Neutrino Non-Standard Interactions at forward neutrino experiments and beyond

FLArE Far Forward Physics working group meeting

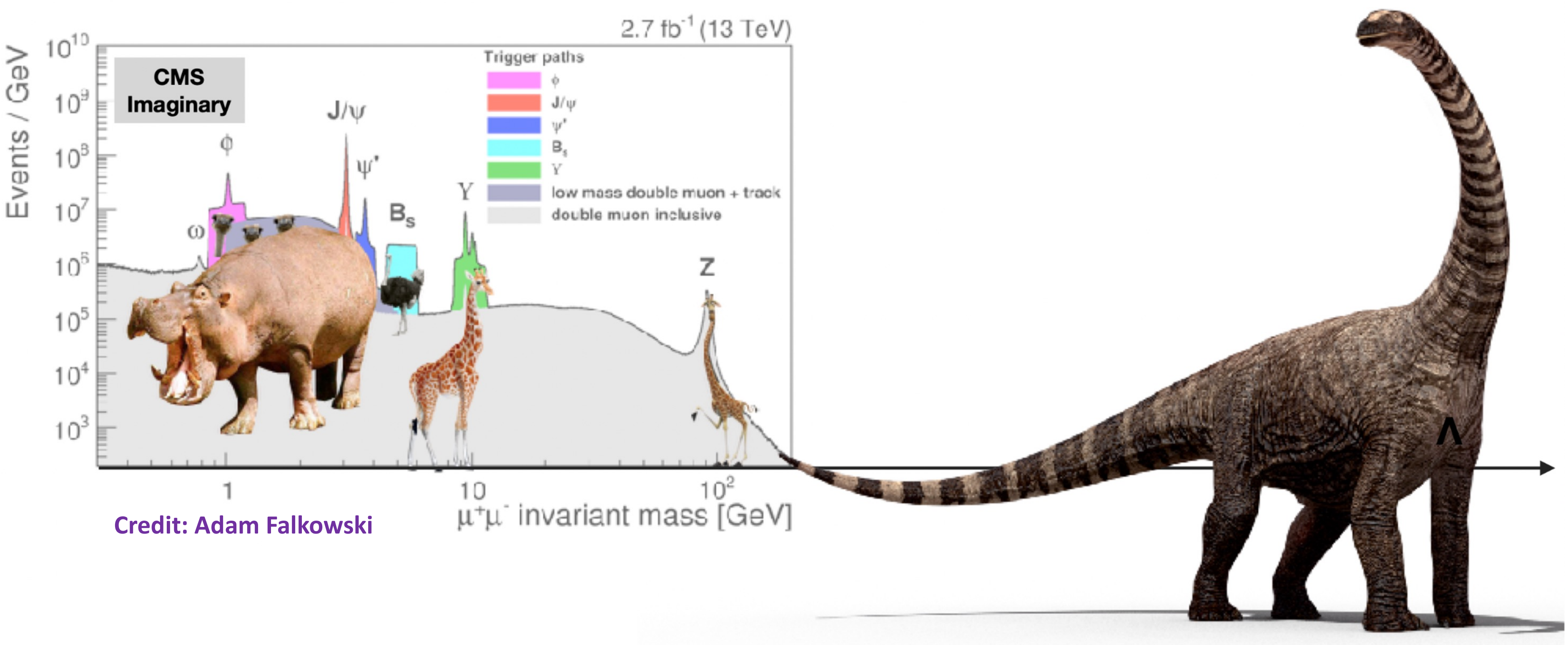
September 5th, 2023

Zahra Tabrizi

Neutrino Theory Network (NTN) fellow

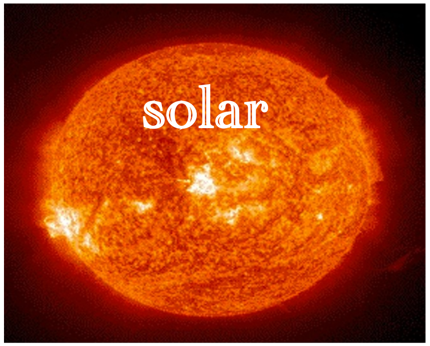
Northwestern University

Fantastic Beasts and Where To Find Them

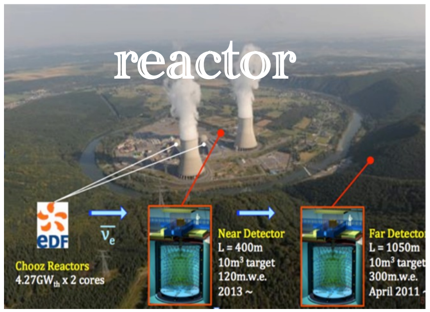


Credit: Adam Falkowski

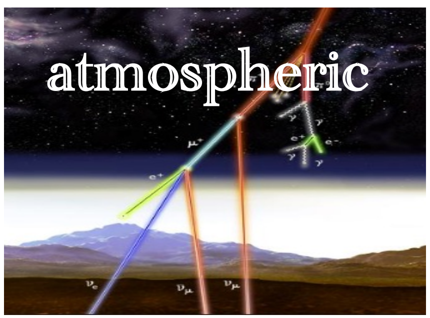
Status of Neutrino Physics in 2023



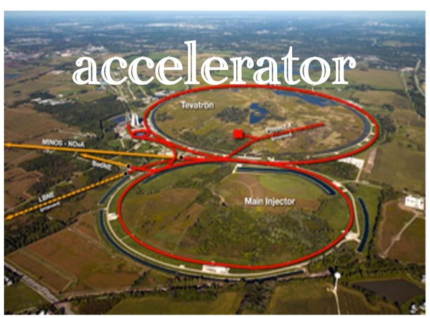
Super-Kamiokande, Borexino, SNO



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



IceCube, Super-Kamiokande



T2K, MINOS, NOvA

mixing angles:

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

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

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

mass squared differences:

Δm^2_{21} @ 3%

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

Future: DUNE, T2HK , JUNO

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

Also:
Mass scale? Dirac or Majorana?
Sterile?

Questions:

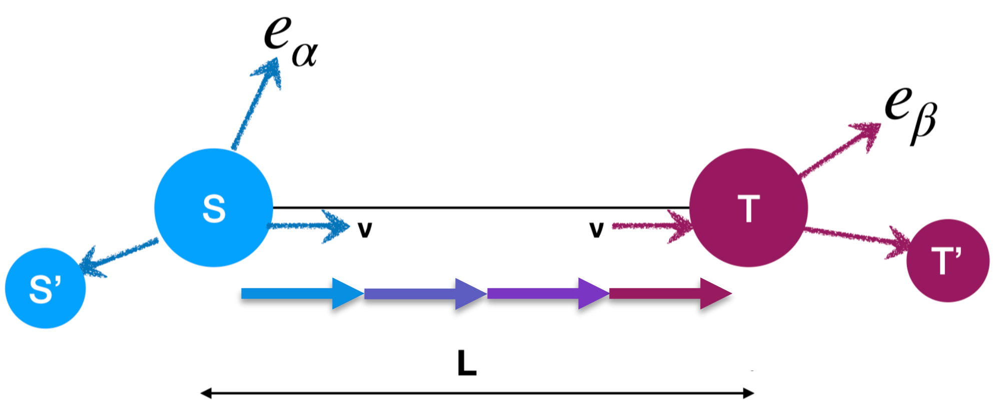
- How can we systematically use different neutrino experiments for BSM searches?

- How can we connect results to other particle physics experiments?

- Can neutrino experiments probe compelling new physics beyond the reach of high energy colliders?

"Heavy" New Physics?

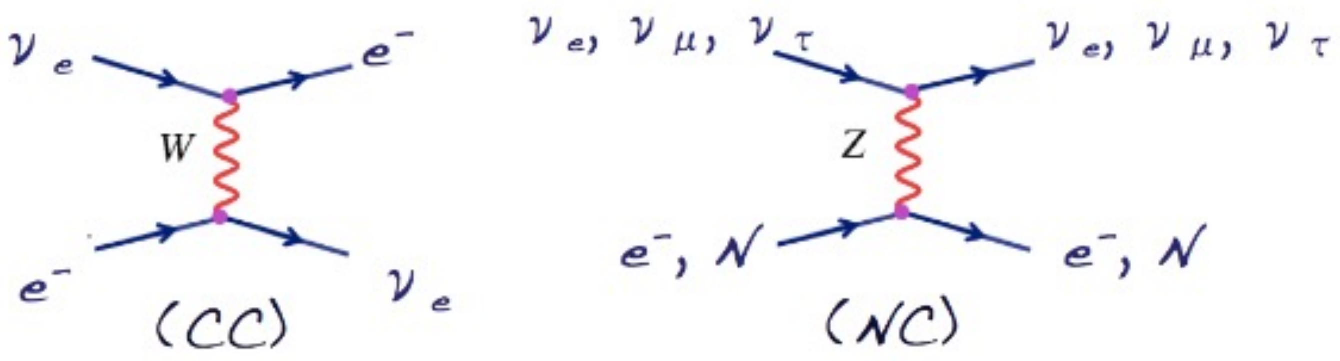
Affects Neutrino Interactions: Indirect Search



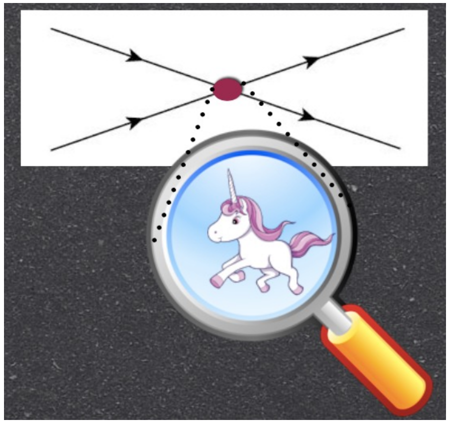
Observable: rate of detected events

$\sim$ (flux)×(det. cross section) × (oscillation)

- Coherent CC and NC forward scattering of neutrinos



- New 4-fermion interactions



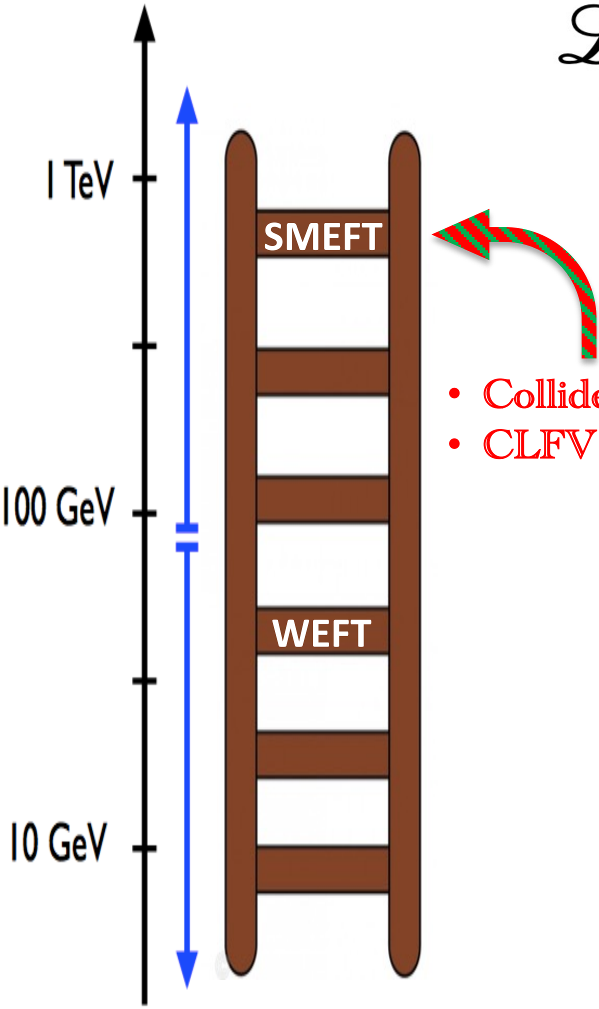
- Observable effects at neutrino production/propagation/detection?
- Using "EFT" formalism to "systematically" explore NP beyond the neutrino masses and mixing

Why EFT?

- One consistent framework to probe different aspects of particle interactions;
- Constraints from different low/high experiments can be meaningfully compared;
- Results can be translated into specific new physics models;
- We can probe very heavy particles, often beyond the reach of present colliders, by precisely measuring low-energy observables;

What's the place of neutrino experiments in this program?

EFT ladder



- Colliders
- CLFV

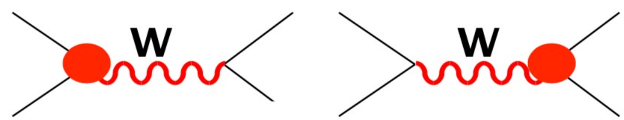
SMEFT: minimal EFT above the weak scale

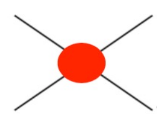
$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \mathscr{L}_{D=5} + \boxed{\mathscr{L}_{D=6}}$$

Known SM Lagrangian

Gives neutrino Masses

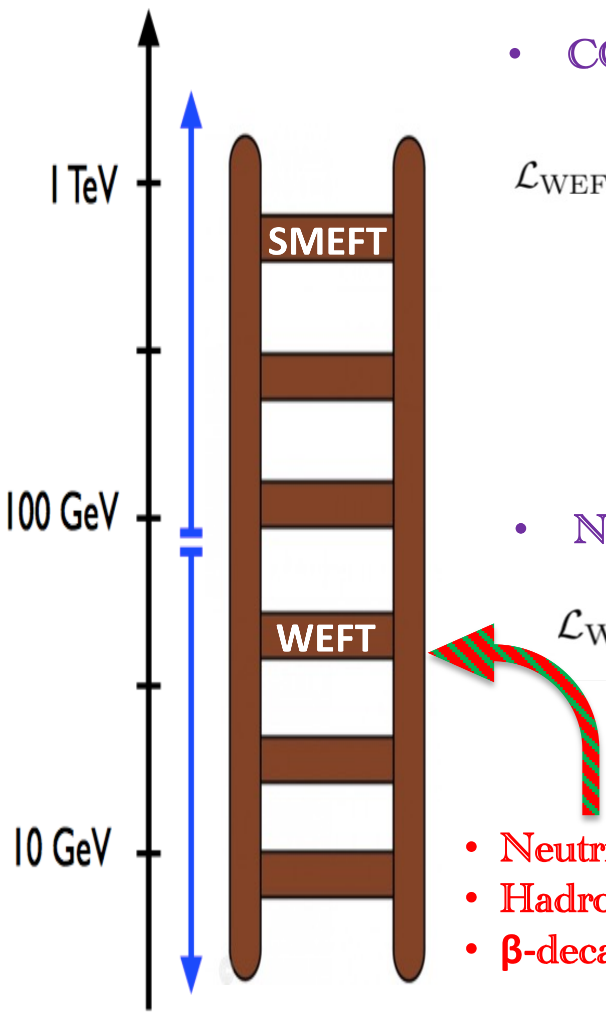
+





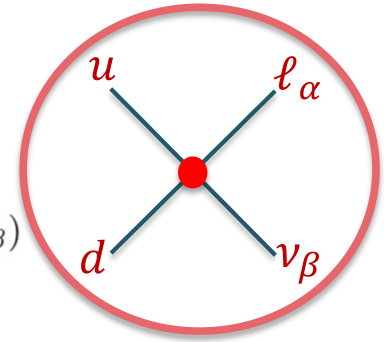
$$O_{lq}^{(3)} = (\bar{l}\gamma^\mu \sigma^a l)(\bar{q}\gamma_\mu \sigma^a q)$$
$$O_{qde} = (\bar{l}e)(\bar{d}q) + \text{h.c.}$$
$$O_{lq} = (\bar{l}_a e)\epsilon^{ab}(\bar{q}_b u) + \text{h.c.}$$
$$O_{lq}^t = (\bar{l}_a \sigma^{\mu\nu} e)\epsilon^{ab}(\bar{q}_b \sigma_{\mu\nu} u) + \text{h.c.}$$

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



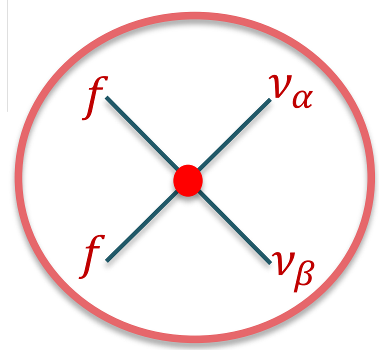
- CC: New left/right handed, (pseudo)scalar and tensor interactions

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



- NC: New left and right handed interactions

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



- Neutrino experiments
- Hadron Decays
- β-decays

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

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

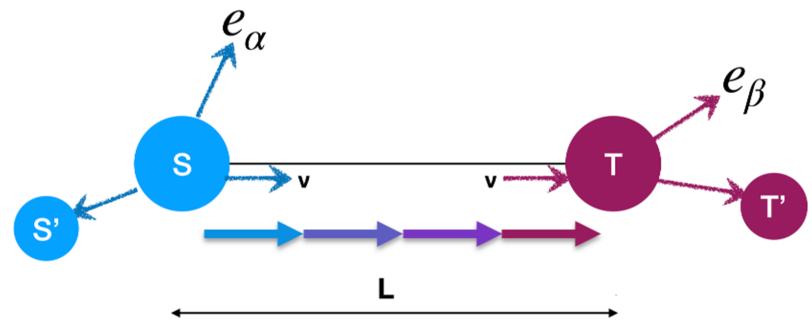
Falkowski, González-Alonso, *ZT*, JHEP (2019)

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

EFT at neutrino experiments

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

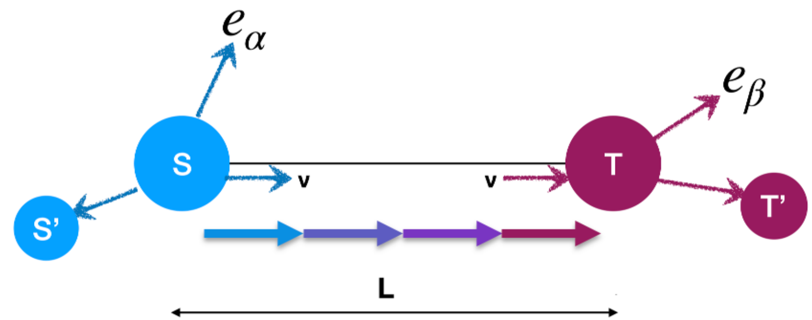
Falkowski, González-Alonso, *ZT*, JHEP (2020)

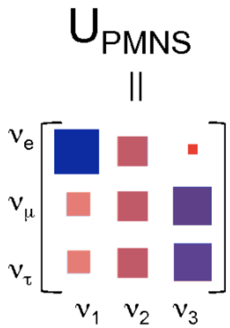


EFT at neutrino experiments

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

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





Observable: rate of detected events

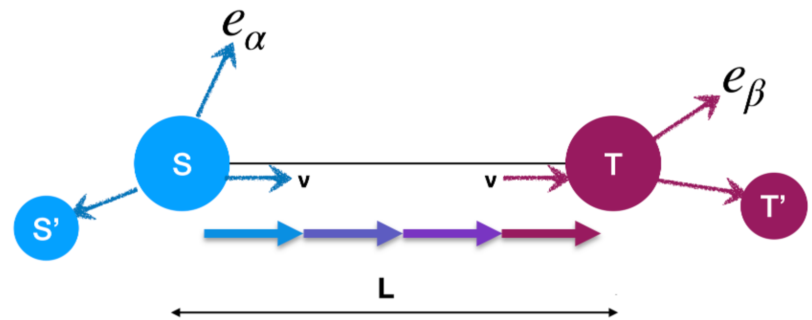
~(flux)×(det. cross section)×(oscillation)

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

EFT at neutrino experiments

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

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

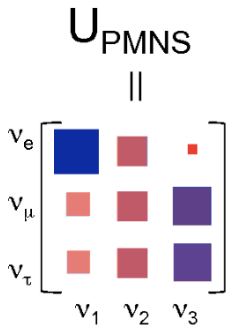


Observable: rate of detected events

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

CC EFT

NC EFT



depend on the kinematic and spin variables

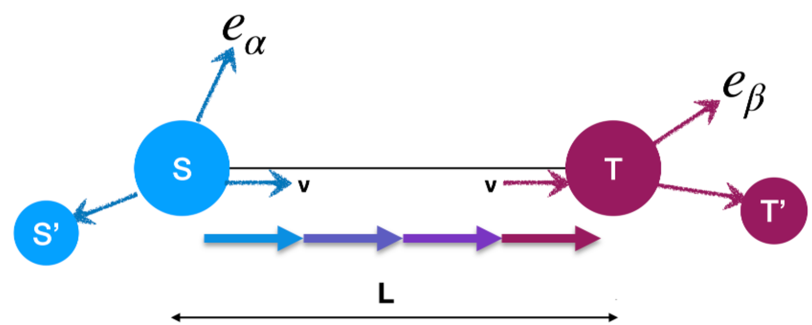
$$\mathcal{M}^P_{\alpha k} = U^*_{\alpha k} A^P_L + \sum_X [\epsilon_X U]^*_{\alpha k} A^P_X$$

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

EFT at neutrino experiments

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

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

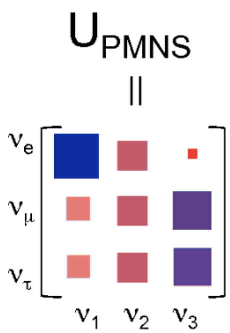


Observable: rate of detected events

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

CC EFT

NC EFT



depend on the kinematic and spin variables

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

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

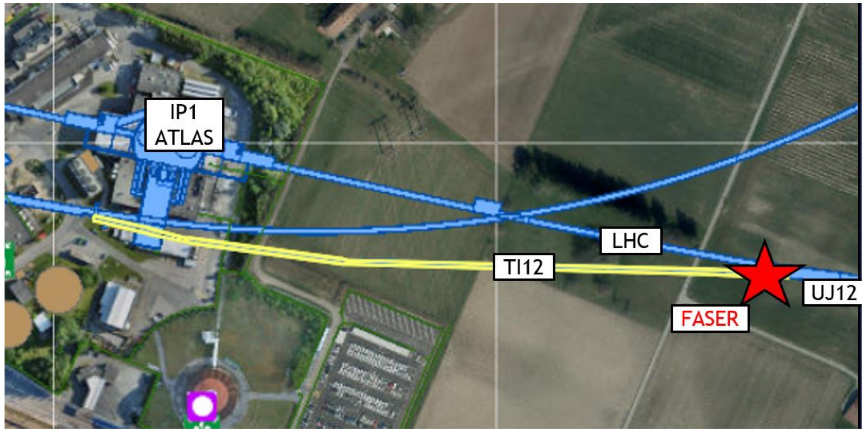
Corrections on fluxes/cross sections

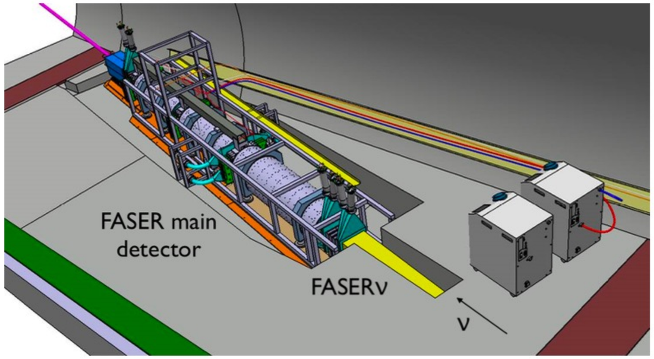
$$\sigma^{Total} = \sigma^{SM} + \varepsilon_X \sigma^{Int} + \varepsilon_X{}^2 \sigma^{NP} \sim \sigma^{SM}(1 + \varepsilon_X\, d_{XL} + \varepsilon_X{}^2\, d_{XX})$$

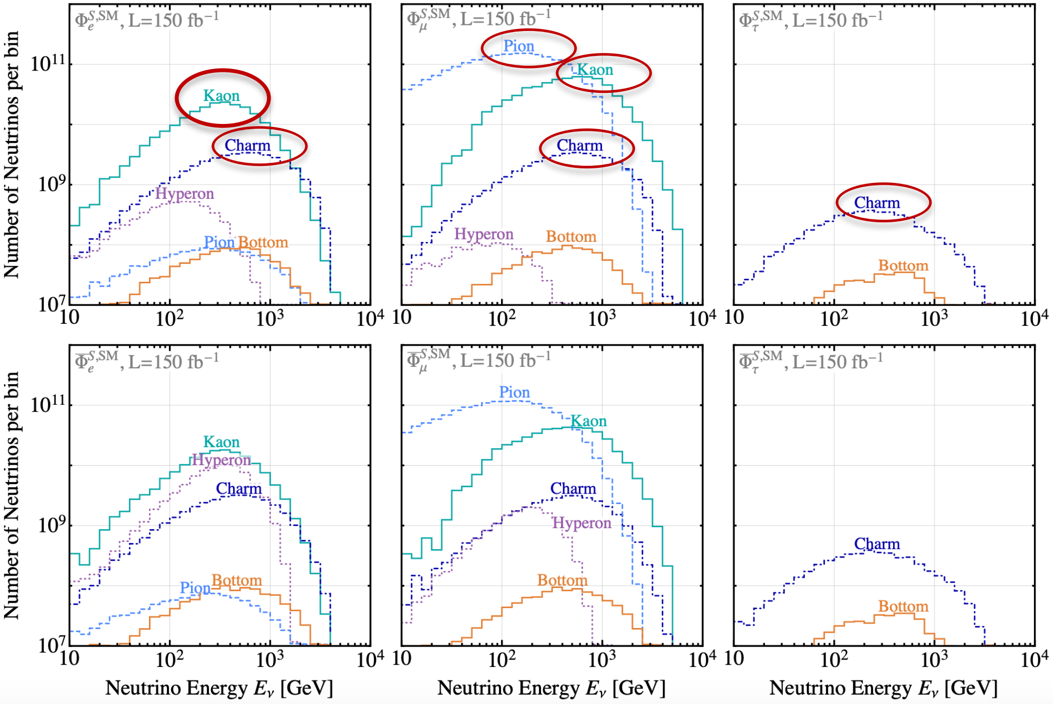
$$\phi^{Total} = \phi^{SM} + \varepsilon_X \phi^{Int} + \varepsilon_X{}^2 \phi^{NP} \sim \phi^{SM}(1 + \varepsilon_X\, p_{XL} + \varepsilon_X{}^2\, p_{XX})$$

FASERν

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







Within the SM:

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

Pion decay

Production

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

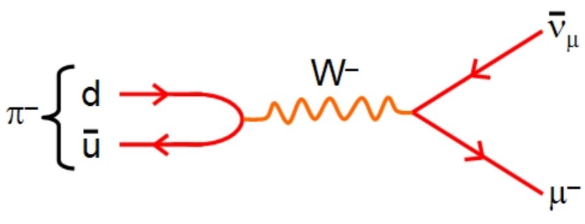
Due to the pseudoscalar nature of the pion, it is sensitive only to axial (ε_L-ε_R) and pseudo-scalar (ε_P) interactions.

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

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

~-27

~700!



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

- 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!

Charm decay

Production

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

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

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

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

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

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

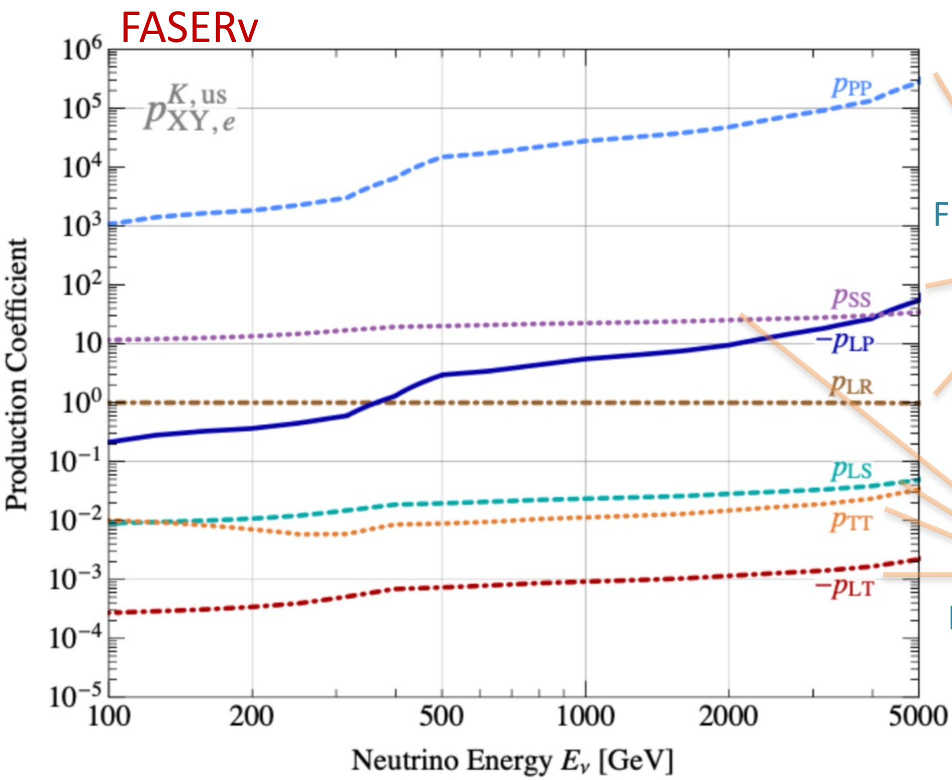
Large overall flux normalization for charm decay as well!

kaon decay

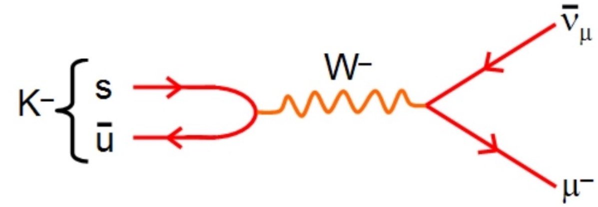
Production

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

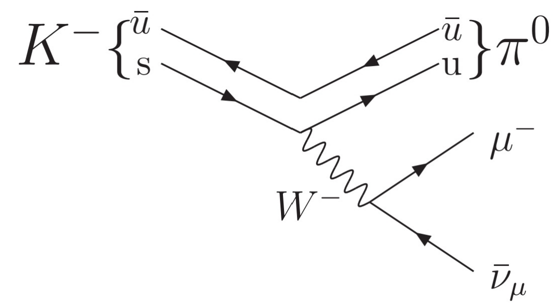
Both 2-body and 3-body kaon decays contribute:



From 2-b decay



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



From 3-b decay

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

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

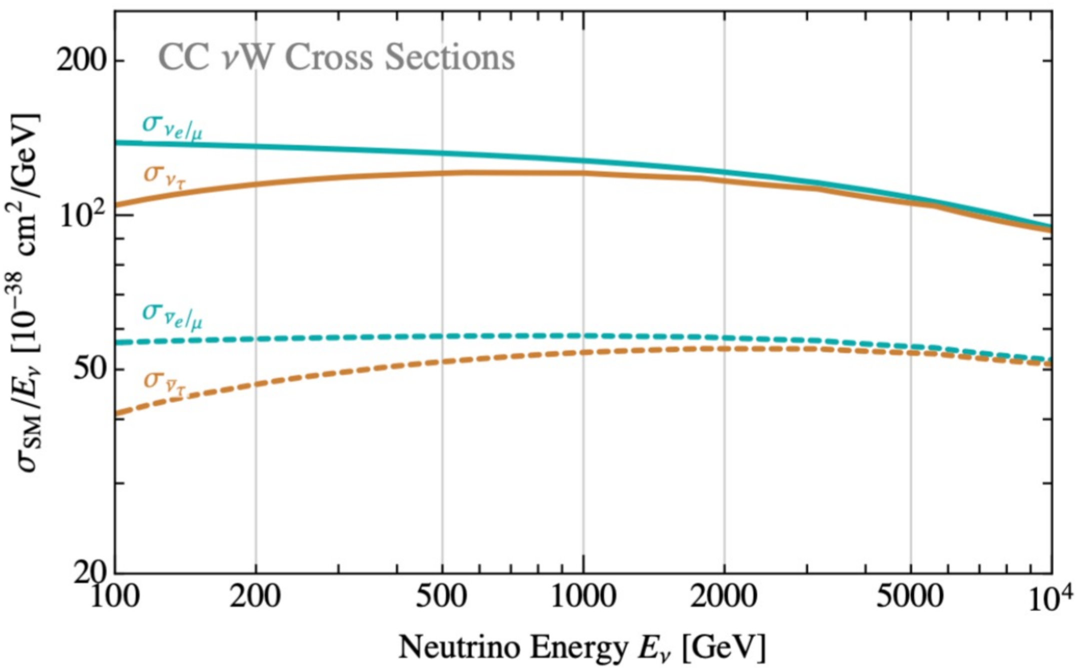
$$\langle \pi^- | \bar{s}\sigma^{\mu\nu} u | K^0 \rangle = i\frac{p_K^\mu p_\pi^\nu - p_\pi^\mu p_K^\nu}{m_K} B_T(q^2)\,,$$

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

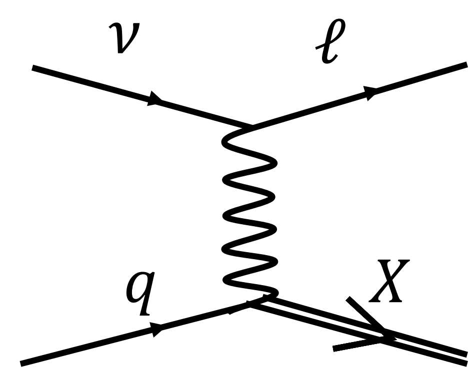
DIS

Detection

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



Deep Inelastic Scattering

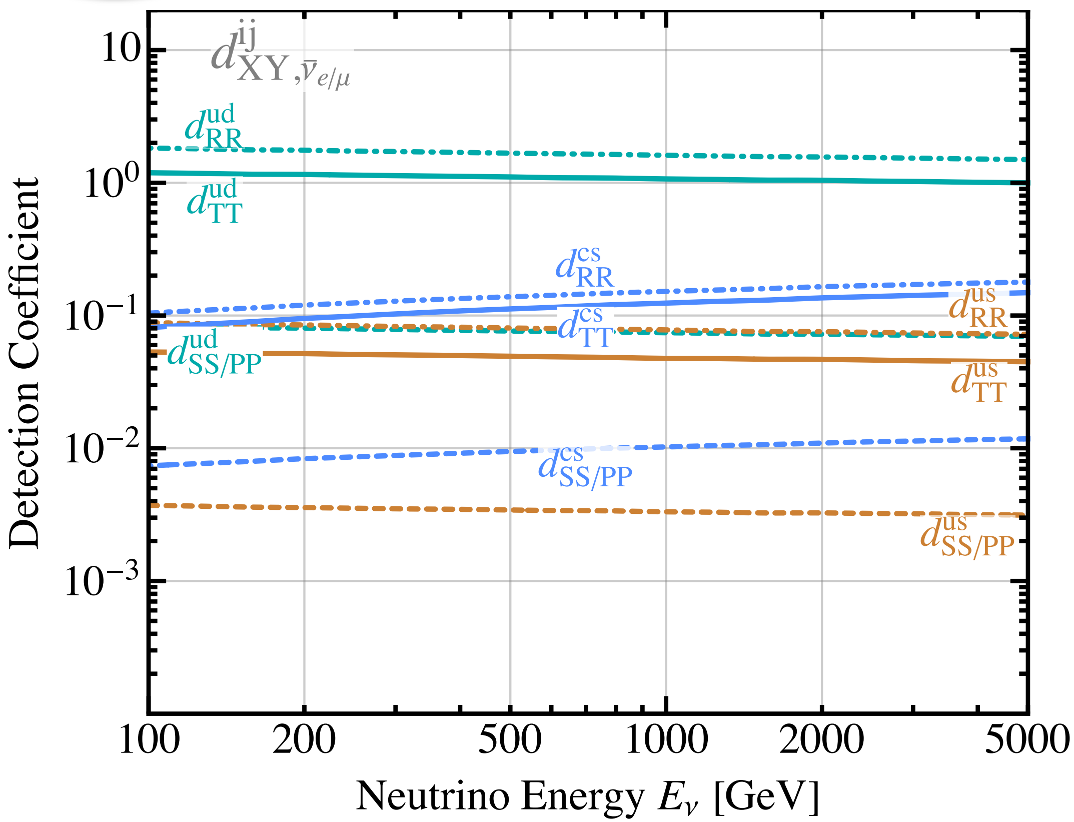


DIS detection, simple to include NSI

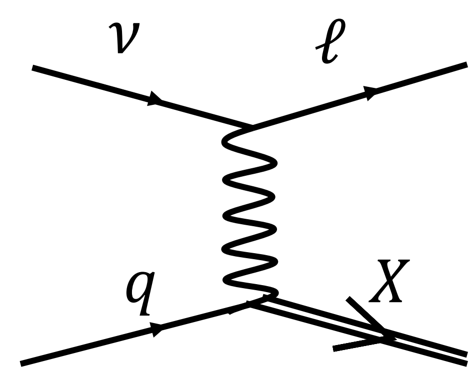
(compared to QE and Resonances)

Detection

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



Deep Inelastic Scattering

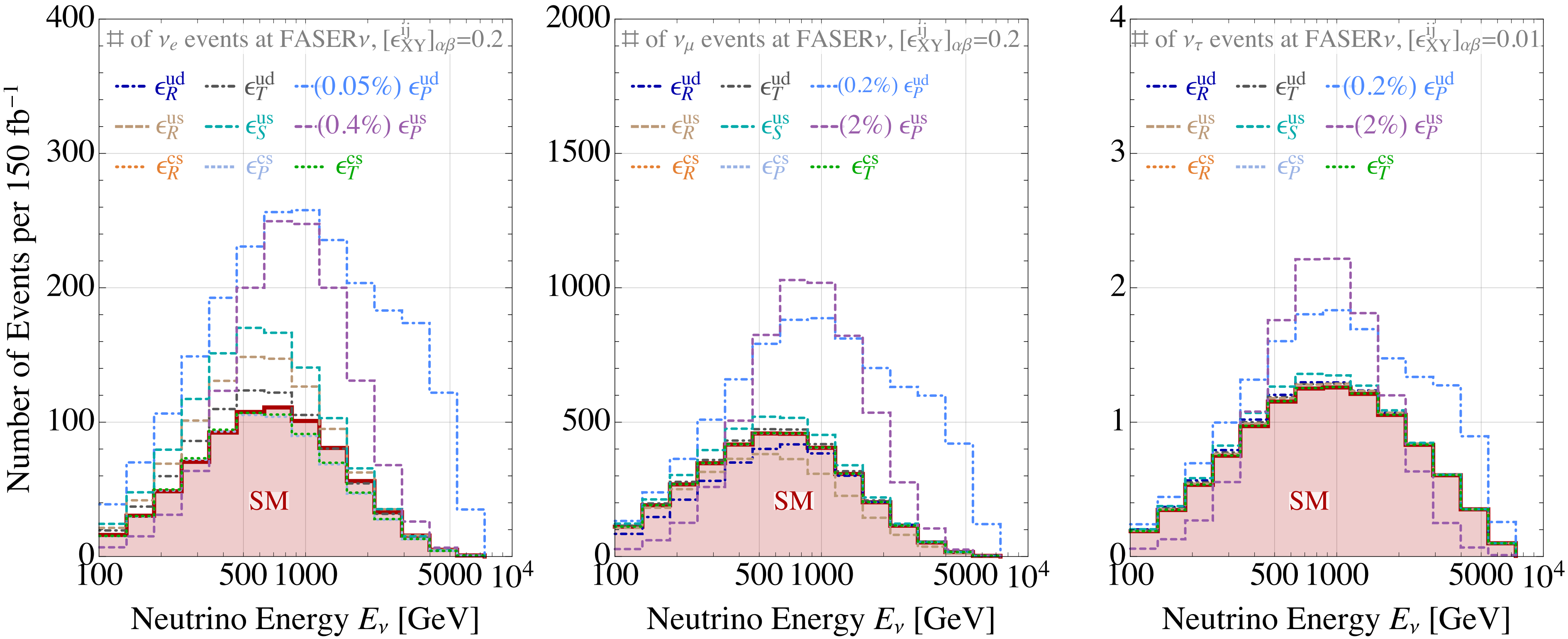


$$\sigma^{Total} \sim \sigma^{SM}(1+\varepsilon_X\, d_{XL} + \varepsilon_X{}^2\, d_{XX})$$

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

EFT at FASERν

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



➢ **Results are statistics dominated: ν_e~1000, ν_μ~5000, ν_τ~10**

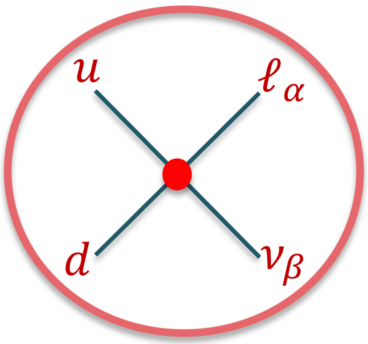
➢ **Optimistic systematic uncertainties:** 5% on ν_e, 10% on ν_μ, 15% on ν_τ

➢ **Conservative systematic uncertainties:** 30% on ν_e, 40% on ν_μ, 50% on ν_τ

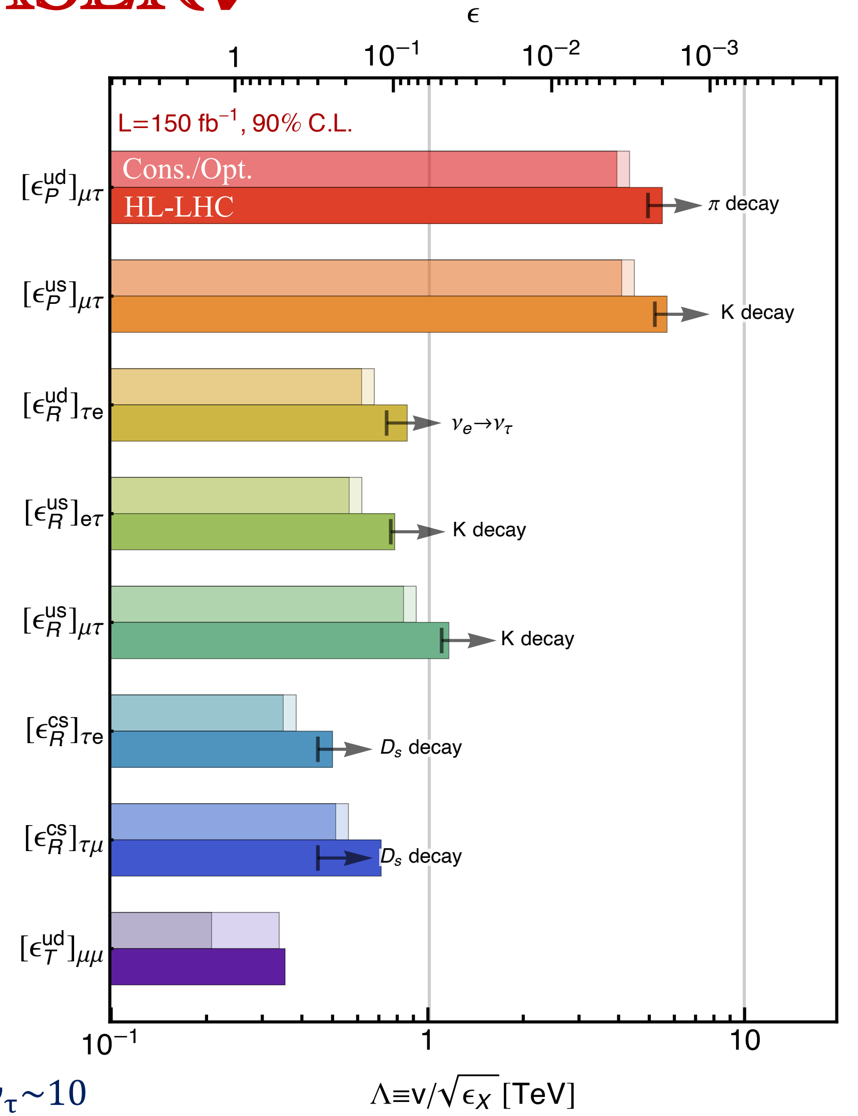
EFT at FASERν

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

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



- Neutrino detectors can identify flavor: 81 operators at FASERν
- New physics reach at multi-TeV
- Complementary or dominant constraints



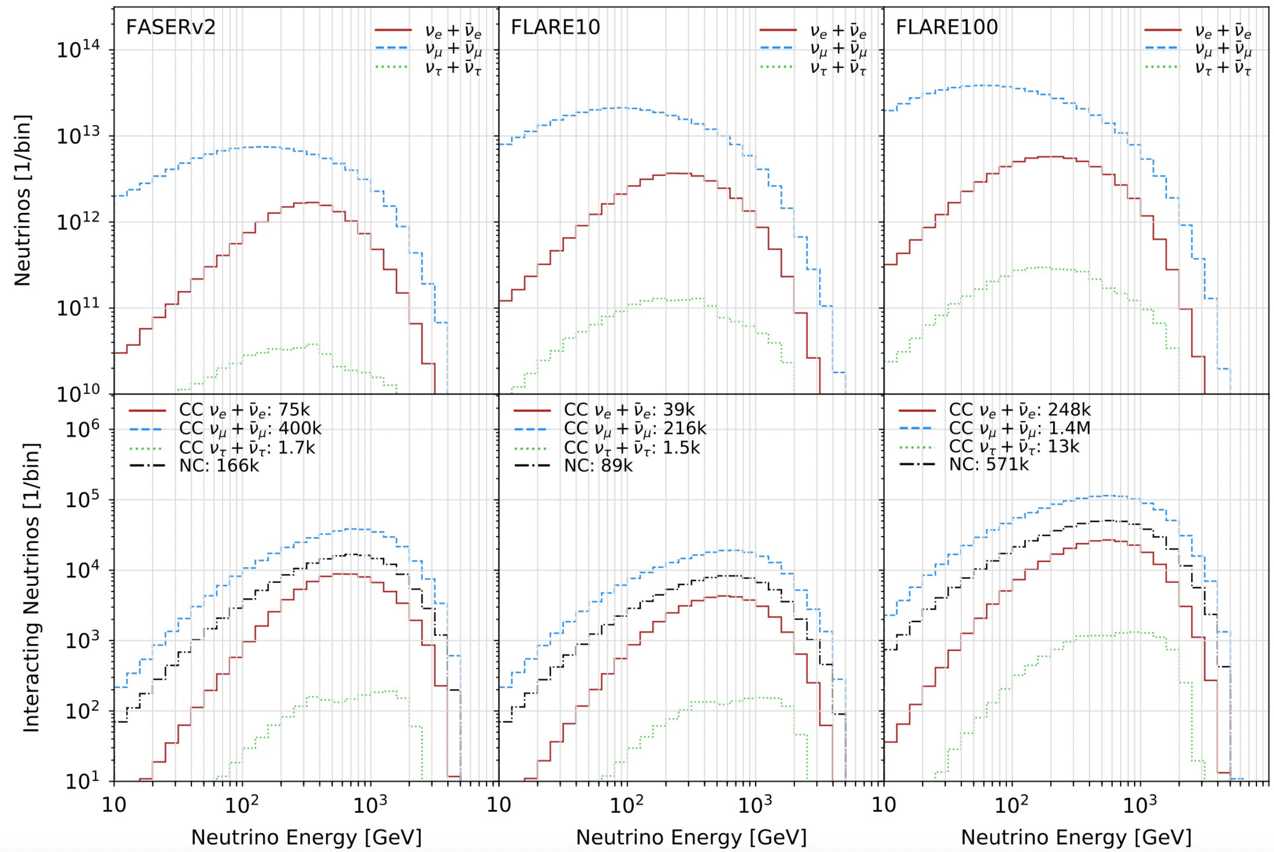
➢ Results are statistics dominated: $\nu_e \sim 1000$, $\nu_\mu \sim 5000$, $\nu_\tau \sim 10$
➢ Optimistic systematic uncertainties: 5% on ν_e, 10% on ν_μ, 15% on ν_τ
➢ Conservative systematic uncertainties: 30% on ν_e, 40% on ν_μ, 50% on ν_τ

Other FPF Experiments

Rates scale linearly wrt volume/Luminosity: X

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

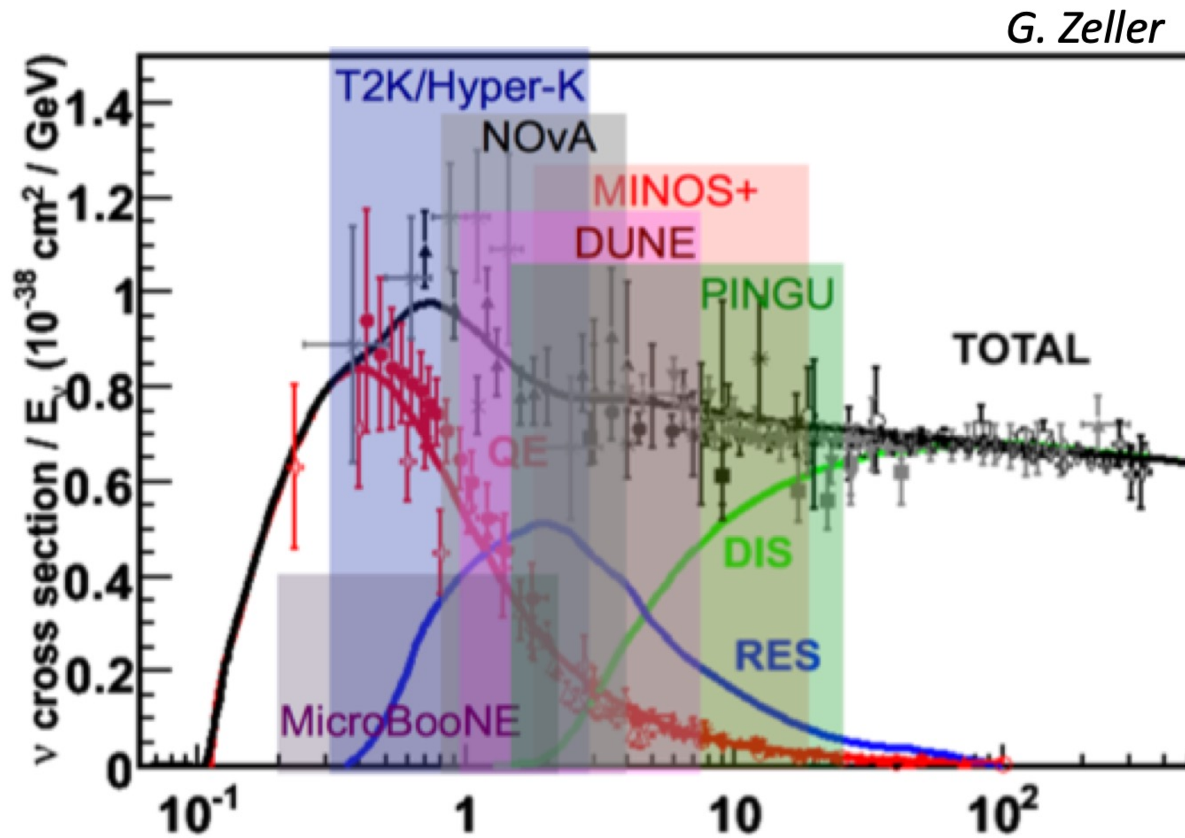
off-diagonal $\varepsilon \sim ({}^{X_2}/_{X_1})^{1/4}$



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

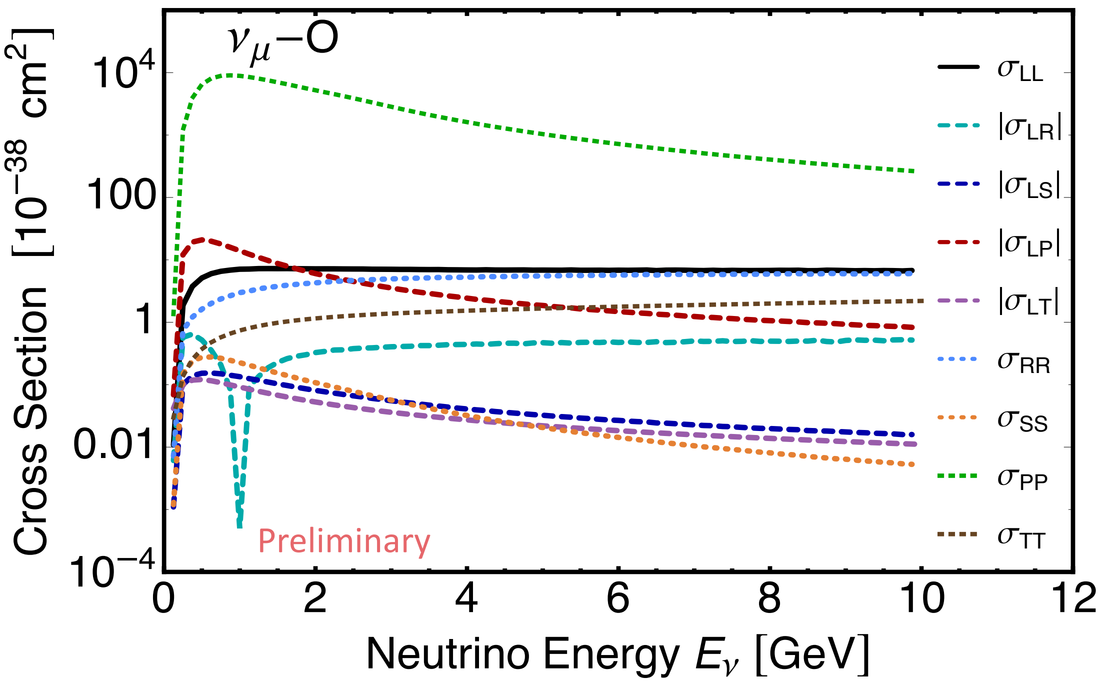
Long Baseline Accelerator Experiments

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



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

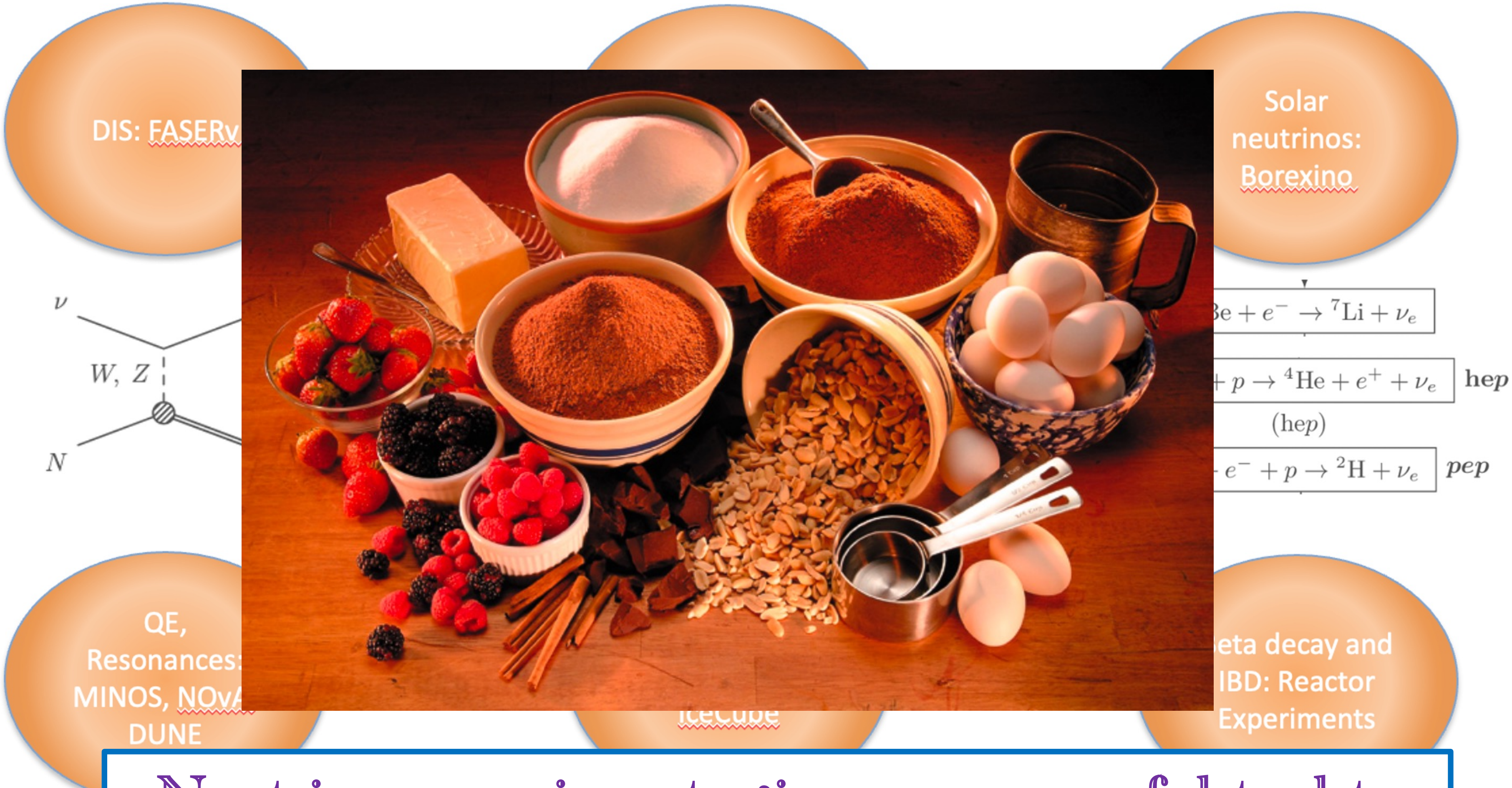
Quasi-Elastic scattering at the nucleon level



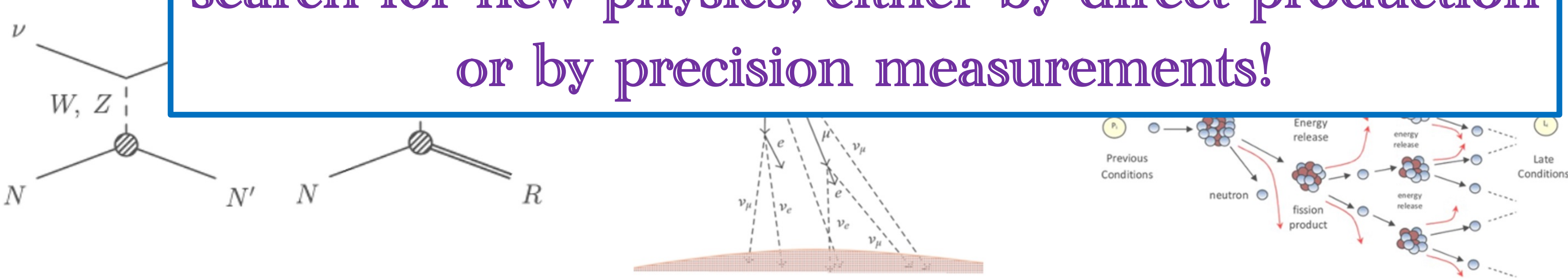
- 10^3 times x-section enhancement
- Much higher statistics

Kopp, Rocco, *ZT*, 2023.XXXXX

Can neutrino experiments have access to new physics at 100 TeV scale?



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



Conclusion:

- We can probe very heavy particles, often beyond the reach of present colliders, by precisely measuring low-energy observables using the EFT formalism.
- We have proposed a systematic approach to neutrino oscillations/scatterings in the SMEFT framework.
- We applied the formalism to FASERν experiment, however the formalism can be readily extended to other types of neutrino experiments.
- Unlike other probes (meson decays, ATLAS and CMS analyses, etc.) neutrino experiments have the unique capability to identify the neutrino flavor. This is crucial complementary information in case excesses are found elsewhere in the future.
- Future directions: Systematic model-independent global analyses of new physics in neutrino oscillation experiments with:

    i) Power counting of EFT effects;

    ii) Extraction of oscillation parameters in presence of general new physics;

    iii) Comparison between the sensitivity of oscillation and other experiments.

Any Questions?

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

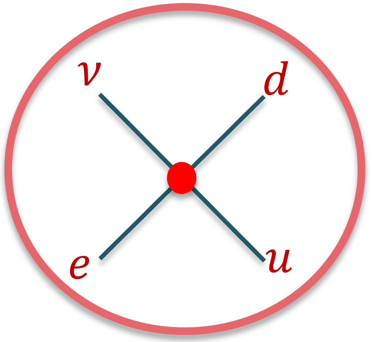
WEFT Power Counting

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

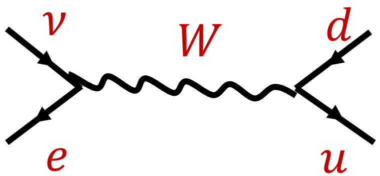
Liao et al, *JHEP* 08 (2020) 162

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

Specific New Physics Models

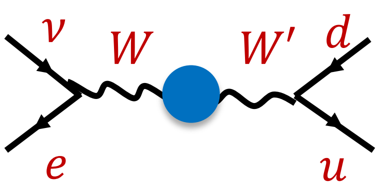


ε_L: measures deviations of the W boson to quarks and leptons, compared to the SM prediction



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

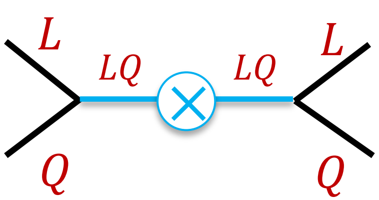
ε_R : left-right symmetric $SU(3)_C x SU(2)_L x SU(2)_R x U(1)_X$ models introduce new charged vector bosons W' coupling to right-handed quarks



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

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

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



$$(LQ)(LQ)$$

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

WEFT-SMEFT Matching:

SMEFT:

$$\mathcal{L} \supset \frac{g_{L,0} g_{Y,0}}{\sqrt{g_{L,0}^2 + g_{Y,0}^2}} A_\mu \sum_f Q_f (\bar{e}_I \bar{\sigma}_\mu e_I + e_I^c \sigma_\mu \bar{e}_I^c)$$
$$+ \left[\frac{[g_L^{We}]_{IJ}}{\sqrt{2}} W_\mu^+ \bar{\nu}_I \bar{\sigma}_\mu e_J + W_\mu^+ \frac{[g_L^{Wq}]_{IJ}}{\sqrt{2}} \bar{u}_I \bar{\sigma}_\mu d_J + \frac{[g_R^{Wq}]_{IJ}}{\sqrt{2}} W_\mu^+ u_I^c \sigma_\mu \bar{d}_J^c + \text{h.c.} \right]$$
$$+ Z_\mu \sum_{f=u,d,e,\nu} [g_L^{Zf}]_{IJ} \bar{f}_I \bar{\sigma}_\mu f_J + Z_\mu \sum_{f=u,d,e} [g_R^{Zf}]_{IJ} f_I^c \sigma_\mu \bar{f}_J^c .$$

+

Chirality conserving $(I, J = 1, 2, 3)$	Chirality violating $(I, J = 1, 2, 3)$
$[O_{\ell q}]_{IIJJ} = (\bar{\ell}_I \bar{\sigma}_\mu \ell_I)(\bar{q}_J \bar{\sigma}^\mu q_J)$	$[O_{\ell equ}]_{IIJJ} = (\bar{\ell}_I^j \bar{e}_I^c)\epsilon_{jk}(\bar{q}_J^k \bar{u}_J^c)$
$[O_{\ell q}^{(3)}]_{IIJJ} = (\bar{\ell}_I \bar{\sigma}_\mu \sigma^i \ell_I)(\bar{q}_J \bar{\sigma}^\mu \sigma^i q_J)$	$[O_{\ell equ}^{(3)}]_{IIJJ} = (\bar{\ell}_I^j \bar{\sigma}_{\mu\nu} \bar{e}_I^c)\epsilon_{jk}(\bar{q}_J^k \bar{\sigma}_{\mu\nu} \bar{u}_J^c)$
$[O_{\ell u}]_{IIJJ} = (\bar{\ell}_I \bar{\sigma}_\mu \ell_I)(u_J^c \sigma^\mu \bar{u}_J^c)$	$[O_{\ell edq}]_{IIJJ} = (\bar{\ell}_I^j \bar{e}_I^c)(d_J^c q_J^j)$
$[O_{\ell d}]_{IIJJ} = (\bar{\ell}_I \bar{\sigma}_\mu \ell_I)(d_J^c \sigma^\mu \bar{d}_J^c)$	
$[O_{eq}]_{IIJJ} = (e_I^c \sigma_\mu \bar{e}_I^c)(\bar{q}_J \bar{\sigma}^\mu q_J)$	
$[O_{eu}]_{IIJJ} = (e_I^c \sigma_\mu \bar{e}_I^c)(u_J^c \sigma^\mu \bar{u}_J^c)$	
$[O_{ed}]_{IIJJ} = (e_I^c \sigma_\mu \bar{e}_I^c)(d_J^c \sigma^\mu \bar{d}_J^c)$	

One flavor $(I = 1, 2, 3)$	Two flavors $(I < J = 1, 2, 3)$
$[O_{\ell\ell}]_{IIII} = \frac{1}{2}(\bar{\ell}_I \bar{\sigma}_\mu \ell_I)(\bar{\ell}_I \bar{\sigma}^\mu \ell_I)$	$[O_{\ell\ell}]_{IIJJ} = (\bar{\ell}_I \bar{\sigma}_\mu \ell_I)(\bar{\ell}_J \bar{\sigma}^\mu \ell_J)$
	$[O_{\ell\ell}]_{IJJI} = (\bar{\ell}_I \bar{\sigma}_\mu \ell_J)(\bar{\ell}_J \bar{\sigma}^\mu \ell_I)$
$[O_{\ell e}]_{IIII} = (\bar{\ell}_I \bar{\sigma}_\mu \ell_I)(e_I^c \sigma^\mu \bar{e}_I^c)$	$[O_{\ell e}]_{IIJJ} = (\bar{\ell}_I \bar{\sigma}_\mu \ell_I)(e_J^c \sigma^\mu \bar{e}_J^c)$
	$[O_{\ell e}]_{JJII} = (\bar{\ell}_J \bar{\sigma}_\mu \ell_J)(e_I^c \sigma^\mu \bar{e}_I^c)$
	$[O_{\ell e}]_{IJJI} = (\bar{\ell}_I \bar{\sigma}_\mu \ell_J)(e_J^c \sigma^\mu \bar{e}_I^c)$
$[O_{ee}]_{IIII} = \frac{1}{2}(e_I^c \sigma_\mu \bar{e}_I^c)(e_I^c \sigma^\mu \bar{e}_I^c)$	$[O_{ee}]_{IIJJ} = (e_I^c \sigma_\mu \bar{e}_I^c)(e_J^c \sigma^\mu \bar{e}_J^c)$

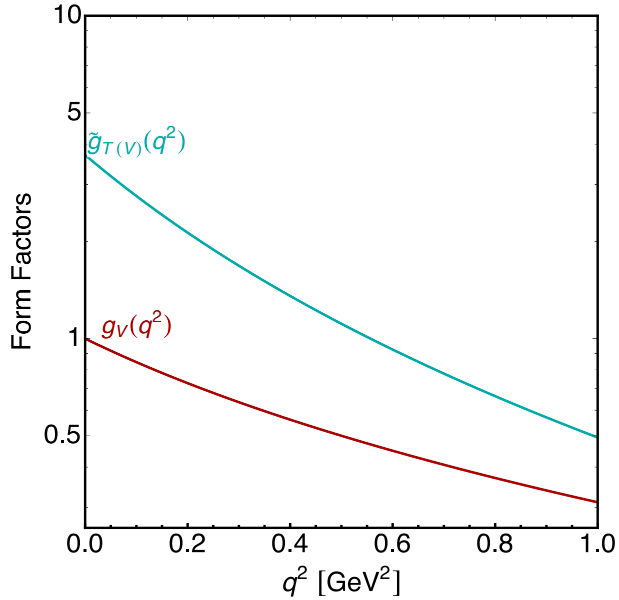
WEFT:

$$\mathcal{L}_{\text{eff}} \supset -\frac{2\tilde{V}_{ud}}{v^2} \Big[\left(1 + \epsilon_L^{de_J}\right) (\bar{e}_J \bar{\sigma}_\mu \nu_J)(\bar{u} \bar{\sigma}^\mu d) + \epsilon_R^{de}(\bar{e}_J \bar{\sigma}_\mu \nu_J)(u^c \sigma^\mu \bar{d}^c)$$
$$+ \frac{\epsilon_S^{de_J} + \epsilon_P^{de_J}}{2}(e_J^c \nu_J)(u^c d) + \frac{\epsilon_S^{de_J} - \epsilon_P^{de_J}}{2}(e_J^c \nu_J)(\bar{u} \bar{d}^c) + \epsilon_T^{de_J}(e_J^c \sigma_{\mu\nu} \nu_J)(u^c \sigma_{\mu\nu} d) + \text{h.c.} \Big]$$

QE matrix elements at the nucleon level

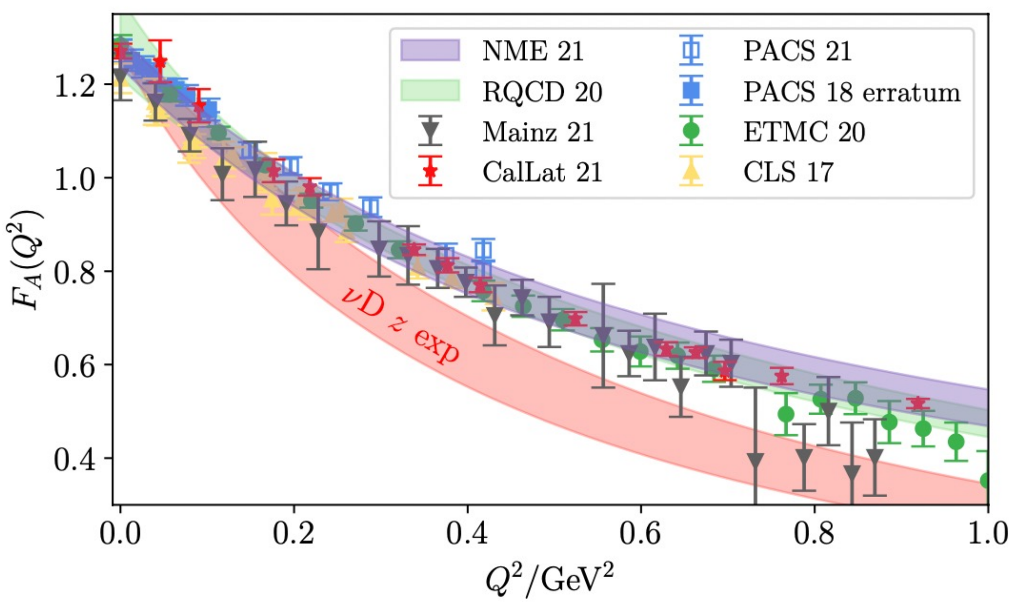
$$\langle p(p_p)|\,\bar{u}\gamma_\mu d\,|n(p_n)\rangle = \bar{u}_p(p_p)\left[g_V(q^2)\,\gamma_\mu - i\,\frac{\tilde{g}_{T(V)}(q^2)}{2M_N}\,\sigma_{\mu\nu}q^\nu + \frac{\tilde{g}_S(q^2)}{2M_N}\,q_\mu\right]u_n(p_n)$$

$$\langle p(p_p)|\,\bar{u}\gamma_\mu\gamma_5 d\,|n(p_n)\rangle = \bar{u}_p(p_p)\left[g_A(q^2)\gamma_\mu - i\,\frac{\tilde{g}_{T(A)}(q^2)}{2M_N}\sigma_{\mu\nu}q^\nu + \frac{\tilde{g}_P(q^2)}{2M_N}q_\mu\right]\gamma_5 u_n(p_n)$$



constrained by eN scattering

Kopp, Rocco, *ZT*, in preparation



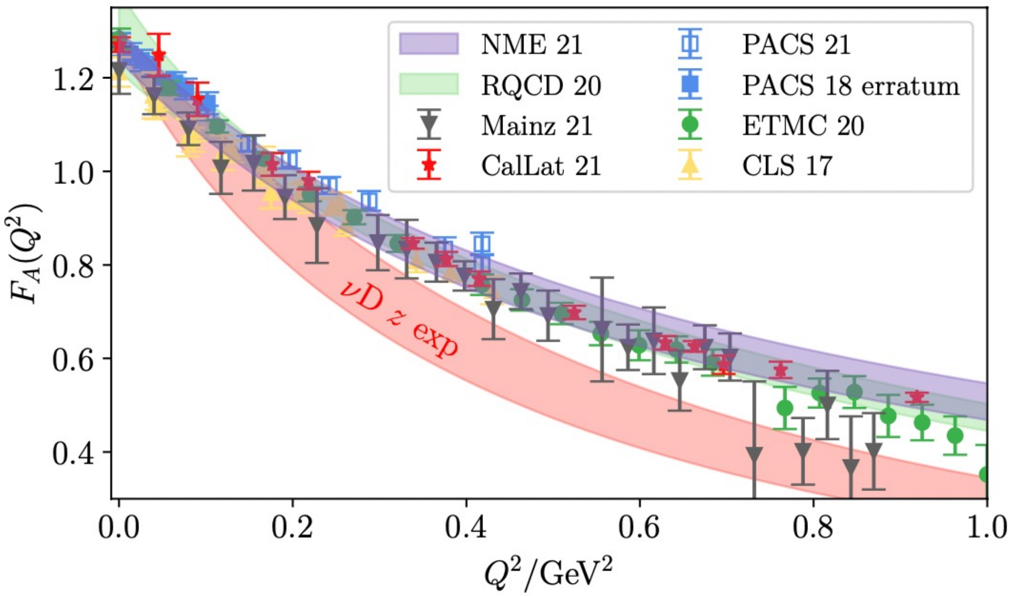
poorly constrained by expt.

Meyer et al, 2201.01839

QE matrix elements at the nucleon level

$$\langle p(p_p)|\, \bar{u}\gamma_\mu d \,|n(p_n)\rangle = \bar{u}_p(p_p)\left[g_V(q^2)\,\gamma_\mu - i\,\frac{\tilde{g}_{T(V)}(q^2)}{2M_N}\sigma_{\mu\nu}q^\nu + \frac{\tilde{g}_S(q^2)}{2M_N}q_\mu\right]u_n(p_n)$$

$$\langle p(p_p)|\, \bar{u}\gamma_\mu\gamma_5 d \,|n(p_n)\rangle = \bar{u}_p(p_p)\left[g_A(q^2)\gamma_\mu - i\,\frac{\tilde{g}_{T(A)}(q^2)}{2M_N}\sigma_{\mu\nu}q^\nu + \frac{\tilde{g}_P(q^2)}{2M_N}q_\mu\right]\gamma_5 u_n(p_n)$$



poorly constrained by expt.

Meyer et al, 2201.01839

QE matrix elements at the nucleon level

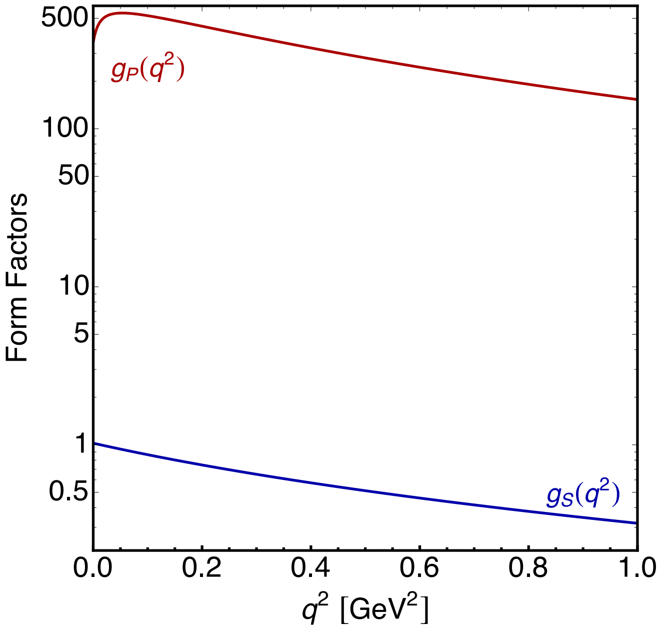
$$
\begin{aligned}
\langle p(p_p)|\,\bar{u}\,d\,|n(p_n)\rangle &= g_S(q^2)\;\bar{u}_p(p_p)\,u_n(p_n)\\
\langle p(p_p)|\,\bar{u}\,\gamma_5\,d\,|n(p_n)\rangle &= g_P(q^2)\;\bar{u}_p(p_p)\,\gamma_5\,u_n(p_n)\\
\langle p(p_p)|\,\bar{u}\,\sigma_{\mu\nu}\,d\,|n(p_n)\rangle &= \bar{u}_p(p_p)\Big[g_T(q^2)\,\sigma_{\mu\nu} + g_T^{(1)}(q^2)\,(q_\mu\gamma_\nu - q_\nu\gamma_\mu)\\
&+\; g_T^{(2)}(q^2)\,(q_\mu P_\nu - q_\nu P_\mu) + g_T^{(3)}(q^2)\,\big(\gamma_\mu \not{q}\gamma_\nu - \gamma_\nu\not{q}\gamma_\mu\big)\Big]\,u_n(p_n)
\end{aligned}
$$

- conservation of the vector current (CVC):

$$g_S(q^2) = \frac{\delta M_N^{\rm QCD}}{\delta m_q} g_V(q^2) + \frac{q^2/2\overline{M}_N}{\delta m_q}\tilde{g}_S(q^2)$$

- partial conservation of the axial current (PCAC):

$$g_P(q^2) = \frac{\overline{M}_N}{\overline{m}_q} g_A(q^2) + \frac{q^2/2\overline{M}_N}{(2\overline{m}_q)}\tilde{g}_P(q^2)$$

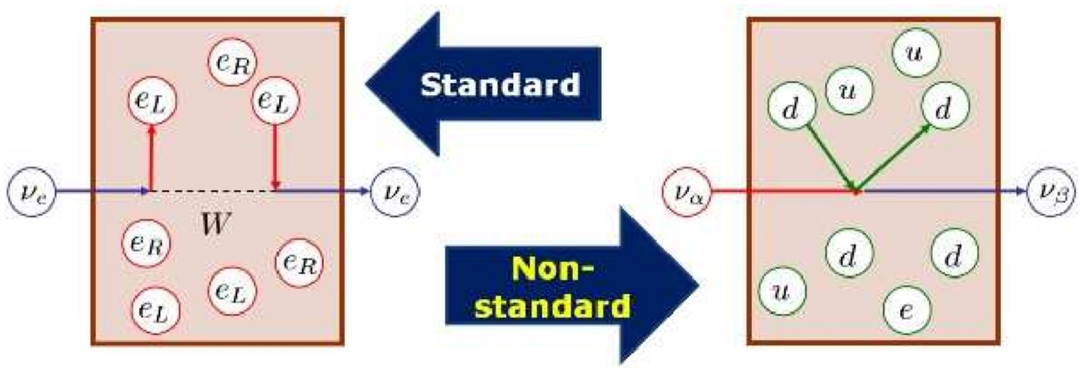


- We need axial form factor for NP as well
- Much larger statistics
- Large pseudo-scalar form factor (no q/M suppression)
- Different energy scale compare to beta decay experiments

Kopp, Rocco, *ZT*, in preparation

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)

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

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

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.

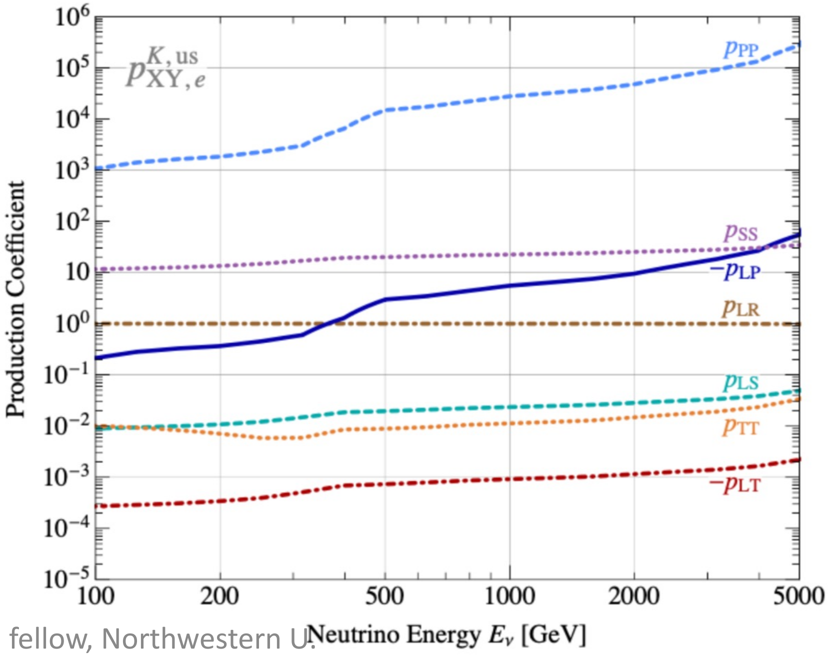
Comparing QM and QFT

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)

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

EFT at FASERν

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

- Low Energy WEFT:

(Independent of the underlying high-energy theory)

  - ✓ β-decays
  - ✓ Leptonic pion decays
  - ✓ (Semi-)Leptonic kaon decays
  - ✓ Hadronic τ decays

- High Energy SMEFT:

(Bounds are less robust)

  - ✓ LHC
  - ✓ CLFV

Bounds shown in bold face have been calculated in this work

Flavor Experiments — Colliders

Coupling	Low energy (WEFT)		High energy / CLFV (SMEFT)	
	90 % CL bound	process	90 % CL bound	process
$[\epsilon_P^{ud}]_{ee}$	$\mathbf{4.6\times10^{-7}}$	$\boldsymbol{\Gamma_{\pi\to e\nu}/\Gamma_{\pi\to\mu\nu}}$		
$[\epsilon_P^{ud}]_{e\mu}$	7.3×10^{-6}	$\Gamma_{\pi\to e\nu}/\Gamma_{\pi\to\mu\nu}$ [7]	$\mathbf{2.0\times10^{-8}}$	$\boldsymbol{\mu\to e}$ **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]
$[\epsilon_P^{ud}]_{\mu e}$	$\mathbf{2.6\times10^{-3}}$	$\boldsymbol{\Gamma_{\pi\to e\nu}/\Gamma_{\pi\to\mu\nu}}$	$\mathbf{2.0\times10^{-8}}$	$\boldsymbol{\mu\to e}$ **conversion**
$[\epsilon_P^{ud}]_{\mu\mu}$	$\mathbf{9.4\times10^{-5}}$	$\boldsymbol{\Gamma_{\pi\to e\nu}/\Gamma_{\pi\to\mu\nu}}$		
$[\epsilon_P^{ud}]_{\mu\tau}$	$\mathbf{2.6\times10^{-3}}$	$\boldsymbol{\Gamma_{\pi\to e\nu}/\Gamma_{\pi\to\mu\nu}}$		
$[\epsilon_P^{ud}]_{\tau e}$	$\mathbf{9.0\times10^{-2}}$	$\boldsymbol{\Gamma_{\tau\to\pi\nu}}$	$5.8\times10^{-3(*)}/4.4\times10^{-4}$	LHC [65] / τ decay [64]
$[\epsilon_P^{ud}]_{\tau\mu}$	$\mathbf{9.0\times10^{-2}}$	$\boldsymbol{\Gamma_{\tau\to\pi\nu}}$	$5.8\times10^{-3(*)}$	LHC [65]
$[\epsilon_P^{ud}]_{\tau\tau}$	8.4×10^{-3}	τ-decay [65]	$5.8\times10^{-3(*)}$	LHC [65]
$[\epsilon_P^{us}]_{ee}$	$\mathbf{1.1\times10^{-6}}$	$\boldsymbol{\Gamma_{K\to e\nu}/\Gamma_{K\to\mu\nu}}$		
$[\epsilon_P^{us}]_{e\mu}$	$\mathbf{2.1\times10^{-5}}$	$\boldsymbol{\Gamma_{K\to e\nu}/\Gamma_{K\to\mu\nu}}$	$\mathbf{6.2\times10^{-7}}$	$\boldsymbol{\mu\to e}$ **conversion**
$[\epsilon_P^{us}]_{e\tau}$	$\mathbf{2.1\times10^{-5}}$	$\boldsymbol{\Gamma_{K\to e\nu}/\Gamma_{K\to\mu\nu}}$	7.1×10^{-2}	LHC [64]
$[\epsilon_P^{us}]_{\mu e}$	$\mathbf{2.3\times10^{-3}}$	$\boldsymbol{\Gamma_{K\to e\nu}/\Gamma_{K\to\mu\nu}}$	$\mathbf{6.2\times10^{-7}}$	$\boldsymbol{\mu\to e}$ **conversion**
$[\epsilon_P^{us}]_{\mu\mu}$	$\mathbf{2.2\times10^{-4}}$	$\boldsymbol{\Gamma_{K\to e\nu}/\Gamma_{K\to\mu\nu}}$		
$[\epsilon_P^{us}]_{\mu\tau}$	$\mathbf{2.3\times10^{-3}}$	$\boldsymbol{\Gamma_{K\to e\nu}/\Gamma_{K\to\mu\nu}}$		
$[\epsilon_P^{us}]_{\tau e}$	$\mathbf{6.4\times10^{-2}}$	$\boldsymbol{\Gamma_{\tau\to K\nu}/\Gamma_{K\to\mu\nu}}$	$\mathbf{3.1\times10^{-2(*)}}/8.1\times10^{-2}$	**LHC (data [66])**/τ-decay [64]
$[\epsilon_P^{us}]_{\tau\mu}$	$\mathbf{6.4\times10^{-2}}$	$\boldsymbol{\Gamma_{\tau\to K\nu}/\Gamma_{K\to\mu\nu}}$	$\mathbf{3.1\times10^{-2(*)}}$	**LHC (data [66])**
$[\epsilon_P^{us}]_{\tau\tau}$	1.3×10^{-2}	τ-decay [67]	$\mathbf{3.1\times10^{-2(*)}}$	**LHC (data [66])**
$[\epsilon_P^{cs}]_{ee}$	$\mathbf{4.8\times10^{-3}}$	$\boldsymbol{\Gamma_{D_s\to e\nu}}$	1.3×10^{-2}	LHC [68]
$[\epsilon_P^{cs}]_{e\mu}$	$\mathbf{4.6\times10^{-3}}$	$\boldsymbol{\Gamma_{D_s\to e\nu}}$	1.3×10^{-2} / $\mathbf{2.7\times10^{-6}}$	LHC [68] / $\boldsymbol{\mu\to e}$ **conversion**
$[\epsilon_P^{cs}]_{e\tau}$	$\mathbf{4.6\times10^{-3}}$	$\boldsymbol{\Gamma_{D_s\to e\nu}}$	1.3×10^{-2} / 1.9×10^{-2}	LHC / τ-decays [64, 68]
$[\epsilon_P^{cs}]_{\mu e}$	$\mathbf{8.9\times10^{-3}}$	$\boldsymbol{\Gamma_{D_s\to\mu\nu}}$	2.0×10^{-2} / $\mathbf{2.7\times10^{-6}}$	LHC [68] / $\boldsymbol{\mu\to e}$ **conversion**
$[\epsilon_P^{cs}]_{\mu\mu}$	$\mathbf{1.0\times10^{-3}}$	$\boldsymbol{\Gamma_{D_s\to\mu\nu}}$	2.0×10^{-2}	LHC [68]
$[\epsilon_P^{cs}]_{\mu\tau}$	$\mathbf{8.9\times10^{-3}}$	$\boldsymbol{\Gamma_{D_s\to\mu\nu}}$	2.0×10^{-2}	LHC [68]
$[\epsilon_P^{cs}]_{\tau e}$	$\mathbf{2.0\times10^{-1}}$	$\boldsymbol{\Gamma_{D_s\to\tau\nu}}$	1.6×10^{-2} / 1.9×10^{-2}	LHC / τ-decays [64]
$[\epsilon_P^{cs}]_{\tau\mu}$	$\mathbf{2.0\times10^{-1}}$	$\boldsymbol{\Gamma_{D_s\to\tau\nu}}$	2.5×10^{-2}	LHC [68]
$[\epsilon_P^{cs}]_{\tau\tau}$	$\mathbf{3.2\times10^{-2}}$	$\boldsymbol{\Gamma_{D_s\to\tau\nu}}$	2.5×10^{-2}	LHC [68]

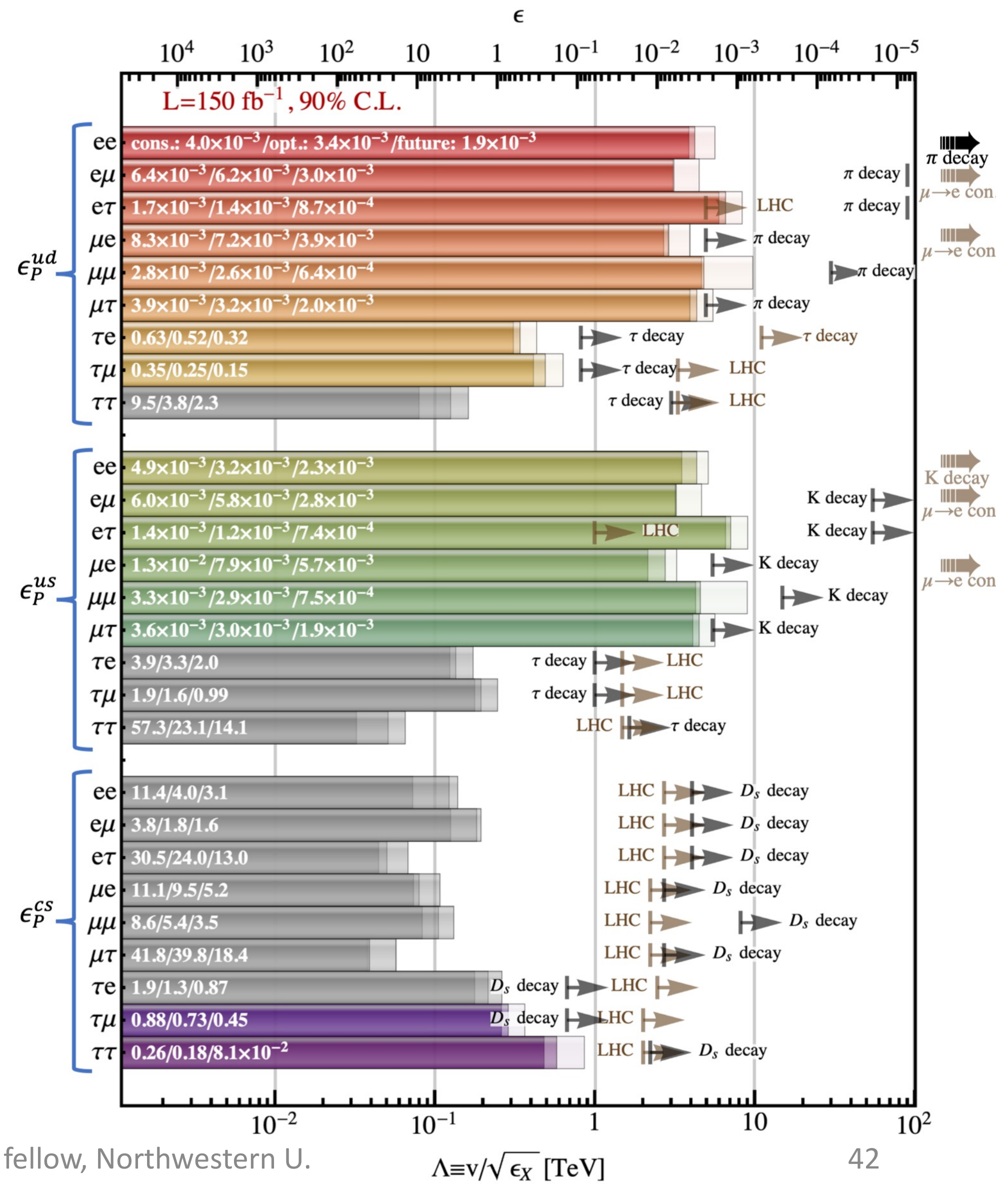
EFT at FASERν

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

- FASERν: colored bars
- Low Energy WEFT:

  (Independent of the underlying high-energy theory)
  - ✓ β-decays
  - ✓ Leptonic pion decays
  - ✓ (Semi-)Leptonic kaon decays
  - ✓ Hadronic τ decays
- High Energy SMEFT:

  (Bounds are less robust)
  - ✓ LHC
  - ✓ CLFV



EFT at FASERν

Turning on one interaction at a time: Right handed

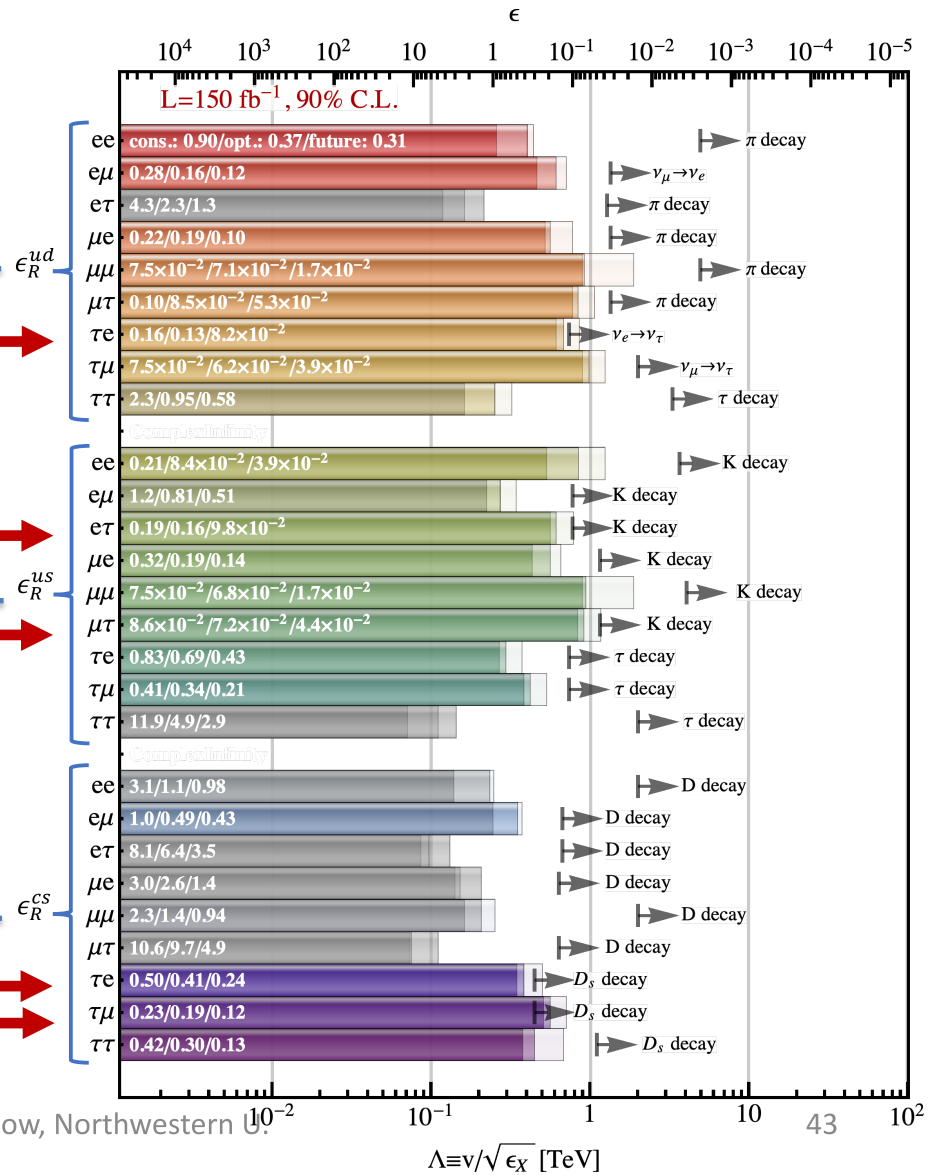
A. Falkowski, M. González-Alonso, J. Kopp, Y. Soreq, ZT
JHEP 10 (2021) 086

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



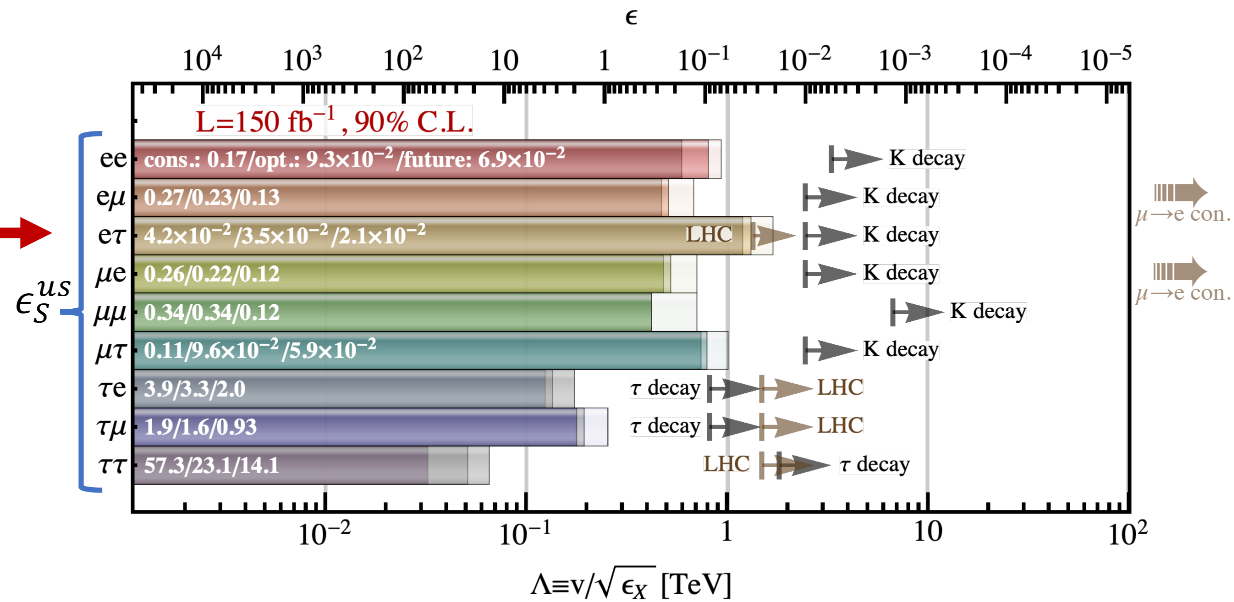
EFT at FASERν

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



EFT at FASERν

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