Neutrino Opportunities at a Muon Collider

Artwork by Sandbox Studio, Chicago with Ana Kova

International
MUON Collider
Collaboration

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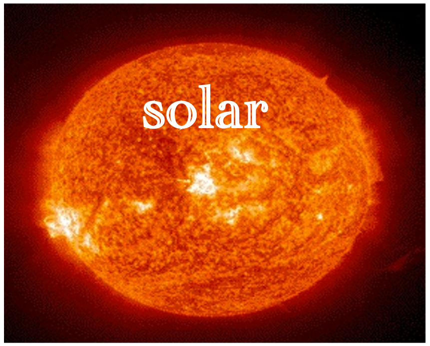
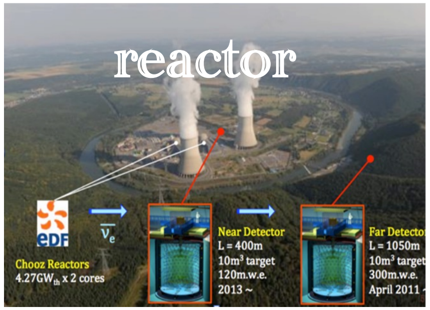
Outline:

- Synergies with Neutrino Factories
- Dedicated Neutrino Detector at a MC
- MC as a High Energy Neutrino Beam
- Conclusion

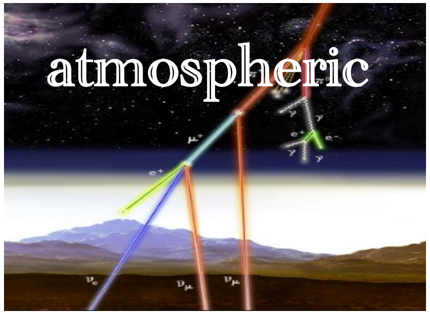
Status of Neutrino Physics in 2023



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?

Neutrino Factories

Do we still need a Neutrino Factory?

High beam luminosity +
Large fiducial mass

→

Ideal to investigate
rare/new neutrino
interactions

- Equal numbers of electron/muon (anti)neutrinos;
- Very high luminosity for both muon and electron flavor content;
- Well known neutrino energy spectra at tens of GeV;
- Very well determined beam intensity;

- The only experiment to over constrain oscillation for 3-neutrino paradigm;
- In case of anomalies, a NF would be ideal to investigate them;

Neutrino Factories

New neutrino states

Light Dark Matter

Searches for LFV

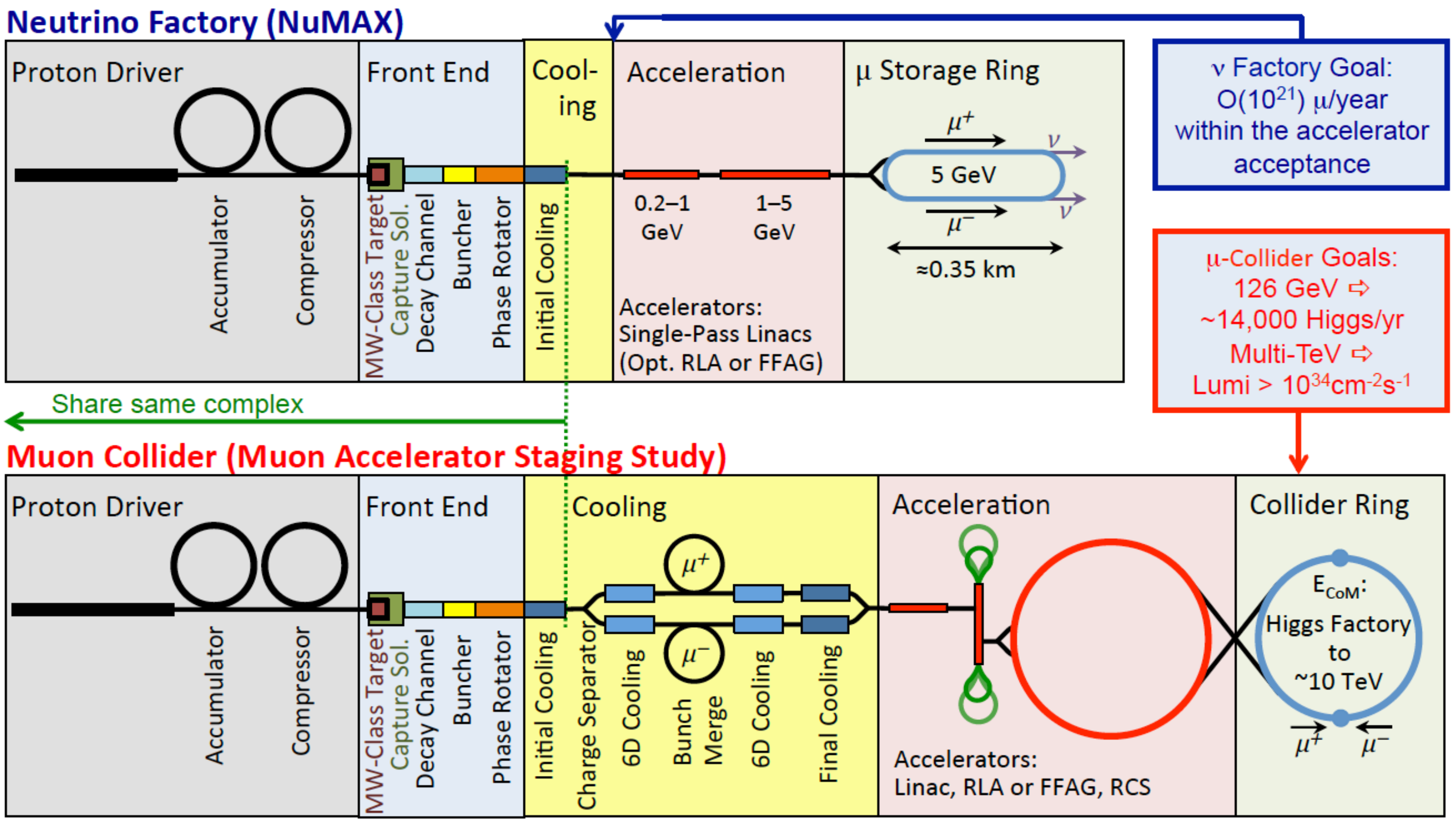
ALPs

Heavy BSM using EFT

....

Given its unique beam characteristics, NF will be remarkable to explore a much wider range of new physics!

Synergies with a Muon Collider

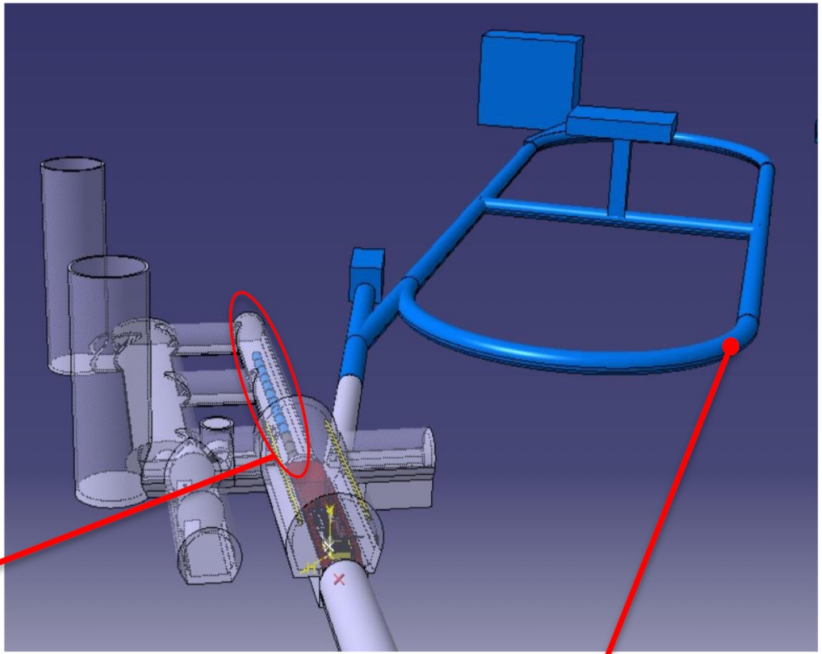


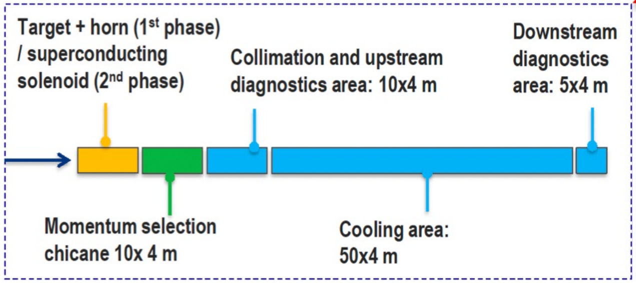
- **Muon production, capture, and cooling would directly benefit a neutrino factory;**
- **The need for a Cooling Demonstrator Facility (CDF) as part of a Muon Collider R&D program might breathe new life into the nuSTORM concept;**

IMCC Demonstrator

- ☐ Rich physics opportunities;
- ☐ The need to prepare for a post-DUNE program;

Detailed studies of a NF complex is needed





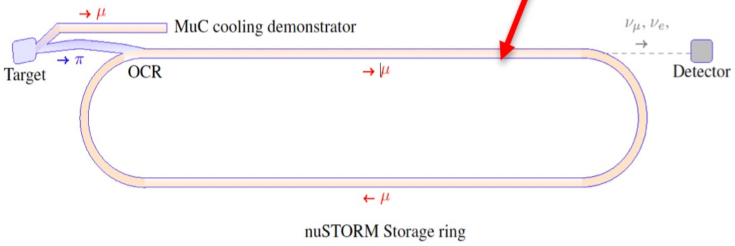
Target + horn (1st phase) / superconducting solenoid (2nd phase)

Collimation and upstream diagnostics area: 10x4 m

Downstream diagnostics area: 5x4 m

Momentum selection chicane 10x 4 m

Cooling area: 50x4 m



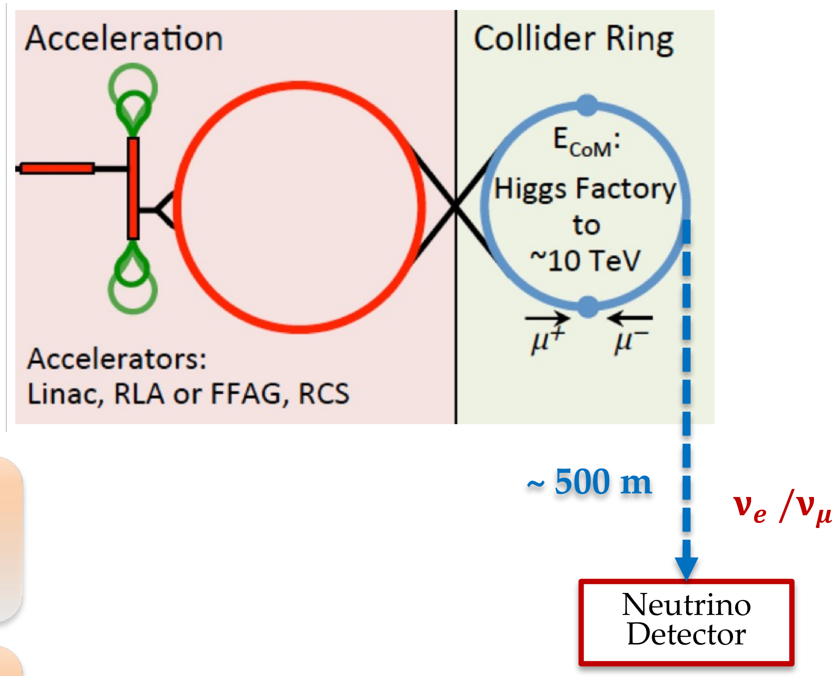
Oscillation at Muon Colliders?
Unlikely?

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!

Neutrino Fixed Target Experiment at a Muon Collider

Why would a Muon Collider Help?



No oscillation, but:

Very high beam luminosity

Precisely known energy spectra

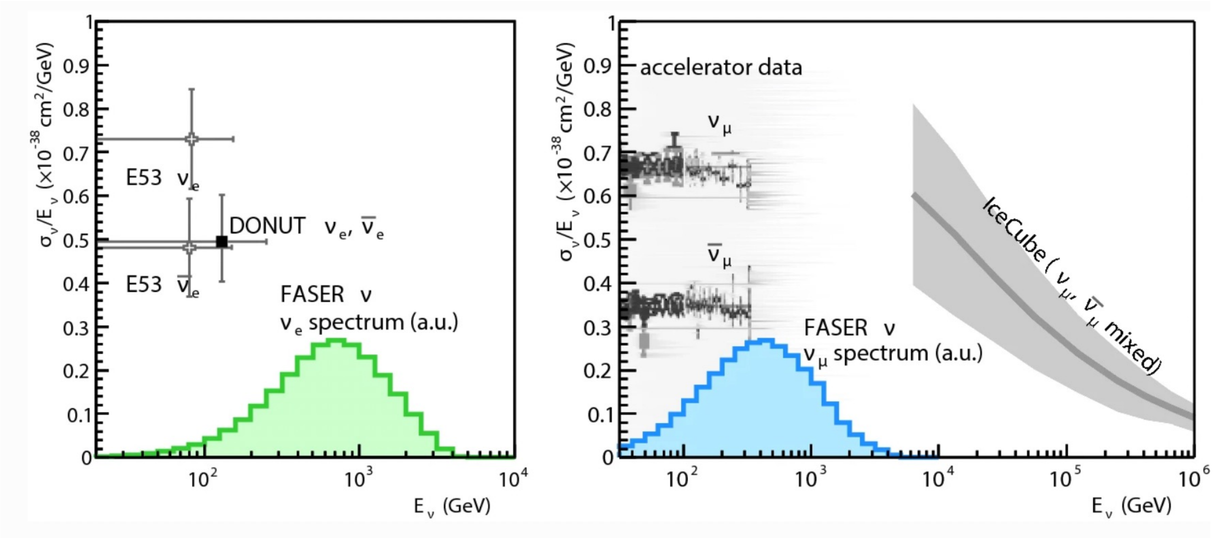
Equal numbers of e/μ (anti)neutrinos

Very well determined beam intensity

- Ideal to investigate rare/new neutrino interactions
- Search for BSM physics

Case 1: SM Search (Precision in Neutrino Cross Section Measurements)

FASER Collaboration, 2020

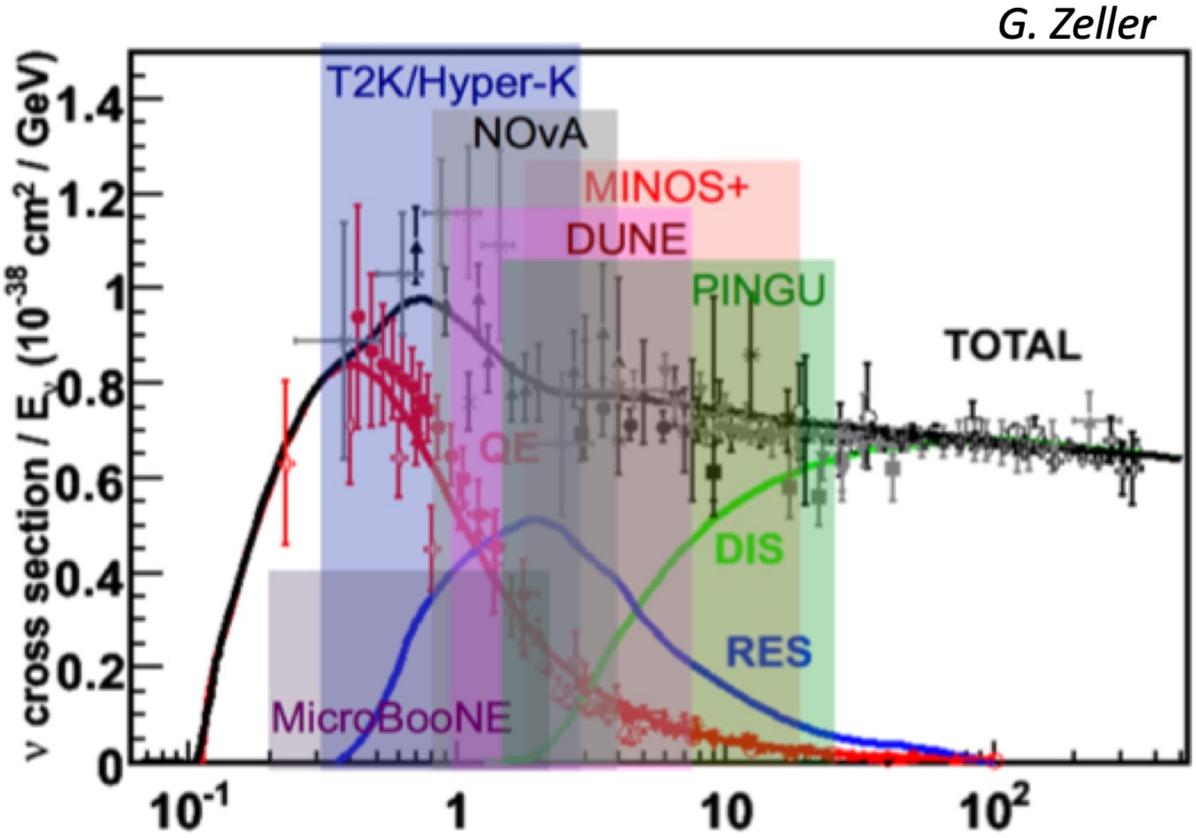


- ☐ Currently no high energy ν_e beam
- ☐ A lot of ν_μ, but not well known beam

- Well known beam, direct extraction of the x-sections with much greater precision
- DIS dominates, we can probe nucleon structure at low Bjorken x and high Q^2

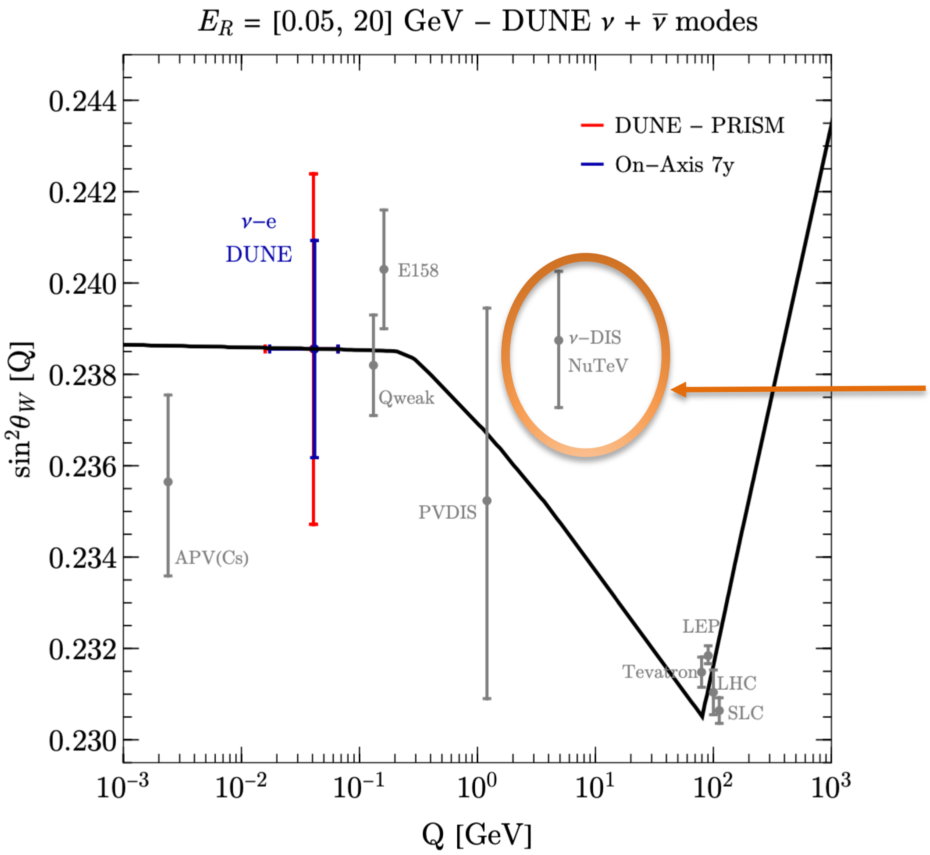
Long Baseline Accelerator Experiments

- 0.1-10 GeV energy range: cross section is much more involved!



J.A. Formaggio, G. Zeller, Reviews of Modern Physics, 84 (2012)

Physics Case 2: 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 ⟨Q⟩ ≃ 4.5 GeV.

Deviates from the LEP measurement at 3σ level.

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

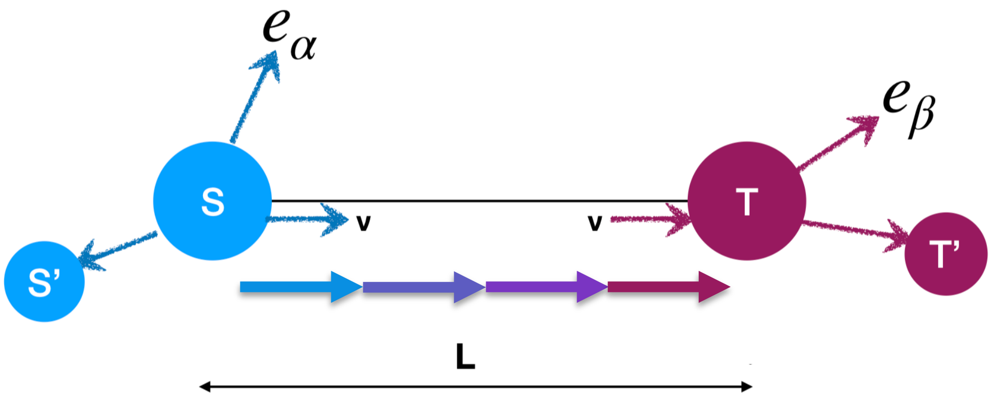
$$\sin^2\theta_W(\langle Q^2\rangle = 20\ \mathrm{GeV}^2) = 0.2277 \pm 0.0013 \pm 0.0009$$

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

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

How about "Heavy" New Physics?

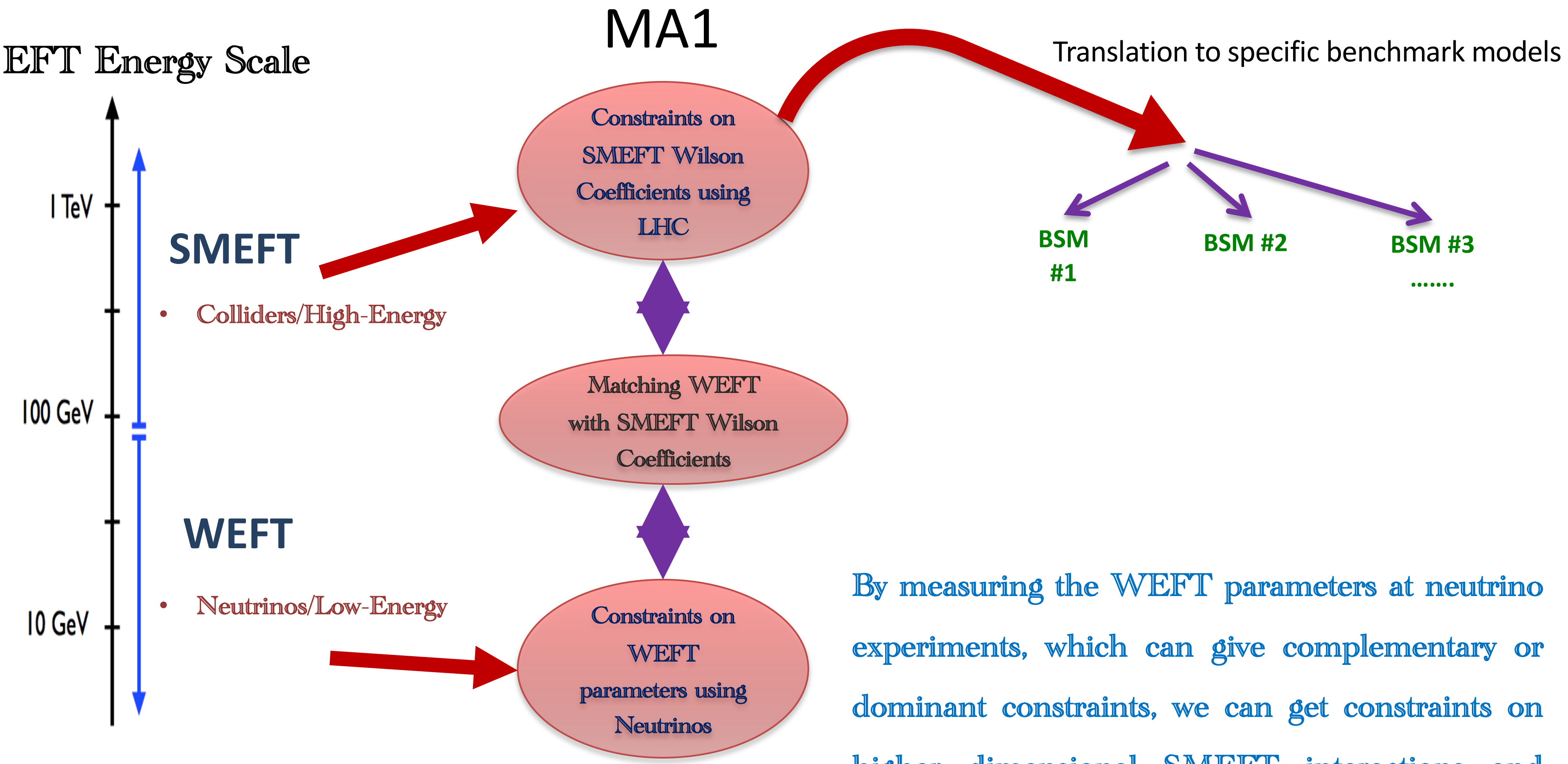
Affect Neutrino Interactions: Indirect Searches



Observable: rate of detected events

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

Physics Case 3: Indirect BSM Searches (SMEFT)



EFT Energy Scale

MA1

SMEFT

- Colliders/High-Energy

WEFT

- Neutrinos/Low-Energy

Constraints on SMEFT Wilson Coefficients using LHC

Matching WEFT with SMEFT Wilson Coefficients

Constraints on WEFT parameters using Neutrinos

Translation to specific benchmark models

BSM #1

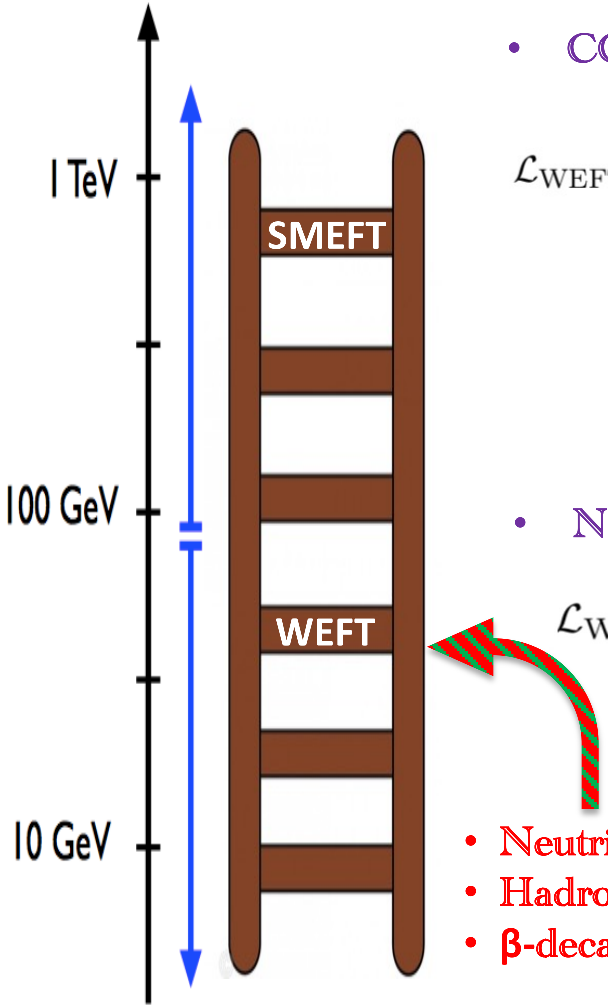
BSM #2

BSM #3

…….

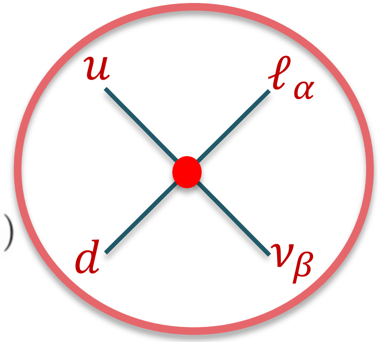
By measuring the WEFT parameters at neutrino experiments, which can give complementary or dominant constraints, we can get constraints on higher dimensional SMEFT interactions and compare the results with high energy colliders.

EFT ladder WEFT: Effective Lagrangian defined at a low scale



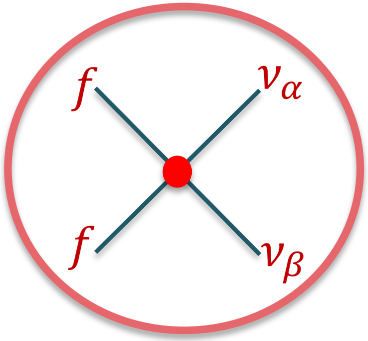
- CC: New left/right handed, (pseudo)scalar and tensor interactions

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



- NC: New left and right handed interactions

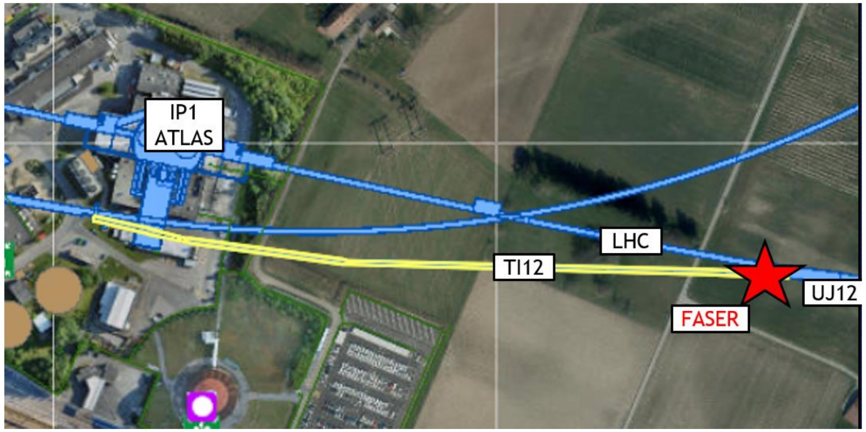
$$\mathcal{L}_{\rm WEFT} \supset -\frac{2}{v^2}\epsilon^{fX}_{\alpha\beta}(\bar\nu_\alpha\gamma^\mu P_L\nu_\beta)\left(\bar f\gamma_\mu P_X f\right)$$

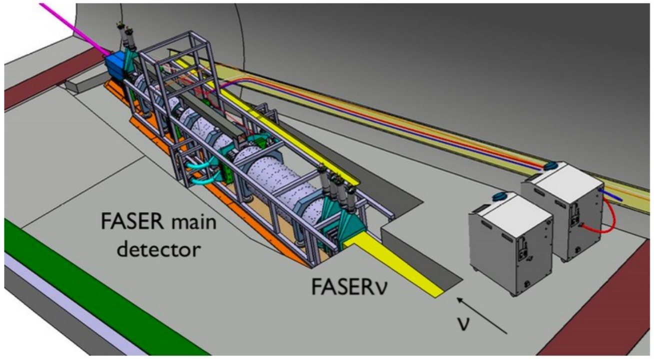


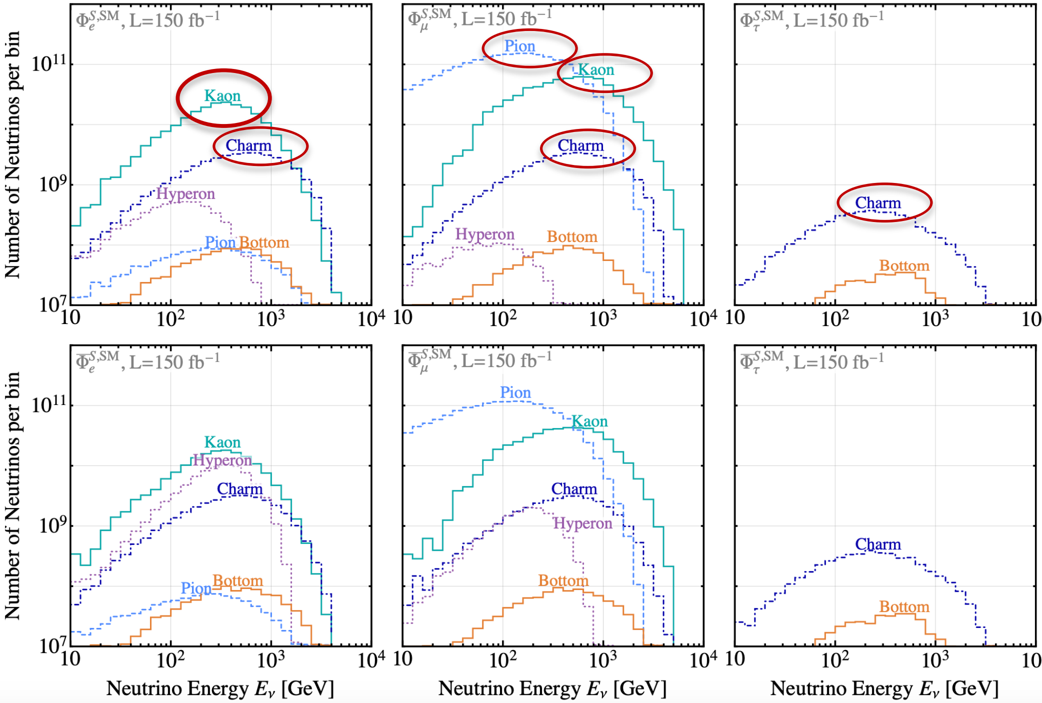
- Neutrino experiments
- Hadron Decays
- β-decays

FASERν-like Detector?

- Downstream of ATLAS at of 480 m;
- Ideal for detecting high-energy neutrinos at LHC;
- 1.1-t of tungsten material;
- Several production modes;
- Pion and Kaon decays are the dominant ones;
- All (anti)neutrino flavors are available;







Within the SM:

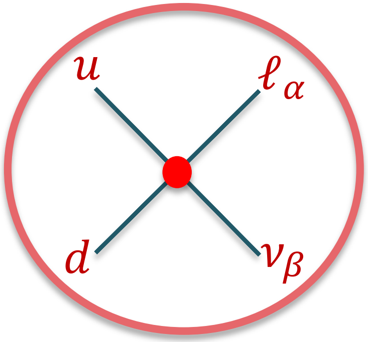
$\nu_e \sim 1000$, $\nu_\mu \sim 5000$, $\nu_\tau \sim 10$

EFT at FASERν

Falkowski, González-Alonso, Kopp, Soreq, *ZT*, JHEP (2021)

- FASERν: colored bars

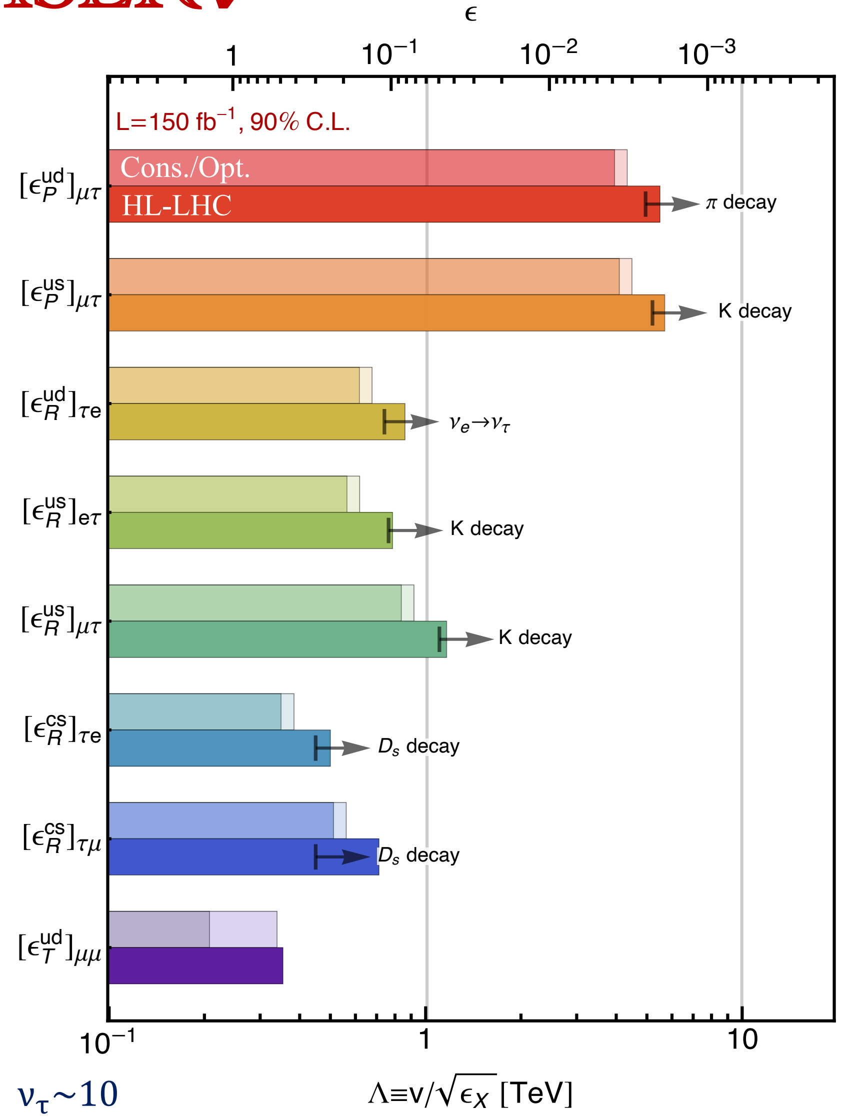
- Top: Conservative/Optimistic flux uncertainties
- Bottom: High luminosity LHC



- Neutrino detectors can identify flavor: 81 operators at FASERν

- New physics reach at multi-TeV

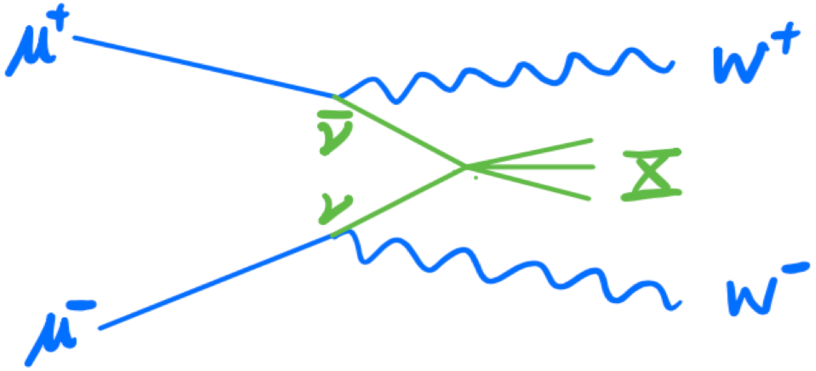
- Complementary or dominant constraints



- ➢ Results are statistics dominated: $\nu_e \sim 1000$, $\nu_\mu \sim 5000$, $\nu_\tau \sim 10$
- ➢ Optimistic systematic uncertainties: 5% on ν_e, 10% on ν_μ, 15% on ν_τ
- ➢ Conservative systematic uncertainties: 30% on ν_e, 40% on ν_μ, 50% on ν_τ

W/O a Dedicated Neutrino Detector:

- **High energy Muon Collider as a high energy Neutrino Collider**



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

Talk by Ian Low at ACE

SMEFT:

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

Flavor-conserving 4-lepton operators

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

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

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

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:

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

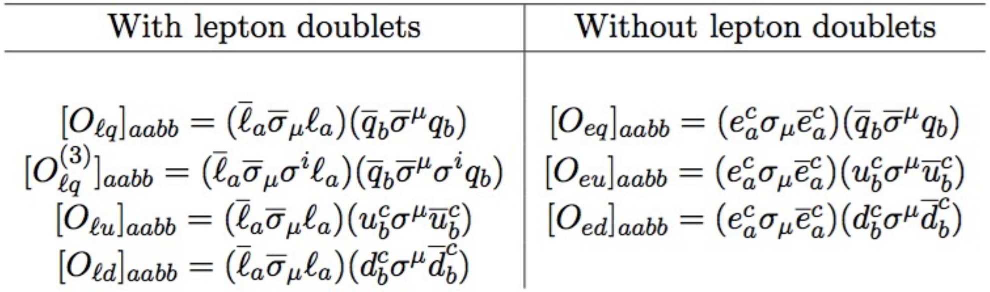
SMEFT:

Chirality-conserving 2 lepton-2 quark operators

$\mu^+\mu^-$

$\mu^\pm\nu$

$\nu\,\bar\nu$



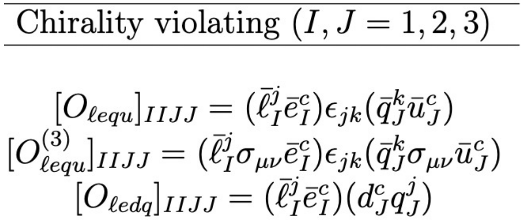
With lepton doublets	Without lepton doublets
$[O_{\ell q}]_{aabb} = (\bar\ell_a\bar\sigma_\mu\ell_a)(\bar q_b\bar\sigma^\mu q_b)$	$[O_{eq}]_{aabb} = (e^c_a\sigma_\mu\bar e^c_a)(\bar q_b\bar\sigma^\mu q_b)$
$[O^{(3)}_{\ell q}]_{aabb} = (\bar\ell_a\bar\sigma_\mu\sigma^i\ell_a)(\bar q_b\bar\sigma^\mu\sigma^i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

$\mu^+\mu^-$

Chirality-Violating 2 lepton-2 quark operators

$\mu^+\mu^-$

$\mu^\pm\nu$



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

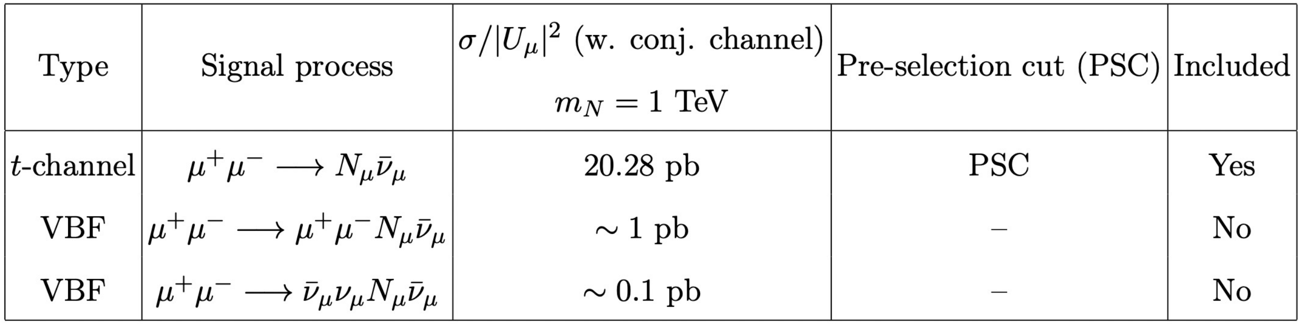
- vertex corrections to the Z and W interactions with leptons:

$$\mathcal{L}_{\rm SMEFT} \supset \sqrt{g_L^2+g_Y^2}\,Z^\mu \sum_{q=u,d}\left[\bar q\bar\sigma_\mu\left((T^q_3 - s^2_\theta Q_q) + \boxed{\delta g_L^{Zq}}\right) q + q^c\sigma_\mu\left(-s^2_\theta Q_q + \boxed{\delta g_R^{Zq}}\right)\bar q^c\right]$$
$$+\left[W^{\mu+}\bar u\bar\sigma_\mu\left(V_{ud} + \boxed{\delta g_L^{Wq_1}}\right) d + \text{h.c.}\right].$$

A Dark Sector Factory? e.g. HNL

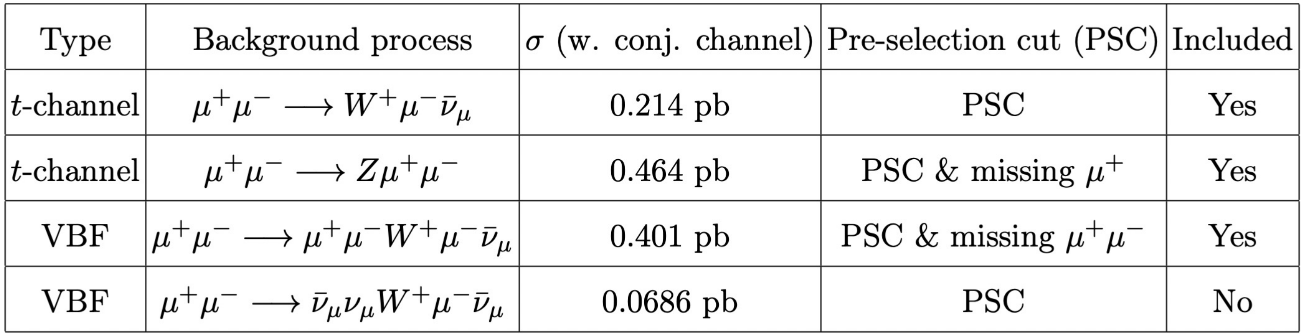
$$\mathcal{L} \supset \frac{gU_\ell}{\sqrt{2}} \left(W_\mu \bar{l}_L \gamma^\mu N + \text{h.c.}\right) - \frac{gU_\ell}{2\cos\theta_w} Z_\mu \left(\bar{\nu}_L \gamma^\mu N + \bar{N} \gamma^\mu \bar{\nu}_L\right) - U_\ell \frac{m_N}{v} h \left(\bar{\nu}_L N + \bar{N} \nu_L\right)$$

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.

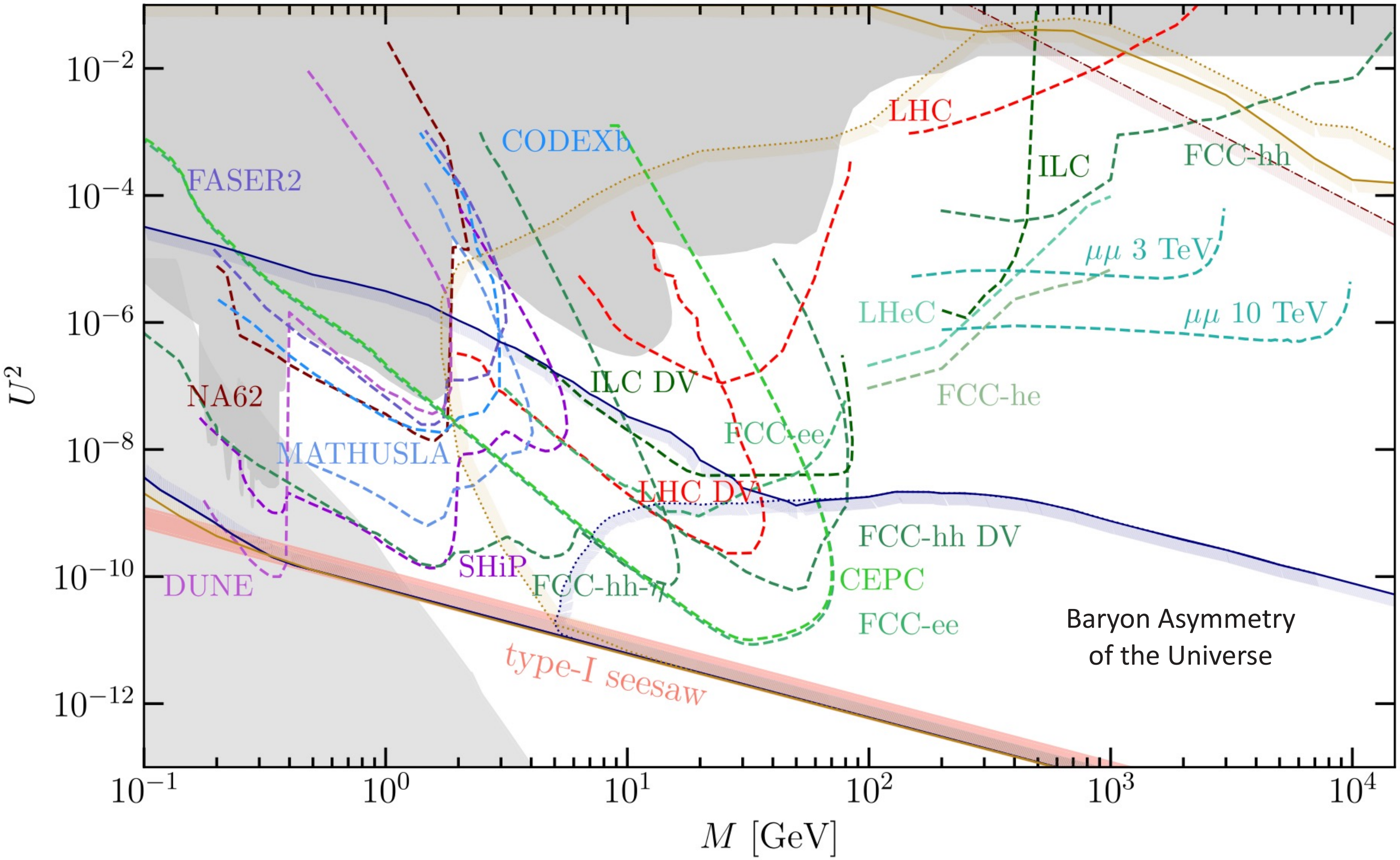


Type	Background process	σ (w. conj. channel)	Pre-selection cut (PSC)	Included
t-channel	$\mu^+\mu^- \longrightarrow W^+\mu^-\bar{\nu}_\mu$	0.214 pb	PSC	Yes
t-channel	$\mu^+\mu^- \longrightarrow Z\mu^+\mu^-$	0.464 pb	PSC & missing μ^+	Yes
VBF	$\mu^+\mu^- \longrightarrow \mu^+\mu^- W^+\mu^-\bar{\nu}_\mu$	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



Baryon Asymmetry
of the Universe

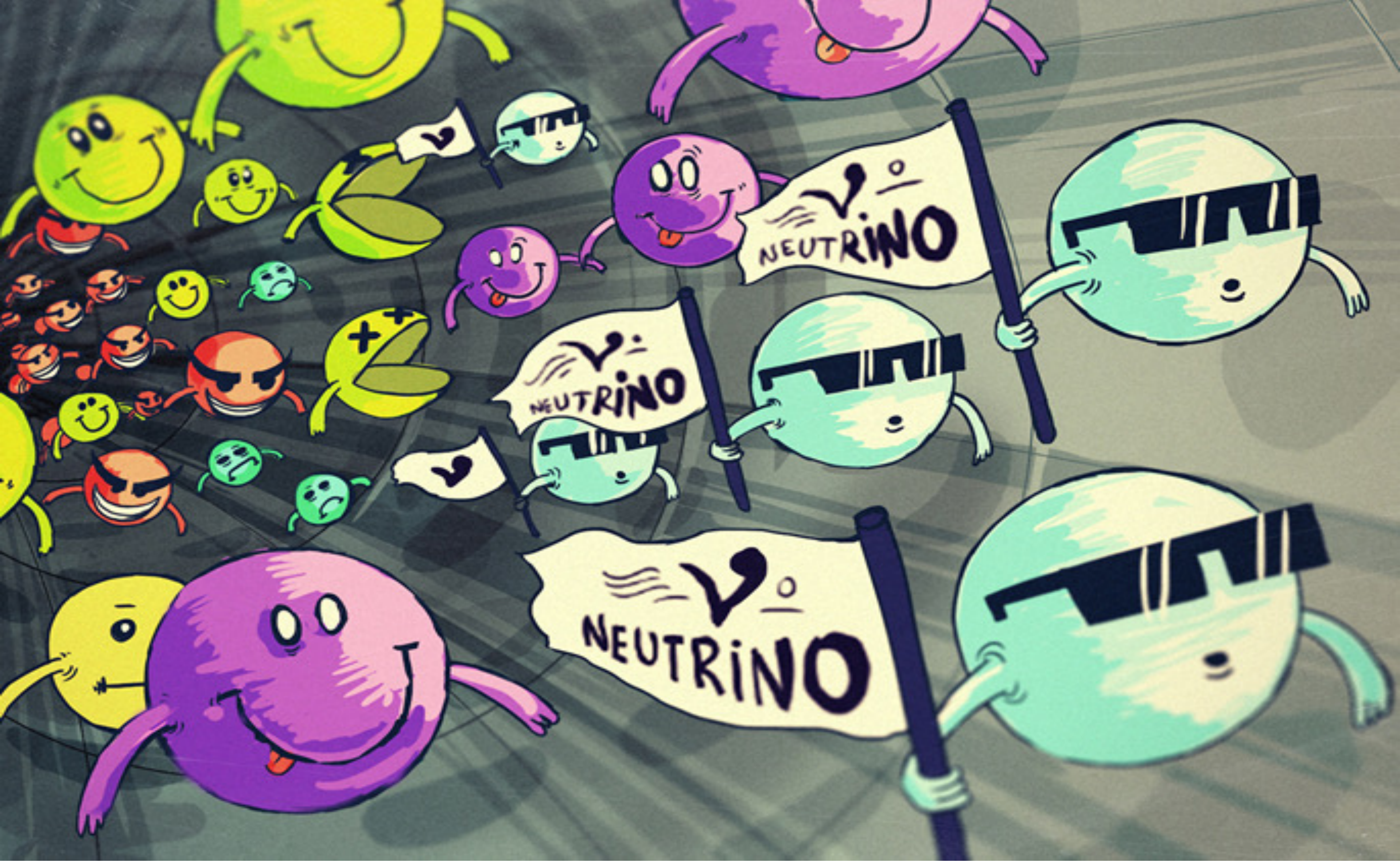
Detector Requirements:

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.

Conclusion:

- The rich physics opportunities at a NF and the need to prepare for a post-DUNE neutrino physics program indicates that detailed studies of a neutrino factory complex, its physics reach and detectors are once again timely and needed;
- The need for a Cooling Demonstrator Facility (CDF) as part of a Muon Collider R&D program might breathe new life into the NF concept;
- We can use a dedicated neutrino detector at a high energy MC for precision measurements on neutrino interactions (DIS x-section, weak mixing angle, etc.);
- Direct dark sector searches (HNL, ALPs, light DM, erc);
- We can probe very heavy particles by precisely measuring neutrino interactions using the EFT formalism;
- Unlike other probes (meson decays, ATLAS and CMS analyses, etc.) a neutrino detector has the unique capability to identify the neutrino flavors. This is crucial complementary information in case excesses are found elsewhere in the future;
- We are NOT yet prepared to identify all the interesting things we can do!



Thanks for your attention