EFT at FASERν: An experiment to probe them all

HiDDeN Webinar Series

11 January 2022

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Neutrino Theory Network (NTN) fellow

Northwestern University

Based on:

"EFT at FASERν"
A. Falkowski, M. Gonzalez-Alonso, J. Kopp, Y. Soreq, Z. Tabrizi,
JHEP 10 (2021), 086 [arXiv: 2105.12136 [hep-ph]]

"Consistent QFT description of non-standard neutrino interactions"
A. Falkowski, M. González-Alonso and Z. Tabrizi,
JHEP 11 (2020), 048 [arXiv:1910.02971 [hep-ph]]

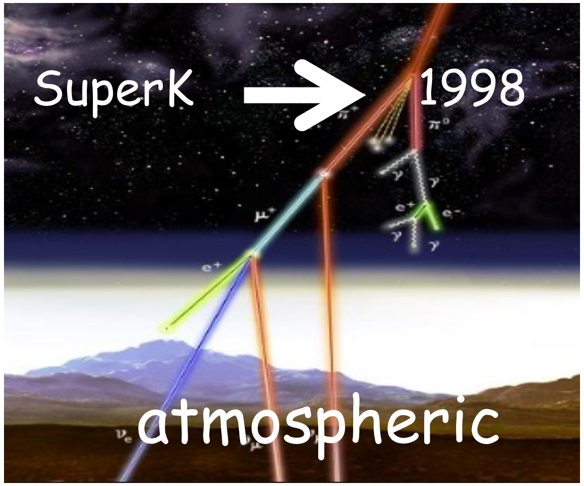
"Reactor neutrino oscillations as constraints on Effective Field Theory"
A. Falkowski, M. González-Alonso and Z. Tabrizi,
JHEP 1905, 173 (2019) [arXiv:1901.04553 [hep-ph]]

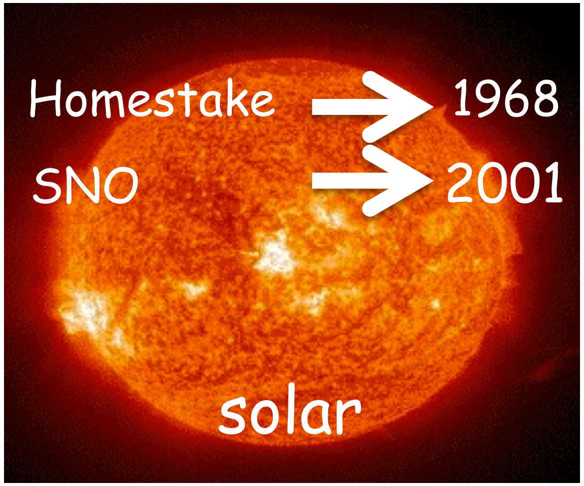
Outline

- Why EFT?
- EFT ladder
- EFT at neutrino experiments
  - FASERν
- Non-Oscillation experiments
- Conclusion

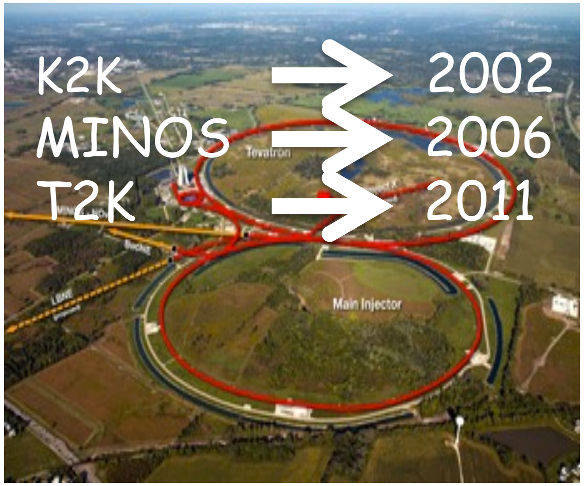
Neutrinos are massless in the SM!

However in nature.....





Neutrino oscillation needs masses and mixing!



The mass and flavor eigenstates do not coincide

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

The coefficient of the linear combination of neutrino mass eigenstates that couple to each flavor eigenstate!

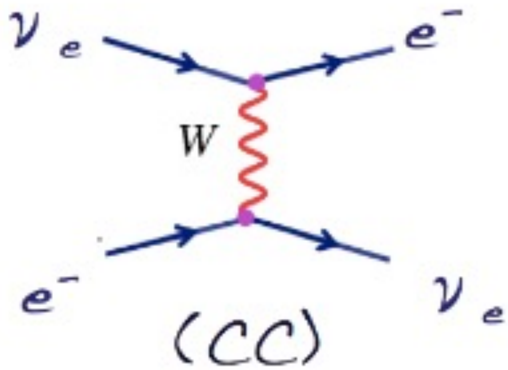
Oscillation probability in vacuum:

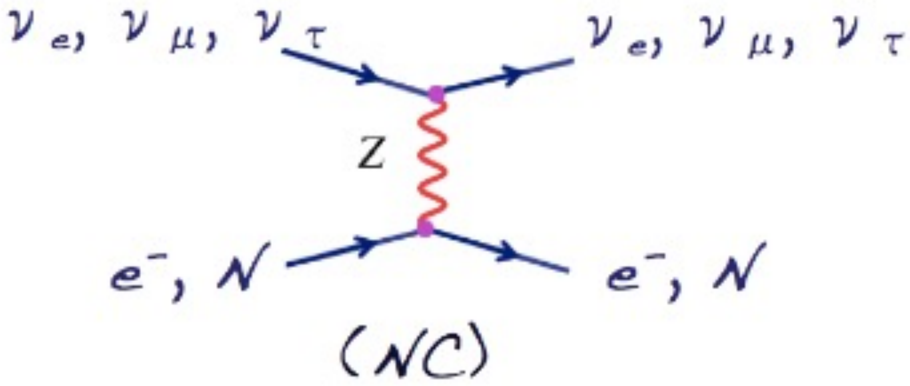
$$\Delta m^2_{kj} \equiv m^2_k - m^2_j$$

$$P_{\nu_\alpha \to \nu_\beta}(L,E) = \delta_{\alpha\beta} - 4 \sum_{k>j} \Re\mathfrak{e}\left[U^*_{\alpha k}\, U_{\beta k}\, U_{\alpha j}\, U^*_{\beta j}\right] \sin^2\left(\frac{\Delta m^2_{kj} L}{4E}\right)$$
$$+ 2 \sum_{k>j} \Im\mathfrak{m}\left[U^*_{\alpha k}\, U_{\beta k}\, U_{\alpha j}\, U^*_{\beta j}\right] \sin\left(\frac{\Delta m^2_{kj} L}{2E}\right)$$

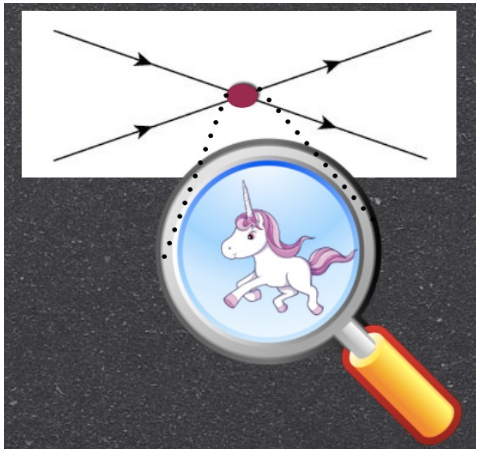
Oscillation experiments are sensitive not only to neutrino masses and mixing, but also to how neutrinos interact with matter.

- Coherent CC and NC forward scattering of neutrinos





New effective 4-fermion interactions between leptons and quarks may give observable effects in neutrino production, propagation, and detection.



How to use EFT language to "systematically" explore new physics beyond the neutrino masses and mixing in neutrino experiments?

Why EFT?

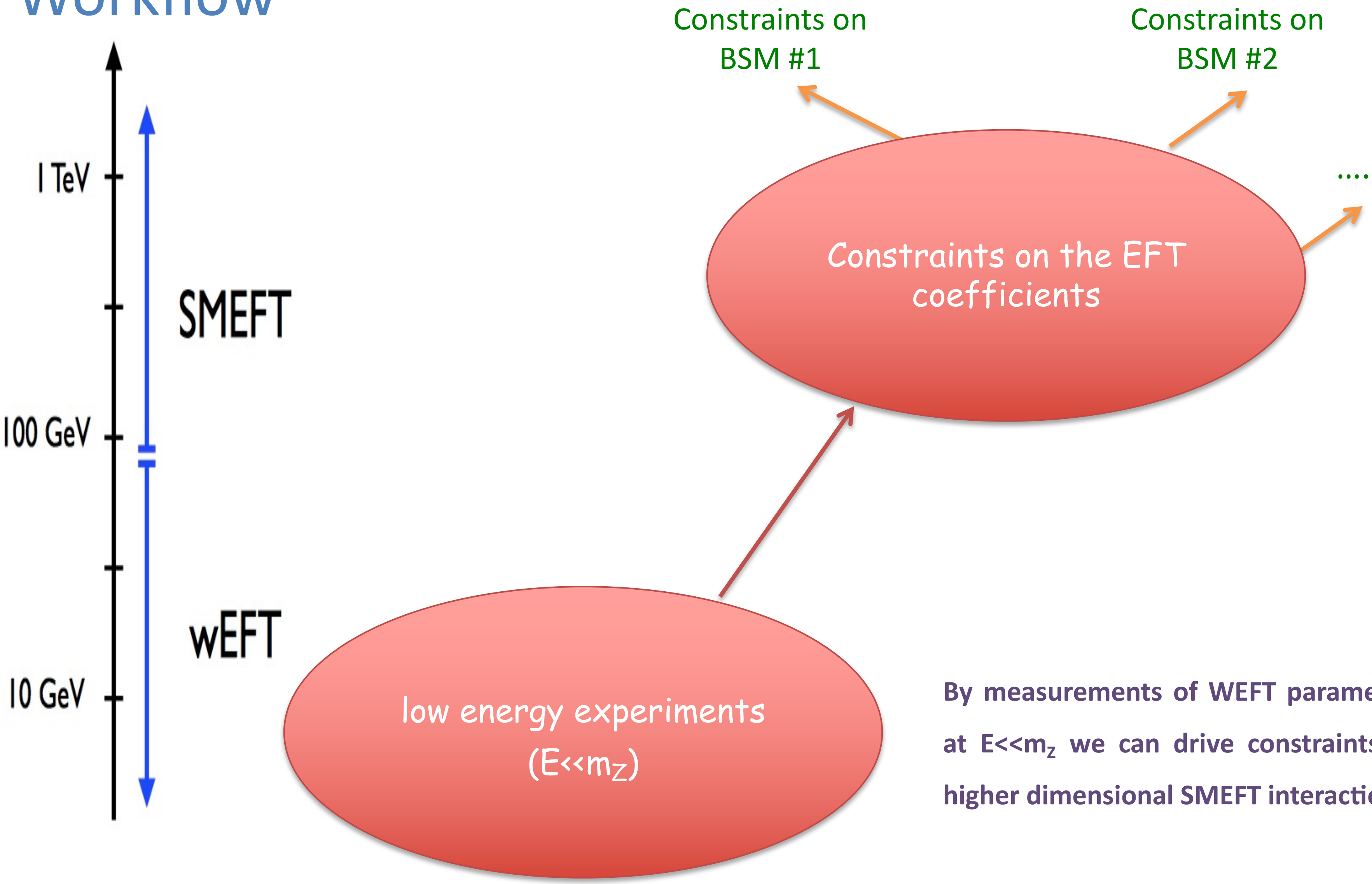
- Wealth of low-energy observables probing different aspects of particle interactions are described within one consistent framework.

- Constraints from different observables can be meaningfully compared.

- Results obtained in the language of EFT can be translated into constraints on particular new physics models.

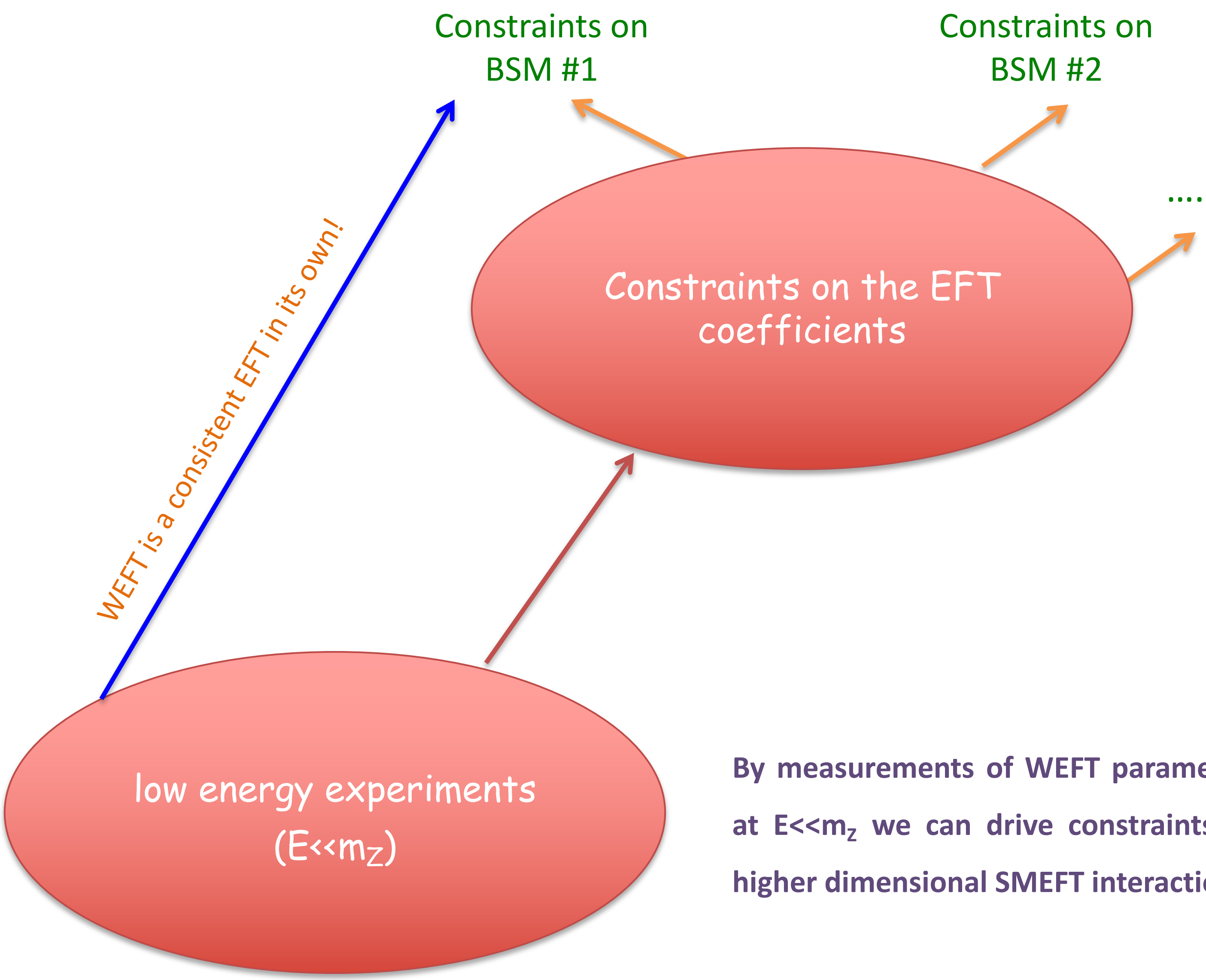
The point is that one can probe very heavy particles, often beyond the reach of present colliders, by precisely measuring low-energy observables.

Workflow



By measurements of WEFT parameters at $E \ll m_Z$ we can drive constraints on higher dimensional SMEFT interactions.

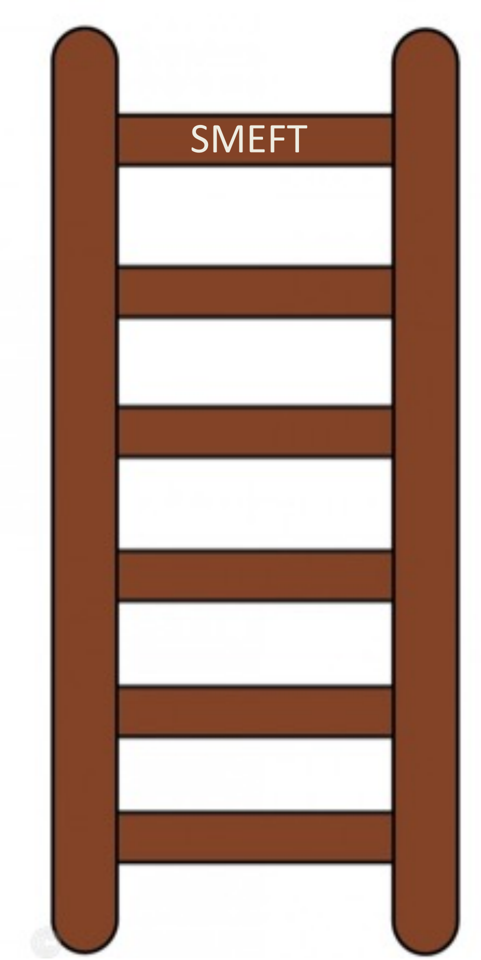
Workflow



By measurements of WEFT parameters at $E \ll m_Z$ we can drive constraints on higher dimensional SMEFT interactions.

Approach:

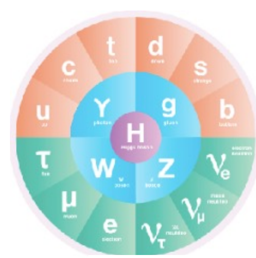
$E > m_Z$



- If BSM particles are much heavier than the Z boson mass and the EWSB is linearly realized, then the relevant effective theory above the weak scale is the so-called SMEFT.
- It has the same particle content and local symmetry as the SM, but differs by the presence of higher-dimensional (non-renormalizable) interactions in the Lagrangian.

$$\mathcal{L}_{\text{SM EFT}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda_L}\mathcal{L}^{D=5} + \boxed{\frac{1}{\Lambda^2}\mathcal{L}^{D=6}}$$

- The SMEFT framework allows one to describe effects of new physics beyond the SM in a model independent way



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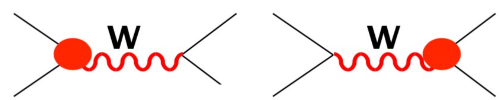
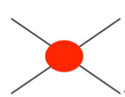
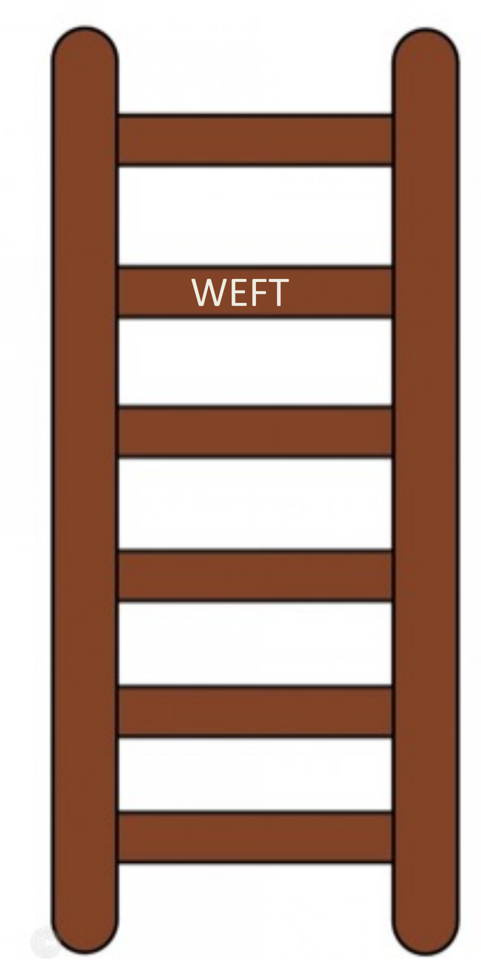


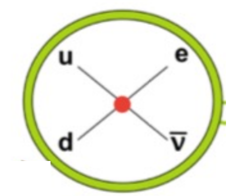


$$O_{lq}^{(3)} = (\bar{l}\gamma^\mu\sigma^a l)(\bar{q}\gamma_\mu\sigma^a q)$$
$$O_{qde} = (\bar{l}e)(\bar{d}q) + \text{h.c.}$$
$$O_{lq} = (\bar{l}_a e)\epsilon^{ab}(\bar{q}_b u) + \text{h.c.}$$
$$O_{lq}^{t} = (\bar{l}_a\sigma^{\mu\nu} e)\epsilon^{ab}(\bar{q}_b\sigma_{\mu\nu} u) + \text{h.c.}$$

Approach:

$E \ll m_Z$





- In particular, considering the CC interactions of neutrinos.

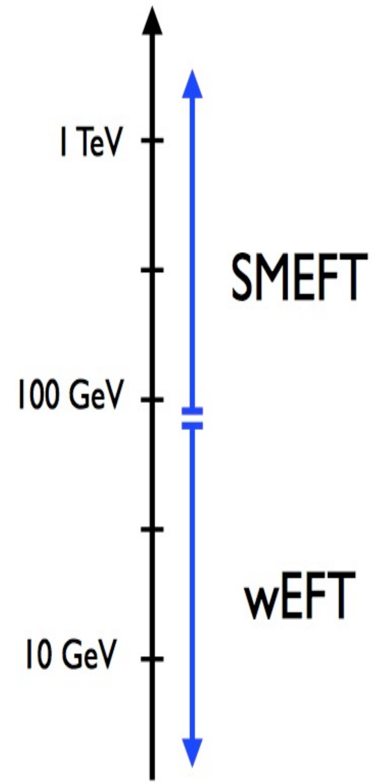
- At this scale heavy particles such as W and Z bosons, Higgs and top can be integrated out from the SMEFT, leading to Weak EFT (WEFT).

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

- Apart from the SM-like V-A interactions ($1+\varepsilon_L$), right-handed (ε_R), scalar (ε_S), pseudoscalar (ε_P), and tensor (ε_T) interactions are allowed.

Matching WEFT and SMEFT parameters:

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



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

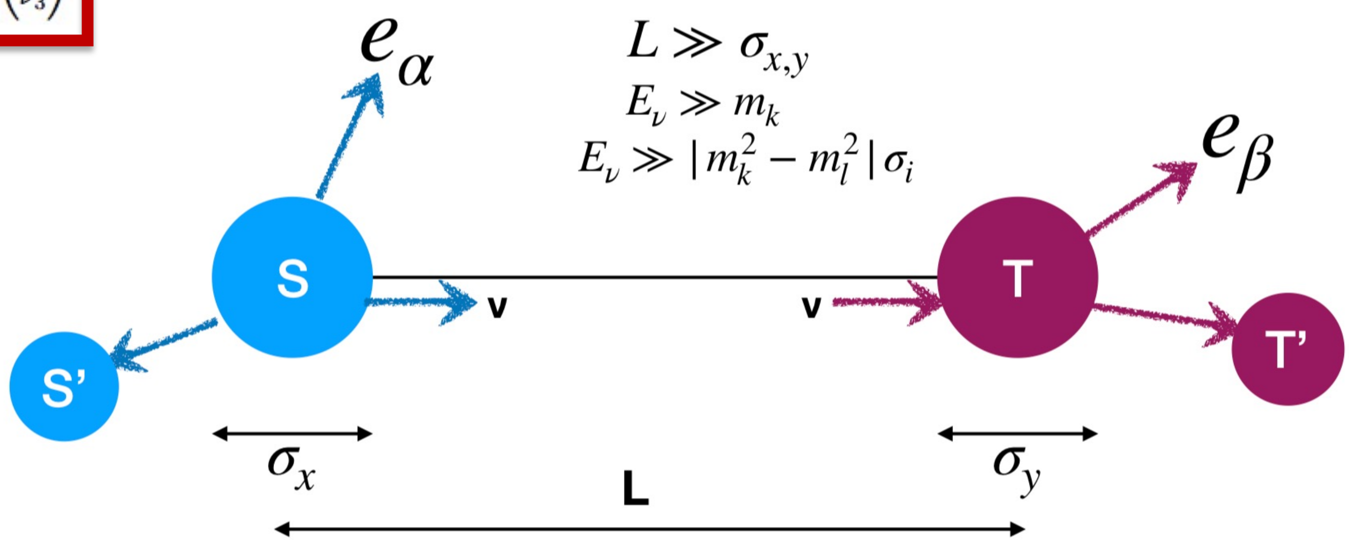
A. Falkowski, M. González-Alonso, ZT
JHEP 05 (2019) 173

QFT Description

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

A. Falkowski, M. González-Alonso, ZT
arXiv: 1910.02971

$$L \gg \sigma_{x,y}$$
$$E_\nu \gg m_k$$
$$E_\nu \gg |m_k^2 - m_l^2| \sigma_i$$



$$-\frac{2V_{ud}}{\mathrm{v}^2}\Bigg[\left[1+\epsilon_L\right]_{\alpha\beta}\bar{e}_\alpha\gamma_\mu P_L\nu_\beta\cdot\bar{u}_L\gamma^\mu d_L$$
$$+\left[\epsilon_R\right]_{\alpha\beta}\bar{e}_\alpha\gamma_\mu P_L\nu_\beta\cdot\bar{u}_R\gamma^\mu d_R$$
$$+\frac{1}{2}\bar{e}_\alpha P_L\nu_\beta\cdot\bar{u}\left[\epsilon_S-\epsilon_P\gamma_5\right]_{\alpha\beta}d$$
$$+\frac{1}{4}\left[\epsilon_T\right]_{\alpha\beta}\bar{e}_\alpha\sigma_{\mu\nu}P_L\nu_\beta\cdot\bar{u}_R\sigma^{\mu\nu}d_L\Bigg]+\text{h.c.}$$

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

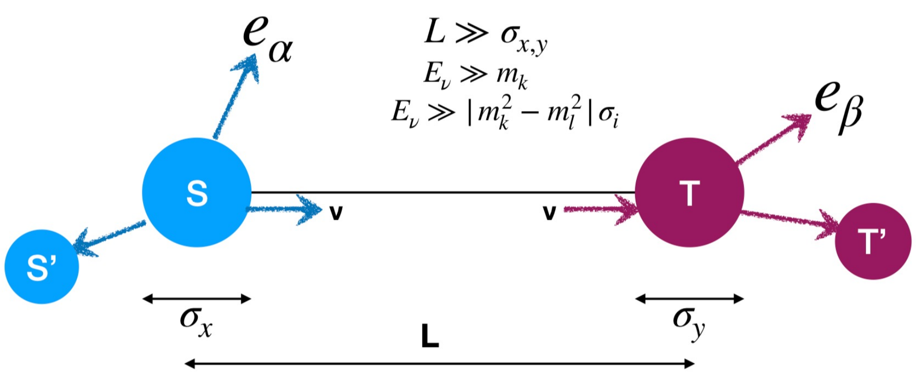
depends on the kinematic and spin variables

QFT Description

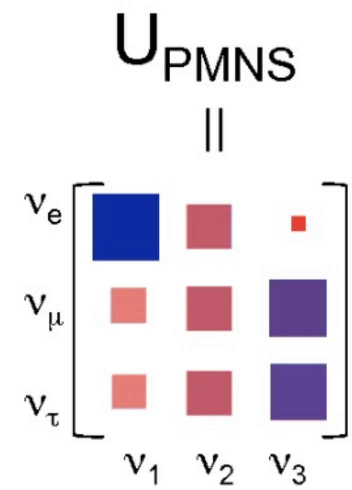
A. Falkowski, M. González-Alonso, ZT
arXiv: 1910.02971

Observable: **rate of detected events**

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



EFT at Oscillation Experiments:



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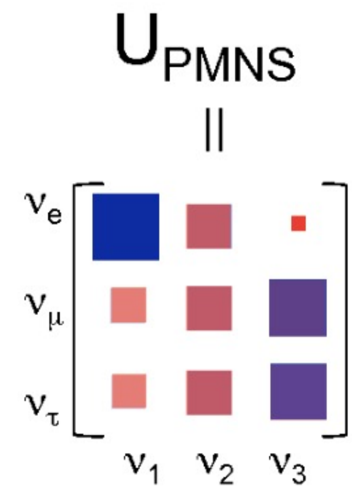
arXiv: 1910.02971, JHEP (2020)...

SM

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

EFT at Oscillation Experiments:



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arXiv: 1910.02971, JHEP (2020)…

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

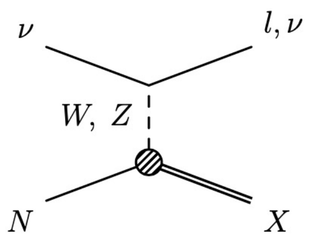
Production and detection coefficients, depend on amplitudes

One needs to calculate these coefficients for different production and detection processes.

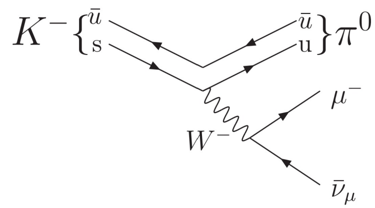
$$\mathcal{M}^P_{\alpha k} = U^*_{\alpha k}A^P_L + \sum_X [\epsilon_X U]^*_{\alpha k}A^P_X$$
$$\mathcal{M}^D_{\beta k} = U_{\beta k}A^D_L + \sum_X [\epsilon_X U]_{\beta k}A^D_X$$

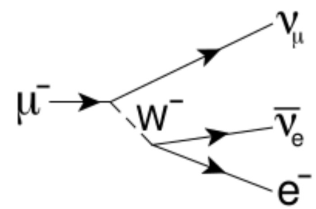
$$p_{XY} \equiv \frac{\int d\Pi_{P'} A^P_X \bar{A}^P_Y}{\int d\Pi_{P'}|A^P_L|^2}, \quad d_{XY} \equiv \frac{\int d\Pi_D A^D_X \bar{A}^D_Y}{\int d\Pi_D |A^D_L|^2}.$$

DIS: FASERν



Kaon/Muon decay: ISODAR, KDAR





Solar neutrinos: Borexino

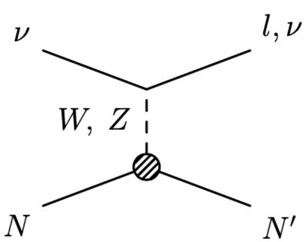
^{7}Be $\quad {}^7\mathrm{Be} + e^- \to {}^7\mathrm{Li} + \nu_e$

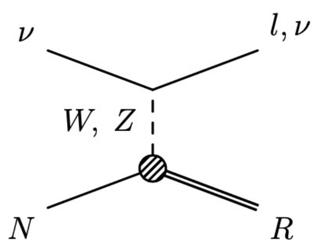
${}^3\mathrm{He} + p \to {}^4\mathrm{He} + e^+ + \nu_e$ **hep**

(hep)

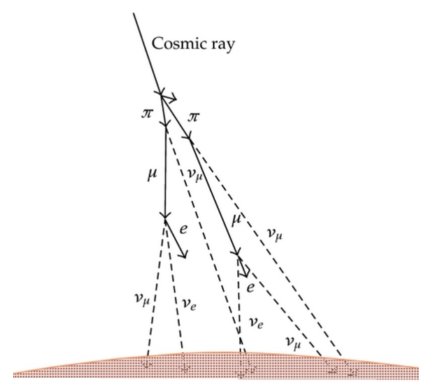
$p + e^- + p \to {}^2\mathrm{H} + \nu_e$ ***pep***

QE, Resonances: MINOS, NOvA, DUNE

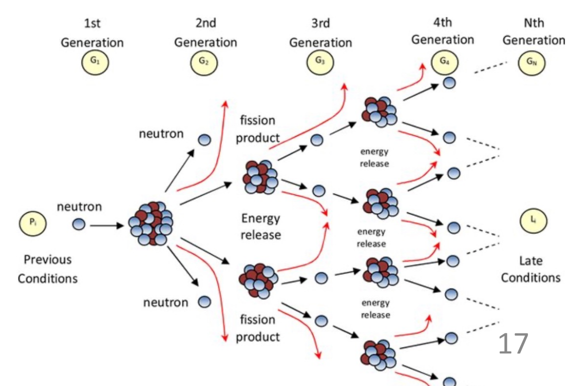




Atmospheric Neutrinos: IceCube



Beta decay and IBD: Reactor Experiments

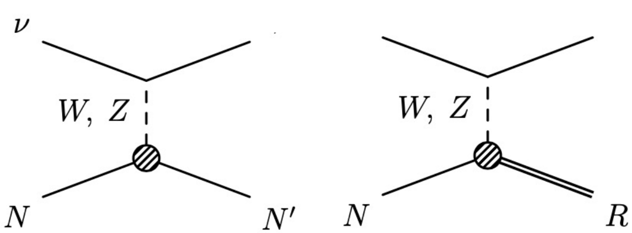


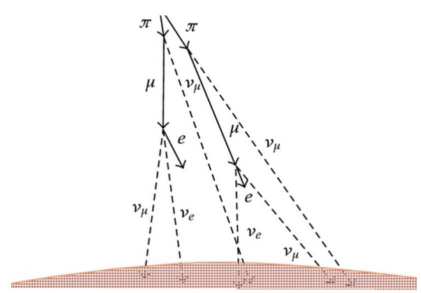
DIS: FASERν

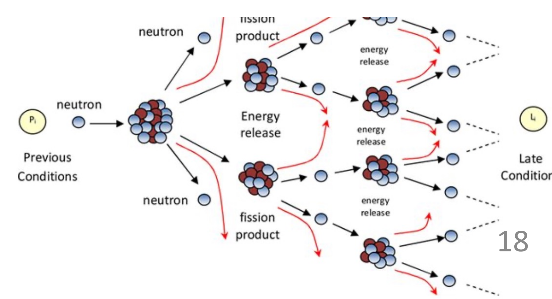
Kaon/Muon decay:

Solar neutrinos:

Well…

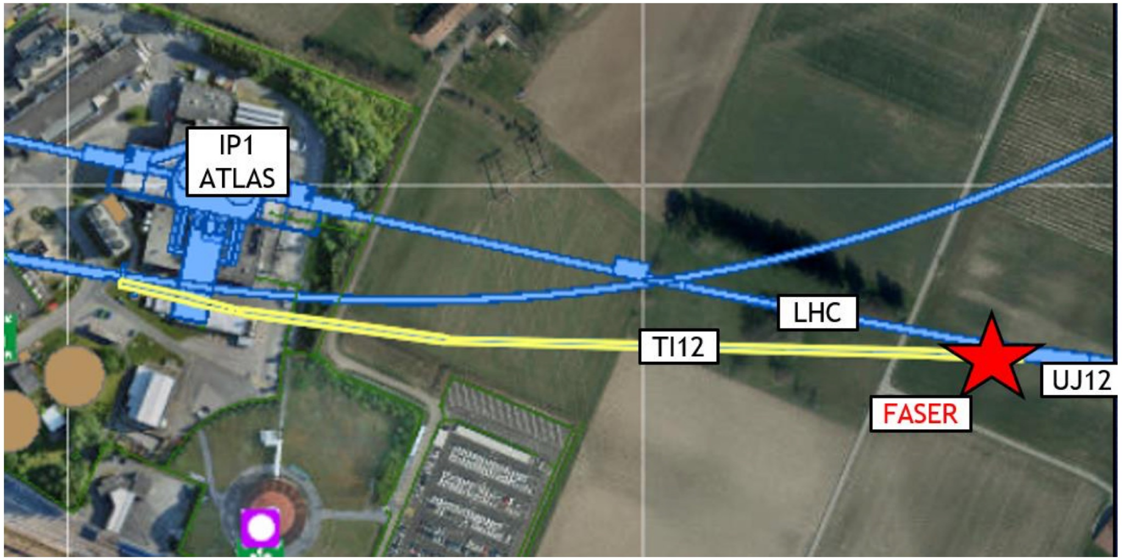


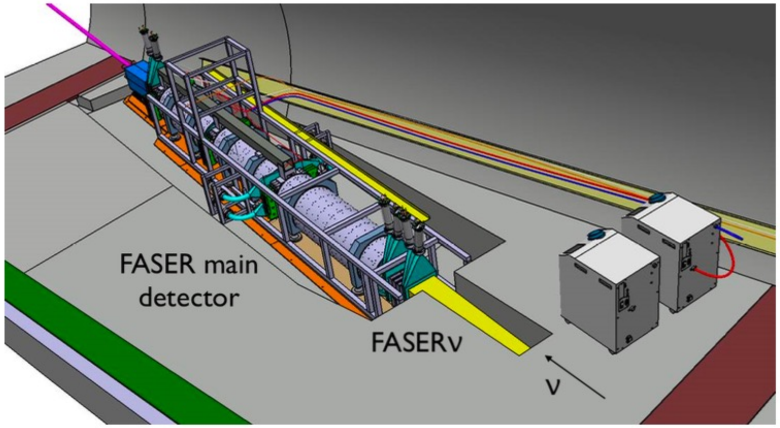




EFT at FASERν

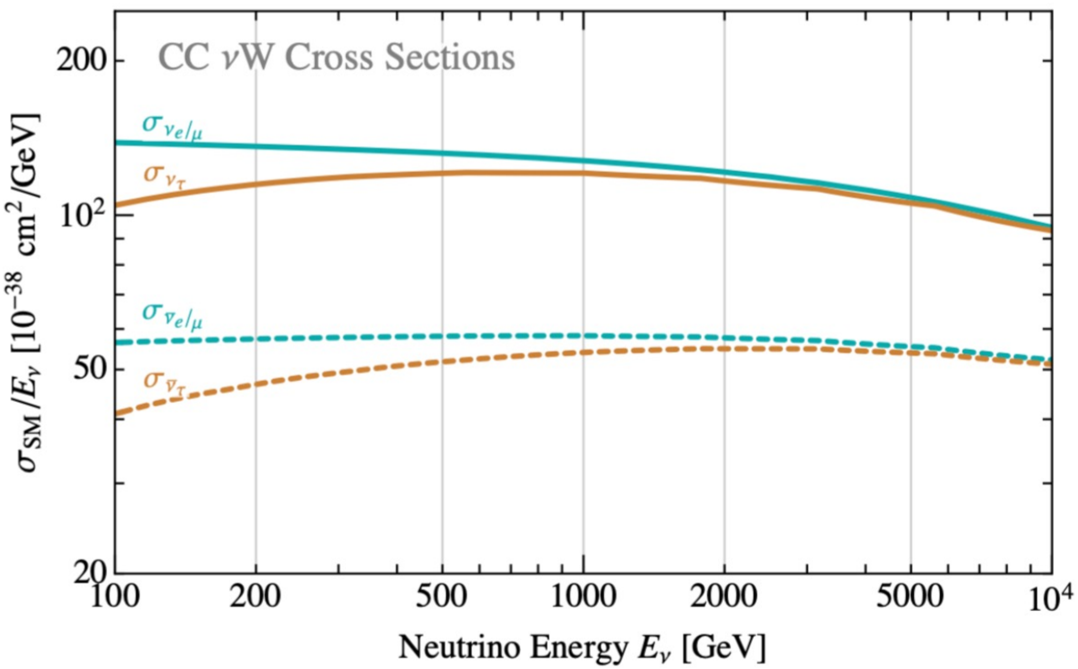
- will be located downstream of the ATLAS interaction point at a distance of 480 m.
- Ideal for detecting high-energy neutrinos produced at LHC.
- 1.2-t of tungsten material.

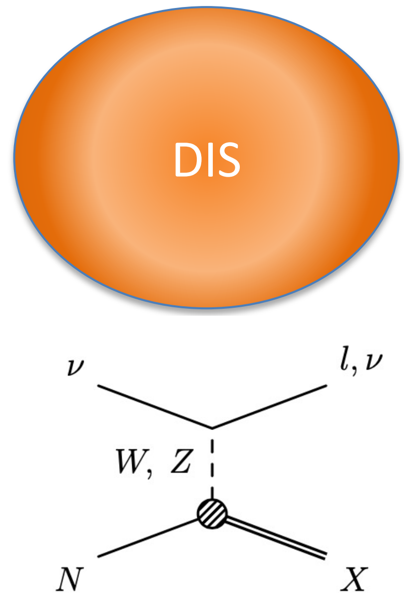




A. Falkowski, M. González-Alonso, J. Kopp, Y. Soreq, **ZT**
JHEP 10 (2021) 086

Why FASERν?





DIS detection, easy to include NP
(compared with QE and Resonances)

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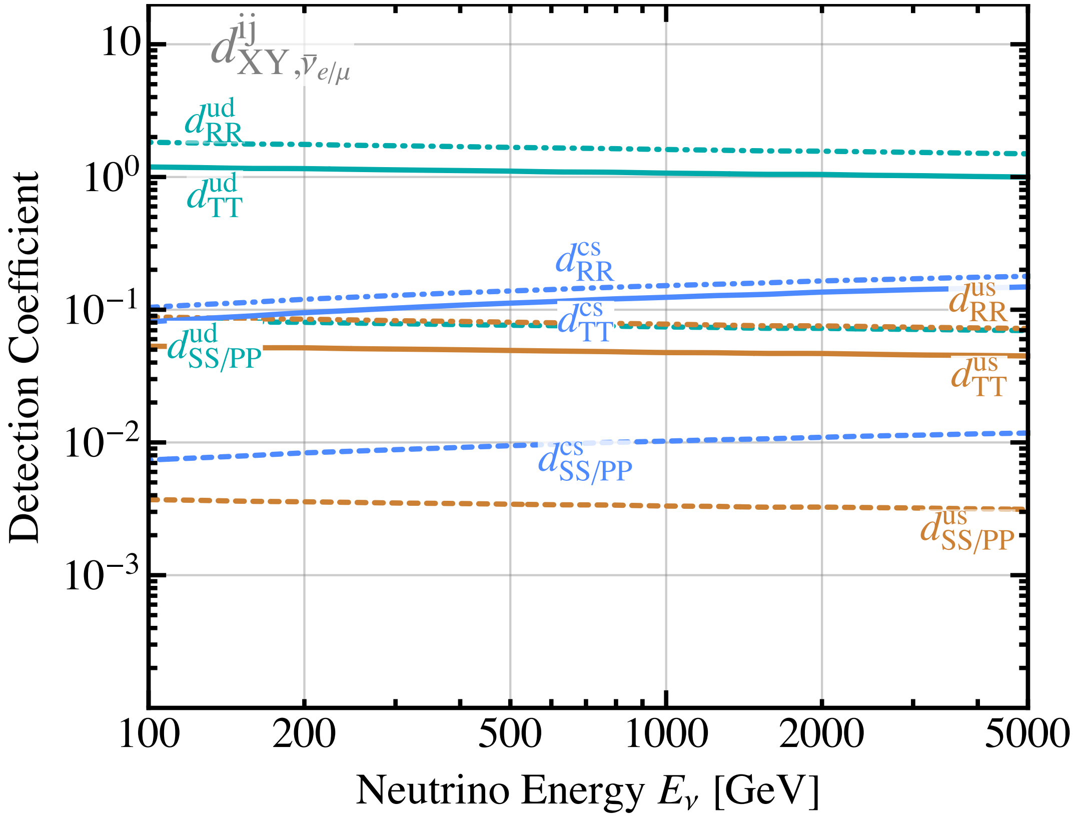
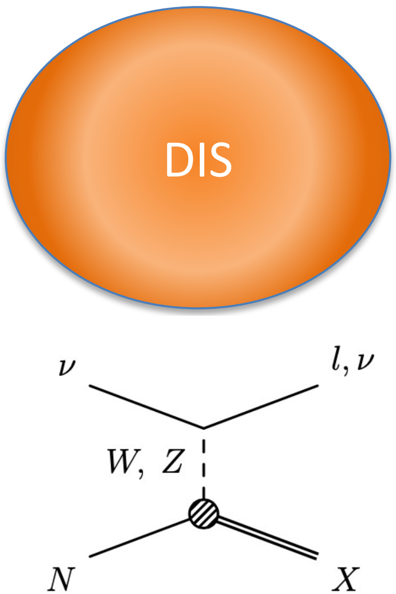


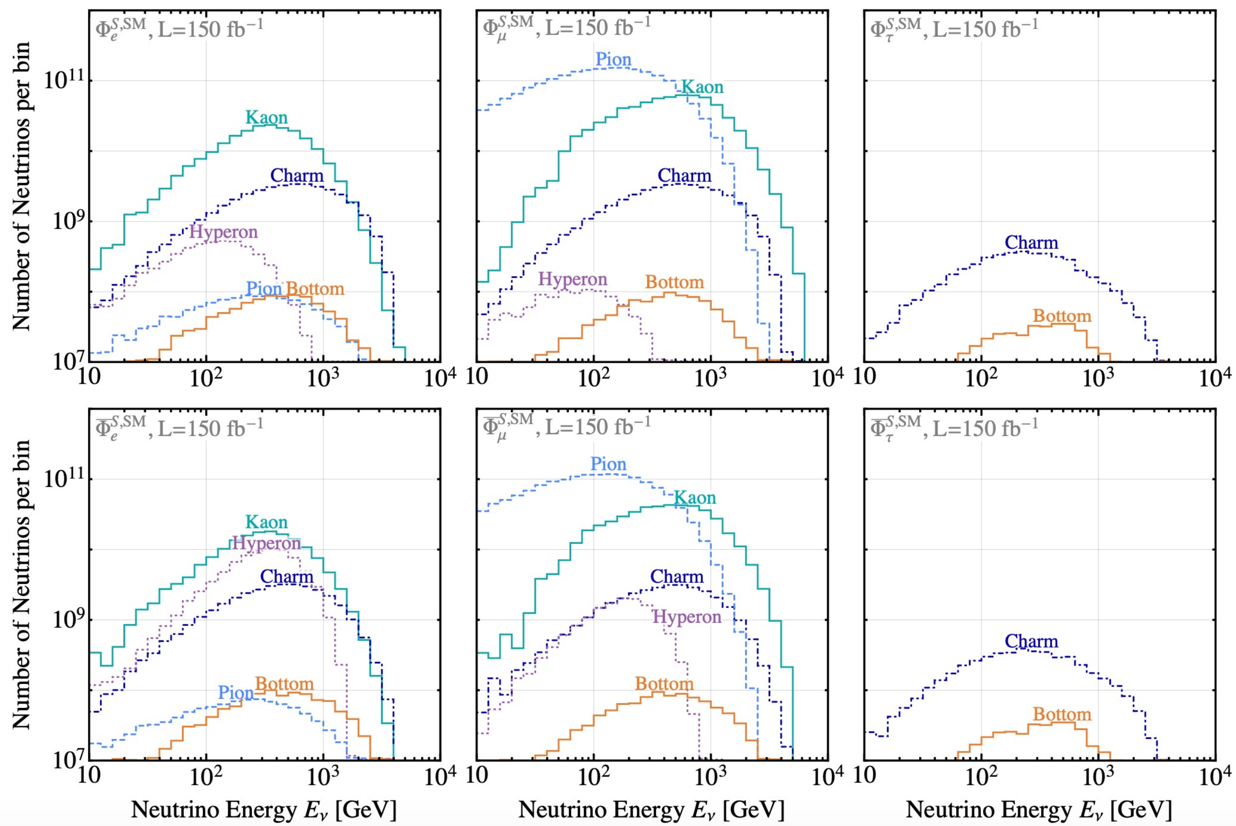


- No new physics at the linear order!
- Good sensitivity to the right handed and tensor interactions.

based on arXiv:2105.08270

Why FASERν?

- Several production modes
- Pion and Kaon decays are the dominant ones
- All (anti)neutrino flavors are available



Generators		FASERν		
light hadrons	heavy hadrons	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$
SIBYLL	SIBYLL	1343	6072	21.2
DPMJET	DPMJET	4614	9198	131
EPOSLHC	Pythia8 (Hard)	2109	7763	48.9
QGSJET	Pythia8 (Soft)	1437	7162	24.5

Pion decay

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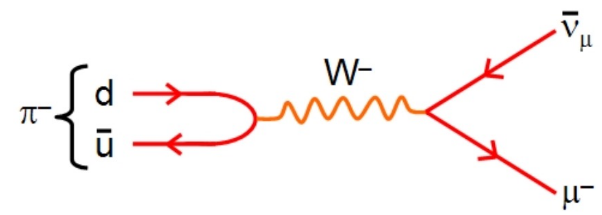
JHEP 10 (2021) 086

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



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

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

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

Pion decay

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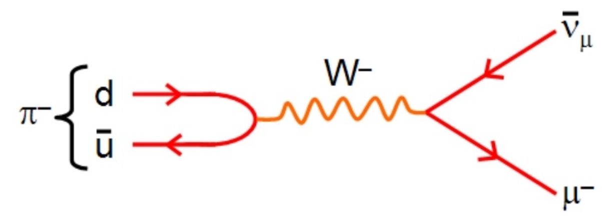
Due to the pseudoscalar nature of the pion, it is sensitive only to axial (ϵ_L-ϵ_R) and pseudo-scalar (ϵ_P) interactions.

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

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

~700!



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

We will have a great chiral enhancement for the pseudoscalar NP!

kaon decay

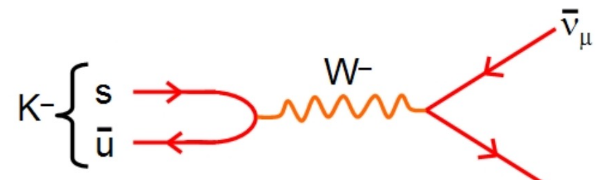
A. Falkowski, M. González-Alonso, J. Kopp, Y. Soreq, **ZT**
JHEP 10 (2021) 086

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

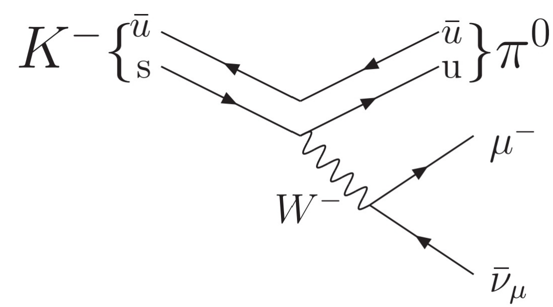
$$p_{XY,\alpha}^{S,jk} \equiv \frac{\int dE_S \frac{\phi_S(E_S)}{E_S} \sum_i \beta_i^S(E_S) \int d\Pi_{P_i'} A_{X,\alpha}^{S_i,jk} A_{Y,\alpha}^{S_i,jk*}}{\int dE_S \frac{\phi_S(E_S)}{E_S} \sum_{i'j'k'} \beta_{i'}^S(E_S) \int d\Pi_{P_{i'}'} |A_{L,\alpha}^{S_i,j'k'}|^2}$$

Energy distribution of $K^{\pm}$, K_L or K_S

Thanks to Felix Kling



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



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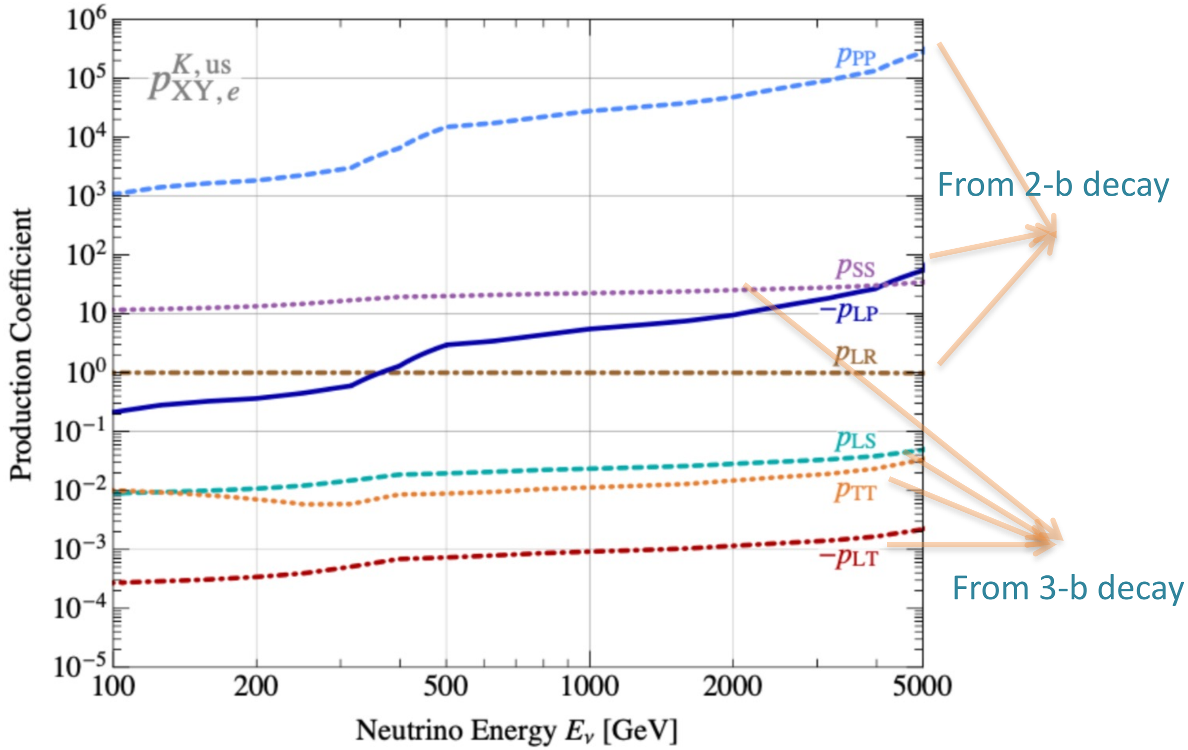

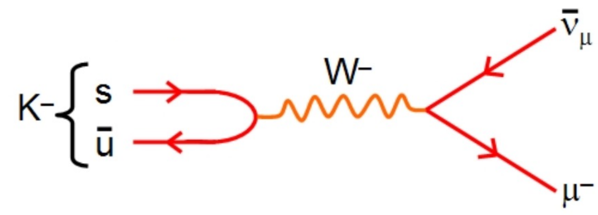

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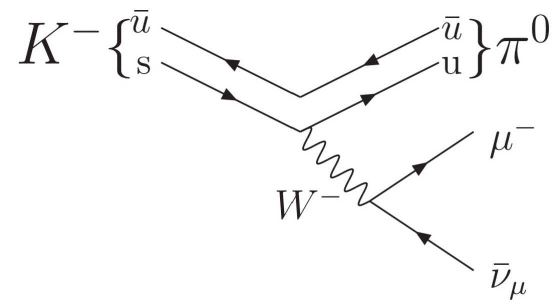
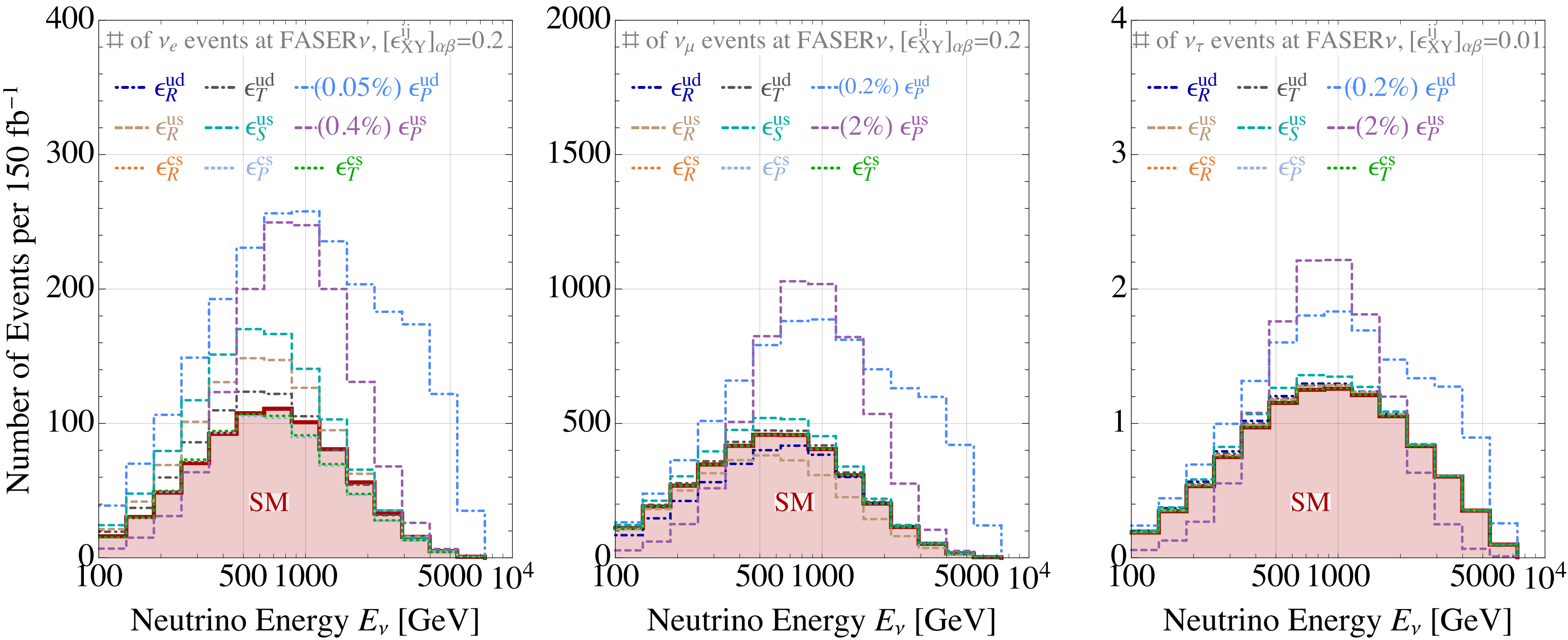


We see ``more'' chiral-enhancement for the decay into electrons!!!

EFT at FASERν



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RESULTS

Turning on one interaction at a time: Pseudo-Scalar

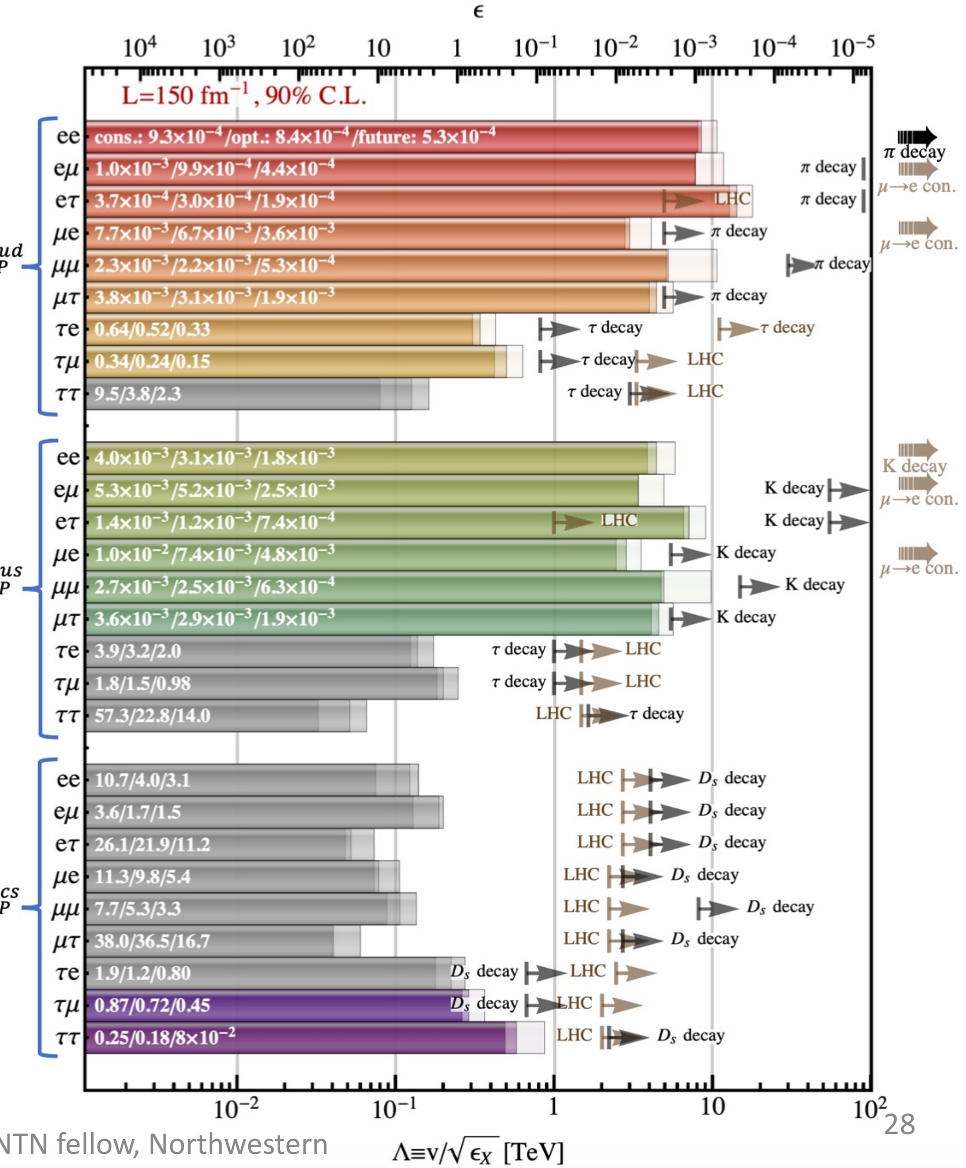
A. Falkowski, M. González-Alonso, J. Kopp, Y. Soreq, **ZT**
JHEP 10 (2021) 086

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

From pion decay and DIS → ϵ_P^{ud}

From kaon decay and DIS → ϵ_P^{us}

From charm decay and DIS → ϵ_P^{cs}



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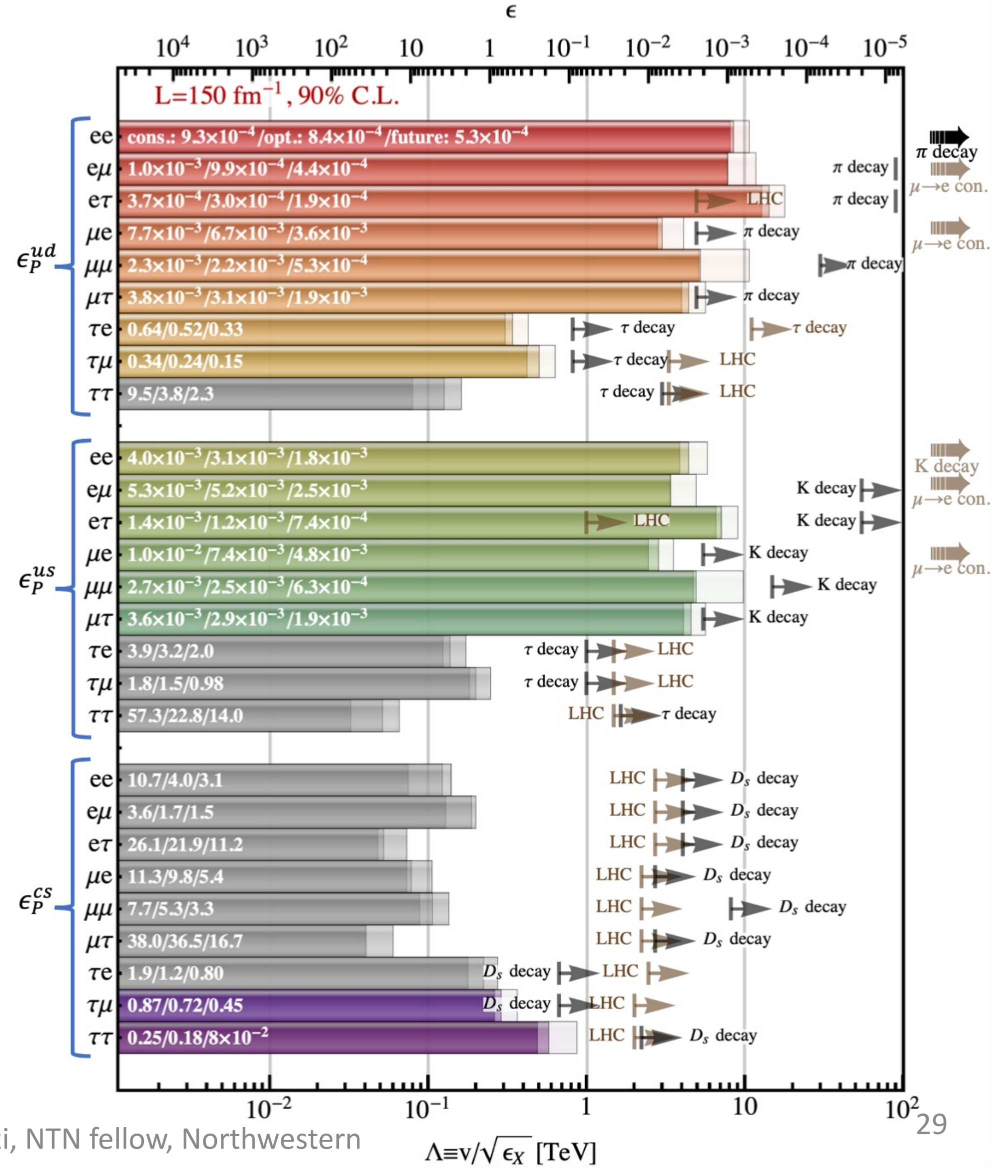
- The rates scale linearly wrt volume:

  diagonal $\varepsilon \sim (V_2/V_1)^{1/2}$

  off-diagonal $\varepsilon \sim (V_2/V_1)^{1/4}$

- 20 times larger lum. gives ~ 4 (2) times better sensitivity for (off-)diagonal elements



RESULTS

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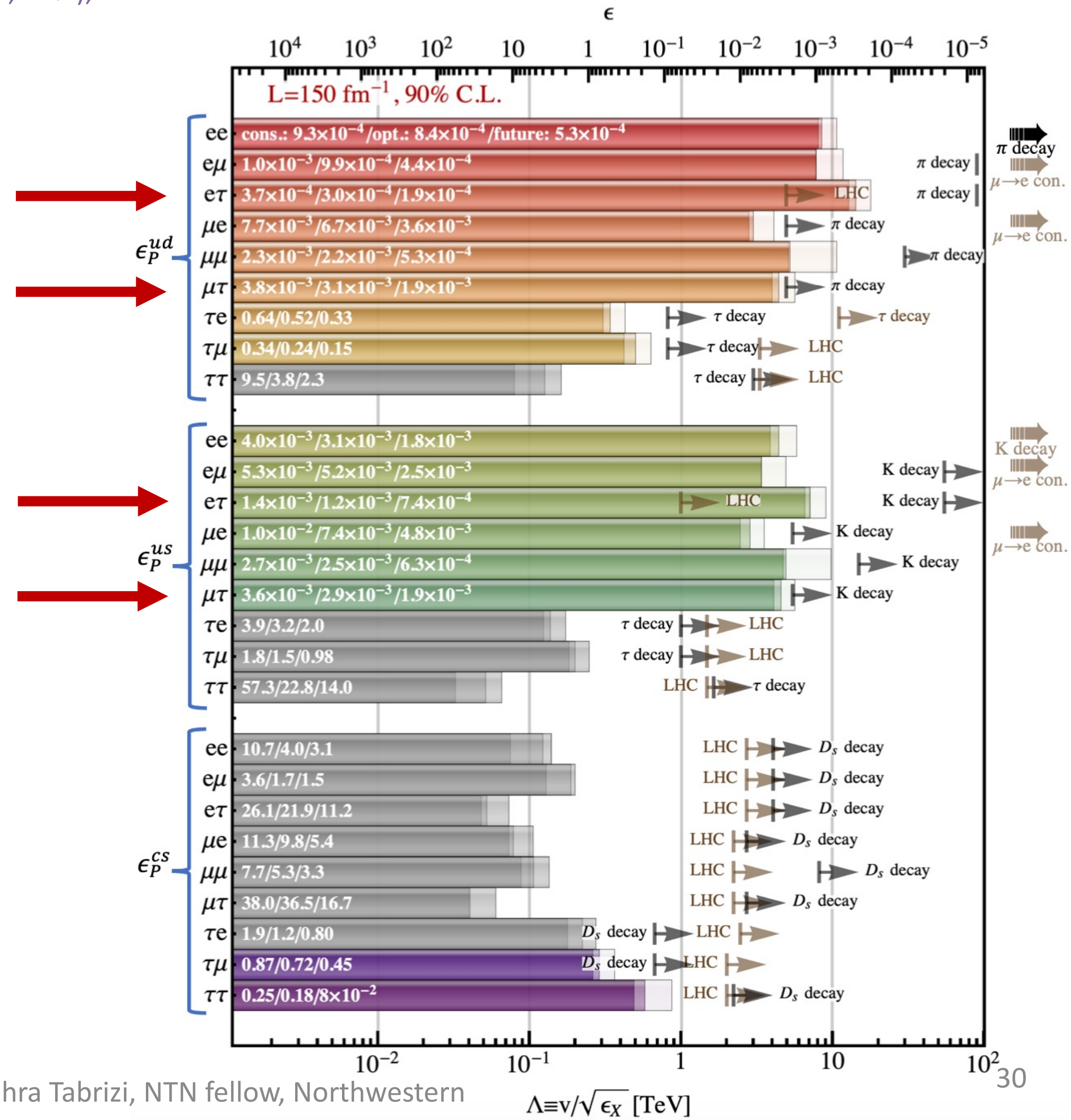


RESULTS

Turning on one interaction at a time: Right handed

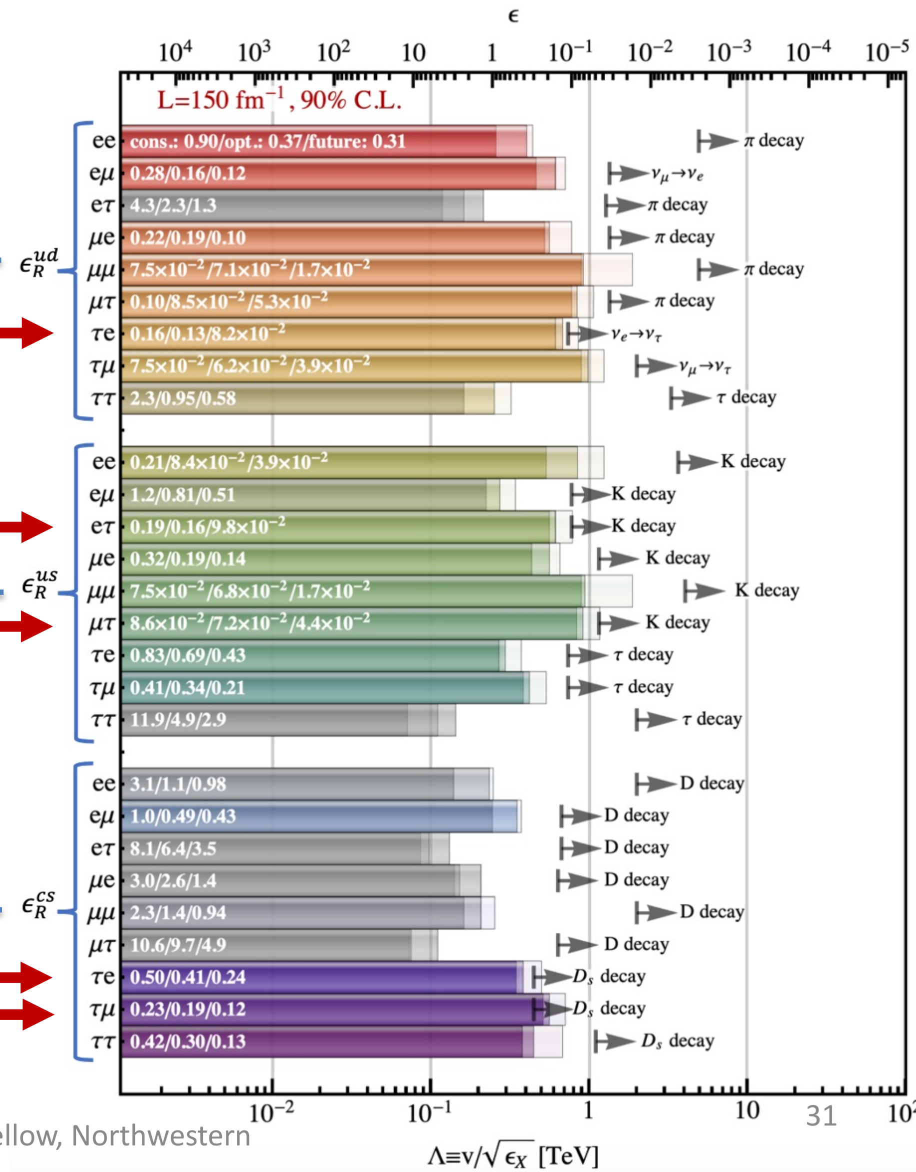
A. Falkowski, M. González-Alonso, J. Kopp, Y. Soreq, ZT
JHEP 10 (2021) 086

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



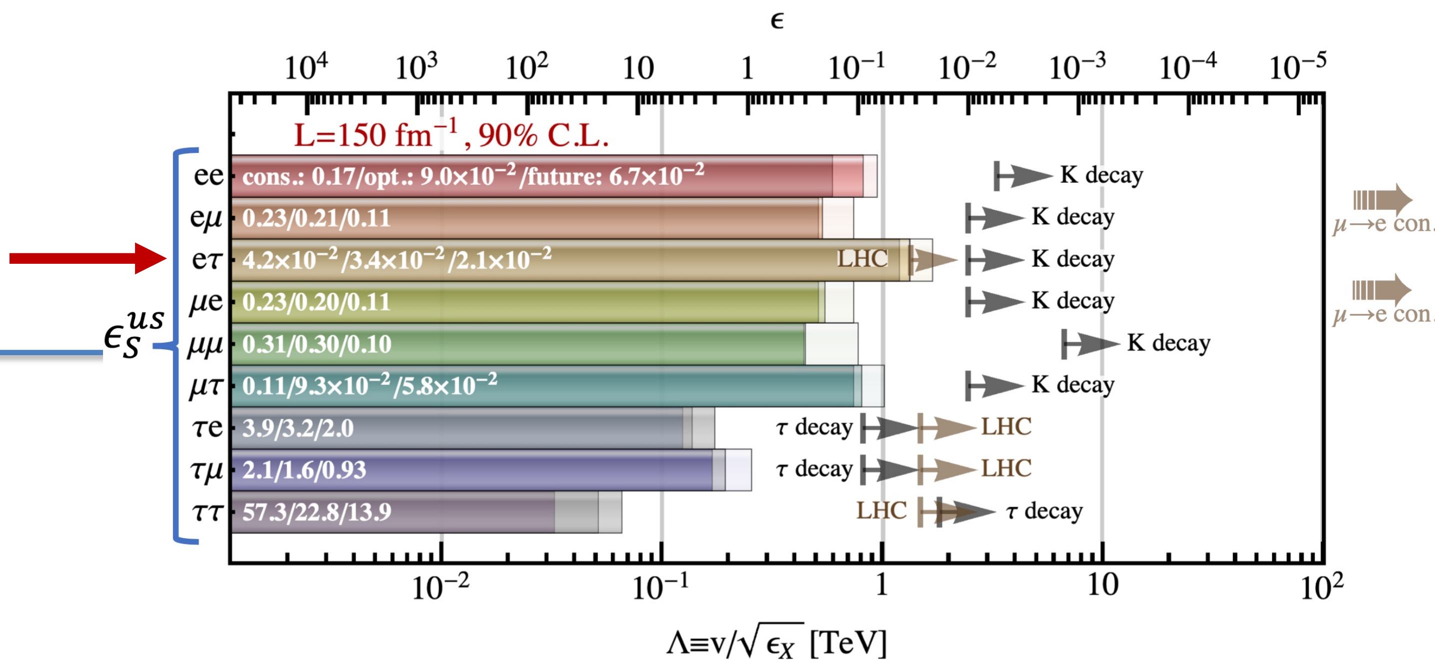
RESULTS

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

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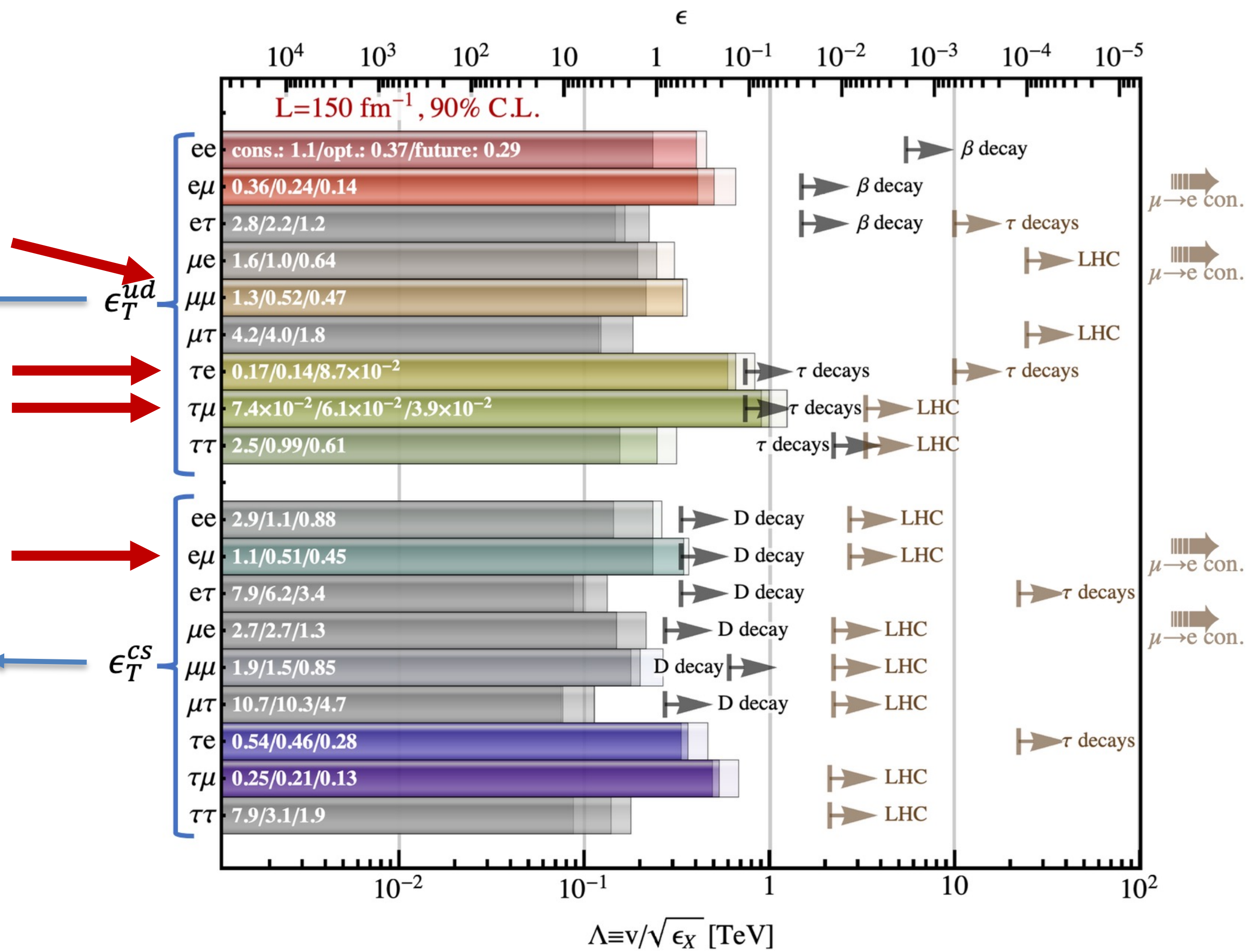
Optimistic (5%, 10%, 15%) and Pessimistic (30%, 40%, 50%), uncertainties on electron muon and tau neutrinos

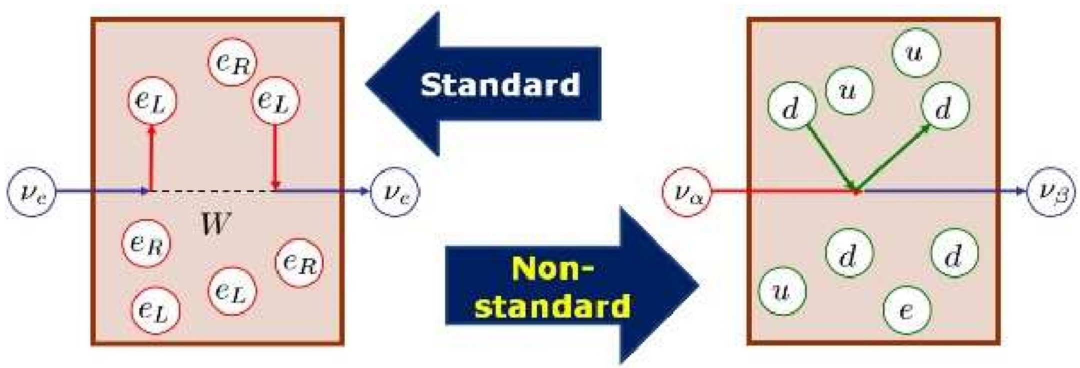
From DIS

From charm decay and DIS



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)

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

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

QFT vs QM-NSI

- Can one "validate" QM-NSI approach from the QFT results?
- If yes, relation between NSI parameters and Lagrangian (EFT) parameters?
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$$\epsilon^s_{\alpha\beta} = \sum_X p_{XL}[\epsilon_X]^*_{\alpha\beta}, \quad \epsilon^d_{\beta\alpha} = \sum_X d_{XL}[\epsilon_X]_{\alpha\beta}$$

A. Falkowski, M. González-Alonso, ZT
arXiv: 1910.02971

Comparing QM and QFT

At the linear order we have:

A. Falkowski, M. González-Alonso, ZT
JHEP 10 (2021) 086

Neutrino Process	NSI Matching with EFT
ν_e produced in beta decay	$\epsilon^s_{e\beta} = [\epsilon_L]^*_{e\beta} - [\epsilon_R]^*_{e\beta} - \frac{g_T}{g_A}\frac{m_e}{f_T(E_\nu)}[\epsilon_T]^*_{e\beta}$
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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

A. Falkowski, M. González-Alonso, ZT
JHEP 10 (2021) 086

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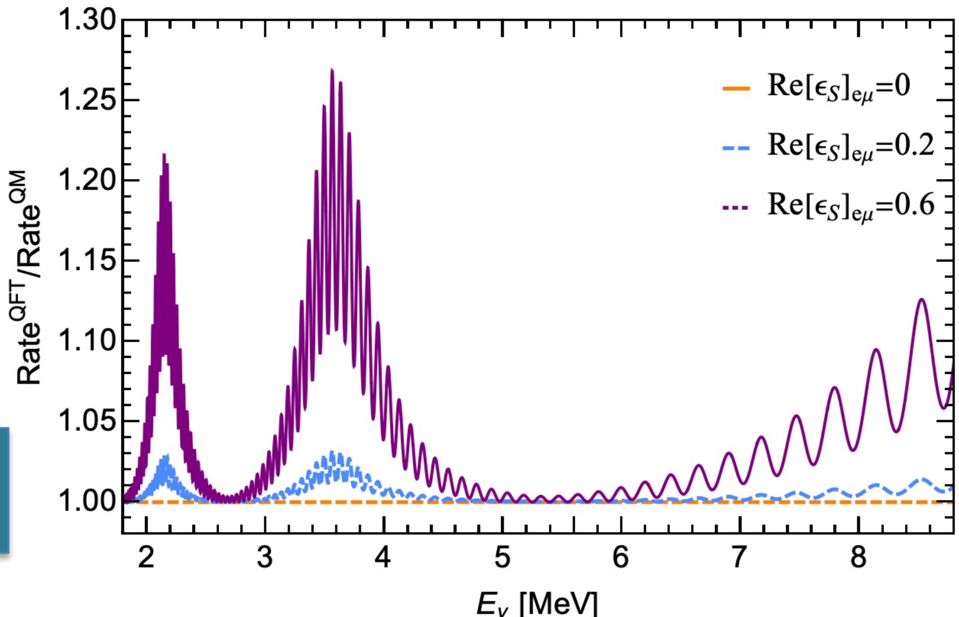
We can compare the QFT and QM rates at all orders.

e.g. at KamLAND experiment

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

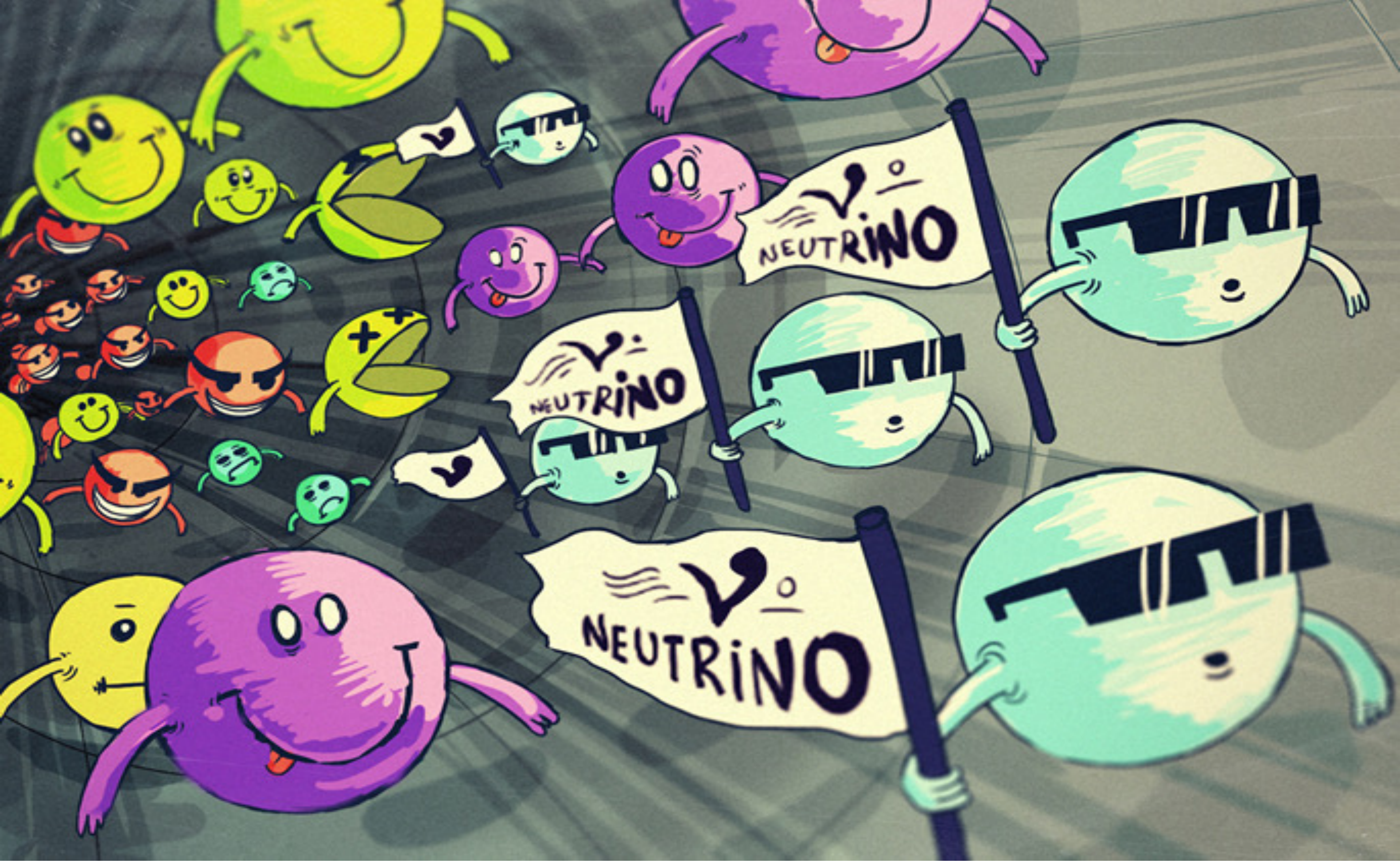


Conclusion:

- We have proposed a systematic approach to neutrino experiments in the SMEFT framework.

- We applied the formalism to FASERν experiment, however the formalism can be readily extended to other types of neutrino experiments.

- Constraints of the order of 10^{-3} (10 TeV) can be derived for pseudo-scalar interaction at FASERν. In total 81 different operators can be probed at FASERν.



Thanks for your attention

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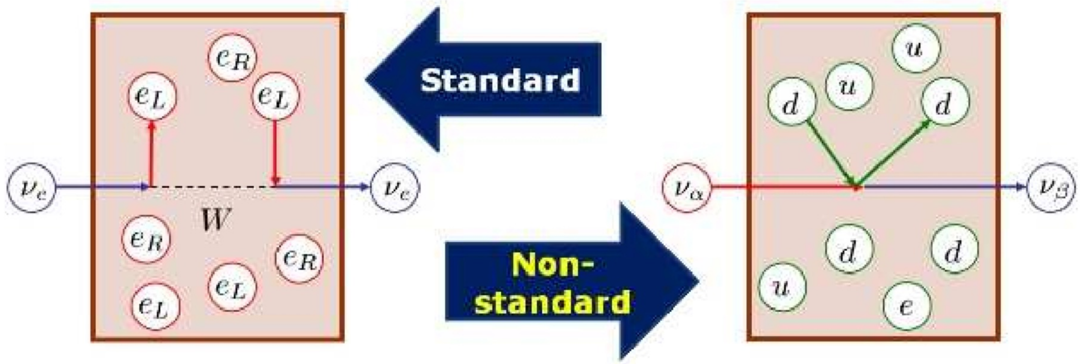

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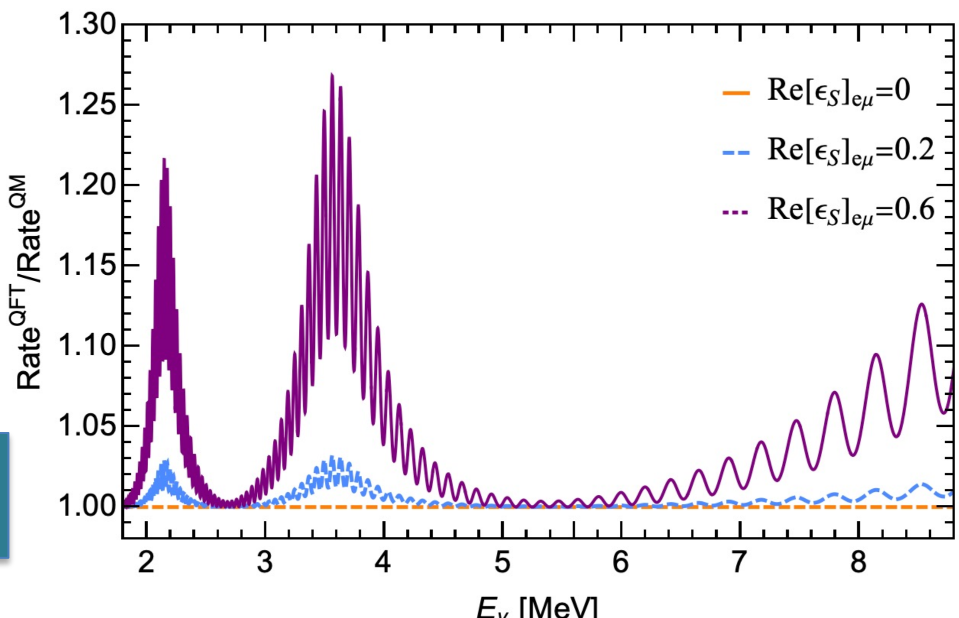
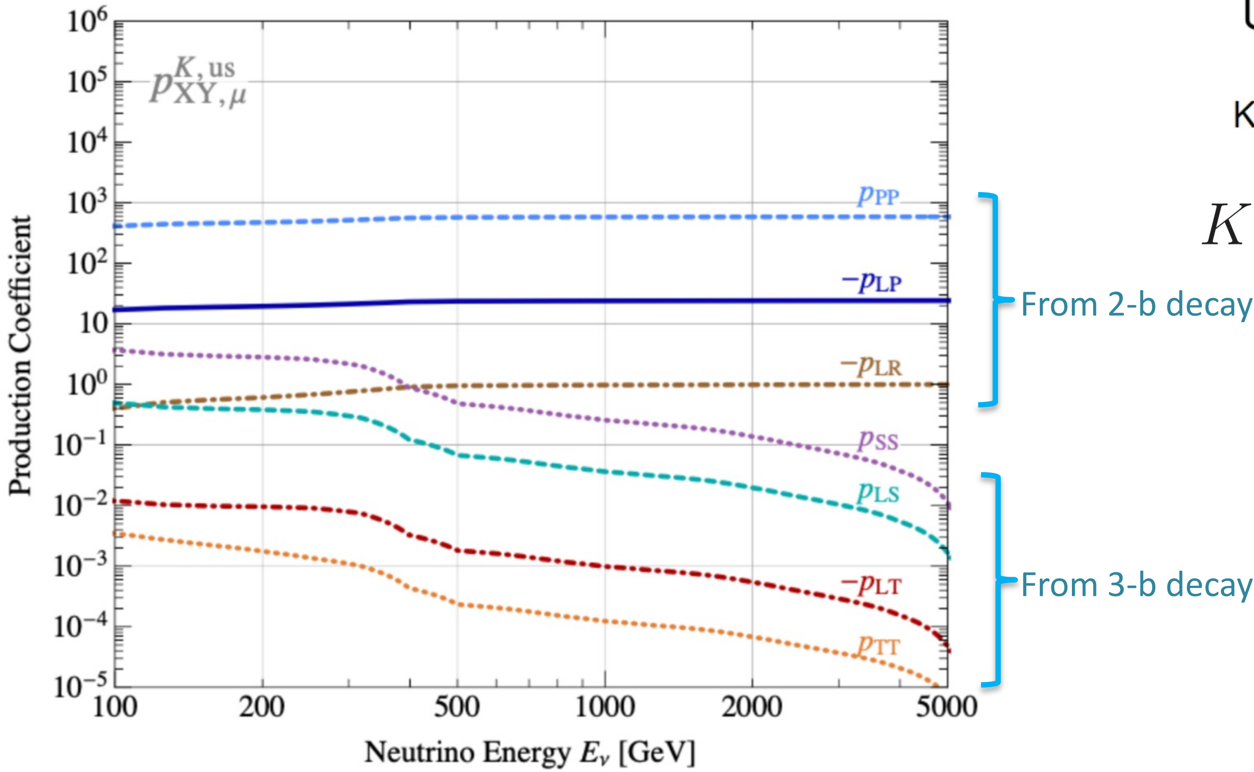
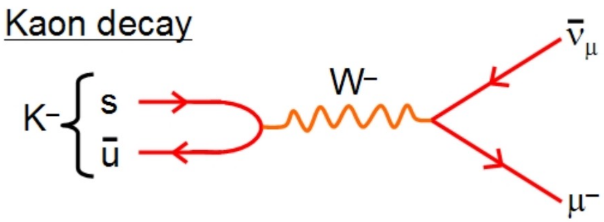


Kaon Decay:

A. Falkowski, M. González-Alonso, J. Kopp, Y. Soreq, ZT
arXiv: 2105.12136

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





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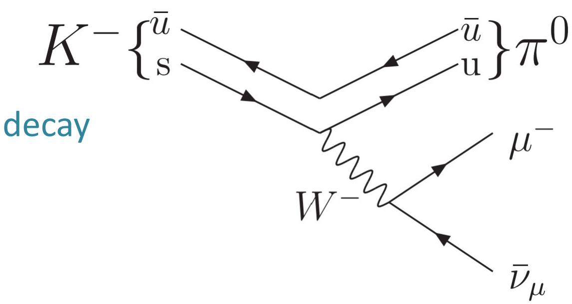

We see chiral-enhancement for the decay into muons!

EFT at FASERν

A. Falkowski, M. González-Alonso, J. Kopp, Y. Soreq, ZT
arXiv: 2105.12136

(pseudo)probability:

$$\tilde{P}_{\alpha\beta}\big|_{L=0} \simeq \Big(1 + 2\sum_{X,j,k} p^{jk}_{XL,\alpha}|\epsilon^{jk}_{X,\alpha\beta}|\cos\phi^{jk}_{X,\alpha\beta}\Big)\delta_{\alpha\beta} + \sum_{X,Y,j,k} |\epsilon^{jk}_{X,\alpha\beta}|^2 p^{jk}_{XY,\alpha} + \sum_{X,Y,r,s} |\epsilon^{rs}_{X,\beta\alpha}|^2 d^{rs}_{XY,\beta}\,,$$

Only the diagonal elements at the linear order

Off diagonal elements at the quadratic order

No oscillation, only zero-distance effect!