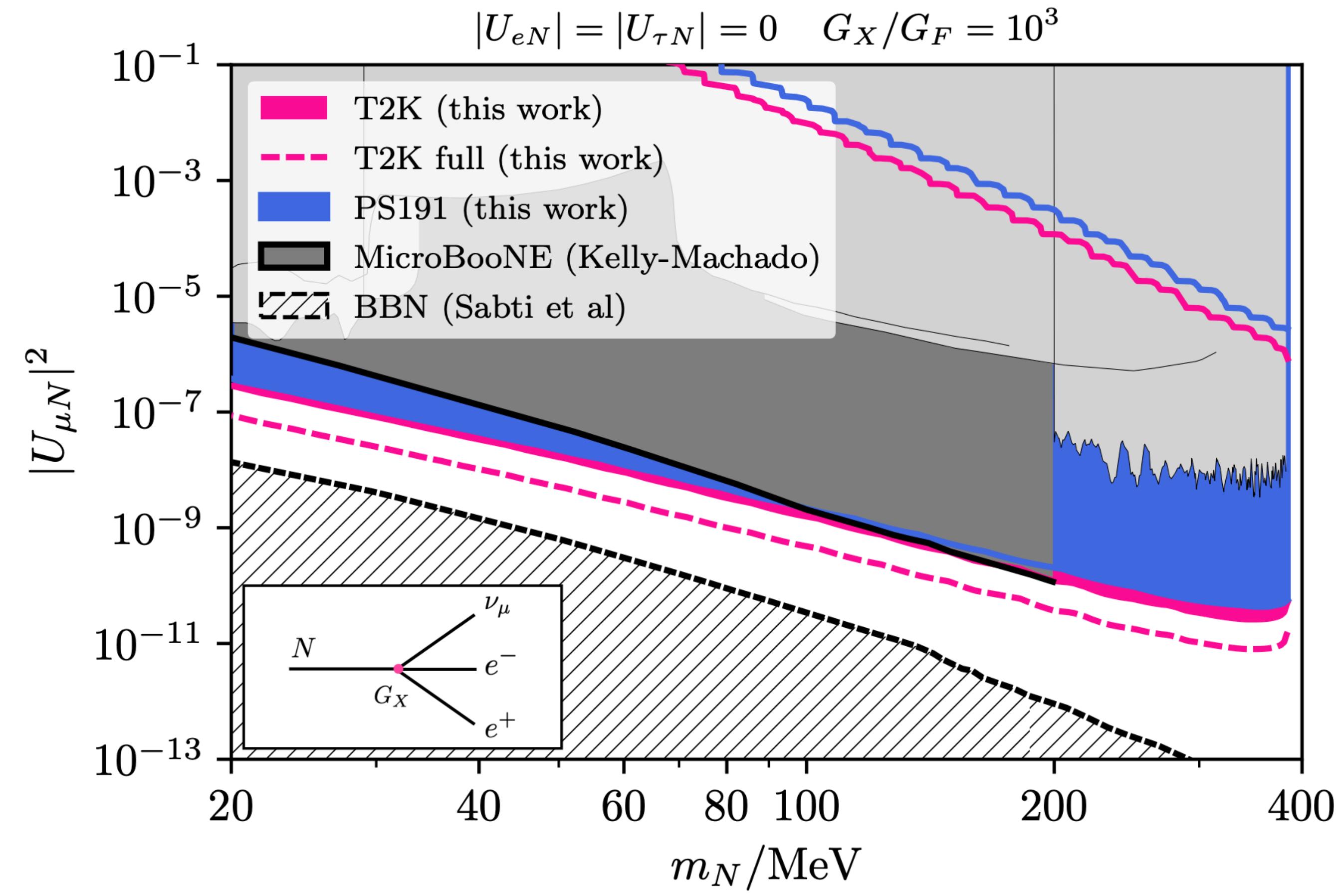
$$P_{N \rightarrow X} \simeq \frac{\ell_{\text{det}}}{\gamma \beta} \Gamma_{N \rightarrow X}$$

Very sensitive to additional contribution to decay rate

$$\Gamma_{N \rightarrow \nu e^+ e^-} = \Gamma^{\text{weak}} + \Gamma^{\text{new-physics}}$$

Consider a four-fermion vectorial interaction:

$$\mathcal{L} \supset \frac{G_X}{\sqrt{2}} (\bar{N} \gamma^\mu N) (\bar{\ell}_\beta \gamma_\mu \ell_\beta) + \text{h.c.}$$



If decay proceeds via neutrino mixing,
the new force ought to be stronger than weak.

Decay-in-flight searches

T2K near detector (ND280)

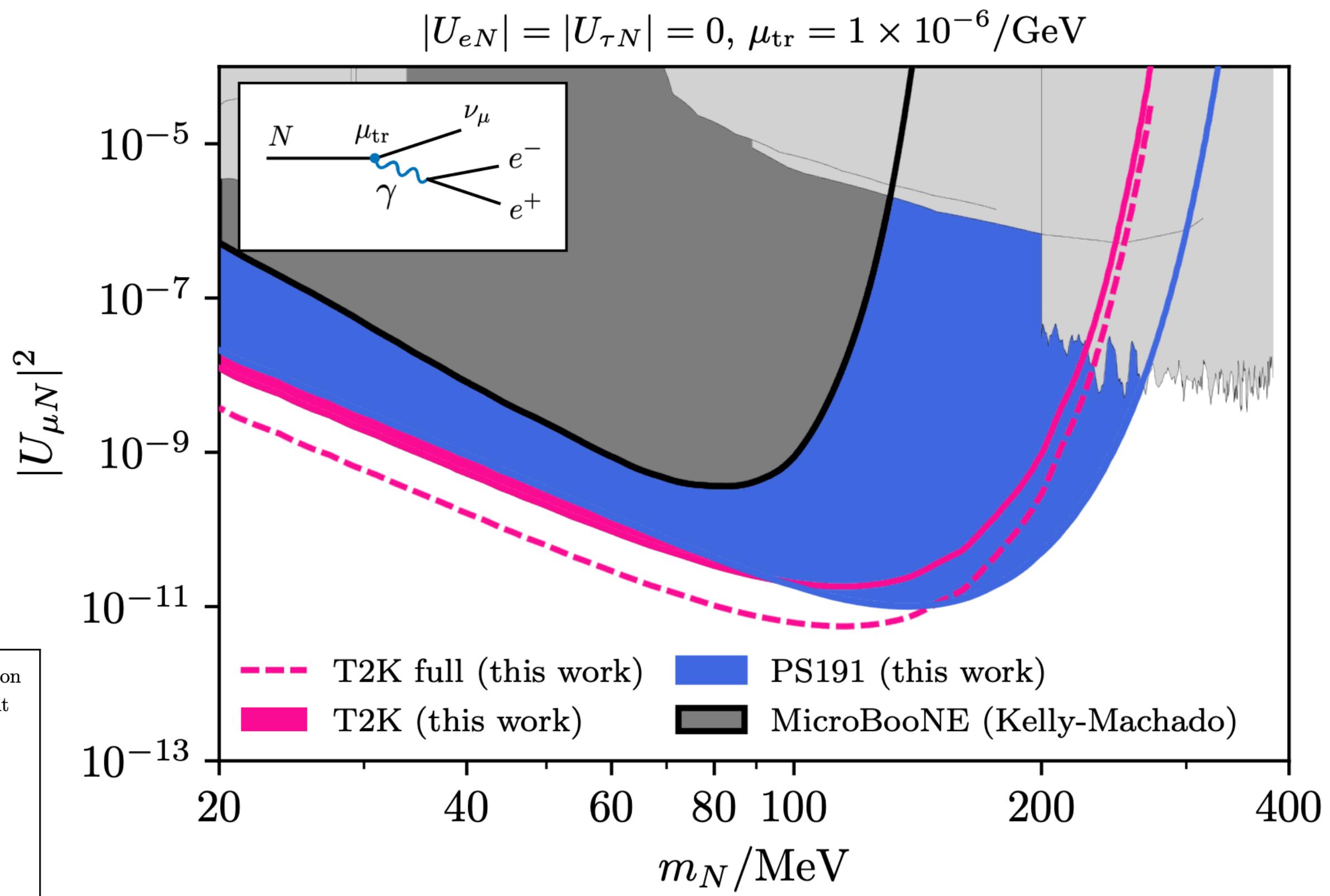
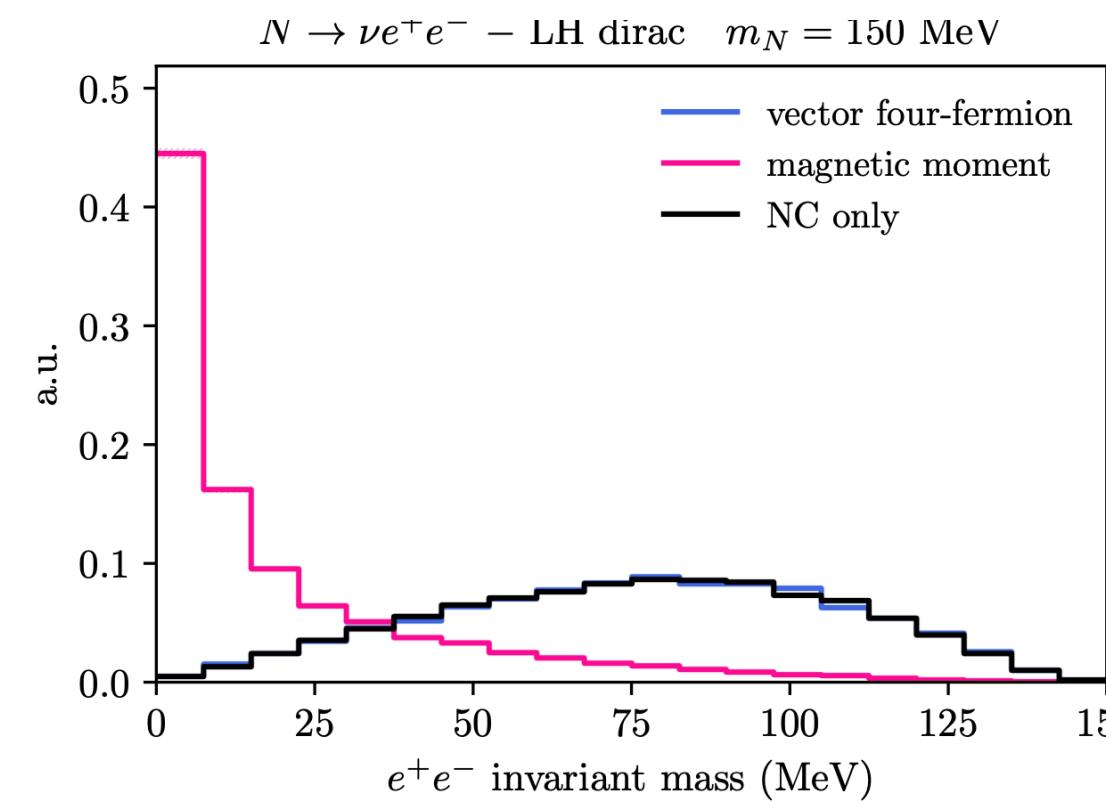
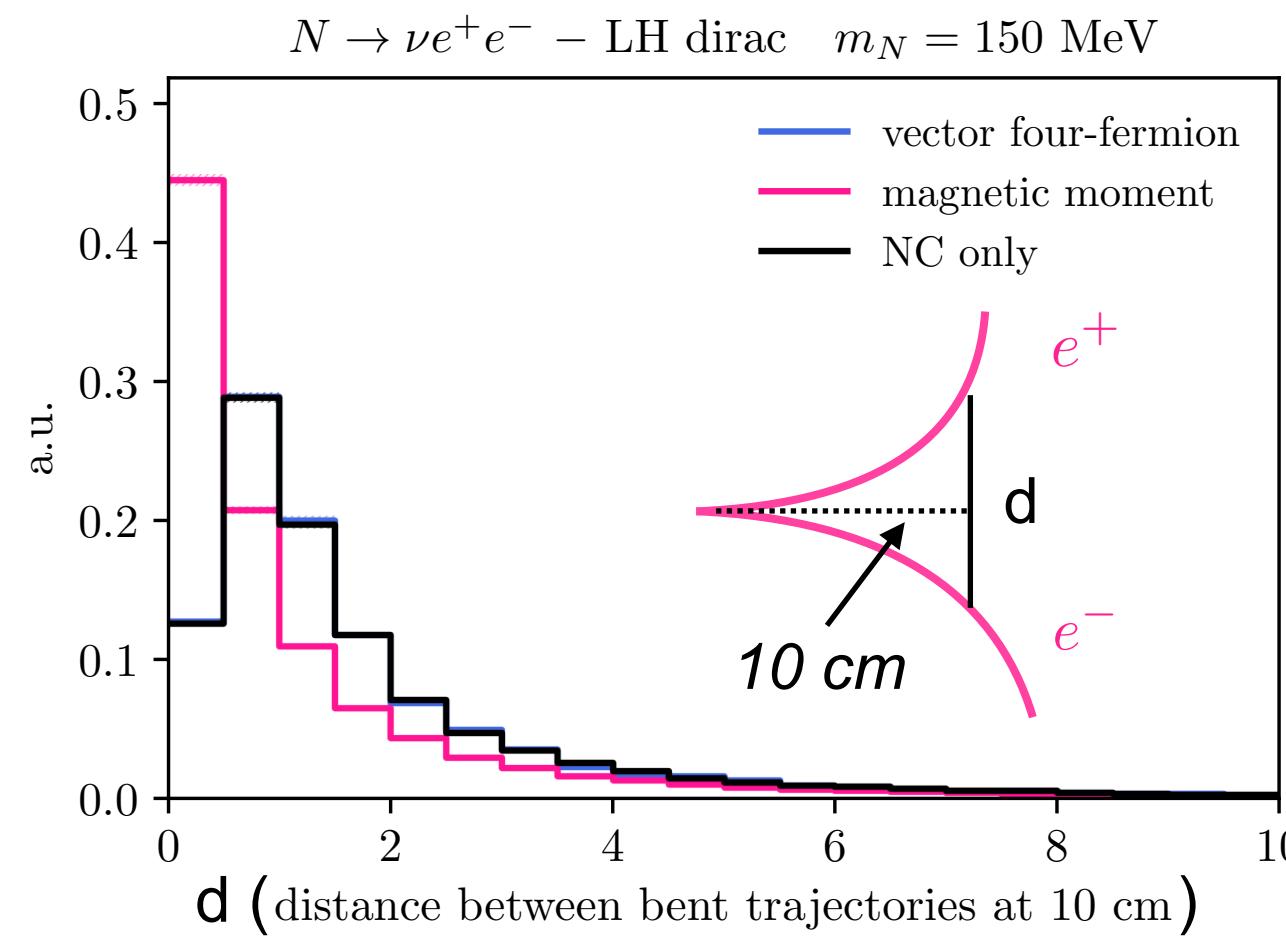
C. Argüelles, N. Foppiani, MH [arxiv:2109.03831](https://arxiv.org/abs/2109.03831)

The decays do not have to proceed via mixing. Consider a transition magnetic moment operator:

$$\mathcal{L} \supset \frac{\mu_{\text{tr}}}{2} \bar{\nu}_\alpha \sigma^{\mu\nu} N F_{\mu\nu}$$

Main decay into real photons: unfortunately, no good for low-density detectors like ND280.

But virtual photon rate is still competitive. Collimated e^+e^- : a greater challenge, but magnetic field ($B = 0.2$ T) helps.



Decay-in-flight searches

T2K near detector (ND280)

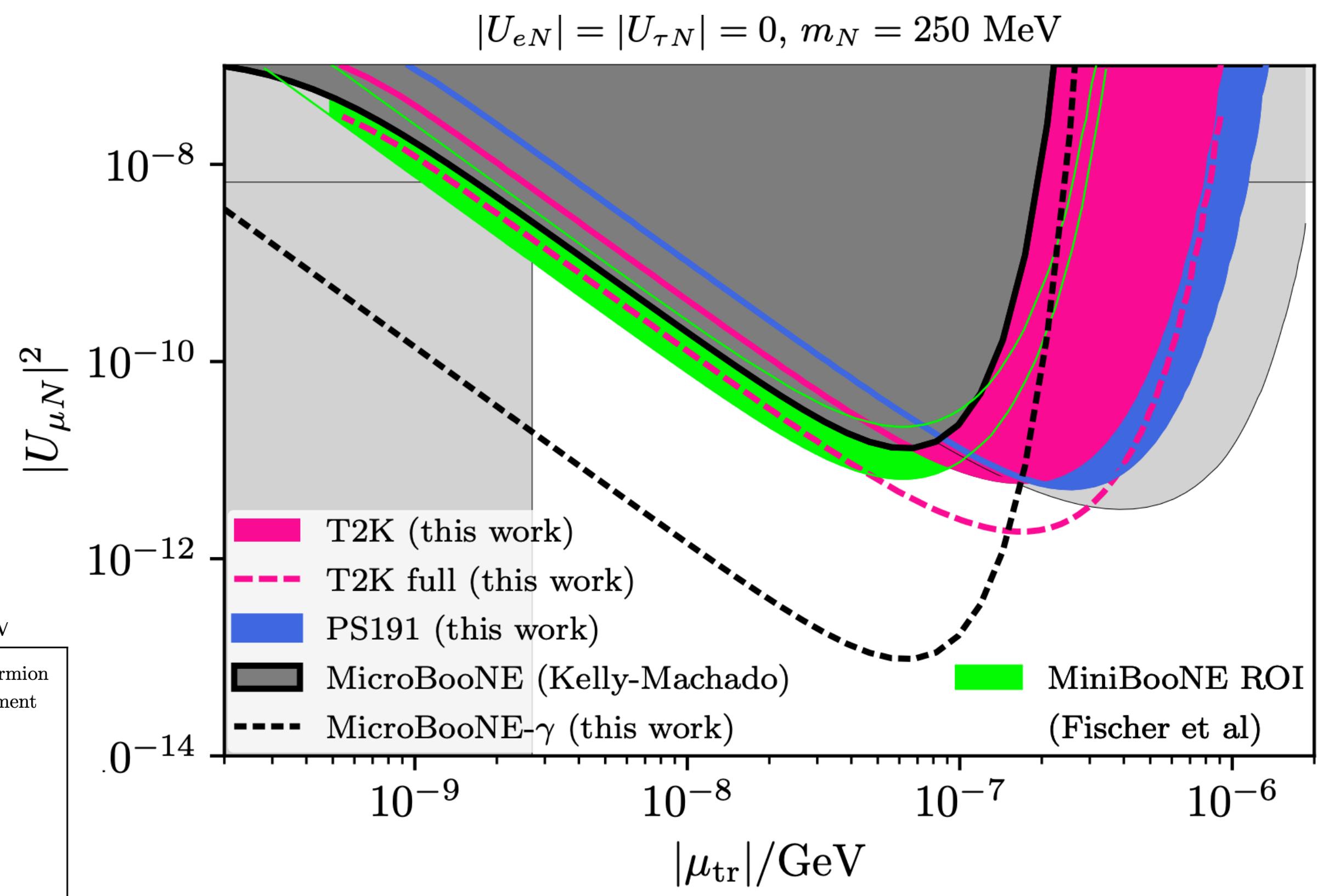
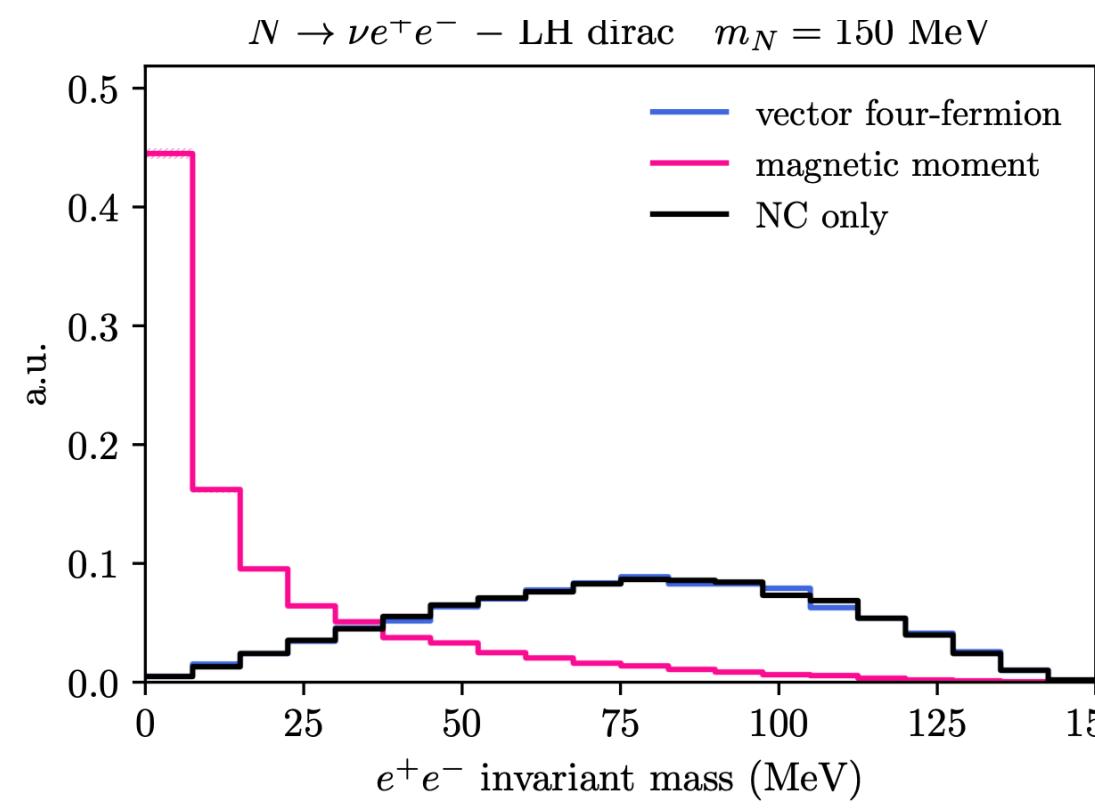
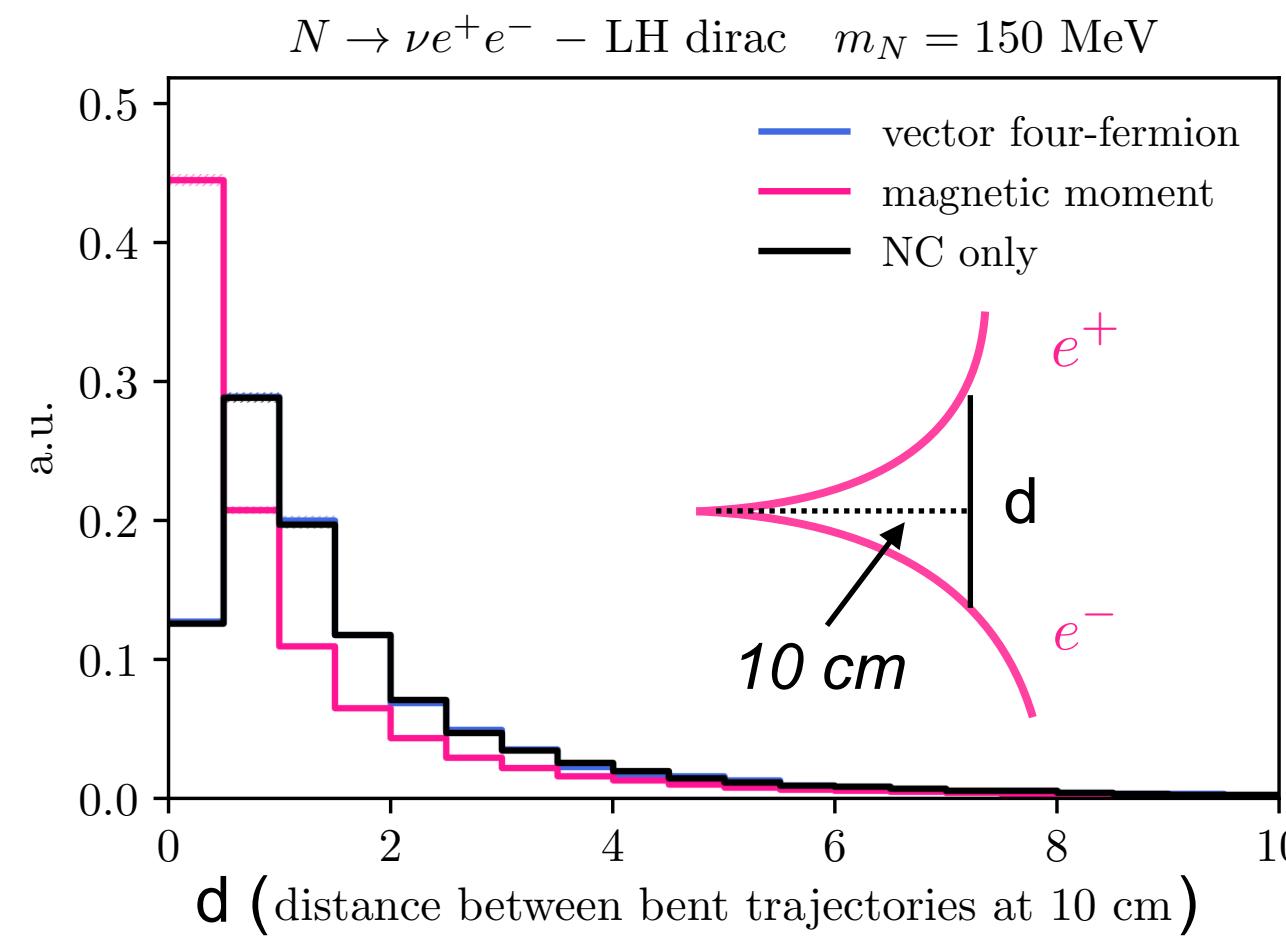
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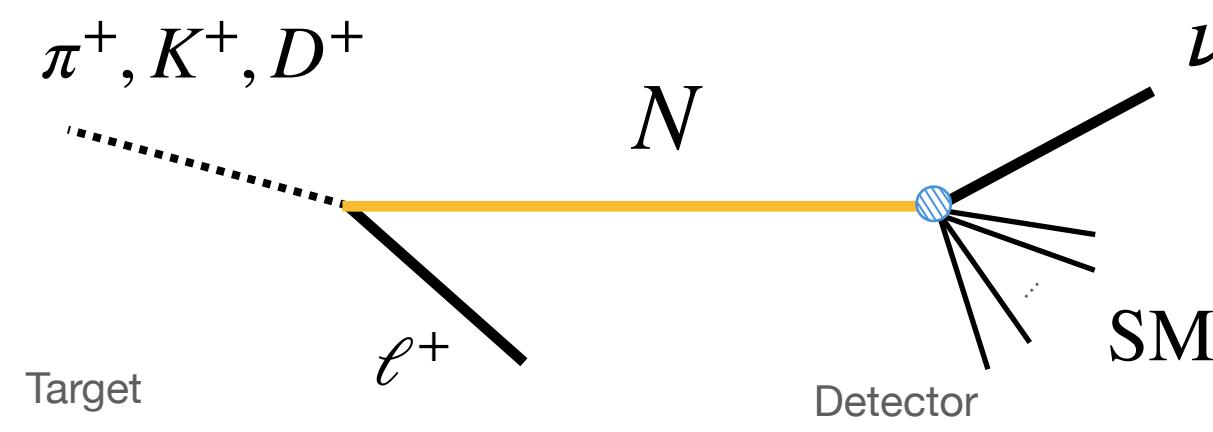


MicroBooNE (high-density LAr detector) can do significantly better with the photon channel, but backgrounds are more severe.

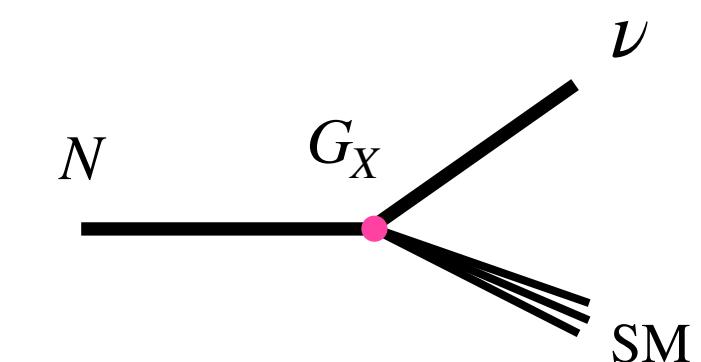
Dark decay channels of HNLs



Charged meson decays and DIF



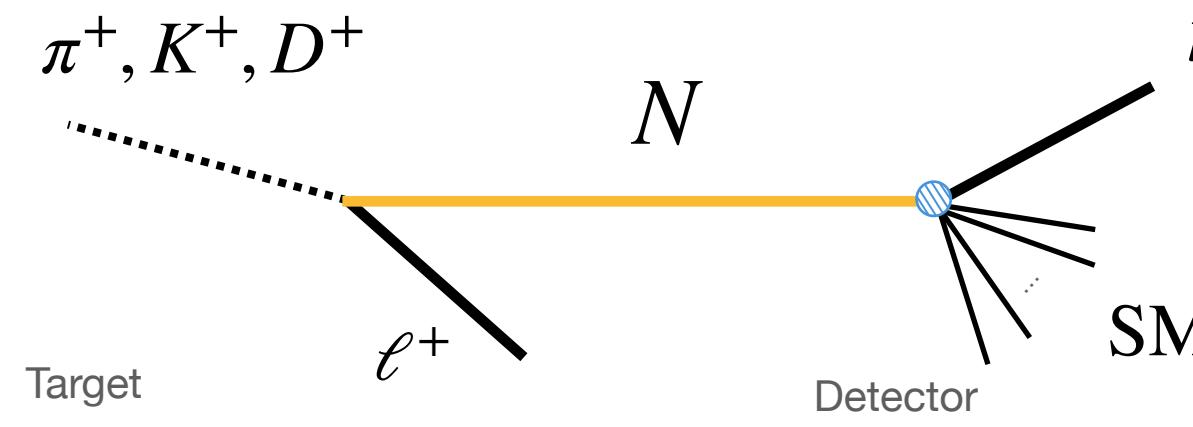
$$\Gamma_{N \rightarrow \nu \text{ SM}}^{\text{G}_X} / \Gamma_{N \rightarrow \nu \text{ SM}}^{\text{G}_F}$$



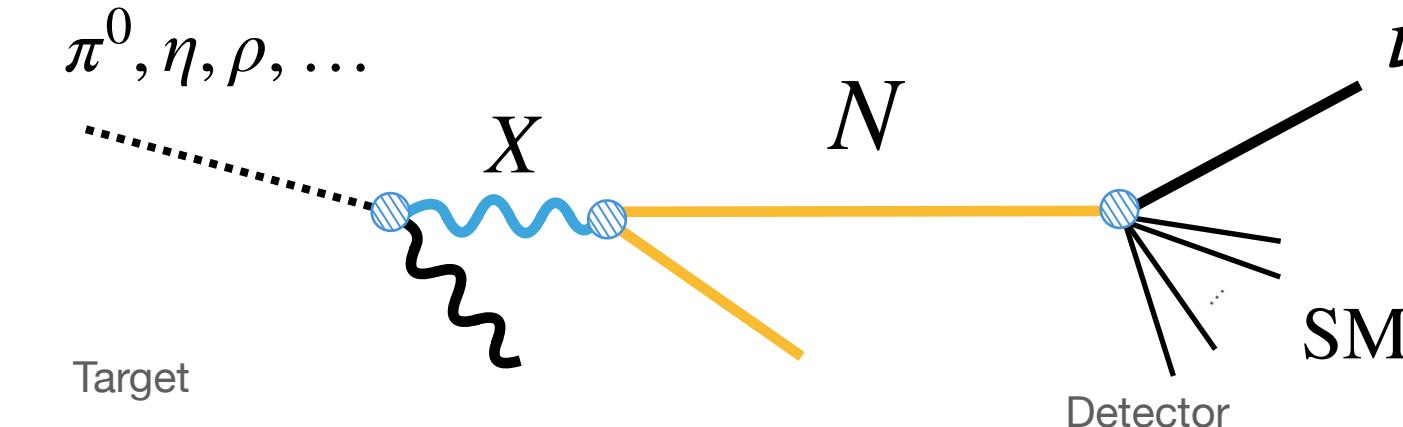
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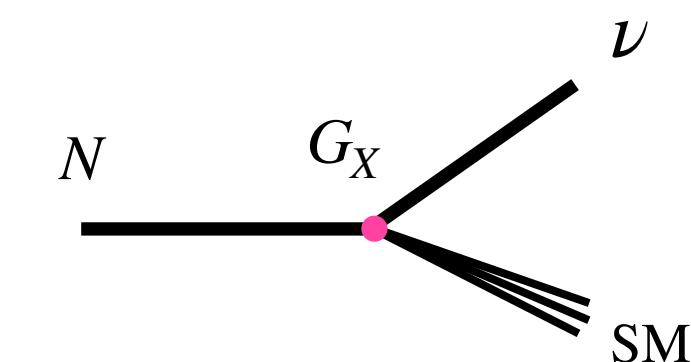
Charged meson decays and DIF



Neutral meson decays and DIF



1

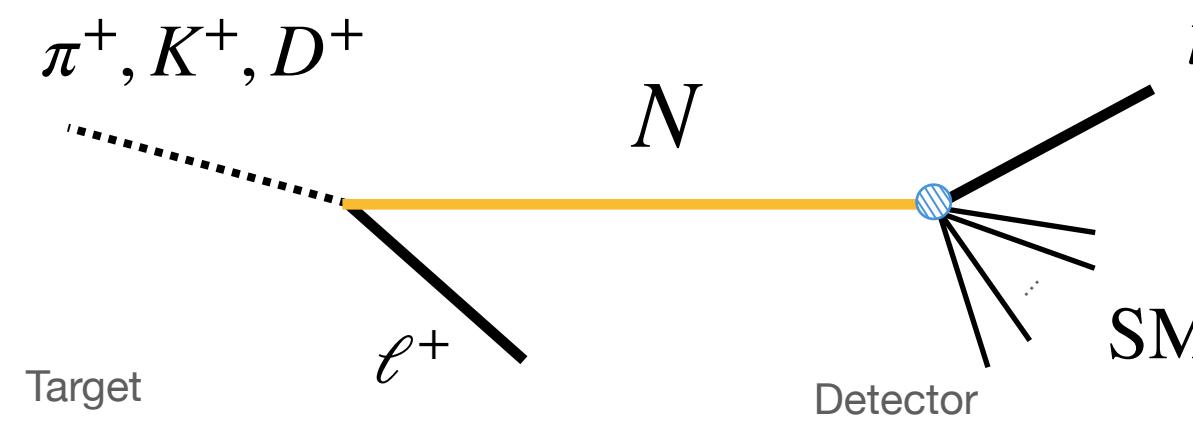


$$\Gamma_{N \rightarrow \nu \text{ SM}}^{G_X} / \Gamma_{N \rightarrow \nu \text{ SM}}^{G_F}$$

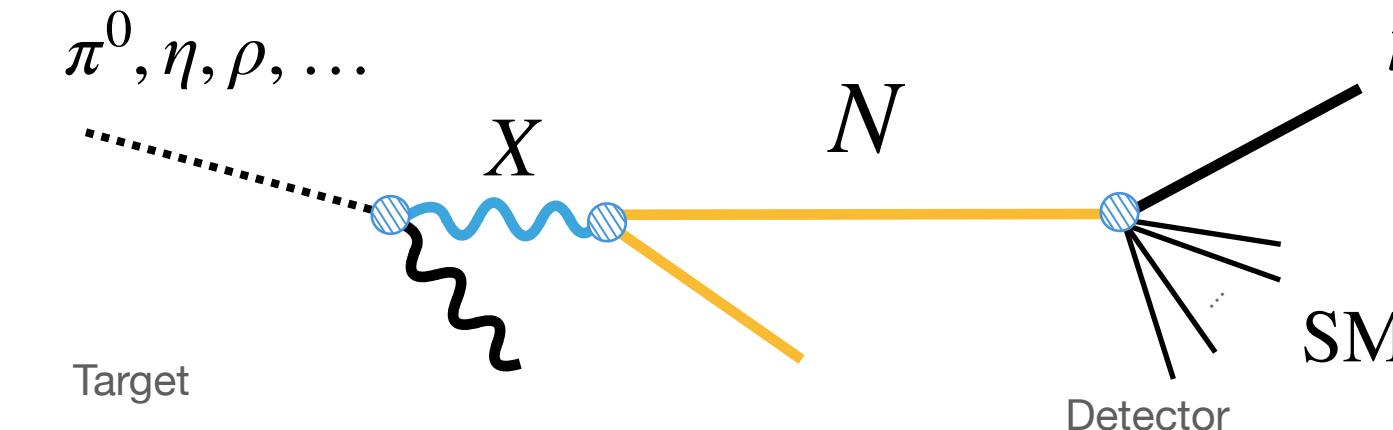
Dark decay channels of HNLs



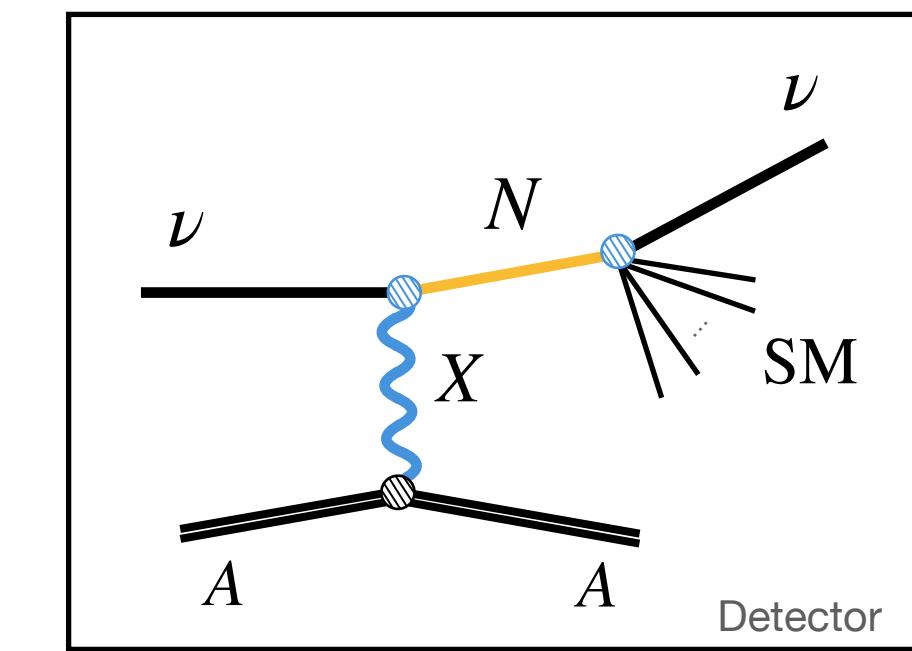
Charged meson decays and DIF



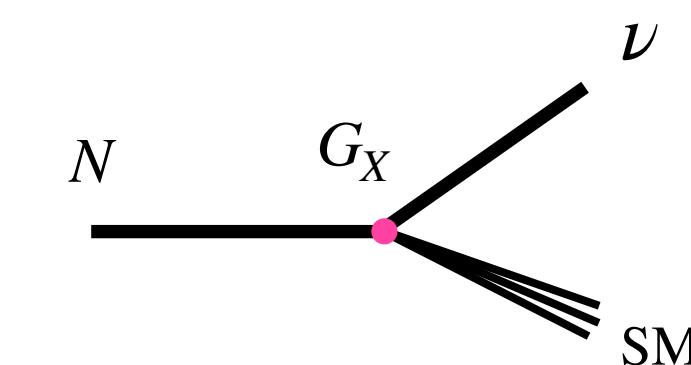
Neutral meson decays and DIF



Upscattering with prompt decay



1



$$\Gamma_{N \rightarrow \nu \text{ SM}}^{G_X} / \Gamma_{N \rightarrow \nu \text{ SM}}^{G_F}$$

Dark Sectors in the MiniBooNE Low-Energy Excess

Particle production inside the detector

E. Bertuzzo et al, [arXiv:1807.09877]

P. Ballett et al, [arxiv:1808.02915]

C. Argüelles, **MH**, Y. Tsai, [arXiv:1812.08768]

P. Ballett, **MH**, S. Pascoli, [arxiv:1903.07589]

A. Abdullahi, **MH**, S. Pascoli, [arXiv:2007.11813]

J. Liu et al, [arXiv:2001.06522]

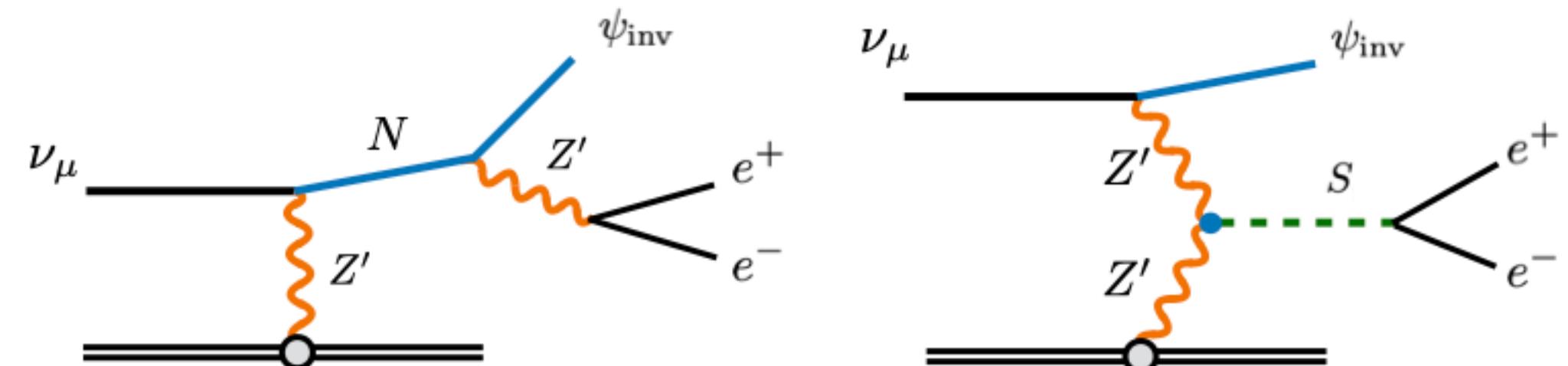
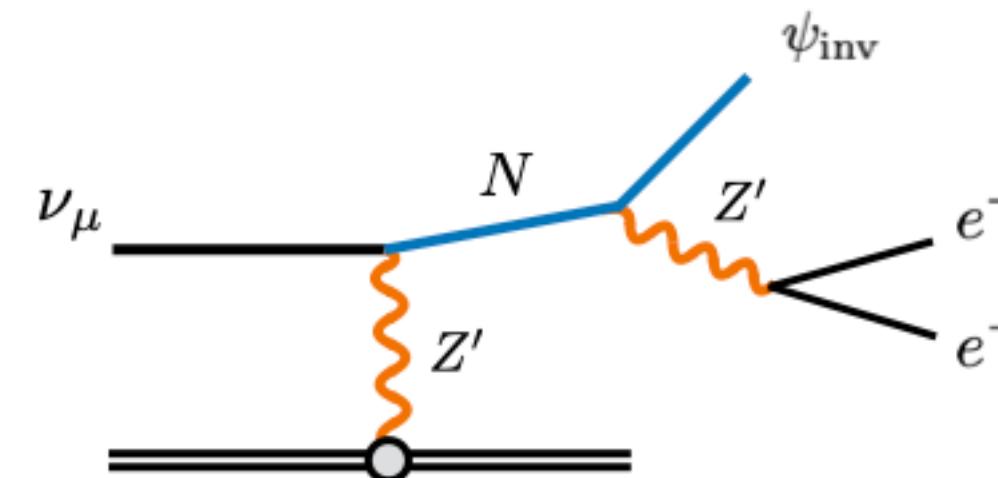
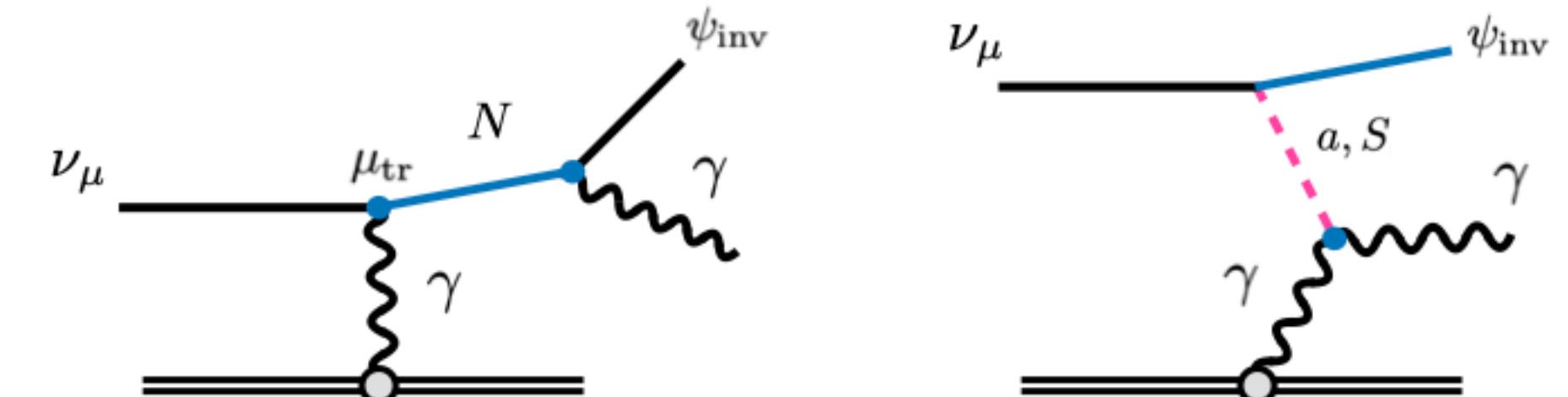
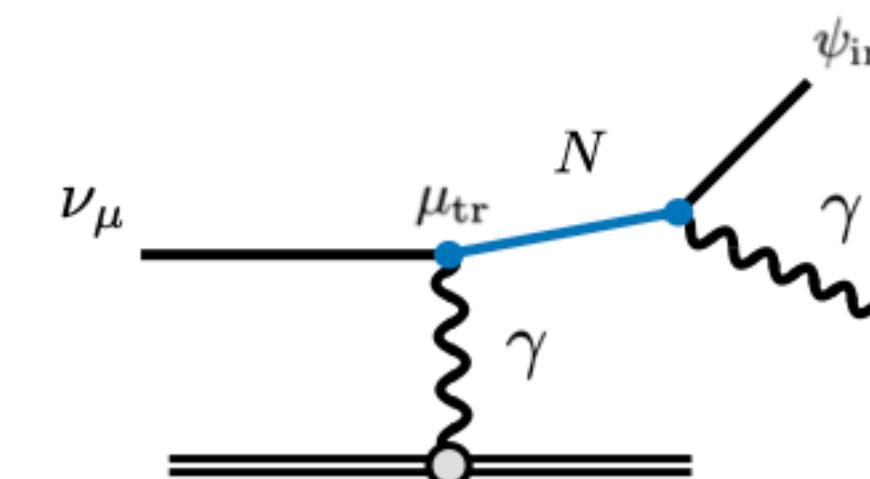
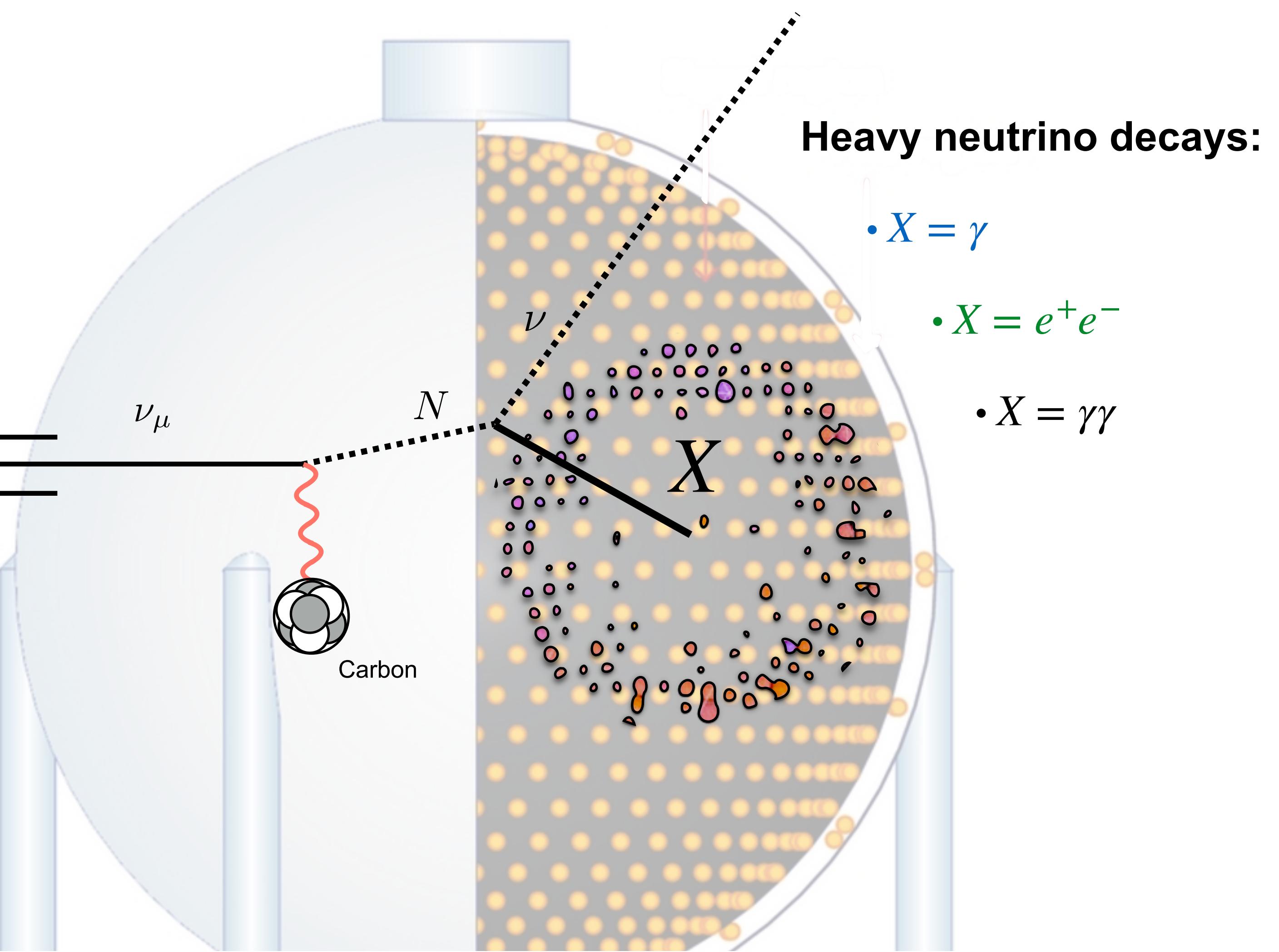
W. Abdallah et al, [arXiv:2202.09373]

B. Dutta et al, [arxiv:2006.01319]

A. Datta et al, [arXiv:2005.08920]

B. Dutta et al, [arxiv:2006.01319]

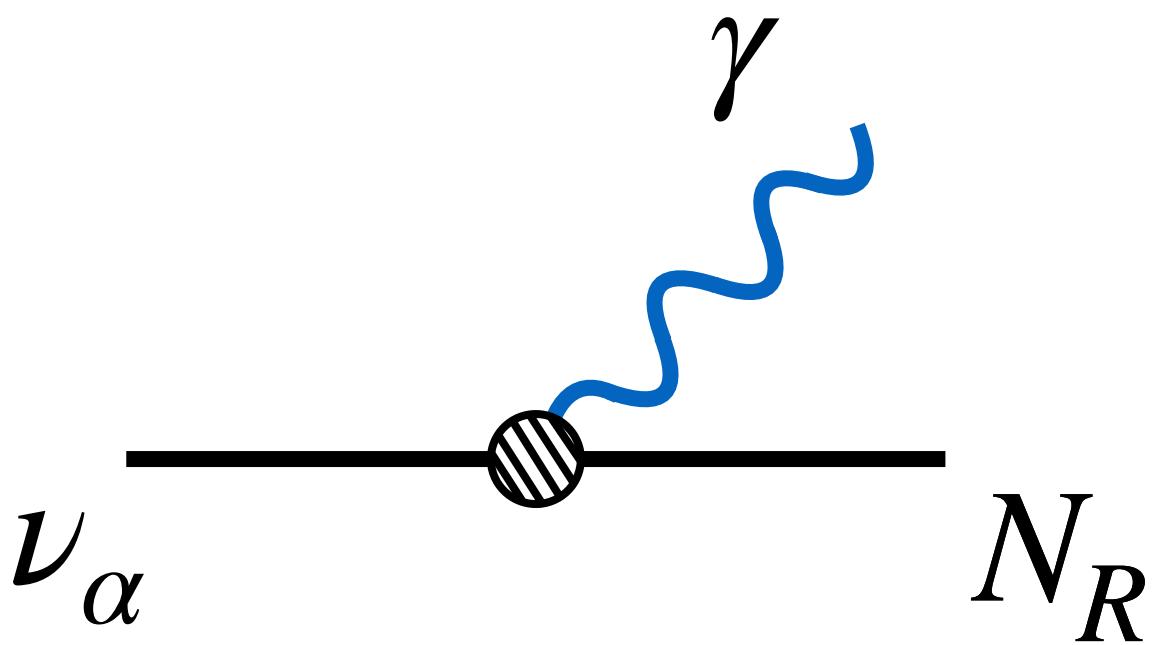
S. Bansal et al, [arXiv:2210.05706]



Transition magnetic moment

The model

$$\mathcal{L} \supset \frac{1}{\Lambda^2} \bar{L} \tilde{H} \sigma^{\mu\nu} N_R \left(C_B^\alpha B_{\mu\nu} + C_W^\alpha W_{\mu\nu}^a \sigma_a \right) \xrightarrow{\text{EWSB}} \text{Dimension-5 operator}$$
$$\mathcal{L} \supset d_{\alpha N} \bar{\nu}_\alpha \sigma_{\mu\nu} F^{\mu\nu} N_R$$



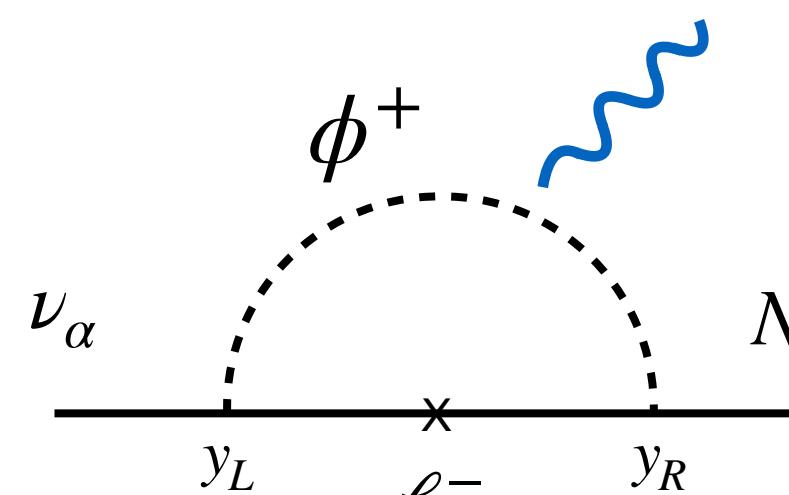
Transition magnetic moment == Dipole portal

Transition magnetic moment

The model

$$\mathcal{L} \supset \frac{1}{\Lambda^2} \bar{L} \tilde{H} \sigma^{\mu\nu} N_R \left(C_B^\alpha B_{\mu\nu} + C_W^\alpha W_{\mu\nu}^a \sigma_a \right) \xrightarrow{\text{EWSB}} \text{Dimension-5 operator} \\ \mathcal{L} \supset d_{\alpha N} \bar{\nu}_\alpha \sigma_{\mu\nu} F^{\mu\nu} N_R$$

Points to keep in mind:



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

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

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

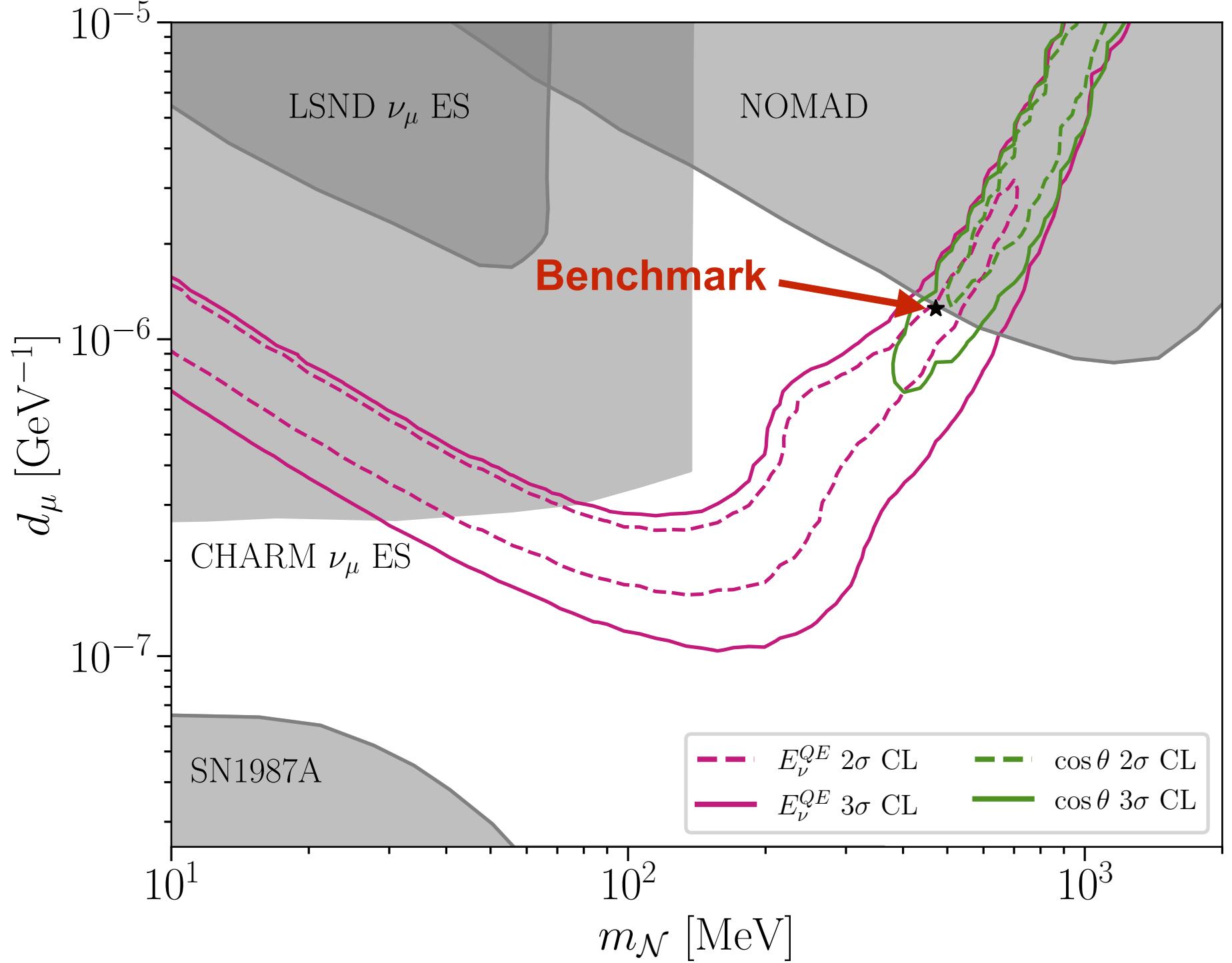
No mixing.

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

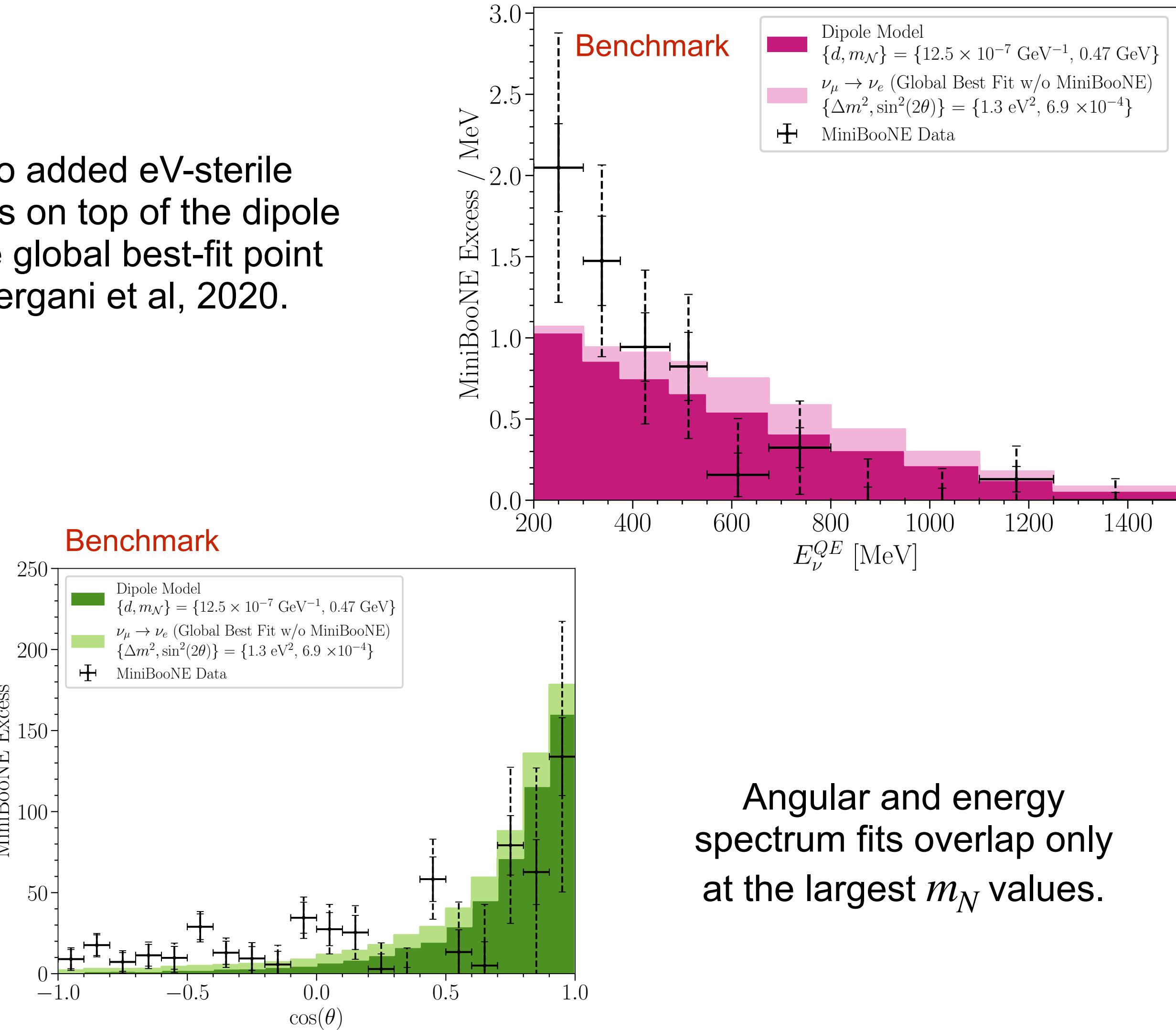
Transition magnetic moment

MiniBooNE region of interest

N. Kamp, **MH**, 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, 2020.



Performed a fit to the MiniBooNE low-energy excess.

Updates previous fit in Vergani et al arXiv:2105.06470 with:

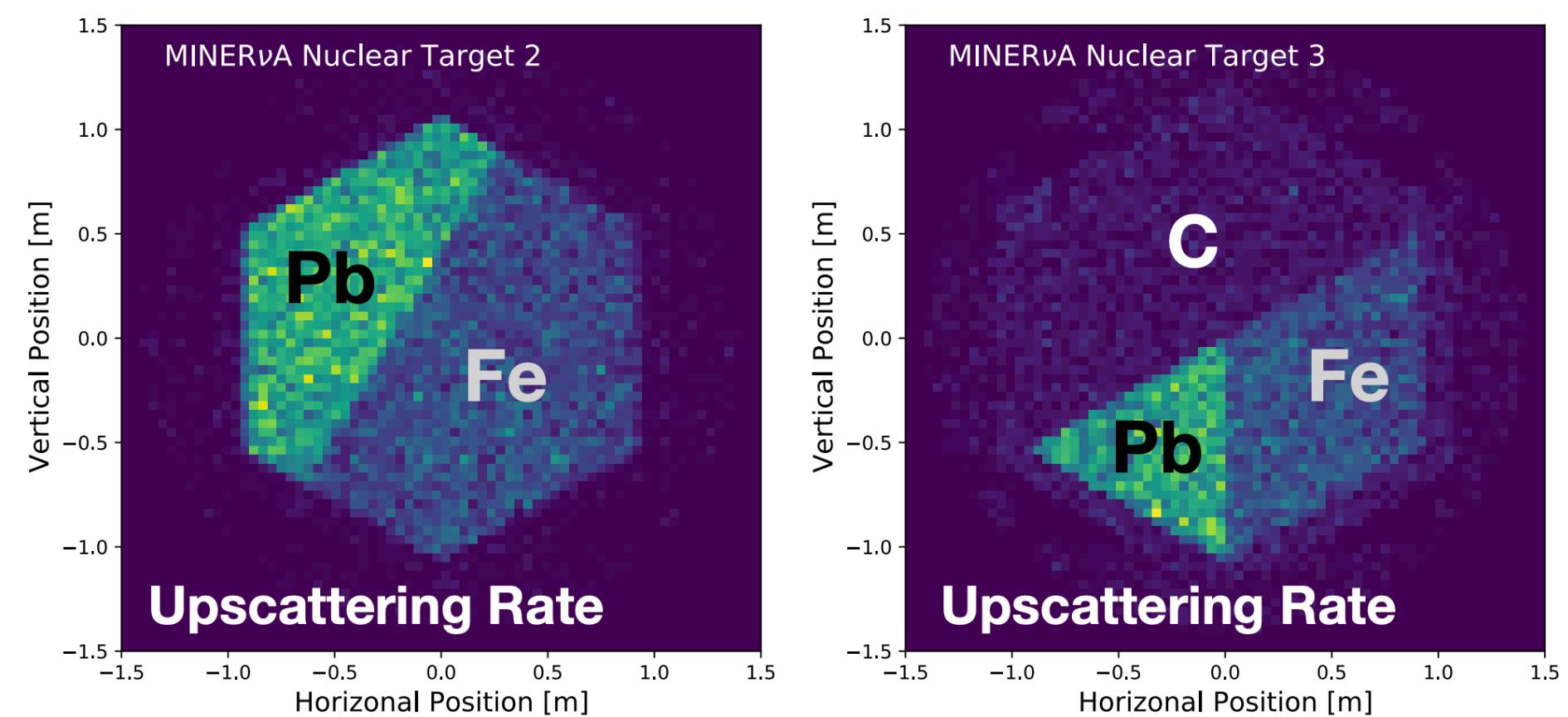
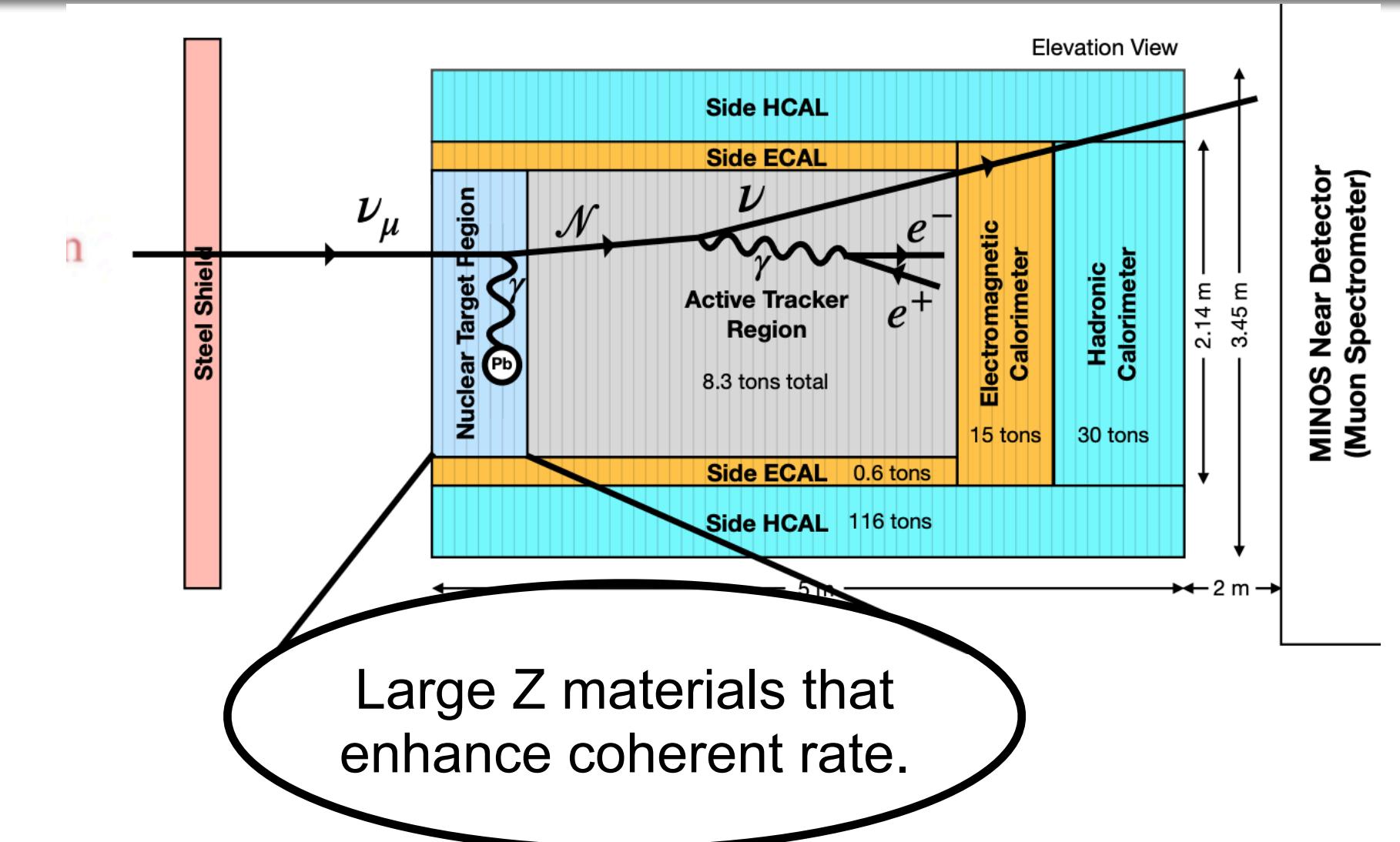
- 1) detector simulation in [LeptonInjector](#)
- 2) coherent cross-sections from [DarkNews](#) (improved nuclear FFs).

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

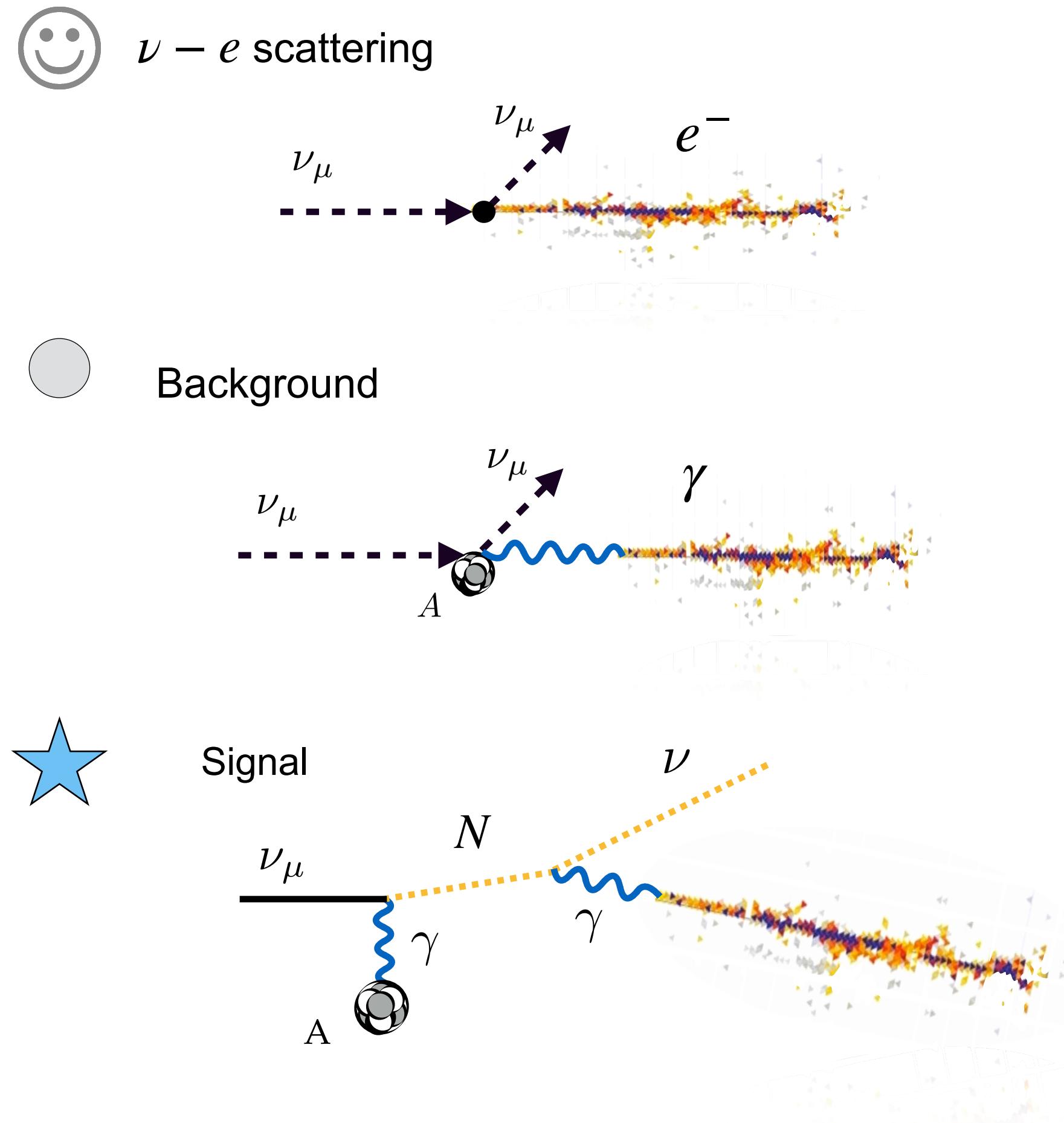
Transition magnetic moment

MINERvA limits from $\nu - e$ scattering measurement

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



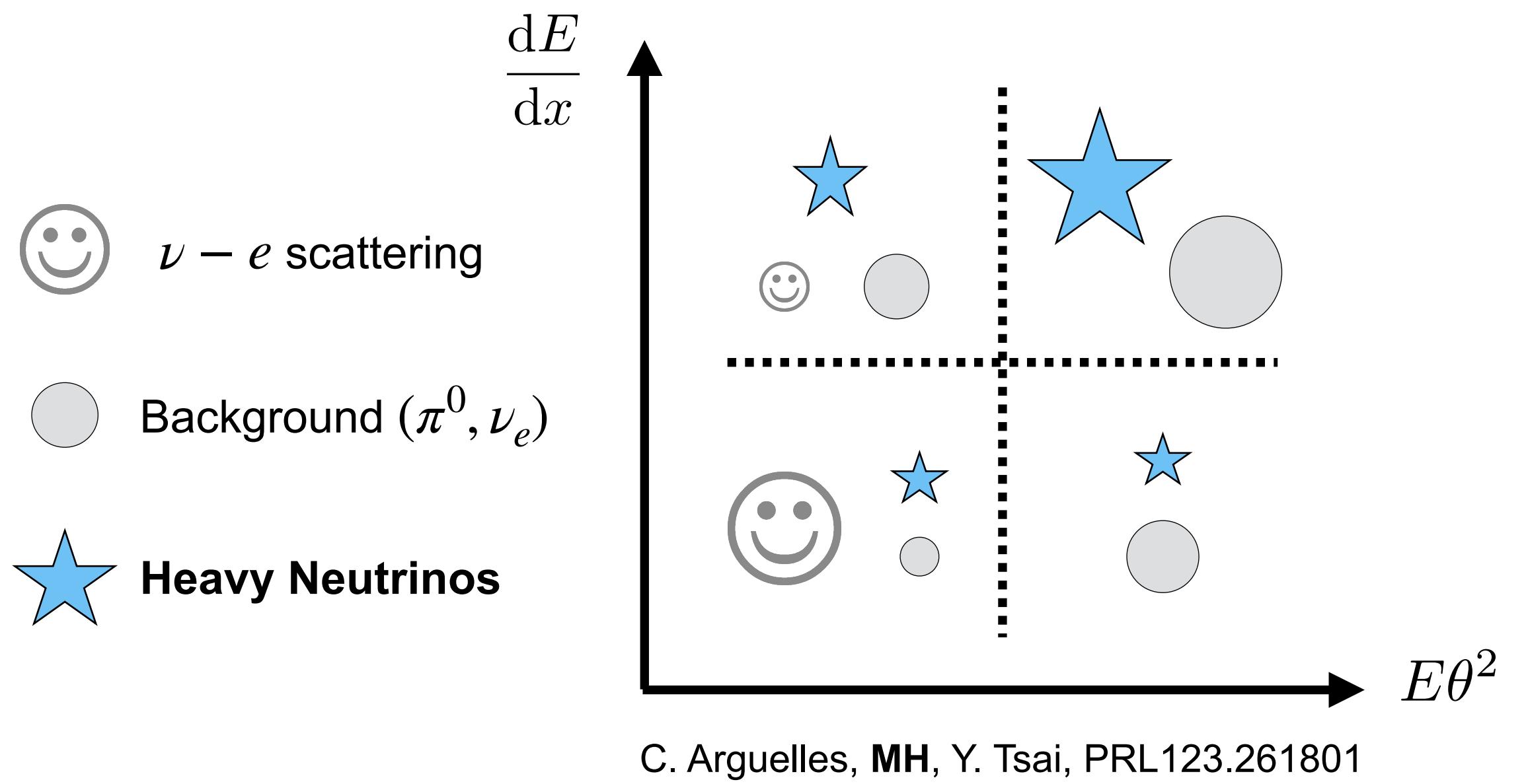
MINERvA nuclear targets from [LeptonInjector](#)



Transition magnetic moment

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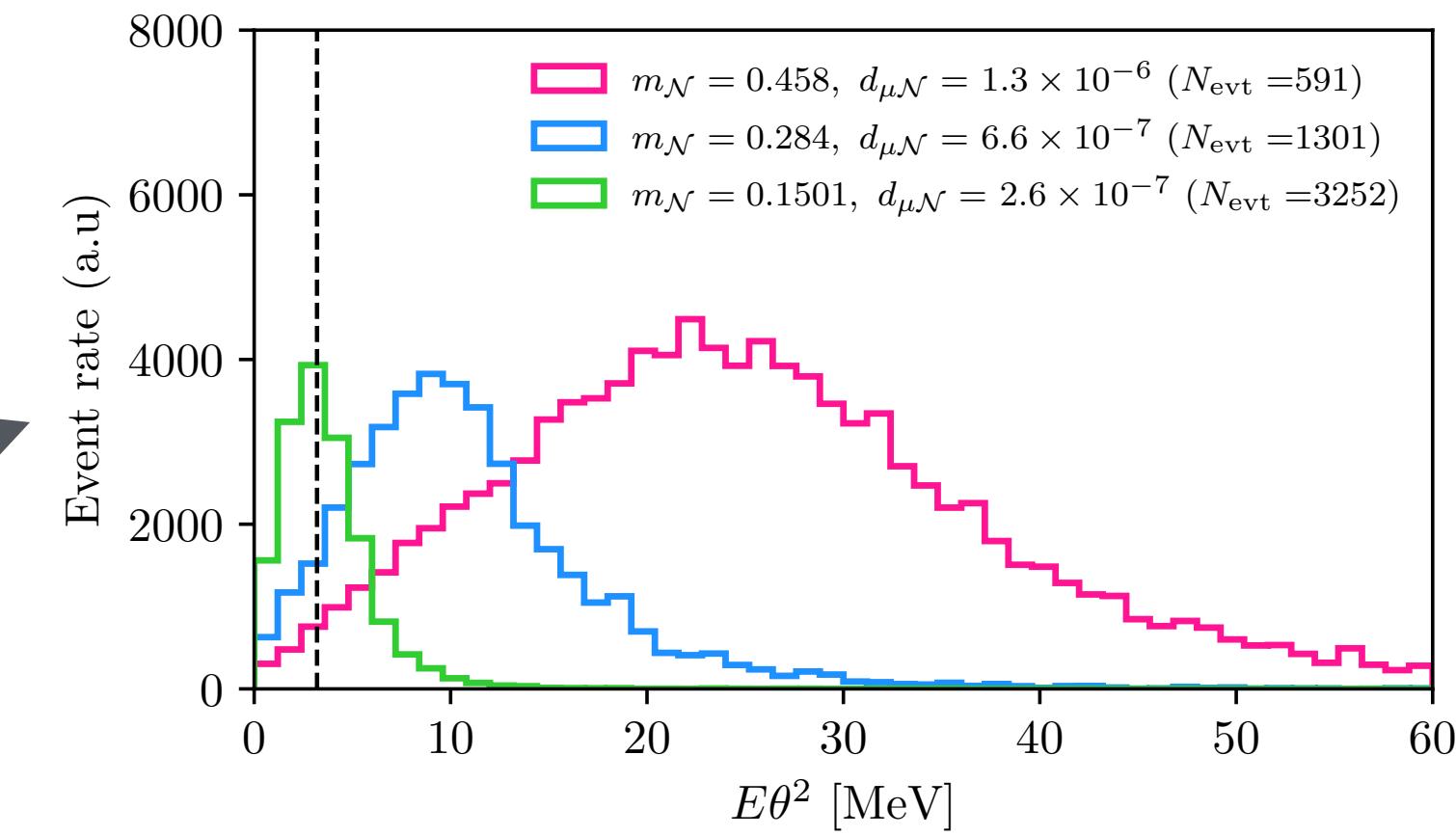
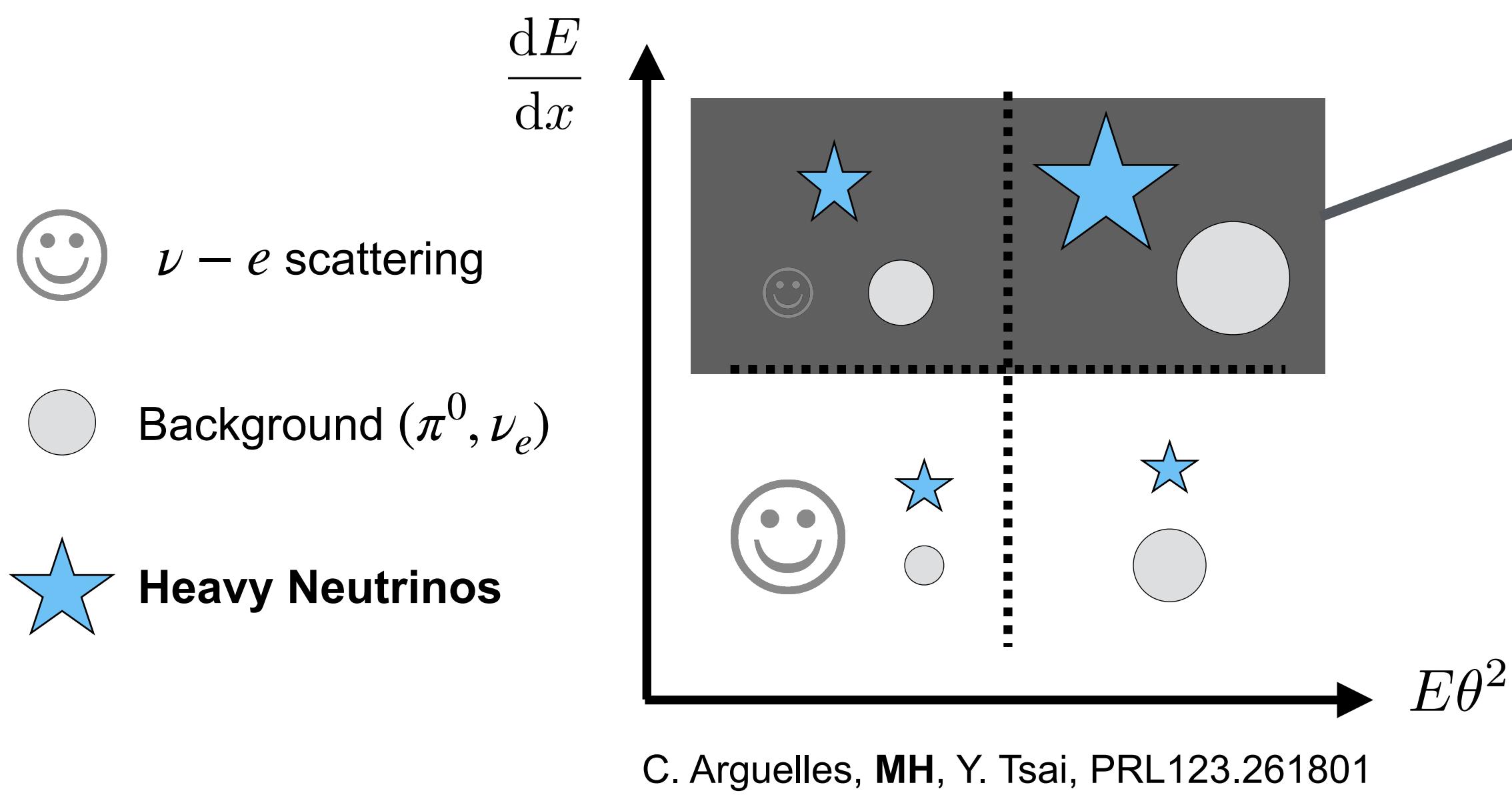
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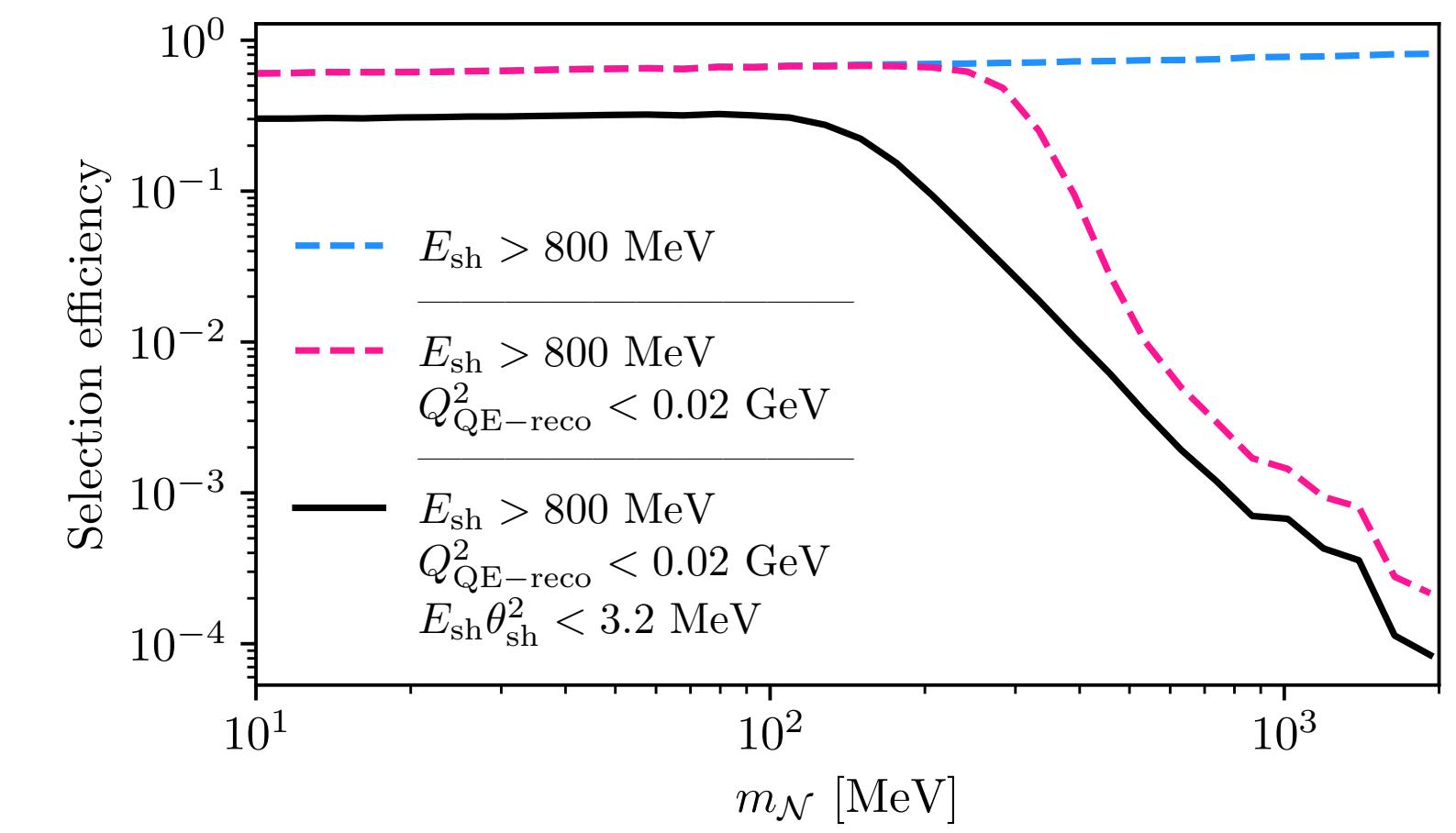


This hurts us badly,
but there are a huge
number of N
that decay inside the
volume of the analysis.

MINERvA uses the fact that

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

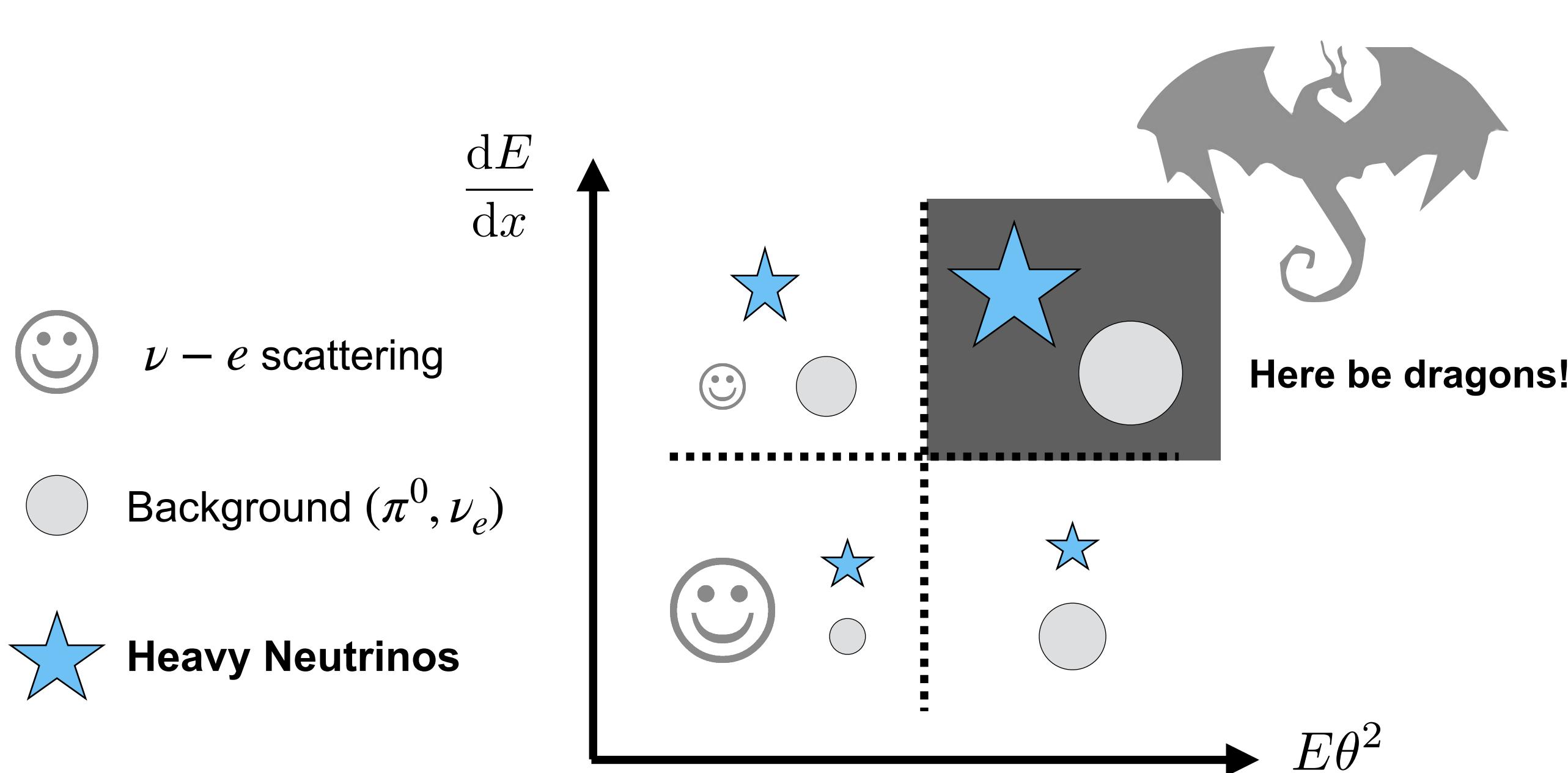
for $\nu - e$ scattering.



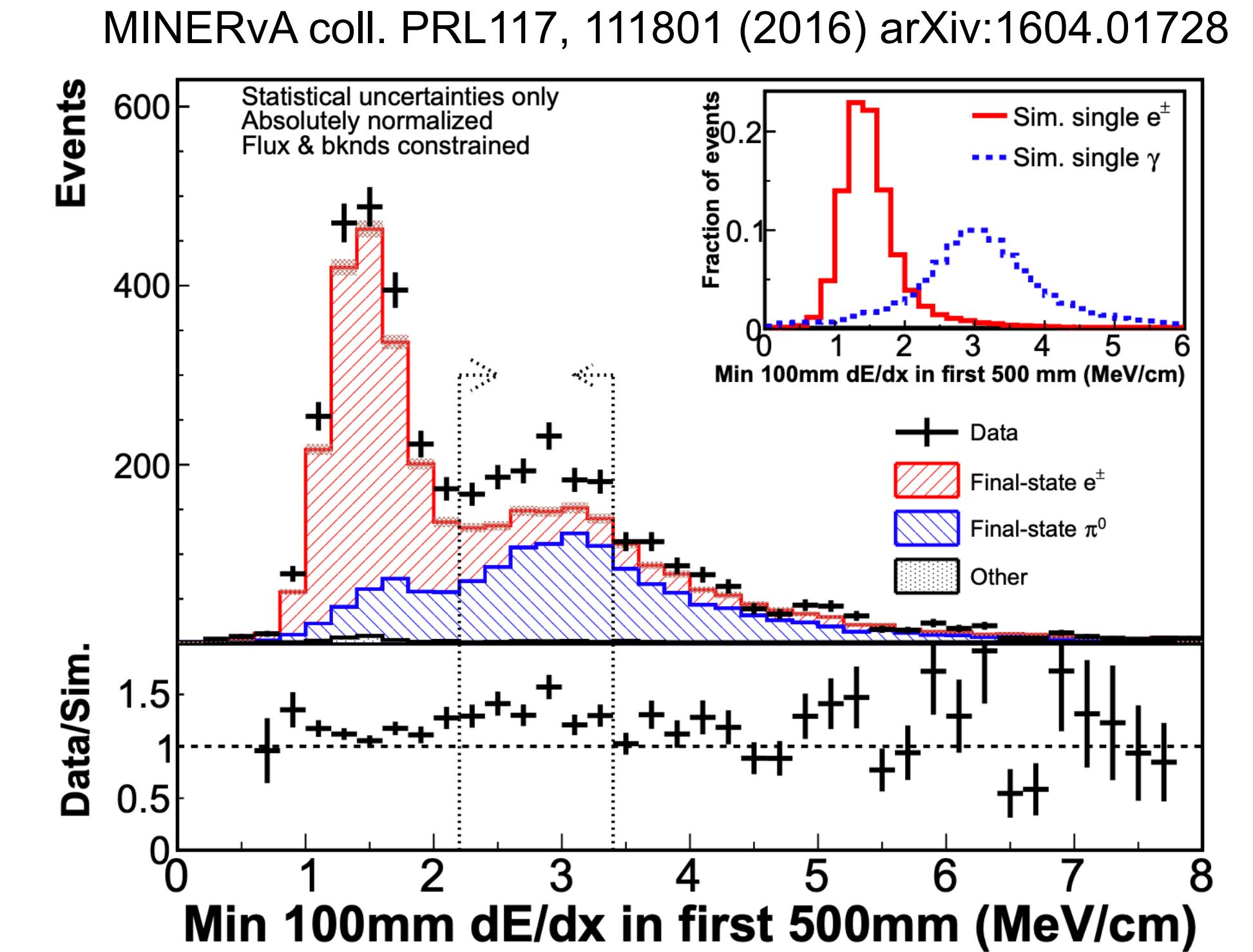
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C. Arguelles, **MH**, Y. Tsai, PRL123.261801



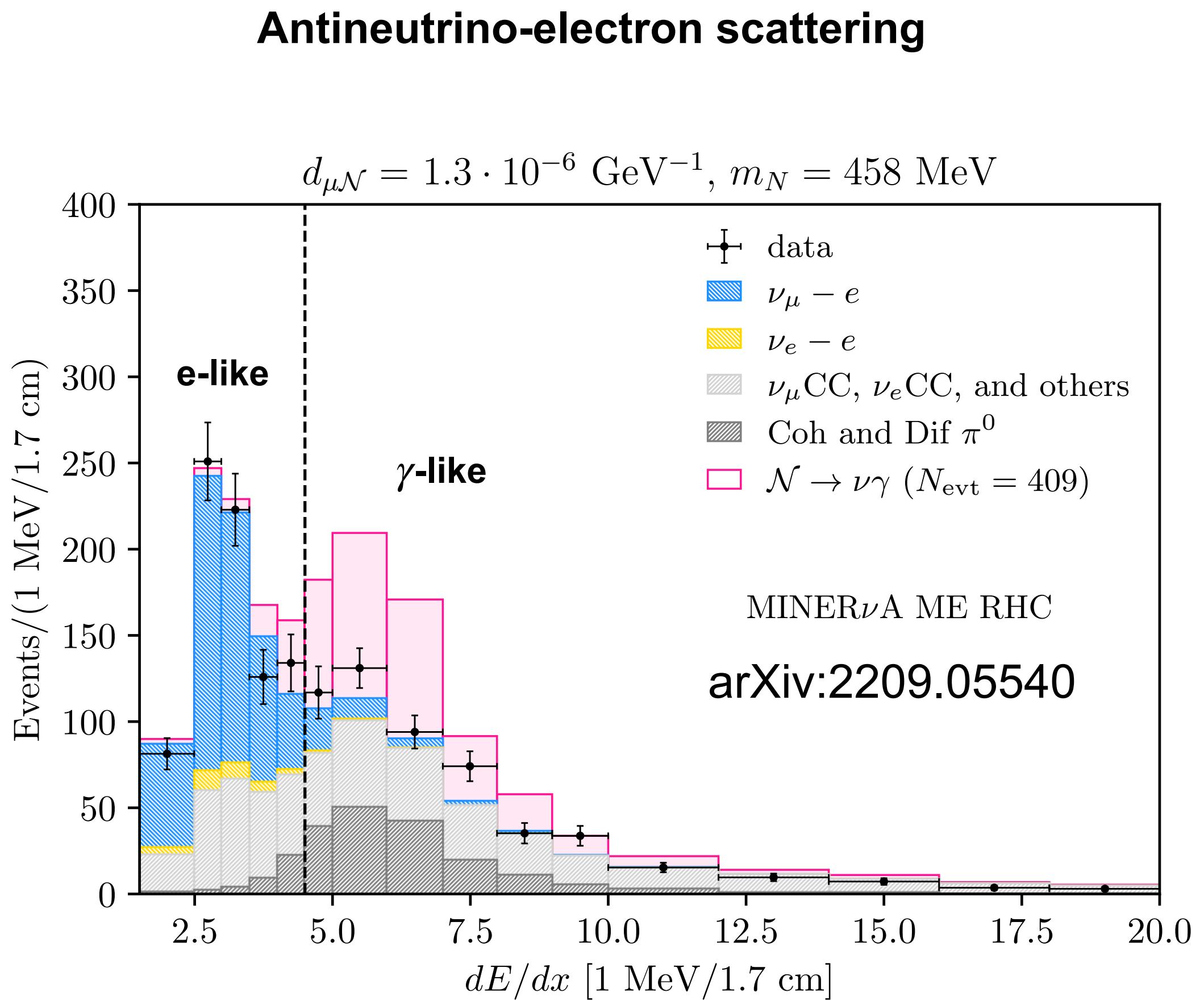
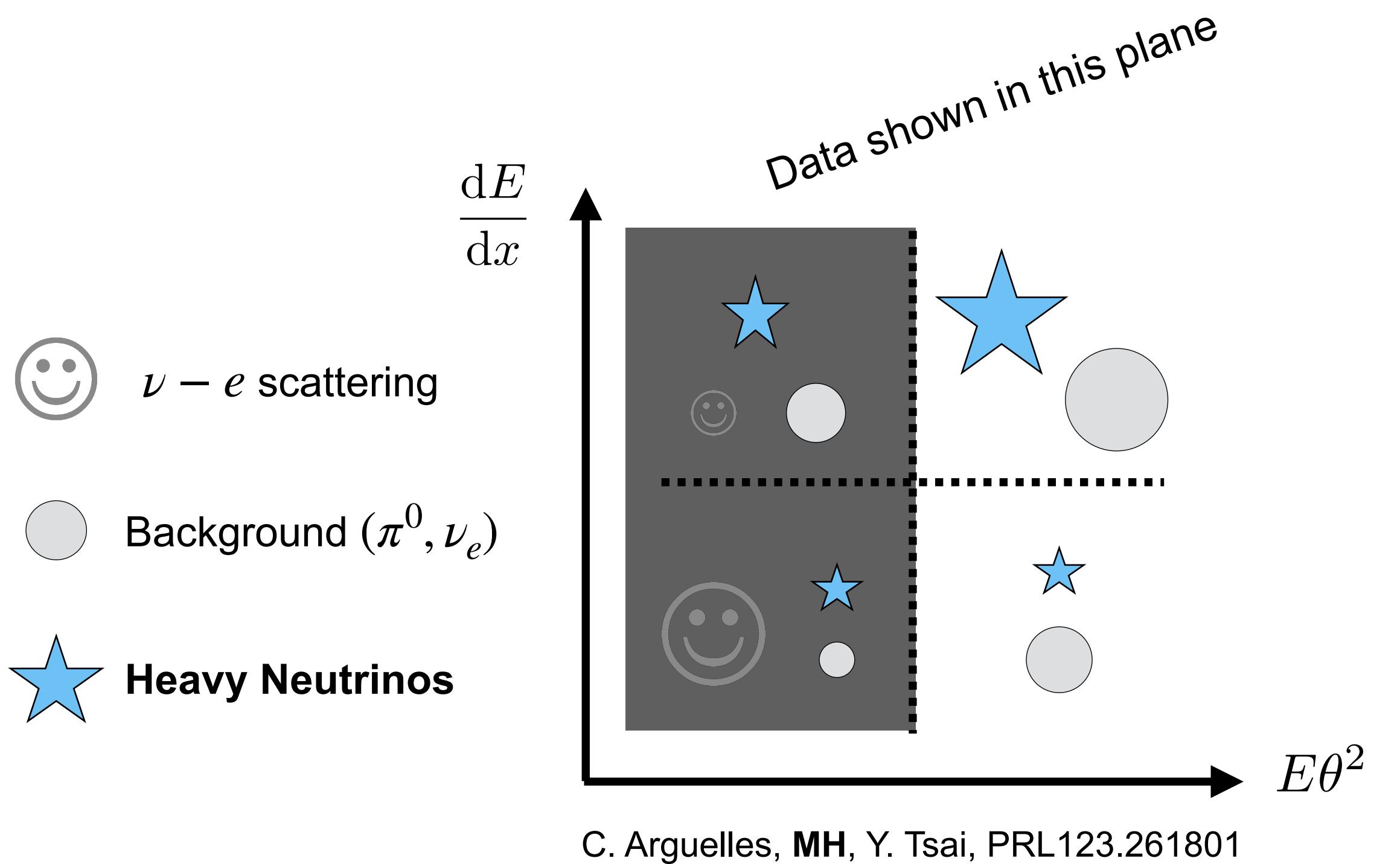
* Excess of events attributed to diffractive π^0 production
(In this case, they see a hadronic vertex)

Interesting piece of data that can be studied already.

Transition magnetic moment

MINERvA limits from $\nu - e$ scattering measurement

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J. M. Conrad, M. H. Shaevitz, and M. Uchida, arXiv:2206.07100

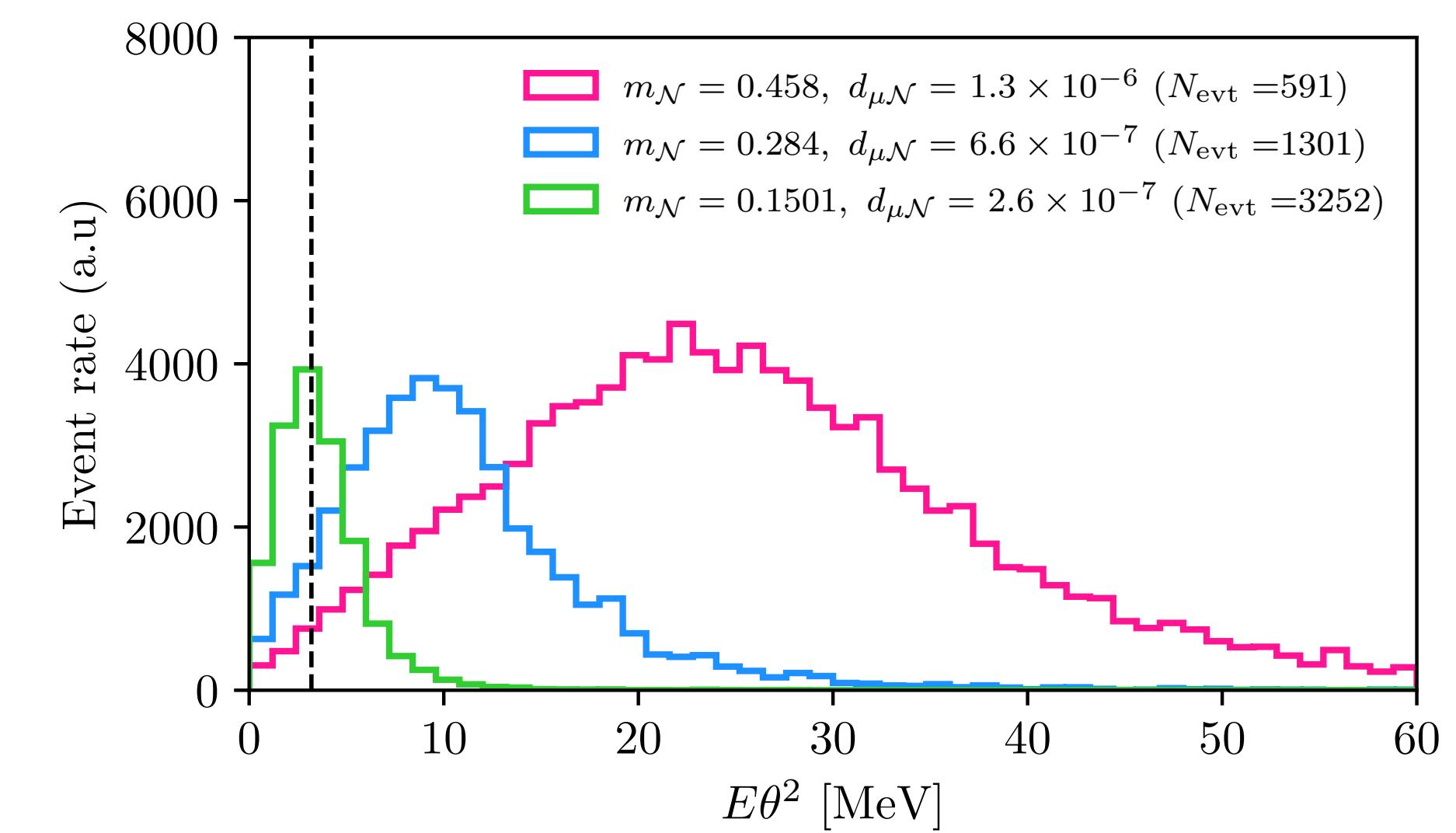
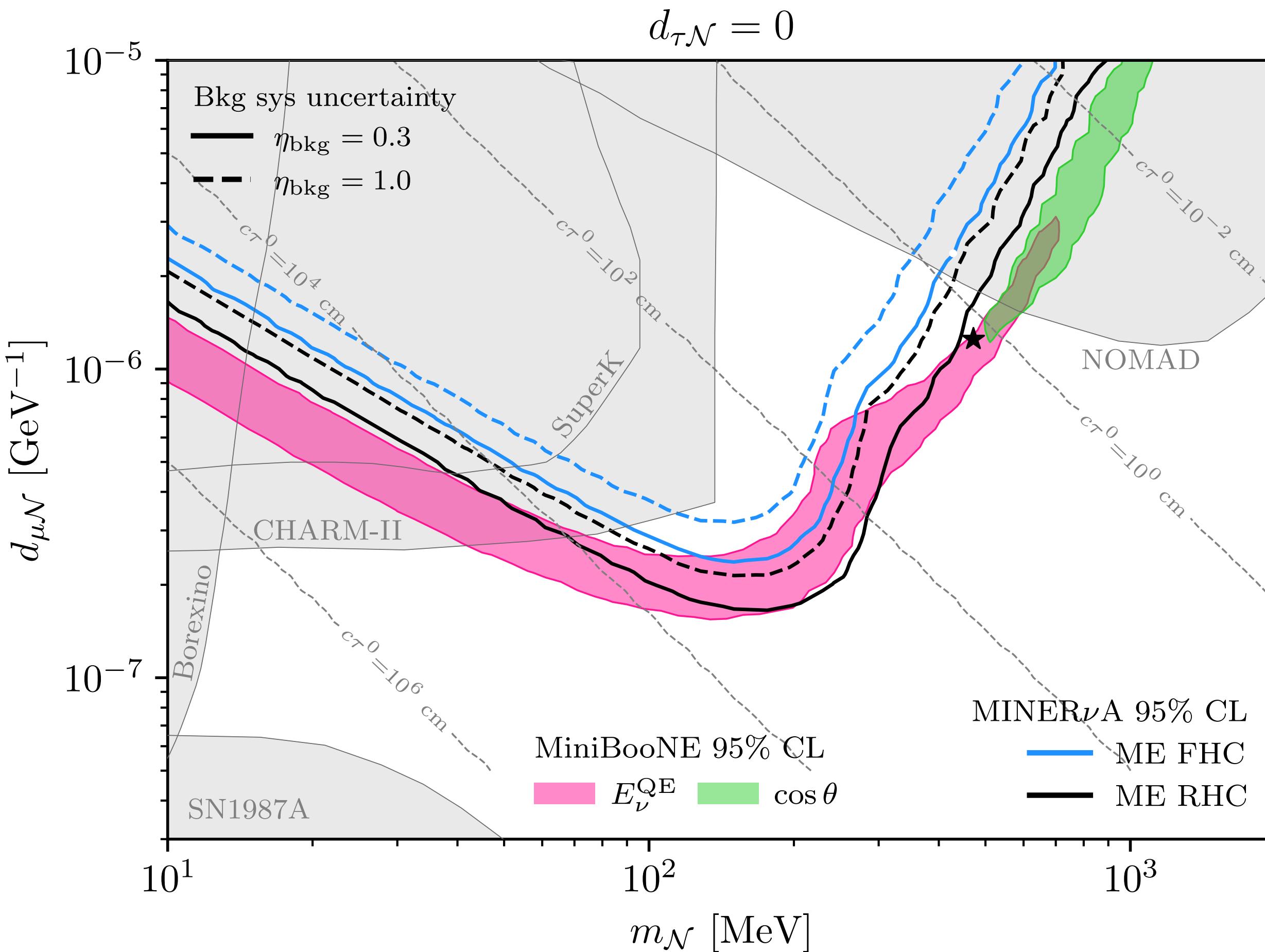


Post-tuning of backgrounds.
Assign 30% and 100% uncertainty to cover it.

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

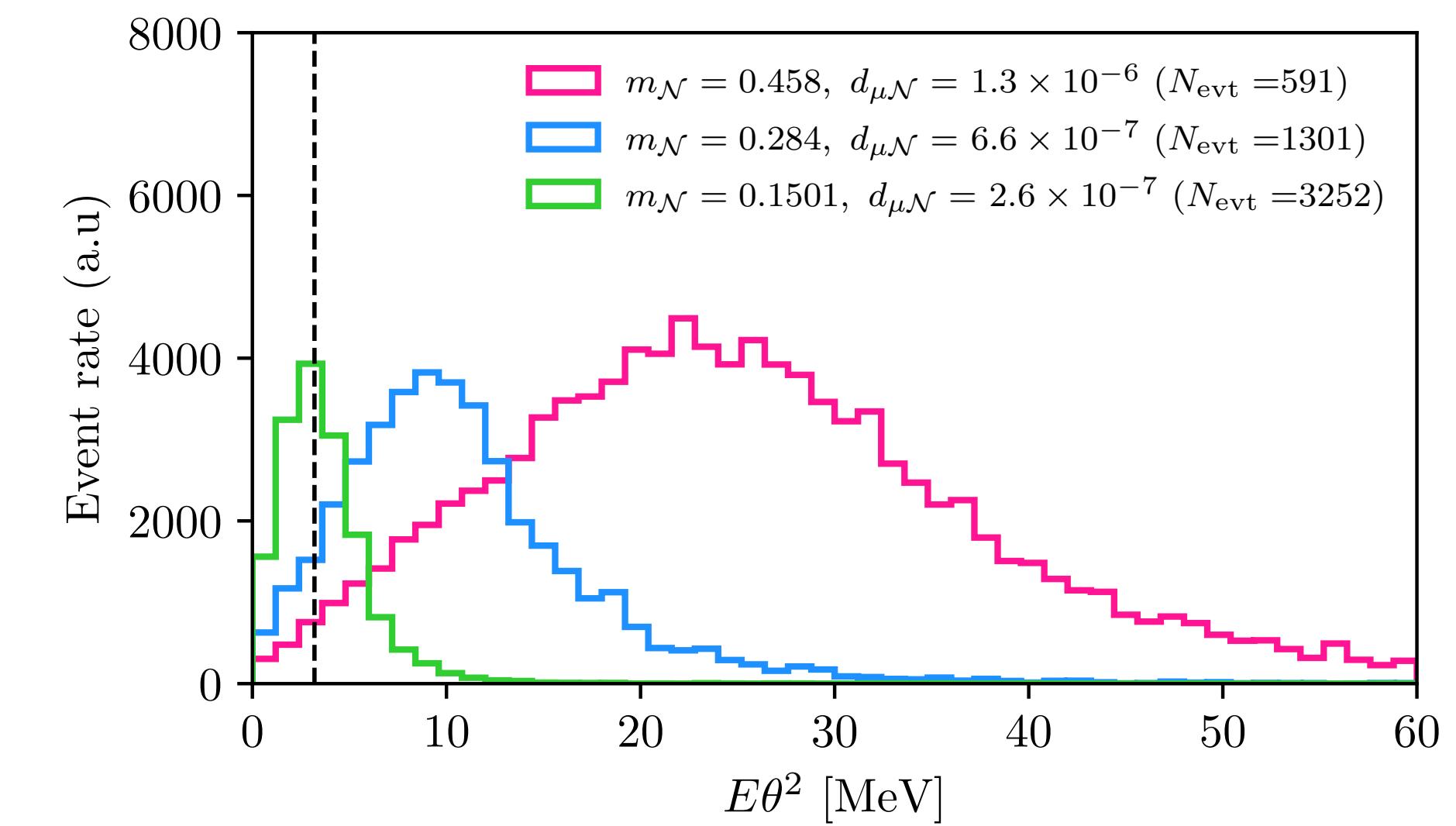
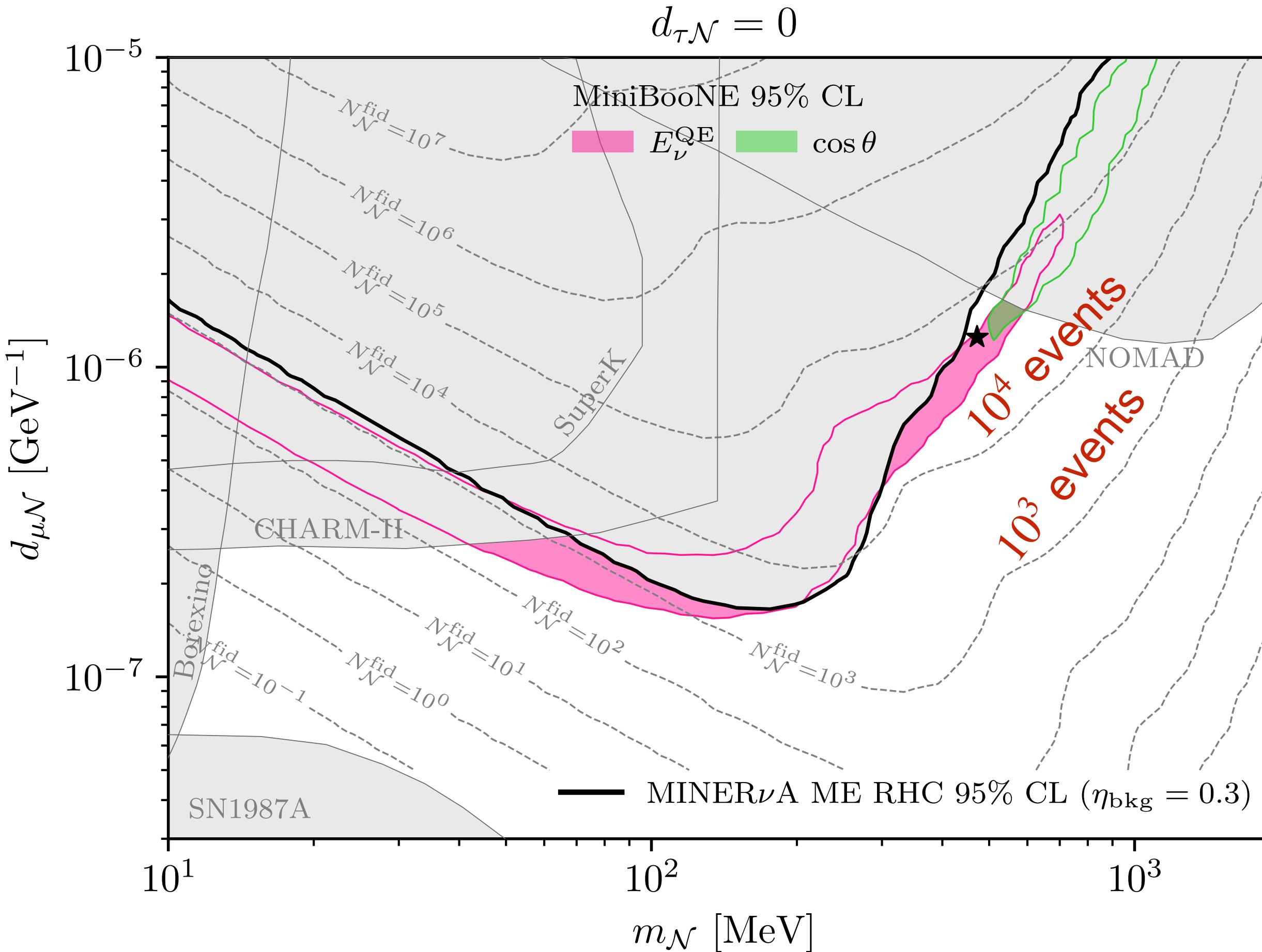


Angle cuts hurt us badly,

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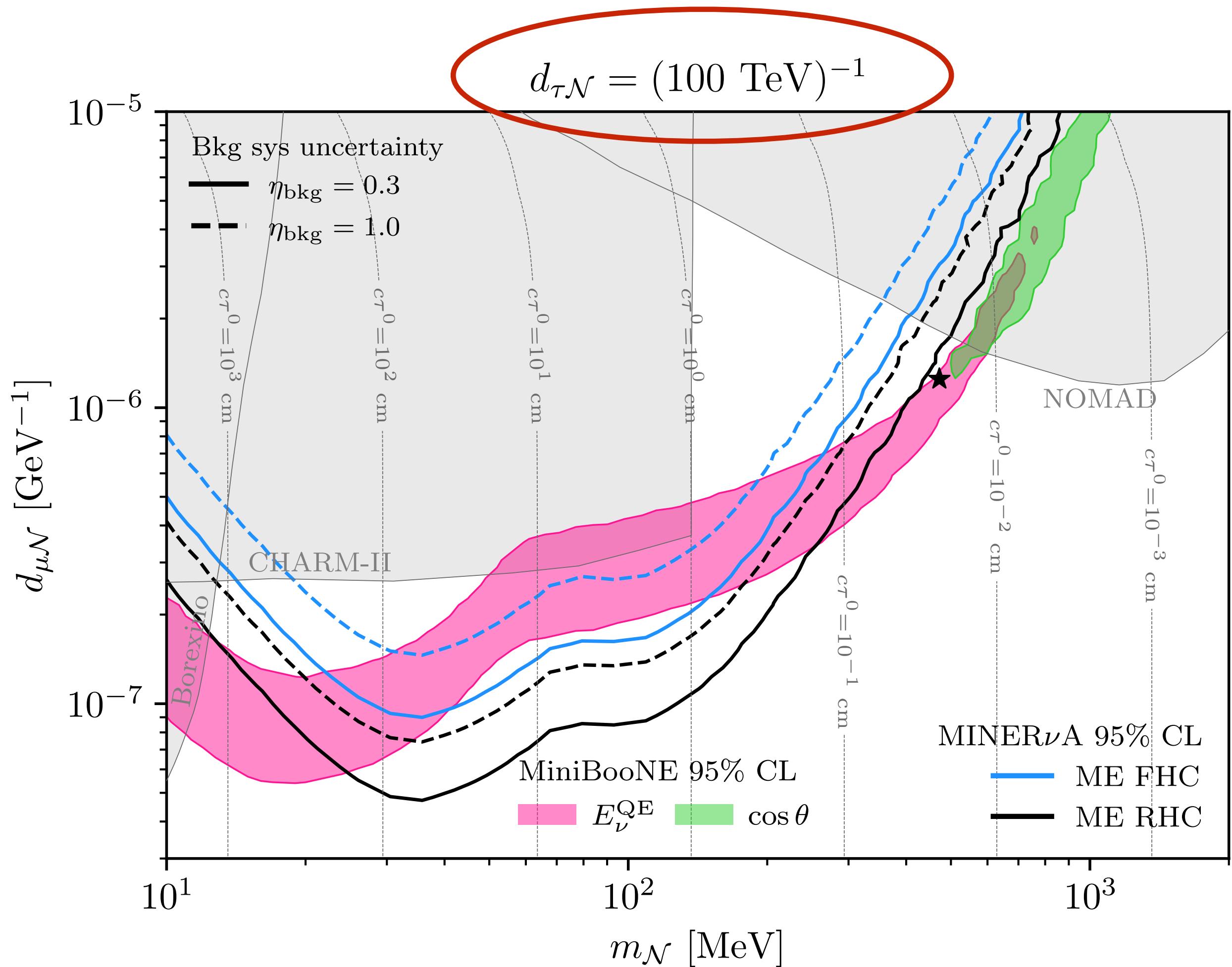
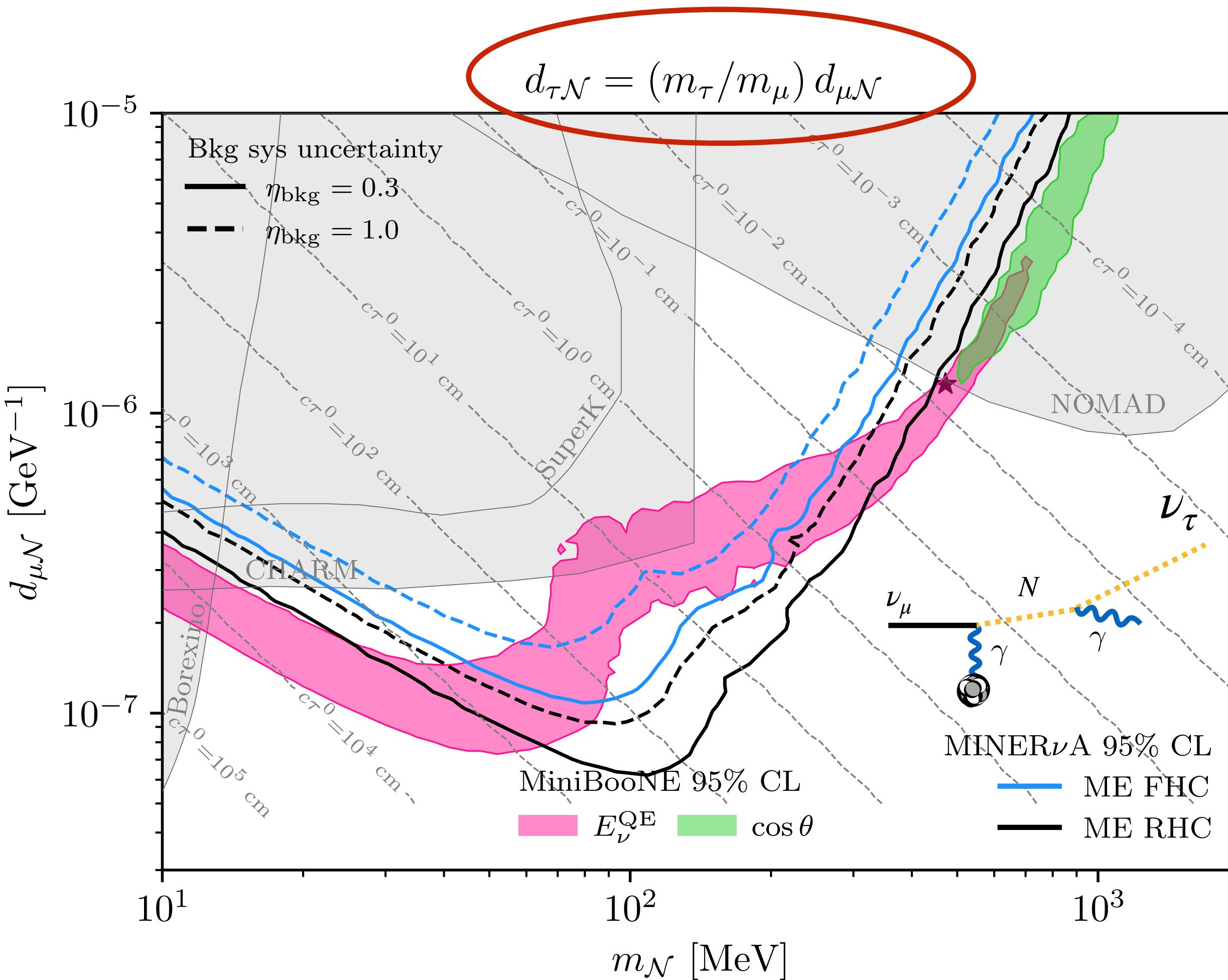


Angle cuts hurt us badly,
but there are a huge number of N
that decay inside the volume of the analysis.

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

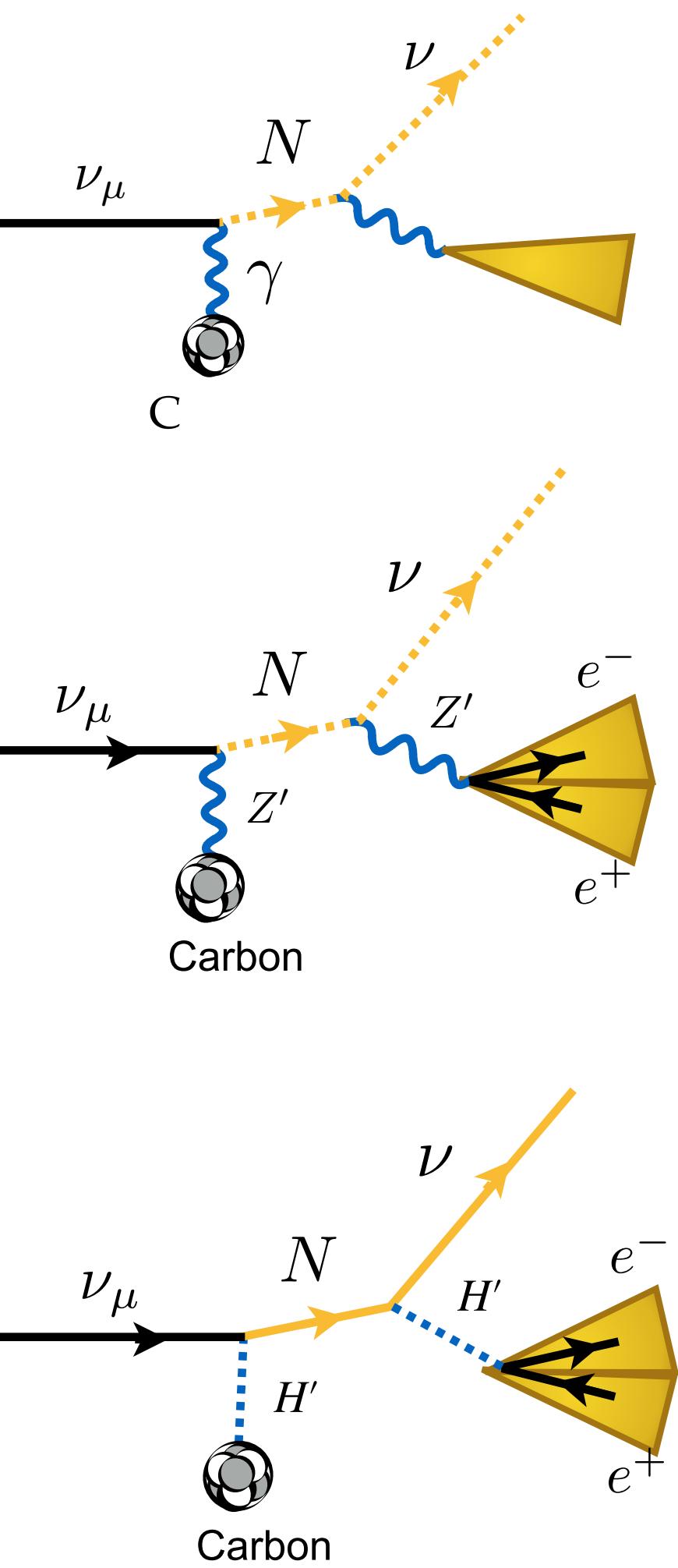


Neutrino scattering signatures

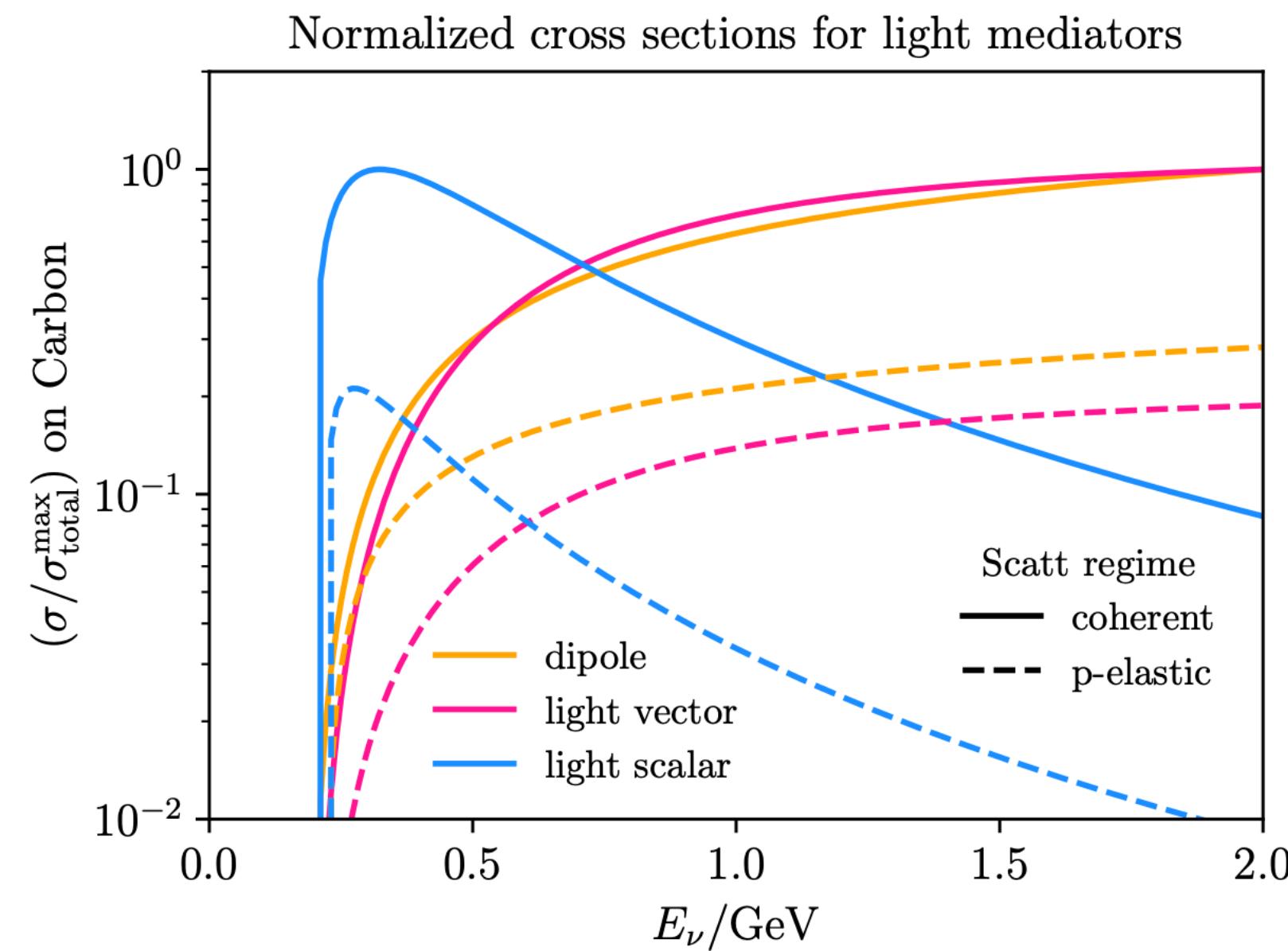
Searches for EM final state

- E. Bertuzzo et al, [arXiv:1807.09877]
 P. Ballett et al, [arxiv:1808.02915]
 C. Argüelles, **MH**, Y. Tsai, [arXiv:1812.08768]
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Upscattering cross sections in different models:

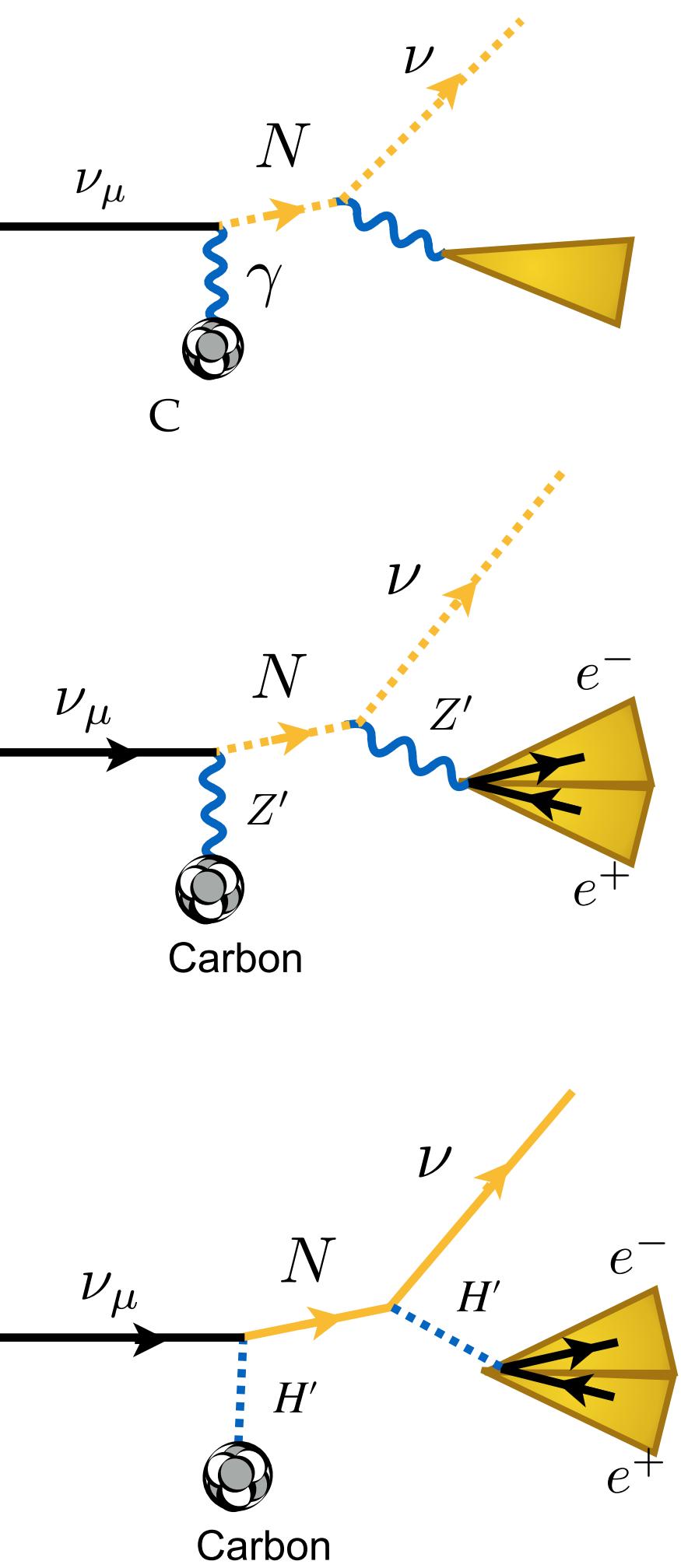


Not all neutrino experiments would see the same physics. Importance of complementarity.

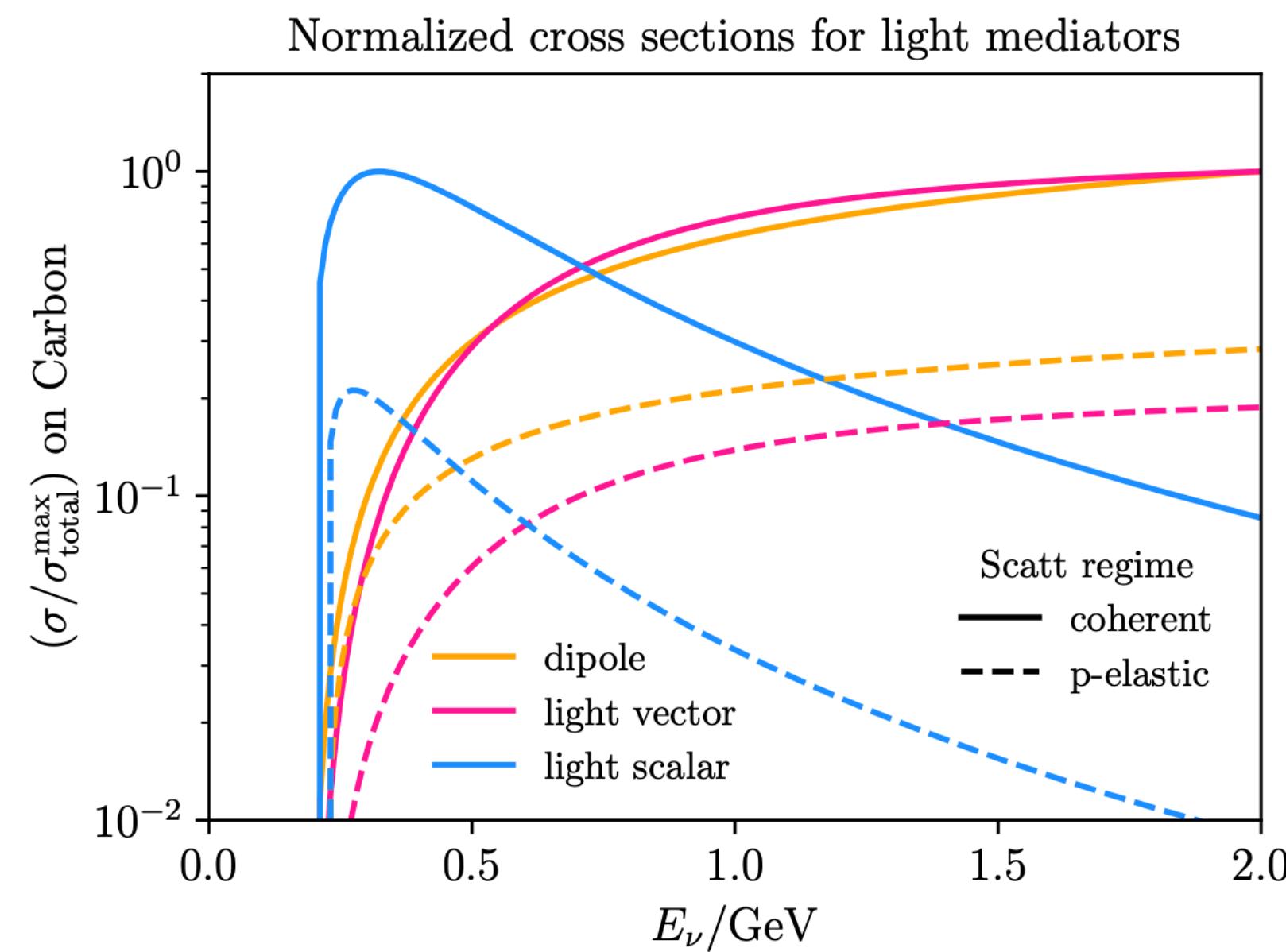
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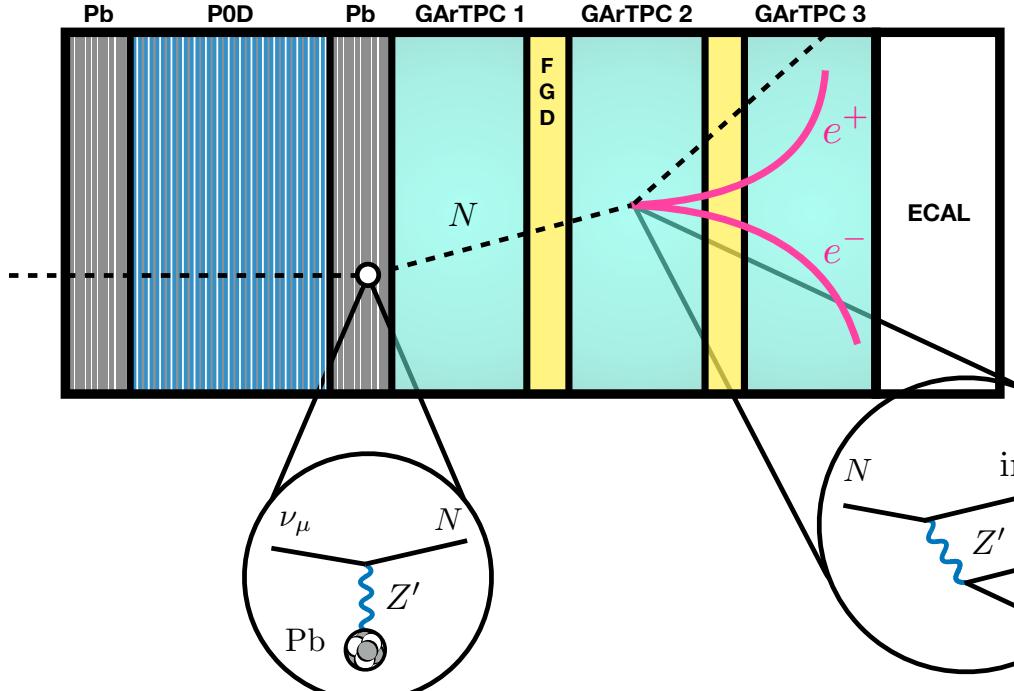
Not all neutrino experiments would see the same physics. Importance of complementarity.

Summary of the current datasets explored:

MINERvA $\nu - e$ scattering

Phenomenological studies

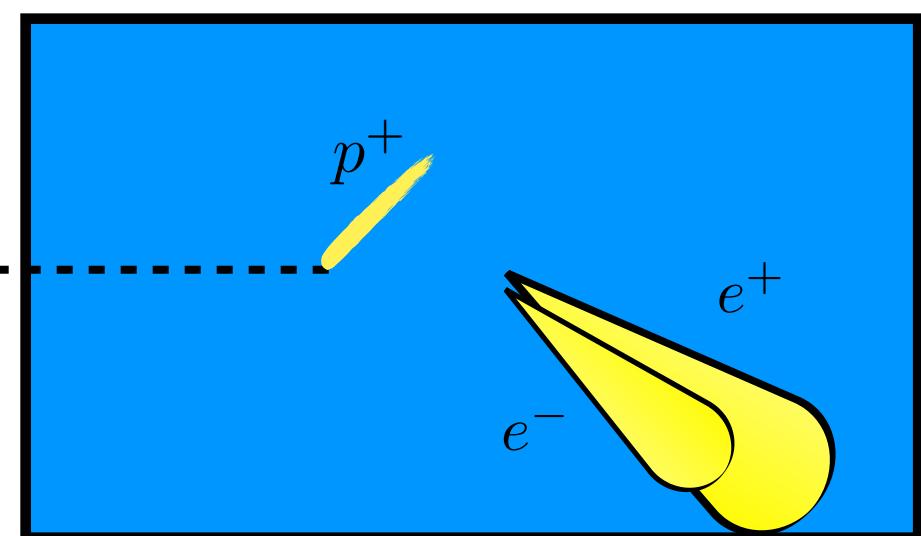
C. Argüelles, **MH**, Y. Tsai,
[\[arXiv:1812.08768\]](#)



T2K e^+e^- and γ searches

Phenomenological studies

C. Arguelles, MH, N. Foppiani,
[arXiv:2205.12273](#)



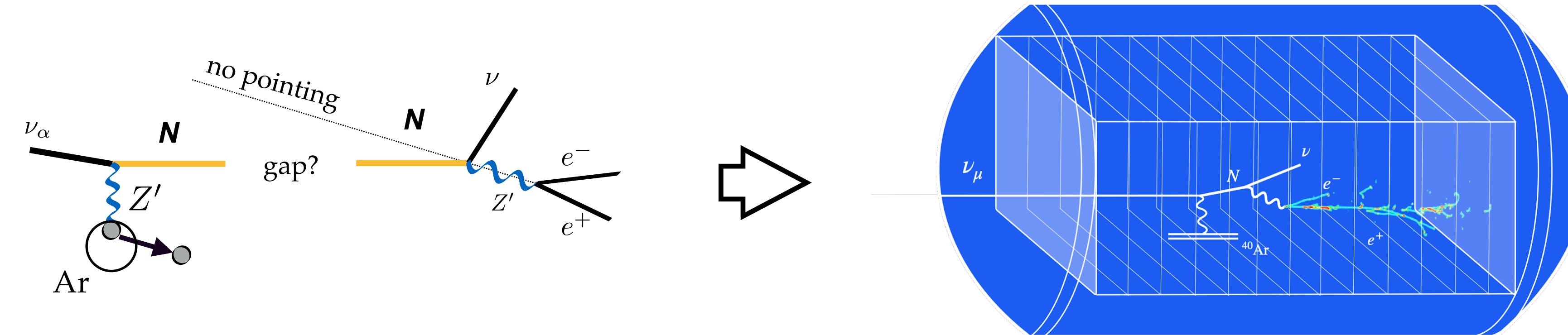
MicroBooNE e^+e^- and γ searches

Currently on-going

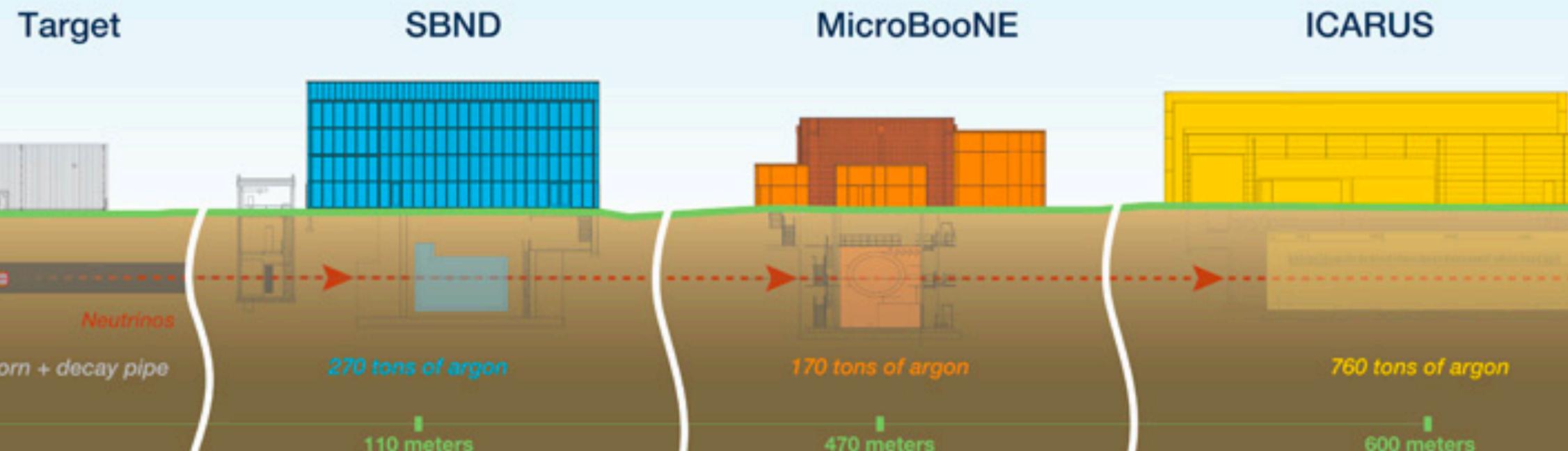
Upscattering in dense neutrino detectors

Searches for e+e- at the SBN program

New generation of Liquid Argon detectors at Fermilab can search for (e+e-) events as a test of MiniBooNE results.



Short-Baseline Neutrino Program at Fermilab



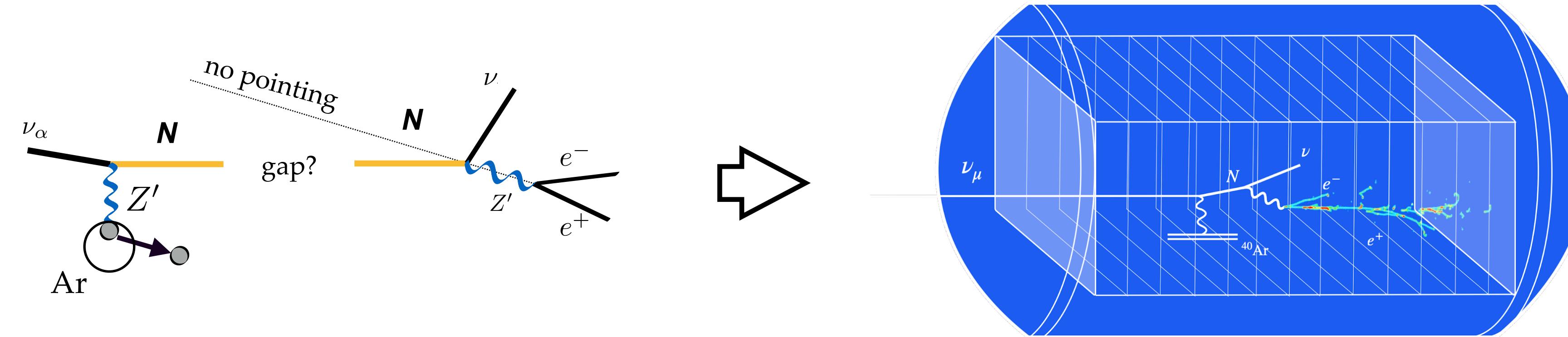
Short-Baseline Neutrino Program uniquely positioned to put this class of models to test.

Dedicated searches are crucial to address this chapter of the MiniBooNE saga.

Upscattering in dense neutrino detectors

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MicroBooNE

Pseudo-single photon events:

$$\theta_{ee} < 35^\circ$$

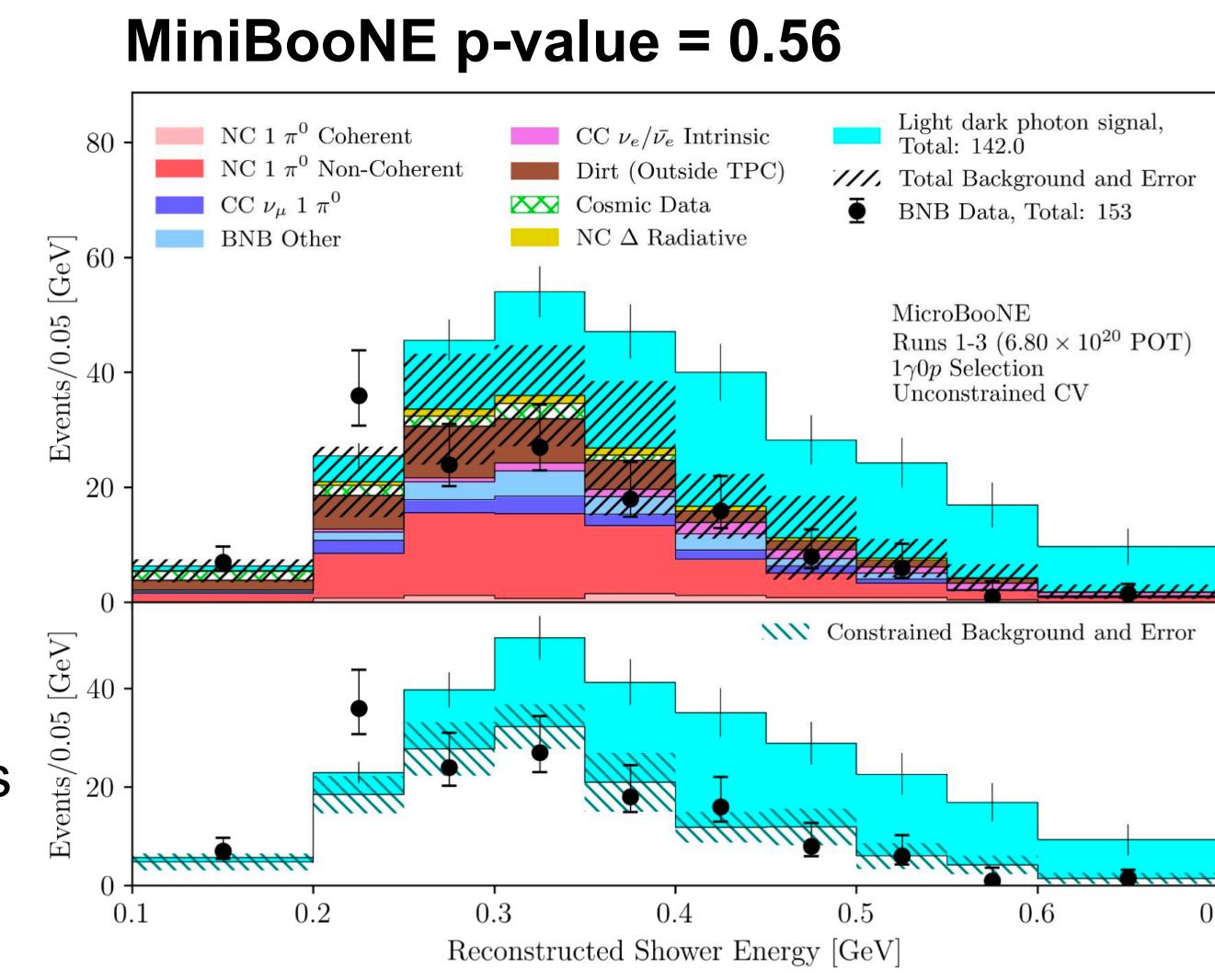
Overlapping pairs assumed to fall within the single-photon selection at MicroBooNE.

*MicroBooNE Coll.,
PRL 128, 111801*

Light dark photon

$$m_{Z'} = 30 \text{ MeV}$$

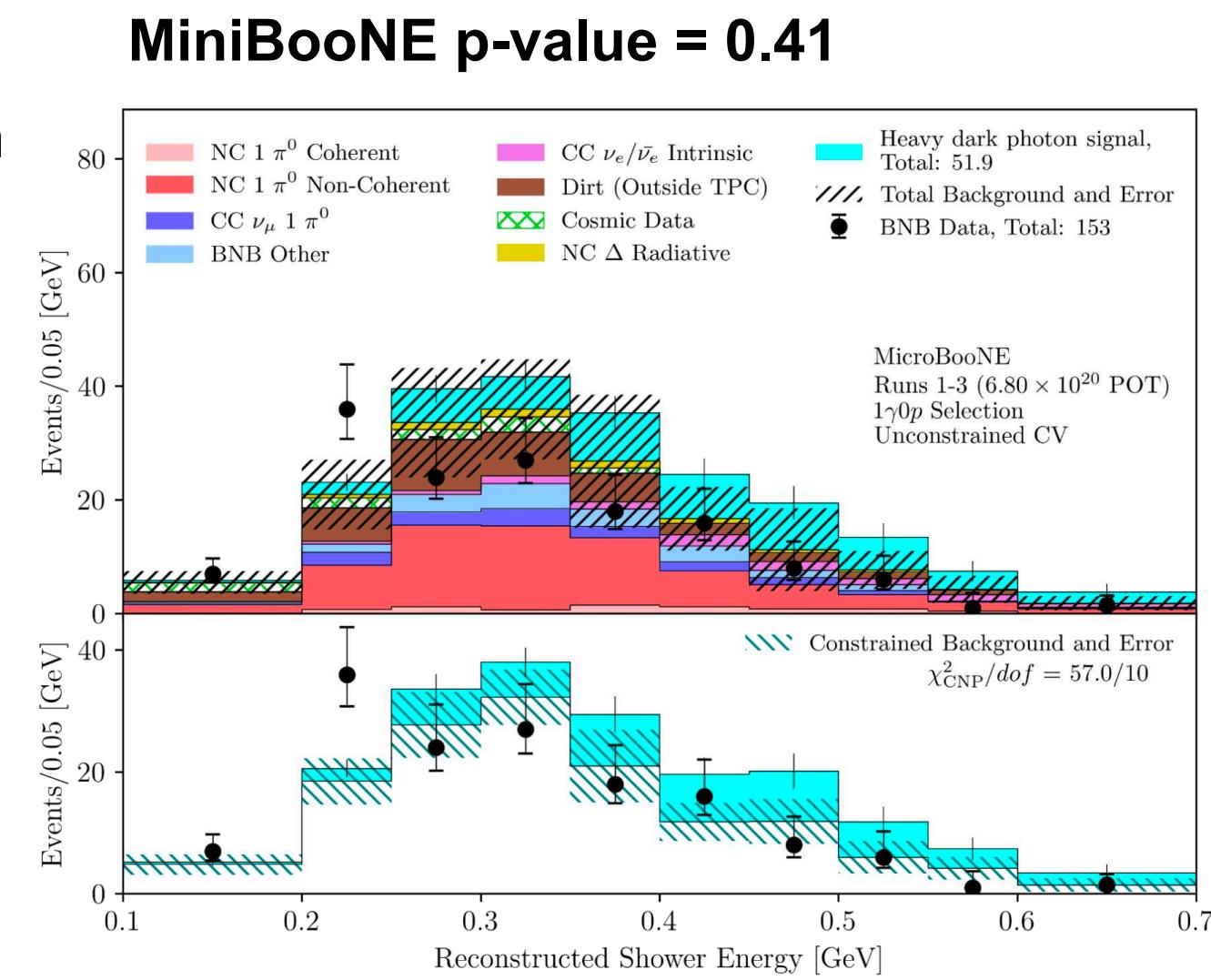
Coherent enhancement
 $\sigma \propto Z^2$,
means argon
Leads to higher rates



Heavy dark photon

$$m_{Z'} = 1.25 \text{ GeV}$$

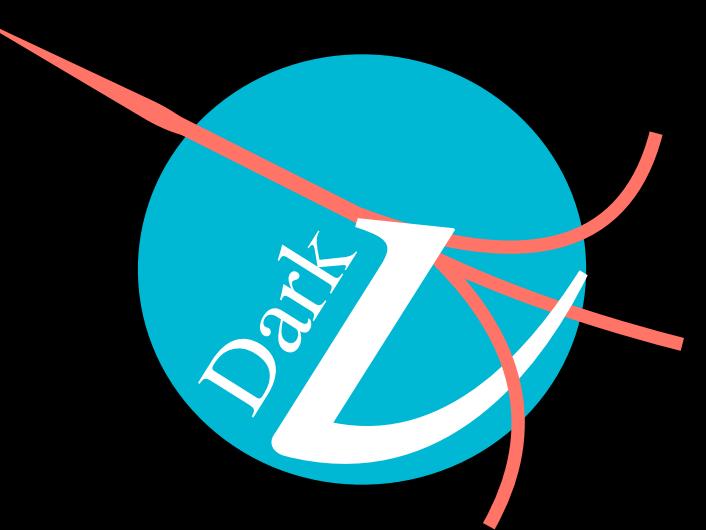
Incoherent piece is sizeable.



DarkNews Generator

A. Abdullahi, J. Hoefken, MH, D. Massaro, S. Pascoli, [arXiv:2207.04137](https://arxiv.org/abs/2207.04137)

DarkNews is a lightweight MC generator for new physics in neutrino-nucleus scattering.
Including vector, scalar, and dipole mediators in upscattering processes to up to 3 HNLs.



`pip install DarkNews`
github.com/mhostert/DarkNews-generator

```
DarkNews-generator - zsh - mhostert

[DE] [DE] [NEWS]

Model:
  1 majorana heavy neutrino(s).
  kinetically mixed Z'

Experiment:
  MicroBooNE
  fluxfile loaded: ../fluxes/MiniBooNE_FHC.dat
  POT: 1.225e+21
  nuclear targets: ['Ar40']
  fiducial mass: [85.0] tonnes

Note that the directory tree for this run already exists.

Generating Events using the neutrino-nucleus upscattering

nu(mu) Ar40 --> N4  Ar40 --> nu_light e+ e- Ar40
Helicity conserving upscattering.
N4 decays via off-shell Z'.
Predicted (790 +/- 9.5) events.
```

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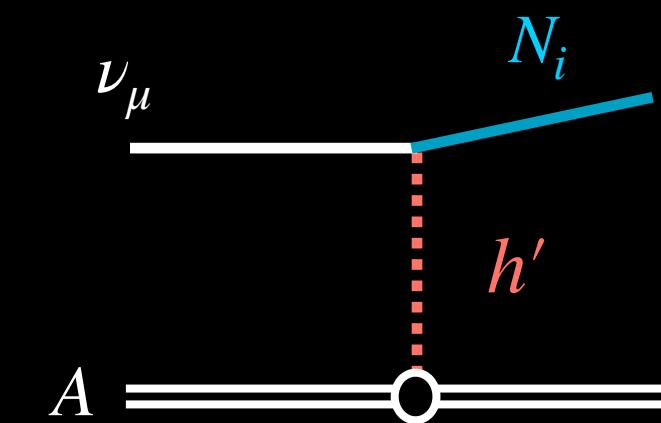
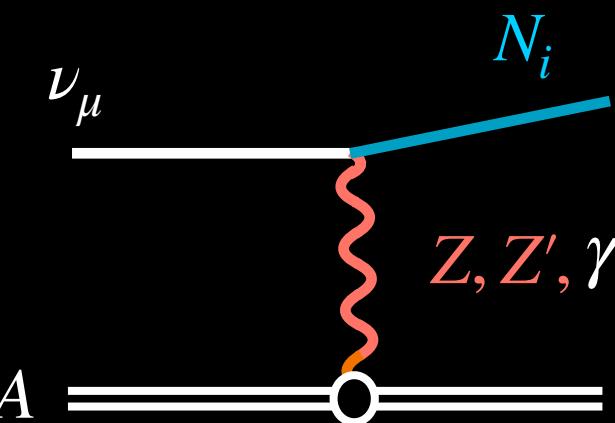
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DarkNews-generator - zsh - mhostert
[DEEPLINK] [NEWS]
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Modeling several processes for GeV-scale accelerator experiments:

Scattering:

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



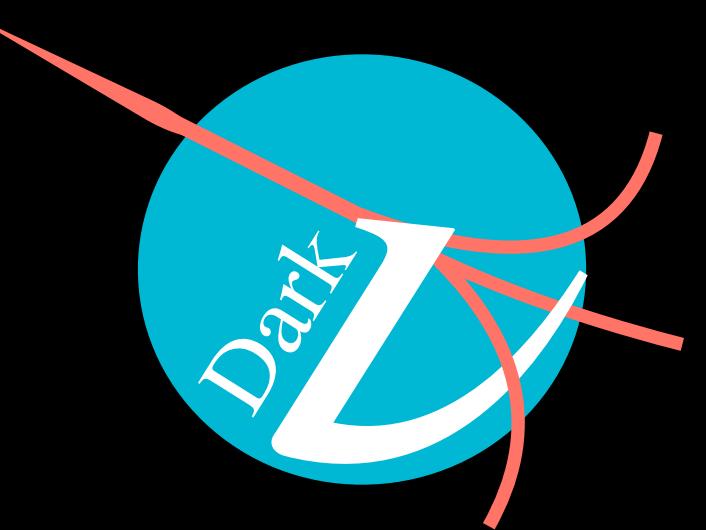
Helicity conserving or flipping upscattering $\nu \rightarrow N$

Two scattering regimes:

- Coherent nucleus scattering (Nuclear Data Tables Fourier-Bessel FFs)
- Scattering on free nucleons (proton & neutron dipole FFs).

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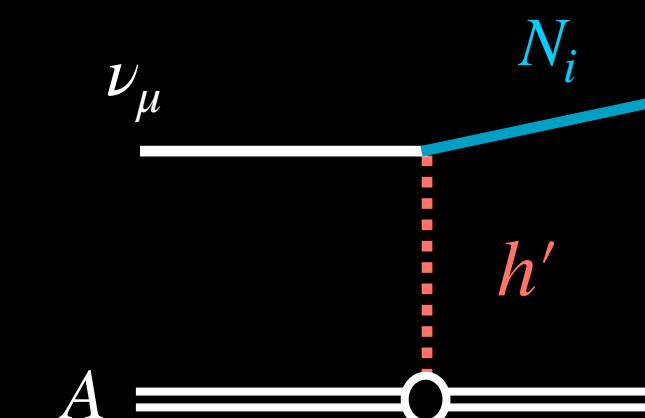
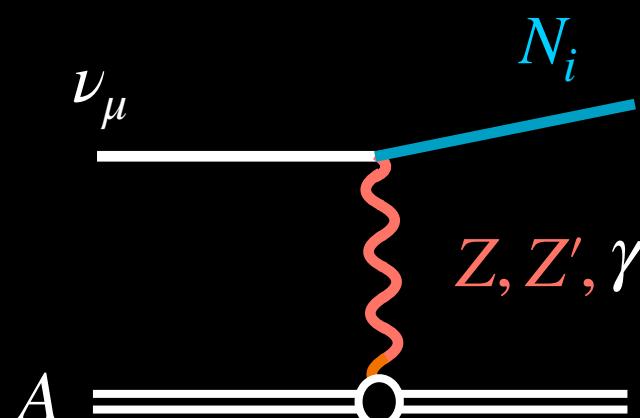
```
DarkNews-generator - zsh - mhostert
DEEPLINKS [REDACTED]
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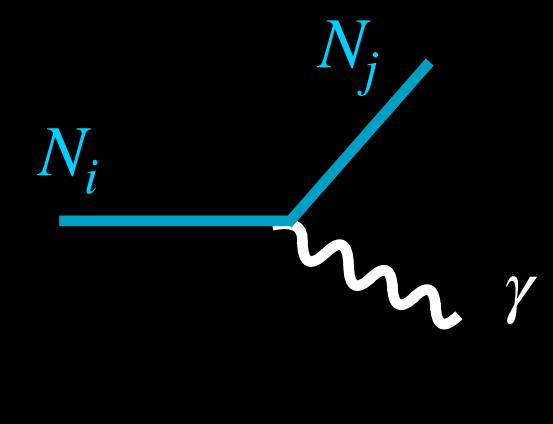
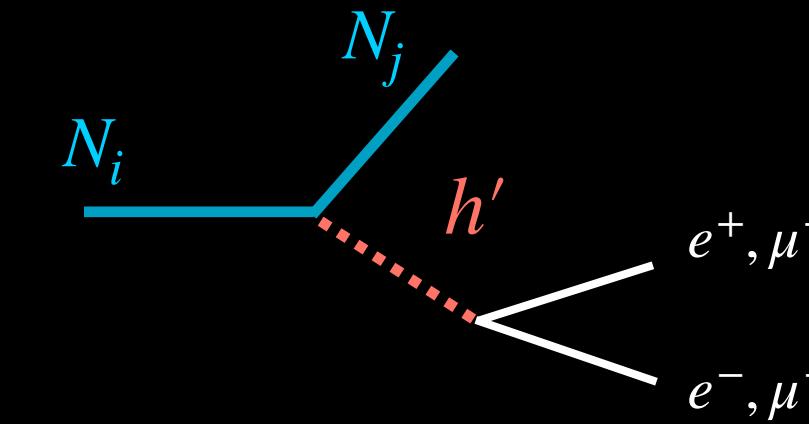
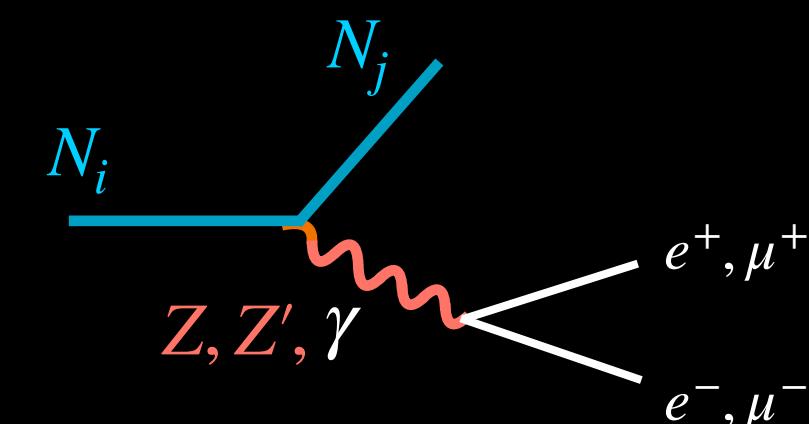
Helicity conserving or flipping upscattering $\nu \rightarrow N$

HNL decay:

$$N \rightarrow \nu \ell^+ \ell^-$$

or

$$N \rightarrow \nu \gamma$$



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

DarkNews pipeline

User input

Model parameters

Pre-defined models with
 Z, Z', h', γ mediators.

Experimental parameters

- Neutrino flux and exposure,
- Nuclear targets and fiducial mass.

DarkNews pipeline

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Sample differential rates

Use vegas to sample the event rate,

$$\frac{dN}{dQ^2 dPS} = \frac{d\sigma}{dQ^2} \left(\frac{d\Gamma_{N \rightarrow \nu X}}{dPS} \frac{1}{\Gamma_{\text{tot}}} \right)$$

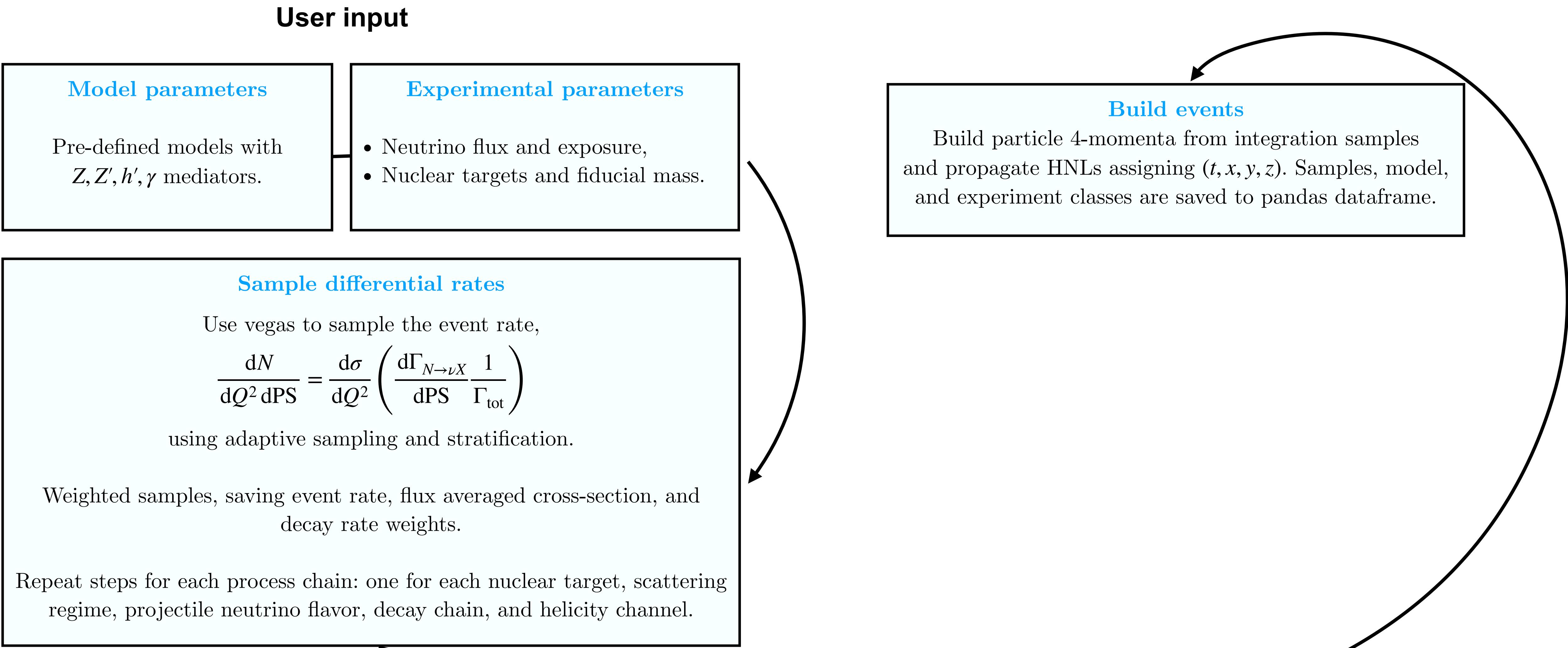
using adaptive sampling and stratification.

Weighted samples, saving event rate, flux averaged cross-section, and decay rate weights.

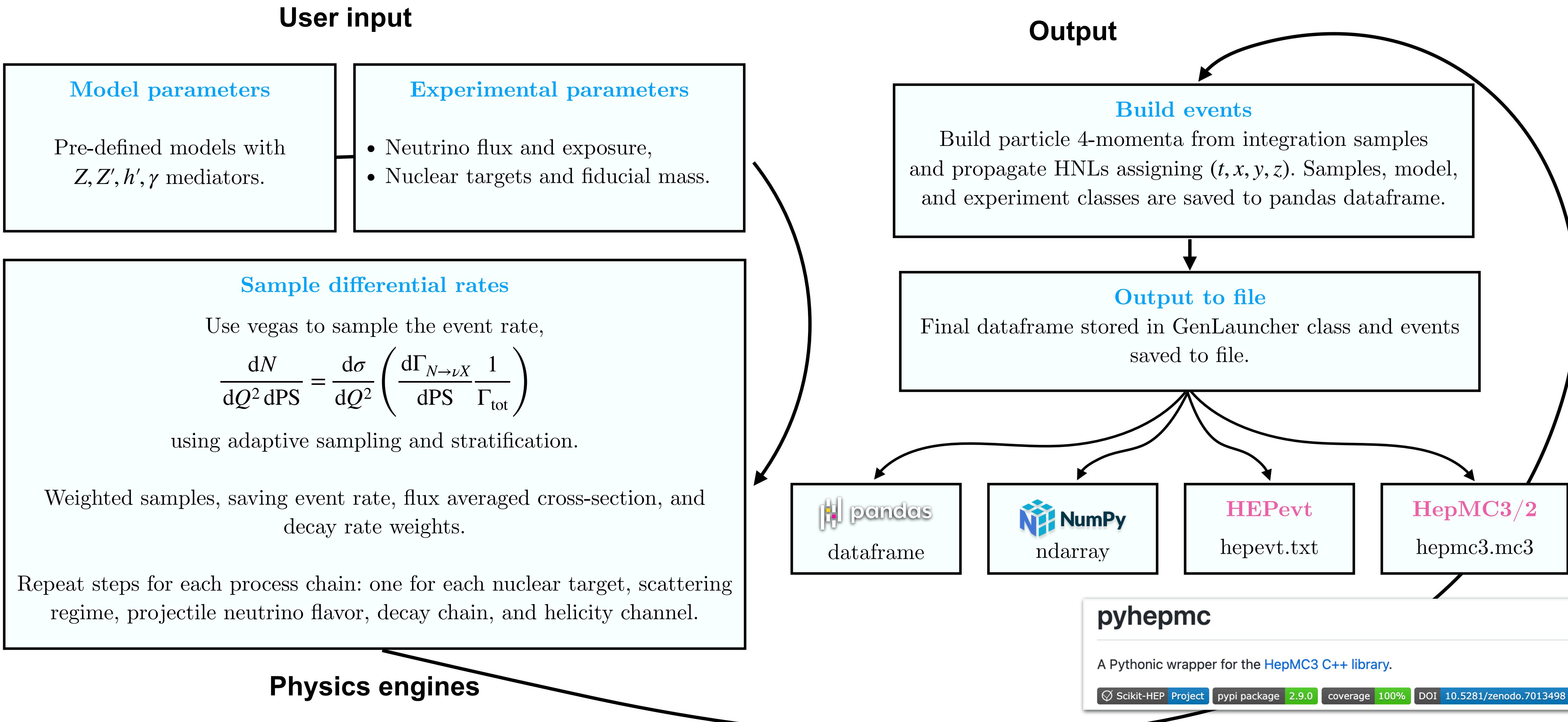
Repeat steps for each process chain: one for each nuclear target, scattering regime, projectile neutrino flavor, decay chain, and helicity channel.

Physics engines

DarkNews pipeline



DarkNews pipeline



Conclusions:

Thank you!
mhostert@pitp.ca

Neutrino experiments provide a key probe of decay-in-flight of new particles (esp. below the kaon mass).

Closing gaps between cosmology and laboratory in HNL models, except when decay interaction is stronger-than-Weak (TMM or light dark photon and scalars).

T2K ND280, MicroBooNE, and PS-191 provide leading limits in large regions of parameter space.

At the largest interaction strengths, new forces lead to neutrino-production of HNL inside dirt/detector.

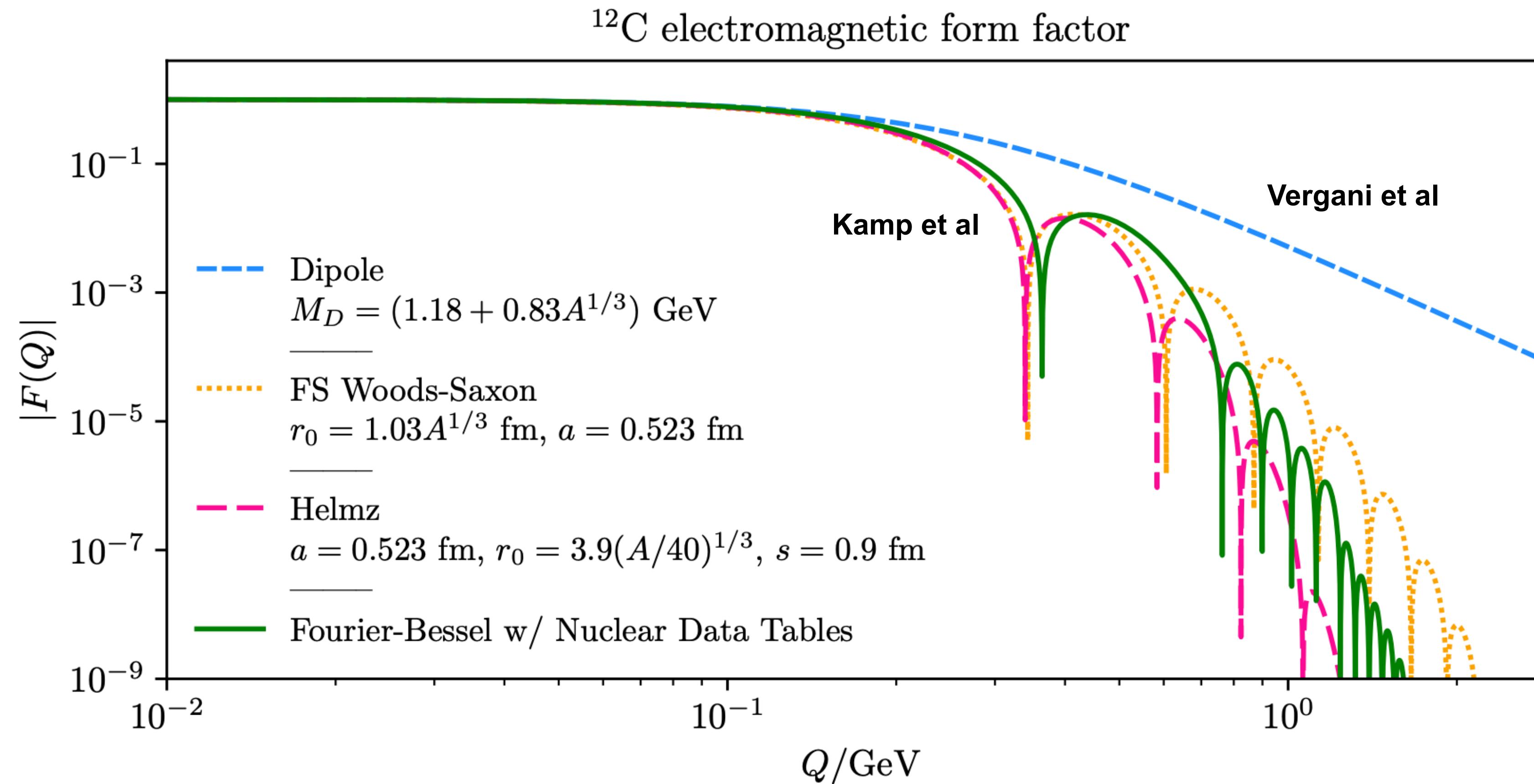
For TMM (transition magnetic moment) is not dead yet.

Large angle and dE/dx data of MINERvA could probe all parameter space of MiniBooNE.

DarkNews publicly available. It simulates upscattering + decay signatures in accelerator beams.

github.com/mhostert/DarkNews-generator

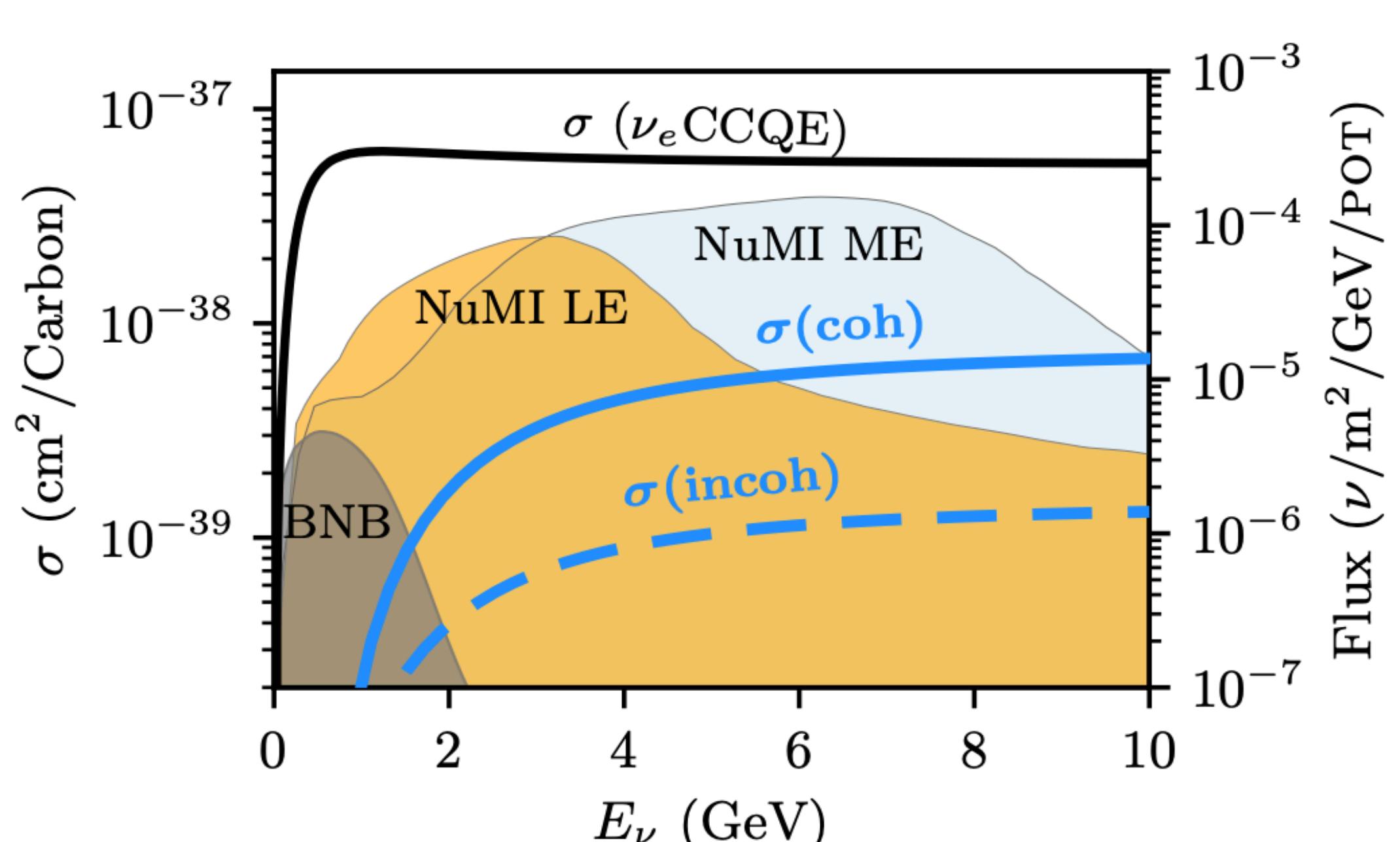
Nuclear Form Factors



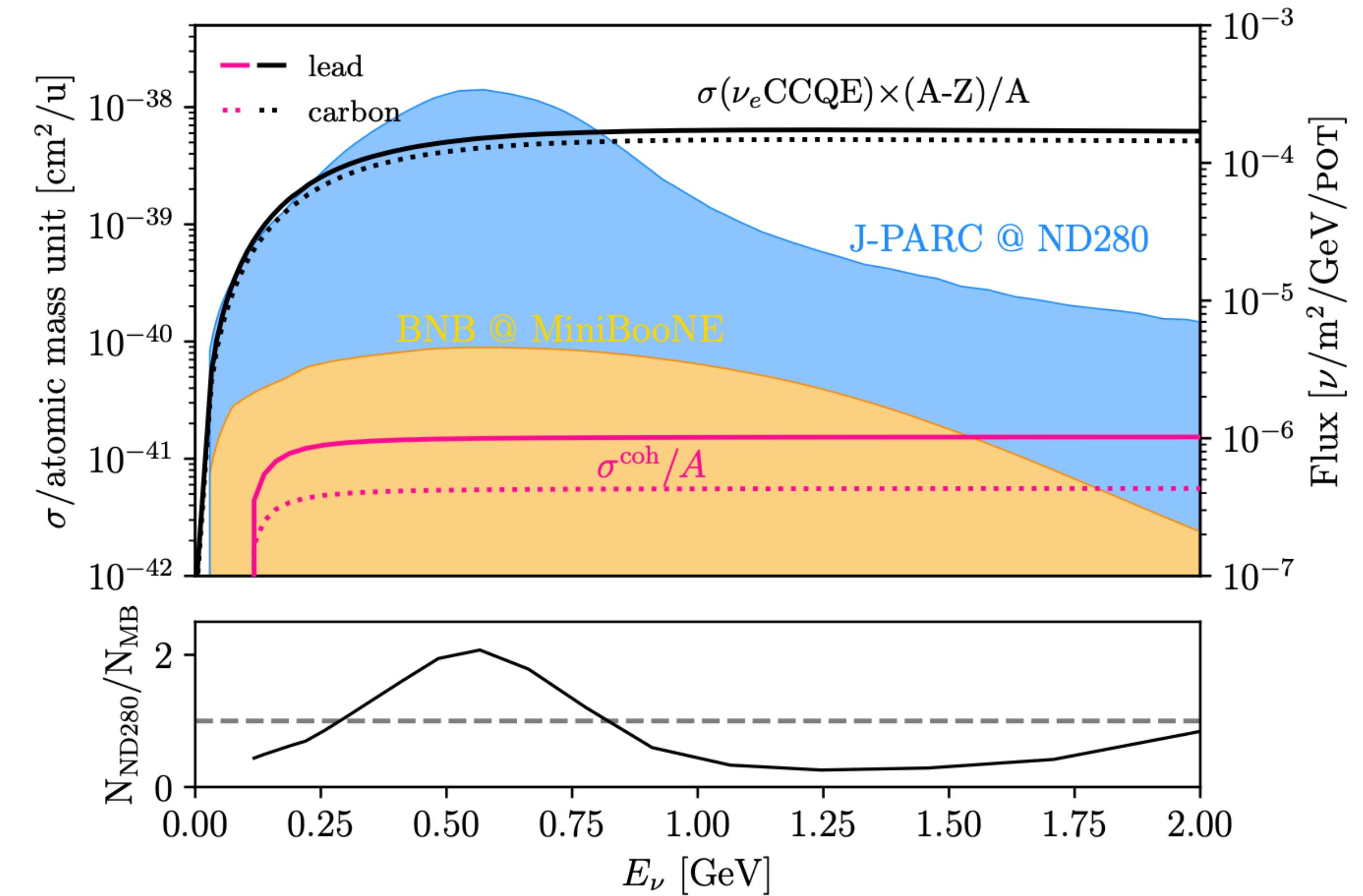
Transition magnetic moment

MINERvA limits from $\nu - e$ scattering measurement

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



Dark Photon model



Transition Magnetic Moment

Dark neutrinos

Heavy neutrinos interacting via the dark photon

E. Bertuzzo et al., [arXiv:1807.09877]

P. Ballett et al, [arxiv:1808.02915]

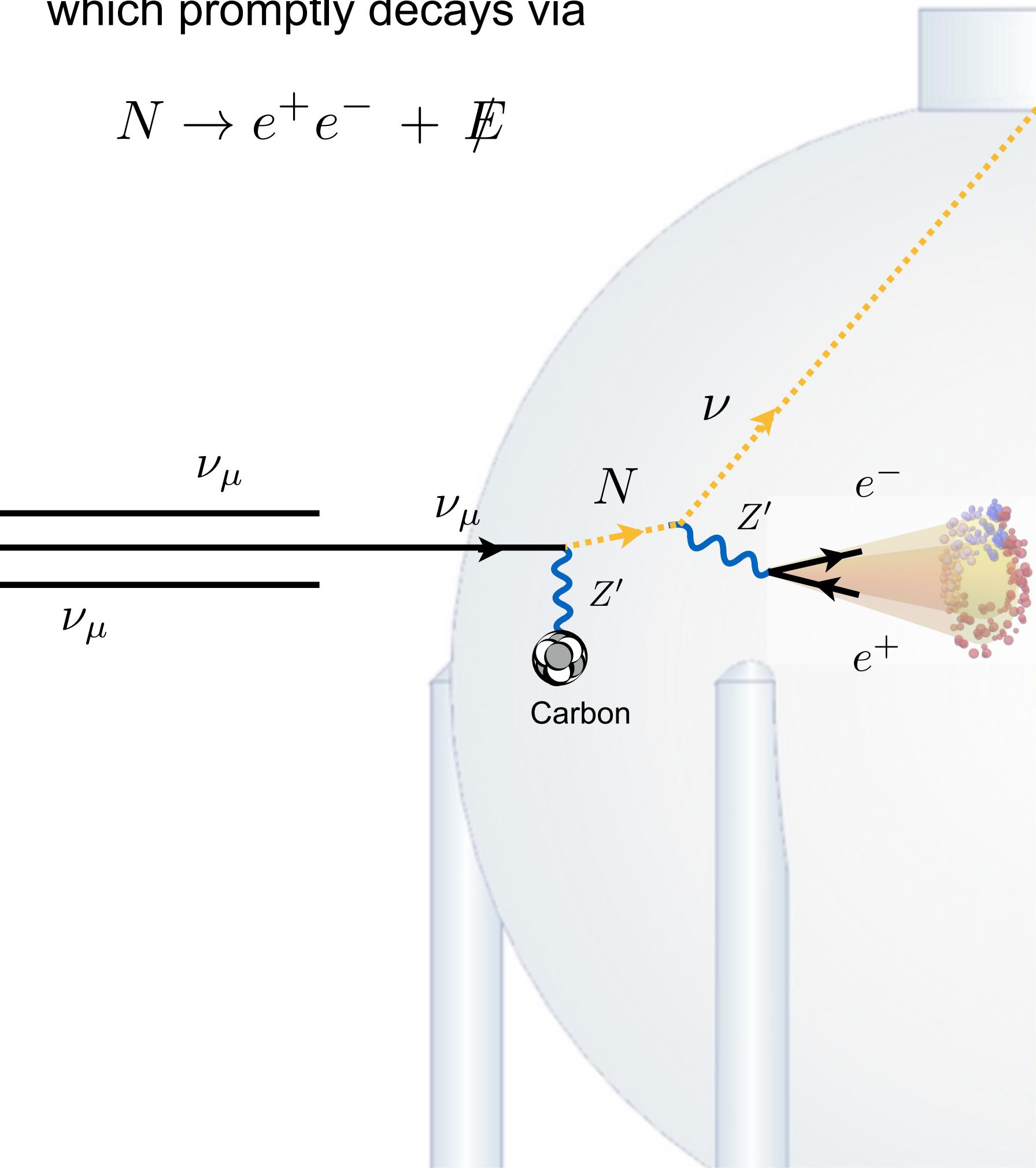
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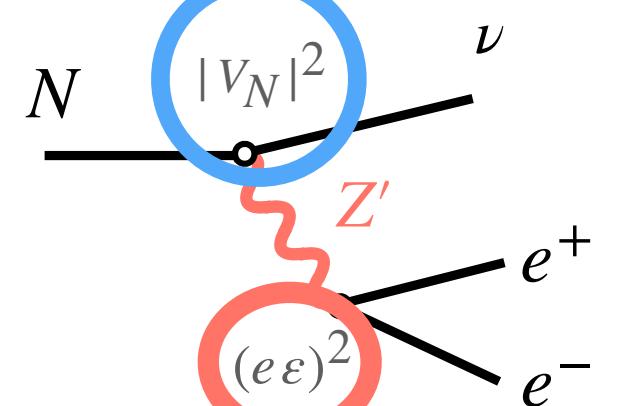
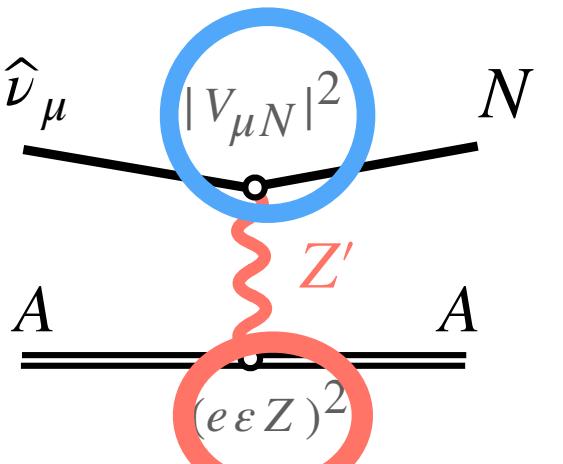
A. Abdullahi, MH, S. Pascoli, [arXiv:2007.11813]

Neutrinos up-scatter into HNL,
which promptly decays via

$$N \rightarrow e^+ e^- + \cancel{E}$$



$$\mathcal{L} \supset \mathcal{L}_{\nu\text{-mass}} + \frac{m_{Z'}^2}{2} Z'^\mu Z'_\mu + Z'_\mu \left(e \epsilon J_{\text{EM}}^\mu + \sum_{i,j}^{n+3} V_i \bar{\nu}_i \gamma^\mu \nu_j \right)$$



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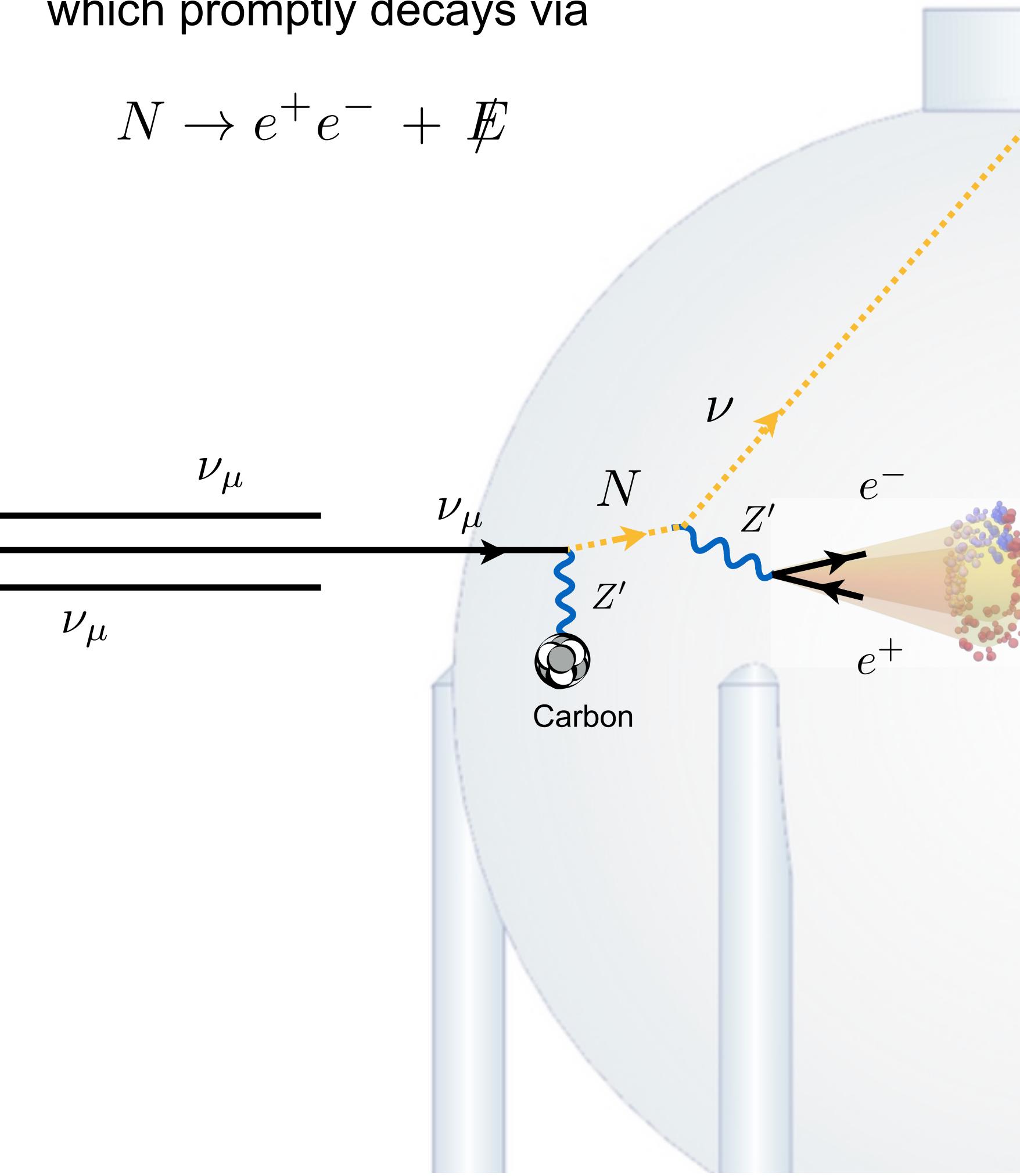
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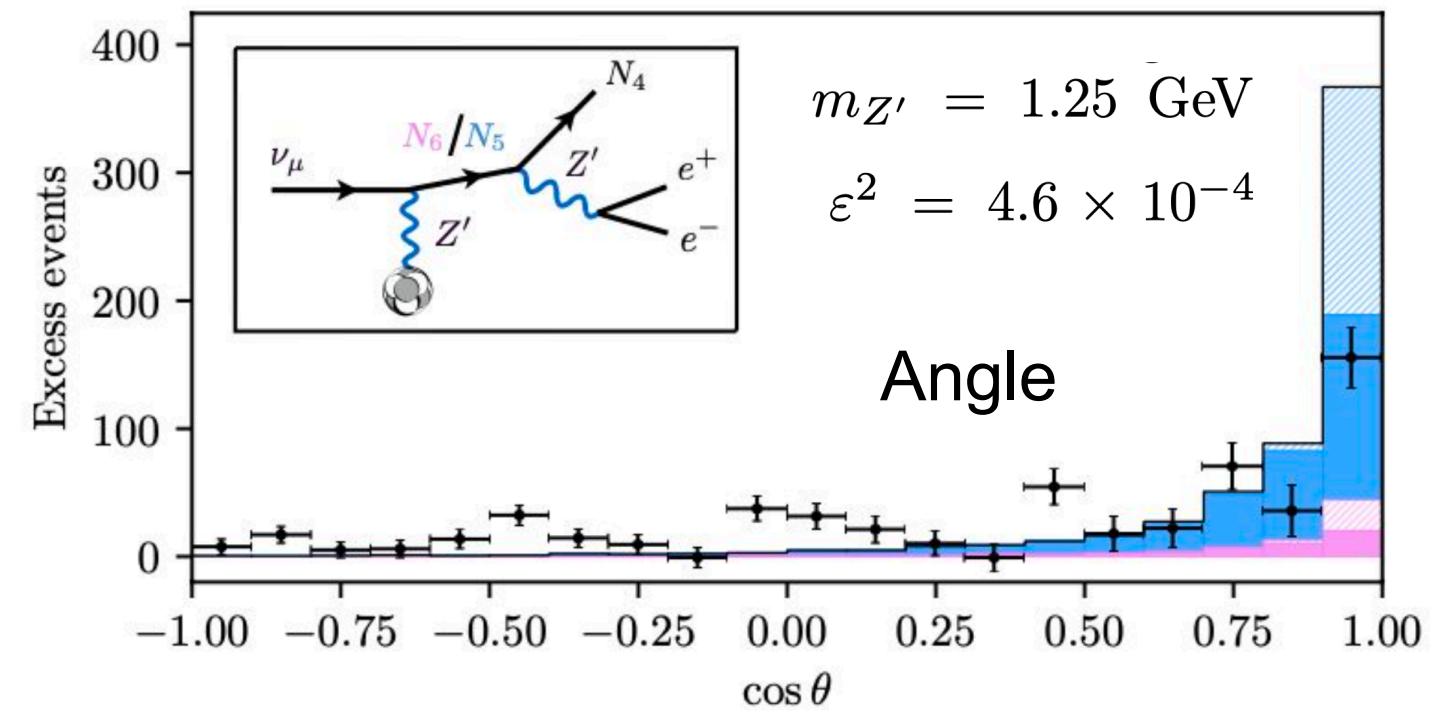
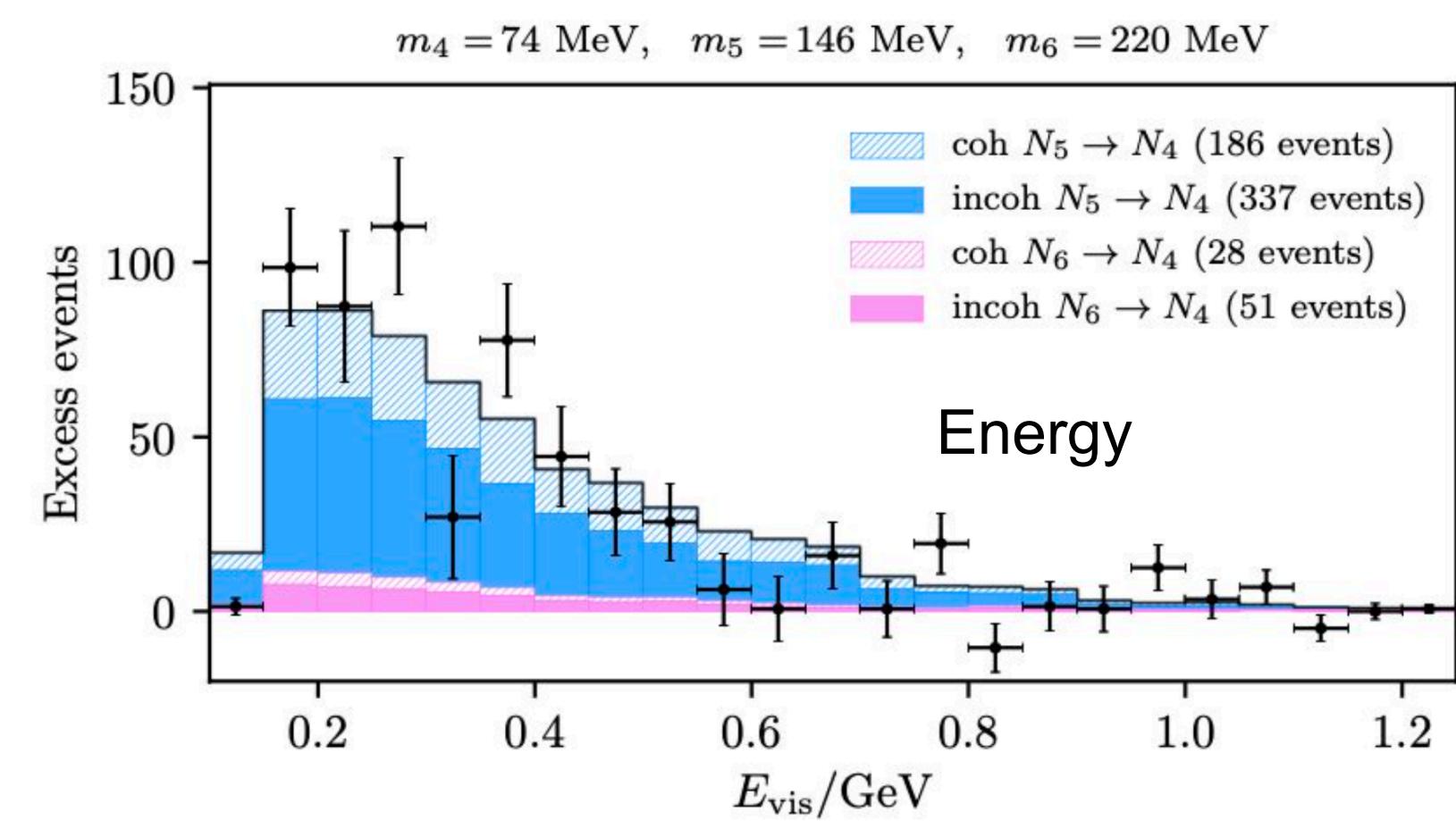
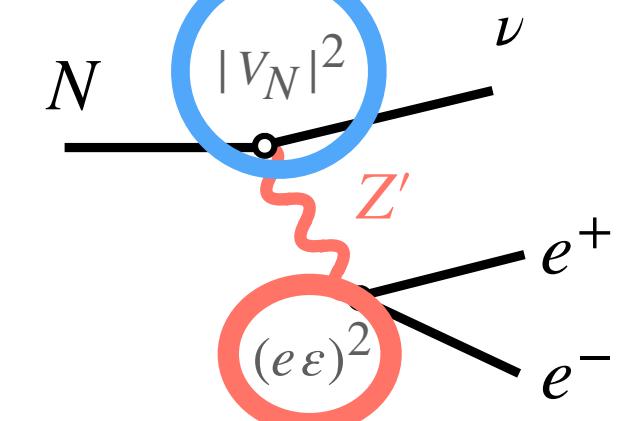
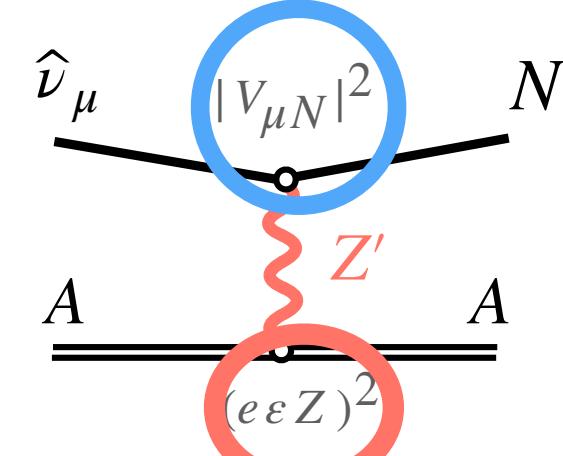
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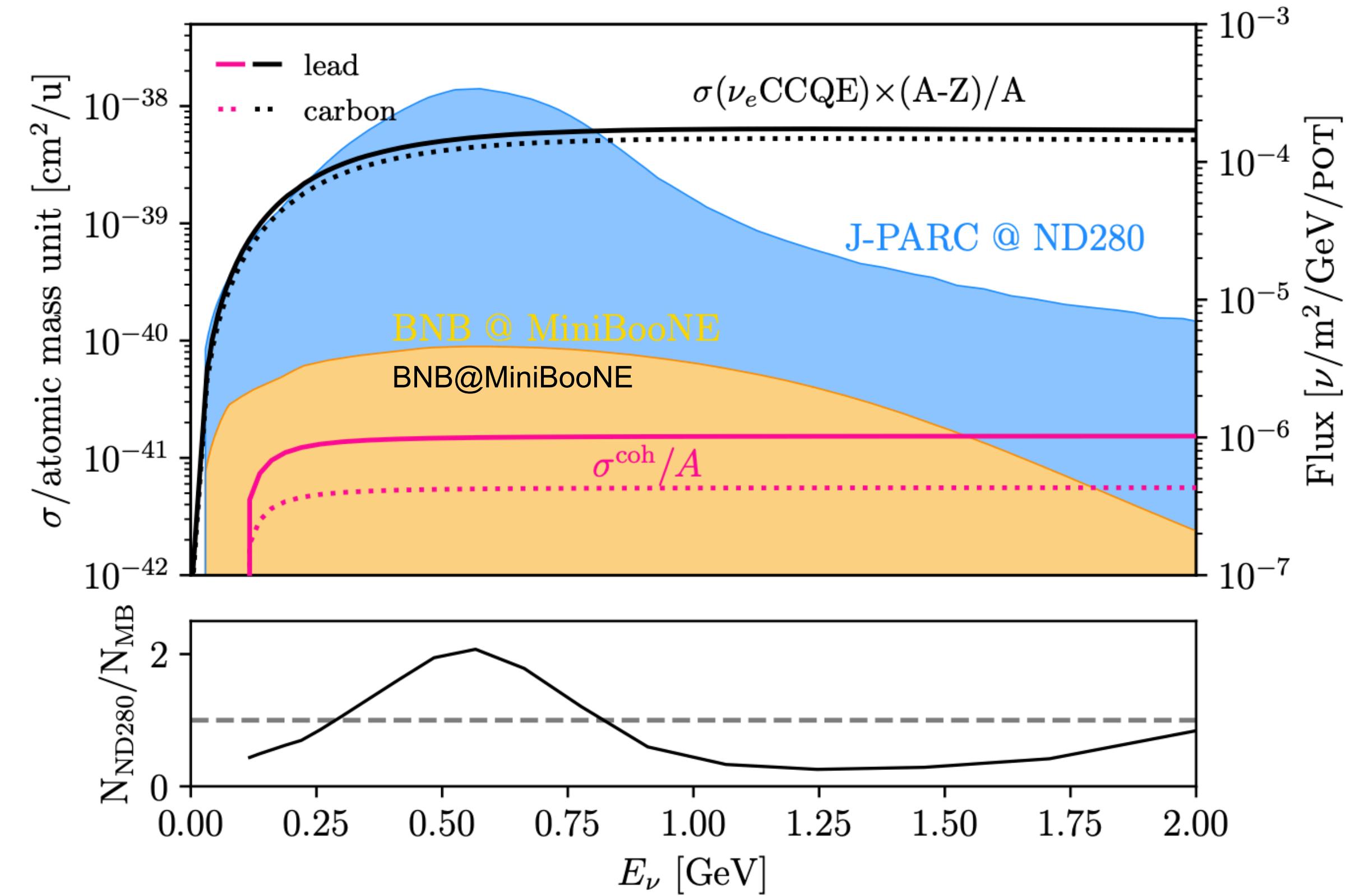
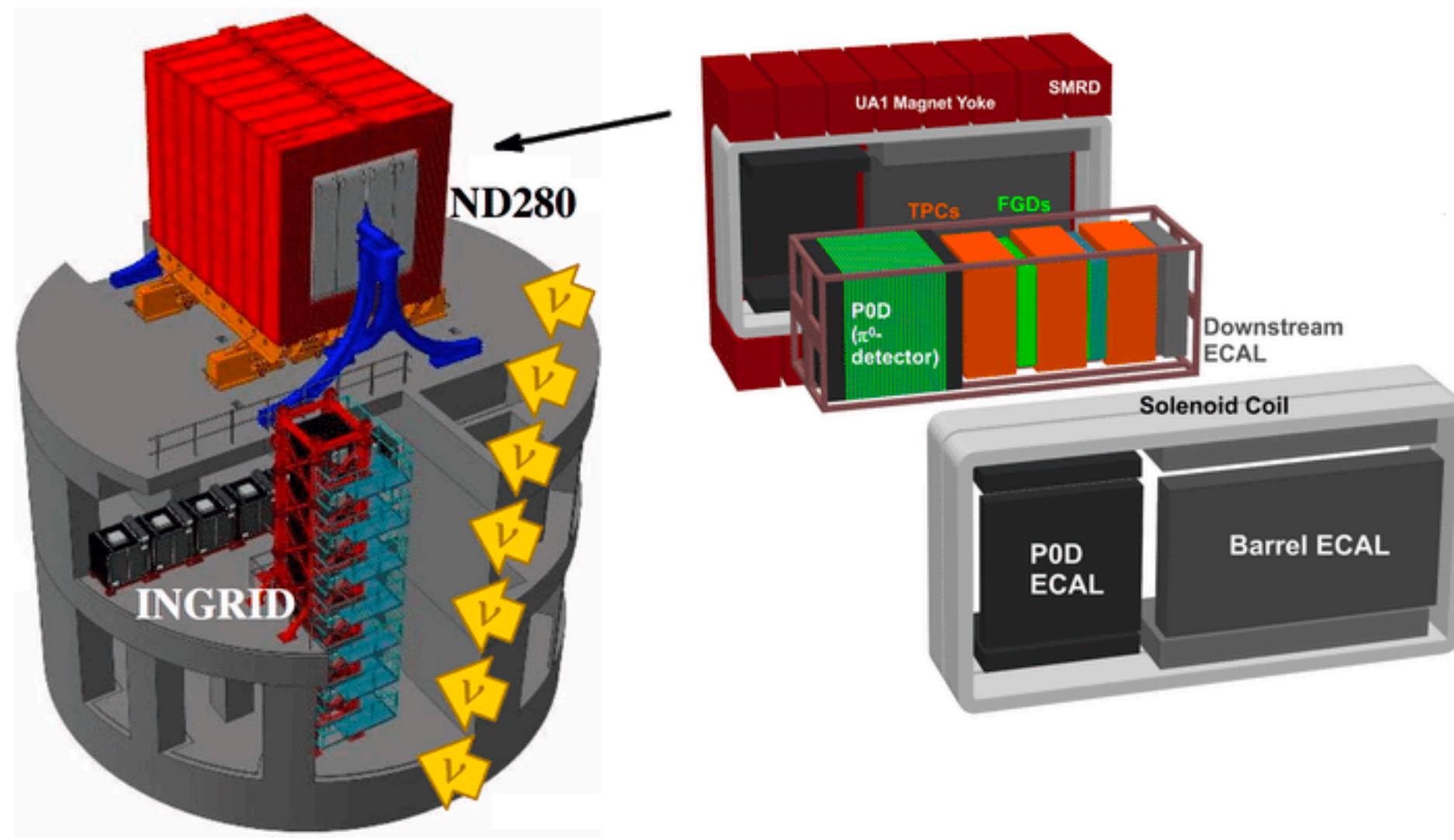
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Dark Neutrino Sectors

Upscattering at the T2K near detector

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



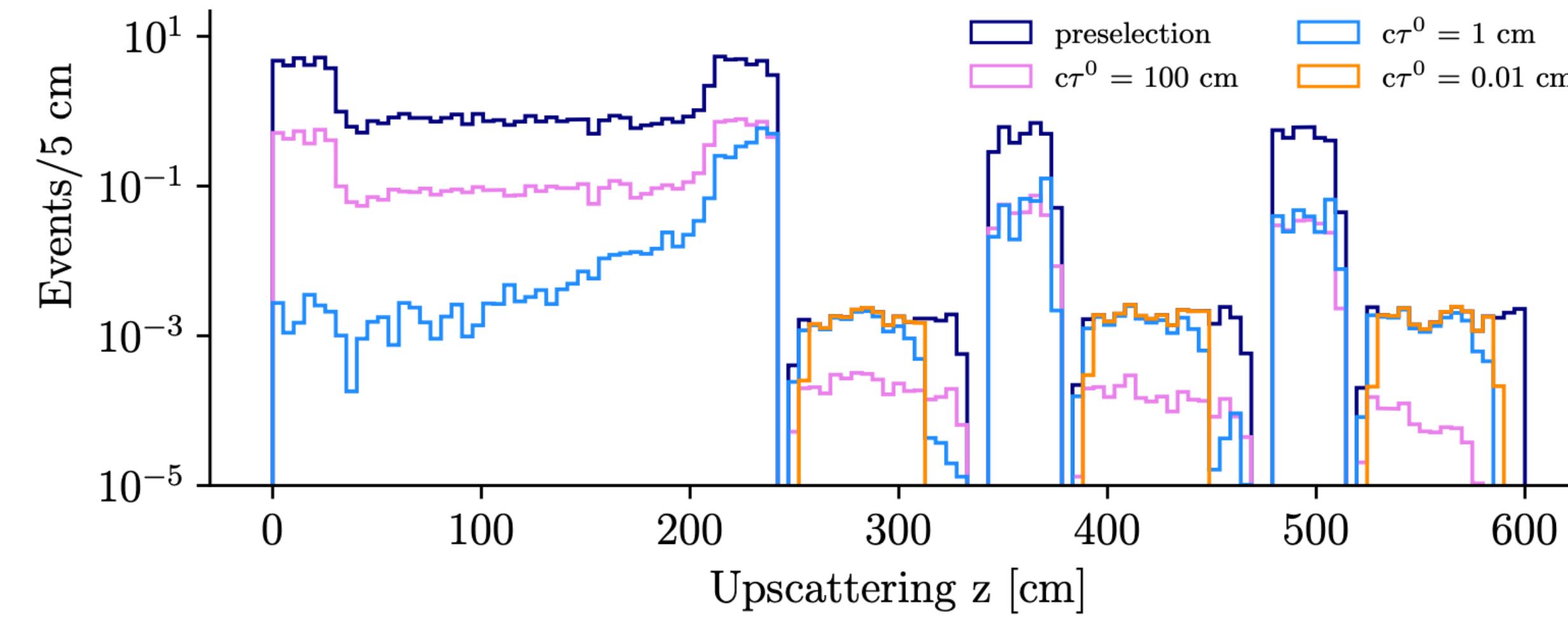
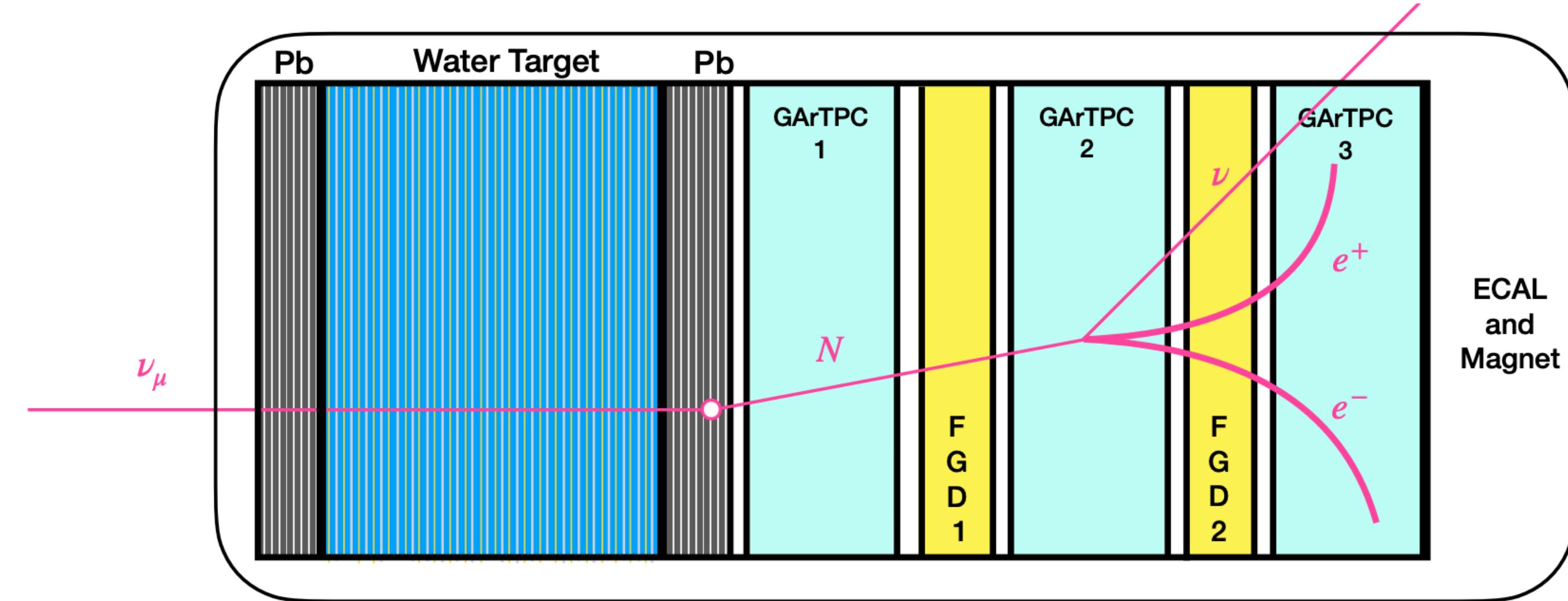
J-PARC beam is more intense and peaks in a similar energy range to the Booster Beam.

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

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



Benefit of this detector:

Heavy **lead** plates

+ Gaseous Argon modules

+ Magnetic field to separate e^+e^-

Dark Neutrino Sectors

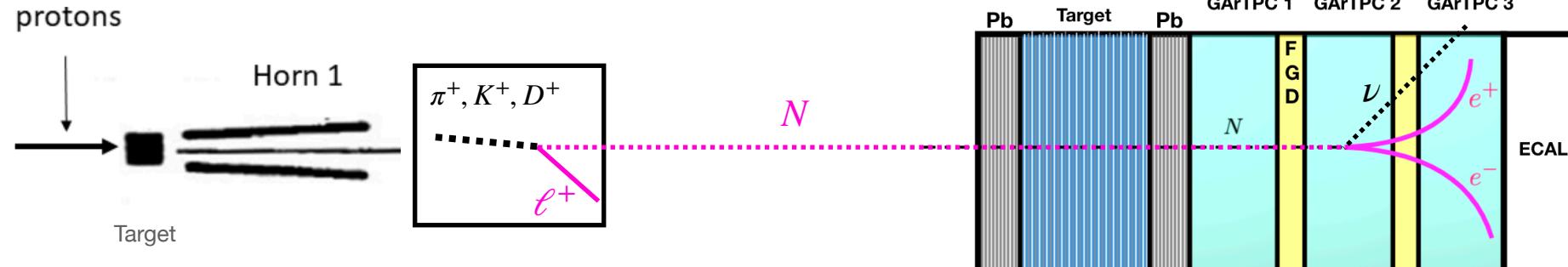
Upscattering at the T2K near detector

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

T2K search:



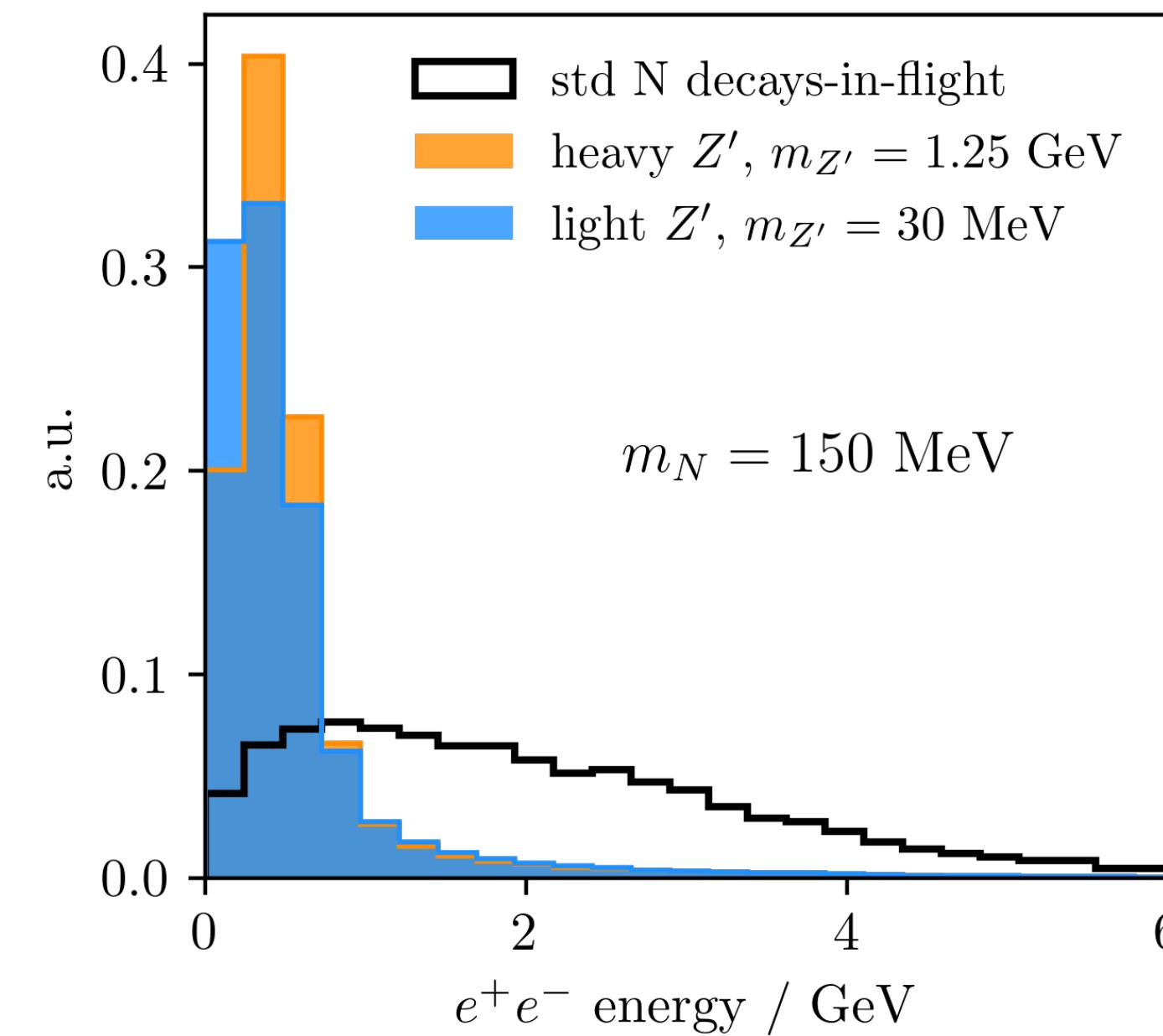
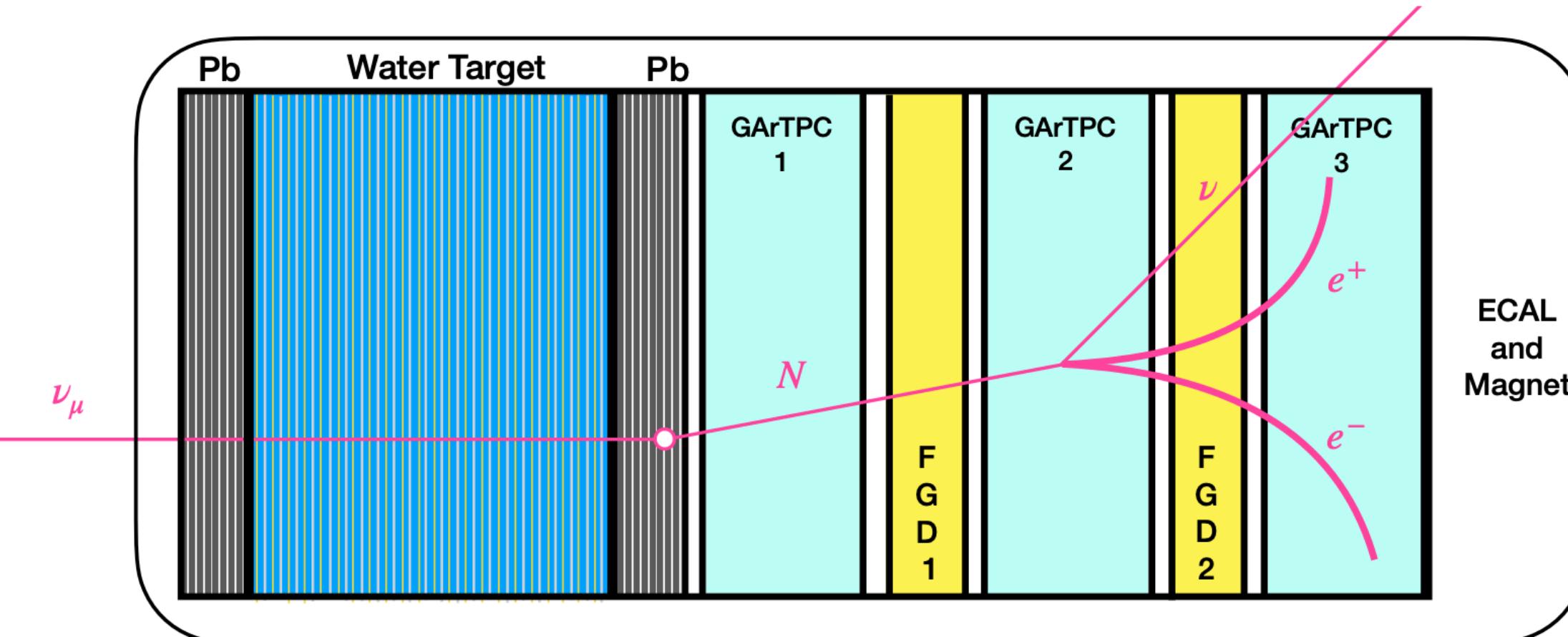
+ Heavy lead plates

+ Gaseous Argon modules

+ Magnetic field to separate e^+e^-

**No events were observed.
Backgrounds were < 1.**

Our signal:



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

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

Dark Neutrino Sectors

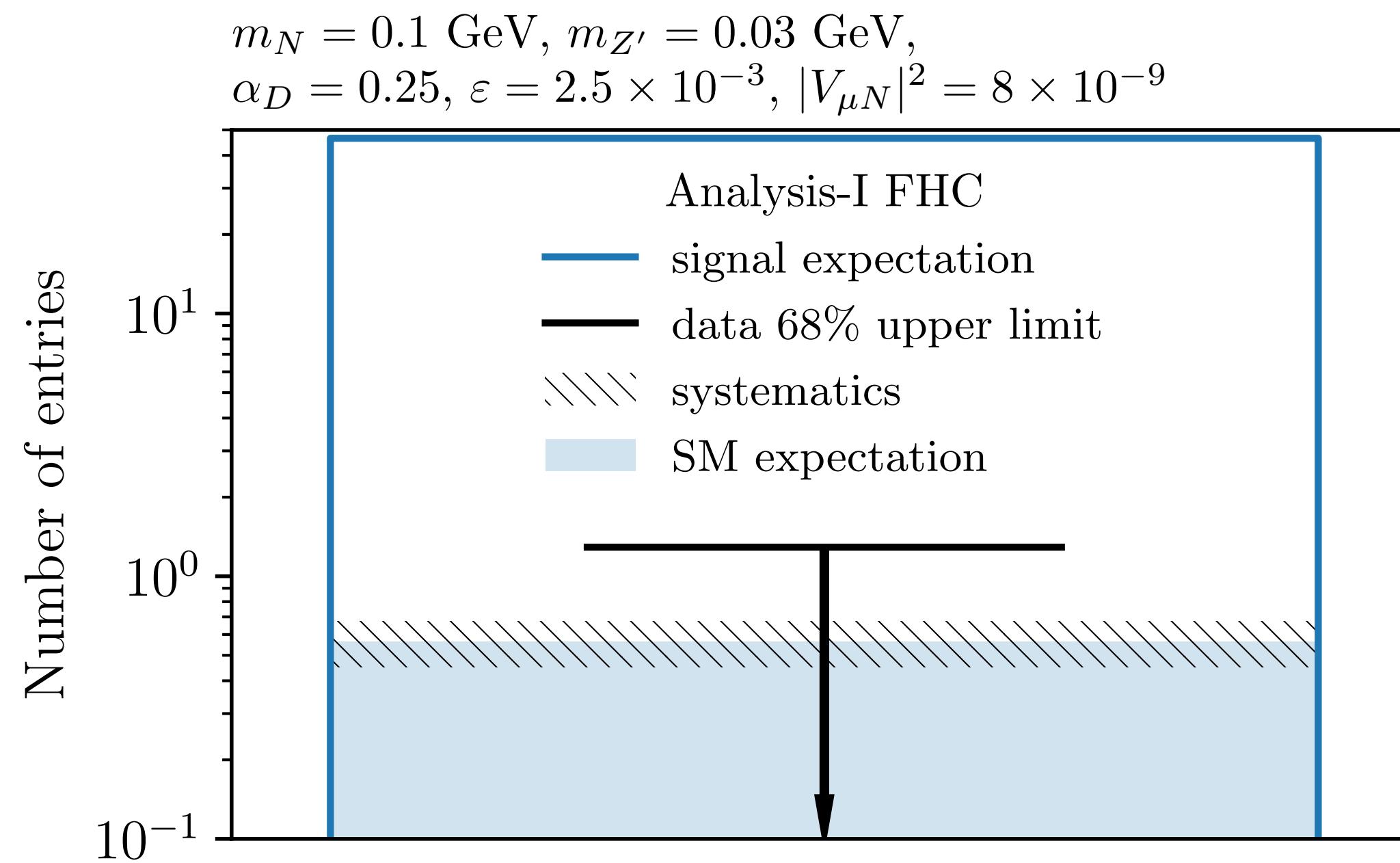
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See also, Vedran Brdar et al, arXiv:2007.14411

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

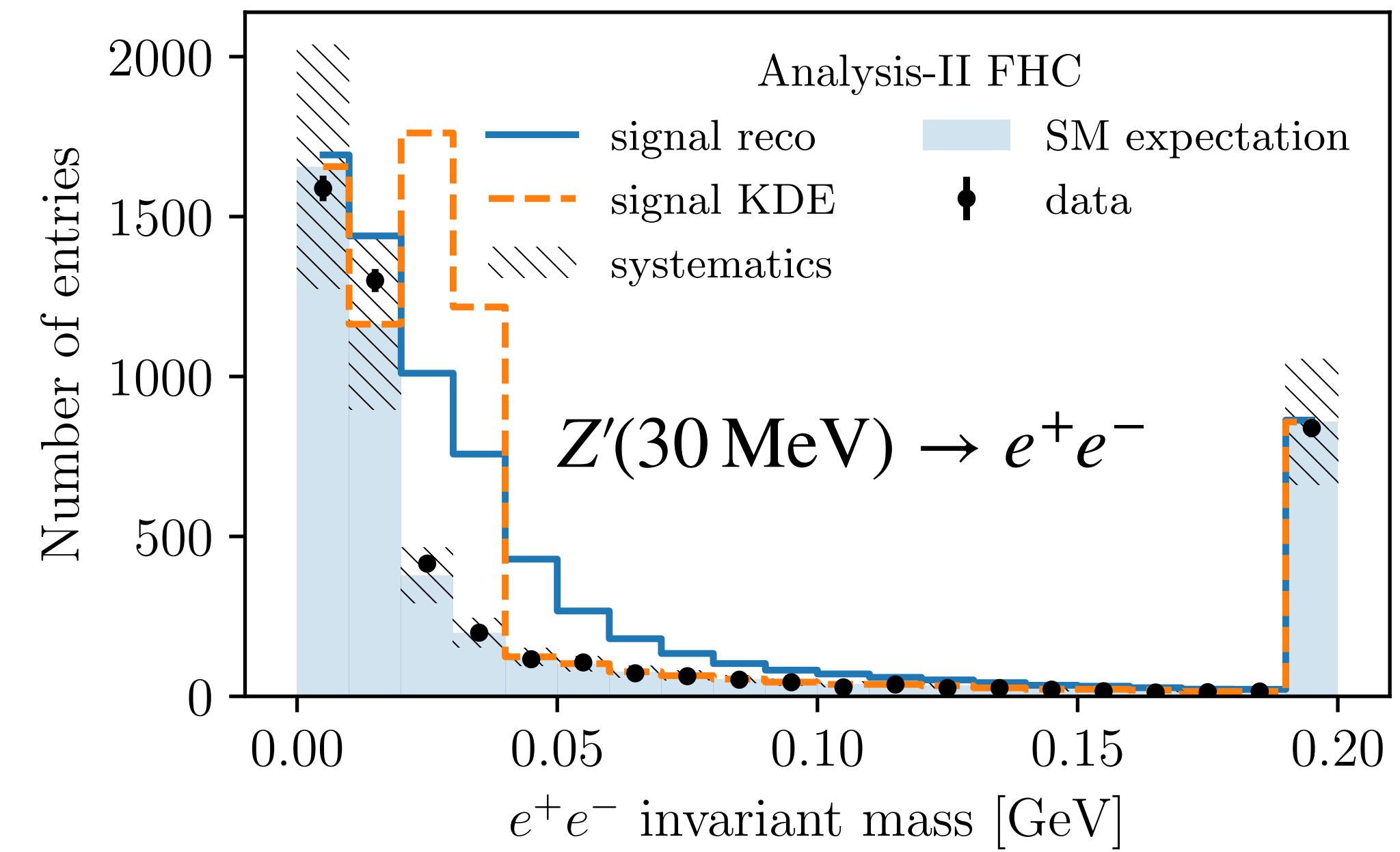
Dataset I — The T2K search for the decay in flight of HNLs



Single bin. No events observed.

(Nearly-)Background-free search.

Dataset II — The T2K search for single photons



Scatterings and decay inside FGD.

Backgrounds and smaller target mass means this dataset is less sensitive than Dataset I. But only one that targets promptly-decaying cases.

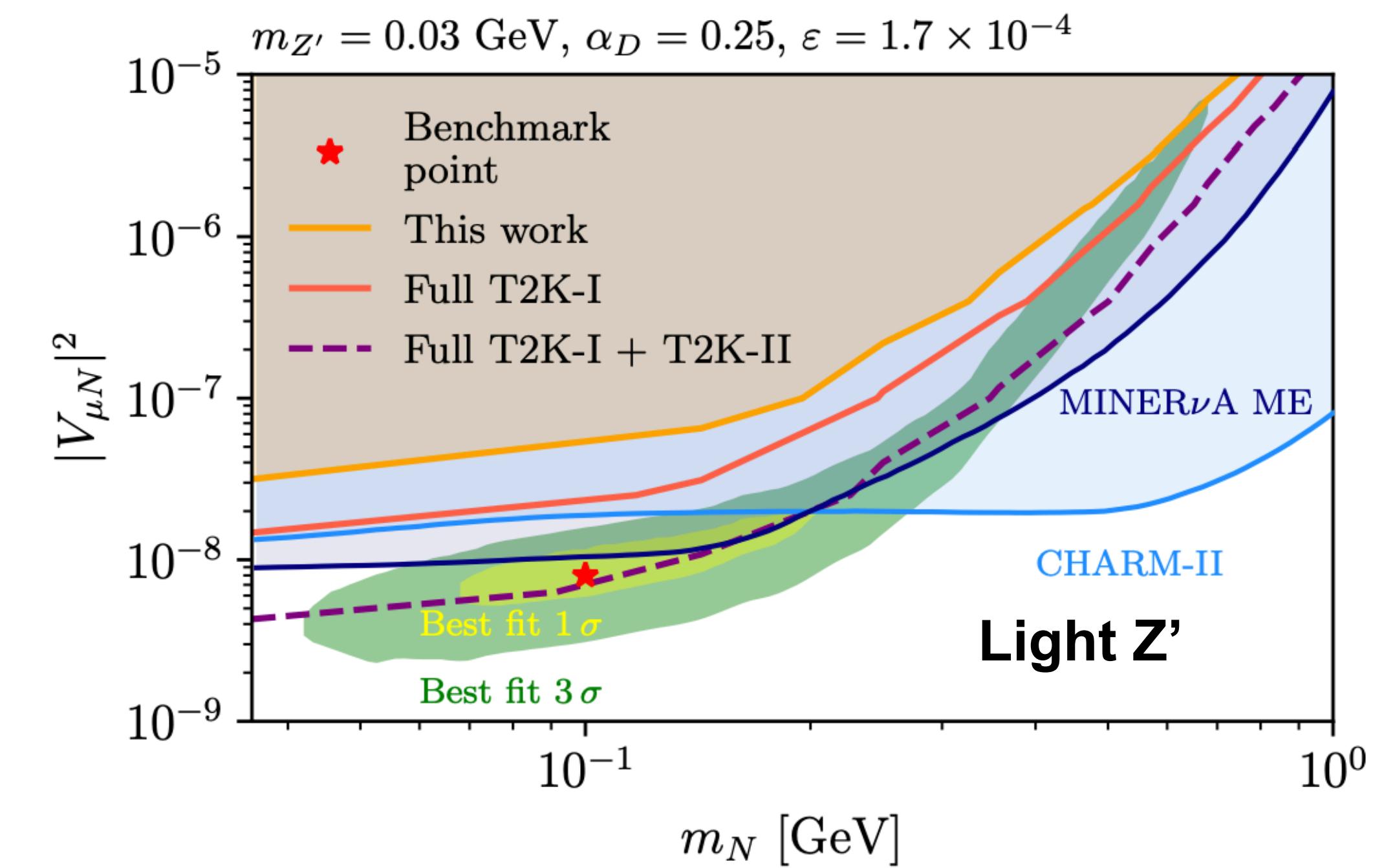
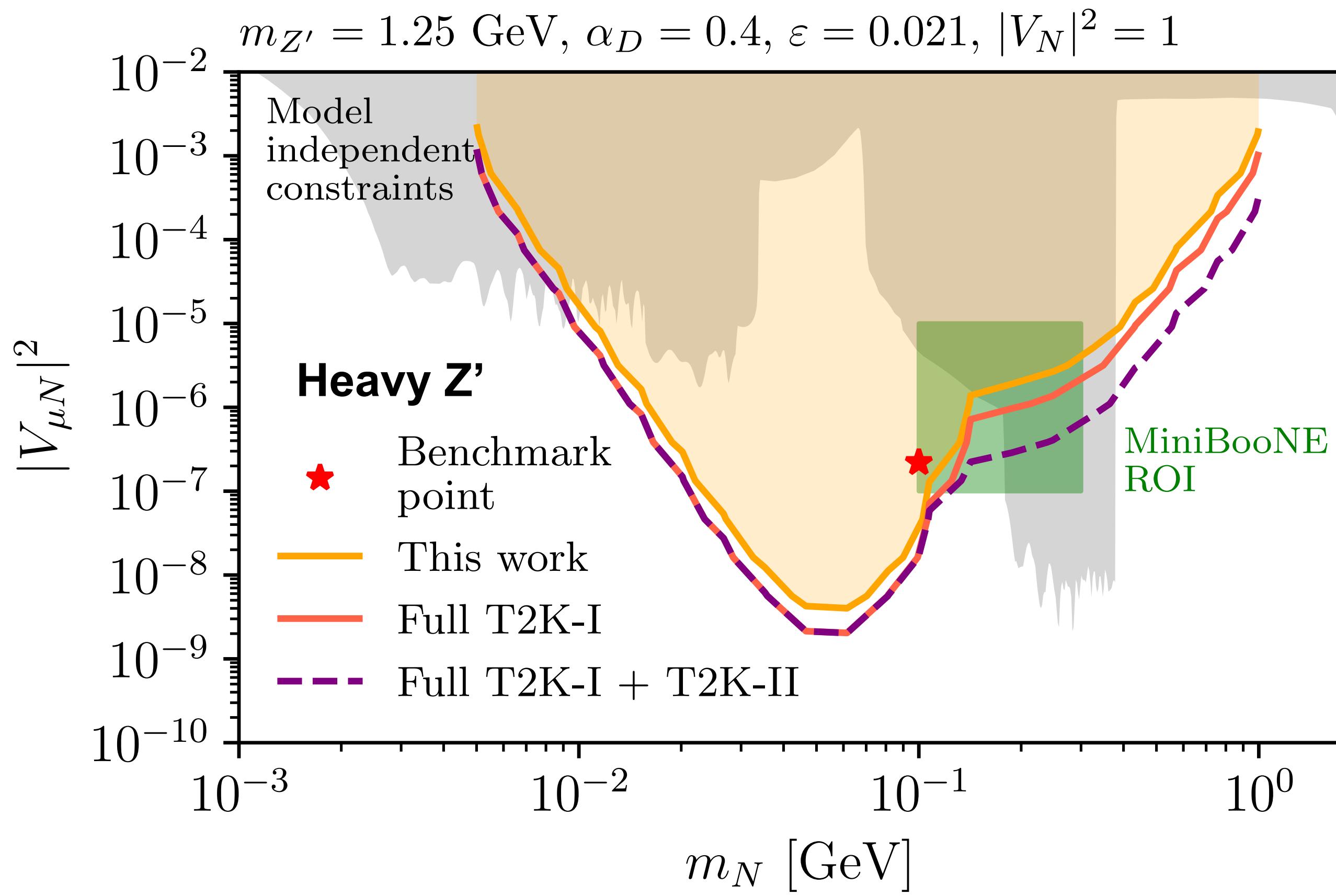
Dark Neutrino Sectors

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 available yet.

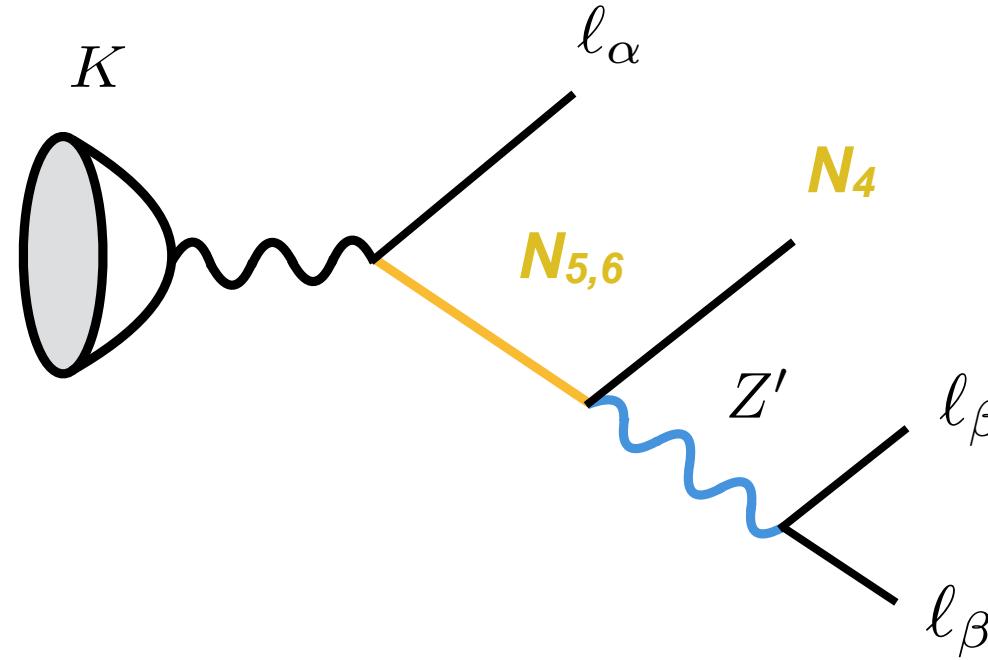
e^+e^- models with $c\tau_N^0/m_N \gtrsim 3$ cm/GeV
are in tension with T2K data.

Prompt decays at Kaon factories

Three charged lepton signatures

Rare leptonic kaon decays

Peak search + (displaced) e+e- vertex



At **NA62**, would expect ~ 3000 events in existing data for our *benchmark*.

$$|p_K - p_\ell| = m_{5,6}$$

$$m_{\text{miss}} = |p_K - p_\ell - p_{ee}| = m_4$$

$$m_{ee} < m_{5,6} - m_4$$

Existing measurements:

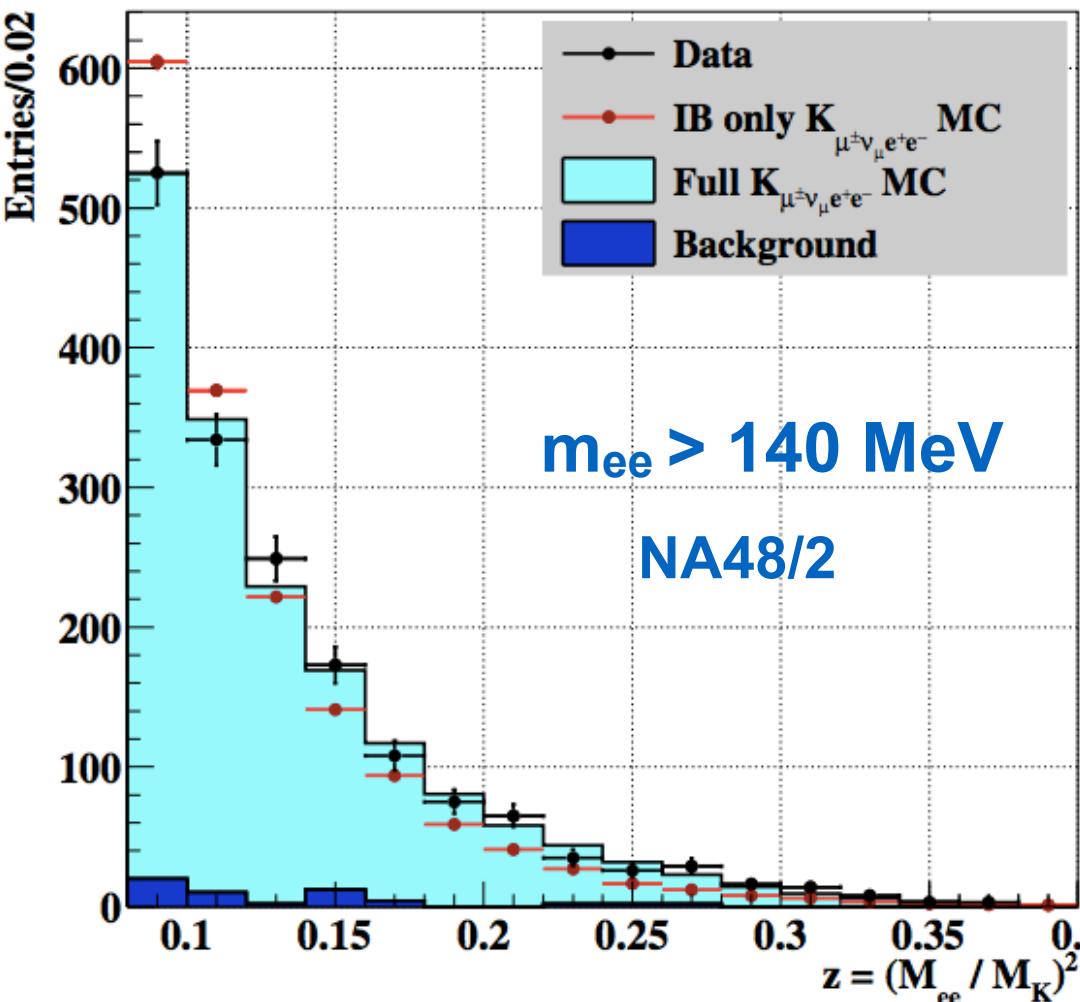
$$\text{BR}(K^+ \rightarrow \mu^+ \nu e^+ e^-) = (7.81 \pm 0.21 \text{ stat.}) \times 10^{-8} \text{ @ NA48/2}$$

$$\text{BR}(K^+ \rightarrow \mu^+ \nu \mu^+ \mu^-) < 4.7 \times 10^{-7} \text{ @ E787}$$

Both SM process will be measured by NA62.

New physics challenges:

M. S. Atiya *et al.*, PRL.63, 2177 (1989)



Main challenge comes from pion Dalitz decays at $m_{ee} < 140$ MeV

$$K^+ \rightarrow \mu^+ \nu_\mu (\pi^0 \rightarrow \gamma e^+ e^-)$$

Additional cuts can reduce pi+ decay backgrounds:

$$K^+ \rightarrow (\pi^+ \rightarrow \mu^+ \nu) e^+ e^- \quad m_{\mu\nu} > 150 \text{ MeV}$$

Ultimately, depends on exp resolution, but BGs can also be reduced with displaced vertices. At NA62, this is feasible for

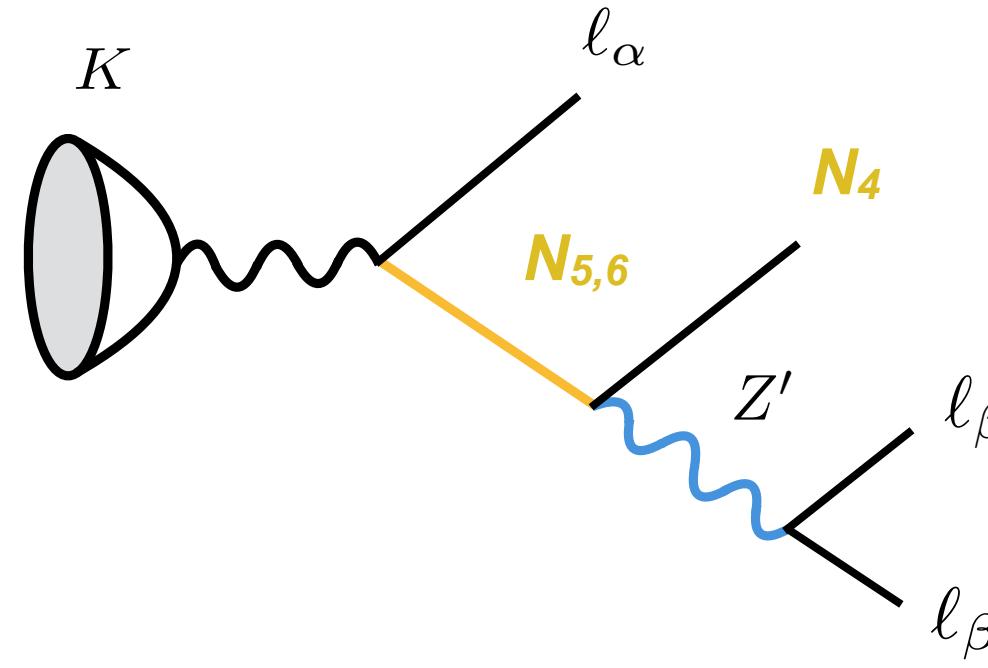
$$C\tau > 10 \text{ ps}$$

Prompt decays at Kaon factories

Three charged lepton signatures

Rare leptonic kaon decays

Peak search + (displaced) e+e- vertex



At **NA62**, would expect ~ 3000 events in existing data for our *benchmark*.

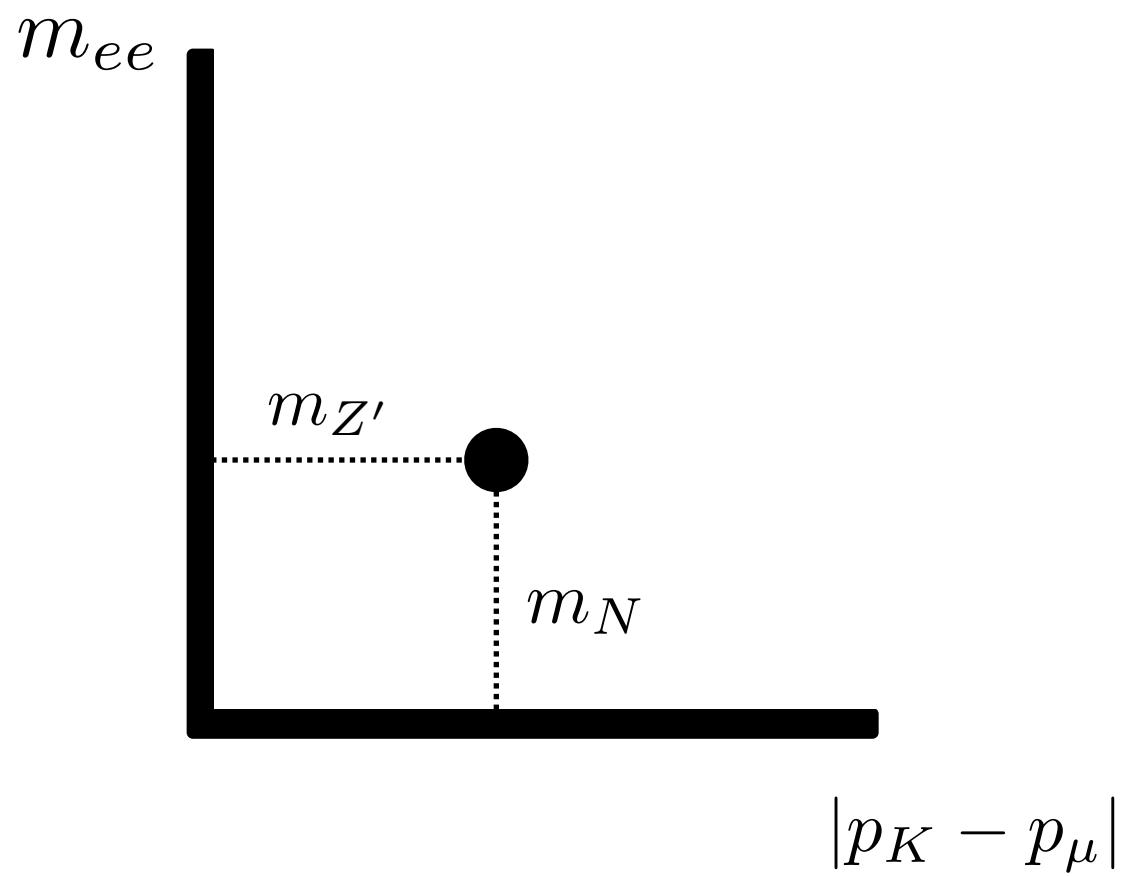
$$|p_K - p_\ell| = m_{5,6}$$

$$m_{\text{miss}} = |p_K - p_\ell - p_{ee}| = m_4$$

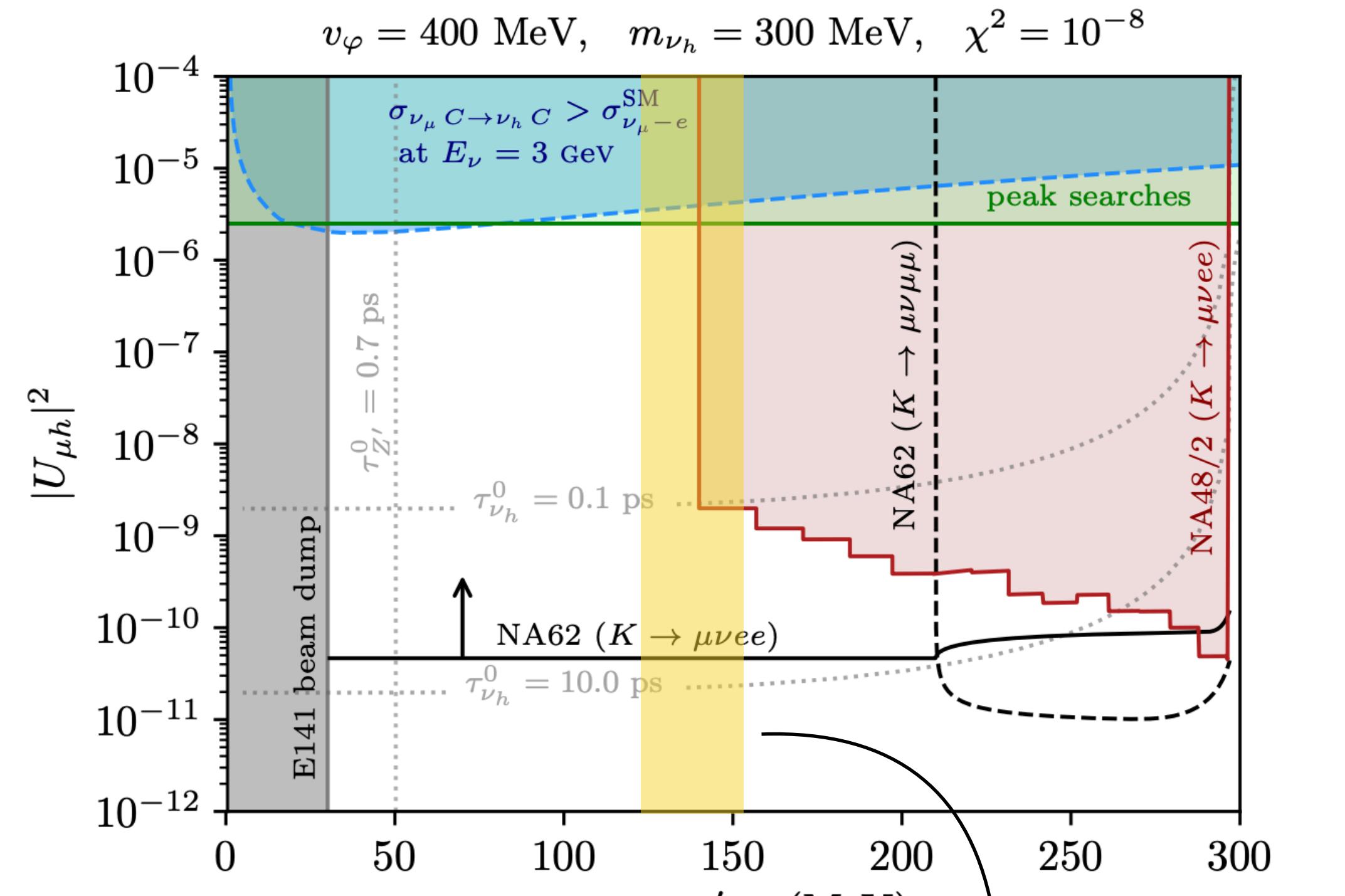
$$m_{ee} < m_{5,6} - m_4$$

Light dark photon case

Smoking gun peak at light dark photon and HNL mass



Bump hunt and displaced vertex search currently being carried out at NA62.

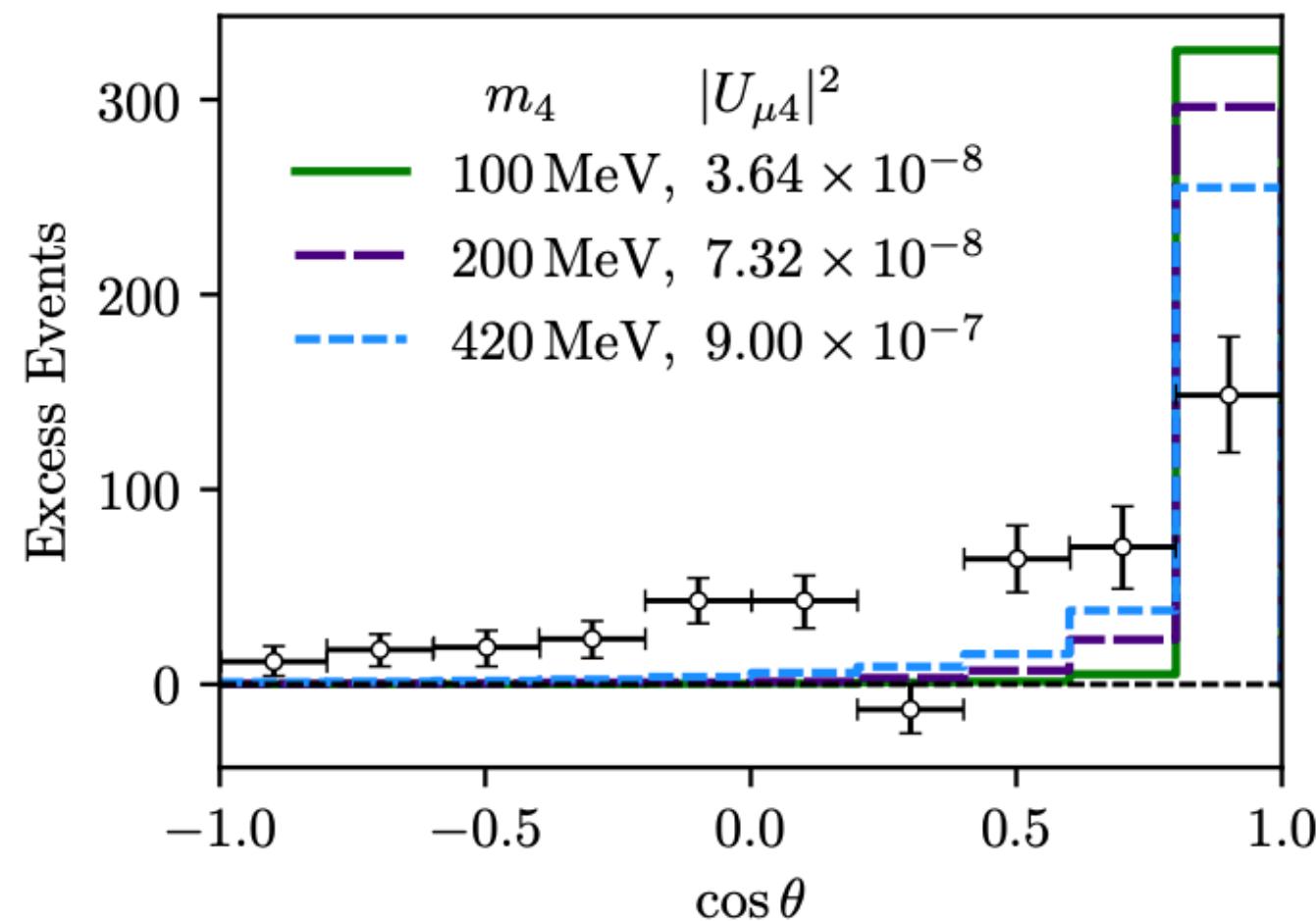
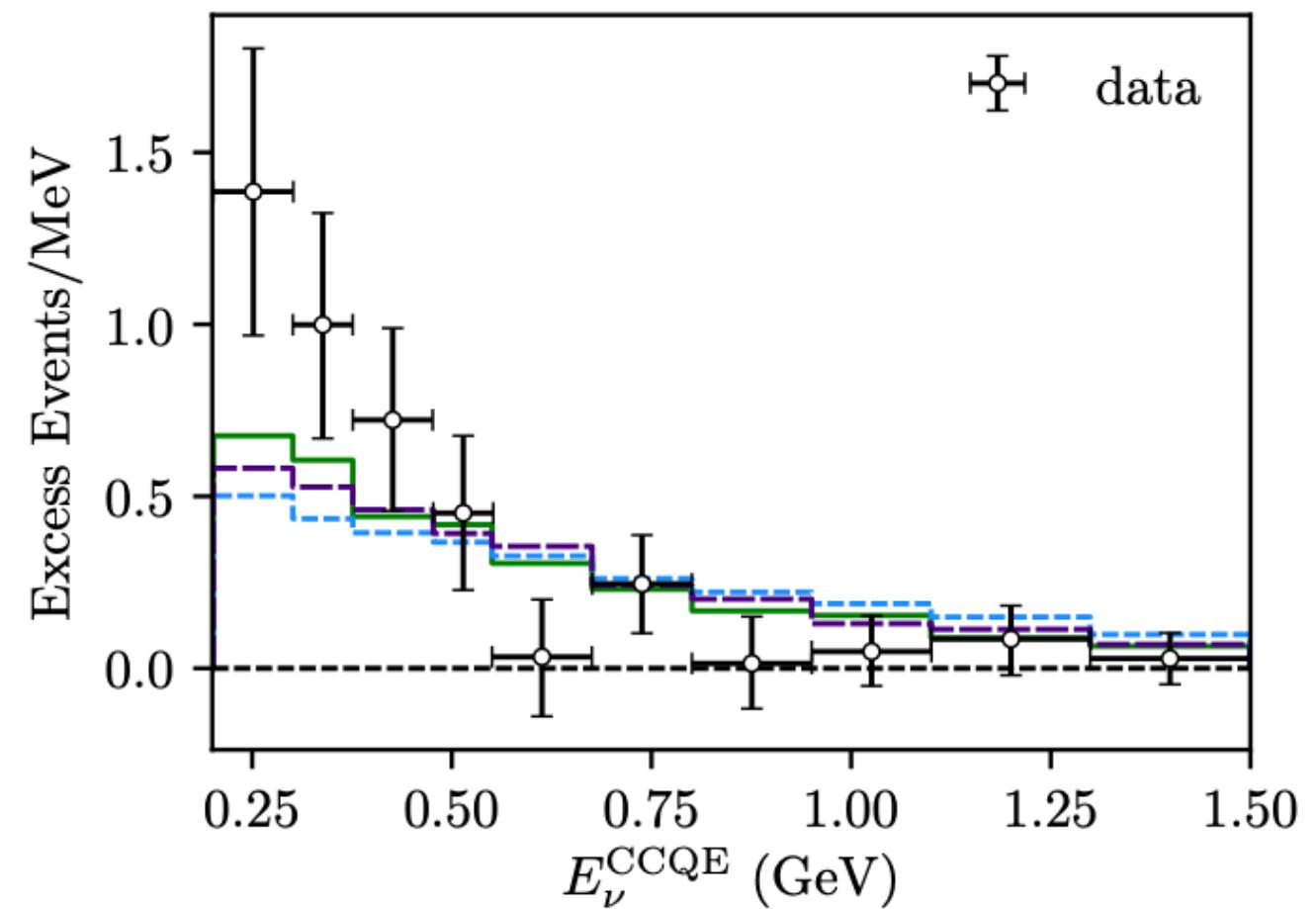


Competing with pion Dalitz decays.

All Distributions

On-shell light Z'

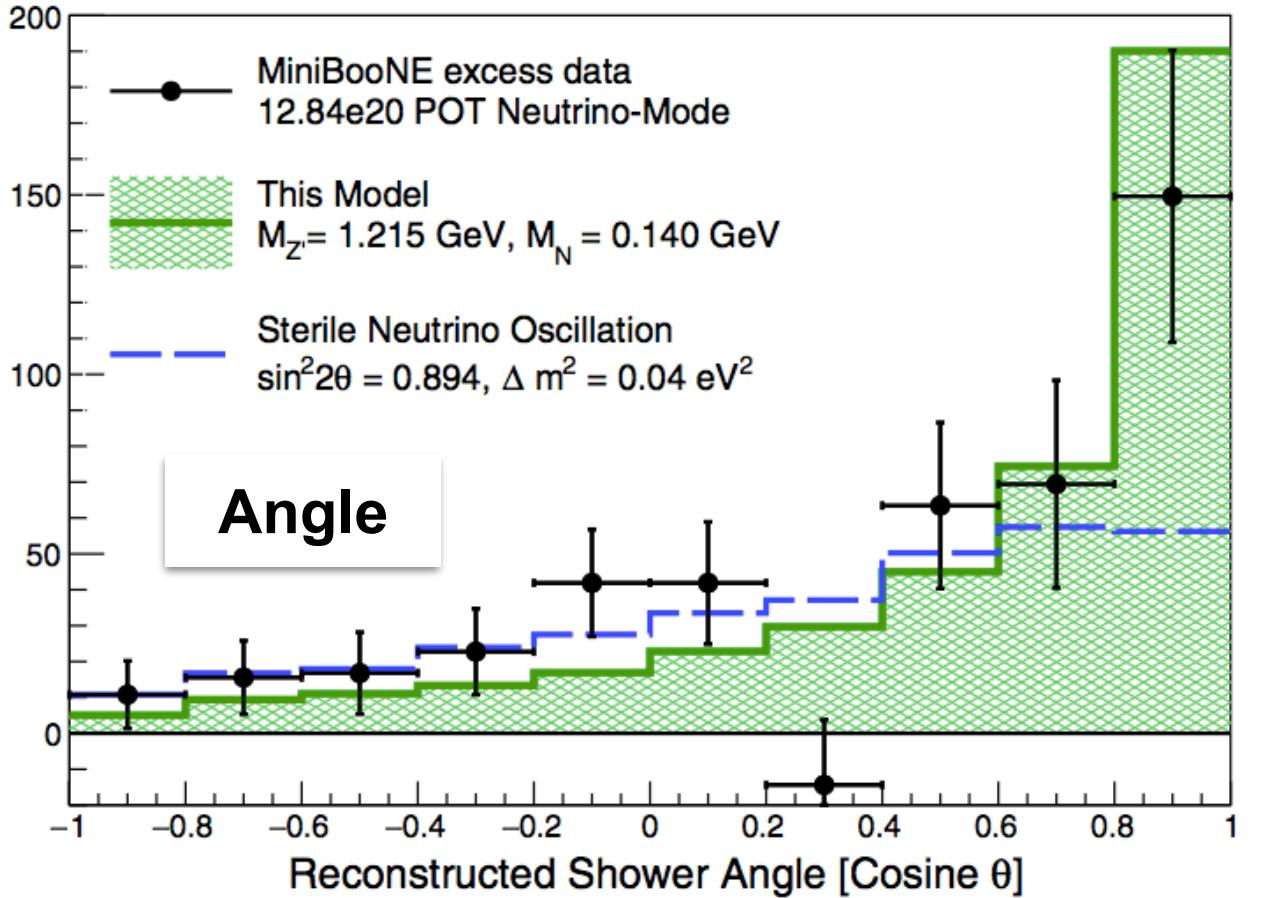
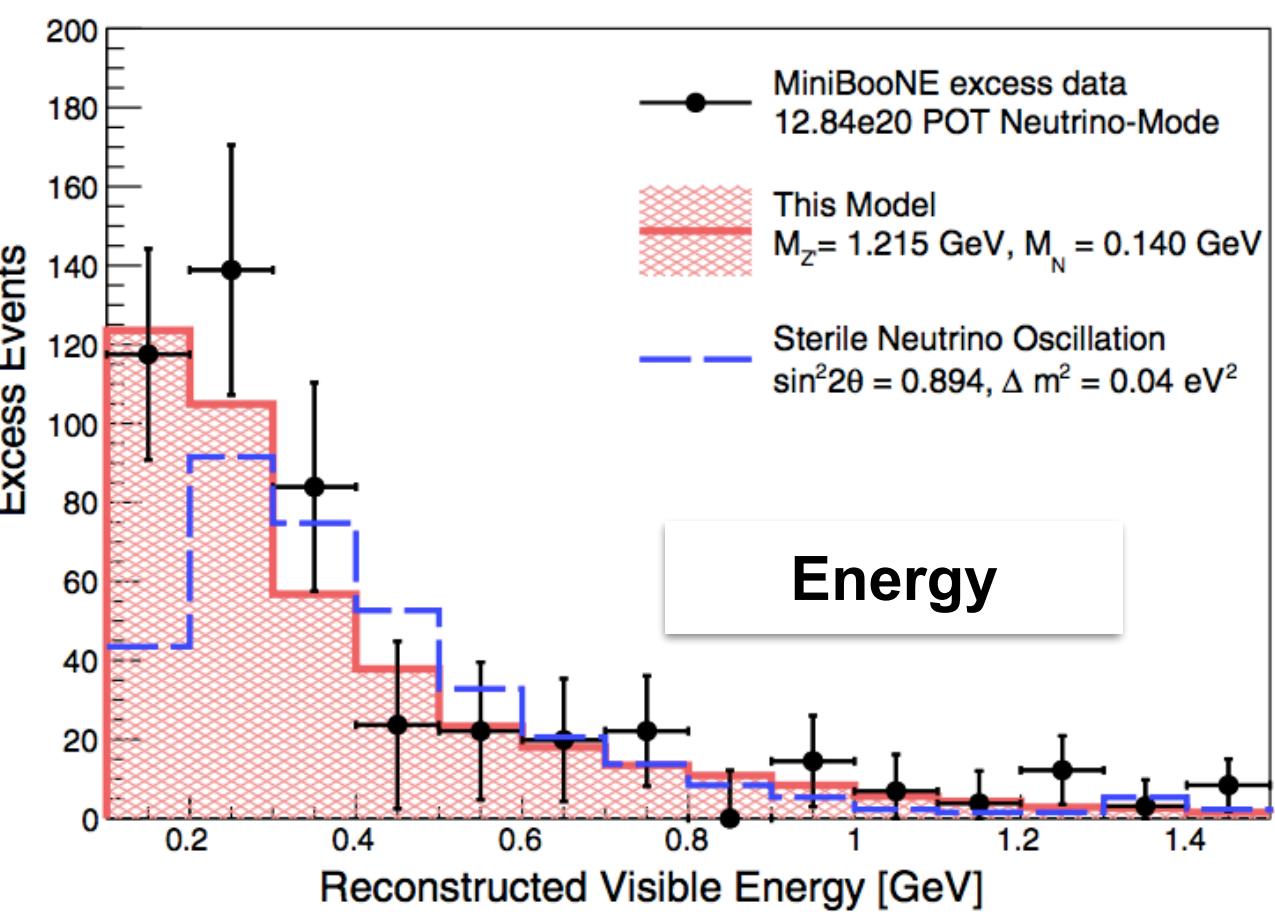
E. Bertuzzo et al., PRL 121.241801
 C. Arguelles, MH, Y. Tsai, PRL 123.261801



MiniBooNE 2018

Off-shell Z' w/ Z-Z' interference

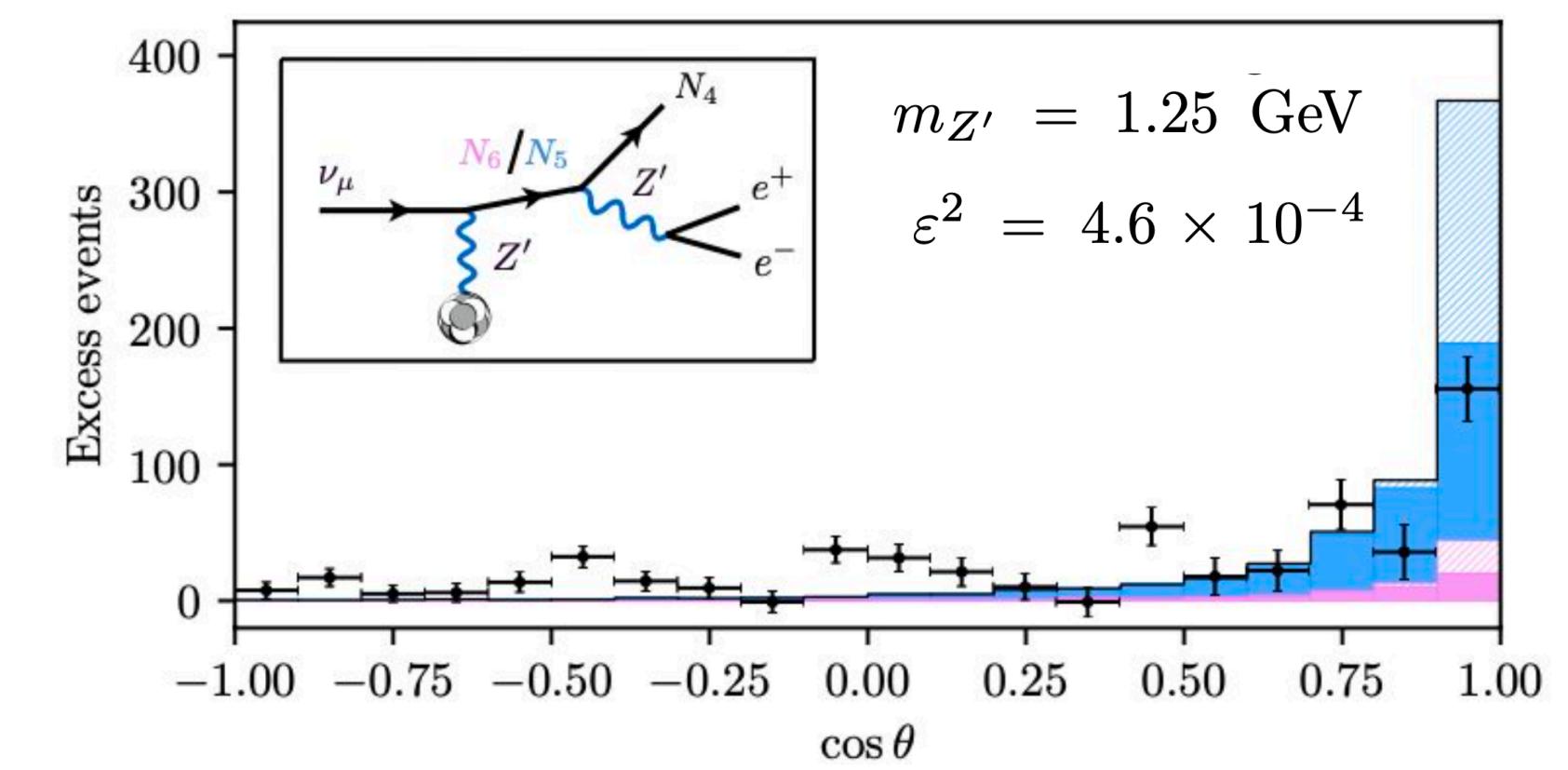
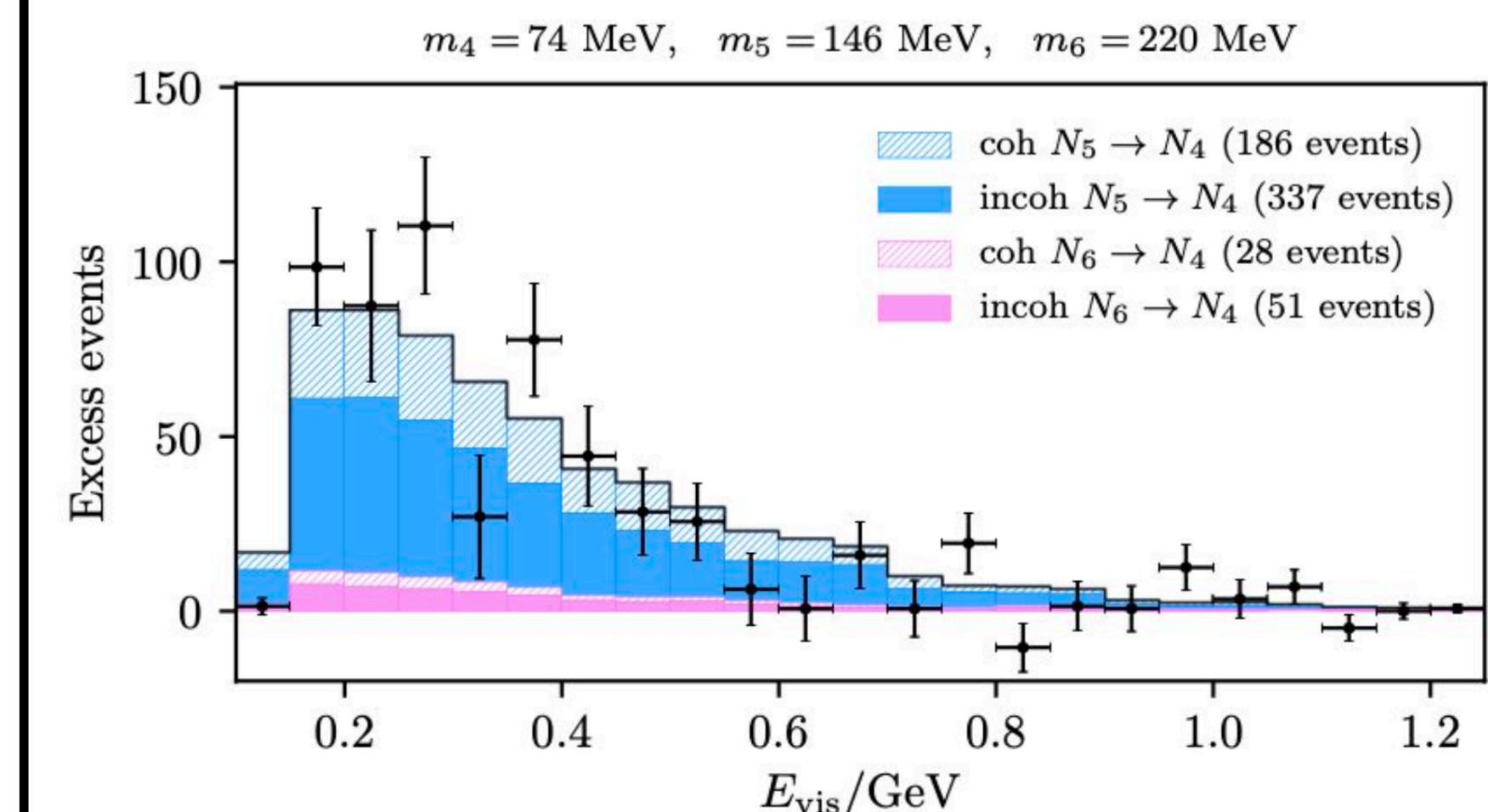
P. Ballett et al, PRD 99.071701



MiniBooNE 2018

Off-shell Z' (no Z-Z' interference)

A. Abdullahi, MH, S. Pascoli, arXiv:[2007.11813](https://arxiv.org/abs/2007.11813)

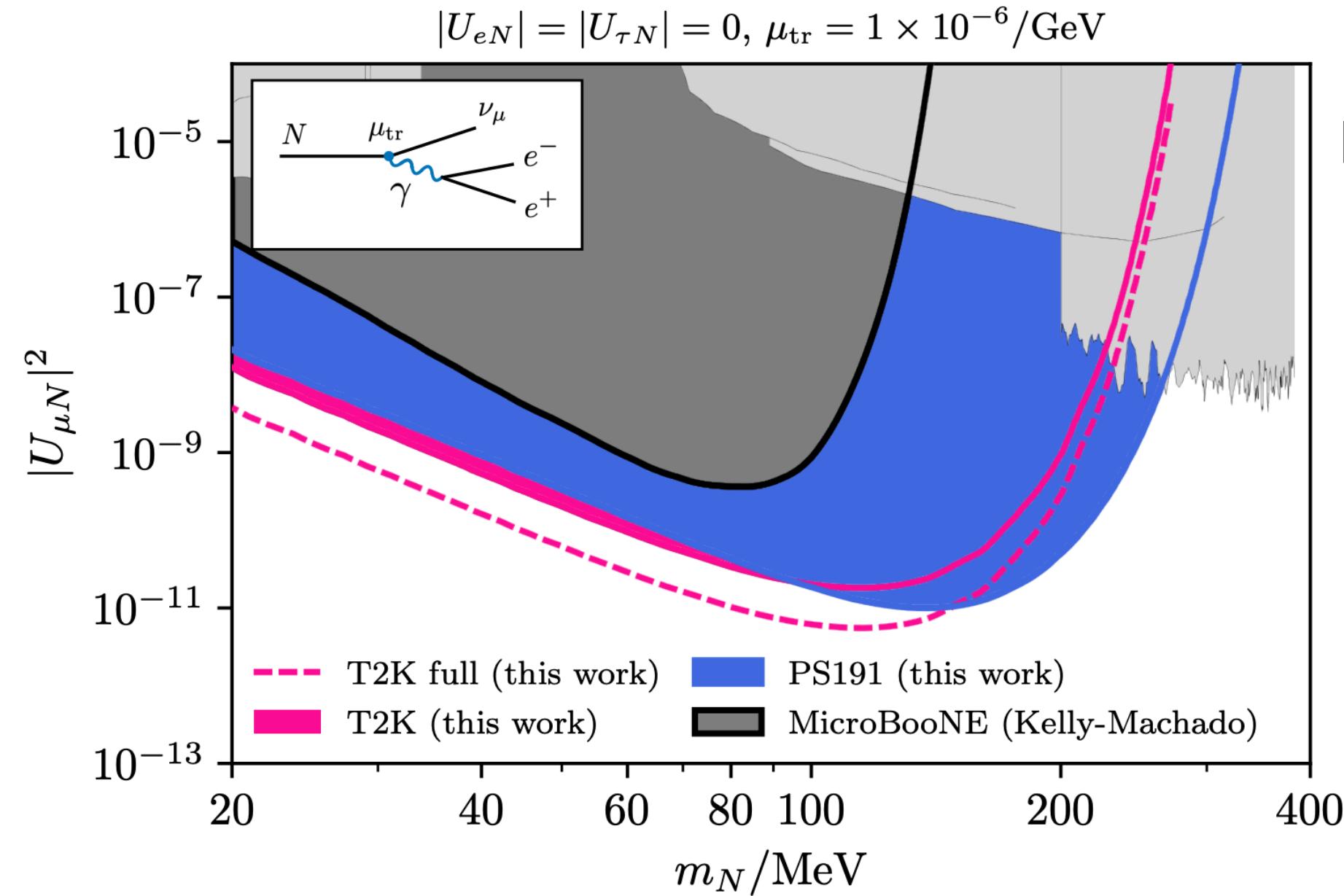


MiniBooNE 2020

Long-lived HNLs Decaying in flight

The role of new forces

C. Argüelles, N. Foppiani, MH [arxiv:2109.03831](https://arxiv.org/abs/2109.03831)



Main decay into real photons: unfortunately, no good for low-density detectors like ND280.

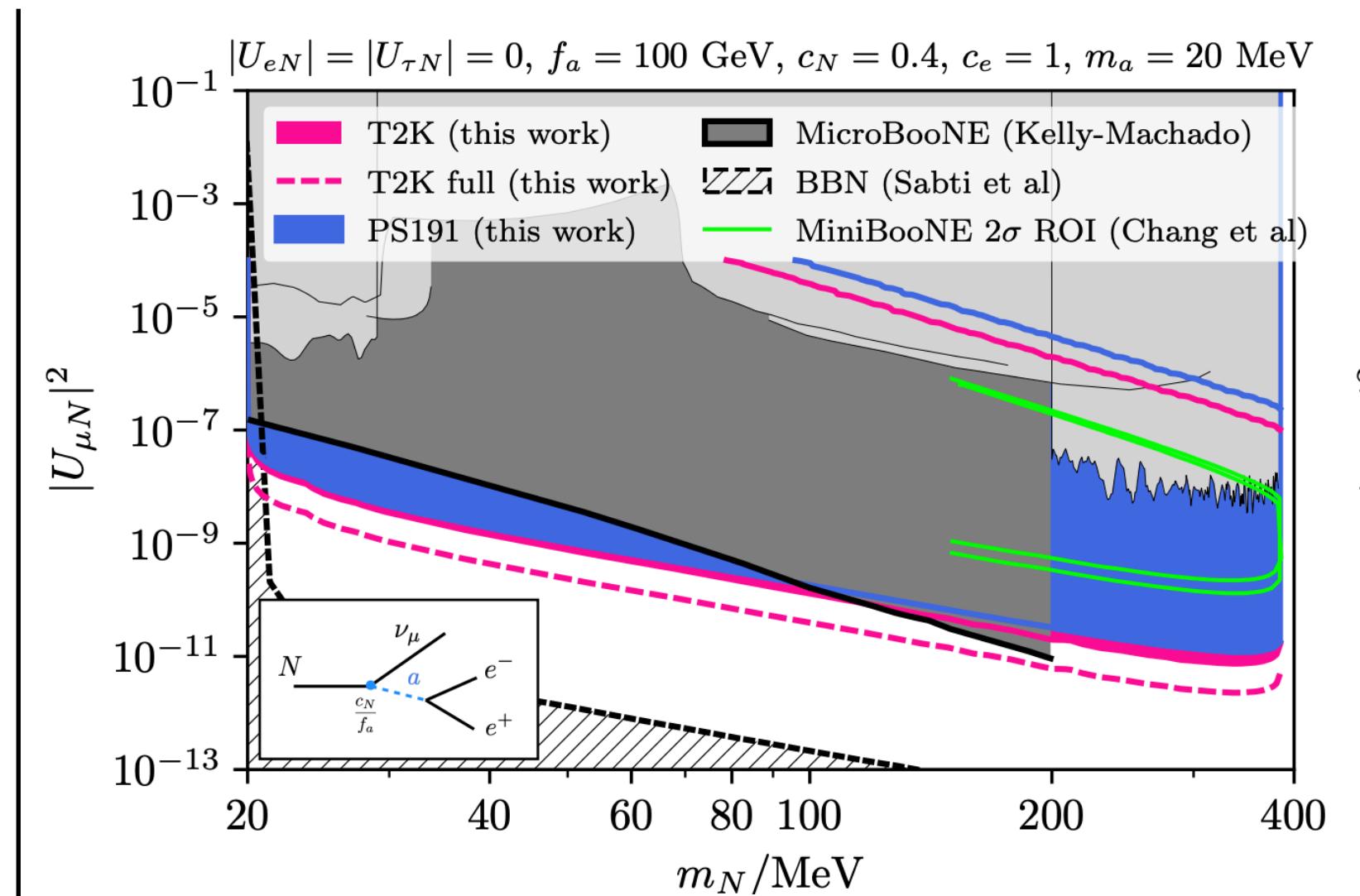
Virtual photon rate is still competitive. Collimated e^+e^- a challenge, but $B = 0.2 \text{ T}$ makes the difference.

Transition magnetic moment

$$-\mathcal{L}_{\text{int}} \supset \frac{\mu_{\text{tr}}}{2} \bar{\nu}_{\alpha} \sigma^{\mu\nu} N F_{\mu\nu} + \text{h.c.}$$

Relaxed BBN limits

HNLs can be long-lived in the Lab, but short-lived in the cosmos.



ALP decays to e^+e^-

$$-\mathcal{L} \supset \frac{\partial_{\mu} a}{2f_a} (c_N \bar{N} \gamma^{\mu} \gamma^5 N + c_e \bar{e} \gamma^{\mu} \gamma^5 e)$$

ALP decays to e^+e^-

$$N \rightarrow \nu a \rightarrow \nu e^+ e^-$$