Neutrino-Collider Synergy for Beyond the Standard Model Searches

Artwork by Sandbox Studio, Chicago with Ana Kova

University of Warsaw

March 26, 2026

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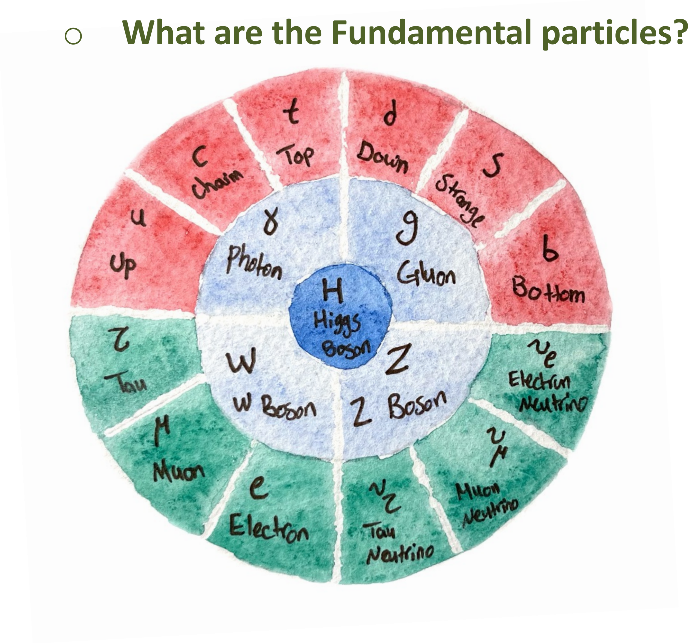
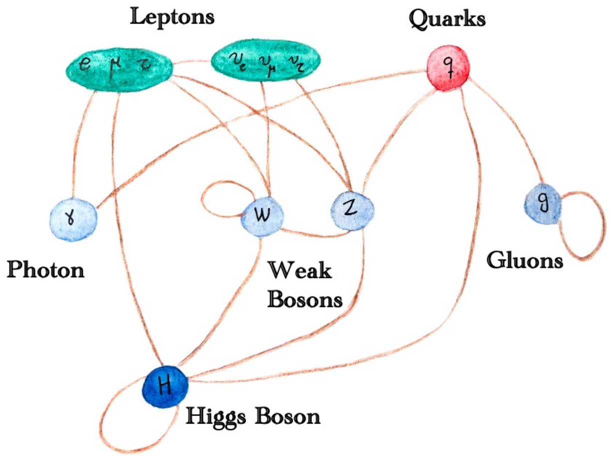
PITTPACC
PITTSBURGH PARTICLE PHYSICS ASTROPHYSICS COSMOLOGY CENTER

Standard Model

- What are the Fundamental particles?



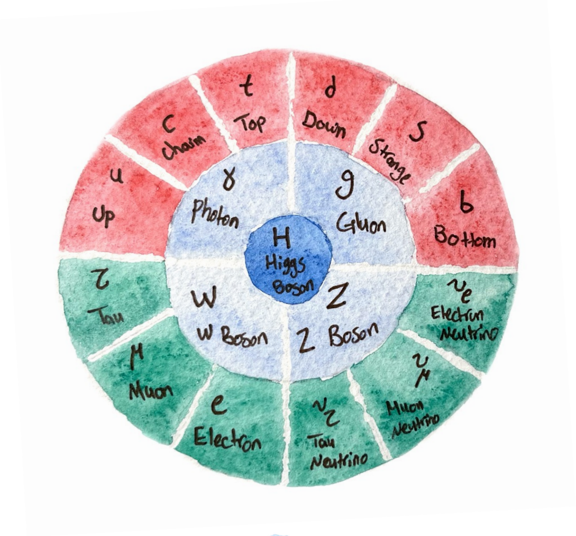
- How do they interact?

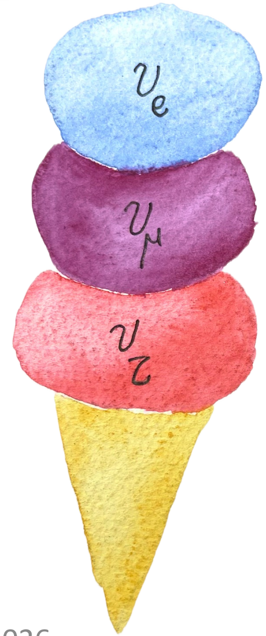


The Standard Model:
"Periodic Table" of
elementary particles

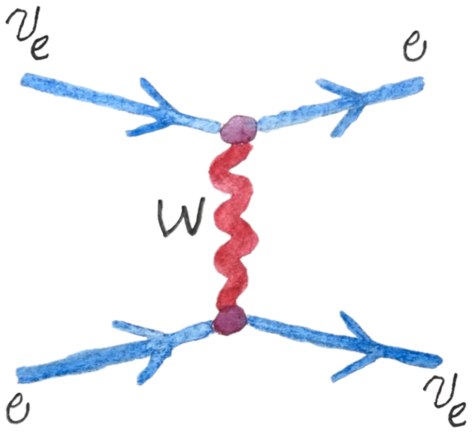
Neutrinos are among the
elementary particles!

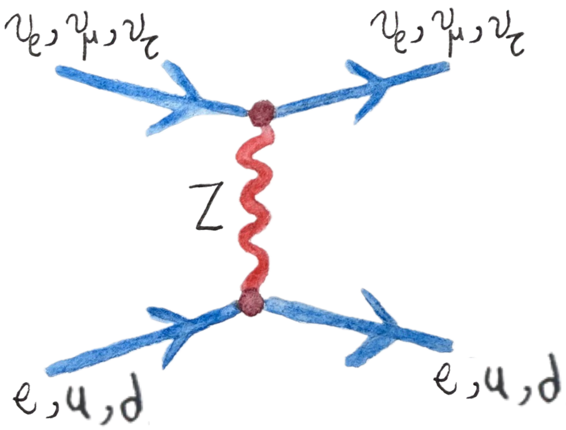
Why are neutrinos special?





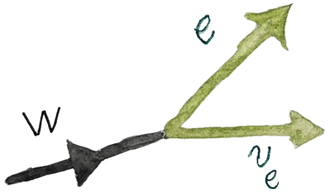
They interact with matter only by W/Z exchange

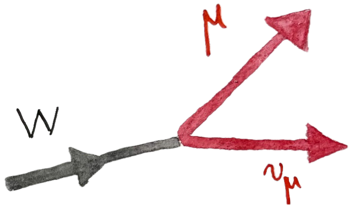


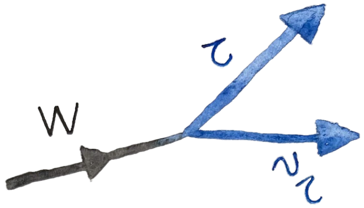


Three known Flavors

We ***define*** the three known flavors of neutrinos by **W** boson decays:

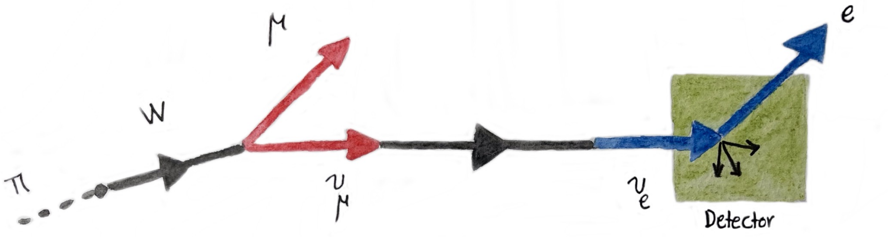






Neutrino Oscillation

They change Flavor



$$\mathscr{H}|\nu_k\rangle = E_k|\nu_k\rangle$$

long enough journey

$$\nu_\mu \longrightarrow \nu_e$$

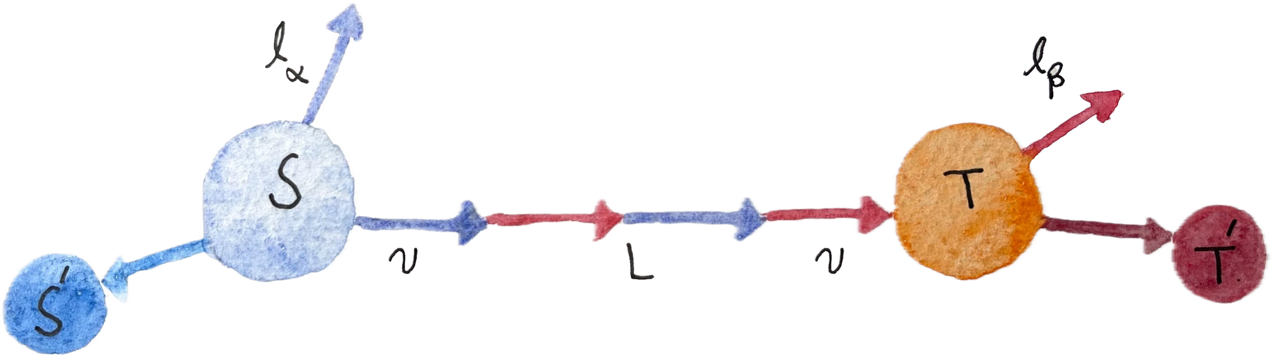
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\text{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

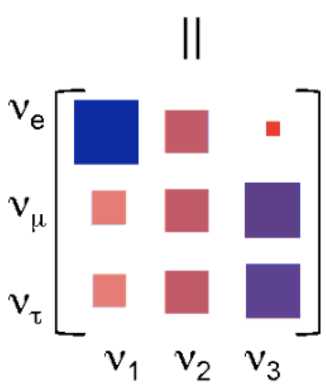
Oscillation Parameters:

$$P_{e\mu}(L) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

$$\boxed{\Delta m^2_{kj} \equiv m^2_k - m^2_j}$$

Oscillation Experiments





Observable: rate of detected events

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

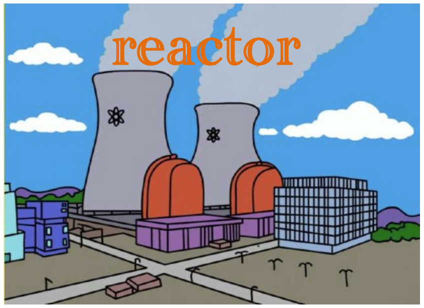
Depend on the kinematics and spin variables!

Depends on mixing angles/masses

Oscillation experiments are sensitive not only to oscillation parameters, but also to how neutrinos interact with matter!

Status of Neutrino Physics in 2026

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, Hyper-K , JUNO

Open oscillation questions:

- CP-phase?
- Mass hierarchy?

Also:

- Neutrino mass mechanism?
- Mass scale?
- Dirac or Majorana?

Status of Neutrino Physics in 2026

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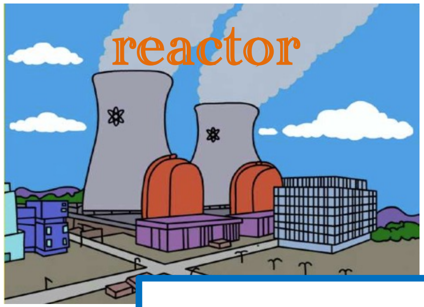


MBL: Daya Bay, RENO, Double Chooz
LBL: KamLAND

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 @ 3%

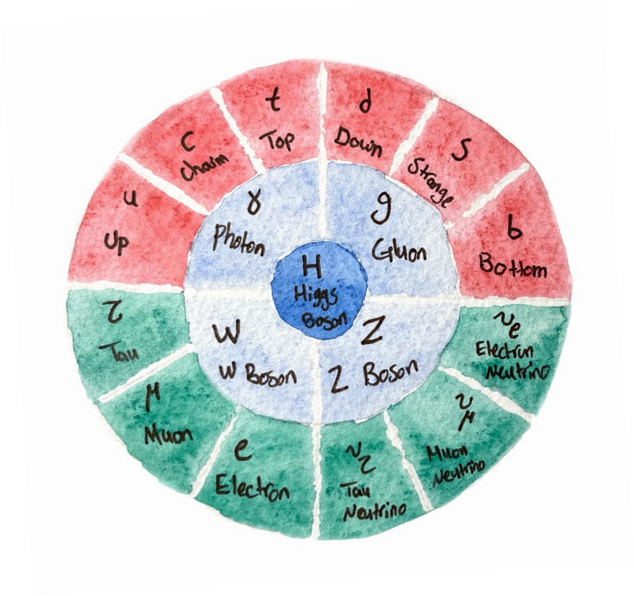
New Neutrino Experiments are being built to answer unknowns in the oscillation picture

- Mass hierarchy?

Also:

- Neutrino mass mechanism?
- Mass scale?
- Dirac or Majorana?

GOAL:



The SM is not wrong…

But there is more than
“reasonable doubt” that it is
incomplete!

- **Precision measurements at neutrino oscillation experiments;**

- **Finding the interplay between the low energy and high energy frontiers in BSM searches;**

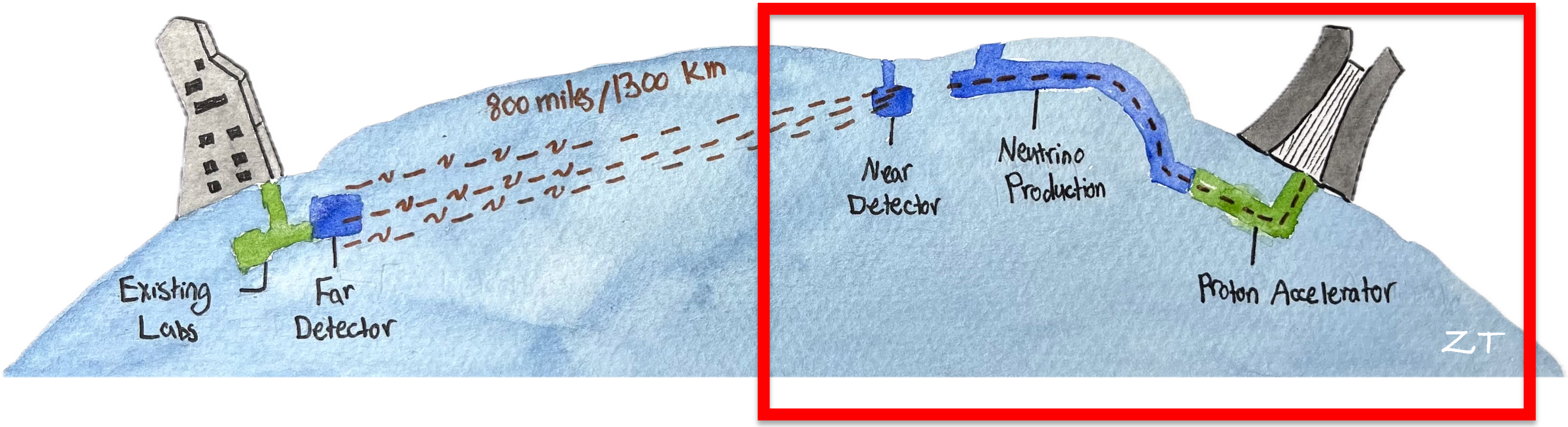
- **Specific BSM examples, by either indirect search, or direct production;**

Accelerator Neutrino Experiments:

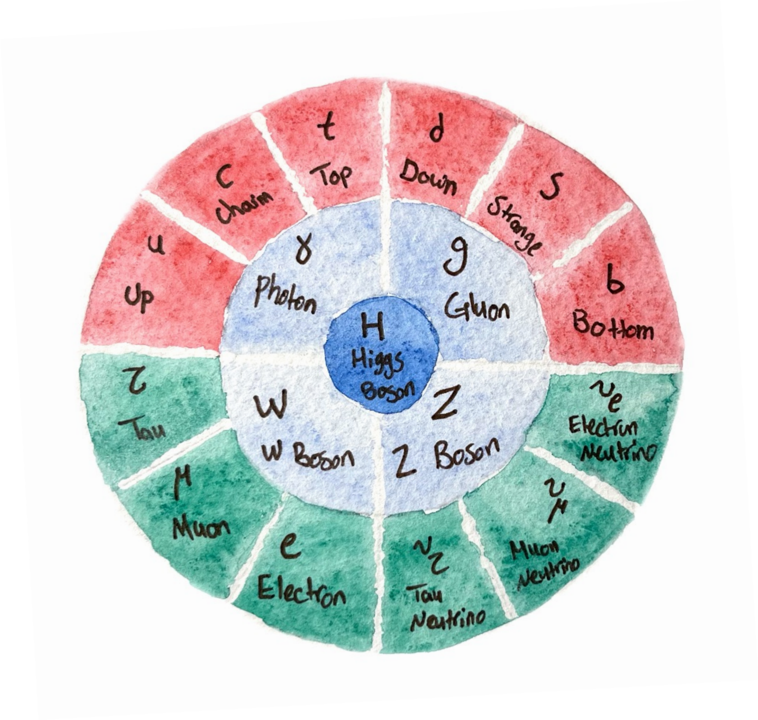
Near Detector: Understanding Systematic Uncertainties

Far Detector: Measuring Oscillation Parameters

- Test SM predictions
- Search for BSM physics



How do we go beyond the SM?



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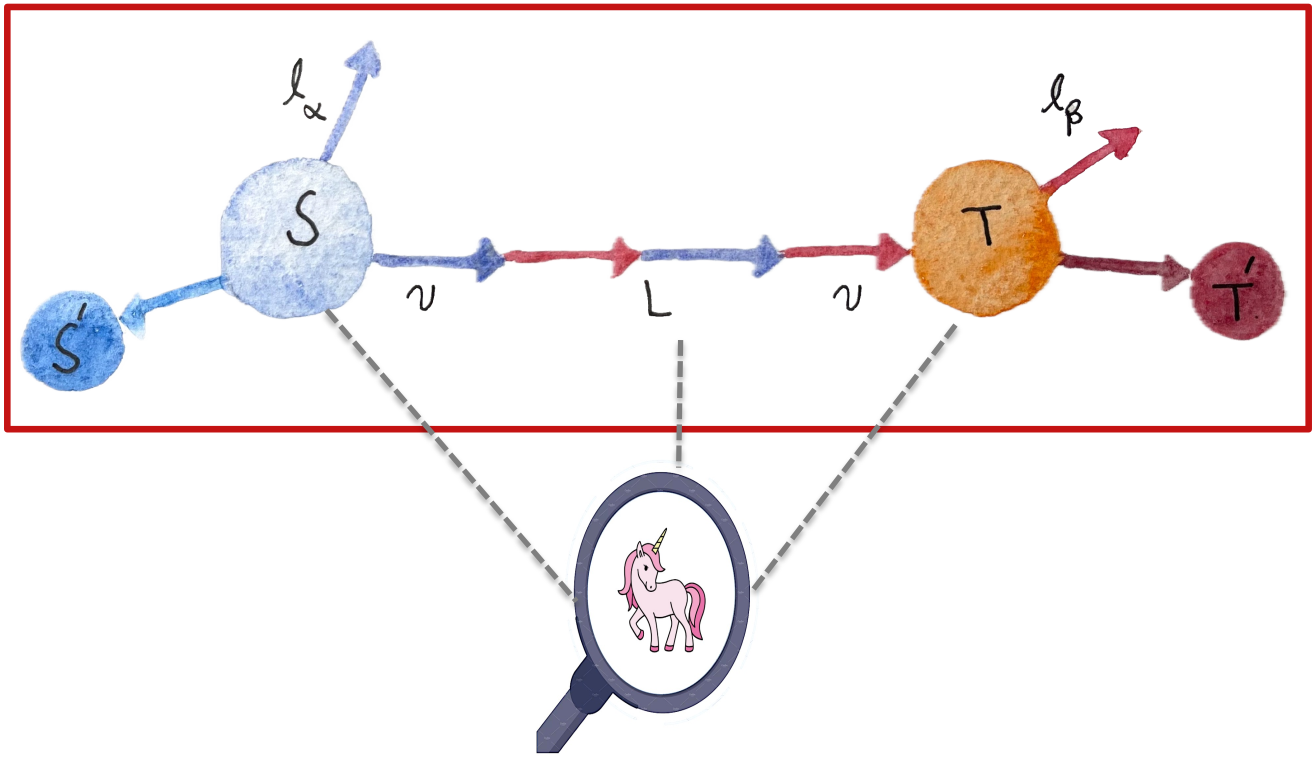
We extend the SM:

- ○ **New Particles**
- ○ **New Interactions**

1. Indirect Effects of Heavy New Physics

Modify Neutrino Interactions

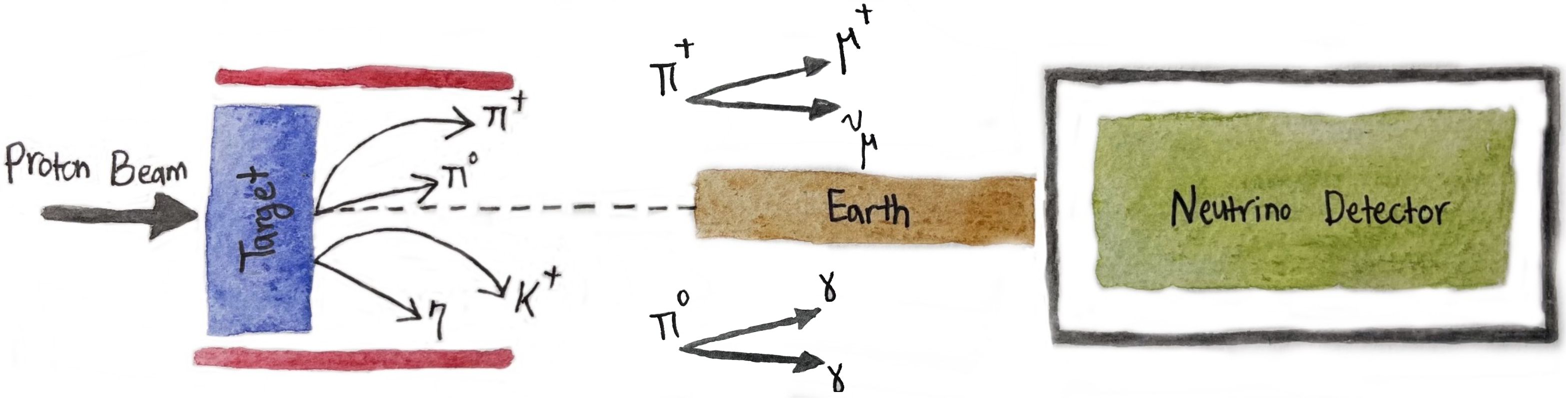


Observable: rate of detected events

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

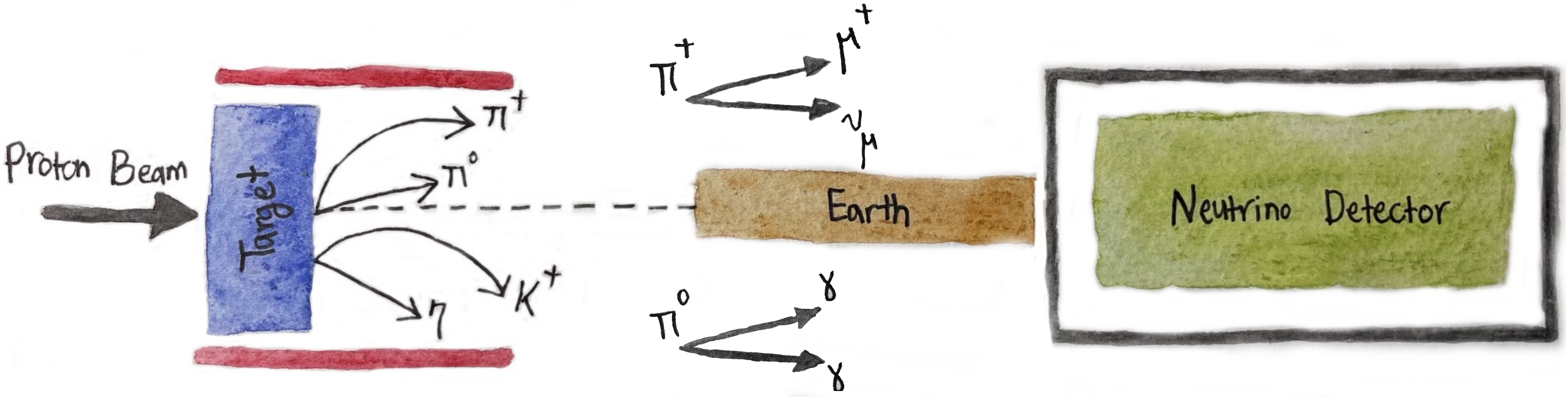
2. Direct Production of New Particles

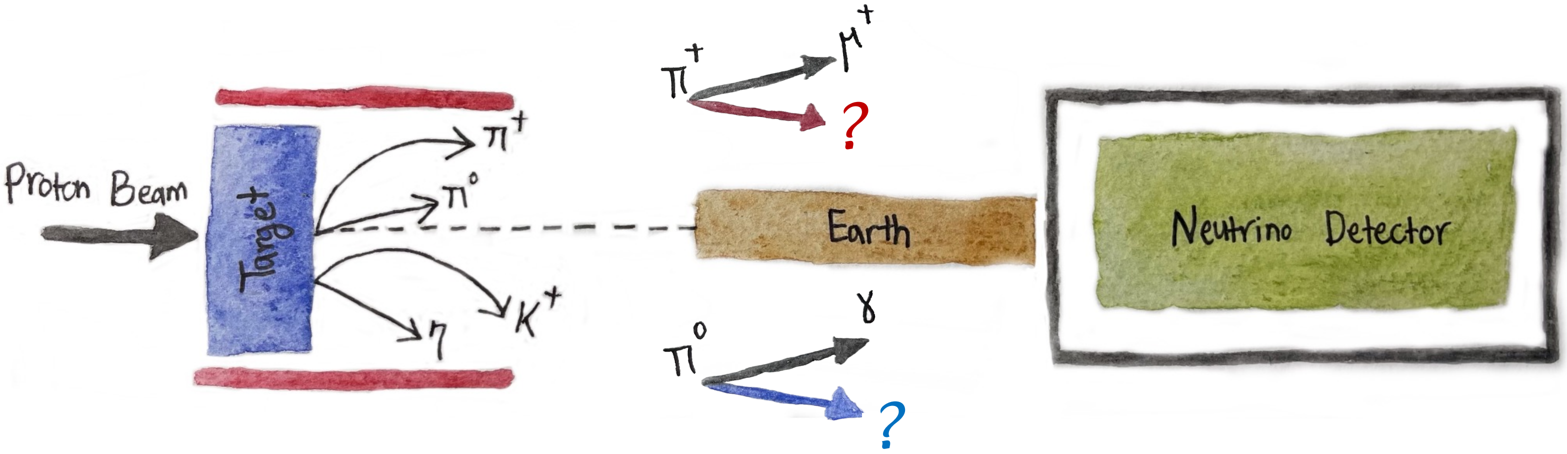
Neutrino Experiments as Dark Sector Factories



2. Direct Production of New Particles

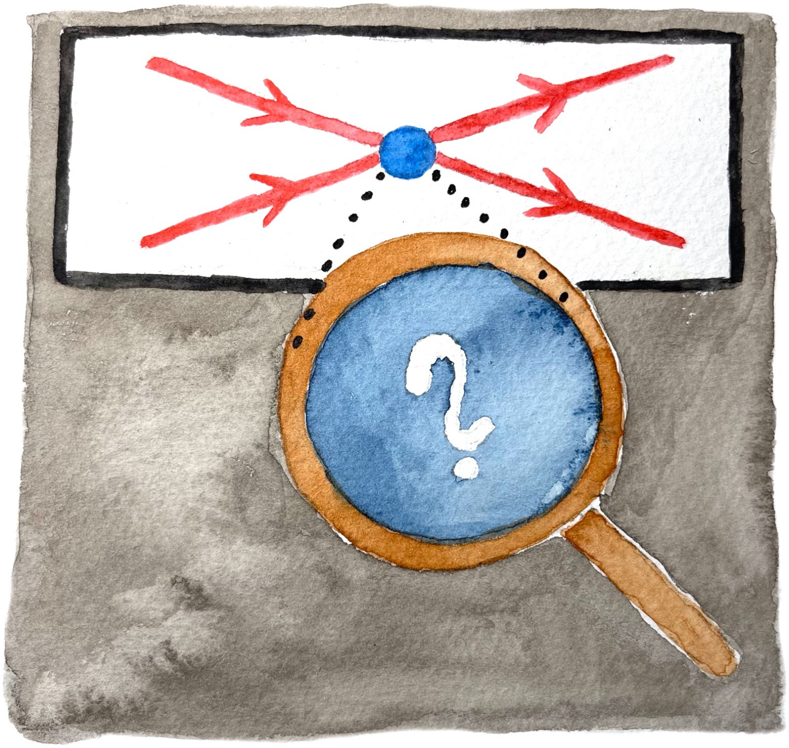
Neutrino Experiments as Dark Sector Factories





Outline

- 1) Indirect Search-EFT:
  - Why EFT?
  - EFT ladder
  - EFT at Neutrino Experiments
- 2) Direct Search:
  - Axion-Like Particles
- Conclusion



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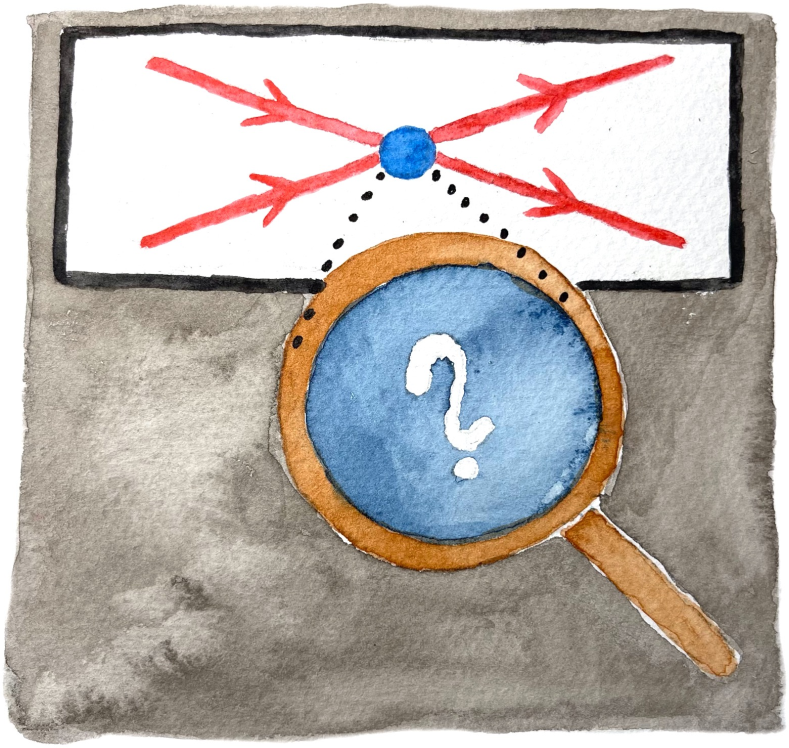
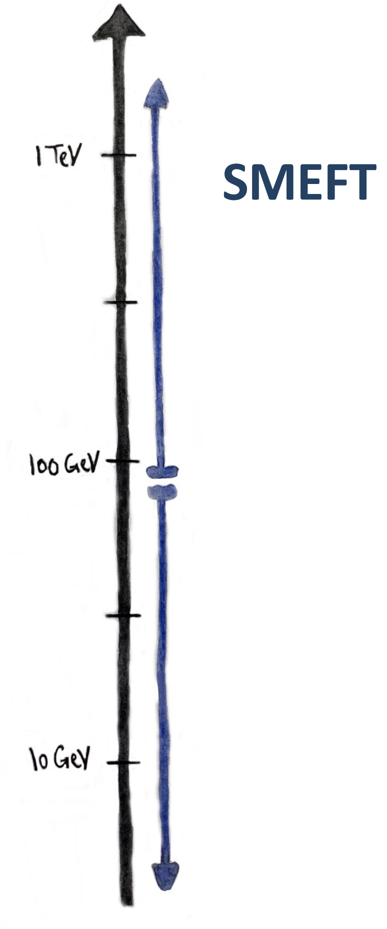


EFT Workflow:

EFT Energy Scale



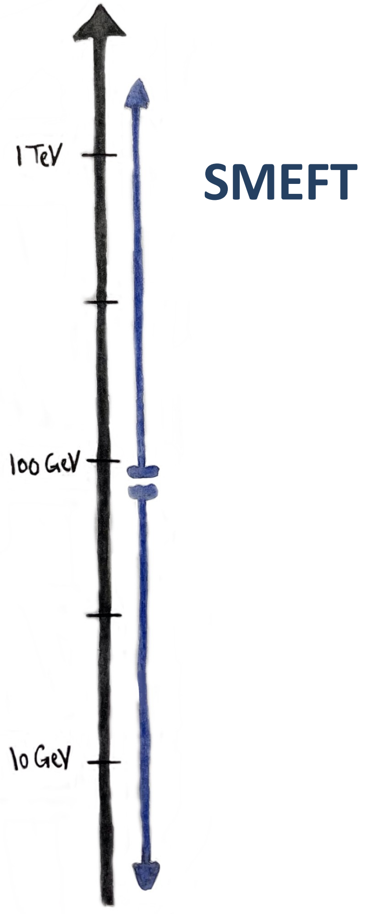
- New physics could be very heavy;
- It may affect the couplings between the SM particles, or induce new interactions;
- SM Effective Field Theory (SMEFT) is a systematic framework to describe such effects;

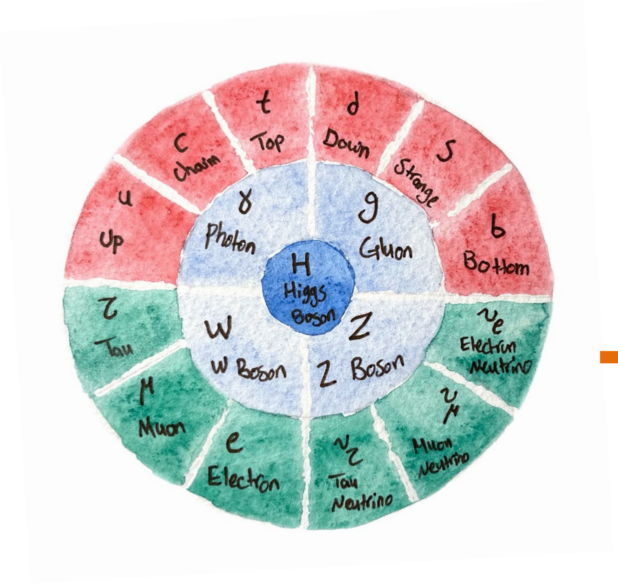
EFT Workflow:

SMEFT: minimal EFT above the weak scale

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

EFT Energy Scale





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EFT Workflow:

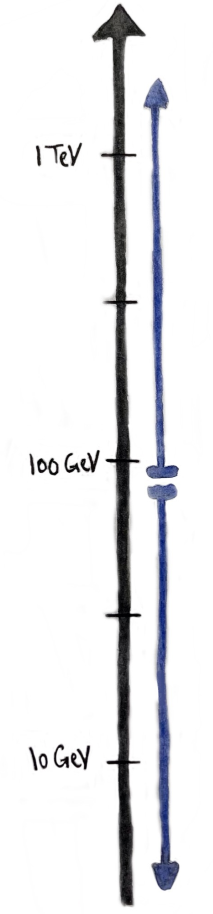
SMEFT: minimal EFT above the weak scale

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

Known SM Lagrangian

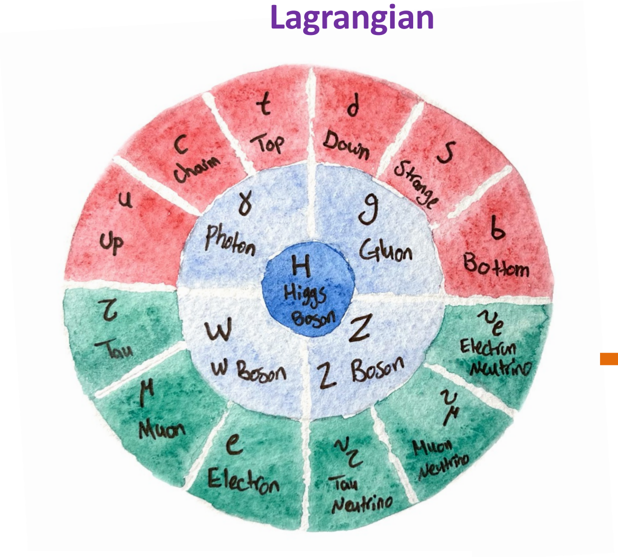
Gives neutrino Masses

EFT Energy Scale



SMEFT

- Colliders



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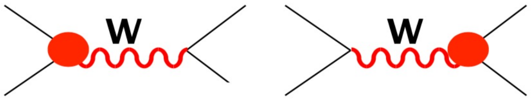
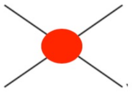




$$O_{lq}^{(3)} = (\bar{l}\gamma^{\mu}\sigma^{a}l)(\bar{q}\gamma_{\mu}\sigma^{a}q)$$

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

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

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

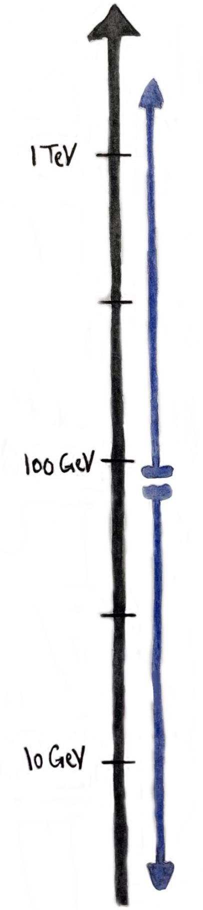
2499 distinct D=6 operators in the Warsaw basis, including flavor structure and CP conjugates

Grzadkowski, Iskrzynski, Misiak, Rosiek JHEP (2010)

EFT Workflow:

EFT Energy Scale

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



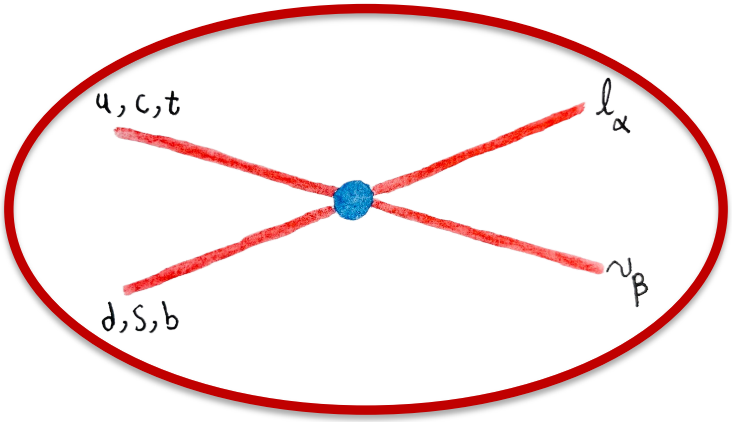
SMEFT

- Colliders

WEFT

- Neutrino experiments
- Hadron Decays
- β-decays

New 4-Fermion Interactions:



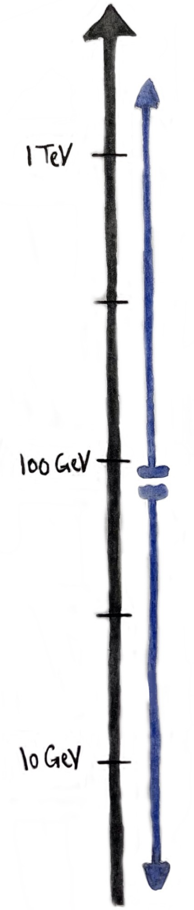
$\propto \epsilon_{\alpha\beta}$

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

EFT Workflow:

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

EFT Energy Scale



SMEFT

- Colliders

WEFT

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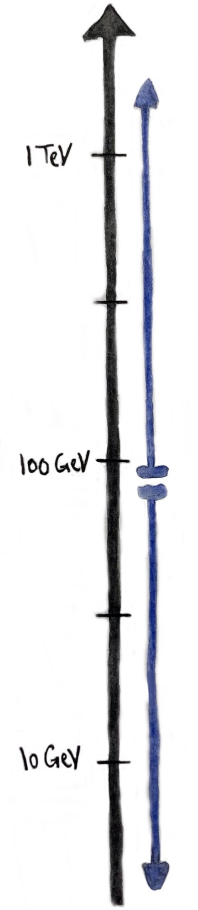
$$
\begin{aligned}
[\epsilon_L]_{\alpha\beta} &\approx \frac{v^2}{\Lambda^2 V_{ud}}\left(V_{ud}[c^{(3)}_{Hl}]_{\alpha\beta} + V_{jd}[c^{(3)}_{Hq}]_{1j}\delta_{\alpha\beta} - V_{jd}[c^{(3)}_{lq}]_{\alpha\beta 1j}\right)\\
[\epsilon_R]_{\alpha\beta} &\approx \frac{v^2}{2\Lambda^2 V_{ud}}[c_{Hud}]_{11}\delta_{\alpha\beta},\\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

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

EFT Workflow:

EFT Energy Scale



SMEFT

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WEFT

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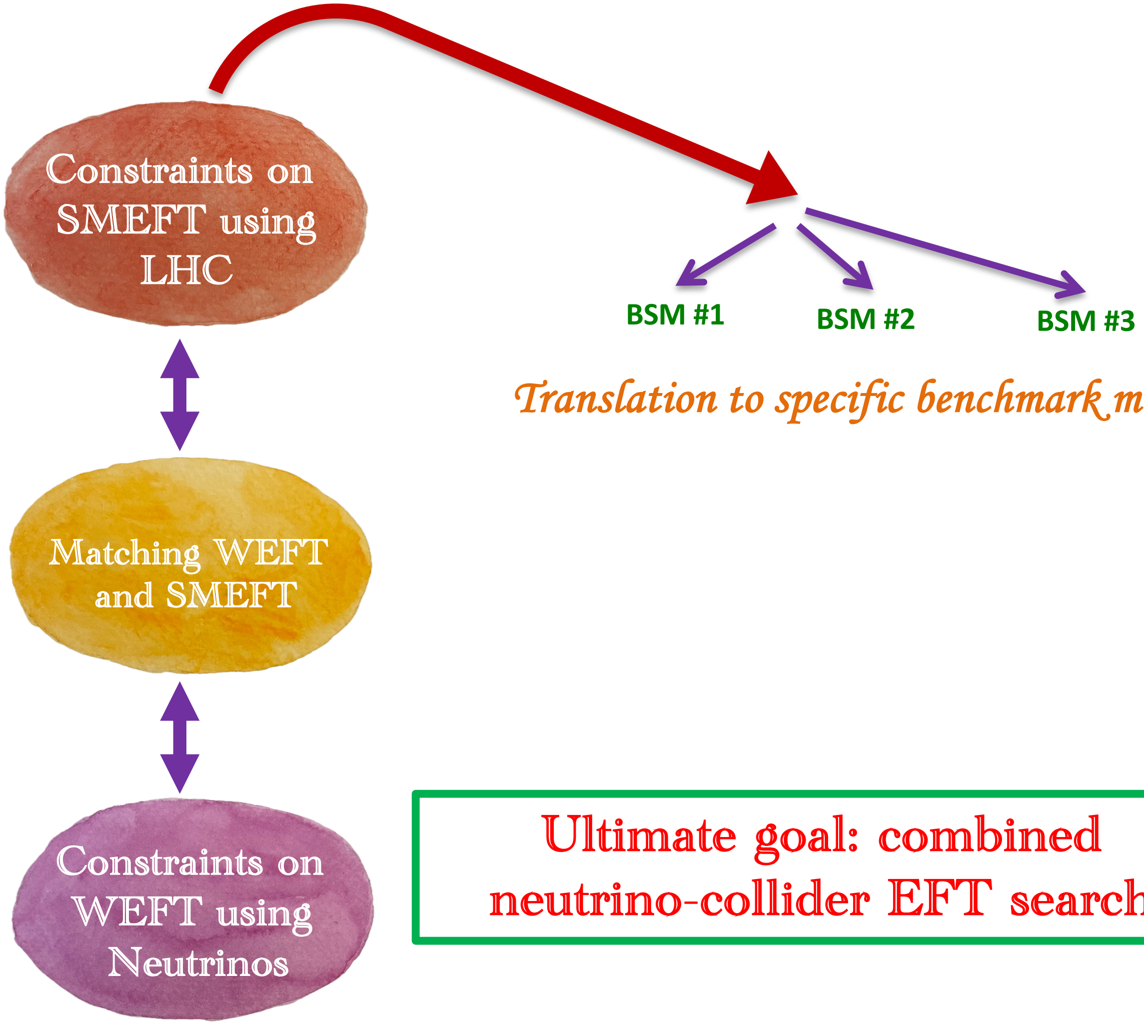


Constraints on SMEFT using LHC

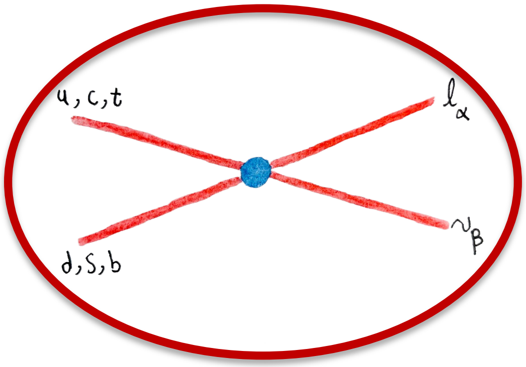
Matching WEFT and SMEFT

Constraints on WEFT using Neutrinos

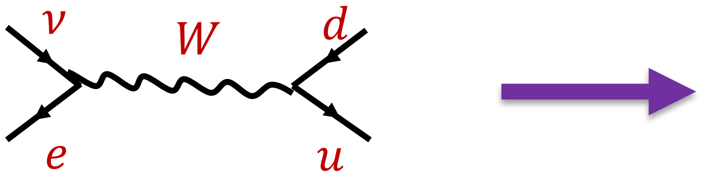
Translation to specific benchmark models

Ultimate goal: combined neutrino-collider EFT search

Translation to specific New Physics Models

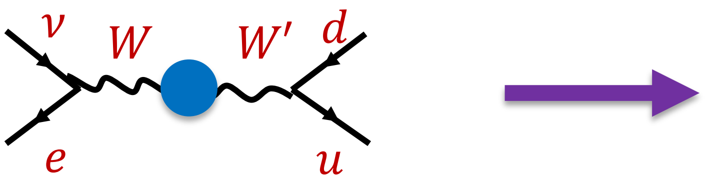


ε_L: measures deviations of the W boson to quarks and leptons, compared to the SM prediction



$$-\frac{g^W_{\nu e}\, g^W_{ud}}{4m_W^2} V_{ud}\,\bar{e}\gamma_\mu(1-\gamma_5)\nu_e \cdot \bar{u}\gamma^\mu(1-\gamma_5)d$$

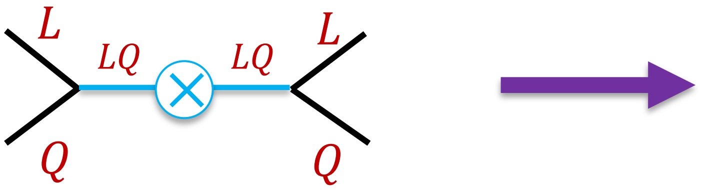
ε_R : left-right symmetric $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_X$ models introduce new charged vector bosons W' coupling to right-handed quarks



$$\bar{e}\gamma_\mu(1-\gamma_5)\nu_e \cdot \bar{u}\gamma^\mu(1+\gamma_5)d$$

$$\epsilon_R \sim \frac{m_W^2}{m_{W'}^2}$$

$\varepsilon_{S,P,T}$: In leptoquark models, new scalar particles couple to both quarks and leptons



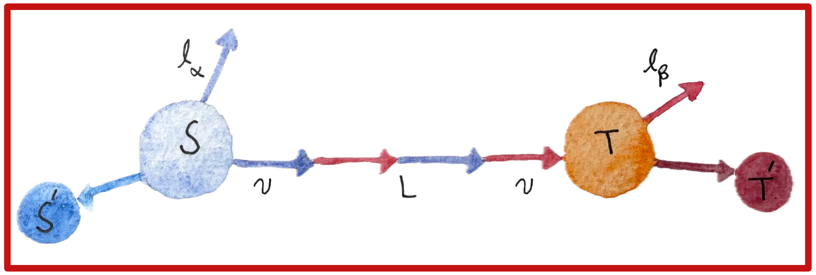
$$(LQ)(LQ)$$

$$\epsilon_{S,P,T} \sim \frac{\mathrm{v}^2}{m_{LQ}^2}$$

EFT at neutrino experiments

We developed the systematic QFT approach to neutrino oscillations in the SMEFT framework!

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



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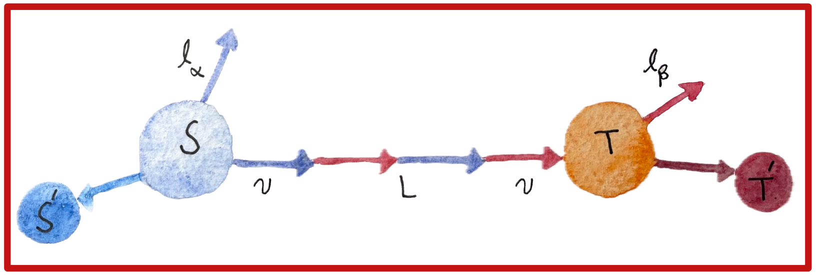

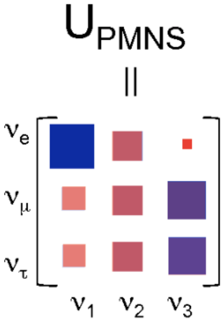

Observable: rate of detected events

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

$$R^{SM}_{\alpha\beta} = \Phi^{SM}_{\alpha}\sigma^{SM}_{\beta}\sum_{k,l} e^{-i\frac{L\Delta m^2_{kl}}{2E_\nu}} U^*_{\alpha k}U_{\alpha l}U_{\beta k}U^*_{\beta l}$$

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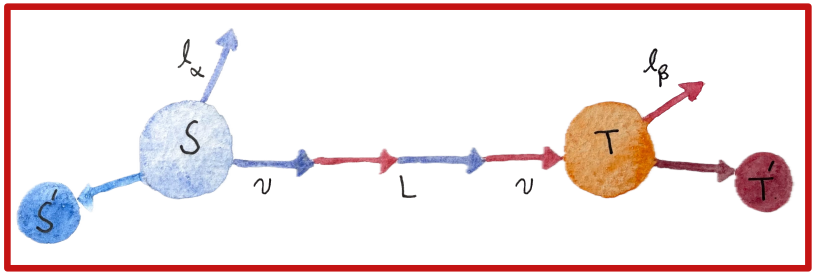
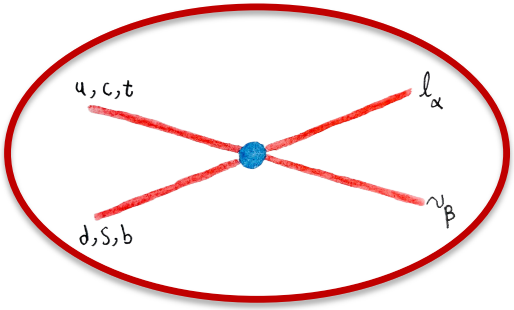


Observable: rate of detected events

$$\text{Rate} \sim \underbrace{(\text{flux})\times(\text{det. cross section})}\times(\text{oscillation})$$

We start from the CC WEFT Lagrangian



Production/Detection amplitudes

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 to fluxes/cross sections

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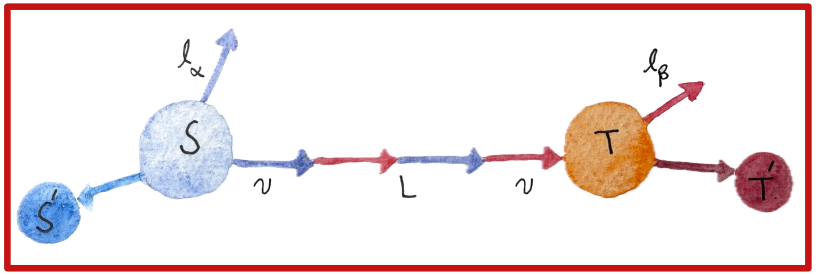
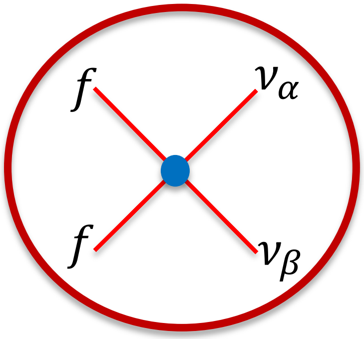


Observable: rate of detected events

$$\text{Rate} \sim (\text{flux})\times(\text{det. cross section})\times\underbrace{(\text{oscillation})}$$

NC WEFT Lagrangian

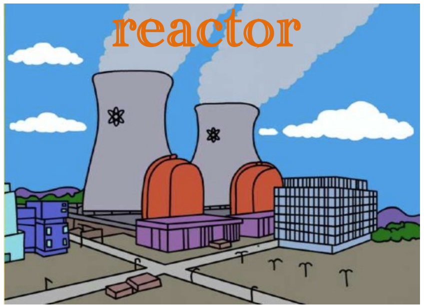


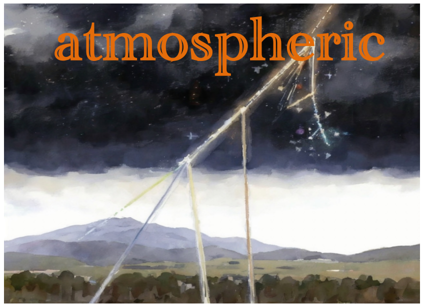
Modifies Matter Potential

$$\mathcal{H}_{\rm F} = \frac{1}{2E}\left(U\,\mathbb{M}^2\,U^\dagger + \mathbb{A}\right) \pm\sqrt{2}G_F N_e \begin{pmatrix} \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{\mu e} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{\tau e} & \varepsilon_{\tau\mu} & \varepsilon_{\tau\tau} \end{pmatrix}$$

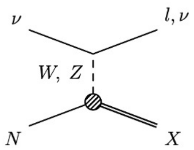
Corrections to Oscillation Probability

Different mechanism for neutrino production, detection and propagation

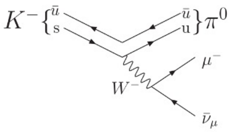


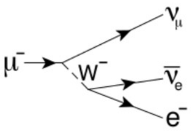


DIS: FASERν



Kaon/Muon decay: ISODAR, KDAR





Solar neutrinos: Borexino

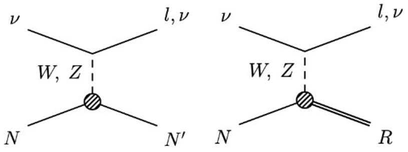
^{7}Be $\boxed{^7\text{Be}+e^-\to{}^7\text{Li}+\nu_e}$

$\boxed{^3\text{He}+p\to{}^4\text{He}+e^++\nu_e}$ **hep**

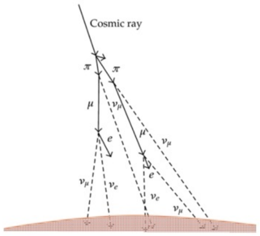
(hep)

$\boxed{p+e^-+p\to{}^2\text{H}+\nu_e}$ ***pep***

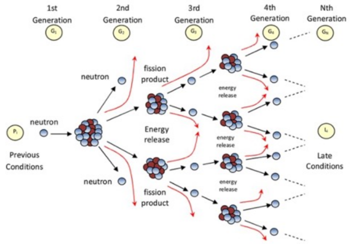
QE, Resonances: MINOS, NOvA, DUNE



Atmospheric Neutrinos: IceCube



Beta decay and IBD: Reactor Experiments



First step in building our toolbox:

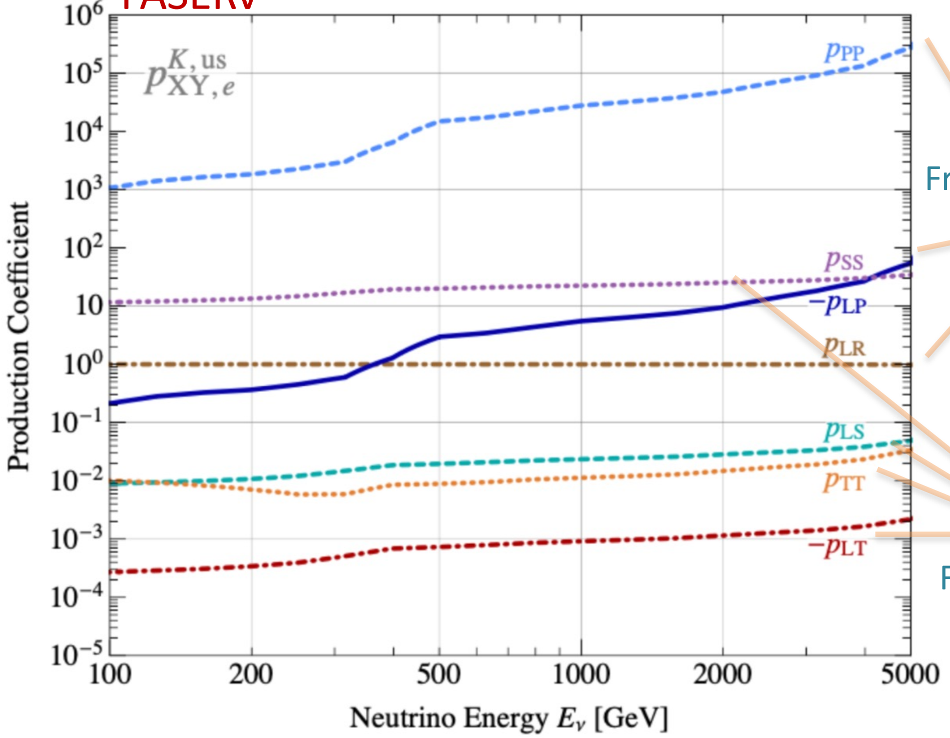
Calculating fluxes, cross sections and oscillation probabilities for each experiment in the presence of EFT effects!

Corrections on Neutrino Fluxes from Kaon decay

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

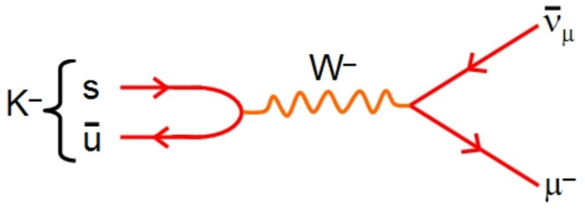
Both 2-body and 3-body kaon decays contribute:

FASERν



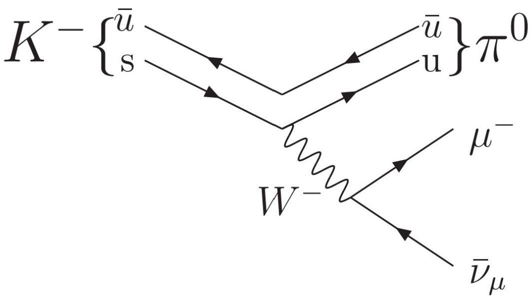
Huge flux correction for kaon decay! Depends on neutrino energy!

From 2-b decay



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

From 3-b decay



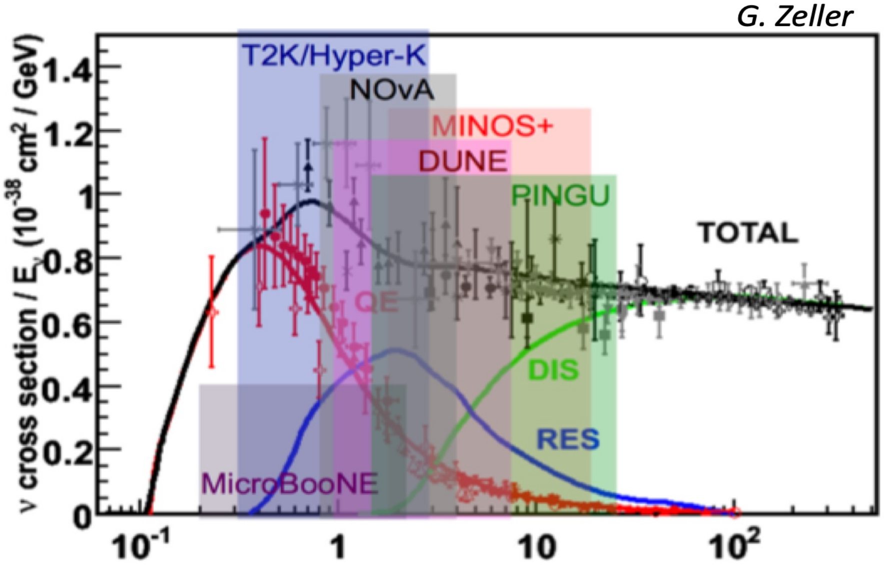
$$\langle \pi^- | \bar{s}\gamma^\mu u | K^0 \rangle = P^\mu f_+(q^2) + q^\mu f_-(q^2)\,,$$

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

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

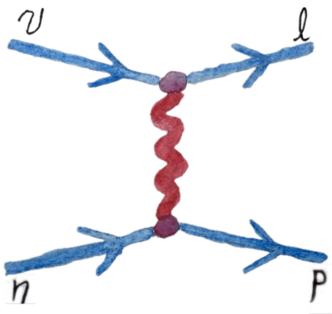
Cross Sections at Accelerator Experiments

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

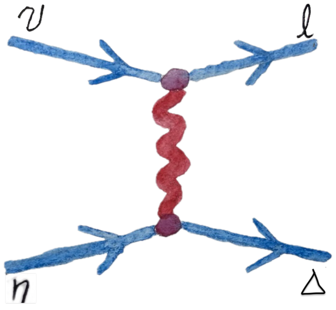


G. Zeller

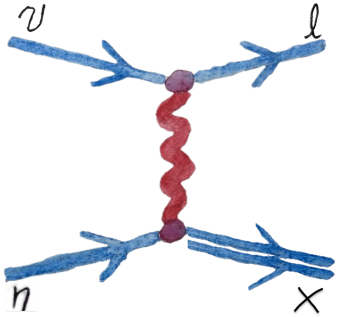
Quasi-Elastic Scattering



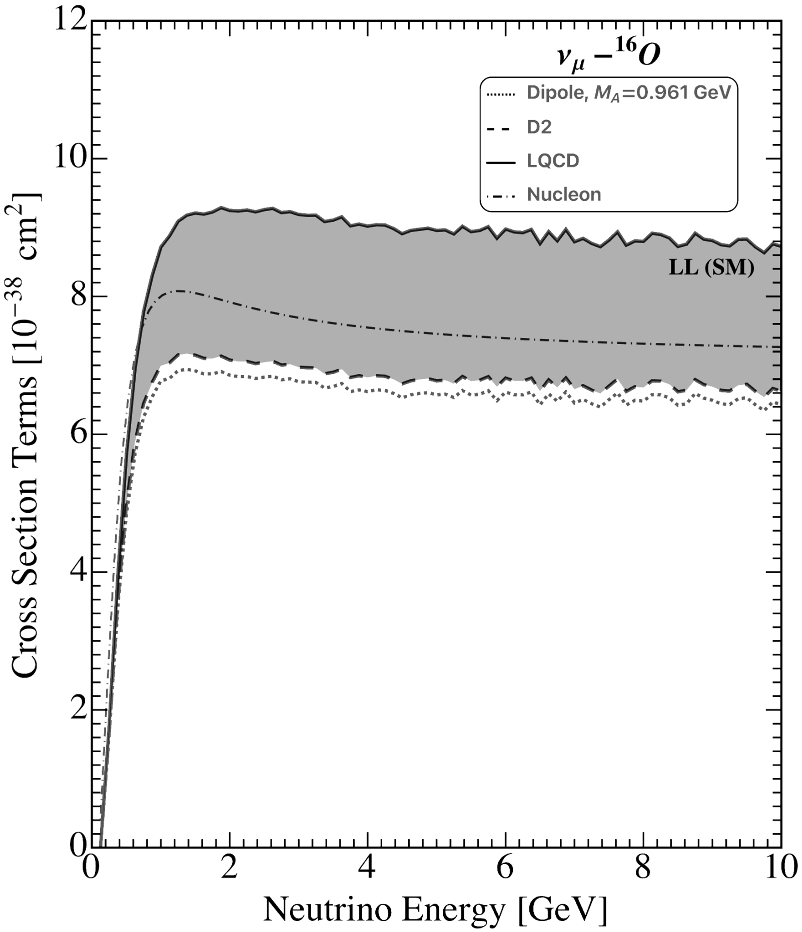
Resonance Production



Deep Inelastic Scattering



CCQE Neutrino-Nucleus Cross Sections in the SM

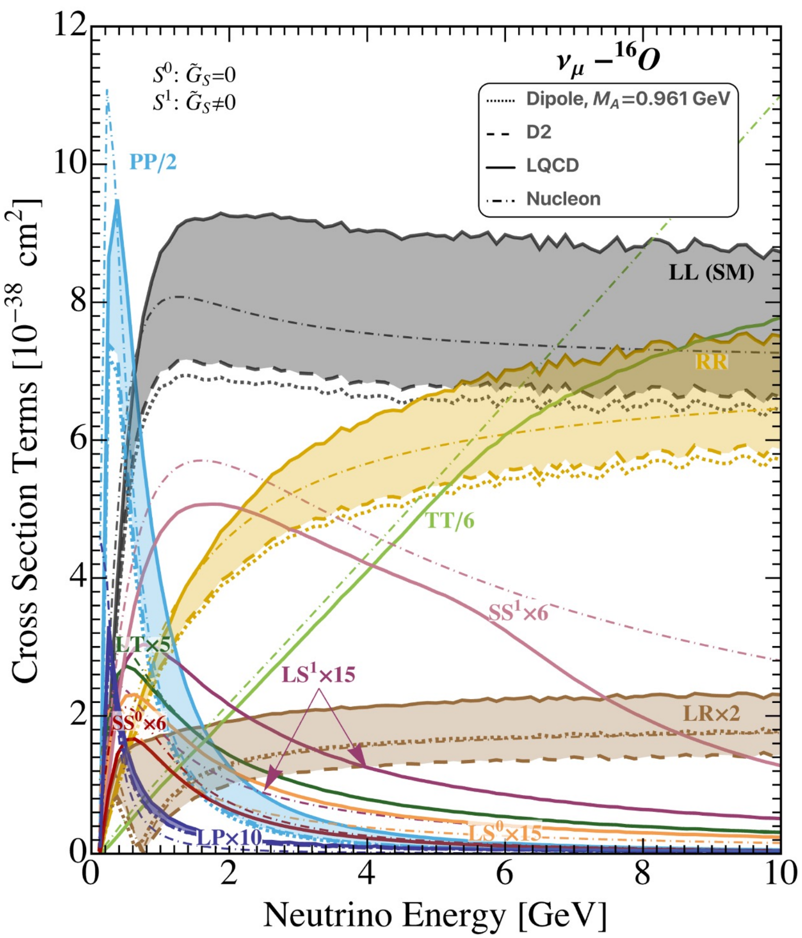


Kopp, Rocco, ZT,
JHEP (2024)

- z-expansion fit to LQCD and D2 data;
- Nuclear effects;
- Comparison with nucleon scattering

Large uncertainties from form factors even in the SM!

CCQE Neutrino-Nucleus Cross Sections with EFT



Kopp, Rocco, ZT,
JHEP (2024)

- ○ z-expansion fit to LQCD and D2 data;
- ○ Nuclear effects;
- ○ Comparison with nucleon scattering

Distinct Energy Distributions

Some rough estimations

- Observed rate at the experiment: $\boxed{R_{Obs} = 10^4\ \nu_\mu}$

$10^8\ \nu_\mu$ at
DUNE Near Detector!

- Uncertainty: $\boxed{\sqrt{R_{obs}} = 10^2\ \nu_\alpha \equiv \Delta R}$

- From theory: $\boxed{R_{Th} = R_{SM}(1 + C\,\epsilon^2) = R_{SM} + \Delta R}$

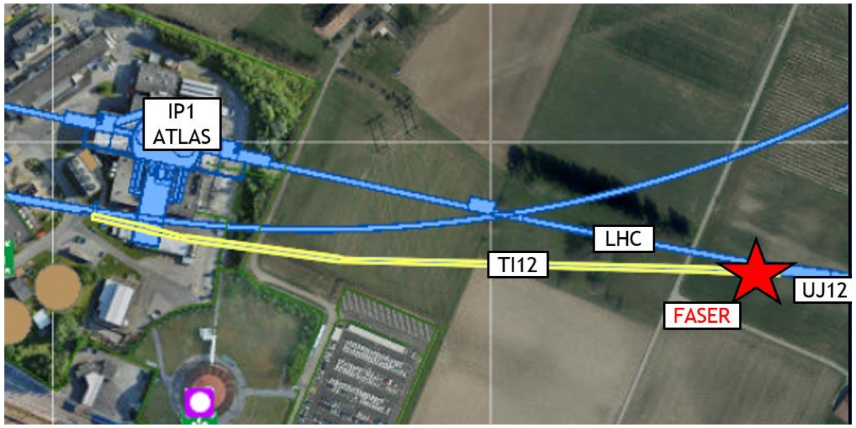
- Limit on ϵ: $\boxed{C\,\epsilon^2 = \frac{\Delta R}{R_{SM}}}$ $\left\{ \boxed{\begin{array}{c} C = 10^3 \\ \epsilon < \frac{10^2}{10^3 \times 10^4} \sim 3\times10^{-3} \end{array}} \right.$

- New Physics Limit: $\boxed{\Lambda \equiv \frac{\text{v}\ [246\ GeV]}{\sqrt{\epsilon}} = 4.5\ \text{TeV}}$

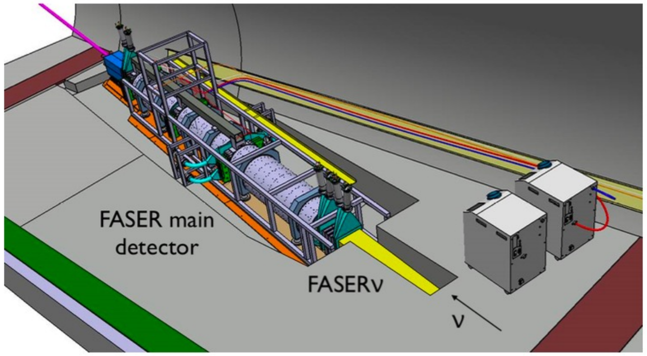
$$C \propto \frac{\sigma_{NP}}{\sigma_{SM}} \text{ or } \frac{\phi_{NP}}{\phi_{SM}}$$

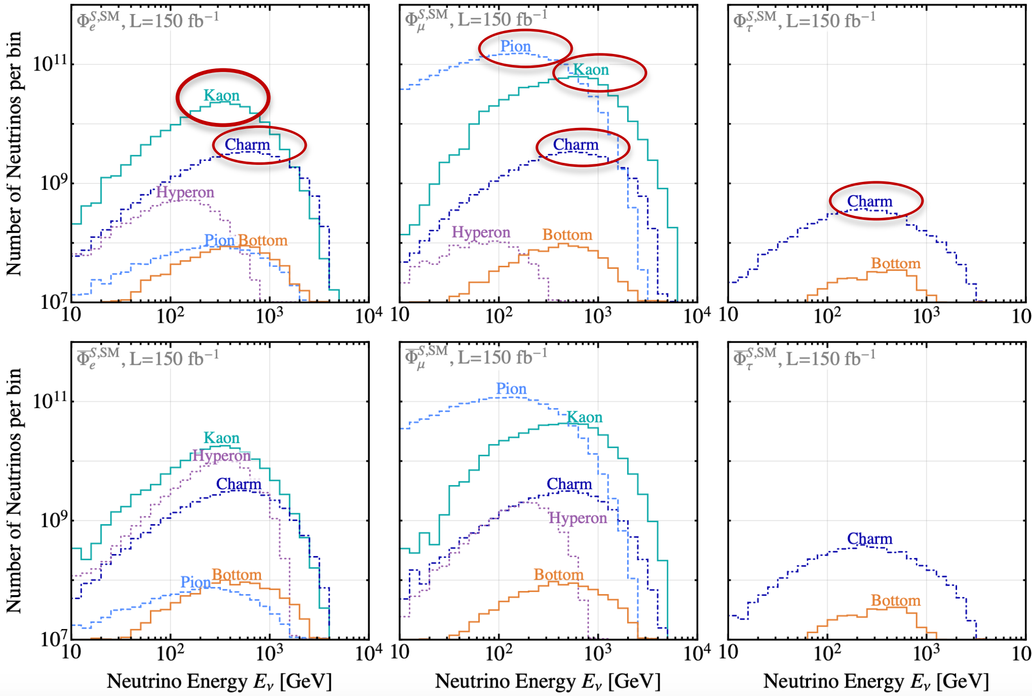
FASERν at LHC

- 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:

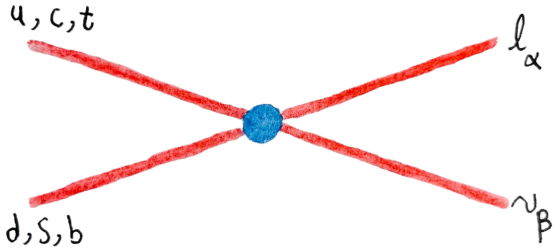
ν_e~1000, ν_μ~5000, ν_τ~10

EFT at FASERν

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

- FASERν: colored bars

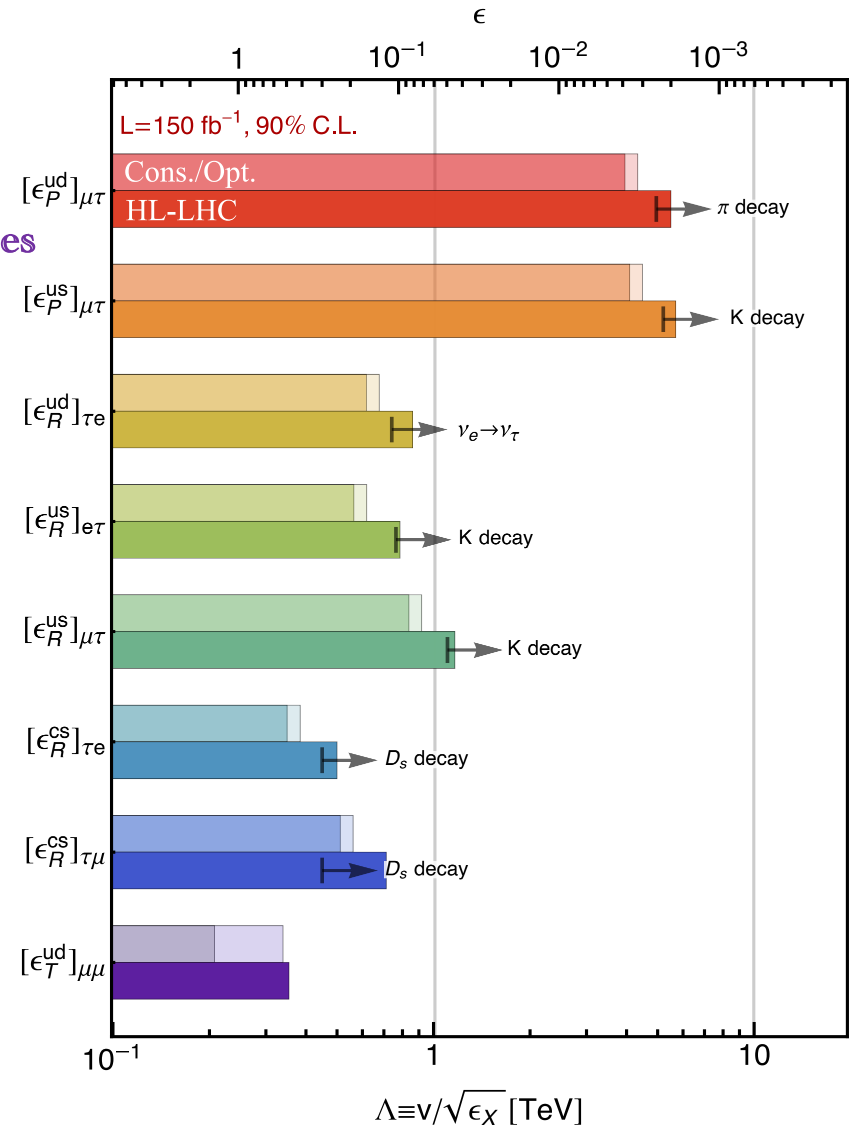
- Top: Conservative/Optimistic flux uncertainties
- Bottom: High luminosity LHC



- Neutrino detectors can identify flavor: 81 operators at FASERν

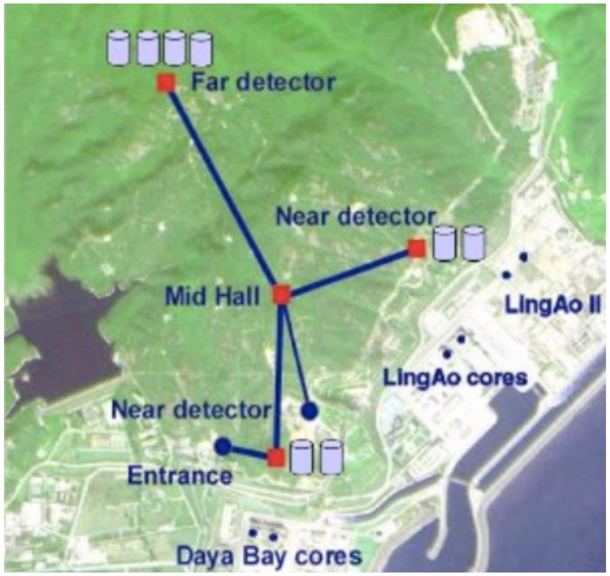
- New physics reach at multi-TeV

- Complementary or dominant constraints



Reactor Experiments

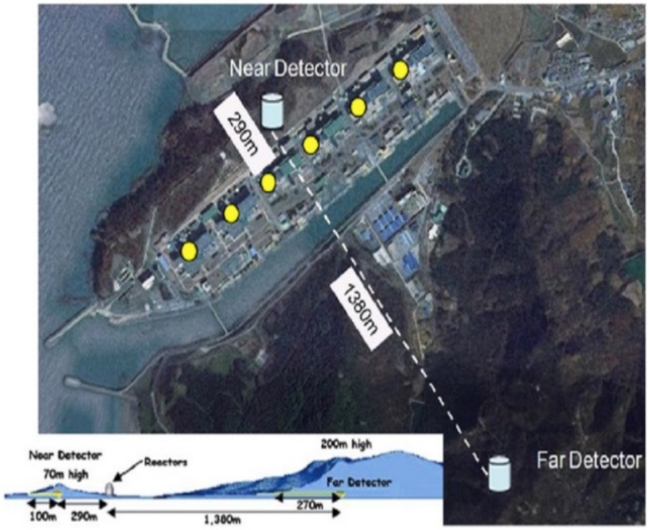
Goal: measured θ_{13} mixing angle



Daya Bay:

- 6 reactor cores;
- 8 anti-neutrino detectors;
- 3 near and far experimental halls located at 400 m, 512 m and 1610 m;
- Has observed ~ 4 million anti-neutrino events in 1958 days of data taking;

Daya Bay Collaboration, D. Adey et al.,
arXiv:1809.02261



RENO:

- 6 reactor cores;
- 2 near and far anti-neutrino detectors located at 367 m and 1440 m;
- Has observed ~ 1 million anti-neutrino events in 2200 days of data taking

RENO Collaboration, G. Bak et al.,
arXiv:1806.00248

EFT in Reactor Experiments

▬ WEFT

▬ SM

$$
\begin{aligned}
P_{\bar{\nu}_e\to\bar{\nu}_e}(L,E_\nu) \;=\;& 1-\sin^2\underline{\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right)}\sin^2\left(\underline{2\tilde{\theta}_{13}}-\underline{\alpha_D\frac{m_e}{E_\nu-\Delta}-\alpha_P\frac{m_e}{f_T(E_\nu)}}\right)\\
&+\underline{\sin\left(\frac{\Delta m_{31}^2 L}{2E_\nu}\right)\sin(2\tilde{\theta}_{13})}\left(\underline{\beta_D\frac{m_e}{E_\nu-\Delta}-\beta_P\frac{m_e}{f_T(E_\nu)}}\right)+\mathcal{O}(\epsilon_X^2)
\end{aligned}
$$

A. Falkowski, M. González-Alonso, ZT
JHEP 05 (2019) 173

- Correlation between oscillation and WEFT parameters

$$
\alpha_D=\tfrac{g_S}{3g_A^2+1}\mathrm{Re}\,[S]-\tfrac{3g_Ag_T}{3g_A^2+1}\mathrm{Re}\,[T]\,, \qquad \alpha_P=\frac{g_T}{g_A}\mathrm{Re}\,[T]
$$

$$
\beta_D=\tfrac{g_S}{3g_A^2+1}\mathrm{Im}\,[S]-\tfrac{3g_Ag_T}{3g_A^2+1}\mathrm{Im}\,[T]\,, \qquad \beta_P=\frac{g_T}{g_A}\mathrm{Im}\,[T]
$$

$$
\begin{aligned}
[S] &\equiv e^{i\delta_{\mathrm{CP}}}\left(s_{23}[\epsilon_S]_{e\mu}+c_{23}[\epsilon_S]_{e\tau}\right)\\
[T] &\equiv e^{i\delta_{\mathrm{CP}}}\left(s_{23}[\hat{\epsilon}_T]_{e\mu}+c_{23}[\hat{\epsilon}_T]_{e\tau}\right)
\end{aligned}
$$

EFT in Reactor Experiments

$$P_{\bar\nu_e\to\bar\nu_e}(L,E_\nu) = 1 - \underline{\sin^2\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right)}\sin^2\left(\underline{2\tilde\theta_{13}}\underline{-\alpha_D\frac{m_e}{E_\nu-\Delta}-\alpha_P\frac{m_e}{f_T(E_\nu)}}\right)$$
$$+\ \underline{\sin\left(\frac{\Delta m^2_{31}L}{2E_\nu}\right)\sin(2\tilde\theta_{13})}\underline{\left(\beta_D\frac{m_e}{E_\nu-\Delta}-\beta_P\frac{m_e}{f_T(E_\nu)}\right)}+\mathcal{O}(\epsilon_X^2)$$

🟪 WEFT

🟩 SM

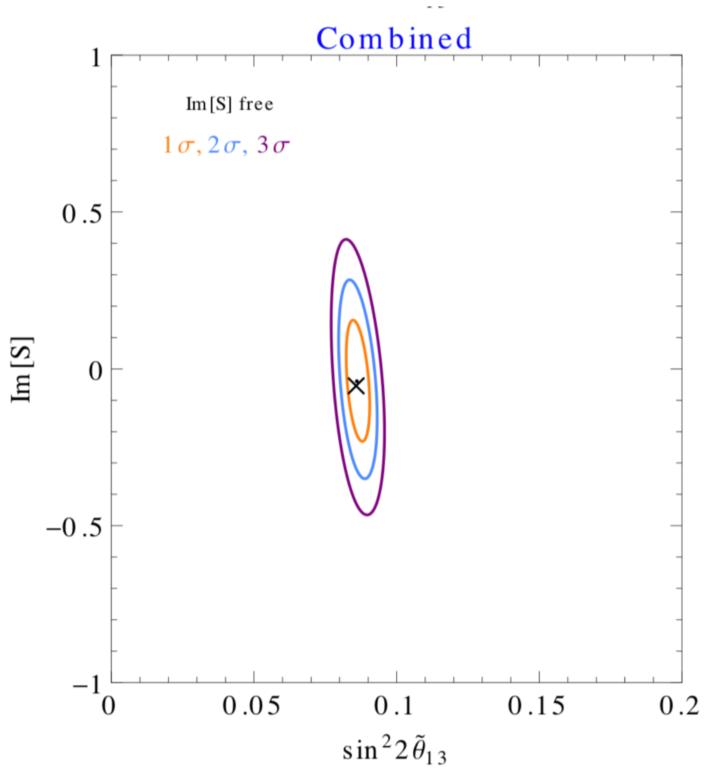
A. Falkowski, M. González-Alonso, ZT
JHEP 05 (2019) 173

- Correlation between oscillation and WEFT parameters

Scalar: $\epsilon_S \neq 0,\ \epsilon_{R,P,T} = 0$

$$\mathrm{Im}\,[S] = 0.08 \pm 0.14$$

- Large degeneracy;
- Different measurements must be combined in a global analysis;



EFT in Reactor Experiments

▬ WEFT

▬ SM

$$\begin{aligned} P_{\bar{\nu}_e\to\bar{\nu}_e}(L,E_\nu) &= 1-\sin^2\underline{\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right)}\sin^2\left(\underline{2\tilde{\theta}_{13}}\,\underline{-\alpha_D\frac{m_e}{E_\nu-\Delta}-\alpha_P\frac{m_e}{f_T(E_\nu)}}\right)\\ &+\underline{\sin\left(\frac{\Delta m^2_{31}L}{2E_\nu}\right)\sin(2\tilde{\theta}_{13})}\,\underline{\left(\beta_D\frac{m_e}{E_\nu-\Delta}-\beta_P\frac{m_e}{f_T(E_\nu)}\right)}+\mathcal{O}(\epsilon_X^2) \end{aligned}$$

A. Falkowski, M. González-Alonso, ZT
JHEP 05 (2019) 173

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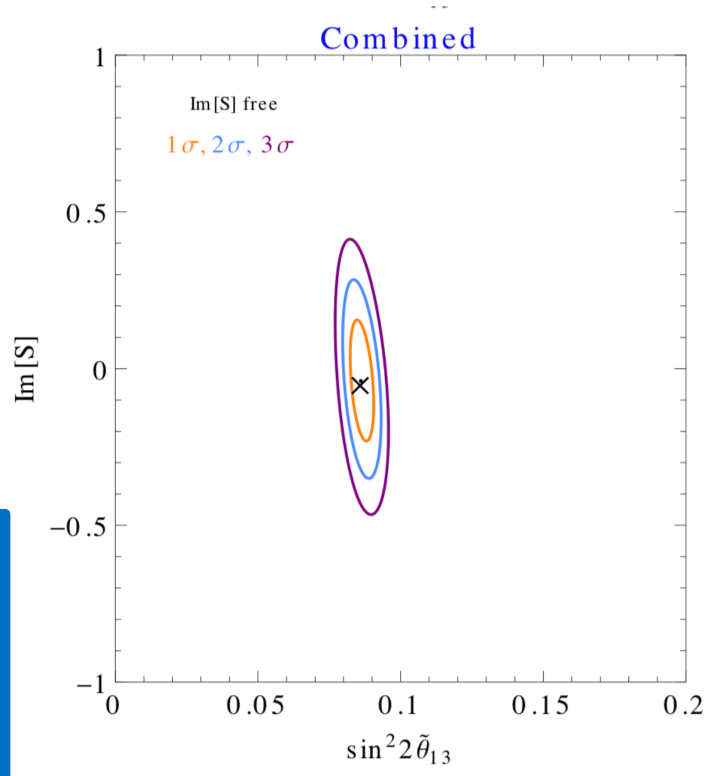


- Large degeneracy;
- Different measurements must be combined in a global analysis;

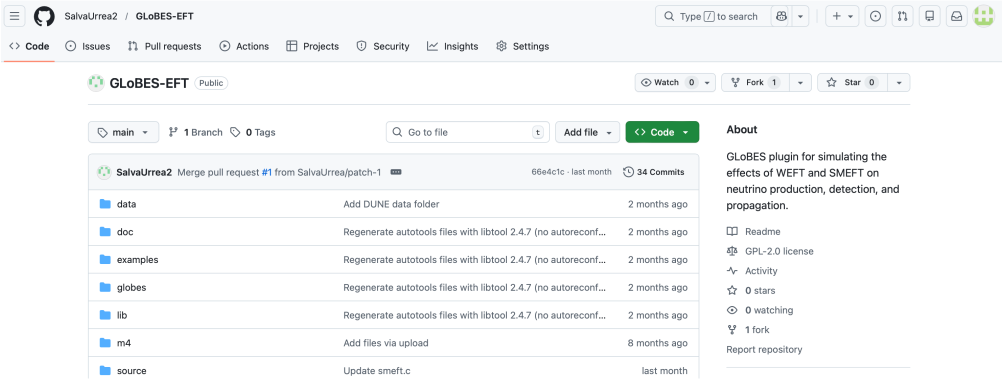
<u>Second step in building our toolbox:</u>

Developing packages to simulate neutrino oscillation experiments in the presence of EFT

GLoBES-EFT Software Package:

- To extract oscillation parameters in the presence of general EFT;
- To perform a SMEFT global fit in neutrino oscillation experiments;
- Publicly available on GitHub;

Kopp, *ZT*, Urrea
JHEP (2026)



SalvaUrrea2 Merge pull request #1 from SalvaUrrea/patch-1 66e4c1c · last month 34 Commits

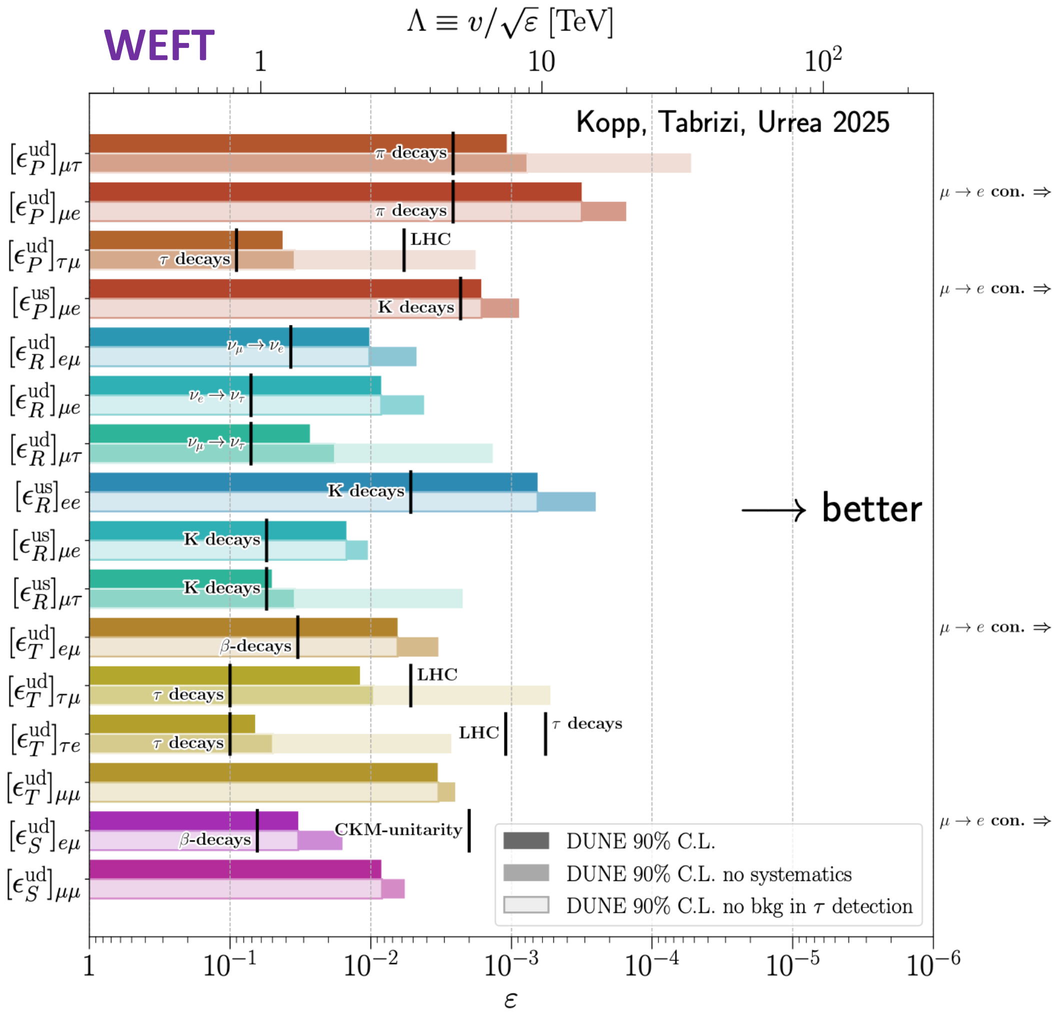
data	Add DUNE data folder	2 months ago
doc	Regenerate autotools files with libtool 2.4.7 (no autoreconf...	2 months ago
examples	Regenerate autotools files with libtool 2.4.7 (no autoreconf...	2 months ago
globes	Regenerate autotools files with libtool 2.4.7 (no autoreconf...	2 months ago
lib	Regenerate autotools files with libtool 2.4.7 (no autoreconf...	2 months ago
m4	Add files via upload	8 months ago
source	Update smeft.c	last month

GLoBES plugin for simulating the effects of WEFT and SMEFT on neutrino production, detection, and propagation.

- **Neutrino *Production*, *oscillation*, and *detection* in presence of EFT;**
- **Accounting for RGE running;**
- **Consistent WEFT/SMEFT matching;**

GLoBES-EFT: simulating neutrino oscillation experiments in the presence of EFT

EFT at DUNE using GLoBES-EFT

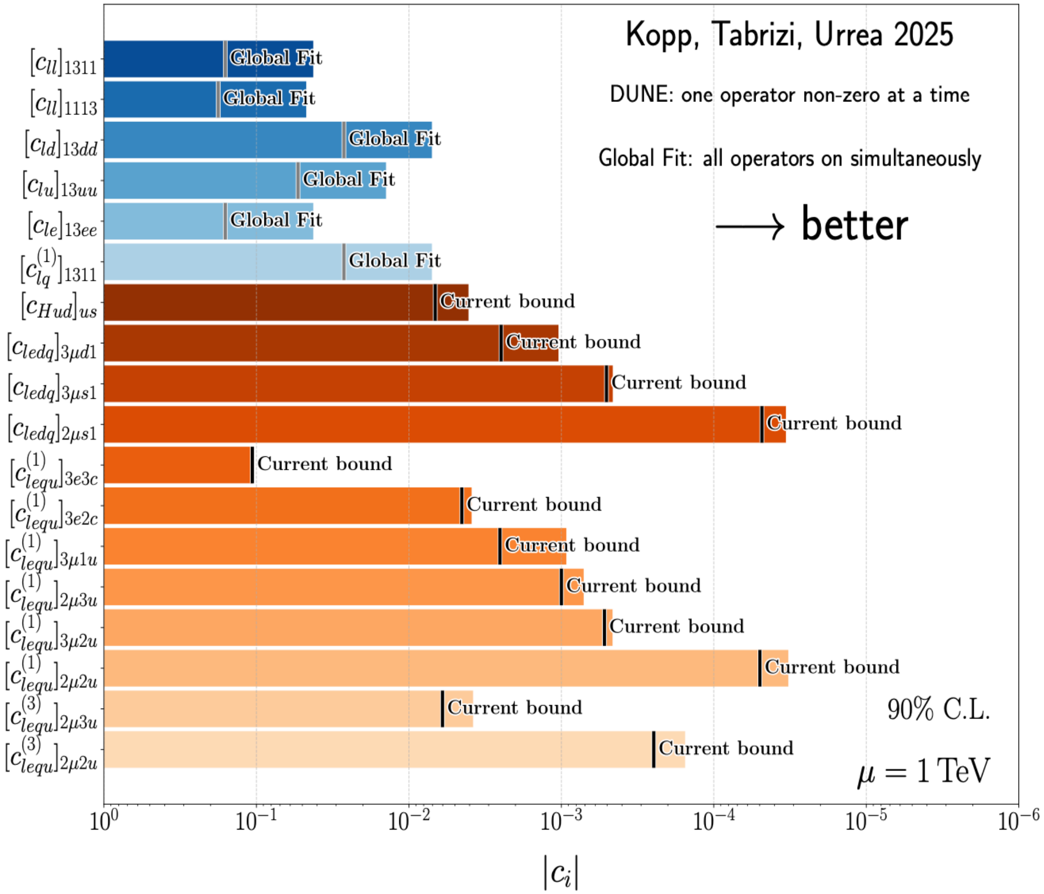


Kopp, ***ZT***, Urrea
JHEP (2026)

Extracting ~10's of TeV Physics from GeV Neutrino Experiments!

EFT at DUNE using GLoBES-EFT

SMEFT

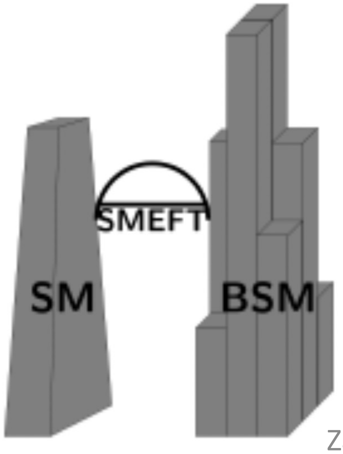


Kopp, *ZT*, Urrea
JHEP (2026)

With GloBES-EFT we can finally do a proper SMEFT global fit in ν experiments!

Indirect Searches: Future Directions

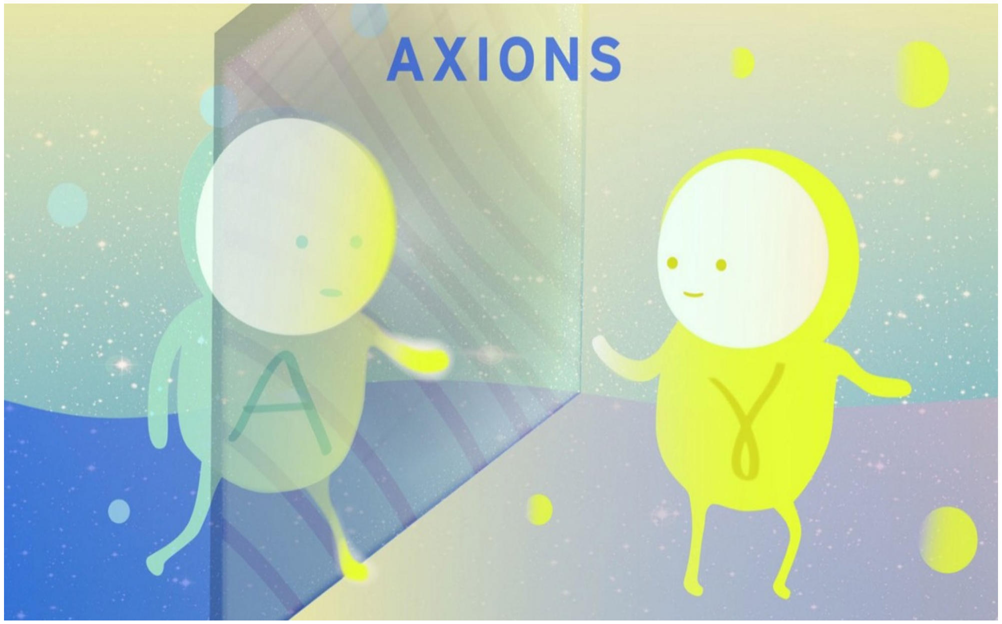
- SMEFT global fit in neutrino oscillation experiments using GLoBES-EFT;
- Extraction of oscillation parameters in presence of general new physics;
- Combining neutrino and collider data;
- Translation to specific new physics models;



- **"Non-Standard Neutrino Interactions at a Muon Collider Neutrino Detector",**
  Kopp, Kling, Ma, Mękała, Reuter, **ZT**
  JHEP (2026) [To Appear]
- **"Effective Field Theory in Long-Baseline Neutrino Oscillation Experiments ",**
  Kopp, **ZT**, Urrea
  JHEP (2026)
- **"Unleashing the power of EFT at Neutrino-Nucleus Scattering",**
  Kopp, Rocco, **ZT**
  JHEP (2024)
- **"Consistent QFT description of non-standard neutrino interactions",**
  Falkowski, Gonzalez-Alonso, Soreq and **ZT**
  JHEP (2020)
- **"EFT at FASERν",**
  Falkowski, Gonzalez-Alonso, Kopp, Soreq and **ZT**
  JHEP (2021)
- **"Reactor neutrino oscillations as constraints on Effective Field Theory",**
  Falkowski, Gonzalez-Alonso, Soreq and **ZT**
  JHEP (2019)
- **"Future DUNE constraints on EFT",**
  Falkowski, Gonzalez-Alonso, Soreq and **ZT**
  JHEP (2018)

Outline

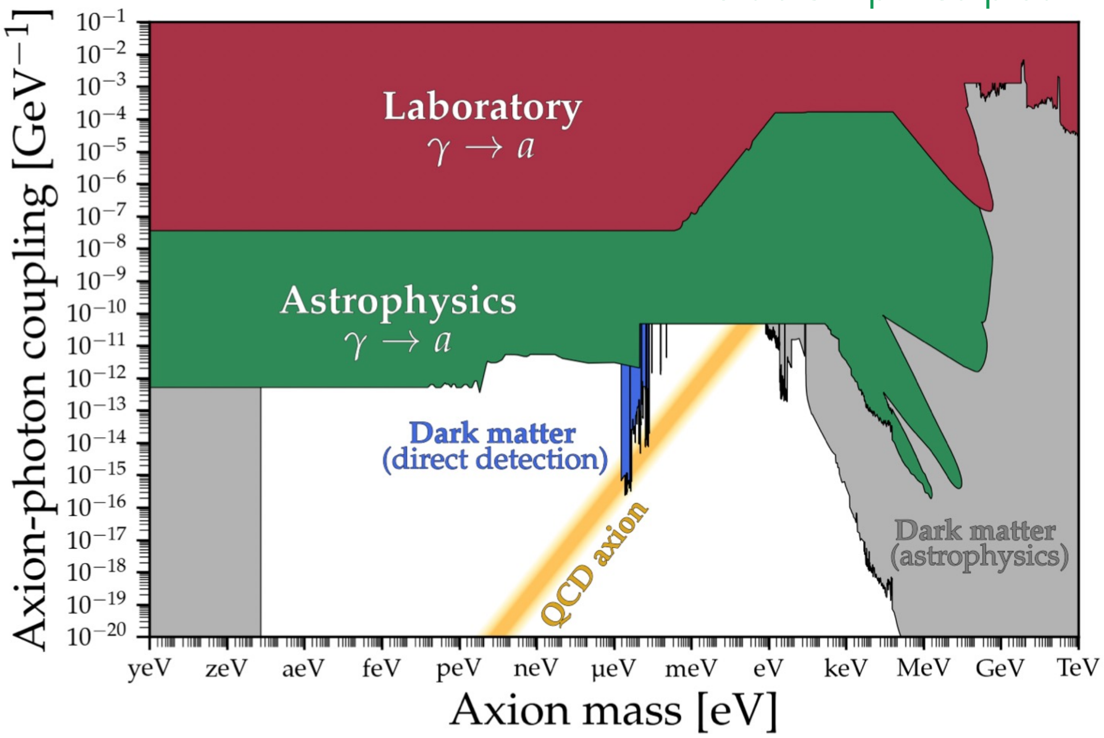
- 1) Indirect Search-EFT:
  - Why EFT?
  - EFT ladder
  - EFT at Neutrino Experiments
- 2) Direct Search:
  - Axion-Like Particles
- Conclusion



Axion-Like Particles (ALPs)

- (Pseudo)scalars, strongly motivated by theory and cosmology;
- It gives a solution to the strong CP problem: Why is CP conserved in QCD?
- They can explain for the 27% of the Universe's energy content constituting dark matter;

Ultra-simplified plot



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

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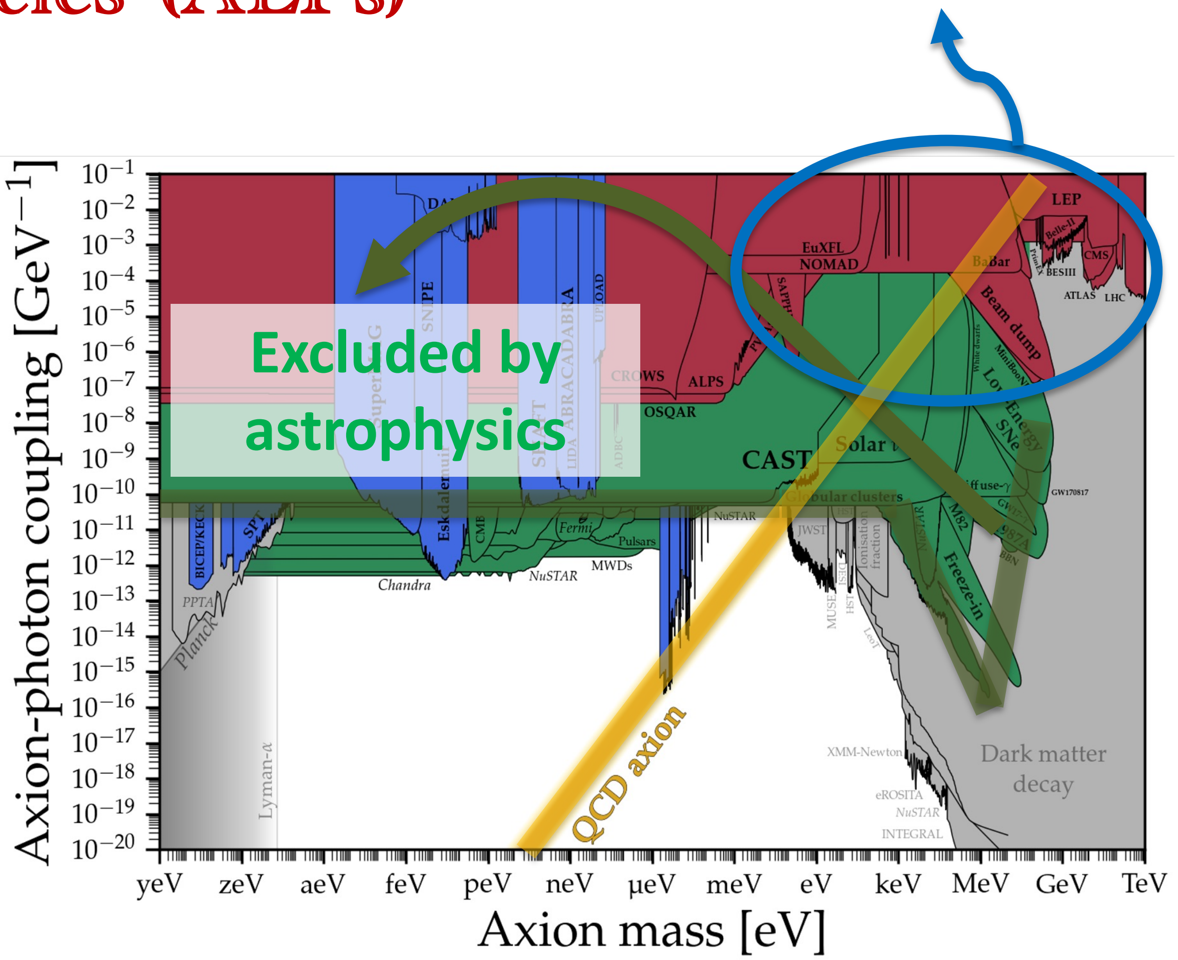
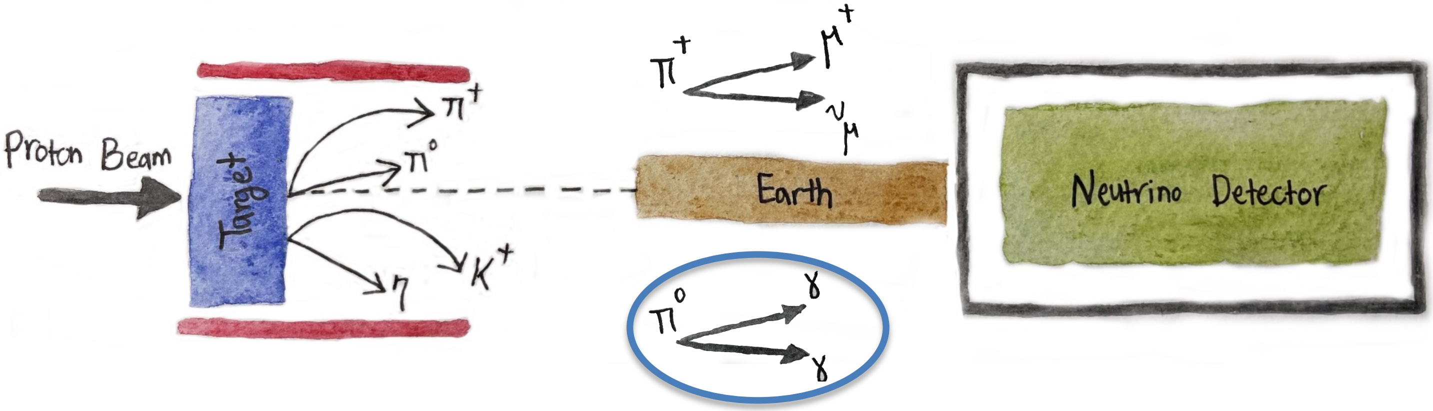


particle physics experiments

Excluded by astrophysics

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

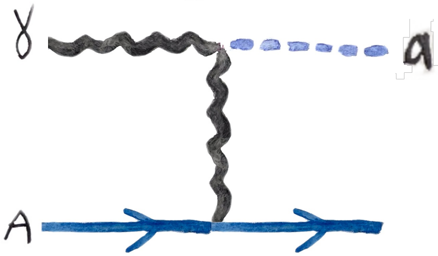
ALP Production/Detection



Using photons to produce ALPs:

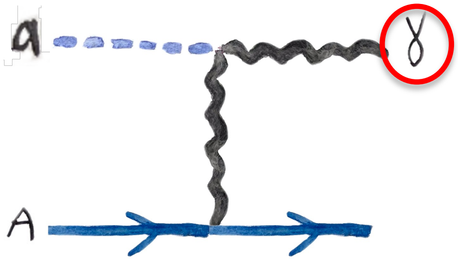
$$\mathcal{L}_{a\gamma\gamma} \supset -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

ALP production

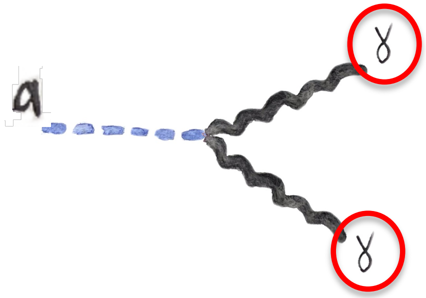


Primakoff scattering

ALP detection

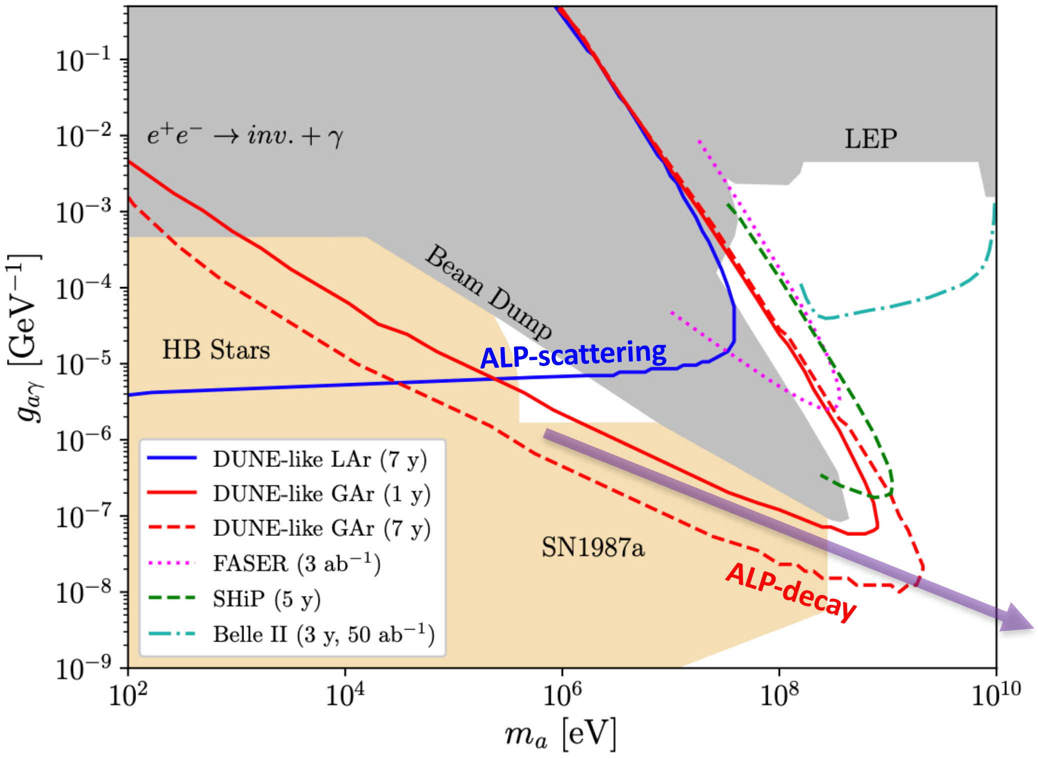


Inverse Primakoff scattering



ALP decay

ALP-γ at DUNE



Blue: ALP-scattering at LAr, 50-t

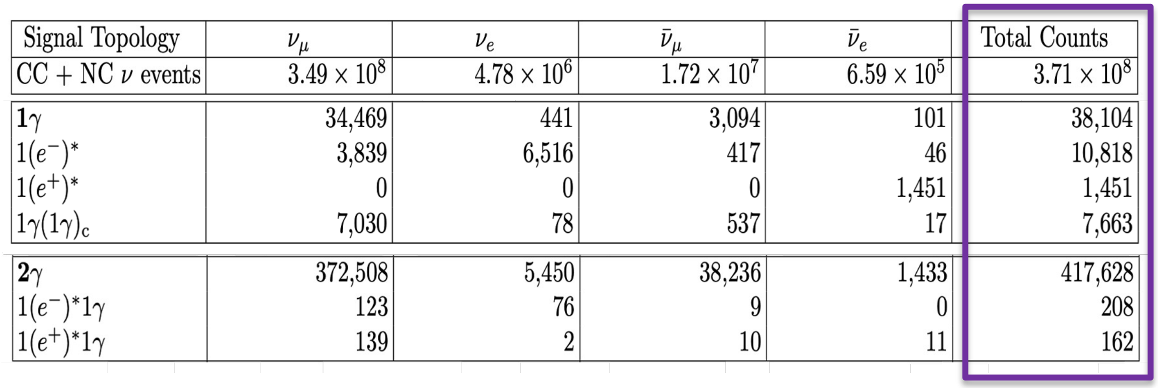
Red: ALP-decay at GAr, 1-t

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

- The only lab-based constraints!
- Gas-detector is the key, due to significantly low background!
- Search strategies applicable to other similar experiments. Example: T2HK

ALP Backgrounds at DUNE

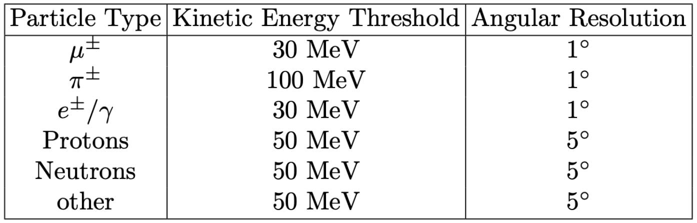
We investigate single photon and di-photon final states:



Signal Topology	ν_μ	ν_e	$\bar{\nu}_\mu$	$\bar{\nu}_e$	Total Counts
CC + NC ν events	3.49×10^8	4.78×10^6	1.72×10^7	6.59×10^5	3.71×10^8
1γ	34,469	441	3,094	101	38,104
$1(e^-)^*$	3,839	6,516	417	46	10,818
$1(e^+)^*$	0	0	0	1,451	1,451
$1\gamma(1\gamma)_c$	7,030	78	537	17	7,663
2γ	372,508	5,450	38,236	1,433	417,628
$1(e^-)^*1\gamma$	123	76	9	0	208
$1(e^+)^*1\gamma$	139	2	10	11	162

Brdar, Dutta, Jang, Kim, Shoemaker, *ZT*, Thompson, Yu PRD (2026)

Initial Cuts:



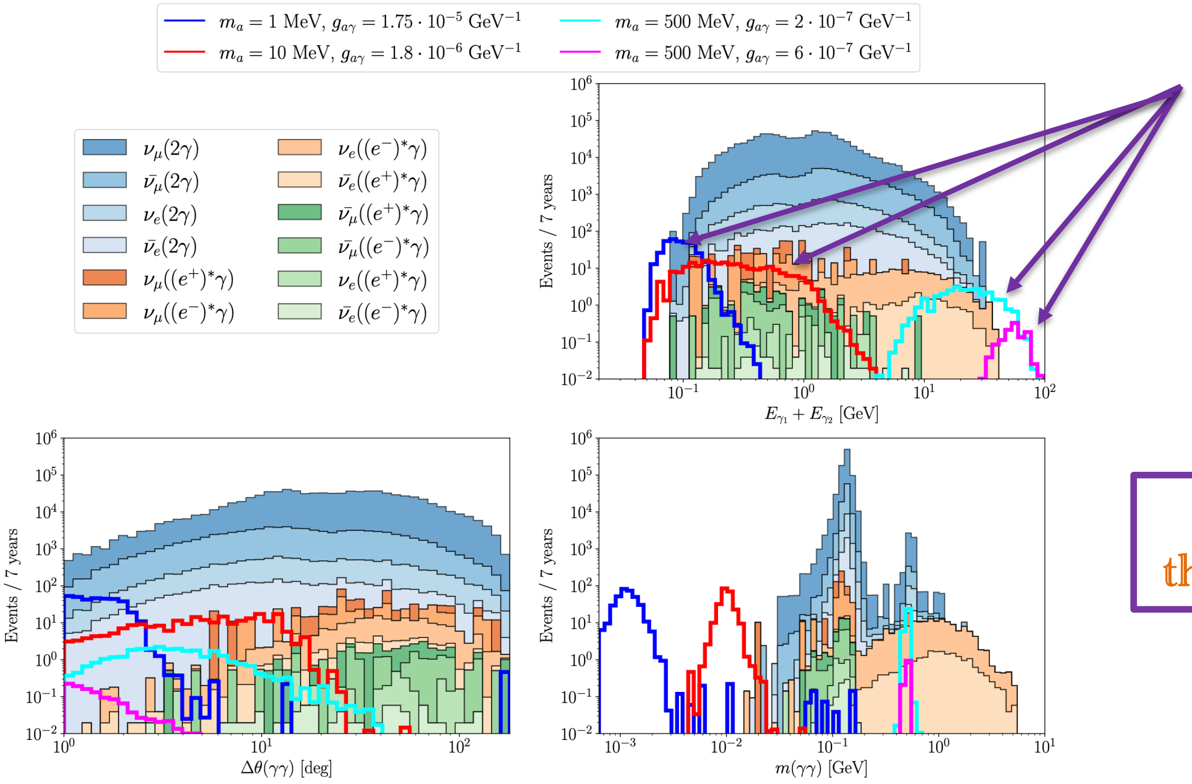
Particle Type	Kinetic Energy Threshold	Angular Resolution
$\mu^\pm$	30 MeV	1°
$\pi^\pm$	100 MeV	1°
$e^\pm/\gamma$	30 MeV	1°
Protons	50 MeV	5°
Neutrons	50 MeV	5°
other	50 MeV	5°

- Many backgrounds;
- Large misID rates;
- What Kinematical cuts would decrease these?

ALP Backgrounds at DUNE

di-photon signal vs background

Brdar, Dutta, Jang, Kim, Shoemaker, *ZT*, Thompson, Yu PRD (2026)



Signal

These cut ensure more than 90% signal efficiency

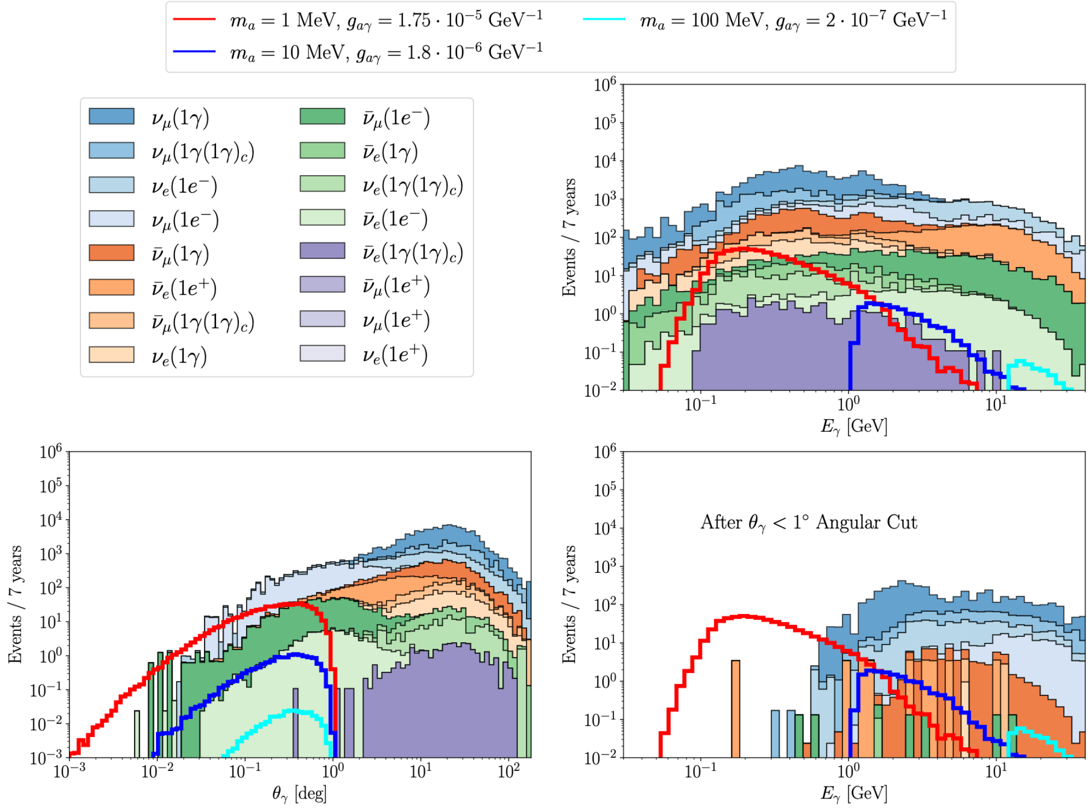
Opening angle cut of $\Delta\theta(\gamma, \gamma) < 20^\circ$

Invariant mass cut of $|m(\gamma, \gamma) - m_a| < 0.05 \times m_a$

ALP Backgrounds at DUNE

Single photon signal vs background

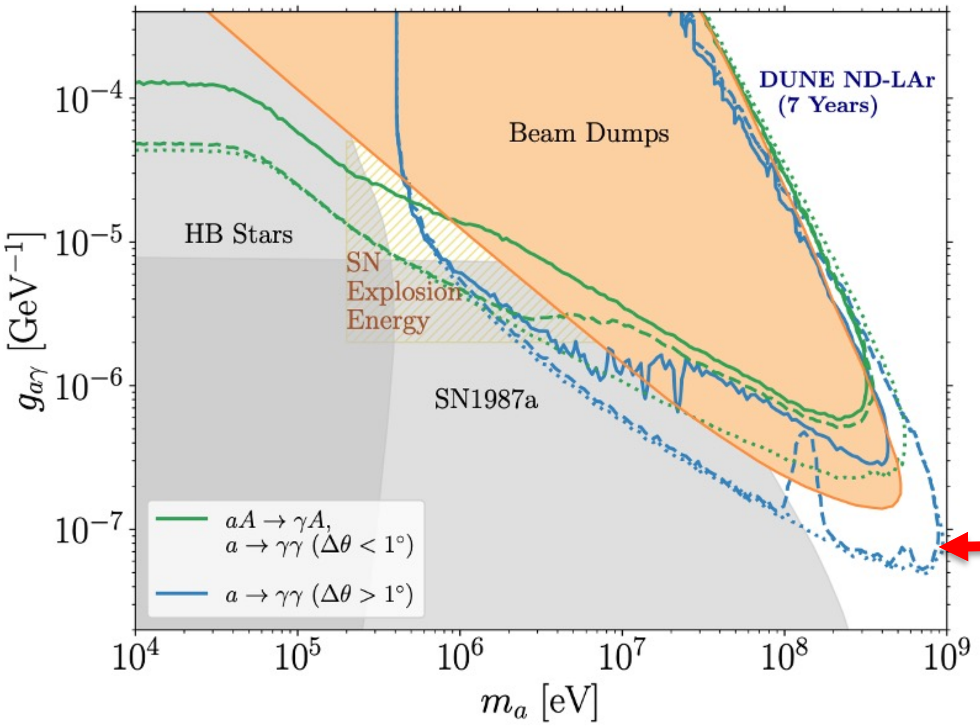
Brdar, Dutta, Jang, Kim, Shoemaker, *ZT*, Thompson, Yu PRD (2026)



A cut on the photon angle keeps > 99% of the signal, while decreasing the background from $\mathcal{O}(10^6)$ to $\mathcal{O}(10^3)$

Cut on photon's angle wrt beam direction: $\theta_\gamma < 1^\circ$

ALP-γ at DUNE post background study



—— No Cuts

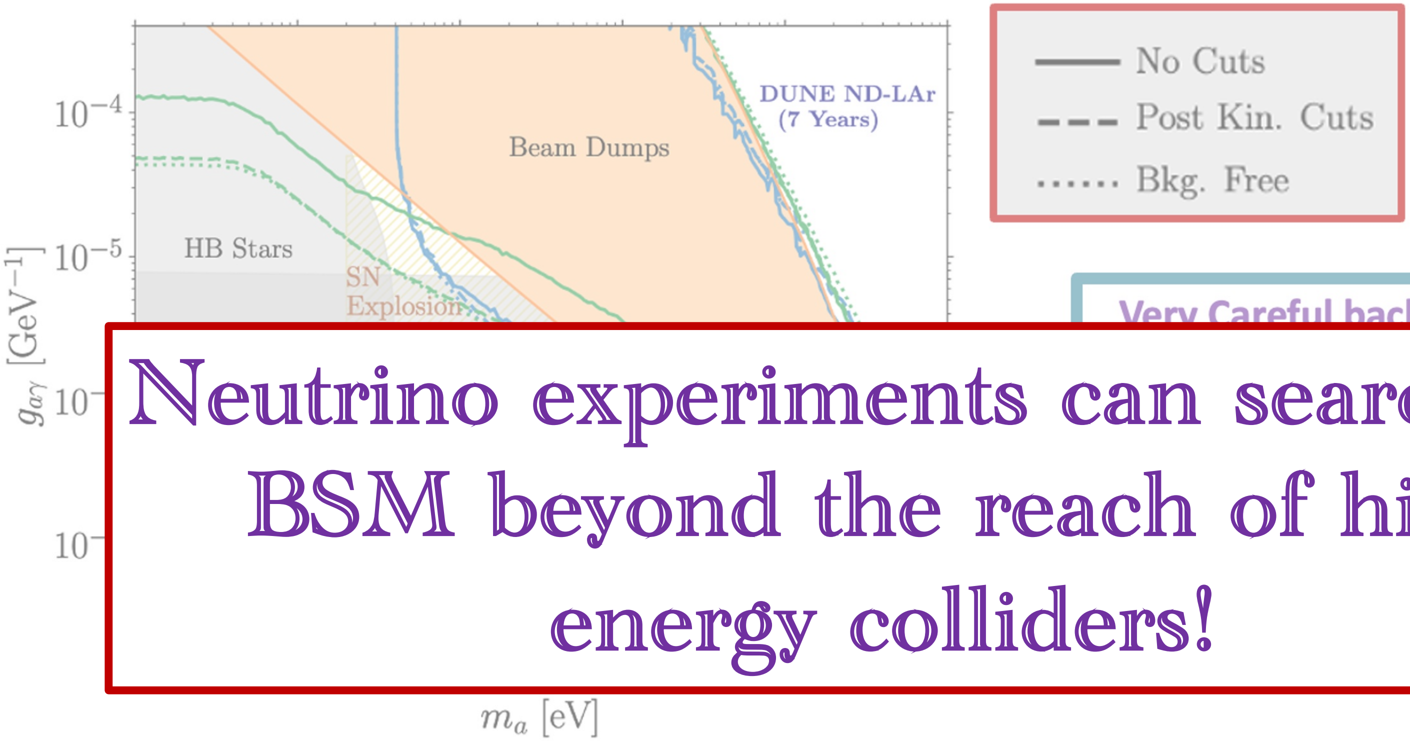
- - - Post Kin. Cuts

······ Bkg. Free

Very Careful background studies: practically background free post kinematical cuts!

Brdar, Dutta, Jang, Kim, Shoemaker, *ZT*, Thompson, Yu
PRD (2026)

ALP-γ at DUNE post background study



Very Careful background studies:
st

Neutrino experiments can search for BSM beyond the reach of high energy colliders!

Brdar, Dutta, Jang, Kim, Shoemaker, *ZT*, Thompson, Yu
PRD (2026)

Dark Sectors: Future Directions

High beam luminosity + Large fiducial mass → Ideal as Dark Sector Factories

Leverage the high statistics to enlarge the physics programs of Hyper-K, DUNE, SBN, …

ALPs

Light Z'

Searches for LFV

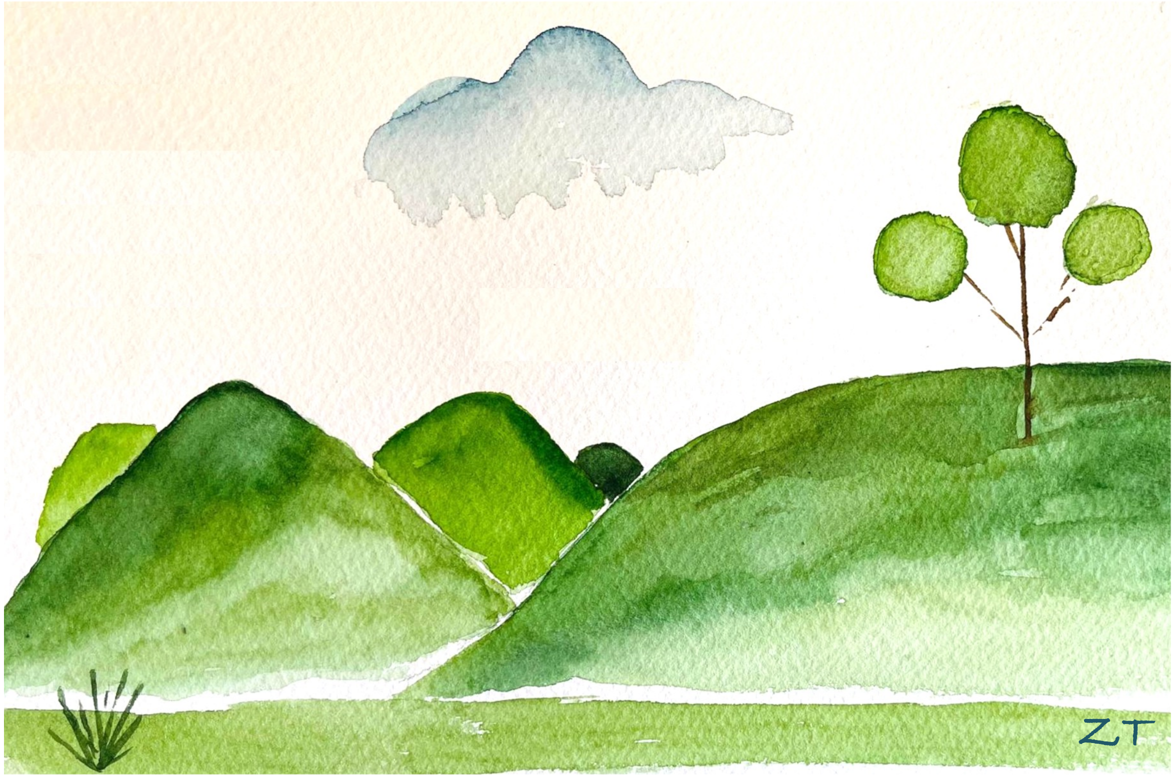
Light Dark Matter

HNLs

……….

- **"Prying Open the Dark Sector Window with SBND Off-Target Mode",**
  Dutta, Goswami, Karthikeyan, Pandey, **ZT**, Thompson, Van de Water
  arXiv: 2603.XXXXX
- **"Finding BSM Needles in Electromagnetic Haystacks at DUNE",**
  Brdar, Dutta, Jang, Kim, Shoemaker, **ZT**, Thompson and Yu
  PRD (2026)
- **"Heavy Neutral Leptons via Axion-Like Particles at Neutrino Facilities'',**
  Abdullahi, de Gouvea, Dutta, Shoemaker and **ZT**,
  PRL (2024)
- **"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)

Fantastic Beasts and How to Find Them With Neutrino Experiments



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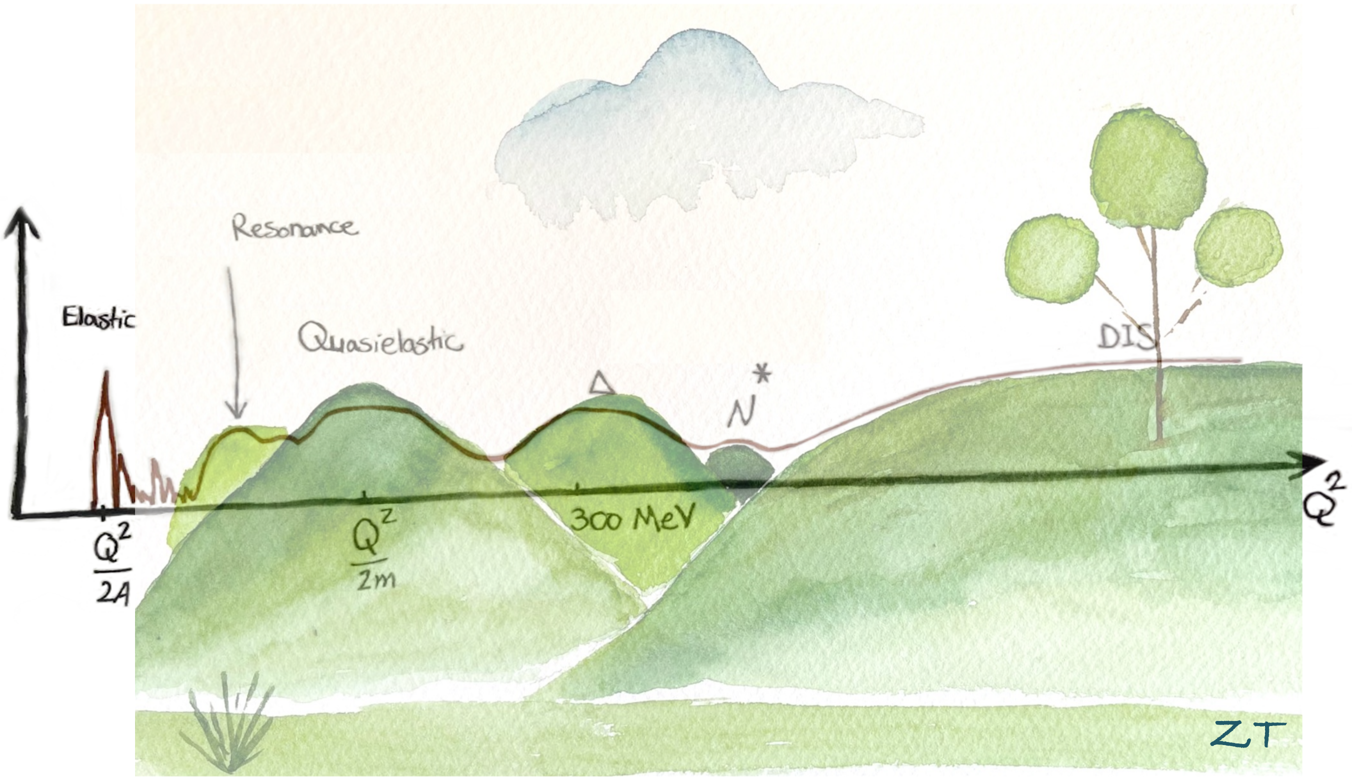

Fantastic Beasts and
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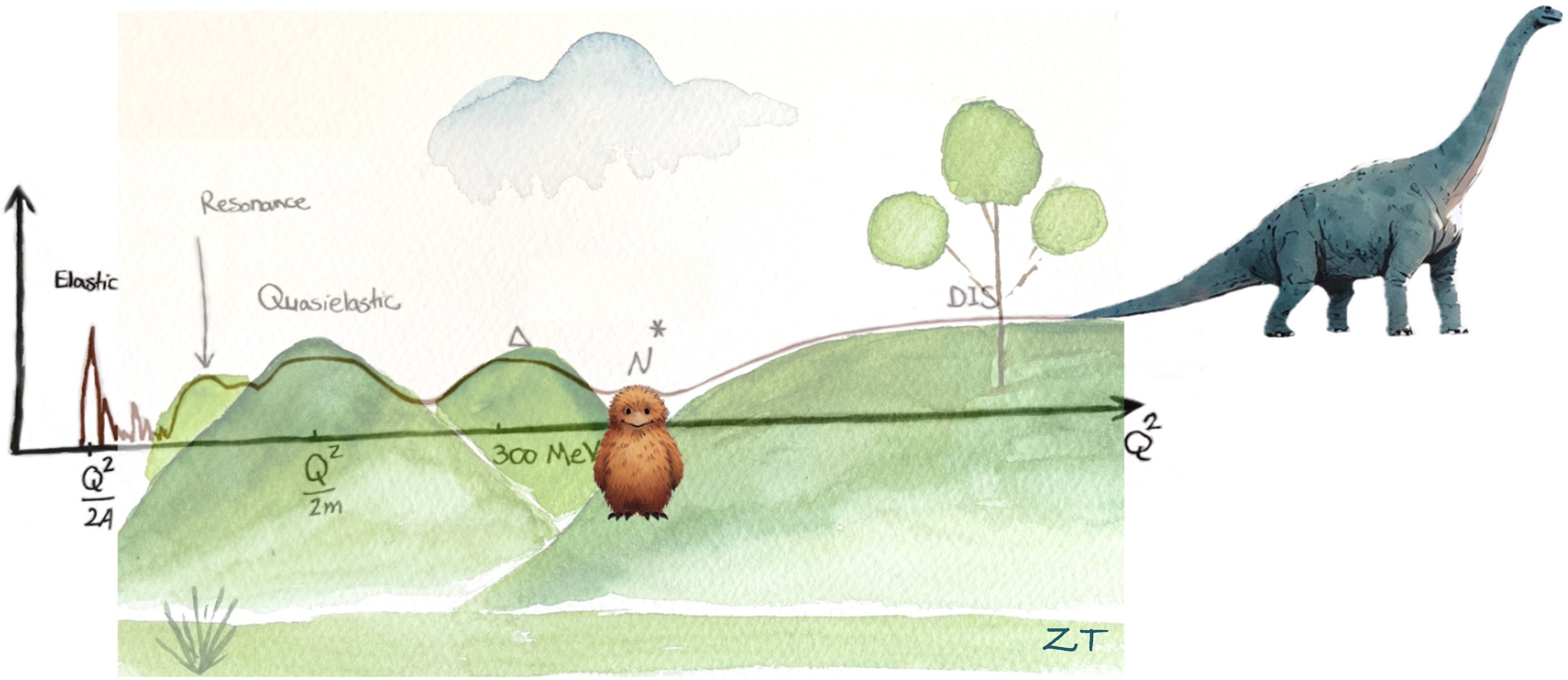

Fantastic Beasts and
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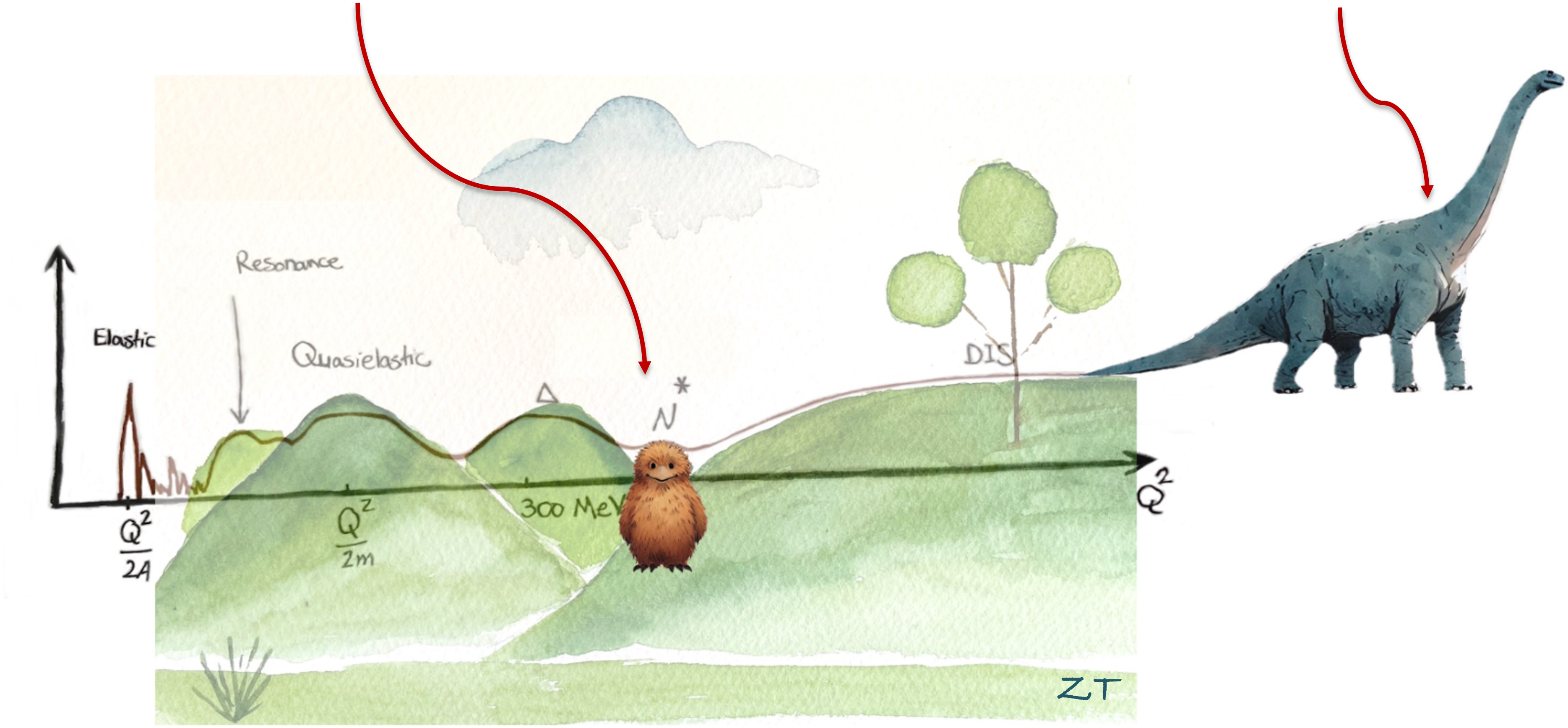
Neutrino Experiments as
Dark Sector Factories
“New Particles”

EFT at Neutrino Experiments:
Indirect Effects of Heavy New Physics
“New Interactions”



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Ultimate goal: unifying
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BSM searches

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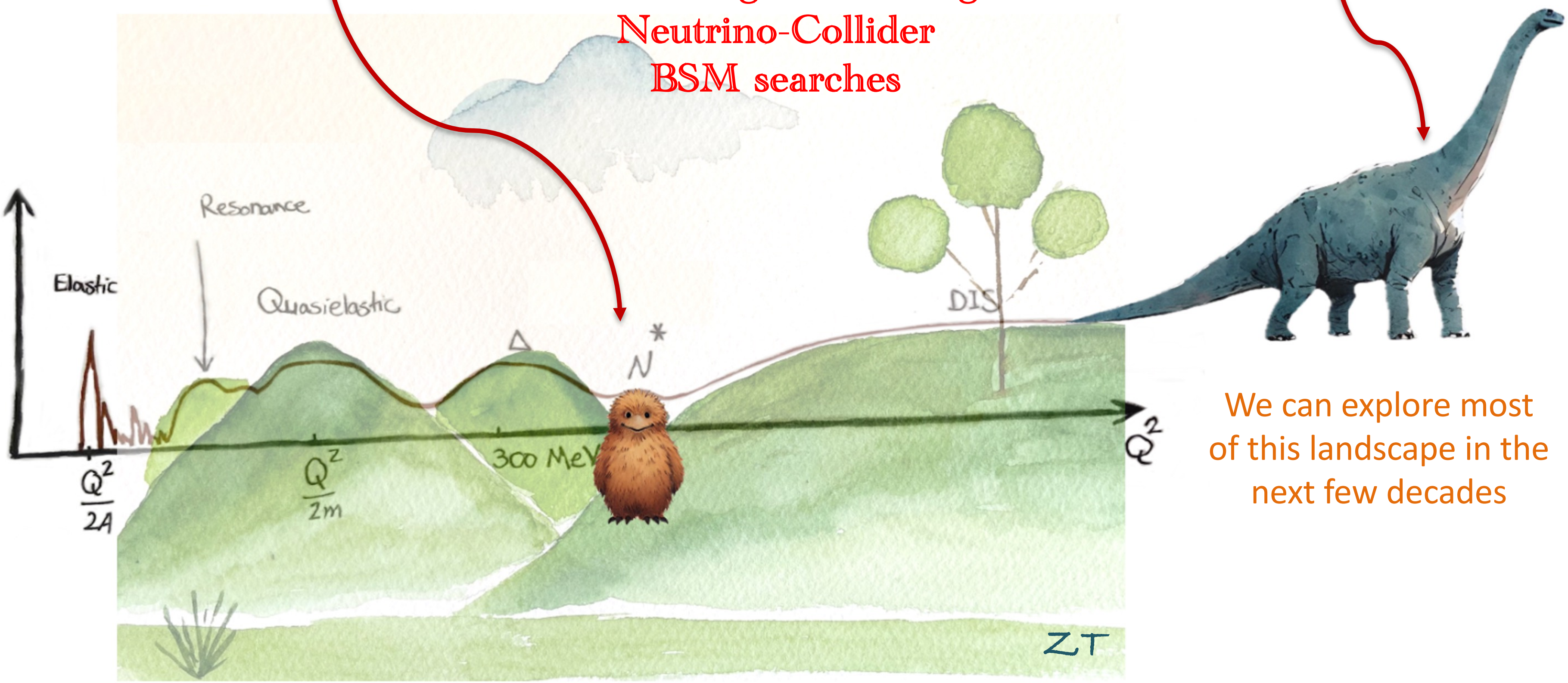

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We can explore most
of this landscape in the
next few decades

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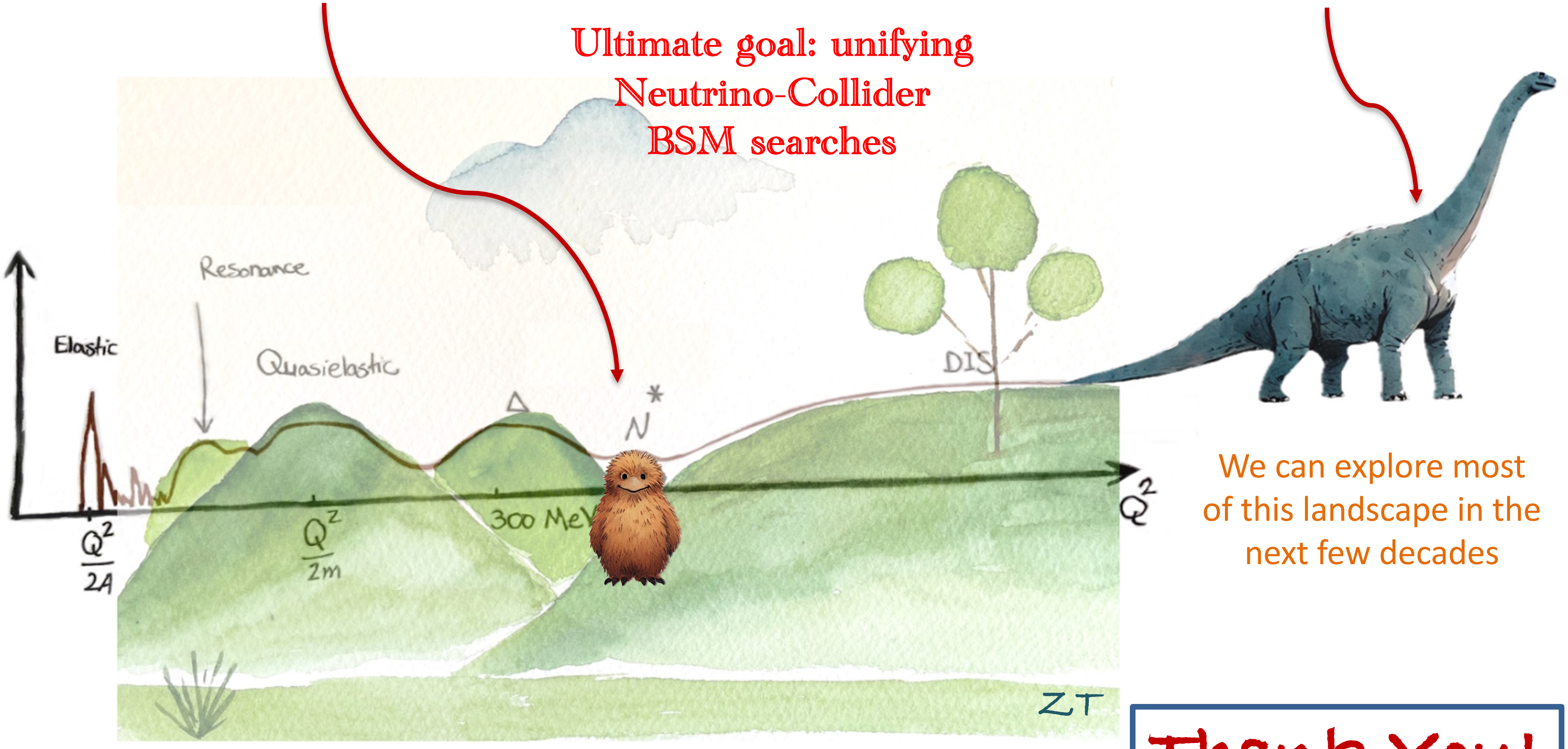

Ultimate goal: unifying
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We can explore most
of this landscape in the
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Thank You!

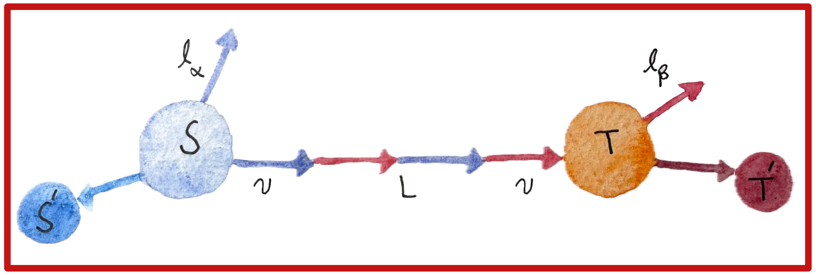
Back up Slides

EFT at neutrino experiments

We developed the systematic QFT approach to neutrino oscillations in the SMEFT framework!

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

But what is new here?!



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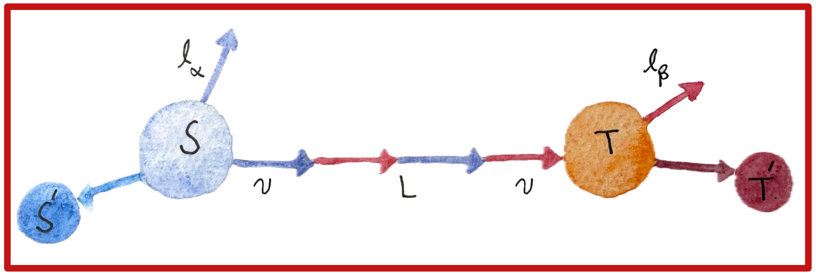


But what is new here?!

Traditional NSI approach: Neutrinos are not pure flavor states!

- Cannot be matched with SMEFT;
- No comparison of results with other experiments;
- Does not capture different kinematic dependence due to new interactions;
- Misses chiral enhancements/suppressions;

Standard NSI approach

NSI parameters

$$|\nu_\alpha^s\rangle = \frac{1}{N_\alpha^s}\left[|\nu_\alpha\rangle + \sum_{\gamma=e,\mu,\tau} \epsilon^s_{\alpha\gamma}|\nu_\gamma\rangle\right]$$

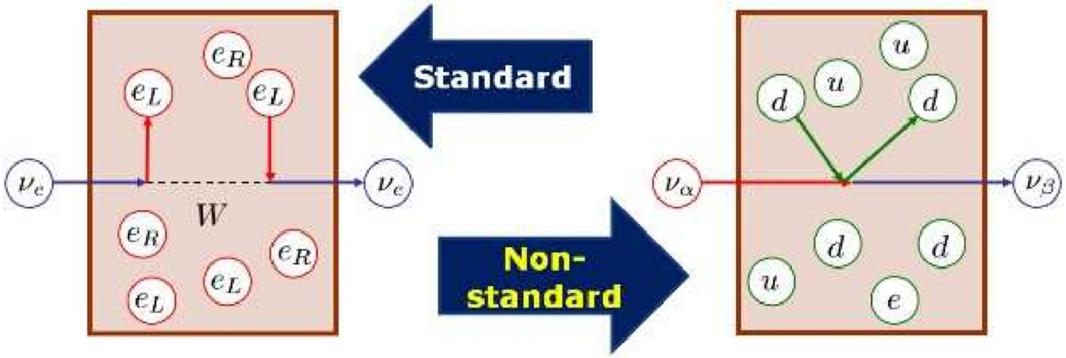
$$\langle\nu_\beta^d| = \frac{1}{N_\beta^d}\left[\langle\nu_\beta| + \sum_{\gamma=e,\mu,\tau}\langle\nu_\gamma|\epsilon^d_{\gamma\beta}\right]$$

Normalization

Take home: Traditional NSI methods do not work. We must use the correct QFT approach for EFT studies!

QM-NSI Description

Neutrinos are not pure flavor states:



Standard NSI approach

NSI parameters

$$|\nu_\alpha^s\rangle = \frac{1}{N_\alpha^s}\left[|\nu_\alpha\rangle + \sum_{\gamma=e,\mu,\tau} \epsilon_{\alpha\gamma}^s |\nu_\gamma\rangle\right]$$

Rotation of flavor states at the source

$$\langle\nu_\beta^d| = \frac{1}{N_\beta^d}\left[\langle\nu_\beta| + \sum_{\gamma=e,\mu,\tau} \langle\nu_\gamma|\epsilon_{\gamma\beta}^d\right]$$

Rotation of flavor states at the detector

Normalization

QM-NSI Description

Neutrinos are not pure flavor states:

$$|\nu_\alpha^s\rangle = \frac{(1+\epsilon^s)_{\alpha\gamma}}{N_\alpha^s}|\nu_\gamma\rangle \ , \quad \langle\nu_\beta^d| = \langle\nu_\gamma|\frac{(1+\epsilon^d)_{\gamma\beta}}{N_\beta^d}$$

Observable: rate of detected events

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

$$R_{\alpha\beta}^{\rm QM} = \Phi_\alpha^{\rm SM}\sigma_\beta^{\rm SM}\sum_{k,l} e^{-i\frac{L\Delta m_{kl}^2}{2E_\nu}}[x_s]_{\alpha k}[x_s]_{\alpha l}^*[x_d]_{\beta k}[x_d]_{\beta l}^*$$

$$x_s \equiv (1+\epsilon^s)U^* \ \& \ x_d \equiv (1+\epsilon^d)^T U$$

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

QM-NSI Description

- Can one “validate” QM-NSI approach from the QFT results?
- If yes, relation between NSI parameters and Lagrangian (EFT) parameters
- Does the matching hold at all orders in perturbation?

QM-NSI Description

- Can one “validate” QM-NSI approach from the QFT results? Yes…
- If yes, relation between NSI parameters and Lagrangian (EFT) parameters?
- Does the matching hold at all orders in perturbation? No…

Observable is the same, we can match the two

(only at the linear level)

$$\epsilon^s_{\alpha\beta} = \sum_X p_{XL}[\epsilon_X]^*_{\alpha\beta}, \quad \epsilon^d_{\beta\alpha} = \sum_X d_{XL}[\epsilon_X]_{\alpha\beta}$$

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

Comparing QM and QFT

Only at the linear order:

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

Neutrino Process	**NSI Matching with EFT**
ν_e produced in beta decay	$\epsilon^s_{e\beta} = [\epsilon_L]^*_{e\beta} - [\epsilon_R]^*_{e\beta} - \frac{g_T}{g_A}\frac{m_e}{f_T(E_\nu)}[\epsilon_T]^*_{e\beta}$
ν_e detected in inverse beta decay	$\epsilon^d_{\beta e} = [\epsilon_L]_{e\beta} + \frac{1-3g_A^2}{1+3g_A^2}[\epsilon_R]_{e\beta} - \frac{m_e}{E_\nu - \Delta}\left(\frac{g_S}{1+3g_A^2}[\epsilon_S]_{e\beta} - \frac{3g_A g_T}{1+3g_A^2}[\epsilon_T]_{e\beta}\right)$
ν_μ produced in pion decay	$\epsilon^s_{\mu\beta} = [\epsilon_L]^*_{\mu\beta} - [\epsilon_R]^*_{\mu\beta} - \frac{m_\pi^2}{m_\mu(m_u+m_d)}[\epsilon_P]^*_{\mu\beta}$

- Different NP interactions appear at the source or detection simultaneously
- Some of the p_{XL}/d_{XL} coefficients depend on the neutrino energy
- There are chiral enhancements in some cases

These correlations, energy dependence etc. cannot be seen in the traditional QM approach.

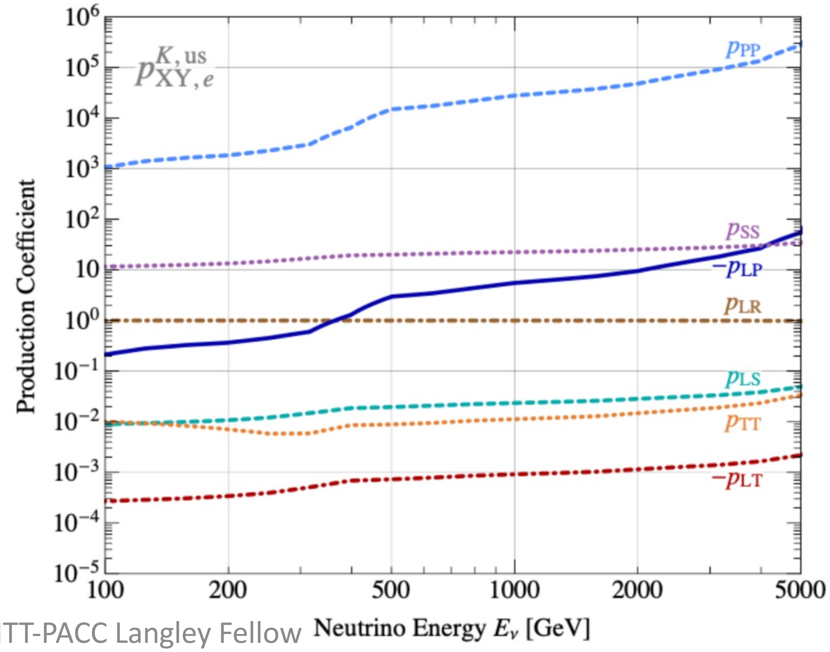
Comparing QM and QFT

Beyond the linear order in new physics parameters, the NSI formula matches the (correct) one derived in the EFT
only if the consistency condition is satisfied

$$p_{XL}p^*_{YL} = p_{XY}, \quad d_{XL}d^*_{YL} = d_{XY}$$

This is always satisfied for new physics correcting V-A interactions only as $p_{LL} = d_{LL} = 1$ by definition

However for non-V-A new physics the consistency condition is not satisfied in general



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

$$p_{XY} \equiv \frac{\int d\Pi_{P'} A^P_X \bar{A}^P_Y}{\int d\Pi_{P'} |A^P_L|^2}, \quad d_{XY} \equiv \frac{\int d\Pi_D A^D_X \bar{A}^D_Y}{\int d\Pi_D |A^D_L|^2}.$$

WEFT Power Counting

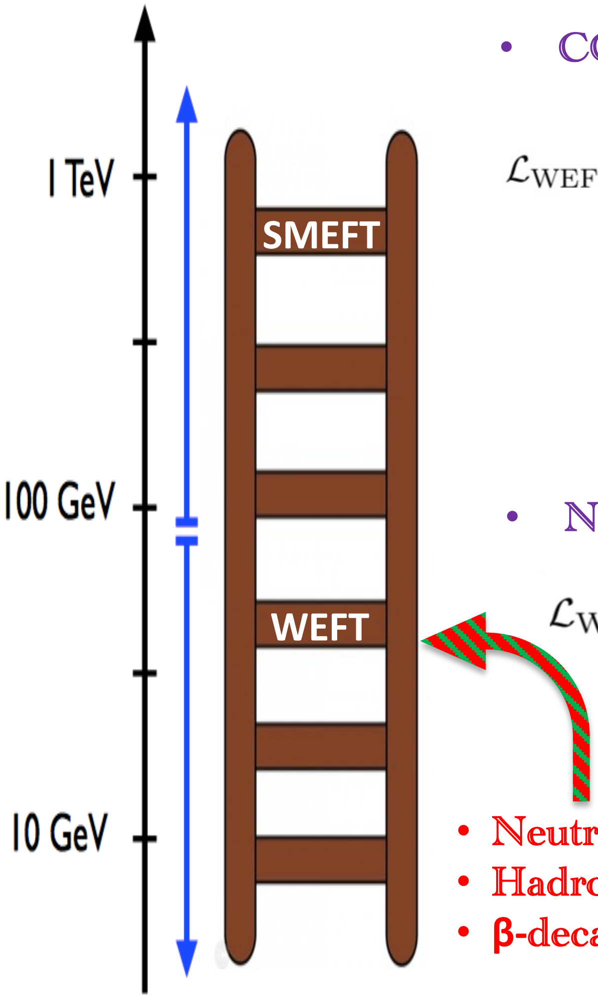
- Dim-6: $\dfrac{\Delta R}{R_{SM}} = c\,\epsilon_X^2$
- Dim-7: Cannot interfere with the SM amplitudes, suppressed!

Liao et al, *JHEP* 08 (2020) 162

- Dim-8: $\dfrac{\Delta R}{R_{SM}} = \sqrt{c}\,\epsilon_8\,E^2/v^2$

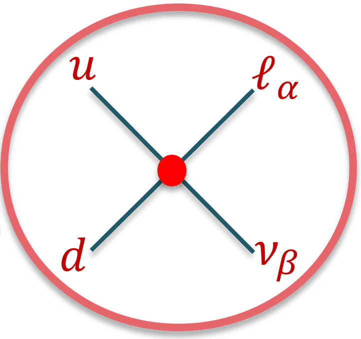
EFT ladder

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



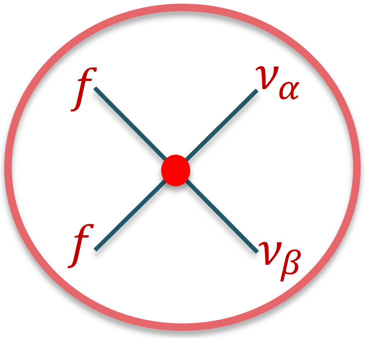
- CC: New left/right handed, (pseudo)scalar and tensor interactions

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



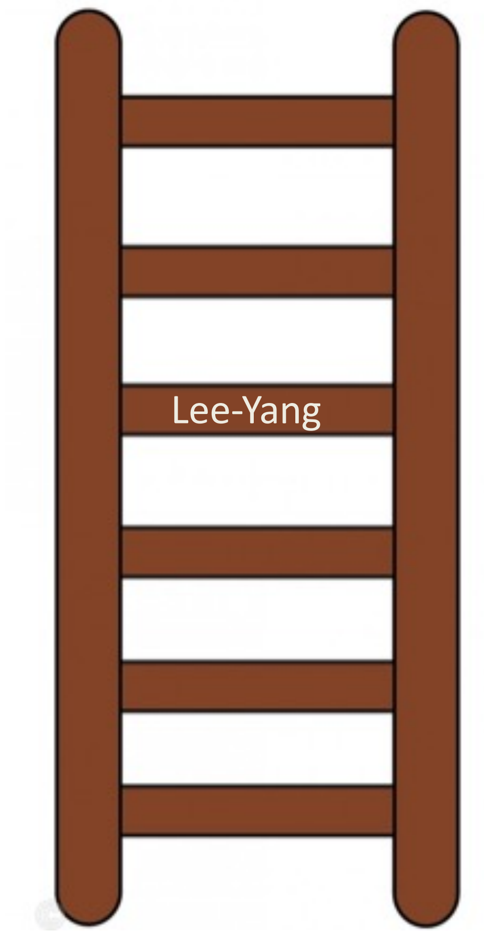
- NC: New left and right handed interactions

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

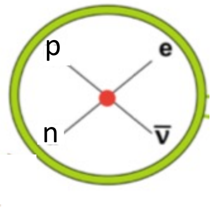


- Neutrino experiments
- Hadron Decays
- β-decays

EFT ladder



$E \ll m_Z$



- At the energy scale of reactor neutrino experiments the relevant degrees of freedom are not quarks, but nucleons and nuclei. Matching this EFT to the WEFT Lagrangian we obtain the Lee-Yang Lagrangian:

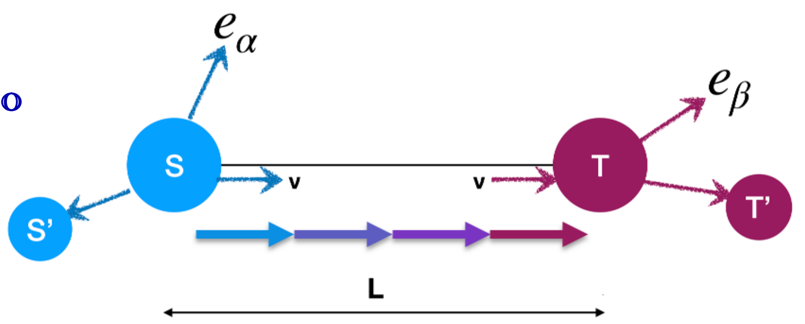
$$\begin{aligned}\mathcal{L}_{\rm LY} \supset\ & -\frac{V_{ud}}{v^2}\Big\{g_V\,[\mathbf{1}+\epsilon_L+\epsilon_R]_{\alpha\beta}\,(\bar{p}\gamma^\mu n)(\bar{\ell}_\alpha\gamma_\mu P_L\nu_\beta)\\ &\quad - g_A\,[\mathbf{1}+\epsilon_L-\epsilon_R]_{\alpha\beta}\,(\bar{p}\gamma^\mu\gamma_5 n)(\bar{\ell}_\alpha\gamma_\mu P_L\nu_\beta)\\ &\quad + g_S[\epsilon_S]_{\alpha\beta}(\bar{p}n)(\bar{\ell}_\alpha P_L\nu_\beta) - g_P[\epsilon_P]_{\alpha\beta}(\bar{p}\gamma_5 n)(\bar{\ell}_\alpha P_L\nu_\beta)\\ &\quad + \frac{1}{2}g_T[\hat{\epsilon}_T]_{\alpha\beta}(\bar{p}\sigma^{\mu\nu}P_L n)(\bar{\ell}_\alpha\sigma_{\mu\nu}P_L\nu_\beta) + \text{h.c.}\Big\},\end{aligned}$$

- Lattice+theory fix the non-perturbative parameters with good precision

$$g_A = 1.2728 \pm 0.0017, \quad g_S = 1.02 \pm 0.11, \quad g_P = 349 \pm 9, \quad g_T = 0.987 \pm 0.055.$$

- T. Bhattacharya et al, Phys. Rev. D94 (2016), no. 5 054508
- M. Gonzalez-Alonso and J. Martin Camalich, Phys. Rev. Lett. 112 (2014), no. 4 042501
- M. Gonzalez-Alonso et al, Prog. Part. Nucl. Phys. 104 (2019) 165–223

EFT at neutrino experiments

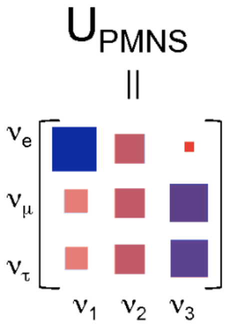


We proposed a systematic approach to neutrino oscillations in the SMEFT framework!

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

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

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

Corrections to fluxes/cross sections

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

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

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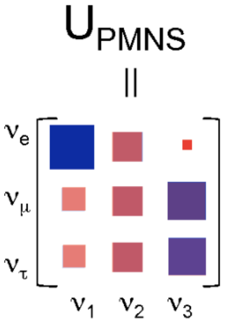

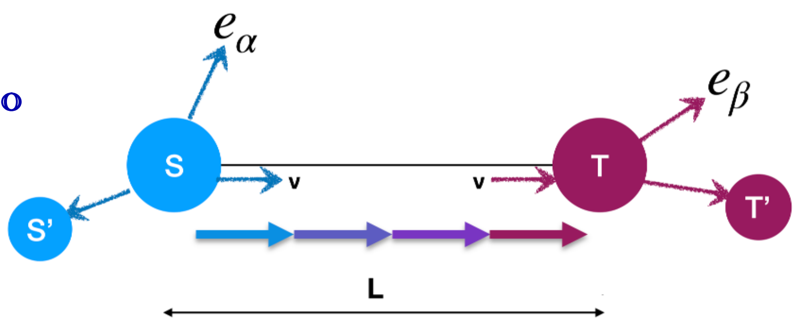

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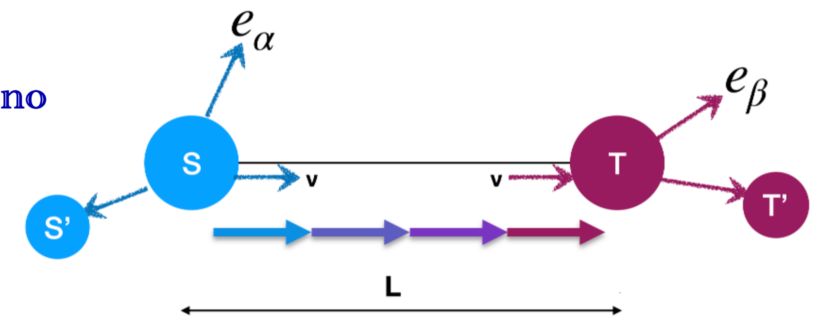
$$\boxed{\begin{aligned} R_{\alpha\beta} = \Phi_\alpha^{\rm SM}\sigma_\beta^{\rm SM}\sum_{k,l} e^{-i\frac{L\Delta m^2_{kl}}{2E_\nu}} & \left[U^*_{\alpha k}U_{\alpha l} + p_{XL}(\epsilon_X U)^*_{\alpha k}U_{\alpha l} + p^*_{XL}U^*_{\alpha k}(\epsilon_X U)_{\alpha l} + p_{XX}(\epsilon_X U)^*_{\alpha k}(\epsilon_X U)_{\alpha l}\right] \\ & \times\left[U_{\beta k}U^*_{\beta l} + d_{XL}(\epsilon_X U)_{\beta k}U^*_{\beta l} + d^*_{XL}U_{\beta k}(\epsilon_X U)^*_{\beta l} + d_{XX}(\epsilon_X U)_{\beta k}(\epsilon_X U)^*_{\beta l}\right]\end{aligned}}$$

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

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

EFT at neutrino experiments

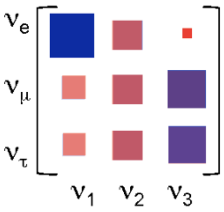


We pioneered a systematic approach to neutrino oscillations in the SMEFT framework!

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

U_{PMNS}

||



Observable: rate of detected events

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

$$\boxed{\begin{aligned}R_{\alpha\beta} = \Phi_\alpha^{\text{SM}}\sigma_\beta^{\text{SM}}\sum_{k,l} e^{-i\frac{L\Delta m^2_{kl}}{2E_\nu}} &[U^*_{\alpha k}U_{\alpha l} + p_{XL}(\epsilon_X U)^*_{\alpha k}U_{\alpha l} + p^*_{XL}U^*_{\alpha k}(\epsilon_X U)_{\alpha l} + p_{XX}(\epsilon_X U)^*_{\alpha k}(\epsilon_X U)_{\alpha l}]\\ &\times[U_{\beta k}U^*_{\beta l} + d_{XL}(\epsilon_X U)_{\beta k}U^*_{\beta l} + d^*_{XL}U_{\beta k}(\epsilon_X U)^*_{\beta l} + d_{XX}(\epsilon_X U)_{\beta k}(\epsilon_X U)^*_{\beta l}]\end{aligned}}$$

$$\mathcal{H}_{\text{F}} = \frac{1}{2E}\left(U\,\mathbb{M}^2\,U^\dagger + \mathbb{A}\right)$$

$$\mathbb{M}^2 = \begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m^2_{21} & 0\\ 0 & 0 & \Delta m^2_{31}\end{pmatrix}, \qquad \mathbb{A} = \begin{pmatrix}A_{\text{CC}} & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{pmatrix}$$

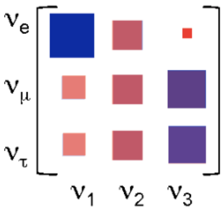
EFT at neutrino experiments

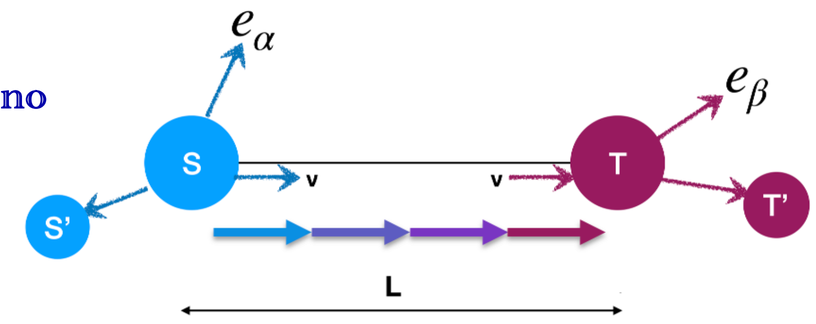
We pioneered a systematic approach to neutrino oscillations in the SMEFT framework!

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

U_{PMNS}

||





Observable: rate of detected events

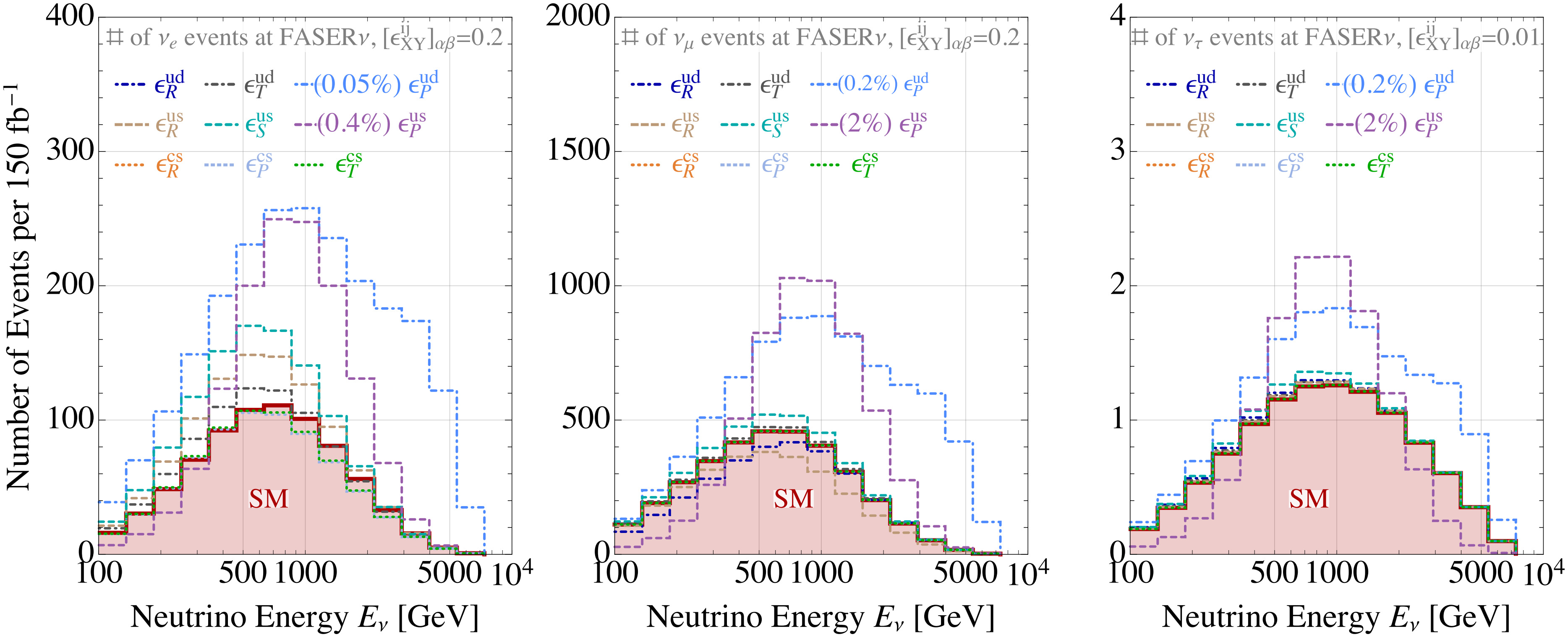
$$\sim \underbrace{(\text{flux})\times(\text{det. cross section})}_{\text{CC EFT}}\times\underbrace{(\text{oscillation})}_{\boxed{\text{NC EFT}}}$$

$$\boxed{\begin{aligned} R_{\alpha\beta} = \Phi_\alpha^{\text{SM}}\sigma_\beta^{\text{SM}}\sum_{k,l} e^{-i\frac{L\Delta m_{kl}^2}{2E_\nu}} &\left[U_{\alpha k}^* U_{\alpha l} + p_{XL}(\epsilon_X U)_{\alpha k}^* U_{\alpha l} + p_{XL}^* U_{\alpha k}^* (\epsilon_X U)_{\alpha l} + p_{XX}(\epsilon_X U)_{\alpha k}^* (\epsilon_X U)_{\alpha l}\right] \\ &\times\left[U_{\beta k} U_{\beta l}^* + d_{XL}(\epsilon_X U)_{\beta k} U_{\beta l}^* + d_{XL}^* U_{\beta k}(\epsilon_X U)_{\beta l}^* + d_{XX}(\epsilon_X U)_{\beta k}(\epsilon_X U)_{\beta l}^*\right] \end{aligned}}$$

$$\mathcal{H}_{\text{F}} = \frac{1}{2E}\left(U\,\mathbb{M}^2\,U^\dagger + \mathbb{A}\right) + \pm\sqrt{2}G_F N_e \begin{pmatrix} \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{\mu e} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{\tau e} & \varepsilon_{\tau\mu} & \varepsilon_{\tau\tau} \end{pmatrix}$$

EFT at FASERν

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



- Analysis is statistics dominated: ν_e~1000, ν_μ~5000, ν_τ~10
- Optimistic systematic uncertainties: 5% on ν_e, 10% on ν_μ, 15% on ν_τ
- Pessimistic systematic uncertainties: 30% on ν_e, 40% on ν_μ, 50% on ν_τ

Pion decay

Production

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

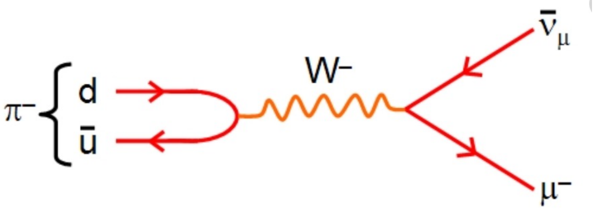
Due to the pseudoscalar nature of the pion, it is sensitive only to axial (ε_L-ε_R) and pseudo-scalar (ε_P) interactions.

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

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

~-27

~700!



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

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

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

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

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

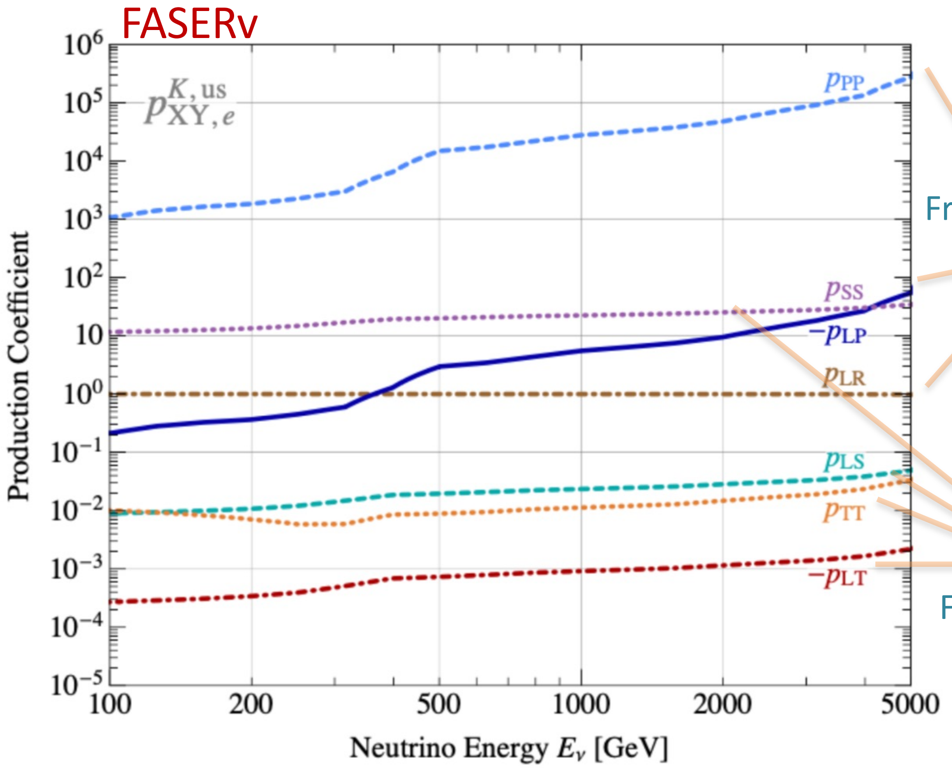
Huge overall flux normalization for pion decay!

kaon decay

Production

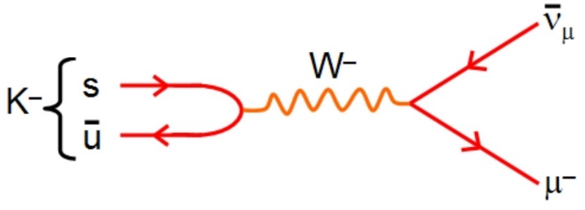
Falkowski, González-Alonso, Kopp, Soreq, ZT, JHEP (2021)

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

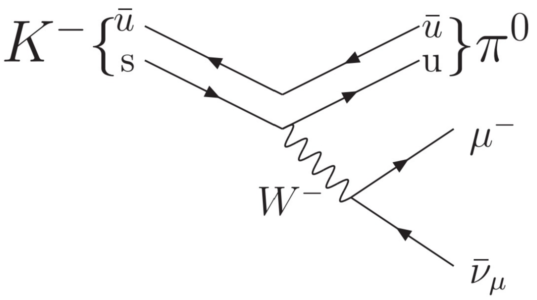


From 2-b decay

From 3-b decay



K⁻(sū) → $\mu^- + \bar\nu_\mu$



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

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

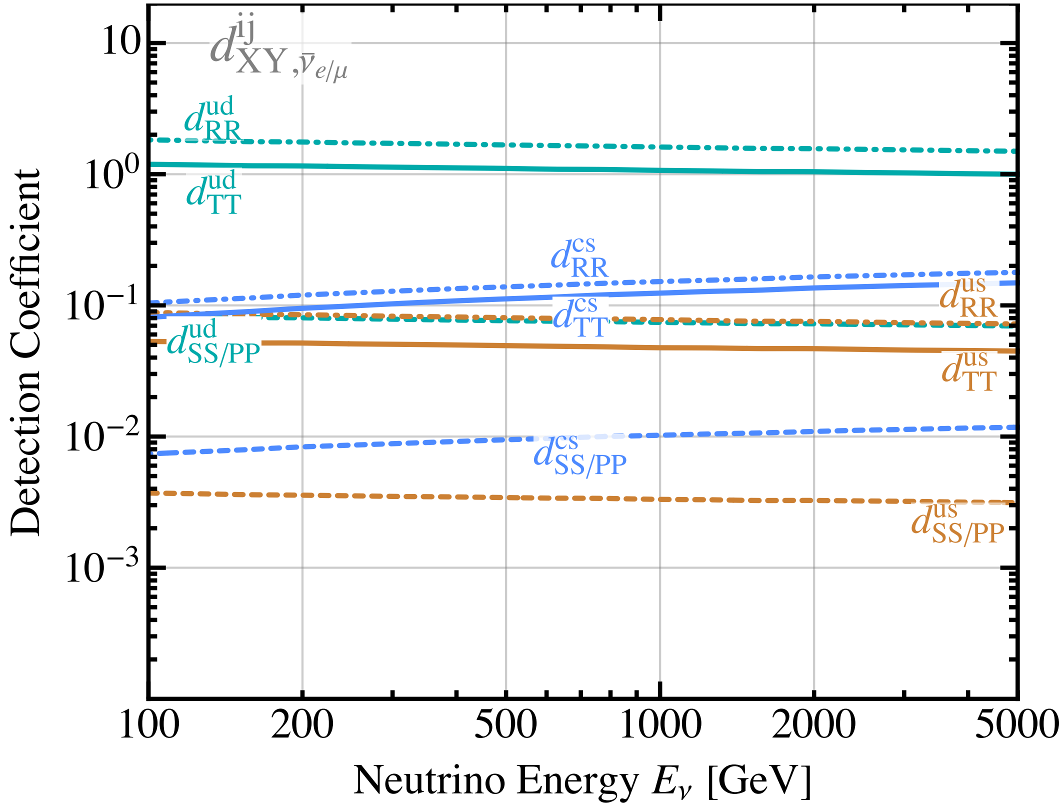
$$\langle \pi^- | \bar s \sigma^{\mu\nu} u | K^0\rangle = i\frac{p_K^\mu p_\pi^\nu - p_\pi^\mu p_K^\nu}{m_K} B_T(q^2)\,,$$

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

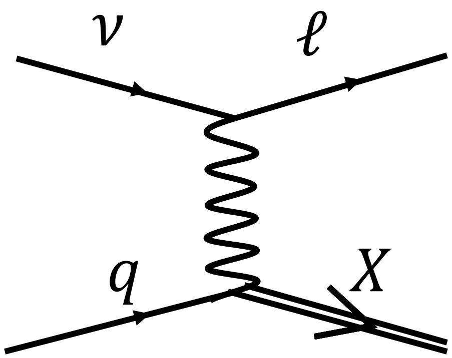
DIS

Detection

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



Deep Inelastic Scattering



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

$\varepsilon_X{}^2$ is more important than ε_X!

RESULTS

Turning on one interaction at a time: Right handed

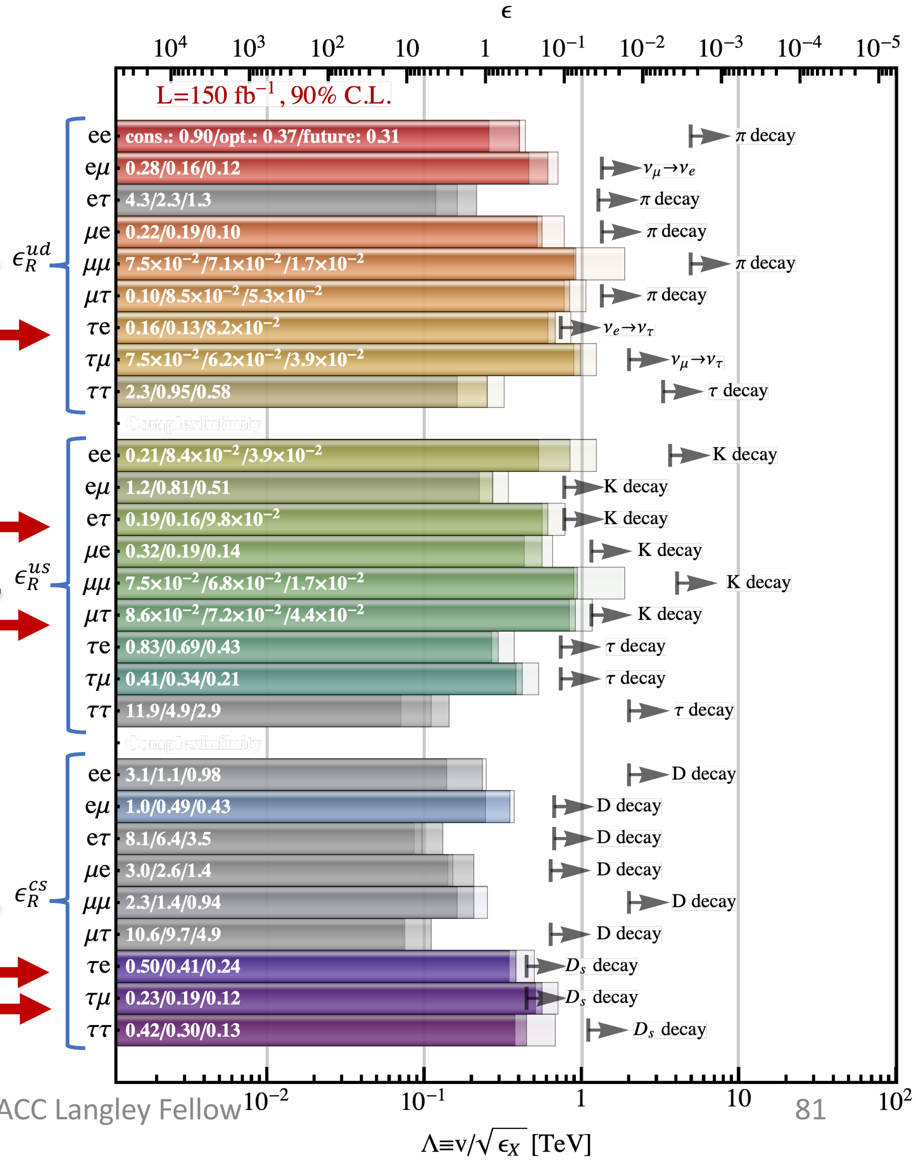
A. Falkowski, M. González-Alonso, J. Kopp, Y. Soreq, **ZT**
JHEP 10 (2021) 086

Optimistic (5%, 10%, 15%) and Pessimistic (30%, 40%, 50%), uncertainties on electron muon and tau neutrinos

From pion decay and DIS

From kaon decay and DIS

From charm decay and DIS

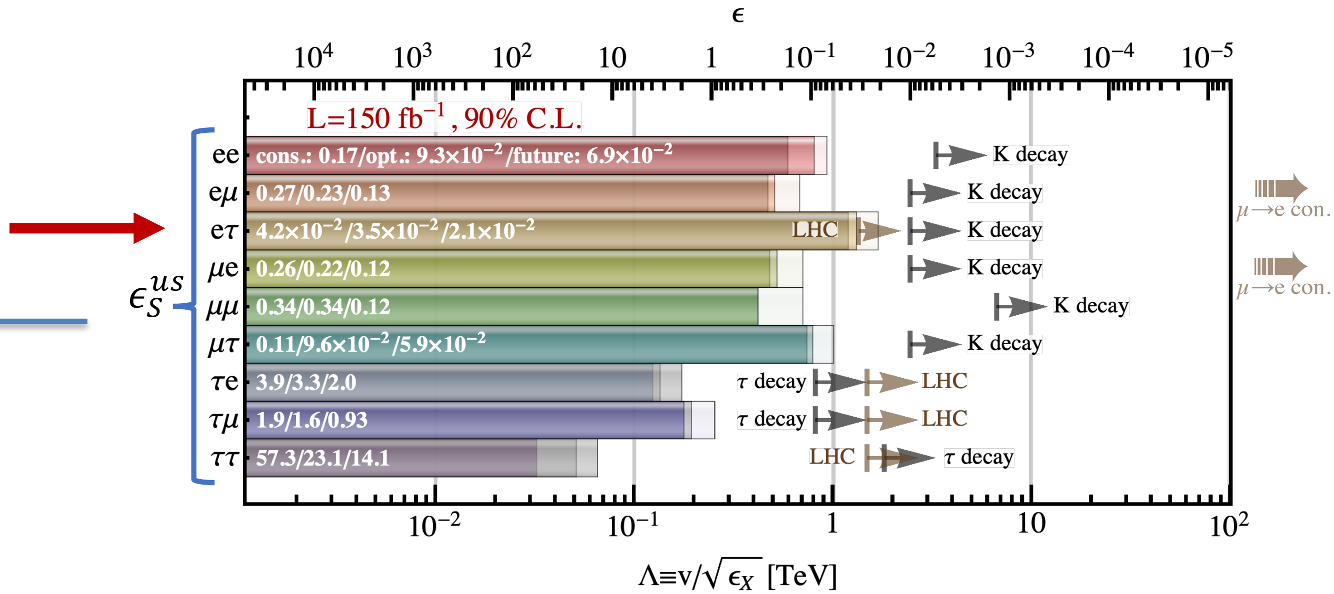


RESULTS

Turning on one interaction at a time: Scalar

A. Falkowski, M. González-Alonso, J. Kopp, Y. Soreq, **ZT**
JHEP 10 (2021) 086

Optimistic (5%, 10%, 15%) and Pessimistic (30%, 40%, 50%), uncertainties on electron muon and tau neutrinos



From kaon decay

RESULTS

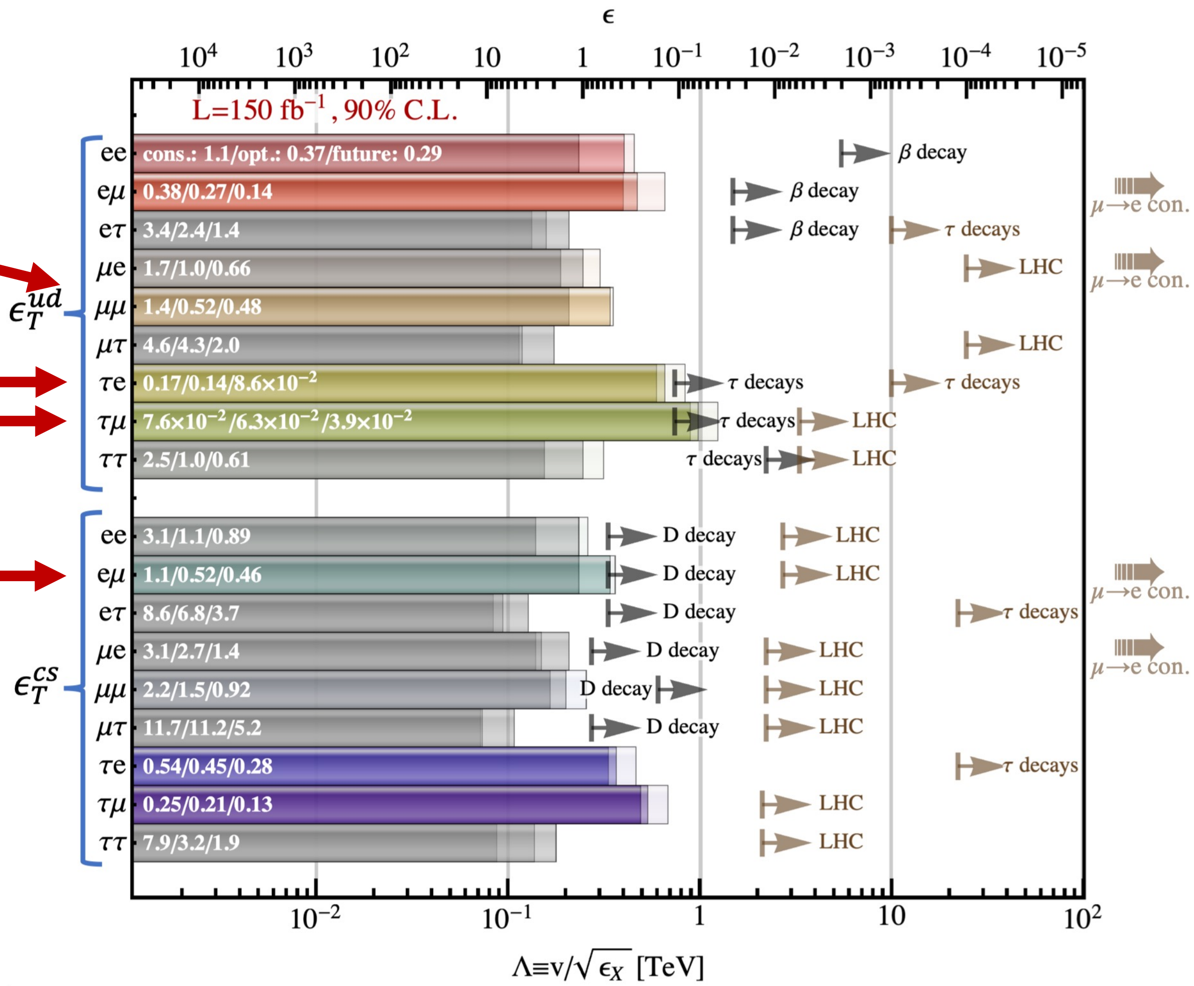
Turning on one interaction at a time: Tensor

A. Falkowski, M. González-Alonso, J. Kopp, Y. Soreq, **ZT**
JHEP 10 (2021) 086

Optimistic (5%, 10%, 15%) and Pessimistic (30%, 40%, 50%), uncertainties on electron muon and tau neutrinos

From DIS

From charm decay and DIS



EFT at FASERν

A. Falkowski, M. González-Alonso, J. Kopp, Y. Soreq, **ZT**
JHEP 10 (2021) 086

Neutrino experiments:

- Many more operators can be probed (81 at FASERν)

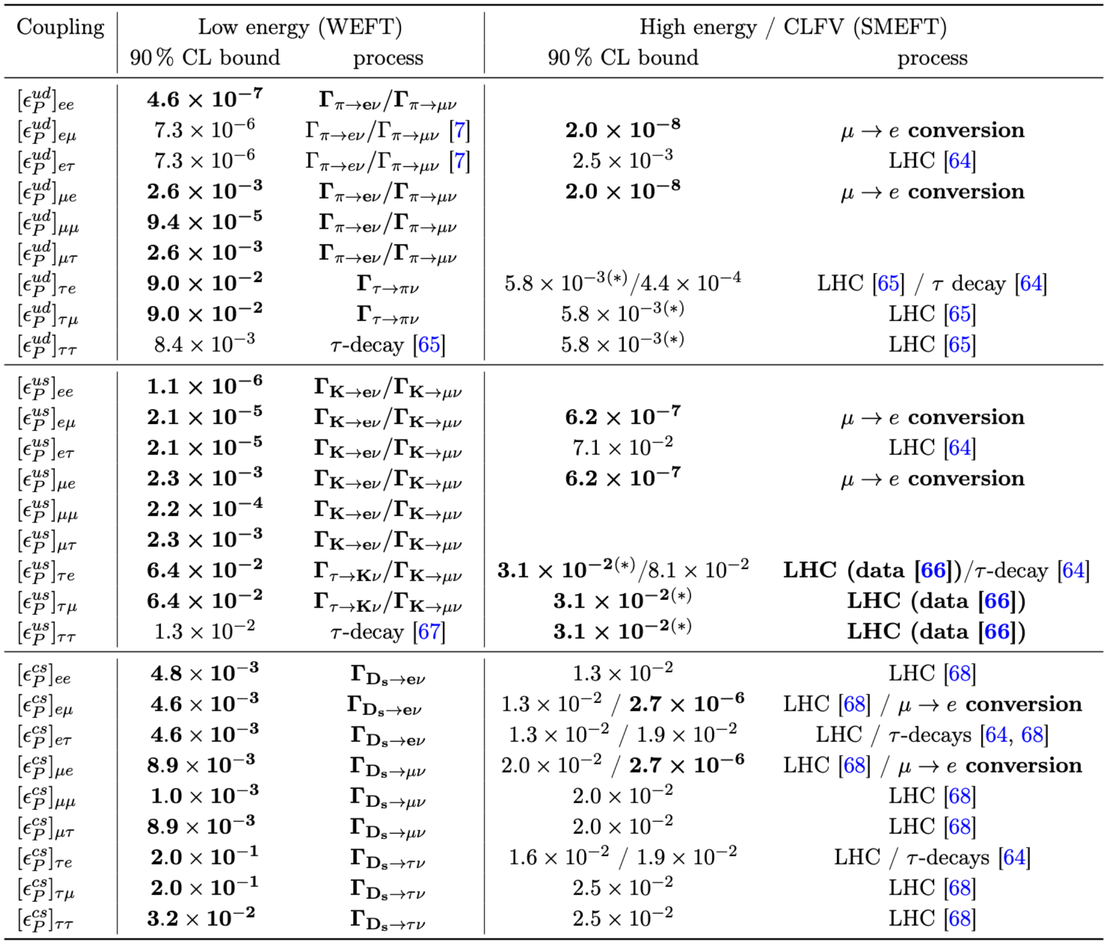
Low energy:

- Independent of the underlying high-energy theory

High-Energy:

- SMEFT is the underlying theory
- Bounds are less robust

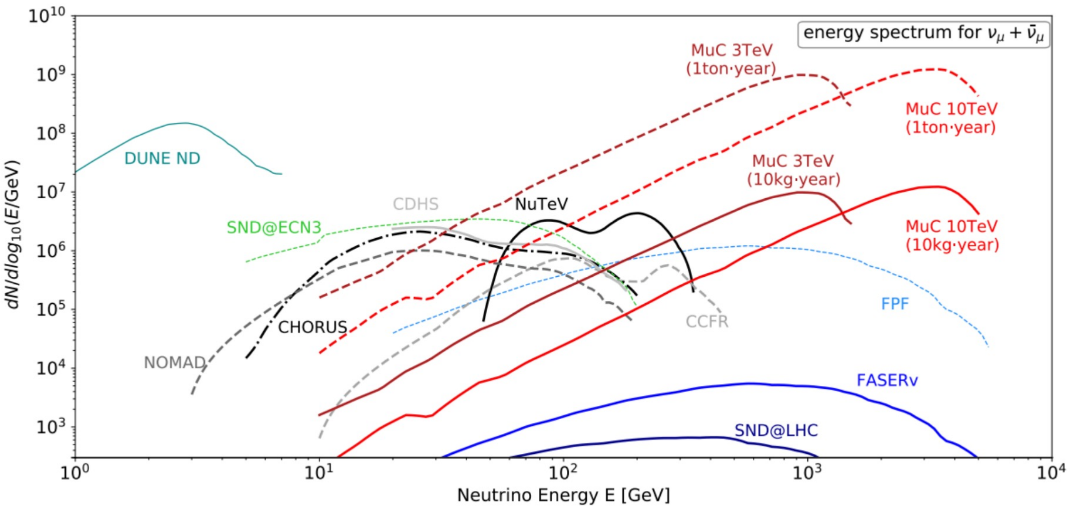
FASERν Flavor Experiments Colliders



Coupling	Low energy (WEFT)		High energy / CLFV (SMEFT)	
	90 % CL bound	process	90 % CL bound	process
$[\epsilon_P^{ud}]_{ee}$	$\mathbf{4.6 \times 10^{-7}}$	$\mathbf{\Gamma_{\pi\to e\nu}/\Gamma_{\pi\to\mu\nu}}$		
$[\epsilon_P^{ud}]_{e\mu}$	7.3×10^{-6}	$\Gamma_{\pi\to e\nu}/\Gamma_{\pi\to\mu\nu}$ [7]	$\mathbf{2.0 \times 10^{-8}}$	$\mu \to e$ **conversion**
$[\epsilon_P^{ud}]_{e\tau}$	7.3×10^{-6}	$\Gamma_{\pi\to e\nu}/\Gamma_{\pi\to\mu\nu}$ [7]	2.5×10^{-3}	LHC [64]
$[\epsilon_P^{ud}]_{\mu e}$	$\mathbf{2.6 \times 10^{-3}}$	$\mathbf{\Gamma_{\pi\to e\nu}/\Gamma_{\pi\to\mu\nu}}$	$\mathbf{2.0 \times 10^{-8}}$	$\mu \to e$ **conversion**
$[\epsilon_P^{ud}]_{\mu\mu}$	$\mathbf{9.4 \times 10^{-5}}$	$\mathbf{\Gamma_{\pi\to e\nu}/\Gamma_{\pi\to\mu\nu}}$		
$[\epsilon_P^{ud}]_{\mu\tau}$	$\mathbf{2.6 \times 10^{-3}}$	$\mathbf{\Gamma_{\pi\to e\nu}/\Gamma_{\pi\to\mu\nu}}$		
$[\epsilon_P^{ud}]_{\tau e}$	$\mathbf{9.0 \times 10^{-2}}$	$\mathbf{\Gamma_{\tau\to\pi\nu}}$	$5.8 \times 10^{-3(*)}/4.4 \times 10^{-4}$	LHC [65] / τ decay [64]
$[\epsilon_P^{ud}]_{\tau\mu}$	$\mathbf{9.0 \times 10^{-2}}$	$\mathbf{\Gamma_{\tau\to\pi\nu}}$	$5.8 \times 10^{-3(*)}$	LHC [65]
$[\epsilon_P^{ud}]_{\tau\tau}$	8.4×10^{-3}	τ-decay [65]	$5.8 \times 10^{-3(*)}$	LHC [65]
$[\epsilon_P^{us}]_{ee}$	$\mathbf{1.1 \times 10^{-6}}$	$\mathbf{\Gamma_{K\to e\nu}/\Gamma_{K\to\mu\nu}}$		
$[\epsilon_P^{us}]_{e\mu}$	$\mathbf{2.1 \times 10^{-5}}$	$\mathbf{\Gamma_{K\to e\nu}/\Gamma_{K\to\mu\nu}}$	$\mathbf{6.2 \times 10^{-7}}$	$\mu \to e$ **conversion**
$[\epsilon_P^{us}]_{e\tau}$	$\mathbf{2.1 \times 10^{-5}}$	$\mathbf{\Gamma_{K\to e\nu}/\Gamma_{K\to\mu\nu}}$	7.1×10^{-2}	LHC [64]
$[\epsilon_P^{us}]_{\mu e}$	$\mathbf{2.3 \times 10^{-3}}$	$\mathbf{\Gamma_{K\to e\nu}/\Gamma_{K\to\mu\nu}}$	$\mathbf{6.2 \times 10^{-7}}$	$\mu \to e$ **conversion**
$[\epsilon_P^{us}]_{\mu\mu}$	$\mathbf{2.2 \times 10^{-4}}$	$\mathbf{\Gamma_{K\to e\nu}/\Gamma_{K\to\mu\nu}}$		
$[\epsilon_P^{us}]_{\mu\tau}$	$\mathbf{2.3 \times 10^{-3}}$	$\mathbf{\Gamma_{K\to e\nu}/\Gamma_{K\to\mu\nu}}$		
$[\epsilon_P^{us}]_{\tau e}$	$\mathbf{6.4 \times 10^{-2}}$	$\mathbf{\Gamma_{\tau\to K\nu}/\Gamma_{K\to\mu\nu}}$	$\mathbf{3.1 \times 10^{-2(*)}}/8.1 \times 10^{-2}$	**LHC (data [66])**/τ-decay [64]
$[\epsilon_P^{us}]_{\tau\mu}$	$\mathbf{6.4 \times 10^{-2}}$	$\mathbf{\Gamma_{\tau\to K\nu}/\Gamma_{K\to\mu\nu}}$	$\mathbf{3.1 \times 10^{-2(*)}}$	**LHC (data [66])**
$[\epsilon_P^{us}]_{\tau\tau}$	1.3×10^{-2}	τ-decay [67]	$\mathbf{3.1 \times 10^{-2(*)}}$	**LHC (data [66])**
$[\epsilon_P^{cs}]_{ee}$	$\mathbf{4.8 \times 10^{-3}}$	$\mathbf{\Gamma_{D_s\to e\nu}}$	1.3×10^{-2}	LHC [68]
$[\epsilon_P^{cs}]_{e\mu}$	$\mathbf{4.6 \times 10^{-3}}$	$\mathbf{\Gamma_{D_s\to e\nu}}$	1.3×10^{-2} / $\mathbf{2.7 \times 10^{-6}}$	LHC [68] / $\mu \to e$ **conversion**
$[\epsilon_P^{cs}]_{e\tau}$	$\mathbf{4.6 \times 10^{-3}}$	$\mathbf{\Gamma_{D_s\to e\nu}}$	1.3×10^{-2} / 1.9×10^{-2}	LHC / τ-decays [64, 68]
$[\epsilon_P^{cs}]_{\mu e}$	$\mathbf{8.9 \times 10^{-3}}$	$\mathbf{\Gamma_{D_s\to\mu\nu}}$	2.0×10^{-2} / $\mathbf{2.7 \times 10^{-6}}$	LHC [68] / $\mu \to e$ **conversion**
$[\epsilon_P^{cs}]_{\mu\mu}$	$\mathbf{1.0 \times 10^{-3}}$	$\mathbf{\Gamma_{D_s\to\mu\nu}}$	2.0×10^{-2}	LHC [68]
$[\epsilon_P^{cs}]_{\mu\tau}$	$\mathbf{8.9 \times 10^{-3}}$	$\mathbf{\Gamma_{D_s\to\mu\nu}}$	2.0×10^{-2}	LHC [68]
$[\epsilon_P^{cs}]_{\tau e}$	$\mathbf{2.0 \times 10^{-1}}$	$\mathbf{\Gamma_{D_s\to\tau\nu}}$	1.6×10^{-2} / 1.9×10^{-2}	LHC / τ-decays [64]
$[\epsilon_P^{cs}]_{\tau\mu}$	$\mathbf{2.0 \times 10^{-1}}$	$\mathbf{\Gamma_{D_s\to\tau\nu}}$	2.5×10^{-2}	LHC [68]
$[\epsilon_P^{cs}]_{\tau\tau}$	$\mathbf{3.2 \times 10^{-2}}$	$\mathbf{\Gamma_{D_s\to\tau\nu}}$	2.5×10^{-2}	LHC [68]

Bounds shown in bold face have been calculated in this work

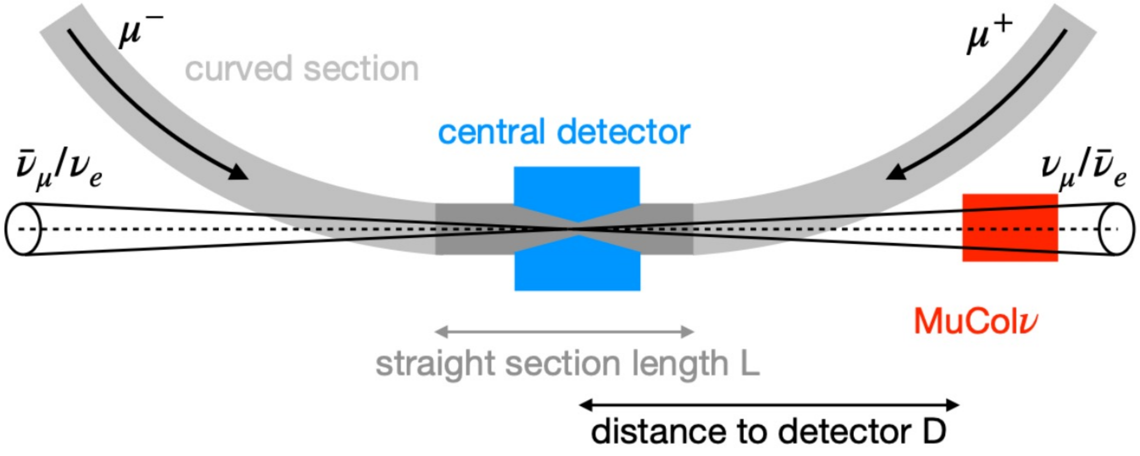
Muon Beam Neutrinos:



$$\boxed{N \sim 10^5 \times \left(\frac{m}{\text{kg}}\right) \times \left(\frac{t}{\text{yr}}\right) \times \left(\frac{L}{50\text{ m}}\right) \times \left(\frac{500\text{ m}}{D}\right)^2}$$

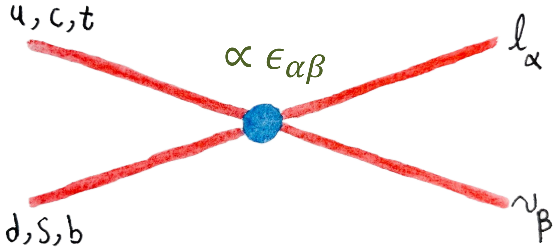
10^7 and 10^9 total interactions at the forward region for the 10 kg·year and 1 ton.year setups

Forward Detectors:
e.g. MuColν
F. Kling, Y. Ma, K. Mękała, J. Reuter, **ZT**
arxiv: 2508.00761



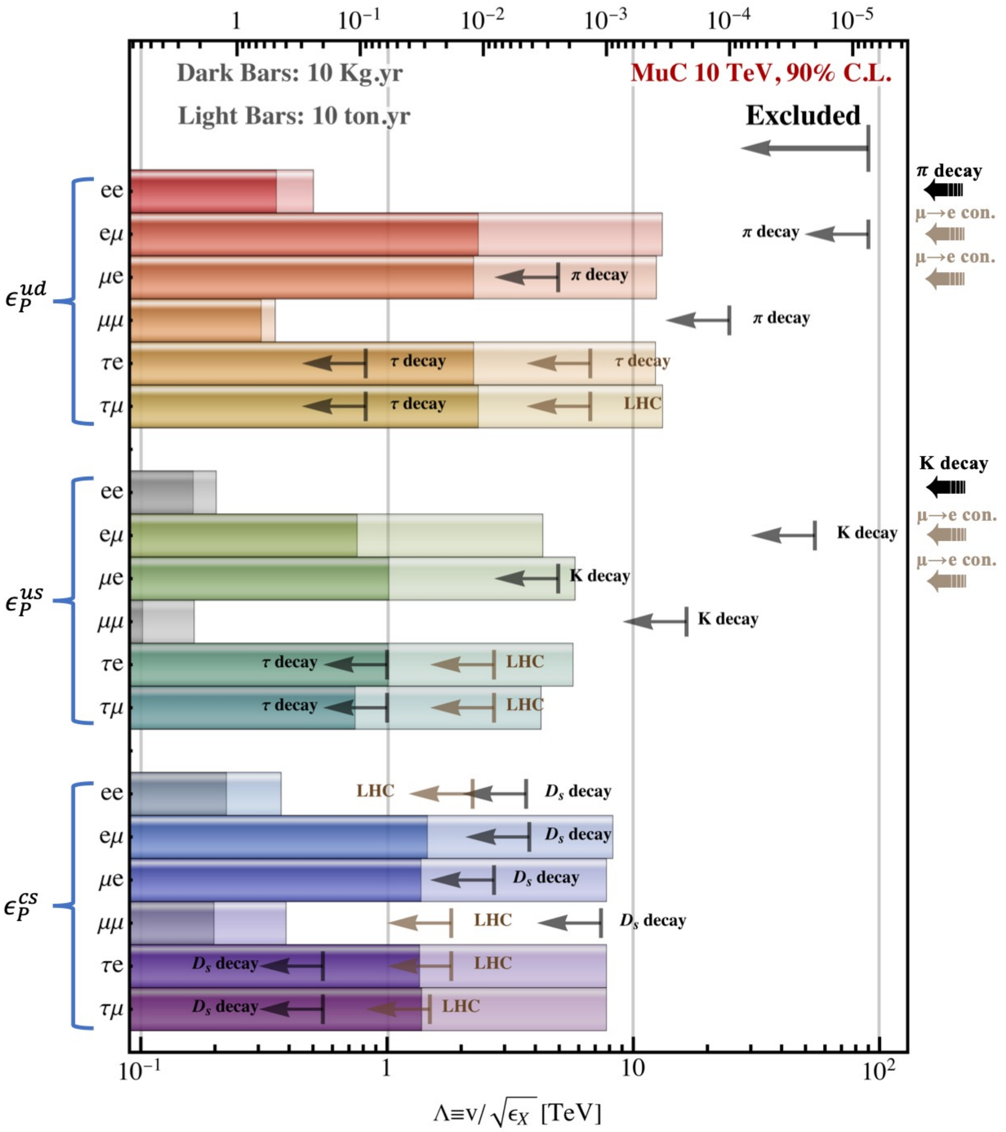
Neutrino EFT:

- MuColν: colored bars
- Dark/Light bars: 10 kg.year/10 ton.year



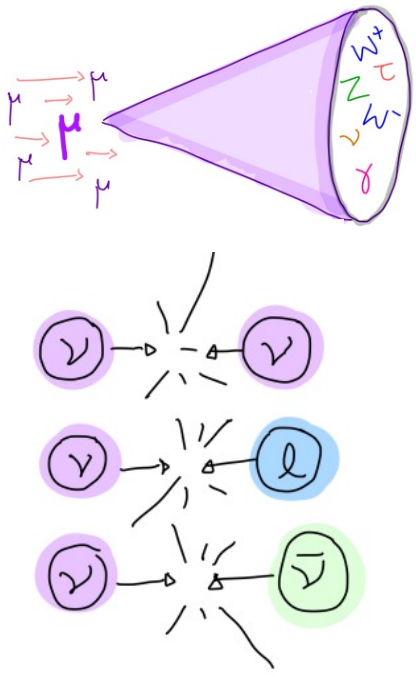
- New physics reach at tens of TeV
- Several dominant constraints

F. Kling, Y. Ma, K. Mękała, J. Reuter, **ZT**
arxiv: 2508.00761



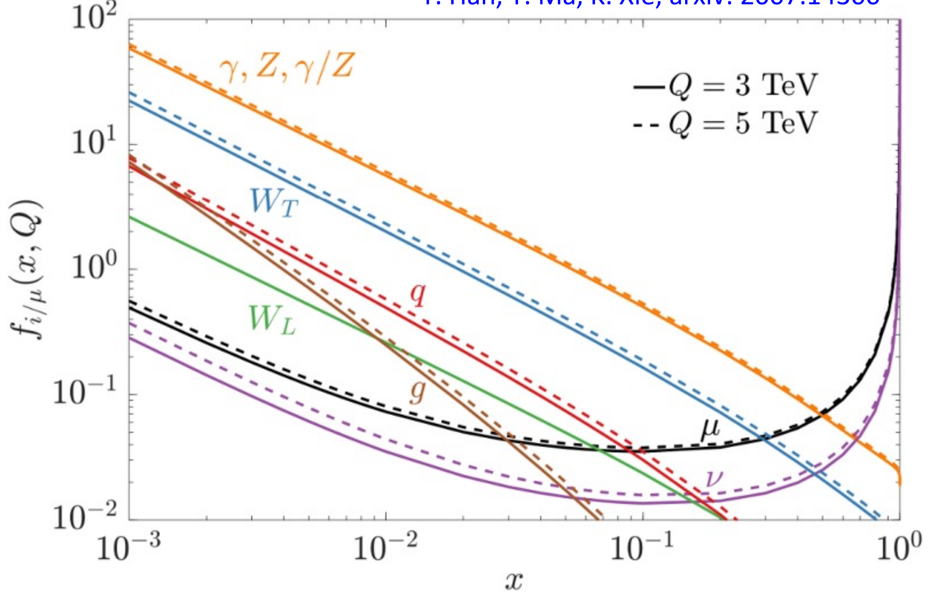
Neutrino-Neutrino Collider?

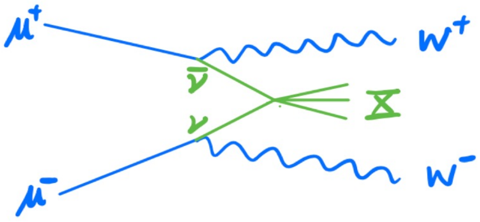
PDF from EW radiation



Credit: Innes Bigaran

T. Han, Y. Ma, K. Xie, arxiv: 2007.14300





High energy Muon Collider as a high energy Neutrino Collider

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

Neutrino-Neutrino Collider?

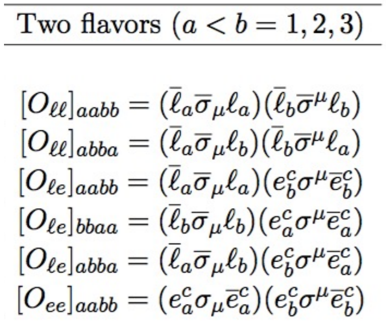
Flavor-conserving 4-lepton operators

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

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

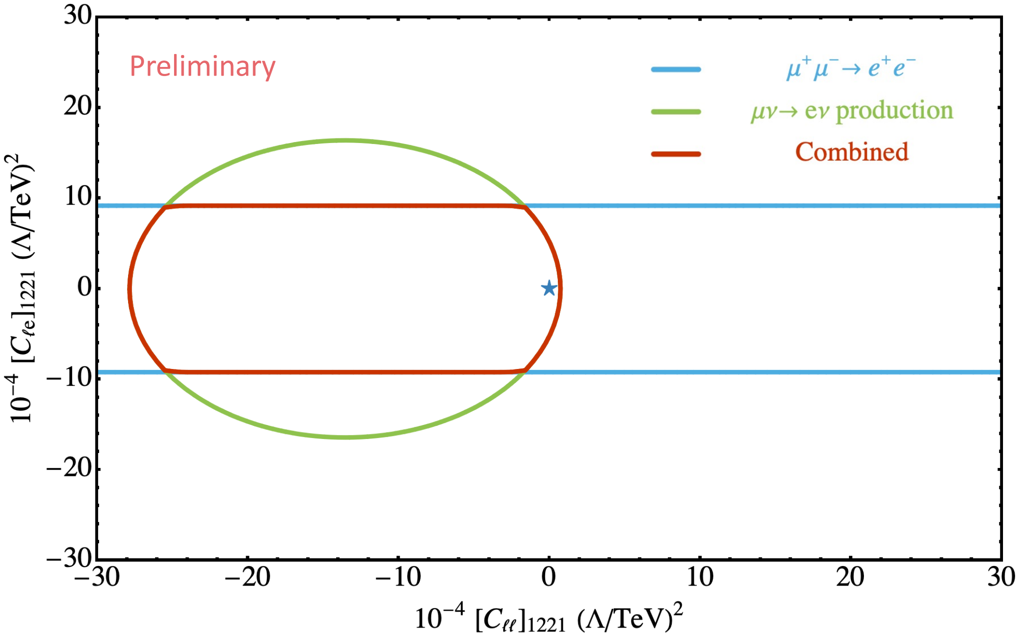
$\mu^\pm\nu$: $[C_{\ell\ell}]$, $[C_{\ell e}]$

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



Two flavors ($a < b = 1, 2, 3$)

$$[O_{\ell\ell}]_{aabb} = (\bar{\ell}_a\bar{\sigma}_\mu\ell_a)(\bar{\ell}_b\bar{\sigma}^\mu\ell_b)$$
$$[O_{\ell\ell}]_{abba} = (\bar{\ell}_a\bar{\sigma}_\mu\ell_b)(\bar{\ell}_b\bar{\sigma}^\mu\ell_a)$$
$$[O_{\ell e}]_{aabb} = (\bar{\ell}_a\bar{\sigma}_\mu\ell_a)(e^c_b\sigma^\mu\bar{e}^c_b)$$
$$[O_{\ell e}]_{bbaa} = (\bar{\ell}_b\bar{\sigma}_\mu\ell_b)(e^c_a\sigma^\mu\bar{e}^c_a)$$
$$[O_{\ell e}]_{abba} = (\bar{\ell}_a\bar{\sigma}_\mu\ell_b)(e^c_b\sigma^\mu\bar{e}^c_a)$$
$$[O_{ee}]_{aabb} = (e^c_a\sigma_\mu\bar{e}^c_a)(e^c_b\sigma^\mu\bar{e}^c_b)$$



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

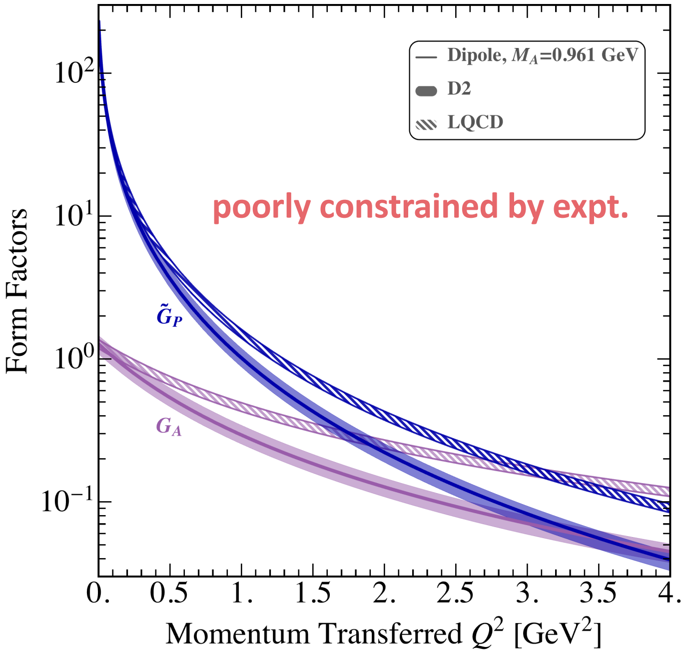
CCQE Hadronic Matrix Elements

Kopp, Rocco, <u>**ZT**</u>, JHEP (2024)

SM-Interactions:

Vector Current: Form Factors well understood (constrained by eN scattering)

Axial Current:


poorly constrained by expt.

NEW-Interactions:

Kopp, Rocco, ZT, JHEP (2024)

- We add new scalar, pseudo-scalar and tensor currents;
- Interference with the SM;
- New Cross Section Contributions;

NEW-Interactions:

Kopp, Rocco, ZT, JHEP (2024)

- We add new scalar, pseudo-scalar and tensor currents;
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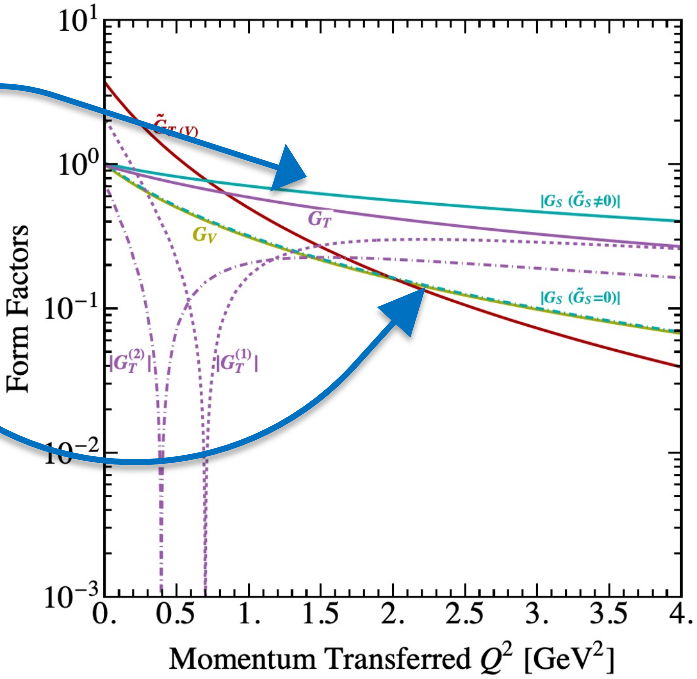


- **Scalar: conservation of the vector current (CVC):**

$$\boxed{G_S(Q^2) = -\frac{\delta M_N^{QCD}}{\delta m_q} G_V(Q^2) + \frac{Q^2/2M_N}{\delta m_q} \tilde{G}_S(Q^2)}$$

  - **We cannot neglect $\tilde{G}_S$ (second class current) anymore!**

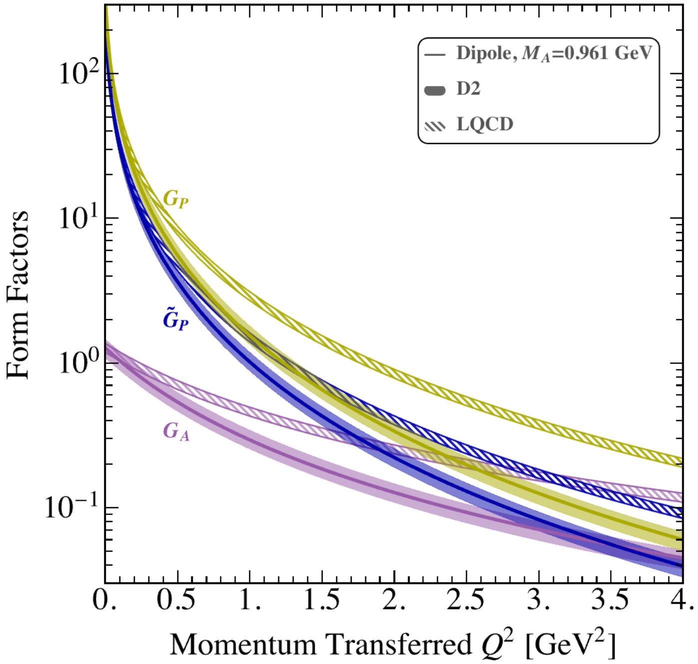
NEW-Interactions:

Kopp, Rocco, ZT, JHEP (2024)

- We add new scalar, pseudo-scalar and tensor currents;
- Interference with the SM;
- New Cross Section Contributions;

- **Pseudo-Scalar: partial conservation of the axial current (PCAC)**

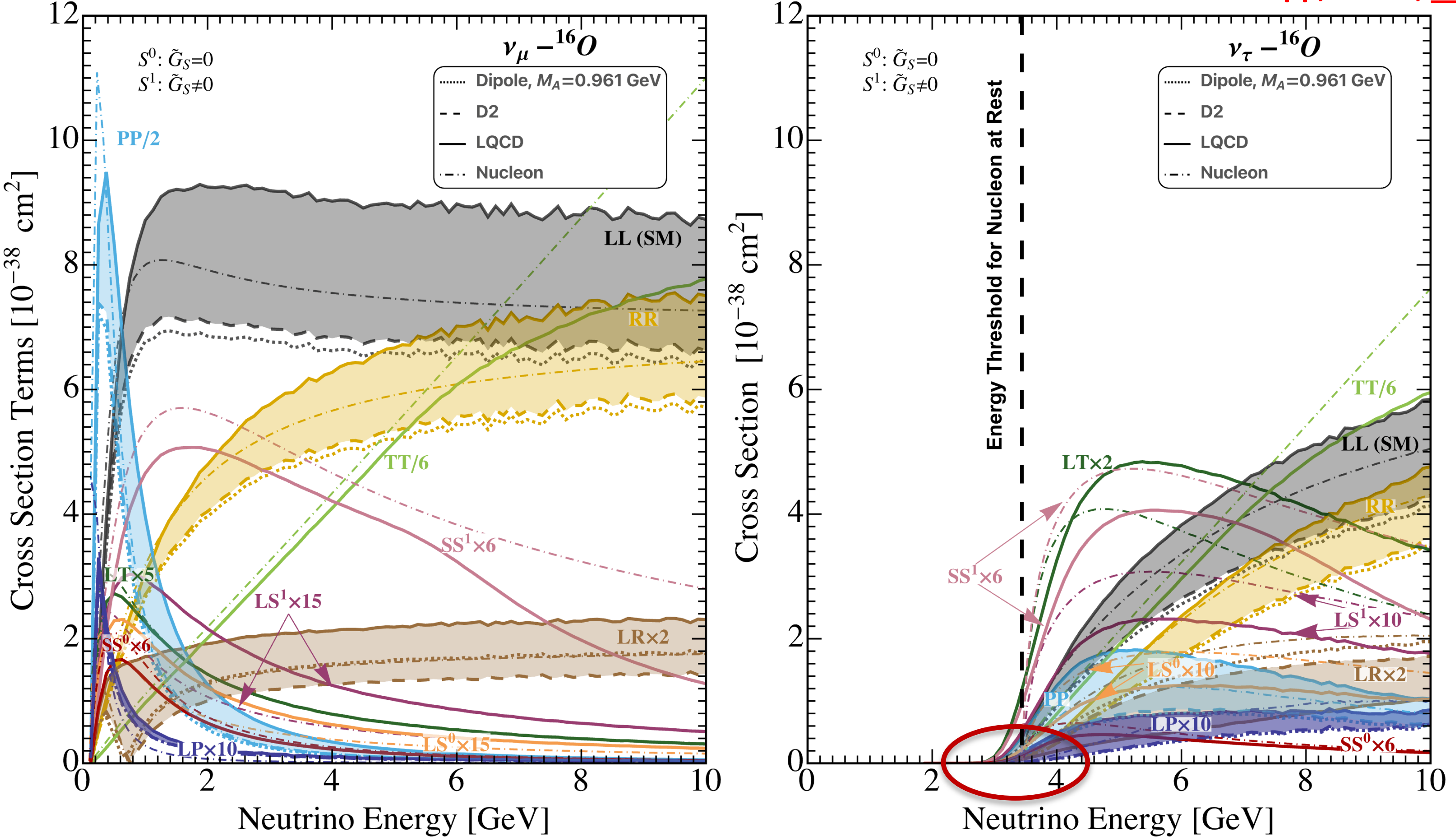
$$G_P(Q^2) = \frac{M_N}{m_q} G_A(Q^2) + \frac{Q^2/2M_N}{2m_q} \tilde{G}_P(Q^2)$$



- D2: neutrino-deuterium data (shaded band)
- RQCD Collaboration (hatched band)

CCQE Neutrino-Nucleus Cross Sections:

Kopp, Rocco, ZT, JHEP (2024)



- ○ CCQE Neutrino-Nucleus Scattering;
- ○ All non-standard interactions;
- ○ For all neutrino Flavors;
- ○ z-expansion fit to LQCD and D2 data;
- ○ Nuclear effects;
- ○ Comparison with nucleon scattering

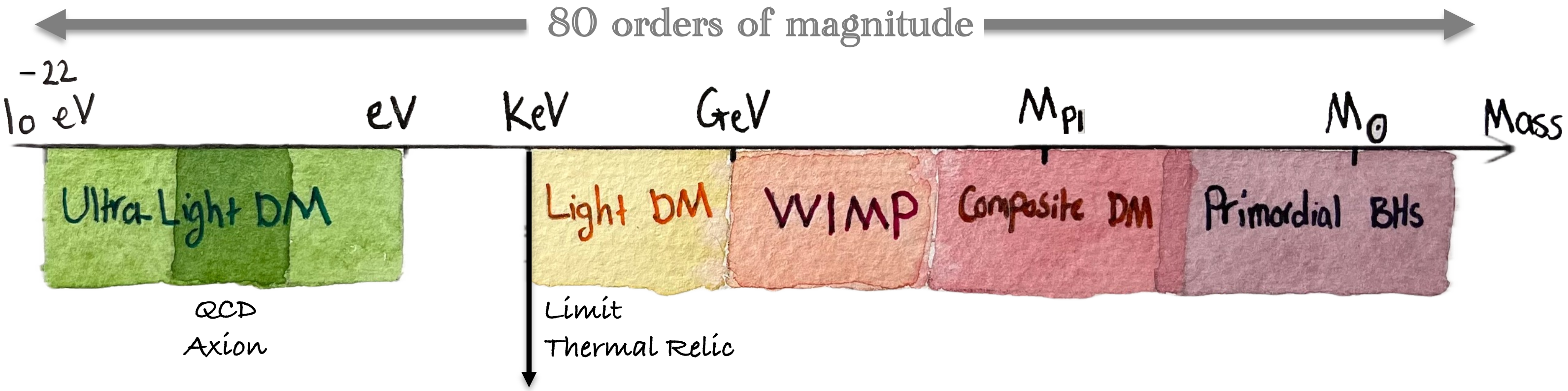
“What is Dark Matter?”

We don’t know!

There could be several kinds, making up a whole “dark sector”

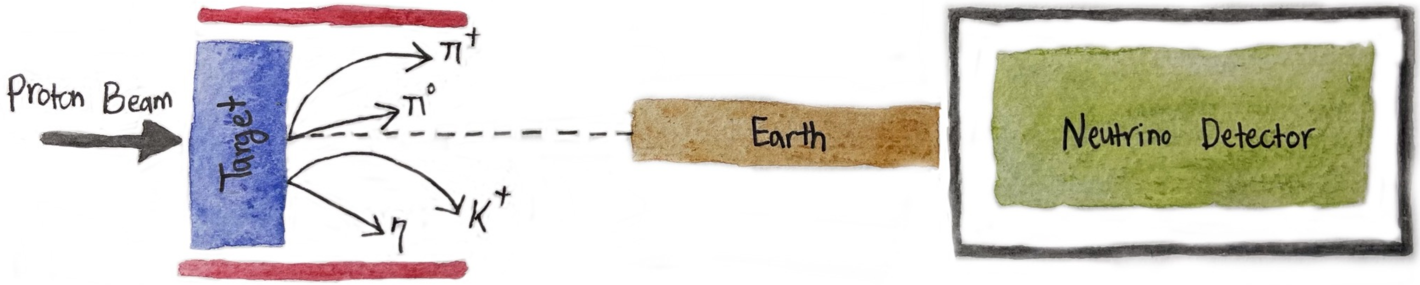
“Where is Dark Matter?”

We don’t know!



80 orders of magnitude

Light Dark Matter

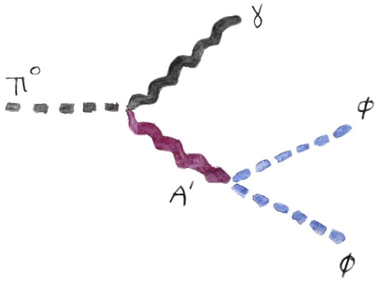


Photons at the target kinetically produce Dark Photons, which decay into dark matter:

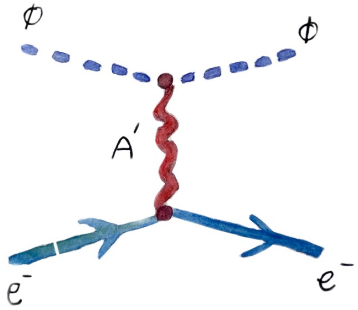
$$\mathcal{L} \supset -\frac{\varepsilon}{2}F^{\mu\nu}F'_{\mu\nu} + \frac{M^2_{A'}}{2}A'_\mu A'^\mu + |D_\mu\phi|^2 - M^2_\phi\,|\phi|^2$$

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

DM production

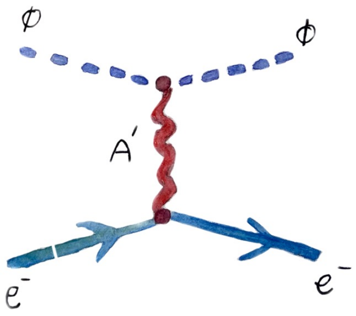


DM detection



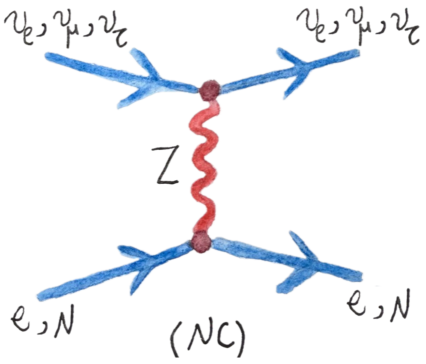
Light Dark Matter

DM signal: elastic scattering on electrons

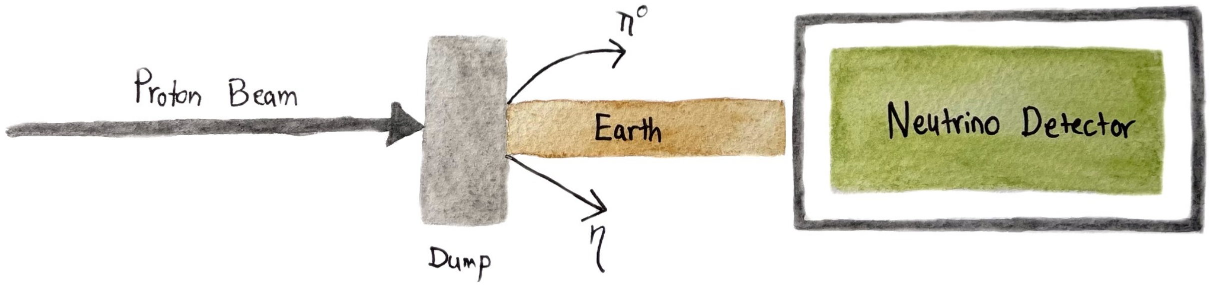


How can we get rid of neutrinos in a neutrino detector?

But so do neutrinos!



Proposing a movable target system at DUNE



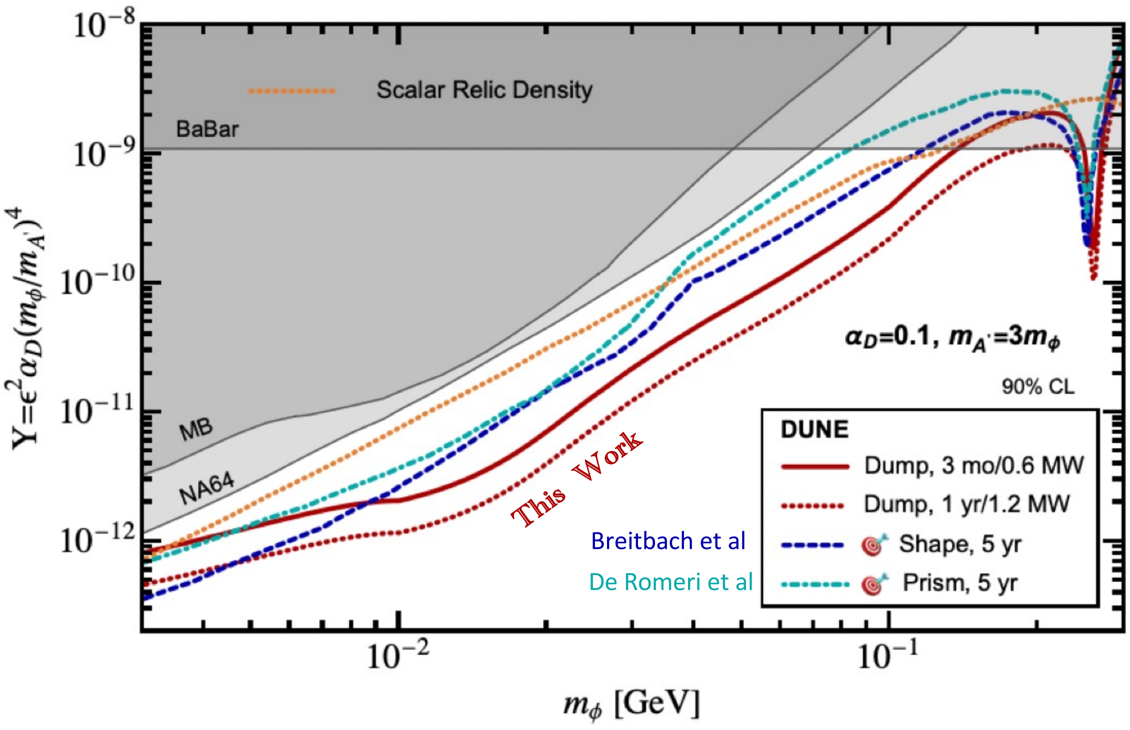
We can dump protons directly to the dump area!

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)

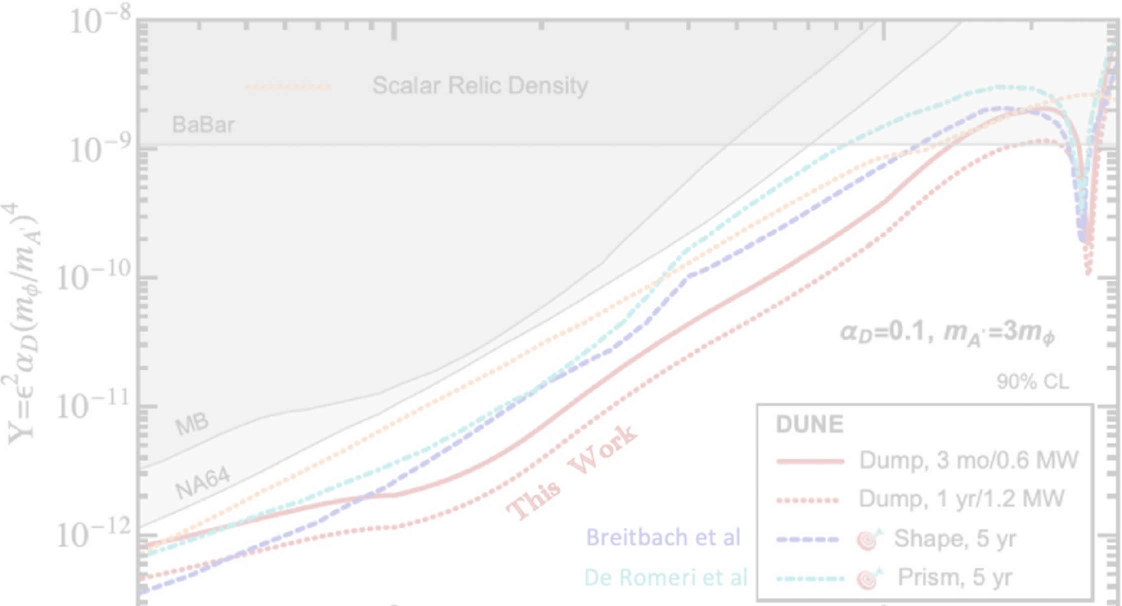
Light Dark Matter at Targetless DUNE



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!

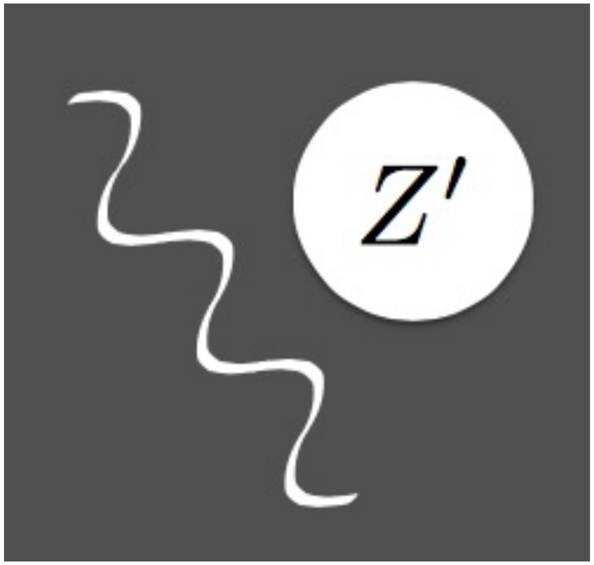
Light Dark Matter at Targetless DUNE



For DM searches, a neutrino detector could even do better than a dedicated DM experiment!

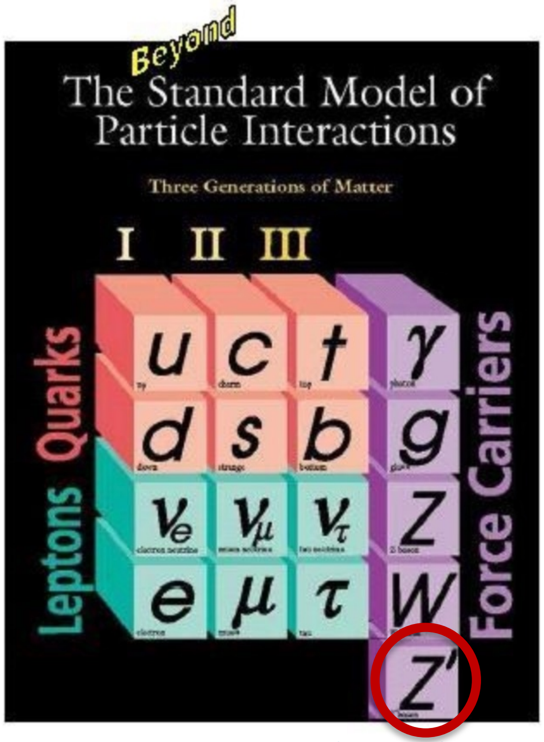
pace

- 1) Direct Search of Dark Sectors:
  - ALPs ✓
  - Light Dark Matter ✓
  - Light Z’
- 2) Indirect Search-EFT:
  - Why EFT?
  - EFT ladder
  - EFT at Neutrino Experiments
- Conclusion



A new gauge boson?

Hypothetical gauge boson that appear in many extensions of the standard model



The Z' Hunter's Guide

- What is its mass?
- Which particles does it talk to?

Light Z'

- **Low Energy Experiments**

  Miranda et al, JHEP (2020)
  Coloma et al, JHEP (2021)
  Caddedu et al, JHEP (2021)

- **Fixed Target Experiments**

  Gninenko, PLB (2012)
  Tsai et al, PRL (2021)
  Bauer et al, JHEP (2018)

- **Neutrino Trident Searches**

  Altmannshofer et al, PRL (2014)
  Ballet et al, JHEP (2019)

- **Neutrino-Electron Scattering**

  Harnic et al, JCAP (2012)
  Lindner et al, JHEP (2018)
  Ballet et al, JHEP (2019)

- **Colliders**

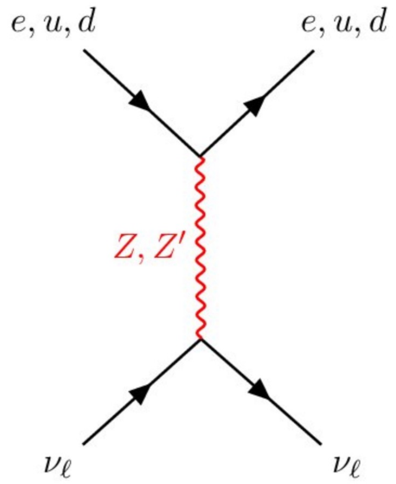
  BaBar Collaboration, PRL (2014)
  BaBar Collaboration, PRL (2017)

- **Cosmology**

  Escudero et al, JHEP (2019)

What can we learn from neutrino experiments?

$$\mathcal{L}_{Z'}^{\text{matter}} = -g'\left(a_u\,\bar{u}\gamma^\alpha u + a_d\,\bar{d}\gamma^\alpha d + a_e\,\bar{e}\gamma^\alpha e \right.$$
$$\left. + b_e\,\bar{\nu}_e\gamma^\alpha P_L\nu_e + b_\mu\,\bar{\nu}_\mu\gamma^\alpha P_L\nu_\mu + b_\tau\,\bar{\nu}_\tau\gamma^\alpha P_L\nu_\tau\right) Z'_\alpha$$



news.fnal.gov

The list is far from being exhaustive!

Light Z'

- Low Energy Experiments

  Miranda et al, JHEP (2020)
  Coloma et al, JHEP (2021)
  Caddedu et al, JHEP (2021)

- Fixed Target Experiments

  Gninenko, PLB (2012)
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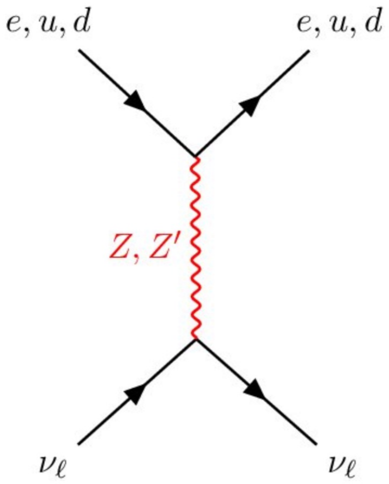
- Cosmology

  Escudero et al, JHEP (2019)

What can we learn from neutrino experiments?

$$\mathcal{L}^{\text{matter}}_{Z'} = -g'\big(a_u\,\bar{u}\gamma^\alpha u + a_d\,\bar{d}\gamma^\alpha d + a_e\,\bar{e}\gamma^\alpha e$$
$$+\, b_e\,\bar{\nu}_e\gamma^\alpha P_L\nu_e + b_\mu\,\bar{\nu}_\mu\gamma^\alpha P_L\nu_\mu + b_\tau\,\bar{\nu}_\tau\gamma^\alpha P_L\nu_\tau\big)Z'_\alpha$$



news.fnal.gov

The list is far from being exhaustive!

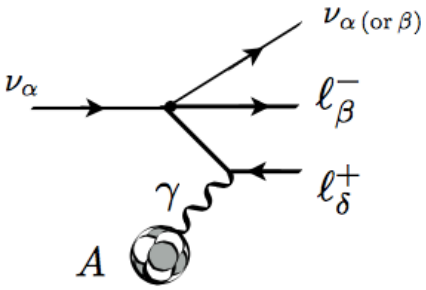
Neutrino Trident Scattering

Production of a **charged lepton pair**

in the scattering of a **neutrino**

in the Coulomb field of a **heavy nucleus/nucleon**

$$\nu_\alpha + \mathcal{N} \rightarrow \nu_\beta + \ell^+_\gamma + \ell^-_\delta + \mathcal{N}$$



CHARM II

PLB (1990)

$$\frac{\sigma_{\text{CHARM II}}}{\sigma_{\text{SM}}} = 1.58 \pm 0.57$$

CCFR

PRL (1991)

$$\frac{\sigma_{\text{CCFR}}}{\sigma_{\text{SM}}} = 0.82 \pm 0.28$$

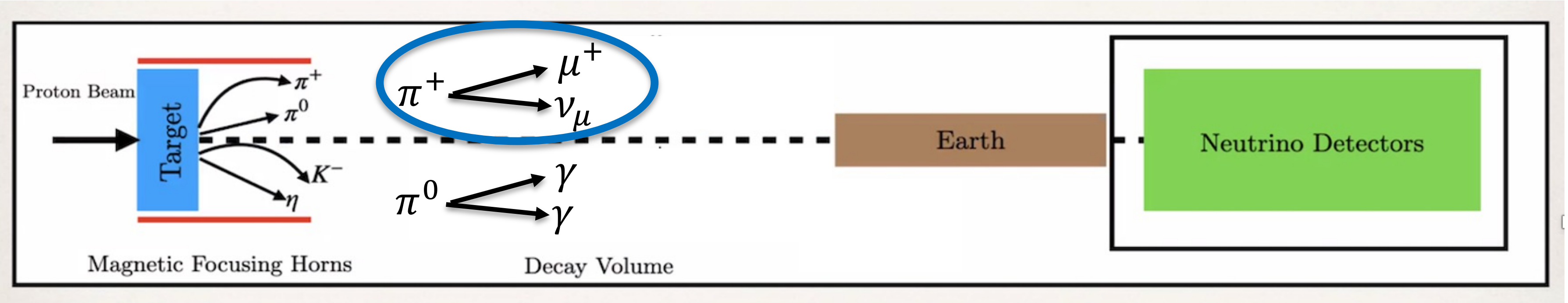
NuTeV

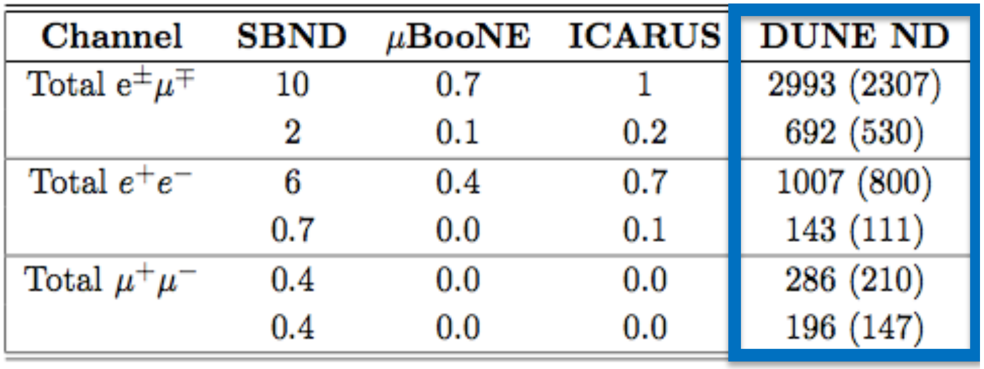
Vancouver 1998,
High energy physics, vol 1

$$\frac{\sigma_{\text{NuTeV}}}{\sigma_{\text{SM}}} = 0.67 \pm 0.27$$

- Very large uncertainties
- Very few events observed (~100)

Trident rates at LAr Detectors





Channel	SBND	μBooNE	ICARUS	DUNE ND
Total $e^\pm\mu^\mp$	10	0.7	1	2993 (2307)
	2	0.1	0.2	692 (530)
Total e^+e^-	6	0.4	0.7	1007 (800)
	0.7	0.0	0.1	143 (111)
Total $\mu^+\mu^-$	0.4	0.0	0.0	286 (210)
	0.4	0.0	0.0	196 (147)

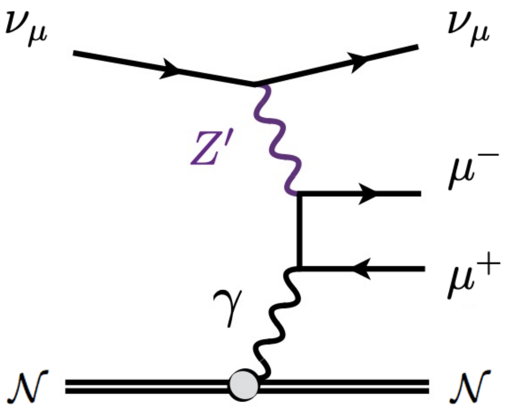
Coherent (upper) and diffractive (lower) trident events for (anti)neutrino mode

More than 9,000 trident events at DUNE!

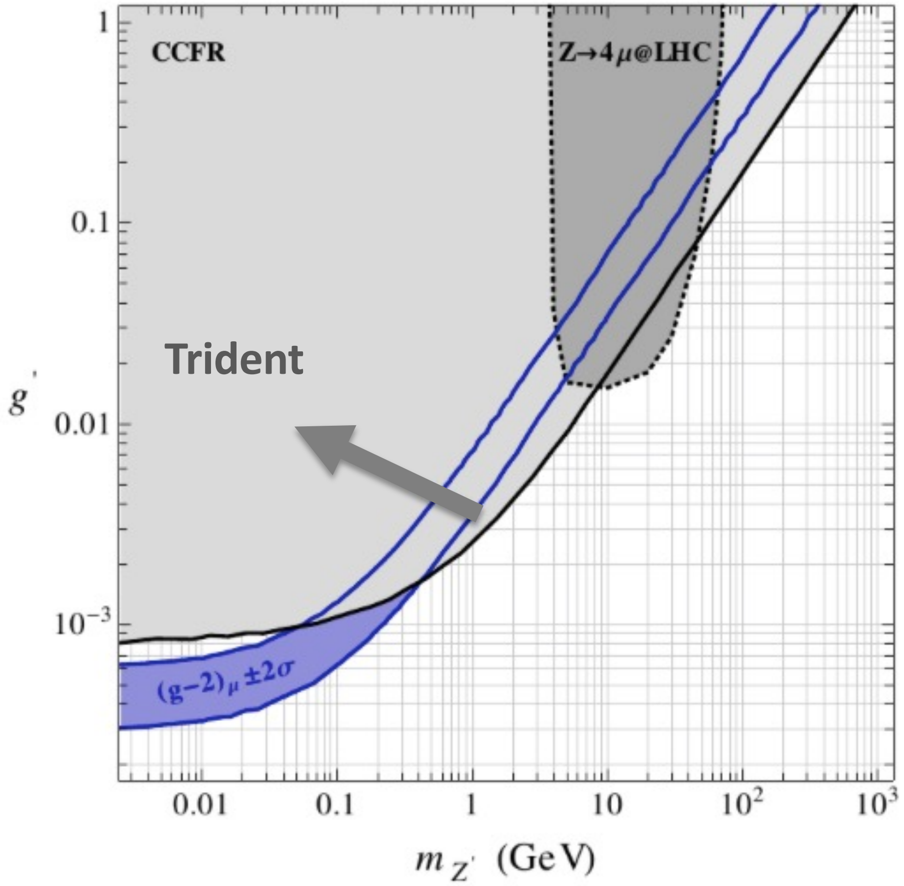
Ballett, Hostert, Pascoli, Perez-Gonzalez, *ZT* and Funchal, PRD (2019)

Light Z’: L_μ-L_τ Model

- Z’ only couples to muon and tau, but not to electrons;
- It can explain the muon (g-2) anomaly;
- Can be best probed using tridents;



HE colliders only have access to large masses!

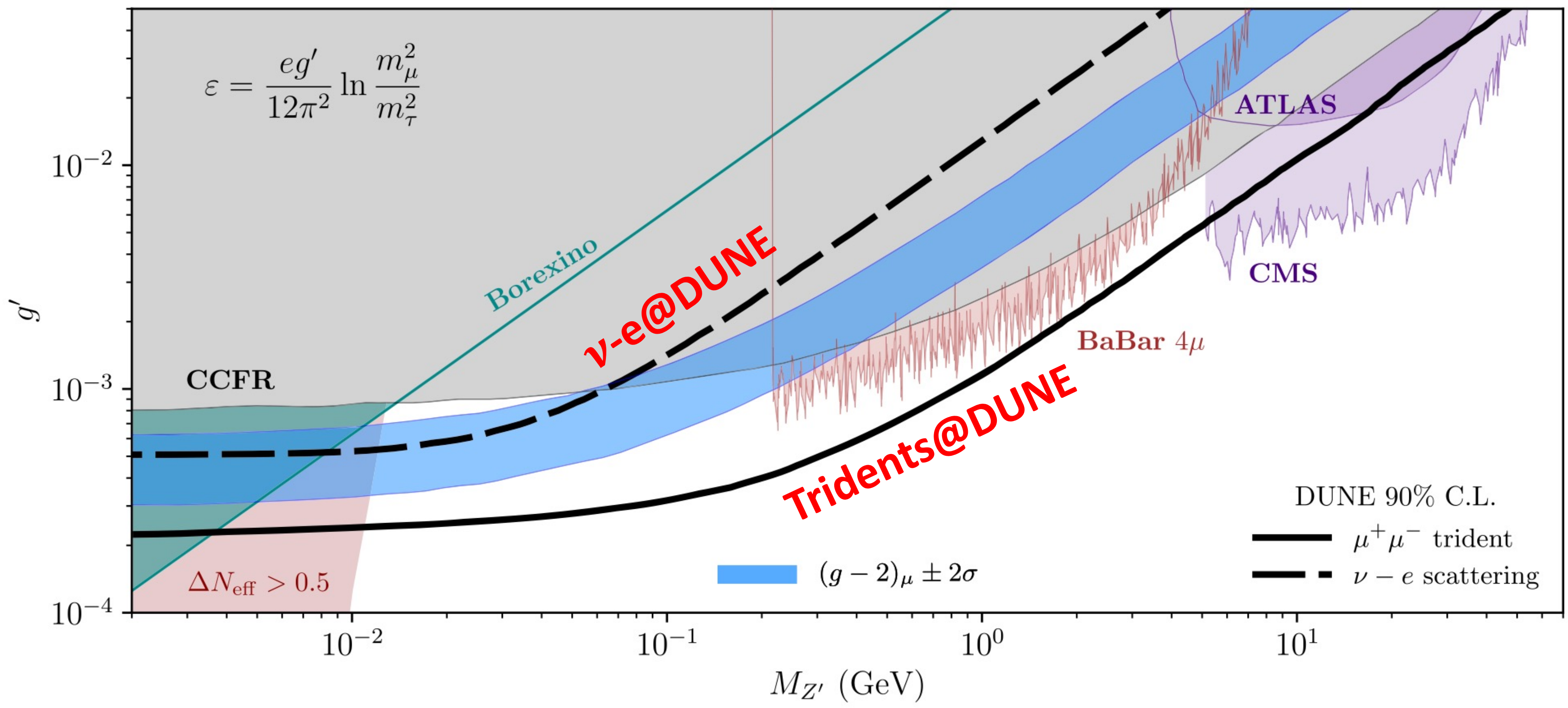


Altmannshofer, Gori, Pospelov, Yavin, PRL (2014)

Light Z’: L_μ-L_τ Model

Ballett, Hostert, Pascoli, Perez-Gonzalez, *ZT* and Funchal, PRD (2019)

DUNE



The whole g-2 region can be probed by DUNE data!

EPA assumptions

1) Neglecting the L contribution ($h^{\mathrm{L}}(q^2,\hat{s})\,\sigma^{\mathrm{L}}_{\nu\gamma}(q^2,\hat{s}) \approx 0$).

2) Taking the T contribution of the cross section to be on-shell ($\sigma^{\mathrm{T}}_{\nu\gamma}(q^2,\hat{s}) \approx \sigma^{\mathrm{T}}_{\nu\gamma}(0,\hat{s})$).

$$\sigma_{\mathrm{t}}(P_i + C_s \to P_f + C_s) \approx \int dP(Q^2,\hat{s})\,\sigma_\gamma(P_i + \gamma \to P_f; \hat{s}, Q^2 = 0)$$

QED

$$\sigma_\gamma^{\mathrm{QED}}(P_i + \gamma \to P_f; \hat{s}, 0) \propto \frac{1}{\hat{s}}$$

Decreases with
increasing transferred
four-momentum

On-shell >> off-shell

Fermi Limit of the SM

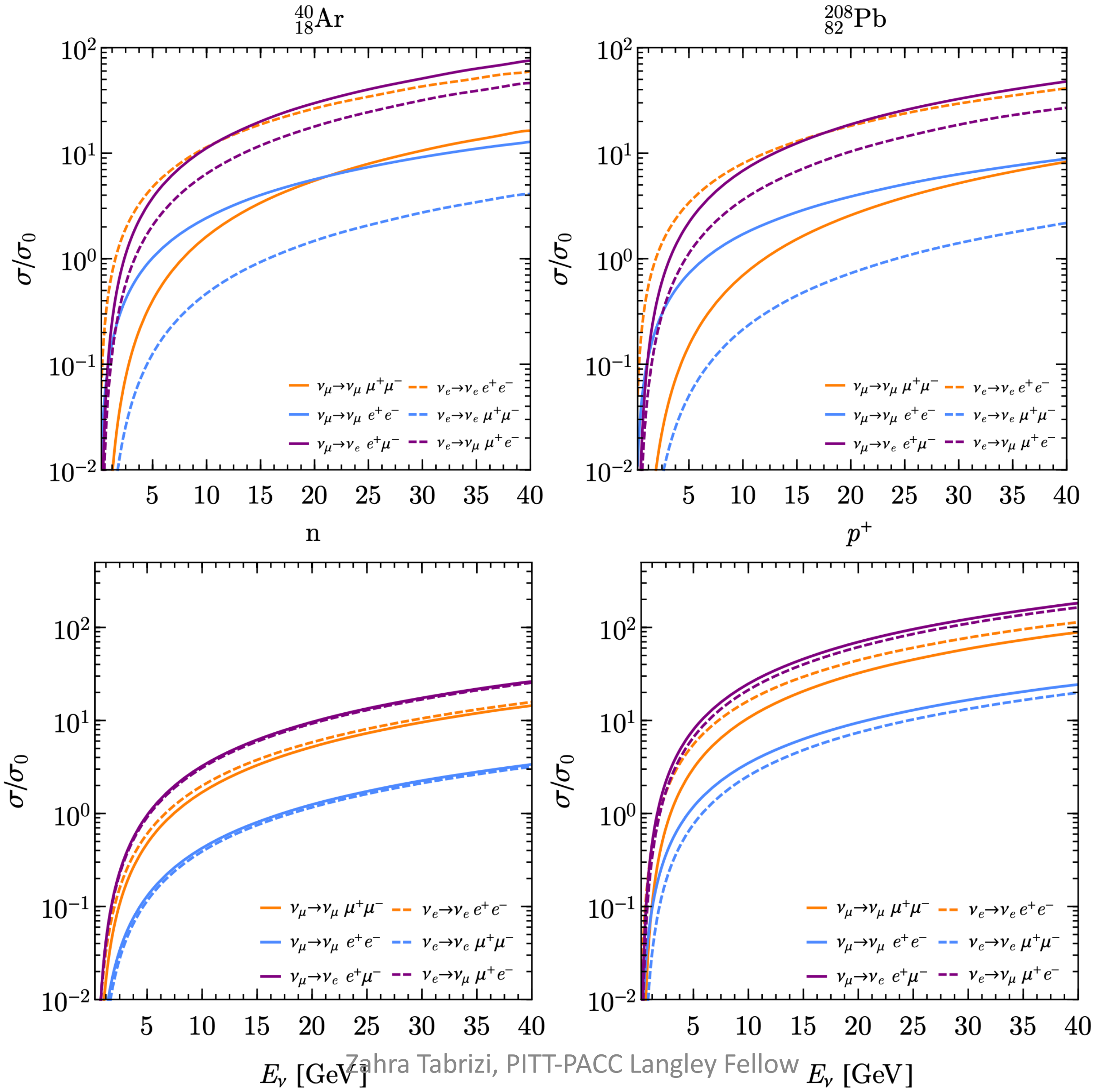
$$\sigma_\gamma^{\mathrm{FL}}(P_i + \gamma \to P_f; \hat{s}, 0) \propto G_{\mathrm{F}}^2\,\hat{s}$$

Increases with
increasing transferred
four-momentum

On-shell << off-shell

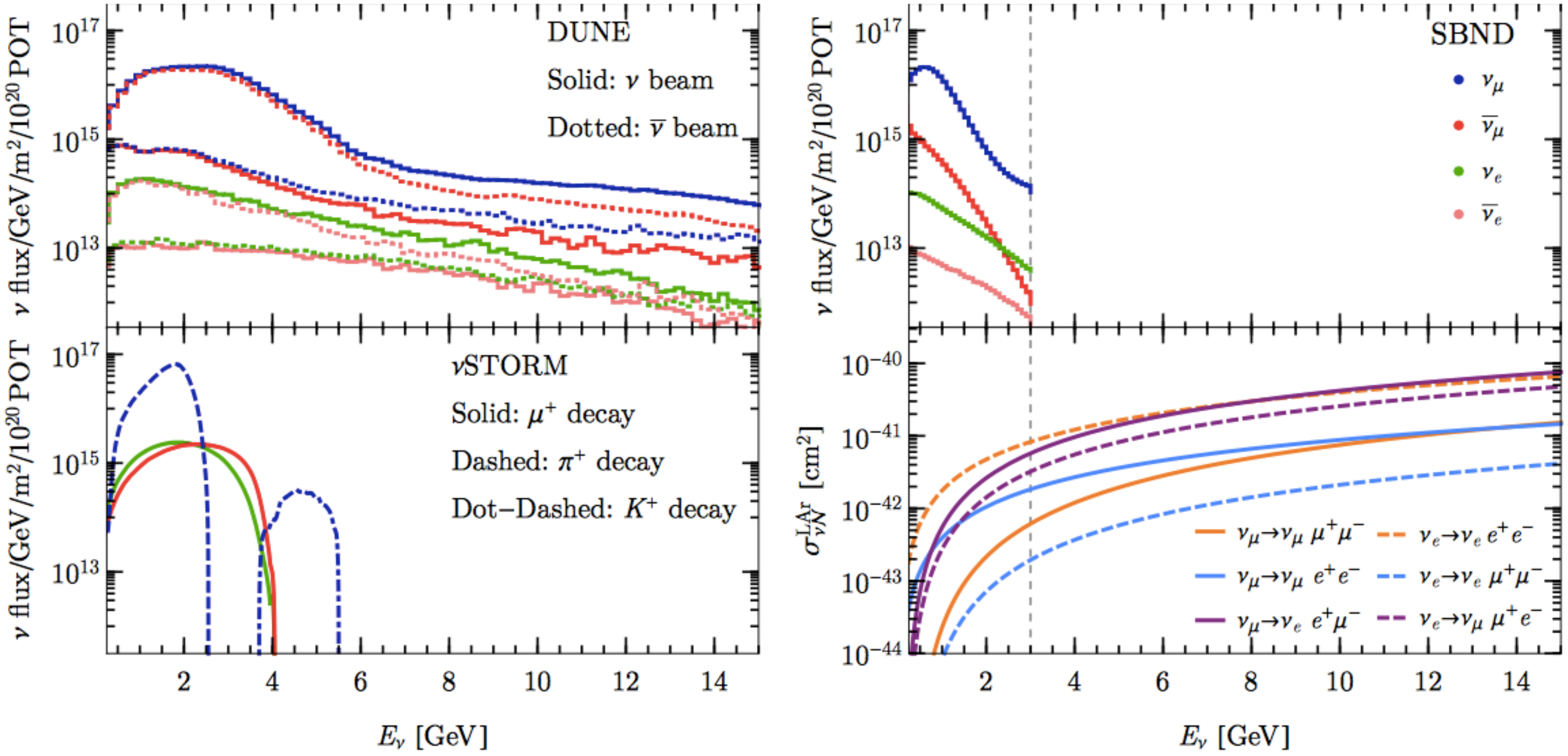
Ballett, Hostert, Pascoli, Perez, **ZT** and Funchal
JHEP **1901**, 119 (2019)

Trident Cross Sections



Trident rates at LAr Detectors

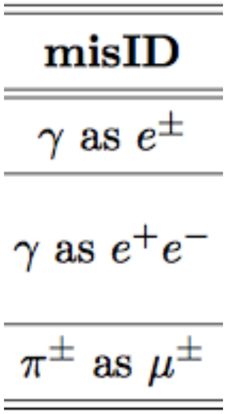
$$N = \text{time} \times \#\text{ of targets} \times \text{efficiency} \times \int_{E_i}^{E_f} dE_\nu \frac{d\phi(E_\nu)}{dE_\nu}\sigma(E_\nu)$$



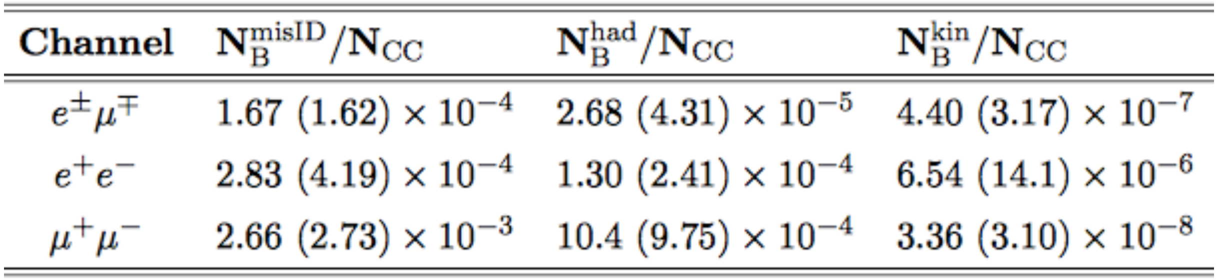
Ballett, Hostert, Pascoli, Perez, **ZT** and Funchal
JHEP **1901**, 119 (2019)

Trident background analysis

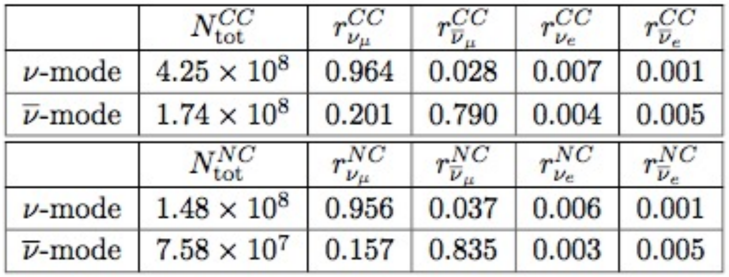
Genuine dilepton production is rare, but misID of particles is the problem.



misID
γ as $e^{\pm}$
γ as $e^{+}e^{-}$
$\pi^{\pm}$ as $\mu^{\pm}$



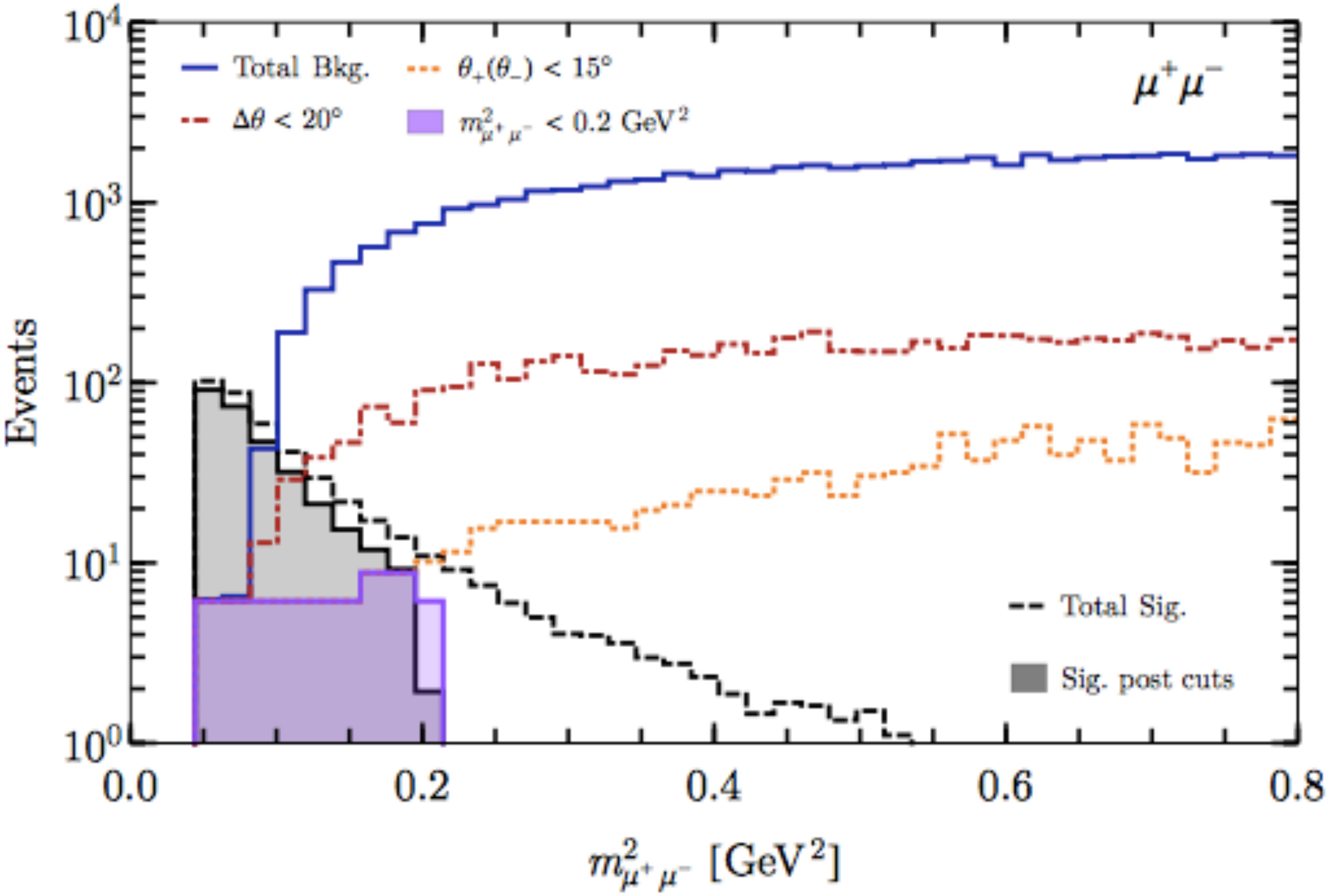
Channel	$\mathrm{N}_{\mathrm{B}}^{\mathrm{misID}}/\mathrm{N}_{\mathrm{CC}}$	$\mathrm{N}_{\mathrm{B}}^{\mathrm{had}}/\mathrm{N}_{\mathrm{CC}}$	$\mathrm{N}_{\mathrm{B}}^{\mathrm{kin}}/\mathrm{N}_{\mathrm{CC}}$
$e^{\pm}\mu^{\mp}$	$1.67\ (1.62) \times 10^{-4}$	$2.68\ (4.31) \times 10^{-5}$	$4.40\ (3.17) \times 10^{-7}$
$e^{+}e^{-}$	$2.83\ (4.19) \times 10^{-4}$	$1.30\ (2.41) \times 10^{-4}$	$6.54\ (14.1) \times 10^{-6}$
$\mu^{+}\mu^{-}$	$2.66\ (2.73) \times 10^{-3}$	$10.4\ (9.75) \times 10^{-4}$	$3.36\ (3.10) \times 10^{-8}$



	N_{tot}^{CC}	$r_{\nu_\mu}^{CC}$	$r_{\overline{\nu}_\mu}^{CC}$	$r_{\nu_e}^{CC}$	$r_{\overline{\nu}_e}^{CC}$
ν-mode	4.25×10^{8}	0.964	0.028	0.007	0.001
$\overline{\nu}$-mode	1.74×10^{8}	0.201	0.790	0.004	0.005
	N_{tot}^{NC}	$r_{\nu_\mu}^{NC}$	$r_{\overline{\nu}_\mu}^{NC}$	$r_{\nu_e}^{NC}$	$r_{\overline{\nu}_e}^{NC}$
ν-mode	1.48×10^{8}	0.956	0.037	0.006	0.001
$\overline{\nu}$-mode	7.58×10^{7}	0.157	0.835	0.003	0.005

Reaching background rates of O(10^{-6}–10^{-5}) times the CC rate is necessary to observe trident events at DUNE ND, which is an attainable goal in a LAr detectors.

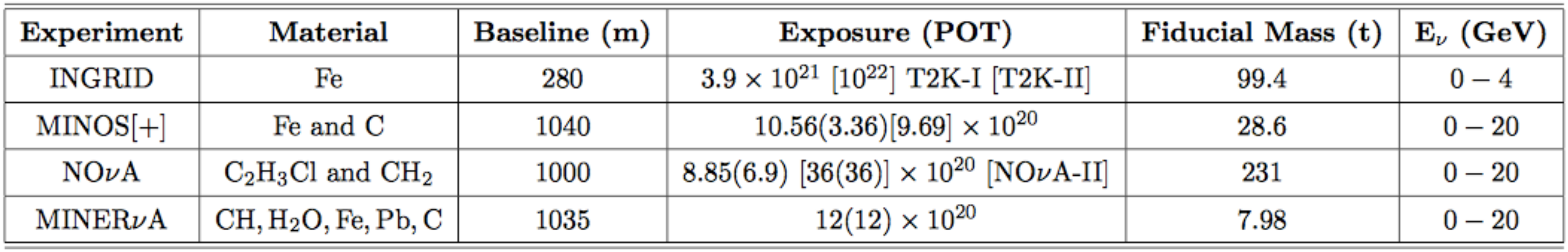
Ballett, Hostert, Pascoli, Perez, **ZT** and Funchal
JHEP **1901**, 119 (2019)



We apply consecutive cuts on the background, starting with cuts on the separation angle Δθ (red), both charged lepton angles to the beamline (θ_+ and θ_-) (orange) and the invariant mass.

Ballett, Hostert, Pascoli, Perez, **ZT** and Funchal
JHEP **1901**, 119 (2019)

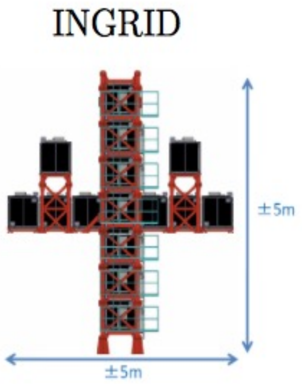
Trident rates at other Near Detectors

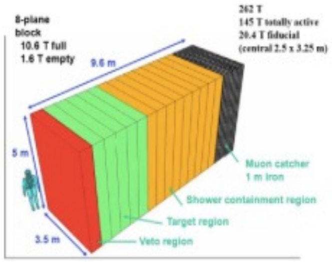


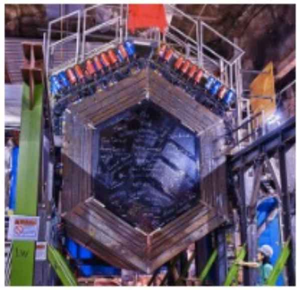
Experiment	**Material**	**Baseline (m)**	**Exposure (POT)**	**Fiducial Mass (t)**	**E_ν (GeV)**
INGRID	Fe	280	3.9×10^{21} [10^{22}] T2K-I [T2K-II]	99.4	$0 - 4$
MINOS[+]	Fe and C	1040	$10.56(3.36)[9.69] \times 10^{20}$	28.6	$0 - 20$
NOνA	C_2H_3Cl and CH_2	1000	$8.85(6.9)$ $[36(36)] \times 10^{20}$ [NOνA-II]	231	$0 - 20$
MINERνA	CH, H_2O, Fe, Pb, C	1035	$12(12) \times 10^{20}$	7.98	$0 - 20$

All have finished data taking or are still running

Trident rates at other Near Detectors







Channel	T2K-I	T2K-II	MINOS	MINOS+	NOνA-I	NOνA-II	MINERνA
Total $e^{\pm}\mu^{\mp}$	563	1444	222 (56)	730	83 (72)	340 (374)	149 (102)
	96	246	46 (11)	151	25 (22)	102 (114)	56 (39)
Total e^+e^-	277	711	61 (15)	62	29 (22)	119 (114)	39 (27)
	24	62	9 (2)	8	4 (4)	16 (21)	10 (7)
Total $\mu^+\mu^-$	30	76	26 (6)	86	9 (9)	37 (47)	18 (13)
	21	54	15 (3)	49	8 (8)	34 (36)	18 (13)

Coherent (upper) and diffractive (lower) trident events for (anti)neutrino mode.

Ballett, Hostert, Pascoli, Perez, **ZT** and Funchal
JHEP **1901**, 119 (2019)

- We study potential constraints which can be placed on a general set of leptophilic Z′ models in the two most likely channels for BSM scattering at the near detector of DUNE: neutrino-electron scattering and neutrino trident scattering.

$$\mathcal{L} \supset -g' Z'_\mu \left[Q^{\rm L}_\alpha \, \overline{L^\alpha_L} \gamma^\mu L^\alpha_L + Q^{\rm R}_\alpha \, \overline{\ell^\alpha_R} \gamma^\mu \ell^\alpha_R + \sum_{\rm N} Q_{\rm N} \, \overline{N_R} \gamma^\mu N_R \right]$$

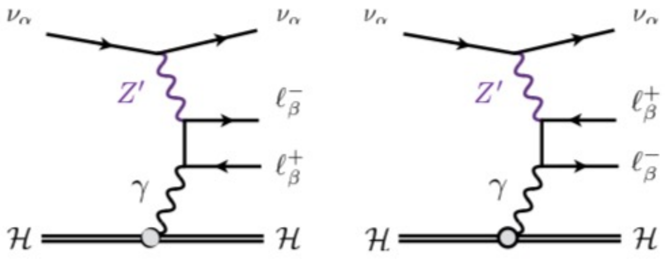
- We focus on the anomaly free leptophilic extensions of the SM:
  $L_\alpha - L_\beta$, $\alpha,\beta = \{e,\mu,\tau\}$, $\alpha \neq \beta$.

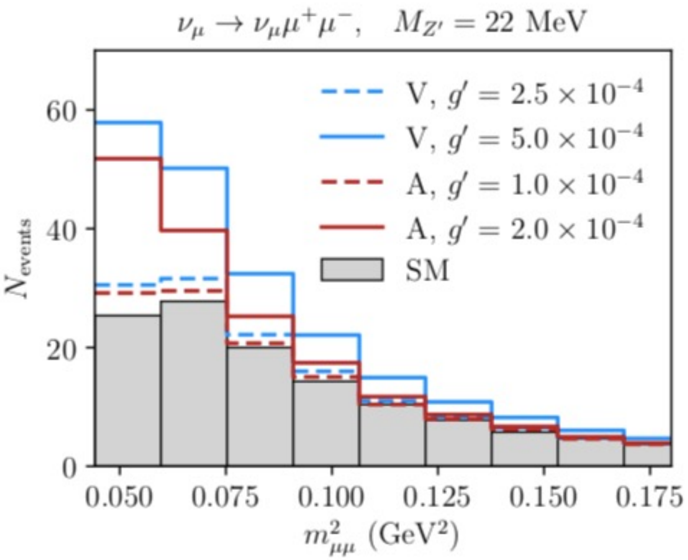
- Anomaly free conditions fix the charges

Ballett, Hostert, Pascoli, Perez-Gonzalez, **ZT** and Funchal
Phys.Rev. **D100** (2019) no.5, 055012

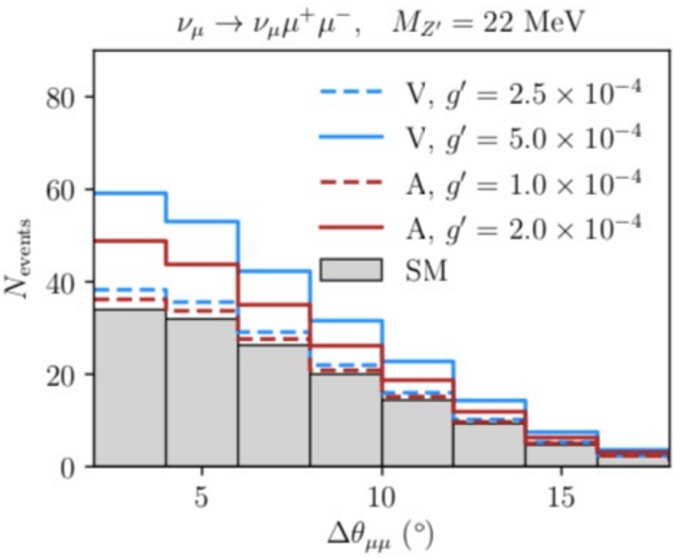
Trident kinematical distributions

$$\hat{V}_{\alpha\beta} = g_V^{\ell_\beta} + \delta_{\alpha\beta} + \frac{Q_\alpha^L Q_\beta^V}{2\sqrt{2}G_F}\frac{(g')^2}{K^2 + M_{Z'}^2}, \quad \hat{A}_{\alpha\beta} = g_A^{\ell_\beta} + \delta_{\alpha\beta} + \frac{Q_\alpha^L Q_\beta^A}{2\sqrt{2}G_F}\frac{(g')^2}{K^2 + M_{Z'}^2}$$





The invariant mass



Charged lepton separation angle

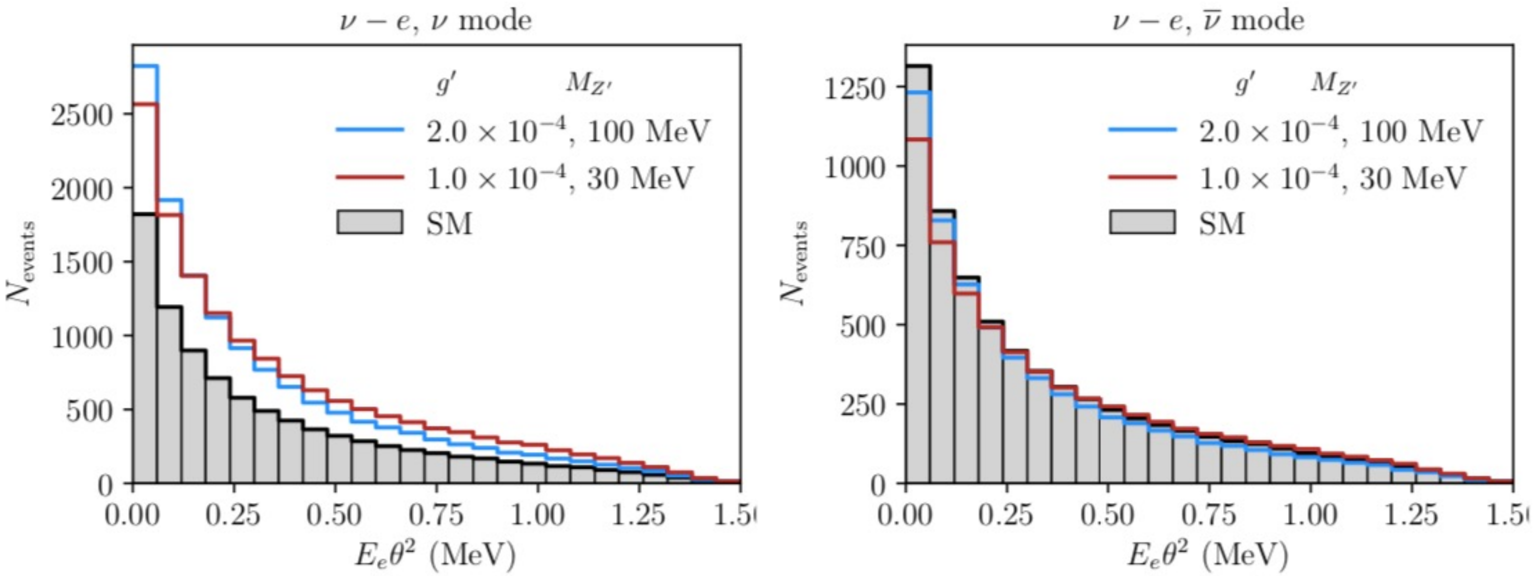
Ballett, Hostert, Pascoli, Perez-Gonzalez, **ZT** and Funchal
Phys.Rev. **D100** (2019) no.5, 055012

Neutrino-Electron scattering

The vector and axial couplings with Z':

$$C_\alpha^{\rm V} = -\frac{1}{2} + 2s_{\rm W}^2 + \delta_{\alpha e} + \frac{Q_e^{\rm V} Q_\alpha^{\rm L}}{2\sqrt{2}G_F}\frac{(g')^2}{M_{Z'}^2 + 2m_e T_e},$$

$$C_\alpha^{\rm A} = -\frac{1}{2} + \delta_{\alpha e} + \frac{Q_e^{\rm A} Q_\alpha^{\rm L}}{2\sqrt{2}G_F}\frac{(g')^2}{M_{Z'}^2 + 2m_e T_e},$$



Ballett, Hostert, Pascoli, Perez-Gonzalez, **ZT** and Funchal
Phys.Rev. **D100** (2019) no.5, 055012

Neutrino-Electron scattering

The vector and axial couplings with Z':

$$C_\alpha^{\mathrm{V}} = -\frac{1}{2} + 2s_{\mathrm{W}}^2 + \delta_{\alpha e} + \frac{Q_e^{\mathrm{V}} Q_\alpha^{\mathrm{L}}}{2\sqrt{2}G_F} \frac{(g')^2}{M_{Z'}^2 + 2m_e T_e},$$

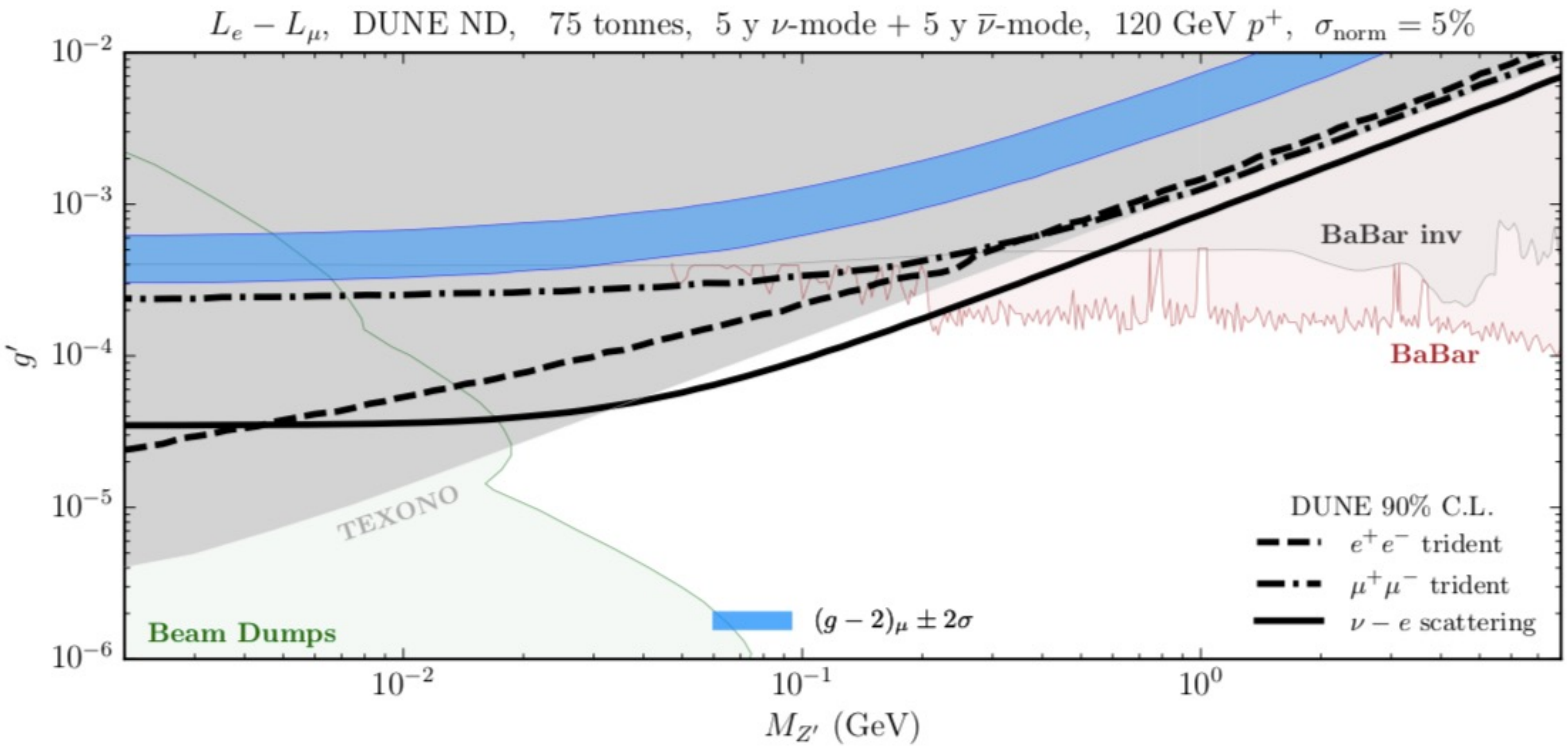
$$C_\alpha^{\mathrm{A}} = -\frac{1}{2} + \delta_{\alpha e} + \frac{Q_e^{\mathrm{A}} Q_\alpha^{\mathrm{L}}}{2\sqrt{2}G_F} \frac{(g')^2}{M_{Z'}^2 + 2m_e T_e},$$

If we allow for kinetic mixing between the Z' and the SM gauge bosons, this kinetic mixing in the $L_\mu - L_\tau$ model also induces a $\nu - e$ coupling:

$$C_\alpha^{\mathrm{V}} = -\frac{1}{2} + 2s_{\mathrm{W}}^2 + \delta_{\alpha e} + \frac{1}{\sqrt{2}G_F} \frac{g'\, e\, \varepsilon(q^2)}{M_{Z'}^2 + 2m_e T_e}$$

L_e-L_μ Model at DUNE:

Ballett, Hostert, Pascoli, Perez-Gonzalez, **ZT** and Funchal
Phys.Rev. **D100** (2019) no.5, 055012



- The main constraint is from neutrino-electron scattering.
- The sensitive trident channels are:
  $\mu^+\mu^-$ and e^+e^-