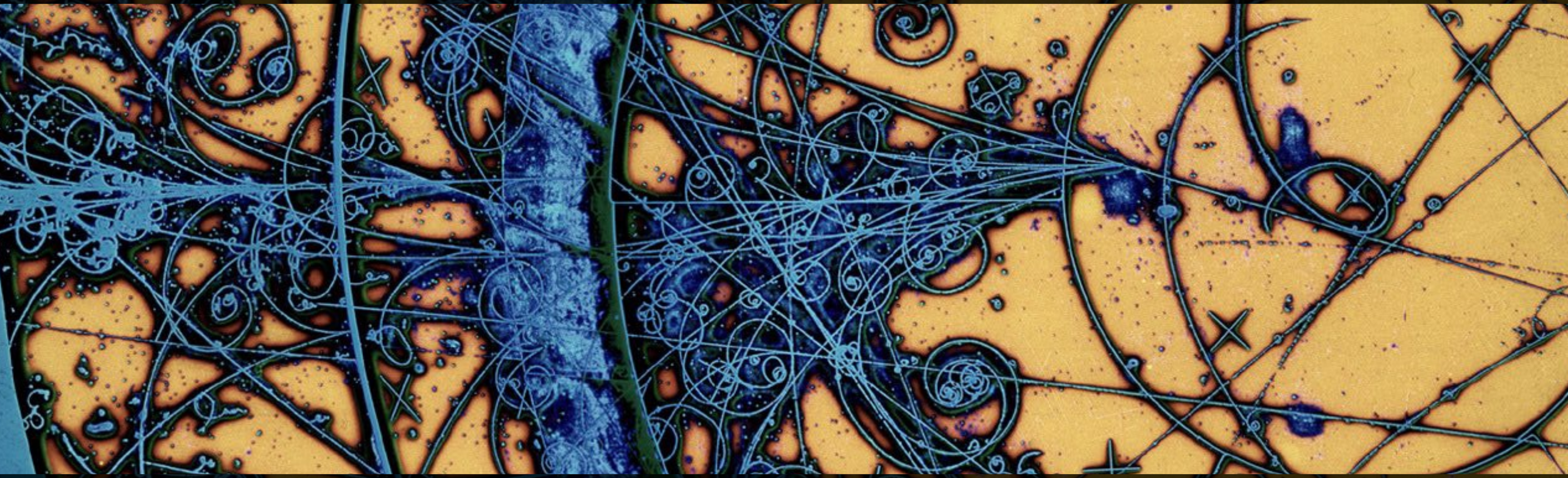
Neutrinos at the Frontiers of Particle Physics: Present and Future

Columbia University, Dec 8th, 2025

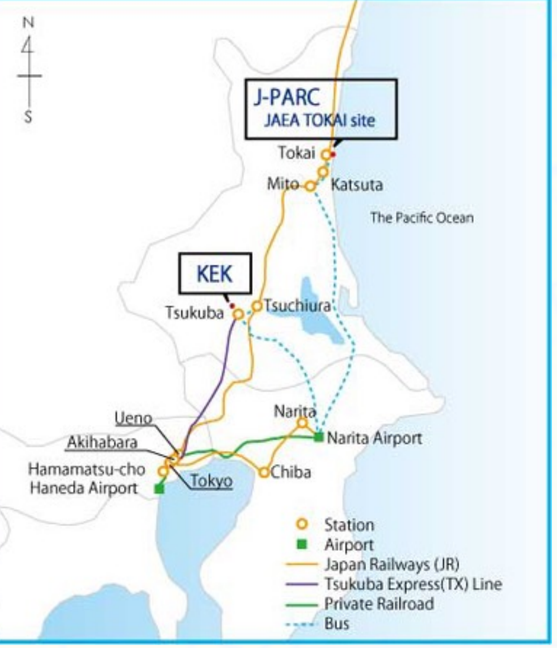


BEBC CERN-EX-66954B-1 © 1998-2025 CERN

Matheus Hostert matheus-hostert@uiowa.edu
University of Iowa

This talk: some aspects **neutrino phenomenology**

- **Neutrino masses and the Standard Model**
- **Neutrino experiments to search for rare phenomena.**
- **Towards novel neutrino beams in a future μ-collider campus.**



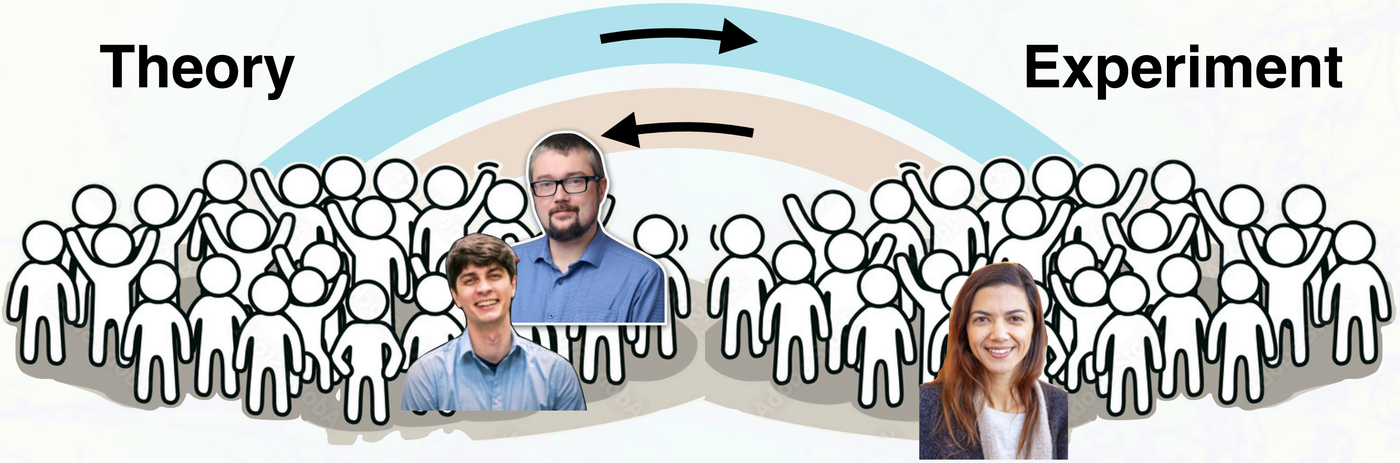
NEAT: Neutrino Experiment and Theory (Workshop)

2nd Short-Baseline Experiment-Theory Workshop, April 2nd to 5th 2024

5th New Physics Opportunities at Neutrino Facilities Workshop (NPN 2025)

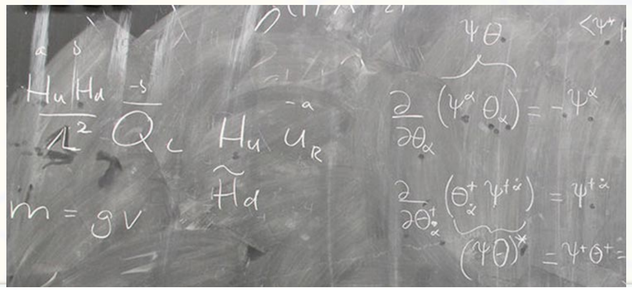
NPν 2025 @ CINCINNATI

Phenomenology



Joint workshops

Fermilab Theory division



CERN theory division

Joint Experimental-Theoretical Physics Seminar

This is the so-called “Wine and Cheese” seminar.

Regular seminars are **Fridays at 3:30 p.m.** in Wilson Hall, One West.

Roadmap

The Standard Model

Understanding the neutrino mass puzzle

Sterile Neutrinos

Signatures, progress, and puzzles

Broader Dark Sectors

Casting a wide net

Neutrinos at a future high-energy frontier

Muon Colliders

Roadmap

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STANDARD MODEL

The SM is not wrong…

But more than “reasonable doubt”
that it is **not** the end of the story.

Incompleteness:

Neutrino masses and mixing

Dark matter

Descriptive rather than predictive:

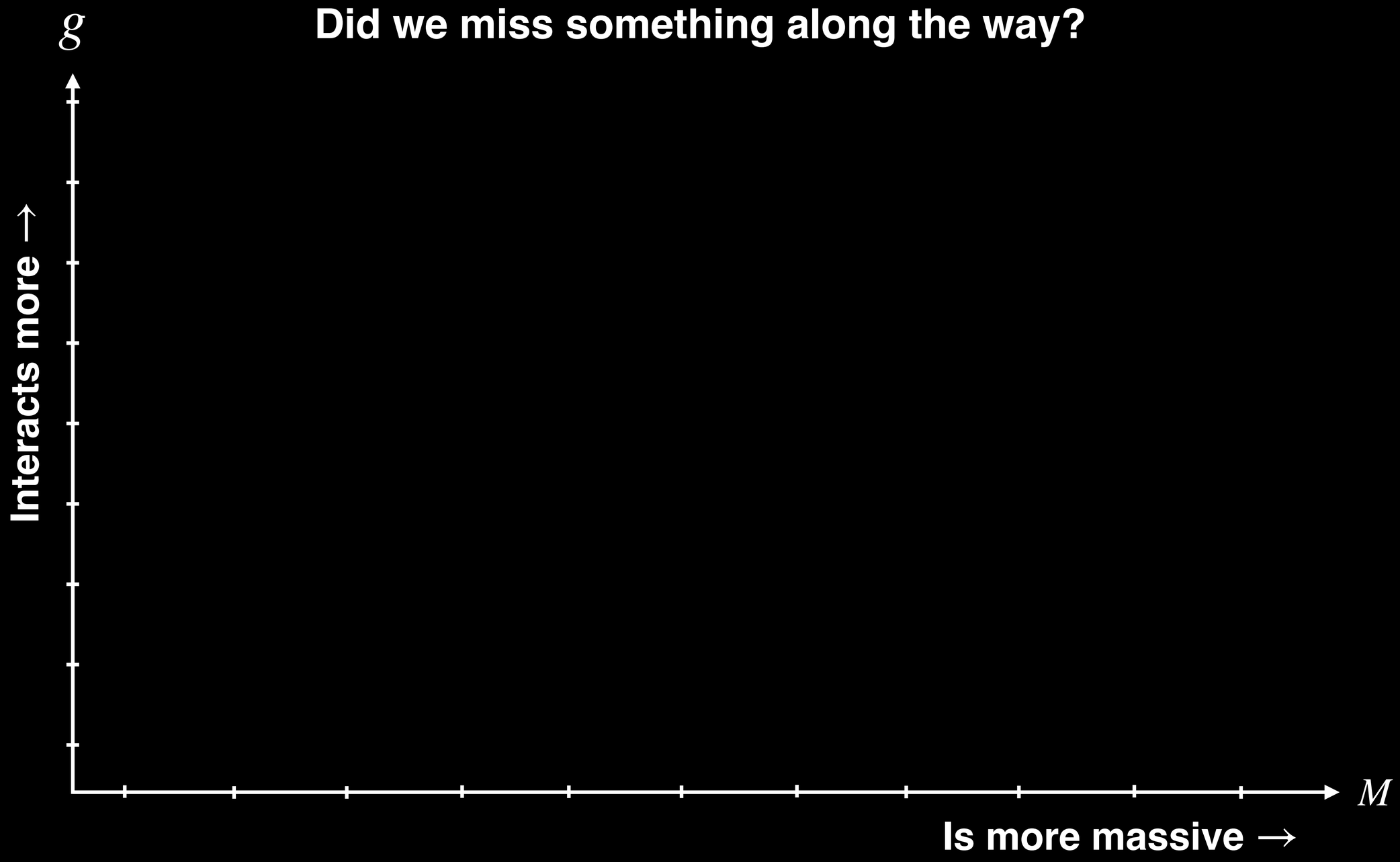
Fermion mass pattern?

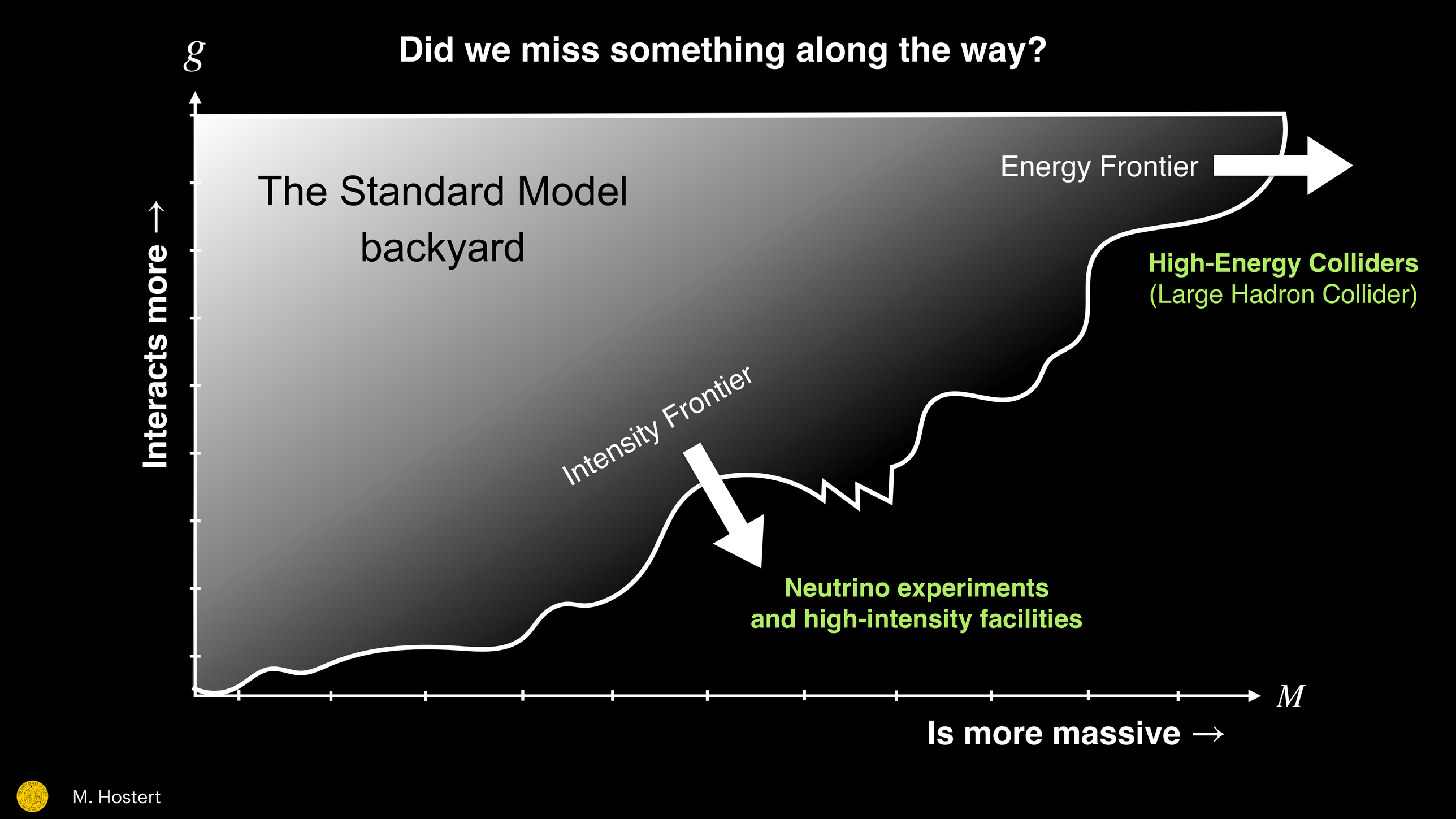
Absence of CP violation in strong force?

Why is the Higgs mass so small?

Matter-antimatter asymmetry?

Did we miss something along the way?




Did we miss something along the way?
g
Interacts more →
The Standard Model backyard
Energy Frontier
High-Energy Colliders
(Large Hadron Collider)
Intensity Frontier
Neutrino experiments
and high-intensity facilities
M
Is more massive →

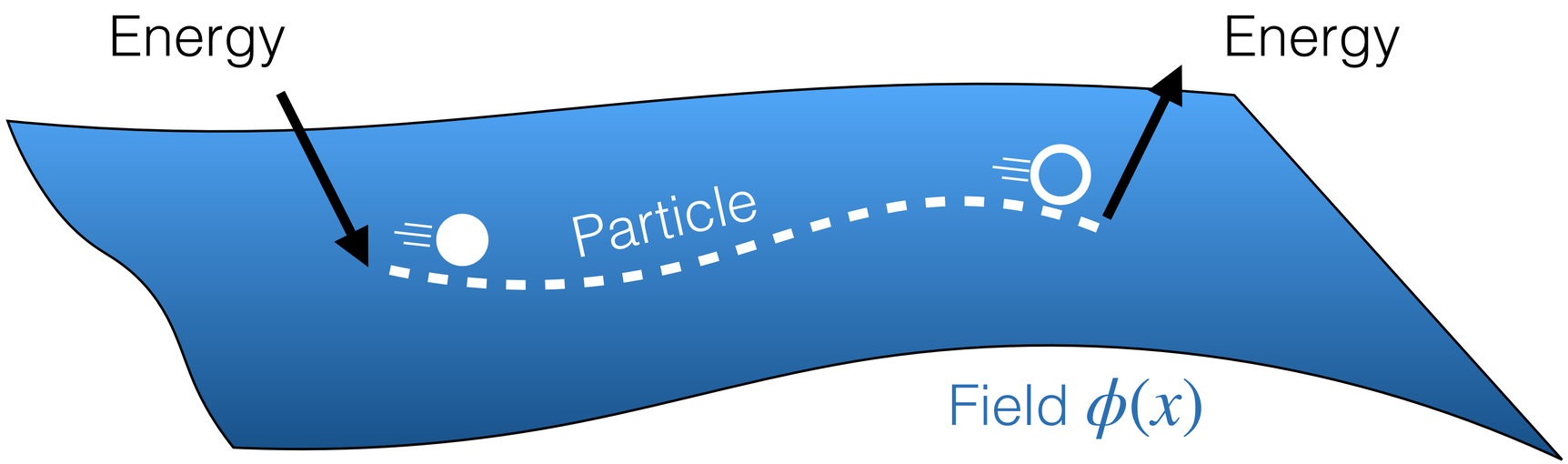
The Standard Model

~ 17 particles?

Quanta Magazine: A New Map of the Standard Model of Particle Physics

Particles and Fields

Particles are the smallest excitations of “**quantum field”**

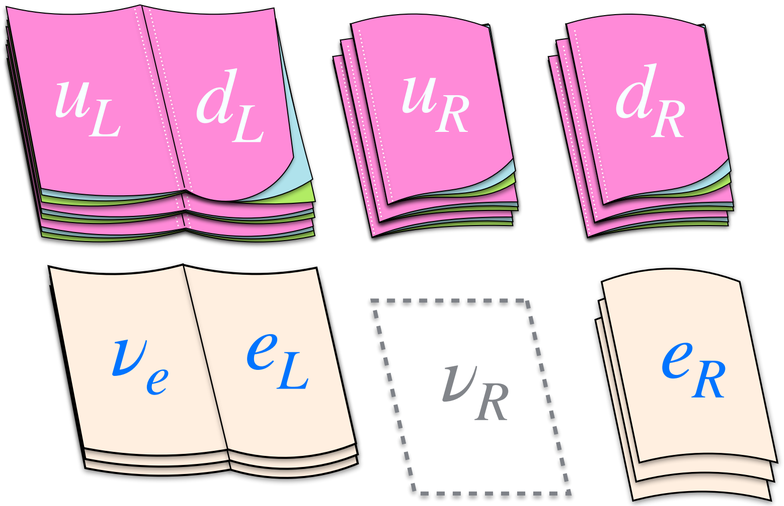


Each particle is associated with its own field

The Standard Model (actually)

More like ~76 different fields…
with a rich symmetry structure.

Matter Content



All Fermions

(Spin-1/2)

The Higgs

The Higgs Boson

(Spin-0)

Dynamics

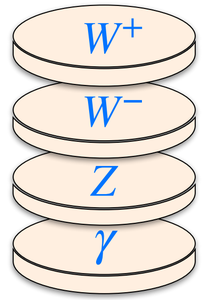
(Symmetries)

Strong Force

$\mathrm{SU}(3)$

Electroweak Force

$\mathrm{SU}(2) \times \mathrm{U}(1)$



The “two" forces and their mediators

Bosons (Spin-1)

The Standard Model (actually)

More like ~76 different fields…
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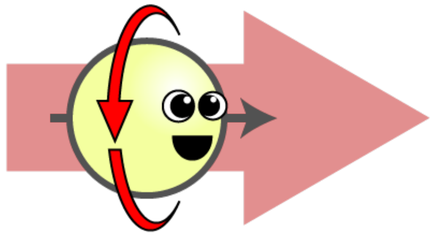
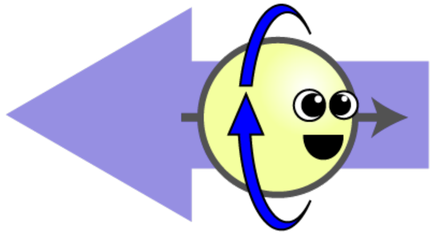
Right-handed $h = +1/2$



Left-handed $h = -1/2$



Chirality or "handedness"

Just another quantum number like charge or spin.

For ultra-relativistic (or massless) particles,
it coincides with **helicity**:

$$h = \frac{\vec{s} \cdot \vec{p}}{|\vec{p}|} = \pm \frac{1}{2}$$

This turns out to be an extremely important in the Standard Model.

https://www.quantumdiaries.org/2011/08/23/the-spin-of-gauge-bosons-vector-particles/

Weak Interactions are “Left-Handed”

Experimental Test of Parity Conservation in Beta Decay*

C. S. Wu, *Columbia University, New York, New York*

AND

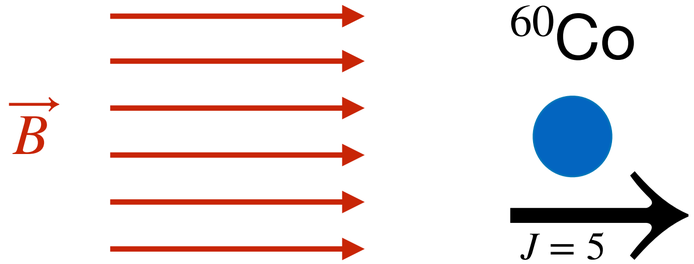
E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson, *National Bureau of Standards, Washington, D. C.*

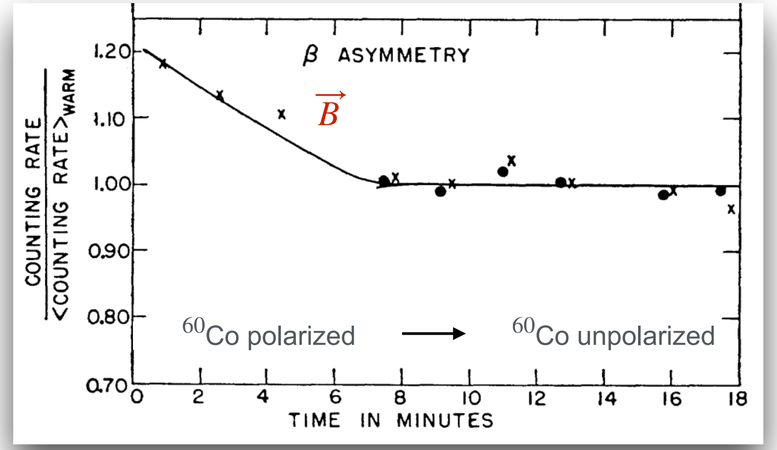
(Received January 15, 1957)

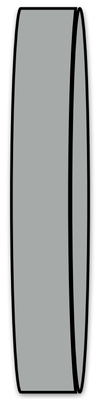
C.S. Wu, “Madame” Wu

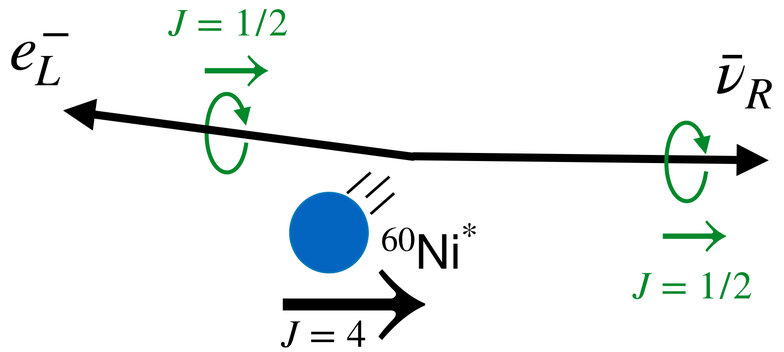
$$^{60}\mathrm{Co} \rightarrow {}^{60}\mathrm{Ni}^{*} + e^{-} + \bar{\nu}_e$$

$$(J = 5) \longrightarrow \left(J = 4 + \frac{1}{2} + \frac{1}{2}\right)$$









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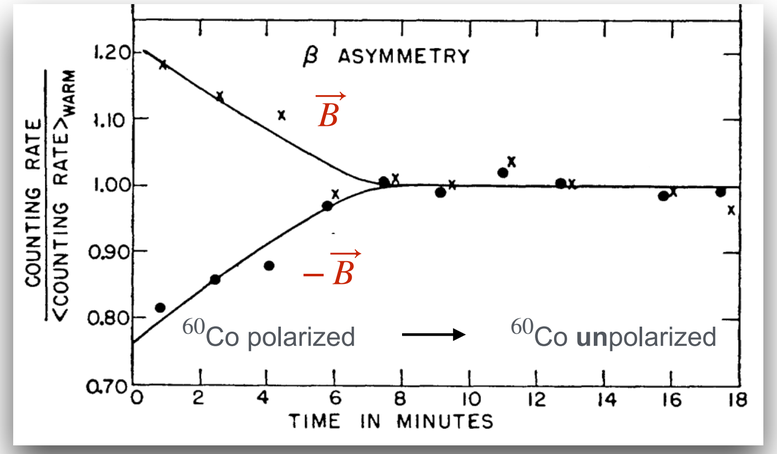
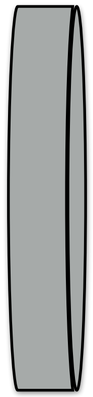
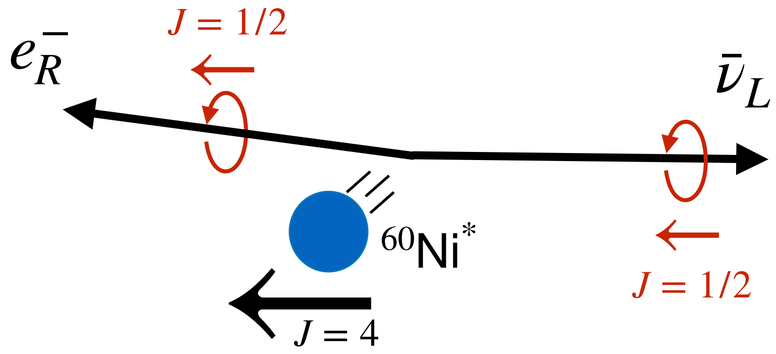


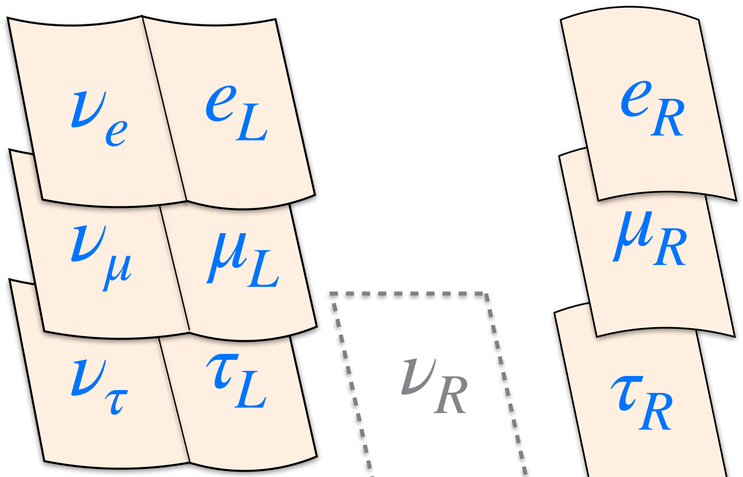
Detector

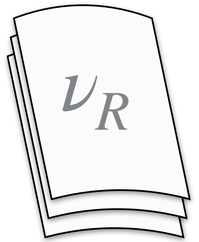




How many neutrinos?

“Sterile” or “right-handed" neutrinos.

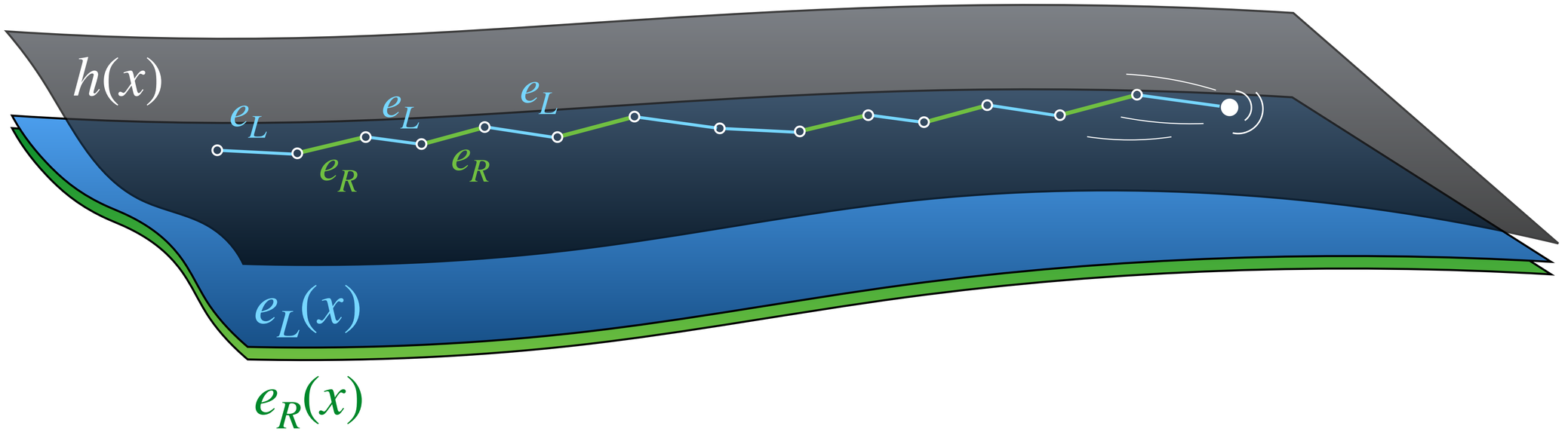




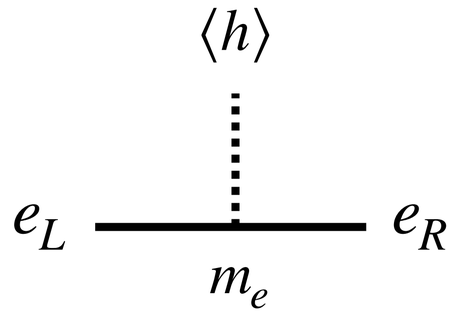
?

If they exist, ν_R neutrinos would not interact with any known force.

Cartoonish picture fermion masses from the Higgs field



Electron-Higgs **interactions** give rise to the electron mass.

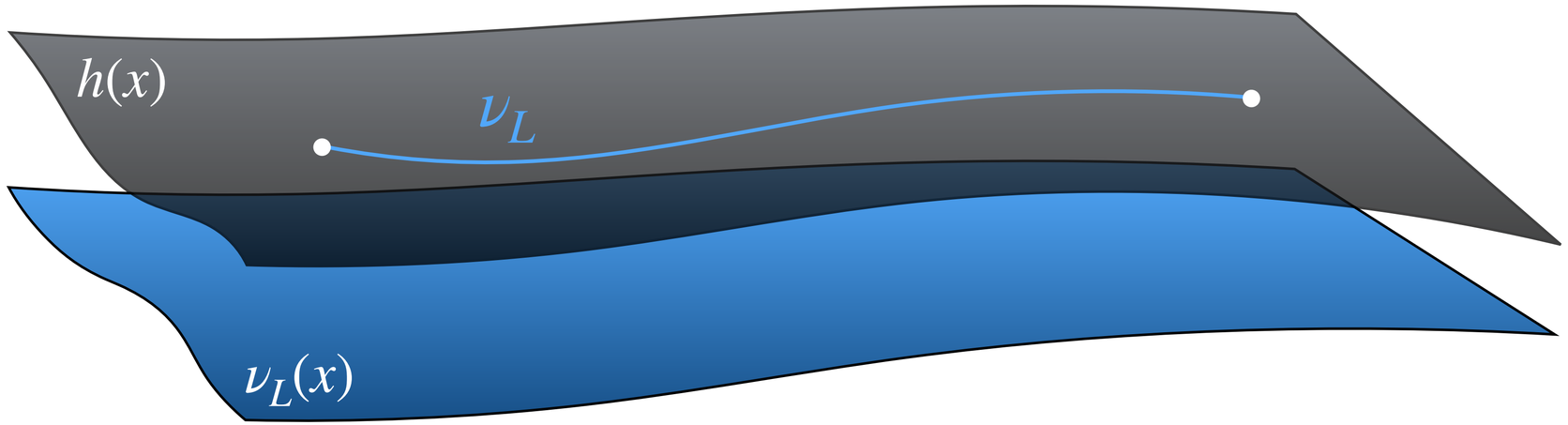


"e_L" and "e_R" are two sides of the same coin:

The Dirac fermion "e"

This is a "phib" (a physics fib): see this nice discussion by M. Strassler

The problem with neutrinos

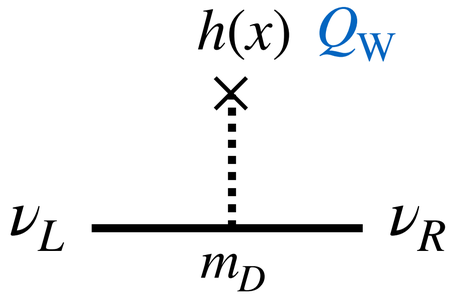


Without ν_R, the Standard Model predicts massless neutrinos.

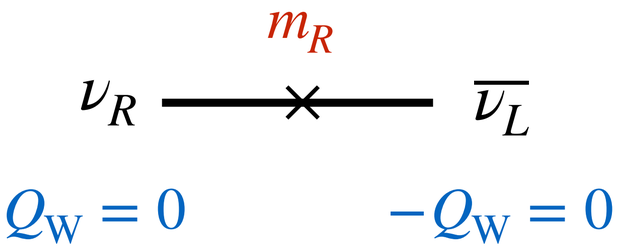
As you know, this is **not** compatible with the fact that neutrinos oscillate!

The Ambiguity of Neutrino Masses

Dirac Mass



Majorana Masses



Neutrinos carry no charge, so **Majorana masses are allowed.**

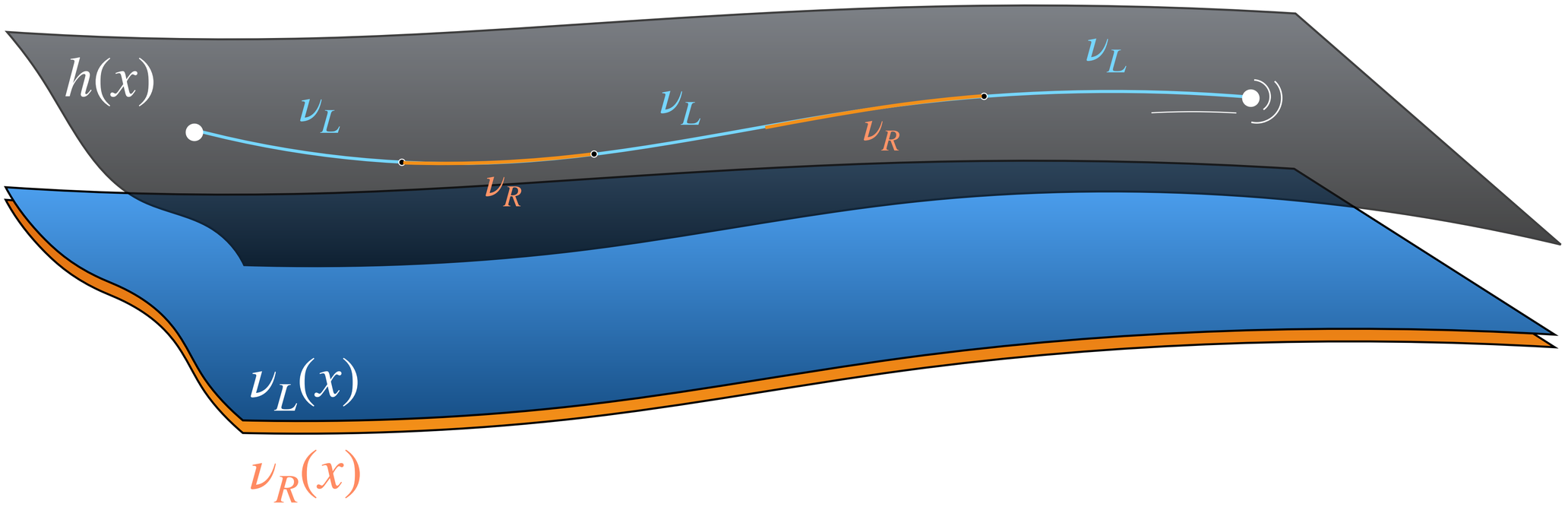
The only fundamental fermion we know of that can do this.

ν_R is “sterile” — it need not carry any (conserved) quantum number.

Dirac Neutrinos

Without a Majorana masses, ν_R is just part of light neutrinos

("ν_L and ν_R are two sides of the same coin")



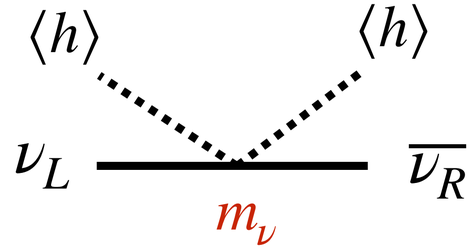
The seesaw mechanism

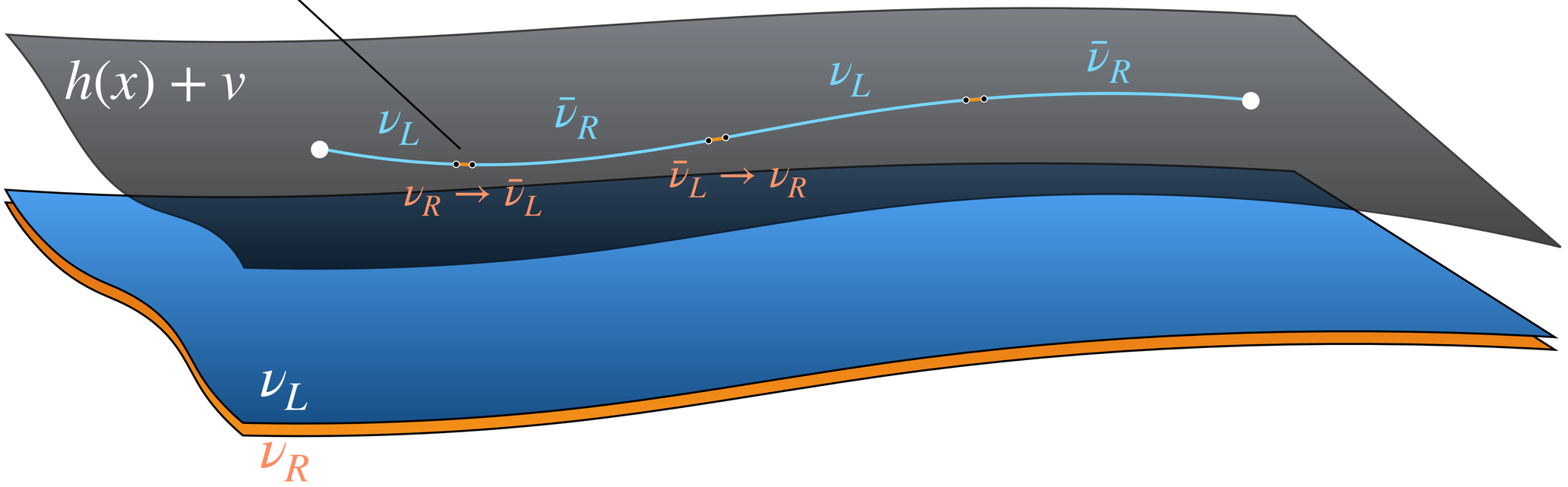
Light Majorana neutrinos become lighter
the heavier the heavy Majorana neutrino becomes.

$$\delta t \delta E > \frac{\hbar}{2} \implies \delta t \sim \frac{1}{m_R}$$

$$\boxed{m_\nu \sim \frac{m_D^2}{m_R}}$$

Effectively:





Roadmap

The Standard Model

Understanding the neutrino mass puzzle

Sterile Neutrinos

Signatures, progress, and puzzles

Broader Dark Sectors

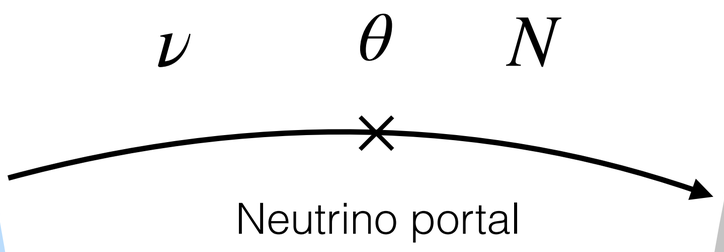
Casting a wide net

Neutrinos at a future high-energy frontier

Muon Colliders

STANDARD MODEL

HIDDEN SECTOR



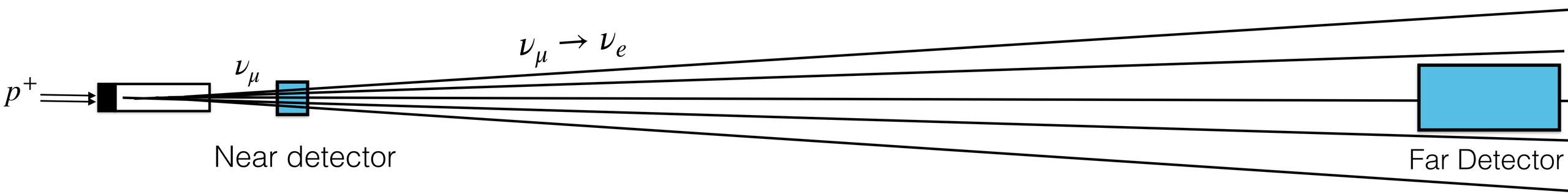
Heavy Neutrinos

New particles carry no SM charge.

New fundamental mass scales.

Light and feebly-coupled particles.

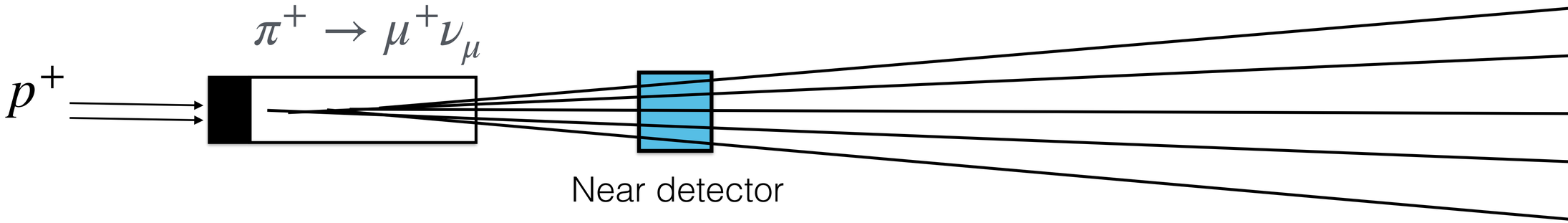
Accelerator Neutrino Experiments

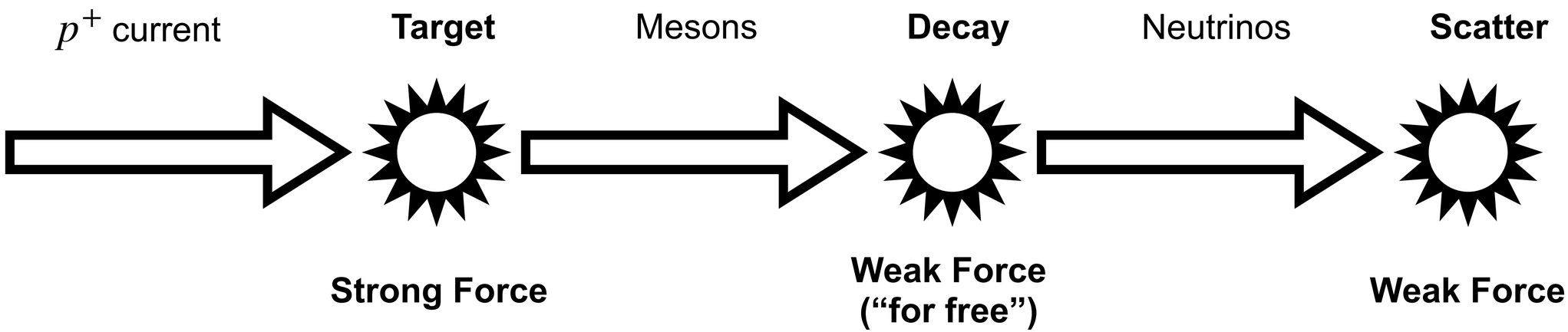


Standard Oscillations

Accelerator Neutrino Experiments

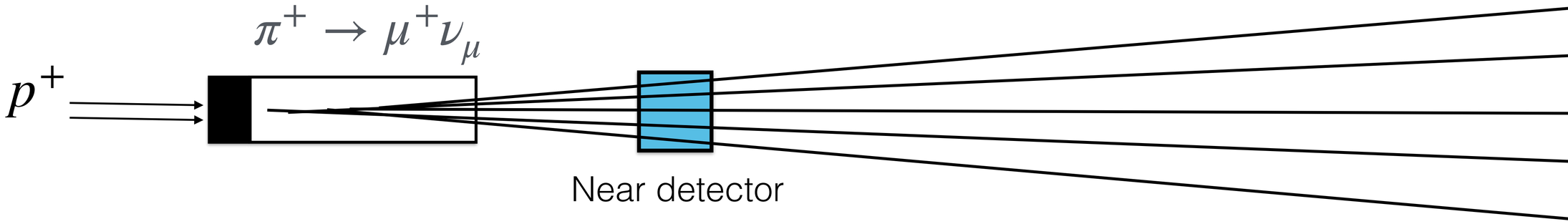
Near detectors / short-baselines

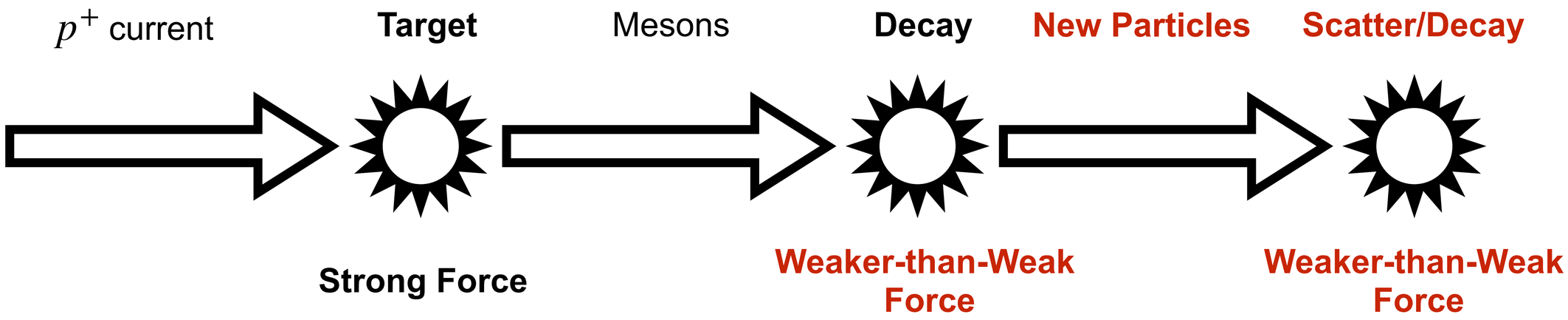




Accelerator Neutrino Experiments

Near detectors / short-baselines





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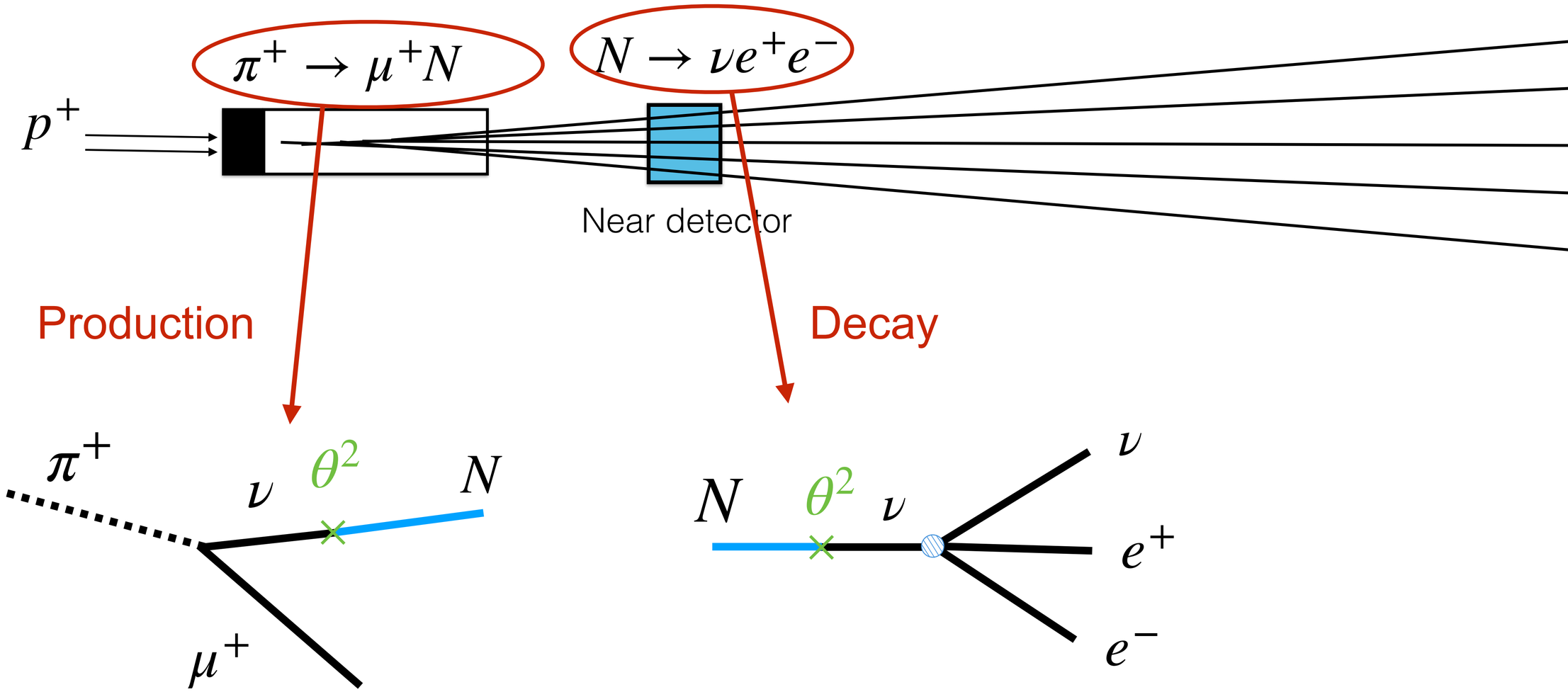

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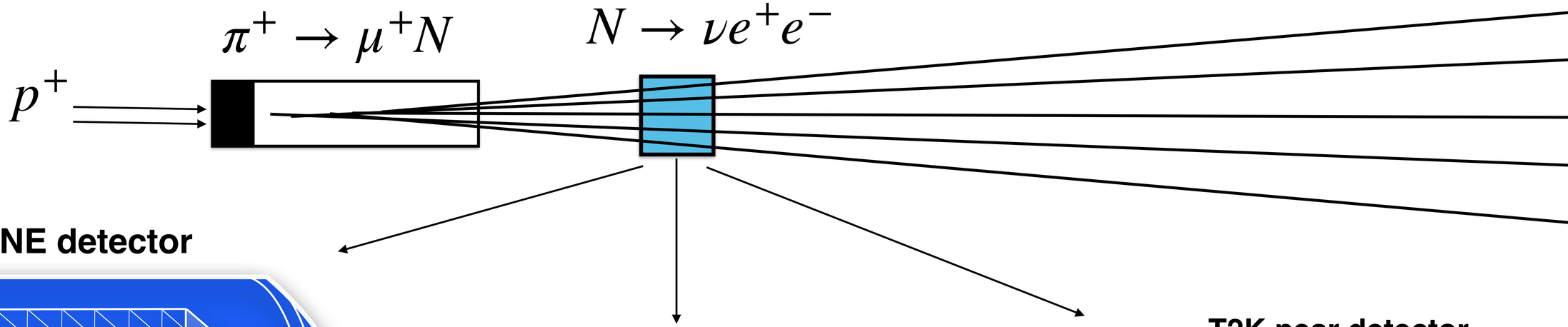
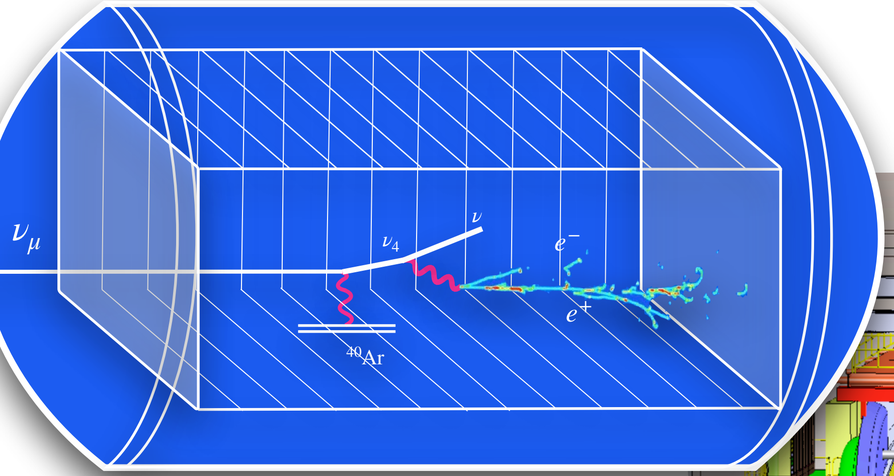
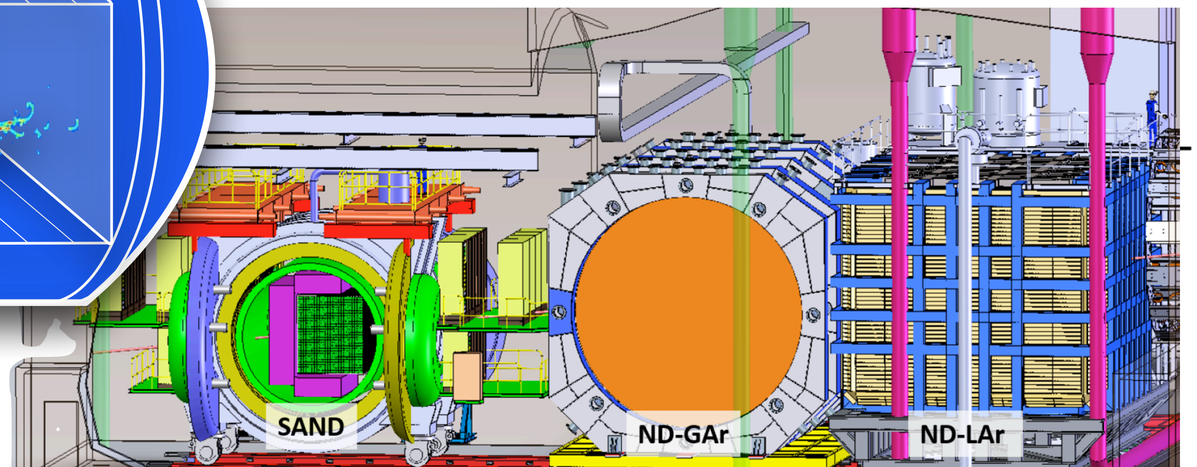


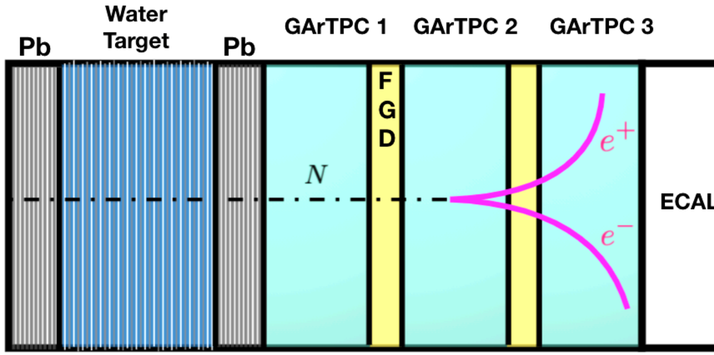
MicroBooNE detector



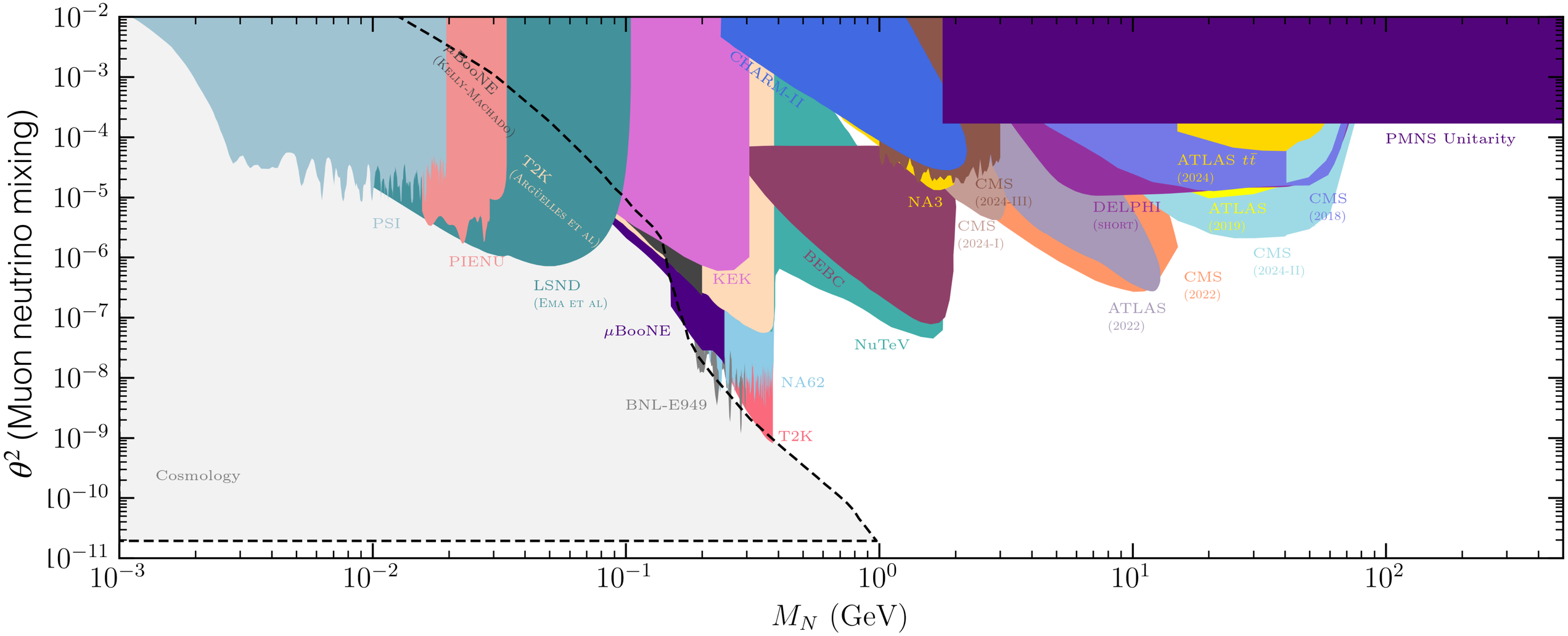
DUNE near detector complex



T2K near detector



Parameter Space of Hypothetical Heavy Neutrinos



M. Hostert

github.com/mhostert/Heavy-Neutrino-Limits

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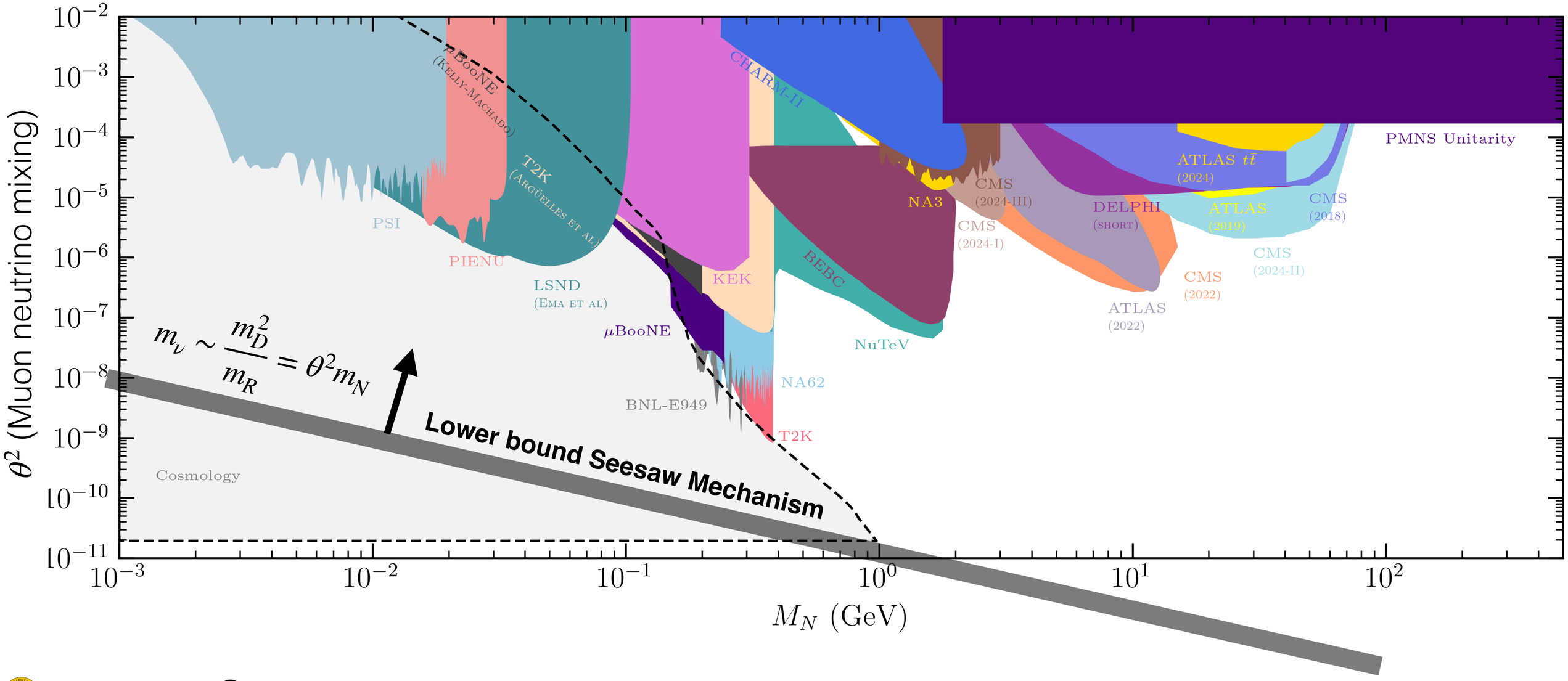

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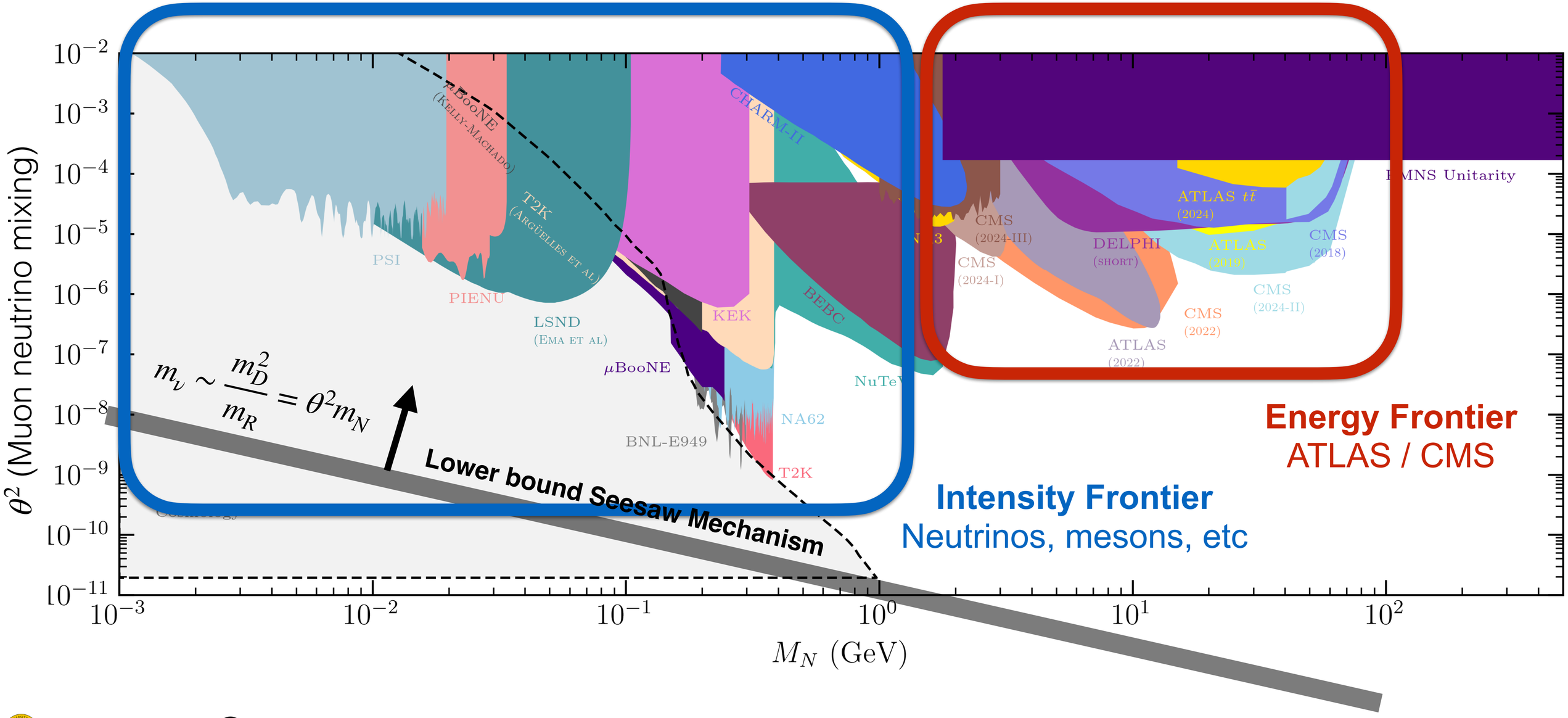

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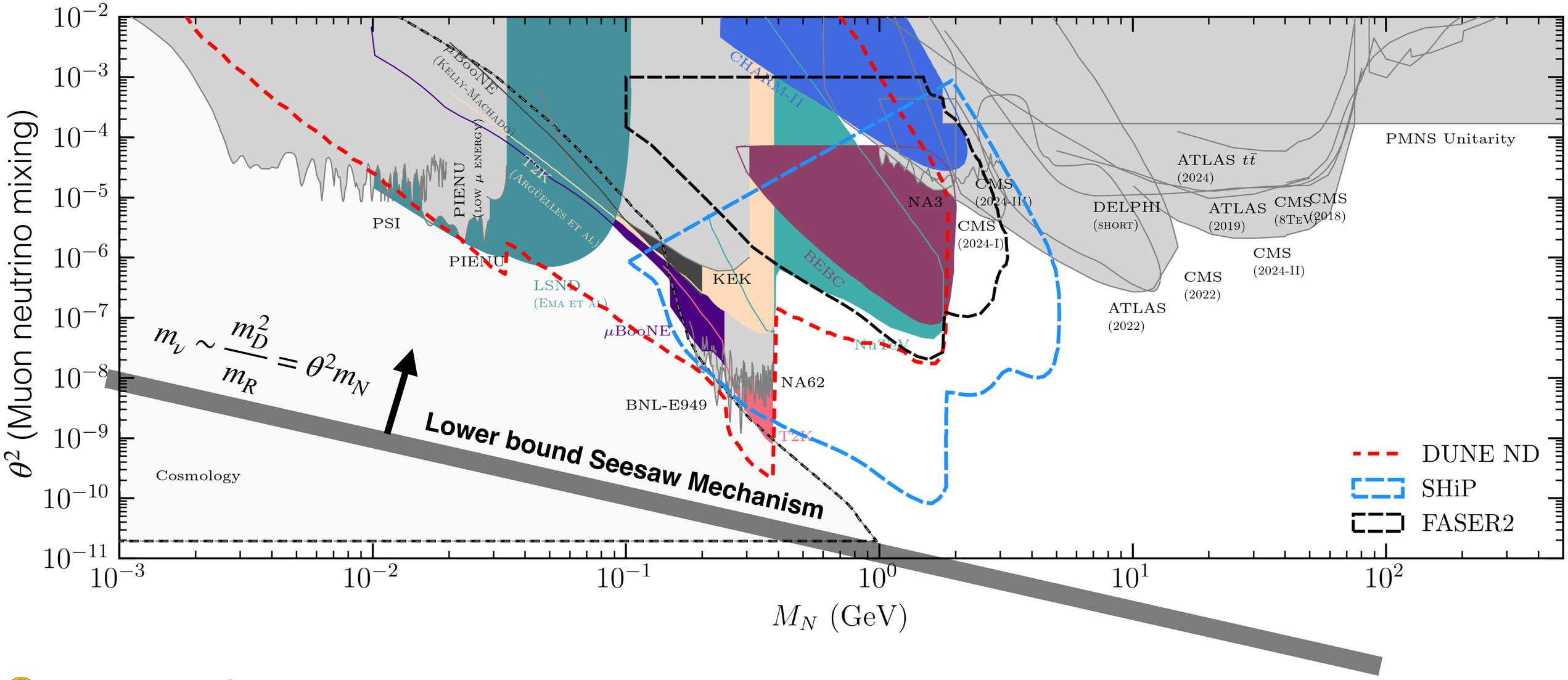

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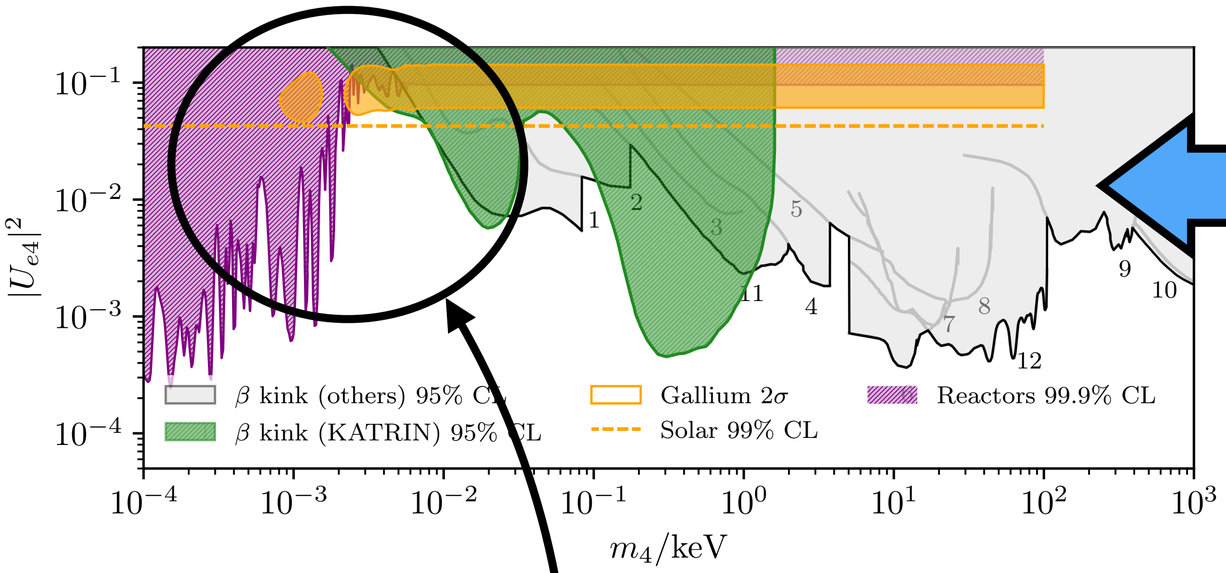
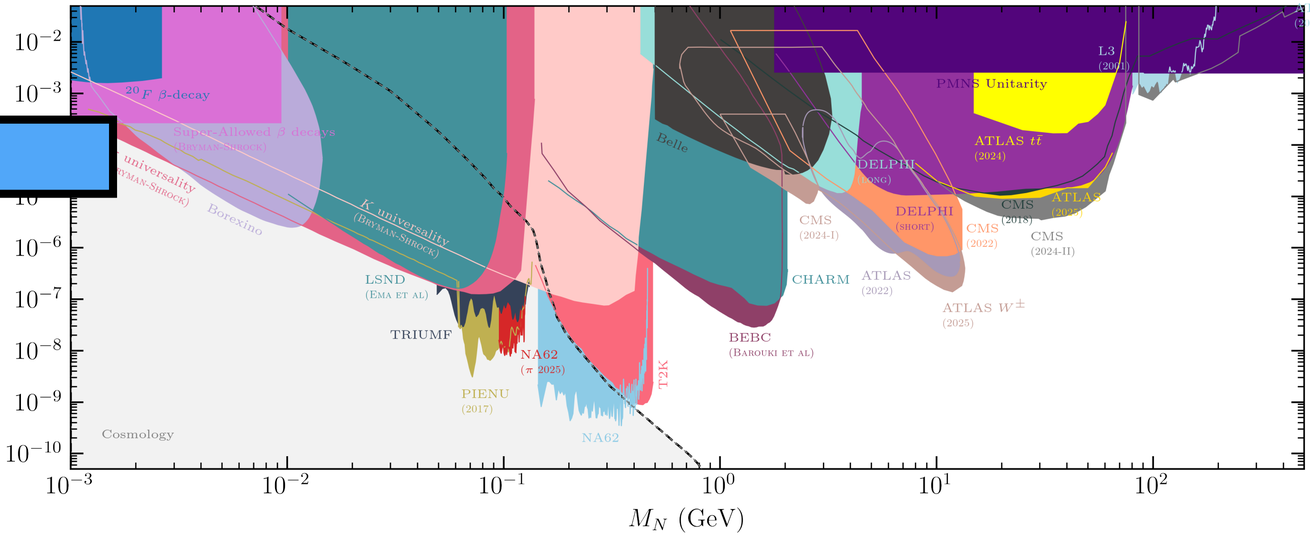
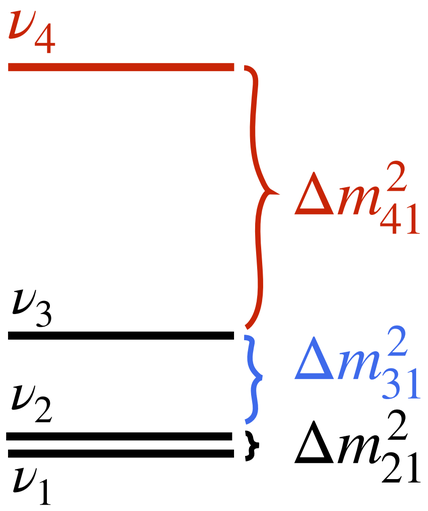




eV-scale sterile-neutrino driven oscillations

"3+1 model"



Article | Open access | Published: 03 December 2025

Search for light sterile neutrinos with two neutrino beams at MicroBooNE

The MicroBooNE Collaboration

Nature **648**, 64–69 (2025) | Cite this article

But see also:

O. Benevides Rodrigues, MH, K. J. Kelly,
B. Littlejohn, P. A. N. Machado, I. Safa, T. Zhou
PRL 135, 081801

Roadmap

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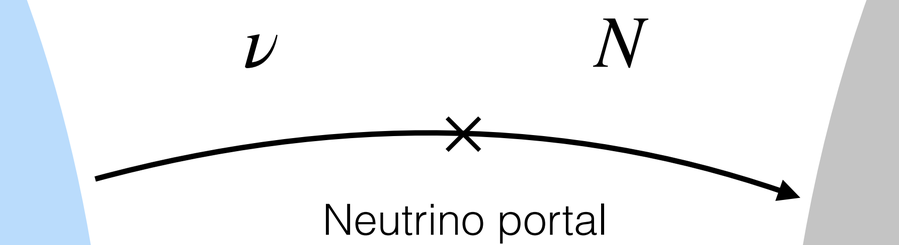
STANDARD MODEL

DARK SECTOR

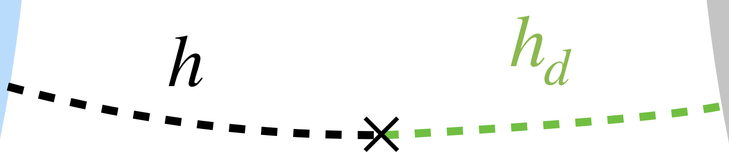


Neutrino portal

Heavy Neutrinos

Photon portal

Dark photons



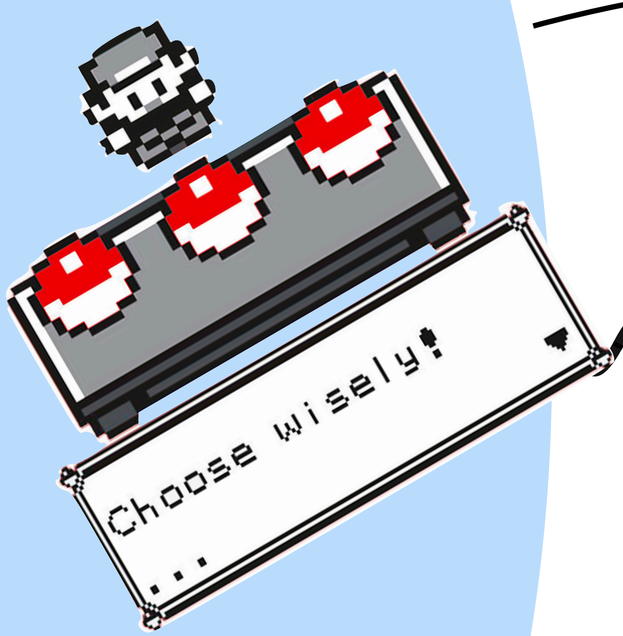
Higgs portal

Dark Higgs

Axions and Axion-like-particles

Axions (goldstone bosons)

STANDARD MODEL



ν N

Neutrino portal

γ γ_d

Photon portal

h h_d

Higgs portal

Axions and Axion-like-particles

DARK SECTION

Heavy Neutrinos

Dark photons

Dark Higgs

Axions (goldstone bosons)

DARK SECTOR

Just the “starter” options.
“Bottom up” approach.

dark matter?

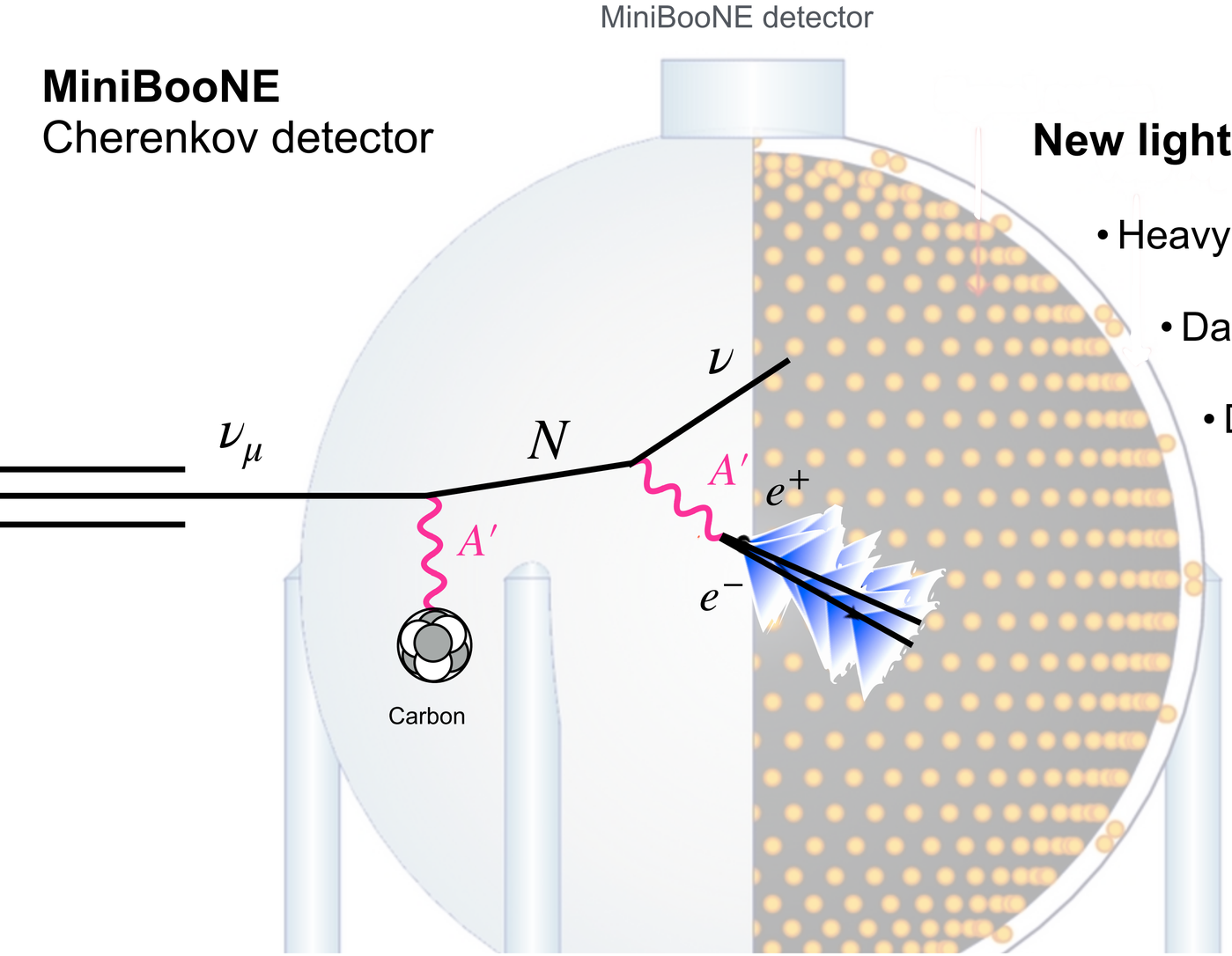
Dark Neutrinos

A multi-portal exploration of dark sectors

E. Bertuzzo, S. Jana, P. A. N. Machado, R. Z. Funchal, PRL 121, 241801 (2018)
P. Ballett, M. Ross-Lonergan, S. Pascoli, PRD 99, 071701 (2019)

C. Argüelles, MH, Y. Tsai, PRL 123, 261801 (2019)
P. Ballett, MH, S. Pascoli, PRD 101, 115025 (2020)
A. Abdullahi, MH, S. Pascoli, PLB 820 136531 (2021)

MiniBooNE
Cherenkov detector



New light particles produced in neutrino interactions:

- Heavy Neutrinos?
- Dark Photons?
- Dark Higgses?

Multi-portal approach
Heavy neutrinos interacting through dark photons:

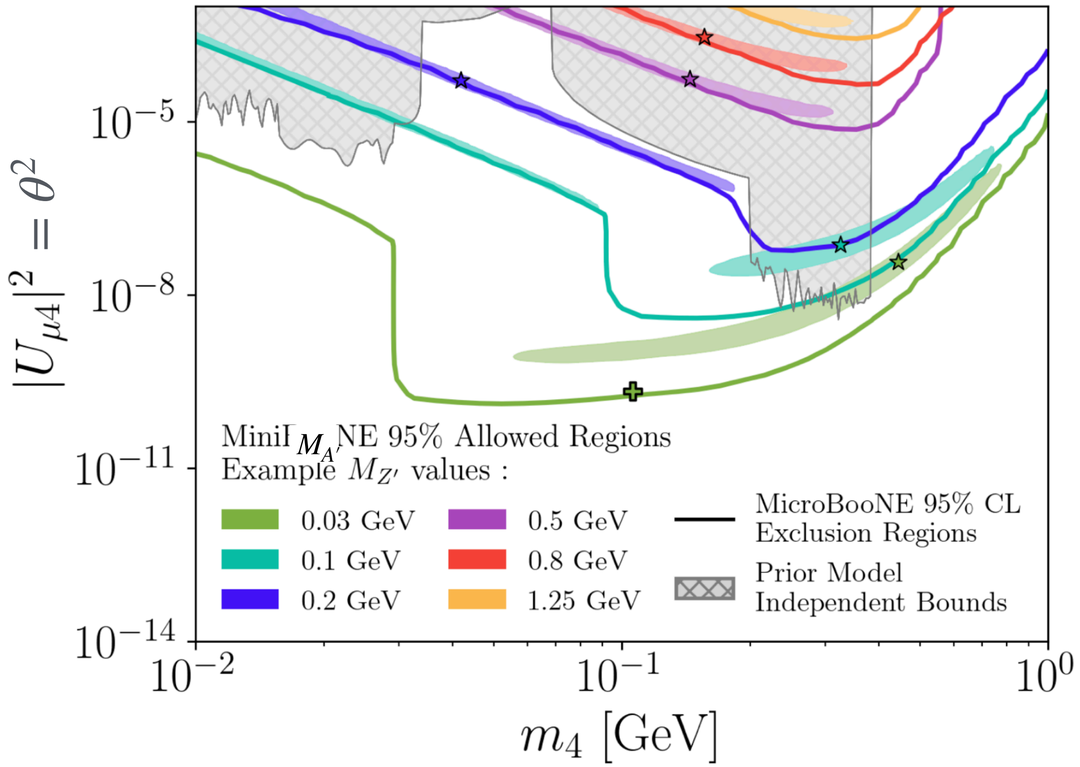
$$N + A'$$

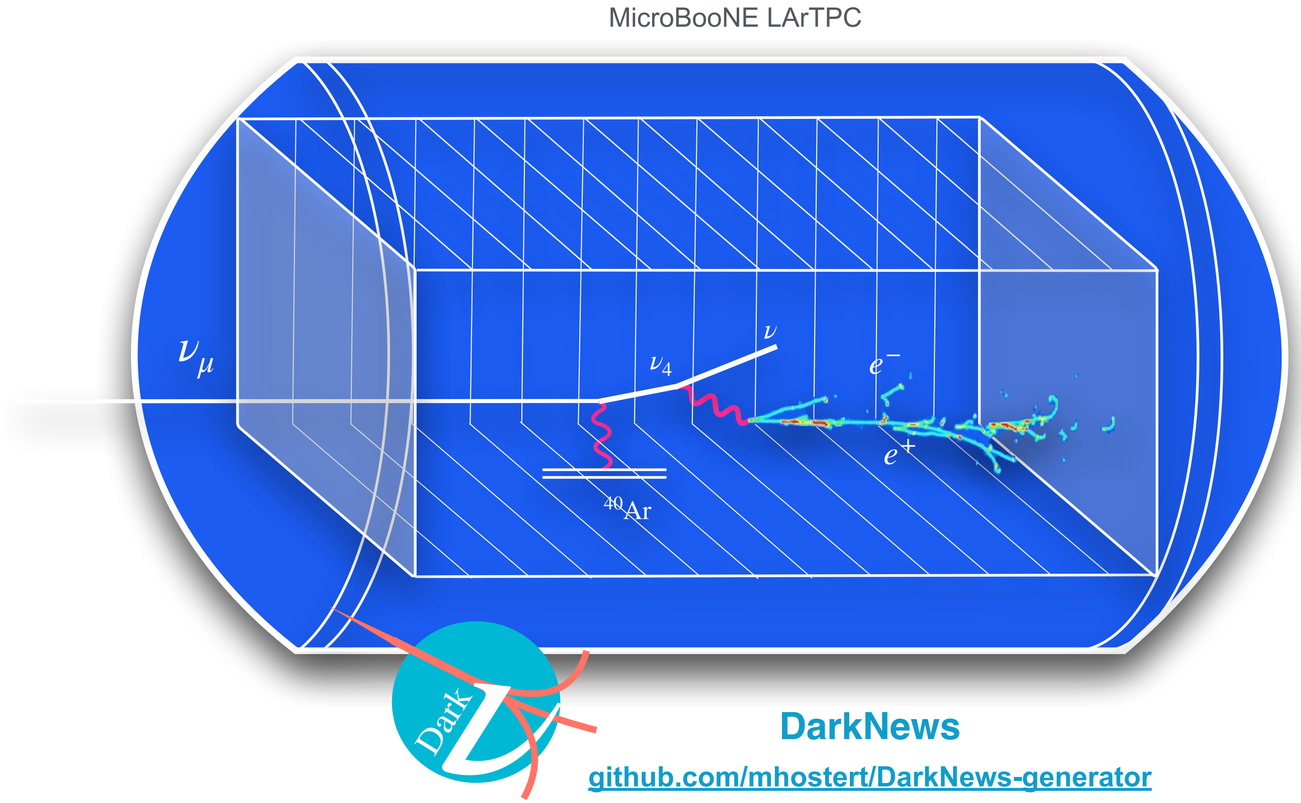
Dark Neutrinos @ MicroBooNE
First (modern) experimental limits on neutrino upscattering

MicroBooNE coll.
+
MOU with A. Abdullahi, MH, D. Massaro, S. Pascoli, J. Zink.
arxiv.org/abs/2502.10900

First dedicated experimental search for neutrino-induced e^+e^- pairs:

MicroBooNE excludes minimal dark neutrino explanations to the MiniBooNE anomaly

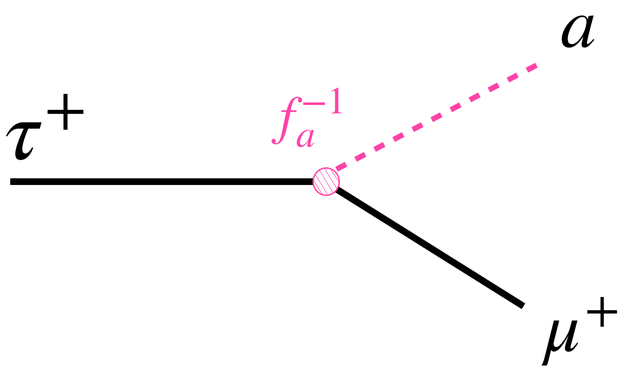




Another example: axion-like-particles

(pseudo-Goldstone bosons from, e.g., flavor symmetries)

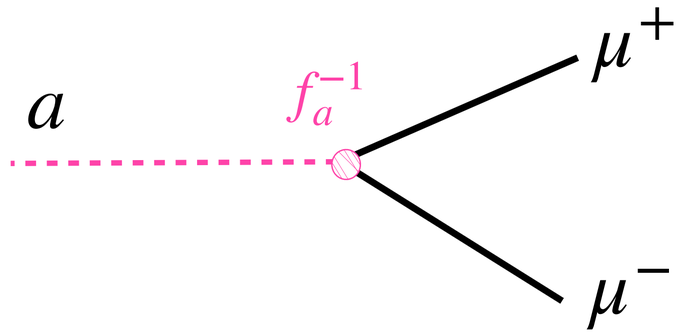
$$\mathscr{L}_{\text{int}} = \frac{\partial_\mu a_\ell}{f_a} \sum_{i,j} c_{\ell_i \ell_j} \left[\bar{\ell}_i \gamma^\mu \gamma^5 \ell_j + \bar{\nu_\ell}_i \gamma^\mu \gamma^5 \nu_{\ell_j} \right]$$



Angular mode of some complex scalar.

Derivatively-coupled → couples preferentially to 3rd family

Messenger of new physics at energy scale f_a

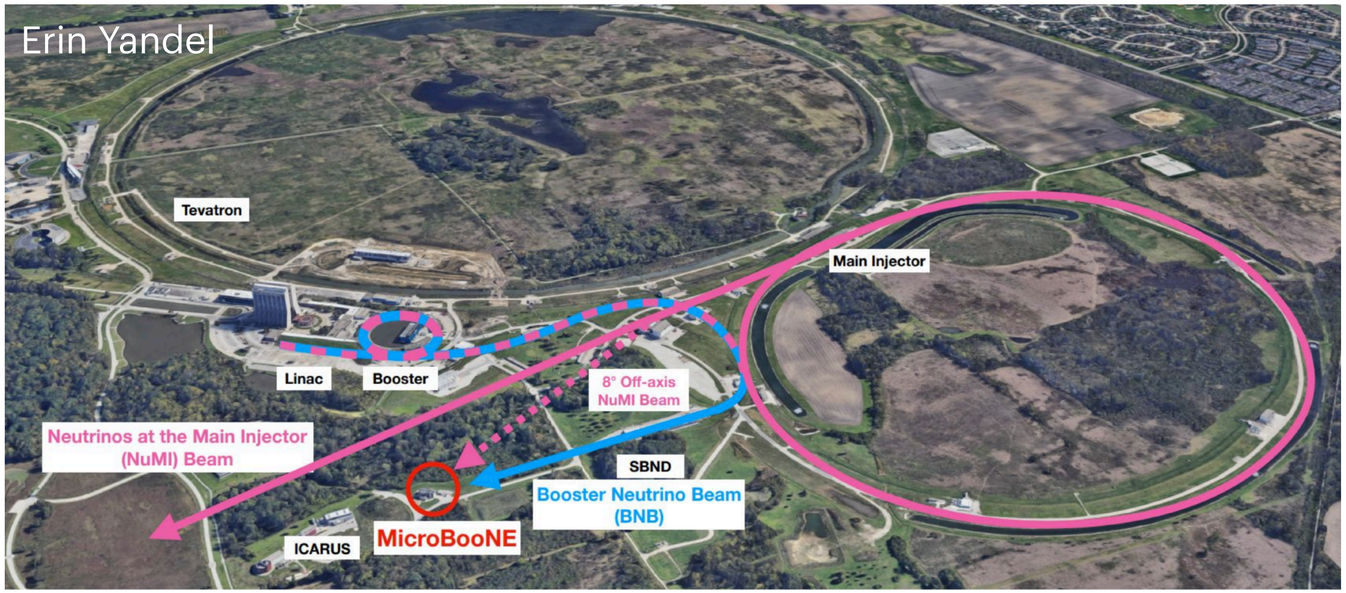


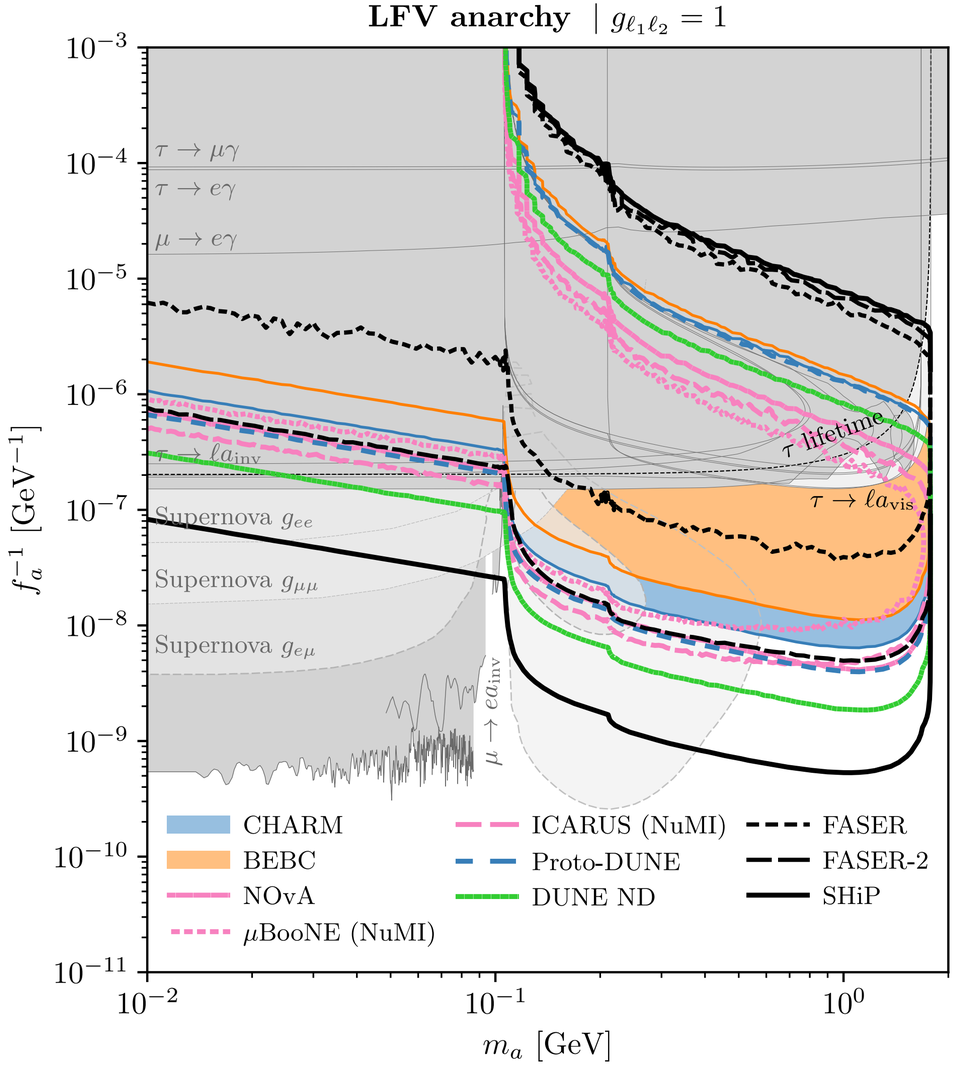
Y. Ema, P. J. Fox, MH, T. Menzo, M. Pospelov, A. Ray, J. Zupan PRD acc, arXiv:2507.15271

Axion-Like-Particle

(pseudo-Goldstone bosons from lepton flavor symmetries)

Using the off-axis NuMI beam at **MicroBooNE** and **ICARUS**.





Y. Ema, P. J. Fox, MH, T. Menzo, M. Pospelov, A. Ray, J. Zupan PRD acc, arXiv:2507.15271

Axion-Like-Particle

(pseudo-Goldstone bosons from lepton flavor symmetries)

Search for Hidden Particles (SHiP)

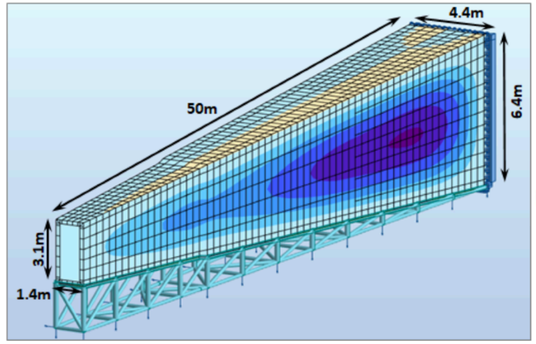
Ep = 400 GeV with $\mathcal{O}(10^{20})$ POT.

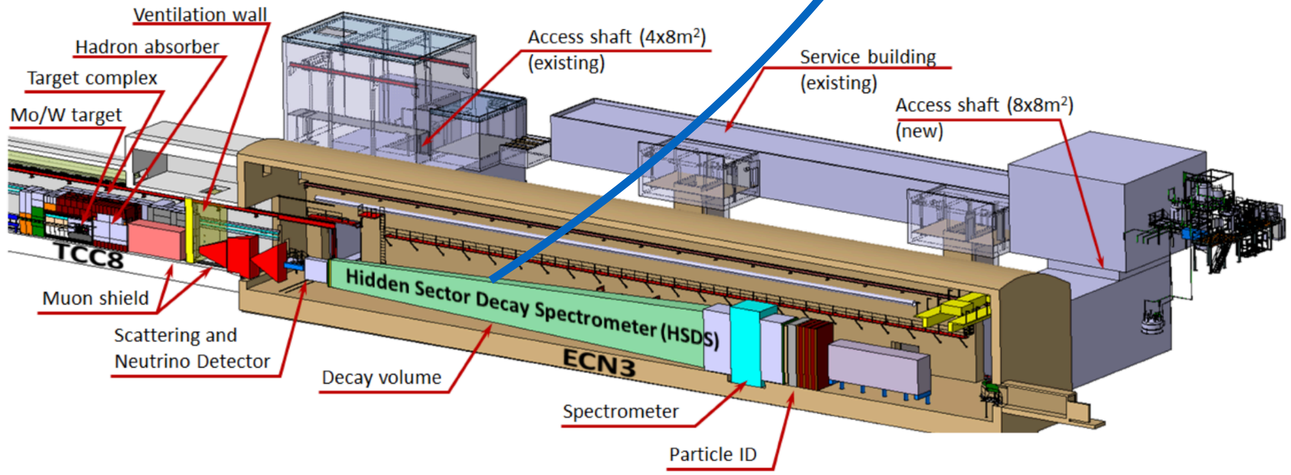
Largest acceptance.

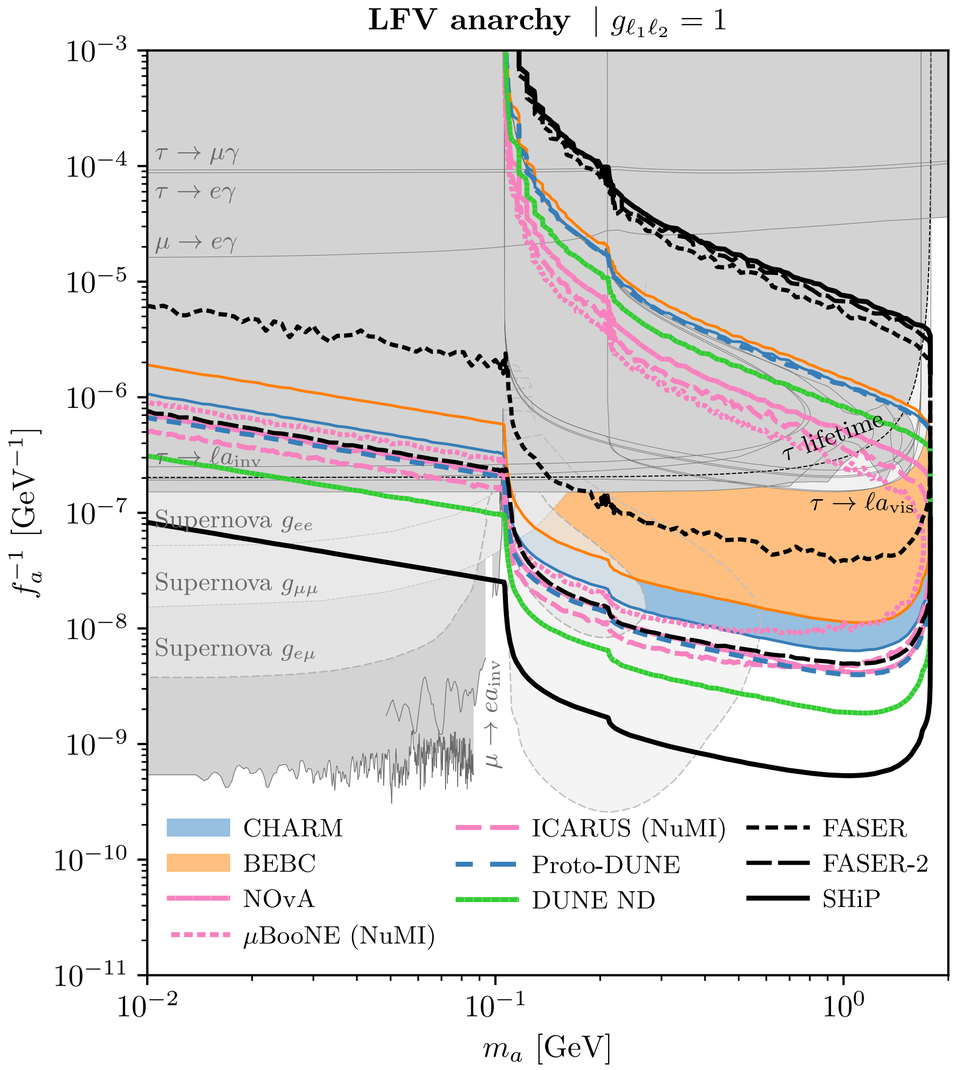
"Commissioning and first data-taking planned for 2031-2033"

SHiP Collaboration & HI-ECN3 Project Team
(ESPPU 2026)

"Pyramidal frustum"







Y. Ema, P. J. Fox, MH, T. Menzo, M. Pospelov, A. Ray, J. Zupan PRD acc, arXiv:2507.15271

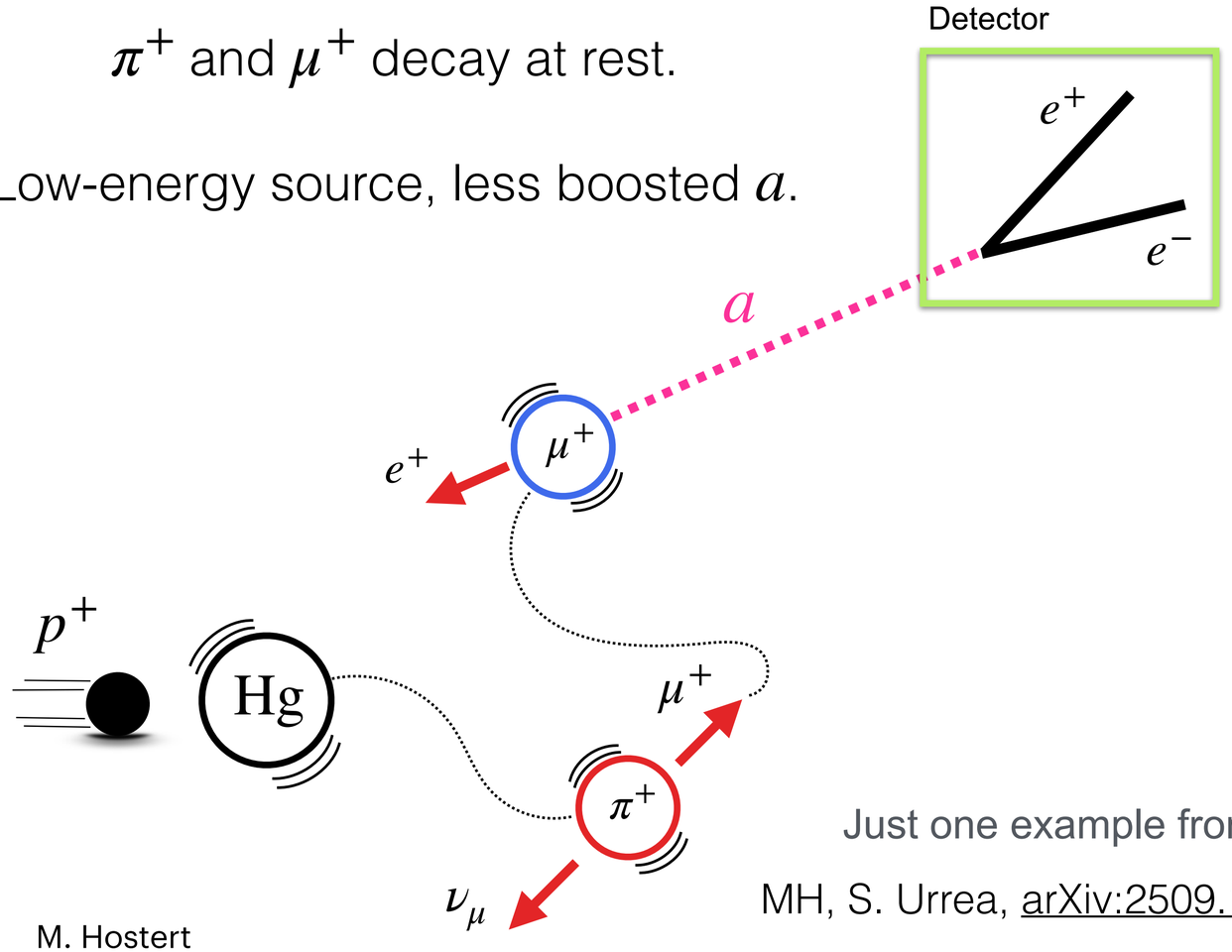
Axion-Like-Particle

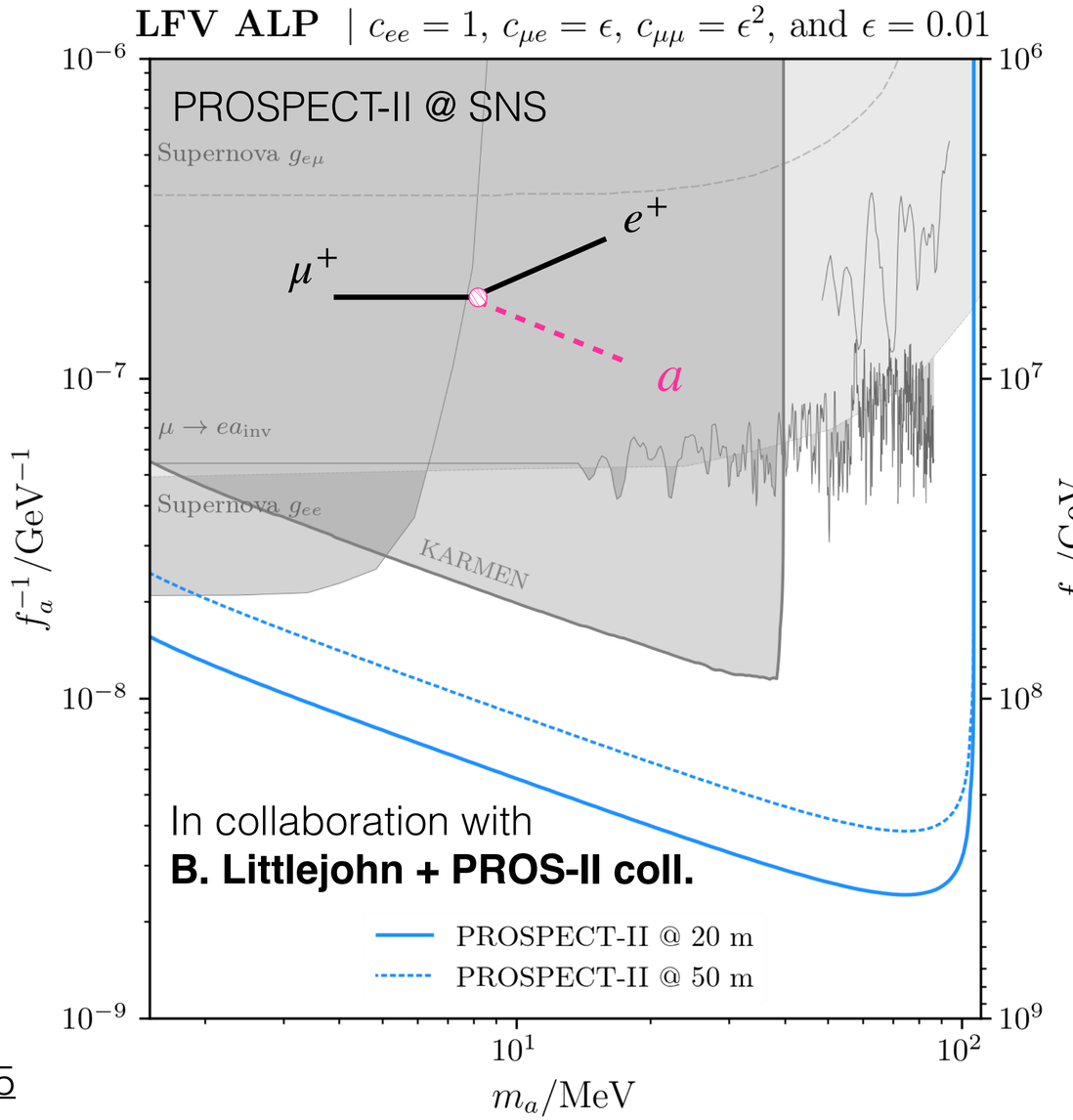
(pseudo-Goldstone bosons from lepton flavor symmetries)

Spallation sources: $N_{\mathrm{POT}} \lesssim N_{\mathrm{Avo}}$

π^+ and μ^+ decay at rest.

Low-energy source, less boosted a.





Just one example from

MH, S. Urrea, arXiv:2509.14085

Roadmap

The Standard Model

Understanding the neutrino mass puzzle

Sterile Neutrinos

Signatures, progress, and puzzles

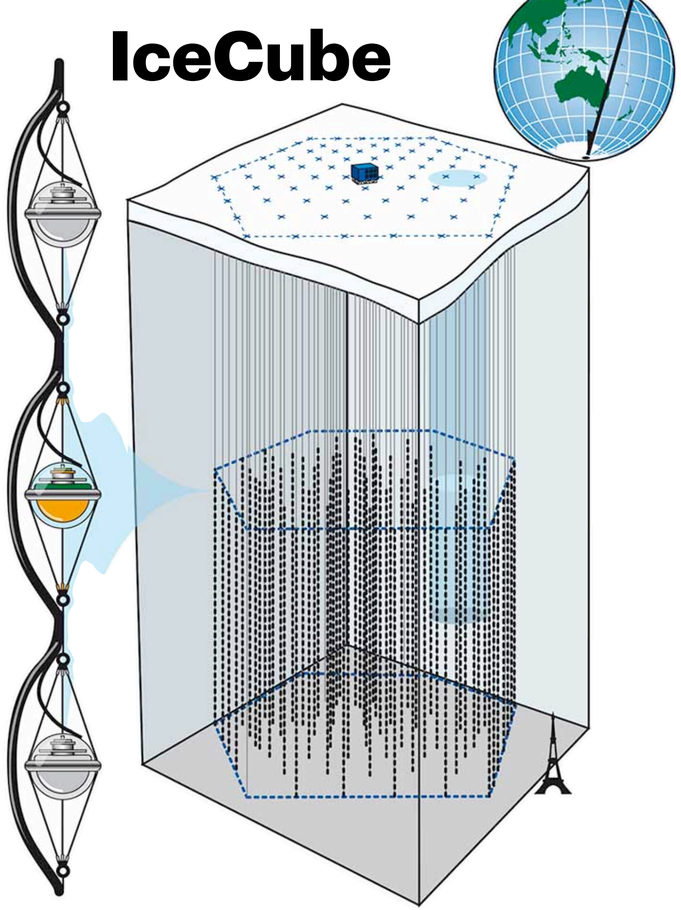
Broader Dark Sectors

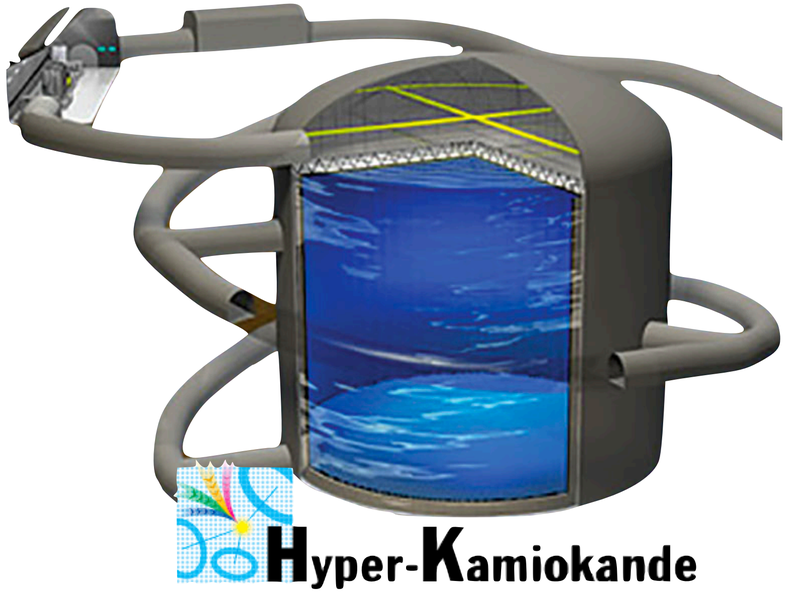
Casting a wide net

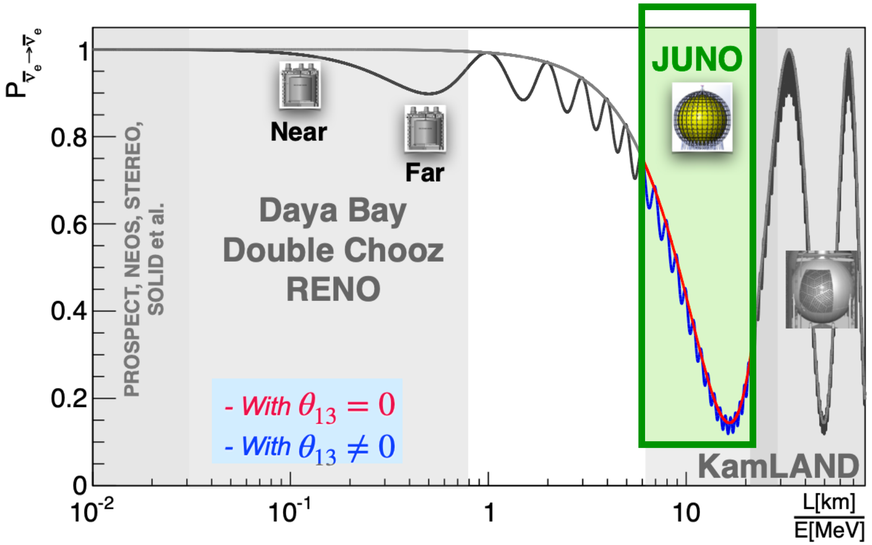
Neutrinos at a future high-energy frontier

Muon Colliders

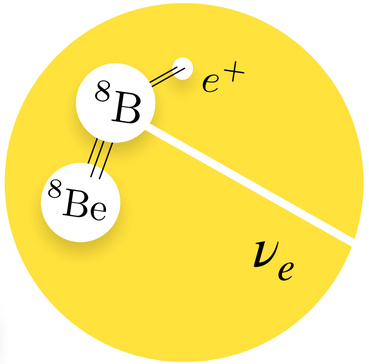
Looking to the future



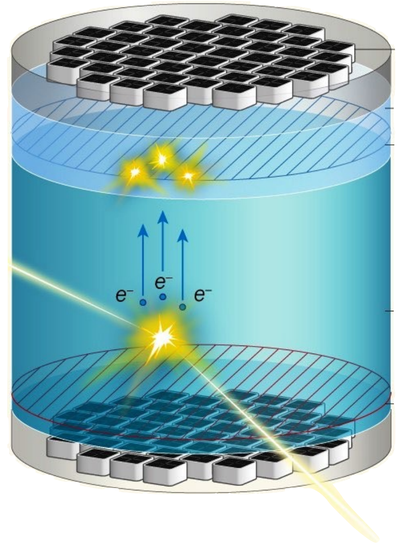


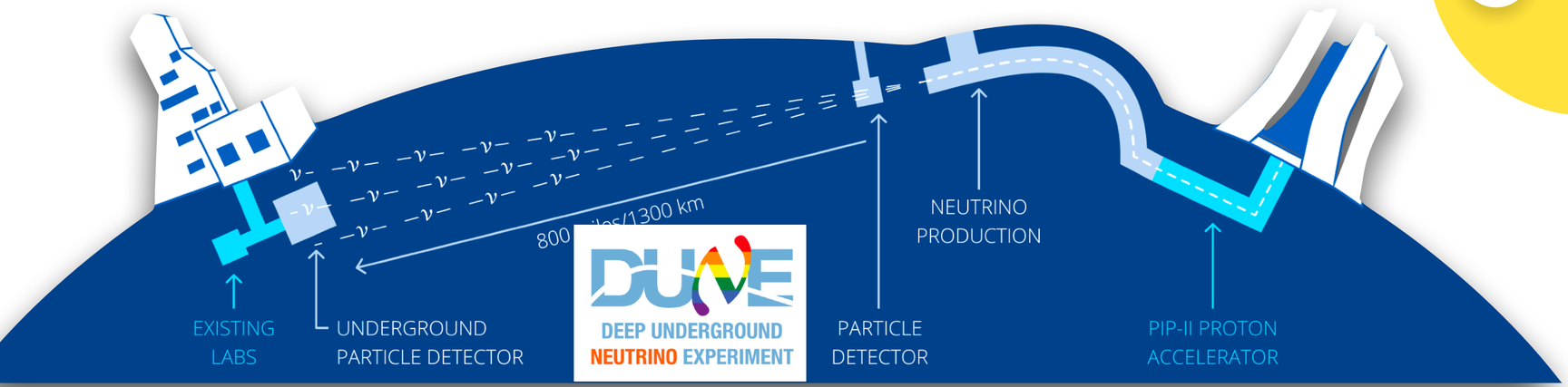


Adapted from P. Ochoa-Ricoux, NPN 2025



XENONnT





Next-generation accelerator neutrinos can boast about:

1) Beam intensity: Multi-MW beams (J-PARC, LBNF) ✓

2) Detector size: DUNE: 10's of kt, HyperK: 100's of kt. ✓

3) Detector granularity: LAr is a microscope on neutrino byproducts ✓

4**) Detector threshold:** dark matter detectors for ν's ✓

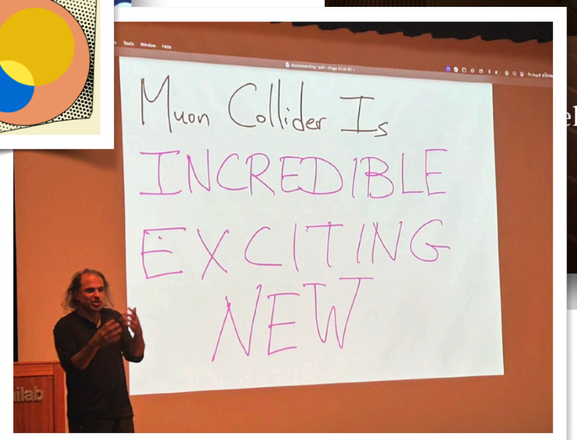
But we are still having to find work-around for **flux systematics**. ?

Beams from a parent particle we understand and can manipulate: Muons!

The Muon Collider

Symmetry Magazine

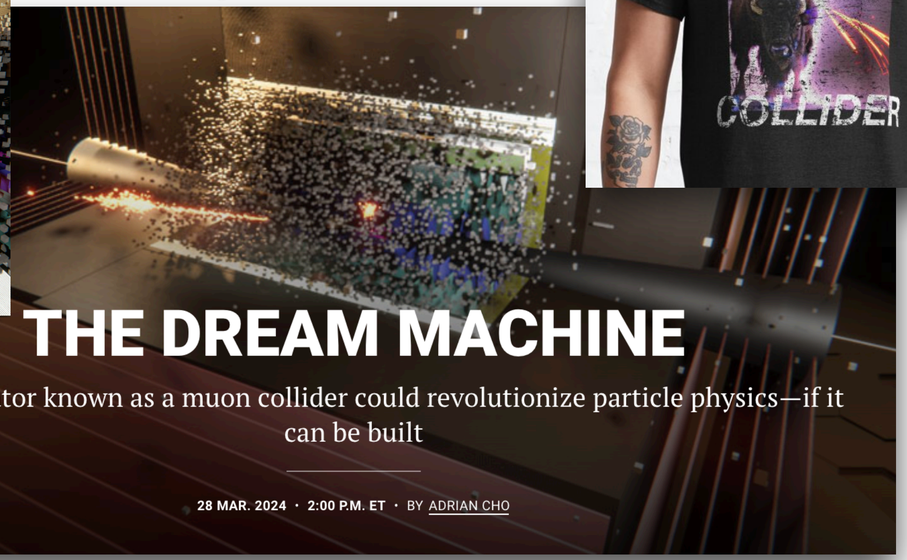
‘This is our Muon Shot’



Particle Physicists Agree on a Road Map for the Next Decade

A “muon shot” aims to study the basic forces of the cosmos. But meager federal budgets could limit its ambitions.

Science Magazine



THE DREAM MACHINE

elerator known as a muon collider could revolutionize particle physics—if it can be built

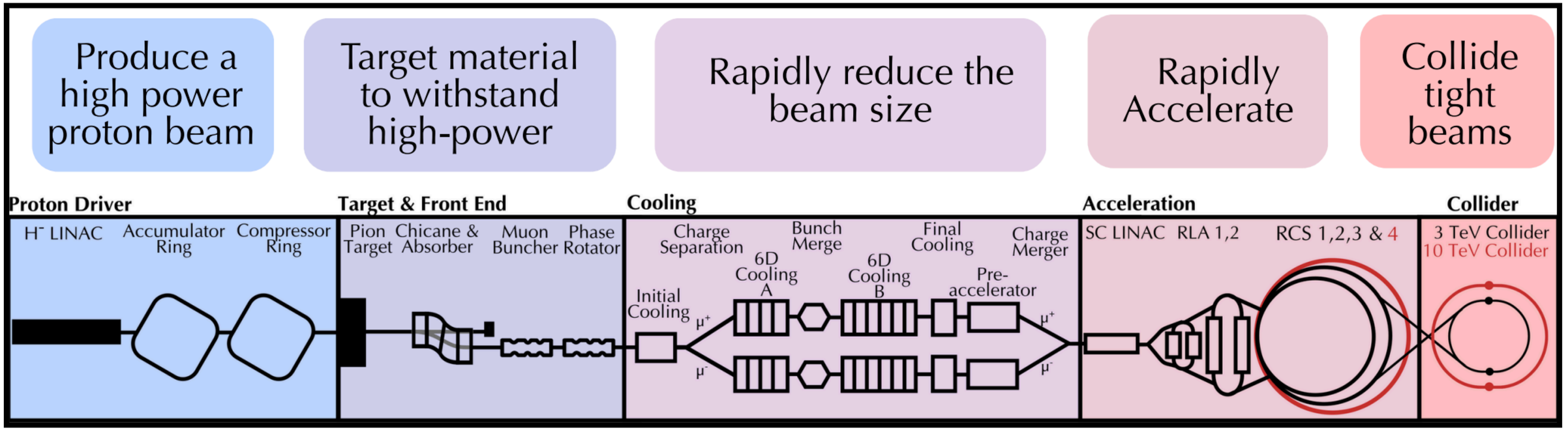
28 MAR. 2024 · 2:00 P.M. ET · BY ADRIAN CHO

“

The challenge, if you want to capture it in one word, is that the muon is unstable.

SERGO JINDARIANI | FERMI NATIONAL ACCELERATOR LABORATORY

R. Taylor, 2nd USMCC meeting 2025



Proton Target

multi-MW and ns-pulsed

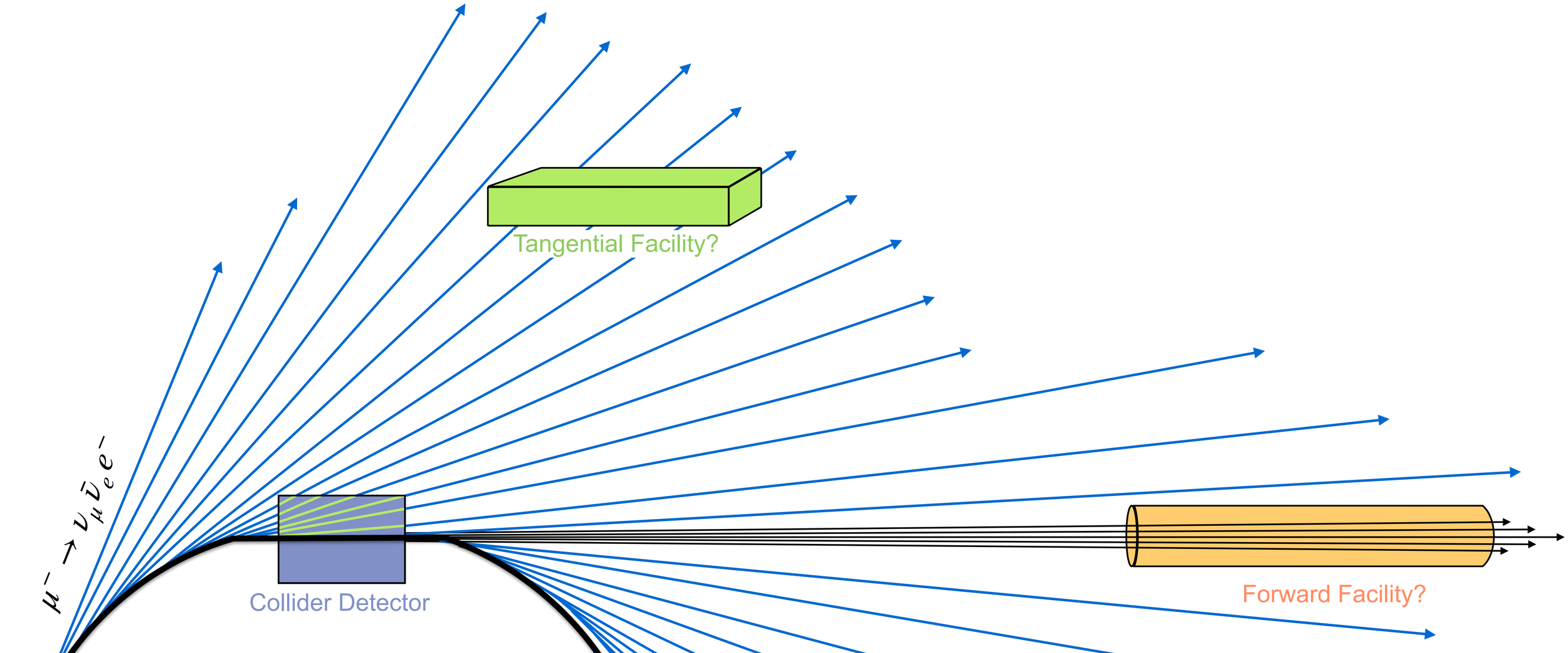
Muon cooling to increase luminosity

Ionization in this case.

Low-energy acceleration

Muon Collider

Forward and **Tangential?** physics: leverage the neutrino byproducts of a MuC.



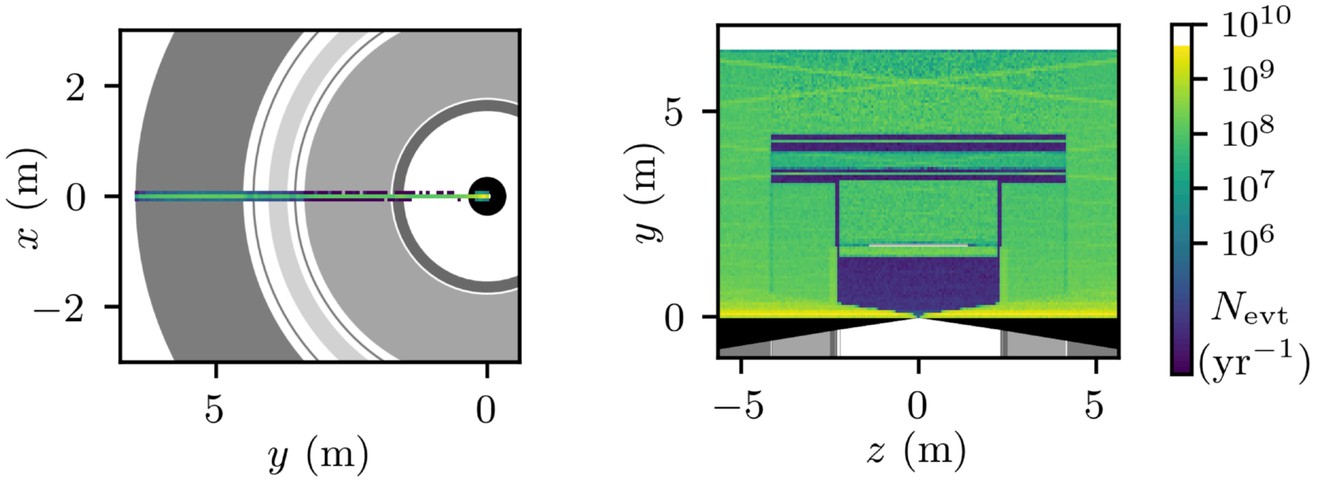
Beam-induced neutrinos

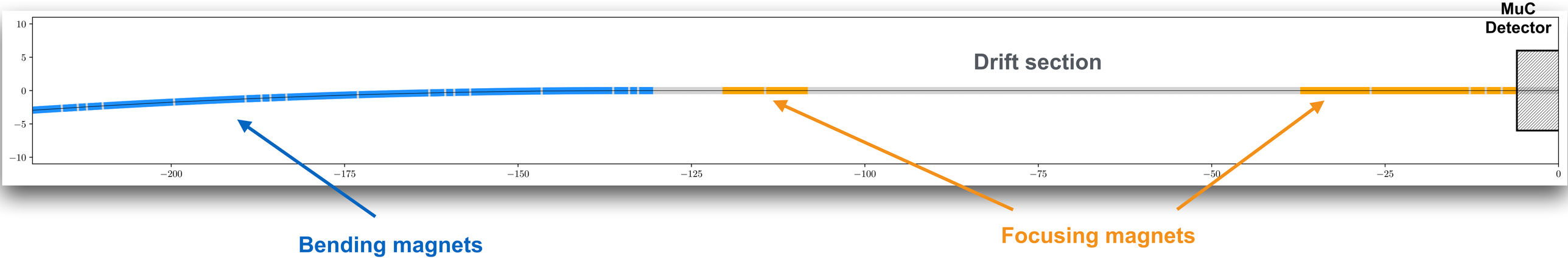
Tangential fluxes

L. Bojorquez-Lopez (Undergrad), **MH**, C. A. Argüelles, Z. Liu

The Neutrino Slice at Muon Colliders

Detector components following IMCC studies





Beam-induced neutrinos
Tangential fluxes

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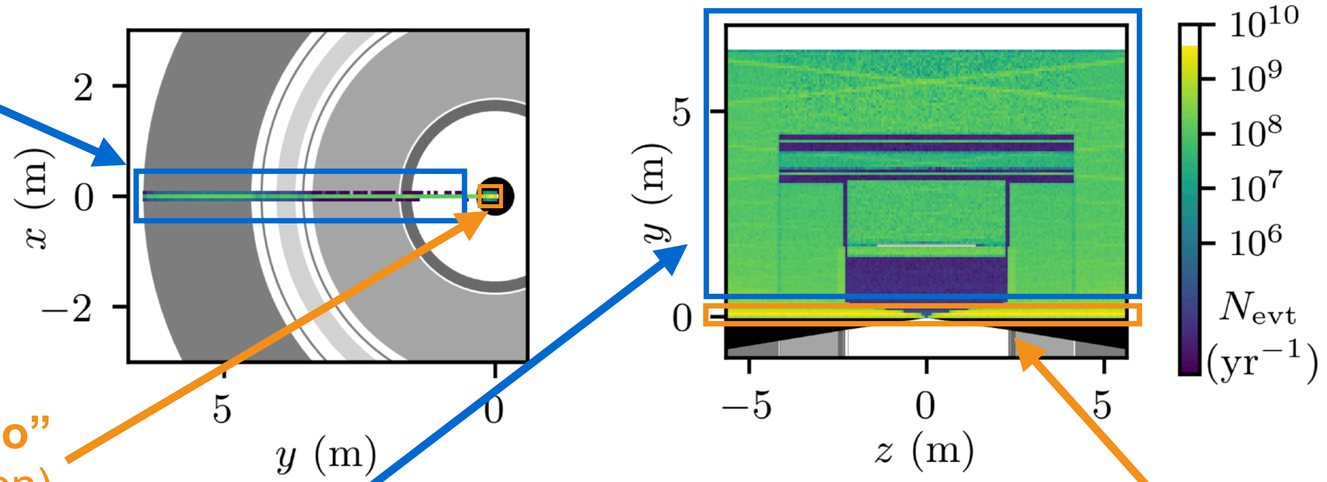
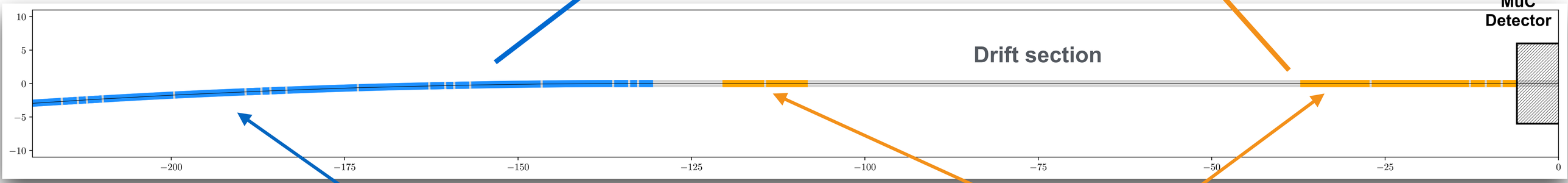
Detector components following IMCC studies

Neutrino "Slice"
(mostly from main ring)

Neutrino "Halo"
(mostly from straight section)





Bending magnets

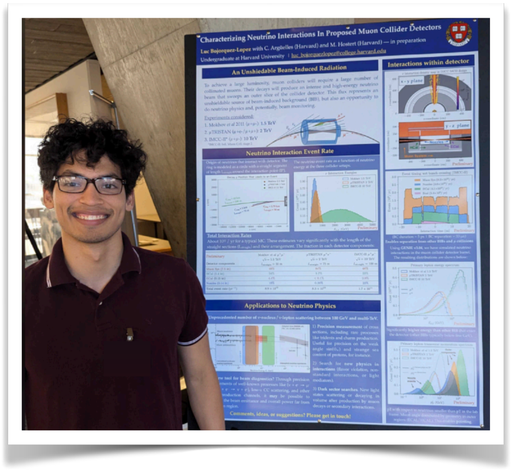
Focusing magnets

Muon Collider

Building toy models of muon collider

More neutrinos than we have ever detected by >3 orders of magnitude.

About 0.5 events per bunch crossing for 10 TeV



Luc Bojorques-Lopez (Harvard)
Inaugural US muon collider community meeting @ Fermilab

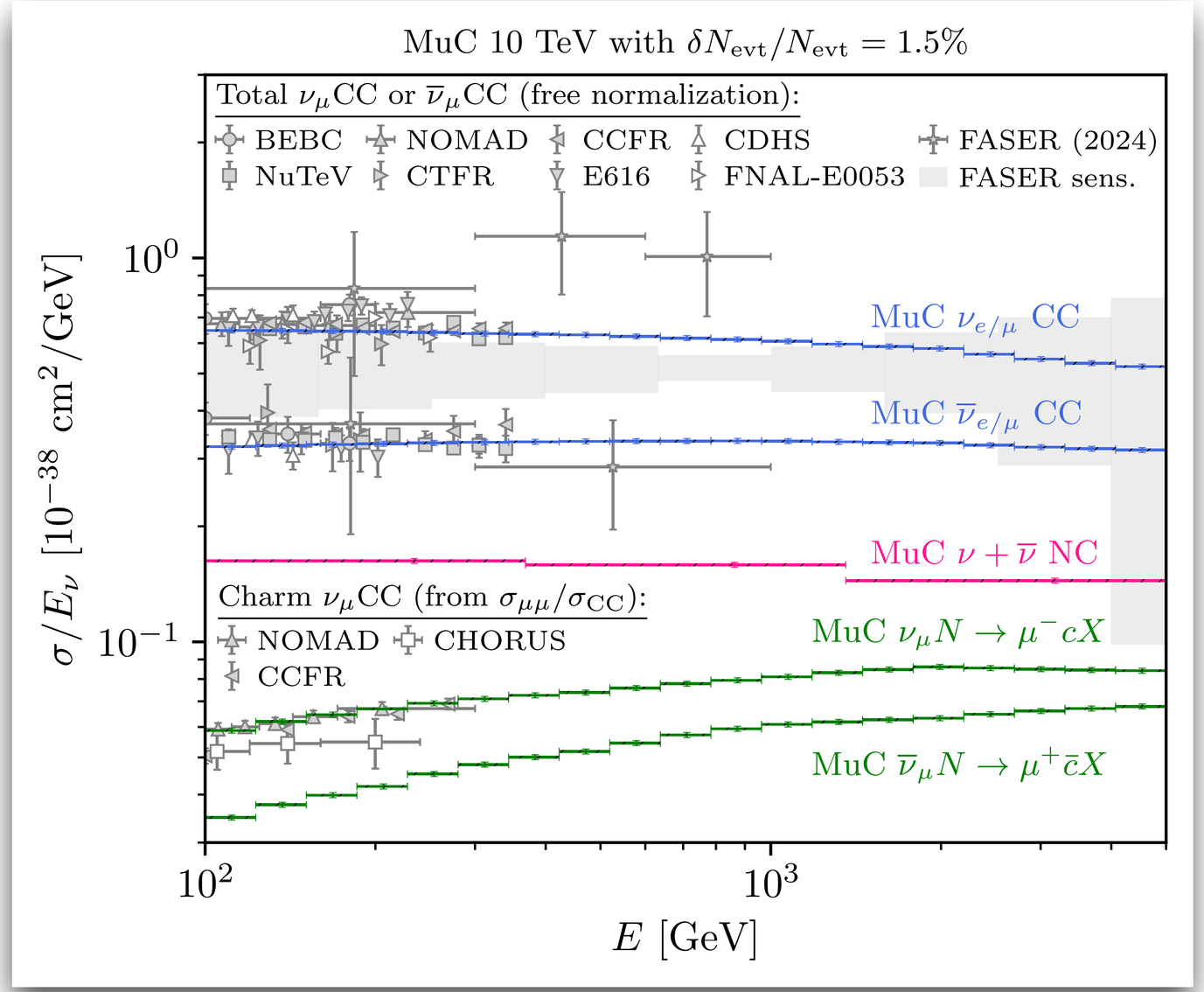
Collider	MuC 10 TeV	MuC 3 TeV	μTRISTAN
Beams	$\mu^+\mu^-$	$\mu^+\mu^-$	$\mu^+\mu^+$
Muons/bunch	1.8×10^{12}	1.8×10^{12}	1.4×10^{10}
bunches/cycle	1	1	40
f_{inj}	5 Hz	5 Hz	50 Hz
C	8.7 km	4.3 km	4.3 km
BIN exclusive reactions in HCAL and ECAL/year			
Total NC	1.5×10^9	4.6×10^8	3.4×10^9
Total ν_e CC	4.7×10^9	1.4×10^9	1.1×10^{10}
Total ν_μ CC	5.4×10^9	1.7×10^9	1.1×10^{10}
ES $\nu_\mu e \to \nu_\mu e$	3.8×10^5	1.1×10^5	0
ES $\bar{\nu}_e e \to \bar{\nu}_e e$	8.6×10^5	2.5×10^5	0
ES $\bar{\nu}_\mu e \to \bar{\nu}_\mu e$	3.4×10^5	9.9×10^4	1.9×10^6
QE $\nu n \to \ell^- p^+$	2.6×10^6	2.5×10^6	2.8×10^7
QE $\bar{\nu} p^+ \to \ell^+ n$	2.7×10^6	2.5×10^6	3.2×10^7
Coh π^0	3.0×10^5	2.9×10^5	3.5×10^6
Res $\bar{\nu}_e e \to \rho^-$	4.2×10^5	7.7×10^5	0
Res $\bar{\nu}_e e \to K^{*-}$	2.6×10^4	4.4×10^4	0
IMD $\nu_\mu e \to \nu_e \mu^-$	4.2×10^6	1.2×10^6	0
IMD $\bar{\nu}_e e \to \bar{\nu}_\mu \mu^-$	1.2×10^6	3.5×10^5	0
ITD $\bar{\nu}_e e \to \bar{\nu}_\tau \tau^-$	9.4×10^3	0	0
Trident e^+e^-	1.2×10^6	2.9×10^5	1.7×10^6
Trident $\mu^\pm e^\mp$	2.9×10^6	6.7×10^5	5.0×10^6

BIN interactions

Neutrino-nucleus scattering measurement

This is what a $1.5\,\%$ uncertainty on TeV neutrino cross sections would look like:

Clearly more works required to understand if feasible at the neutrino slice, but such precision can undoubtedly be achieved with a forward detector if needed.



High Energy ν Interactions

MuC BINs would offer a high-Q^2 probe of fundamental matter with Weak interactions.

Access to many other rare exclusive processes.

Example of classes of exclusive processes

Deep Inelastic Scattering **CC** and NC

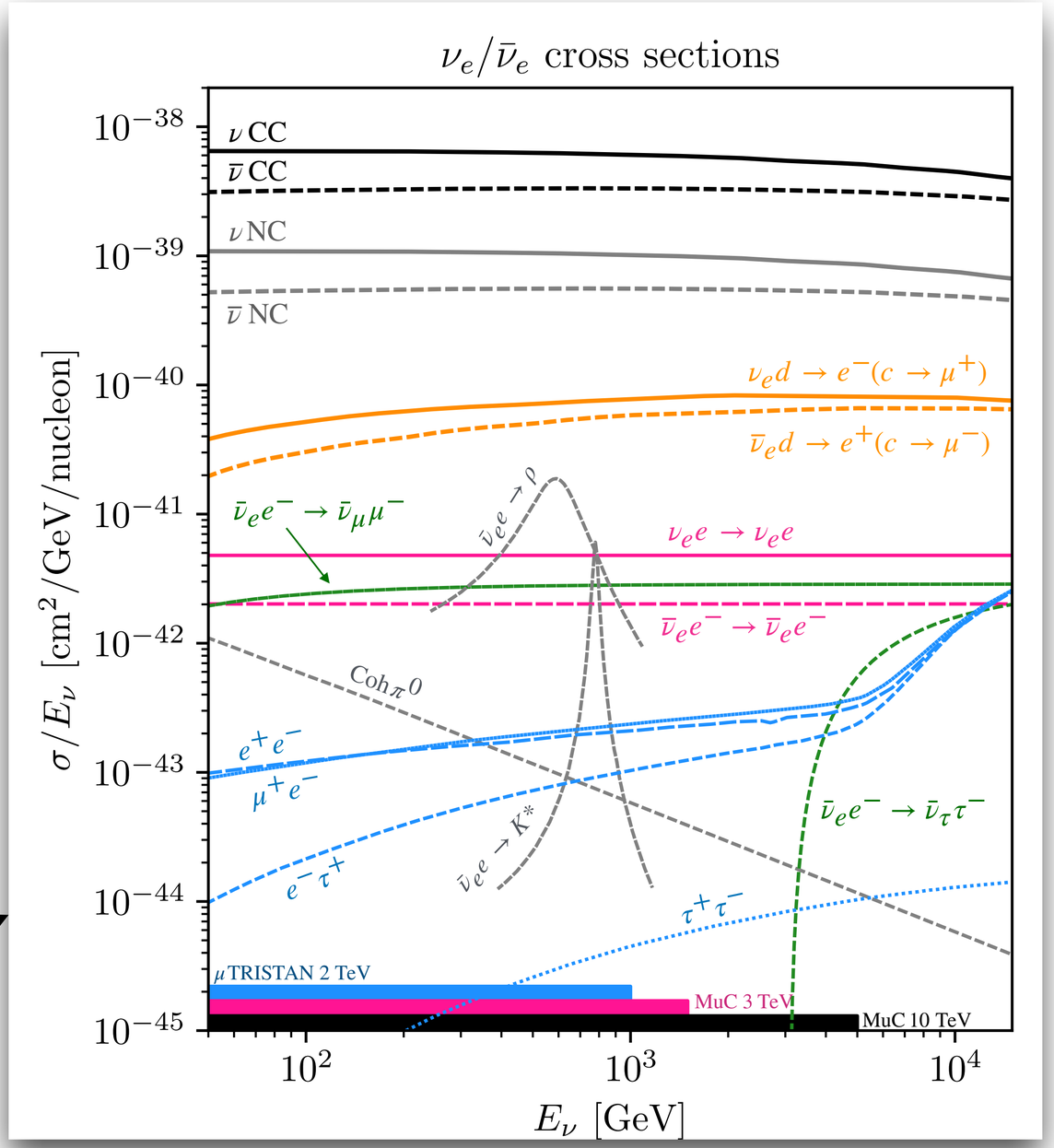
Charm production

Inverse muon(tau) decay

Elastic scattering on electrons

Resonant meson production

Neutrino trident production

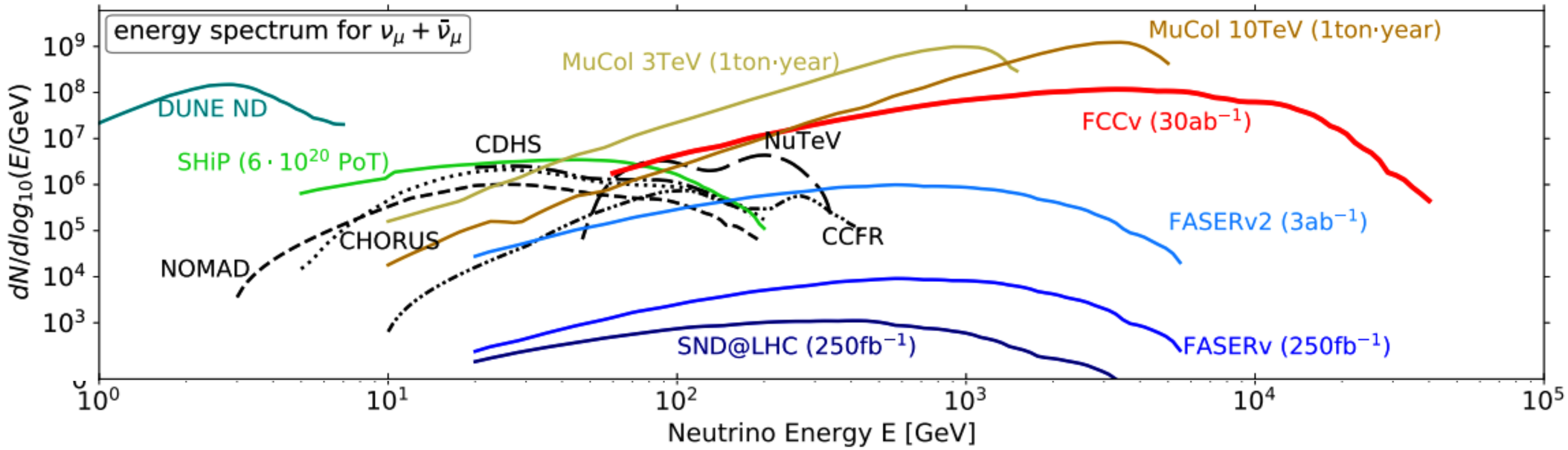


MuC Neutrino Energies

High energy and extremely collimated neutrino beam: $\langle E_\nu^{\mathrm{FASER}} \rangle \lesssim \langle E_\nu^{\text{MuC-10-TeV}} \rangle \lesssim \langle E_\nu^{\mathrm{FCC}} \rangle$

Beam energies are not necessarily new, but flavor composition, sample size, and precision are.

From arXiv:2409.02163



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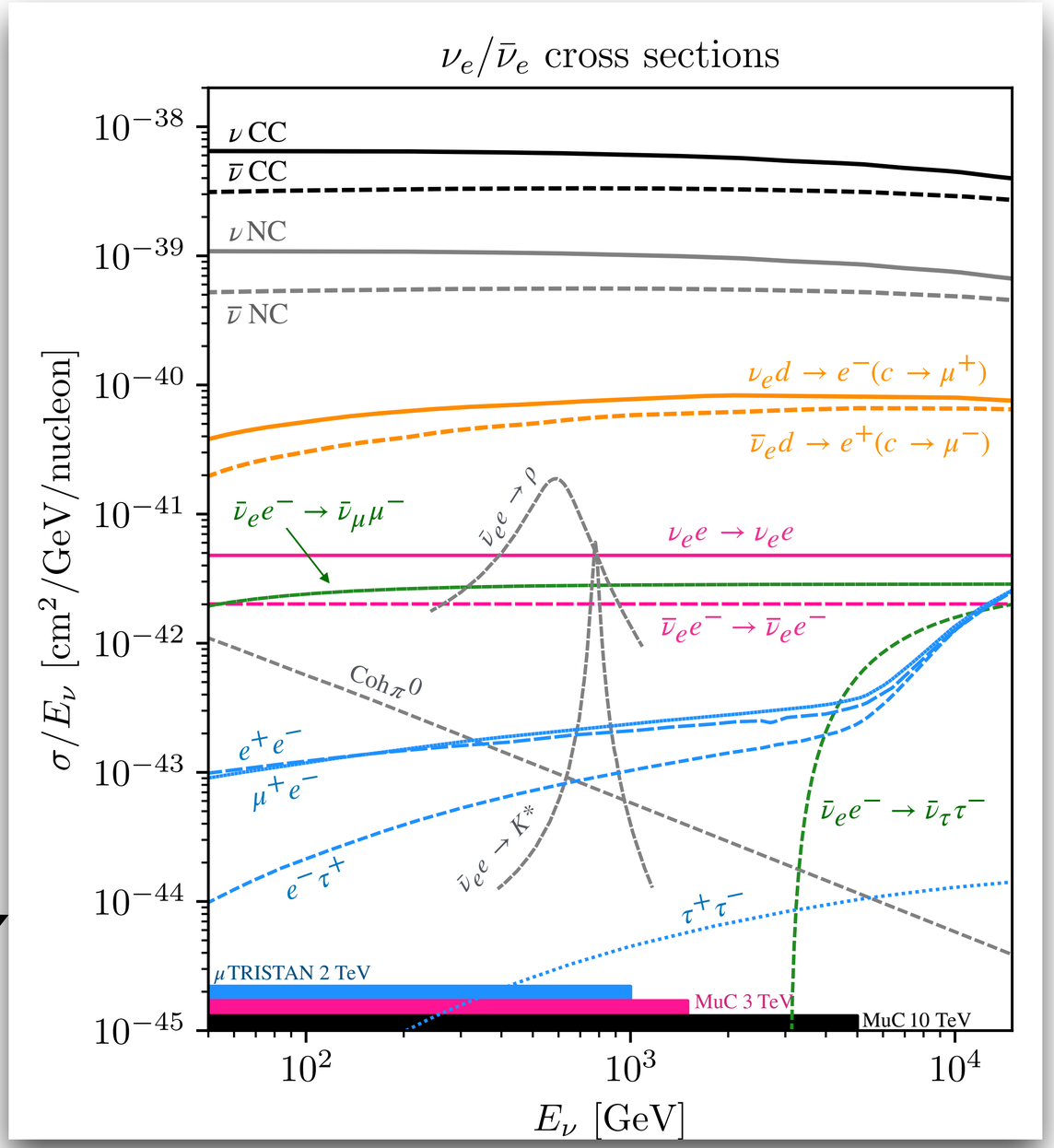
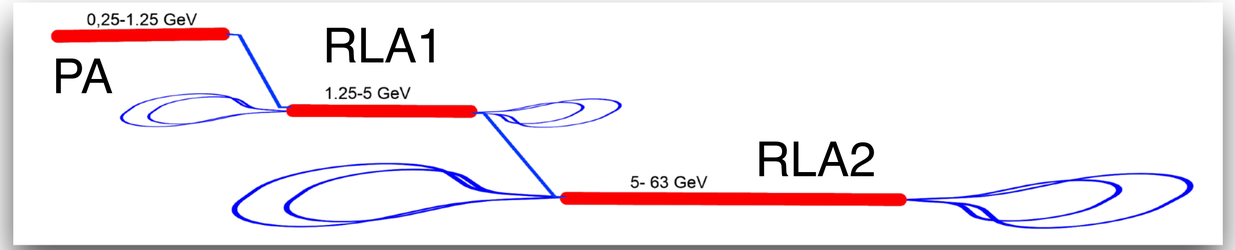
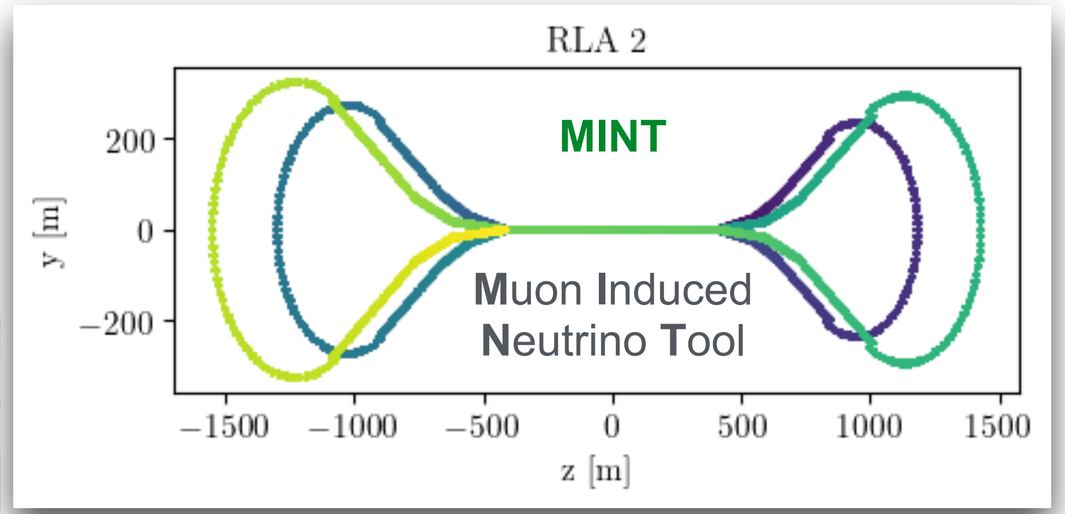


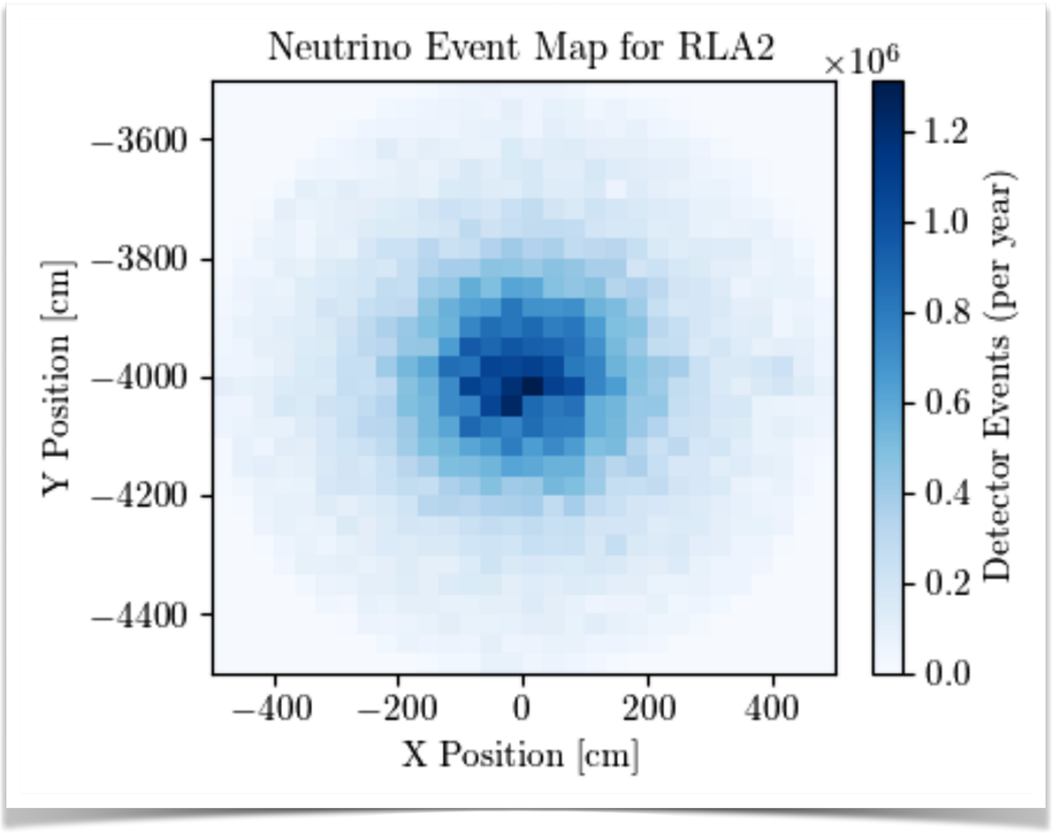
Muon Acceleration Neutrinos?



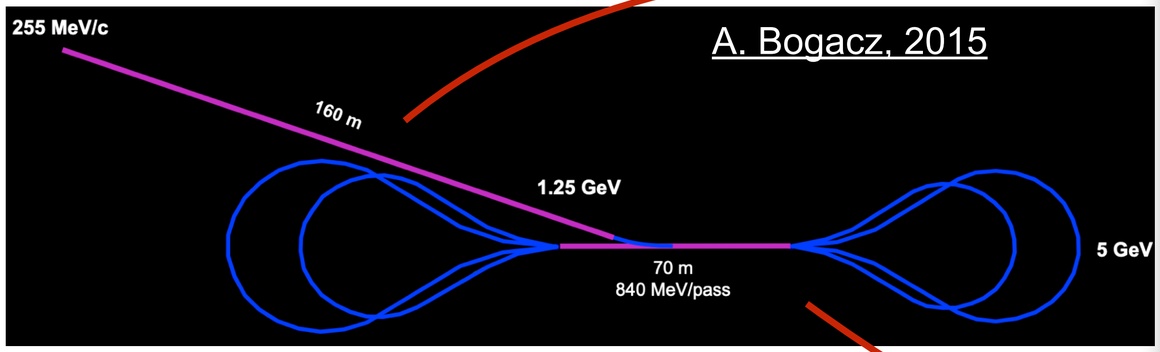
Currently investigating the entire low-energy acceleration stage of the Muon Collider complex.

Joel Choi
(U. Iowa)

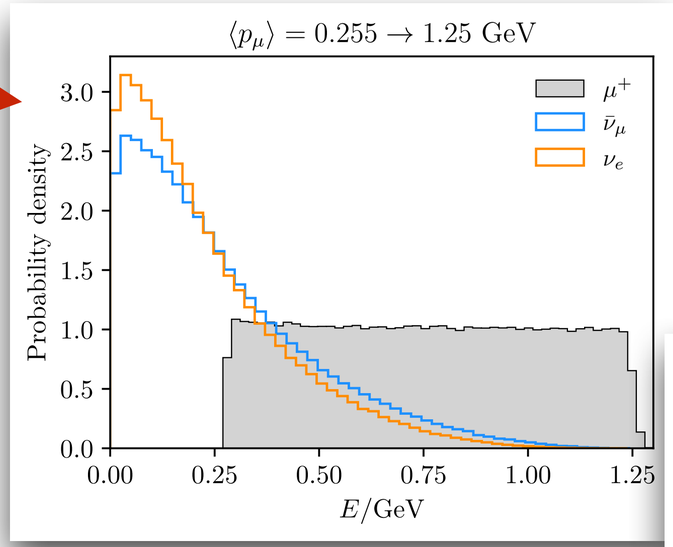




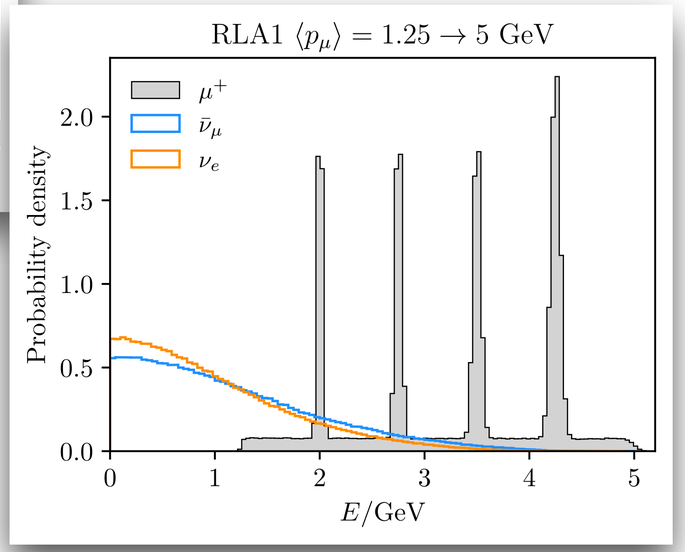
PA

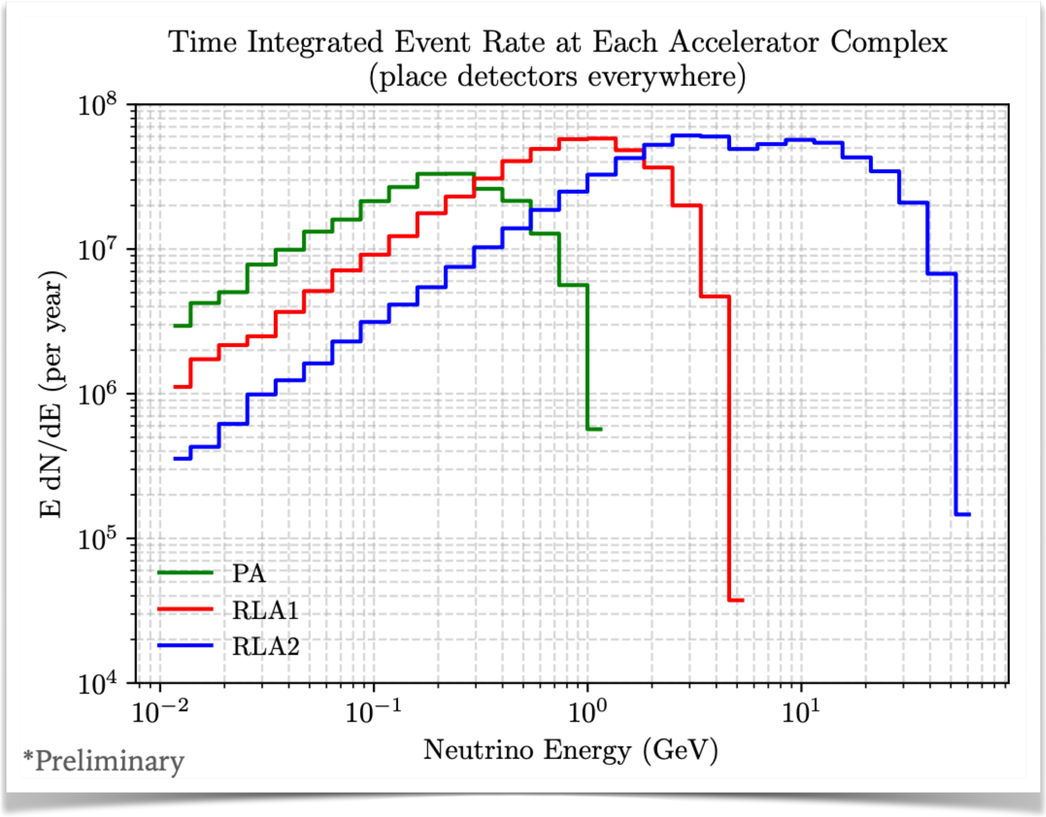


A. Bogacz, 2015



RLA1





Spans a wide range of energies:

Physics from **100's of MeV to the TeV scale** in the same machine.

In fundamental physics there are no guarantees:

A fast (idea → result) turnover is usually the exception in Particle Physics.

Theory work can be fast, but building experiments/collecting data can take time.

Our job is to **explore different topics and energy scales**, learn about **new technologies**, and **advance large-scale projects in science**,

Having an active phenomenology community is a sign of a healthy stream of data and ideas.

The need to cast wide nets makes this a diverse field and that's exciting!

Take Home

There is **“reasonable doubt”** that the SM is incomplete already **at low energies.**

Many possibilities: the challenge is in covering them all. **Need data!**

Particle physics entered a new era of studying **rare phenomena**
and phenomenology will be crucial to help us navigate it.

More neutrinos, but can also hope for “better” neutrinos.

A good time to ask:“Cool, what else can we do with this?”