FPF constraints on Effective Field Theory

2nd Forward Physics Facility Meeting

Zahra Tabrizi

Virginia Tech

27-28 May 2021

VIRGINIA TECH

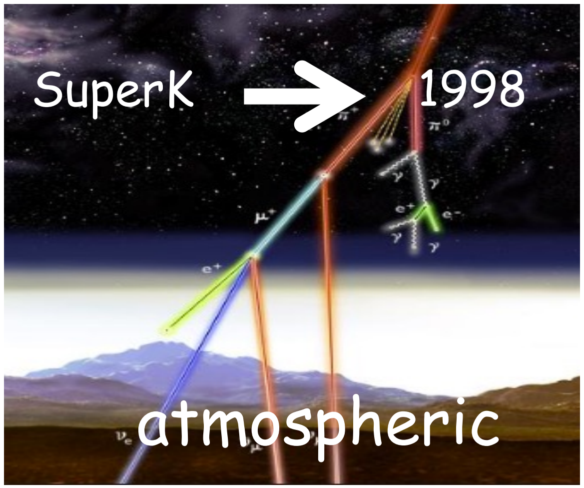
“EFT at FASERν”,

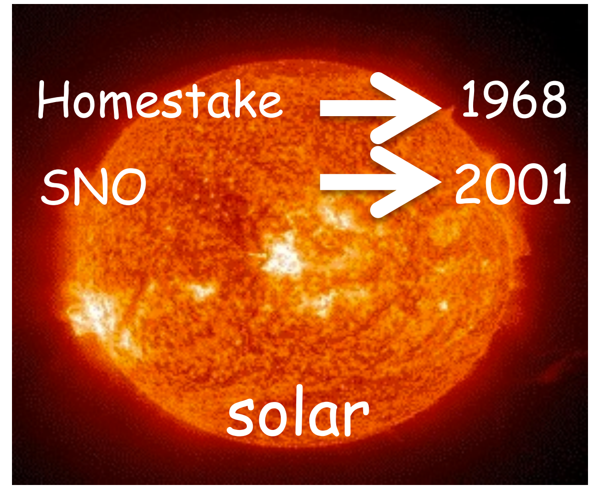
A. Falkowski, M. Gonzalez-Alonso, J. Kopp, Y. Soreq, Z. Tabrizi,

[arXiv: 2104.15136 [hep-ph]]

Neutrinos are massless in the SM!

However in nature.....

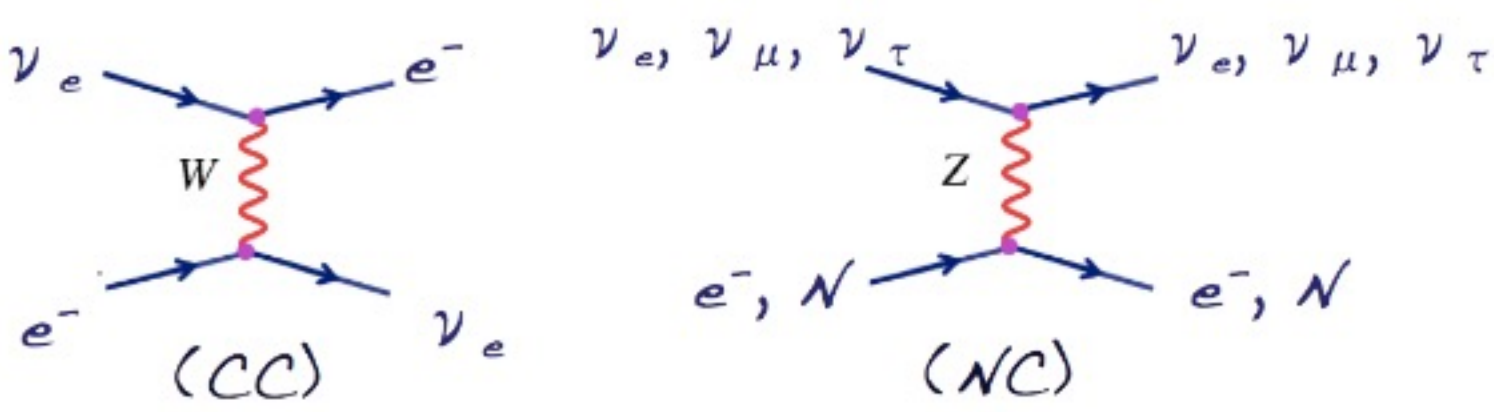




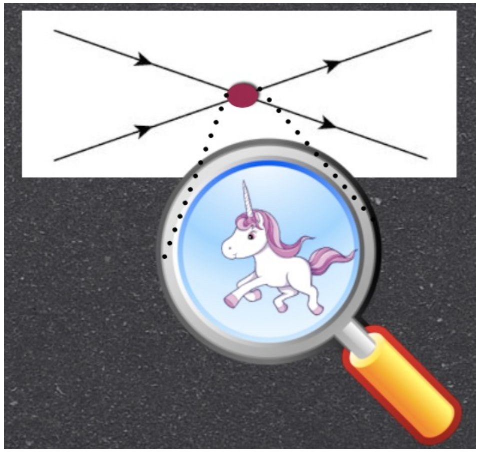
Neutrino oscillation needs masses and mixing!

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?

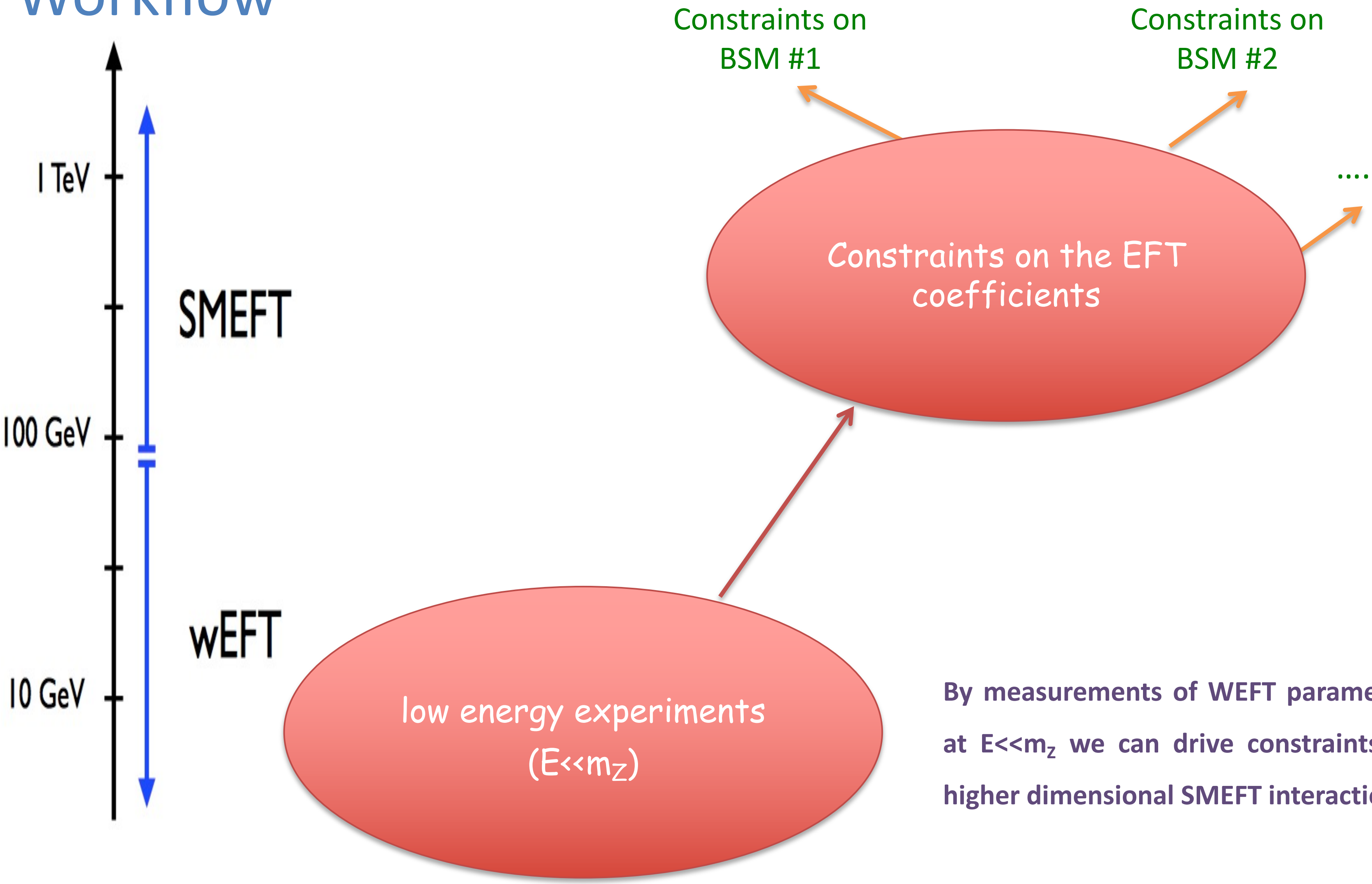
- Wealth of low-energy observables probing different aspects of particle interactions are described within one consistent framework.

- 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.

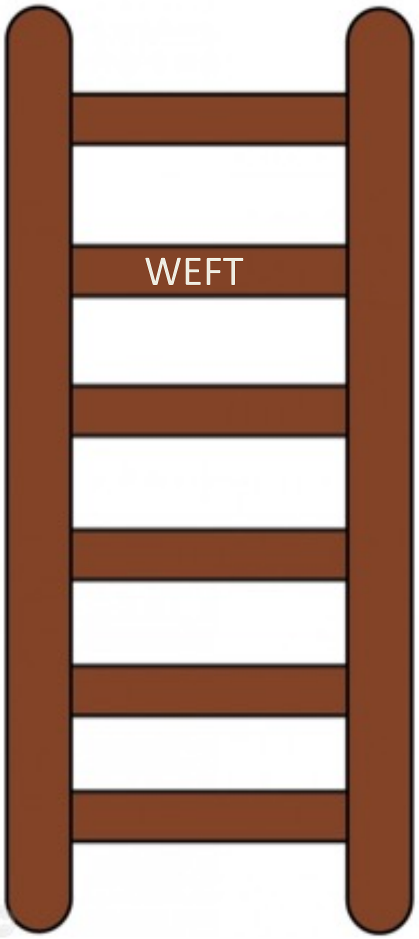
Workflow



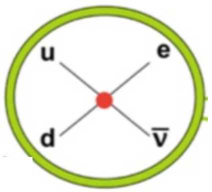
By measurements of WEFT parameters at E<<m_Z we can drive constraints on higher dimensional SMEFT interactions.

Approach:

$E \ll m_Z$



- In particular, considering the CC interactions of neutrinos.

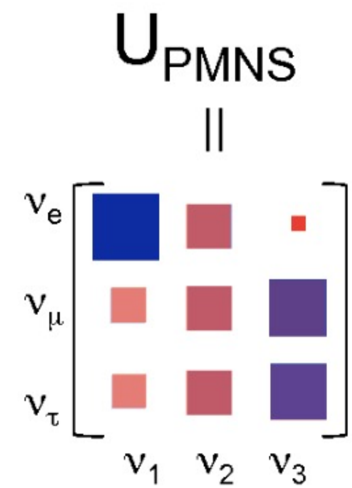


- At this scale heavy particles such as W and Z bosons, Higgs and top can be integrated out from the SMEFT, leading to Weak EFT (WEFT).

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

- 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.

EFT at Oscillation Experiments:



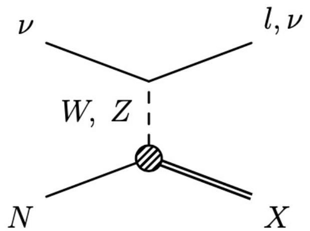
A. Falkowski, M. González-Alonso, ZT
arXiv: 1910.02971, JHEP (2020)…

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

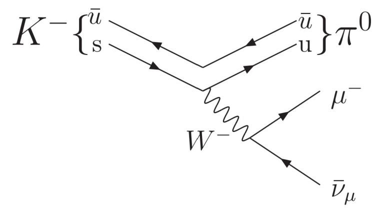
Production and detection coefficients, depend on amplitudes

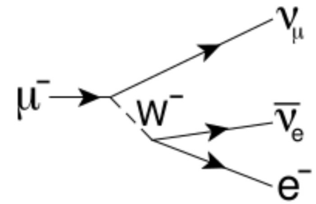
One needs to calculate these coefficients for different production and detection processes.

DIS: FASERν



Kaon/Muon decay: ISODAR, KDAR





Solar neutrinos: Borexino

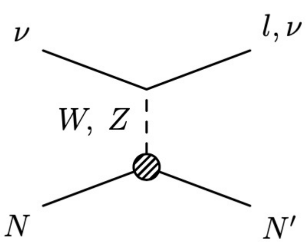
^{7}Be $\quad {}^7\text{Be} + e^- \to {}^7\text{Li} + \nu_e$

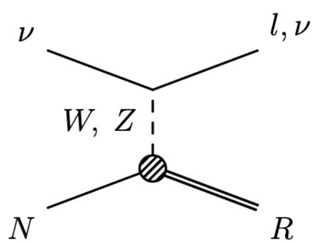
${}^3\text{He} + p \to {}^4\text{He} + e^+ + \nu_e$ **hep**

(hep)

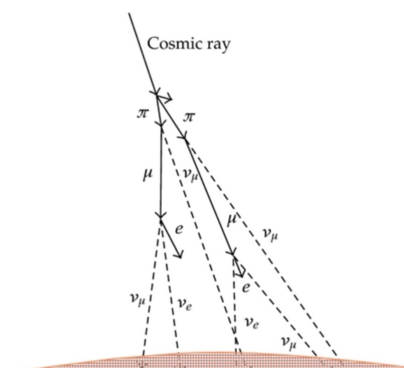
$p + e^- + p \to {}^2\text{H} + \nu_e$ ***pep***

QE, Resonances: MINOS, NOvA, DUNE

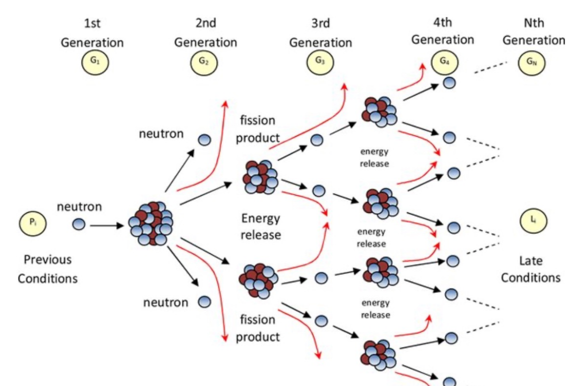




Atmospheric Neutrinos: IceCube



Beta decay and IBD: Reactor Experiments

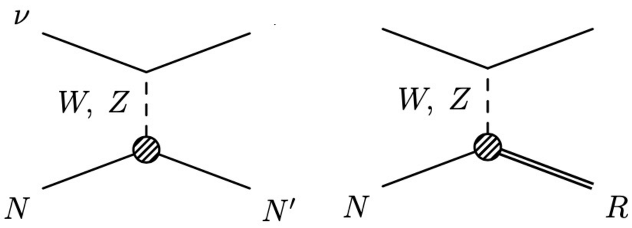


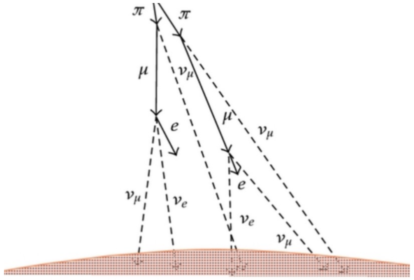
DIS: FASERν

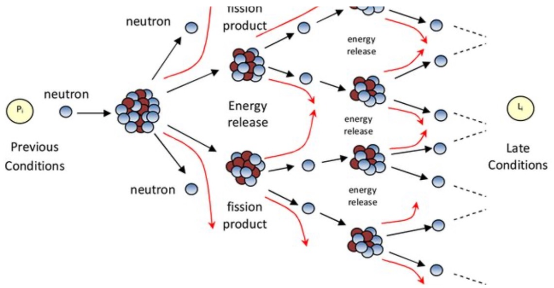
Kaon/Muon decay:

Solar neutrinos:

Well…



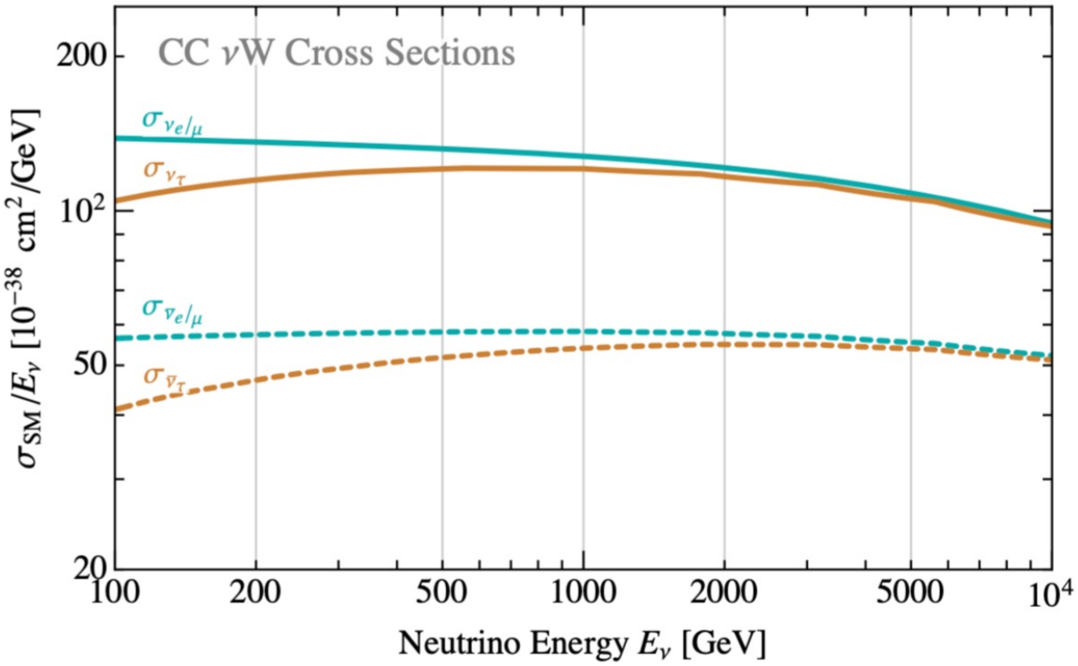


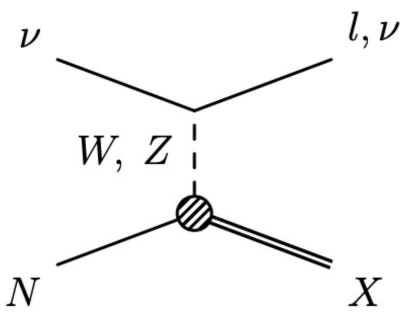


EFT at FASERν

A. Falkowski, M. González-Alonso, J. Kopp, Y. Soreq, ZT
arXiv: 2104.15136

Why FASERν?





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

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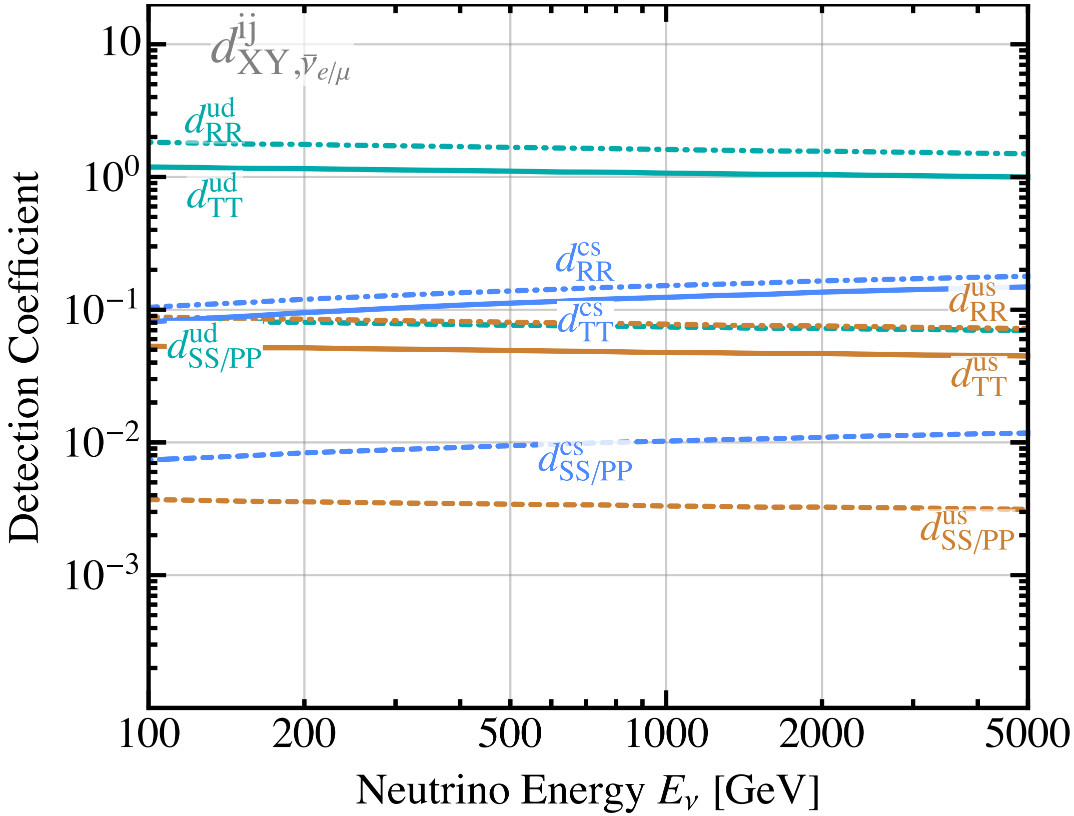
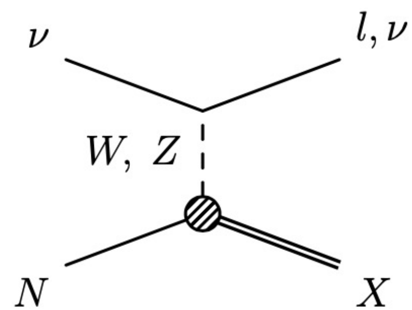




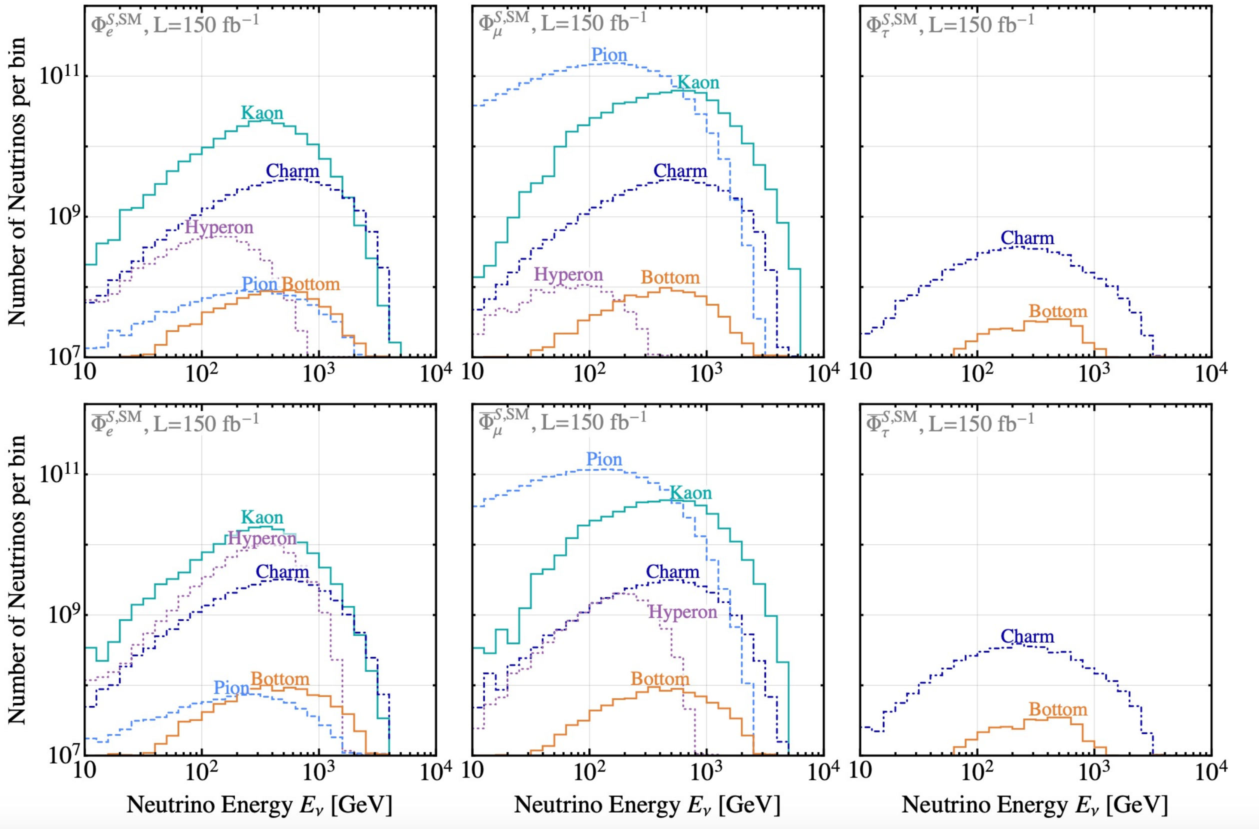
- No new physics at the linear order!
- Good sensitivity to the right handed and tensor interactions.

EFT at FASERν

Thanks to Felix, also based on arXiv:2105.08270

Why FASERν?

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

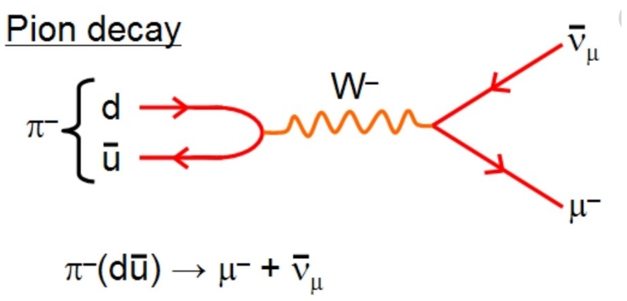


Generators		FASERν		
light hadrons	heavy hadrons	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$
SIBYLL	SIBYLL	1343	6072	21.2
DPMJET	DPMJET	4614	9198	131
EPOSLHC	Pythia8 (Hard)	2109	7763	48.9
QGSJET	Pythia8 (Soft)	1437	7162	24.5

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 (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

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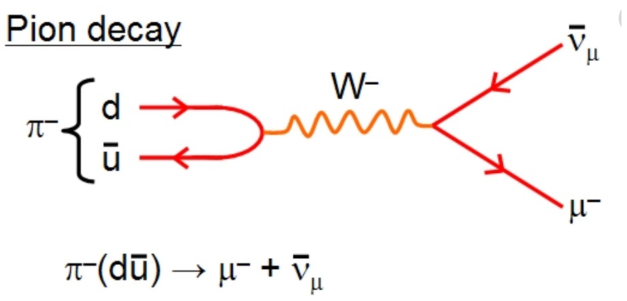


$$p_{LL} = -p_{RL} = 1, \quad p_{PL} = -p_{PR} = -\frac{m_\pi^2}{m_\mu(m_u + m_d)},$$

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

~700!

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

Kaon Decay:

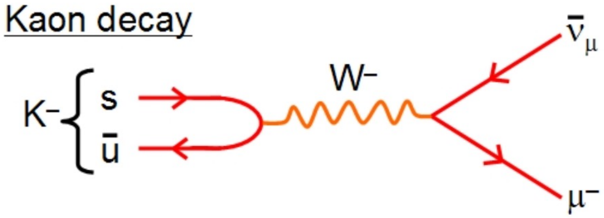
A. Falkowski, M. González-Alonso, J. Kopp, Y. Soreq, ZT
arXiv: 2104.15136

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

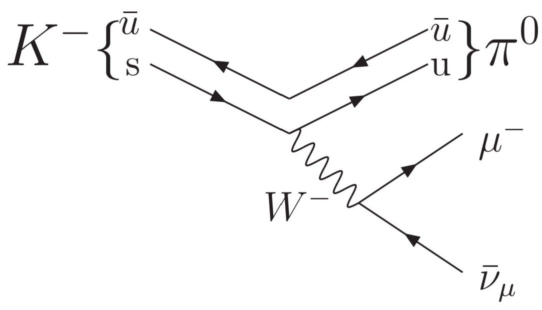
$$p^{S,jk}_{XY,\alpha} \equiv \frac{\int dE_S \frac{\phi_S(E_S)}{E_S} \sum_i \beta_i^S(E_S) \int d\Pi_{P'_i} A^{S_i,jk}_{X,\alpha} A^{S_i,jk*}_{Y,\alpha}}{\int dE_S \frac{\phi_S(E_S)}{E_S} \sum_{i'j'k'} \beta^S_{i'}(E_S) \int d\Pi_{P'_{i'}} |A^{S_i,j'k'}_{L,\alpha}|^2}$$

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

Thanks to Felix



K⁻(sū) → μ⁻ + ν̄μ



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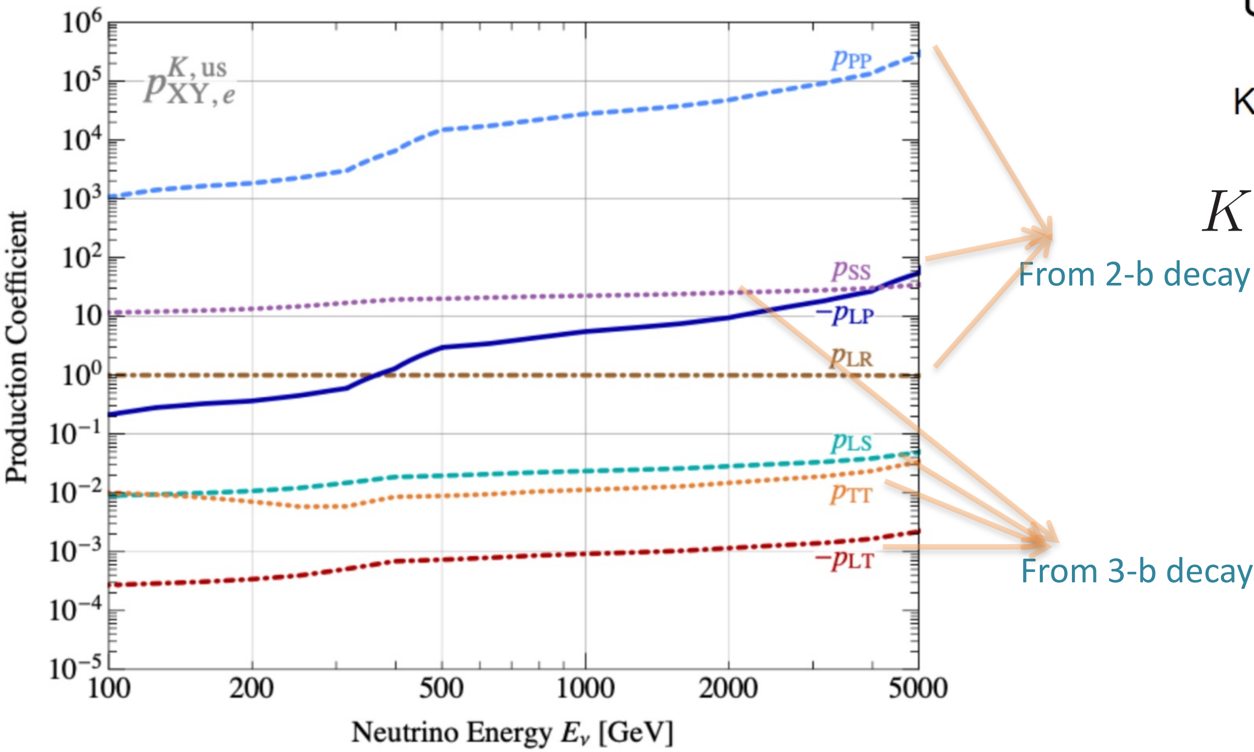

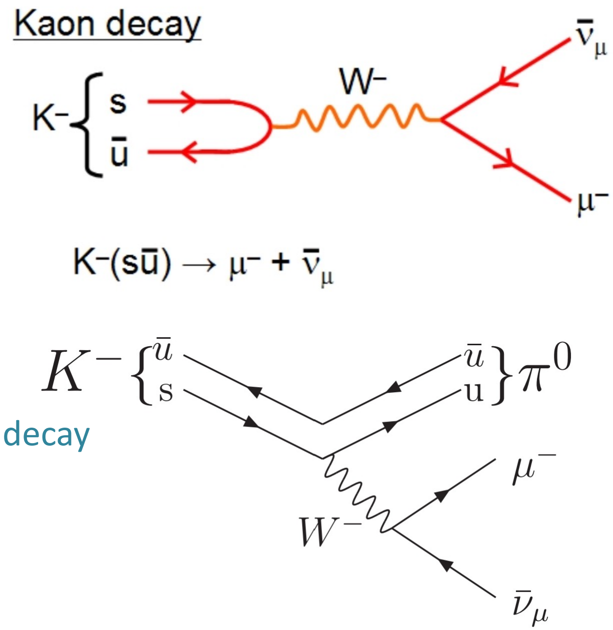

We see ``more'' chiral-enhancement for the decay into electrons!!!

EFT at FASERν

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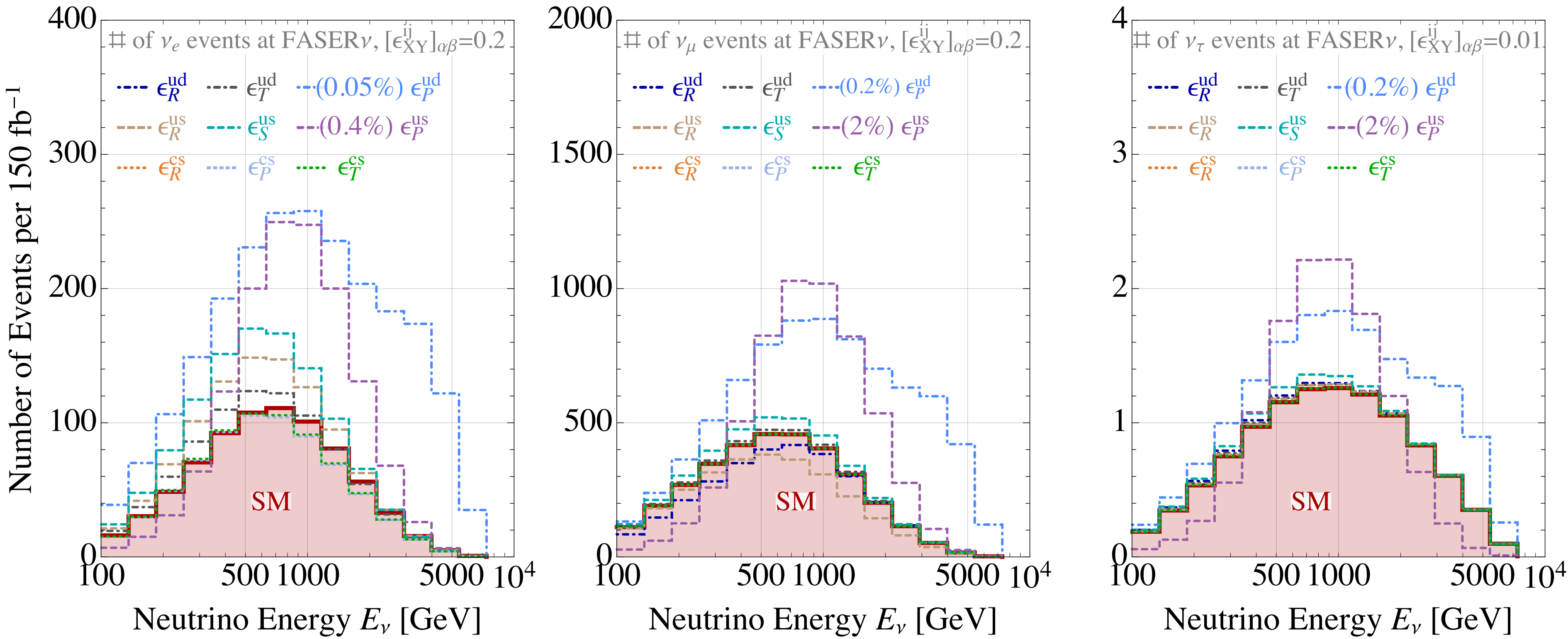


RESULTS

Turning on one interaction at a time: Pseudo-Scalar

A. Falkowski, M. González-Alonso, J. Kopp, Y. Soreq, ZT
arXiv: 2104.15136

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

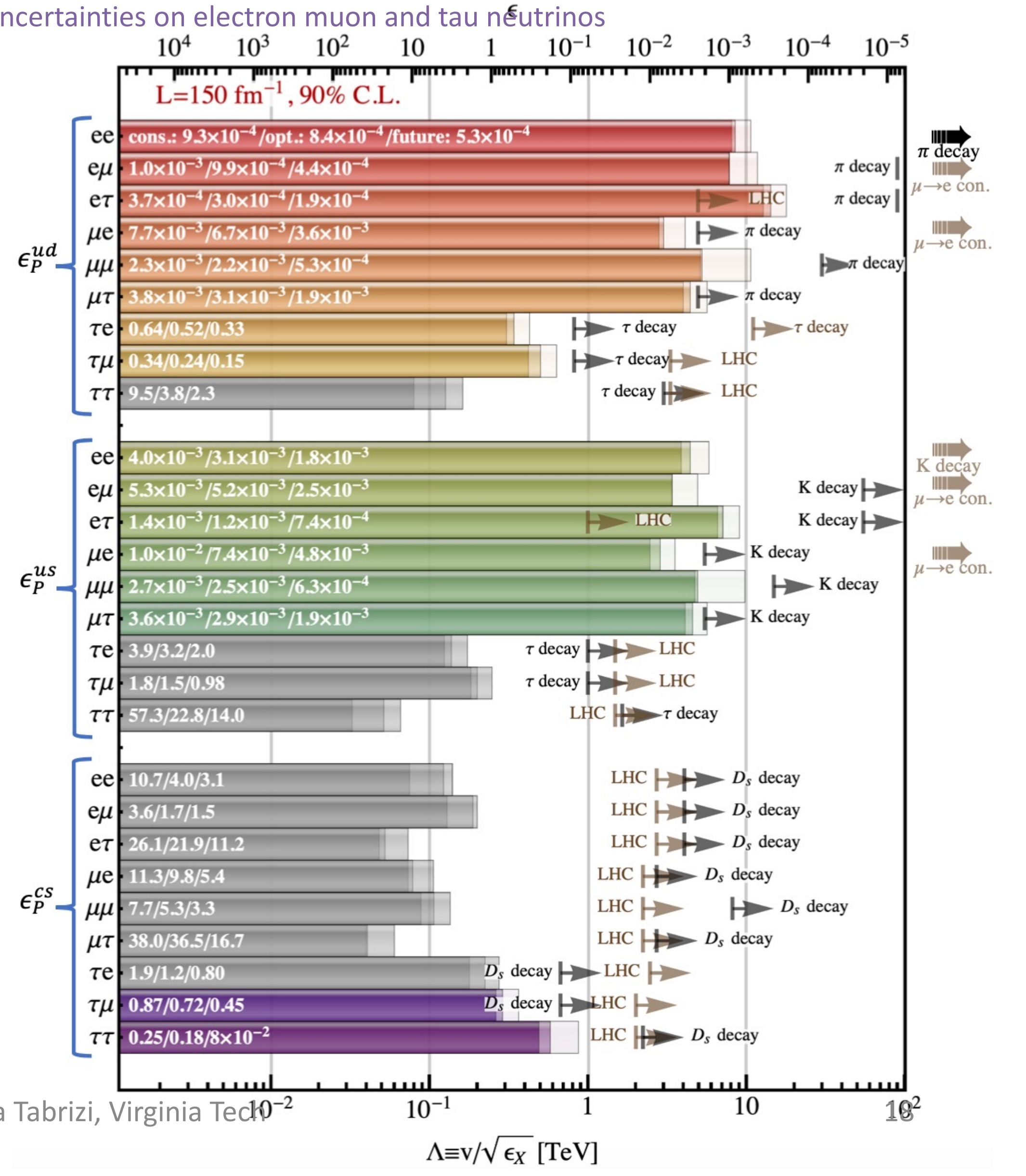
- The rates scale linearly wrt volume:

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

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

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

- Can we have a larger detector?



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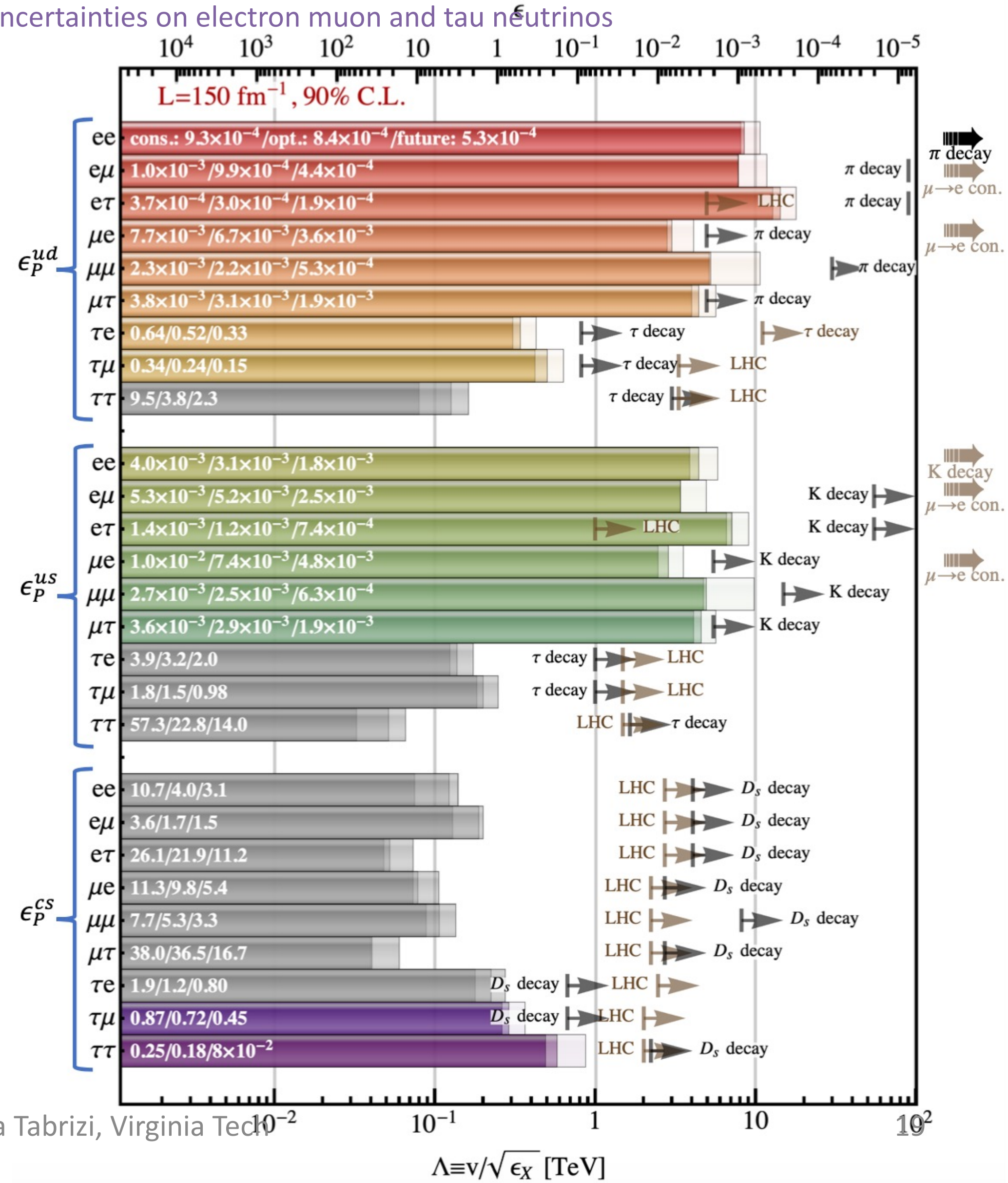
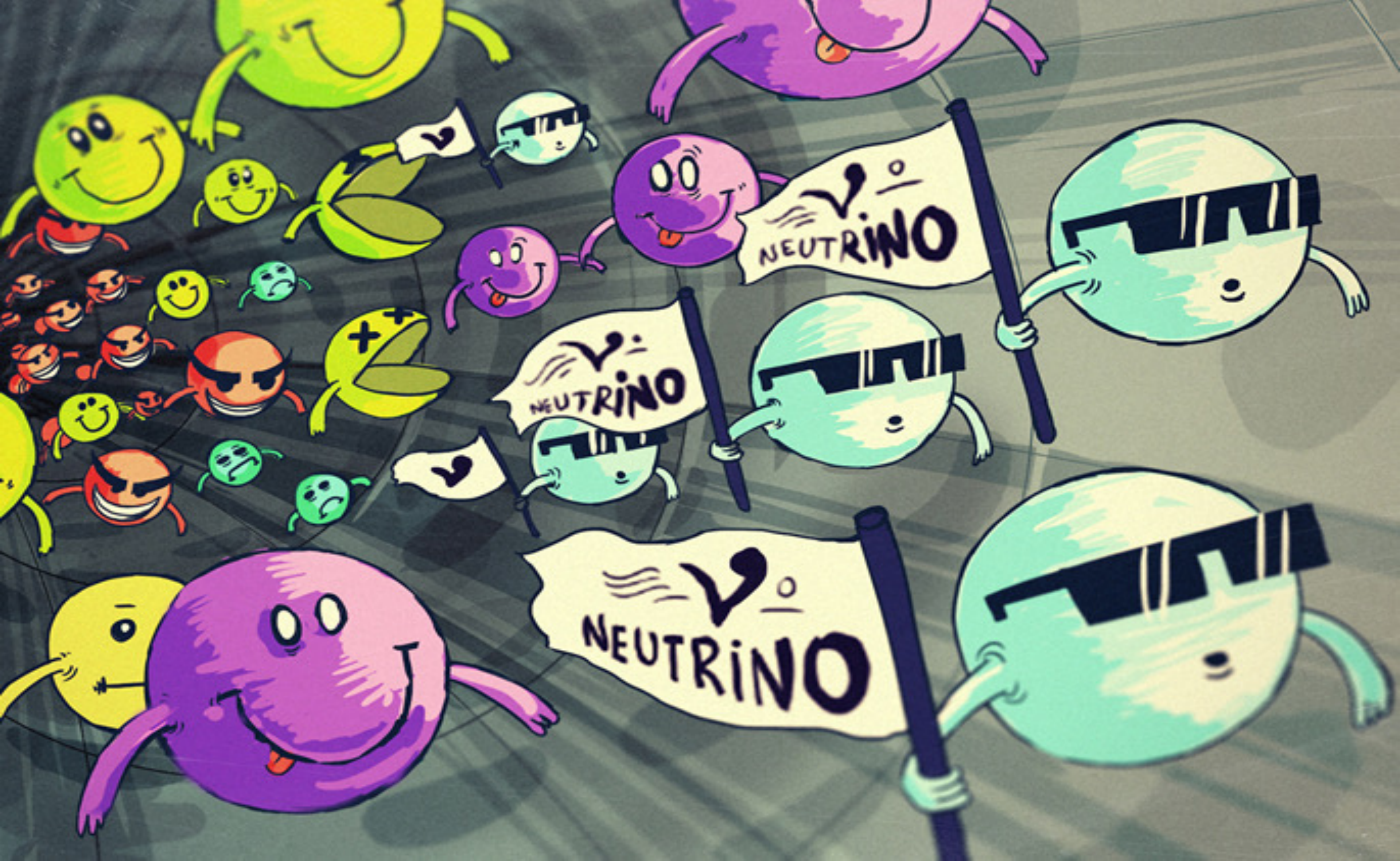
Optimistic (5%, 10%, 15%) and Pessimistic (30%, 40%, 50%), uncertainties on electron muon and tau neutrinos

- We need all the three flavors to probe all the elements!
- We need to detect τ neutrinos, so we need emulsion plates.



Conclusion:

- We have proposed a systematic approach to neutrino oscillations 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} can be derived for pseudo-scalar interaction at FASERν.
- We compared the constraints with other experiments.

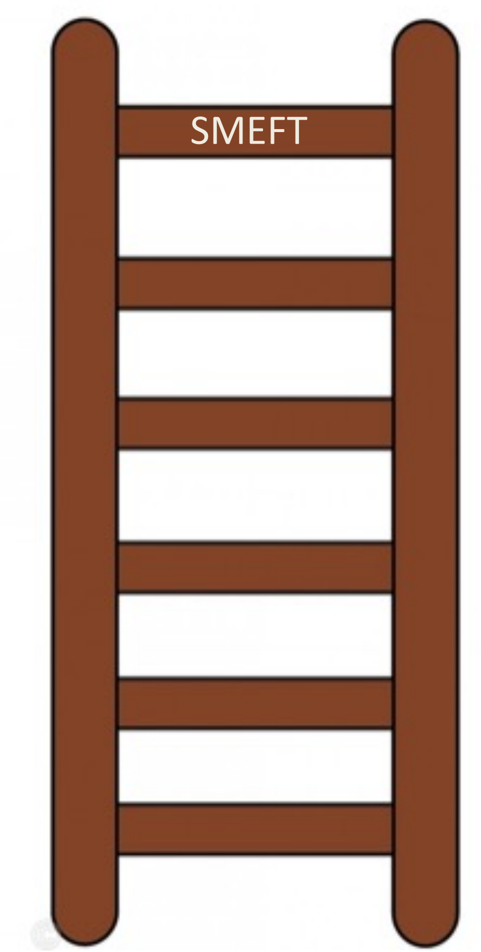


Thanks for your attention

Backup slides

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.

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

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

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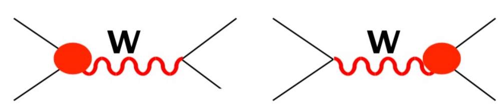
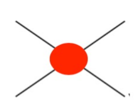




$$O_{lq}^{(3)} = (\bar{l}\gamma^\mu\sigma^a l)(\bar{q}\gamma_\mu\sigma^a q)$$
$$O_{qde} = (\bar{l}e)(\bar{d}q) + \text{h.c.}$$
$$O_{lq} = (\bar{l}_a e)\epsilon^{ab}(\bar{q}_b u) + \text{h.c.}$$
$$O_{lq}^{t} = (\bar{l}_a\sigma^{\mu\nu}e)\epsilon^{ab}(\bar{q}_b\sigma_{\mu\nu}u) + \text{h.c.}$$

Matching WEFT and SMEFT parameters:

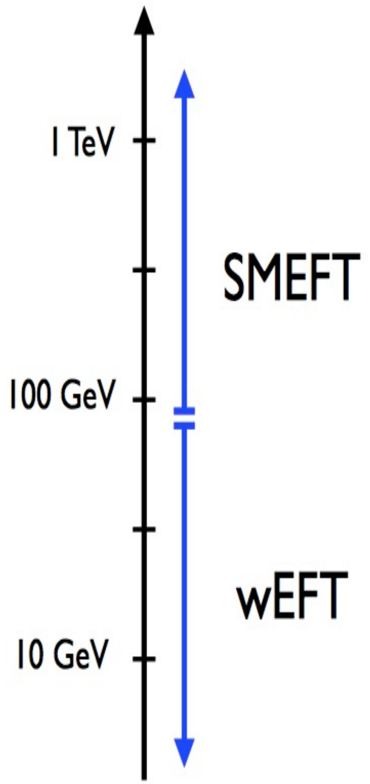
$$[\epsilon_L]_{\alpha\beta} \approx \frac{v^2}{\Lambda^2 V_{ud}} \left(V_{ud}[c^{(3)}_{Hl}]_{\alpha\beta} + V_{jd}[c^{(3)}_{Hq}]_{1j}\delta_{\alpha\beta} - V_{jd}[c^{(3)}_{lq}]_{\alpha\beta 1j} \right)$$

$$[\epsilon_R]_{\alpha\beta} \approx \frac{v^2}{2\Lambda^2 V_{ud}} [c_{Hud}]_{11}\delta_{\alpha\beta},$$

$$[\epsilon_S]_{\alpha\beta} \approx -\frac{v^2}{2\Lambda^2 V_{ud}} \left(V_{jd}[c^{(1)}_{lequ}]^*_{\beta\alpha j1} + [c_{ledq}]^*_{\beta\alpha 11} \right),$$

$$[\epsilon_P]_{\alpha\beta} \approx -\frac{v^2}{2\Lambda^2 V_{ud}} \left(V_{jd}[c^{(1)}_{lequ}]^*_{\beta\alpha j1} - [c_{ledq}]^*_{\beta\alpha 11} \right),$$

$$[\hat{\epsilon}_T]_{\alpha\beta} \approx -\frac{2v^2}{\Lambda^2 V_{ud}} V_{jd}[c^{(3)}_{lequ}]^*_{\beta\alpha j1} ,$$



- 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

Kaon Decay:

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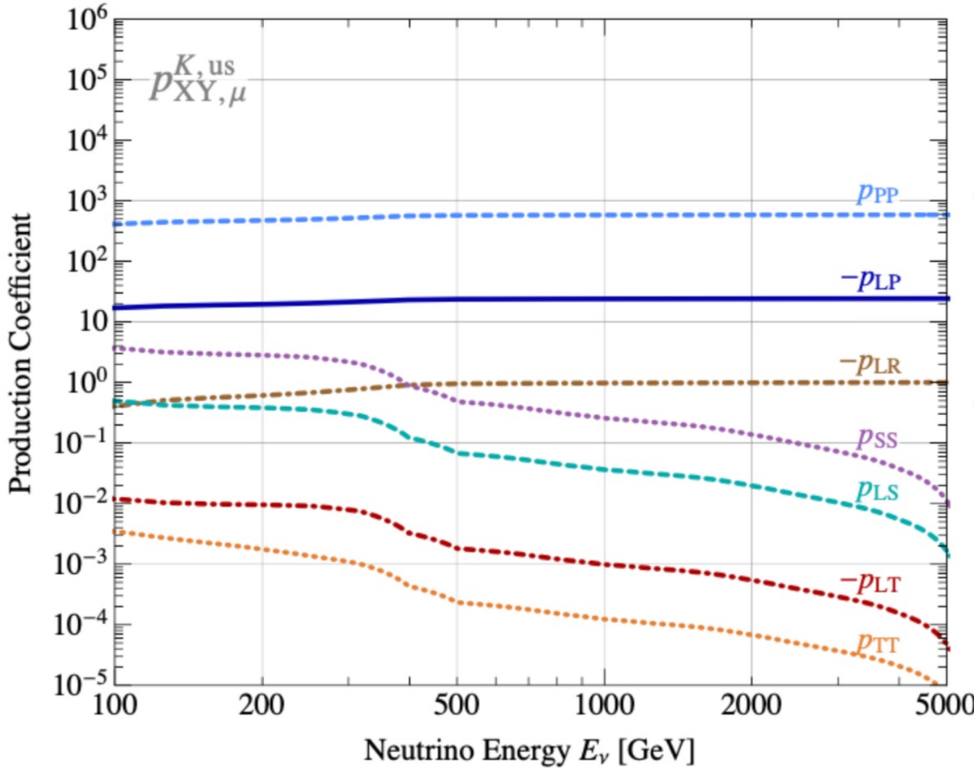
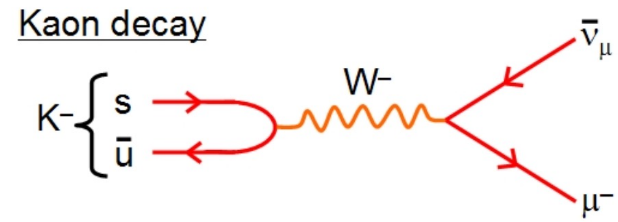
arXiv: 2104.15136

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

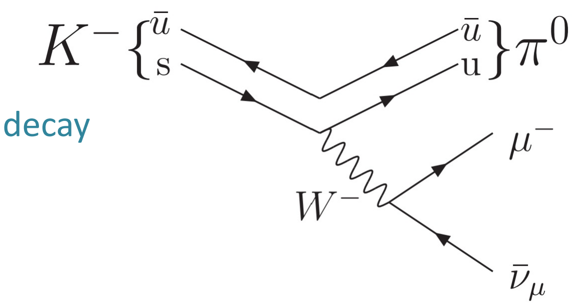


From 2-b decay

From 3-b decay



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



We see chiral-enhancement for the decay into muons!

EFT at FASERν

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(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!

RESULTS

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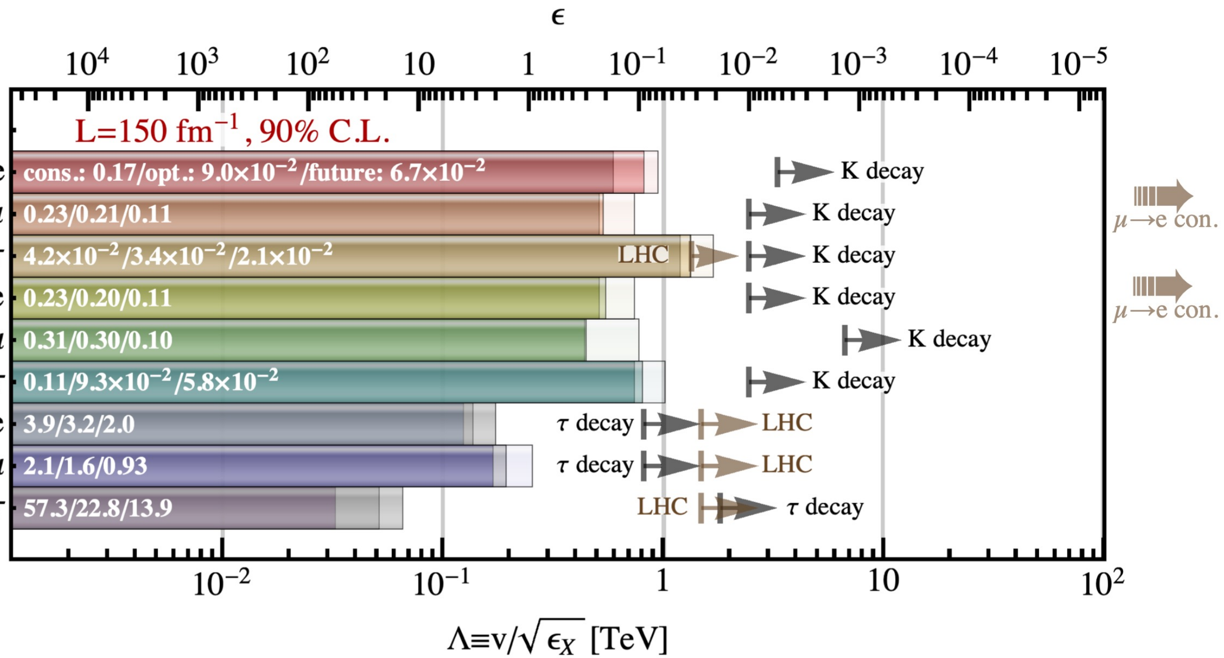
Optimistic (5%, 10%, 15%) and Pessimistic (30%, 40%, 50%), uncertainties on electron muon and tau neutrinos

From kaon decay ← ϵ_S^{us}



RESULTS

Turning on one interaction at a time: Pseudo-Scalar

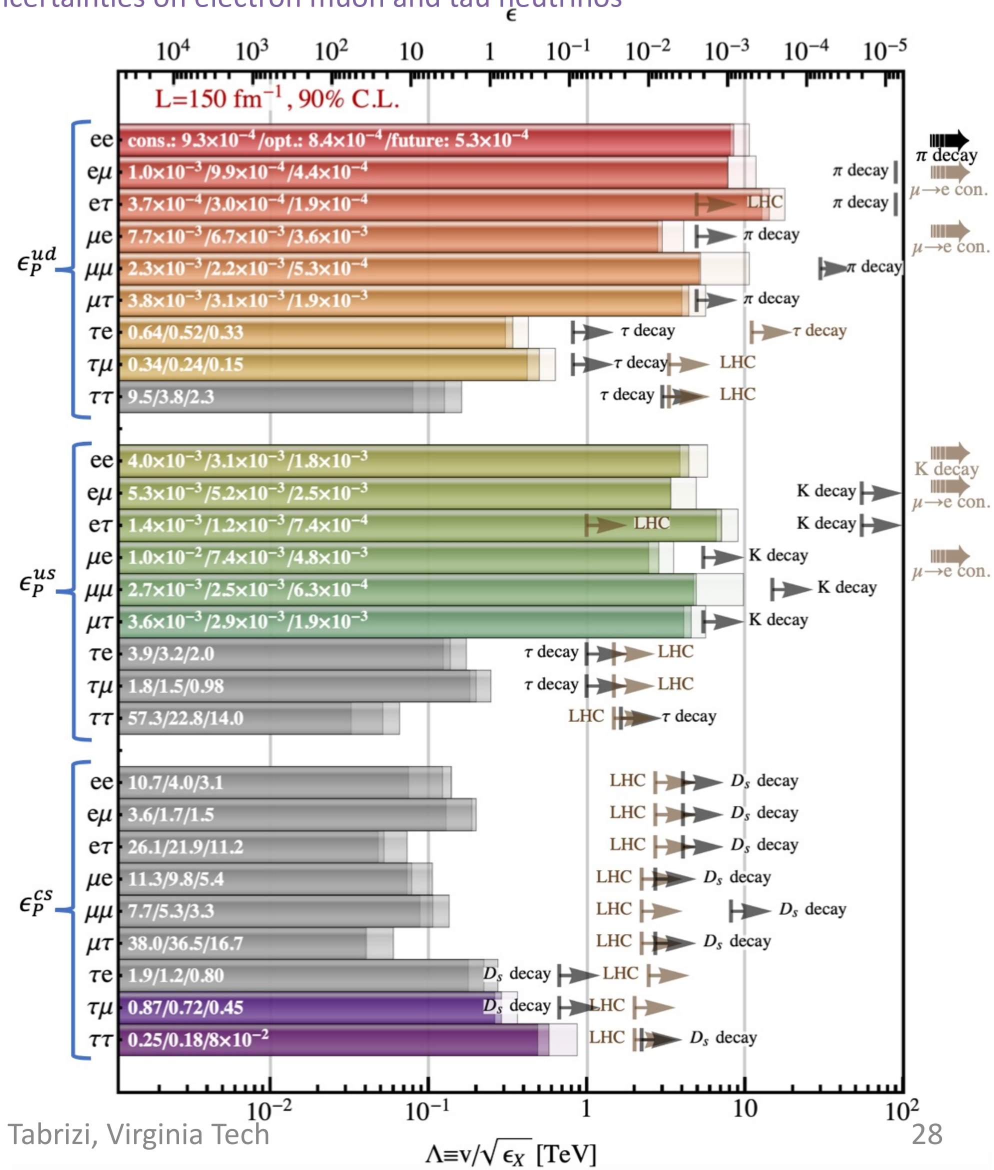
A. Falkowski, M. González-Alonso, J. Kopp, Y. Soreq, ZT
arXiv: 2104.15136

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: 2104.15136

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

From DIS ← ϵ_T^{ud}

From charm decay and DIS ← ϵ_T^{cs}