Artwork by Sandbox Studio, Chicago with Ana Kova

Neutrino Opportunities at a Muon Collider

The Accelerator Complex Evolution (ACE)

June 14-15, 2023

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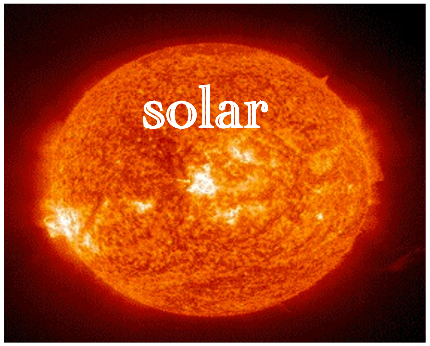
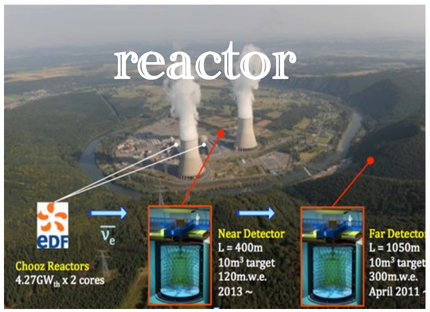
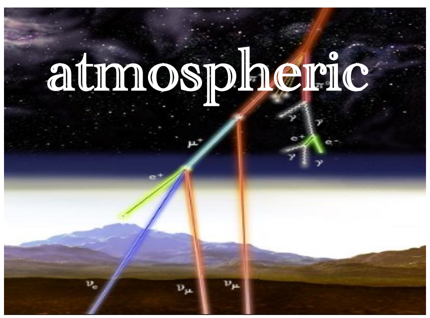
Status of Neutrino Physics in 2022



Super-Kamiokande, Borexino, SNO



MBL: Daya Bay, RENO, Double Chooz
LBL: KamLAND



IceCube, Super-Kamiokande

T2K, MINOS, NOvA

mixing angles:

$sin^2\theta_{12}$ @ 4%

$sin^2\theta_{13}$ @ 3%

$sin^2\theta_{23}$ @ 3%

mass squared differences:

Δm^2_{21} @ 3%

$|\Delta m^2_{31}|$ @ 1%

Future: DUNE, T2HK , JUNO

- Increase the precision
- CP-phase?
- Mass hierarchy?

Also:
Mass scale? Dirac or Majorana?
Sterile?

MuC Synergies with Neutrino Factories

Why a Muon Collider Helps?

High beam luminosity +
Large fiducial mass

→

Ideal to investigate **rare/new** neutrino interactions

$\sigma < 10^{-44}$ cm^2

- Test SM predictions
- Search for BSM physics

- Muon decay is a well understood, equal numbers of electron/muon (anti)neutrinos and muon neutrinos with precisely known energy spectra
- Very high luminosity for both muon and electron flavor content
- Well known neutrino energy spectra
- Very well determined beam intensity

Talk by Alan Bross

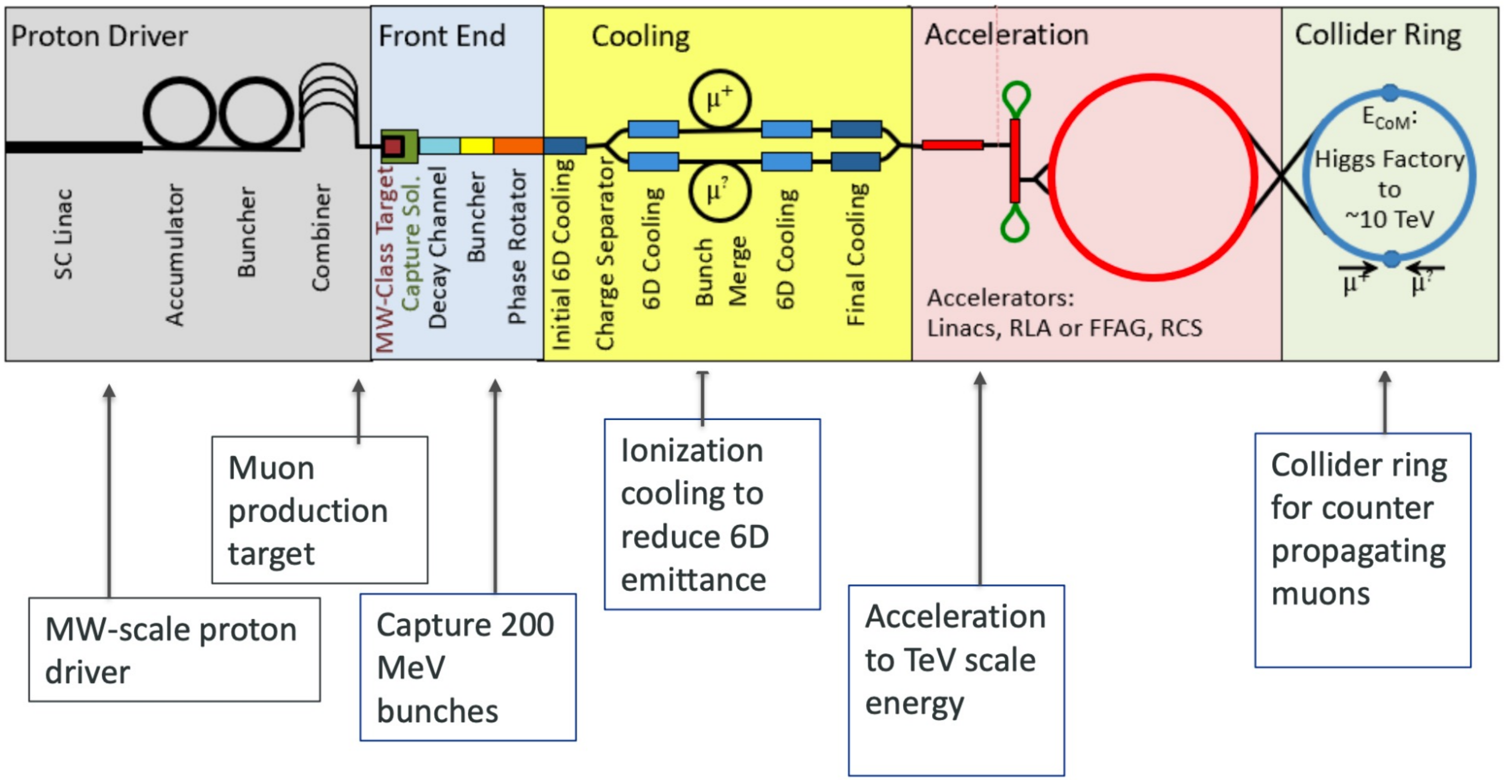
Oscillation at Muon Colliders? Unlikely?

At TeV energy range, the relevant baseline to see oscillation is 10^6 (10^8) km for atmospheric (solar) oscillation parameters.

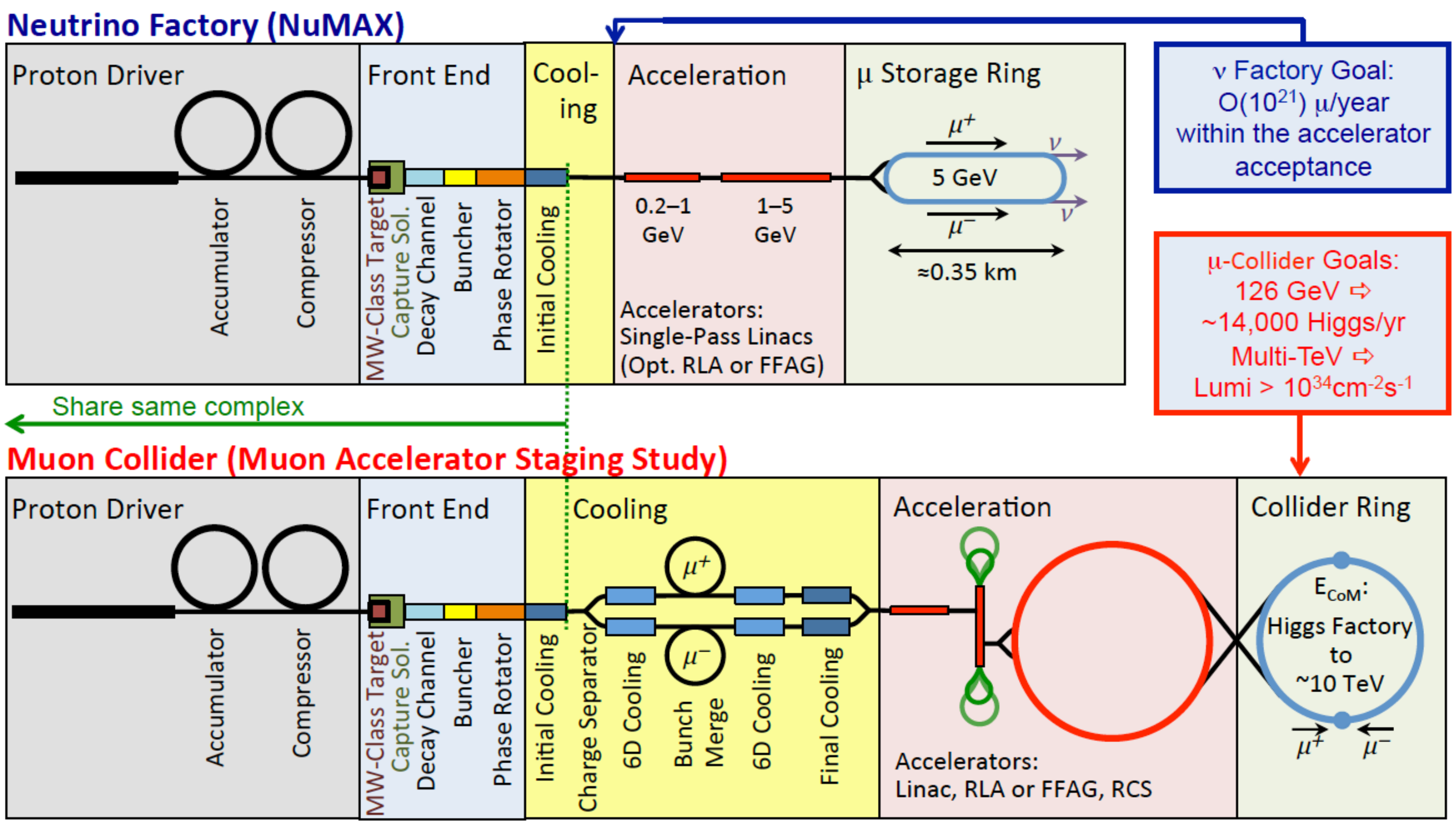
A neutrino detector at the moon?
We are not there yet!

Questions:

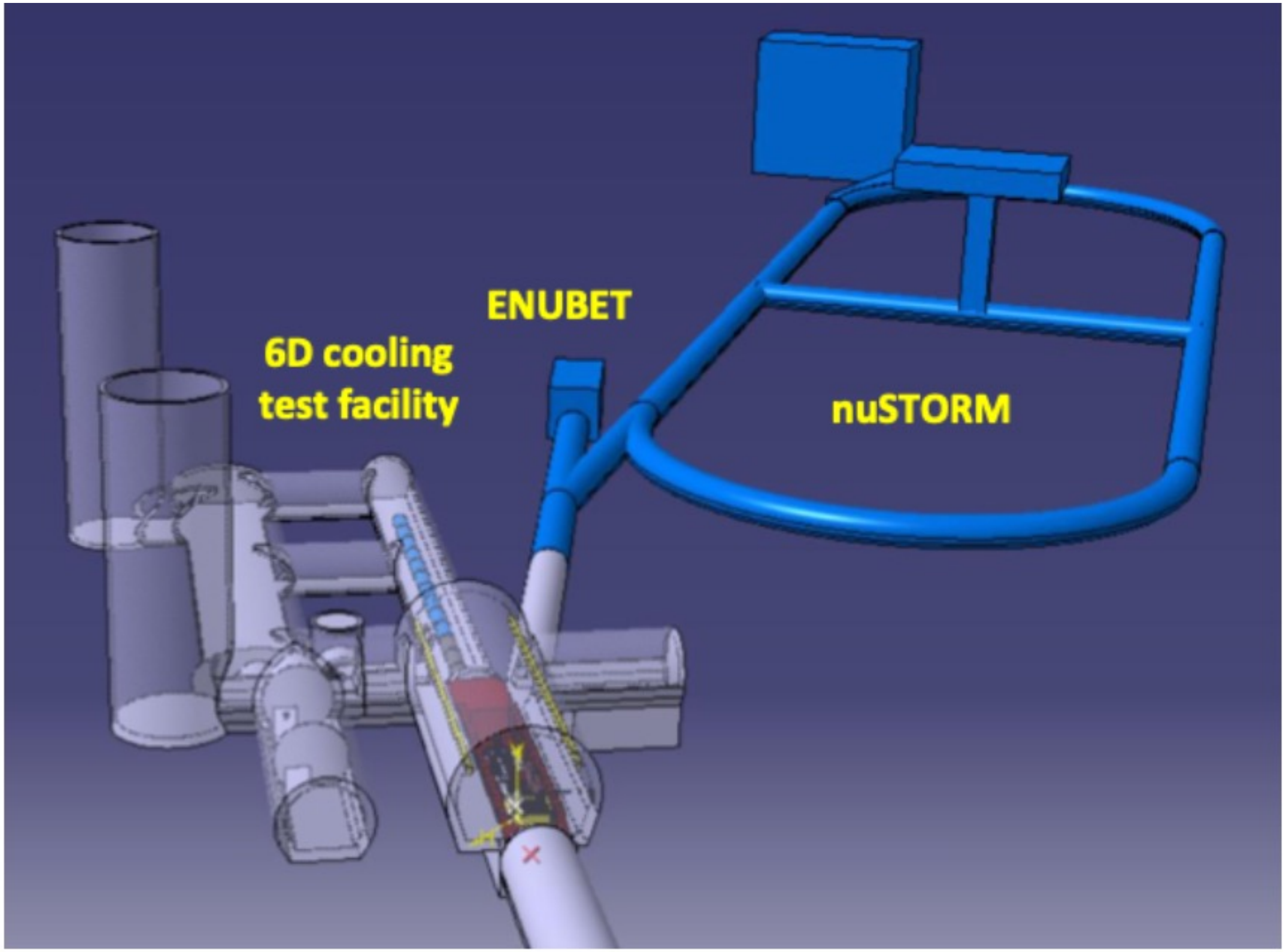
- **What should come after DUNE/Hyper-K?**
- **Will all oscillation questions be answered at DUNE/Hyper-K?**
- **What if we see anomalies?**



- Requires a **1-4 MW** proton beam @ **5-20 GeV**, compressed to **1-3 ns** bunches at a **5-10 Hz** frequency

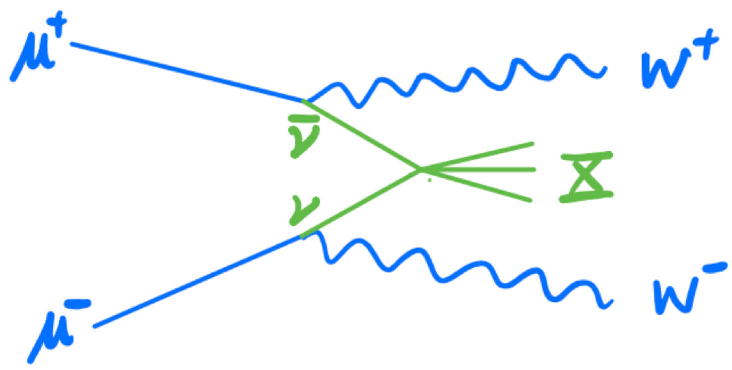

Neutrino Factory (NuMAX)
Proton Driver
Accumulator
Compressor
Front End
MW-Class Target
Capture Sol.
Decay Channel
Buncher
Phase Rotator
Cool-ing
Initial Cooling
Acceleration
0.2–1 GeV
1–5 GeV
Accelerators:
Single-Pass Linacs
(Opt. RLA or FFAG)
μ Storage Ring
5 GeV
≈0.35 km
ν Factory Goal:
O(10^21) μ/year
within the accelerator acceptance
μ-Collider Goals:
126 GeV ⇨
~14,000 Higgs/yr
Multi-TeV ⇨
Lumi > 10^34cm^-2s^-1
Share same complex
Muon Collider (Muon Accelerator Staging Study)
Proton Driver
Accumulator
Compressor
Front End
MW-Class Target
Capture Sol.
Decay Channel
Buncher
Phase Rotator
Cooling
Initial Cooling
Charge Separator
6D Cooling
Bunch Merge
6D Cooling
Final Cooling
Acceleration
Accelerators:
Linac, RLA or FFAG, RCS
Collider Ring
E_CoM:
Higgs Factory
to
~10 TeV

Demonstrator diagram



Direct Neutrino Synergies

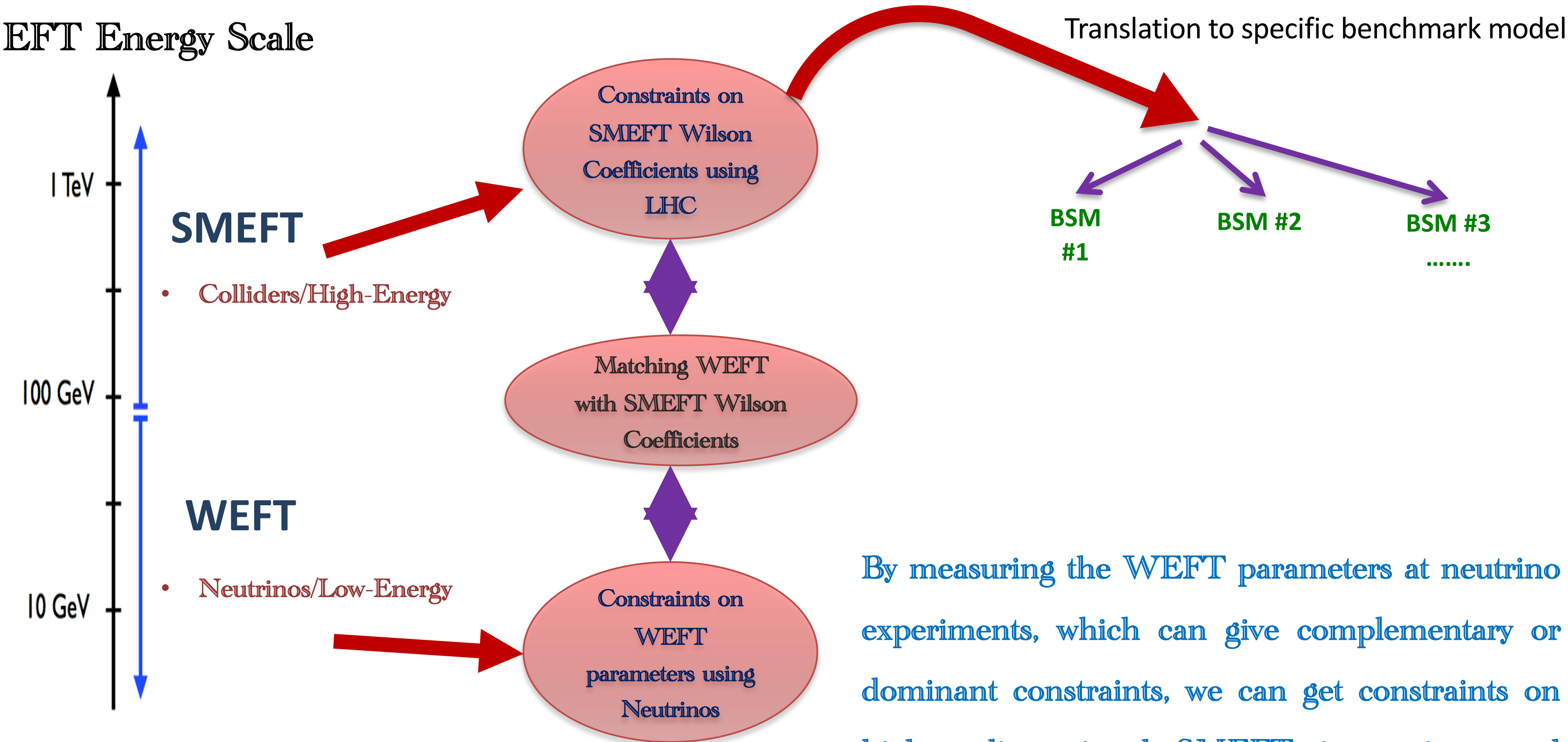
- A high energy muon collider is also a high energy neutrino collier:



Could provide constraints to Non-standard Interactions that are complementary to low-energy probes!

Talk by Ian Low

Indirect BSM Searches (SMEFT)



By measuring the WEFT parameters at neutrino experiments, which can give complementary or dominant constraints, we can get constraints on higher dimensional SMEFT interactions and compare the results with high energy colliders.

SMEFT:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{v^2} O_i^{D=6}$$

Flavor-conserving 4-lepton operators

$\mu^+\mu^-$: $[C_{\ell\ell}]$, $[C_{\ell e}]$, $[C_{ee}]$

$\mu^\pm\nu$: $[C_{\ell\ell}]$, $[C_{\ell e}]$

$\nu\,\bar{\nu}$: $[C_{\ell\ell}]$

Two flavors ($a < b = 1, 2, 3$)
$[O_{\ell\ell}]_{aabb} = (\bar{\ell}_a\bar{\sigma}_\mu\ell_a)(\bar{\ell}_b\bar{\sigma}^\mu\ell_b)$
$[O_{\ell\ell}]_{abba} = (\bar{\ell}_a\bar{\sigma}_\mu\ell_b)(\bar{\ell}_b\bar{\sigma}^\mu\ell_a)$
$[O_{\ell e}]_{aabb} = (\bar{\ell}_a\bar{\sigma}_\mu\ell_a)(e_b^c\sigma^\mu\bar{e}_b^c)$
$[O_{\ell e}]_{bbaa} = (\bar{\ell}_b\bar{\sigma}_\mu\ell_b)(e_a^c\sigma^\mu\bar{e}_a^c)$
$[O_{\ell e}]_{abba} = (\bar{\ell}_a\bar{\sigma}_\mu\ell_b)(e_b^c\sigma^\mu\bar{e}_a^c)$
$[O_{ee}]_{aabb} = (e_a^c\sigma_\mu\bar{e}_a^c)(e_b^c\sigma^\mu\bar{e}_b^c)$

- vertex corrections to the Z and W interactions with leptons:

$$\mathcal{L}_{\rm SMEFT} \supset \frac{g_L}{\sqrt{2}}\left[W^{\mu+}\bar{\nu}_a\bar{\sigma}_\mu(1+\delta g_L^{We_a})e_a + {\rm h.c.}\right] + \sqrt{g_L^2+g_Y^2}Z^\mu e_a^c\sigma_\mu\left(-s_\theta^2 Q_f + \delta g_R^{Ze_a}\right)\bar{e}_a^c$$
$$+\sqrt{g_L^2+g_Y^2}Z^\mu\sum_{f=e,\nu}\bar{f}_a\bar{\sigma}_\mu\left(T_3^f - s_\theta^2 Q_f + \delta g_L^{Zf_a}\right)f_a,$$

SMEFT:

Chirality-conserving 2 lepton-2 quark operators

	With lepton doublets	Without lepton doublets	
$\mu^+\mu^-$	$[O_{\ell q}]_{aabb} = (\bar{\ell}_a \bar{\sigma}_\mu \ell_a)(\bar{q}_b \bar{\sigma}^\mu q_b)$	$[O_{eq}]_{aabb} = (e^c_a \sigma_\mu \bar{e}^c_a)(\bar{q}_b \bar{\sigma}^\mu q_b)$	$\mu^+\mu^-$
$\mu^\pm\nu$	$[O^{(3)}_{\ell q}]_{aabb} = (\bar{\ell}_a \bar{\sigma}_\mu \sigma^i \ell_a)(\bar{q}_b \bar{\sigma}^\mu \sigma^i q_b)$	$[O_{eu}]_{aabb} = (e^c_a \sigma_\mu \bar{e}^c_a)(u^c_b \sigma^\mu \bar{u}^c_b)$	
$\nu\,\bar{\nu}$	$[O_{\ell u}]_{aabb} = (\bar{\ell}_a \bar{\sigma}_\mu \ell_a)(u^c_b \sigma^\mu \bar{u}^c_b)$	$[O_{ed}]_{aabb} = (e^c_a \sigma_\mu \bar{e}^c_a)(d^c_b \sigma^\mu \bar{d}^c_b)$	
	$[O_{\ell d}]_{aabb} = (\bar{\ell}_a \bar{\sigma}_\mu \ell_a)(d^c_b \sigma^\mu \bar{d}^c_b)$		

Chirality-Violating 2 lepton-2 quark operators

	Chirality violating $(I, J = 1, 2, 3)$
$\mu^+\mu^-$	$[O_{\ell equ}]_{IIJJ} = (\bar{\ell}^j_I \bar{e}^c_I)\epsilon_{jk}(\bar{q}^k_J \bar{u}^c_J)$
$\mu^\pm\nu$	$[O^{(3)}_{\ell equ}]_{IIJJ} = (\bar{\ell}^j_I \sigma_{\mu\nu} \bar{e}^c_I)\epsilon_{jk}(\bar{q}^k_J \sigma_{\mu\nu} \bar{u}^c_J)$
	$[O_{\ell edq}]_{IIJJ} = (\bar{\ell}^j_I \bar{e}^c_I)(d^c_J q^j_J)$

- vertex corrections to the Z and W interactions with leptons:

$$\mathcal{L}_{\text{SMEFT}} \supset \sqrt{g_L^2 + g_Y^2}\, Z^\mu \sum_{q=u,d} \left[\overline{q} \overline{\sigma}_\mu \left((T_3^q - s_\theta^2 Q_q) + \delta g_L^{Zq} \right) q + q^c \sigma_\mu \left(-s_\theta^2 Q_q + \delta g_R^{Zq} \right) \overline{q}^c \right]$$
$$+ \left[W^{\mu+} \overline{u} \overline{\sigma}_\mu \left(V_{ud} + \delta g_L^{W q_1} \right) d + \text{h.c.} \right].$$

A Dark Sector Factory? e.g. HNL

$$\mathcal{L} \supset \frac{gU_\ell}{\sqrt{2}} \left(W_\mu \bar{l}_L \gamma^\mu N + \text{h.c.}\right) - \frac{gU_\ell}{2\cos\theta_w} Z_\mu \left(\bar{\nu}_L \gamma^\mu N + \bar{N}\gamma^\mu \bar{\nu}_L\right) - U_\ell \frac{m_N}{v} h \left(\bar{\nu}_L N + \bar{N}\nu_L\right)$$

Peiran Li, Zhen Liu, and Kun-Feng Lyu (2023)

Type	Signal process	$\sigma/\lvert U_\mu\rvert^2$ (w. conj. channel) $m_N = 1$ TeV	Pre-selection cut (PSC)	Included
t-channel	$\mu^+\mu^- \longrightarrow N_\mu \bar{\nu}_\mu$	20.28 pb	PSC	Yes
VBF	$\mu^+\mu^- \longrightarrow \mu^+\mu^- N_\mu \bar{\nu}_\mu$	~ 1 pb	–	No
VBF	$\mu^+\mu^- \longrightarrow \bar{\nu}_\mu \nu_\mu N_\mu \bar{\nu}_\mu$	~ 0.1 pb	–	No

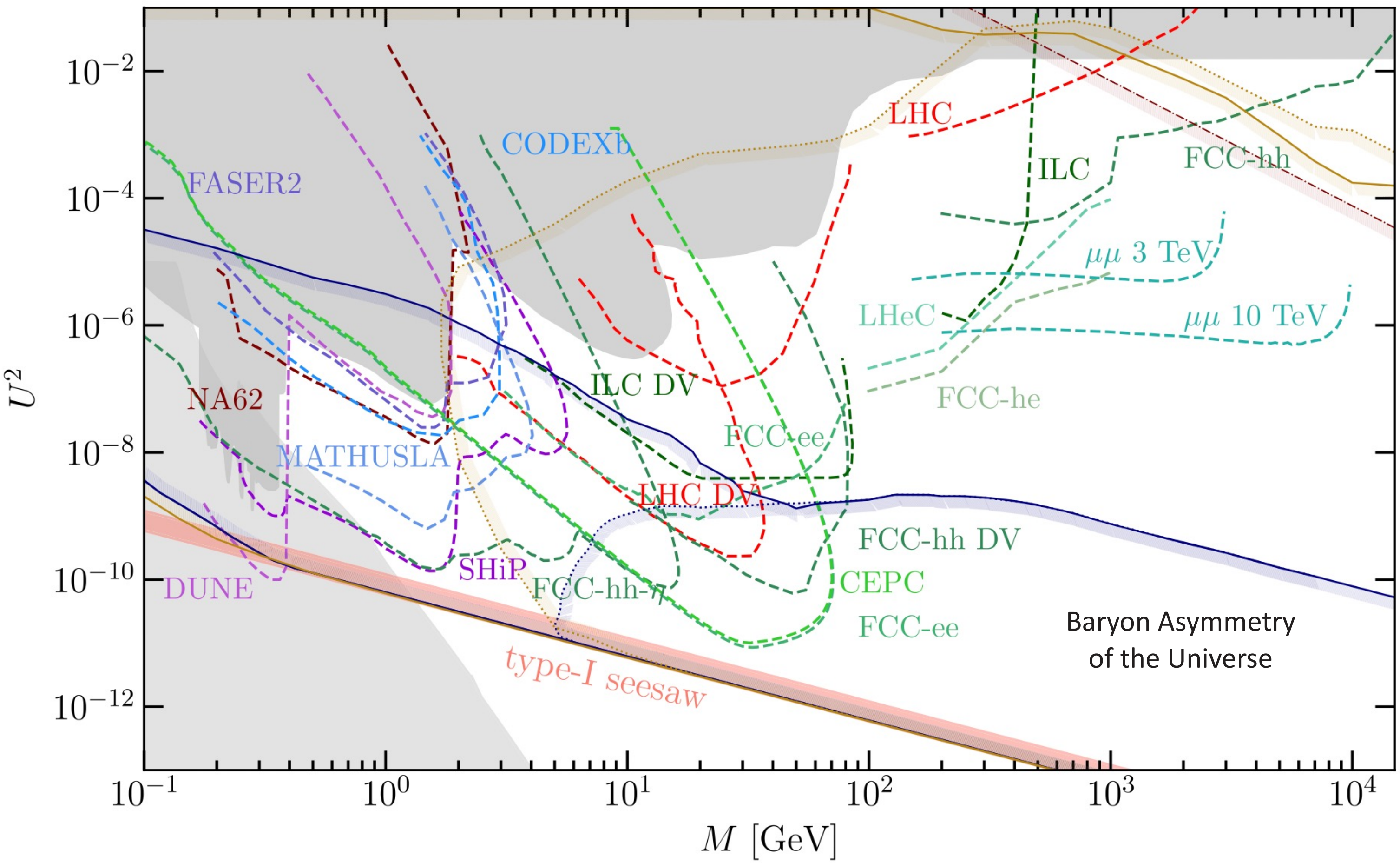
TABLE III. The signal rate for N_μ at 10 TeV. The cross section includes the charge conjugate process.

Type	Background process	σ (w. conj. channel)	Pre-selection cut (PSC)	Included
t-channel	$\mu^+\mu^- \longrightarrow W^+\mu^-\bar{\nu}_\mu$	0.214 pb	PSC	Yes
t-channel	$\mu^+\mu^- \longrightarrow Z\mu^+\mu^-$	0.464 pb	PSC & missing μ^+	Yes
VBF	$\mu^+\mu^- \longrightarrow \mu^+\mu^- W^+\mu^-\bar{\nu}_\mu$	0.401 pb	PSC & missing $\mu^+\mu^-$	Yes
VBF	$\mu^+\mu^- \longrightarrow \bar{\nu}_\mu \nu_\mu W^+\mu^-\bar{\nu}_\mu$	0.0686 pb	PSC	No

TABLE IV. N_μ background at 10 TeV. The cross section includes the charge conjugate process.

HNL consistent with both seesaw and leptogenesis

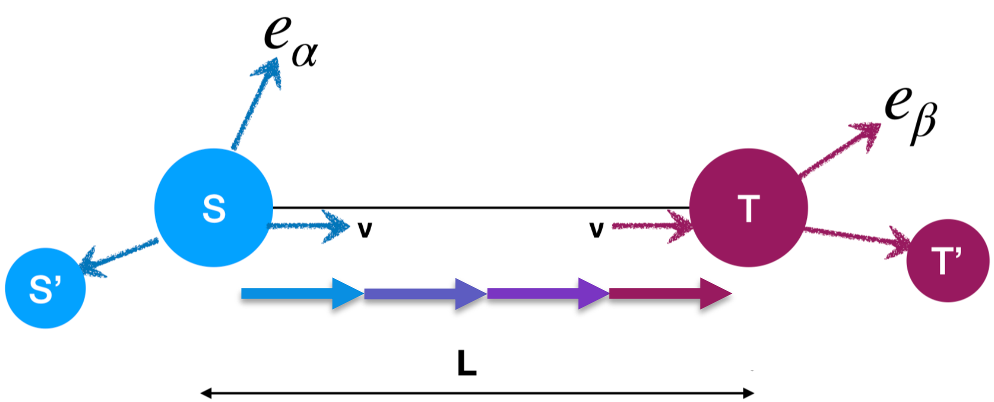
The present and future status of heavy neutral leptons
[2203.08039]



Questions:

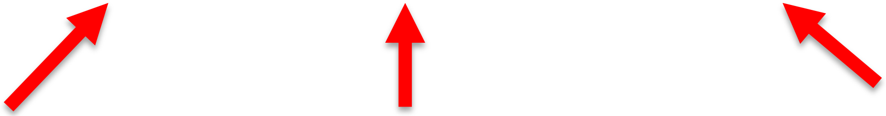
- **What are other direct/indirect searches we can do?**
- **Can we have a dedicated neutrino detector as well?**

A Dedicated Neutrino Detector?

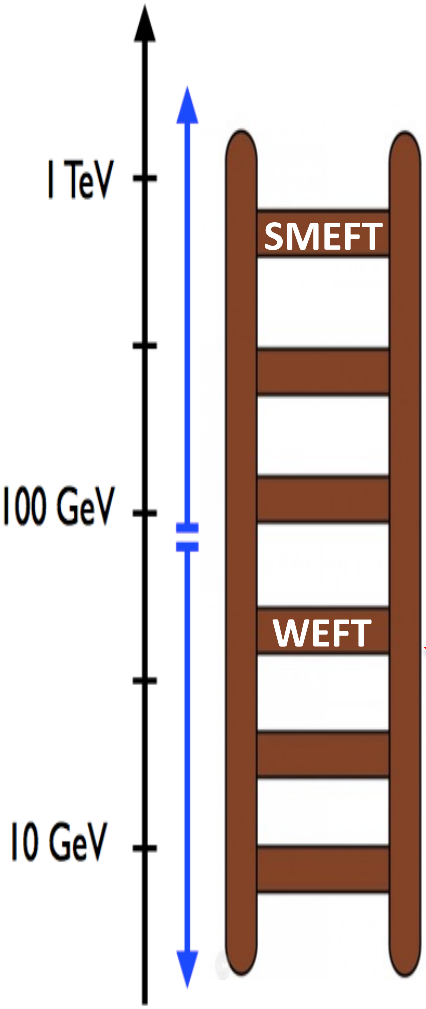


Observable: rate of detected events

~ (flux)×(det. cross section) × (oscillation)

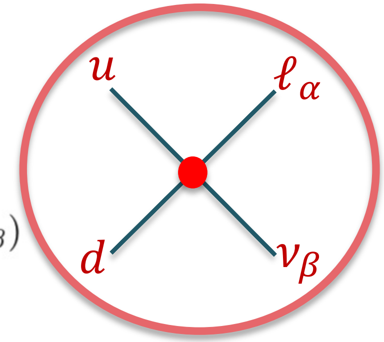


EFT ladder WEFT: Effective Lagrangian defined at a low scale



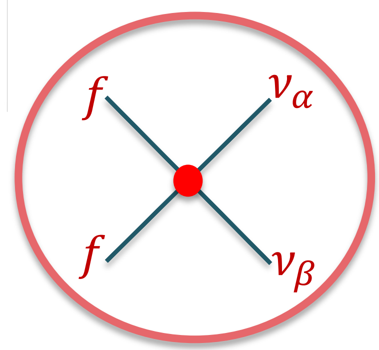
- CC: New left/right handed, (pseudo)scalar and tensor interactions

$$
\begin{aligned}
\mathcal{L}_{\rm WEFT} \supset\ & -\frac{2V_{ud}}{v^2}\Big\{ [\mathbf{1}+\epsilon_L]_{\alpha\beta}(\bar{u}\gamma^\mu P_L d)(\bar{\ell}_\alpha\gamma_\mu P_L\nu_\beta) \\
& +[\epsilon_R]_{\alpha\beta}(\bar{u}\gamma^\mu P_R d)(\bar{\ell}_\alpha\gamma_\mu P_L\nu_\beta) \\
& +\frac{1}{2}[\epsilon_S]_{\alpha\beta}(\bar{u}d)(\bar{\ell}_\alpha P_L\nu_\beta) - \frac{1}{2}[\epsilon_P]_{\alpha\beta}(\bar{u}\gamma_5 d)(\bar{\ell}_\alpha P_L\nu_\beta) \\
& +\frac{1}{4}[\hat{\epsilon}_T]_{\alpha\beta}(\bar{u}\sigma^{\mu\nu}P_L d)(\bar{\ell}_\alpha\sigma_{\mu\nu}P_L\nu_\beta) + \text{h.c.}\Big\}
\end{aligned}
$$



- NC: New left and right handed interactions

$$
\mathcal{L}_{\rm WEFT} \supset -\frac{2}{v^2}\epsilon^{fX}_{\alpha\beta}(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta)\left(\bar{f}\gamma_\mu P_X f\right)
$$



- Neutrino experiments
- Hadron Decays
- β-decays

At the scale m_Z WEFT parameters ε_X map to dim-6 operators in SMEFT

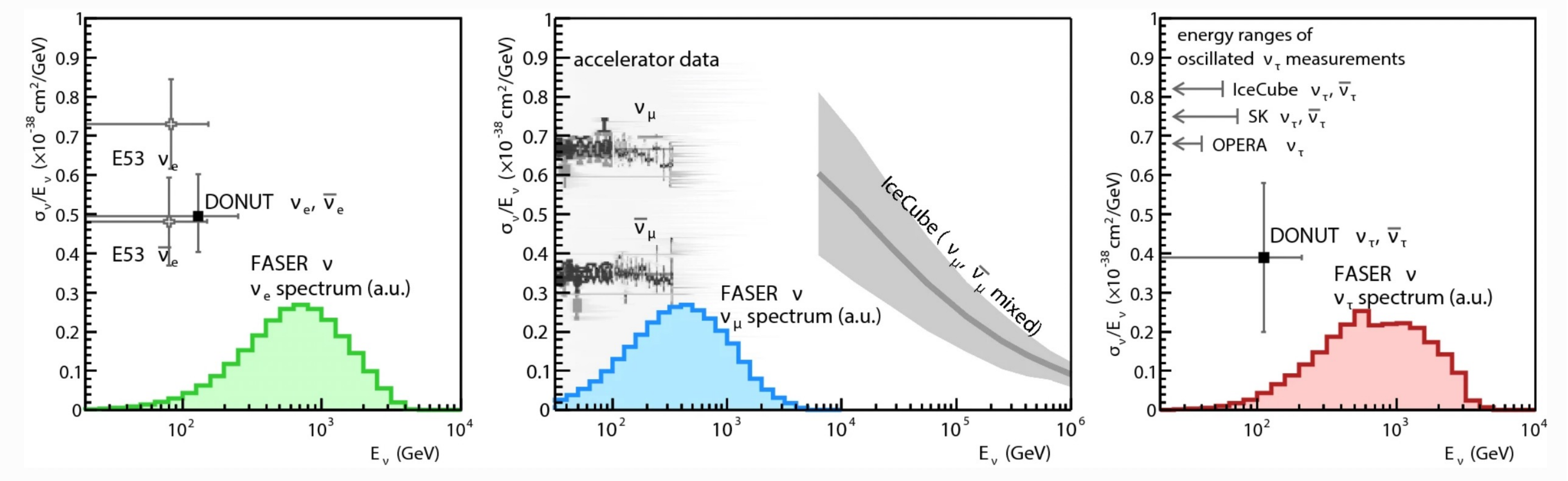
$$
\begin{aligned}
[\epsilon_L]_{\alpha\beta} &\approx \frac{v^2}{\Lambda^2 V_{ud}}\left(V_{ud}[c^{(3)}_{Hl}]_{\alpha\beta} + V_{jd}[c^{(3)}_{Hq}]_{1j}\delta_{\alpha\beta} - V_{jd}[c^{(3)}_{lq}]_{\alpha\beta 1j}\right) \\
[\epsilon_R]_{\alpha\beta} &\approx \frac{v^2}{2\Lambda^2 V_{ud}}[c_{Hud}]_{11}\delta_{\alpha\beta} \\
[\epsilon_S]_{\alpha\beta} &\approx -\frac{v^2}{2\Lambda^2 V_{ud}}\left(V_{jd}[c^{(1)}_{lequ}]^*_{\beta\alpha j1} + [c_{ledq}]^*_{\beta\alpha 11}\right) \\
[\epsilon_P]_{\alpha\beta} &\approx -\frac{v^2}{2\Lambda^2 V_{ud}}\left(V_{jd}[c^{(1)}_{lequ}]^*_{\beta\alpha j1} - [c_{ledq}]^*_{\beta\alpha 11}\right) \\
[\hat{\epsilon}_T]_{\alpha\beta} &\approx -\frac{2v^2}{\Lambda^2 V_{ud}} V_{jd}[c^{(3)}_{lequ}]^*_{\beta\alpha j1}
\end{aligned}
$$

Falkowski, González-Alonso, ZT, JHEP (2019)

- All ε_X arise at $O(\Lambda^{-2})$ in the SMEFT, thus they are equally important.
- No off-diagonal right handed interactions in SMEFT.

Precision in Cross Section Measurements

FASER Collaboration, 2020

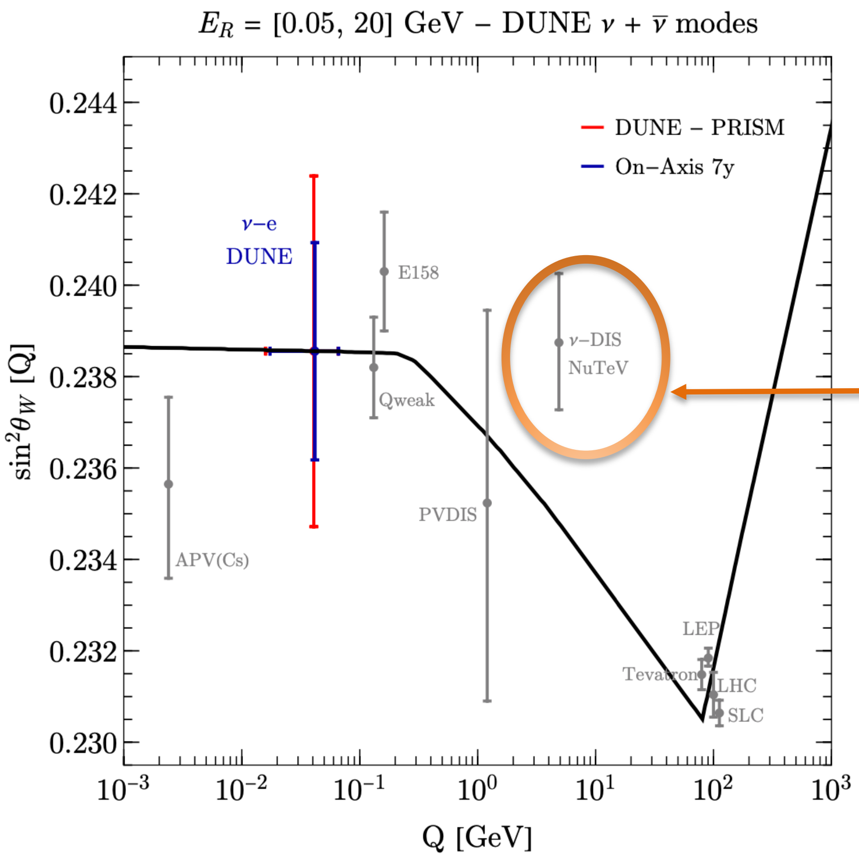


- Precise determination of exclusive neutrino-nucleus cross-sections

The Physics Case for a Neutrino Factory
2203.08094

- DIS dominates the neutrino cross section with nucleons and one can study the nucleon structure at low Bjorken x and high Q^2
- All components of the beam are well-known and the extraction of the neutrino cross sections can be performed directly and with much greater precision

Precision in Weak Mixing Angle



The Physics Case for a Neutrino Factory 2203.08094

The most precise measurement of $\sin^2\theta_W$ using neutrino scattering, at $\langle Q \rangle \simeq 4.5$ GeV.

Deviates from the LEP measurement at 3σ level.

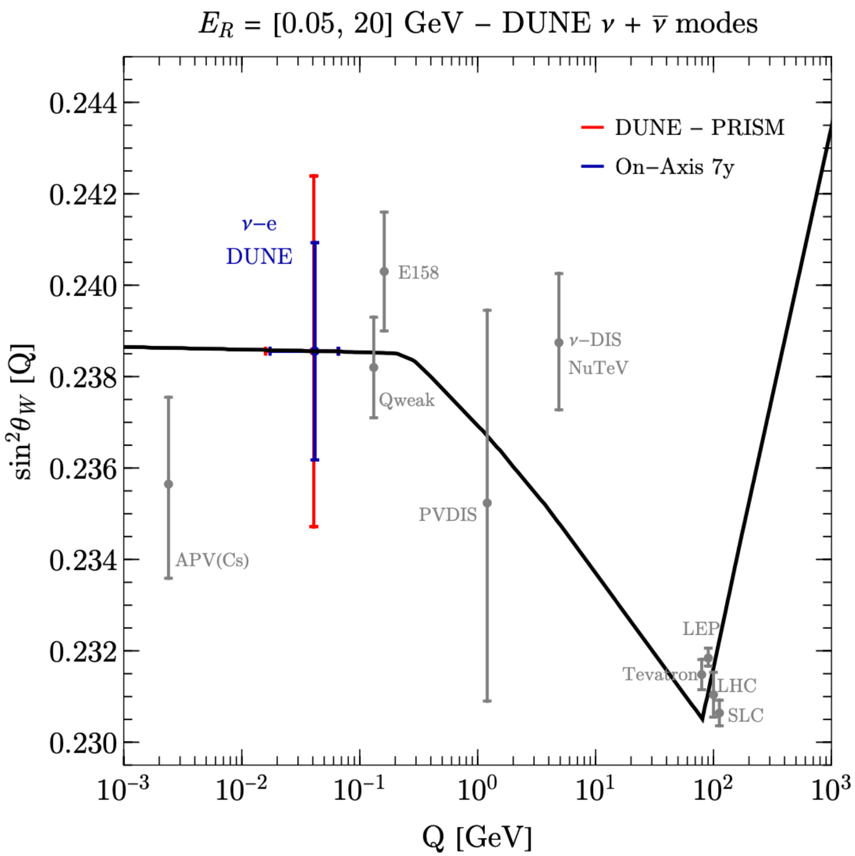
$$R^{\nu(\bar{\nu})} = \frac{\sigma(\nu(\bar{\nu})N \to \nu(\bar{\nu})X)}{\sigma(\nu(\bar{\nu})N \to \ell^{-(+)}X)} \approx g_L^2 + 2g_R^2$$

$$\sin^2\theta_W(\langle Q^2\rangle = 20\ \text{GeV}^2) = 0.2277 \pm 0.0013 \pm 0.0009$$

G. P. Zeller et al. (NuTeV), (2002)

Main uncertainty at NuTeV: Subtraction of the ν_e CC contamination from the NC sample.

Running of the Weak Mixing Angle



The Physics Case for a Neutrino Factory
2203.08094

i) Deep inelastic scattering neutrino-quark scattering: $\hat{s}$= 2xE_ν m_N

ii) Elastic neutrino-e scattering: s = 2$E_\nu m_e$

iii) Elastic neutrino-proton scattering: s = 2$E_\nu m_N$

Questions:

- **What are other interesting SM/BSM searches we can do?**

Detector Requirements:

The Physics Case for a Neutrino Factory
2203.08094

•Highly segmented detectors capable of precision operation at high event rate.

•Excellent muon and electron ID capability.

•Excellent energy resolution.

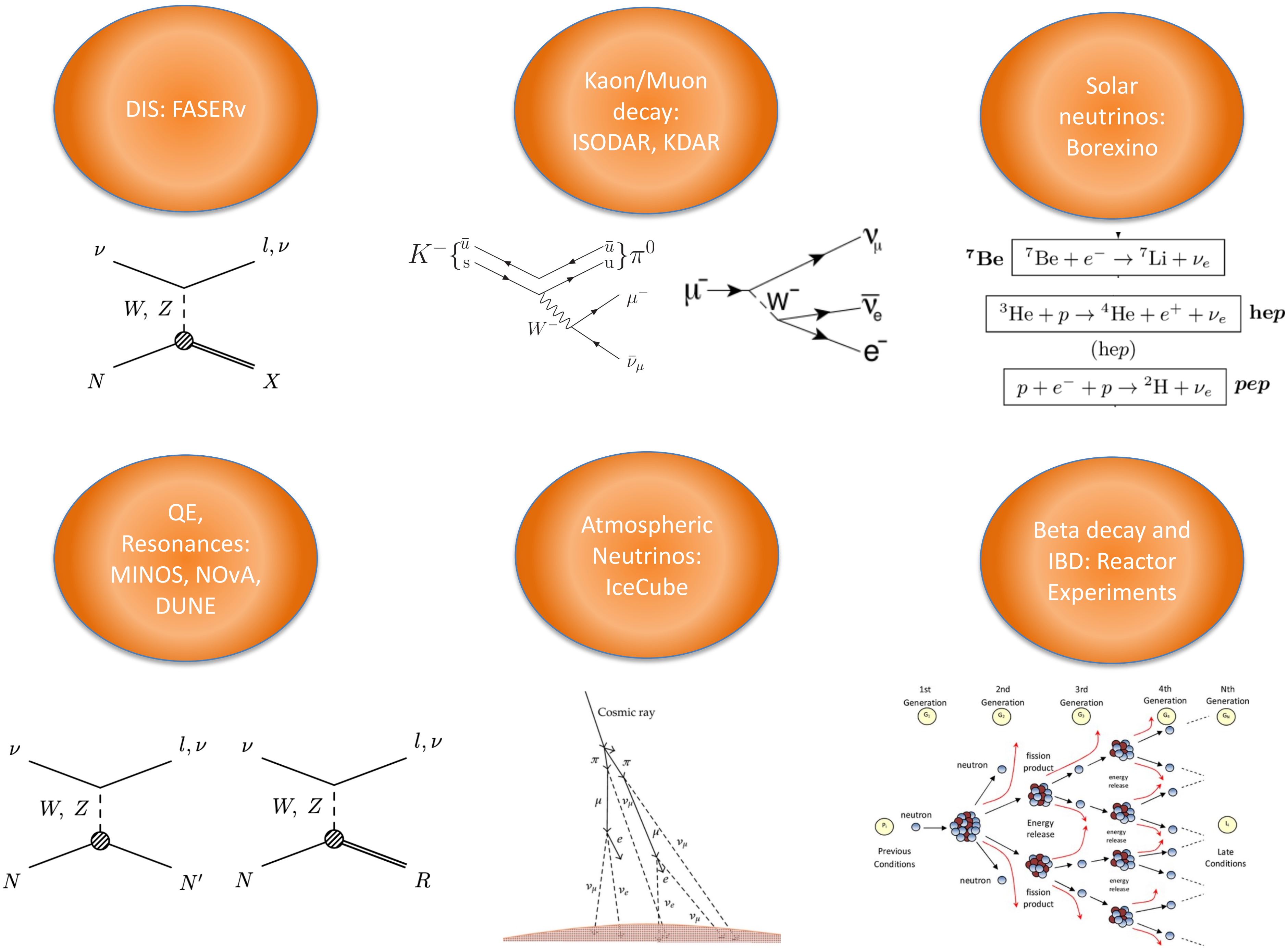
•A magnetized detector for charge identification. In addition, reconstruction via spectrometry can be applied to event reconstruction as opposed to being done via calorimetry. This is particularly important for high-energy neutrino interactions where the outgoing muon's momentum must be measured via spectrometry.

•Excellent particle ID.

•Neutron detection capability (with energy determination).

•A variety of nuclear targets to measure cross-sections as a function of the nuclear target mass number A.

•Micron-scale resolution for charm and tau identification or the capability to tag charm and taus in the final state via kinematics.



DIS: FASERν
Kaon/Muon decay: ISODAR, KDAR
Solar neutrinos: Borexino
QE, Resonances: MINOS, NOvA, DUNE
Atmospheric Neutrinos: IceCube
Beta decay and IBD: Reactor Experiments
ν
l, ν
$W,\ Z$
N
X
$K^- \{^{\bar{u}}_{s}$
$^{\bar{u}}_{u}\} \pi^0$
W^-
μ^-
$\bar{\nu}_\mu$
μ^-
W^-
ν_μ
$\bar{\nu}_e$
e^-
^{7}Be
$^7\mathrm{Be} + e^- \to {}^7\mathrm{Li} + \nu_e$
$^3\mathrm{He} + p \to {}^4\mathrm{He} + e^+ + \nu_e$
hep
(hep)
$p + e^- + p \to {}^2\mathrm{H} + \nu_e$
pep
N'
R
Cosmic ray
π
μ
ν_μ
e
ν_e
1st Generation
2nd Generation
3rd Generation
4th Generation
Nth Generation
neutron
fission product
Energy release
energy release
Previous Conditions
Late Conditions

Neutrino experiments give us a powerful tool to search for new physics, either by direct production or by precision measurements!