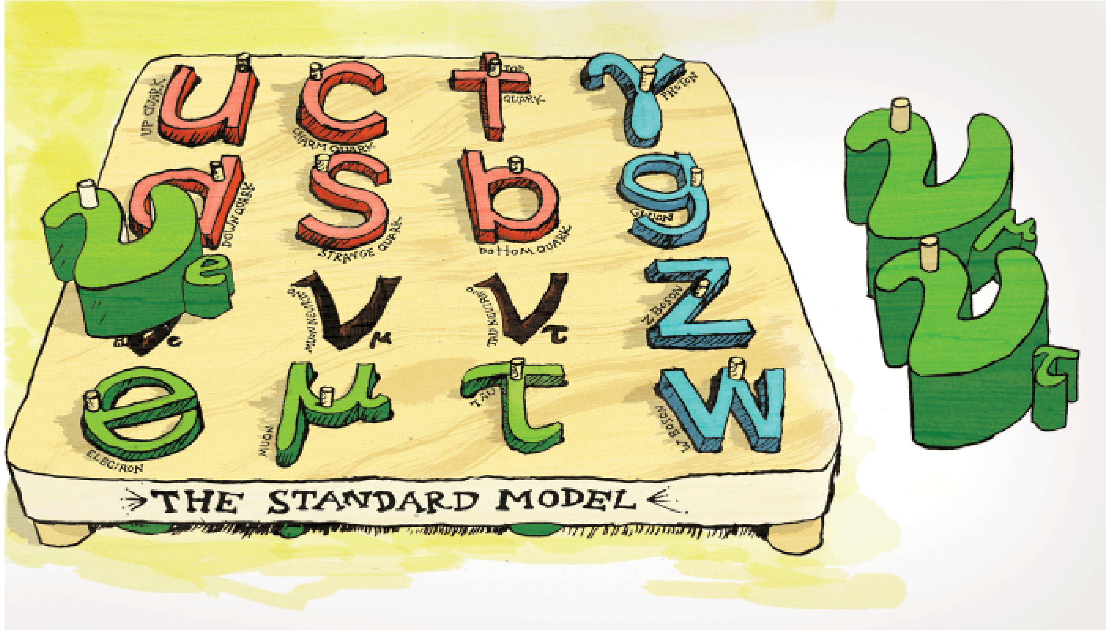
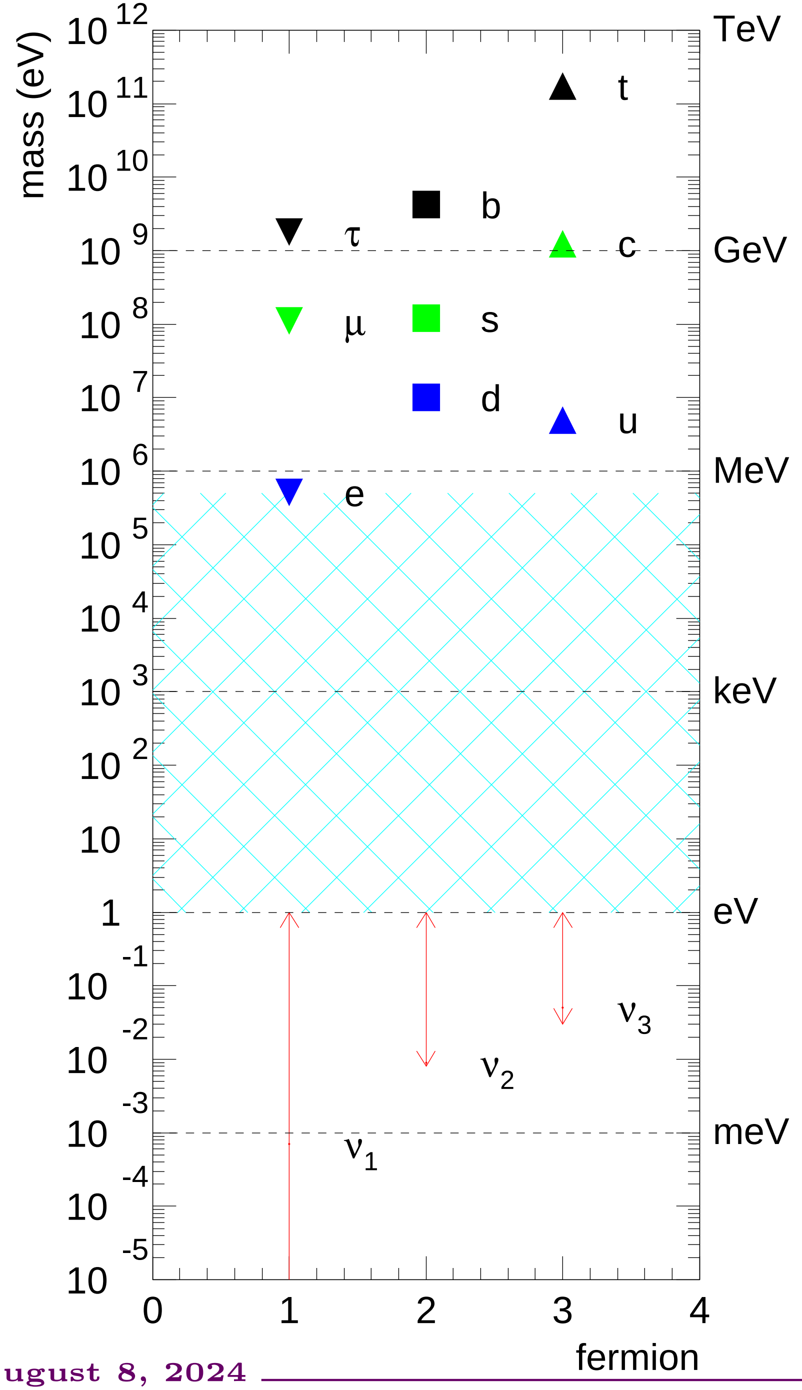
Some Neutrino Physics & Muon Colliders and Storage Rings



Inaugural US Muon Collider Meeting

Fermilab, August 7–9, 2024

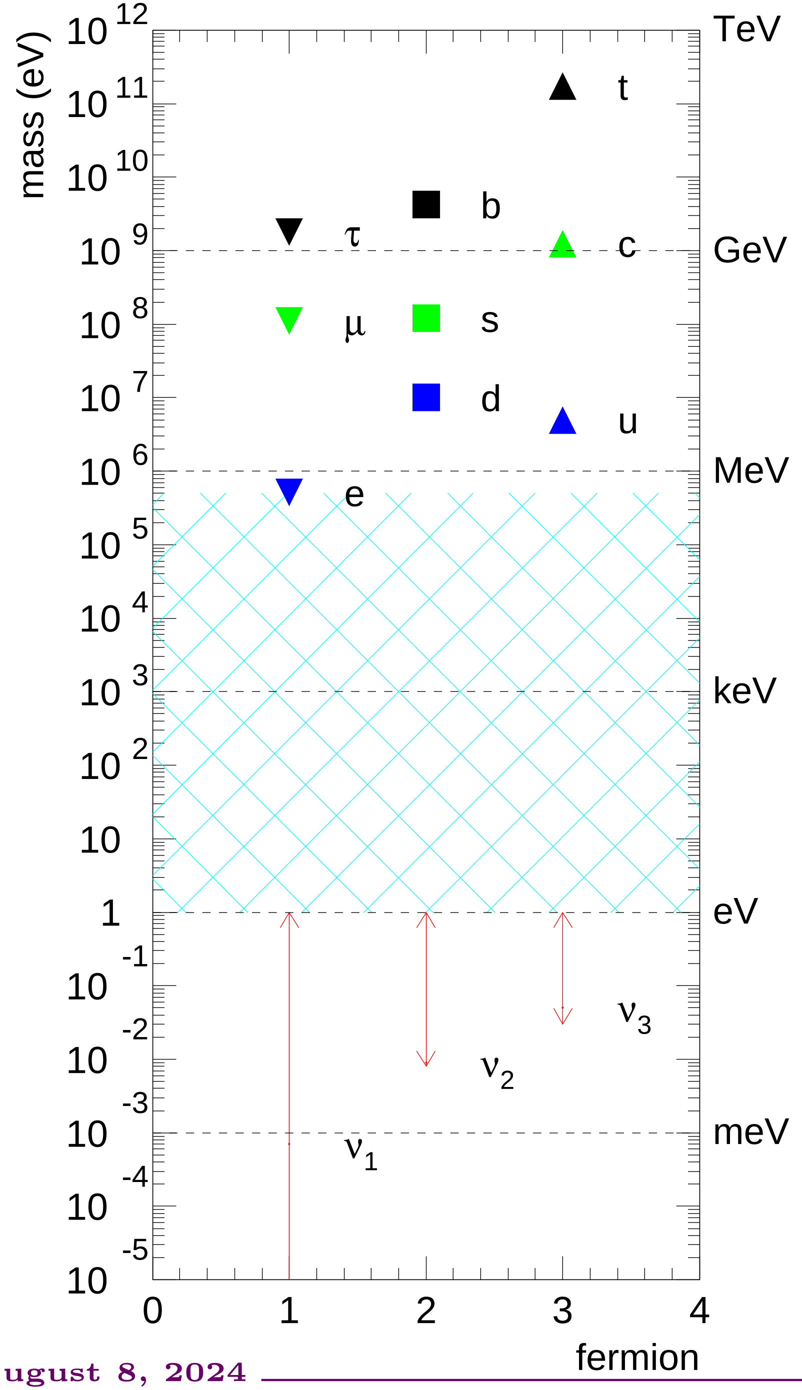
André de Gouvêa – Northwestern University



NEUTRINOS HAVE MASS

[albeit very tiny ones...]

So What?



NEUTRINOS HAVE MASS

[albeit very tiny ones...]

So What?

⇓

NEW PHYSICS

Nonzero neutrino masses imply the existence of new fundamental fields ⇒ New Particles

We know nothing about these new particles. They can be bosons or fermions, very light or very heavy, they can be charged or neutral, experimentally accessible or hopelessly out of reach…

There is only a handful of questions the standard model for particle physics cannot explain (these are personal. Feel free to complain).

- What is the physics behind electroweak symmetry breaking? (Higgs ✓).
- What is the dark matter? (not in SM).
- Why is there so much ordinary matter in the Universe? (not in SM).
- Why does the Universe appear to be accelerating? Why does it appear that the Universe underwent rapid acceleration in the past? (not in SM).

Neutrino Masses, Higgs Mechanism, and a New Mass Scale of Nature

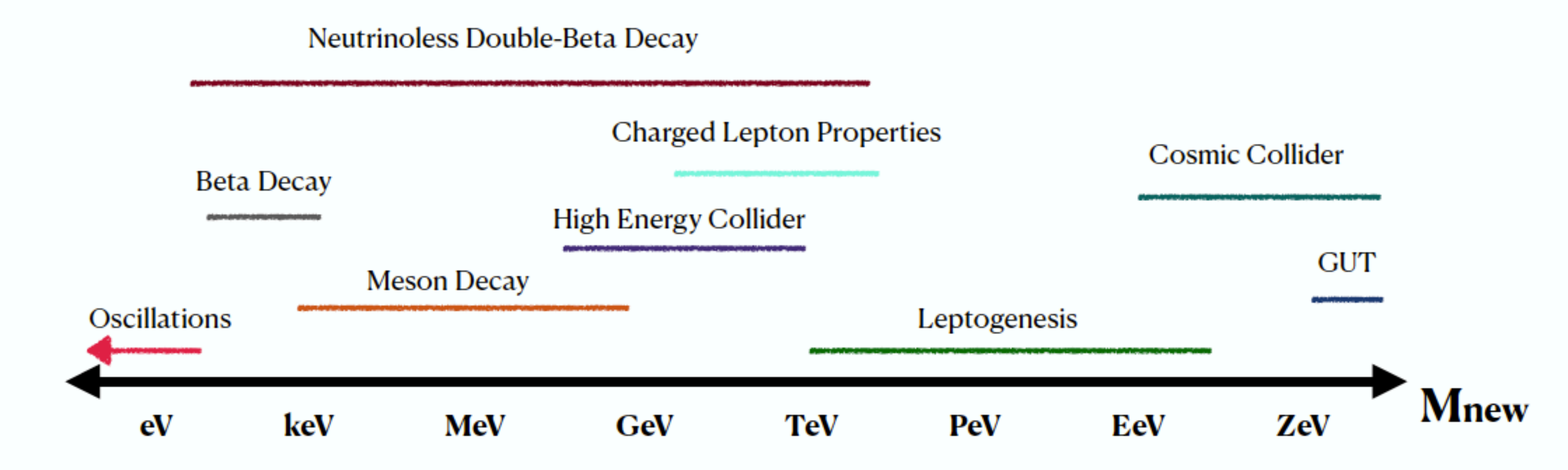
The LHC has revealed that the minimum SM prescription for electroweak symmetry breaking — the one Higgs doublet model — is at least approximately correct. What does that have to do with neutrinos?

The tiny neutrino masses point to three different possibilities.

1. Neutrinos talk to the Higgs boson very, very **weakly**. And **lepton-number must be an exact symmetry** of nature (or broken very, very weakly);
2. Neutrinos talk to a **different Higgs** boson – there is a new source of electroweak symmetry breaking!;
3. Neutrino masses are small because there is **another source of mass** out there — a new energy scale indirectly responsible for the tiny neutrino masses, a la the **seesaw mechanism**.

We are going to need a lot of experimental information from all areas of particle physics in order to figure out what is really going on!

What Is the ν Physics Scale? We Have No Idea!



Different Mass Scales Are Probed in Different Ways, Lead to Different Consequences, and Connect to Different Outstanding Issues in Fundamental Physics.

Piecing the Neutrino Mass Puzzle

Understanding the origin of neutrino masses and exploring the new physics in the lepton sector will require unique **theoretical** and **experimental** efforts . . .

- understanding the fate of lepton-number. Neutrinoless double-beta decay.
- A comprehensive long baseline neutrino program.
- Probes of neutrino properties, including **neutrino scattering experiments.** And what are the neutrino masses anyway? Kinematical probes.
- Precision measurements of charged-lepton properties ($g-2$, edm) and searches for rare processes ($\mu \to e$-conversion the best bet at the moment).
- **Collider experiments. The LHC and beyond may end up revealing the new physics behind small neutrino masses.**
- Neutrino properties affect, in a significant way, the history of the universe. These can be "seen" in cosmic surveys of all types.
- Astrophysical Neutrinos – Supernovae and other Galaxy-shattering phenomena. Ultra-high energy neutrinos and correlations with not-neutrino messengers.

The Muon Path to the Energy Frontier is Intense

If we are ever to build a weak-scale(+) muon collider, we will need to learn how to build, for a finite amount of money, . . .

. . . a multi MW proton source

. . . muon beams

. . . muon storage rings

. . . etc.

The physics case for every one of these components is quite strong in its own right. [IMHO]

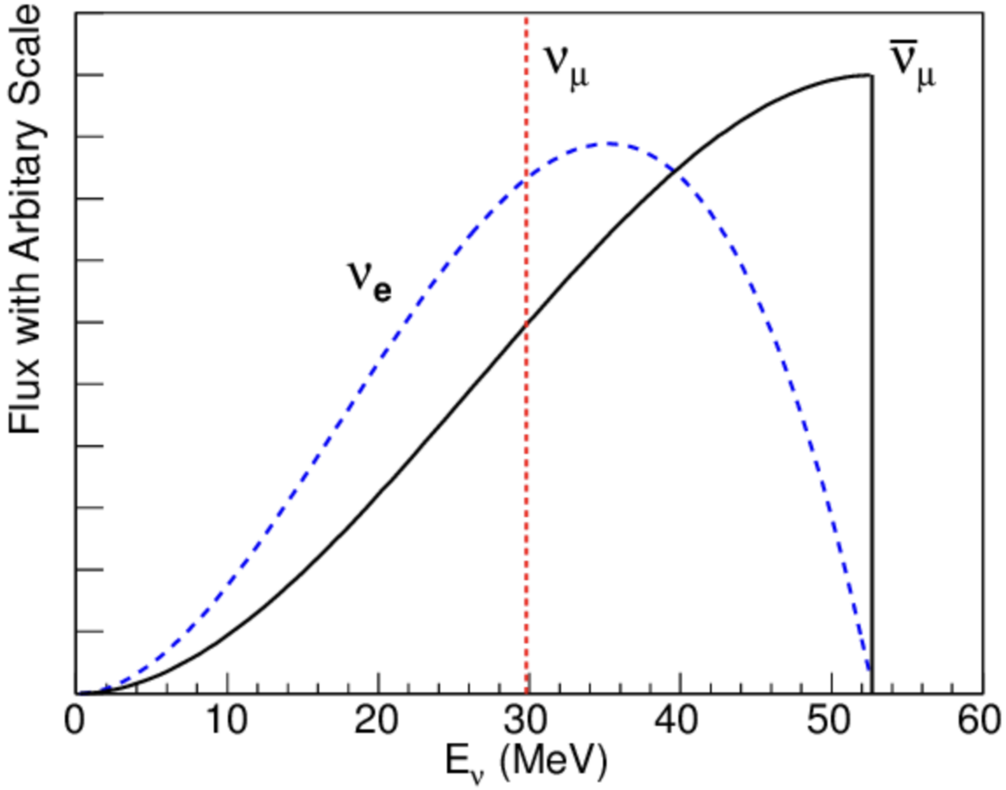
Neutrino Physics at the $\mu^+\mu^-$ Collision Point

- Direct test of neutrino mass models. Neutral heavy leptons, etc.
- Muon Collider as a "Neutrino Collider?" Any luminosity from the decay-daughter-neutrinos to collide? $\nu_\mu + \bar{\nu}_\mu$, and $\nu_\mu + \nu_e$ collisions. Would be amazingly cool . . .
- There is the possibility to study muon–neutrino collisions from W^+ radiation off the muon beam ((i.e., "**neutrino-muon fusion**," $\mu^+ + \mu^- \to W^+(\nu_\mu + \mu)$)) and neutrino–neutrino collisions from double $W^+ + W^-$ radiation (i.e., "**neutrino fusion**," $\mu^+ + \mu^- \to W^+ + W^- + (\nu_\mu + \bar{\nu}_\mu)$). Unique probe of "neutrino-only" forces?

What Could We Learn About?

- Neutrino–neutrino interactions;
- Neutrino interactions with a Dark Sector (LH-portal);
- New channels to look for lepton-number violation. E.g. Type-II Seesaw (Higgs triplet $T = (t^+ +, t^+, t^0)$, $\mu^+\mu^+ \to t^{++} \to W^+W^+$). Potential to inform a hypothetical discovery of $0\nu\beta\beta$?;
- Many more interesting things I haven't thought about. There is a lot of work to do.

Muon-Collider High-Energy Neutrino Fixed-Target Experiments



- Very well characterized beams. We know these shapes "perfectly" and we can modify them in a controlled way by polarizing the muons.
- There are both ν_μ and a $\bar{\nu}_e$ beams. And we should be able to statistically separate them.

. . . and there are LOTS of neutrinos!

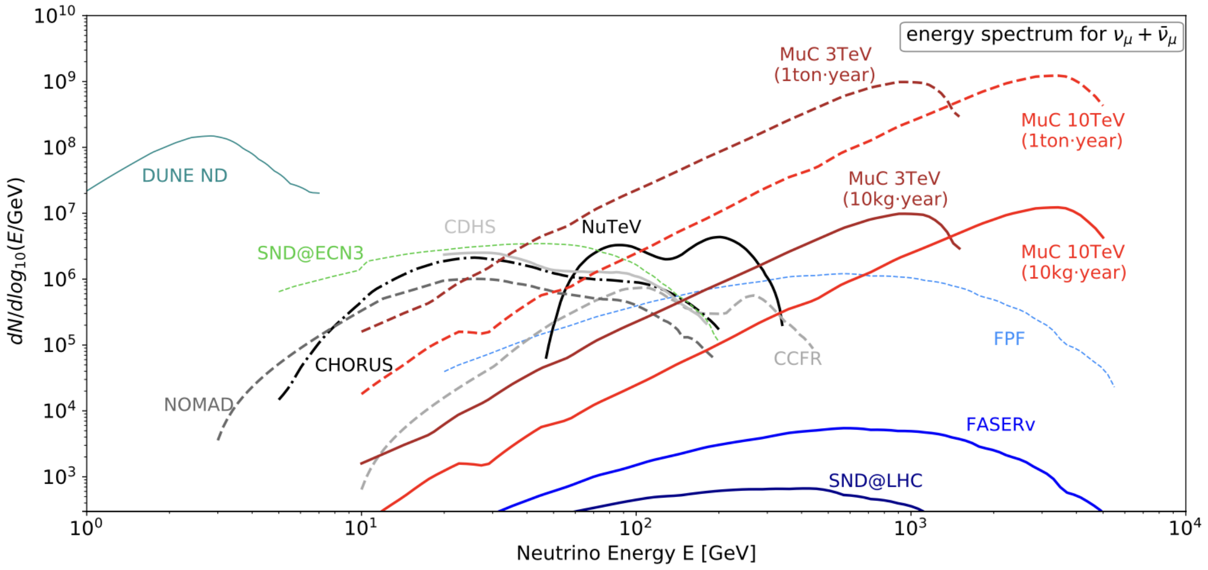


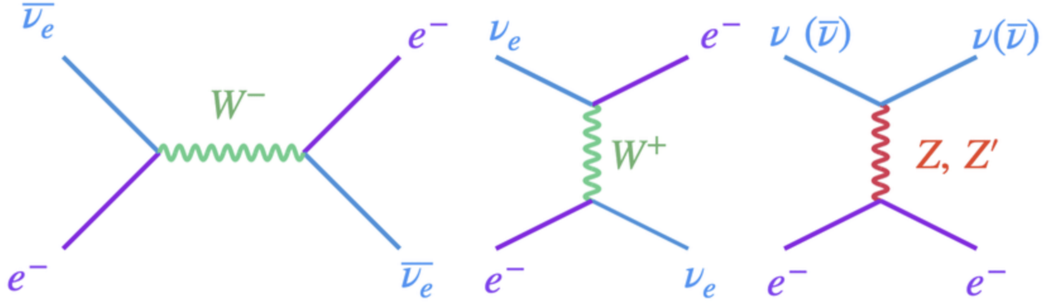
Fig. 2.4: The energy spectrum of neutrino interactions produced by the 3 TeV and 10 TeV MuC in one year, overlaid with the summary plot in Ref. [93] for past and planned neutrino experiments. The solid and dashed lines assume, respectively, a small 10 kg and a realistic 1 ton target mass.

[Interim report for the International Muon Collider Collaboration, arXiv:2407.12450]

Comments on Neutrino–nucleus Interactions:

- Similar in spirit to FASERν (arXiv:1908.02310) with several advantages:
  - Neutrino energy spectrum very well known;
  - Beam has a well-defined flavor (ν_μ and $\bar{\nu}_e$ or vice-versa);
  - Perhaps very narrow beam. Is this good for something? Perhaps different, better targets and detectors?
  - May be an excellent place to do "short-baseline" oscillations. E.g., ν_τ appearance. Could be a very hot topic.
- Neutrino DIS.

On Neutrino–electron Elastic Scattering (and friends):



- **pure electroweak processes** (plus QED higher-order corrections for the purists) involving both the W (for electron-flavor) and the Z.
- ν_e, $\bar{\nu}_e$ and $\nu_{\rm other}$ are different.
- Very clean: the signal is a single recoil electron (very forward) and no other activity. One can probably (?) achieve "zero background" with the right detector.
- Related processes:
  - Inverse-muon decay: $\nu_\mu + e \to \nu_e + \mu$. Signature = single recoil muon.
  - Inverse-tau decay: $\nu_\tau + e \to \nu_e + \tau$. Signature = single recoil tau. (There are no ν_τ in the beam. This is a great way to look for new physics!)
  - Neutrino trident: $\gamma^*\nu \to \ell\bar{\ell}'\nu'$. Signature = two recoil charged-leptons.

What is this Good For?

AdG, Jenkins, hep-ph/0603036;

NuSONG, arXiv:0803.0354;

AdG, Machado, Perez-Gonzalez, Tabrizi, arXiv:1912.06658;

AdG, Thomson, in progress.

- Measure the Weinberg Angle (couplings of the electron to the Z-boson) with neutrinos.
- Measure the neutrino couplings to the Z-boson, including independent measurements for the ν_μ and ν_e. Important: We have never done experiments with high-energy ν_e beams!
- Is the $\nu - Z$ coupling really $V - A$? [Carena, AdG, Freitas, Schmitt, hep-ph/0308053]
- New Physics: new states Z', magnetic moments
- etc.

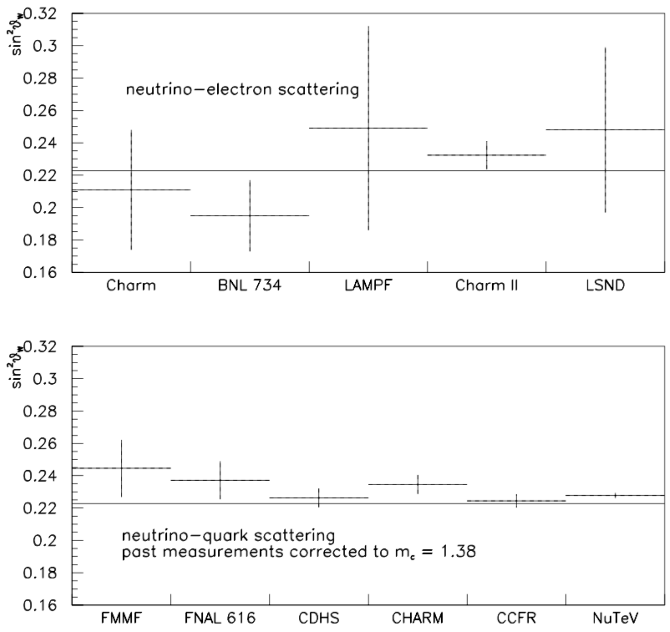


FIG. 4: Measurements of $\sin^2\theta_W$ from past experiments. Top: neutrino-electron elastic scattering experiments. Bottom: neutrino DIS experiments. All DIS results are adjusted to the same charm mass (relevant for experiments not using the PW method). The Standard Model value, indicated by the line, is 0.2227 [12].

[arXiv:0803.0354]

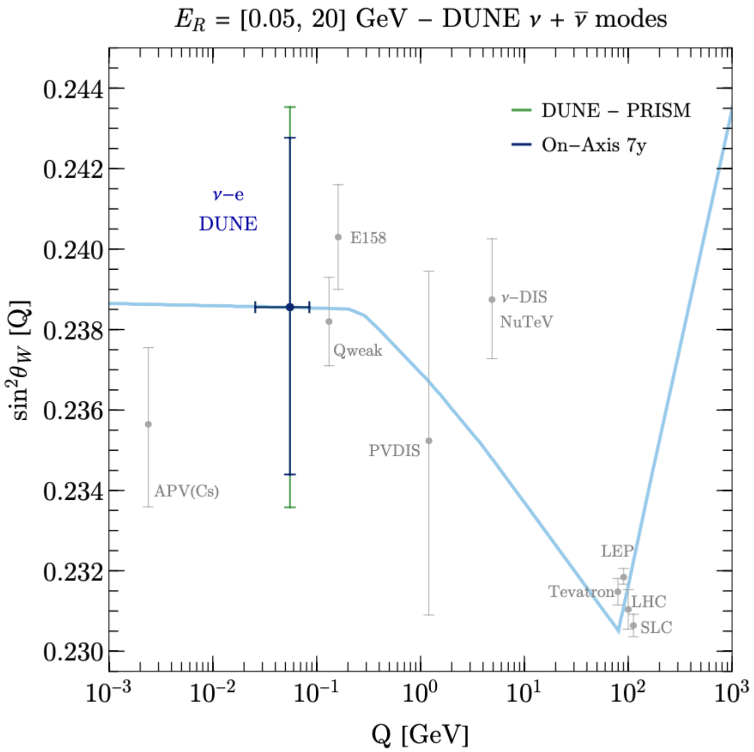


FIG. 4. $\sin^2\theta_W$ in the $\overline{\text{MS}}$ scheme (light blue line) as a function of Q, obtained from a fit to existing data (gray data points), together with the DUNE on-axis (dark blue data point) and DUNE-PRISM (green data point) sensitivities to this angle. The horizontal error bars indicate the range of Q values accessible to DUNE neutrino–electron scattering. Note that the Tevatron, LHC and SLC data points where slightly shifted from $Q = M_Z$ to improve readability.

[arXiv:1912.06658]

TABLE III: Results on the precision of parameter extraction, assuming a 100 ton detector located 100 m from the neutrino source. All limits are taken at 68% confidence. See text for details .

	Assumptions	**Uncertainties** % bkg, % flux	$\sin^2\theta_W$ %	**magnetic moment** 68%	Z' **coupling** ϵ 68%	ρ %
Reactor	3GW, $3 < T < 5$MeV [16]	1, 0.1	0.82	$4.8 \times 10^{-10}\mu_B$	2.0×10^{-3}	1.1
μ^+ ν**-factory**	50GeV, $10^{20}\frac{\text{decays}}{\text{year}}$ [22]	0, 0.1	0.14	$2.5 \times 10^{-11}\mu_B$	2.1×10^{-3}	0.09
μ^- ν**-factory**	50GeV, $10^{20}\frac{\text{decays}}{\text{year}}$ [22]	0, 0.05	0.04	$3.1 \times 10^{-11}\mu_B$	2.0×10^{-3}	0.06
β**-beam** ν_e (^{18}Ne,)	$\gamma = 500$, $1.1 \times 10^{18}\frac{\text{decays}}{\text{yesr}}$ [1]	0, 0.1	0.34	$3.0 \times 10^{-10}\mu_B$	9.8×10^{-4}	0.39
β**-beam** $\bar{\nu}_e$ (^{6}He)	$\gamma = 500$, $2.9 \times 10^{18}\frac{\text{decays}}{\text{yesr}}$ [1]	0, 0.1	0.22	$2.6 \times 10^{-10}\mu_B$	7.7×10^{-4}	0.75
Conventional	NuMI on-axis 3.7×10^{20} POT	0, 3	0.48	$1.8 \times 10^{-10}\mu_B$	2.7×10^{-3}	3.3

[hep-ph/0603036]

"With a high-energy muon collider we can do much, much better"

[in progress]

(Do not quote. This is a less-than-wild guess but there is no reason for you to trust me. Results not yet peer reviewed, uploaded to the archives, discussed in a group meeting, scrutinized by the would-be authors, or even computed in any reliable way.)

In conclusion. . .

- We still **know very little** about the new physics uncovered by neutrino oscillations. I have no idea how much this will change in 20 years. It could, but it doesn't have to.

- **neutrino masses are very small** – we don't know why, but we think it means something important. **neutrino mixing is "weird"** – we don't know why, but we think it means something important.

- We **need more experimental input** (neutrinoless double-beta decay, precision neutrino oscillations, UHE neutrinos, charged-lepton precision measurements, colliders, etc). This is unlikely (?) to change in 20 years.

- **Precision measurements of neutrino oscillations** are sensitive to several new phenomena. **There is at least one clear option – muon storage rings – for what to do after DUNE and Hyper-K.** And a lot of work to do to find out how much more interesting things could get.

- A **High-Energy Muon Storage Ring** is a powerful, unique neutrino fixed-target experiment. The energies are high, the beam is compact, and the neutrino fluxes are well known. And there are both a ν_e and a $\bar{\nu}_\mu$ beam!
- A **Muon Collider** is also a neutrino–muon collider and a neutrino–antineutrino collider. One can also consider initial states with nonzero lepton-flavor (e.g., $\bar{\nu}_\mu \nu_e$ collisions) and nonzero lepton number (e.g. $\nu_\mu \nu_\mu$ collisions). We have never done those before!
- **There is a lot of work to be done**. We have only just begun to scratch the surface on the **synergies between Neutrino Physics, Muon Colliders**, and all the stuff we need to invent to make muons collider with high energies and reasonable luminosity.