Heavy Neutrinos at Hodoscopic Detectors

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Brookhaven Forum 2021

University of Minnesota

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The Outline

- Lamppost seesaw models and secret interactions
- Decay-in-flight searches (PS191 and T2K)
- Upscattering searches (T2K, MiniBooNE, and MicroBooNE)
- Meson decays at NA62

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Harvard Uni

Nicolo Foppiani
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P. Ballett, MH, S. Pascoli arxiv:1903.07589
A. Abdullahi, MH, S. Pascoli arxiv:2007.11813
C. Argüelles, N. Foppiani, MH arxiv:2109.03831

Heavy neutrinos at low scales

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

$$\begin{array}{cccc} (3\text{x}3) & (3\text{x}?) & (?\text{x}?) & (?\text{x}3) \\ M_\nu \sim & M_D & M_N^{-1} & M_D^T \end{array}$$

We know nothing M_N. It may hide **new symmetries** and **new dynamics**.

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$$-\mathscr{L}_{\nu-\text{mass}} \supset \frac{1}{2}\begin{pmatrix}\overline{\nu_L} & \overline{N} & \overline{S}\end{pmatrix}\begin{pmatrix}0 & m & \varepsilon' \\ m & \mu' & \Lambda \\ \varepsilon' & \Lambda & \mu\end{pmatrix}\begin{pmatrix}\nu_L^c \\ N^c \\ S^c\end{pmatrix} + \text{h.c.}$$

(L= -1)

(L= +1)

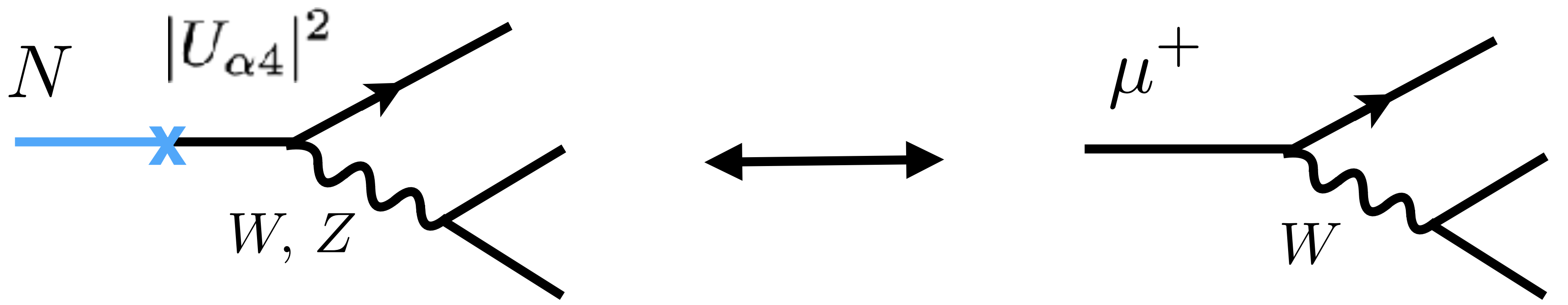
= violating lepton number

$$m_\nu = \frac{\mu m^2 - 2\varepsilon' m\Lambda + \varepsilon'^2\mu'}{\Lambda^2 - \mu\mu'}.$$

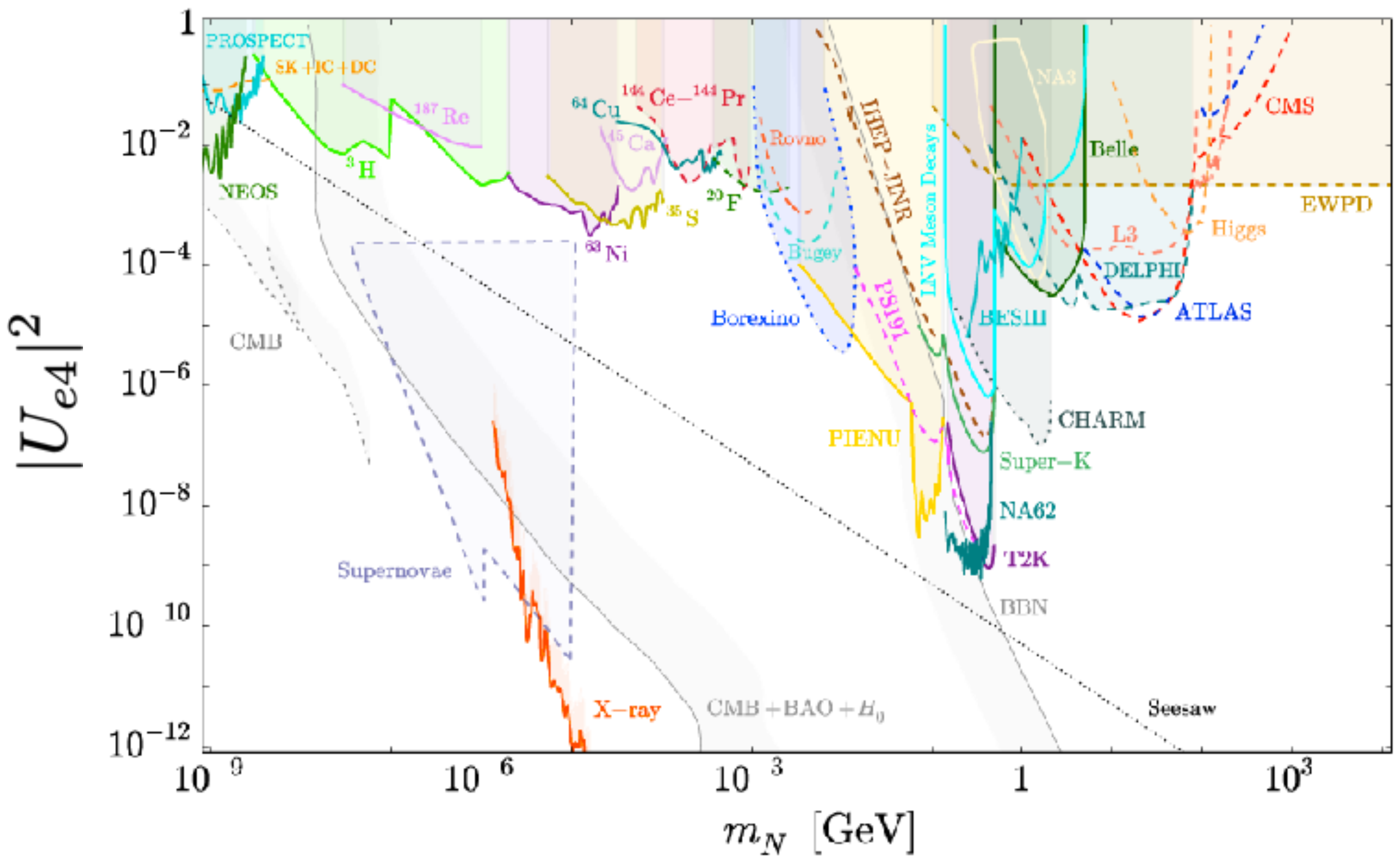
Small neutrino masses in lepton number conservation limit associated with pseudo-Dirac, low-scale seesaw partners.

Important to remain open-minded about the mixing, masses, and interactions of heavy neutrinos.

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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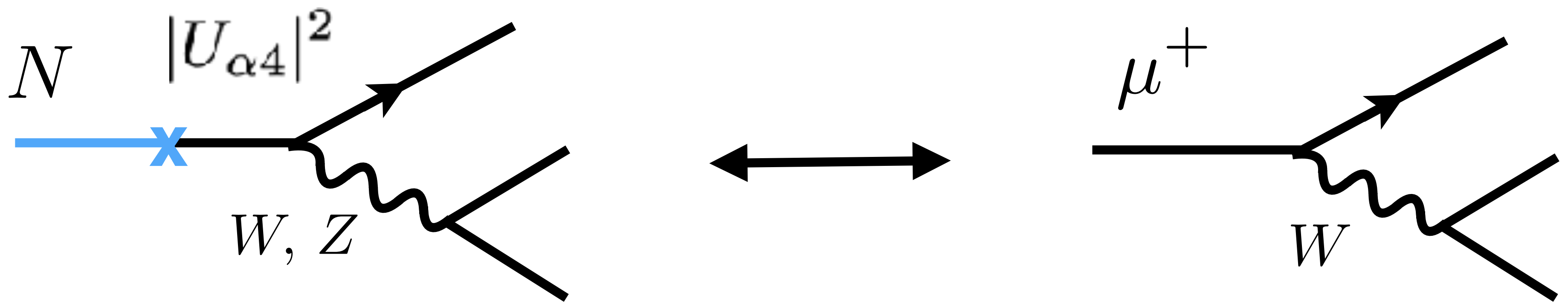

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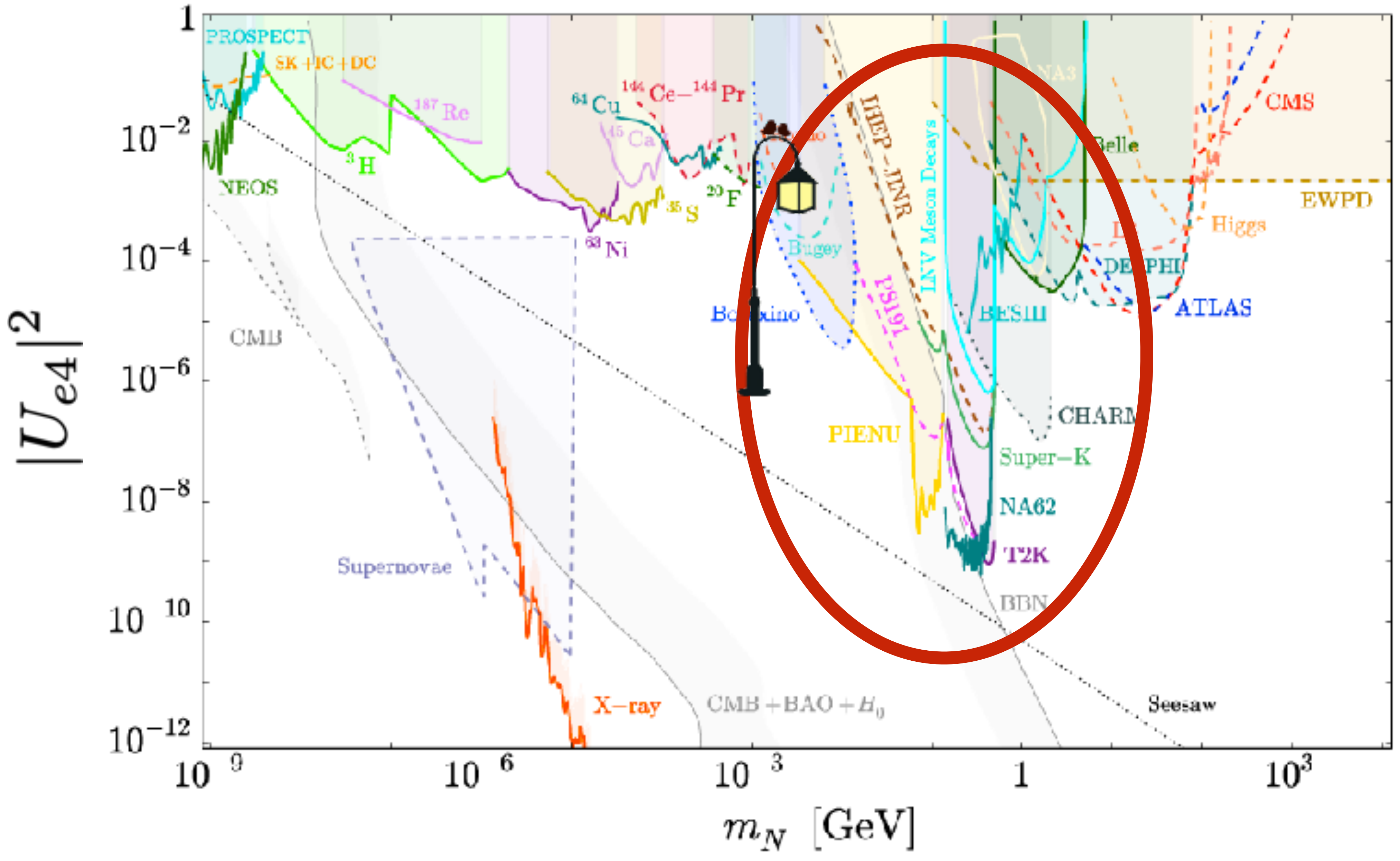


Under the MeV-GeV lamppost:

1) Missing mass in pion or kaon decays

$$\pi/K \to \ell N \quad \longrightarrow \quad (p_{\pi,K} - p_\ell)^2 \stackrel{?}{=} M_N^2$$

2) Decay-in-flight beam dumps / neutrino exps

$\pi/K \to \ell N$ ⟶ N propagates ⟶ N decays visibly

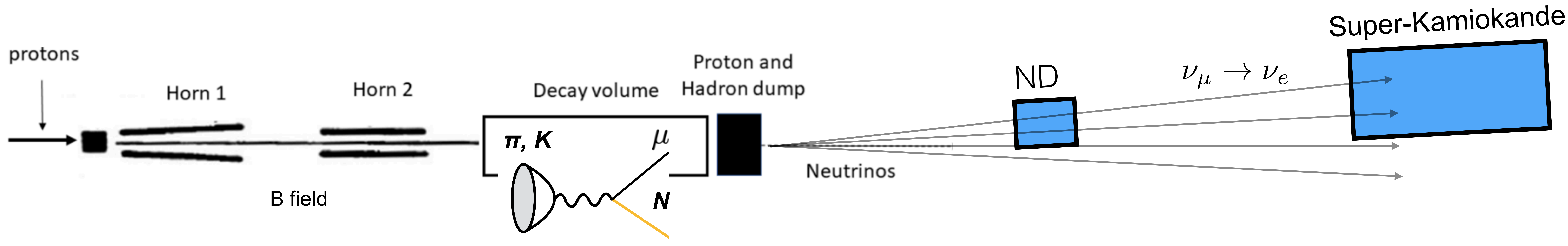
Most progress made with **invisible** or **long-lived HNLs**.

Lifetime is bounded from above due to BBN constraints (t_N < 0.1 s).

In all generality, there is no lower bound.

Decay-in-flight searches
T2K near detector (ND280)

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



Hodoscopic

hodos — path
scopos — observer

describes detectors that precisely reconstruct, track, and identify charged particles.

Especially true for low-density detectors like **Gaseous Argon Time-Projection-Chambers (TPC).**

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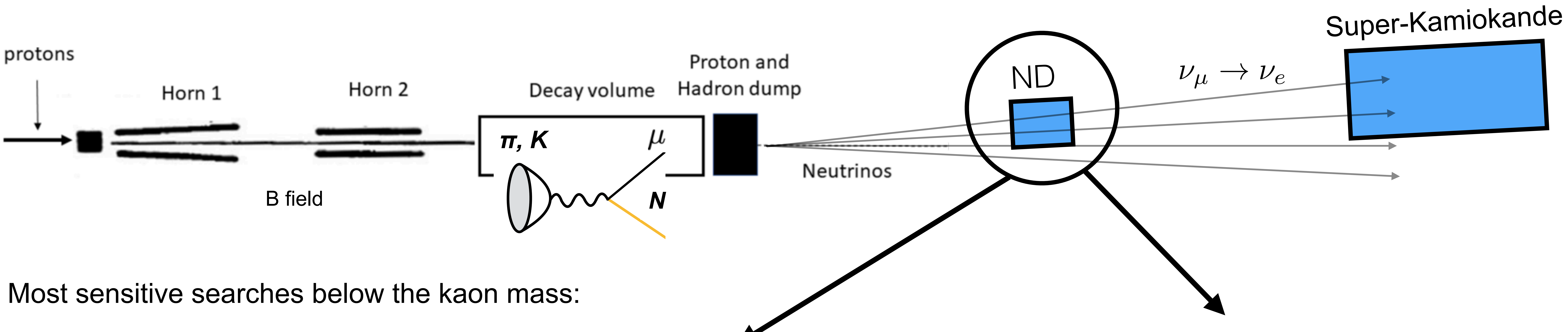
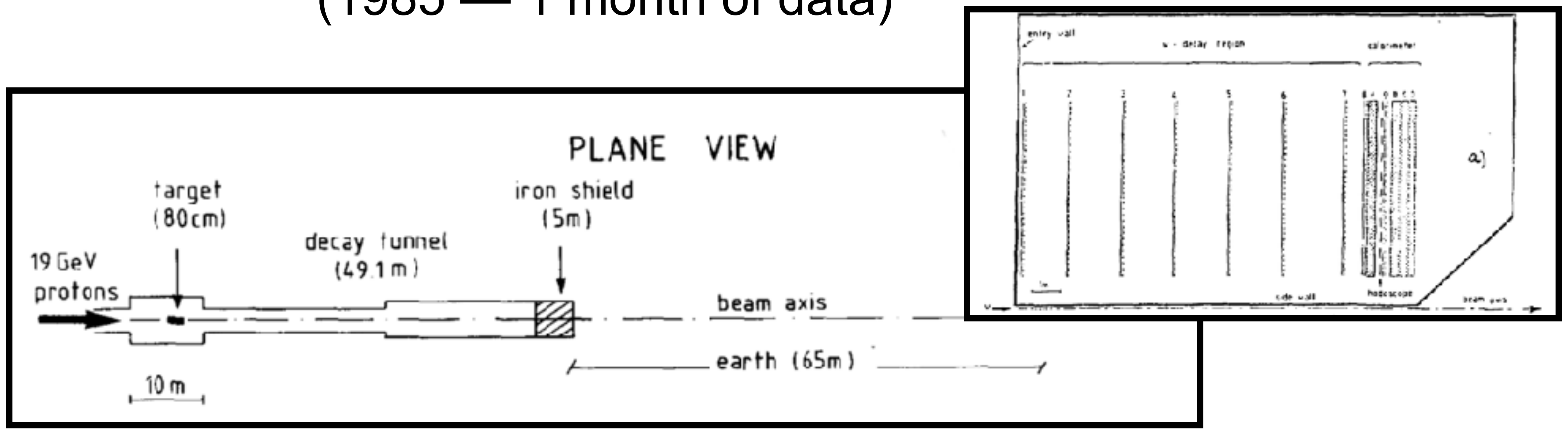


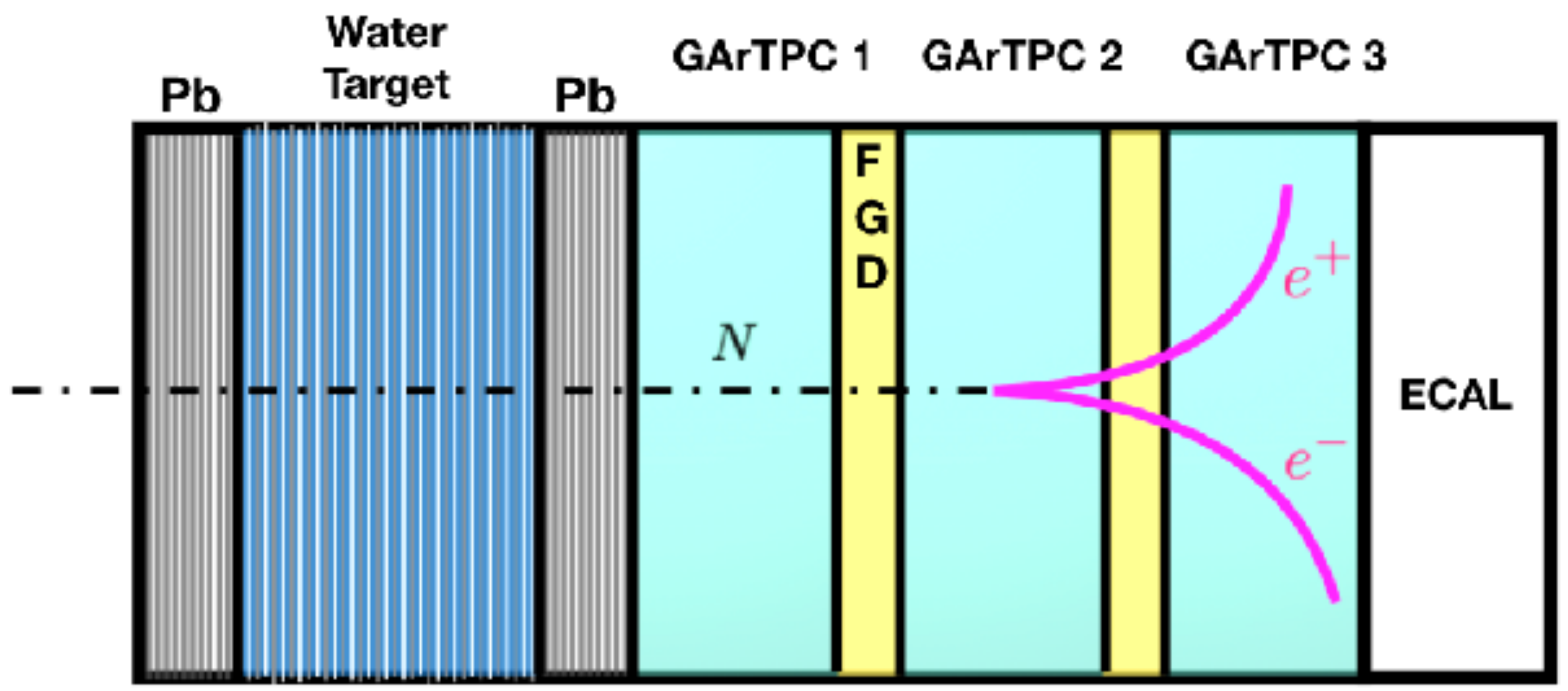
Most sensitive searches below the kaon mass:

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



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

ND280 @ T2K (low-density GAr TPCs)



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

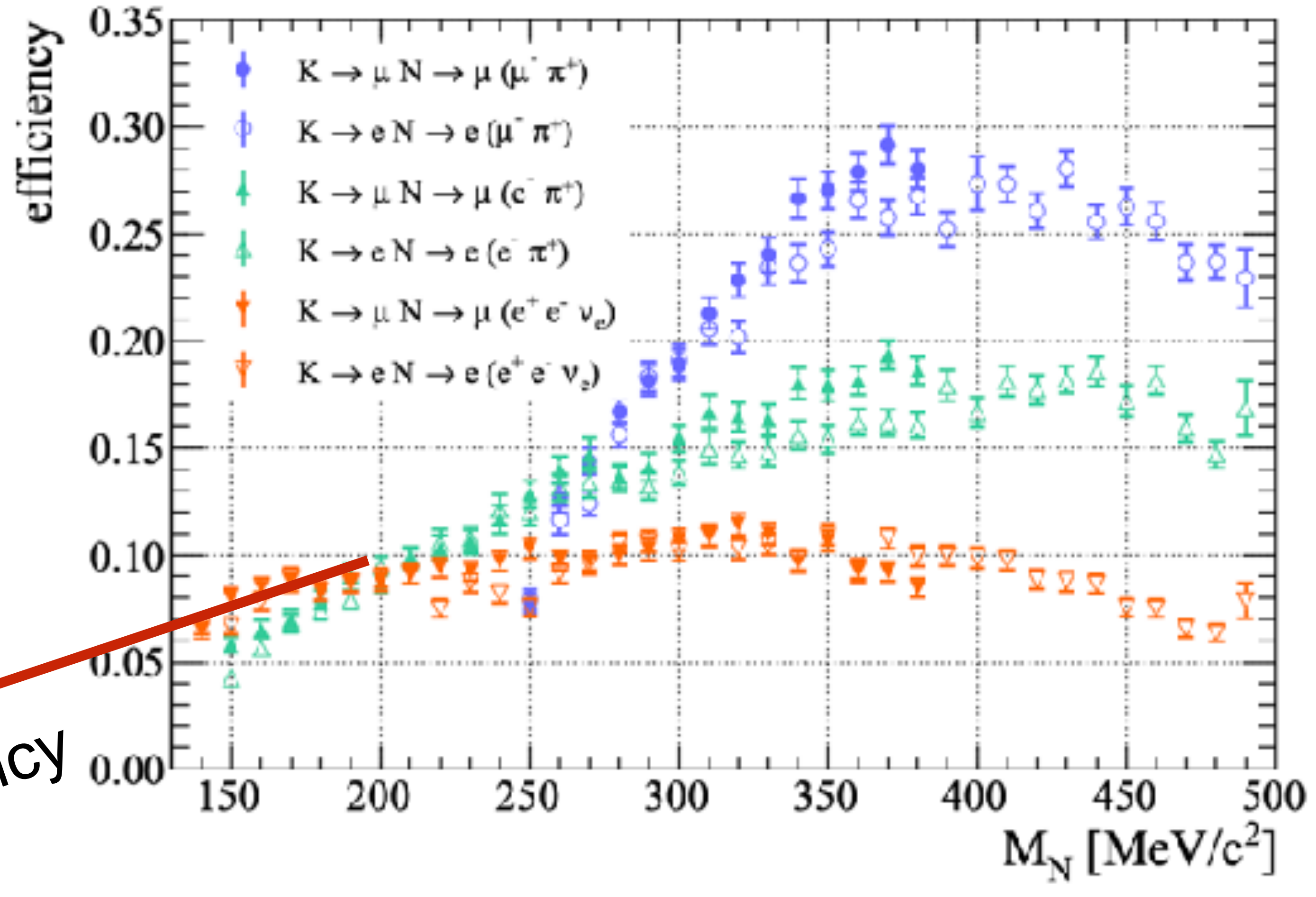
Decay-in-flight searches
T2K near detector (ND280)

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

T2K performed a background-free search in multiple channels, saw no events, and placed constraints on all HNL mixing angles.

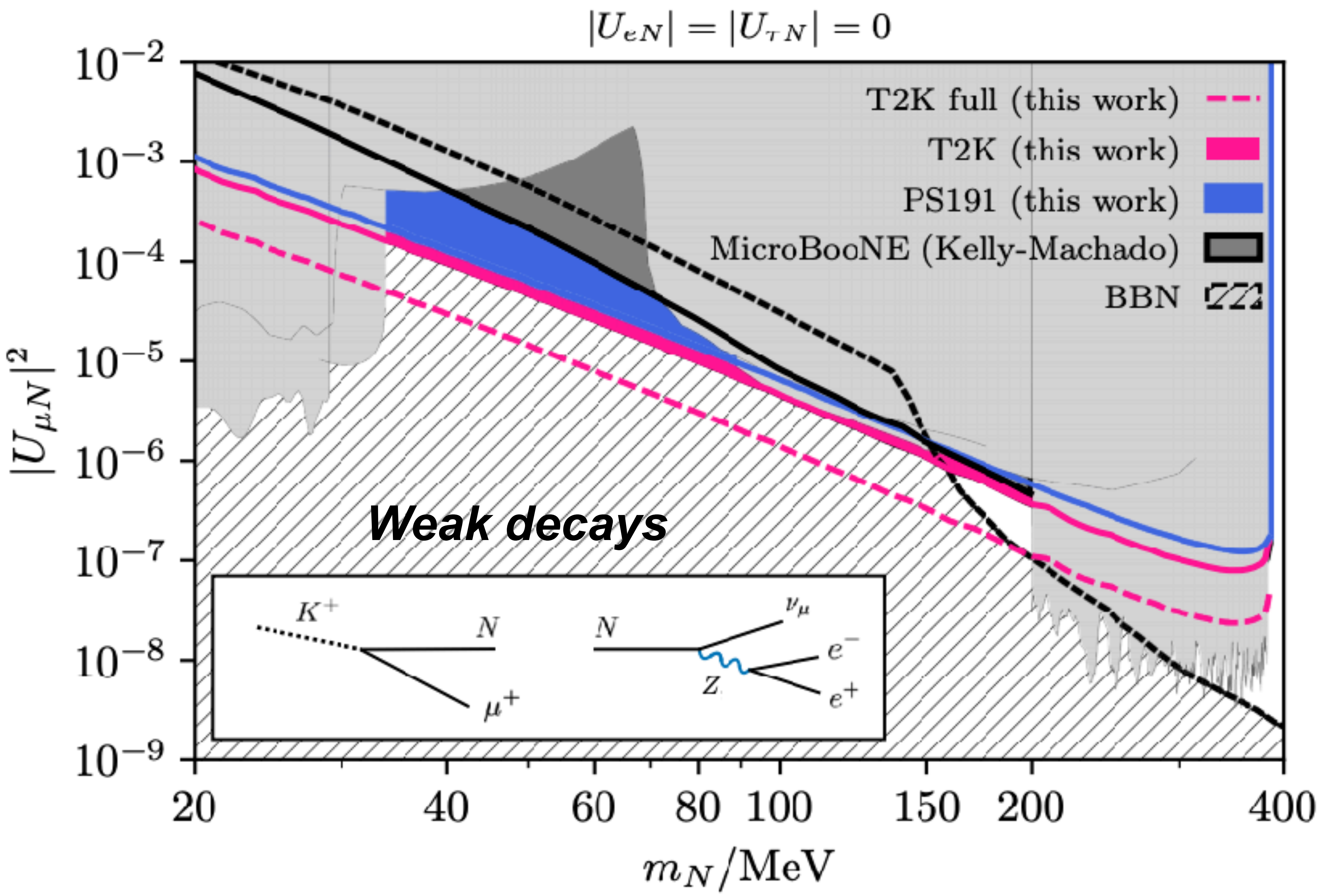
No constraint was placed at $M_N < M_\pi$

We derive new ones by extrapolated the efficiencies.



Extrapolate efficiency to $M_N < M_\pi$

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*.**



* True also for other leptonic decay channels: μμ, μπ, eμ, etc.

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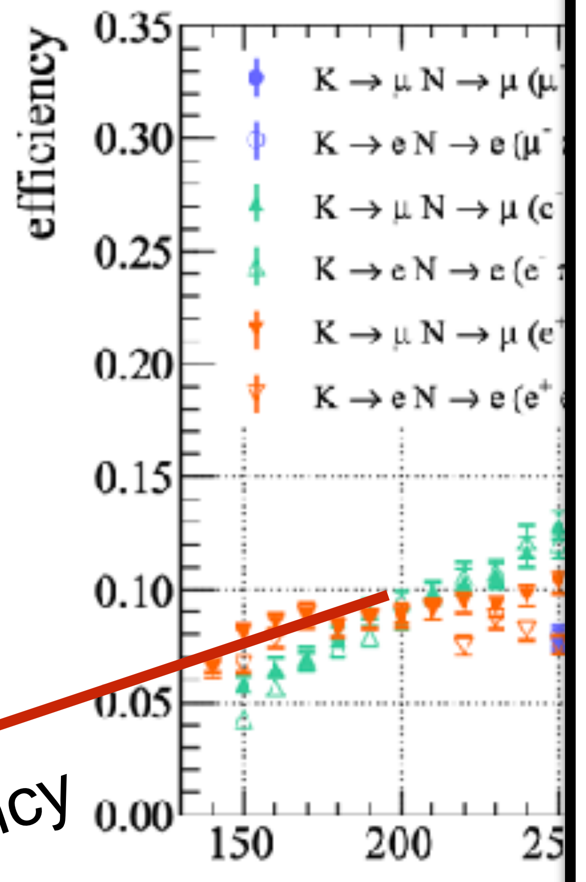

Extrapolate efficiency to $M_N < M_\pi$

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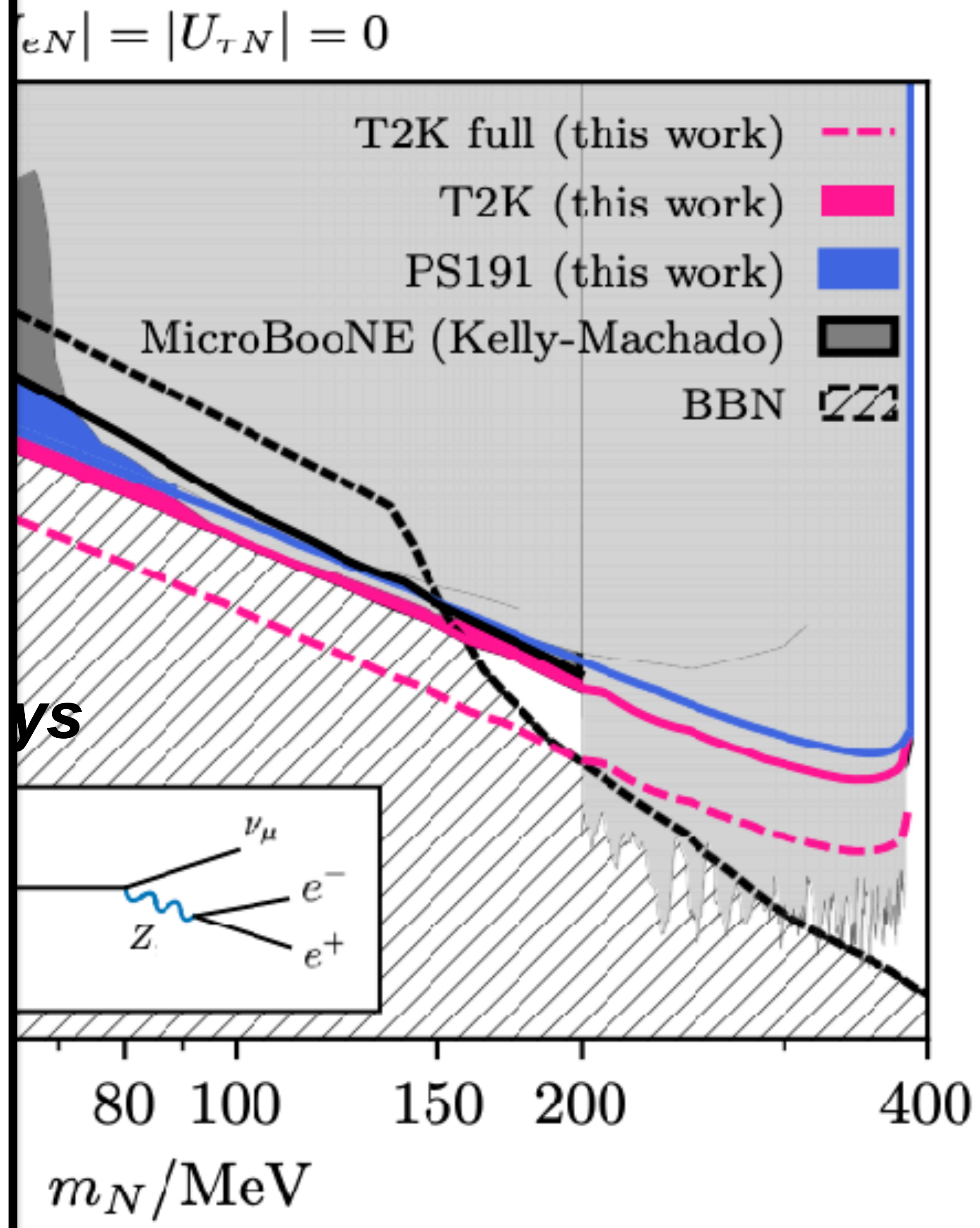
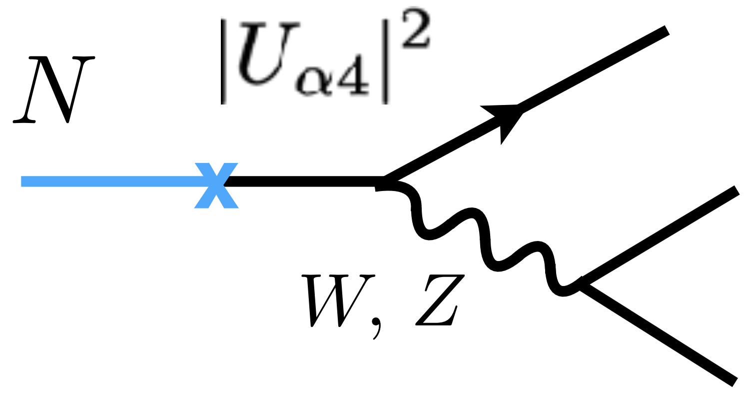


ys

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

$c\tau$ > O(0.1) s.

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



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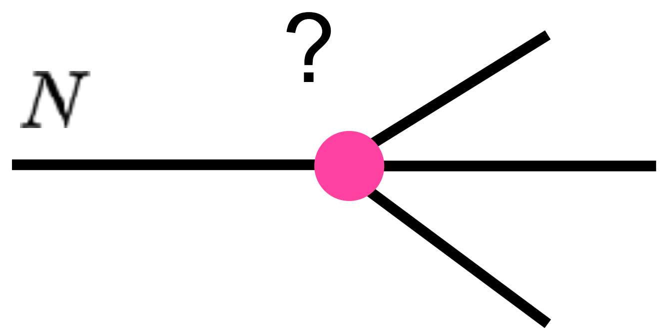
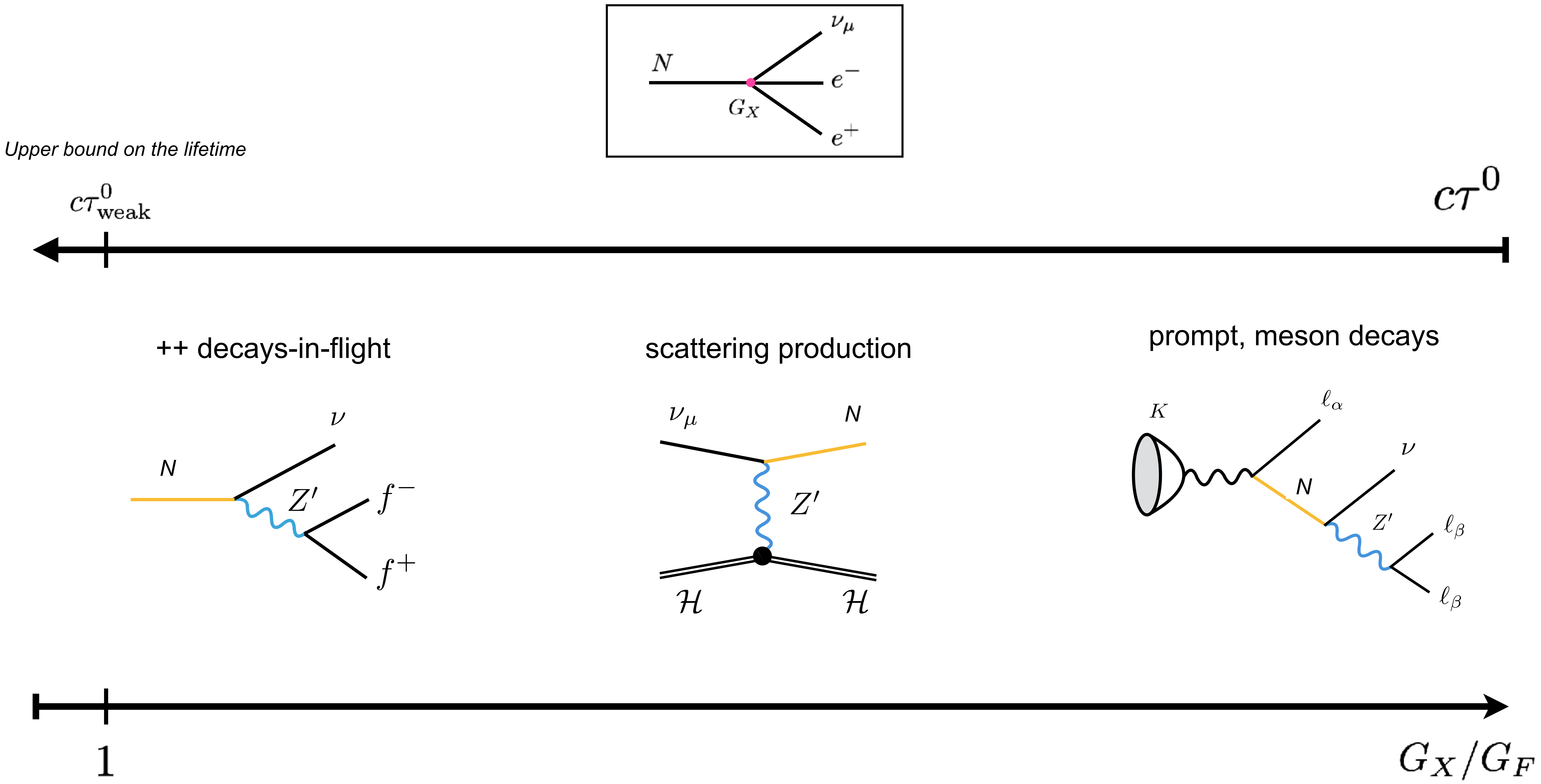


New forces compete with a "weaker-than-weak" rate.

* True also for other leptonic decay channels: μμ, μπ, eμ, etc.



N
ν_μ
e^-
e^+
G_X
Upper bound on the lifetime
$c\tau^0_{\rm weak}$
$c\tau^0$
++ decays-in-flight
scattering production
prompt, meson decays
N
ν
Z'
f^-
f^+
ν_μ
N
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$\mathcal{H}$
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K
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ν
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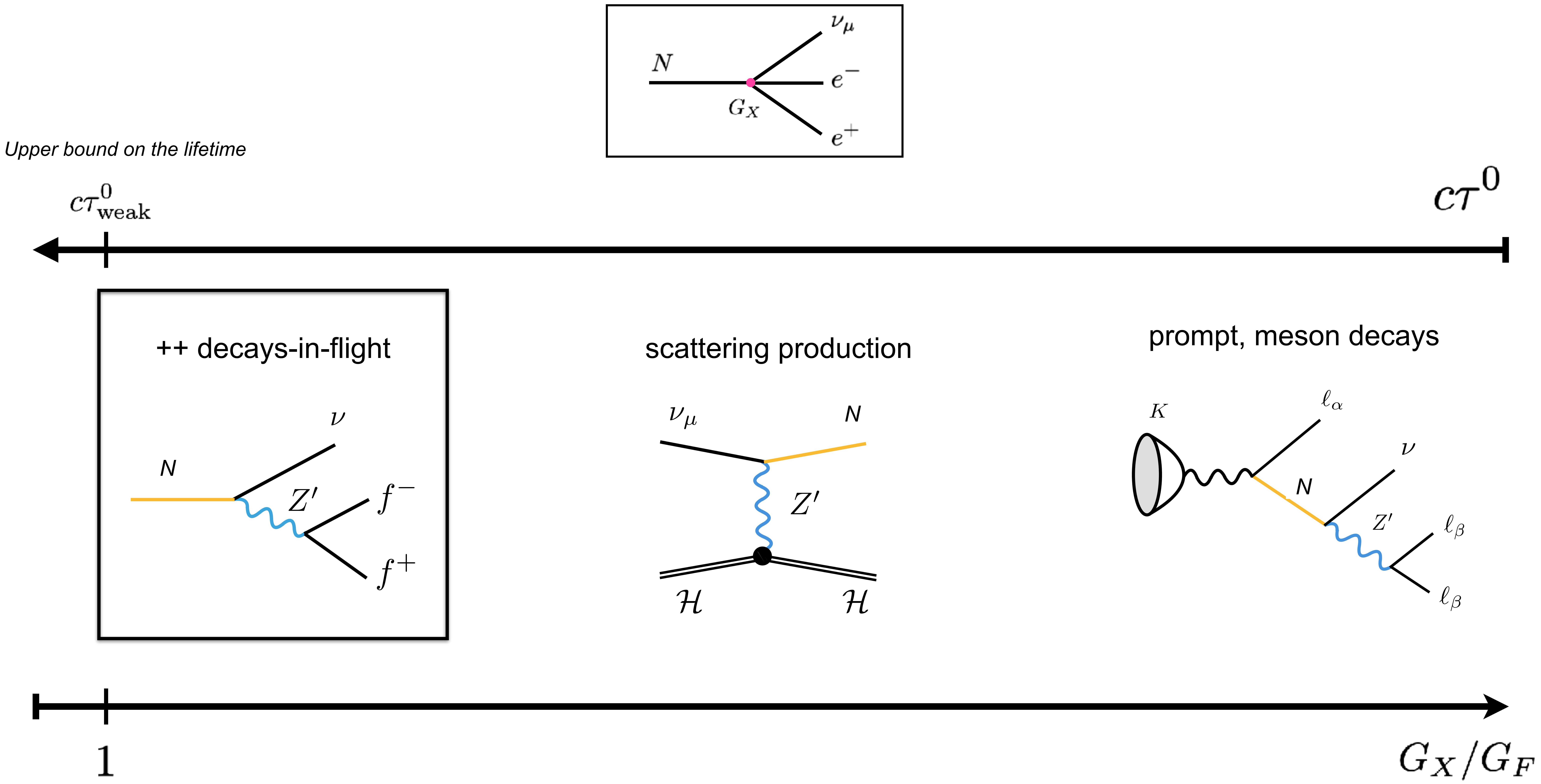
G_X/G_F



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Decay-in-flight searches
T2K near detector (ND280)

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Event rate proportional to new physics decay rate

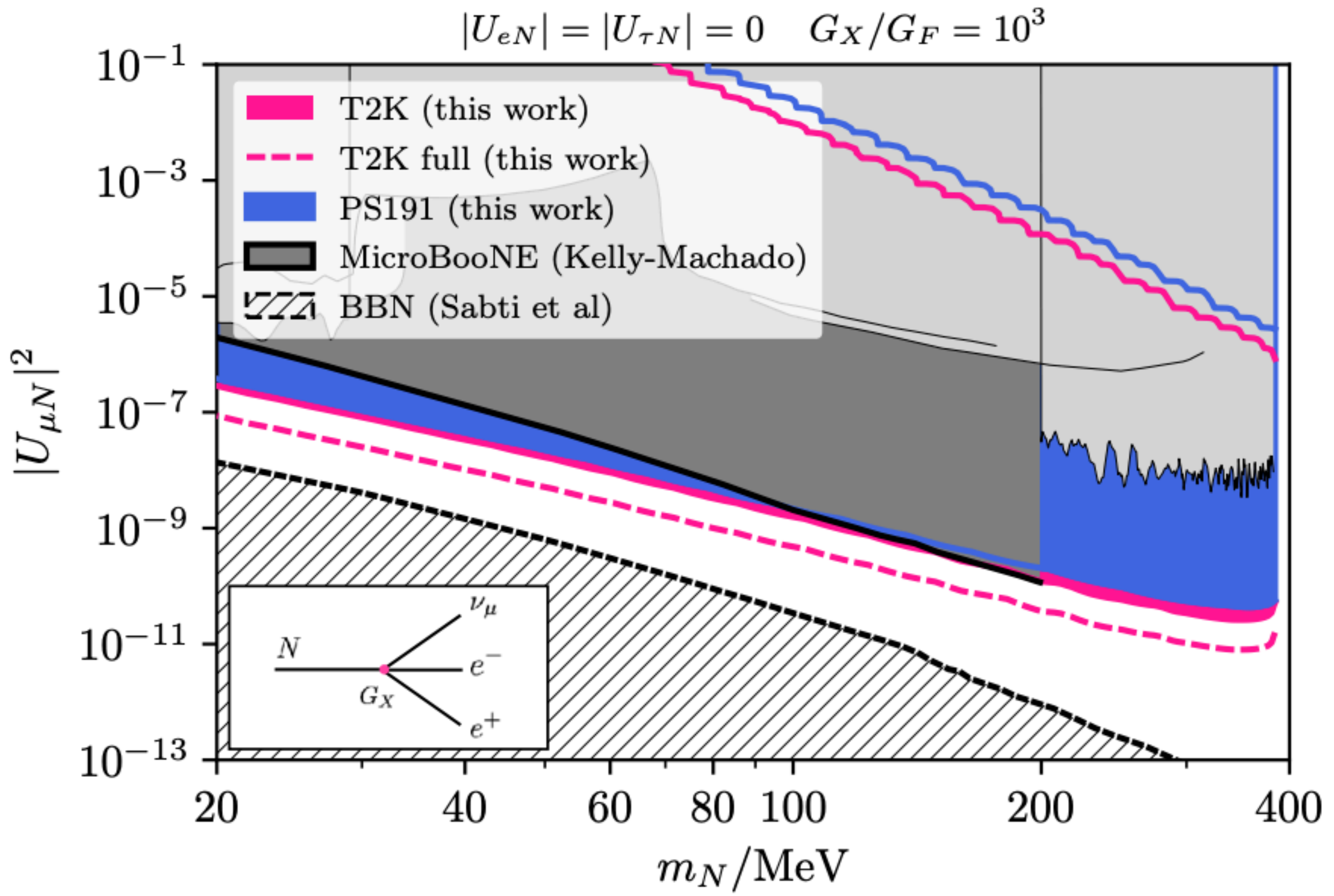
$$P_{N\to X} \simeq \frac{\ell_{\rm det}}{\gamma\beta}\Gamma_{N\to X}$$

Very sensitive to additional contribution to decay rate

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

Consider a four-fermion vectorial interaction:

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



If decay proceeds via neutrino mixing, the new force ought to be stronger than weak
but still unproved parameter space.

Decay-in-flight searches
T2K near detector (ND280)

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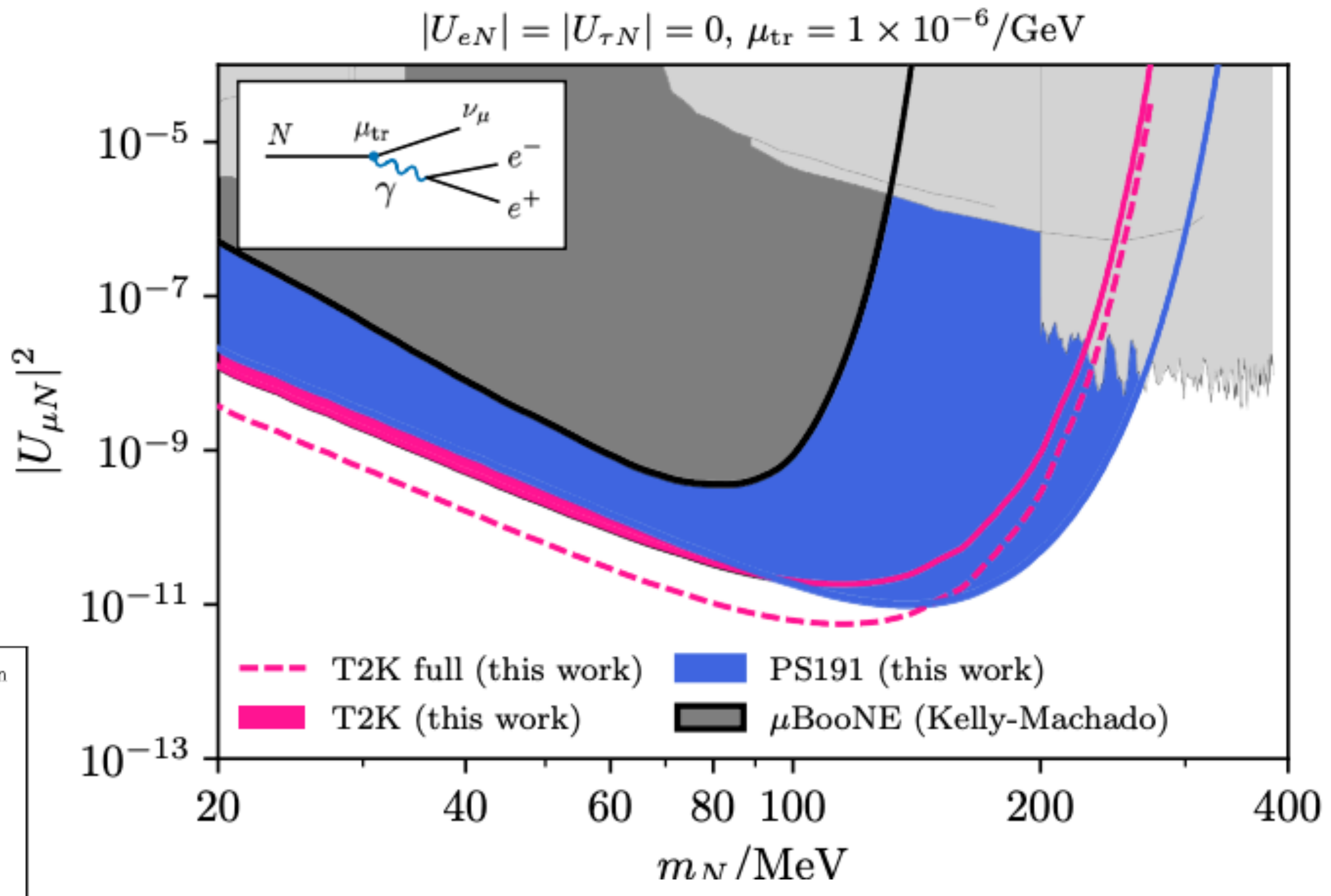
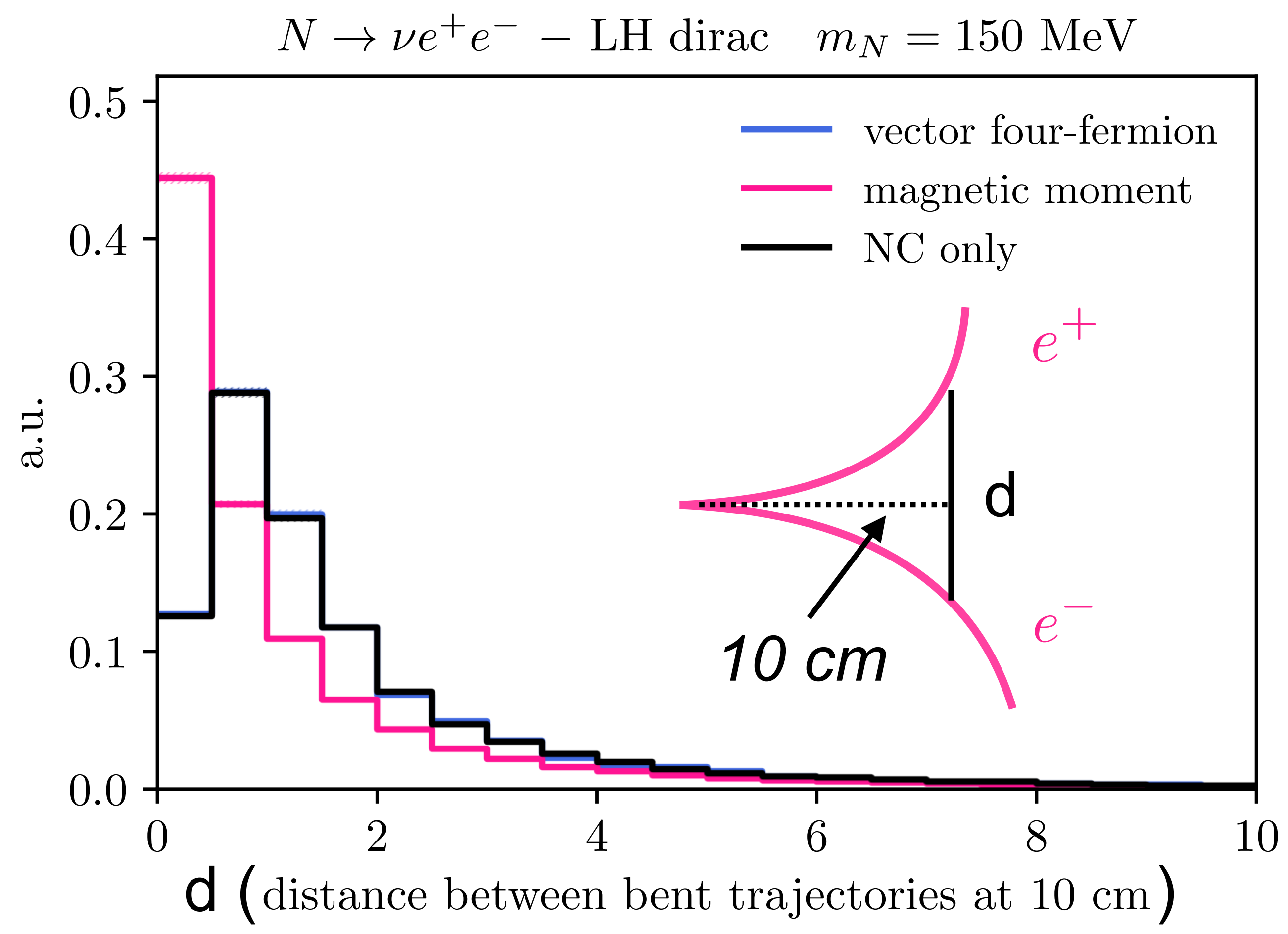
The decays do not have to proceed via mixing. Consider a transition magnetic moment operator:

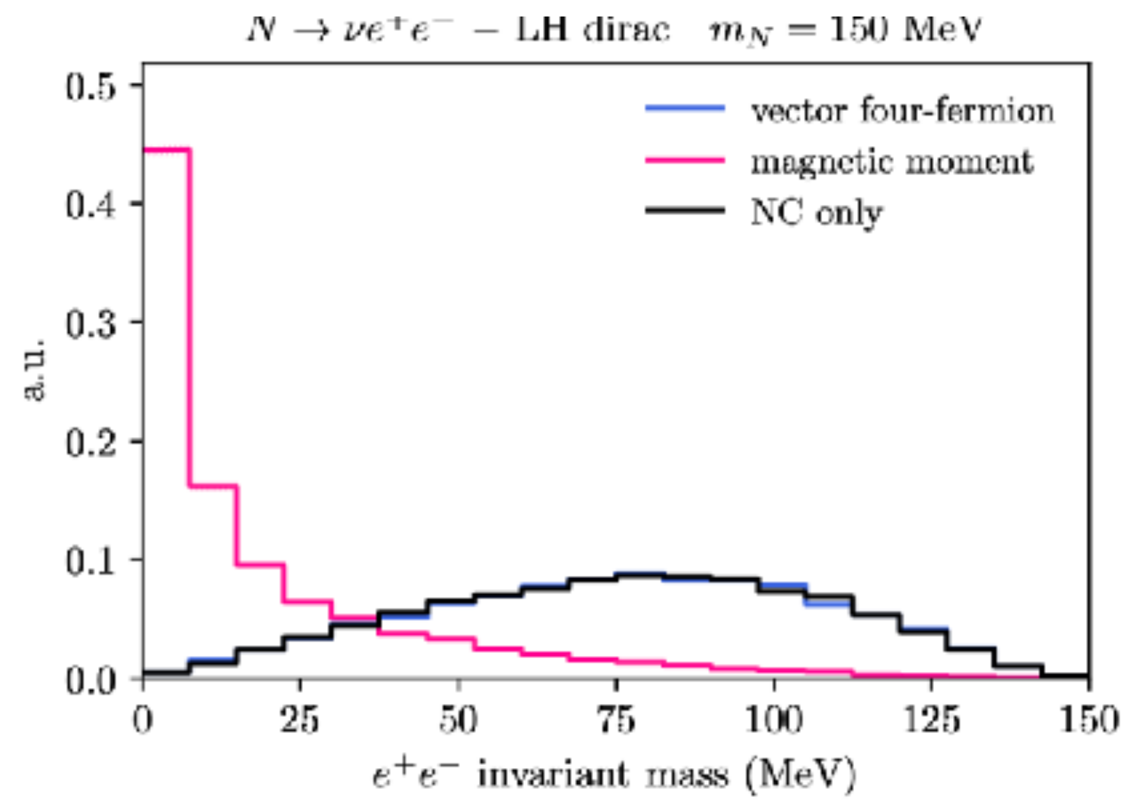
$$\mathcal{L} \supset \frac{\mu_{\rm tr}}{2} \overline{\nu_\alpha} \sigma^{\mu\nu} N F_{\mu\nu}$$

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.







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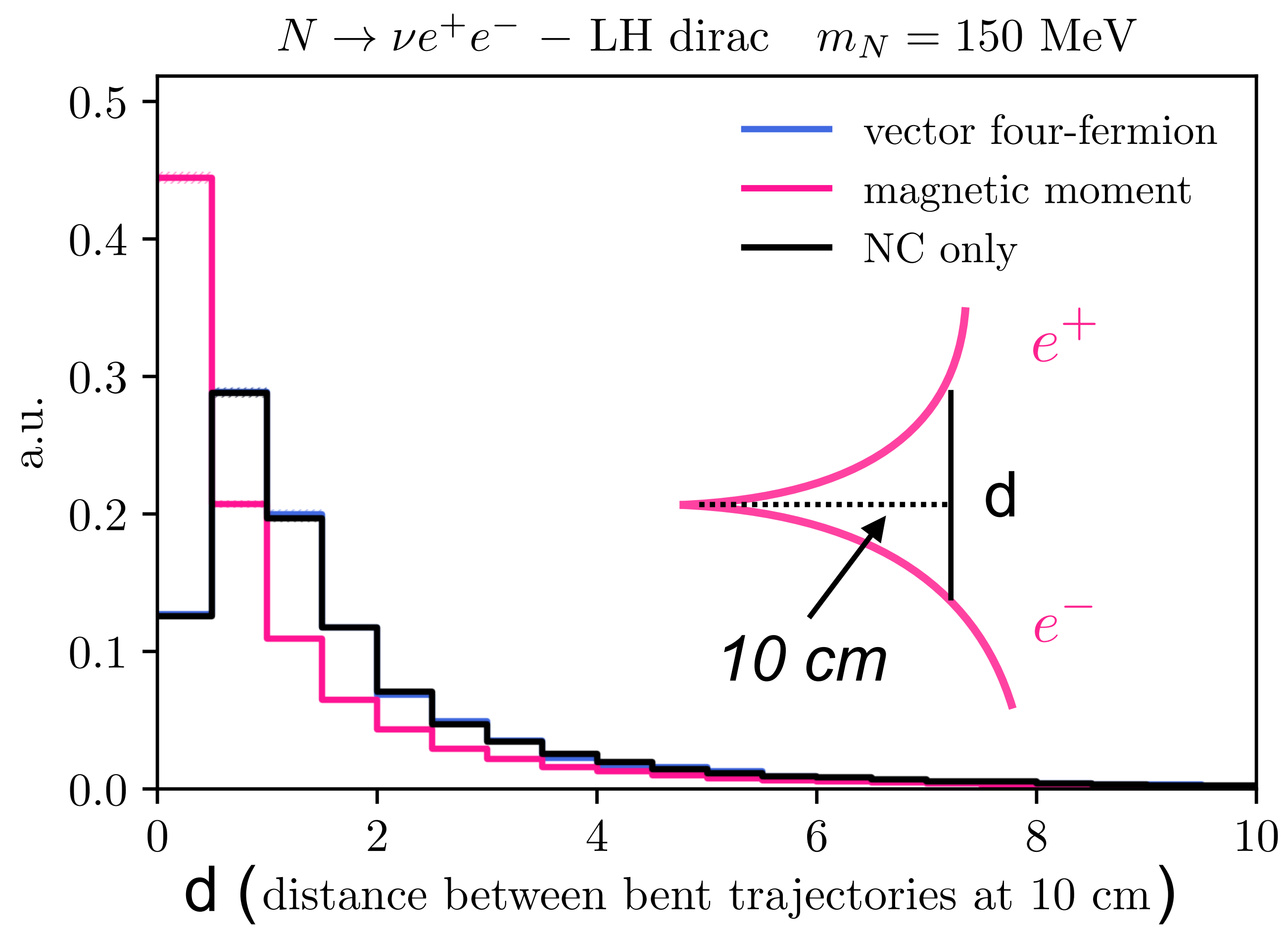
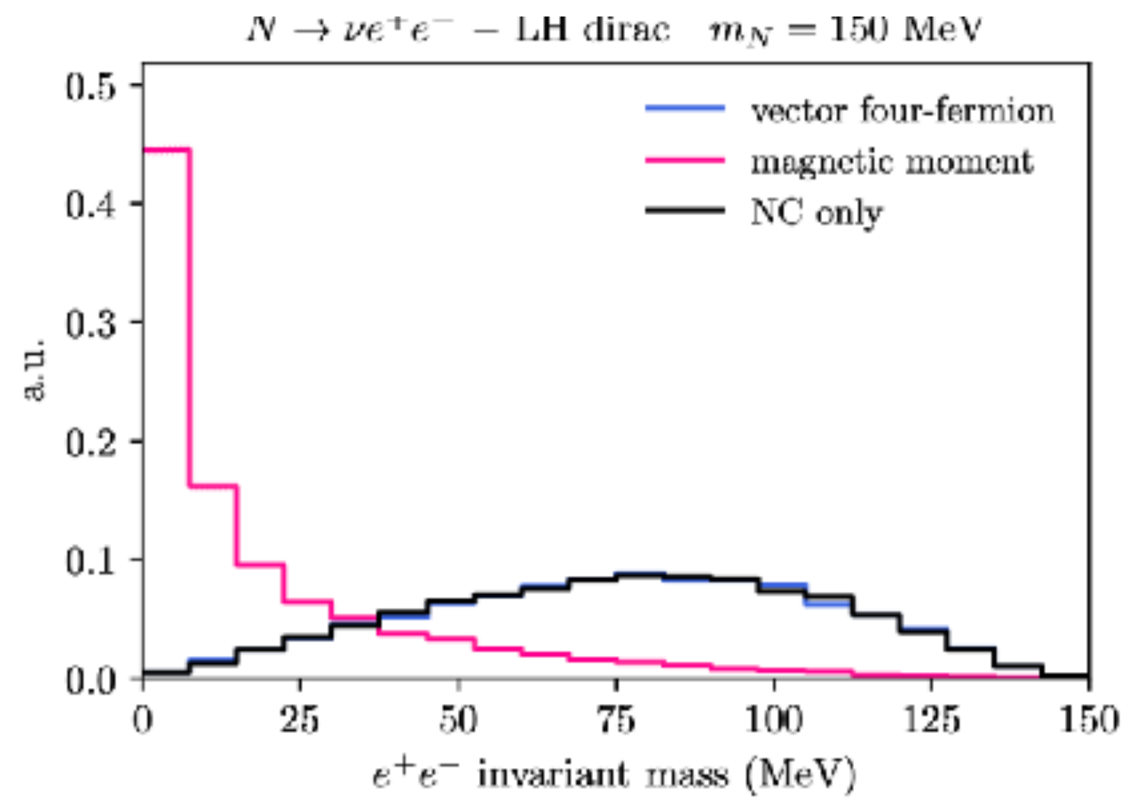
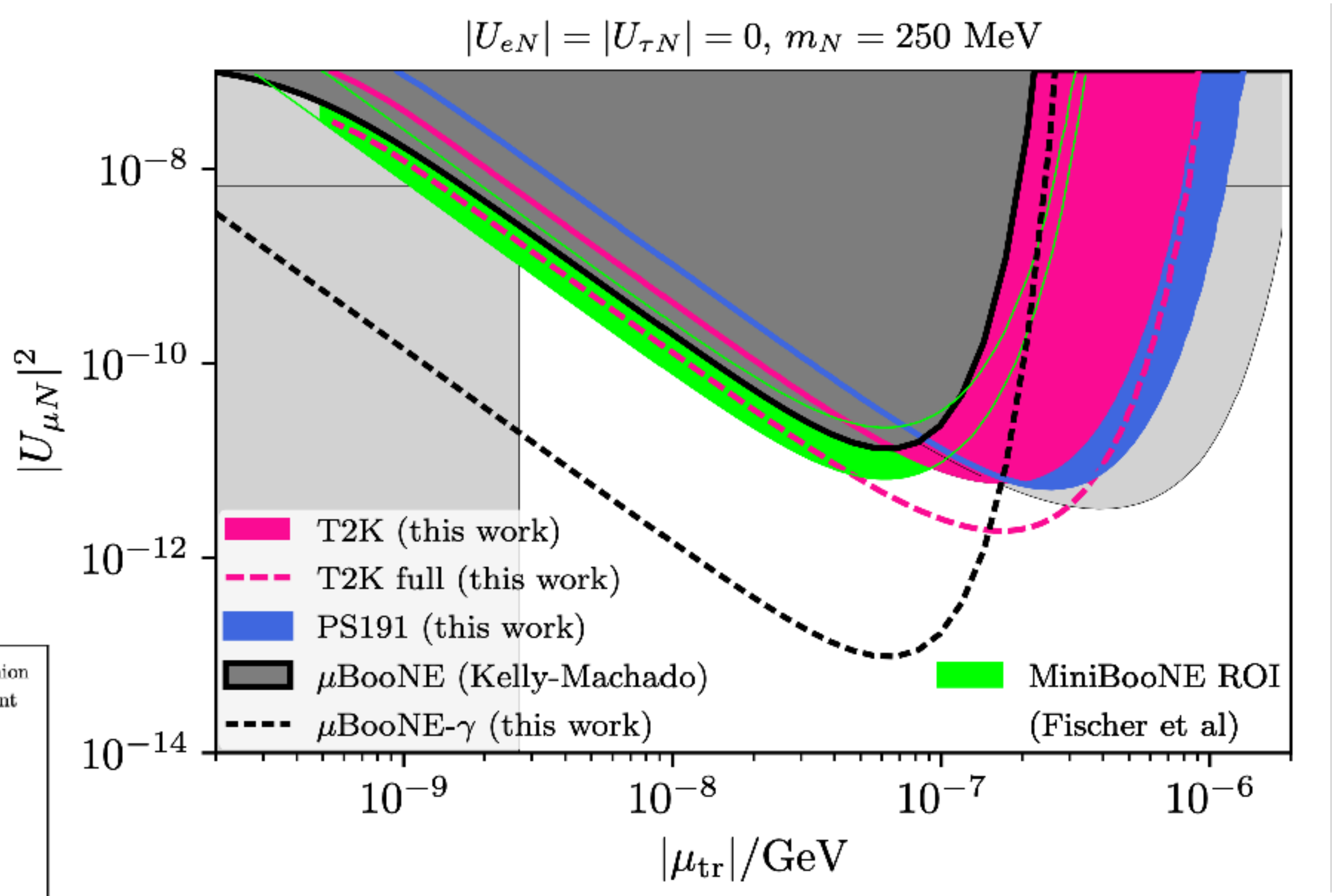
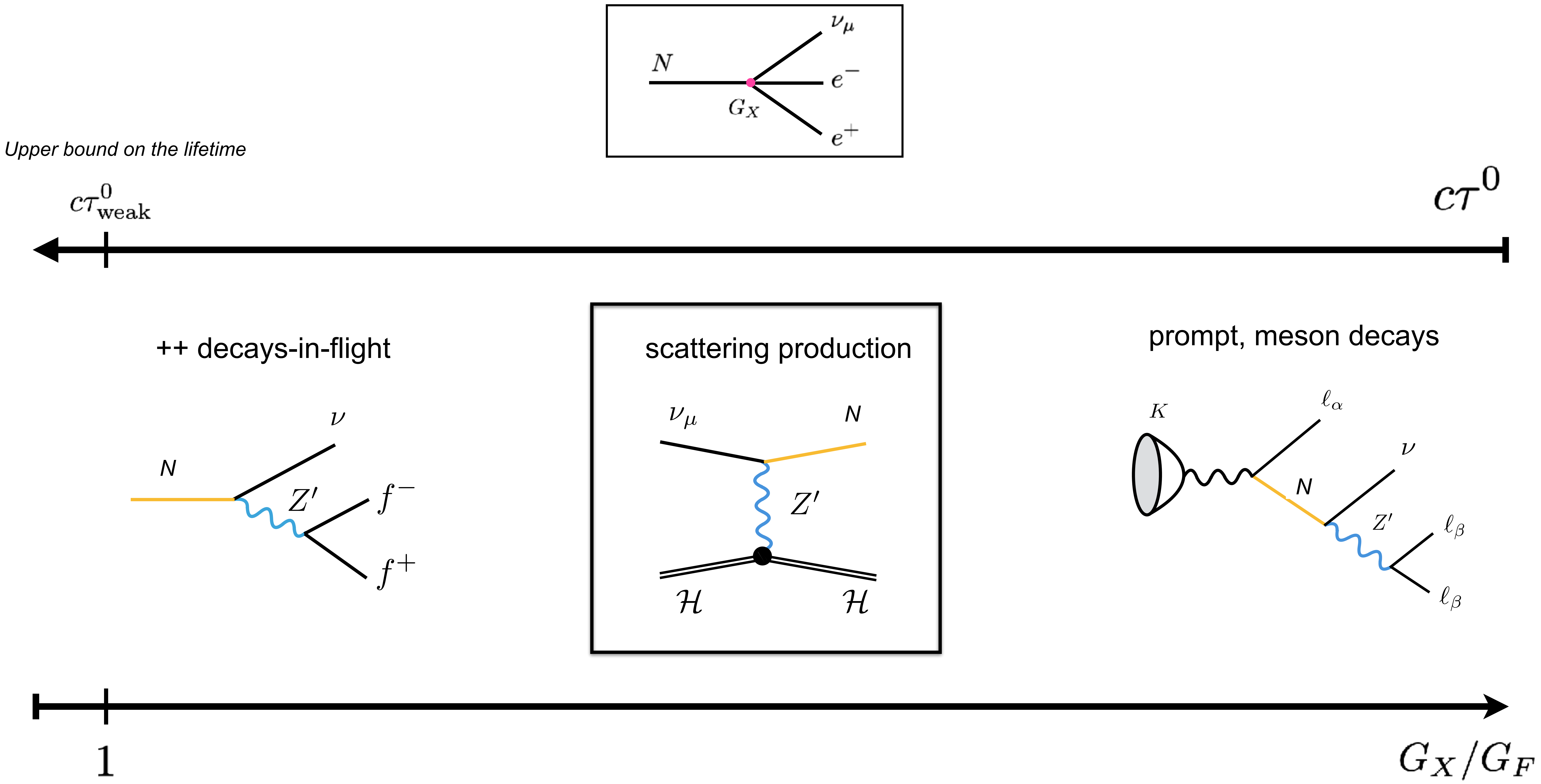






MicroBooNE (high-density LAr detector) can do significantly better with the photon channel, but backgrounds are likely to be severe.



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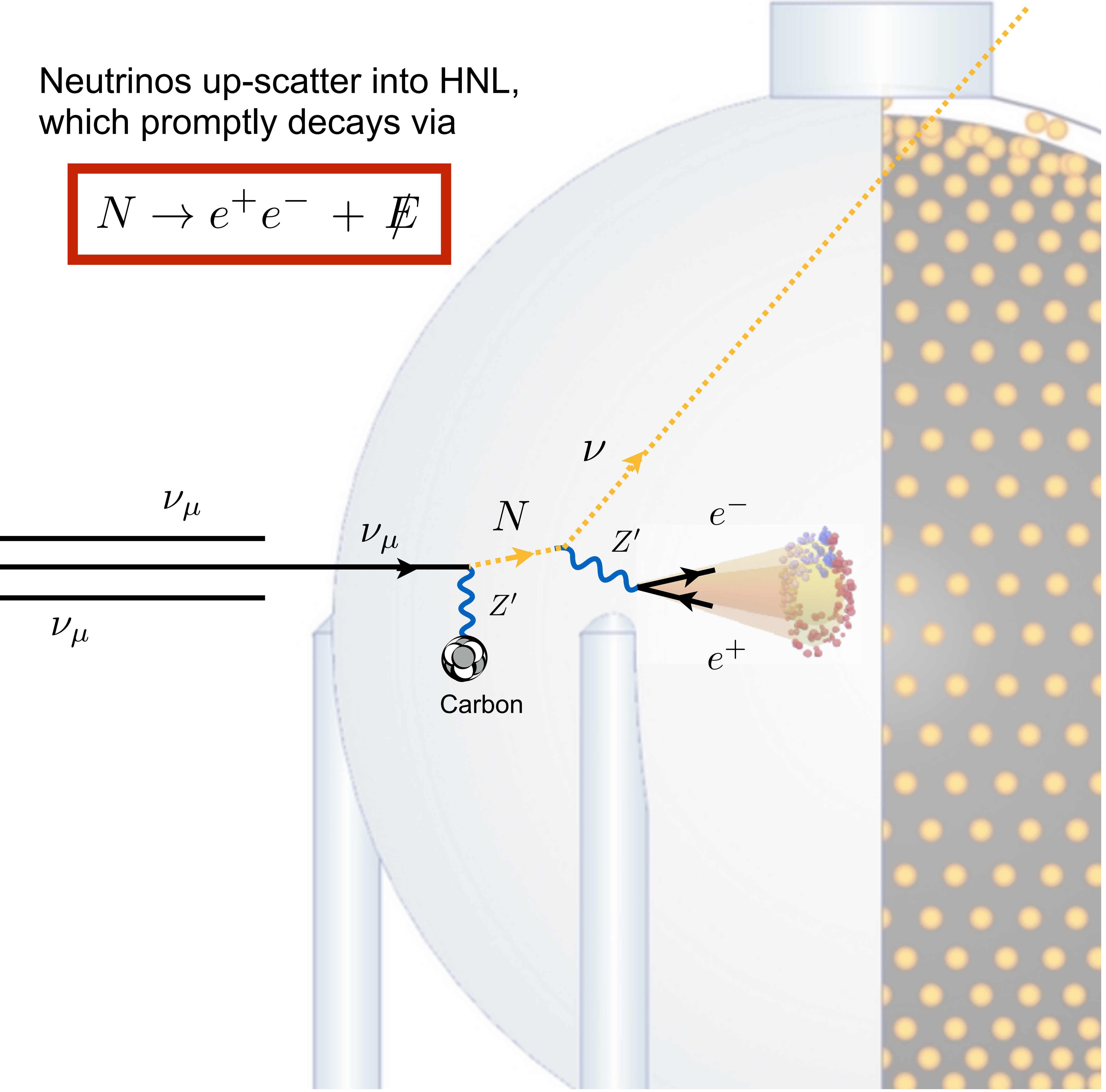
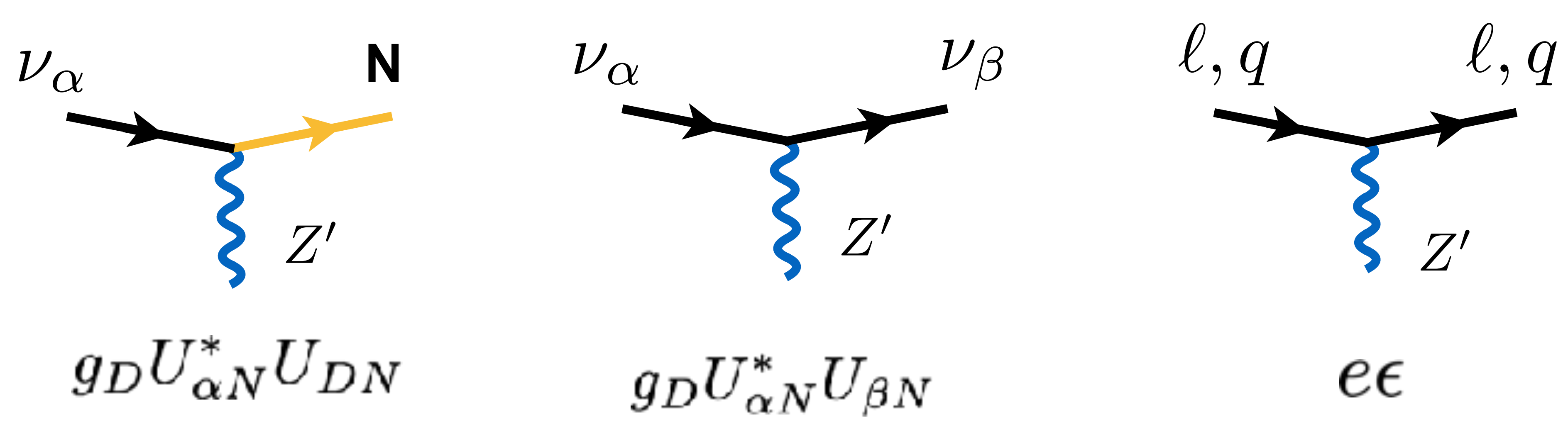
Heavy neutrinos + dark forces to accommodate MiniBooNE

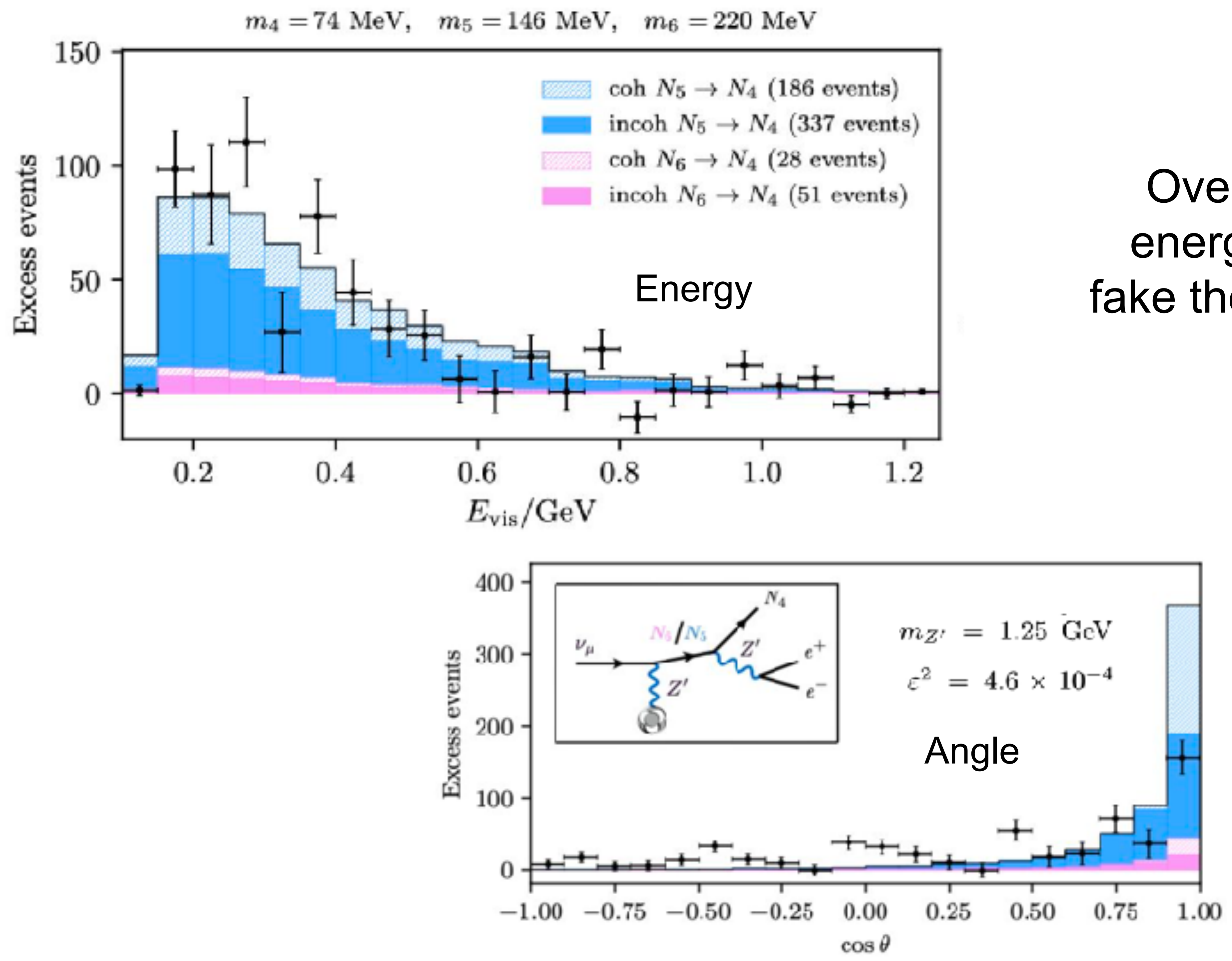
Neutrinos up-scatter into HNL, which promptly decays via

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



Neutrino portal + kinetic mixing.





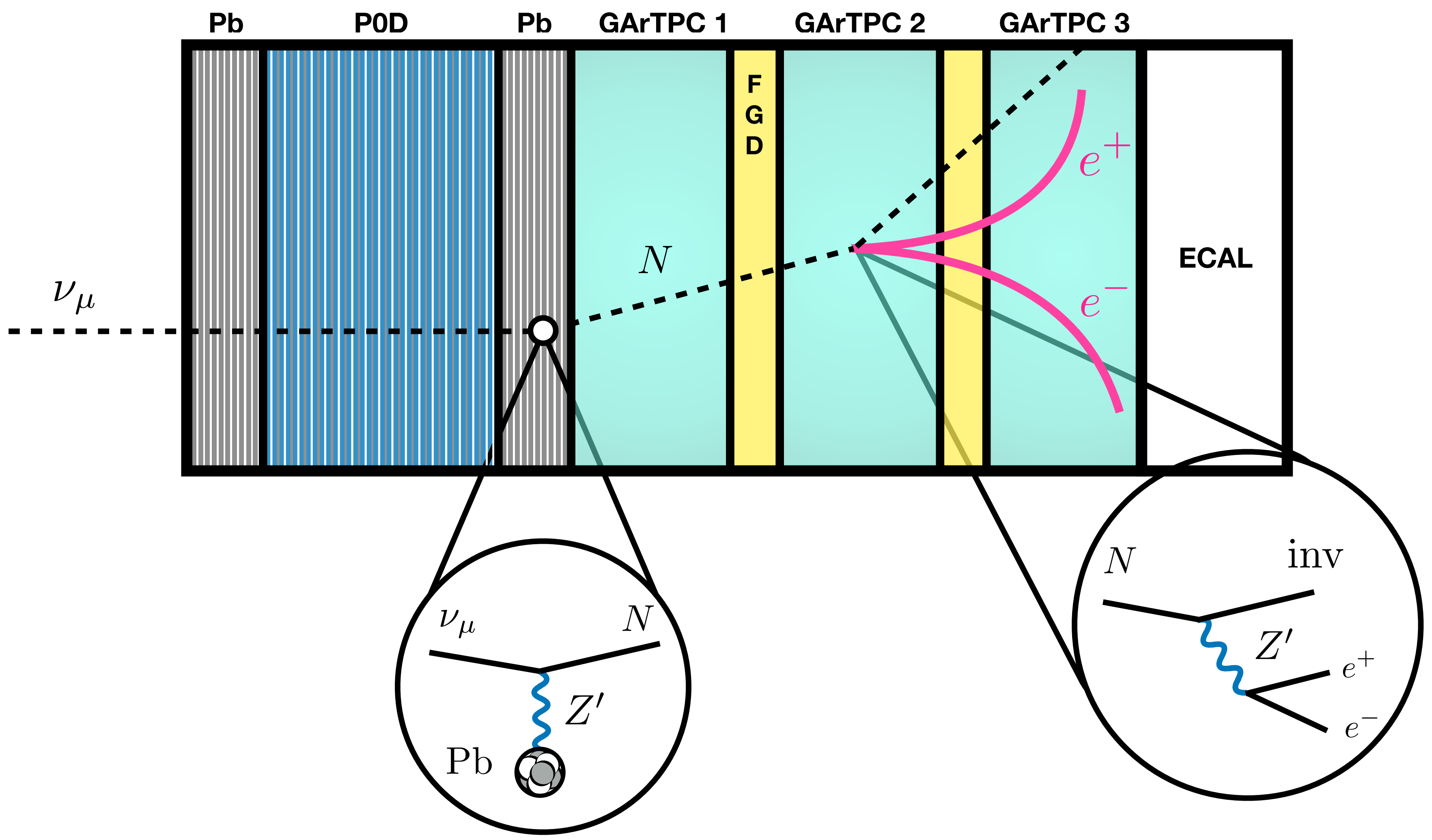
Overlapping as well as energy asymmetric e+e- fake the MiniBooNE excess.

Upscattering in dense neutrino detectors
T2K near detector (ND280)

C. Arguelles, MH, N. Foppiani, in preparation.

T2K Collaboration, Phys. Rev. D 100, 052006 (2019)
See also, Vedran Brdar et al, arXiv:2007.14411

Heavy **lead** plates
+ Gaseous Argon modules
+ Magnetic field to separate e+e-



Constrains events with no hadronic activity at vertex and HNLs w/ finite lifetimes.

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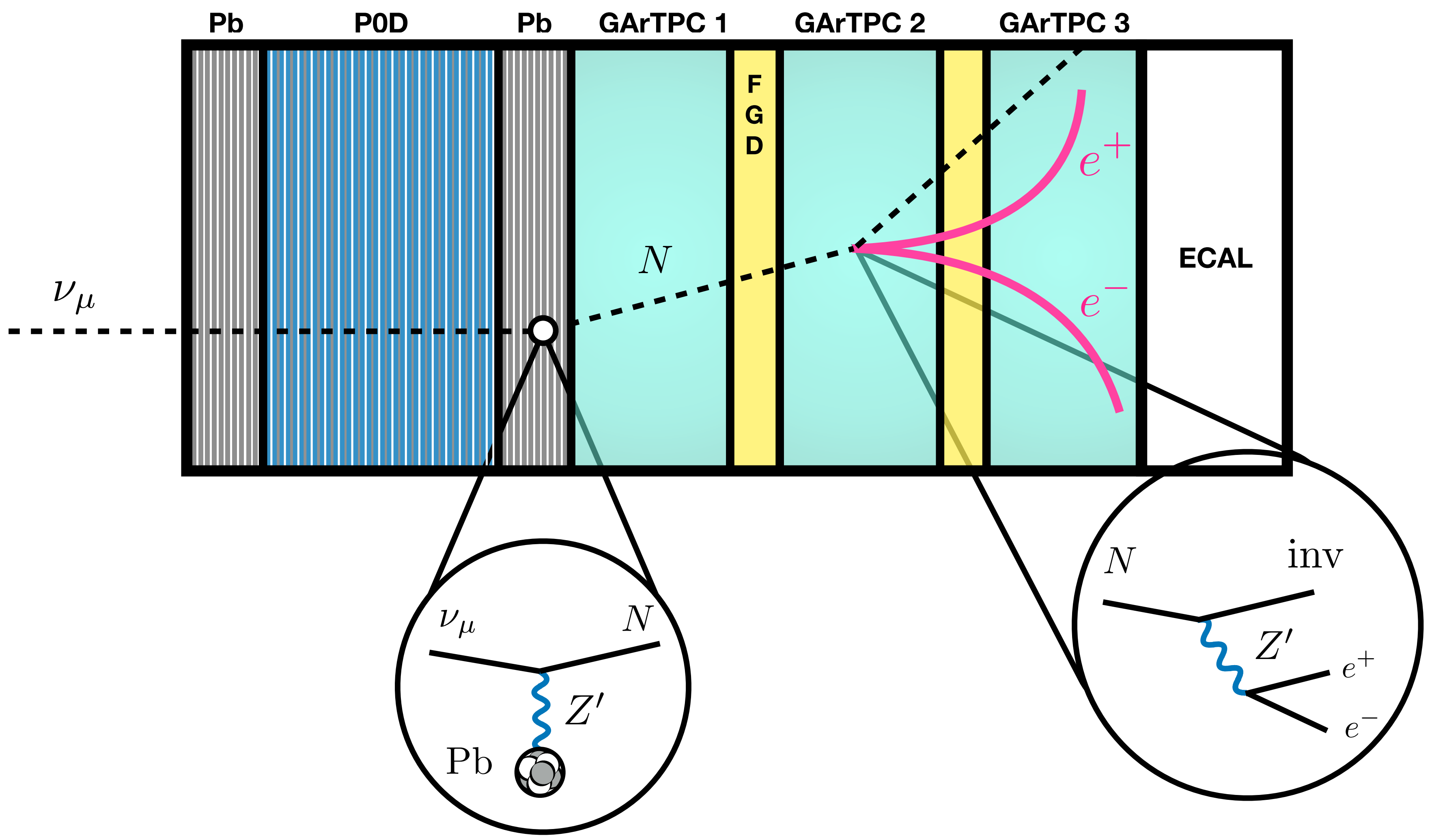

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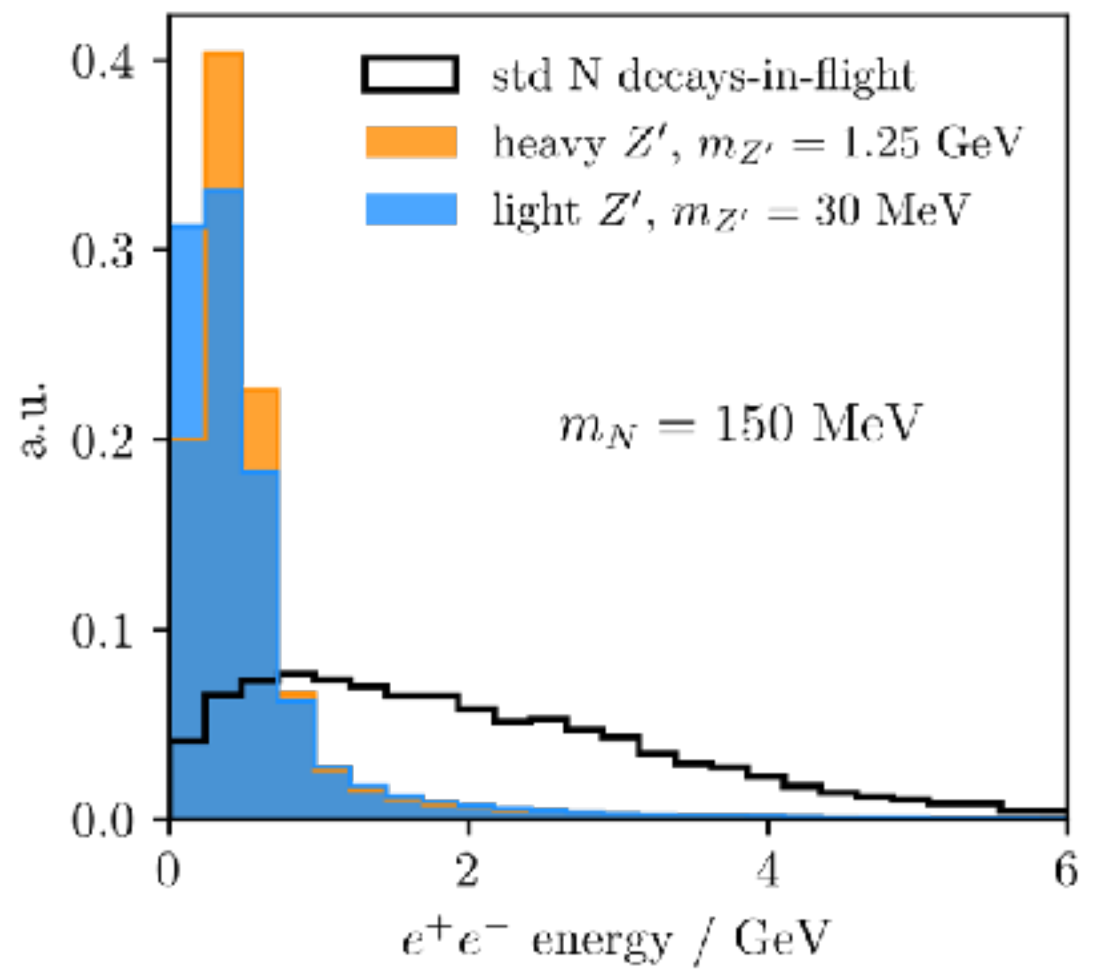
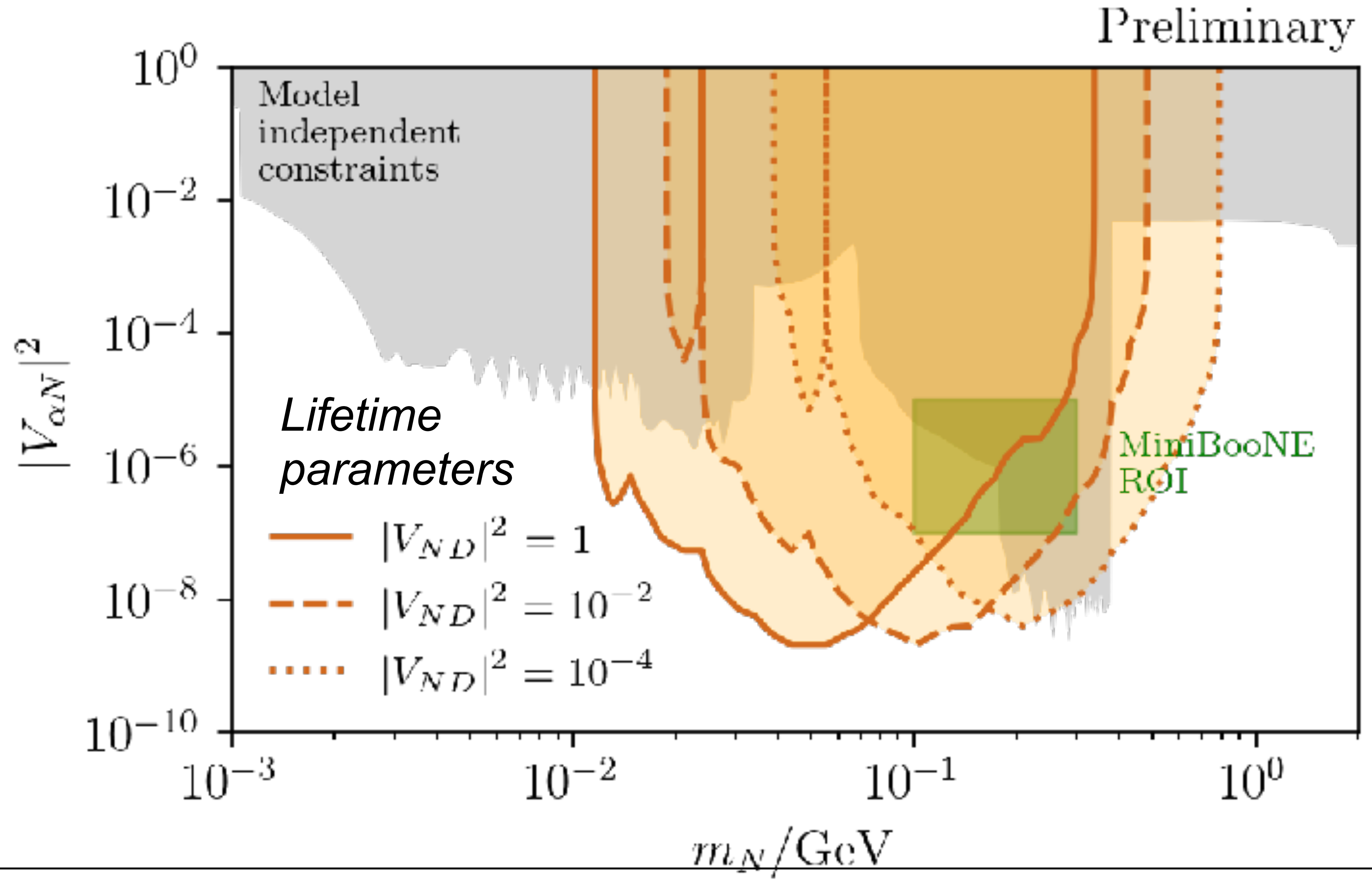


Precludes any signature of upscattering at other neutrino experiments if

ctau > O(5) cm

Scattering signal is softer than DIF one, but efficiencies remain large.

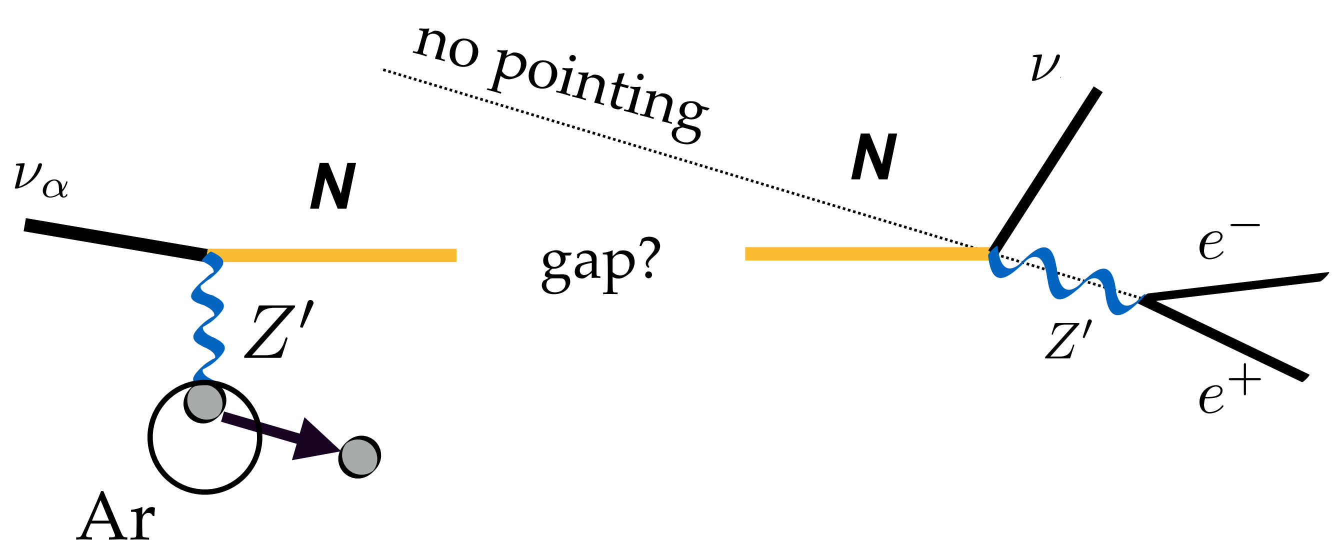
Backgrounds close to the Lead layers are large, so restricted to gaseous volume.

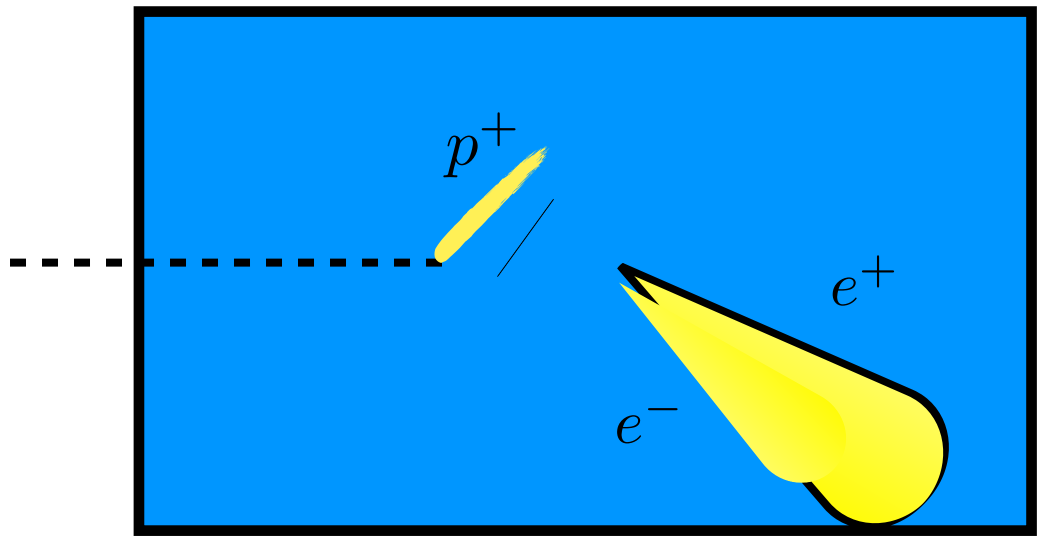


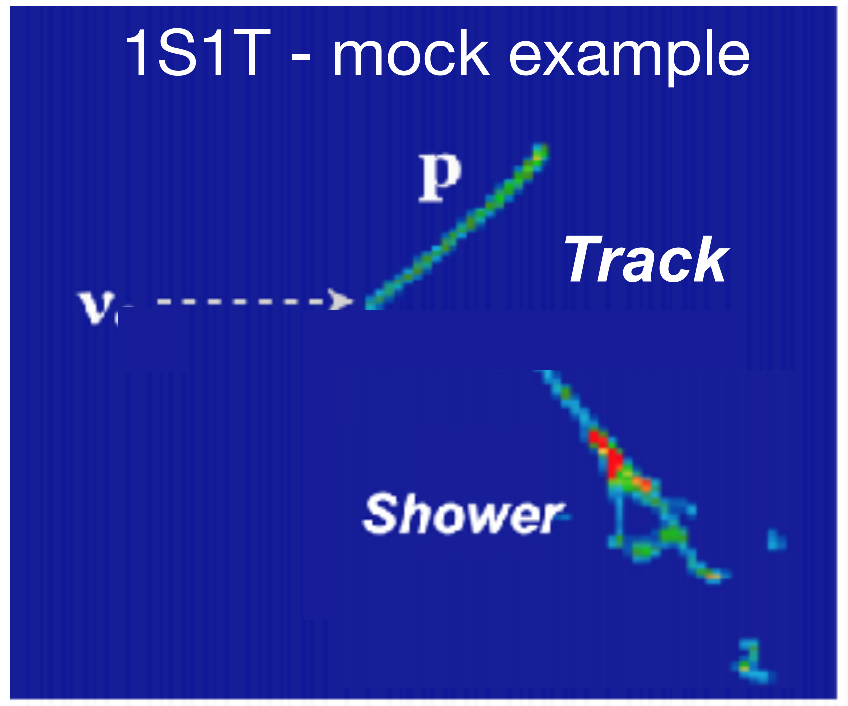
Dark neutrinos @ MicroBooNE

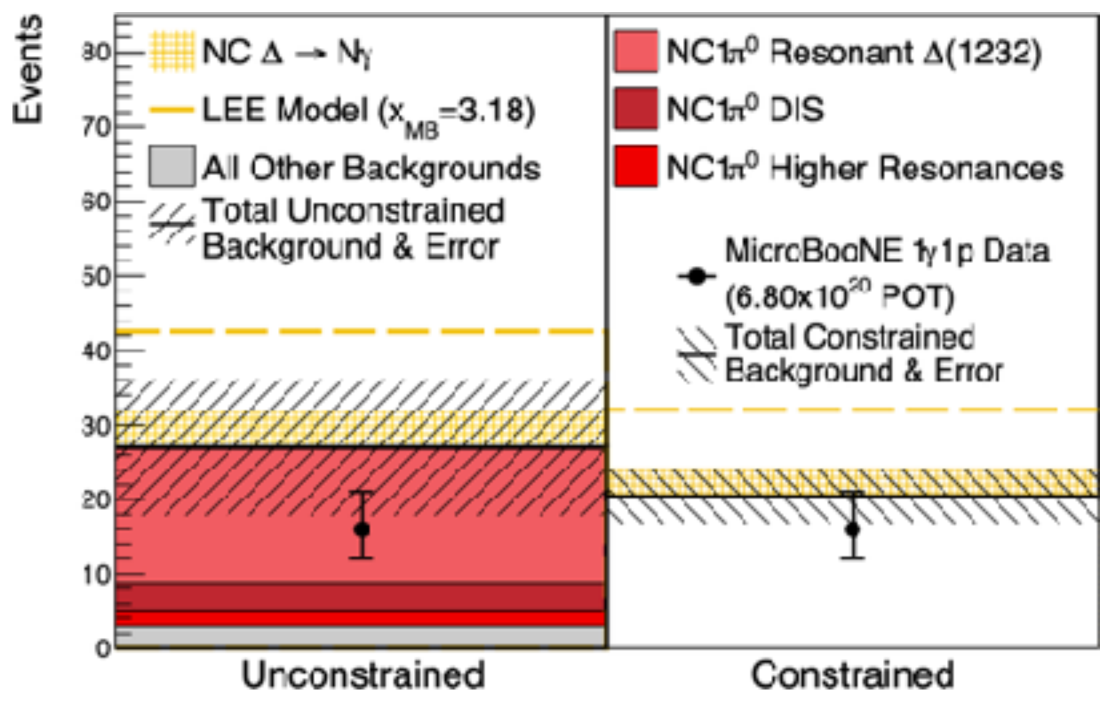
New generation of Liquid Argon detectors at Fermilab can search for (e+e-) events and will test MiniBooNE results.

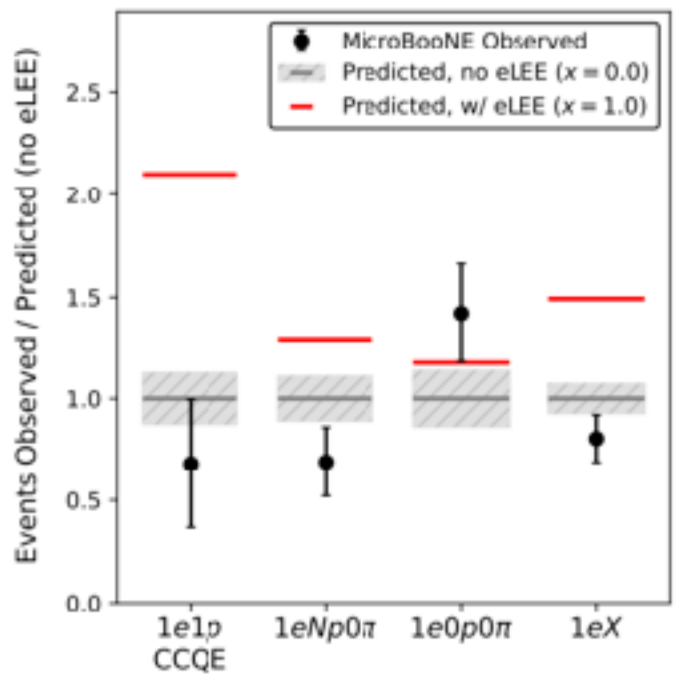
Currently investigating these signatures in LAr together with microBooNE single-photon group.











Negative single photon results

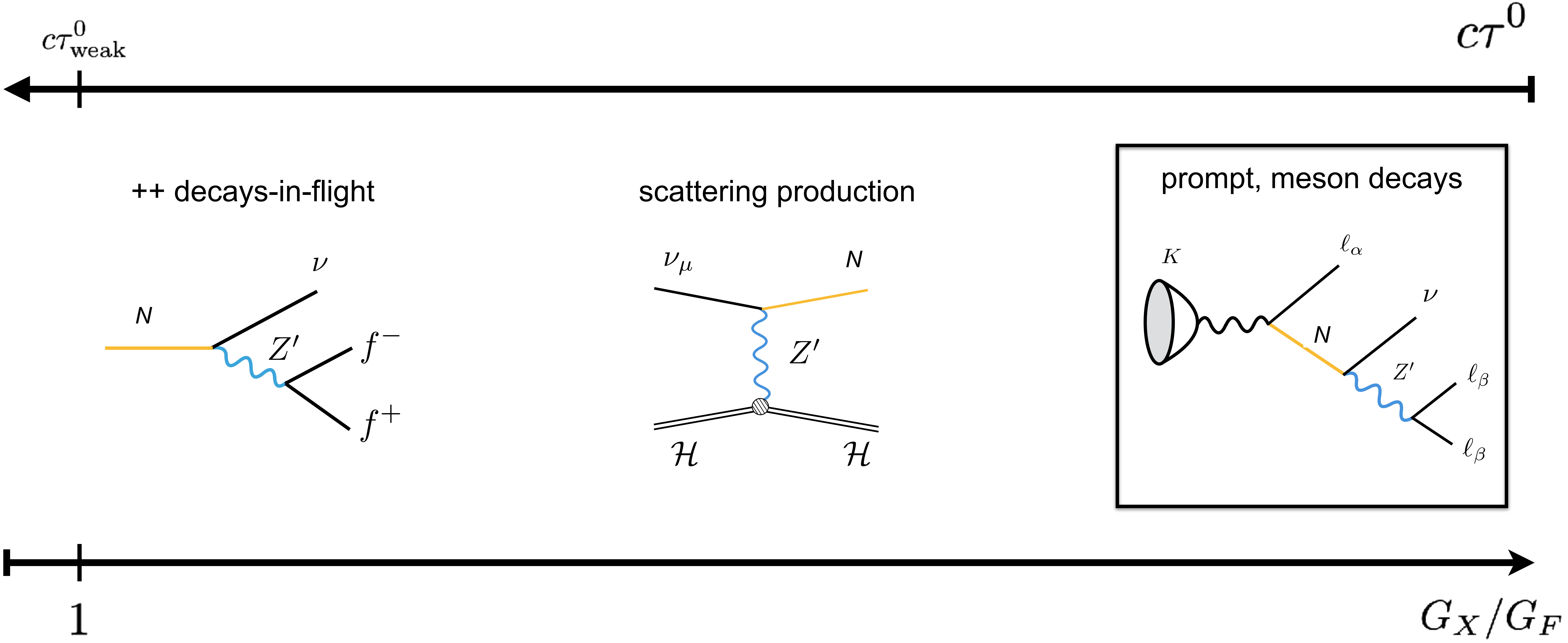
Negative single electron results

No existing results yet

- Coherent single photon
- e+e- pairs
- diphoton pairs

Still a lot of work to do in this direction.

The Impact of Secret Interactions



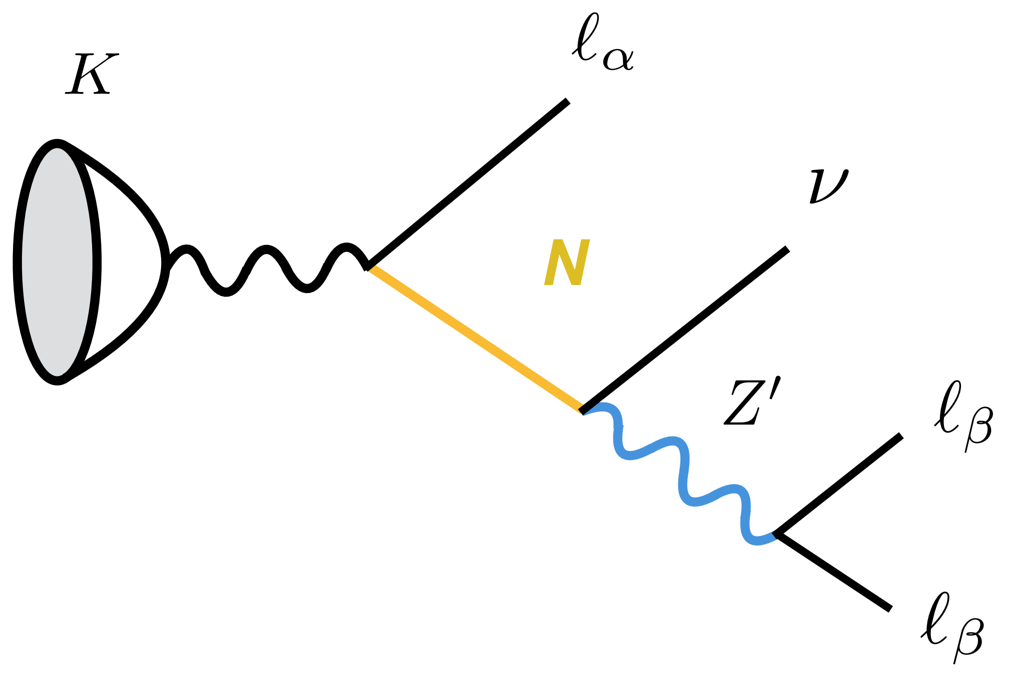
Prompt decays at Kaon factories

Three charged lepton signatures

P. Ballett, MH,a S. Pascoli arxiv:1903.07589
MH, M. Pospelov, arXiv:2012.02142

Rare leptonic kaon decays

Peak search + (displaced) e+e- vertex



Several kinematical constraints

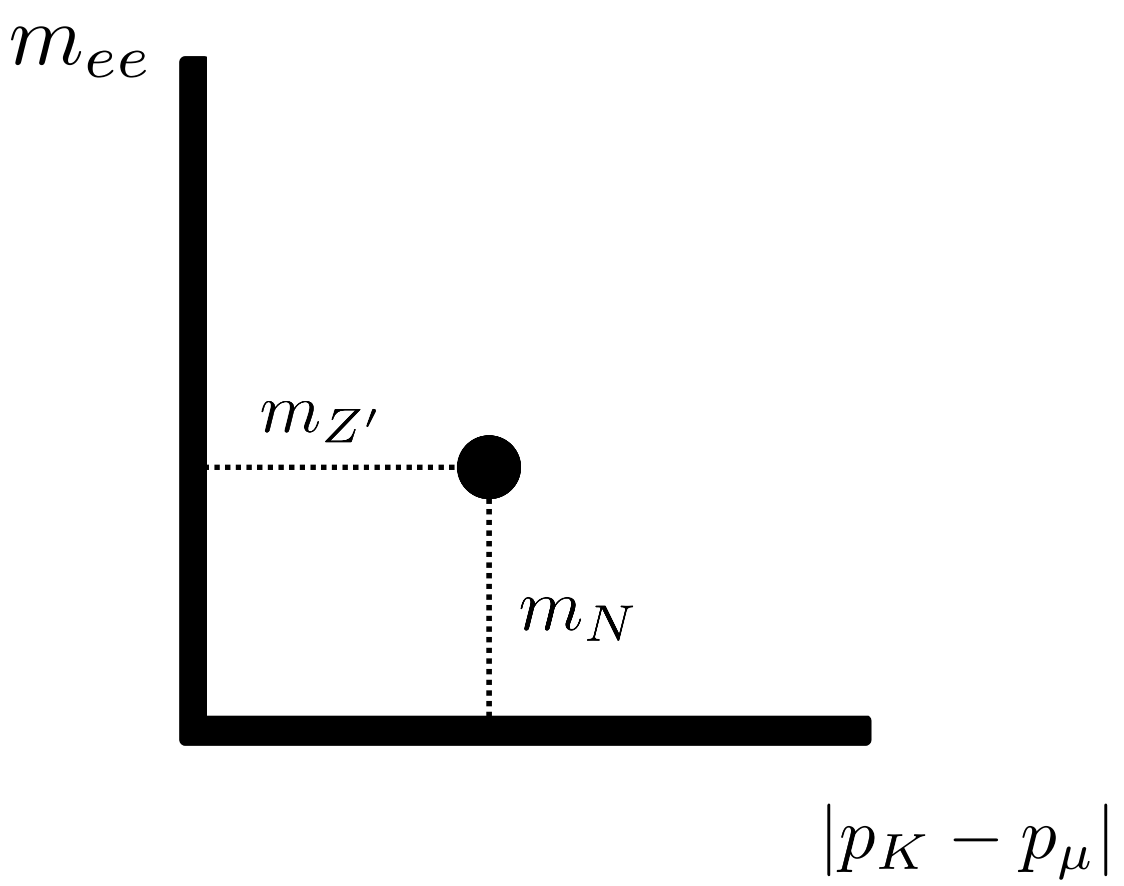
$$|p_K - p_\ell| = m_N$$

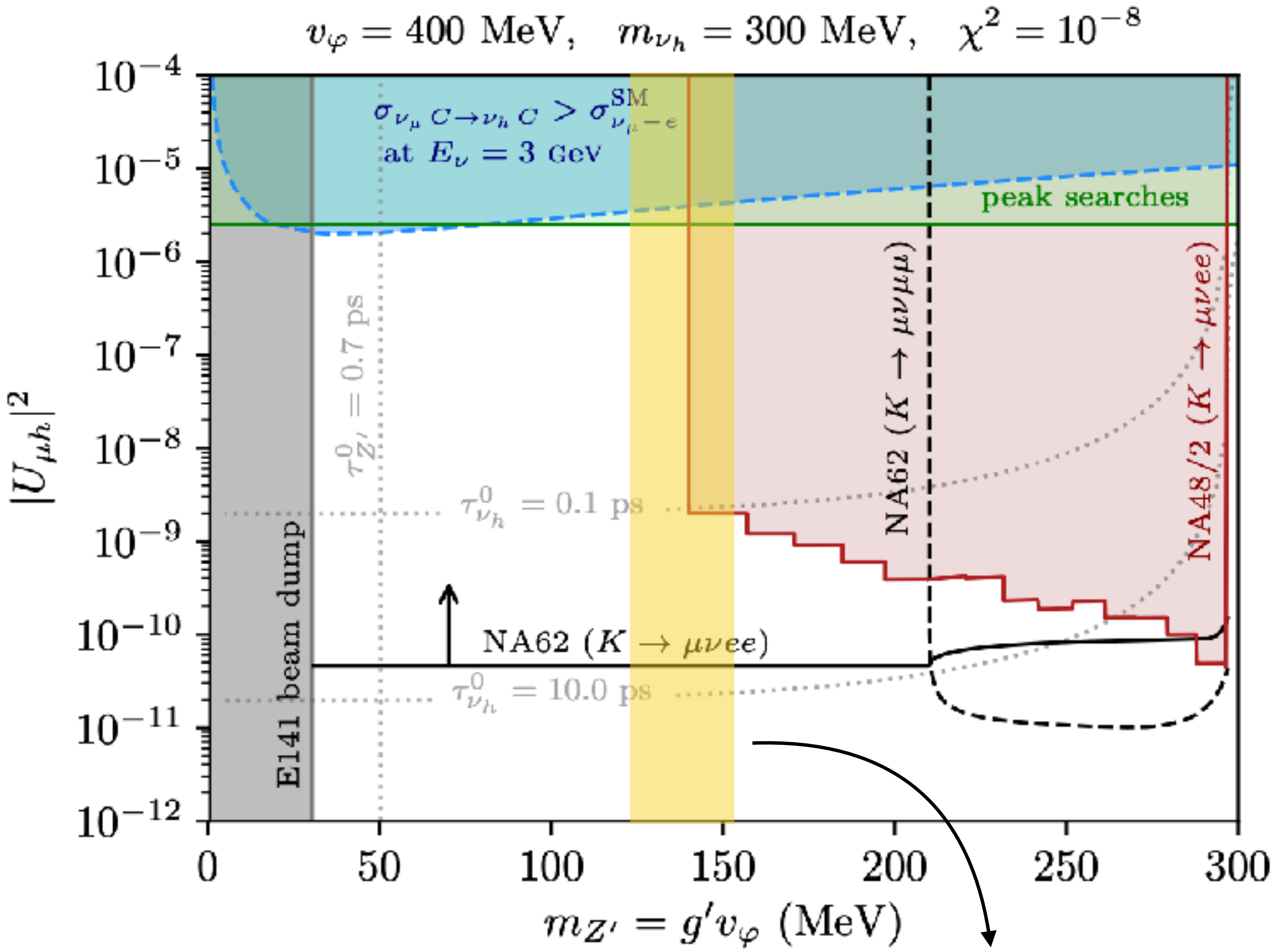
$$m_{\text{miss}} = |p_K - p_\ell - p_{ee}| = 0$$

$m_{ee} = m_{Z'}$ *or* $m_{ee} < m_N$

Light dark photon case

Smoking gun peak at light dark photon and HNL mass





Competing with pion Dalitz decays.

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

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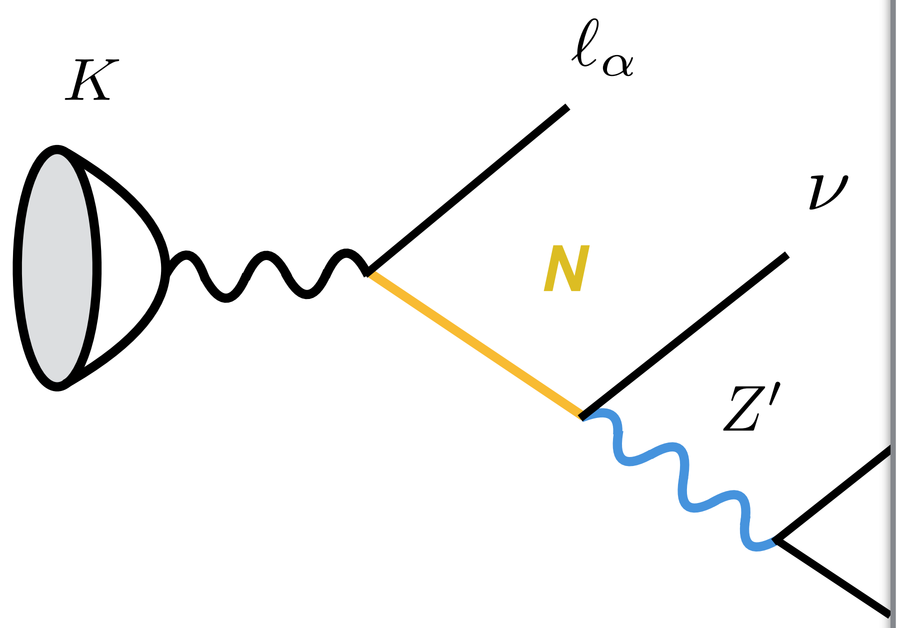

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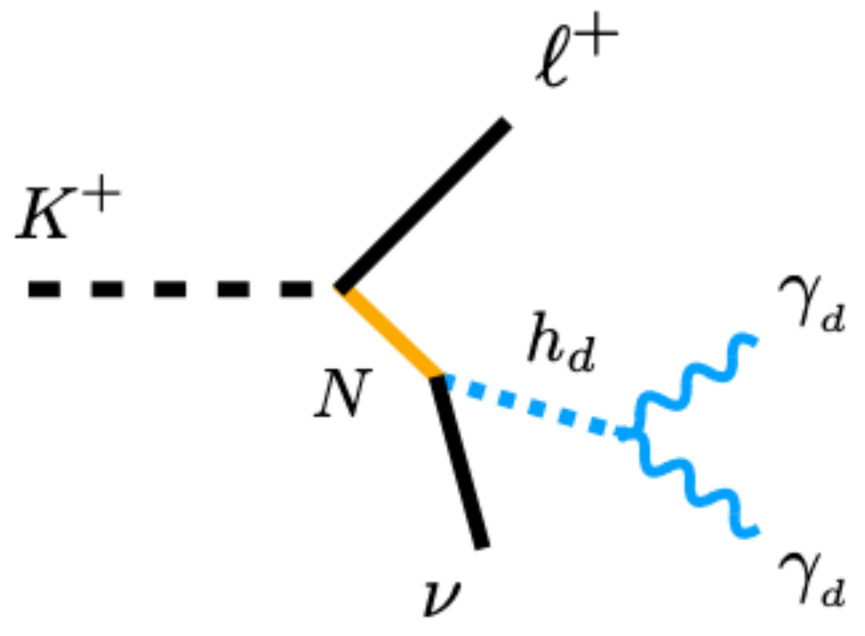
$$m_{ee} = m_{Z'} \quad \textit{or} \quad m_{ee} < m_N$$

Light dark photon case

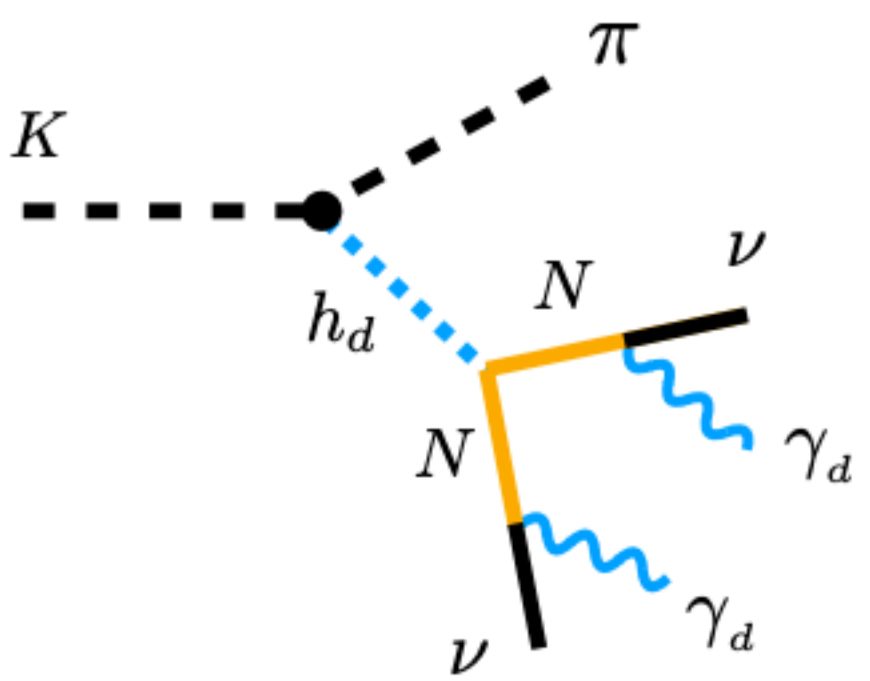
If the dark higgs is light, dilepton will come associated with 4 lepton decays!

These channels are background free and also allow to measure multiple dark sector particle masses.



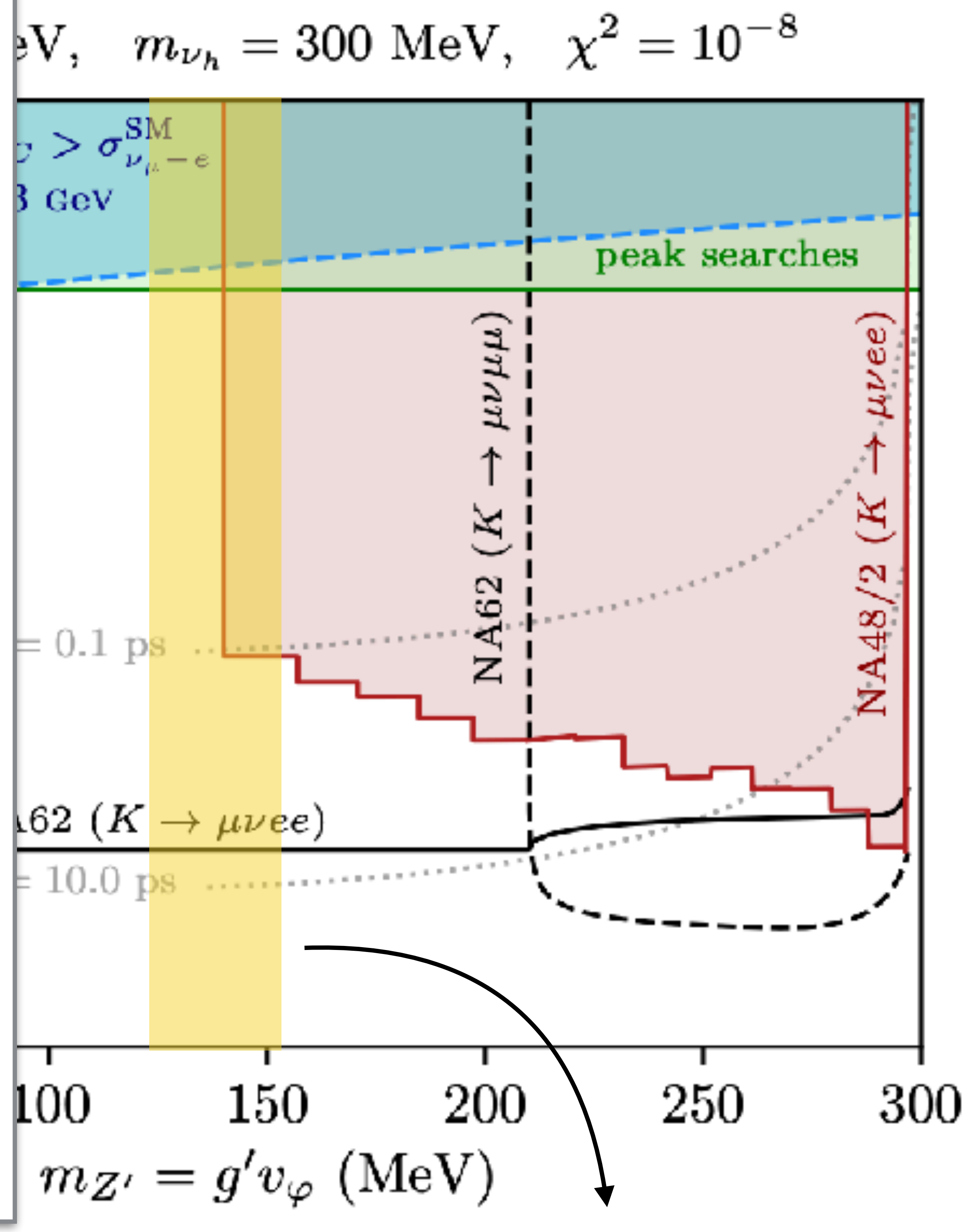
$U(1)_d + N$

$m_N > m_{h_d}$



$U(1)_d + N$

$m_{h_d} > 2m_N$



Competing with pion Dalitz decays.

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

Conclusions

Heavy neutrinos below the kaon mass from low-scale seesaw models still allowed in presence of new interactions.

By reducing the lifetime of the HNLs with a new force, we expect signatures in:
decay in flight —> upscattering —> meson decays

T2K ND280 provides the strongest limits on these particles, both in the minimal as well as the non-minimal macroscopically-lived HNLs

New ideas for explaining MiniBooNE with dilepton currently being tested at μBooNE.

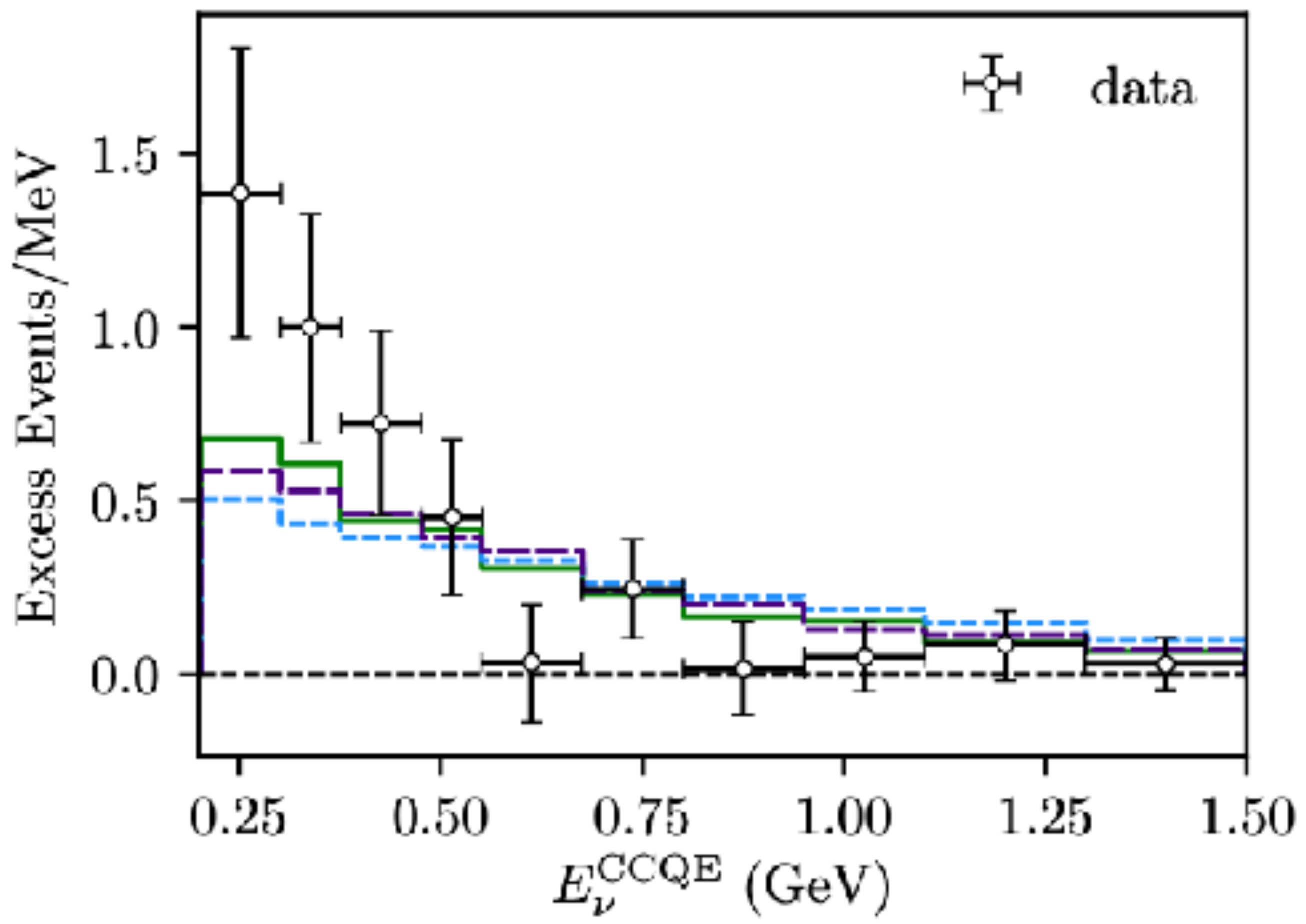
Multi-lepton final states currently being searched for at NA62

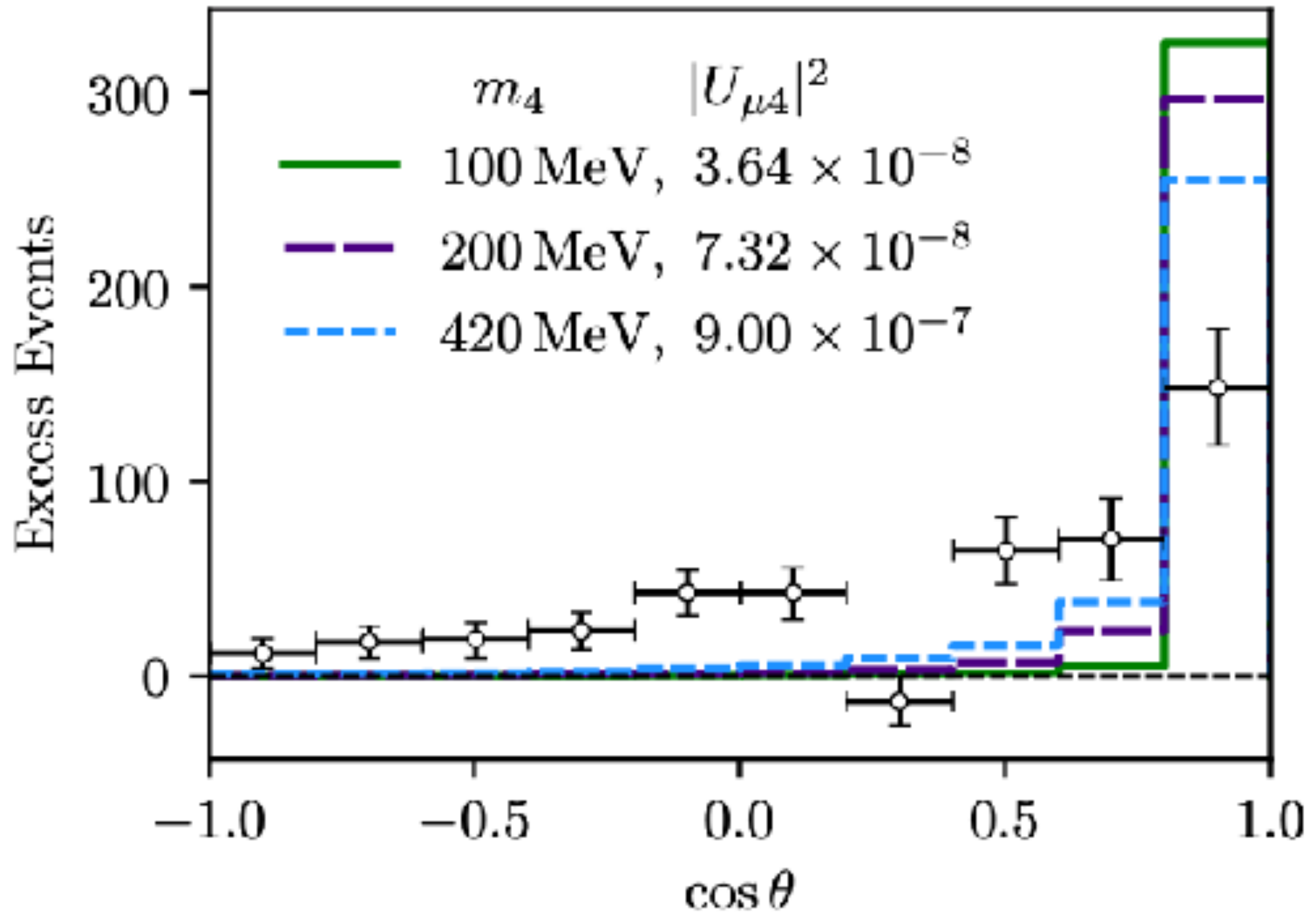
Thank you!

Back-up slides

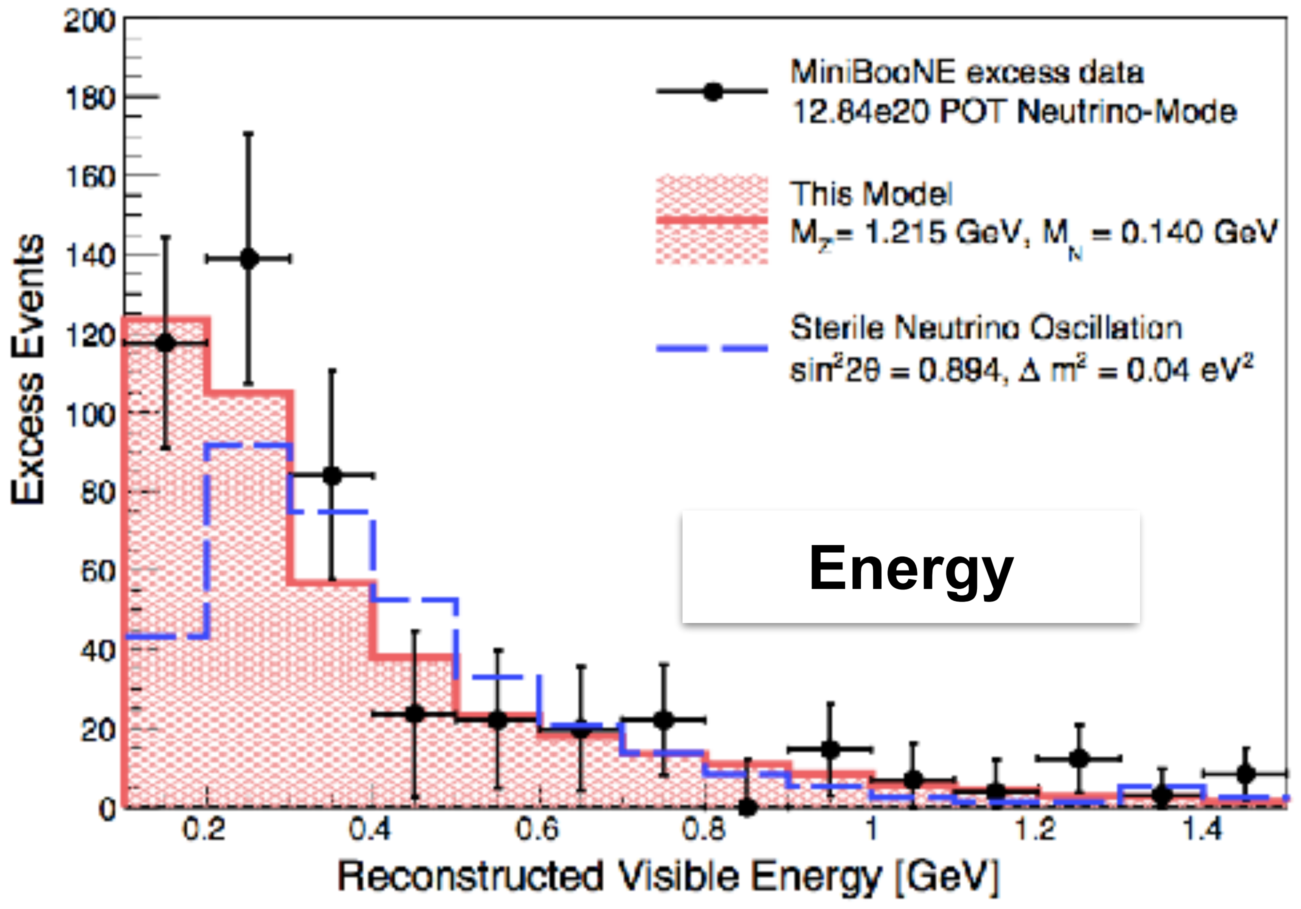
All Distributions

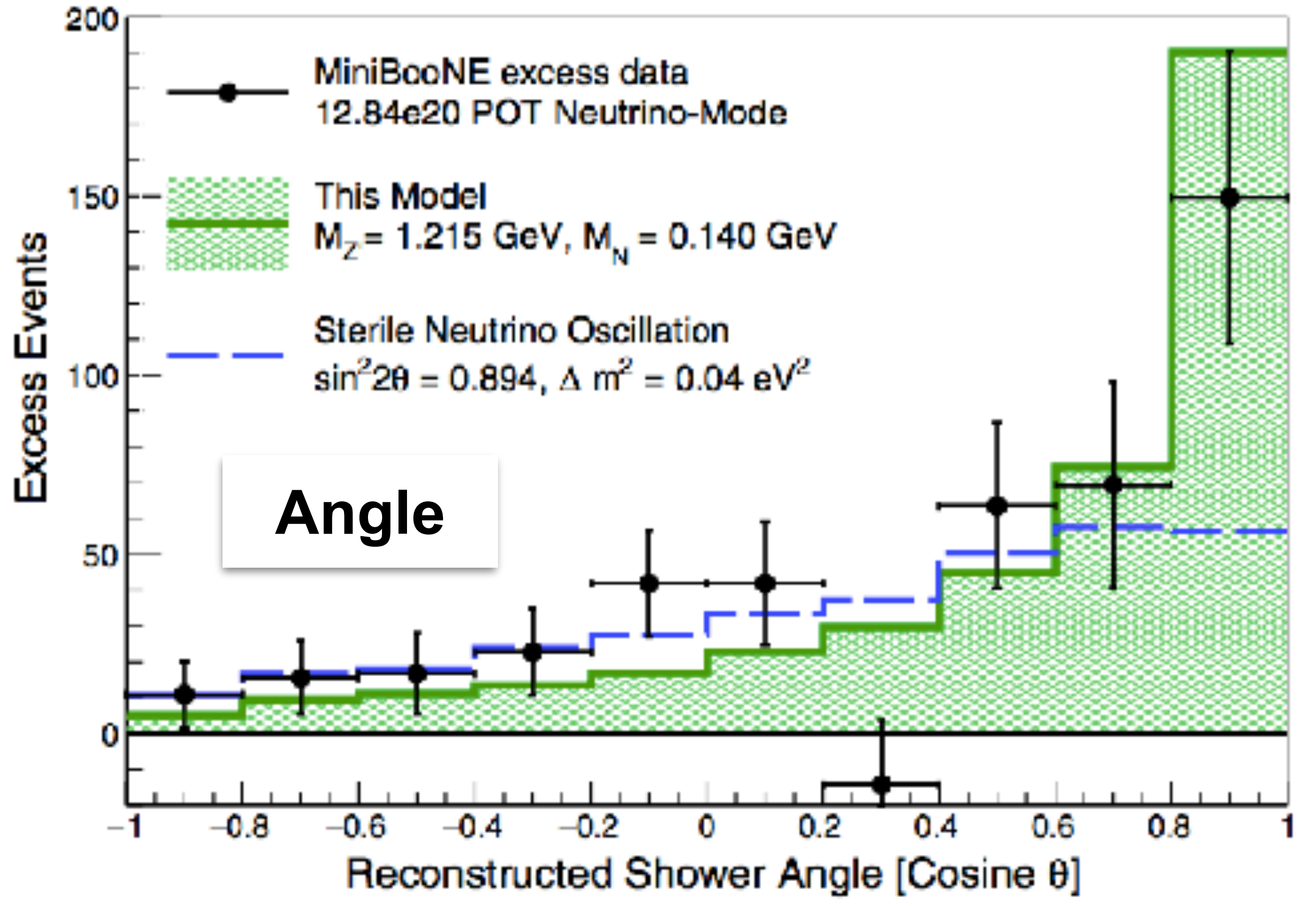
On-shell light Z'	***Off-shell Z' w/ Z-Z' interference***	***Off-shell Z' (no Z-Z' interference)***
E. Bertuzzo et al., PRL121.241801 *C. Arguelles, MH, Y. Tsai, PRL123.261801*	*P. Ballett et al, PRD 99.071701*	A. Abdullahi, MH, S. Pascoli, arXiv:2007.11813



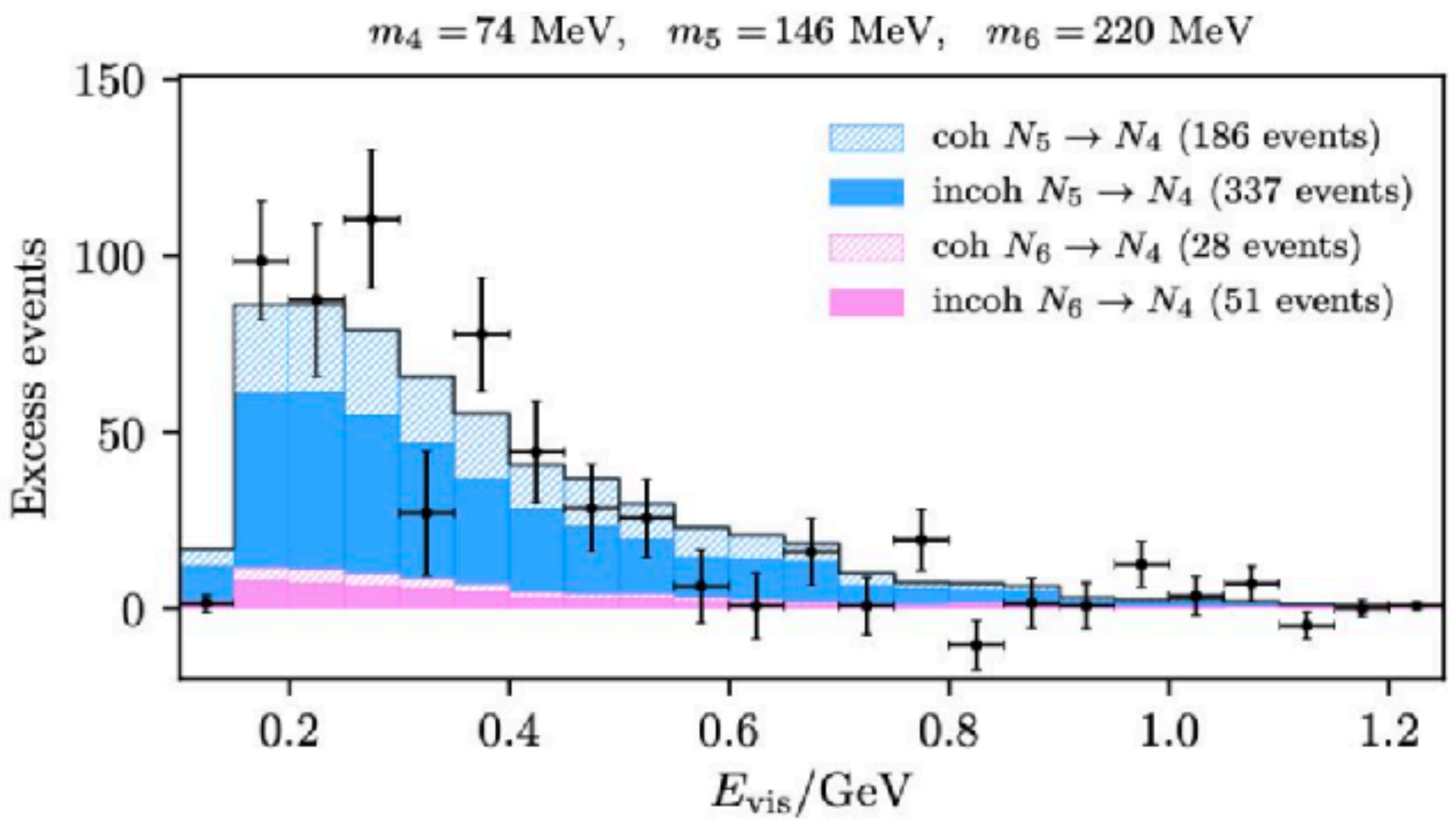


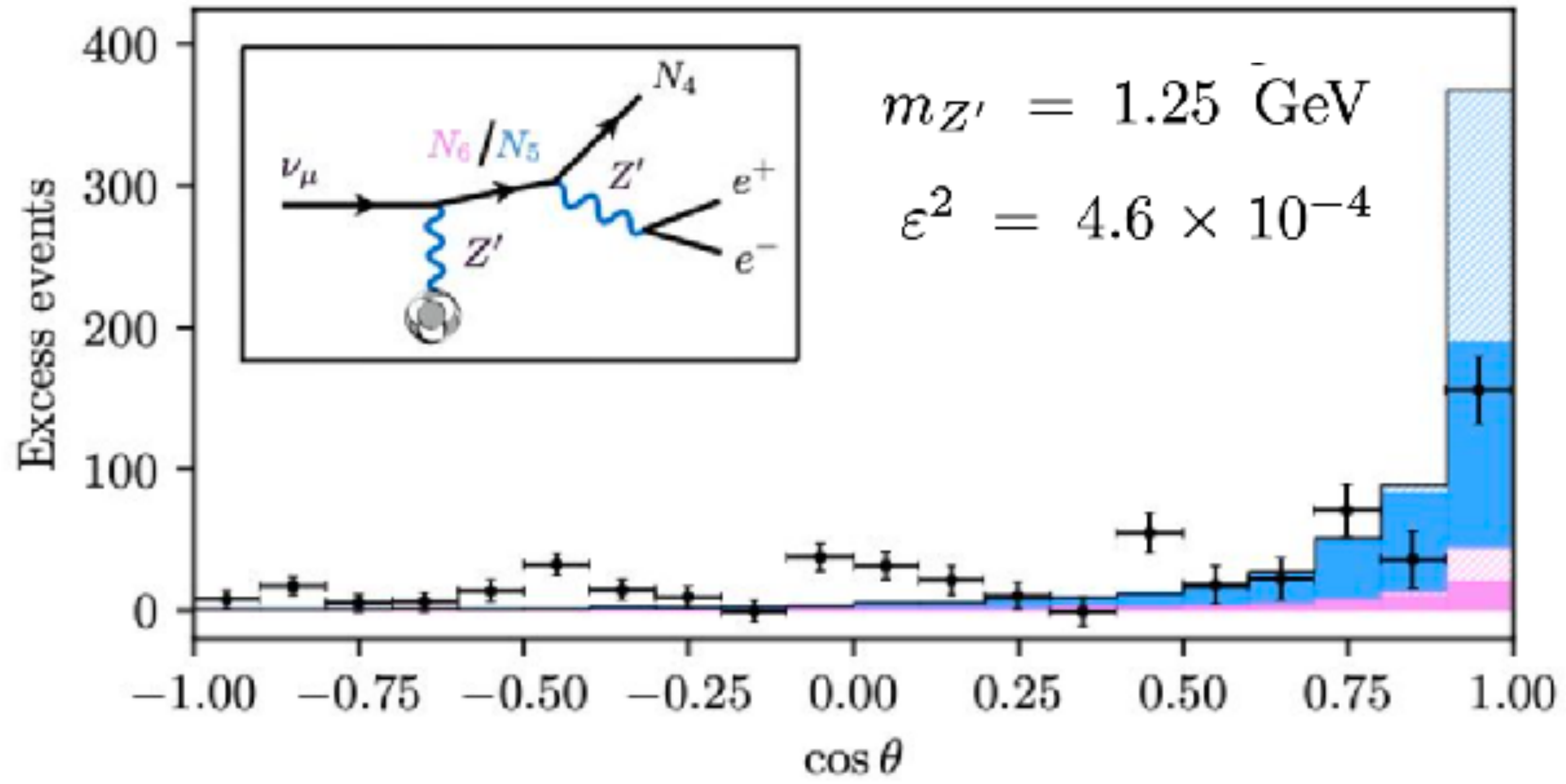
MiniBooNE 2018





MiniBooNE 2018



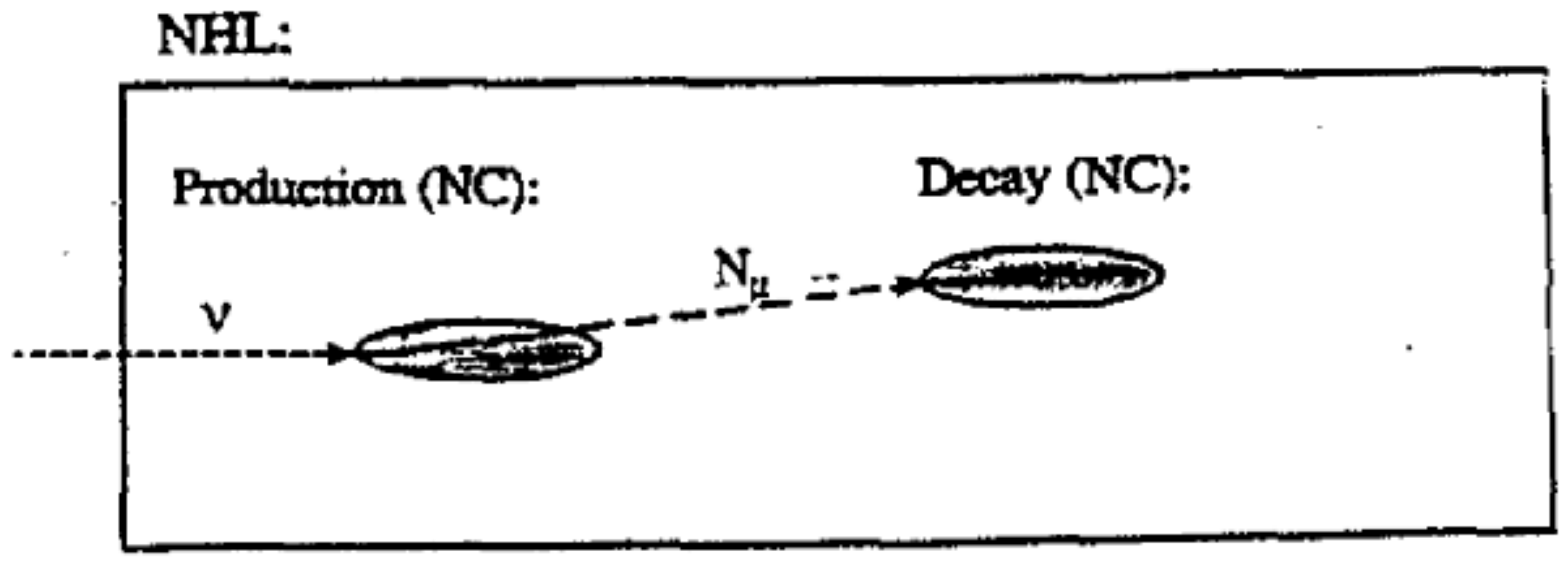


MiniBooNE 2020

"Double-bang" events at CCFR

Experimental anomalies in the 80/90's — not ruled w/ newer hypotheses

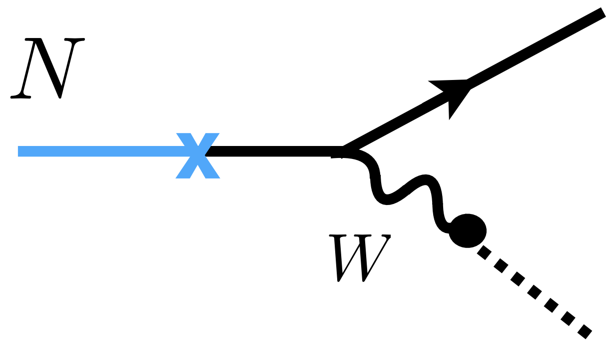
Double-bangs @ CCFR



9 NC/NC observed on a background of $3 \pm 0.2\,(\text{stat.}) \pm 0.4\,(\text{syst.})$

To the best of our knowledge, this is not explained to this date.
P. de Barbaro, doi.org/10.1063/1.43269

Result was not pursued further as standard HNLs would also lead to NC/CC events (N —› μ π).

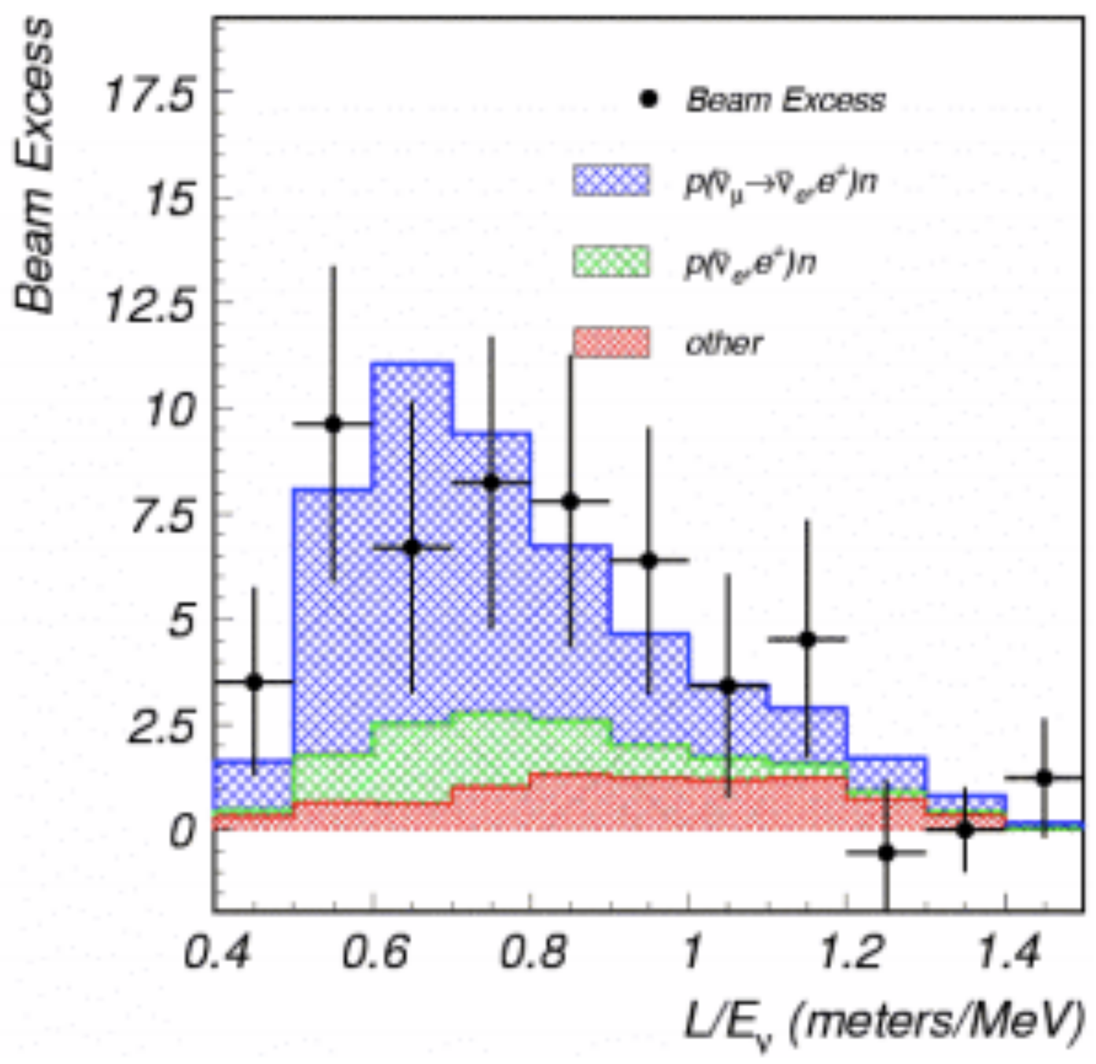


But our dark HNLs only decay via NC channels,

compatible few events at $E_\nu \sim 100$ GeV (DIS cross section is small via Z').

LSND: 1993 - 1998 arXiv:0104049

1) 800 MeV proton beam, 1.8e23 POT!
2) π decay at rest and in flight:12º nu/p beam angle.
3) π- contamination: $\bar{\nu}_e/\bar{\nu}_\mu \sim 8 \times 10^{-4}$
4) Baseline of 30 m
5) ~167 tonnes of liquid scintillator
6) 8.3 m long det along nu beam.

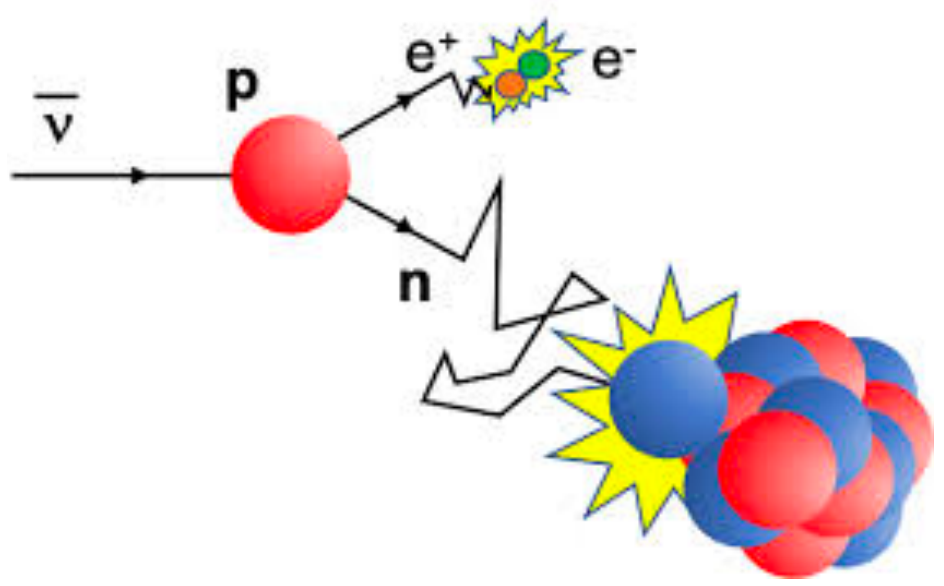


EXCESS: 87.9 ± 22.4 ± 6 EVENTS
3.8 sigma

General idea:

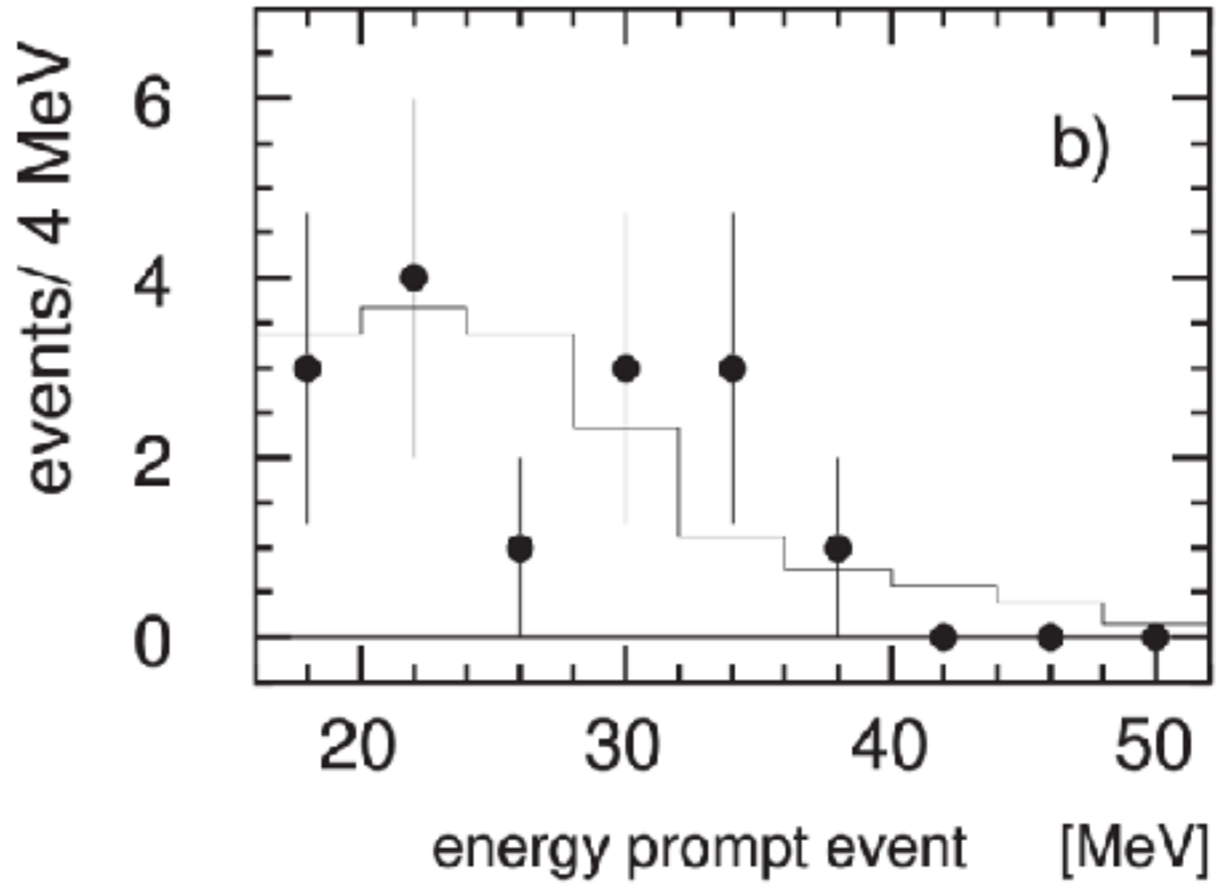
$$\begin{array}{llll} \pi^+ \rightarrow & \mu^+ & + \; \nu_\mu & \\ & \downarrow & & \\ & e^+ & + \; \nu_e & + \; \bar{\nu}_\mu \end{array}$$

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$



KARMEN: 1990 - 2001 arXiv:020302

1) 800 MeV proton beam, 6e22 POT!
2) π decay at rest mostly. Detector 90º from p beam.
3) π- contamination: $\bar{\nu}_e/\bar{\nu}_\mu = 6.4 \cdot 10^{-4}$
4) Baseline of 17.7 m
5) ~57 tonnes of liquid scintillator
6) 3.5 m long det along nu beam.



NO EXCESS

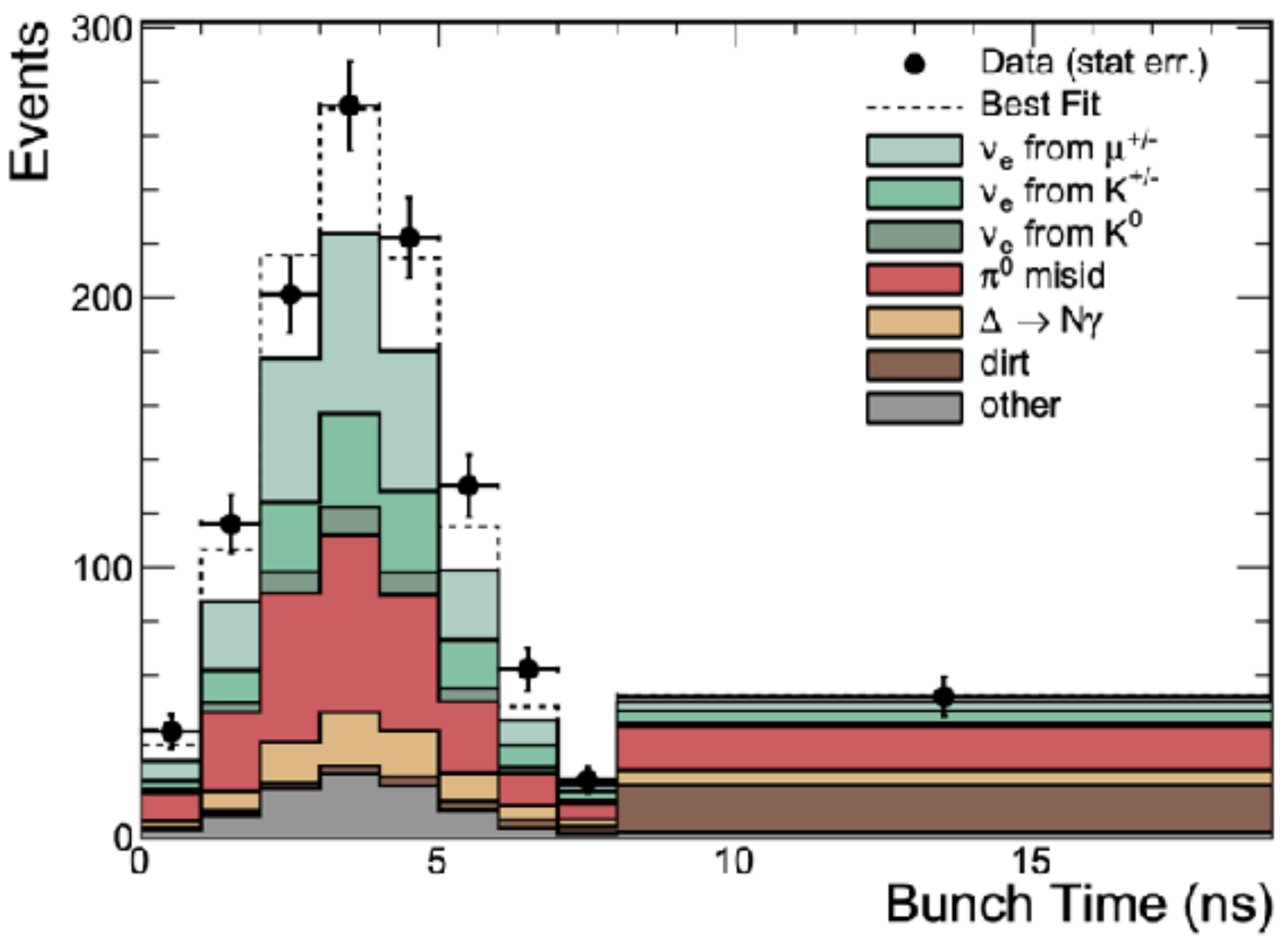
To this day, the most sensitive SBL $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance experiments.

MiniBooNE update 2020

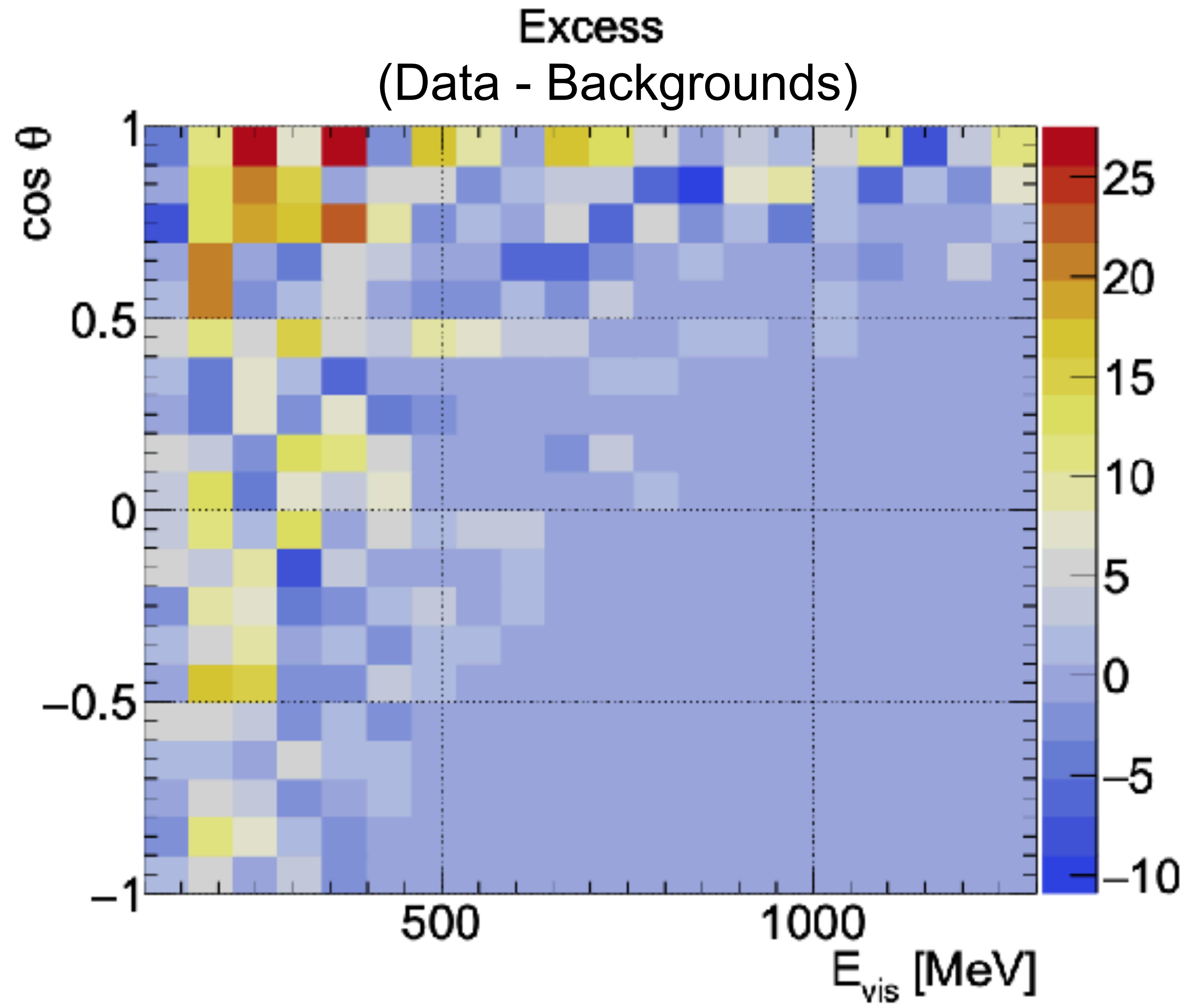
1) Significance increases when restricting to smaller fiducial volume

Fiducial cut	Excess	significance
$R < 500$ cm	560.6 ± 119.6	$4.7\ \sigma$
$R < 400$ cm	472.6 ± 81.7	$5.8\ \sigma$
$R < 300$ cm	208.8 ± 40.3	$5.2\ \sigma$

2) Excess overlaps w/ beam time



3) New 2-D distributions in E vs angle.

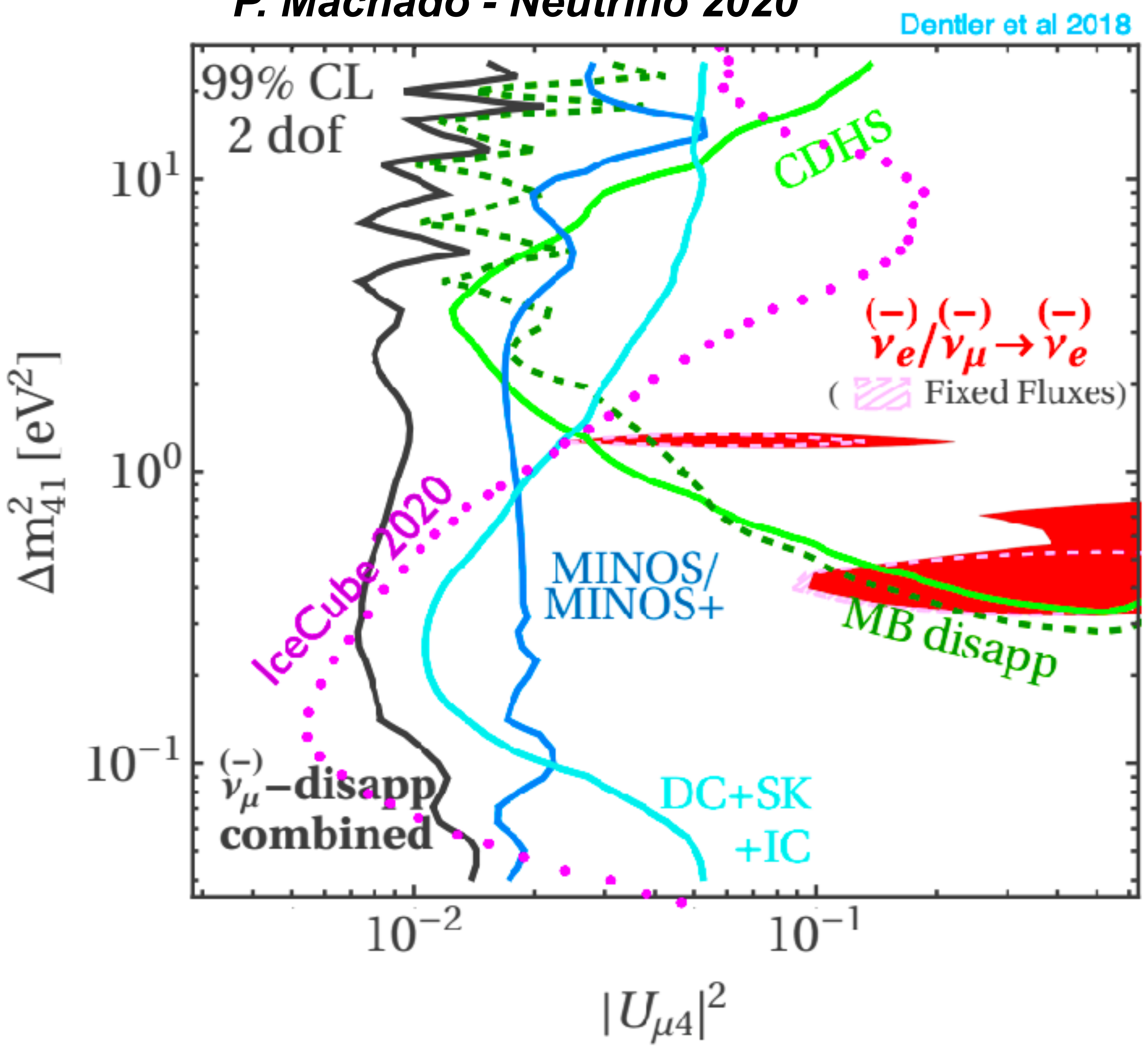


Novel oscillations?

Minimal eV sterile oscillations.

ν_μ disappearance + cosmology excludes this model.

P. Machado - Neutrino 2020



$$1.27\frac{\Delta m^2_{41}[\mathrm{eV}^2]L[\mathrm{m}]}{E[\mathrm{MeV}]} \sim \mathcal{O}(1) \qquad \Delta m^2_{\mathrm{SBL}} \sim 1\,\mathrm{eV}^2$$

to be contrasted with known values of

$$\Delta m^2_{21} \simeq 7.4 \times 10^{-5}\,\mathrm{eV}^2 \qquad |\Delta m^2_{31}| \simeq |\Delta m^2_{32}| \simeq 2.5 \times 10^{-3}\,\mathrm{eV}^2$$

$$P^{3+1}_{\nu_\mu\to\nu_e} = 4|U_{\mu 4}|^2|U_{e4}|^2 \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

$$P^{3+1}_{\nu_\mu\to\nu_\mu} = 1 - 4\,|U_{\mu 4}|^2(1-|U_{\mu 4}|^2)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

An **appearance** signal implies electron- **and muon-flavour disappearance**

Large tension between datasets
— more d.o.f. are not particularly helpful —

New exotic hypothesis to explain MiniBooNE

Open the floodgates to *exotica*

New signatures:
Gninenko 1107.0279 No LSND
Heavy neutrino O(MeV), magnetic moment, decay

Bertuzzo et al 1807.09877, Ballett et al 1808.02916,
Arguelles et al 1812.08768
Heavy neutrino O(1-100MeV), light Z', decay
W. Abdallah et al 2010.06159 ~~No LSND~~

Oscillations+:
Asaadi et al 1712.08019
Resonant matter effect UV challenge

Doring et al 1808.07460, Barenboim et al 1911.02329
eV steriles and extra dimensional shortcuts
not clear

Liao et al 1810.01000
Steriles + NCNSI + CCNSI Baroque

Decay: Delayed signal?

O. Fischer et al 1909.09561
Long lived HNL O(MeV) mag moment

Bai et al 1512.05357, Dentler et al 1911.01427, de Gouvêa et al 1911.01447
Heavy sterile O(keV-MeV) decay to ν_e May work..

Usually involving sterile neutrinos + “new” new physics.

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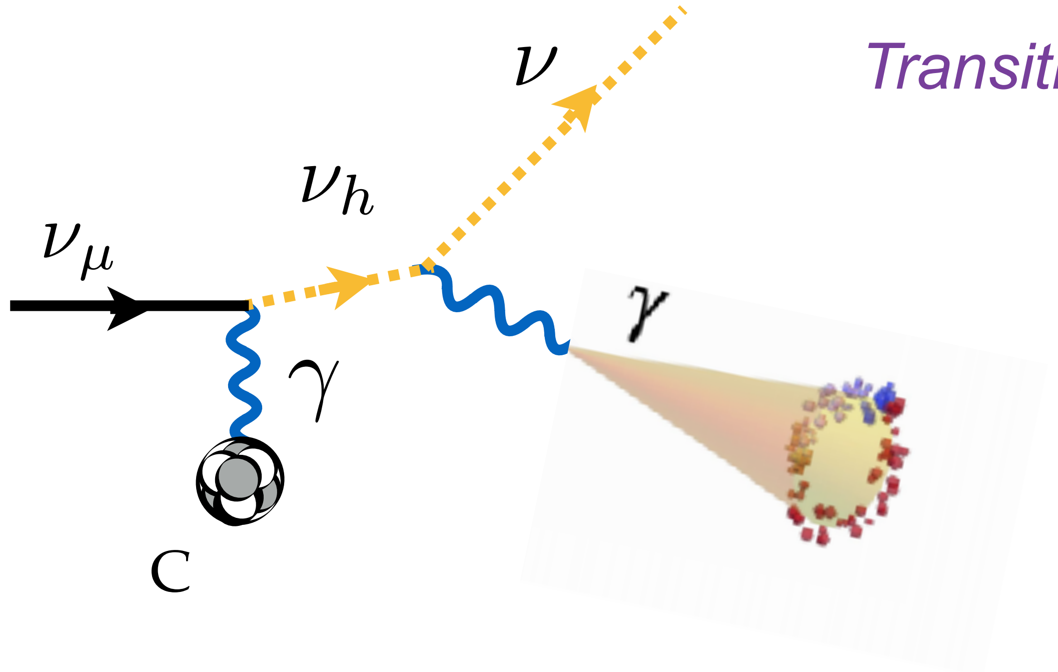
New physics
In scattering



Transition magnetic moment and this talk.

$$\mathcal{L}_\mu = \frac{\mu_\nu^\alpha}{2} F_{\mu\nu}\,\bar{\nu}_L^\alpha \sigma^{\mu\nu} N_R\,.$$

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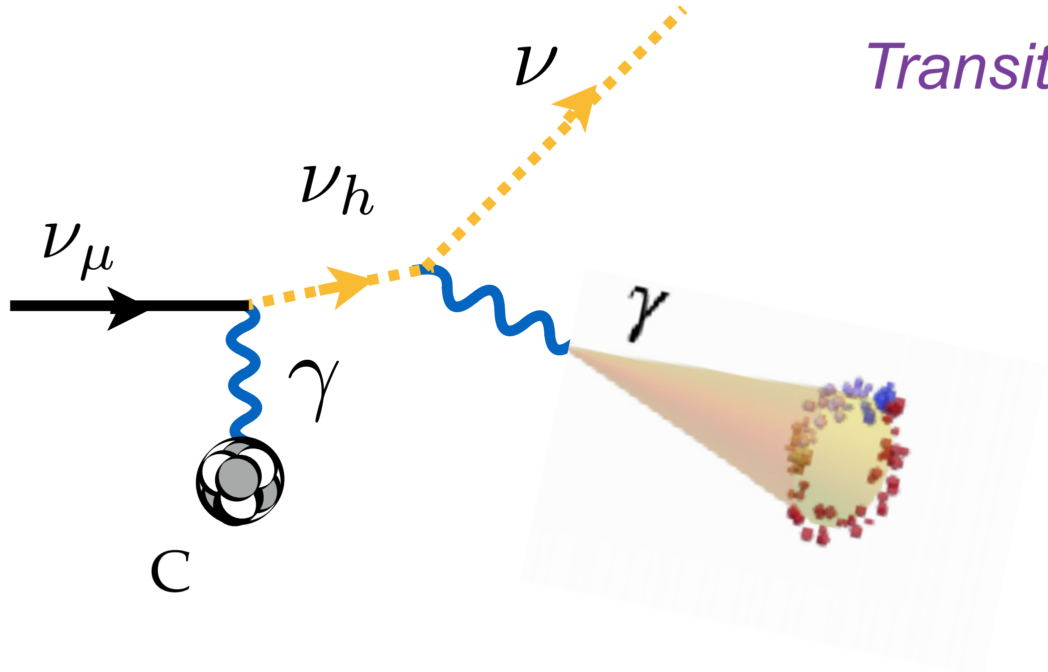

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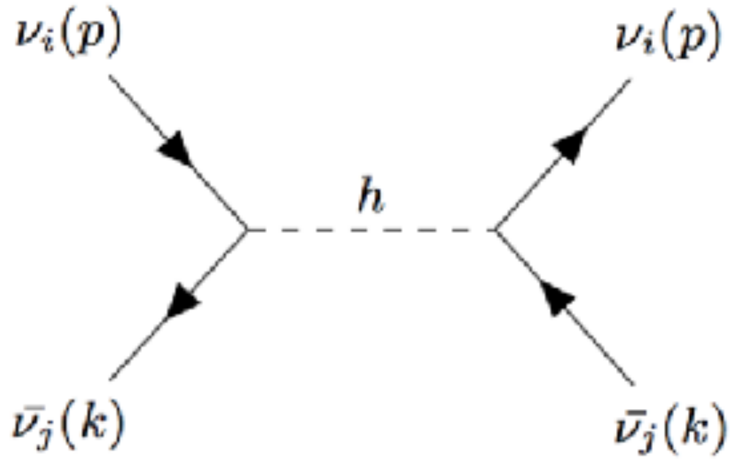
New physics
In propagation

NSI's or even scattering on neutrino over-densities

$$\mathcal{L}_{\rm NC} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \varepsilon_{\alpha\beta}^{f,P} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P f)$$



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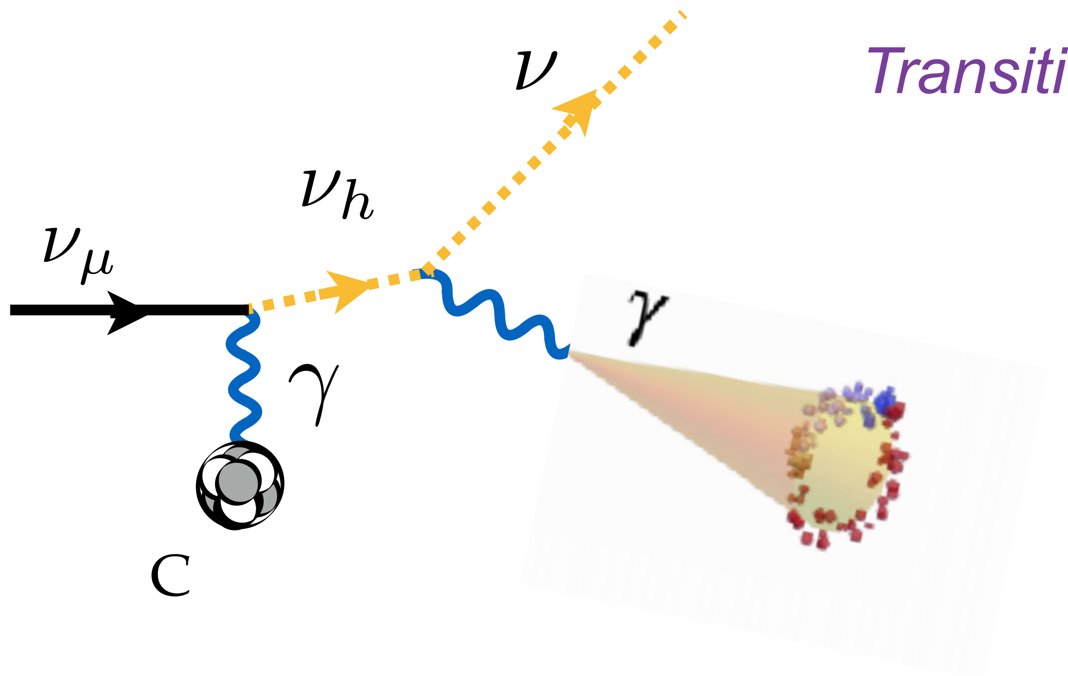

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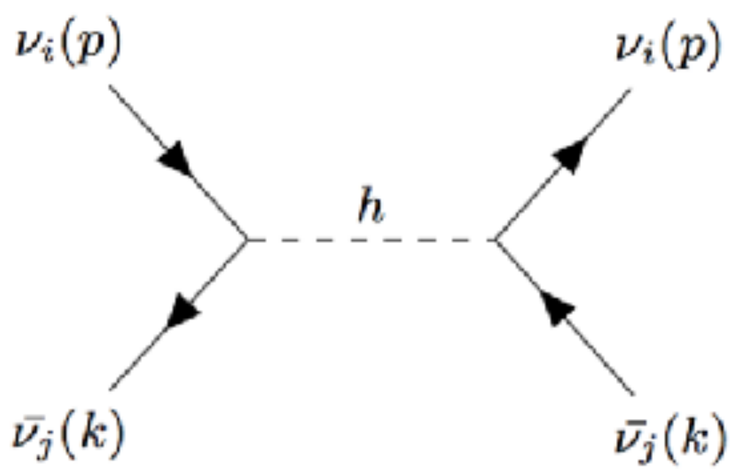
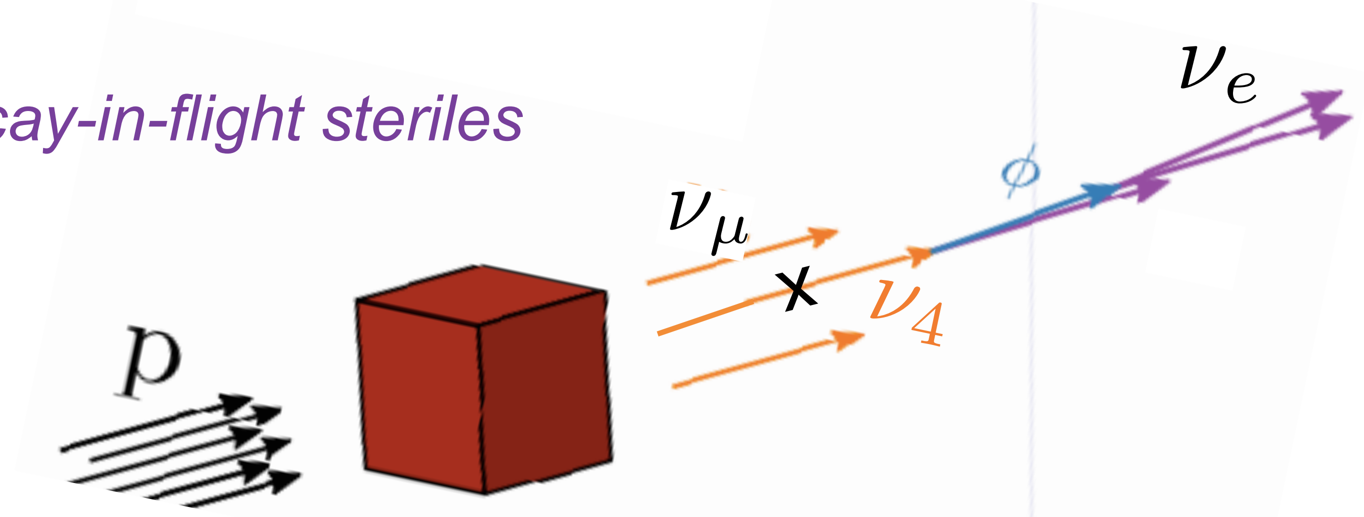


New "visible" states
in the beam

Decay-in-flight steriles



I. Esteban, 10.5281/zenodo.3509890.