Connections to BSM

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NuSTEC Summer School 2024

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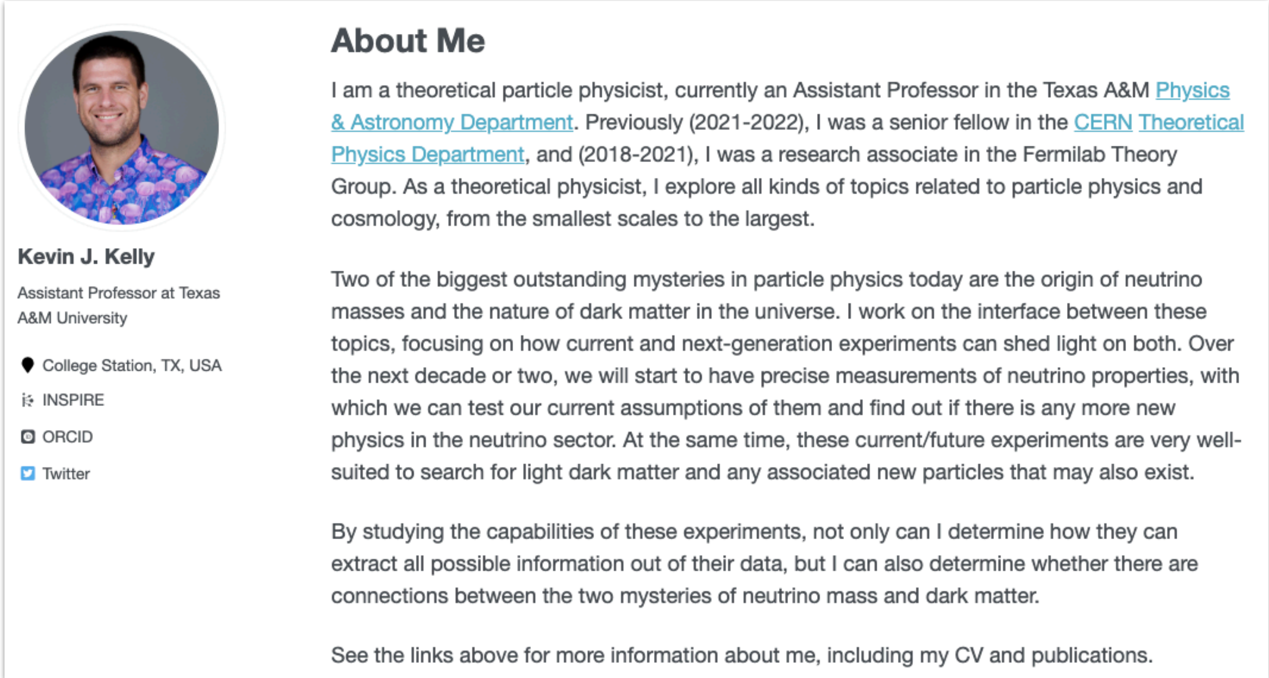
Who am I?



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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.

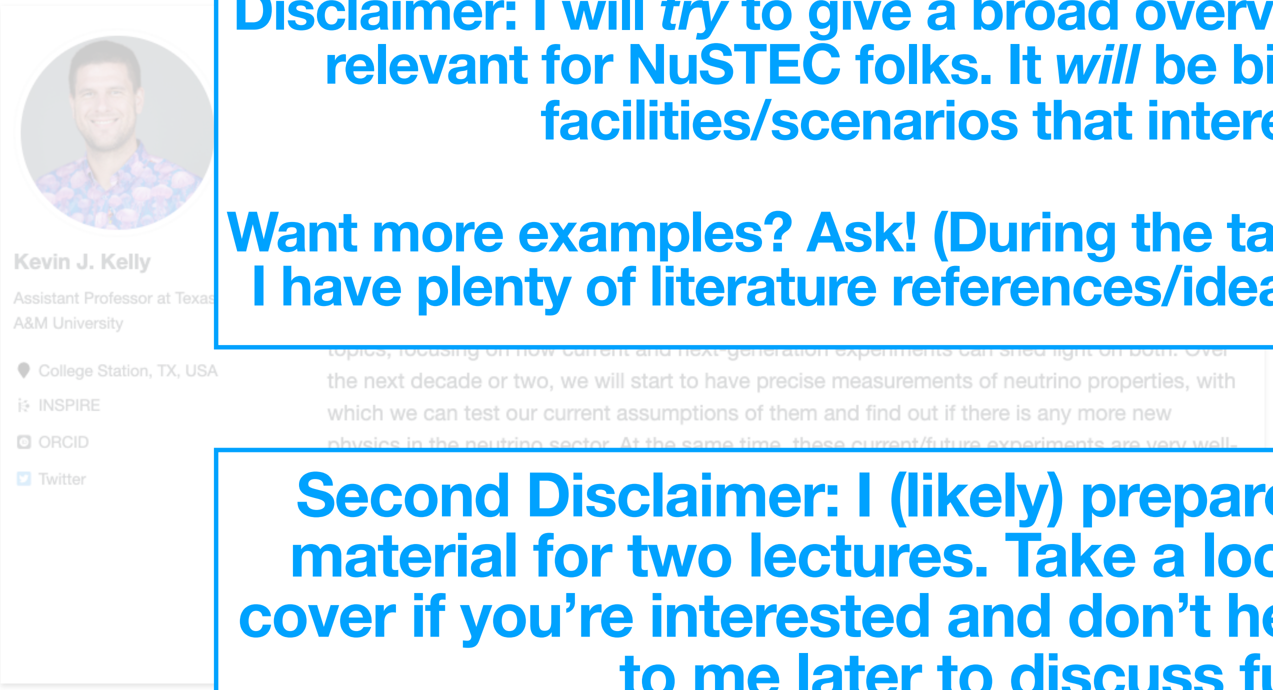
See the links above for more information about me, including my CV and publications.

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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sed

trophysical

- Searches for beyond-the-SM physics at these/ other facilities

f neutrinos/

evolution

Website link1,

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 futher!

Define “SM”

SM: Set of Known particles + Interactions

Quarks
Leptons
Force Carriers
Higgs

$\Longleftrightarrow$ $SU(3)_c \times SU(2)_L \times U(1)_Y$

$\Longrightarrow$ + Massive Neutrinos

$\Longrightarrow$ Mass-sq. Differences, Mixing Angles, . . .

$$\{\theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP}, \Delta m^2_{21}, \Delta m^2_{31}\}$$

$\Longrightarrow$ BSM > Oscillations beyond 3ν

SM topics beyond these lectures

(B)

(with focus on NuSTEC)

- Precision σ Measurements
- Understanding 3ν Paradigm
  - => Data are consistent?
  - => Synergies b/w different experiments
  - => Uncertainties in σ => Impacts
- Reactor + ν Source ("Gallium Anomalies")

→ Talk to Vedran

=> Impact of SM on BSM Searches ✓

How to search for BSM?

⇒ Experiment-dependent! Know SM Contribution to BSM Search

3 Possibilities

1) Little/No SM Background (Bkg → 0)

2) Theoretically Well-understood SM Bkg. ($\sigma_{\text{Bkg.}} \sim$ Stat.)

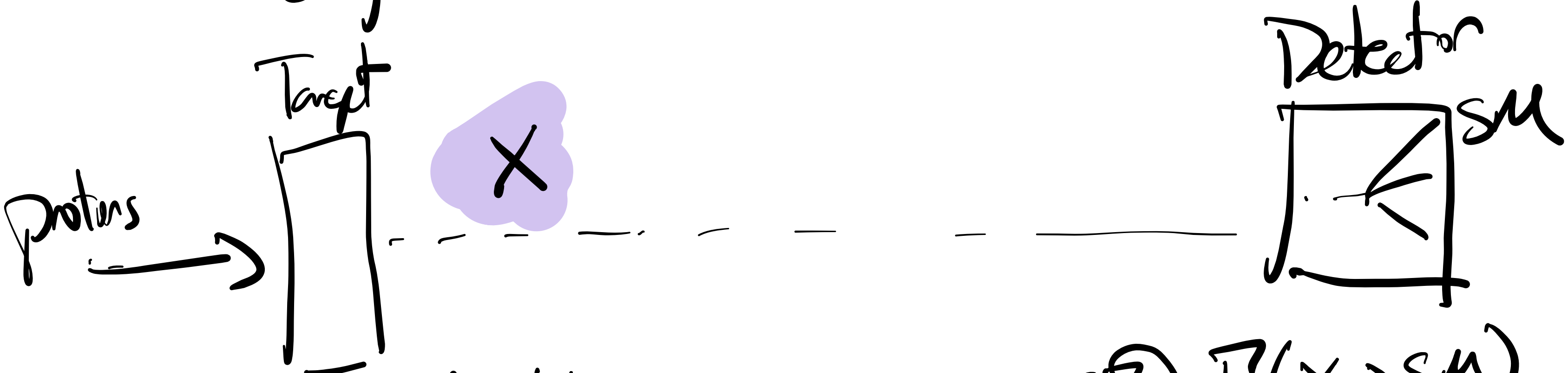
3) Experimentally-Measurable Bkg. ($\sigma_{\text{Bkg.}} \sim$ Syst.)

Scenario 1:

Little-to-no expected SM Background

Case Study

Long-lived Particle Searches



① $SM \to X$

Production Mechanism

② $\Gamma(X \to SM)$

"interesting" Final State

Explicit Model — Dark Photons

$U(1)_D$

$$\mathcal{L} \supset -\frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} - \frac{\varepsilon}{2} F'_{\mu\nu} F^{\mu\nu} + \frac{m_{A'}^2}{2} A'^{\mu} A'_{\mu}$$

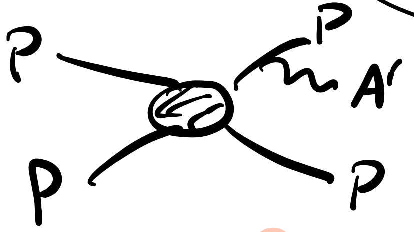
Kinetic Mixing Term

$\varepsilon \ll 1$

Mass $m_{A'}$

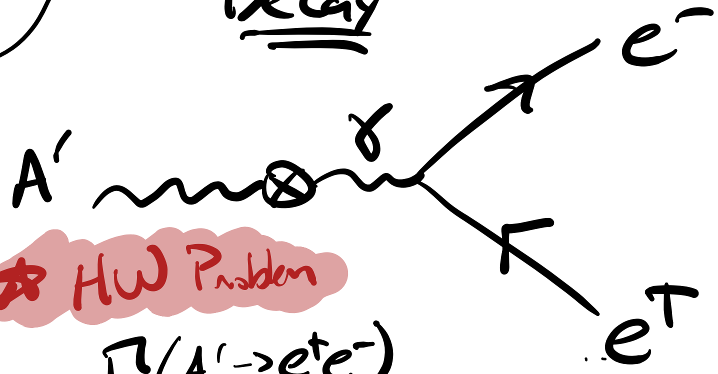
Production

$Br \sim \varepsilon^2$



EM Showers

Decay



★ HW Problem

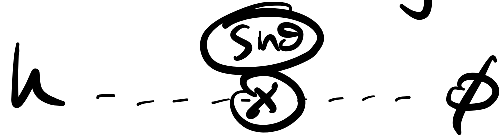
$\Gamma(A' \to e^+e^-)$

Explicit Model — Dark Higgs Bosons

$$\mathcal{L} \supset \delta |H|^2 \phi \quad \text{or} \quad \lambda |H|^2 \phi^2$$

Recall: How SM Higgs Couples to Fermions?

$\sin\theta$ small Mixing Angle



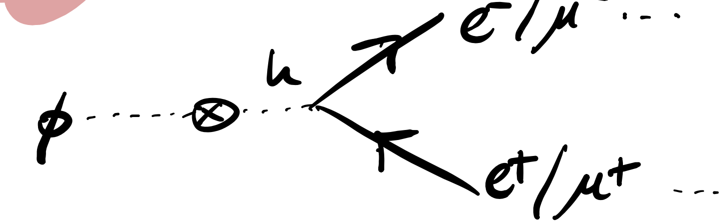
Production

$\propto y_t \sin\theta$

$K^+ \to \pi^+ \phi$

A More HW

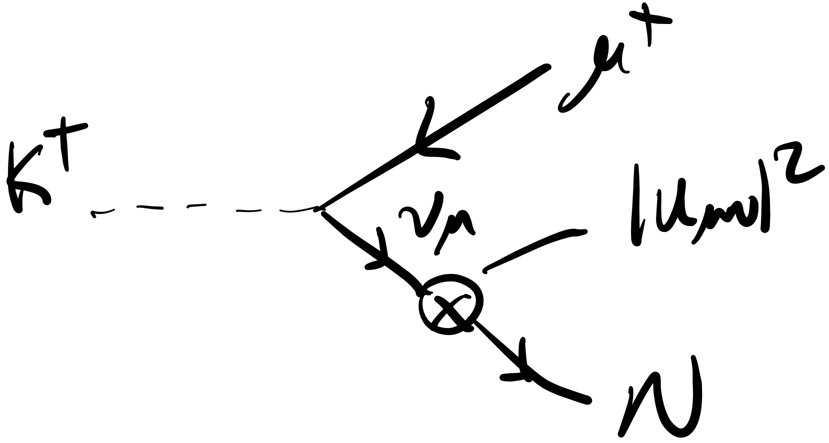
Decay



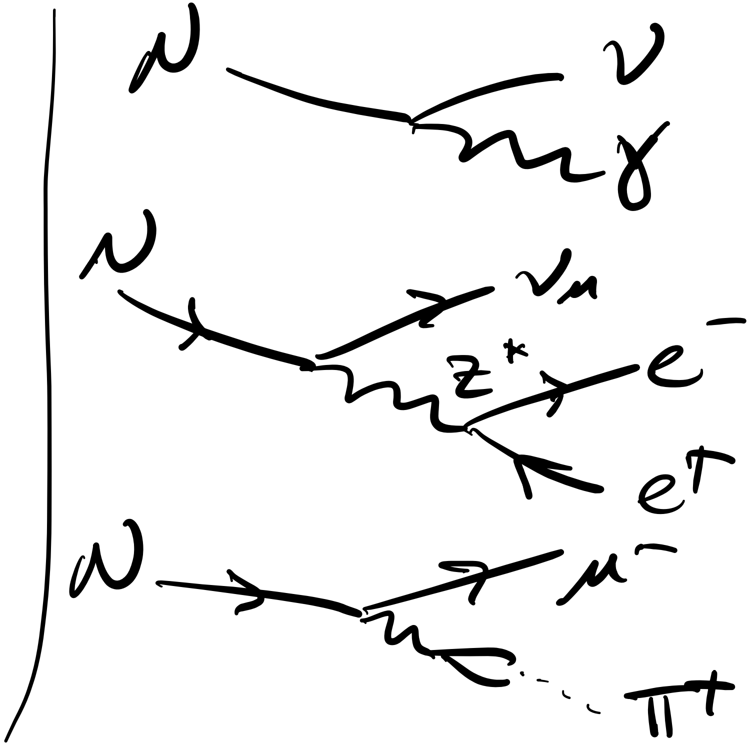
Explicit Model — Heavy Neutral Leptons

⇒ Fermion N mixes with SM Neutrinos

$|U_{\alpha N}|^2 \quad (\alpha = e, \mu, \tau)$

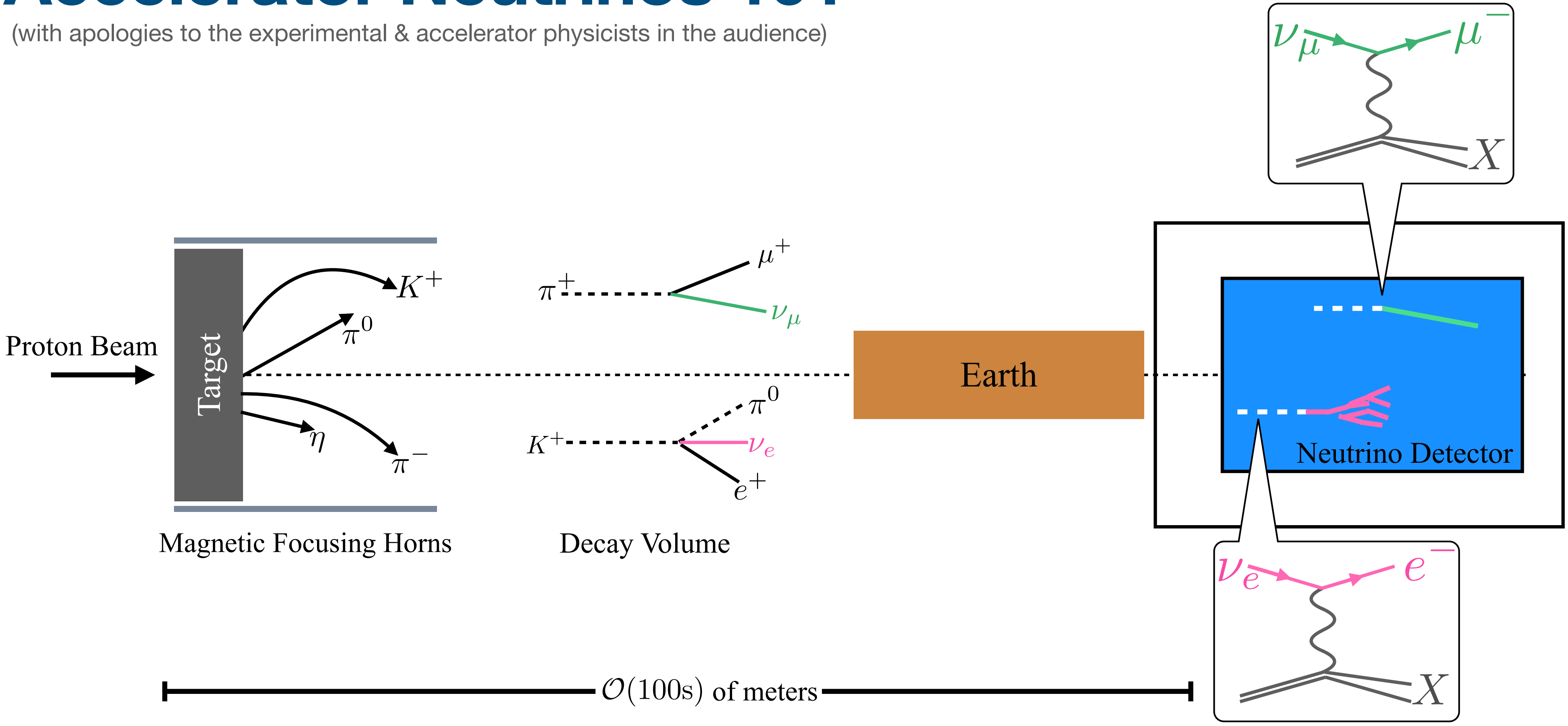


Any ν-producing Process

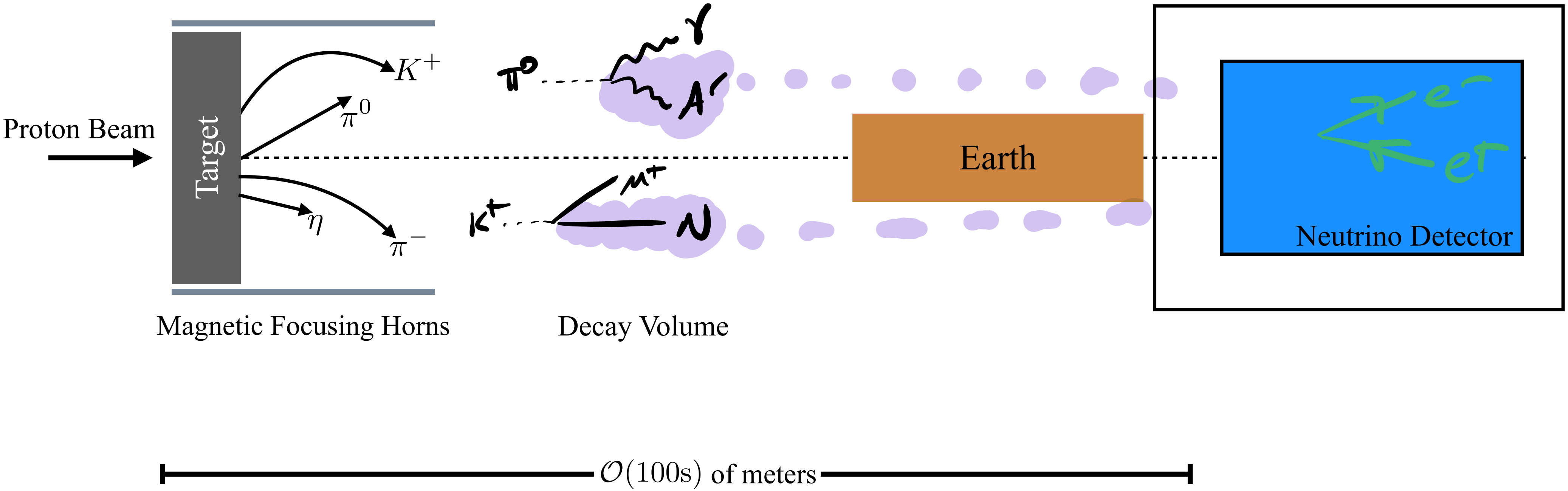


Accelerator Neutrinos 101

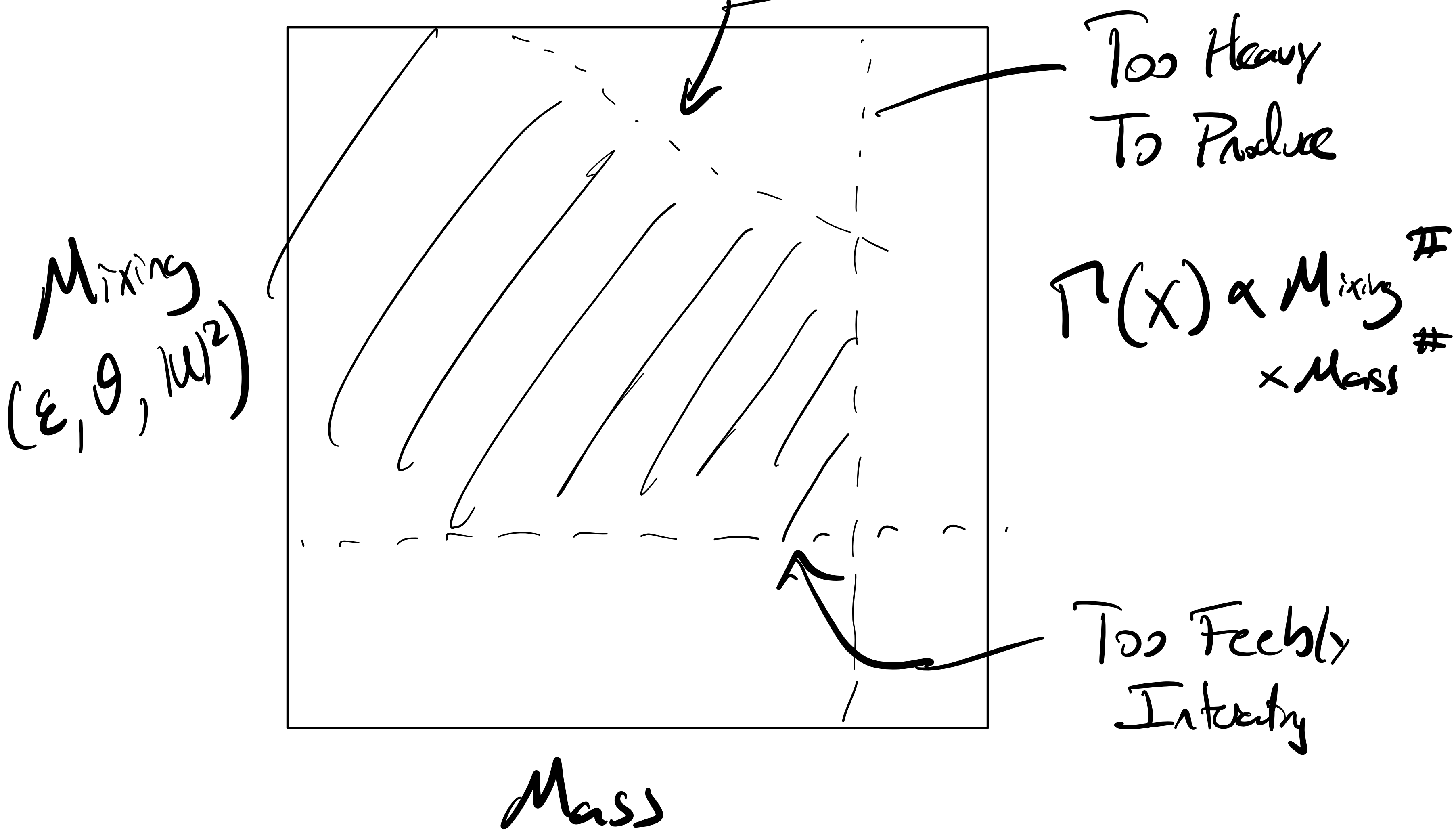
(with apologies to the experimental & accelerator physicists in the audience)



Long-lived particle searches



Back-of-the-envelope Sensitivity



Too Shortlived

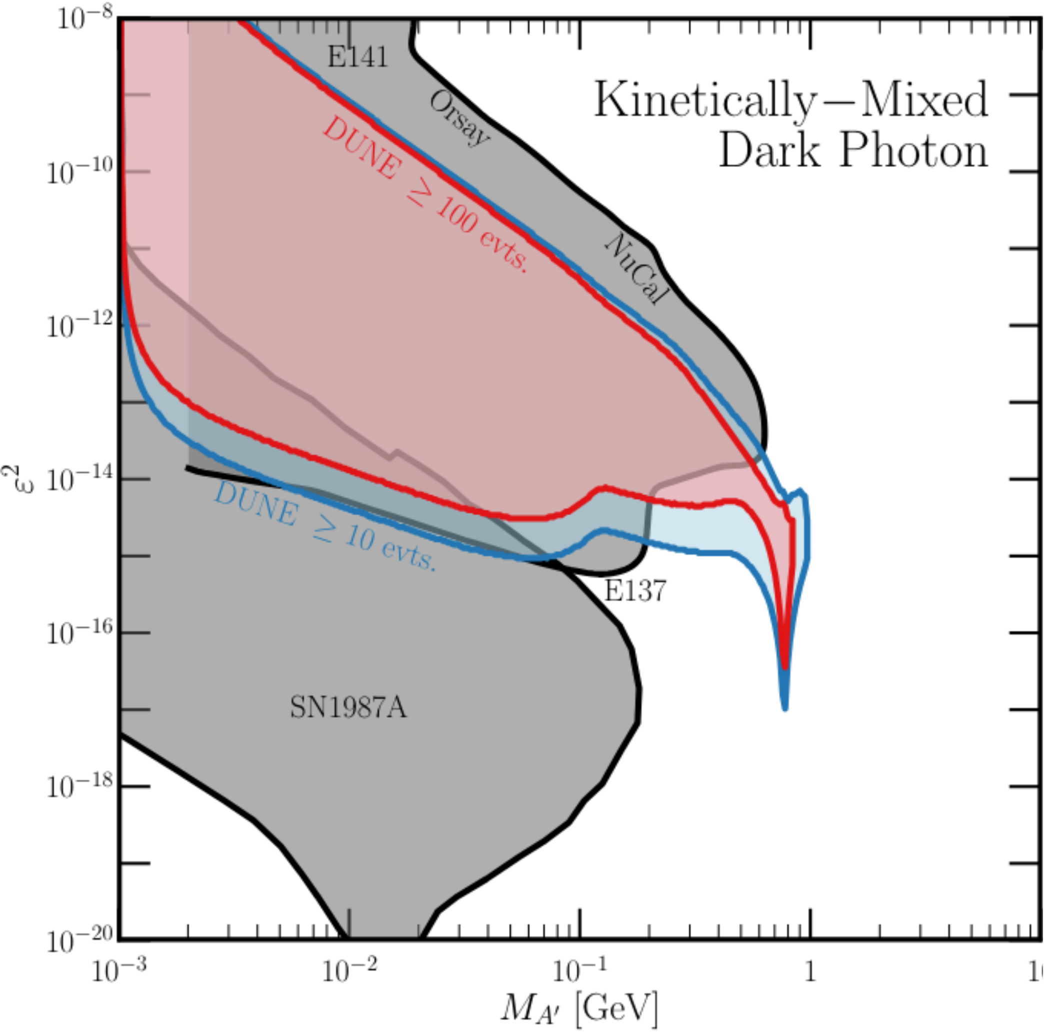
Too Heavy To Produce

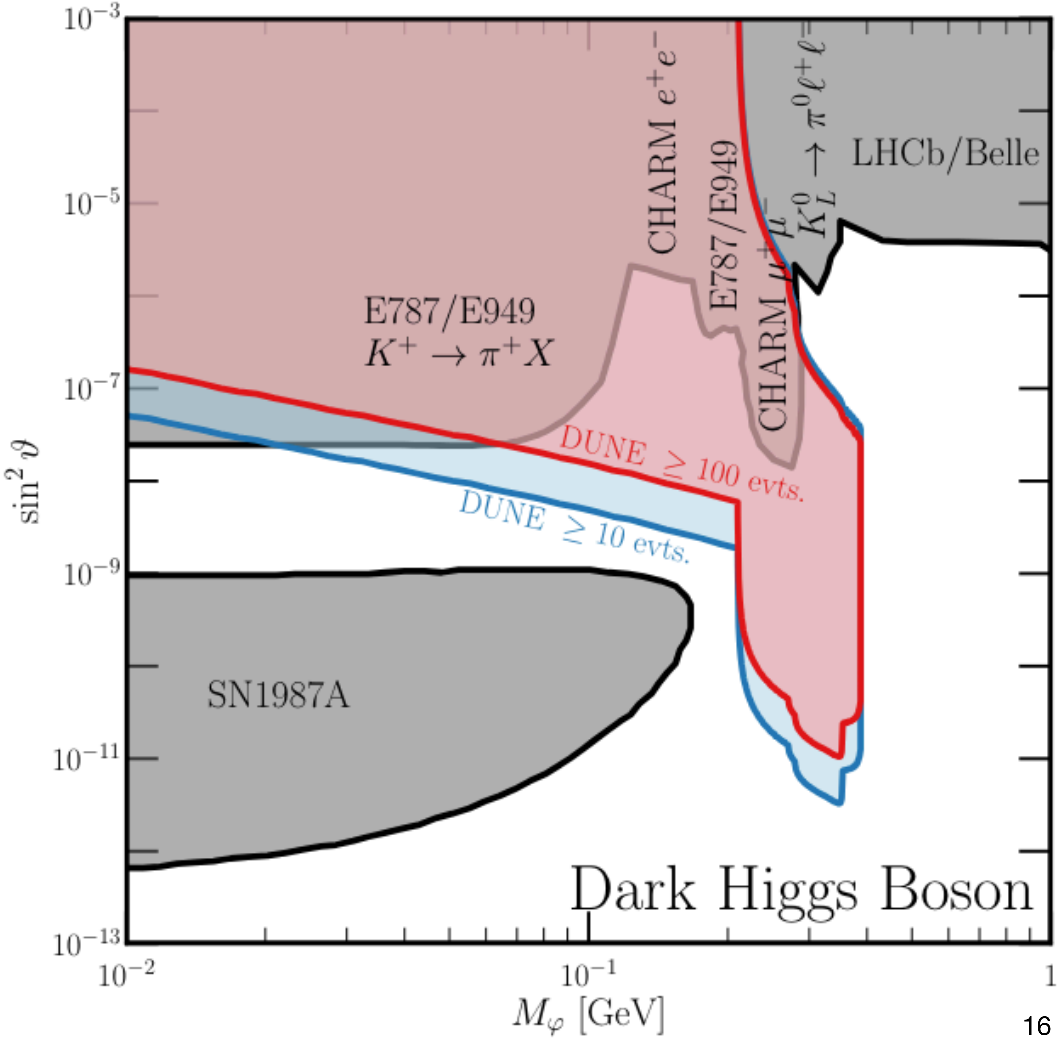
Too Feebly Interacting

$$\Gamma(X) \propto \text{Mixing}^{\#} \times \text{Mass}^{\#}$$

DUNE Sensitivity pt 1

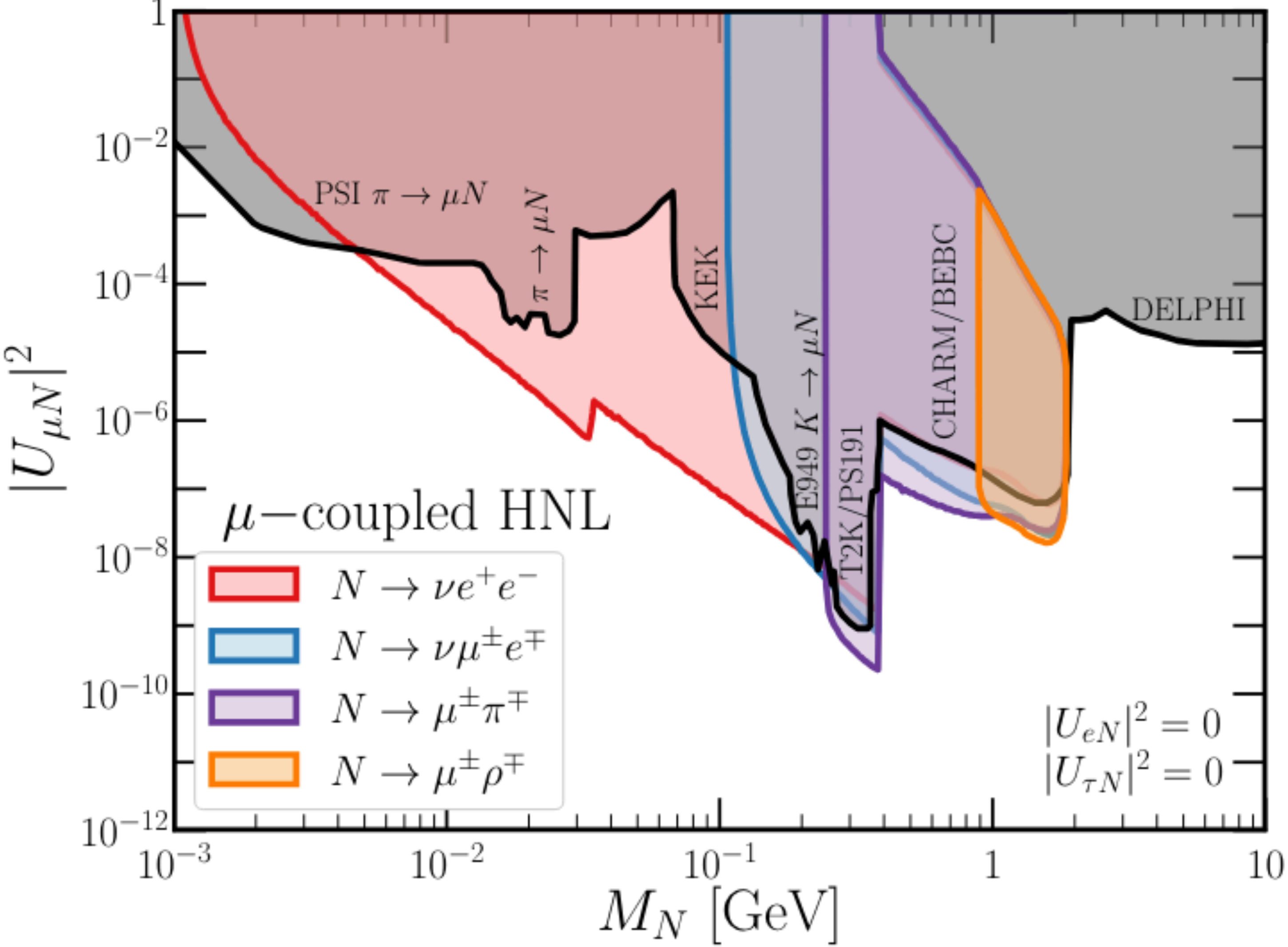
Berryman, de Gouvêa, Fox, Kayser, KJK, Raaf [1912.07622]





DUNE Sensitivity pt 2

Berryman, de Gouvêa, Fox, Kayser, KJK, Raaf [1912.07622]



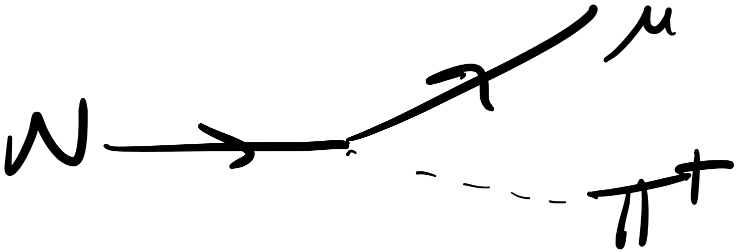
Other HNLs at DUNE Studies?

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

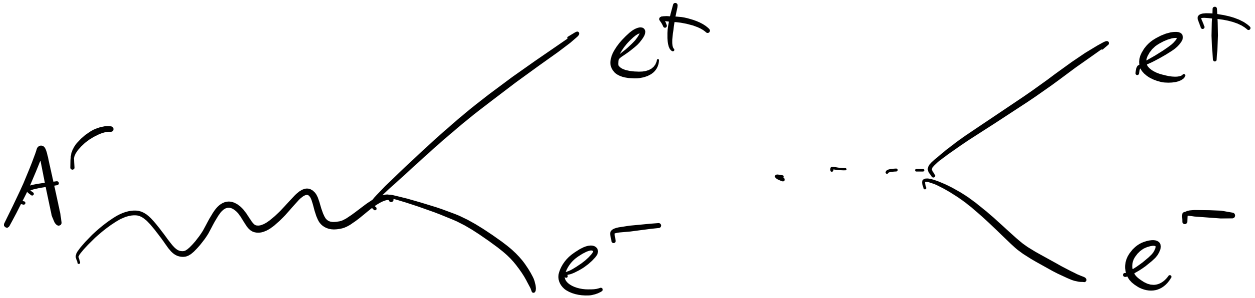
Impact of Backgrounds on LLP Searches

Depends *significantly* on your search of interest

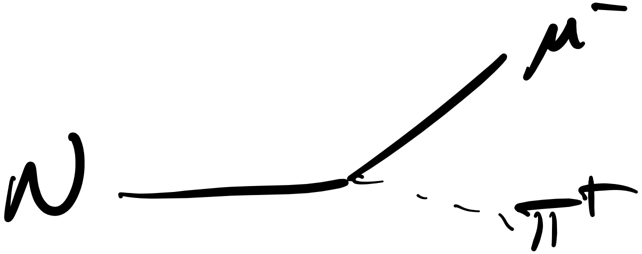
Case 1) Long-lived HNL decaying into a muon and a pion



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

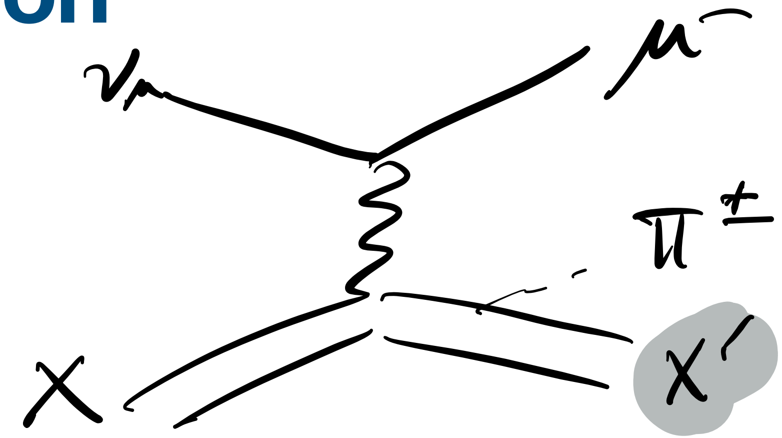


Case 1 — HNL to muon/pion



Rate $\propto$ Volume

VS



CC ν_μ 1π

Rate $\propto$ Mass

$\sigma_{CC\nu_\mu 1\pi} \sim 1\% \times \sigma_{CCQE}$

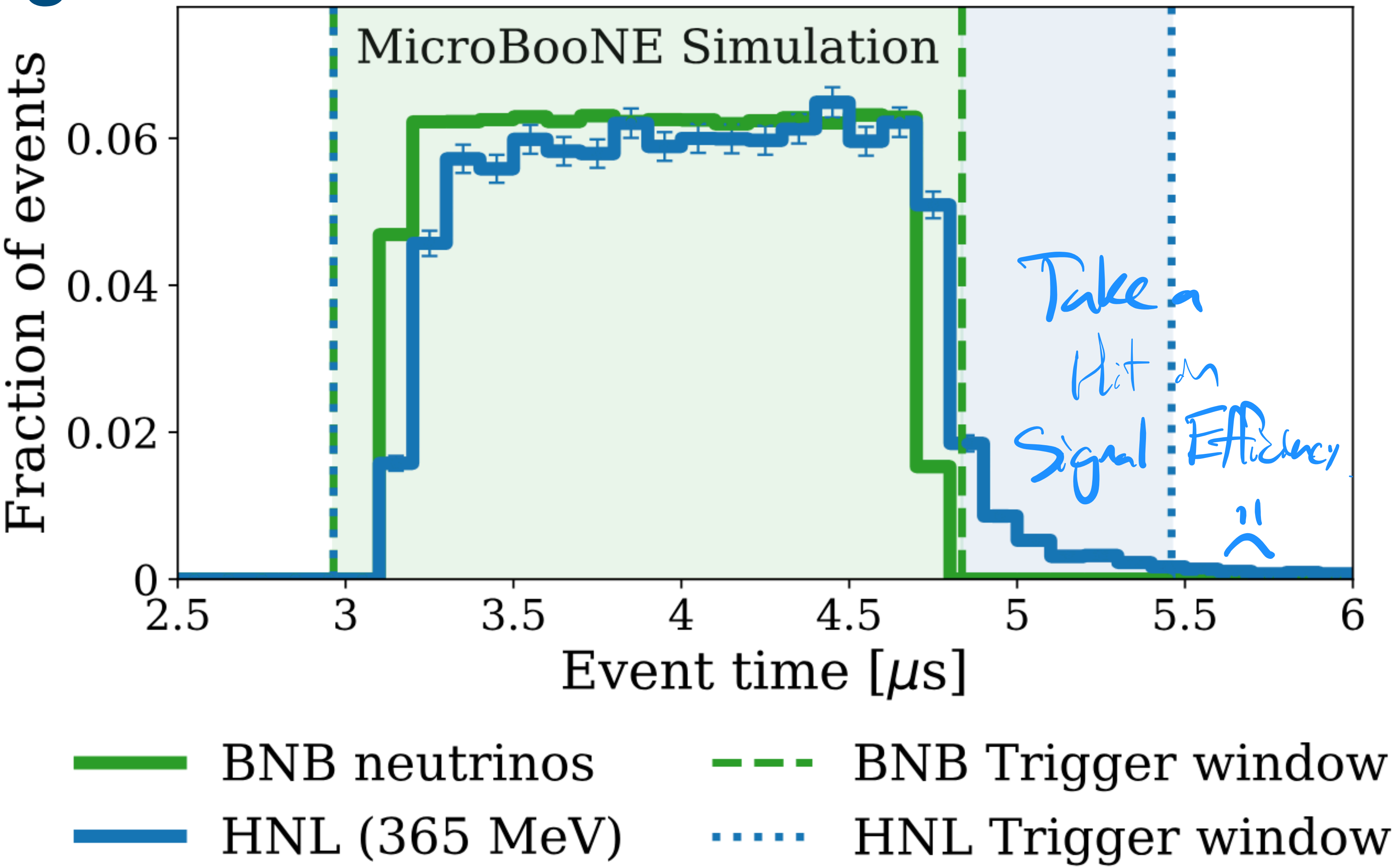
How to Handle

ⓐ Kinematics

ⓑ Timing!

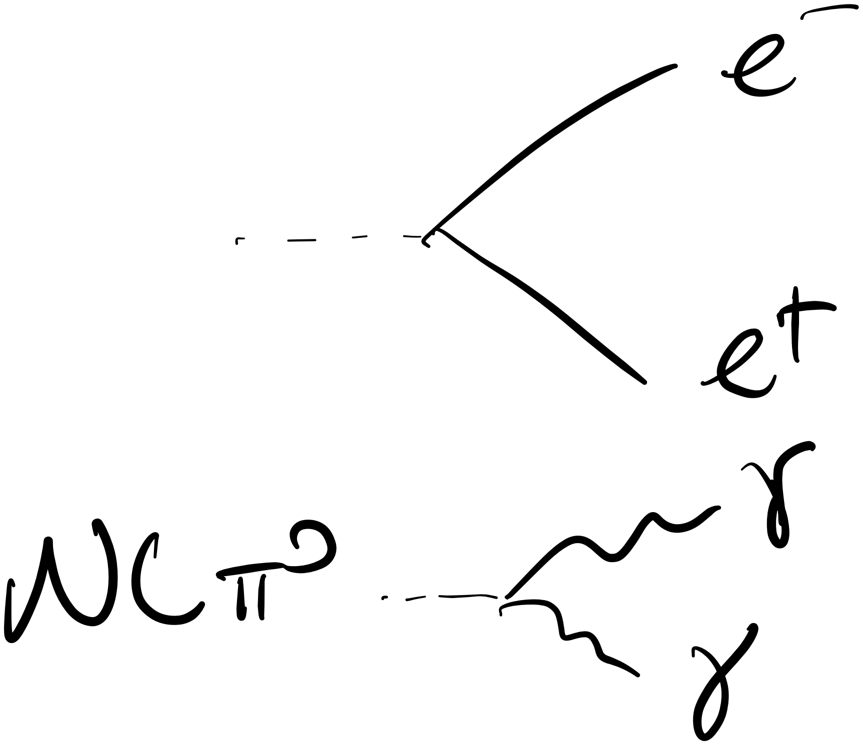
Timing Distributions

MicroBooNE collab. [1911.10545]



Take a Hit on Signal Efficiency ☹

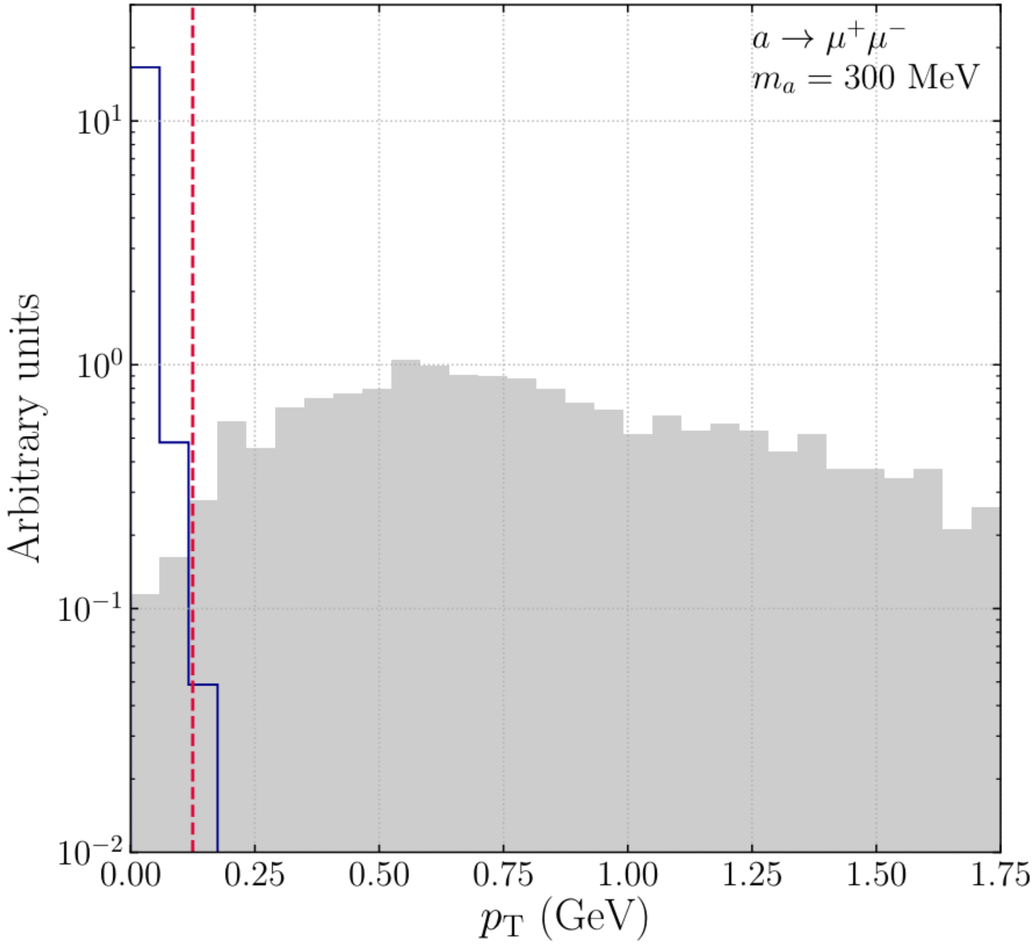
Case 2 — DP/DH to electron/positron



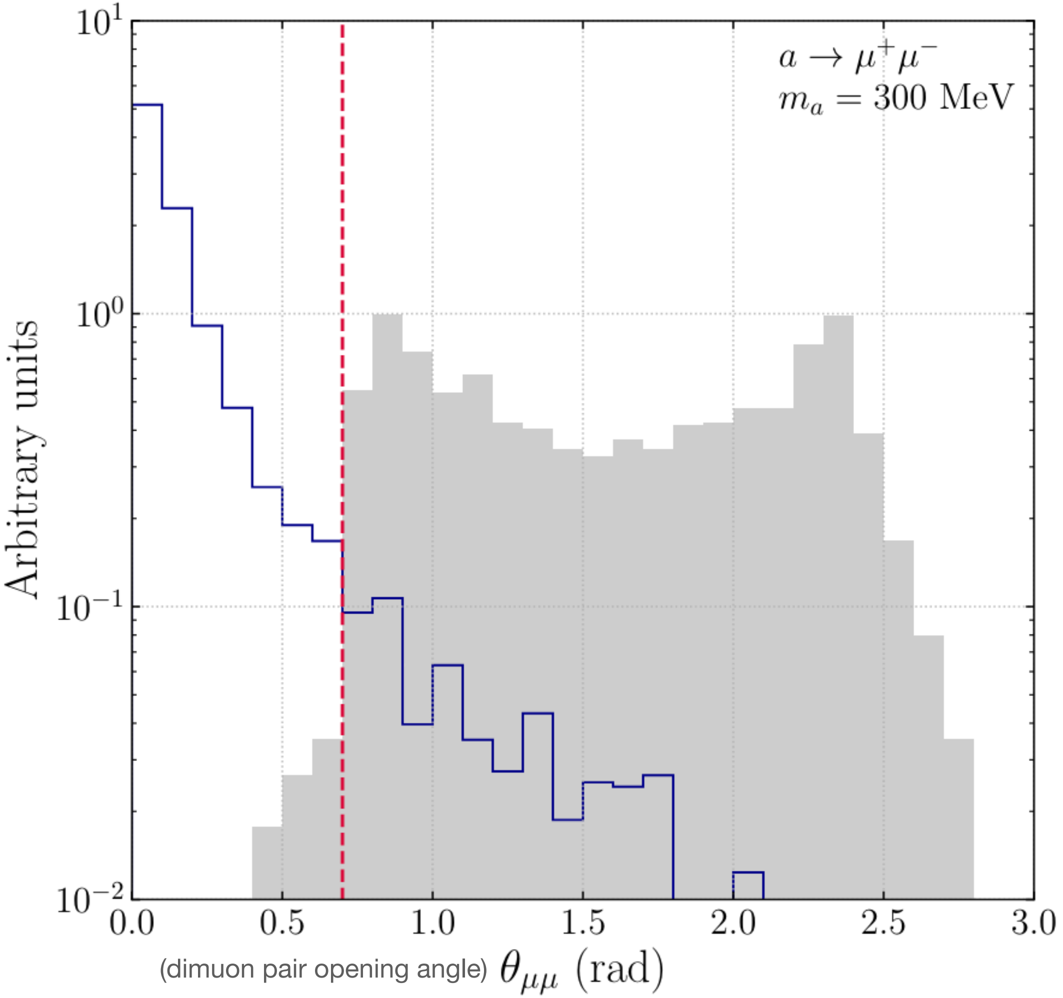
Gaseous

Dimuon event distributions

Coloma et al [2309.06492]



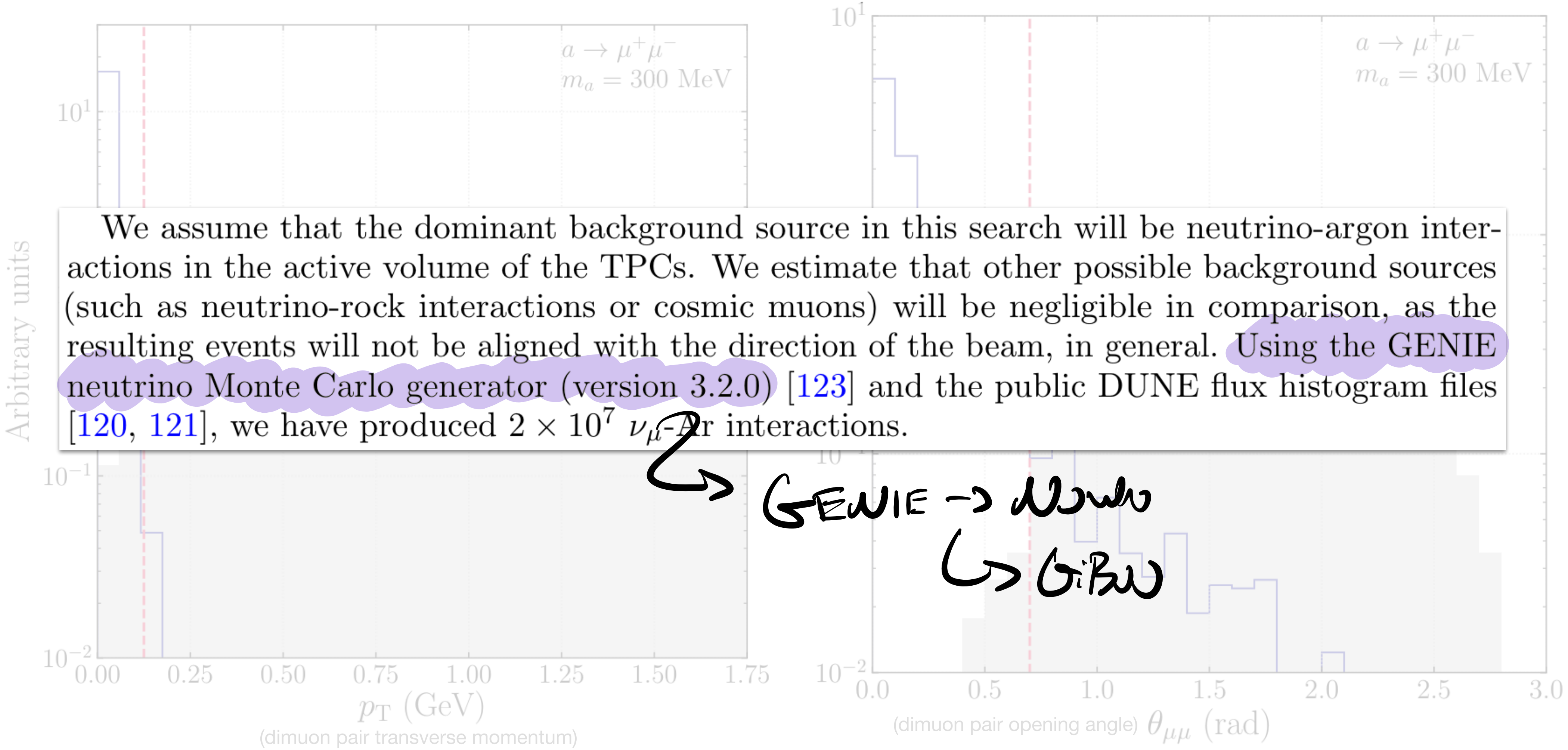
(dimuon pair transverse momentum)



(dimuon pair opening angle)

Dimuon event distributions

Coloma et al [2309.06492]

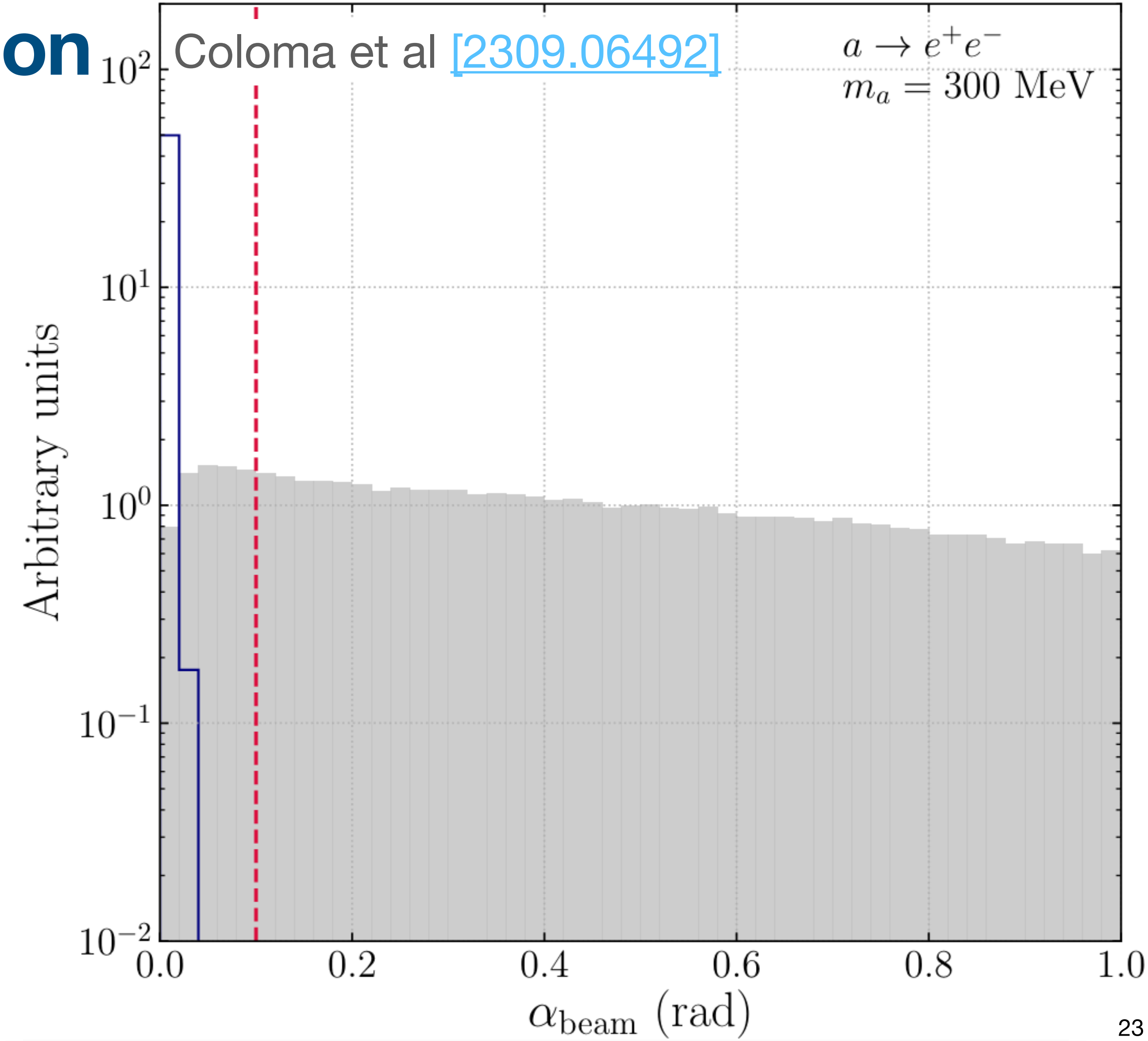


We assume that the dominant background source in this search will be neutrino-argon interactions in the active volume of the TPCs. We estimate that other possible background sources (such as neutrino-rock interactions or cosmic muons) will be negligible in comparison, as the resulting events will not 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 2×10^7 ν_μ-Ar interactions.

↳ GENIE → NuWro

↳ GiBUU

Dielectron Distribution



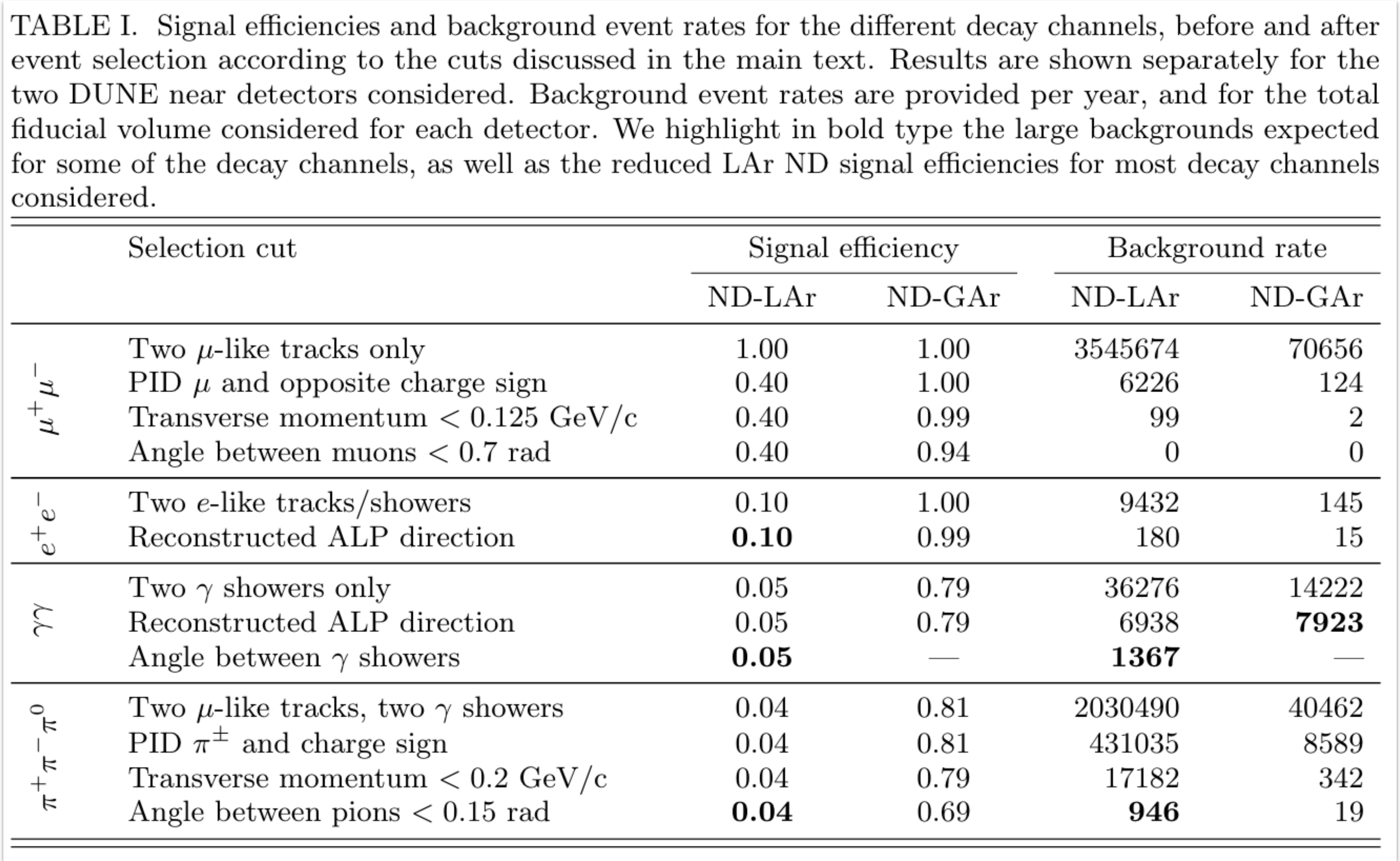


TABLE I. Signal efficiencies and background event rates for the different decay channels, before and after event selection according to the cuts discussed in the main text. Results are shown separately for the two DUNE near detectors considered. Background event rates are provided per year, and for the 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 μ-like tracks only	1.00	1.00	3545674	70656
	PID μ 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	**0.10**	0.99	180	15
$\gamma\gamma$	Two γ showers only	0.05	0.79	36276	14222
	Reconstructed ALP direction	0.05	0.79	6938	**7923**
	Angle between γ showers	**0.05**	—	**1367**	—
$\pi^+\pi^-\pi^0$	Two μ-like tracks, two γ 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	**0.04**	0.69	**946**	19

Coloma et al [2309.06492]

Scenario 2:

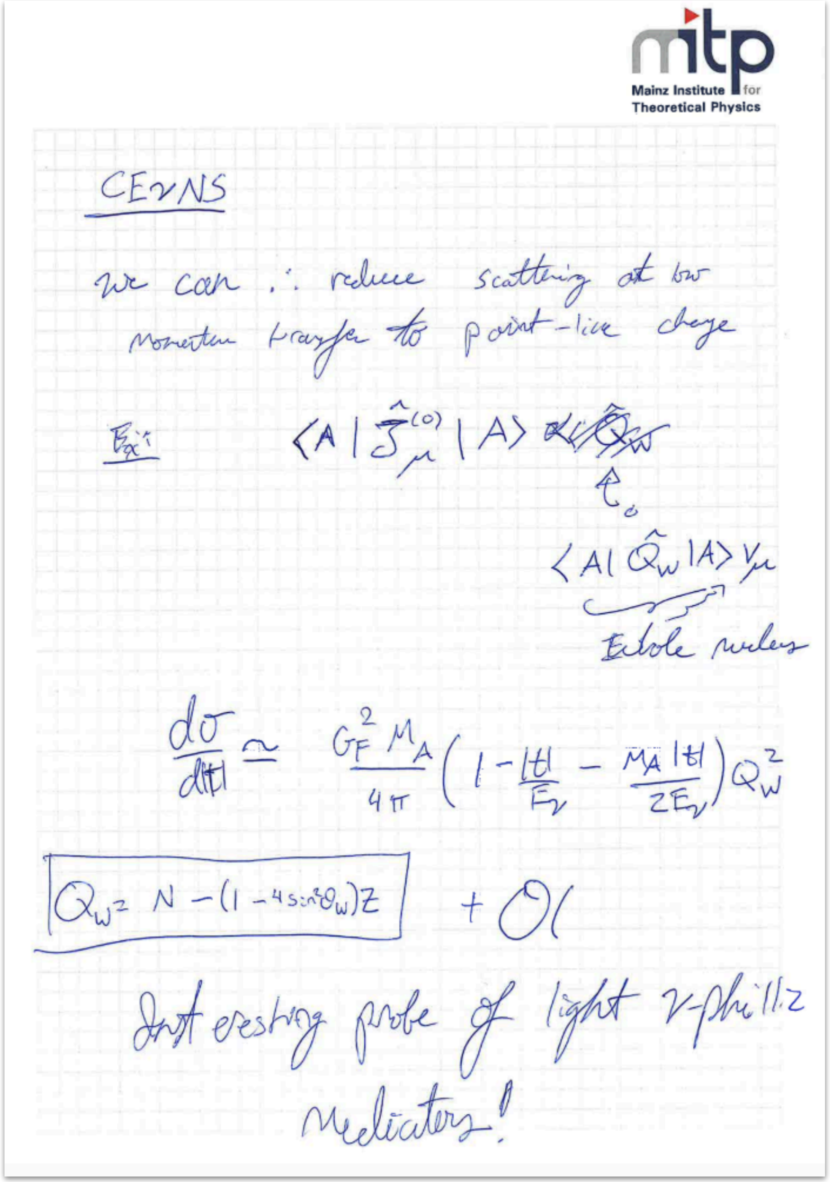
Theoretically Clean SM Background

From Ryan’s second lecture (Thursday 6th June)

SM CEνNS rate depends on:

$$Q_W = N - (\underbrace{1 - 4s_w^2}_{\approx 0})Z$$

$$Q_W \approx N$$



Mainz Institute for Theoretical Physics

CEνNS

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

Ex: $\langle A|\hat{J}^{(0)}_\mu|A\rangle \propto \cancel{\hat{Q}_W}$

$\uparrow$
$\hat{C}_0$

$\underbrace{\langle A|\hat{Q}_W|A\rangle}\, v_\mu$

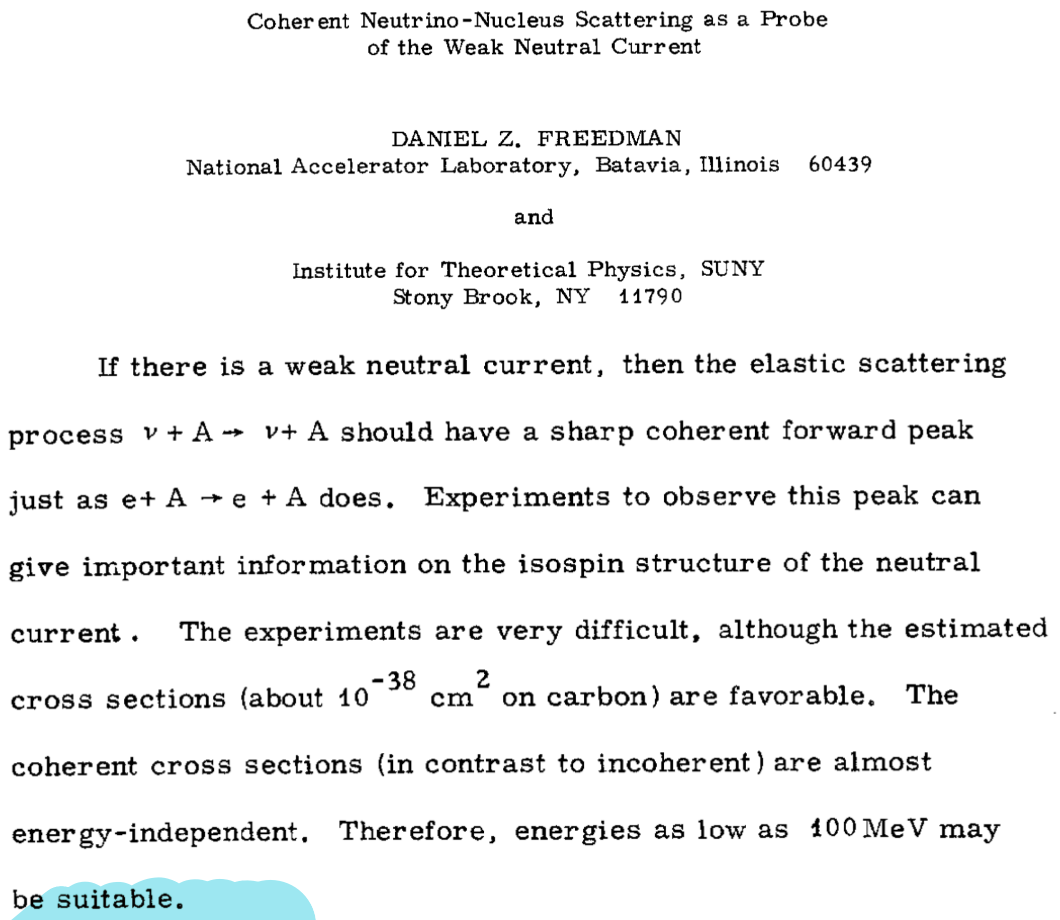
Whole nucleus

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

$$\boxed{Q_W = N - (1 - 4\sin^2\theta_W)Z} + \mathcal{O}($$

Interesting probe of light ν-philic mediators!

Challenge(s) associated with CEνNS



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 $\nu + A \to \nu + A$ should have a sharp coherent forward peak just as $e + A \to e + A$ 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^2 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

$$\frac{d\sigma}{dE_r} = \frac{G_F M_W}{2\pi} Q_W^2 |F(q^2)|^2 \times \left(2 - \frac{m_W E_r}{E_\nu^2}\right)$$

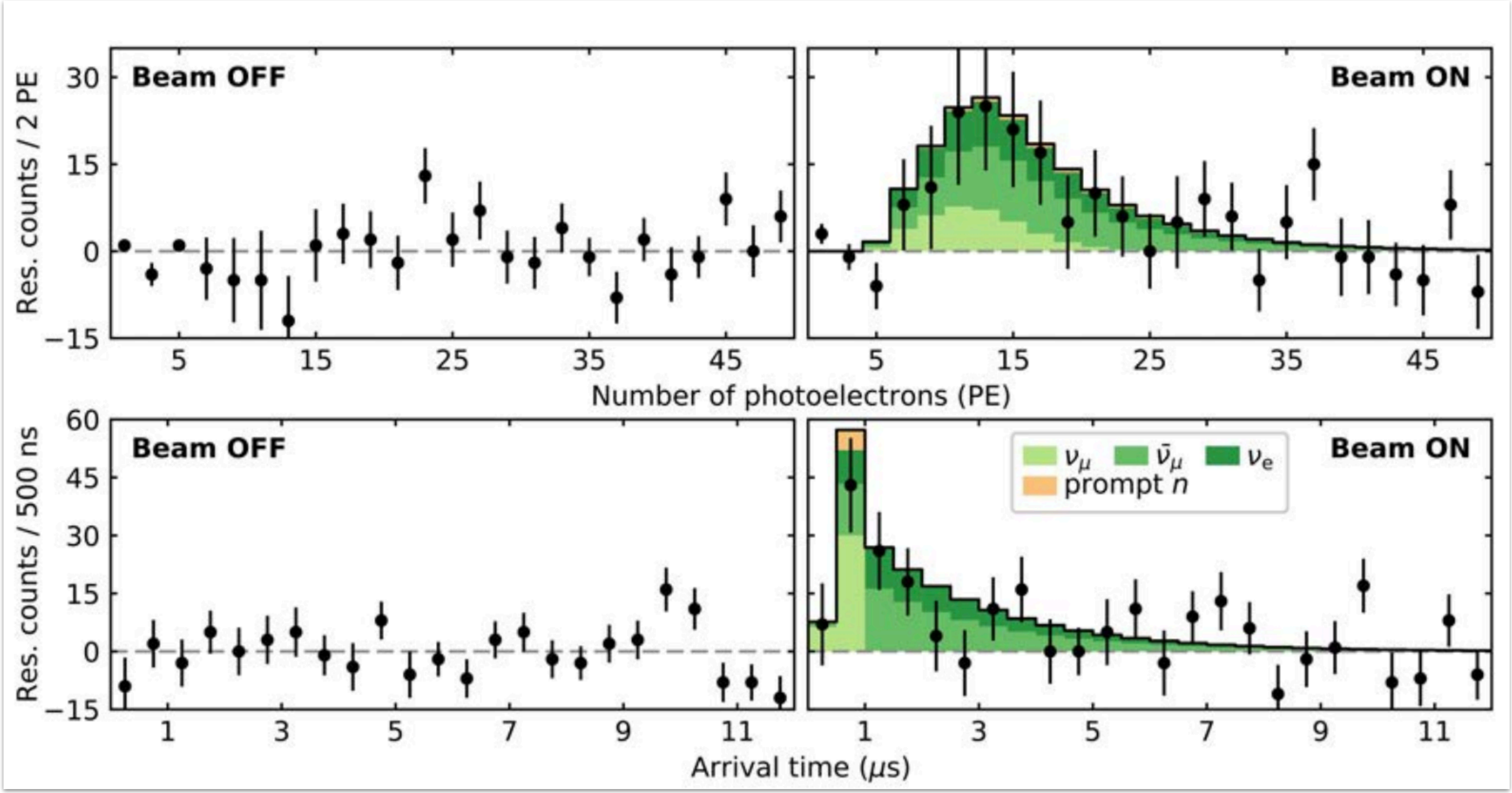
Challenges

① No $\ell^\pm$ Detect

② E_r Small
$\lesssim$ tens of keV

Successes with COHERENT

COHERENT collab., [1708.01294]

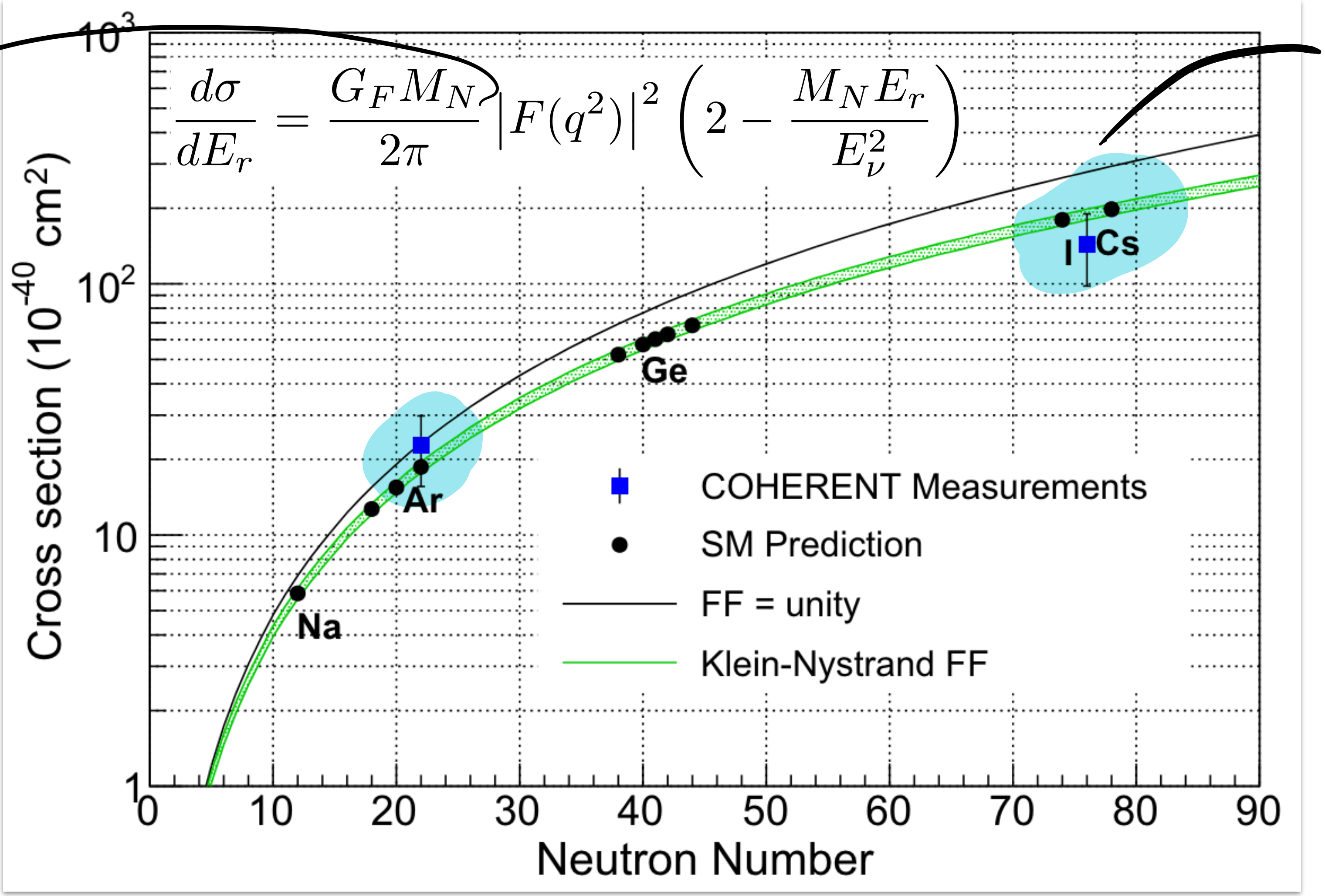


Successes with COHERENT pt. 2

COHERENT collab., [2003.10630]

Q_W^2

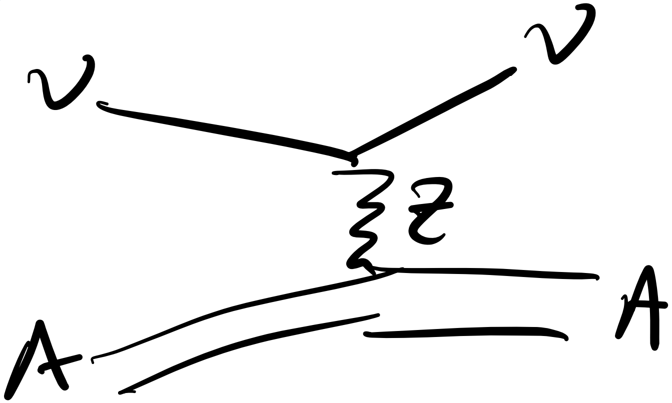
$\sigma \propto N^2$

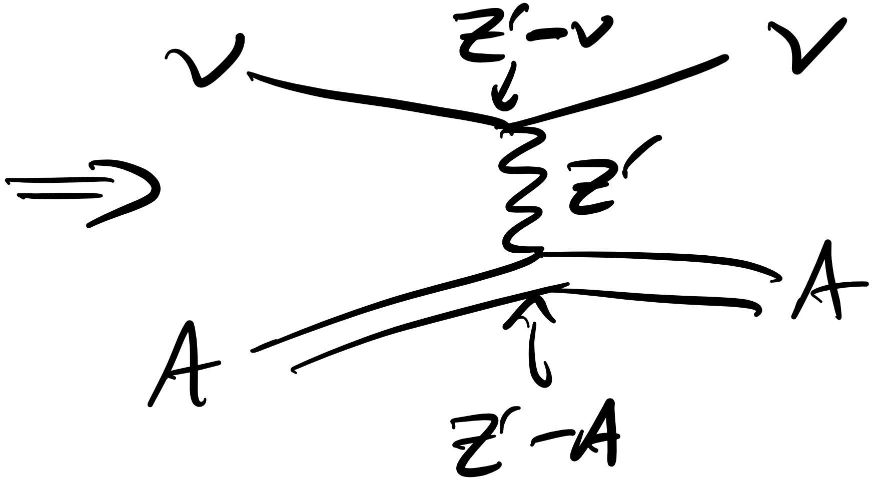


$$\frac{d\sigma}{dE_r} = \frac{G_F M_N}{2\pi} \left|F(q^2)\right|^2 \left(2 - \frac{M_N E_r}{E_\nu^2}\right)$$

Going BSM with CEνNS

e.g. Cadeddu et al, [2008.05022]





$\mathcal{M} \propto Q_w$

$\mathcal{M} \sim Q^{BSM}$

$$\sigma \sim Q_w^2 \Longrightarrow \left(Q_w + Q^{BSM}\right)^2$$

σ Depend on $O(Q^w Q^{BSM})$

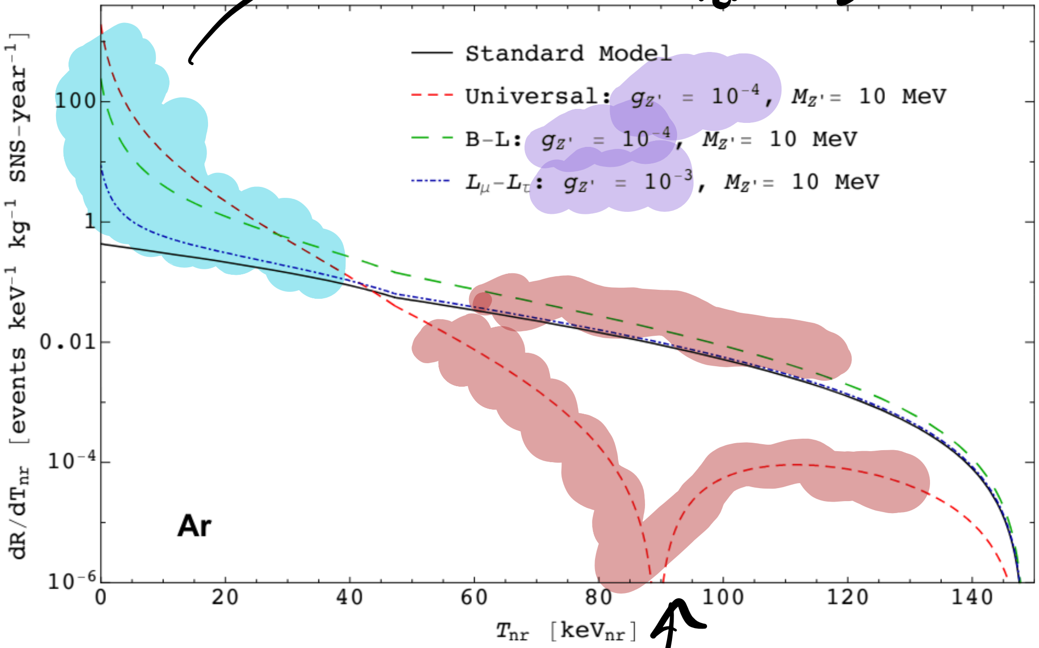
① Const. or Dest. Interference

$$Q_{BSM} = \pm \frac{Q'_\nu Q'_q}{\sqrt{2}\, G_F \left(|q|^2 + M_{Z'}^2\right)}$$

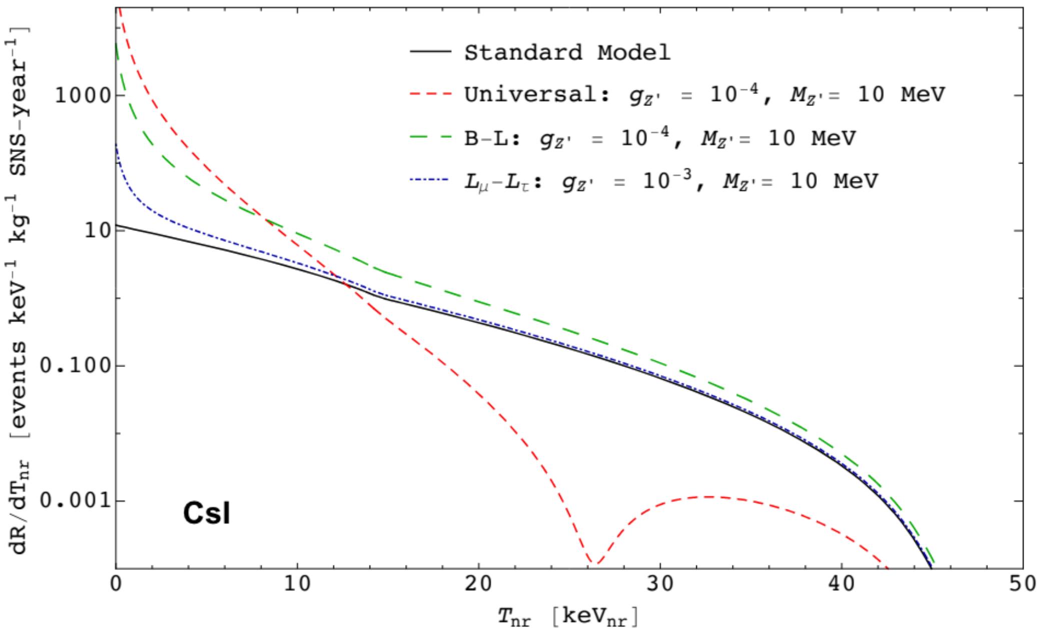
Enhancement From $M_{Z'} \ll M_Z$

Effect on Differential Cross Sections

$$Q^{BSM} \sim \frac{1}{|q|^2 + m_{Z'}^2} \left(\frac{1}{t - M_{Z'}^2} \right)$$

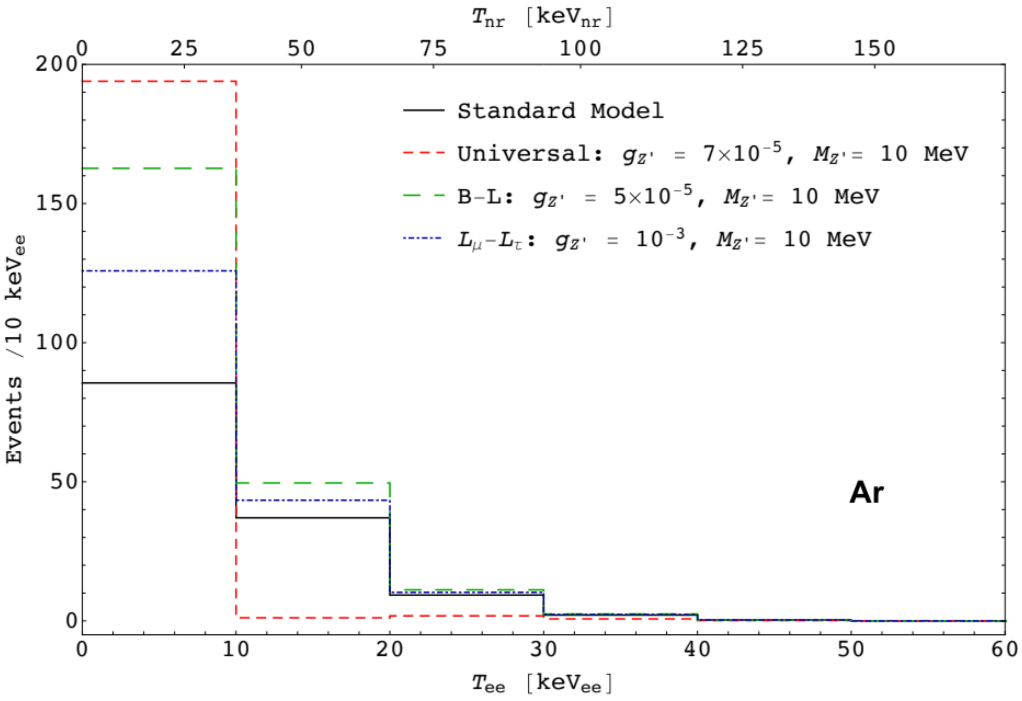


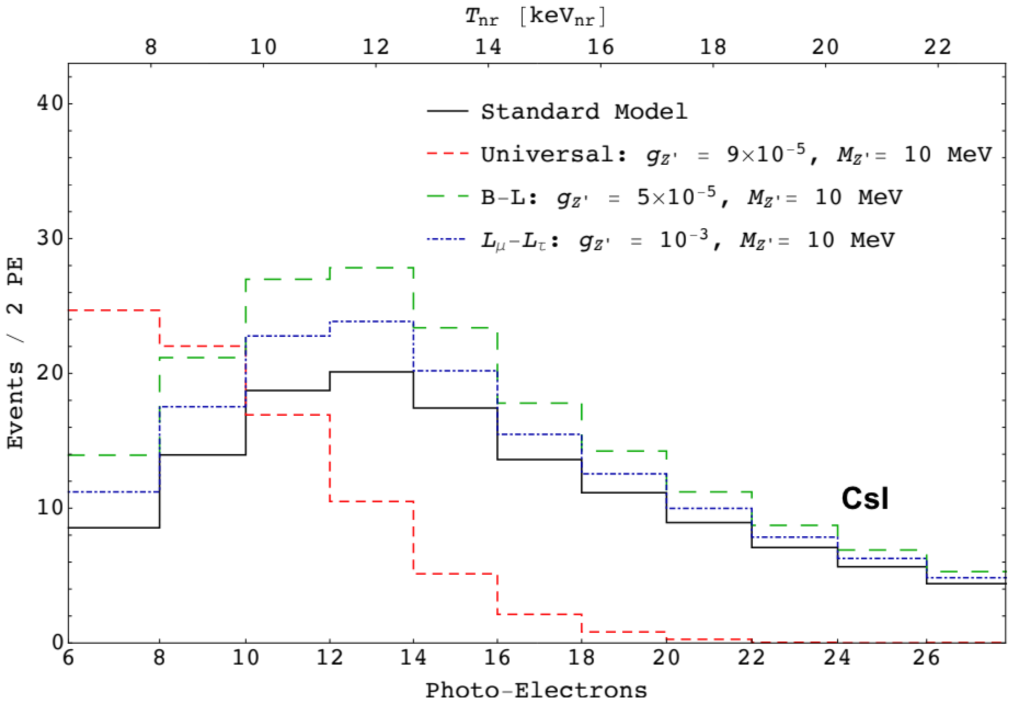
Dest. Int.



Cadeddu et al, [2008.05022]

Effect on CEνNS Event Rates





Cadeddu et al, [2008.05022]

Most "intriguing" BSM U(1) — $L_\mu - L_\tau$

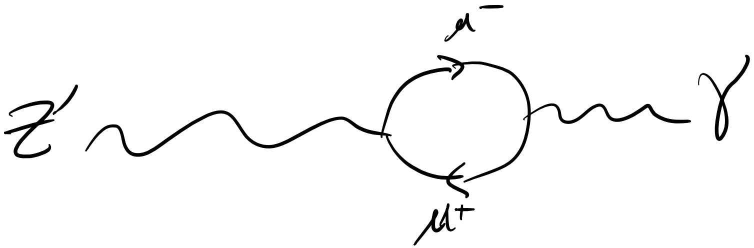
$$\mathcal{L} \supset g V_\mu J^\mu_{(L_\mu - L_\tau)}$$

$(g-2)_\mu$

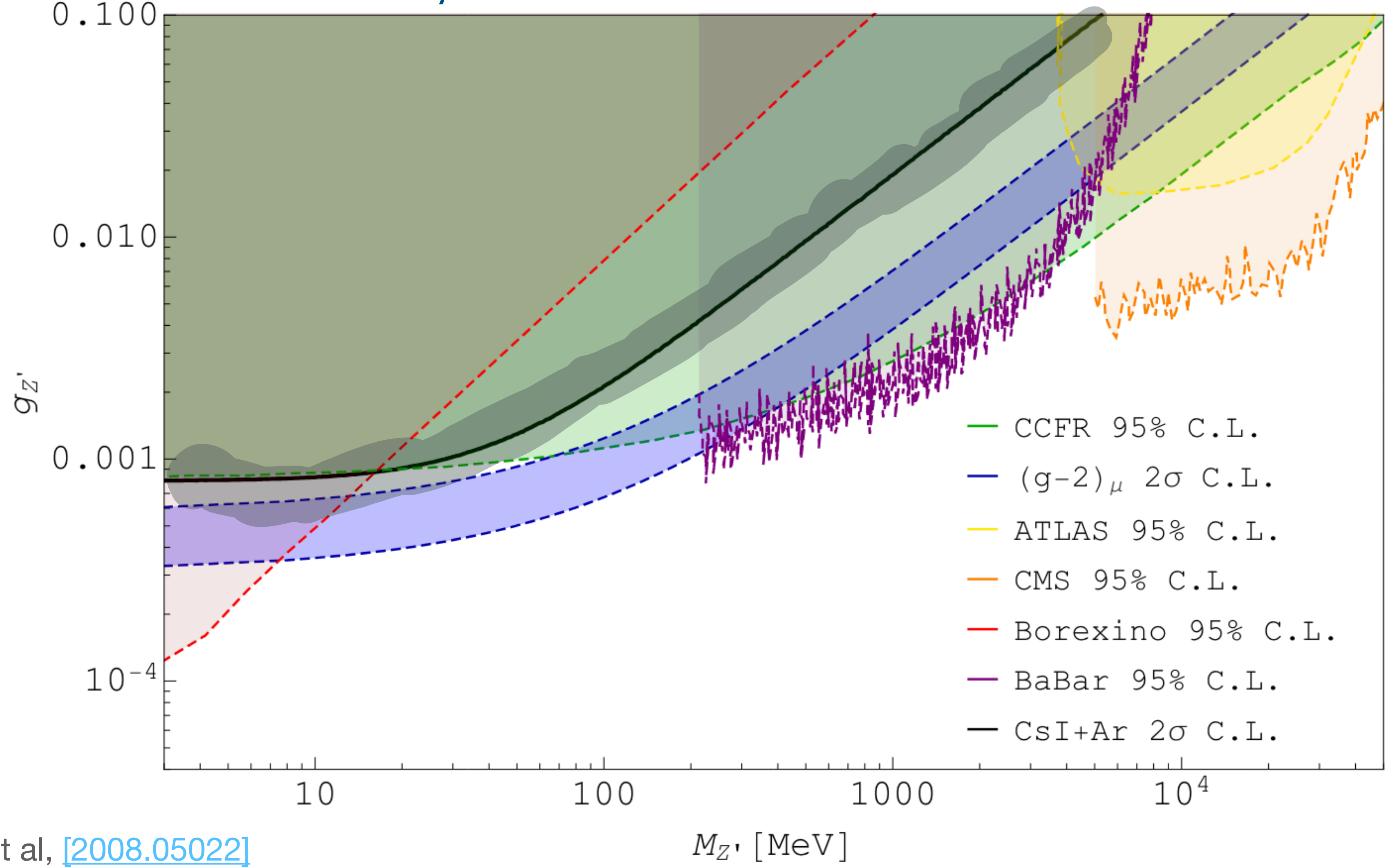
$m_{Z'} \sim 100$ MeV

$g \sim 10^{-3}$

$$\Rightarrow \varepsilon_{\text{eff.}} \sim g \times \log\left(\frac{m_\mu^2}{m_\tau^2}\right)$$

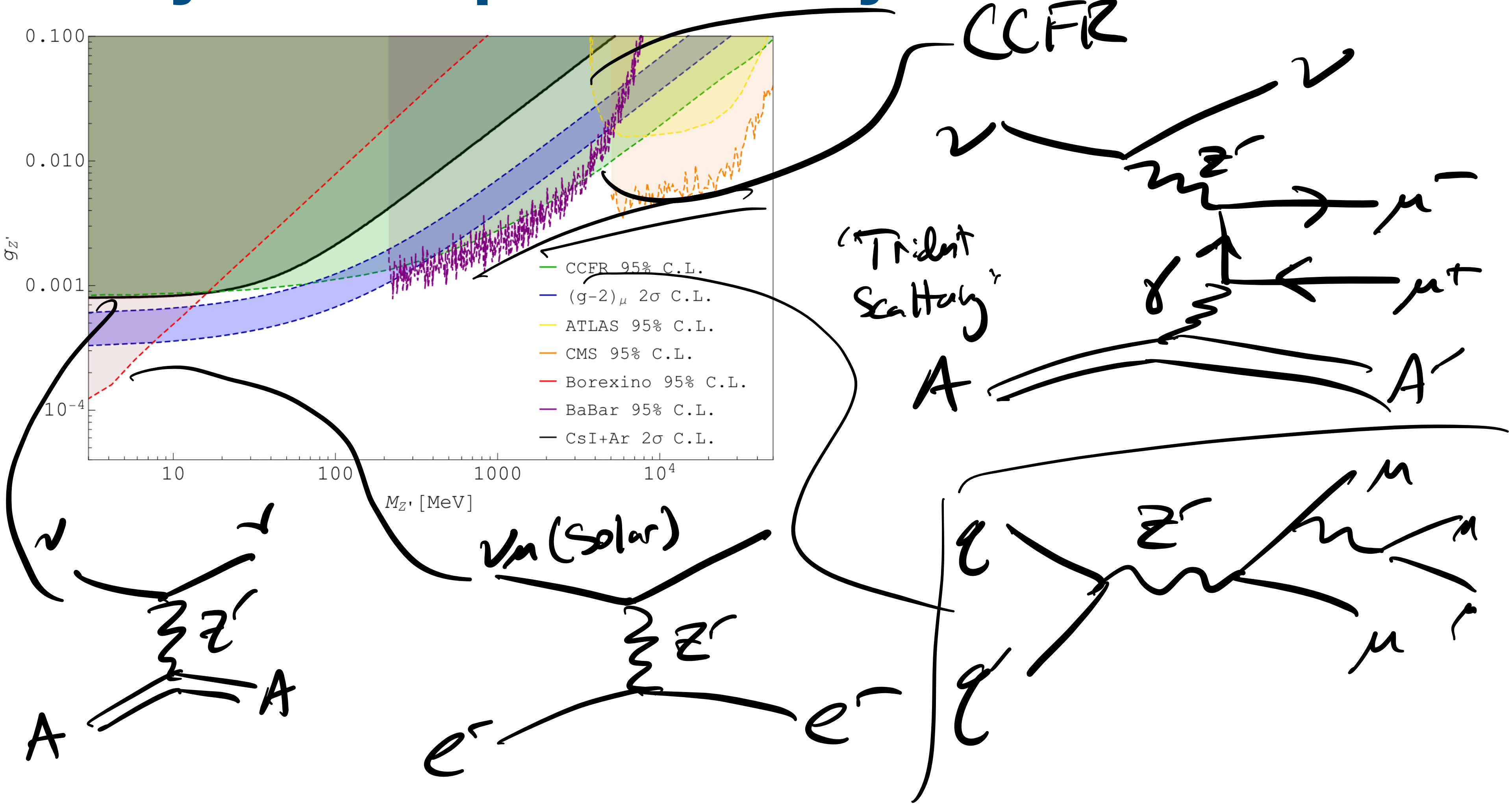


COHERENT and $L_\mu - L_\tau$



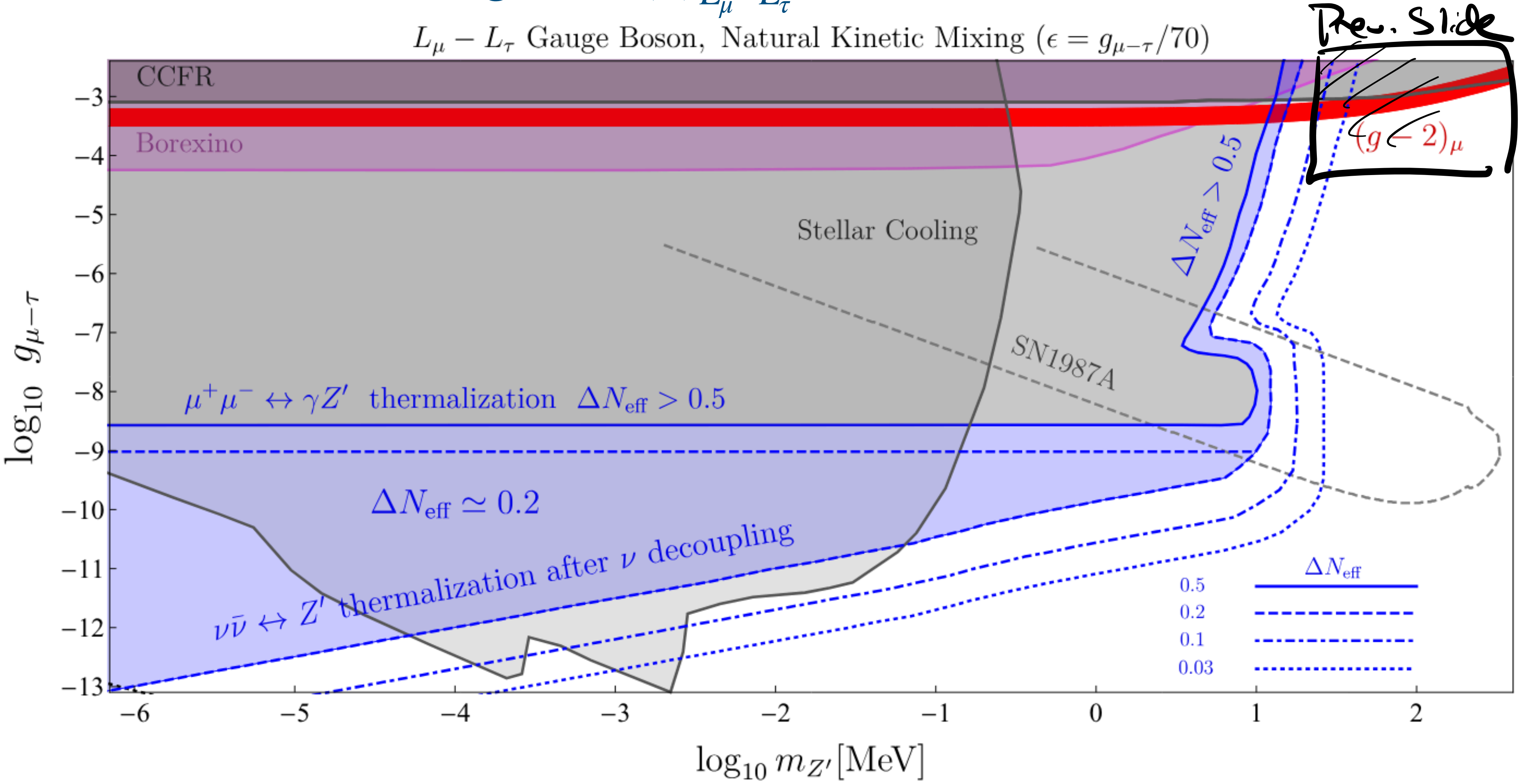
Cadeddu et al, [2008.05022]

Beauty of Complementarity



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

Escudero* et al, [1901.02010]



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