



# Neutrino experiments as constraints on Effective Field Theory

NuCo 2021

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Virginia Tech

28-30 July 2021



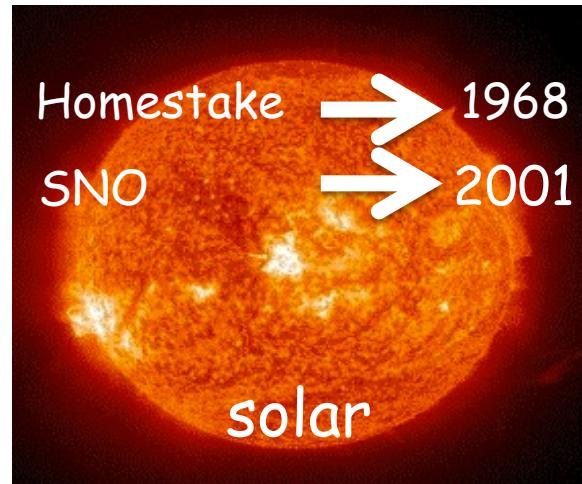
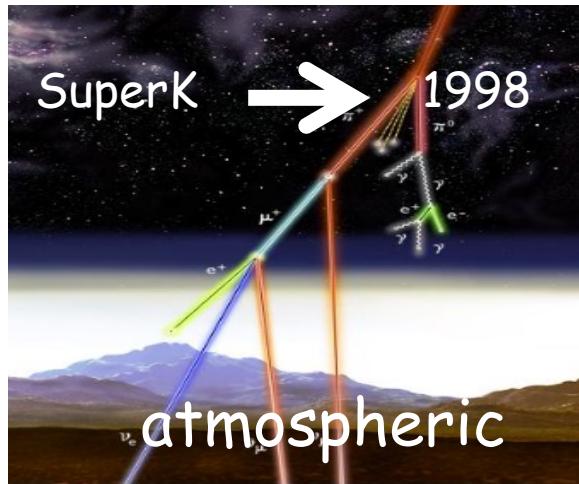
“EFT at FASER $\nu$ ”,

A. Falkowski, M. Gonzalez-Alonso, J. Kopp, Y. Soreq, Z. Tabrizi,

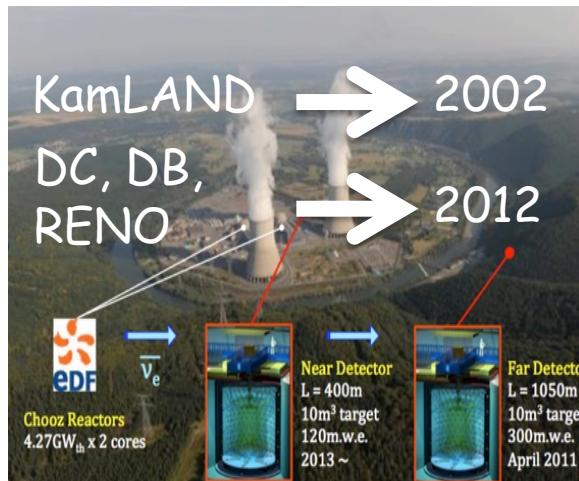
[arXiv: 2105.12136 [hep-ph]]

# Neutrinos are massless in the SM!

However in nature.....

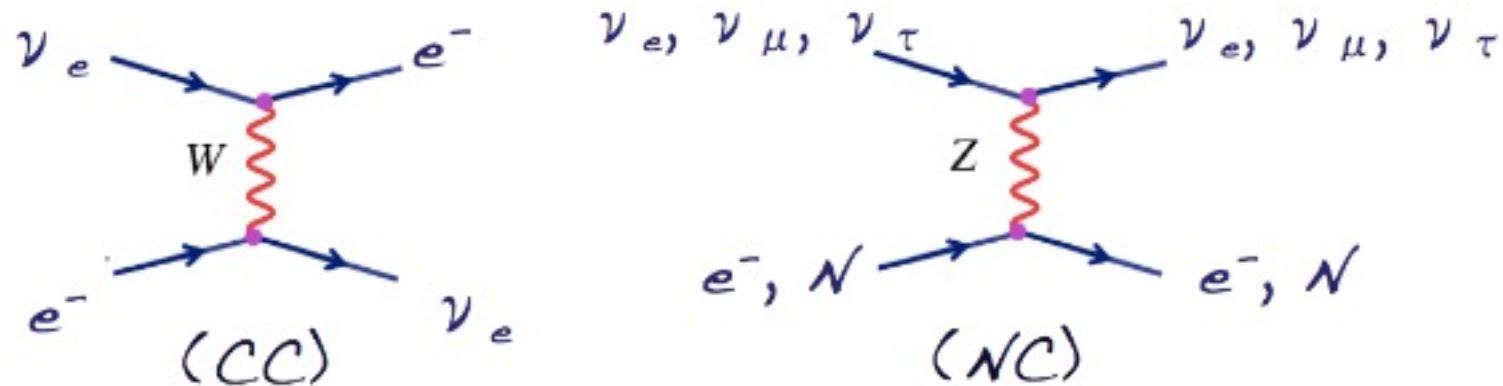


Neutrino oscillation needs masses and mixing!



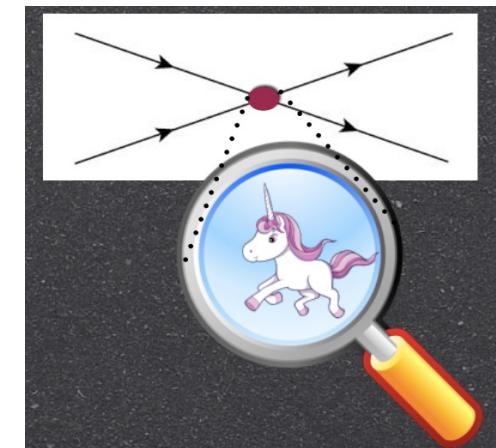
Oscillation experiments are sensitive not only to neutrino masses and mixing, but also to how neutrinos interact with matter.

- 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?

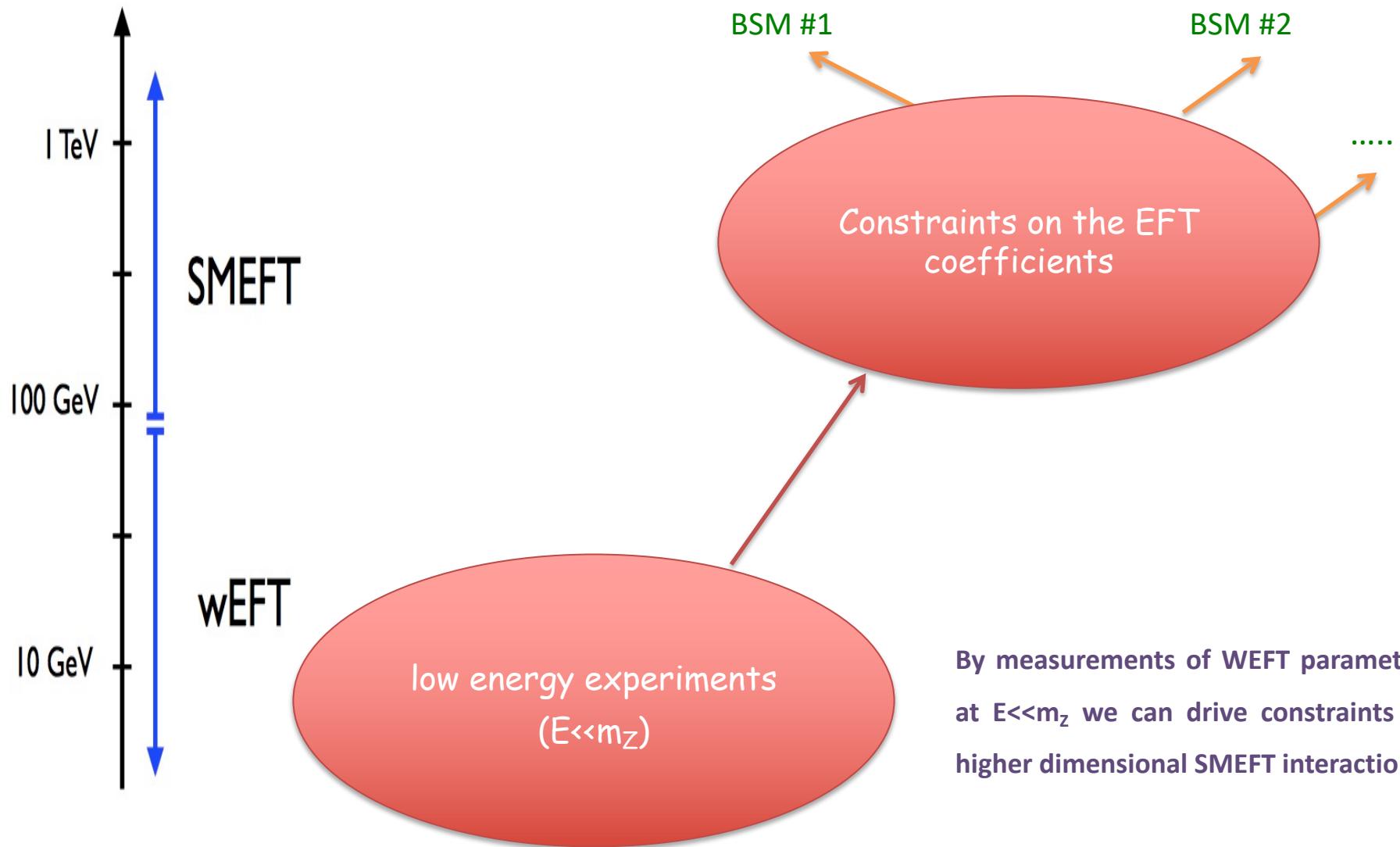


# Why EFT?

- 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



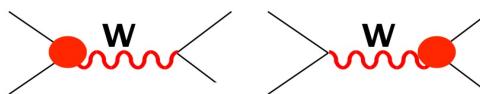
# Approach:

$E > m_Z$

- 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.

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

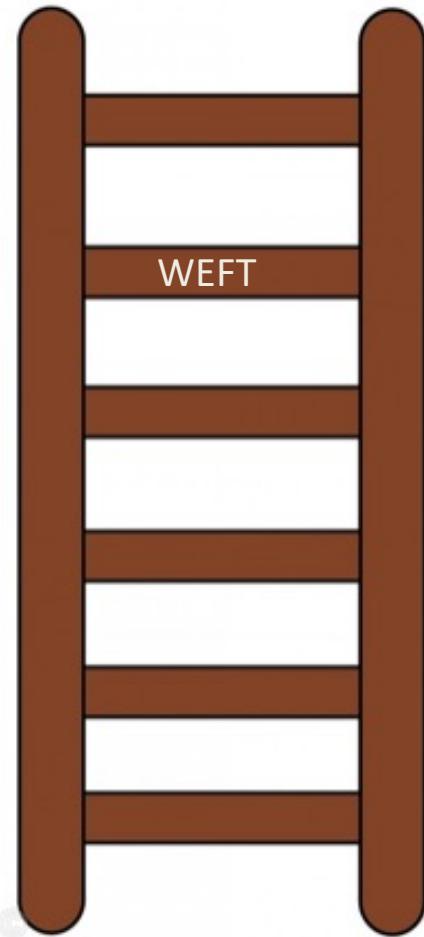
- The SMEFT framework allows one to describe effects of new physics beyond the SM in a model independent way



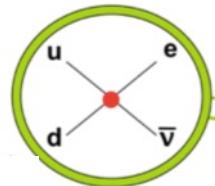
$$\begin{aligned}
 O_{lq}^{(3)} &= (\bar{l}\gamma^\mu\sigma^a l)(\bar{q}\gamma_\mu\sigma^a q) \\
 O_{qde} &= (\bar{l}e)(\bar{d}q) + \text{h.c.} \\
 O_{lq} &= (\bar{l}_a e)\epsilon^{ab}(\bar{q}_b u) + \text{h.c.} \\
 O_{lq}^t &= (\bar{l}_a \sigma^{\mu\nu} e)\epsilon^{ab}(\bar{q}_b \sigma_{\mu\nu} u) +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

# 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).

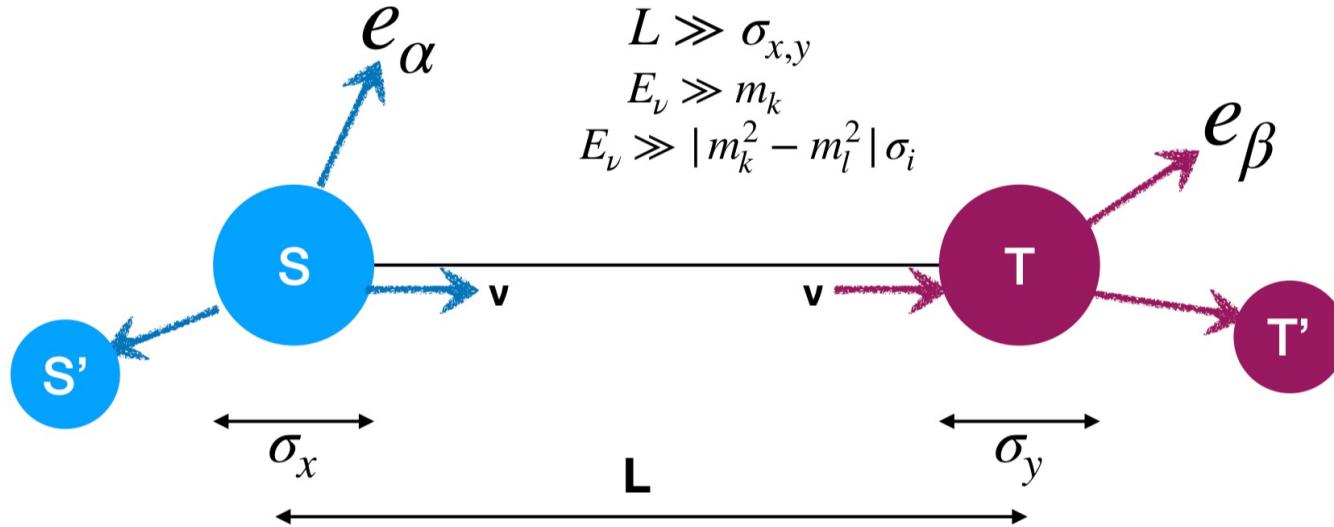


$$\begin{aligned} \mathcal{L}_{\text{WEFT}} \supset & -\frac{2V_{ud}}{v^2} \left\{ [1 + \epsilon_L]_{\alpha\beta} (\bar{u}\gamma^\mu P_L d)(\bar{\ell}_\alpha \gamma_\mu P_L \nu_\beta) \right. \\ & + [\epsilon_R]_{\alpha\beta} (\bar{u}\gamma^\mu P_R d)(\bar{\ell}_\alpha \gamma_\mu P_L \nu_\beta) \\ &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

- Apart from the SM-like V-A interactions ( $1+\epsilon_L$ ), right-handed ( $\epsilon_R$ ), scalar ( $\epsilon_S$ ), pseudoscalar ( $\epsilon_P$ ), and tensor ( $\epsilon_T$ ) interactions are allowed.

# QFT Description

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



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



$$\begin{aligned}
 \mathcal{M}_{\alpha k}^P &= U_{\alpha k}^* A_L^P + \sum_X [\epsilon_X U]_{\alpha k}^* A_X^P \\
 \mathcal{M}_{\beta k}^D &= U_{\beta k} A_L^D + \sum_X [\epsilon_X U]_{\beta k} A_X^D
 \end{aligned}$$

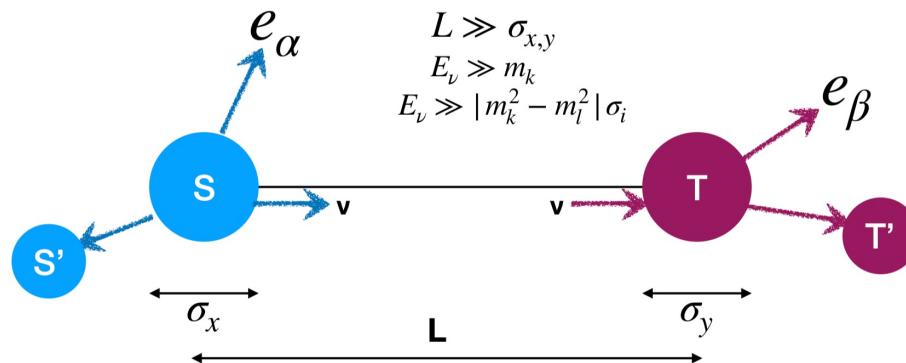
depends on the kinematic and spin variables

# QFT Description

A. Falkowski, M. González-Alonso, ZT  
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Observable: rate of detected events

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



# EFT at Oscillation Experiments:

$U_{PMNS}$

||

$$U_{PMNS} = \begin{bmatrix} v_e & & \\ v_\mu & & \\ v_\tau & & \end{bmatrix} \begin{bmatrix} v_1 & v_2 & v_3 \end{bmatrix}$$

SM

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

# EFT at Oscillation Experiments:

$U_{PMNS}$

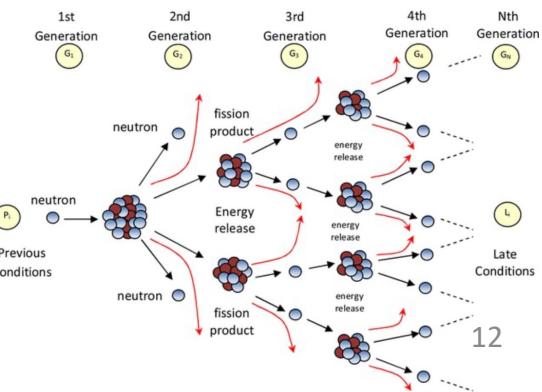
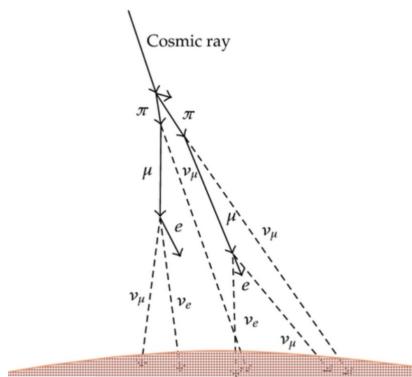
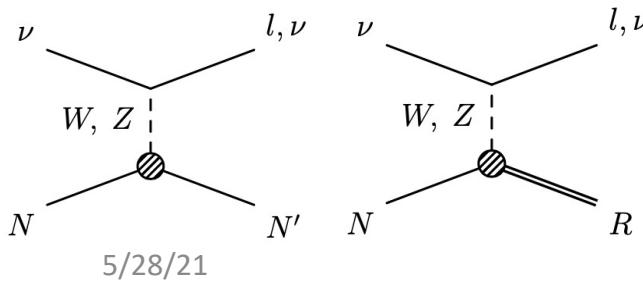
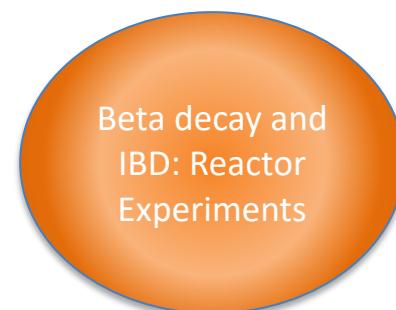
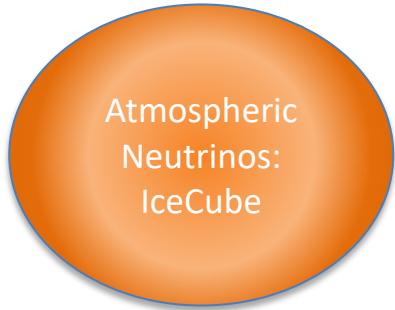
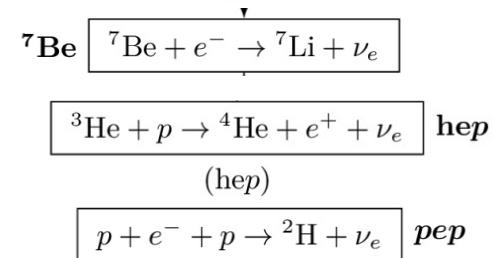
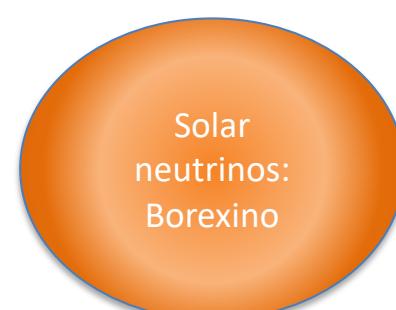
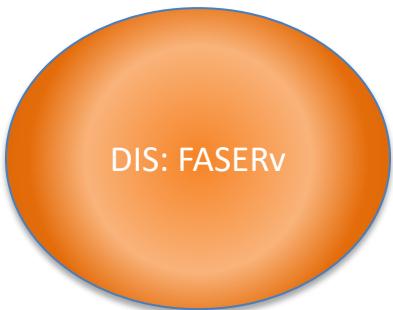
||

$$U_{PMNS} = \begin{bmatrix} v_e & & \\ & v_\mu & \\ & & v_\tau \end{bmatrix} \begin{bmatrix} v_1 & v_2 & v_3 \end{bmatrix}$$

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

Production and detection coefficients, depend on amplitudes

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

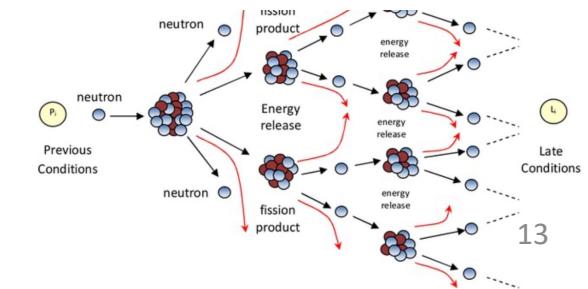
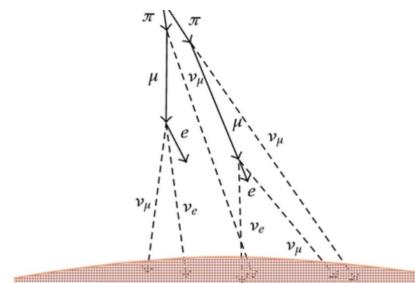
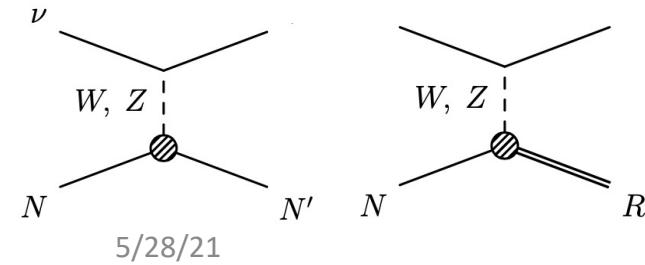


DIS: FASERv

Kaon/Muon  
decay:

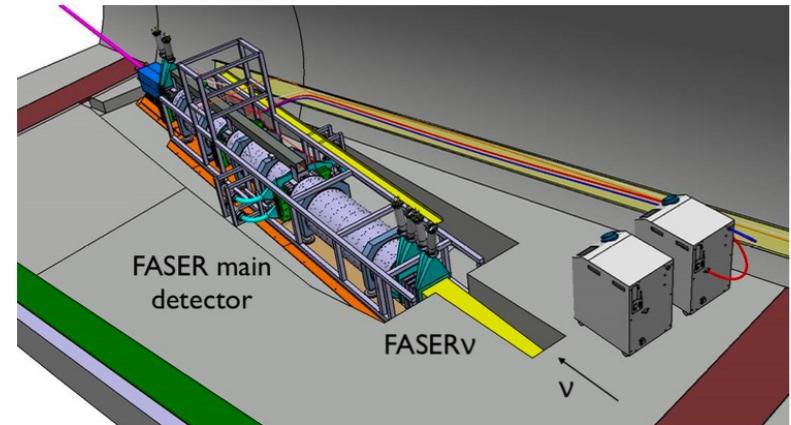
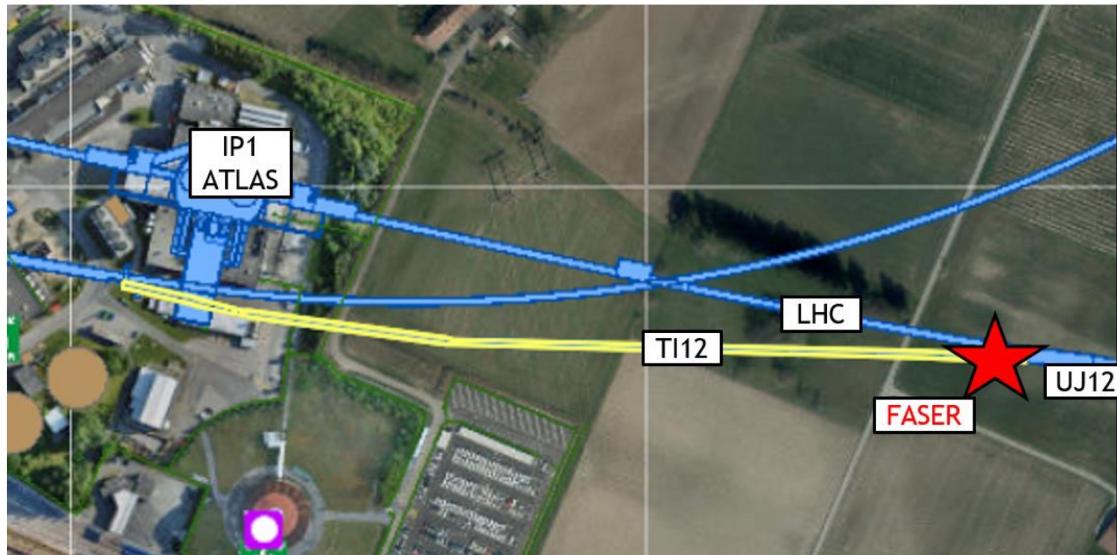
Solar  
neutrinos:

Well...



# EFT at FASERv

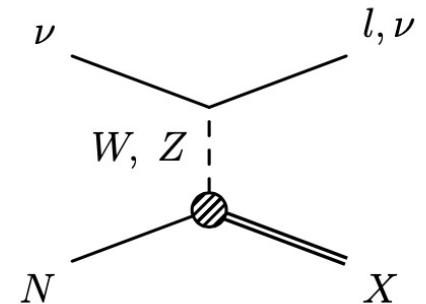
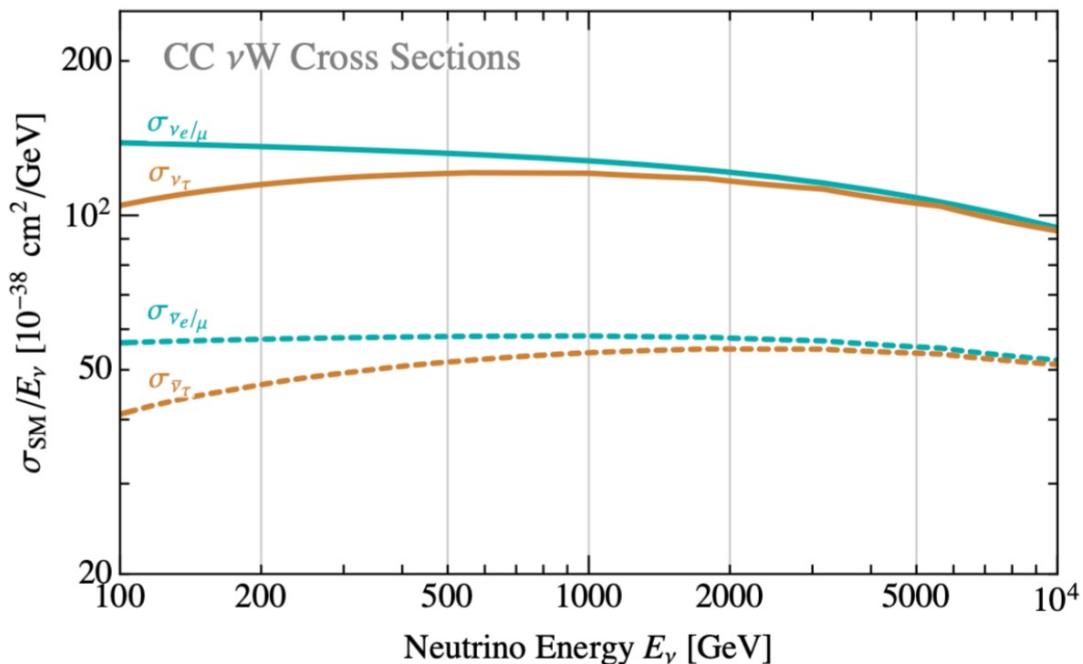
- will be located downstream of the ATLAS interaction point at a distance of 480 m.
- Ideal for detecting high-energy neutrinos produced at LHC.
- 1.2-t of tungsten material.



# EFT at FASERv

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

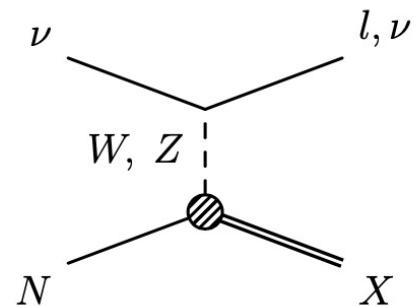
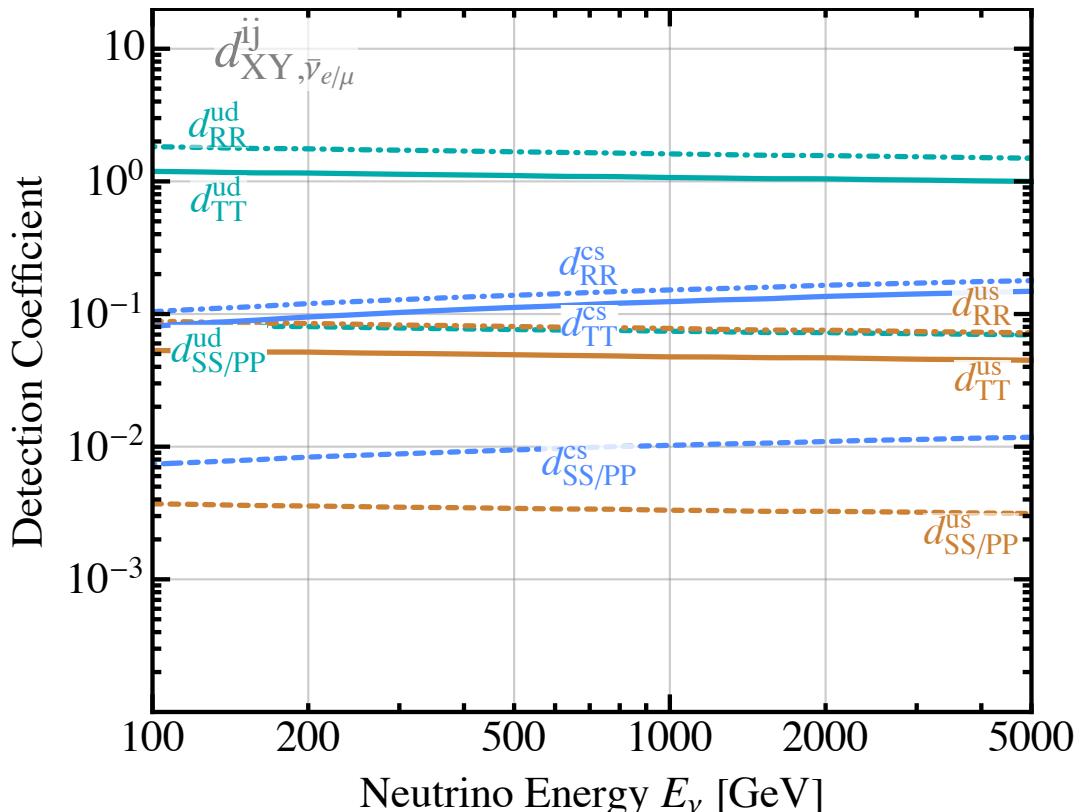
## Why FASERv?



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

# EFT at FASERv

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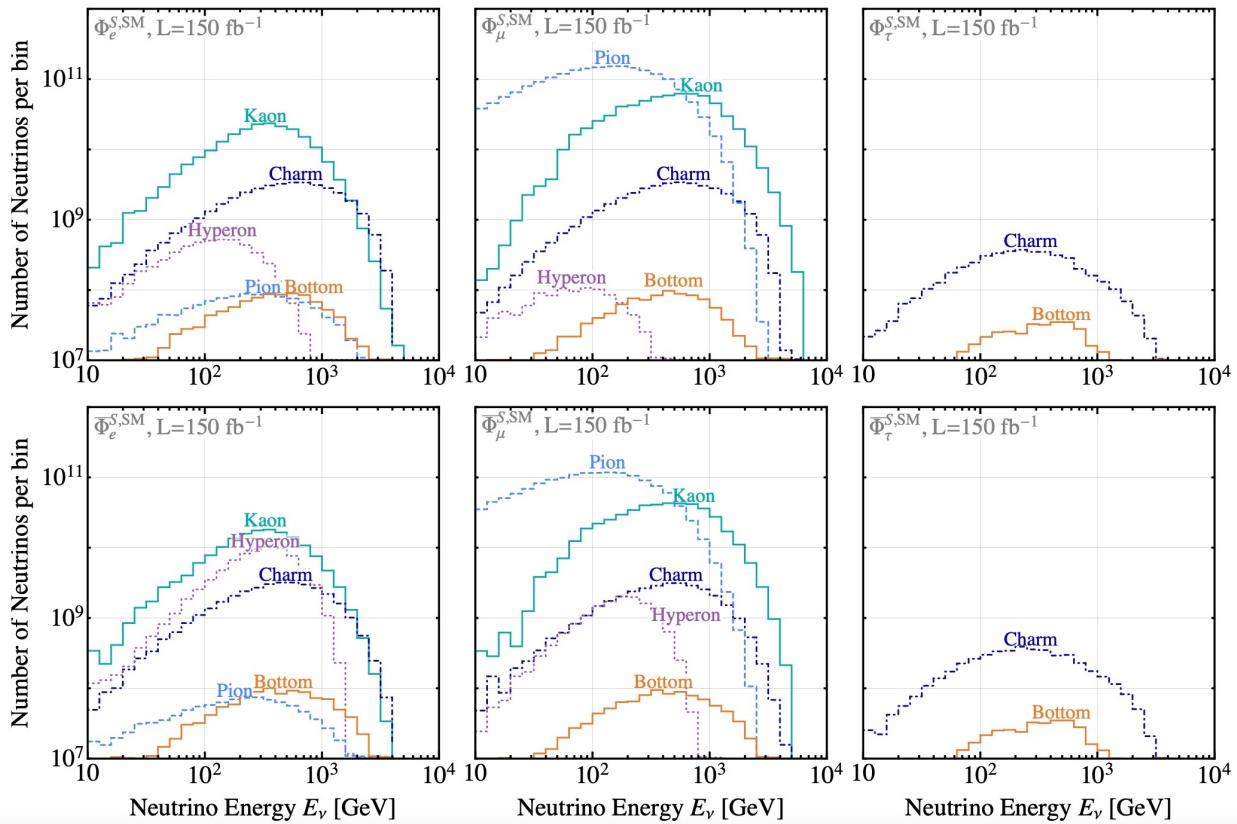
- No new physics at the linear order!
- Good sensitivity to the right handed and tensor interactions.

# EFT at FASER $\nu$

Thanks to Felix, also based on arXiv:2105.08270

## Why FASER $\nu$ ?

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



Generators		FASER $\nu$		
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
EPOS LHC	Pythia8 (Hard)	2109	7763	48.9
QGSJET	Pythia8 (Soft)	1437	7162	24.5

# Leptonic Pion Decay:

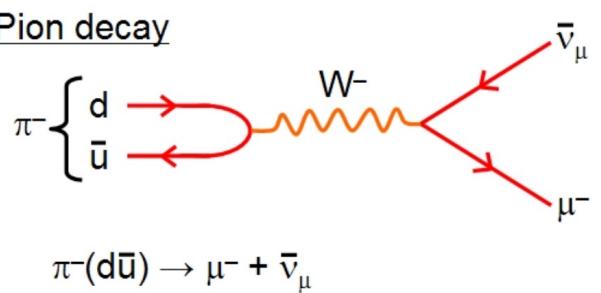
A. Falkowski, M. González-Alonso, ZT  
arXiv: 1910.02971

Due to the pseudoscalar nature of the pion, it is sensitive only to axial ( $\varepsilon_L - \varepsilon_R$ ) and pseudo-scalar ( $\varepsilon_P$ ) 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

## Pion decay



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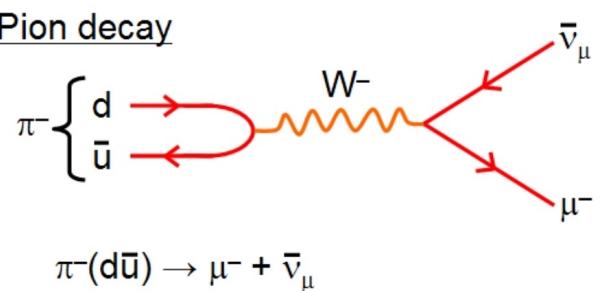
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~700!

Pion decay



- We will have a great chiral enhancement for the pseudoscalar.

# Kaon Decay:

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

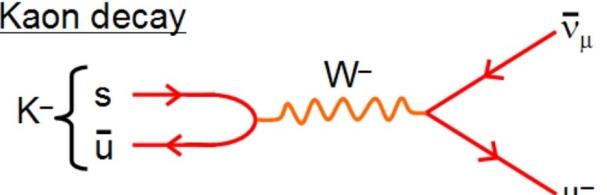
Both 2-body and 3-body kaon decays contribute:

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

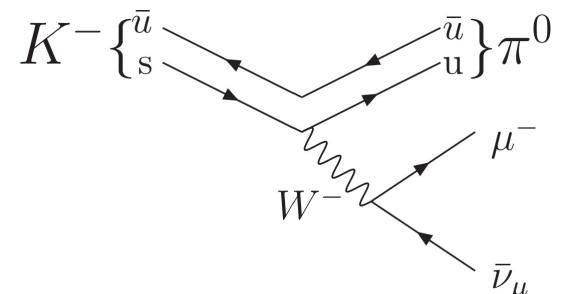
Energy distribution of  $K^\pm$ ,  $K_L$  or  $K_S$

Thanks to Felix

## Kaon decay



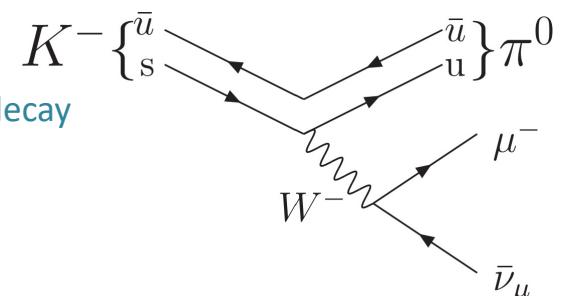
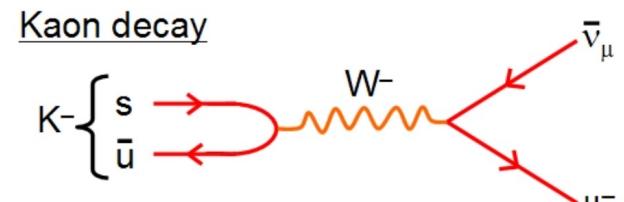
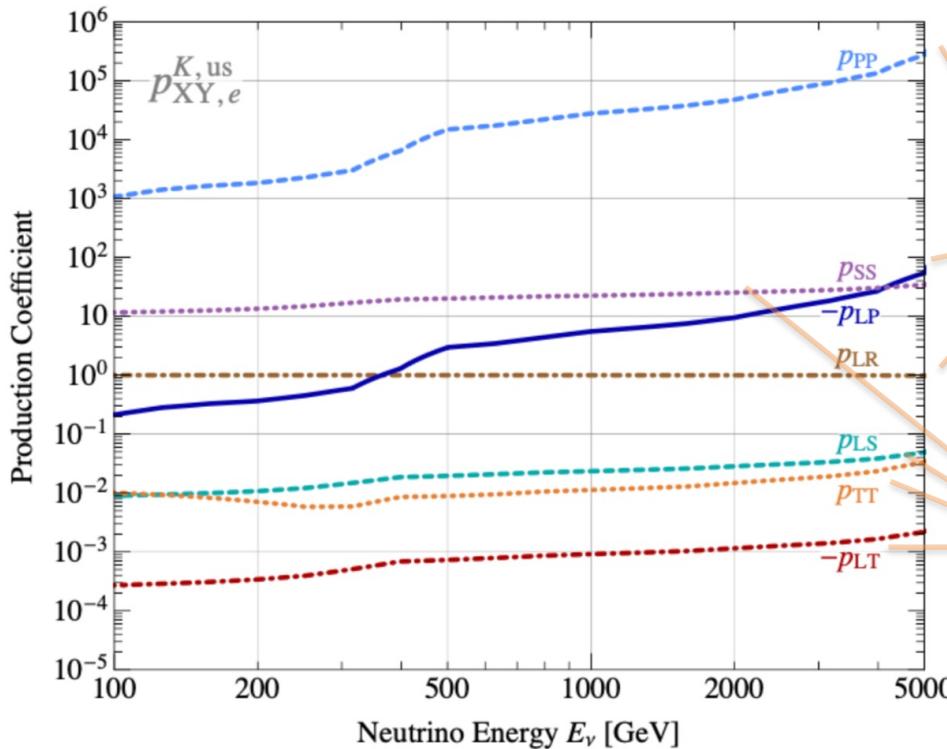
$$K^- (s\bar{u}) \rightarrow \mu^- + \bar{\nu}_\mu$$



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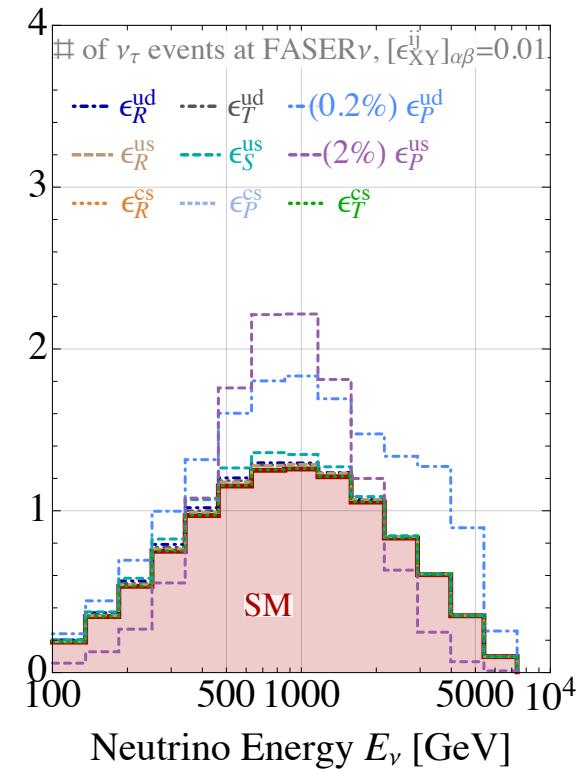
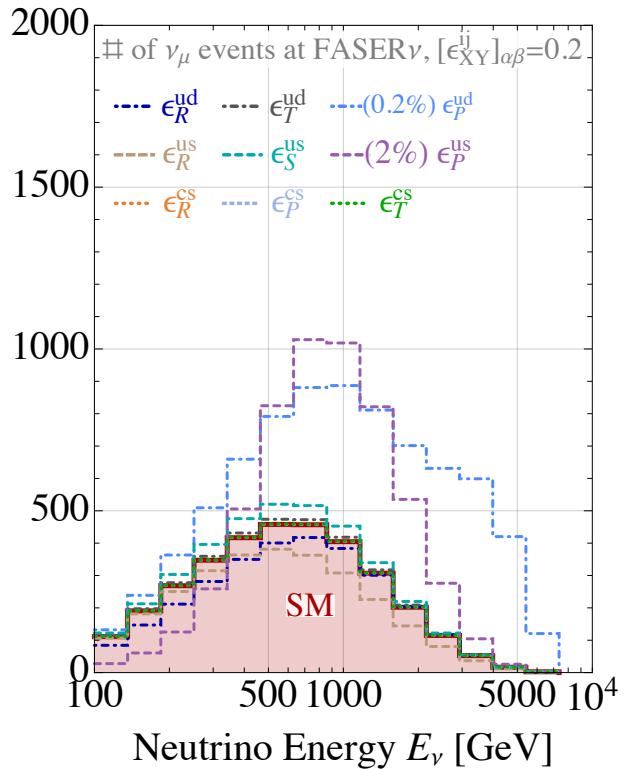
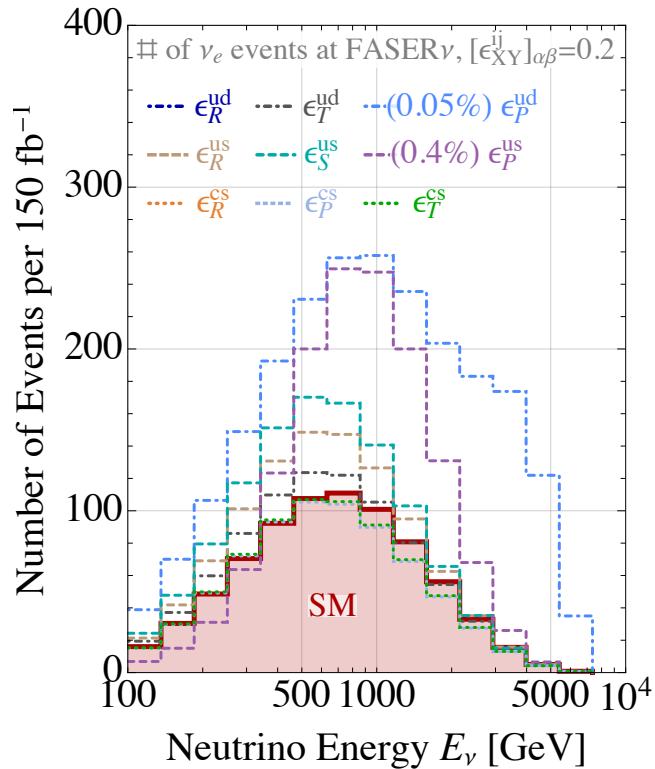
From 2-b decay

From 3-b decay

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

# EFT at FASERv

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

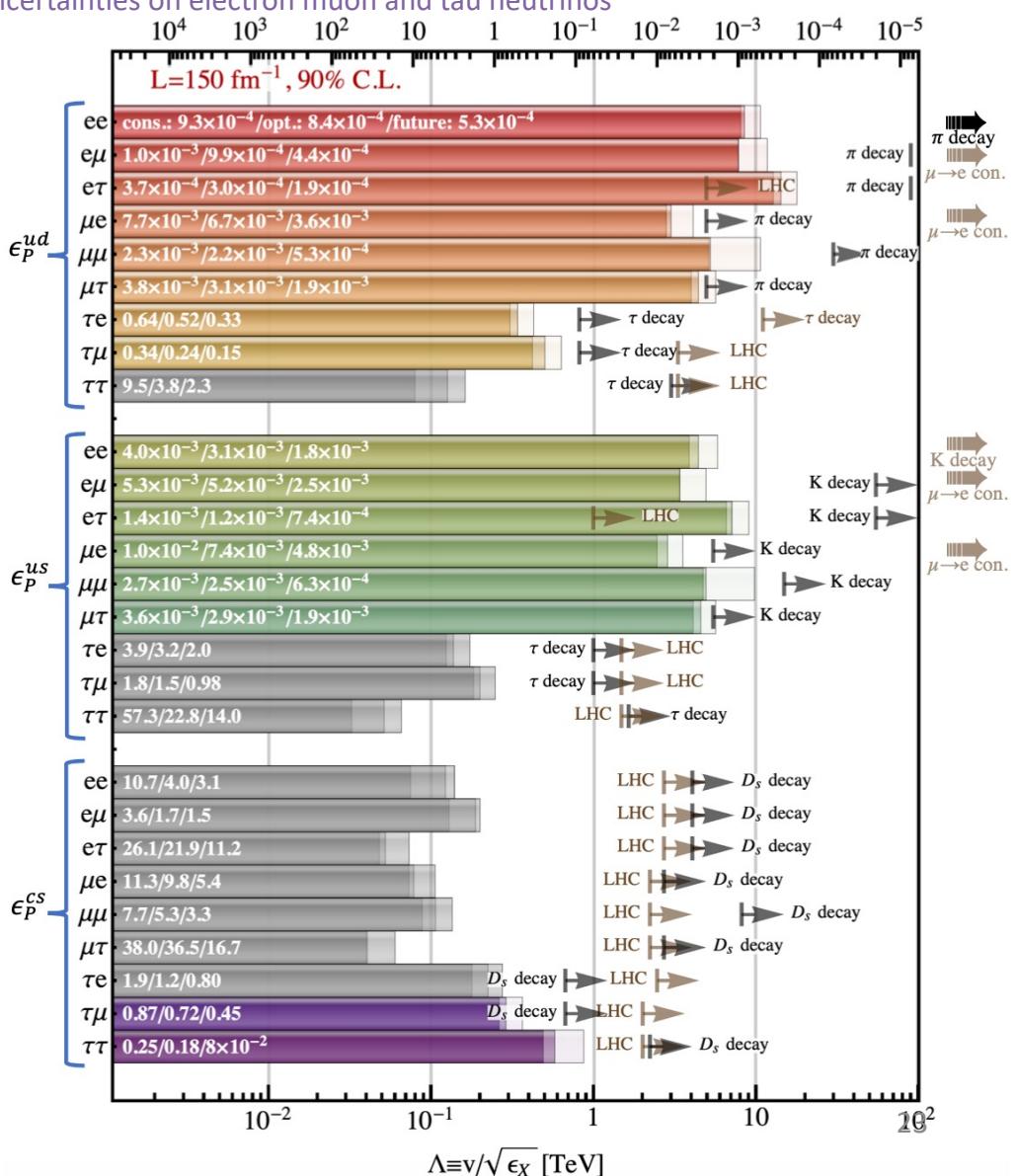


# RESULTS

## Turning on one interaction at a time: Pseudo-Scalar

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

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



## Conclusion:

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



Thanks for your attention

# Backup slides

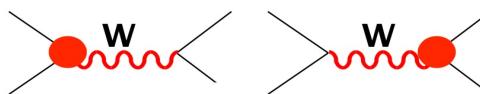
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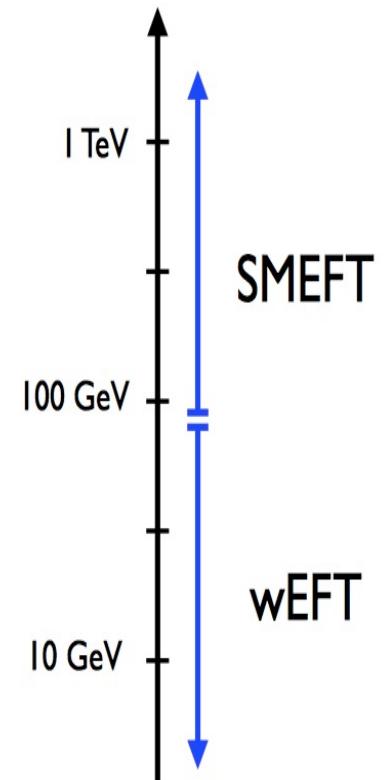
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 O_{lq} &= (\bar{l}_a e) \epsilon^{ab} (\bar{q}_b u) + \text{h.c.} \\
 O_{qcd}^{(4)} &= (\bar{l} \gamma^\mu \omega^\nu l) \epsilon^{ab} (\bar{q}_b \sigma_{\mu\nu} u) + \text{h.c.}
 \end{aligned}$$

## Matching WEFT and SMEFT parameters:

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



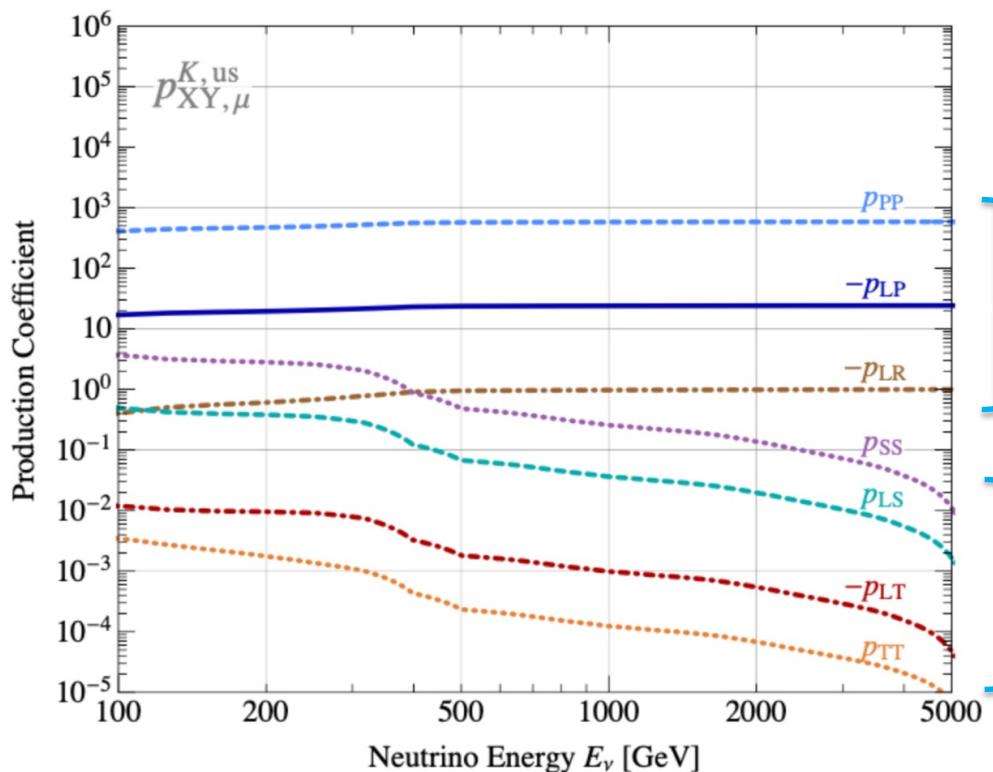
- All  $\epsilon_x$  arise at  $O(\Lambda^{-2})$  in the SMEFT, thus they are equally important.
- No off-diagonal right handed interactions in SMEFT.

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

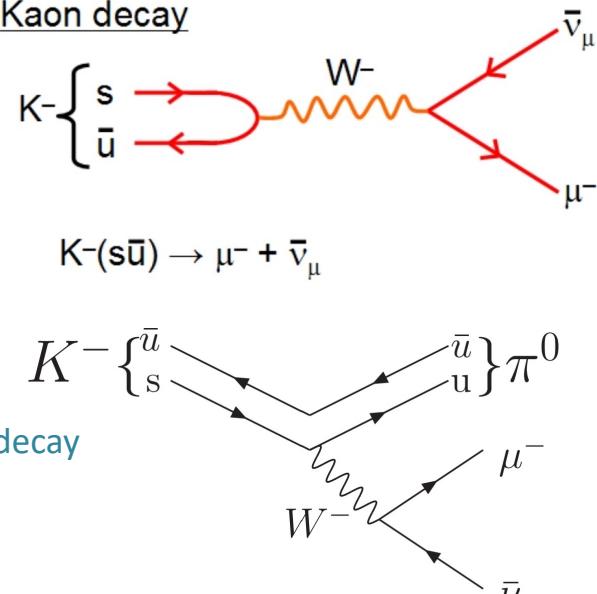
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## Kaon decay



We see chiral-enhancement for the decay into muons!

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arXiv: 2105.12136

(pseudo)probability:

$$\tilde{P}_{\alpha\beta}|_{L=0} \simeq \left( 1 + 2 \sum_{X,j,k} p_{XL,\alpha}^{jk} |\epsilon_{X,\alpha\beta}^{jk}| \cos \phi_{X,\alpha\beta}^{jk} \right) \delta_{\alpha\beta} + \sum_{X,Y,j,k} |\epsilon_{X,\alpha\beta}^{jk}|^2 p_{XY,\alpha}^{jk} + \sum_{X,Y,r,s} |\epsilon_{X,\beta\alpha}^{rs}|^2 d_{XY,\beta}^{rs},$$

Only the diagonal elements at the linear order    Off diagonal elements at the quadratic order

No oscillation, only zero-distance effect!

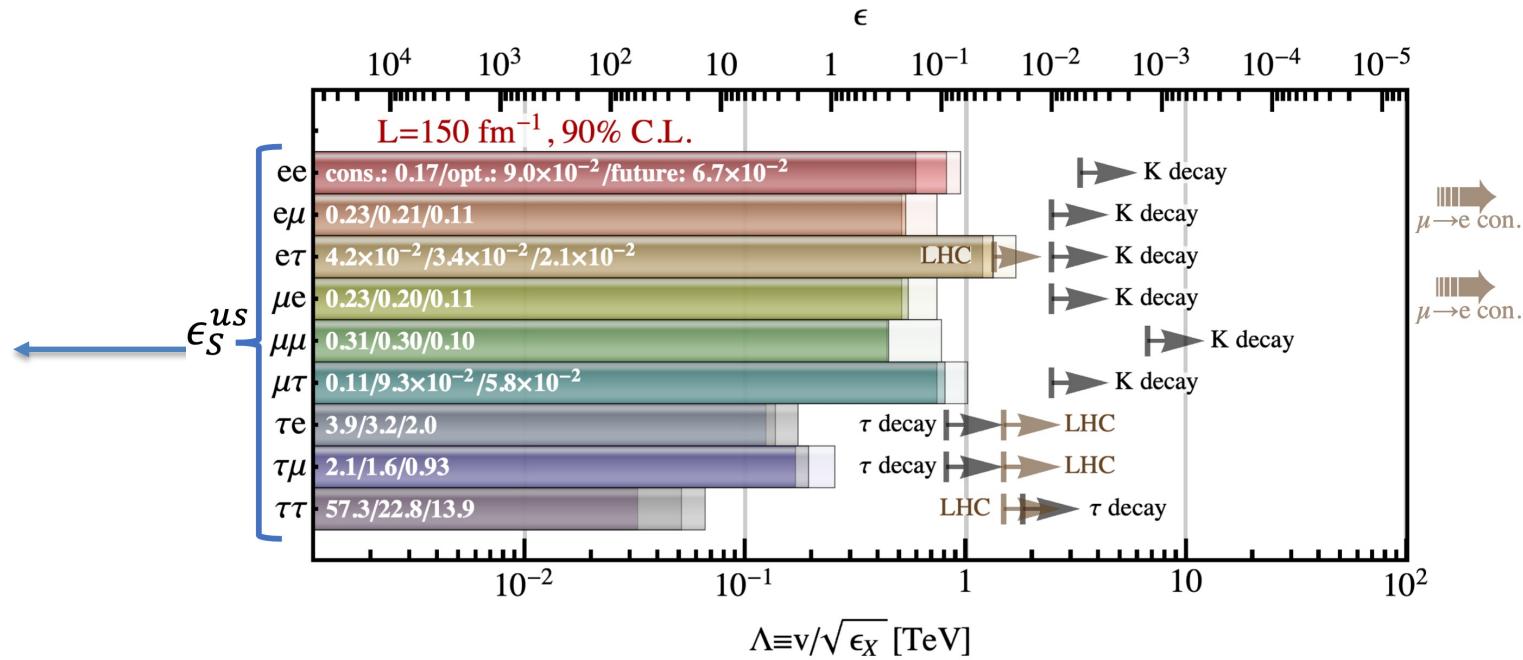
# RESULTS

## Turning on one interaction at a time: Scalar

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

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

From kaon decay



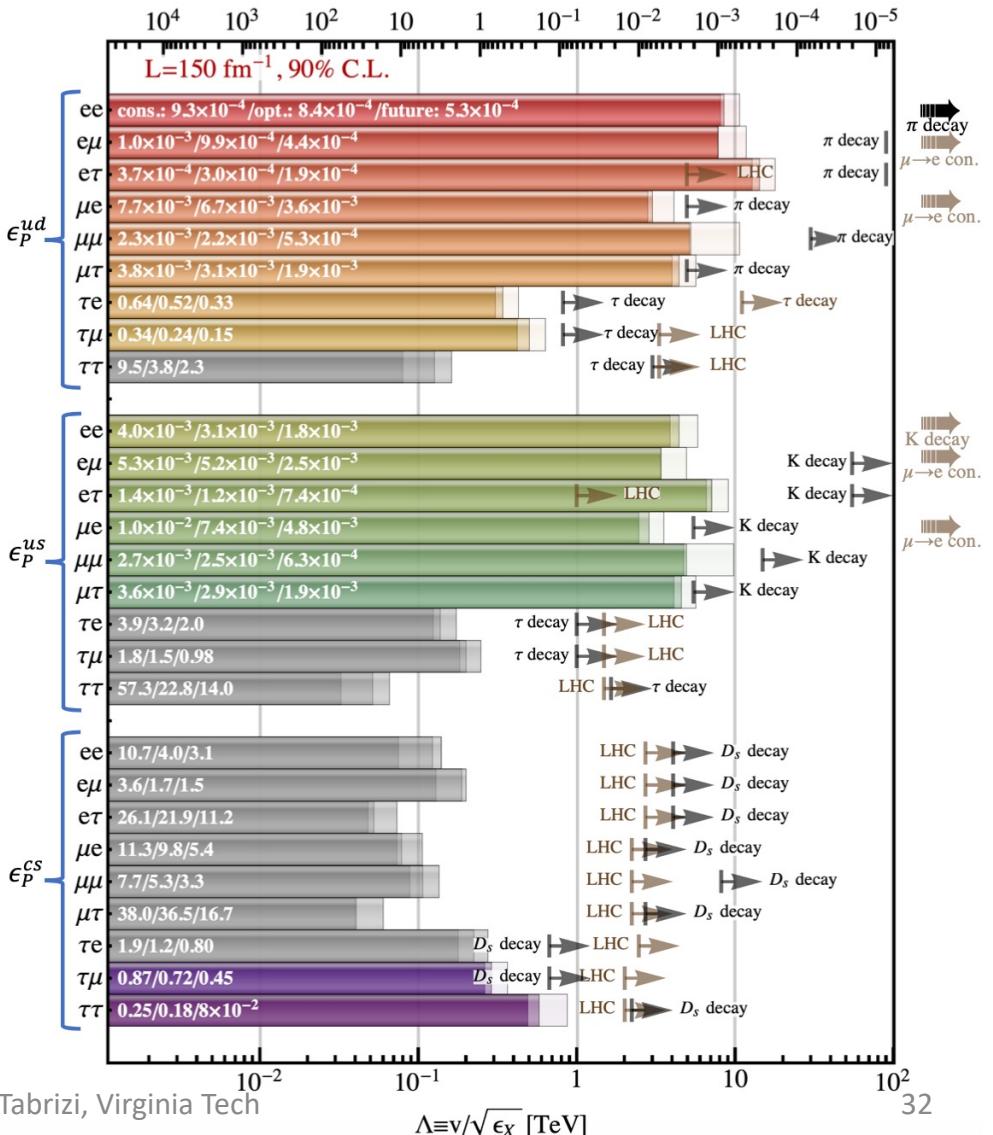
# RESULTS

## Turning on one interaction at a time: Pseudo-Scalar

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

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

From pion decay



From kaon decay



From charm decay



# RESULTS

## Turning on one interaction at a time: Tensor

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

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

