Staging Opportunities: Physics

Artwork by Sandbox Studio, Chicago with Ana Kova

"The Future of High Energy Physics: A New Generation, A New Vision"

March 24-29, 2024

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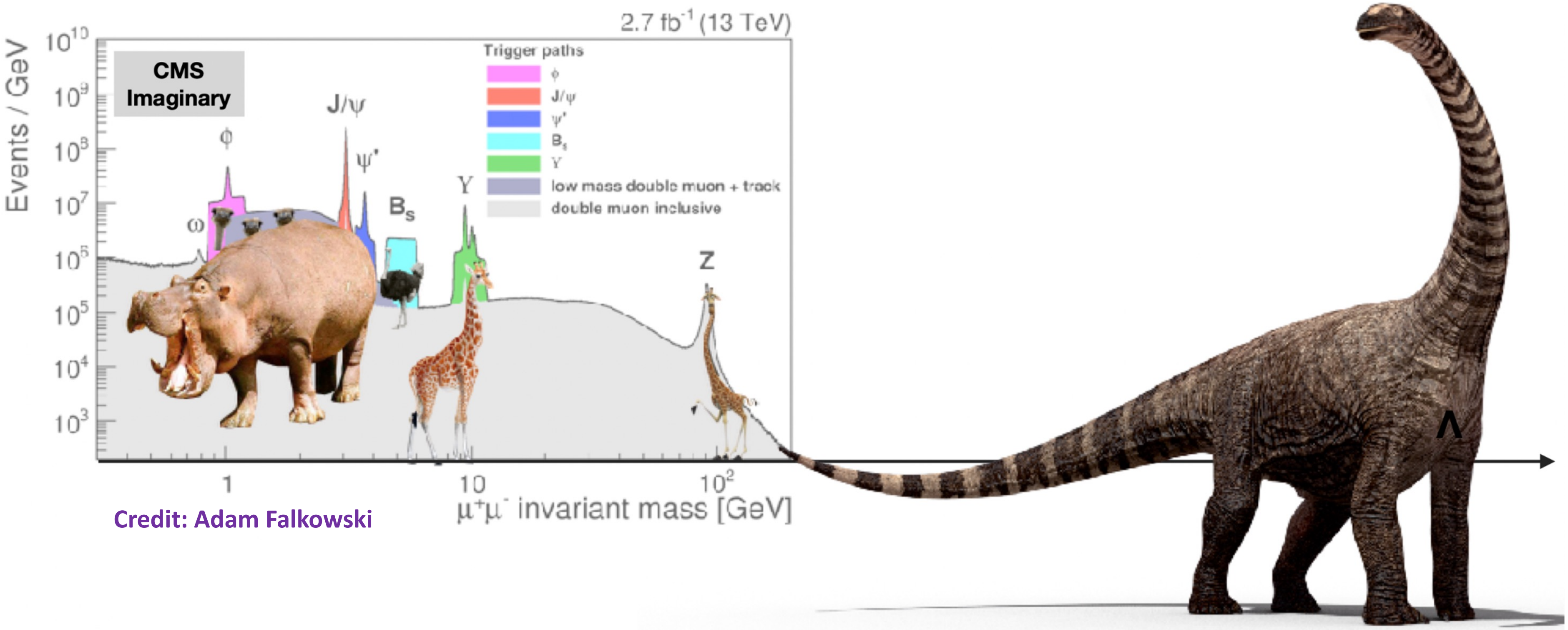
Neutrino Theory Network fellow

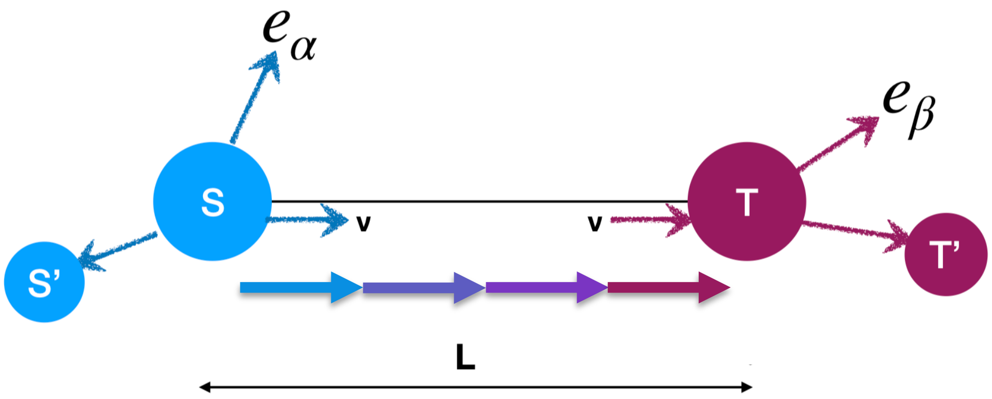
Northwestern University

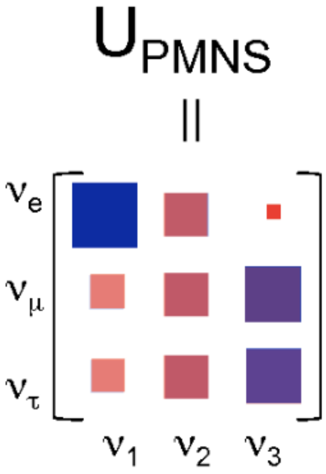
Fantastic Beasts and How to Find Them With Neutrino Detectors



Credit: Adam Falkowski

Oscillation Experiments





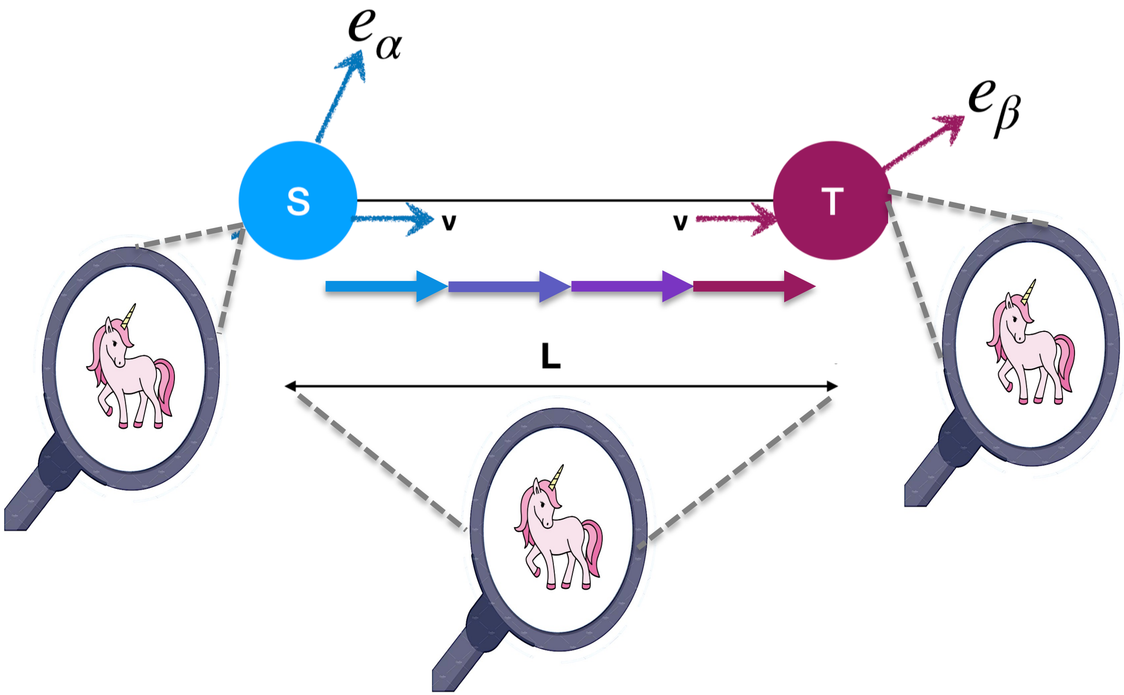
Observable: rate of detected events

$\sim \boxed{\text{(flux)×(det. cross section)}} \times \boxed{\text{(oscillation)}}$

Depend on the kinematics and spin variables!

Depends on mixing angles/masses

New Physics Searches



Observable: rate of detected events

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

Goal:

- Going beyond the oscillation;
- Fully leveraging the potential of these multi-billion dollar experiments;

1) Direct Search of New Physics
2) Indirect Search: EFT

Physics goals of near detectors:

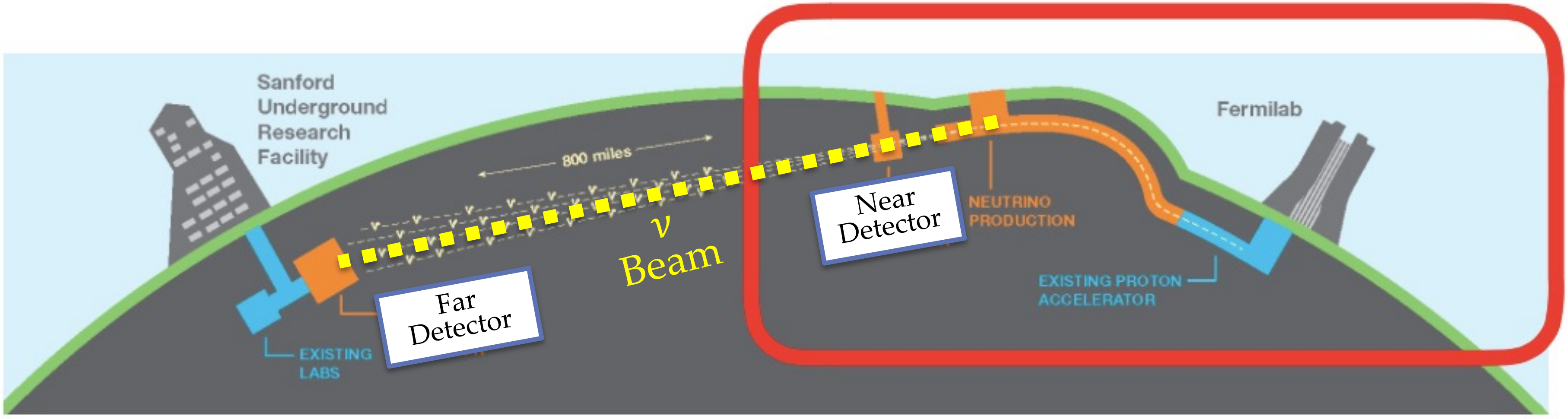
Primary role: Understanding Systematic Uncertainties

High beam luminosity +
Large fiducial mass

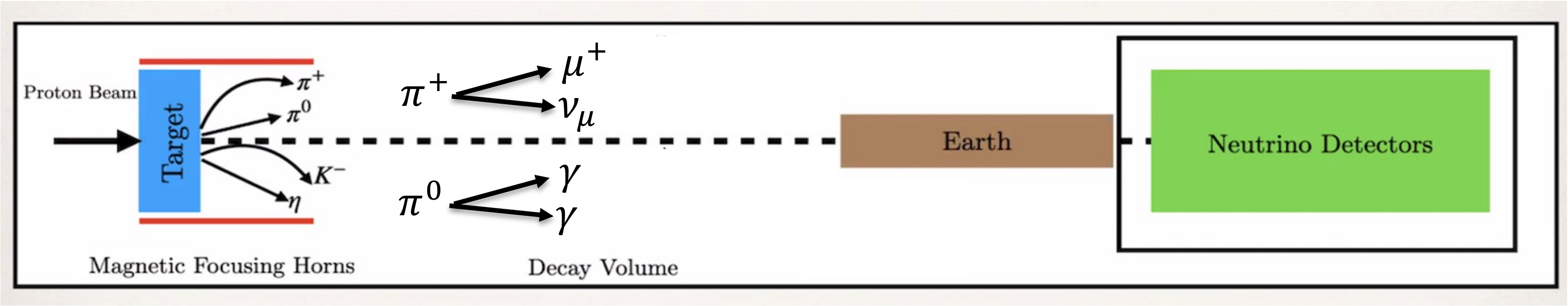
Ideal to investigate
rare/new neutrino
interactions

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

- Test SM predictions
- Search for BSM physics

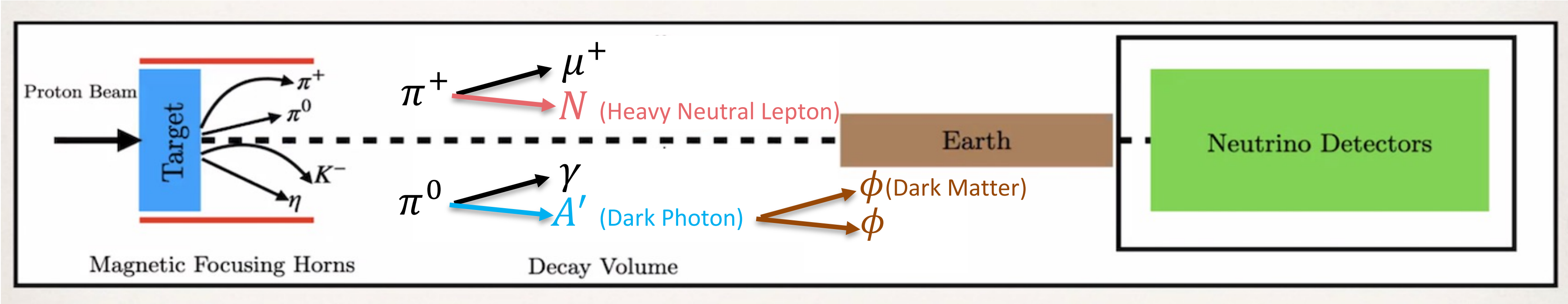


Neutrino Experiments as Dark Sector factories!



Credit: Kevin Kelly

The huge fluxes of neutrinos and photons can be used for BSM searches



Neutrino Experiments as Dark Sector factories!

High beam luminosity + Large fiducial mass → Ideal to investigate rare/new neutrino interactions

	Events per ton-year
ν_μ CC Total	1.64×10^6
ν_μ NC Total	5.17×10^5
$\nu_\mu - e$	135

Light Z'

Light Dark Matter

Searches for LFV

ALPs

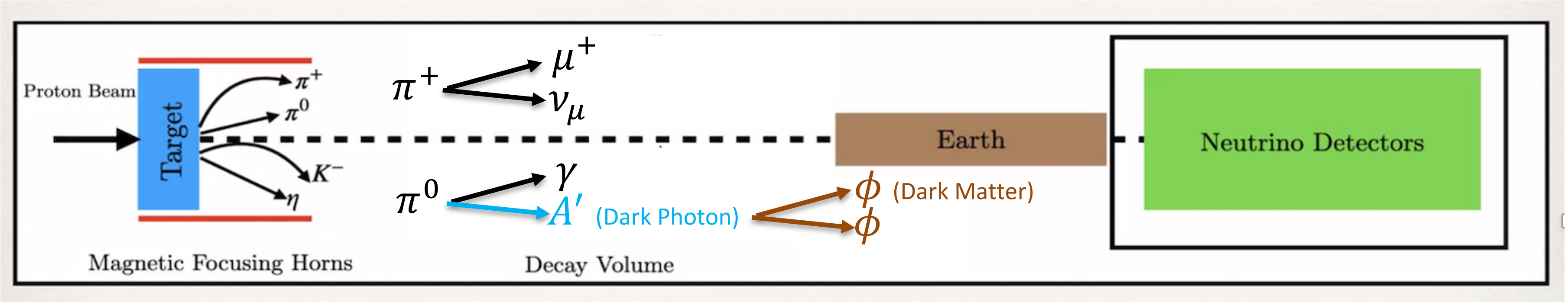
Heavy Neutral Leptons

....

- **"Heavy Neutral Leptons via Axion-Like Particles at Neutrino Facilities",**
  Abdullahi, de Gouvea, Dutta, Shoemaker and **ZT**,
  arXiv: 2311.07713 [hep-ph]
- **"Probing new physics at DUNE operating in a beam-dump mode",**
  Brdar, Dutta, Jang, Kim, Shoemaker, **ZT**, Thompson and Yu,
  PRD (2023)
- **"Axion-like Particles at Future Neutrino Experiments: Closing the Cosmological Triangle",**
  Brdar, Dutta, Jang, Kim, Shoemaker, **ZT,** Thompson and Yu,
  PRL (2021)
- **"Z's in neutrino scattering at DUNE",**
  Ballett, Hostert, Pascoli, Perez-Gonzalez, **ZT** and Funchal,
  PRD (2019)

Light Dark Matter

Credit: Kevin Kelly

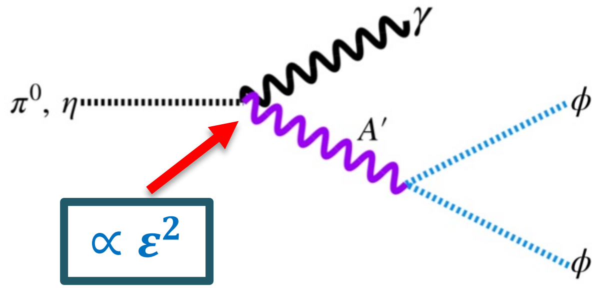


Photons at the target kinetically produce Dark Photons, which decay into dark matter:

$$\mathcal{L} \supset -\frac{\varepsilon}{2}F^{\mu\nu}F'_{\mu\nu} + \frac{M^2_{A'}}{2}A'_\mu A'^\mu + |D_\mu\phi|^2 - M^2_\phi\,|\phi|^2$$

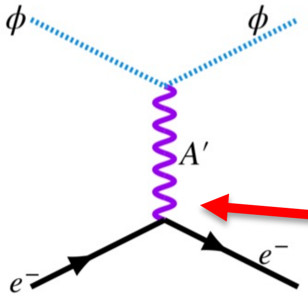
$$\boxed{D_\mu = \partial_\mu - i g_D A'_\mu, \quad g_D = \sqrt{4\pi\alpha_D}}$$

DM production



$\propto \varepsilon^2$

DM detection



$\propto \varepsilon^2$

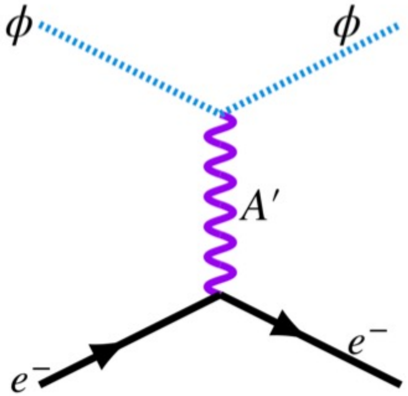
De Romeri, Kelly, Machado, PRD (2019)

(also Beam bremsstrahlung and Resonance production)

DM event rate $\sim \varepsilon^4 \alpha_D$

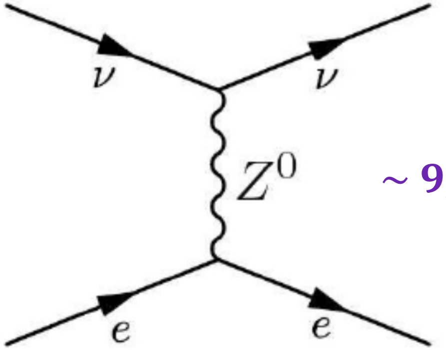
Light Dark Matter

DM signal: elastic scattering on electrons



How can we get rid of neutrinos in a neutrino detector?

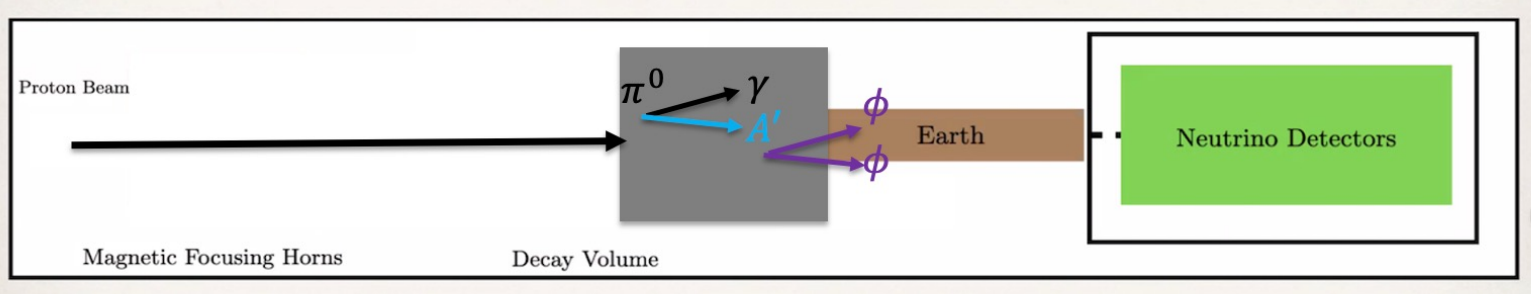
But so do neutrinos!



$\sim \mathbf{9,400}\ \boldsymbol{\nu - e}$ events / year!

Proposing a movable target system at DUNE

Credit: Kevin Kelly



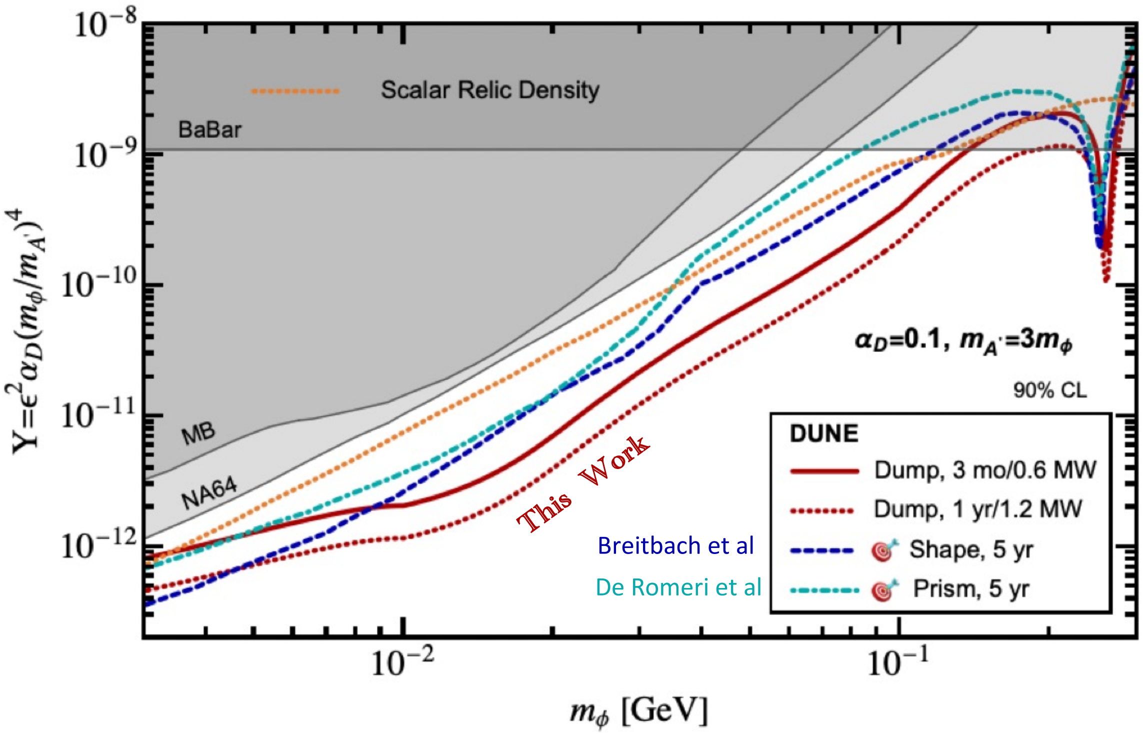
We can dump protons directly to the dump area!

Gains:

- Shorter distance between the source and the detector → more DM signal;
- Charged mesons absorbed in the Al beam dump before decay;
- The ν flux decreases → Much less ν background.

Brdar, Dutta, Jang, Kim, Shoemaker, ***ZT***, Thompson, Yu
PRD (2023)

Light Dark Matter at Targetless DUNE



Brdar, Dutta, Jang, Kim, Shoemaker, *ZT*, Thompson, Yu
PRD (2023)

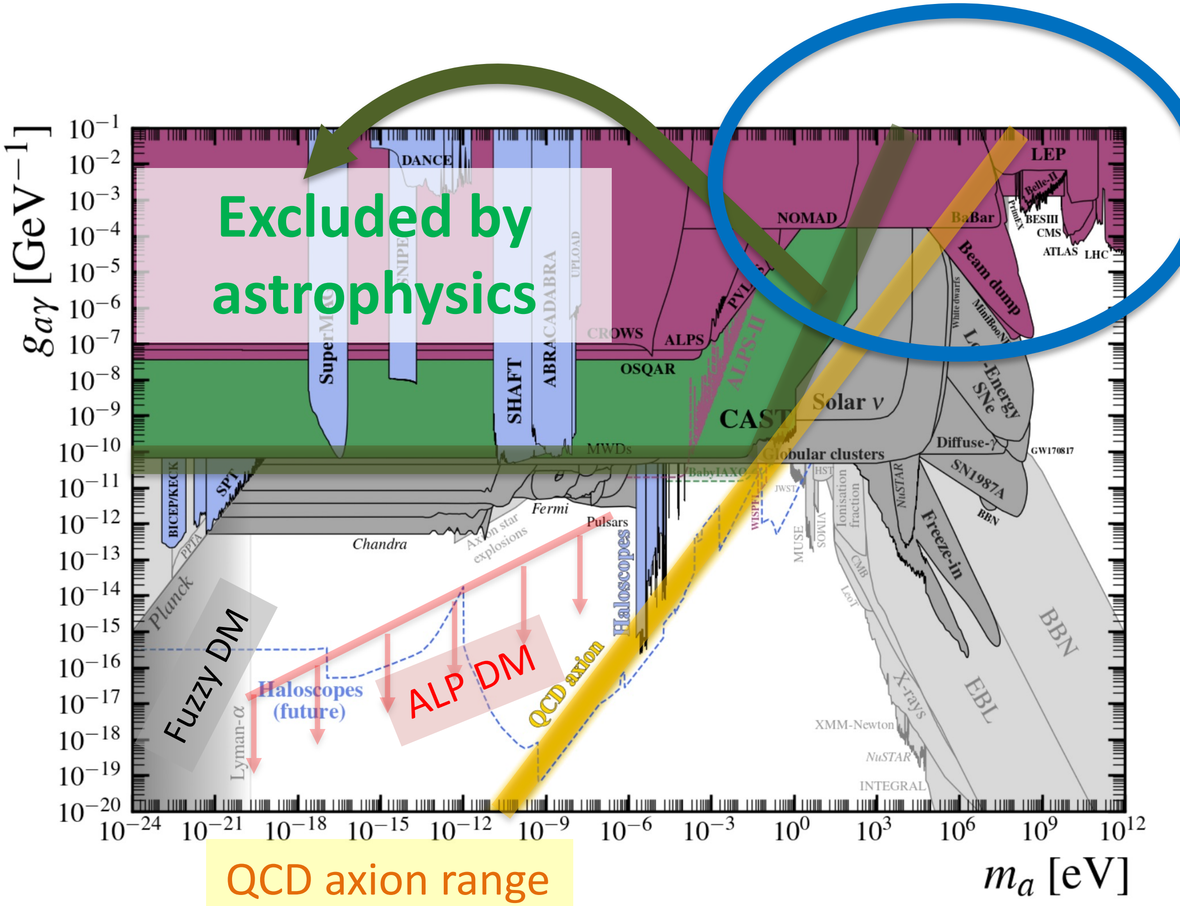
Target-less DUNE can probe the parameter space for thermal relic DM in only 3 months!

Axion-Like Particles (ALPs)

- (pseudo)scalars, strongly motivated by theory and cosmology;

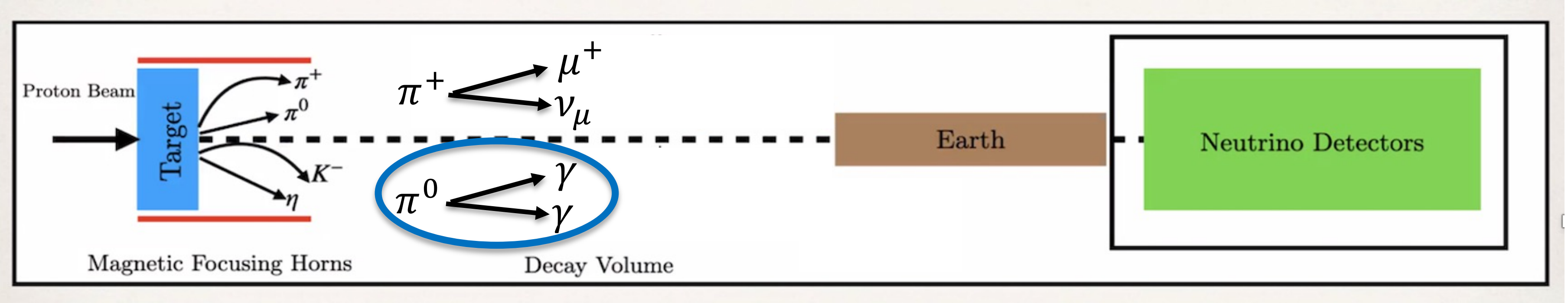
- Why is CP conserved in QCD? Solution to the strong CP problem (QCD axion);

- DM candidates;



Ciaran O'Hare
https://cajohare.github.io/AxionLimits

ALPs at Neutrino Experiments

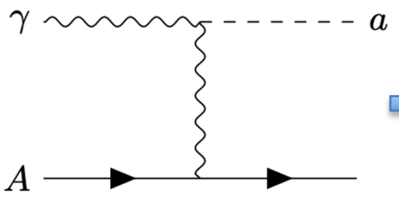


Credit: Kevin Kelly

Using photons to produce ALPs:

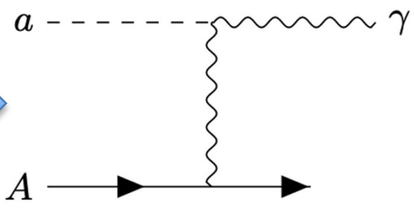
$$\mathcal{L}_{a\gamma\gamma} \supset -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

ALP production

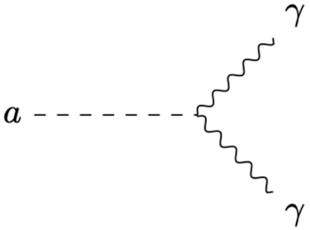


Primakoff scattering

ALP detection



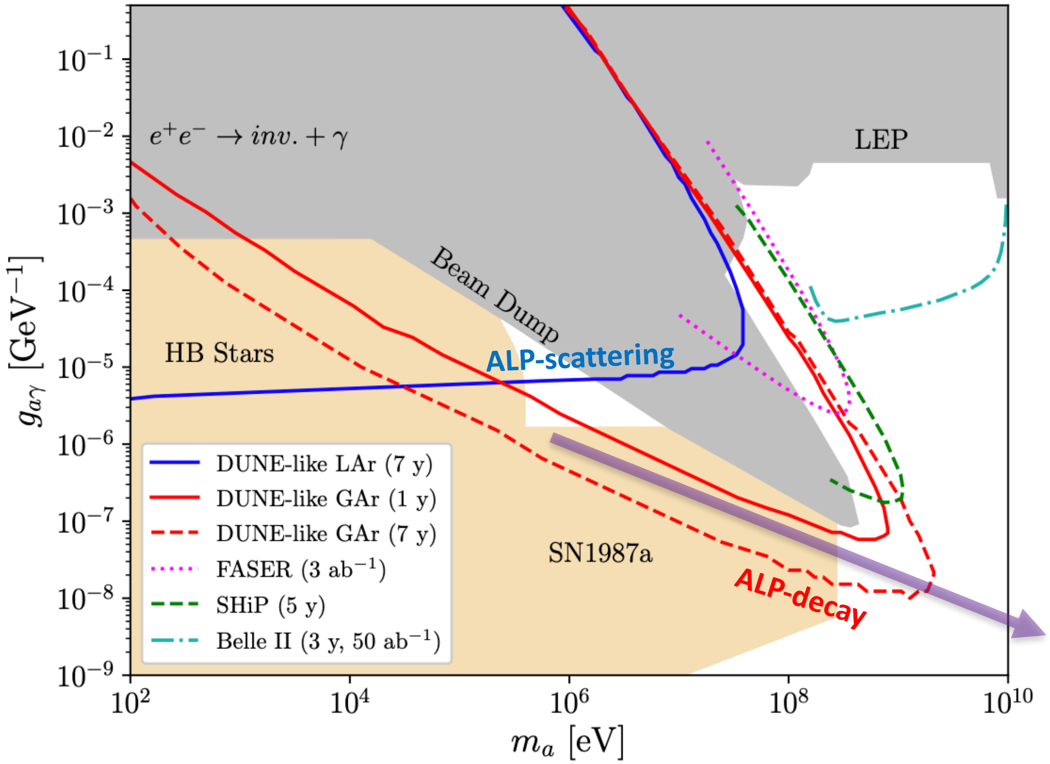
Inverse Primakoff scattering



ALP decay

Primakoff process: Coherent conversion of $\gamma \rightarrow a$ with Z^2 enhancement

ALP-γ at DUNE



Brdar, Dutta, Jang, Kim, Shoemaker, ZT, Thompson, Yu
PRL (2021)

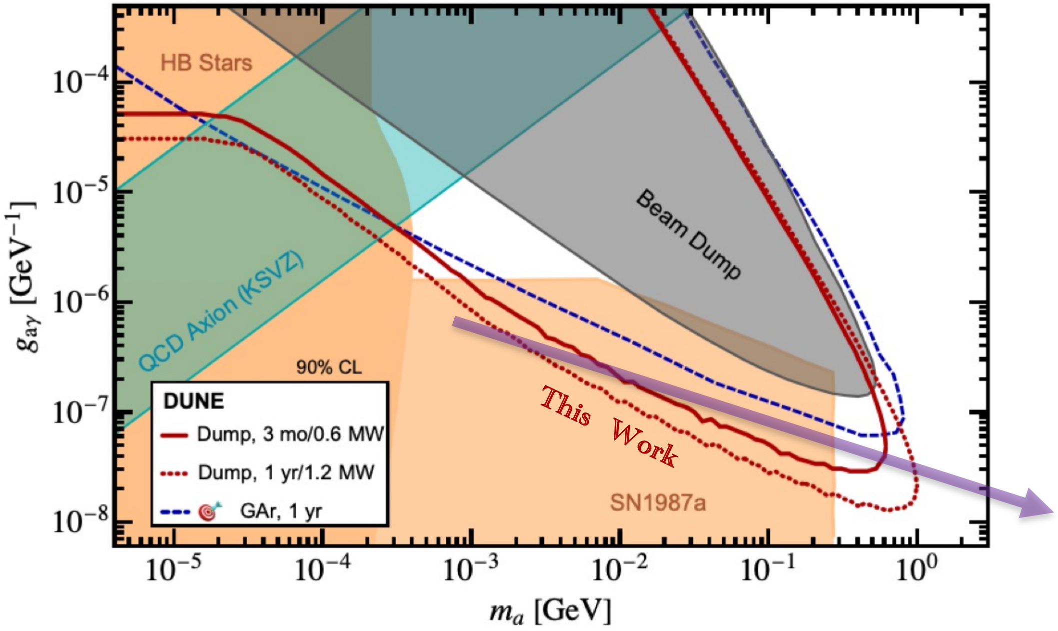
ALP-scattering at LAr, 50-t

ALP-decay at GAr, 1-t

No Background (?)

- The only lab-based constraints!
- Gas-detector is the key, due to significantly low background!

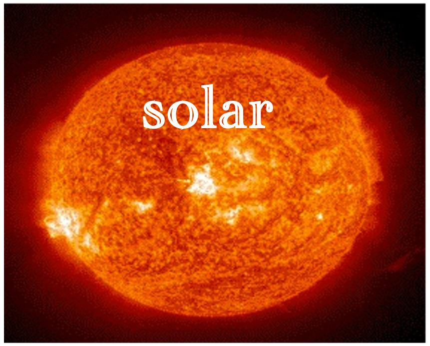
ALP-γ at Target-less DUNE

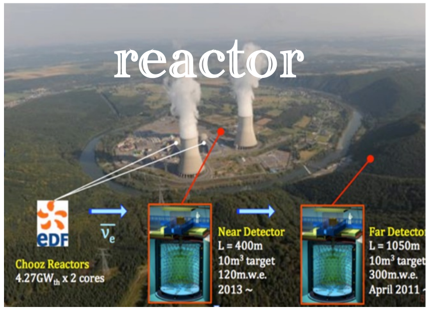


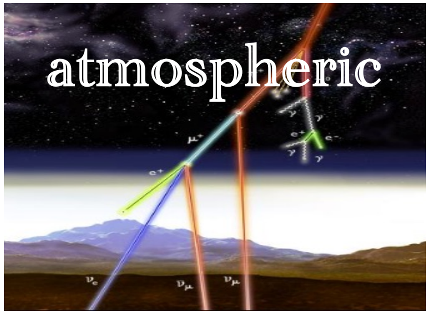
- The only lab-based constraints!
- Can probe QCD-axion
- 3 months target-less DUNE can do better than 1 yr GAr

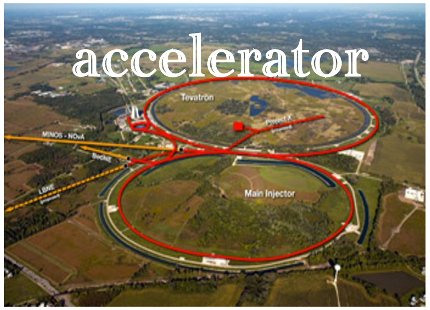
Brdar, Dutta, Jang, Kim, Shoemaker, ***ZT***, Thompson, Yu
PRL (2021)

Brdar, Dutta, Jang, Kim, Shoemaker, ***ZT***, Thompson, Yu
PRD (2023)









Precision Measurements at Oscillation Experiments

- ○ **Tons of data;**
- ○ **Identify neutrino flavor;**
- ○ **More sensitive to some HE operators;**

Goal:

A systematic analysis of NP using neutrino experiments;
Connecting the results to other precision experiments;

EFT Workflow:

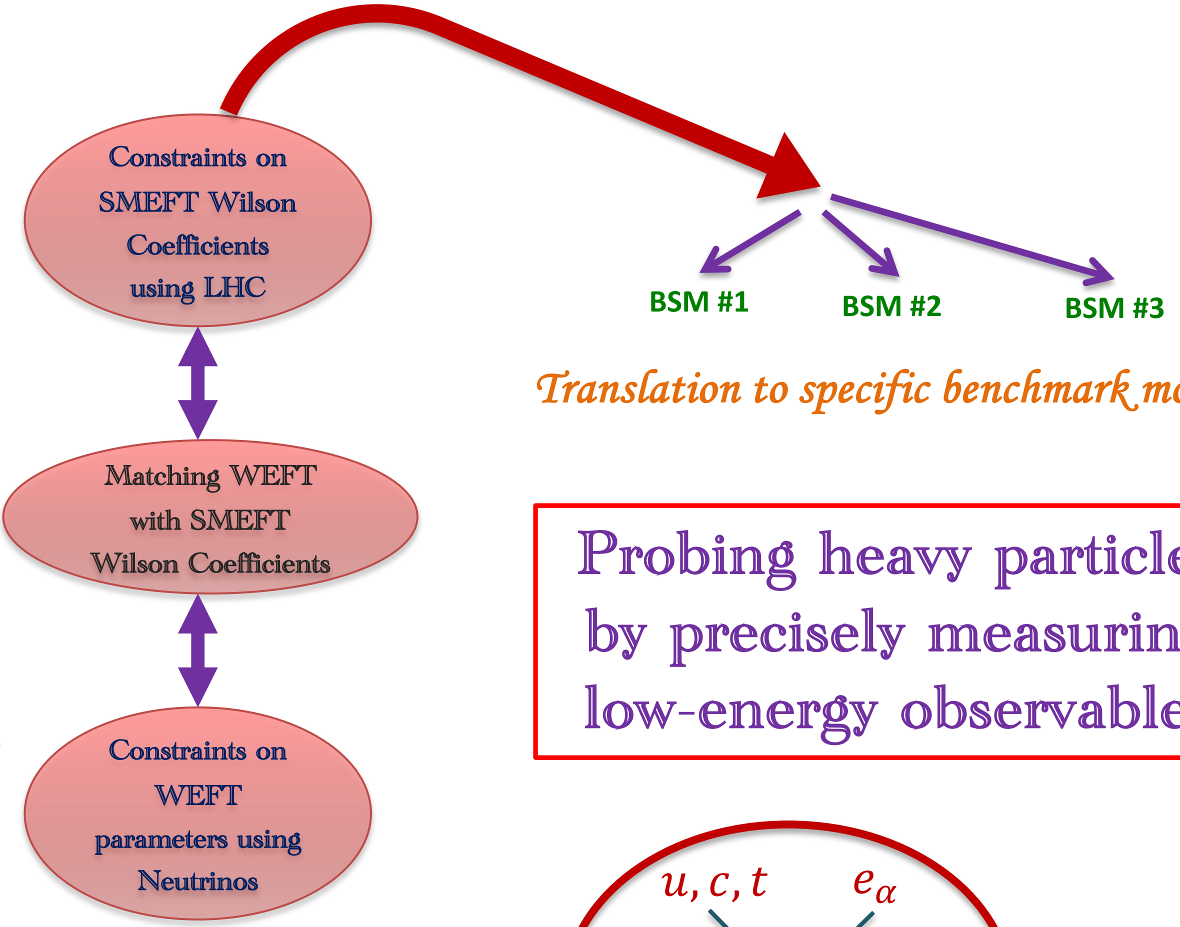
EFT Energy Scale

SMEFT

- Colliders
- CLFV

WEFT

- Neutrino experiments
- Hadron Decays
- β-decays



Constraints on SMEFT Wilson Coefficients using LHC

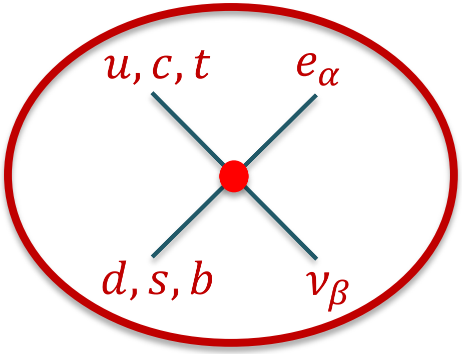
Matching WEFT with SMEFT Wilson Coefficients

Constraints on WEFT parameters using Neutrinos

BSM #1 **BSM #2** **BSM #3**

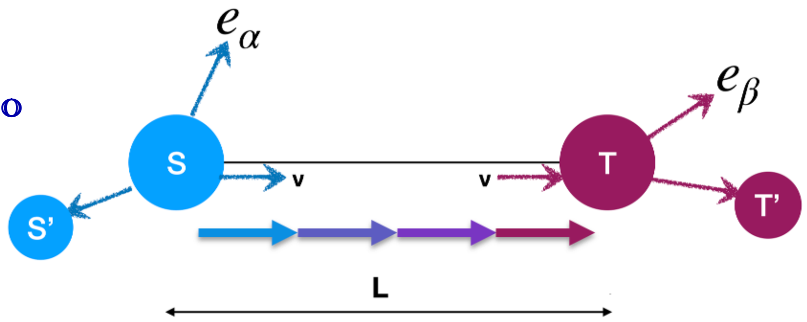
Translation to specific benchmark models

Probing heavy particles by precisely measuring low-energy observables



$\propto \epsilon_{\alpha\beta}$

EFT at neutrino experiments

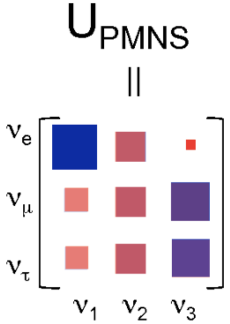


We proposed a systematic approach to neutrino oscillations in the SMEFT framework!

Falkowski, González-Alonso, *ZT*, JHEP (2020)

Observable: rate of detected events

$$\sim\underbrace{(\text{flux})\times(\text{det. cross section})}_{\boxed{\text{CC EFT}}}\times\underbrace{(\text{oscillation})}_{\text{NC EFT}}$$



depend on the kinematic and spin variables

$$\mathcal{M}^P_{\alpha k} = U^*_{\alpha k} A^P_L + \sum_X [\epsilon_X U]^*_{\alpha k} A^P_X$$

$$\mathcal{M}^D_{\beta k} = U_{\beta k} A^D_L + \sum_X [\epsilon_X U]_{\beta k} A^D_X$$

Corrections on fluxes/cross sections

$$\sigma^{Total} = \sigma^{SM} + \varepsilon_X \sigma^{Int} + \varepsilon_X{}^2 \sigma^{NP} \sim \sigma^{SM}(1+\varepsilon_X\, d_{XL} + \varepsilon_X{}^2\, d_{XX})$$

$$\phi^{Total} = \phi^{SM} + \varepsilon_X \phi^{Int} + \varepsilon_X{}^2 \phi^{NP} \sim \phi^{SM}(1+\varepsilon_X\, p_{XL} + \varepsilon_X{}^2\, p_{XX})$$

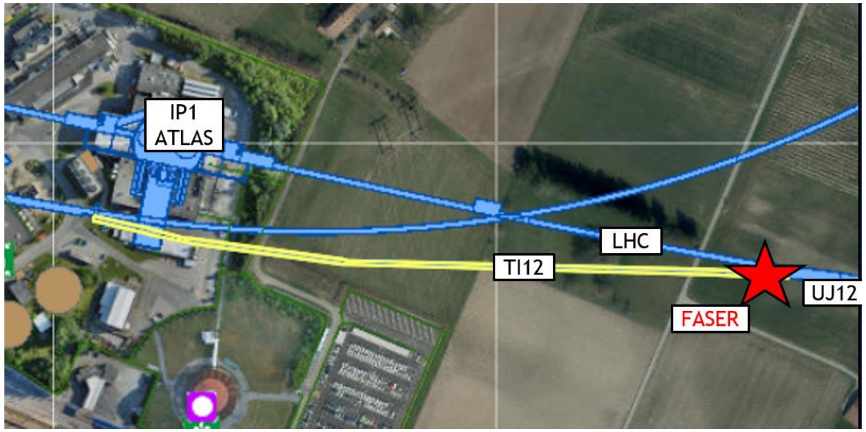
EFT at neutrino experiments

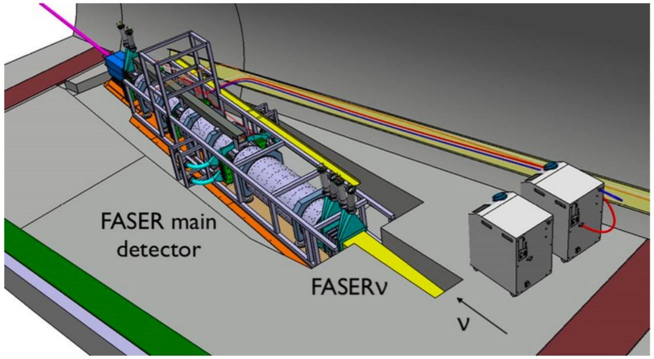
- Observed rate at the experiment: $\boxed{R_{Obs} = 10^4\ \nu_\mu}$
- Uncertainty: $\boxed{\sqrt{R_{obs}} = 10^2\ \nu_\alpha \equiv \Delta R}$
- From theory: $\boxed{R_{Th} = R_{SM}(1 + C\,\epsilon^2) = R_{SM} + \Delta R}$
- Limit on ϵ: $\boxed{C\,\epsilon^2 = \frac{\Delta R}{R_{SM}}}\ \left\{ \boxed{\begin{array}{c} C = 10^3 \\ \epsilon < \frac{10^2}{10^3\times 10^4} \sim 3\times 10^{-3} \end{array}} \right.$
- New Physics Limit: $\boxed{\Lambda \equiv \frac{\mathrm{V}\,[246\ GeV]}{\sqrt{\epsilon}} = 4.5\ \mathrm{TeV}}$

$$C \propto \frac{\sigma_{NP}}{\sigma_{SM}} \text{ or } \frac{\phi_{NP}}{\phi_{SM}}$$

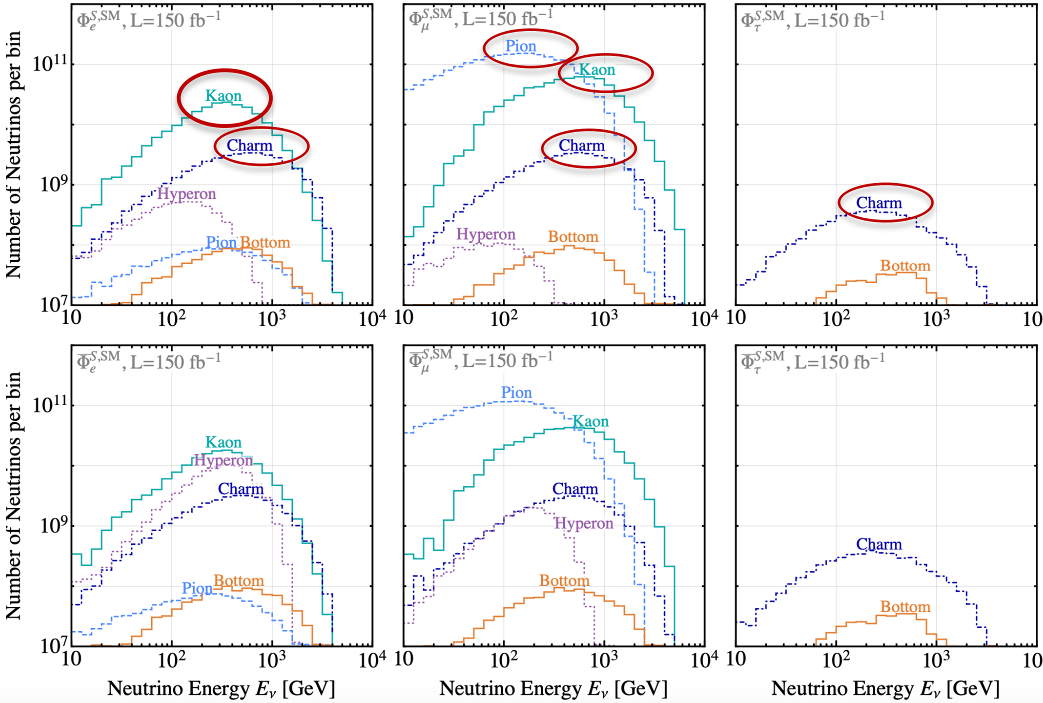
FASERν

- 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;





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



Within the SM:

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

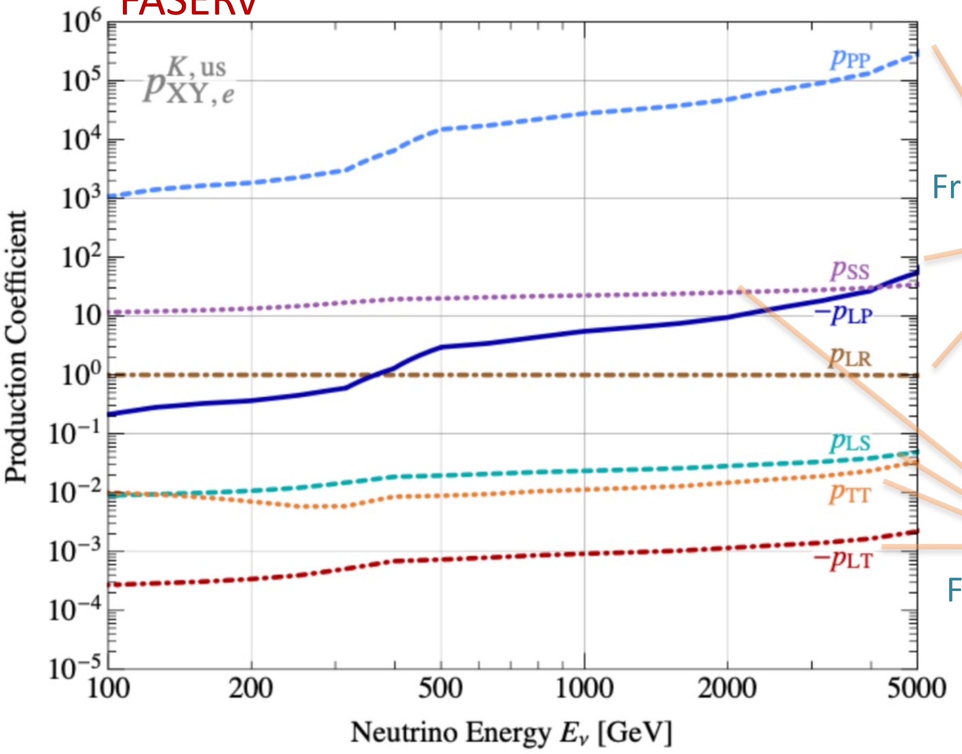
kaon decay

Production

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

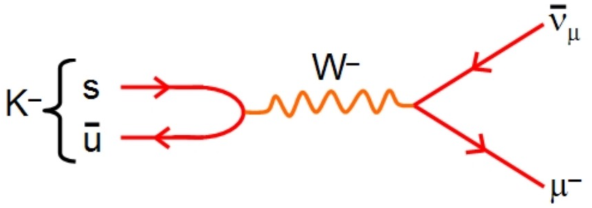
Both 2-body and 3-body kaon decays contribute:

FASERν

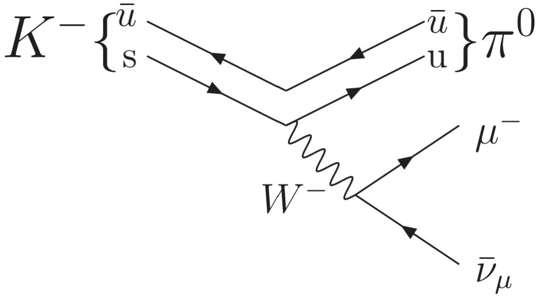


From 2-b decay

From 3-b decay



$K^-(s\bar{u}) \rightarrow \mu^- + \bar{\nu}_\mu$



$$\langle \pi^- | \bar{s}\gamma^\mu u | K^0 \rangle = P^\mu f_+(q^2) + q^\mu f_-(q^2)\,,$$

$$\langle \pi^- | \bar{s}u | K^0 \rangle = -\frac{m_K^2 - m_\pi^2}{m_s - m_u} f_0(q^2)\,,$$

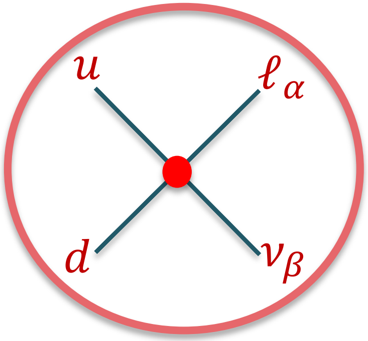
$$\langle \pi^- | \bar{s}\sigma^{\mu\nu} u | K^0 \rangle = i\frac{p_K^\mu p_\pi^\nu - p_\pi^\mu p_K^\nu}{m_K} B_T(q^2)\,,$$

Depends on energy distribution of $K^\pm$, K_L or K_S at each experiments

EFT at FASERν

- FASERν: colored bars

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

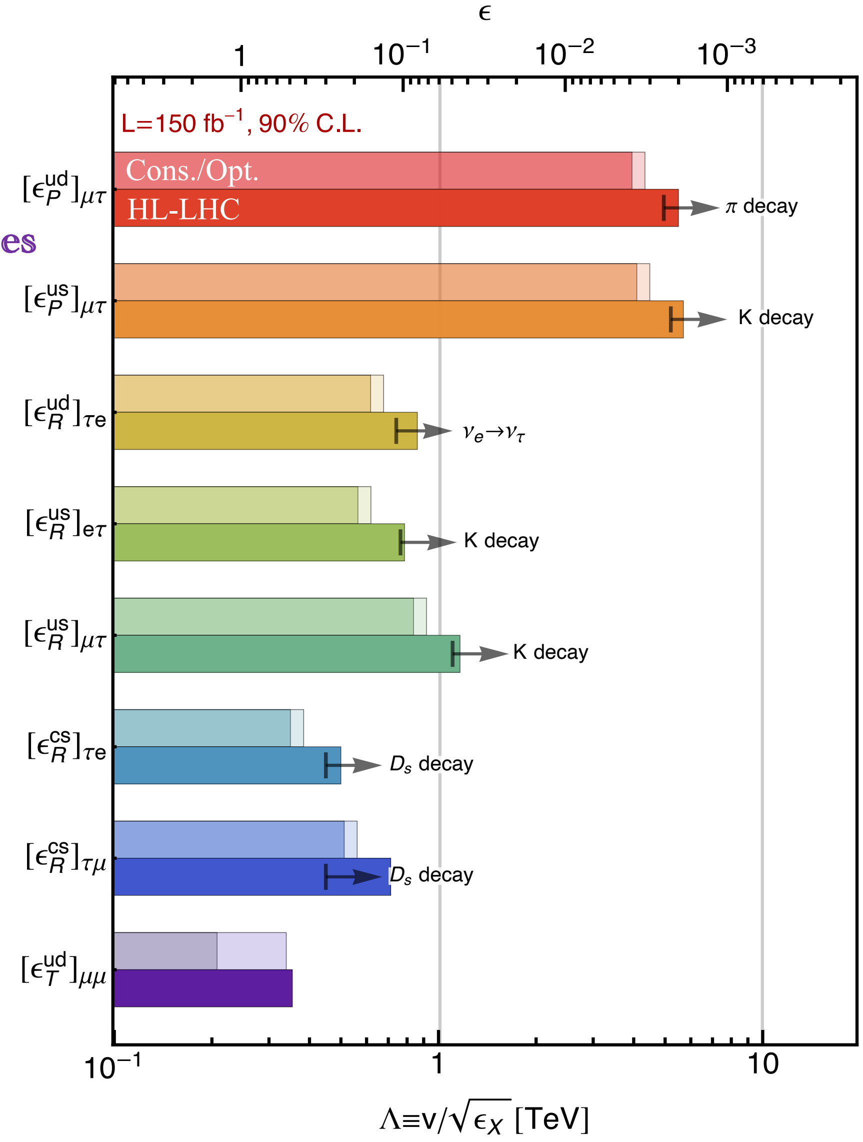


- Neutrino detectors can identify flavor: 81 operators at FASERν

- New physics reach at multi-TeV

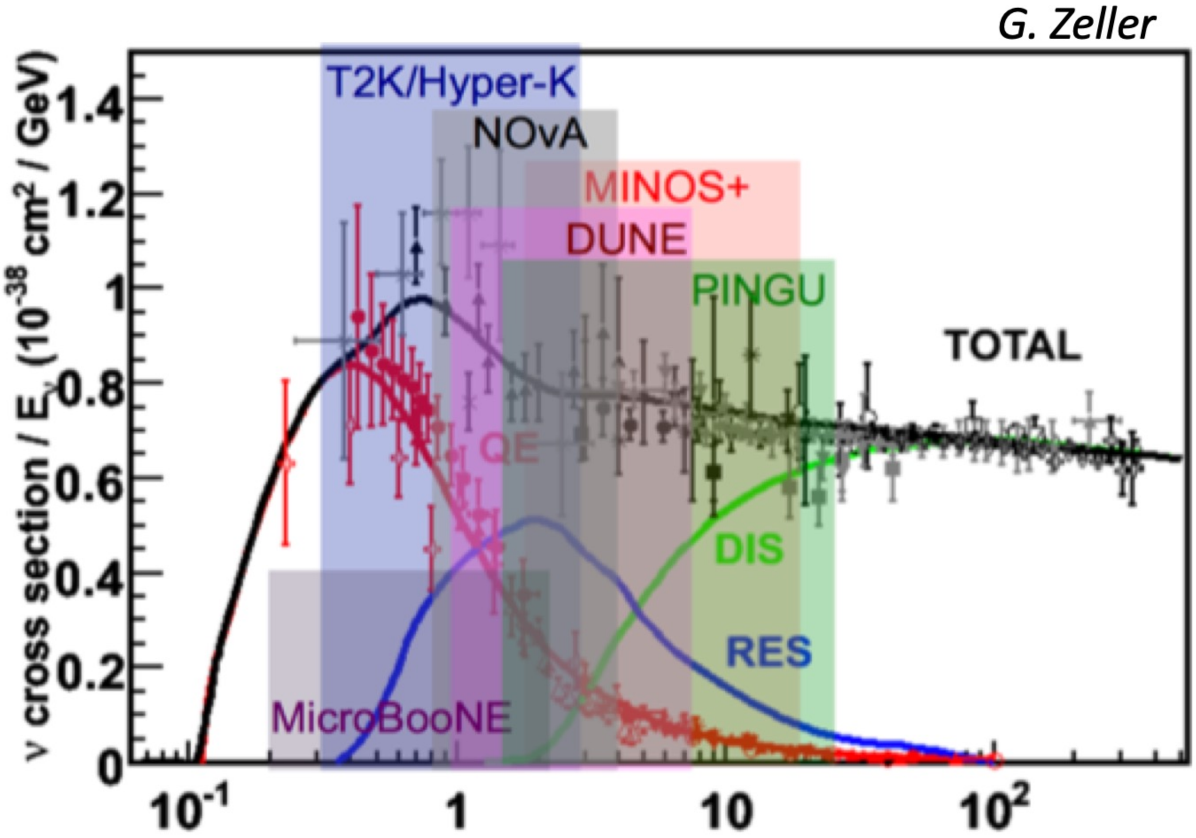
- Complementary or dominant constraints

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



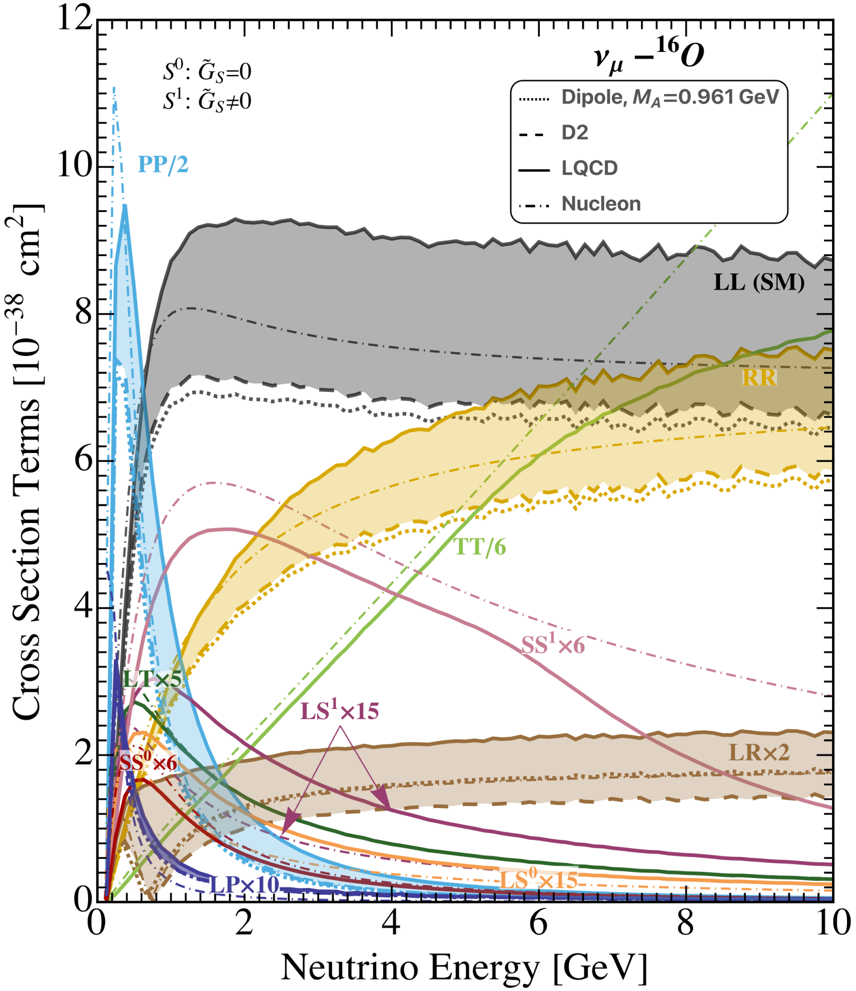
Long Baseline Accelerator Experiments

- 0.1-5 GeV: Cross section is much more involved!



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

EFT at Neutrino-Nucleus Quasi-Elastic Scattering

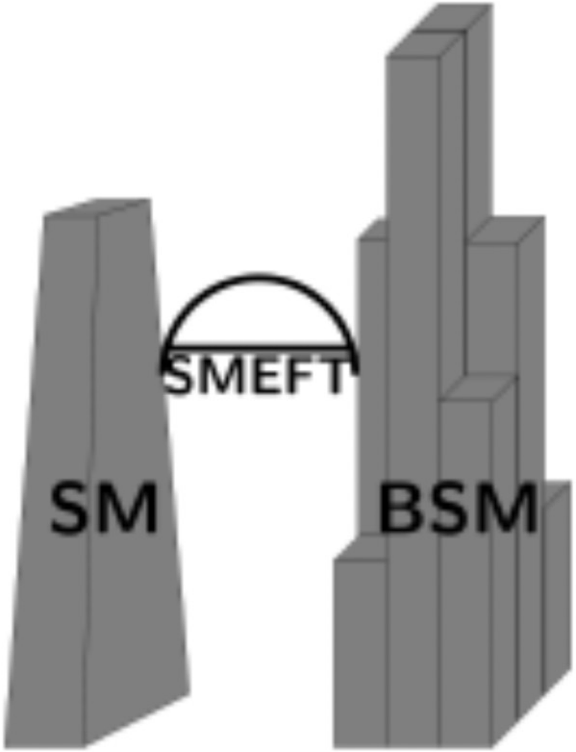


Kopp, Rocco, *ZT*
arXiv: 2401.07902

Extracting 10 TeV physics from GeV neutrino experiments!

Indirect Searches: Future Directions

- EFT global fit in neutrino oscillation experiments;
- Extraction of oscillation parameters in presence of general new physics;
- Preparing a public software package and implementing the EFT results: e.g. GLoBES-EFT;
- Comparison between the sensitivity of oscillation and other low/high energy experiments;



Neutrino Oscillation at Muon Colliders? Unlikely?

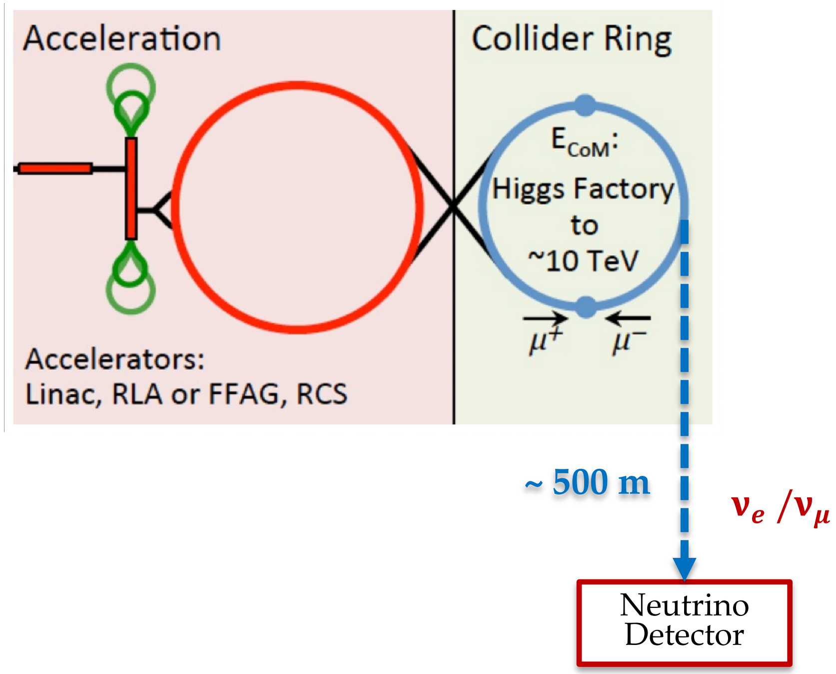
At TeV energy range, the relevant baseline to see oscillation is 10^6 (10^8) km for atmospheric (solar) oscillation parameters.

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:



~ 500 m

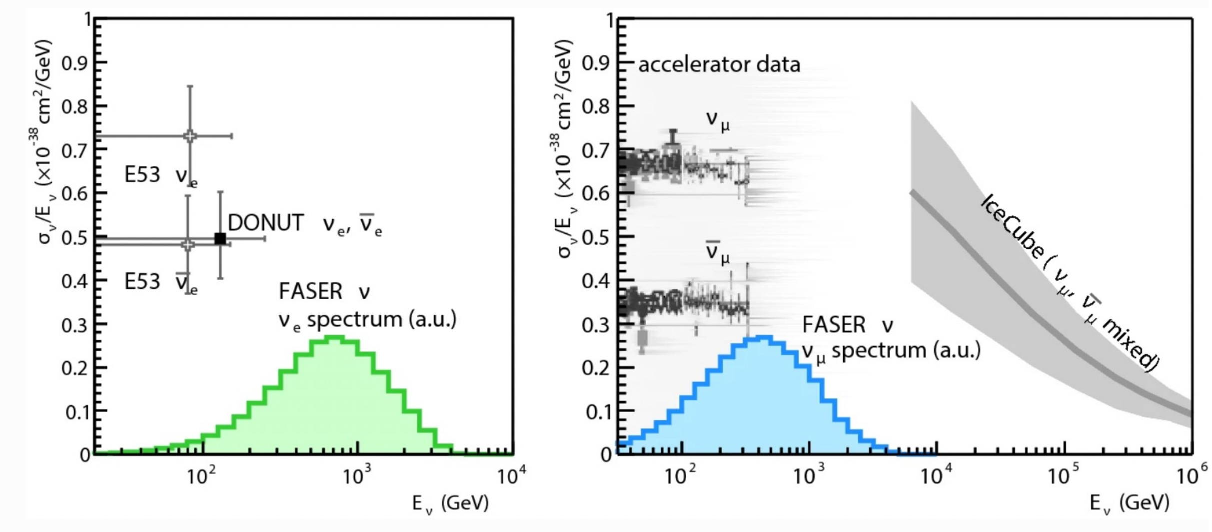
ν_e / ν_μ

Neutrino Detector

- *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;*

Precision in Neutrino Cross Section Measurements:

FASER Collaboration, 2020



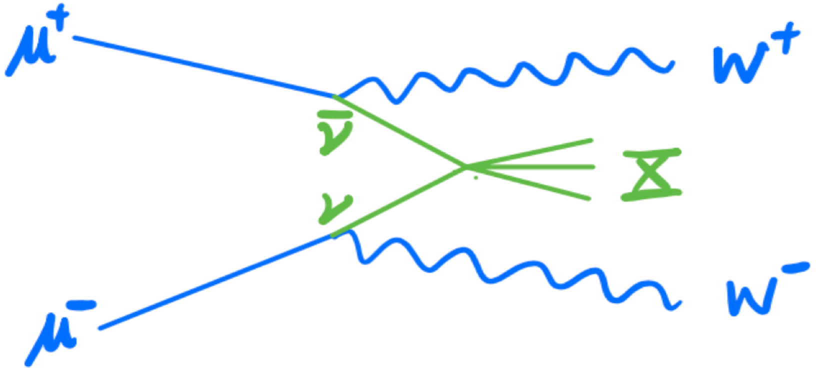
- ☐ Currently no high energy ν_e beam
- ☐ A lot of ν_μ, but not well known beam

The Physics Case for a Neutrino Factory
2203.08094

- 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

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:

Flavor-conserving 4-lepton operators

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

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

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

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

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:

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

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

$\mu^+\mu^-$

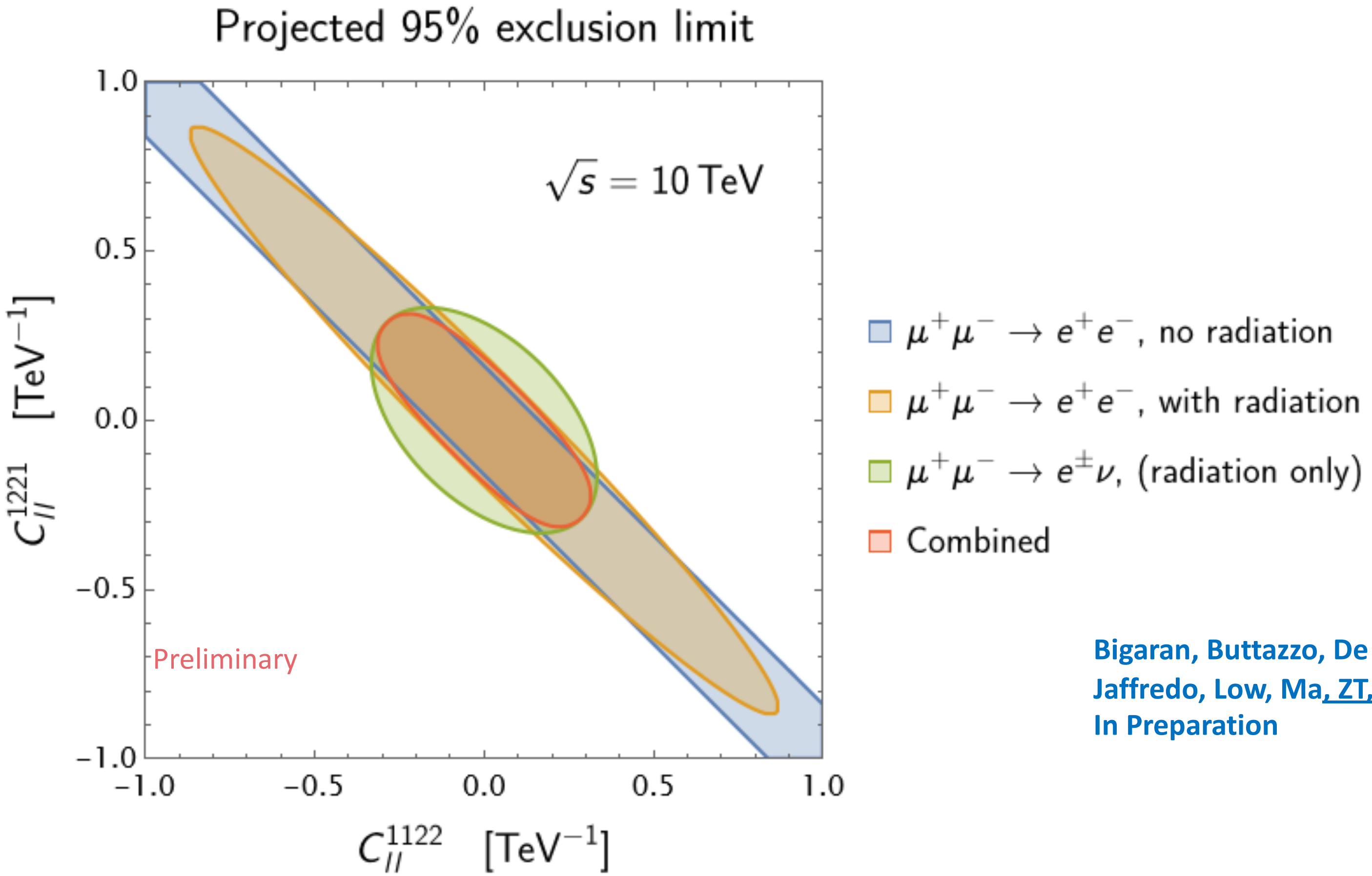
$\mu^\pm\nu$

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:

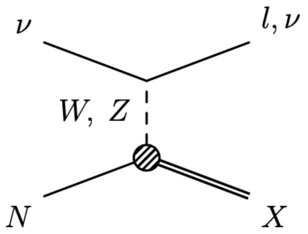
$$\mathcal{L}_{\rm SMEFT} \supset \sqrt{g_L^2+g_Y^2}\,Z^\mu \sum_{q=u,d}\left[\bar{q}\bar{\sigma}_\mu\left((T_3^q - s_\theta^2 Q_q) + \boxed{\delta g_L^{Zq}}\right) q + q^c\sigma_\mu\left(-s_\theta^2 Q_q + \boxed{\delta g_R^{Zq}}\right)\bar{q}^c\right]$$

$$+ \left[W^{\mu+}\overline{u}\overline{\sigma}_\mu\left(V_{ud} + \boxed{\delta g_L^{Wq_1}}\right) d + \text{h.c.}\right].$$

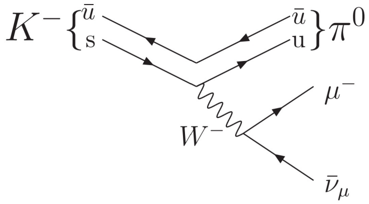


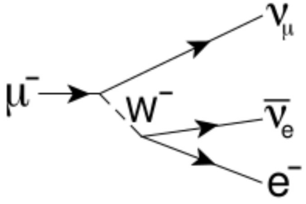
Bigaran, Buttazzo, De Gouvea, Han,
Jaffredo, Low, Ma, ZT, Xie,
In Preparation

DIS: FASERν



Kaon/Muon decay: ISODAR, KDAR





Solar neutrinos: Borexino

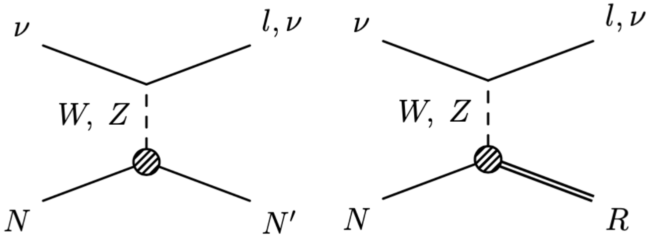
⁷Be $\boxed{{}^7\mathrm{Be} + e^- \rightarrow {}^7\mathrm{Li} + \nu_e}$

$\boxed{{}^3\mathrm{He} + p \rightarrow {}^4\mathrm{He} + e^+ + \nu_e}$ **hep**

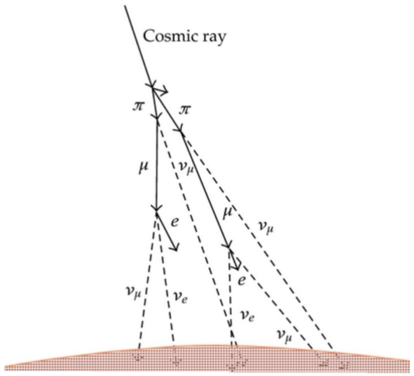
(hep)

$\boxed{p + e^- + p \rightarrow {}^2\mathrm{H} + \nu_e}$ ***pep***

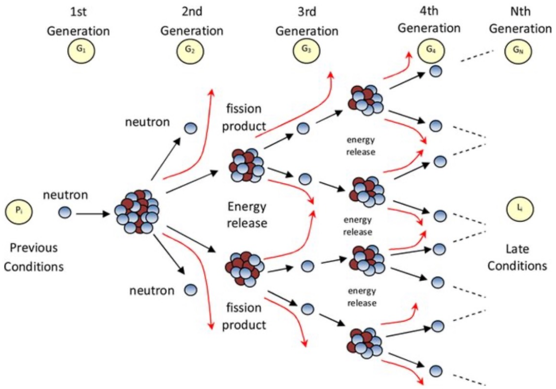
QE, Resonances: MINOS, NOvA, DUNE



Atmospheric Neutrinos: IceCube

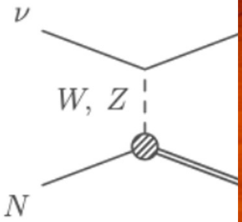


Beta decay and IBD: Reactor Experiments



DIS: FASERν

Solar neutrinos: Borexino



$$\text{Be} + e^- \rightarrow {}^7\text{Li} + \nu_e$$

$$+ p \rightarrow {}^4\text{He} + e^+ + \nu_e \quad \textbf{hep}$$

(hep)

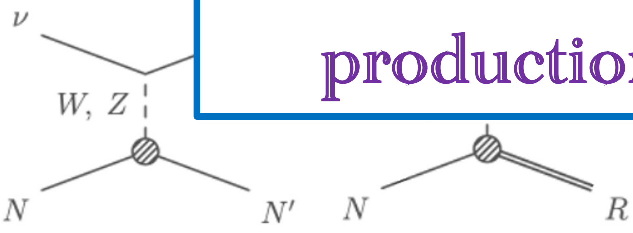
$$e^- + p \rightarrow {}^2\text{H} + \nu_e \quad \textit{pep}$$

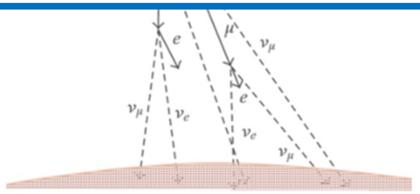
QE, Resonances: MINOS, NOvA, DUNE

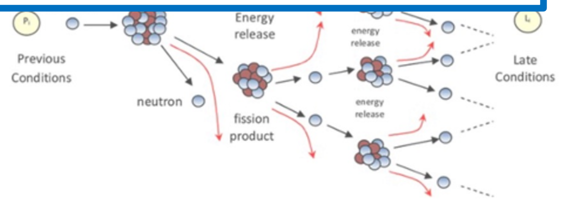
IceCube

eta decay and IBD: Reactor Experiments

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







If we become more inclusive we might find the beast right here!

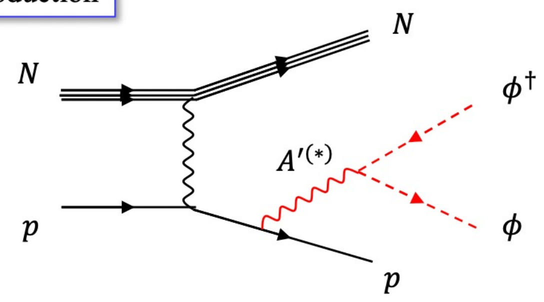
Any Questions?

I'M NOW GOING TO OPEN THE FLOOR TO QUESTIONS.

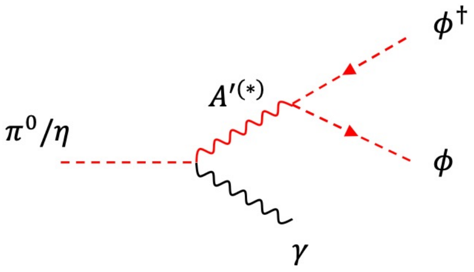
Back up Slides

Production and Detection of Dark Matter

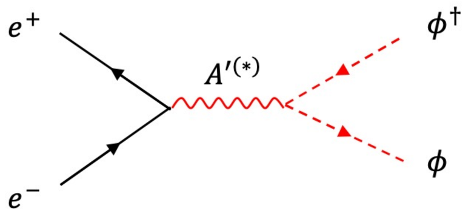
DM production



Beam bremsstrahlung

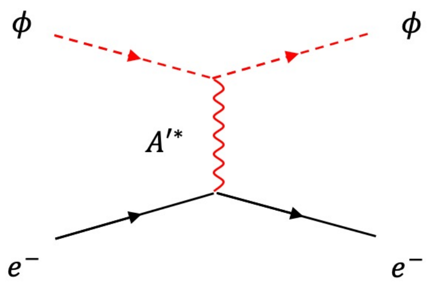


Neutral meson decays



Resonance production

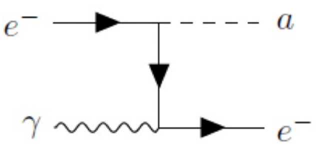
DM detection



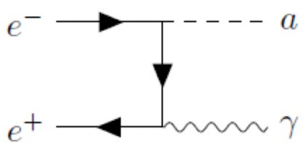
Elastic scattering with an electron

Production and Detection of ALPs

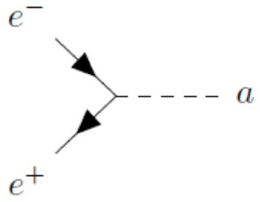
ALP production



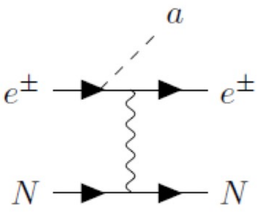
Compton



Associated production

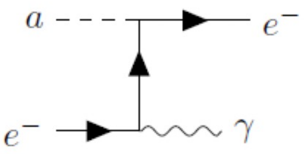


Resonant production

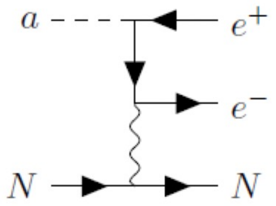


ALP-bremsstrahlung

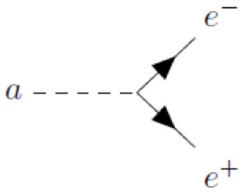
ALP detection



Inverse Compton



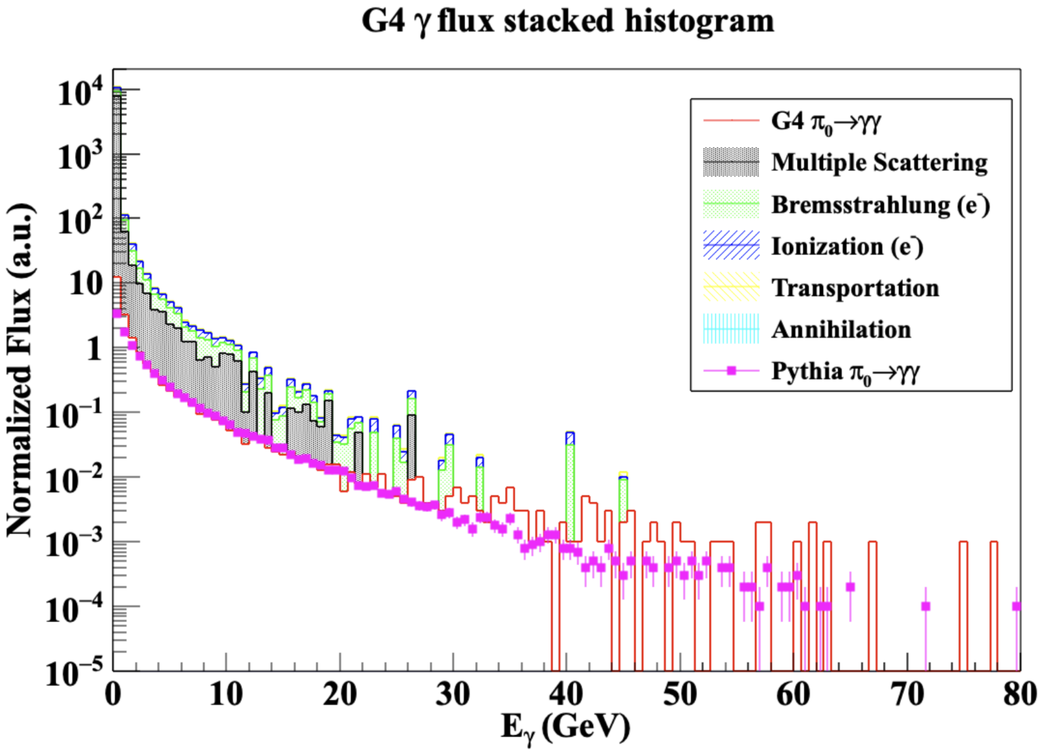
External pair conversion



Di-lepton decay

Axion Like Particles (ALPs) at DUNE:

Photon Flux from GEANT4 Simulation



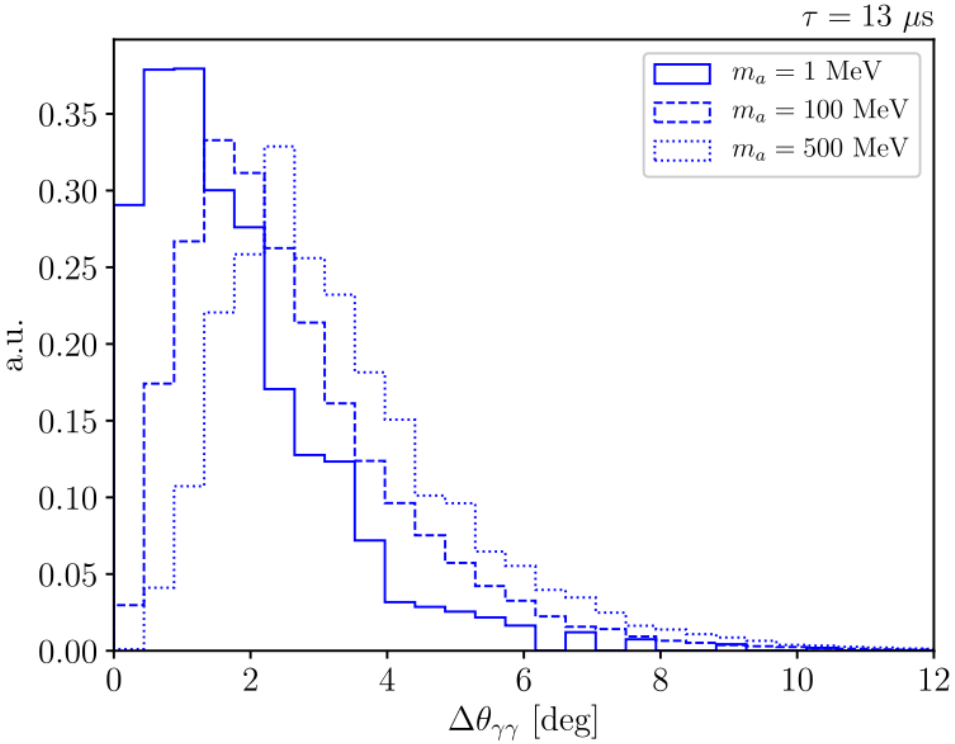
V. Brdar, B. Dutta, W. Jang, D. Kim, I. Shoemaker, **ZT**, A. Thompson, J. Yu
Phys.Rev.Lett. 126 (2021) 20, 201801

Axion Like Particles (ALPs) at DUNE:

- Coherent π^0 production $\nu + A \rightarrow \nu + A + \pi^0$

In GAr:

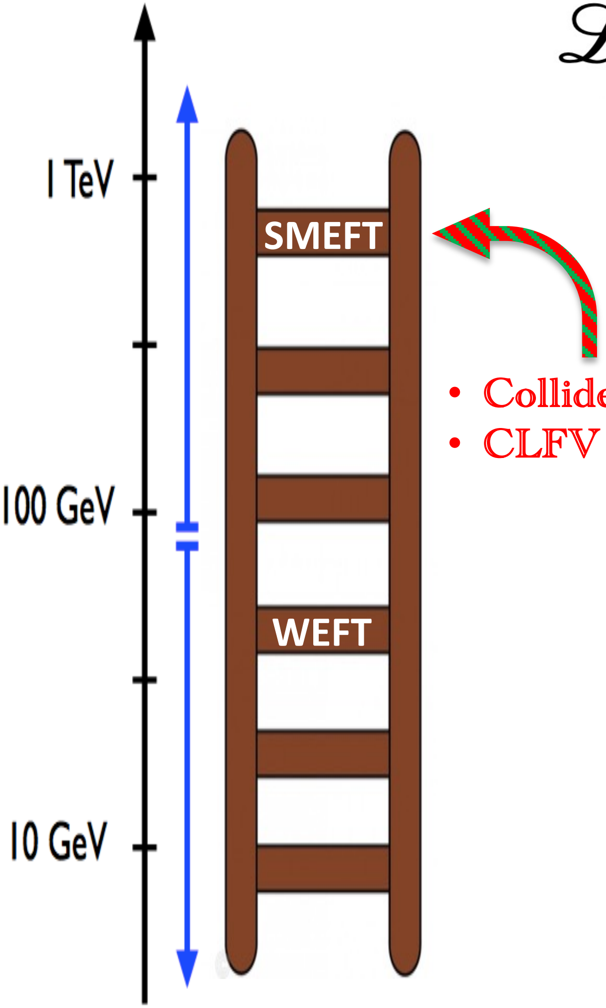
- We expect ~ 10^6 NC events;
- Vetoing events with hadronic activity remove ~ 80%;
- A cut on the opening angle removes the rest;



V. Brdar, B. Dutta, W. Jang, D. Kim, I. Shoemaker, **ZT**, A. Thompson, J. Yu
Phys.Rev.Lett. 126 (2021) 20, 201801

EFT ladder

SMEFT: minimal EFT above the weak scale



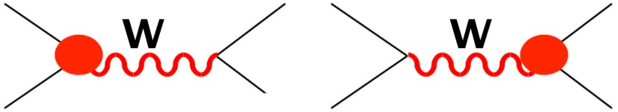
- Colliders
- CLFV

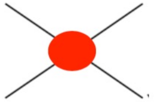
$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \mathscr{L}_{D=5} + \boxed{\mathscr{L}_{D=6}}$$

Known SM Lagrangian

Gives neutrino Masses

+





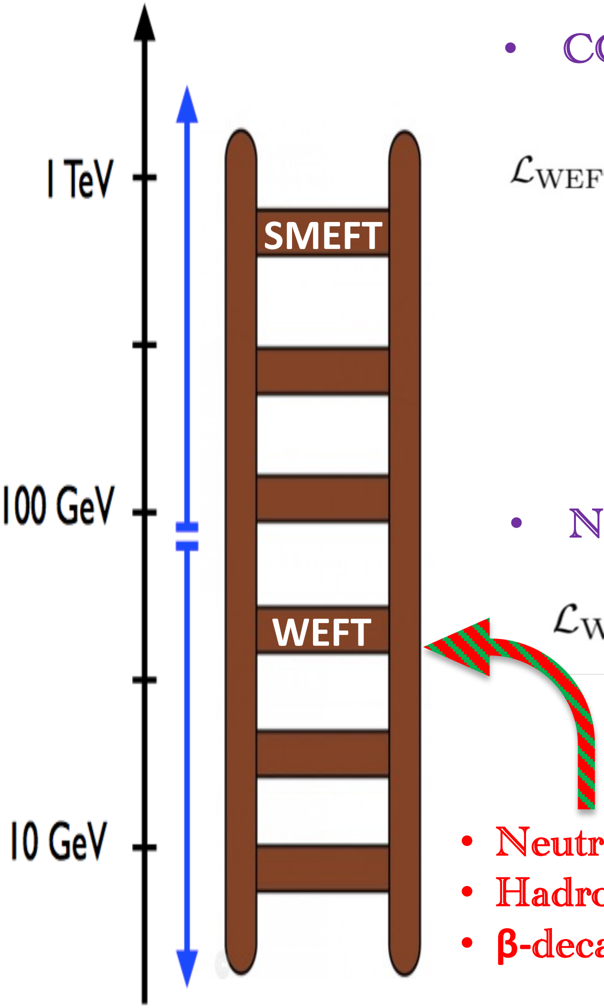
$$O_{lq}^{(3)} = (\bar{l}\gamma^{\mu}\sigma^{a}l)(\bar{q}\gamma_{\mu}\sigma^{a}q)$$

$$O_{qde} = (\bar{l}e)(\bar{d}q) + \text{h.c.}$$

$$O_{lq} = (\bar{l}_a e)\epsilon^{ab}(\bar{q}_b u) + \text{h.c.}$$

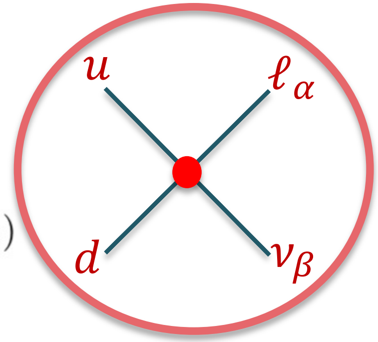
$$O_{lq}^{t} = (\bar{l}_a\sigma^{\mu\nu}e)\epsilon^{ab}(\bar{q}_b\sigma_{\mu\nu}u) + \text{h.c.}$$

EFT ladder WEFT: Effective Lagrangian defined at a low scale μ ~ 2 GeV



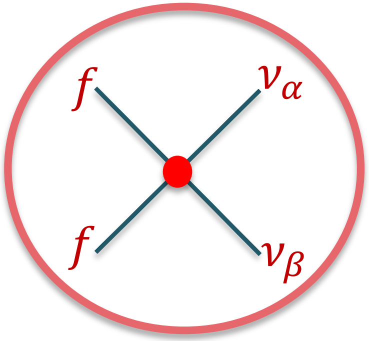
- CC: New left/right handed, (pseudo)scalar and tensor interactions

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



- NC: New left and right handed interactions

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



- 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.

Pion decay

Production

Falkowski, González-Alonso, *ZT*, JHEP (2020)

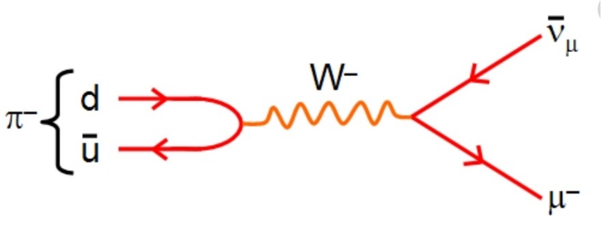
Due to the pseudoscalar nature of the pion, it is sensitive only to axial (ε_L-ε_R) and pseudo-scalar (ε_P) interactions.

$$p_{LL} = -p_{RL} = 1, \quad p_{PL} = -p_{PR} = -\frac{m_\pi^2}{m_\mu(m_u + m_d)},$$

$$p_{RR} = 1, \quad p_{PP} = \frac{m_\pi^4}{m_\mu^2(m_u + m_d)^2}.$$

~-27

~700!



$\pi^-(d\bar{u}) \to \mu^- + \bar{\nu}_\mu$

- Larger $p_{XY} \implies$ smaller ϵ!

$$\phi^{Total} \sim \phi^{SM}(1+\varepsilon_X\, p_{XL} + \varepsilon_X{}^2\, p_{XX})$$

$$\langle 0|\, \bar{d}\gamma^\mu\gamma_5 u\, |\pi^+(p_\pi)\rangle = i p_\pi^\mu f_\pi$$

$$\langle 0|\, \bar{d}\gamma_5 u\, |\pi^+(p_\pi)\rangle = -i\frac{m_\pi^2}{m_u + m_d} f_\pi$$

Huge overall flux normalization for pion decay!

Charm decay

Production

Falkowski, González-Alonso, ZT, JHEP (2020)

$$p^{D,cs}_{LL,\alpha} = p^{D,cs}_{RR,\alpha} = -p^{D,cs}_{LR,\alpha} = 1\,,$$

$$p^{D,cs}_{PL,\alpha} = -p^{D,cs}_{PR,\alpha} = -\frac{m^2_{D_s}}{m_{\ell_\alpha}(m_c+m_s)} \simeq -1.6,\ -27,\ -5.5\times 10^3 \qquad \text{for } \alpha=\tau,\ \mu,\ e$$

$$p^{D,cs}_{PP,\alpha} = \frac{m^4_{D_s}}{m^2_{\ell_\alpha}(m_c+m_s)^2} \simeq 2.5,\ 710,\ 3.0\times 10^7 \qquad \text{for } \alpha=\tau,\ \mu,\ e$$

- Larger $p_{XY} \Longrightarrow$ smaller ϵ!

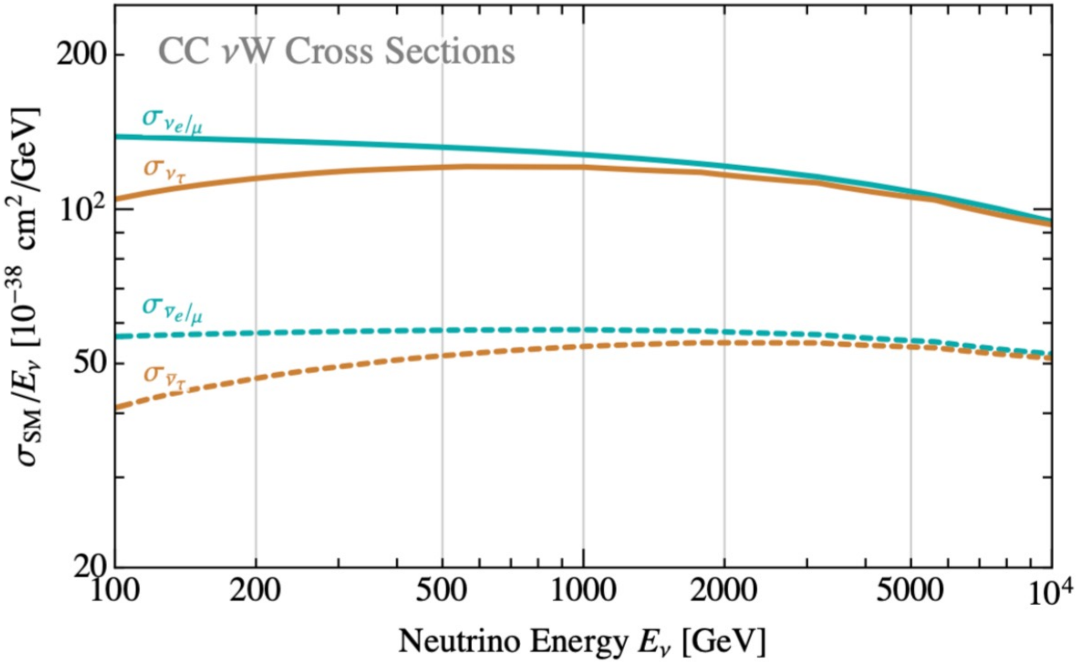
$$\boxed{\phi^{Total} \sim \phi^{SM}(1+\varepsilon_X\, p_{XL} + \varepsilon_X{}^2\, p_{XX})}$$

Large overall flux normalization for charm decay as well!

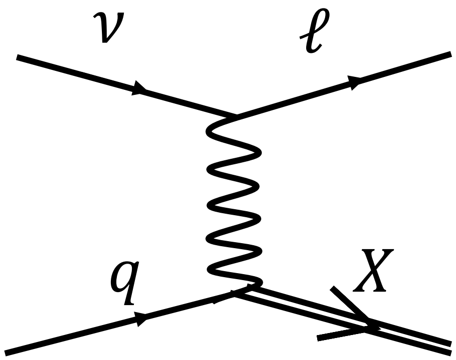
DIS

Detection

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



Deep Inelastic Scattering

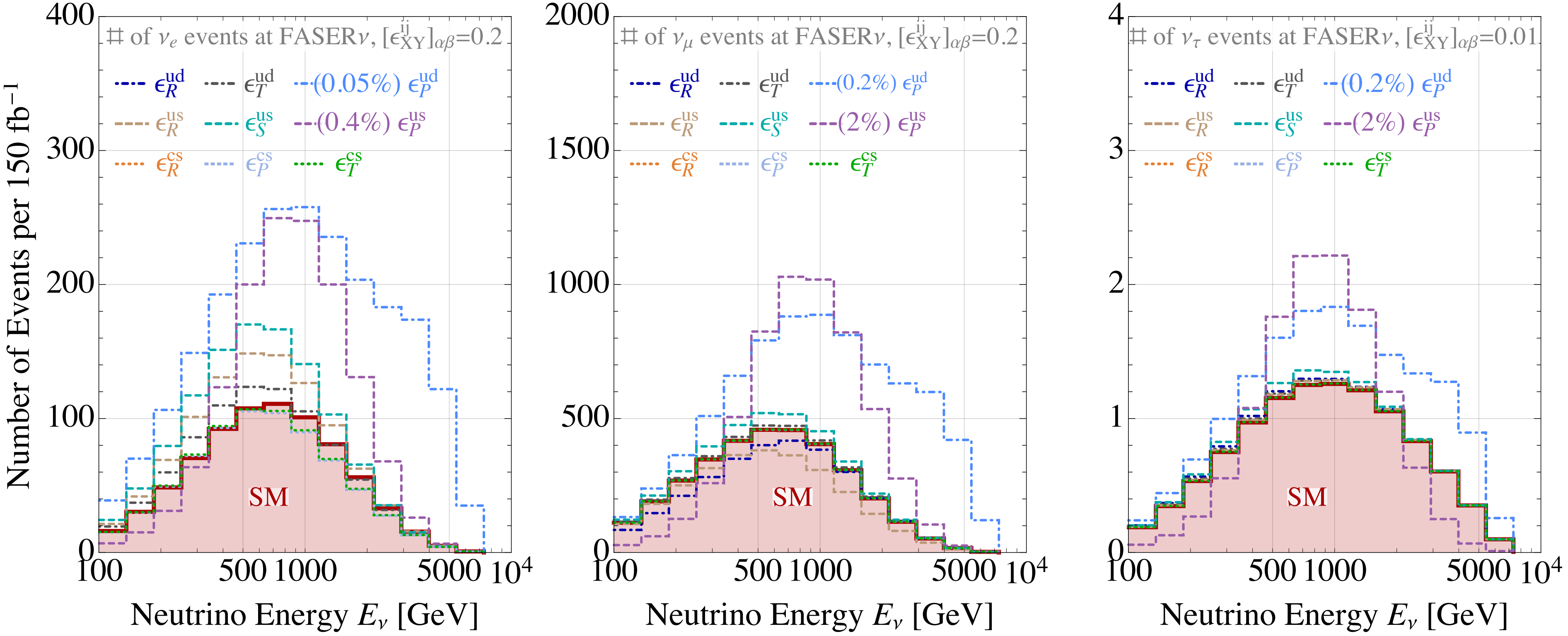


DIS detection, simple to include NSI

(compared to QE and Resonances)

EFT at FASERν

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



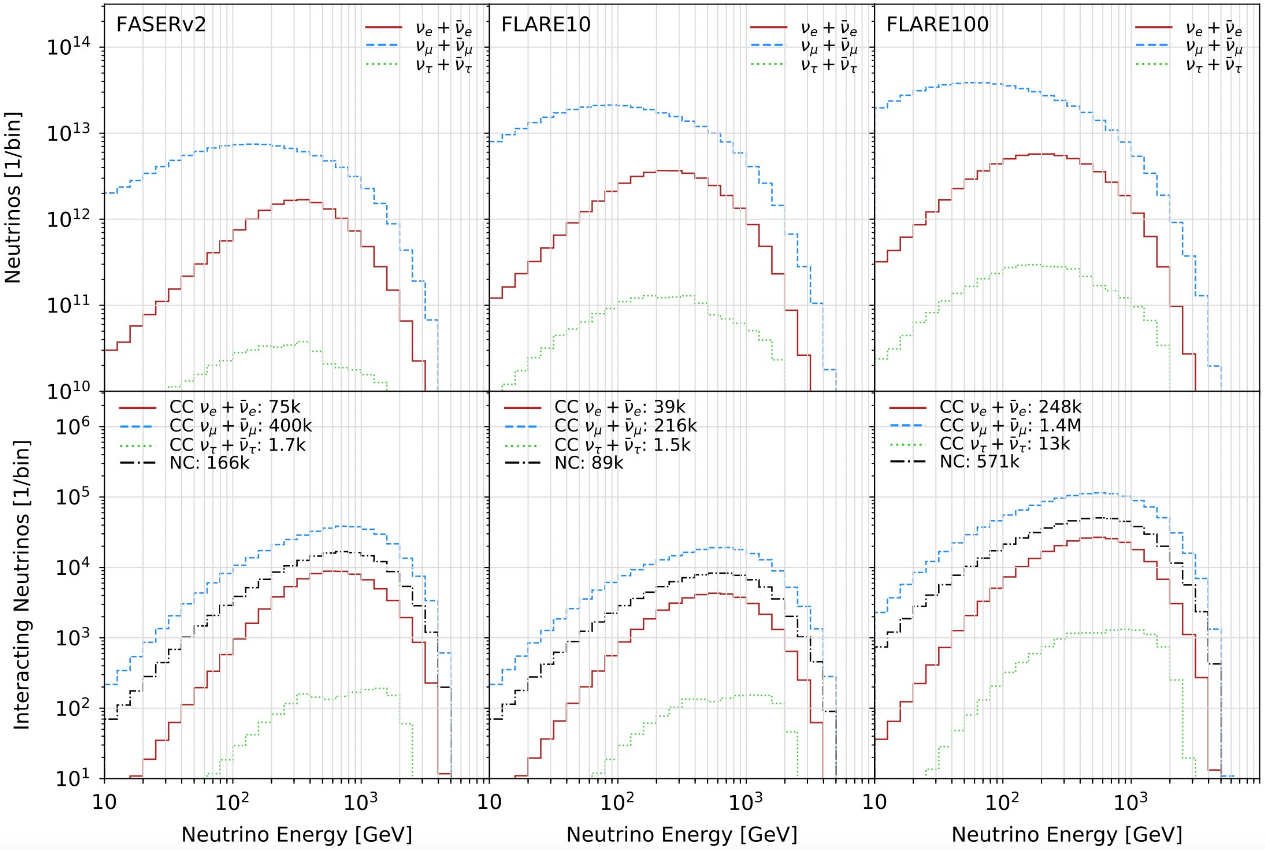
- **Results are statistics dominated:** $\nu_e \sim 1000$, $\nu_\mu \sim 5000$, $\nu_\tau \sim 10$
- **Optimistic systematic uncertainties:** 5% on ν_e, 10% on ν_μ, 15% on ν_τ
- **Conservative systematic uncertainties:** 30% on ν_e, 40% on ν_μ, 50% on ν_τ

Other FPF Experiments

Rates scale linearly wrt volume/Luminosity: X

diagonal $\varepsilon \sim \left({}^{X_2}/_{X_1}\right)^{1/2}$

off-diagonal $\varepsilon \sim \left({}^{X_2}/_{X_1}\right)^{1/4}$



- FASERv2:
  75 times more events,
  ~ 9 (3) times better sensitivity for (off-) diagonal elements;
- FLArE10:
  40 times more events,
  ~ 6 (2.5) times better sensitivity;
- FLArE100:
  300 times more events,
  ~ 17 (4) times better sensitivity;

Neutrino 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.

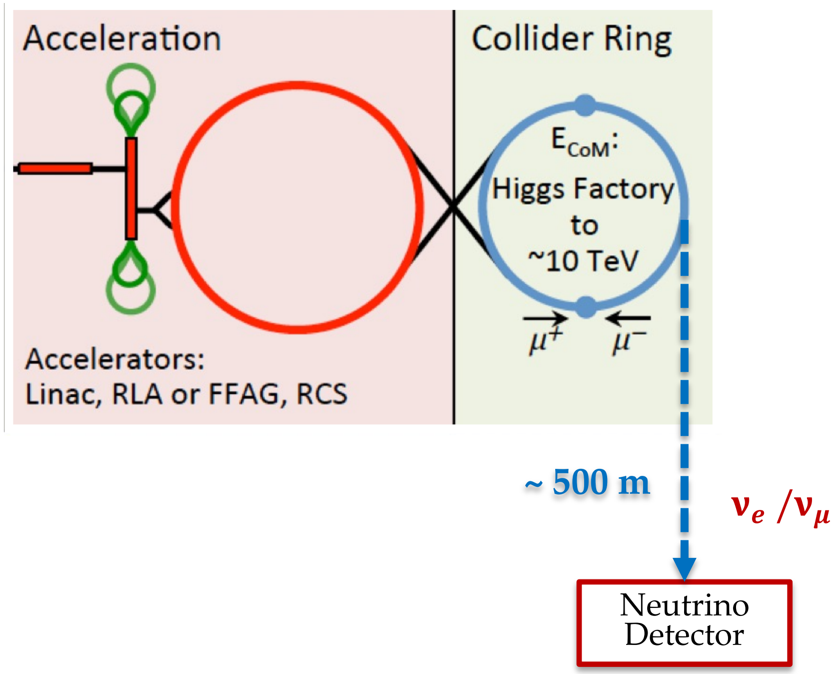
A neutrino detector at the moon?
We are not there yet!

Neutrino Fixed Target Experiment at a Muon Collider

Why would a Muon Collider Help?

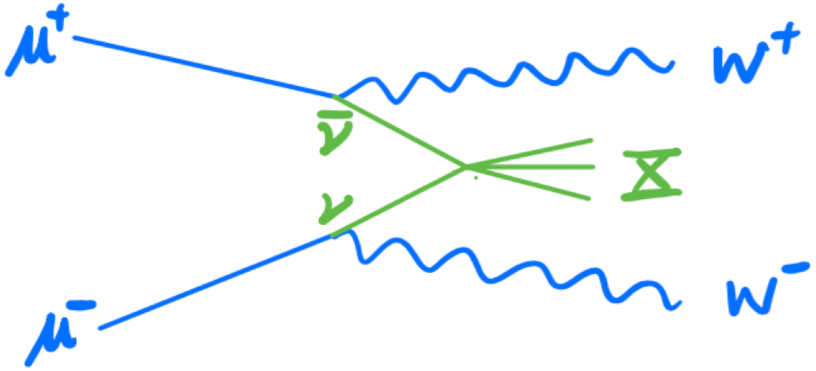
No oscillation, but:

- New neutrino states
- Light Dark Matter
- Searches for LFV
- ALPs
- Heavy BSM using EFT
- ………..



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:

Flavor-conserving 4-lepton operators

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

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

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

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

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

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

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

SMEFT:

Chirality-conserving 2 lepton-2 quark operators

$\mu^+\mu^-$
$\mu^\pm\nu$
$\nu\,\bar\nu$

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

$\mu^+\mu^-$

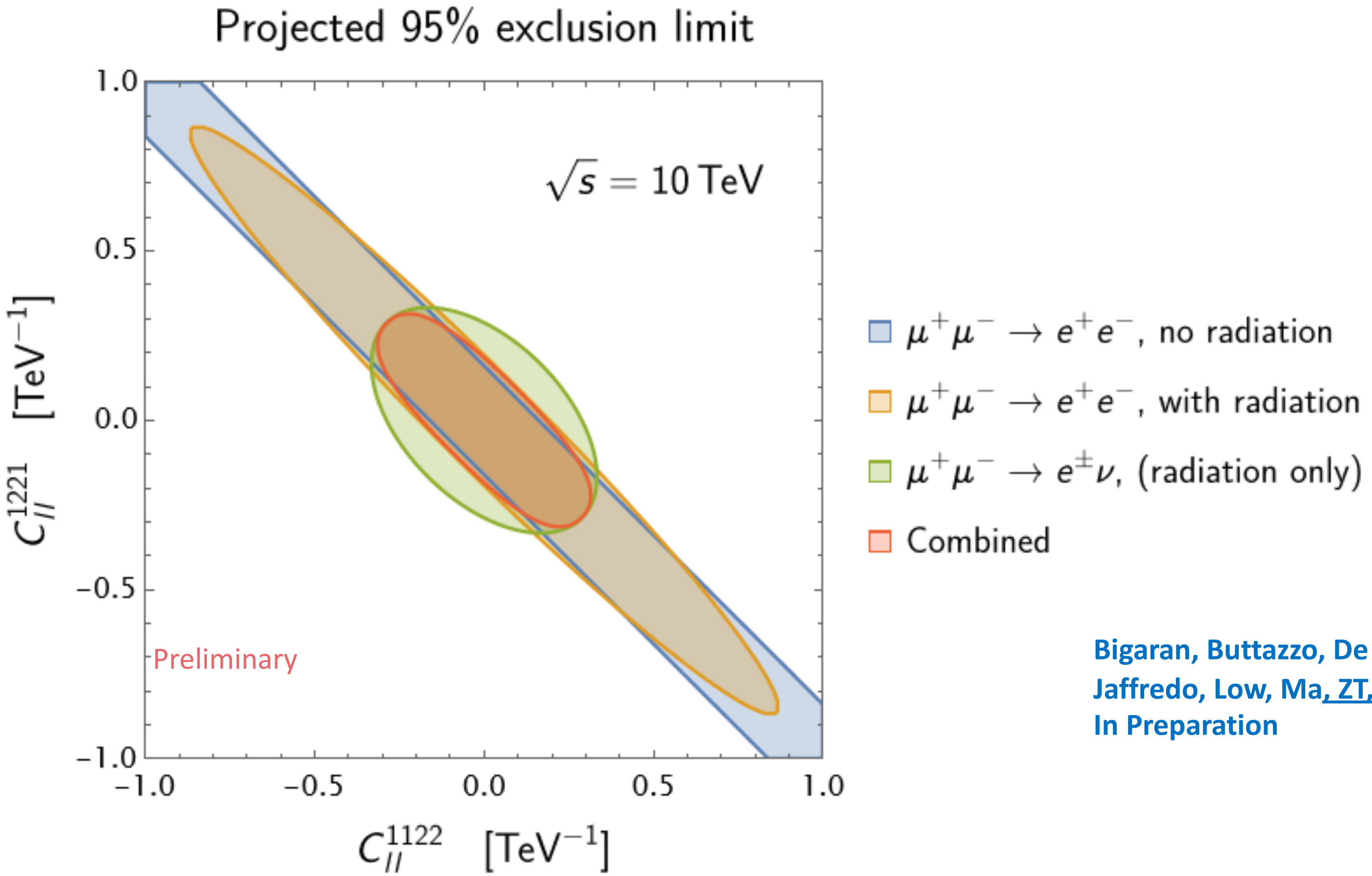
Chirality-Violating 2 lepton-2 quark operators

$\mu^+\mu^-$
$\mu^\pm\nu$

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:

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



**Bigaran, Buttazzo, De Gouvea, Han,
Jaffredo, Low, Ma, ZT, Xie,
In Preparation**