

# Connections to BSM

**Kevin J. Kelly, Texas A&M University**  
**NuSTEC Summer School 2024**  
[kjkelly@tamu.edu](mailto:kjkelly@tamu.edu)

# Who am I?



**Kevin J. Kelly**

Assistant Professor at Texas  
A&M University

📍 College Station, TX, USA

🔗 INSPIRE

📄 ORCID

🐦 Twitter

## About Me

I am a theoretical particle physicist, currently an Assistant Professor in the Texas A&M [Physics & Astronomy Department](#). Previously (2021-2022), I was a senior fellow in the [CERN Theoretical Physics Department](#), and (2018-2021), I was a research associate in the Fermilab Theory Group. As a theoretical physicist, I explore all kinds of topics related to particle physics and cosmology, from the smallest scales to the largest.

Two of the biggest outstanding mysteries in particle physics today are the origin of neutrino masses and the nature of dark matter in the universe. I work on the interface between these topics, focusing on how current and next-generation experiments can shed light on both. Over the next decade or two, we will start to have precise measurements of neutrino properties, with which we can test our current assumptions of them and find out if there is any more new physics in the neutrino sector. At the same time, these current/future experiments are very well-suited to search for light dark matter and any associated new particles that may also exist.

By studying the capabilities of these experiments, not only can I determine how they can extract all possible information out of their data, but I can also determine whether there are connections between the two mysteries of neutrino mass and dark matter.

See the links above for more information about me, including my CV and publications.

Website [link1](#), [link2](#)

## My interests:

- Neutrino phenomenology (earth-based experiments, solar/atmospheric/astrophysical detections)
- Searches for beyond-the-SM physics at these/other facilities
- Cosmology, especially the impact of neutrinos/light new physics on cosmological evolution
- ...

# Who am I?



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**Disclaimer: I will *try* to give a broad overview of BSM searches relevant for NuSTEC folks. It *will* be biased towards the facilities/scenarios that interest me 🙄**

**Want more examples? Ask! (During the talk, in the breaks, etc.) I have plenty of literature references/ideas not in these slides**

**Second Disclaimer: I (likely) prepared way too much material for two lectures. Take a look at what I didn't cover if you're interested and don't hesitate to reach out to me later to discuss further!**

Website [link1](#),

# Define “SM”

# SM topics beyond these lectures

# How to search for BSM?

# Scenario 1:

Little-to-no expected SM Background

# Case Study



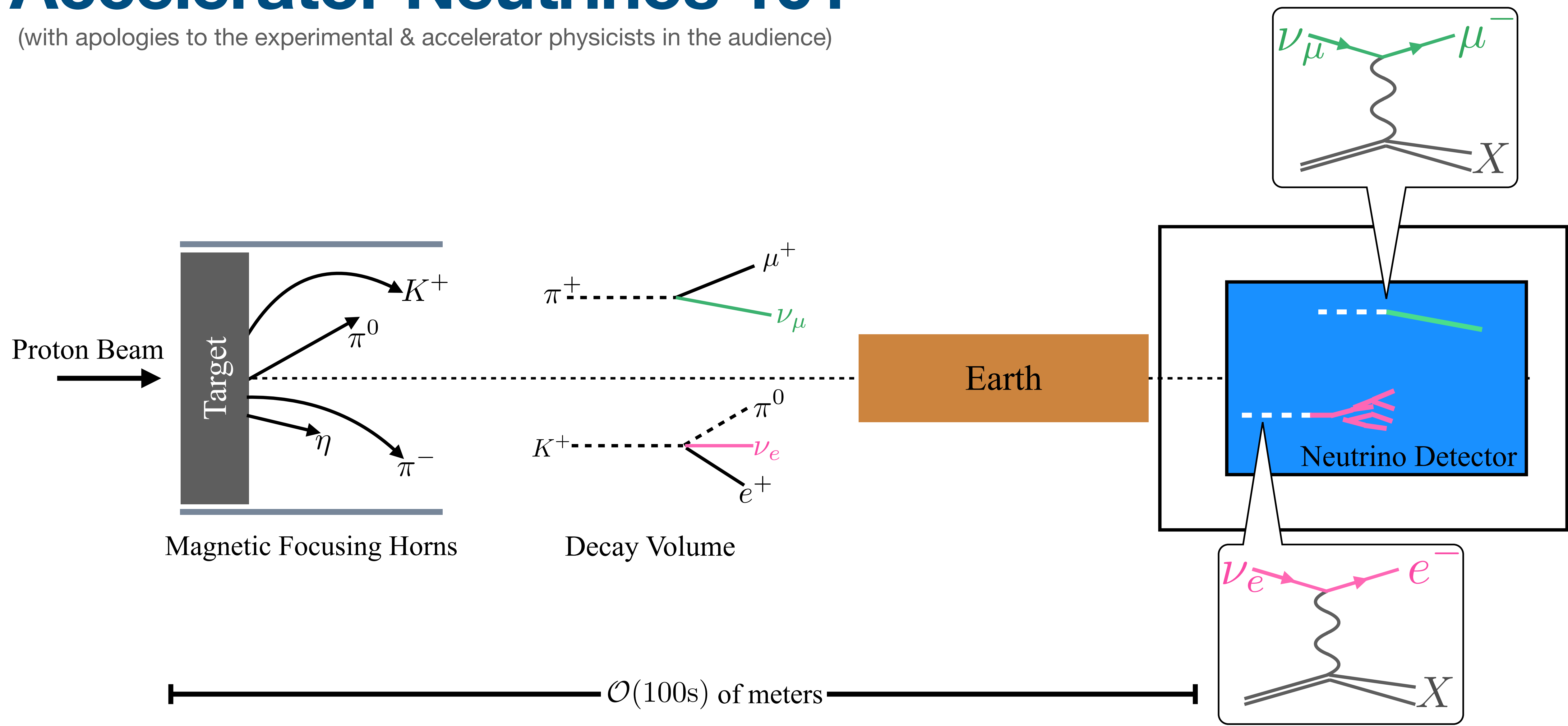
# Explicit Model — Dark Photons

# Explicit Model — Dark Higgs Bosons

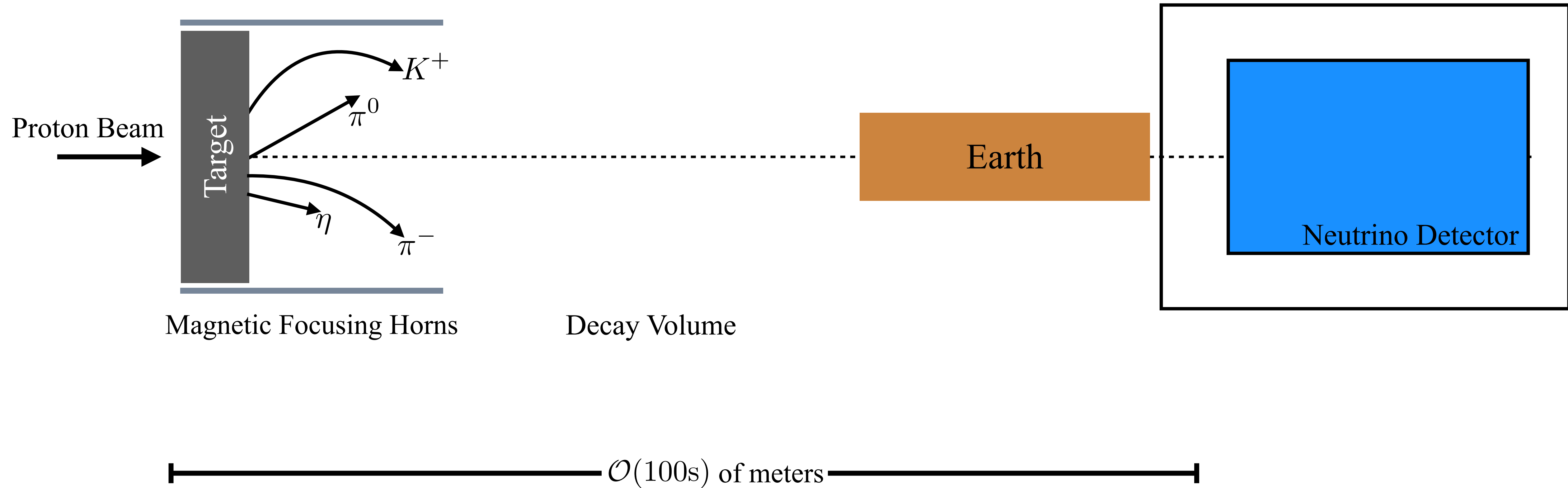
# Explicit Model — Heavy Neutral Leptons

# Accelerator Neutrinos 101

(with apologies to the experimental & accelerator physicists in the audience)

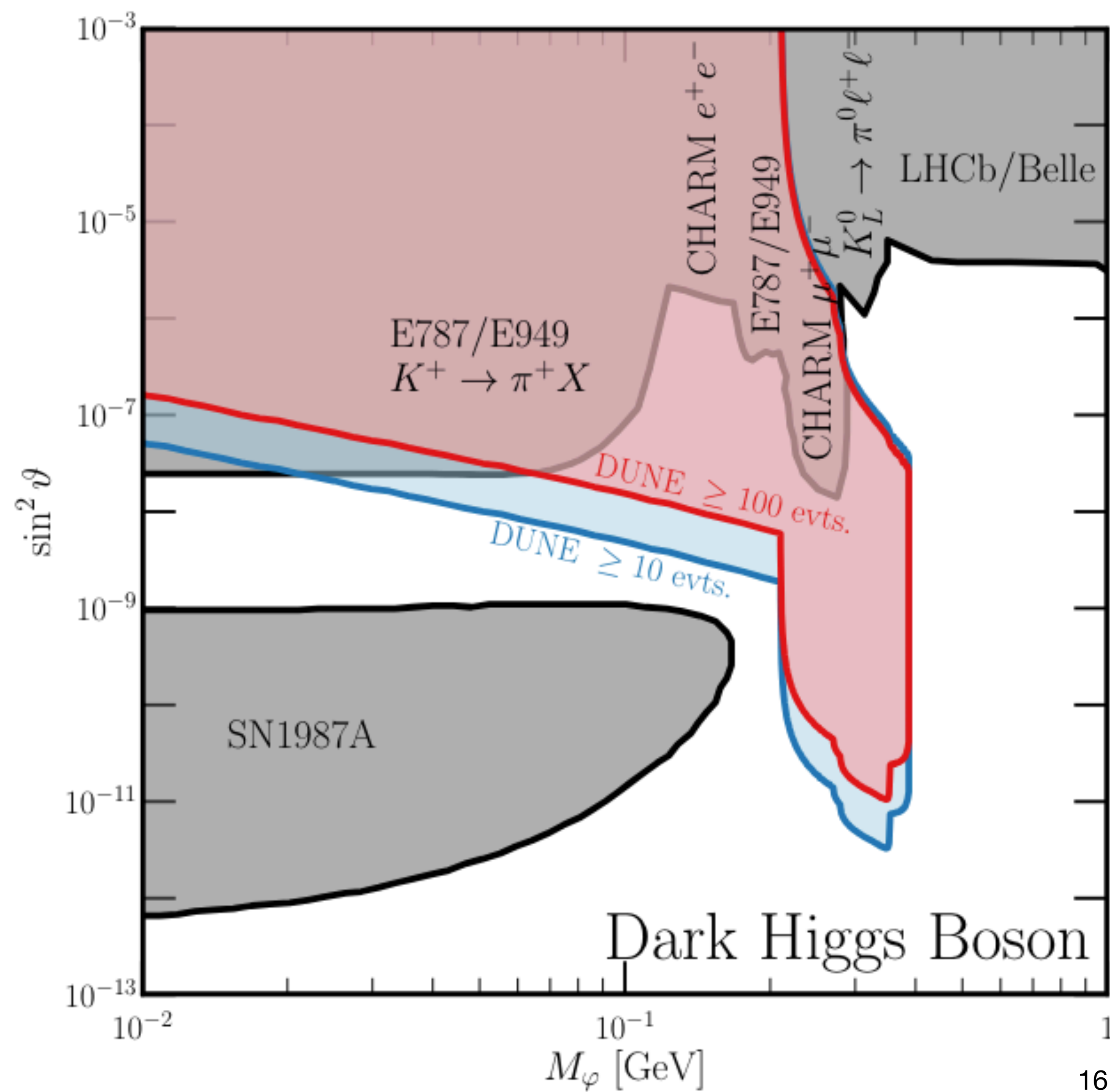
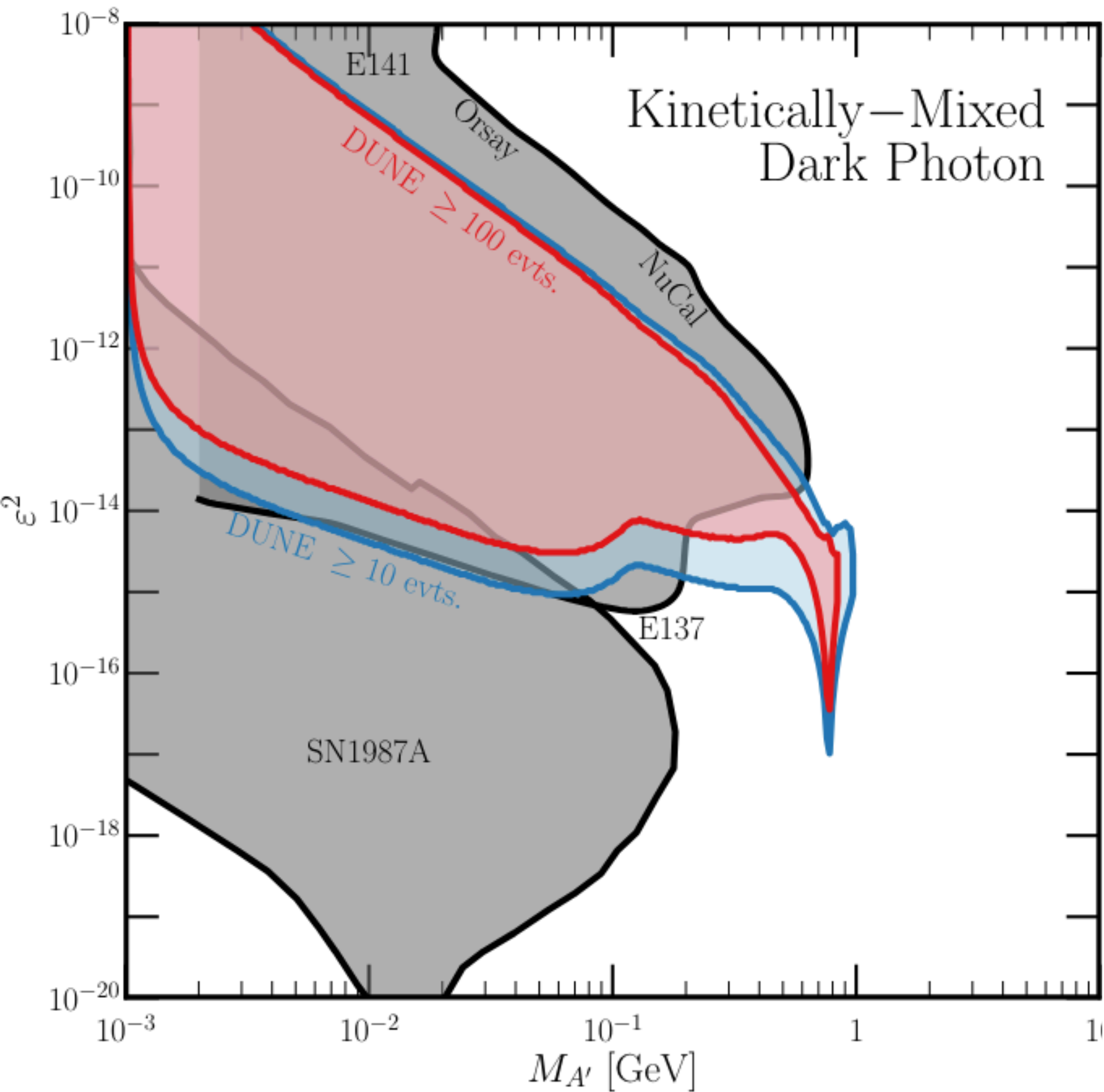


# Long-lived particle searches

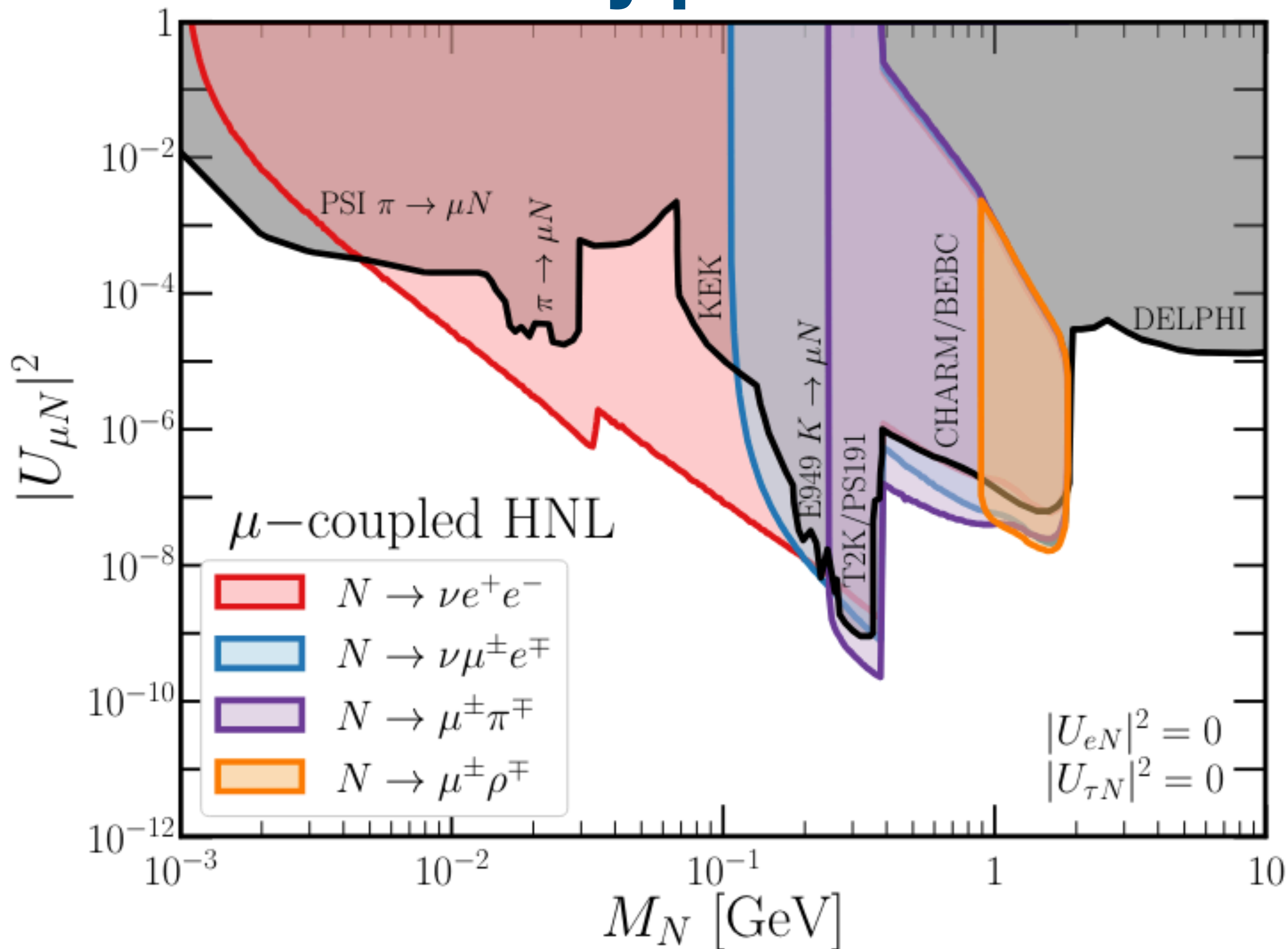


# Back-of-the-envelope Sensitivity

# DUNE Sensitivity pt 1



# DUNE Sensitivity pt 2



Other HNLs at DUNE Studies?

Ballett et al [1905.00284],  
 Coloma et al [2007.03701],  
 Breitbach et al [2102.03383]...



# Impact of Backgrounds on LLP Searches

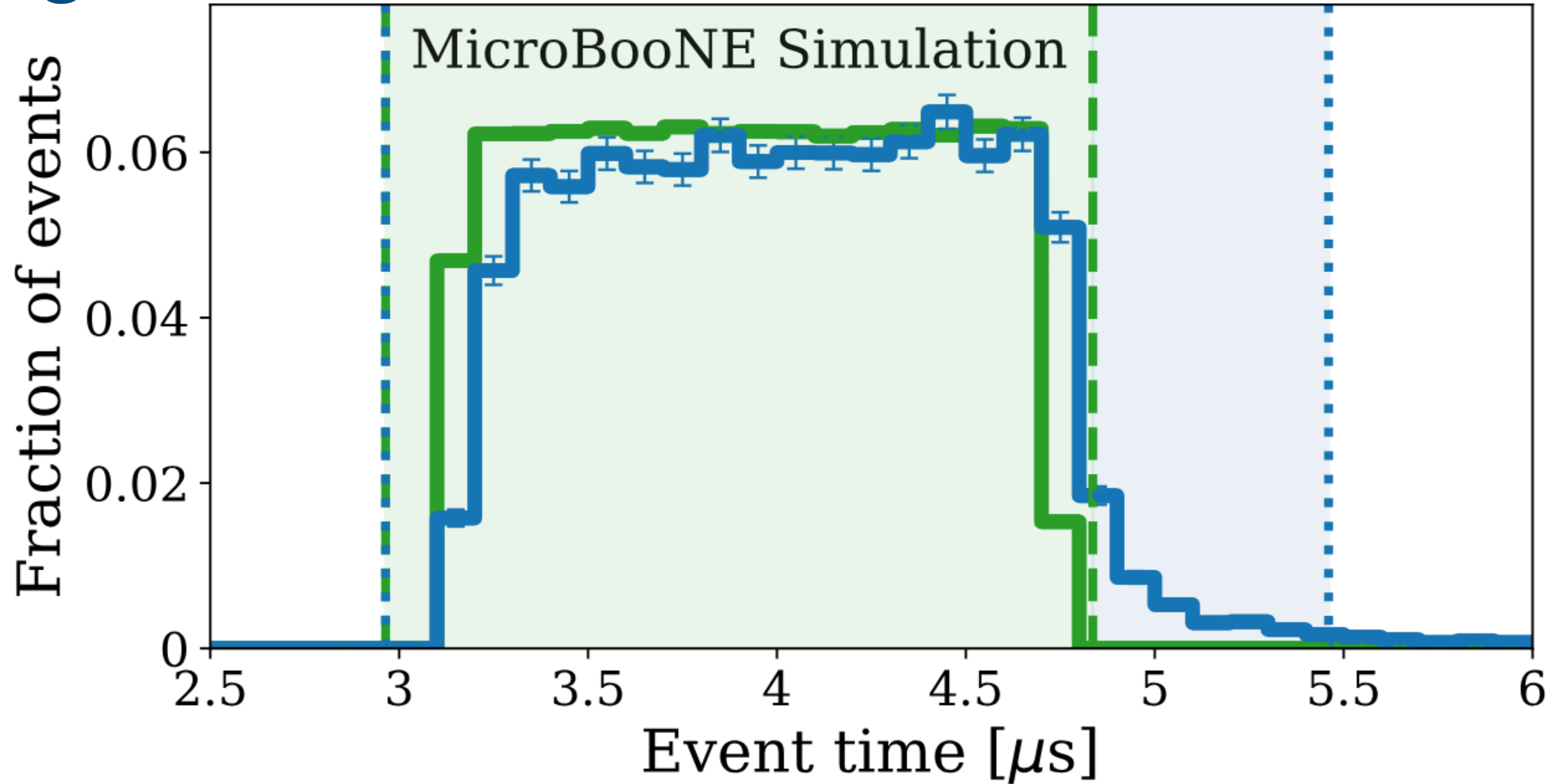
Depends *significantly* on your search of interest

**Case 1) Long-lived HNL decaying into a muon and a pion**

**Case 2) Dark photon/Higgs decaying into an electron/positron pair**

# Case 1 — HNL to muon/pion

# Timing Distributions

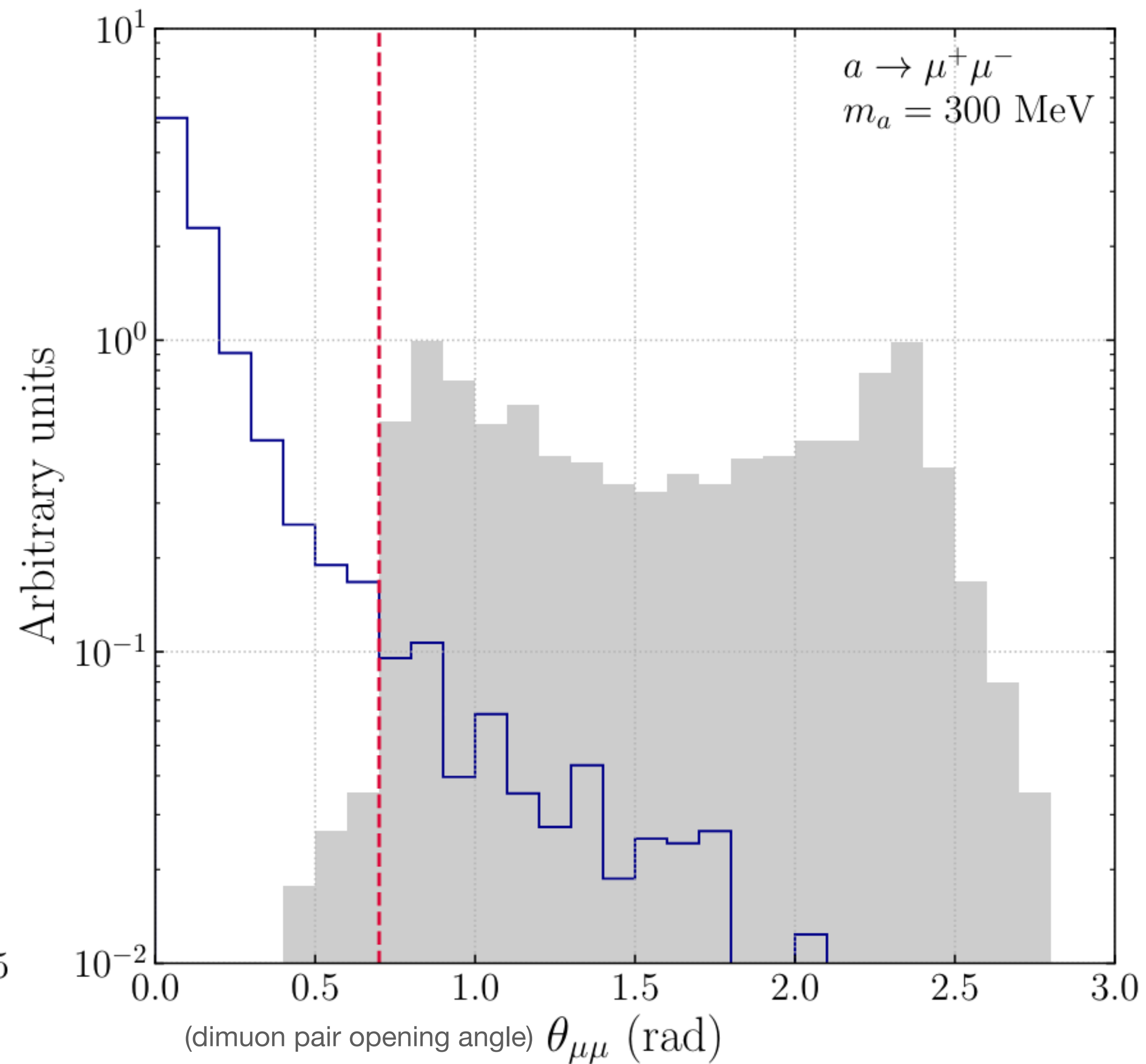
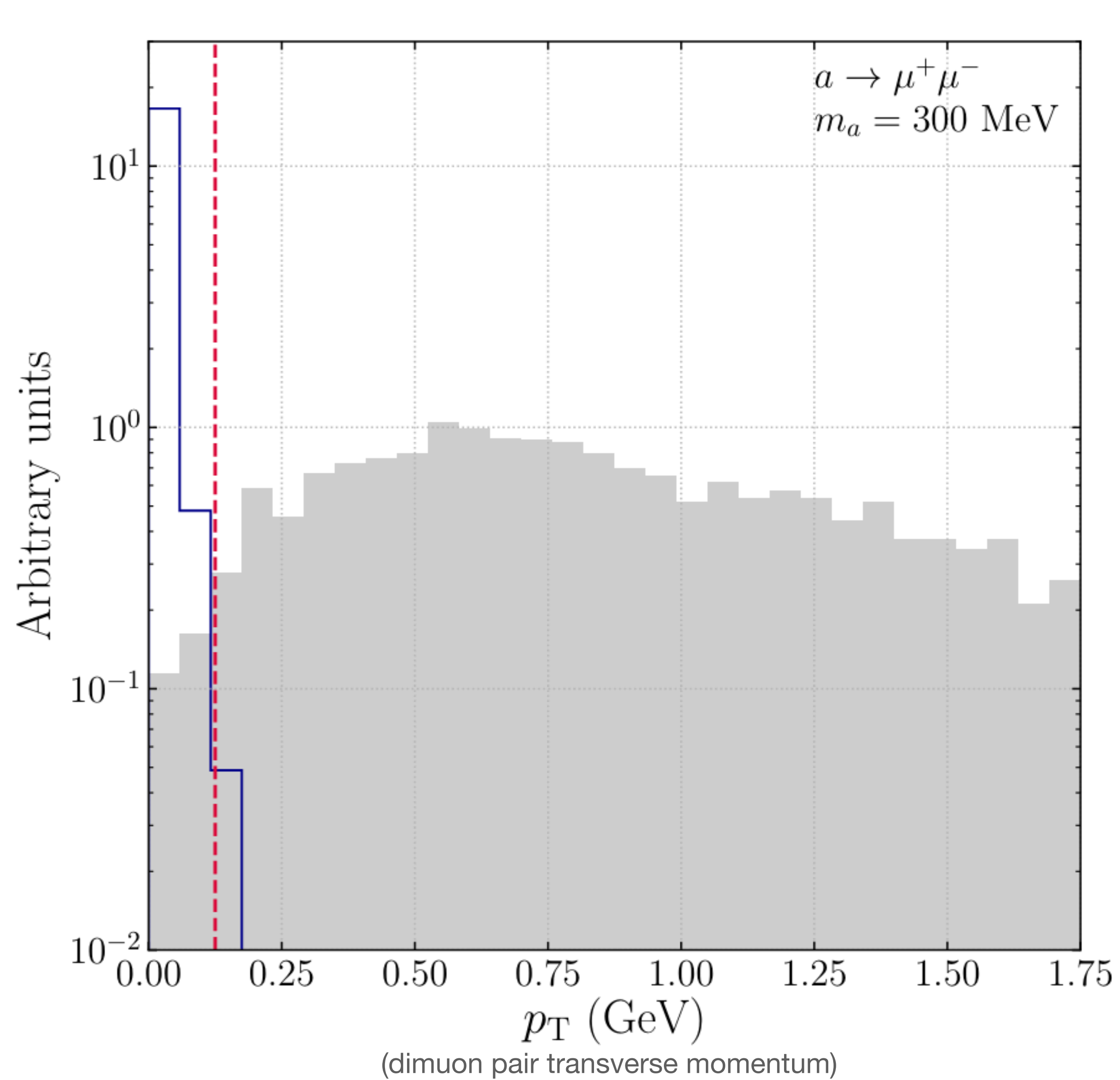


- BNB neutrinos
- HNL (365 MeV)
- BNB Trigger window
- HNL Trigger window

# Case 2 — DP/DH to electron/positron

# Dimuon event distributions

Coloma et al [\[2309.06492\]](#)



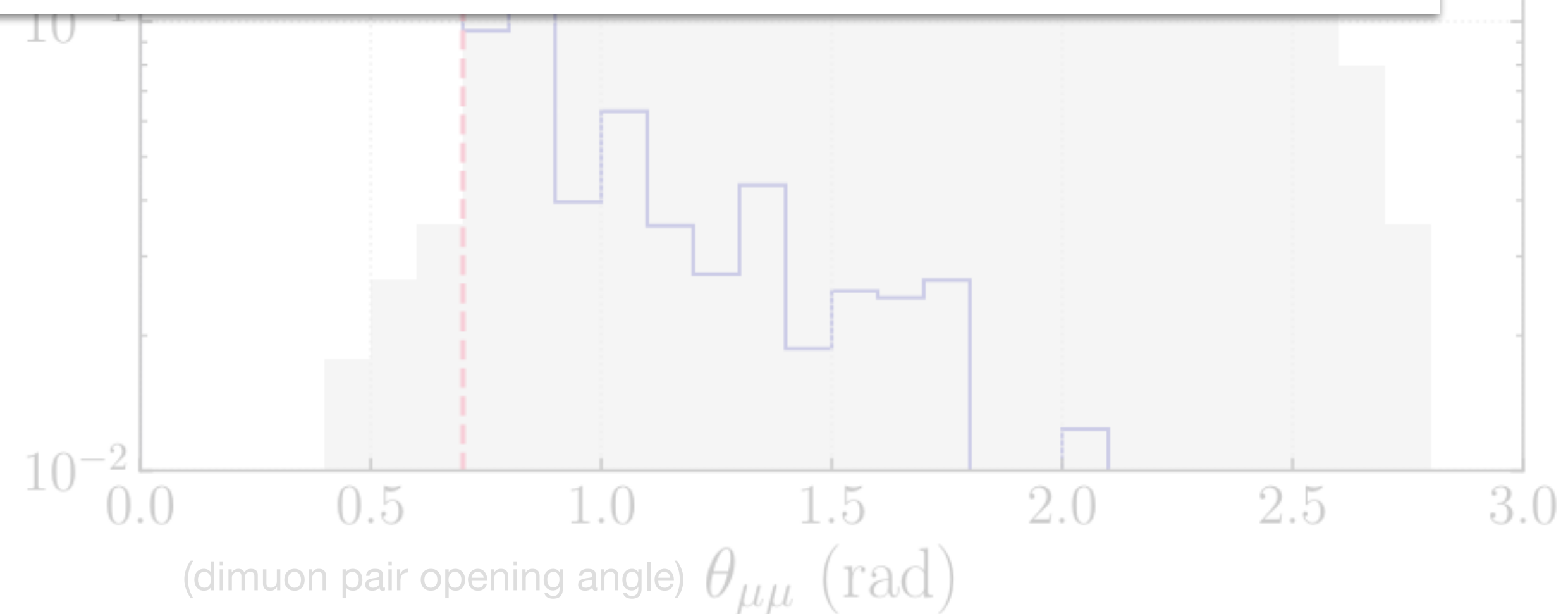
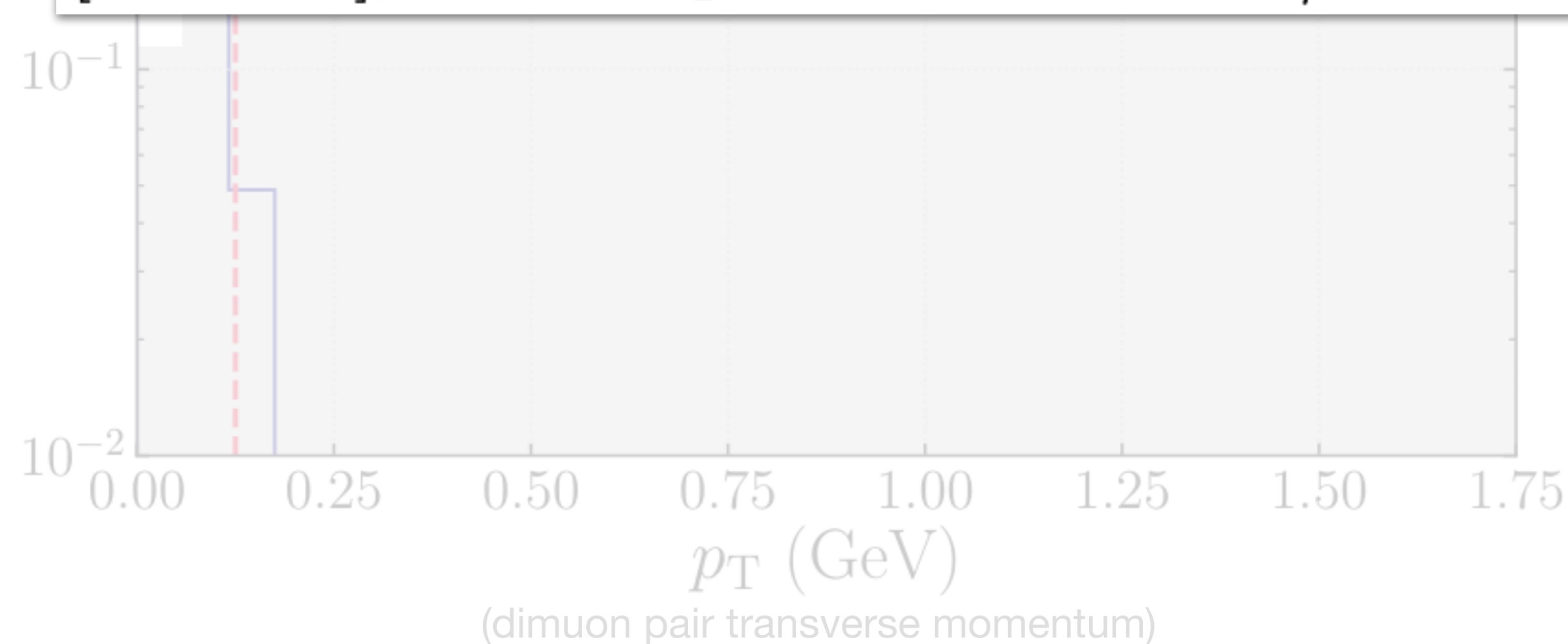
# Dimuon event distributions

Coloma et al [\[2309.06492\]](#)



Arbitrary units

We assume that the dominant background source in this search will be neutrino-argon interactions in the active volume of the TPCs. We estimate that other possible background sources (such as neutrino-rock interactions or cosmic muons) will be negligible in comparison, as the resulting events will not be aligned with the direction of the beam, in general. Using the GENIE neutrino Monte Carlo generator (version 3.2.0) [123] and the public DUNE flux histogram files [120, 121], we have produced  $2 \times 10^7$   $\nu_\mu$ -Ar interactions.



# Dielectron Distribution

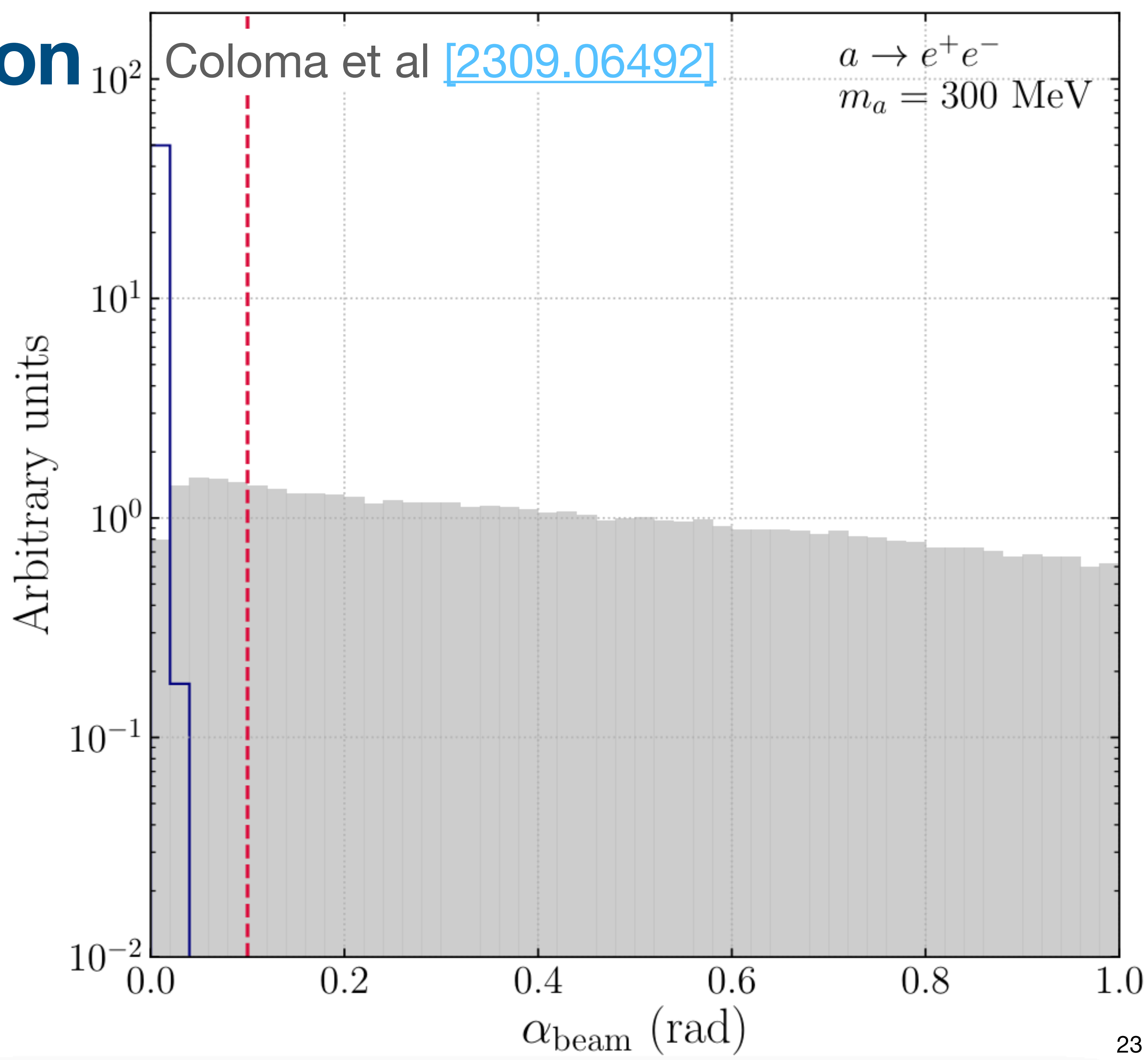


TABLE I. Signal efficiencies and background event rates for the different decay channels, before and after event selection according to the cuts discussed in the main text. Results are shown separately for the two DUNE near detectors considered. Background event rates are provided per year, and for the total fiducial volume considered for each detector. We highlight in bold type the large backgrounds expected for some of the decay channels, as well as the reduced LAr ND signal efficiencies for most decay channels considered.

Selection cut		Signal efficiency		Background rate	
		ND-LAr	ND-GAr	ND-LAr	ND-GAr
$\mu^+\mu^-$	Two $\mu$ -like tracks only	1.00	1.00	3545674	70656
	PID $\mu$ and opposite charge sign	0.40	1.00	6226	124
	Transverse momentum $< 0.125$ GeV/c	0.40	0.99	99	2
	Angle between muons $< 0.7$ rad	0.40	0.94	0	0
$e^+e^-$	Two $e$ -like tracks/showers	0.10	1.00	9432	145
	Reconstructed ALP direction	<b>0.10</b>	0.99	180	15
$\gamma\gamma$	Two $\gamma$ showers only	0.05	0.79	36276	14222
	Reconstructed ALP direction	0.05	0.79	6938	<b>7923</b>
	Angle between $\gamma$ showers	<b>0.05</b>	—	<b>1367</b>	—
$\pi^+\pi^-\pi^0$	Two $\mu$ -like tracks, two $\gamma$ showers	0.04	0.81	2030490	40462
	PID $\pi^\pm$ and charge sign	0.04	0.81	431035	8589
	Transverse momentum $< 0.2$ GeV/c	0.04	0.79	17182	342
	Angle between pions $< 0.15$ rad	<b>0.04</b>	0.69	<b>946</b>	19



# Scenario 2: Theoretically Clean SM Background

# From Ryan's second lecture (Thursday 6th June)

SM CE $\nu$ NS rate depends on:

CE $\nu$ NS

We can  $\therefore$  reduce scattering at low momentum transfer to point-like charge

$$\frac{E_{\nu}^2}{q^2} \quad \langle A | \hat{J}_{\mu}^{(0)} | A \rangle \propto \frac{1}{Q^2} \langle A | \hat{Q}_W | A \rangle v_{\mu}$$

$\uparrow$   
Feynman rules

$$\frac{d\sigma}{d\Omega} \approx \frac{G_F^2 M_A^2}{4\pi} \left( 1 - \frac{|t|}{E_{\nu}} - \frac{M_A |t|}{2E_{\nu}} \right) Q_W^2$$

$$Q_W^2 = N - (1 - 4s_W^2)Z^2 + \mathcal{O}(\dots)$$

Interesting probe of light  $\nu$ -philliz mediators!

# Challenge(s) associated with CE $\nu$ NS

Coherent Neutrino-Nucleus Scattering as a Probe  
of the Weak Neutral Current

DANIEL Z. FREEDMAN  
National Accelerator Laboratory, Batavia, Illinois 60439

and

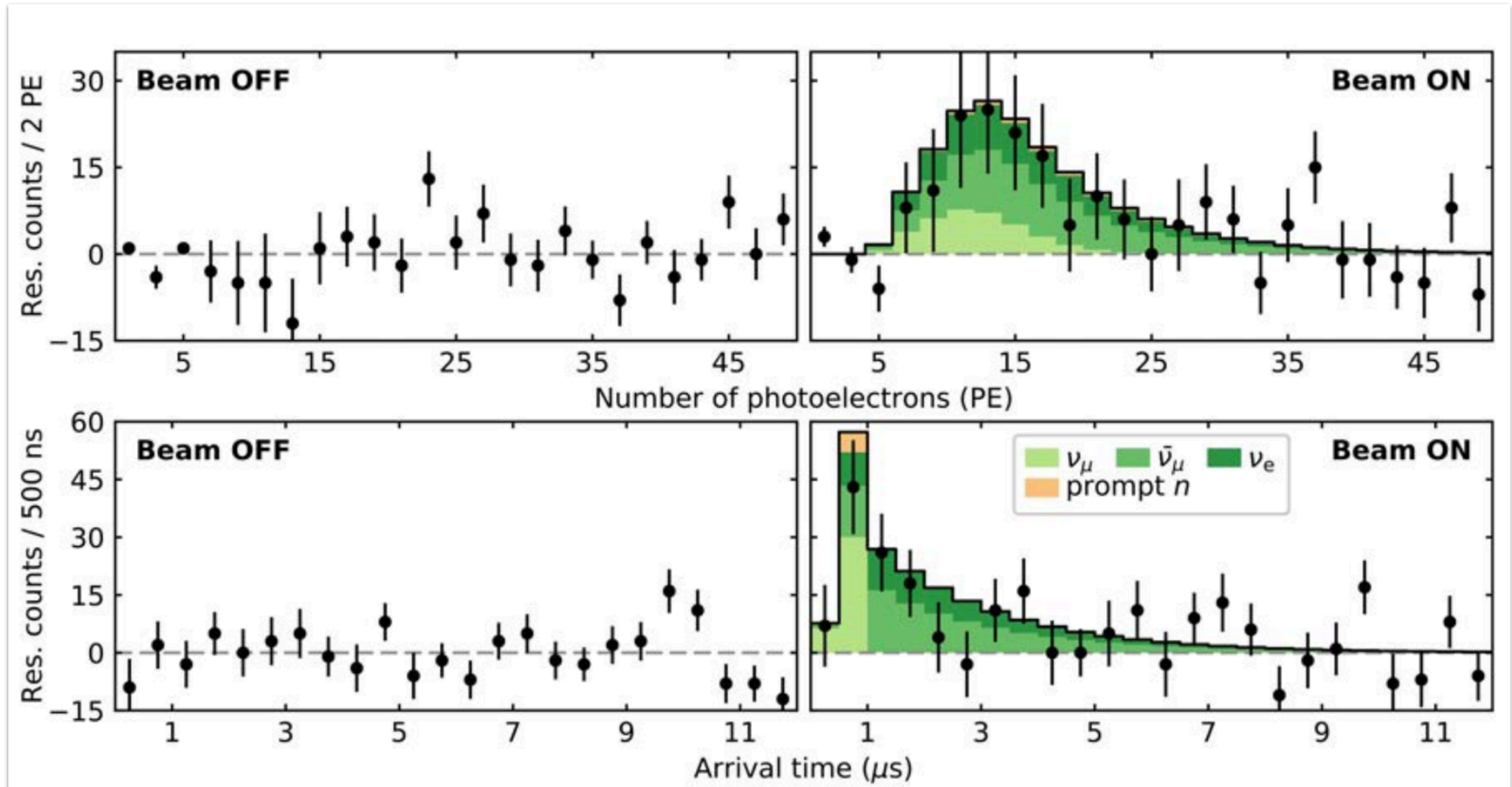
Institute for Theoretical Physics, SUNY  
Stony Brook, NY 11790

If there is a weak neutral current, then the elastic scattering process  $\nu + A \rightarrow \nu + A$  should have a sharp coherent forward peak just as  $e + A \rightarrow e + A$  does. Experiments to observe this peak can give important information on the isospin structure of the neutral current. The experiments are very difficult, although the estimated cross sections (about  $10^{-38}$  cm<sup>2</sup> on carbon) are favorable. The coherent cross sections (in contrast to incoherent) are almost energy-independent. Therefore, energies as low as 100 MeV may be suitable.

[Freedman, 1973](#)

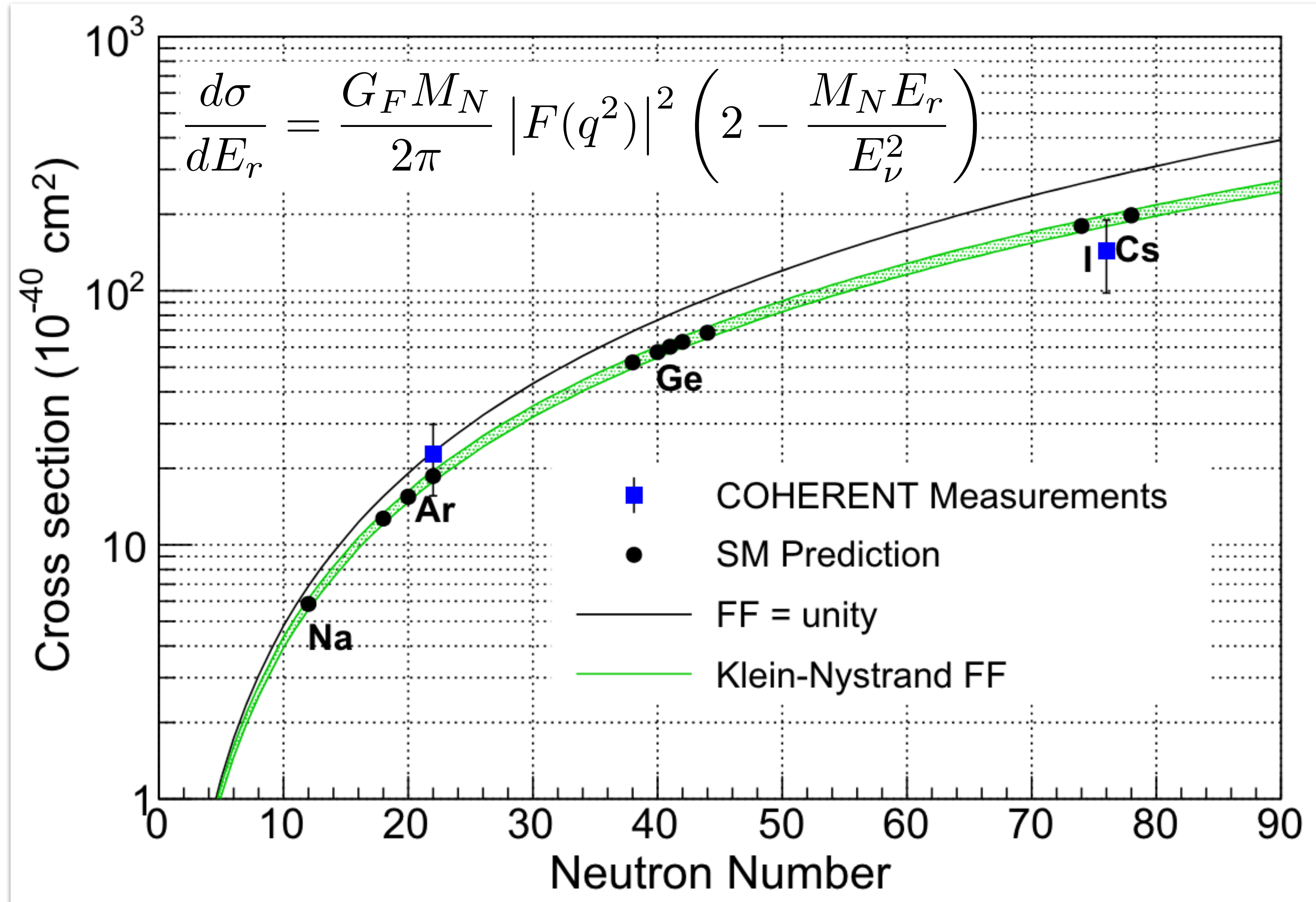
# Successes with COHERENT

COHERENT collab., [\[1708.01294\]](#)



# Successes with COHERENT pt. 2

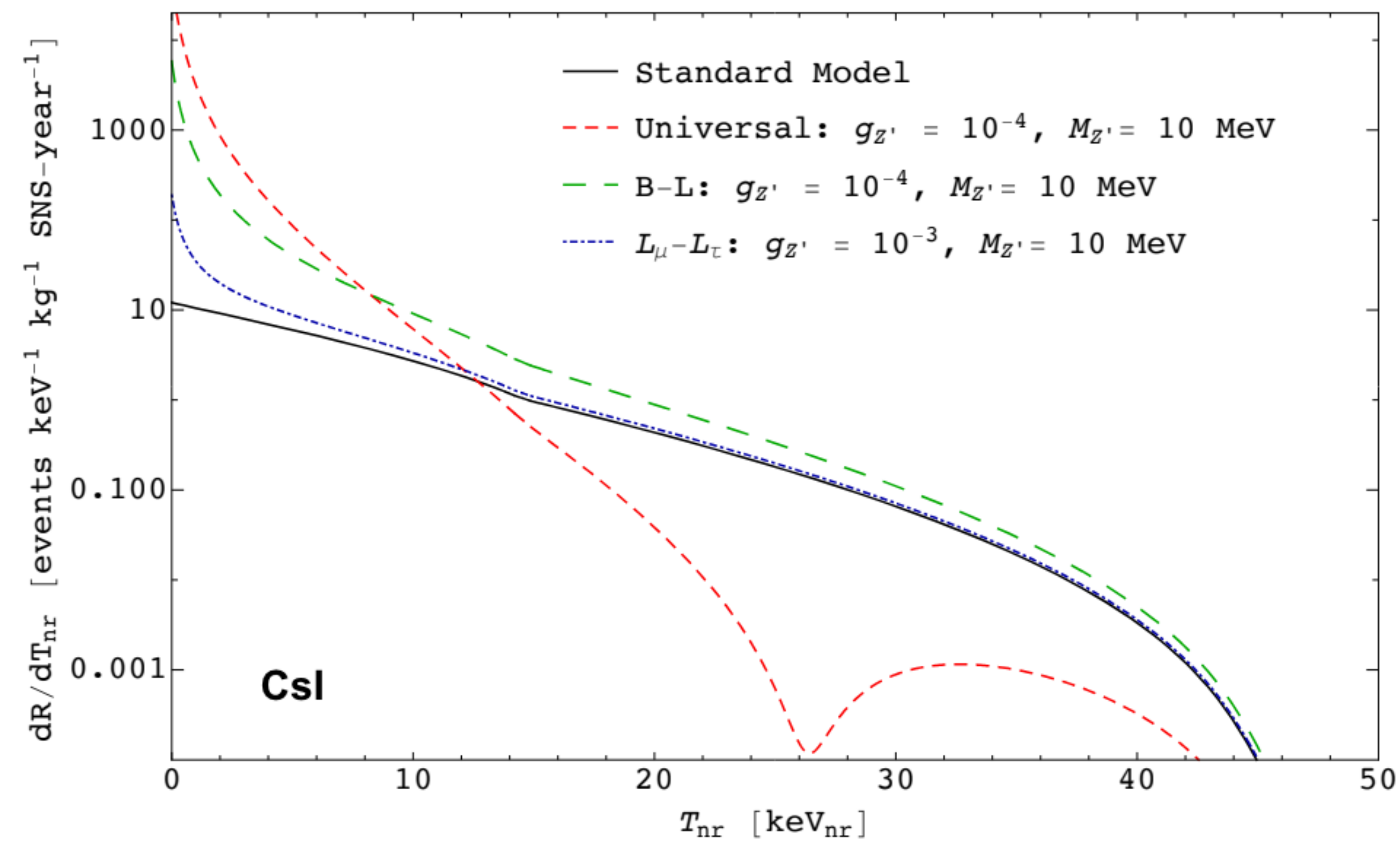
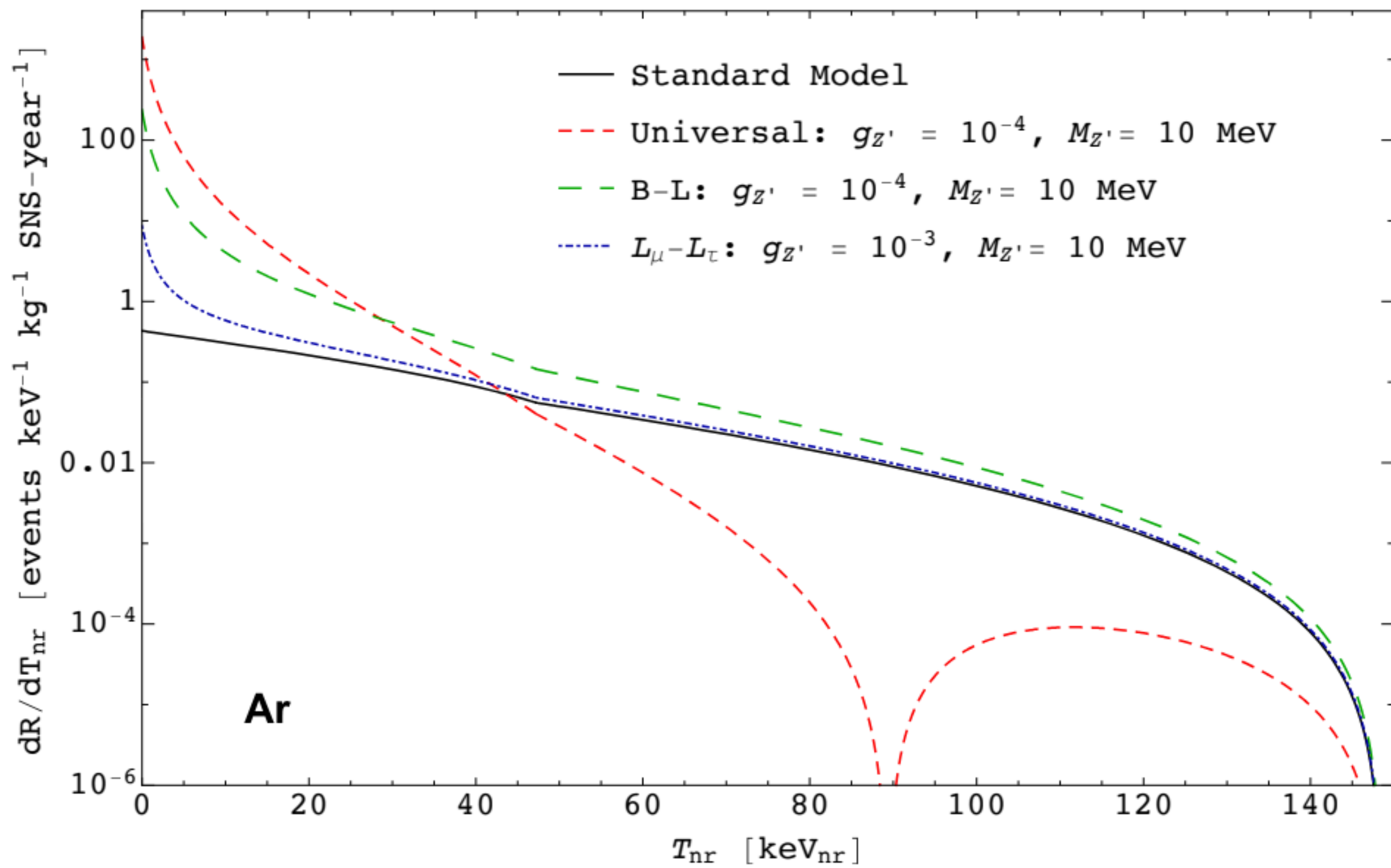
COHERENT collab., [\[2003.10630\]](#)



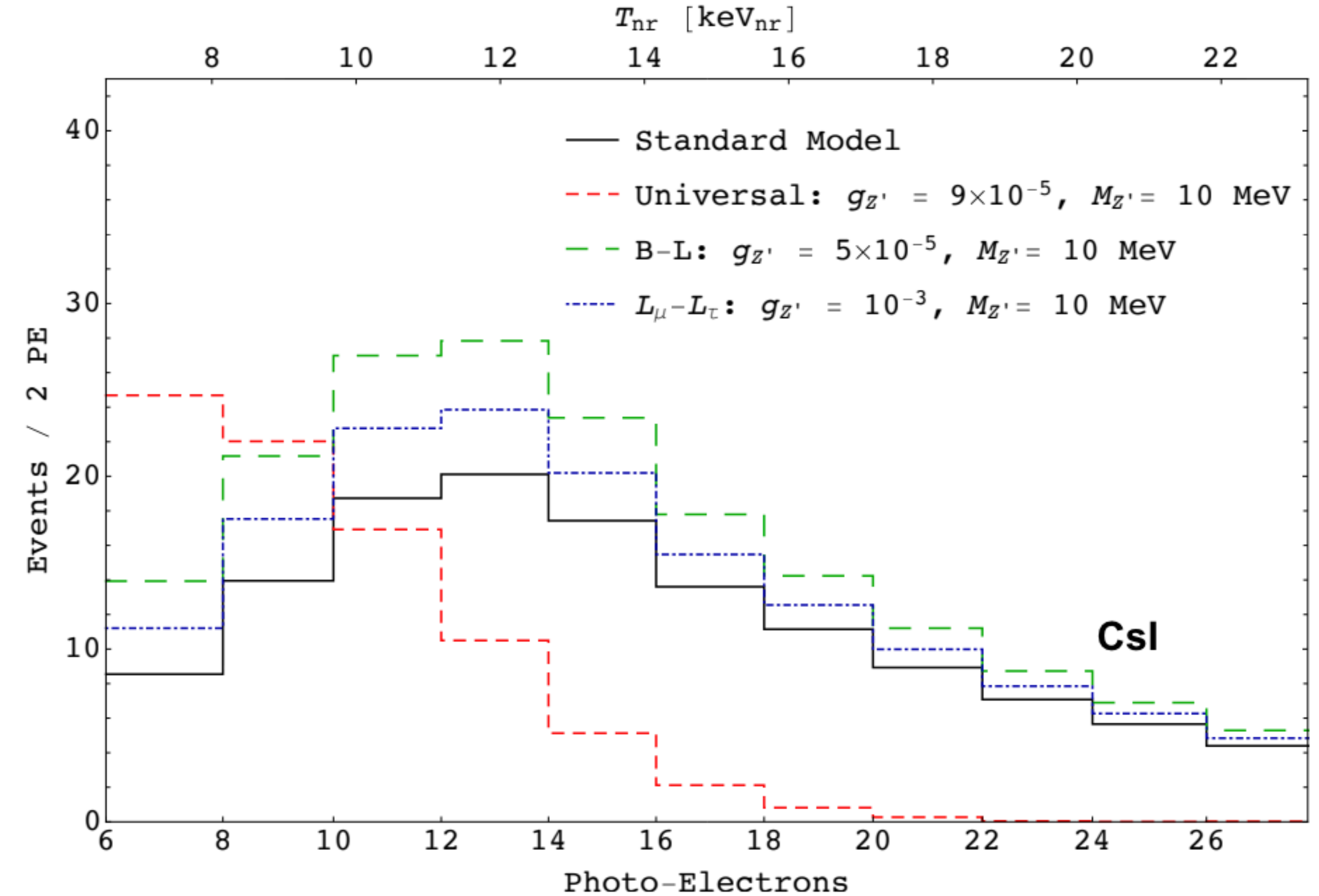
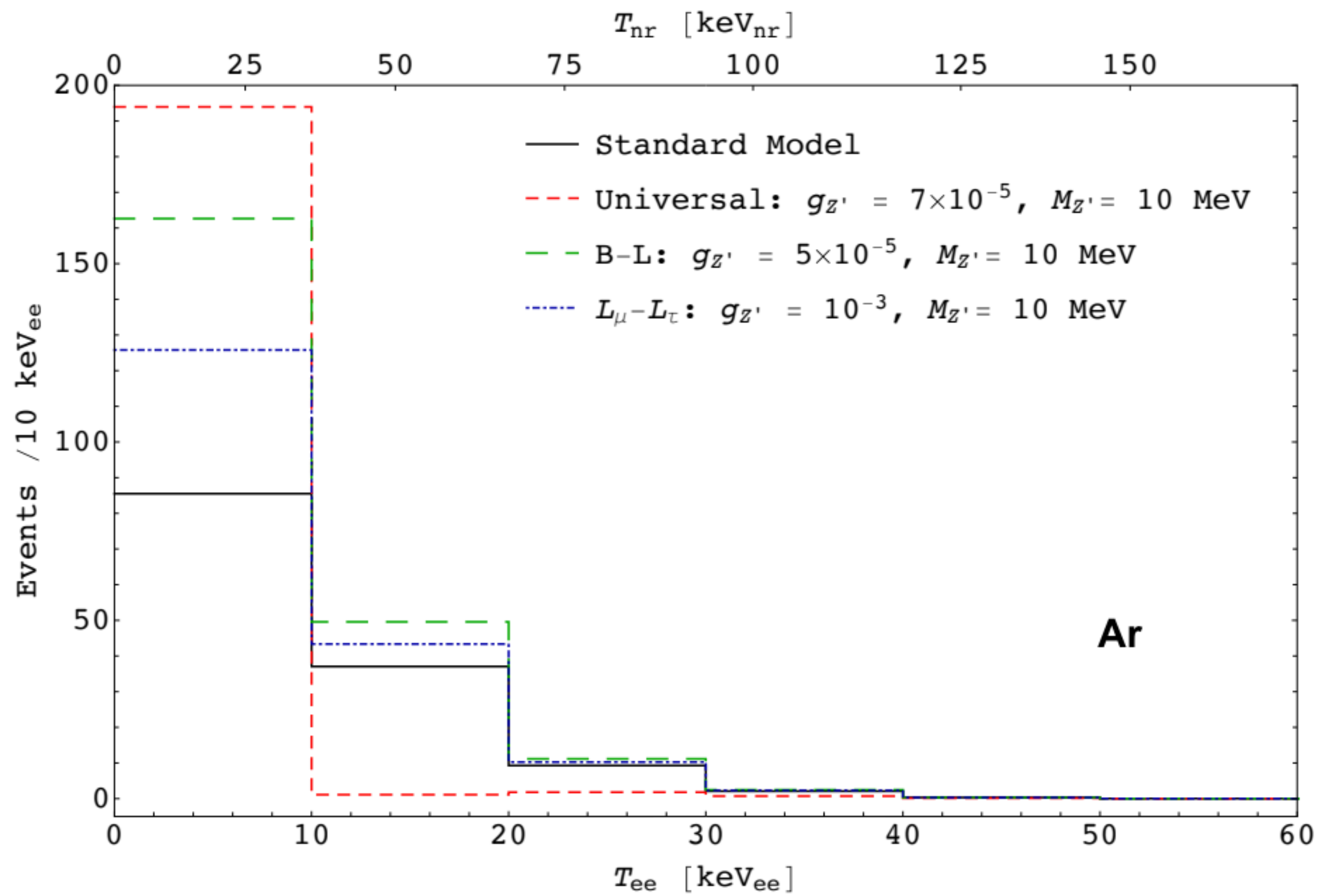
# Going BSM with $CE_{\nu}NS$

e.g. Cadeddu et al, [\[2008.05022\]](#)

# Effect on Differential Cross Sections



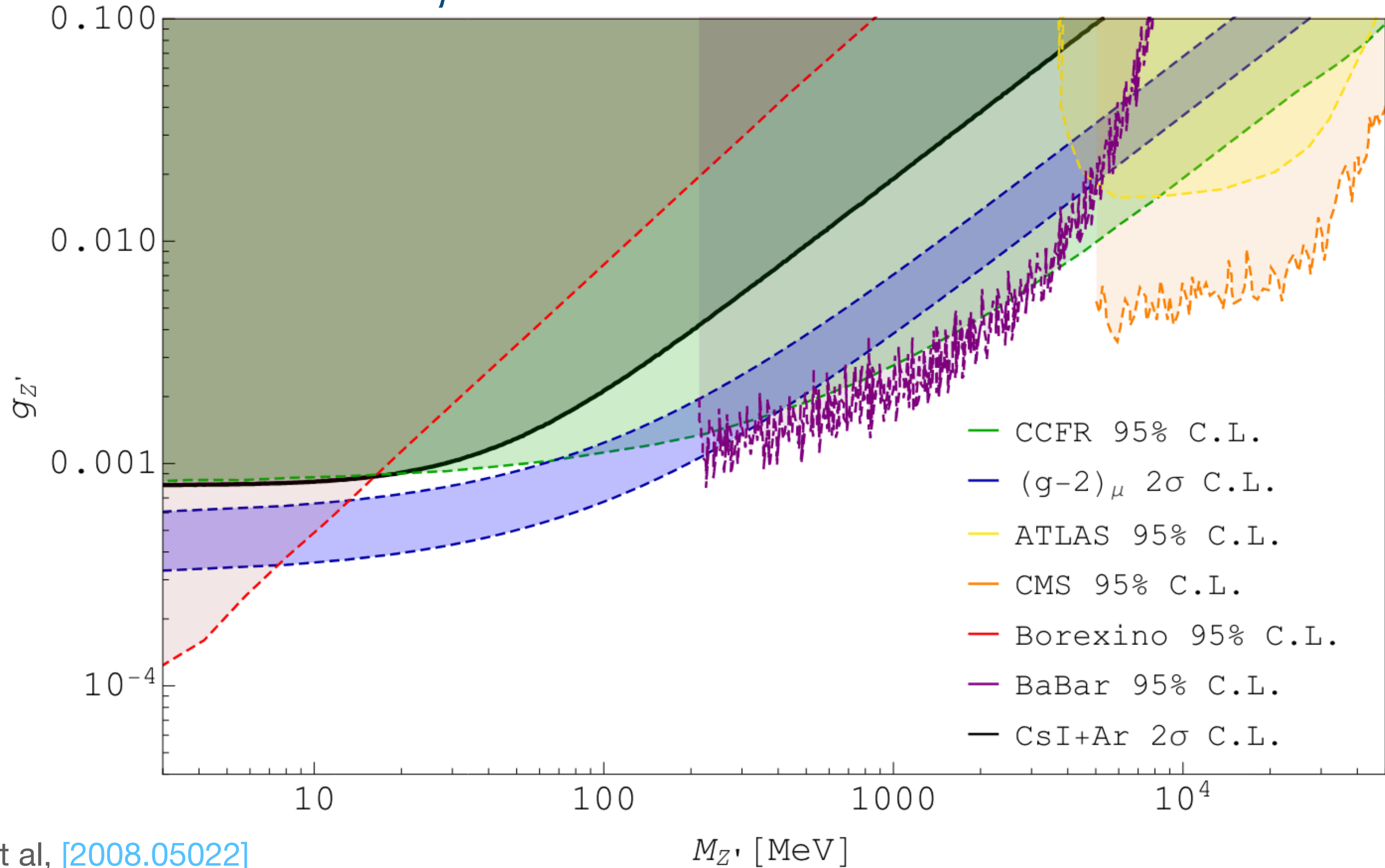
# Effect on $CE_{\nu}NS$ Event Rates



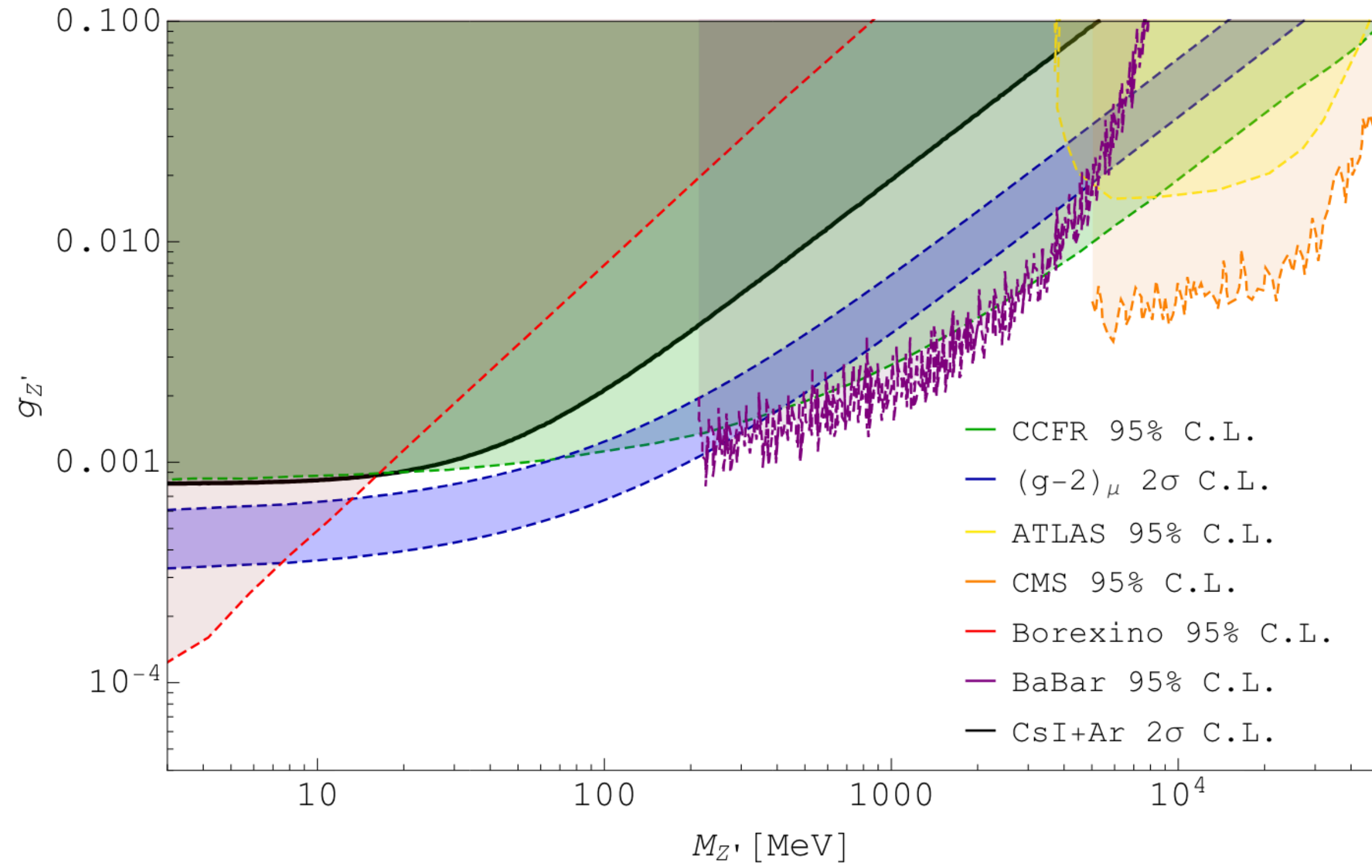


**Most “intriguing” BSM U(1) —  $L_\mu - L_\tau$**

# COHERENT and $L_\mu - L_\tau$



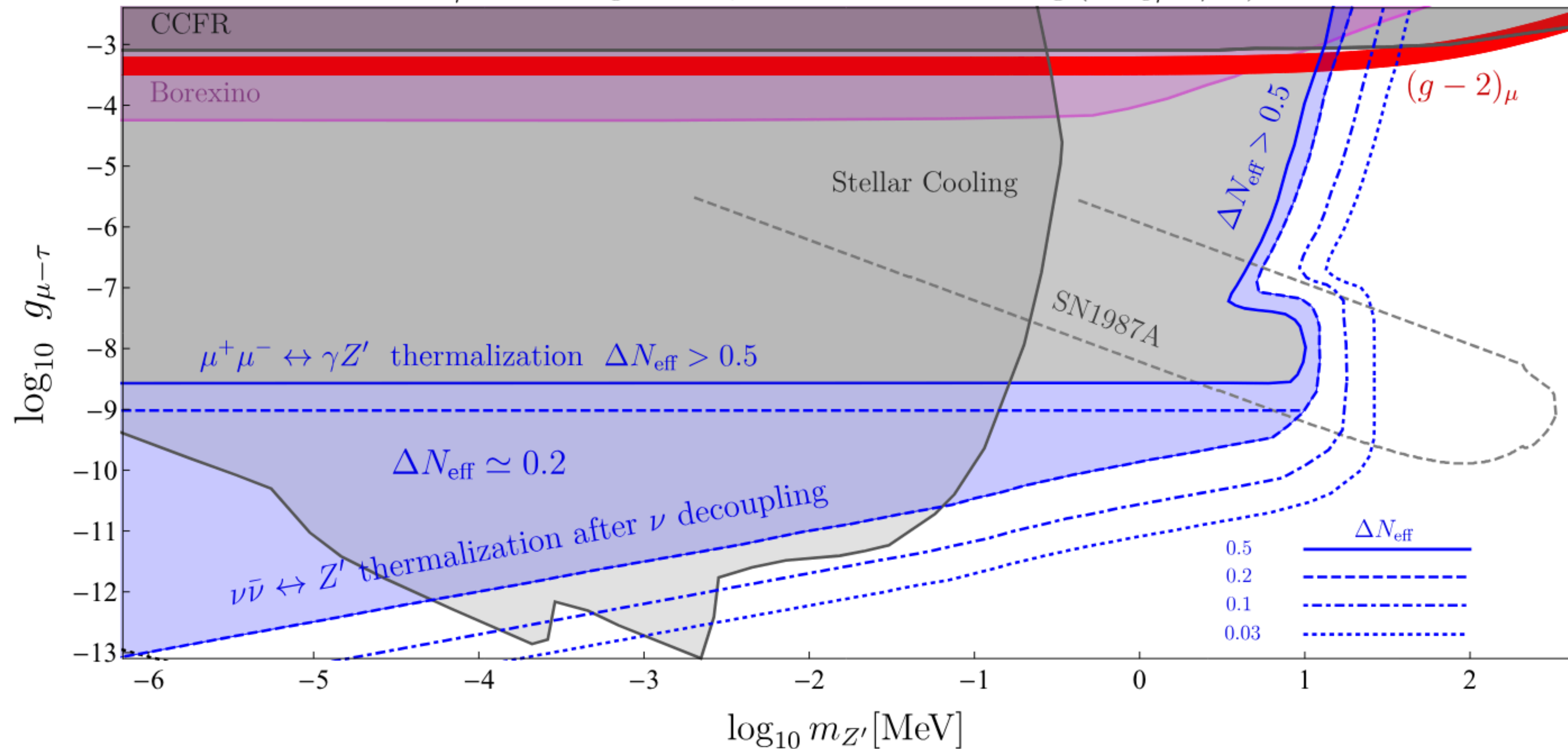
# Beauty of Complementarity



# Aside: Broad thinking re: $U(1)_{L_\mu - L_\tau}$

Escudero\* et al, [\[1901.02010\]](#)

$L_\mu - L_\tau$  Gauge Boson, Natural Kinetic Mixing ( $\epsilon = g_{\mu-\tau}/70$ )



# Scenario 2 pt. 2

# Back to our Simple “Dark Photon” $U(1)$

...plus one more ingredient

# Impact in Neutrino Facilities?

# Advantages of Light DM in Neutrino Beam



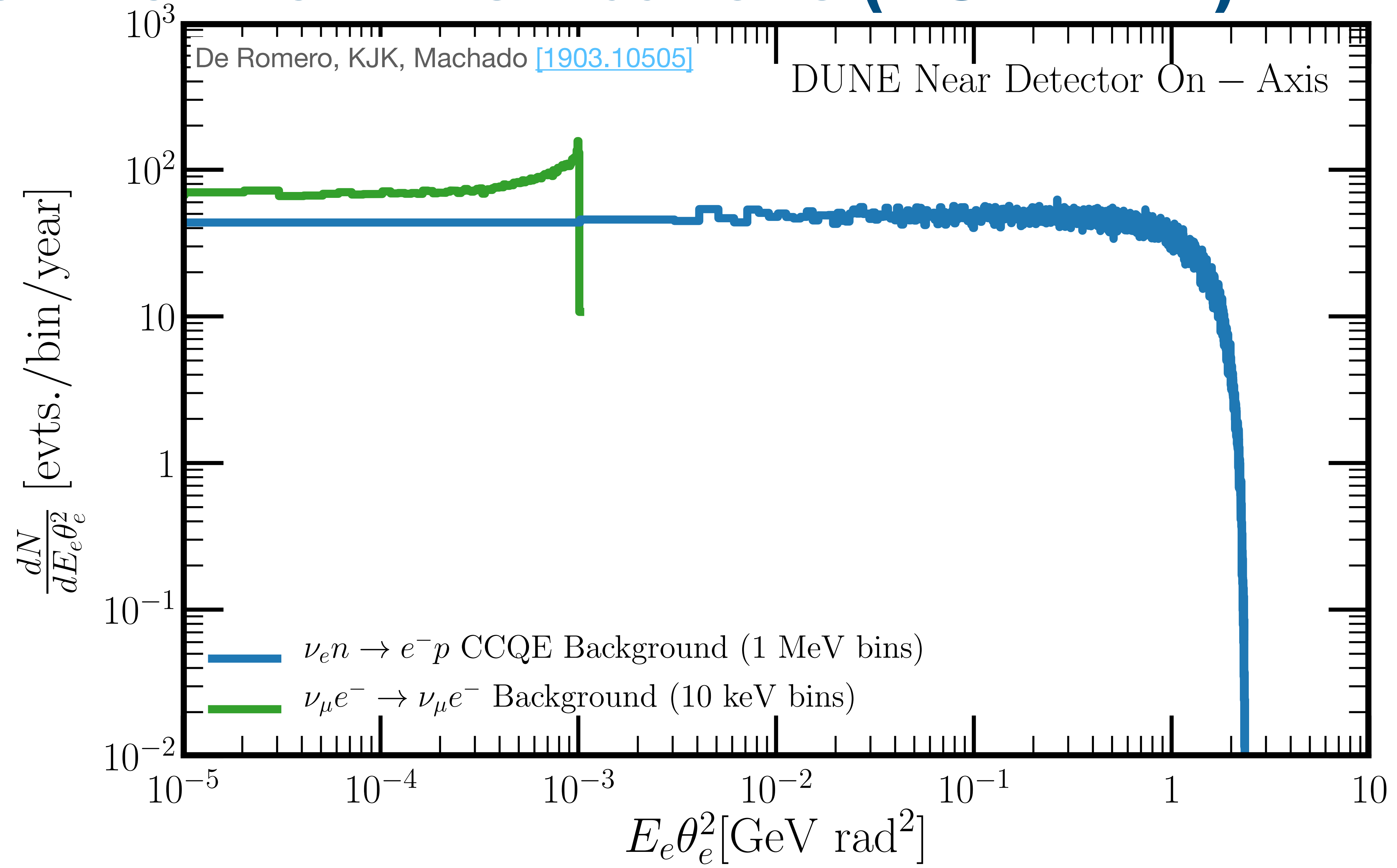
# Problems of Light DM in Neutrino Beam!

Why is this an existential problem?

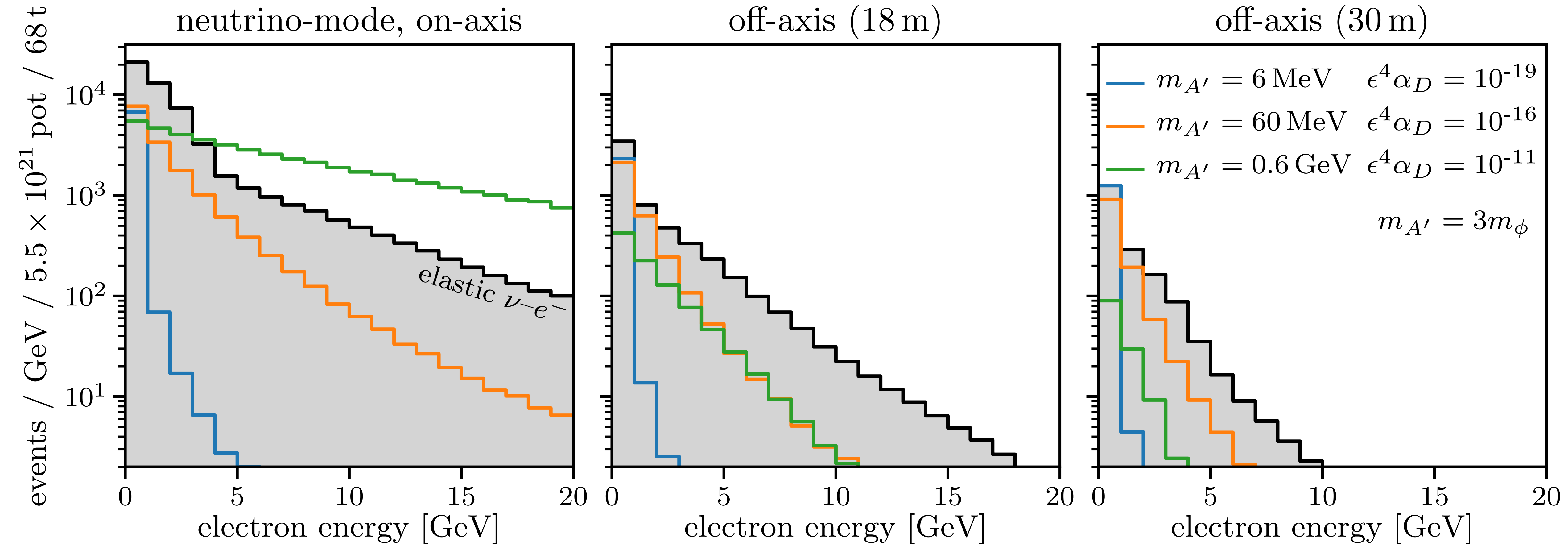
# Aside: $\nu e$ ES vs. $\nu_e$ CCQE

Consider the following two processes:

# Real-life Event Distributions (DUNE ND)



# DM Signal vs. Neutrino Background

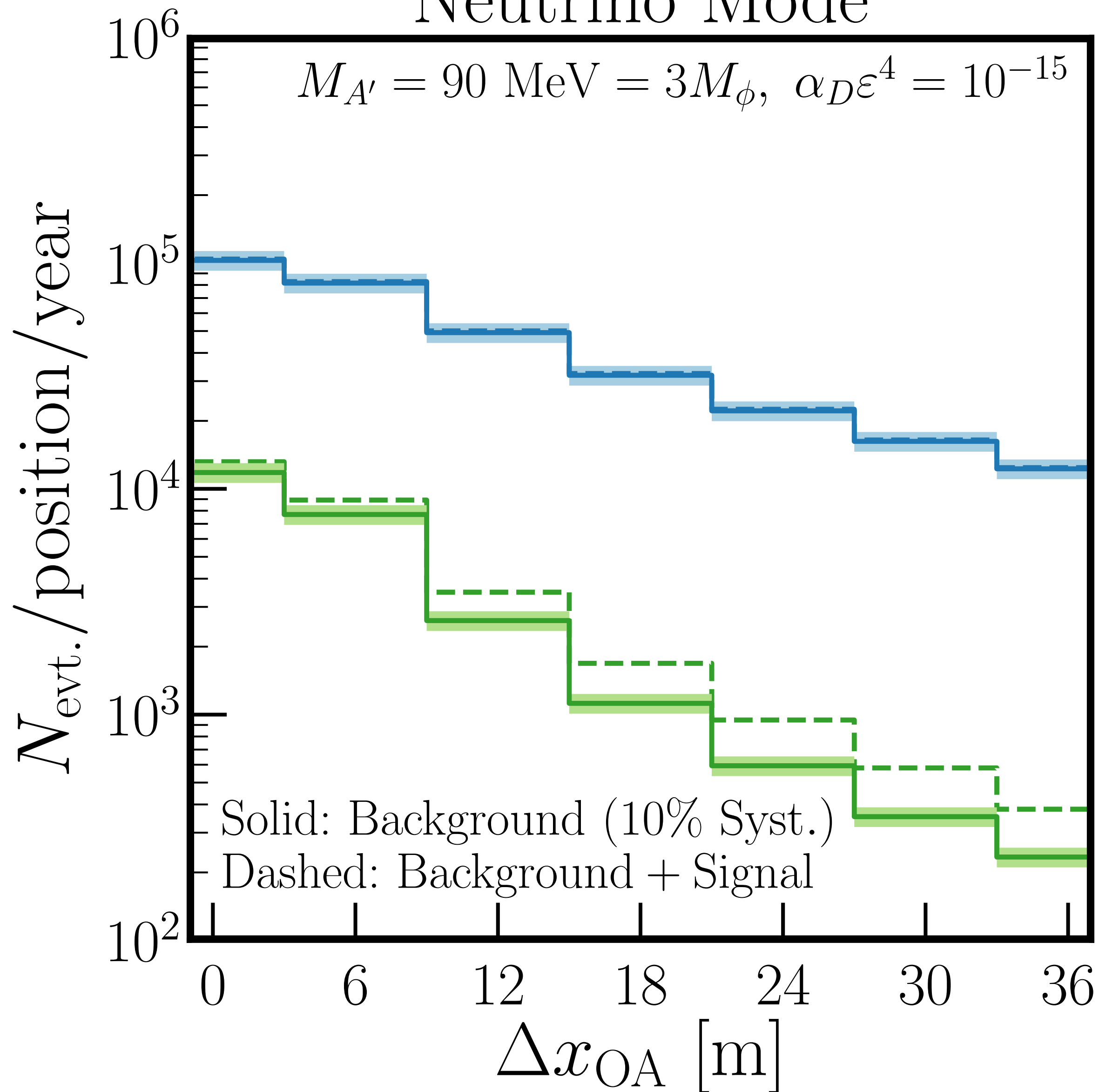


# Why go off-axis?

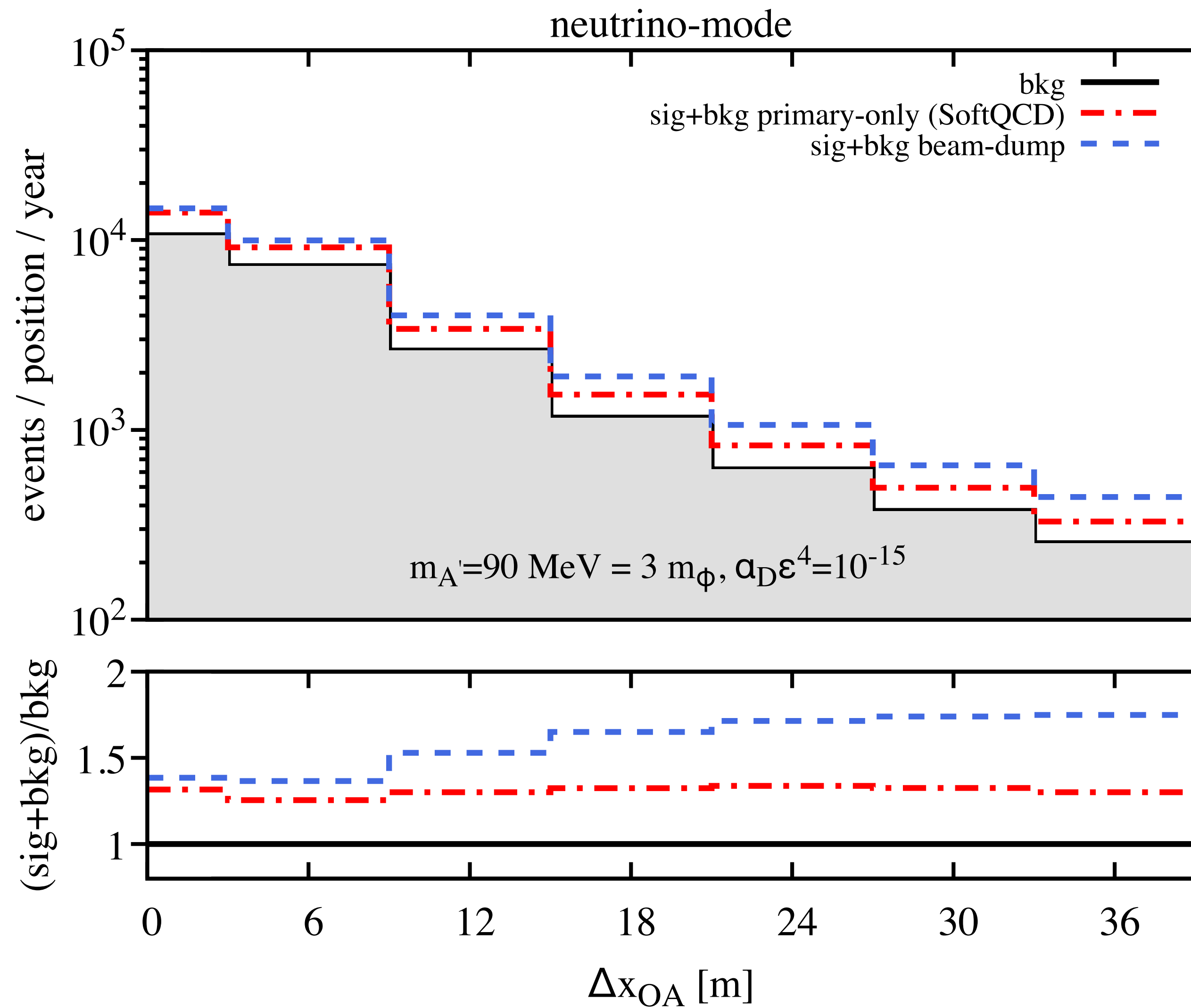
# On- vs. off-axis

Neutrino Mode

$$M_{A'} = 90 \text{ MeV} = 3M_\phi, \quad \alpha_D \varepsilon^4 = 10^{-15}$$

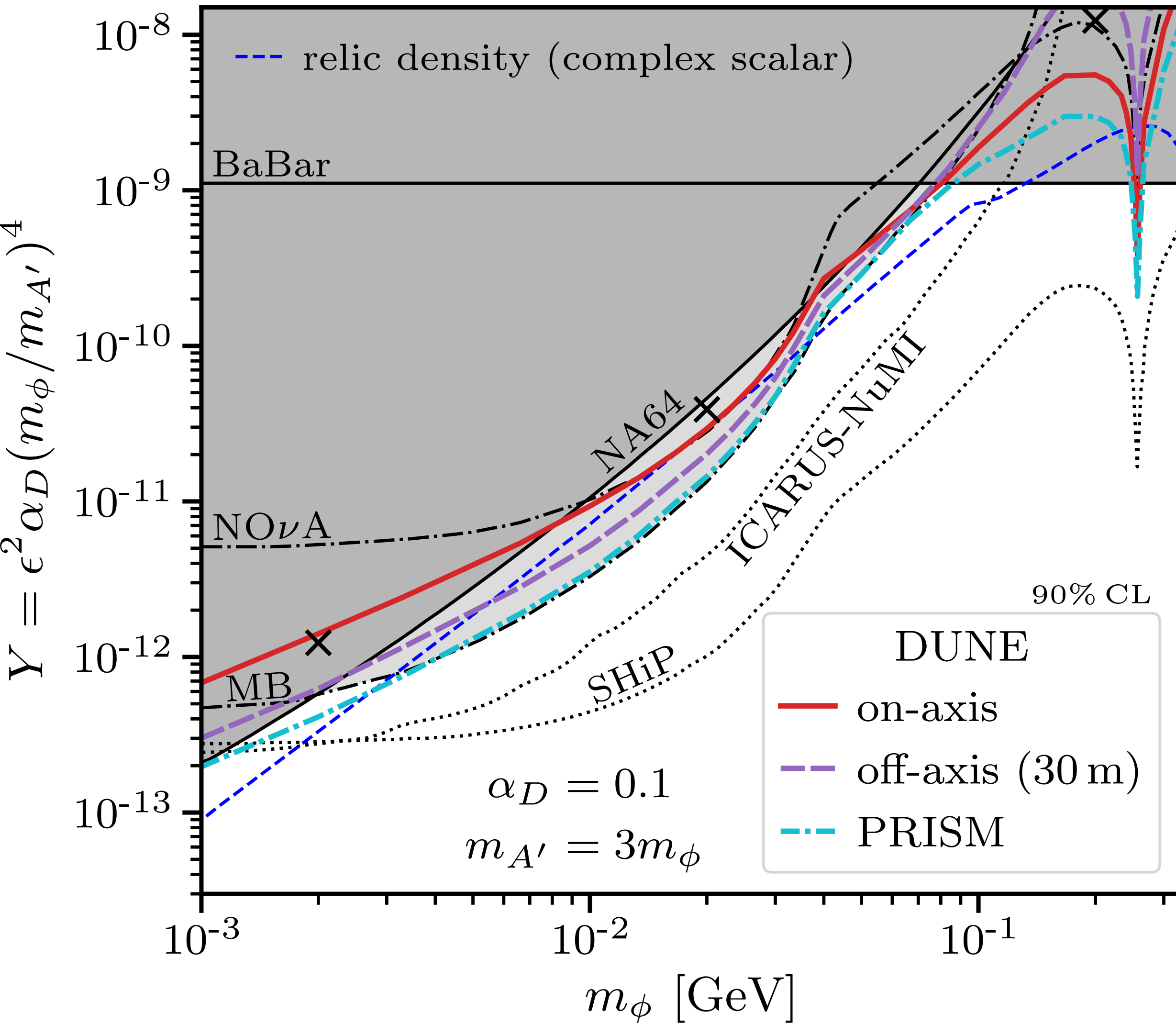


Breitbach et al [\[2102.03383\]](#)

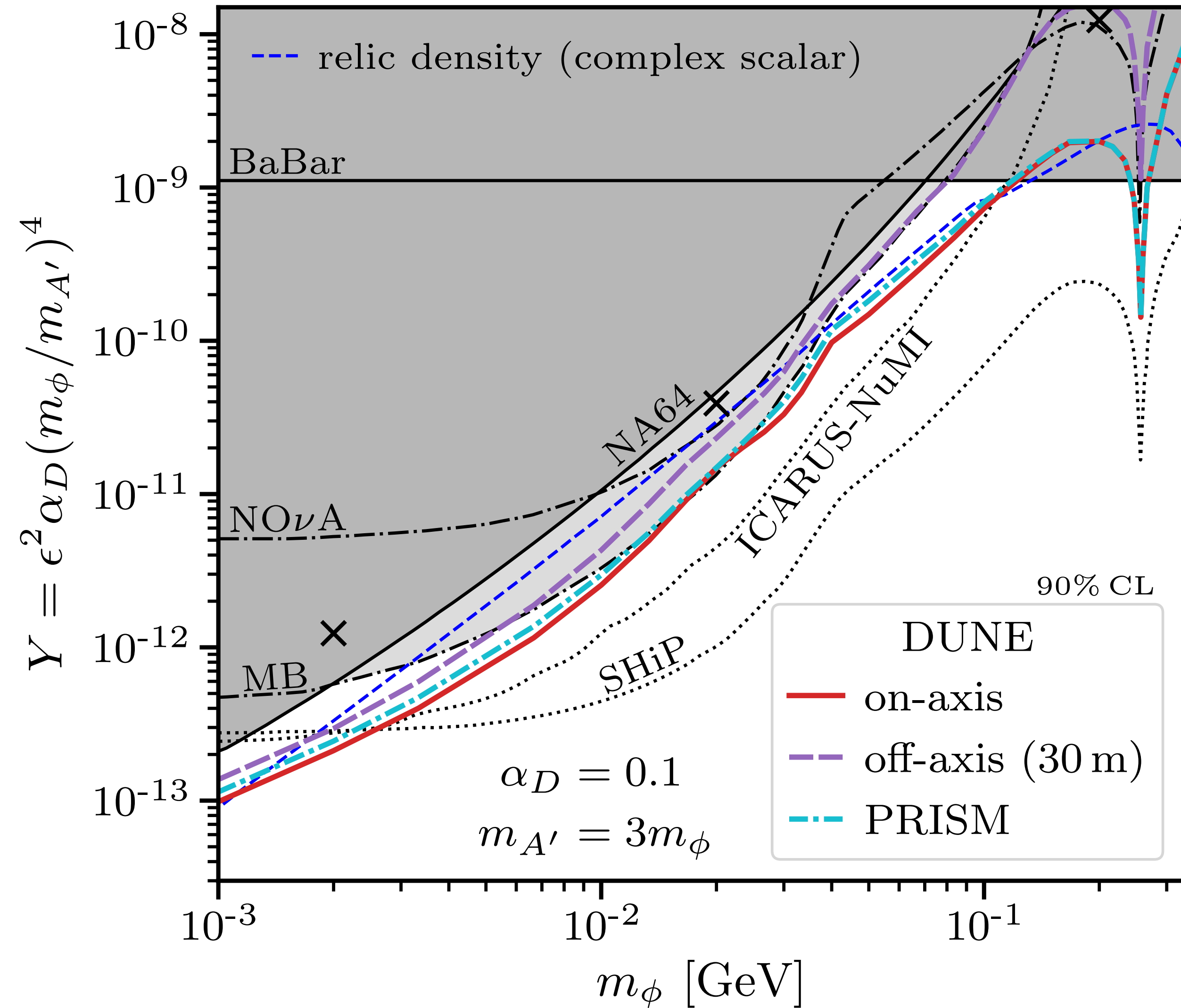


# Sensitivity

total rates analysis

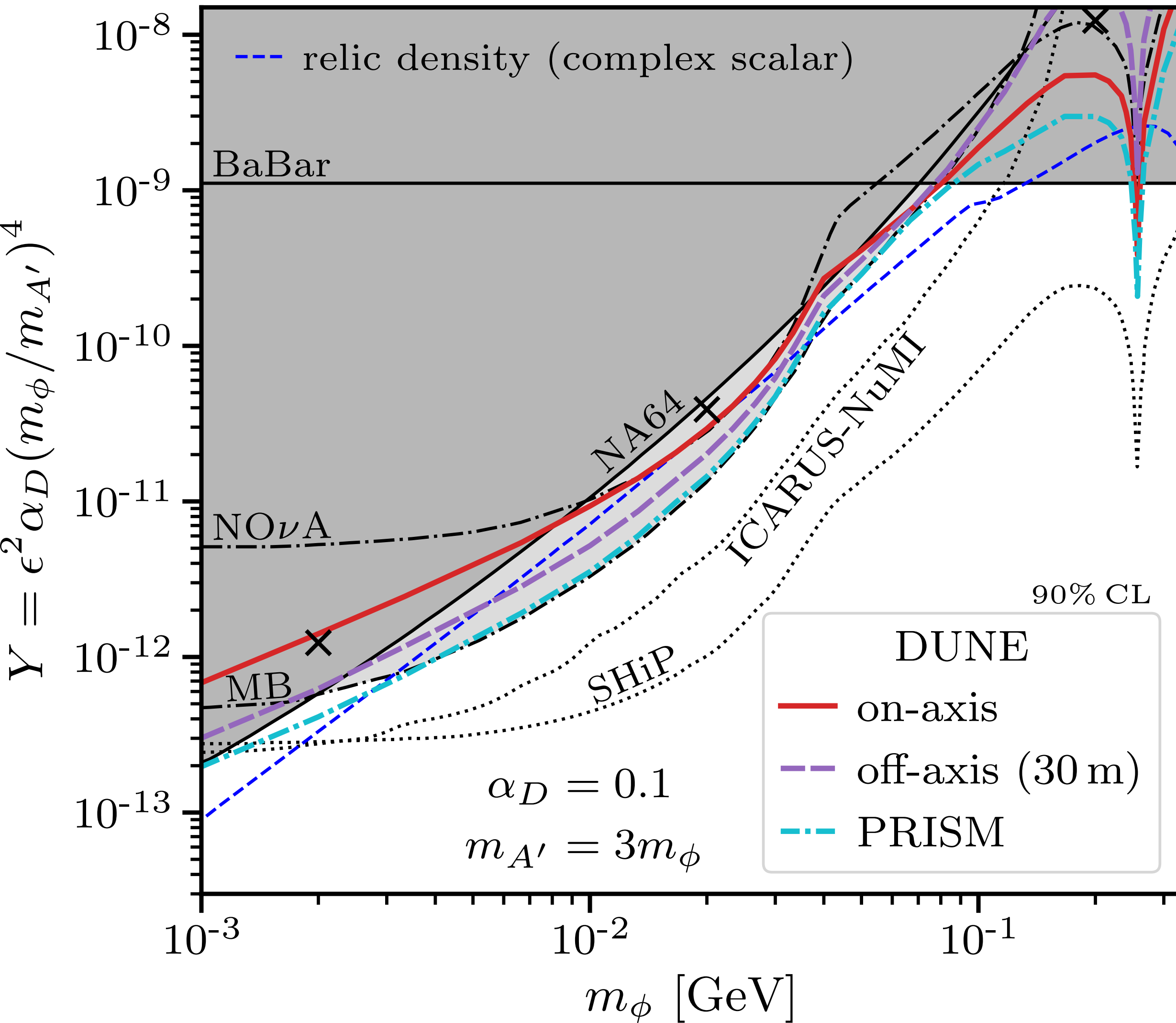


spectral analysis ( $\Delta E = 250$  MeV)



# Sensitivity

total rates analysis



spectral analysis ( $\Delta E = 250$  MeV)

