EFT at Neutrino Experiments

The Mitchell Conference on Collider, Dark Matter and Neutrino Physics

May 24-27, 2022

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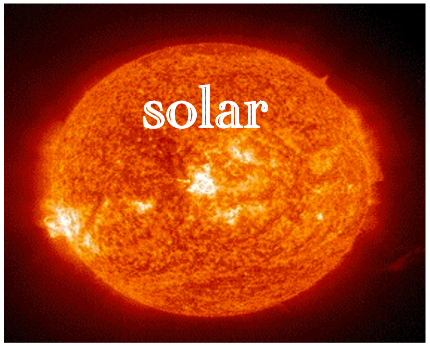
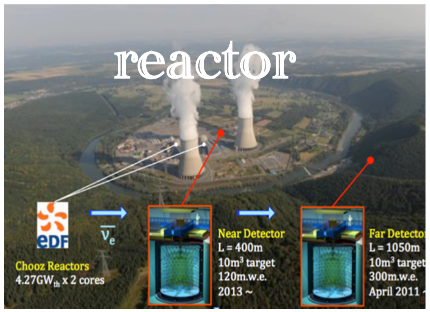
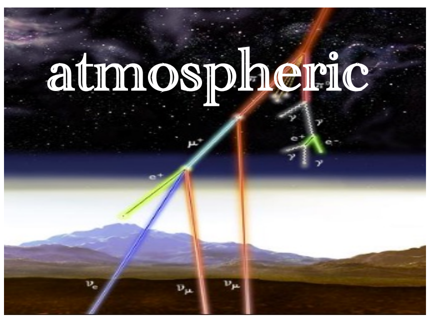
Status of Neutrino Physics in 2022



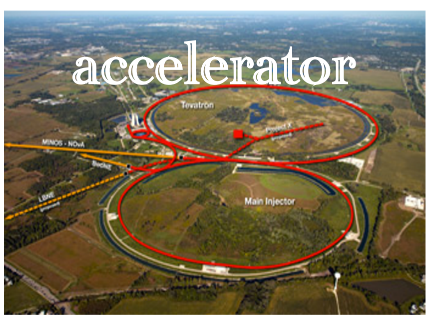
Super-Kamiokande, Borexino, SNO



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 reasonable new physics beyond the reach of high energy colliders?**

Neutrino experiments can become an ingredient in the broad program of precision measurements

Physics goals of near detectors:

Primary role: Understanding Systematic Uncertainties

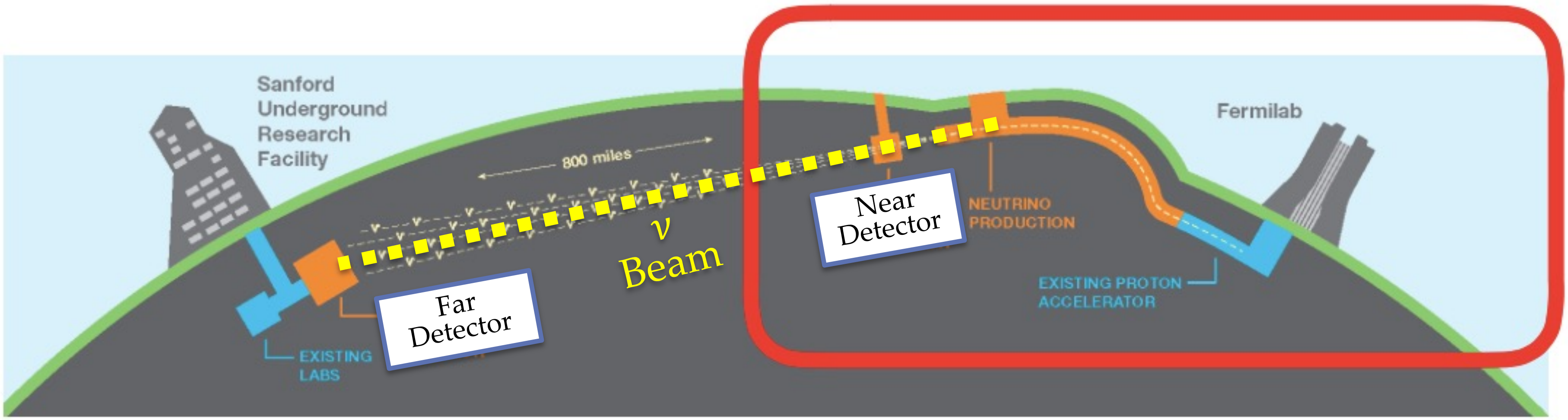
High beam luminosity +
Large fiducial mass

→

Ideal to investigate **rare/new** neutrino interactions

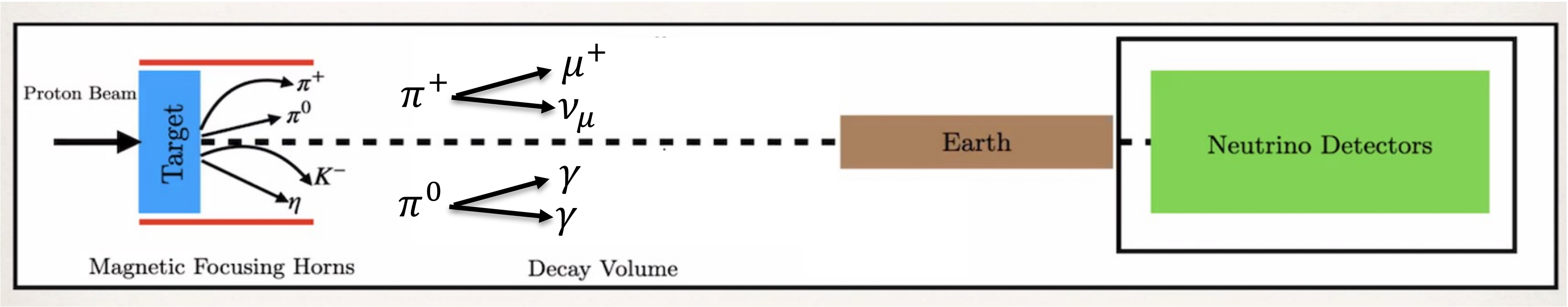
$\sigma < 10^{-44}\ \mathrm{cm}^2$

- Test SM predictions
- Search for BSM physics



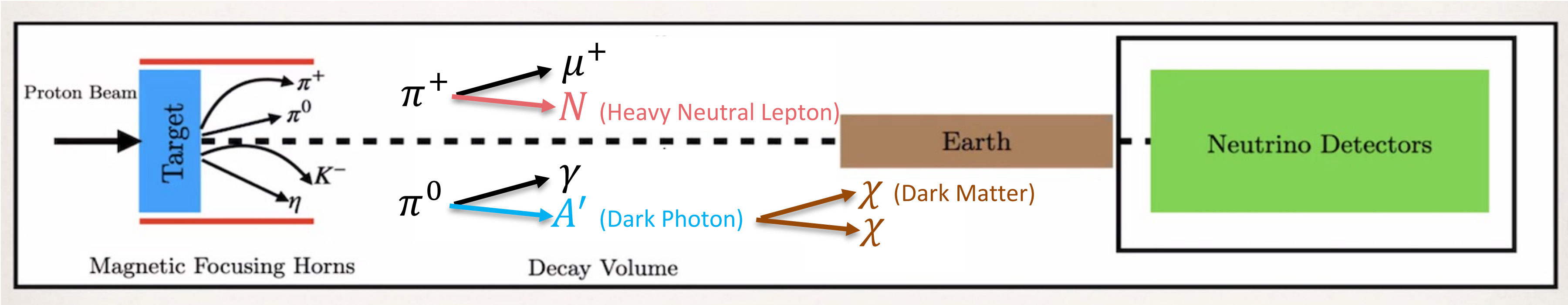
Neutrino Experiments as Dark Sector factories!

1) Direct Production of New Physics



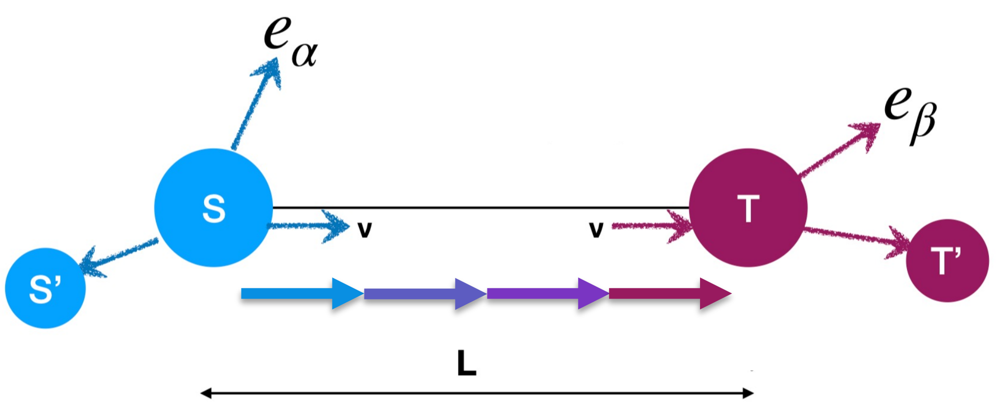
Credit: Kevin Kelly

The huge fluxes of neutrinos and photos can be used for BSM searches



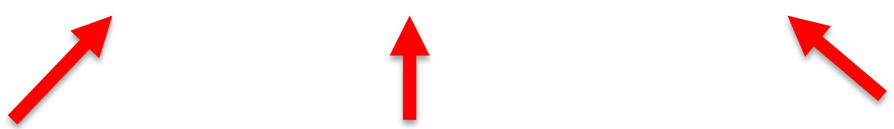
How about "Heavy" New Physics?

2) Affect Neutrino Interactions: Indirect Search



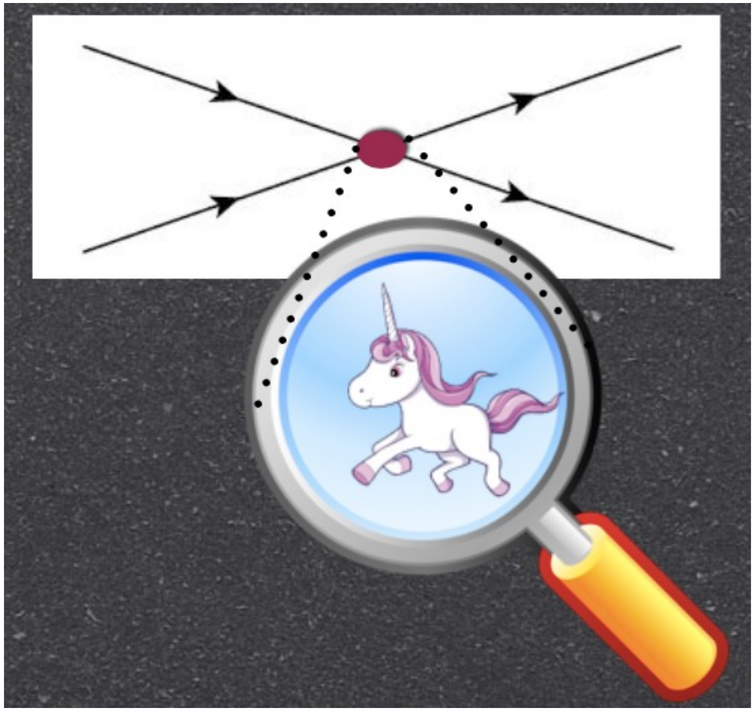
Observable: rate of detected events

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

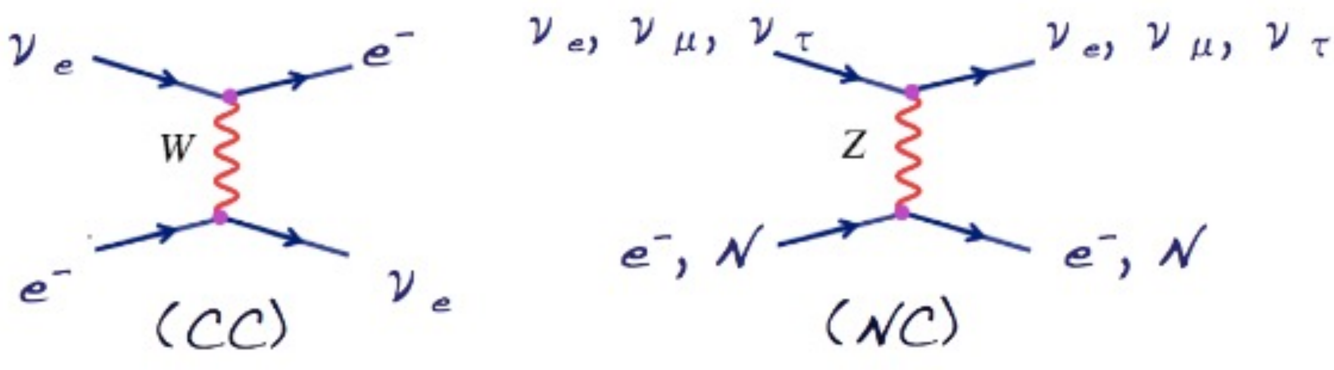


Indirect Search-EFT:

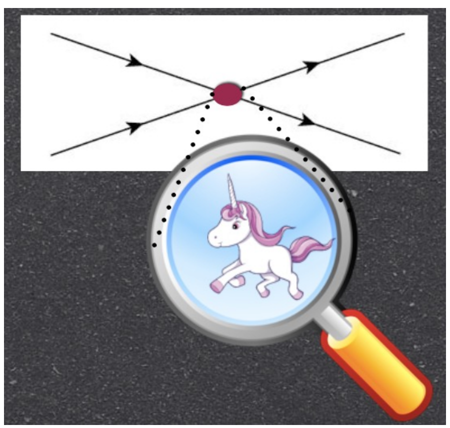
- Why EFT?
- EFT ladder
- EFT at Neutrino Experiments
- Conclusion



- Coherent CC and NC forward scattering of neutrinos

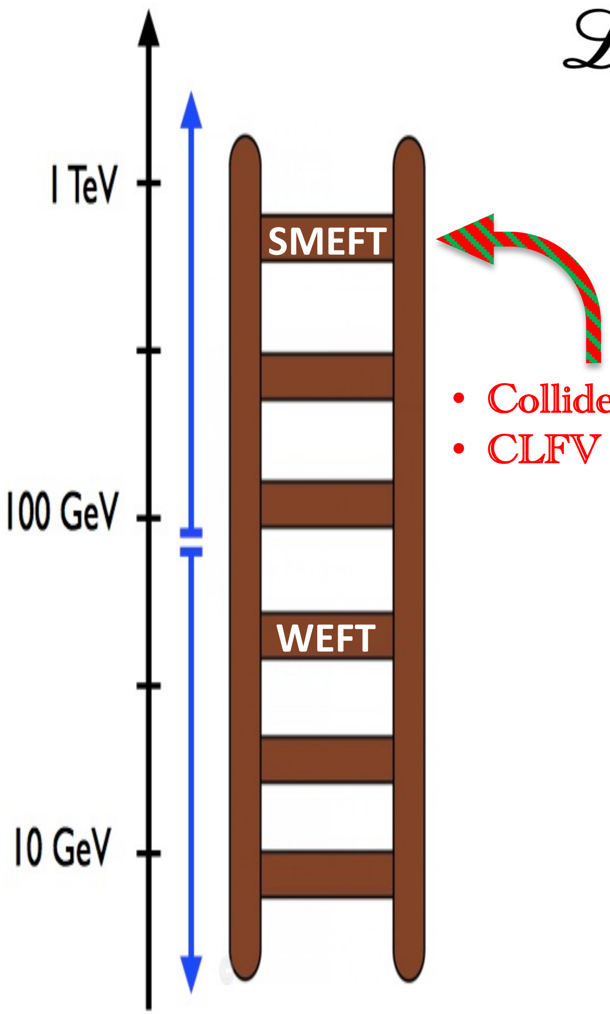


- New 4-fermion interactions



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

EFT ladder



- Colliders
- CLFV

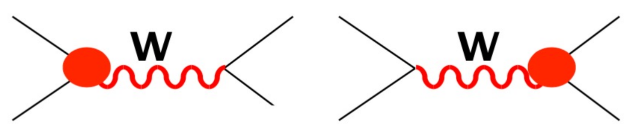
SMEFT: minimal EFT above the weak scale

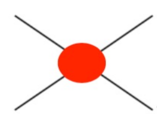
$$\mathscr{L}_{\mathrm{SMEFT}} = \mathscr{L}_{\mathrm{SM}} + \mathscr{L}_{D=5} + \boxed{\mathscr{L}_{D=6}}$$

Known SM Lagrangian

Gives neutrino Masses

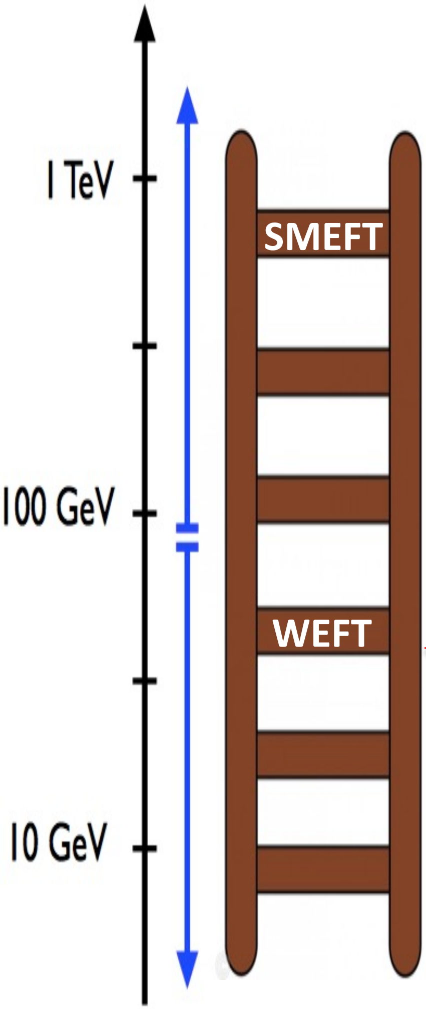
+





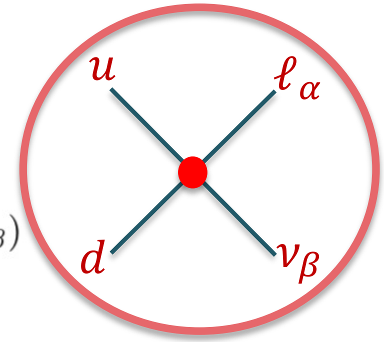
$$O_{lq}^{(3)} = (\bar{l}\gamma^{\mu}\sigma^{a}l)(\bar{q}\gamma_{\mu}\sigma^{a}q)$$
$$O_{qde} = (\bar{l}e)(\bar{d}q) + \mathrm{h.c.}$$
$$O_{lq} = (\bar{l}_a e)\epsilon^{ab}(\bar{q}_b u) + \mathrm{h.c.}$$
$$O_{lq}^{t} = (\bar{l}_a\sigma^{\mu\nu}e)\epsilon^{ab}(\bar{q}_b\sigma_{\mu\nu}u) + \mathrm{h.c.}$$

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



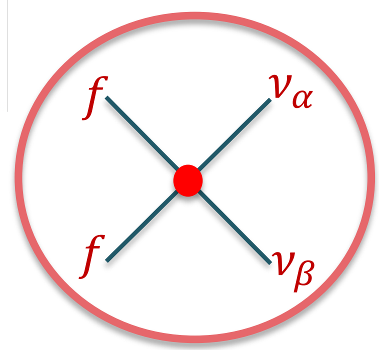
- CC: New left/right handed, (pseudo)scalar and tensor interactions

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



- 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

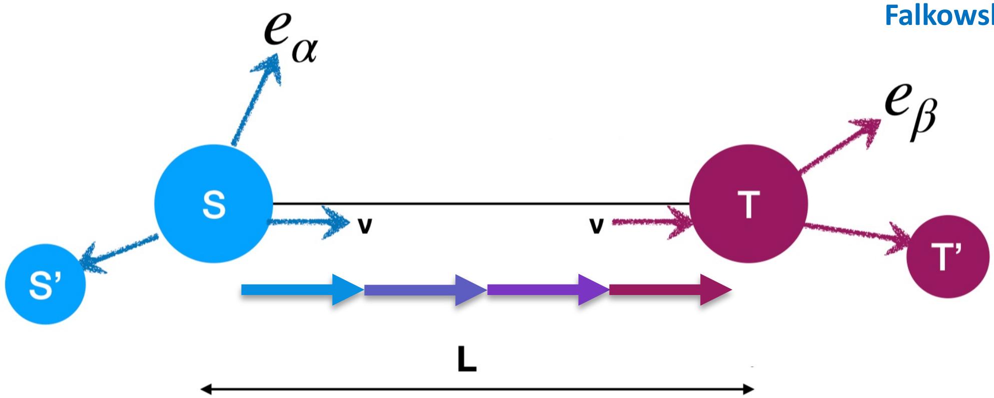
$$
\begin{aligned}
[\epsilon_L]_{\alpha\beta} &\approx \frac{v^2}{\Lambda^2 V_{ud}}\left(V_{ud}[c_{Hl}^{(3)}]_{\alpha\beta} + V_{jd}[c_{Hq}^{(3)}]_{1j}\delta_{\alpha\beta} - V_{jd}[c_{lq}^{(3)}]_{\alpha\beta 1j}\right)\\
[\epsilon_R]_{\alpha\beta} &\approx \frac{v^2}{2\Lambda^2 V_{ud}}[c_{Hud}]_{11}\delta_{\alpha\beta}\\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

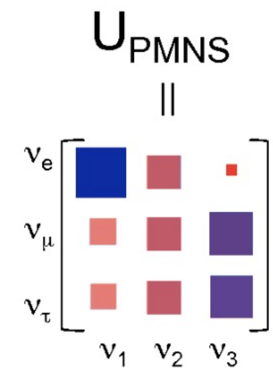
Falkowski, González-Alonso, *ZT*, JHEP (2019)

- 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

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

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

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

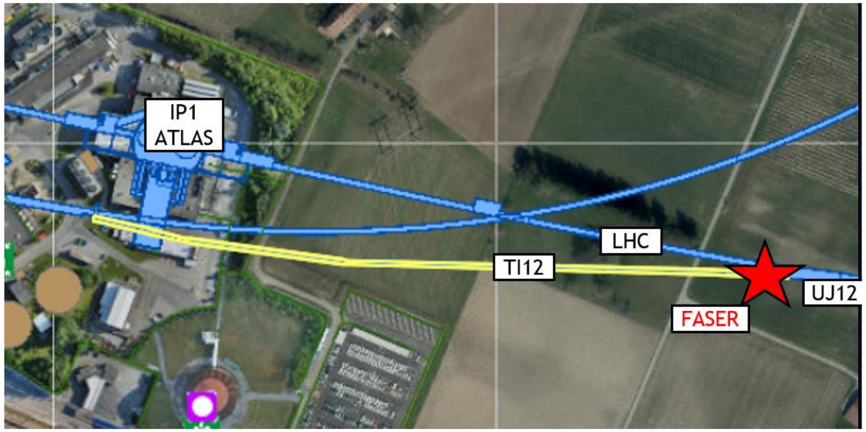
$$\sigma^{Total} = \sigma^{SM} + \varepsilon_X \sigma^{Int} + \varepsilon_X{}^2 \sigma^{NP} \sim \sigma^{SM}(1+\varepsilon_X\, d_{XL} + \varepsilon_X{}^2\, d_{XX})$$

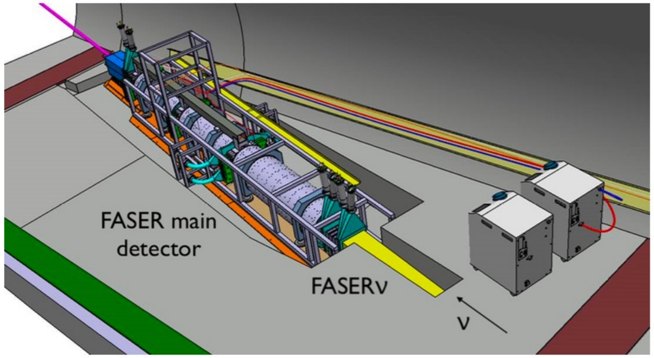
$$\phi^{Total} = \phi^{SM} + \varepsilon_X \phi^{Int} + \varepsilon_X{}^2 \phi^{NP} \sim \phi^{SM}(1+\varepsilon_X\, p_{XL} + \varepsilon_X{}^2\, p_{XX})$$

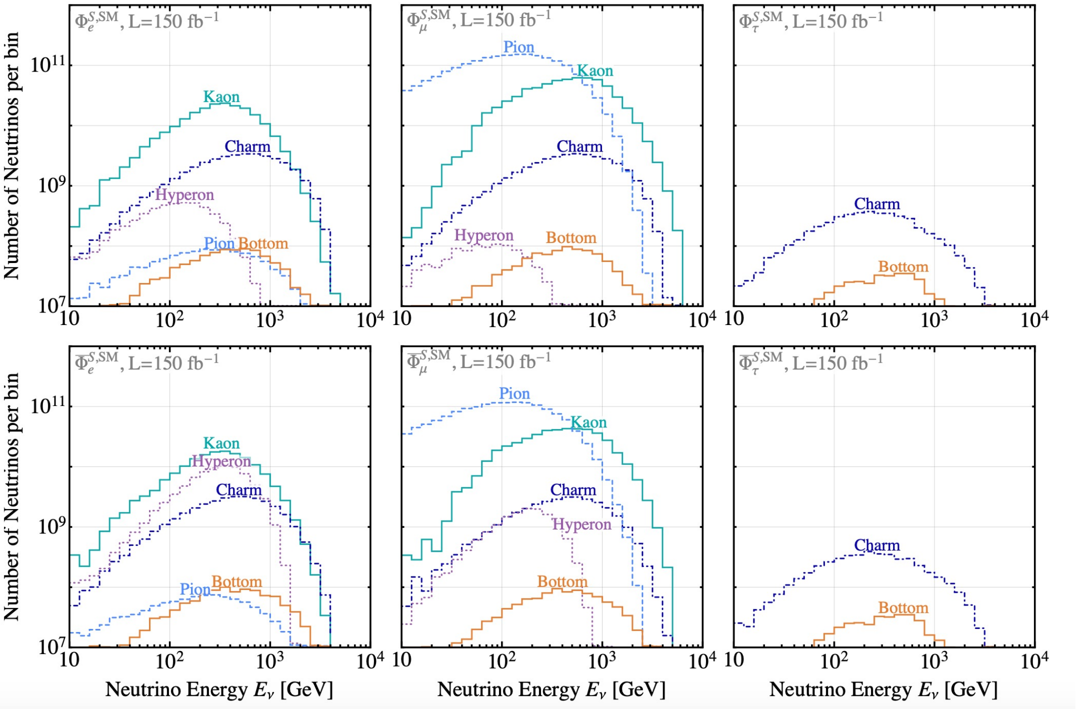
$$-\frac{2V_{ud}}{v^2}\Bigg\{\left[1+\epsilon_L\right]_{\alpha\beta} \bar{e}_\alpha \gamma_\mu P_L \nu_\beta \cdot \bar{u}_L \gamma^\mu d_L + \left[\epsilon_R\right]_{\alpha\beta} \bar{e}_\alpha \gamma_\mu P_L \nu_\beta \cdot \bar{u}_R \gamma^\mu d_R + \frac{1}{2}\bar{e}_\alpha P_L \nu_\beta \cdot \bar{u}\left[\epsilon_S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

FASERν Experiment

- 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;

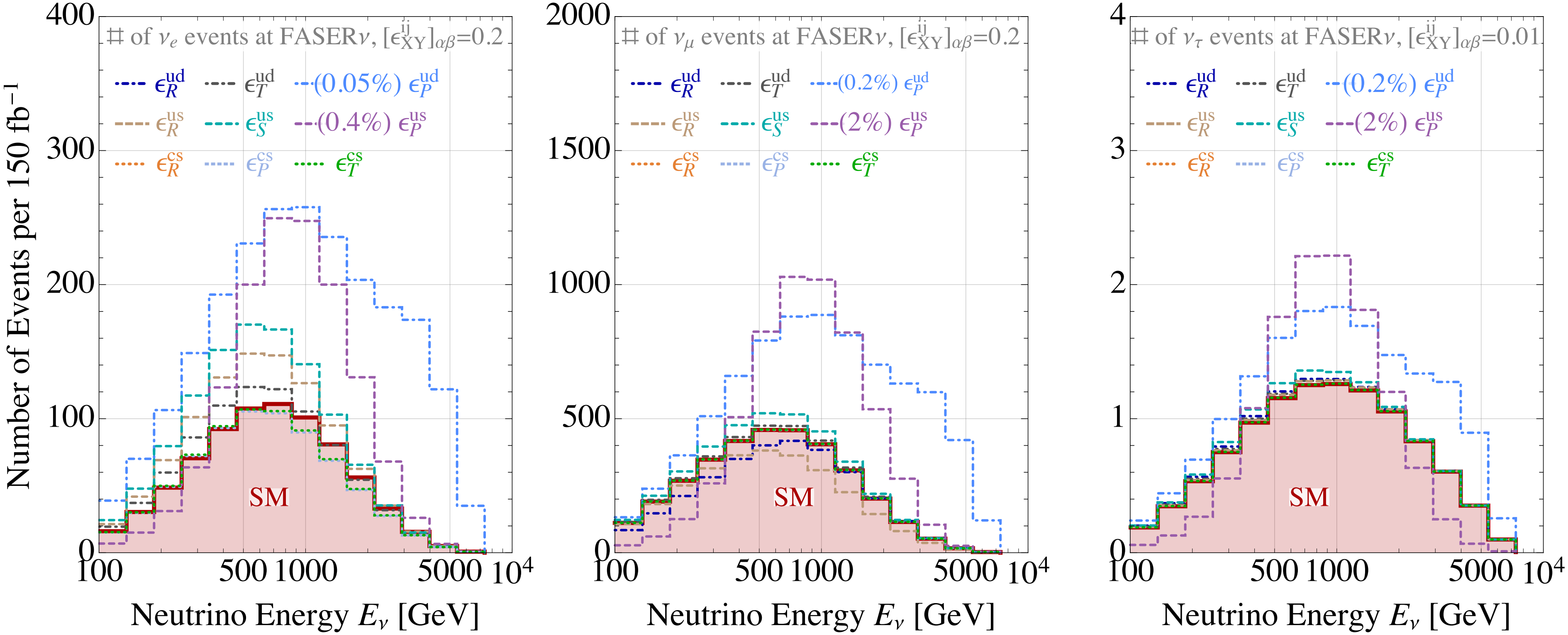






EFT at FASERν

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

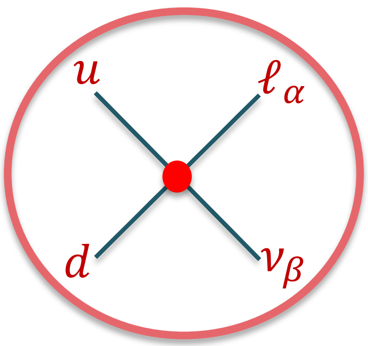


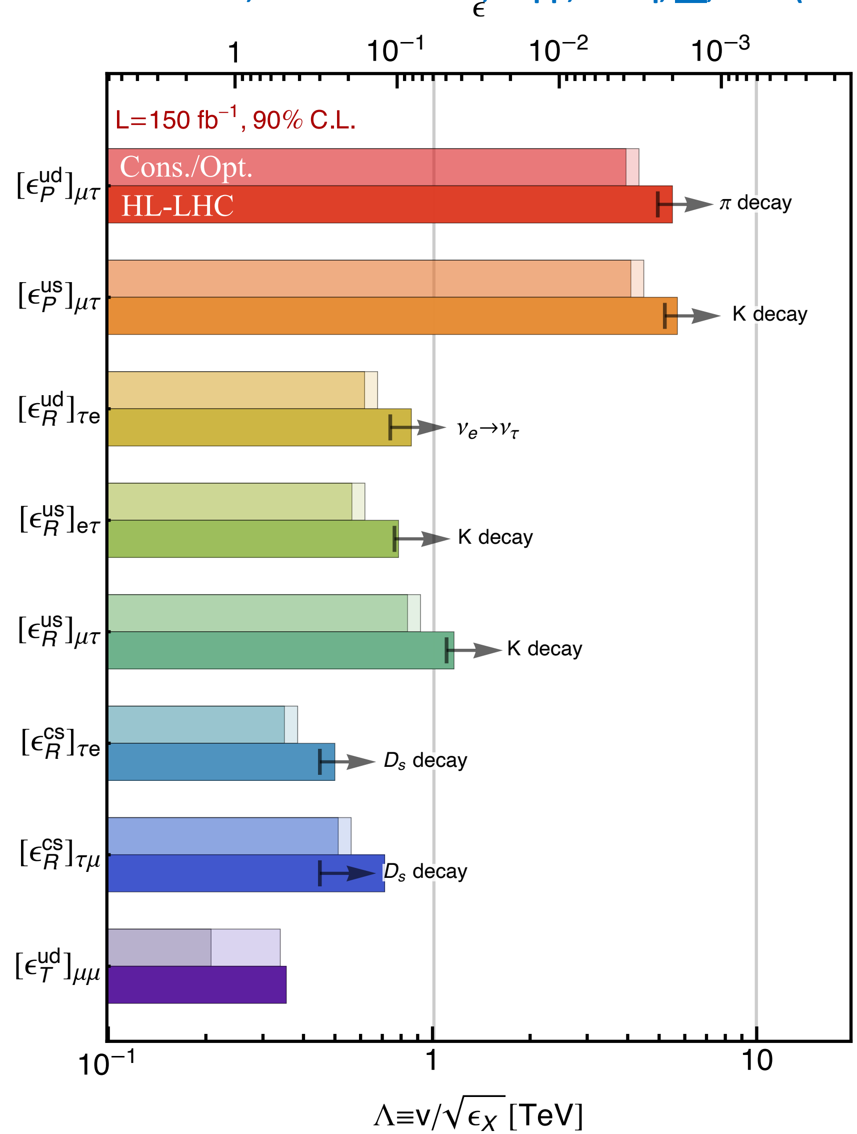
- Analysis is statistics dominated: $\nu_e \sim 1000$, $\nu_\mu \sim 5000$, $\nu_\tau \sim 10$
- Optimistic systematic uncertainties: 5% on ν_e, 10% on ν_μ, 15% on ν_τ
- Conservative systematic uncertainties: 30% on ν_e, 40% on ν_μ, 50% on ν_τ

EFT at FASERν

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

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





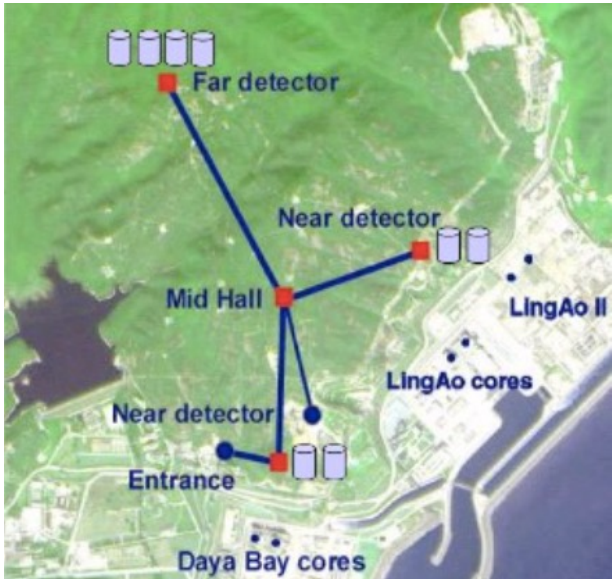
- Neutrino detectors can identify flavor: 81 operators at FASERν
- New physics reach at multi-TeV
- Complementary or dominant constraints

Reactor Experiments

Daya Bay:

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

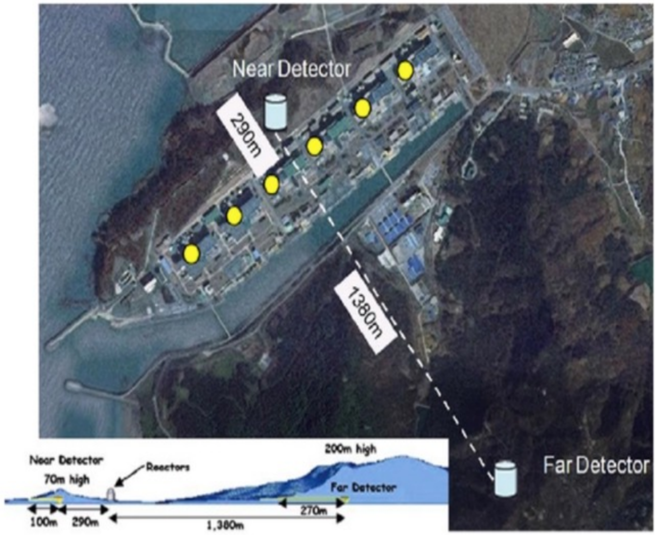
Daya Bay Collaboration, D. Adey et al., (2018)



RENO:

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

RENO Collaboration, G. Bak et al., (2018)

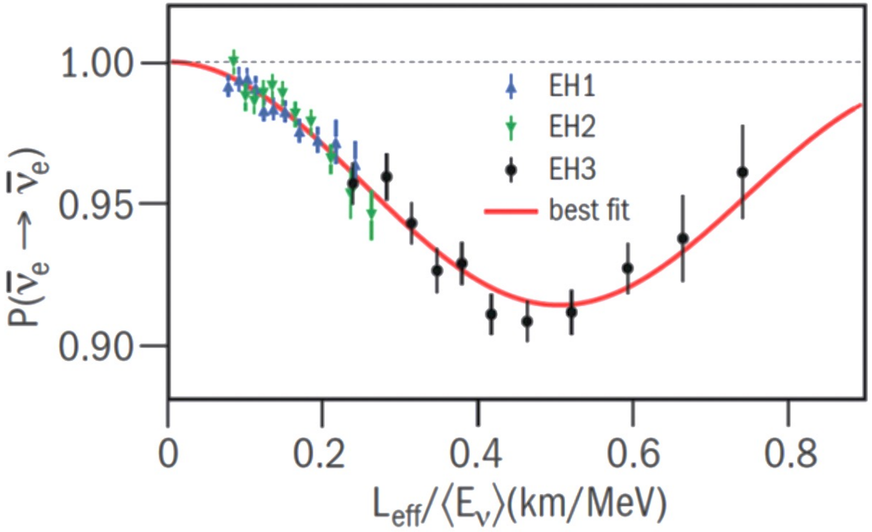


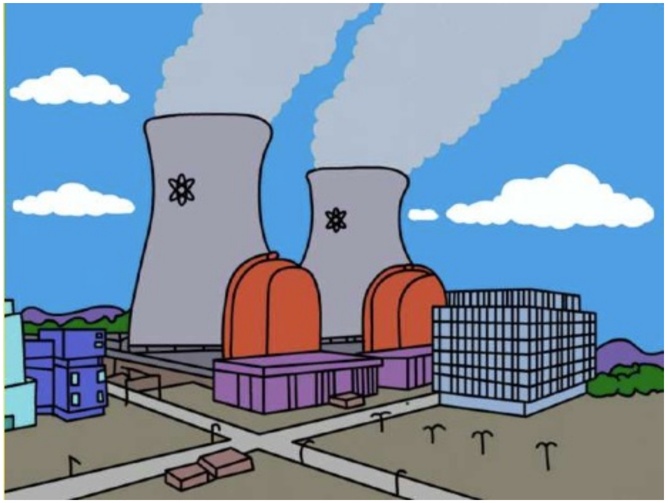
Reactor Experiments

Oscillation probability in the SM:

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

$$P_{\bar{\nu}_e \to \bar{\nu}_e}(L, E_\nu) \quad = \quad 1 - \sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right) \sin^2\left(2\theta_{13}\right)$$





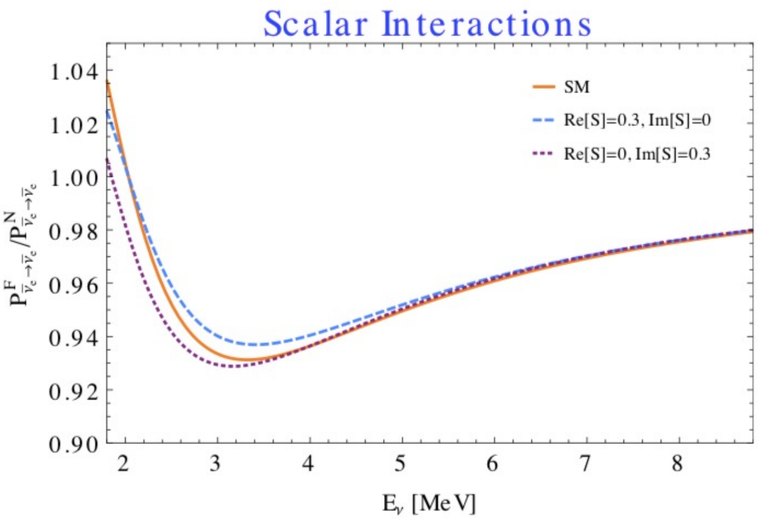
$$\sin^2(2\tilde{\theta}_{13}) = 0.0841 \pm 0.0027$$

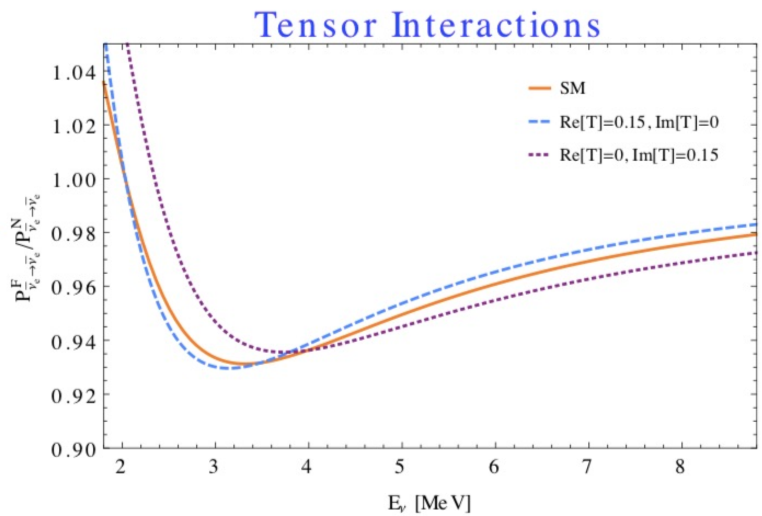
EFT at Reactor Experiments

Oscillation probability in the SM+Scalar+Tensor:

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

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





$$[S] \equiv e^{i\delta_{CP}}\left(s_{23}[\epsilon_S]_{e\mu}+c_{23}[\epsilon_S]_{e\tau}\right) \qquad \alpha_D=\frac{g_S}{3g_A^2+1}\mathrm{Re}\,[S]-\frac{3g_Ag_T}{3g_A^2+1}\mathrm{Re}\,[T], \qquad \alpha_P=\frac{g_T}{g_A}\mathrm{Re}\,[T]$$

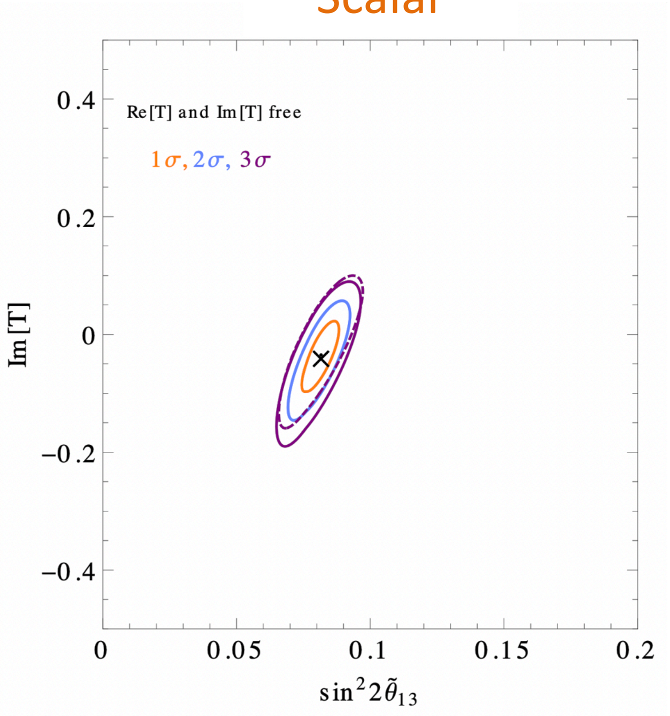
$$[T] \equiv e^{i\delta_{CP}}\left(s_{23}[\hat{\epsilon}_T]_{e\mu}+c_{23}[\hat{\epsilon}_T]_{e\tau}\right) \qquad \beta_D=\frac{g_S}{3g_A^2+1}\mathrm{Im}\,[S]-\frac{3g_Ag_T}{3g_A^2+1}\mathrm{Im}\,[T], \qquad \beta_P=\frac{g_T}{g_A}\mathrm{Im}\,[T]$$

The S/T interactions shift the amplitude and also distort the E_ν spectrum

EFT at Reactor Experiments

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

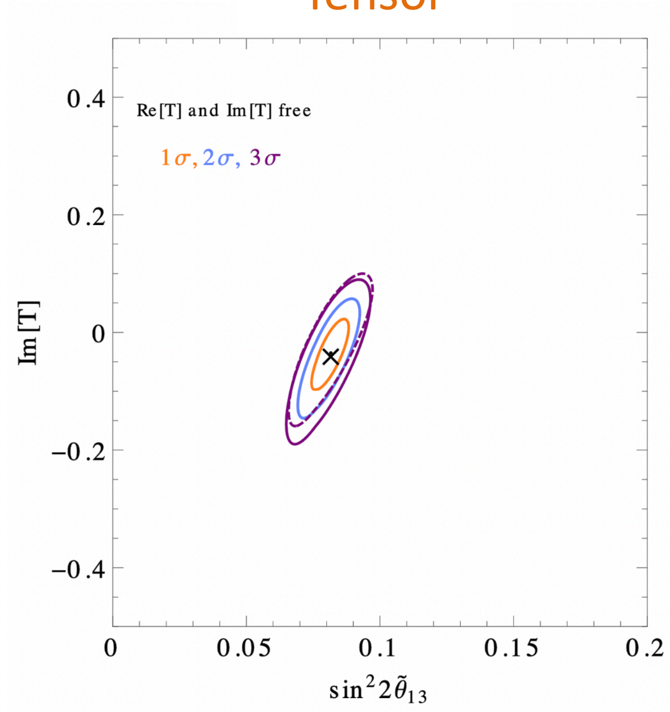
Scalar



$$\mathrm{Re}\,[S] = 0.95 \pm 0.37$$

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

Tensor



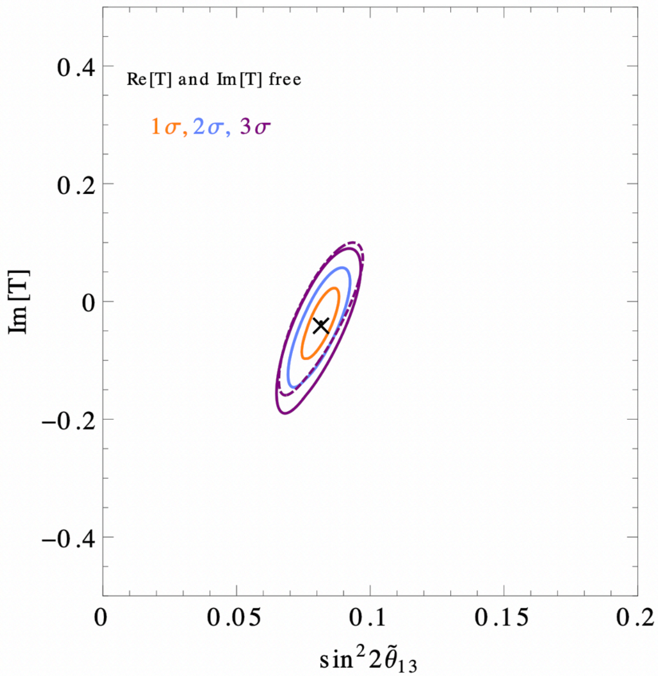
$$\mathrm{Re}\,[T] = -0.26 \pm 0.14$$

$$\mathrm{Im}\,[T] = -0.034 \pm 0.042$$

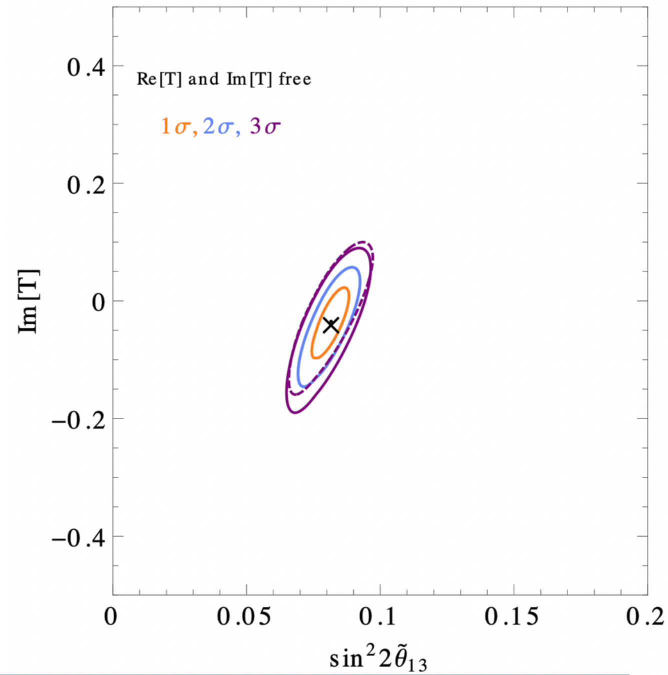
EFT at Reactor Experiments

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

Scalar

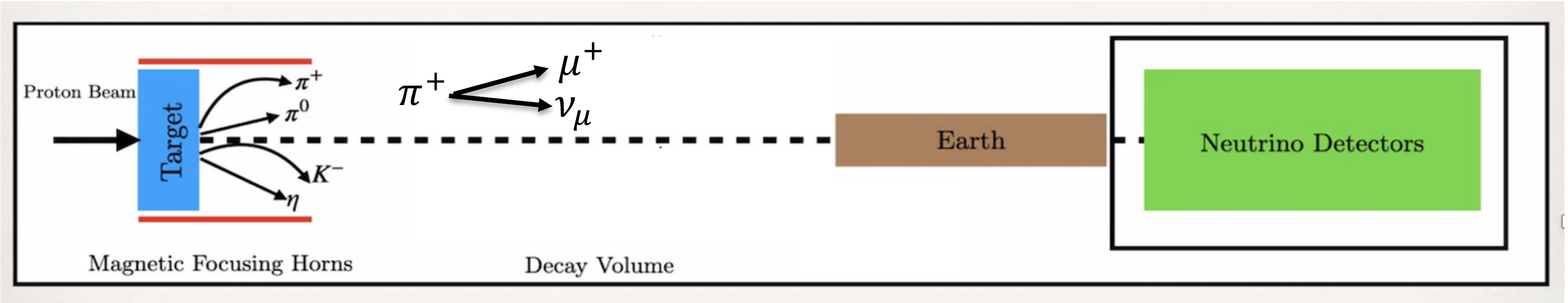


Tensor

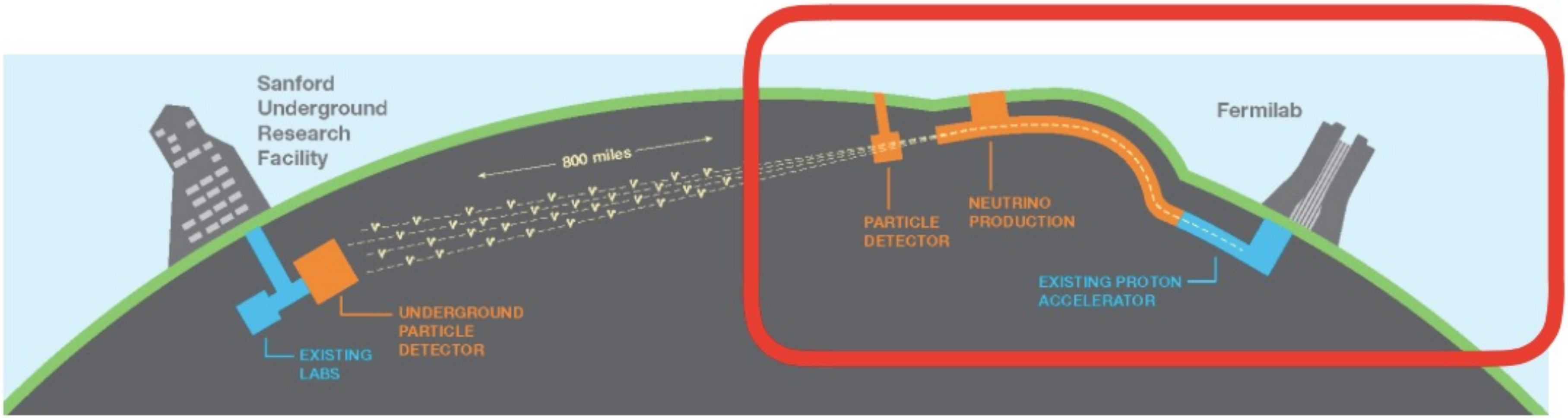


- EFT-θ_{13} degeneracy
- Combining with other experiments will increase the sensitivity to NP

Long Baseline Accelerator Experiments



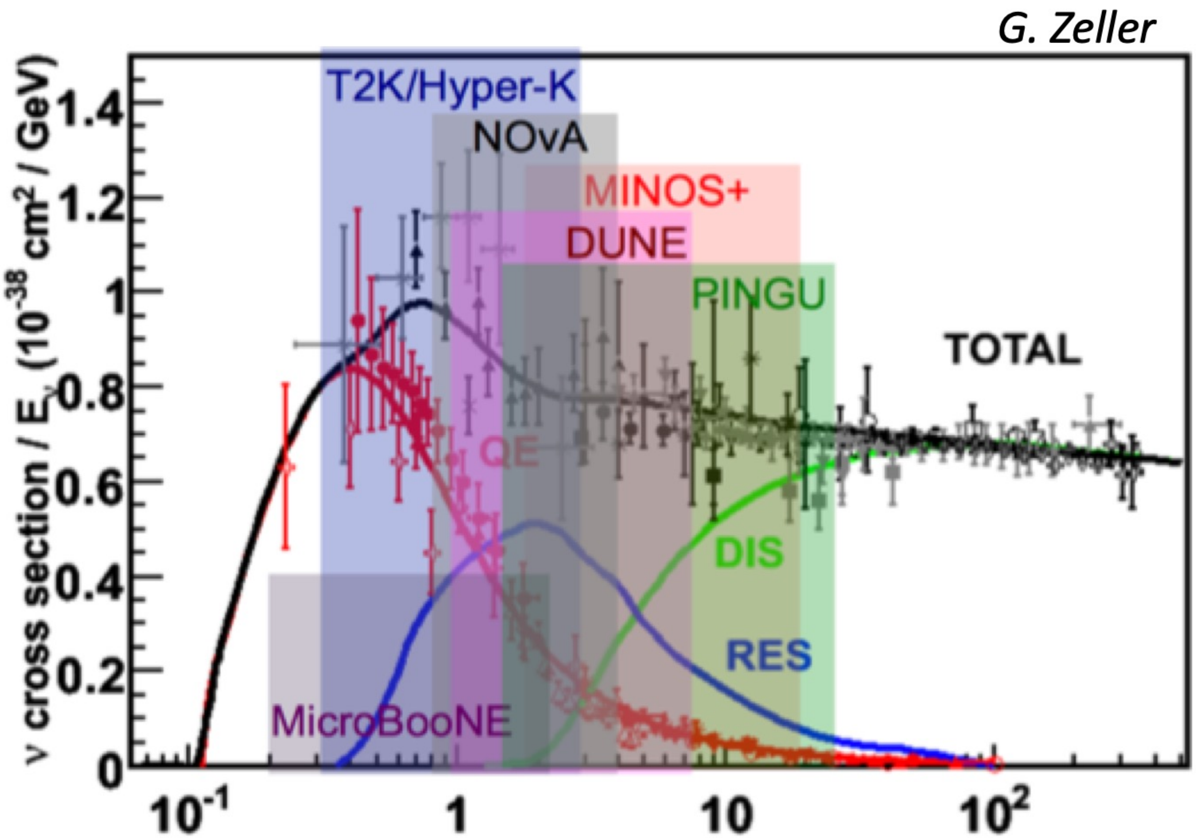
Credit: Kevin Kelly



High beam luminosity + Large fiducial mass → Ideal to investigate (rare) neutrino interactions

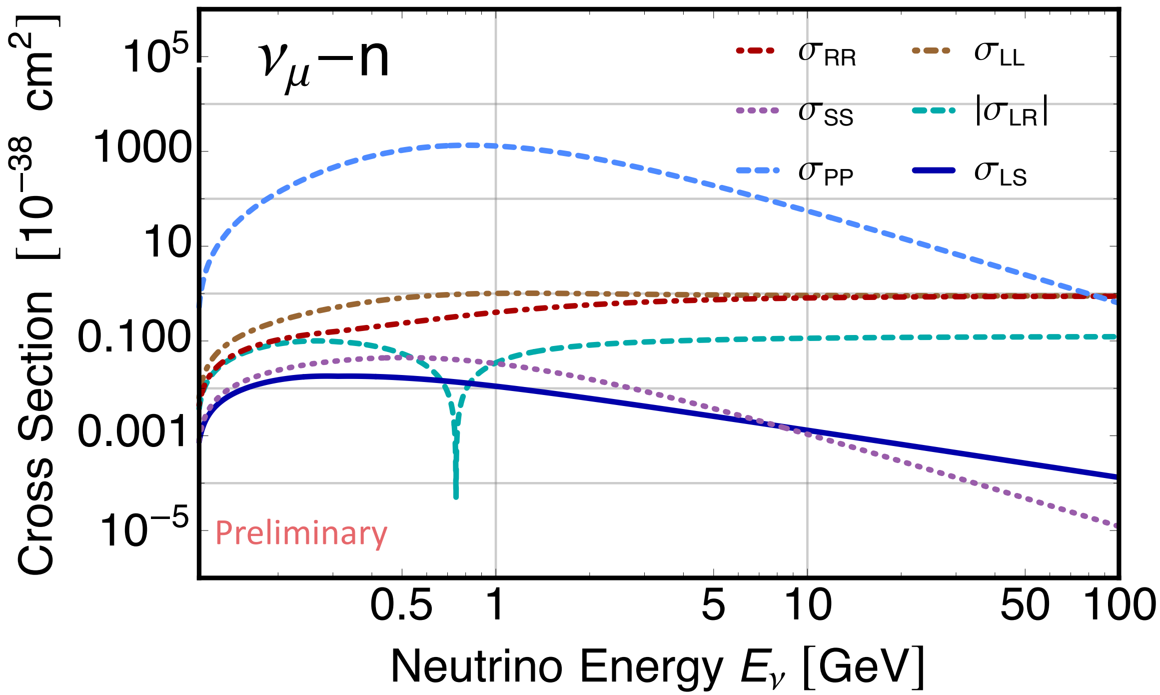
Long Baseline Accelerator Experiments

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



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

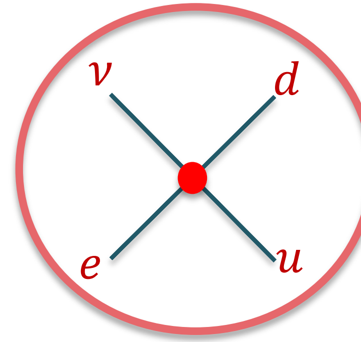
e.g.: Quasi-Elastic scattering at the nucleon level



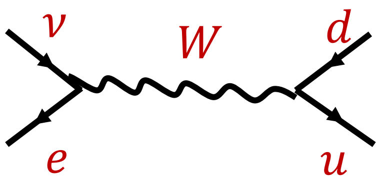
Kopp, Rocco, *ZT*, in preparation

Can these detectors have access to new physics at 100 TeV scale?

Specific New Physics Models

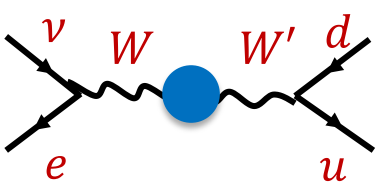


ε_L: measures deviations of the W boson to quarks and leptons, compared to the SM prediction



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

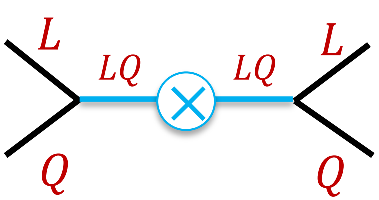
ε_R : left-right symmetric $SU(3)_C xSU(2)_L xSU(2)_R xU(1)_X$ models introduce new charged vector bosons W' coupling to right-handed quarks



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

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

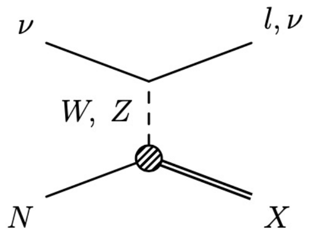
$\varepsilon_{S,P,T}$: In leptoquark models, new scalar particles couple to both quarks and leptons



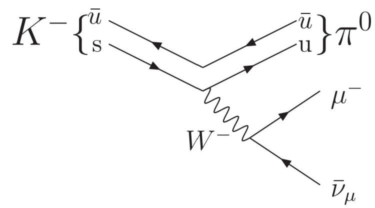
$$(LQ)(LQ)$$

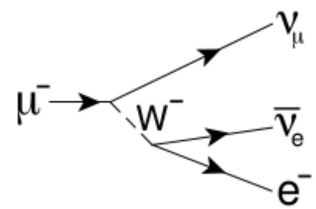
$$\epsilon_{S,P,T} \sim \frac{\mathrm{v}^2}{m_{LQ}^2}$$

DIS: FASERν



Kaon/Muon decay: ISODAR, KDAR





Solar neutrinos: Borexino

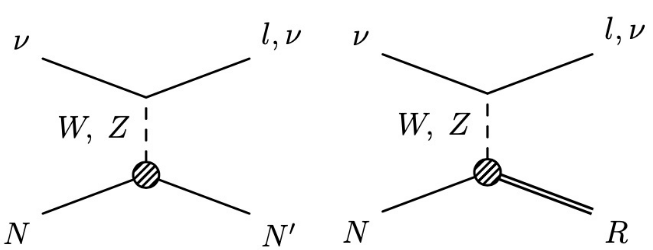
⁷Be $^{7}\mathrm{Be} + e^- \to {}^{7}\mathrm{Li} + \nu_e$

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

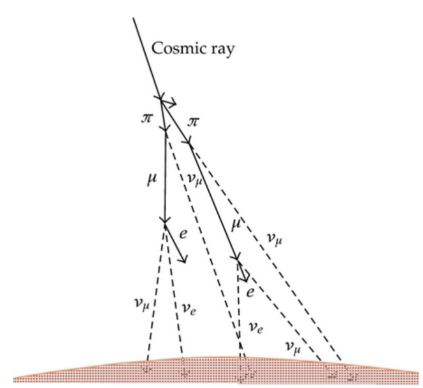
(hep)

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

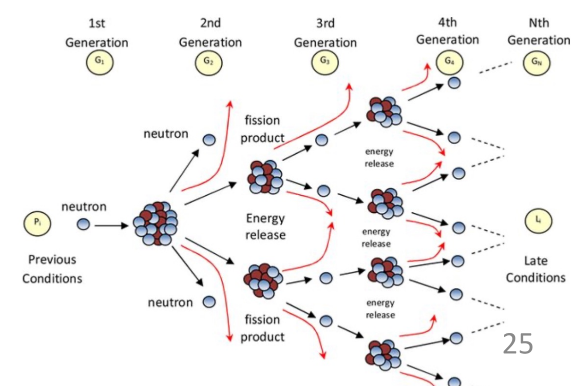
QE, Resonances: MINOS, NOvA, DUNE



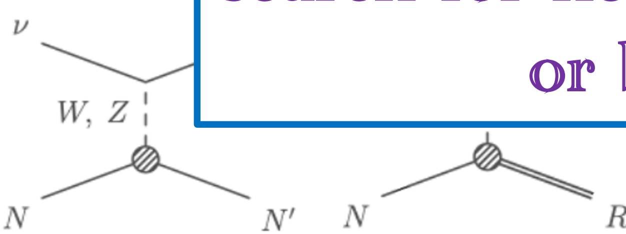
Atmospheric Neutrinos: IceCube

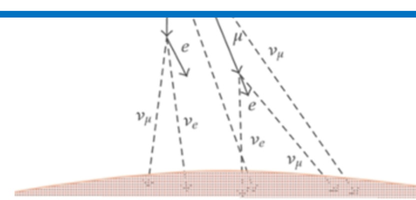


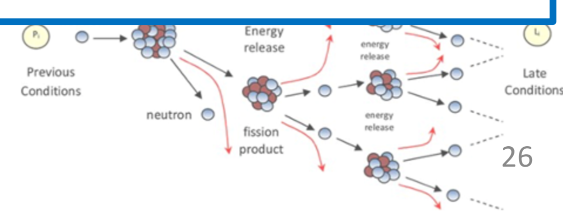
Beta decay and IBD: Reactor Experiments



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 experiments in the SMEFT framework.

- 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.

Back up Slides

WEFT Power Counting

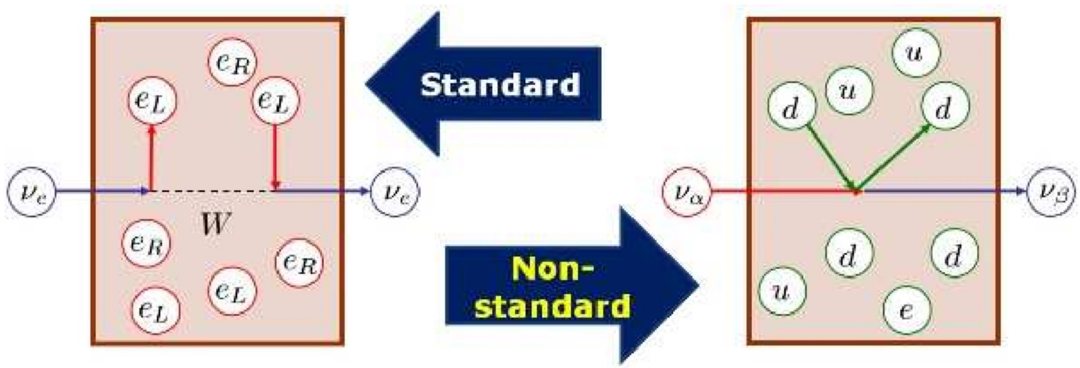
- Dim-6: $$\frac{\Delta R}{R_{SM}} = c\,\epsilon_X^2$$
- Dim-7: Cannot interfere with the SM amplitudes, suppressed!

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

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

QM-NSI Description

Neutrinos are not pure flavor states:



Standard NSI approach

NSI parameters

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

Rotation of flavor states at the source

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

Rotation of flavor states at the detector

Normalization

QM-NSI Description

Neutrinos are not pure flavor states:

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

Observable: rate of detected events

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

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

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

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

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- Can one "validate" QM-NSI approach from the QFT results?
- If yes, relation between NSI parameters and Lagrangian (EFT) parameters?
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(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	$\epsilon^s_{e\beta} = [\epsilon_L]^*_{e\beta} - [\epsilon_R]^*_{e\beta} - \frac{g_T}{g_A}\frac{m_e}{f_T(E_\nu)}[\epsilon_T]^*_{e\beta}$
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ν_μ produced in pion decay	$\epsilon^s_{\mu\beta} = [\epsilon_L]^*_{\mu\beta} - [\epsilon_R]^*_{\mu\beta} - \frac{m_\pi^2}{m_\mu(m_u+m_d)}[\epsilon_P]^*_{\mu\beta}$

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- Some of the p_{XL}/d_{XL} coefficients depend on the neutrino energy
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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

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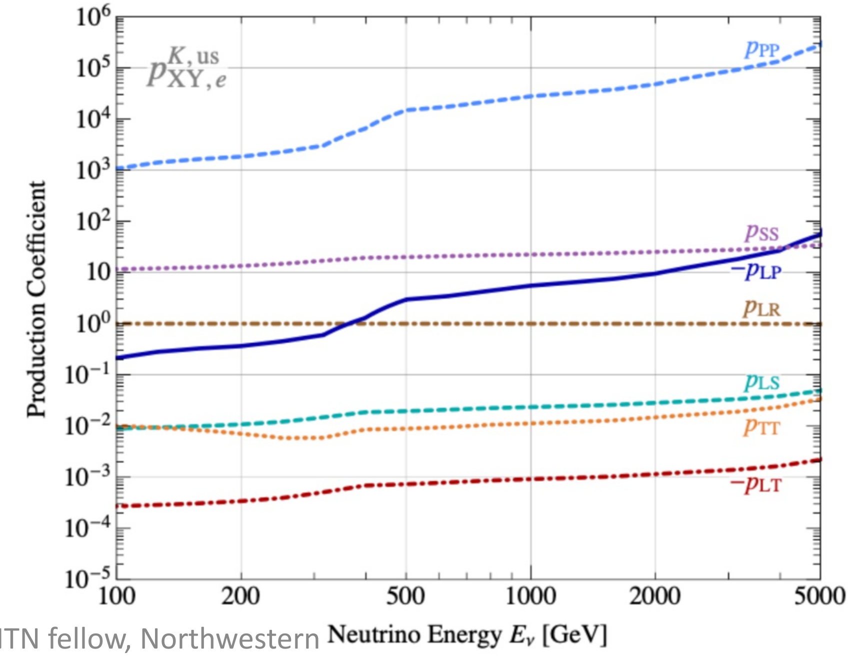
This is always satisfied for new physics correcting V-A interactions only as $p_{LL} = d_{LL} = 1$ by definition

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

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

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



RESULTS

Turning on one interaction at a time: Right handed

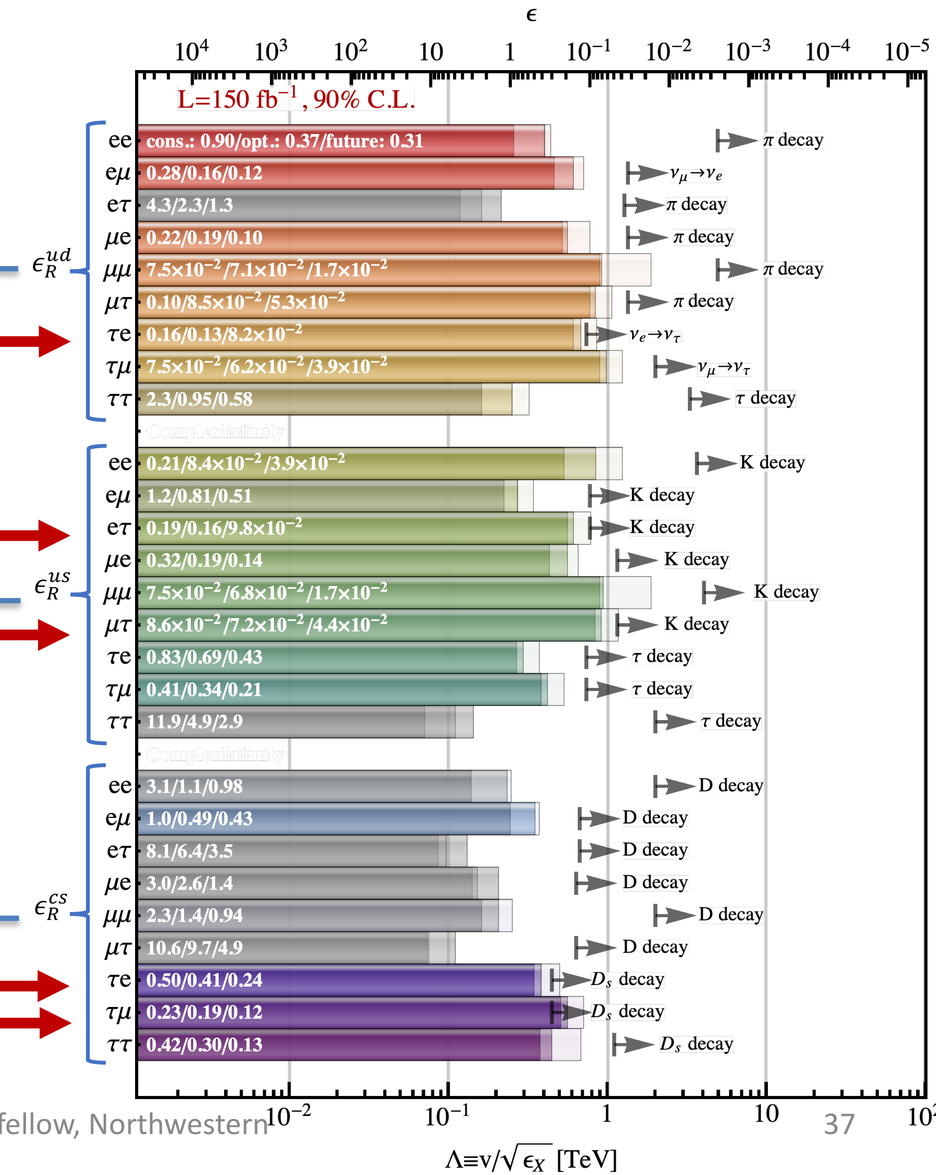
A. Falkowski, M. González-Alonso, J. Kopp, Y. Soreq, ZT
JHEP 10 (2021) 086

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

From pion decay and DIS

From kaon decay and DIS

From charm decay and DIS



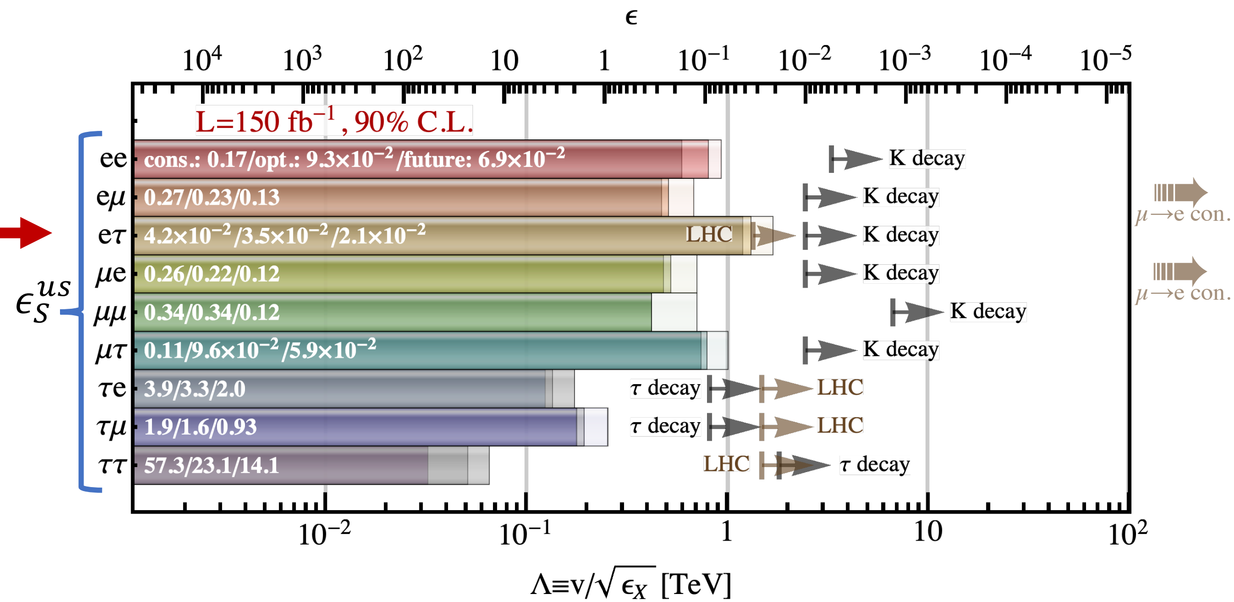
RESULTS

Turning on one interaction at a time: Scalar

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

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

From kaon decay



RESULTS

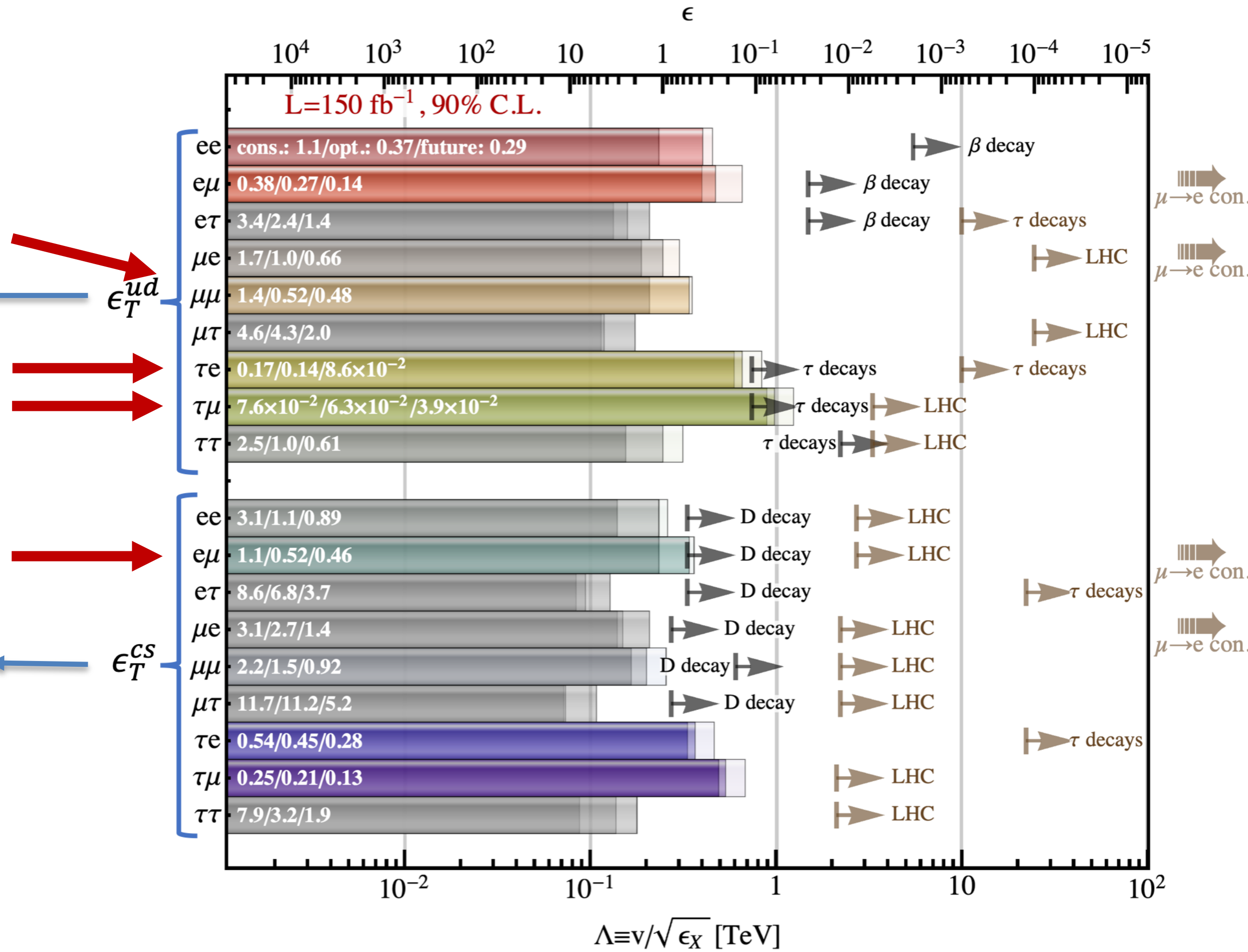
Turning on one interaction at a time: Tensor

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

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

From DIS

From charm decay and DIS



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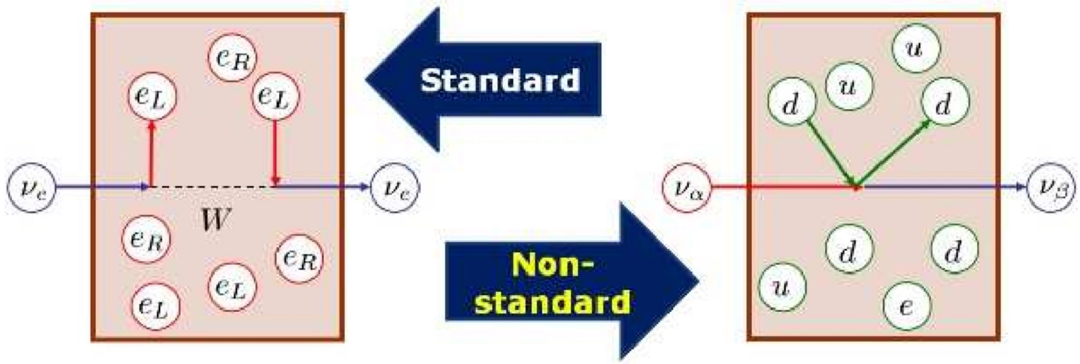

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A. Falkowski, M. González-Alonso, J. Kopp, Y. Soreq, **ZT**
JHEP 11 (2020) 048

Comparing QM and QFT

A. Falkowski, M. González-Alonso, J. Kopp, Y. Soreq, ZT
JHEP 11 (2020) 048

At the linear order we have:

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A. Falkowski, M. González-Alonso, J. Kopp, Y. Soreq, ZT
JHEP 11 (2020) 048

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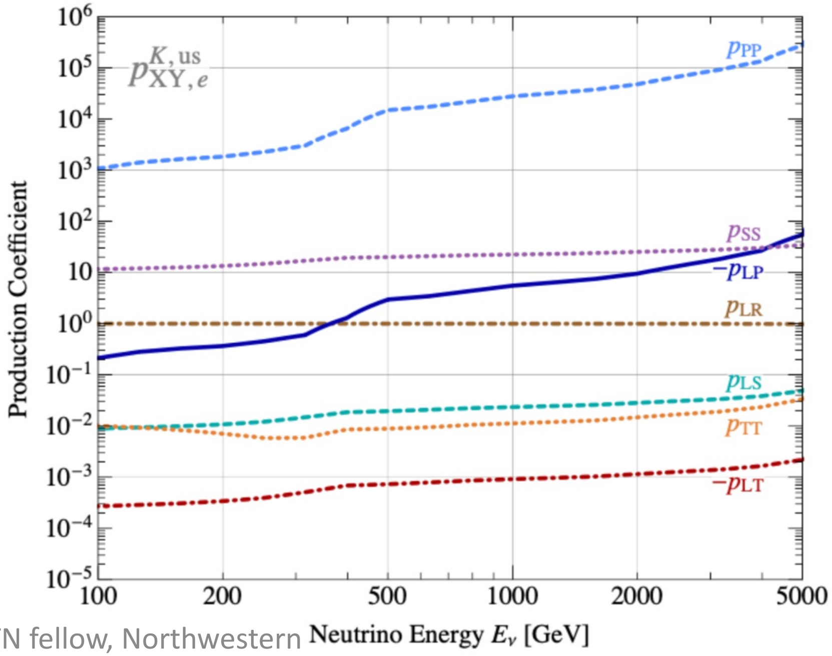

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Pion decay

Production

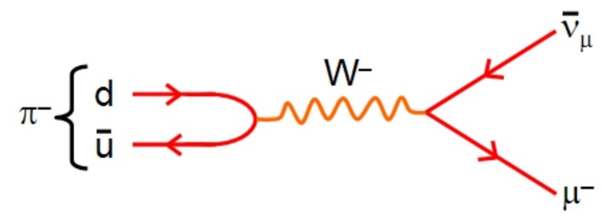
Falkowski, González-Alonso, *ZT*, JHEP (2020)

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



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

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

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

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

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

Pion decay

Production

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

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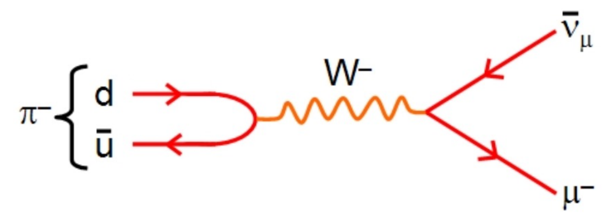

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~700!

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

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ε_X and $\varepsilon_X{}^2$ are equally important!

kaon decay

Production

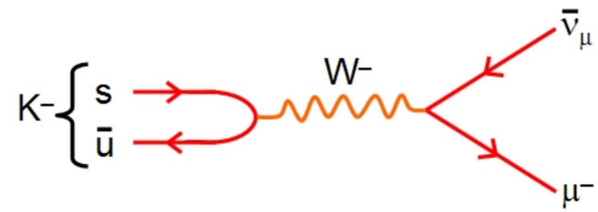
Falkowski, González-Alonso, Kopp, Soreq, *ZT*, JHEP (2021)

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

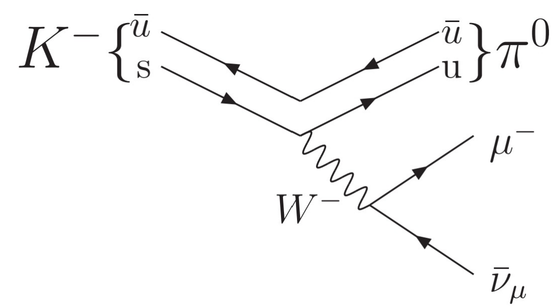
$$p^{S,jk}_{XY,\alpha} \equiv \frac{\int dE_S \frac{\phi_S(E_S)}{E_S} \sum_i \beta_i^S(E_S) \int d\Pi_{P'_i} A^{S_i,jk}_{X,\alpha} A^{S_i,jk*}_{Y,\alpha}}{\int dE_S \frac{\phi_S(E_S)}{E_S} \sum_{i'j'k'} \beta_{i'}^S(E_S) \int d\Pi_{P'_{i'}} |A^{S_i,j'k'}_{L,\alpha}|^2}$$

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

Depends on the experimental details



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



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

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

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

“FlaviaNet Working Group on Kaon Decays Collaboration”, EPJ (2010)

kaon decay

Production

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

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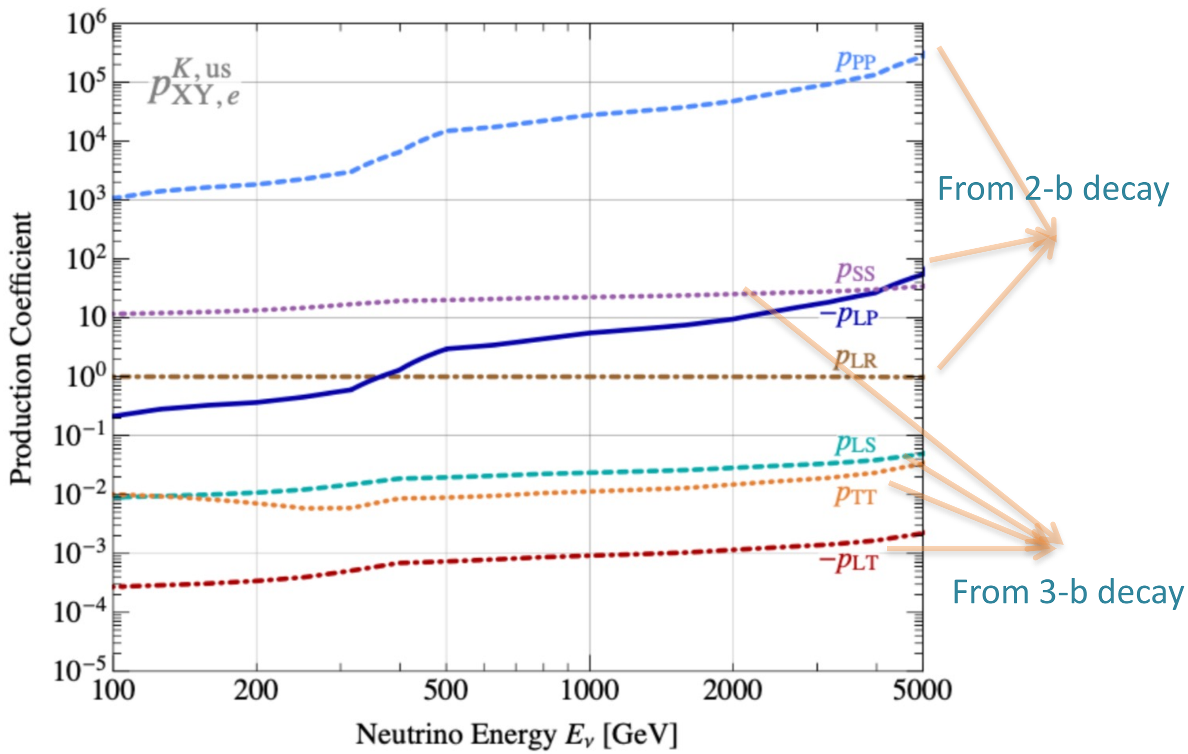

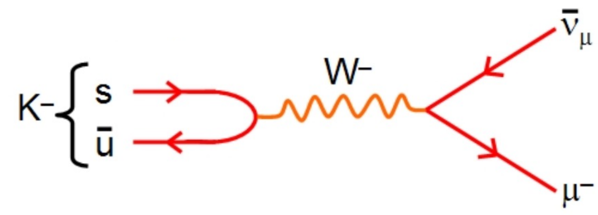

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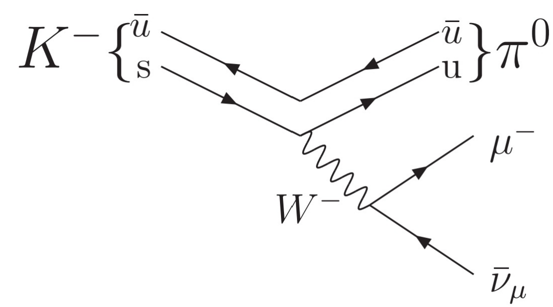


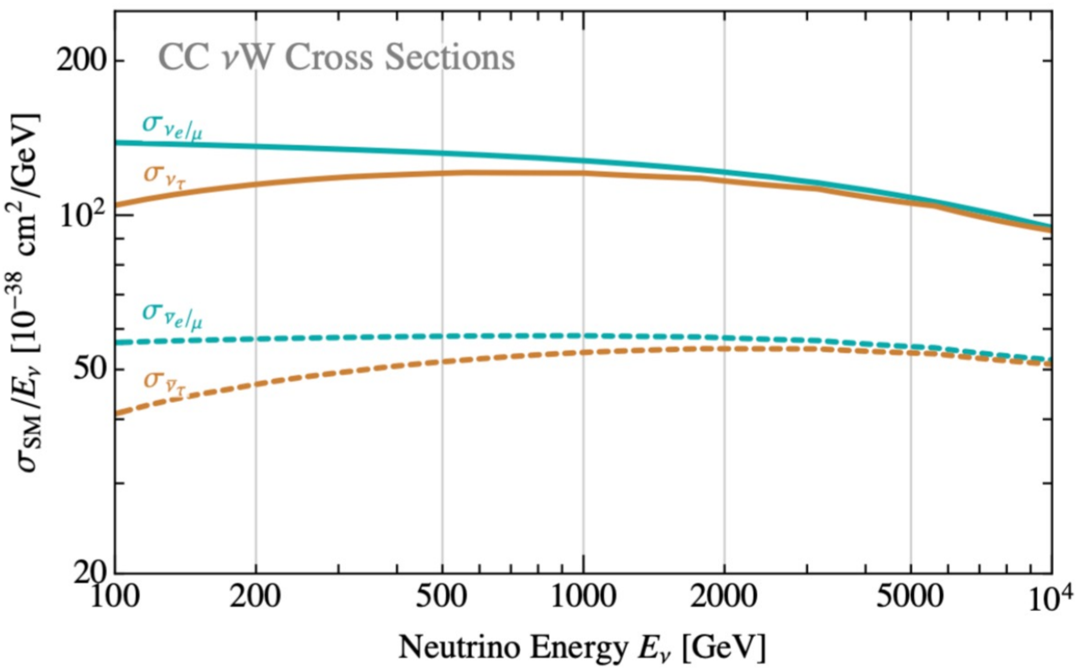
$$\phi^{Total} \sim \phi^{SM}(1+\varepsilon_X\, p_{XL} + \varepsilon_X{}^2\, p_{XX})$$

ε_X and $\varepsilon_X{}^2$ are equally important!

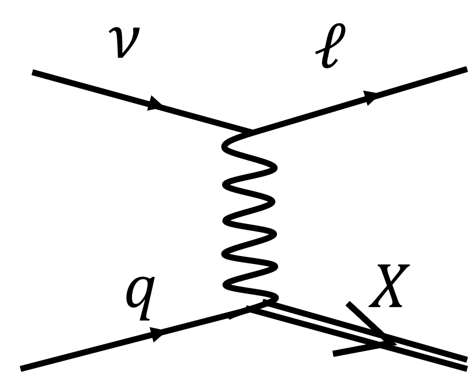
DIS

Detection

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



Deep Inelastic Scattering



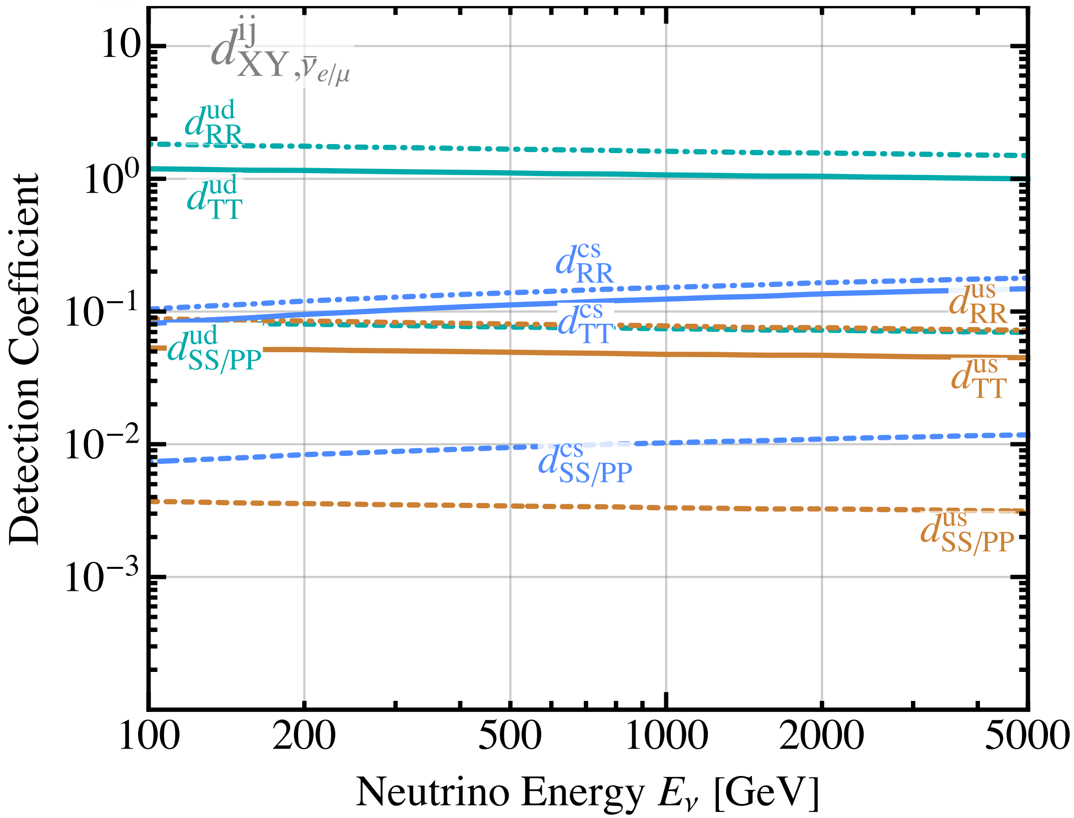
DIS detection, easy to include NP

(compared to QE and Resonances)

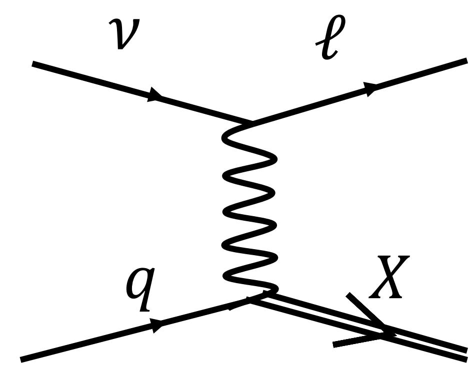
DIS

Detection

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



Deep Inelastic Scattering



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

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

EFT at FASERν

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

FASERν   Flavor Experiments   Colliders

Neutrino experiments:

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

Low energy:

- Independent of the underlying high-energy theory

High-Energy:

- SMEFT is the underlying theory
- Bounds are less robust

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

Bounds shown in bold face have been calculated in this work

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:

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

kaon decay

Production

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

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

$$f_-(q^2) = \frac{m_K^2 - m_\pi^2}{q^2}\Big(f_0(q^2) - f_+(q^2)\Big)\,, \tag{A.9}$$

from which it also follows that $f_0(0) = f_+(0)$. For the independent form factors $f_+(q^2)$, $f_0(q^2)$ we adopt the FlaviaNet dispersive parameterization [92]:

$$\begin{aligned} f_+(q^2) &= f_+(0) + \Lambda_+ \frac{q^2}{m_\pi^2} + \mathcal{O}(q^4)\,, \\ f_0(q^2) &= f_+(0) + \big(\log C - G(0)\big)\frac{m_\pi^2}{m_K^2 - m_\pi^2}\frac{q^2}{m_\pi^2} + \mathcal{O}(q^4)\,, \end{aligned} \tag{A.10}$$

where $G(0) = 0.0398(44)$ is calculated theoretically, and $\Lambda_+ = 0.02422(116)$ as well as $\log C = 0.1998(138)$ are obtained on the lattice [93]. The $N_f = 2+1+1$ value of $f_+(0)$ according to FLAG'19 is $f_+(0) = 0.9706(27)$ [53]. For the tensor form factor we use the parameterization

$$B_T(q^2) \approx B_T(0)\big(1 - s_T^{K\pi} q^2\big), \tag{A.11}$$

with $B_T(0)/f_+(0) = 0.68(3)$ and $s_T^{K\pi} = 1.10(14)\,\mathrm{GeV}^{-2}$ [94].

RESULTS

Turning on one interaction at a time: Right handed

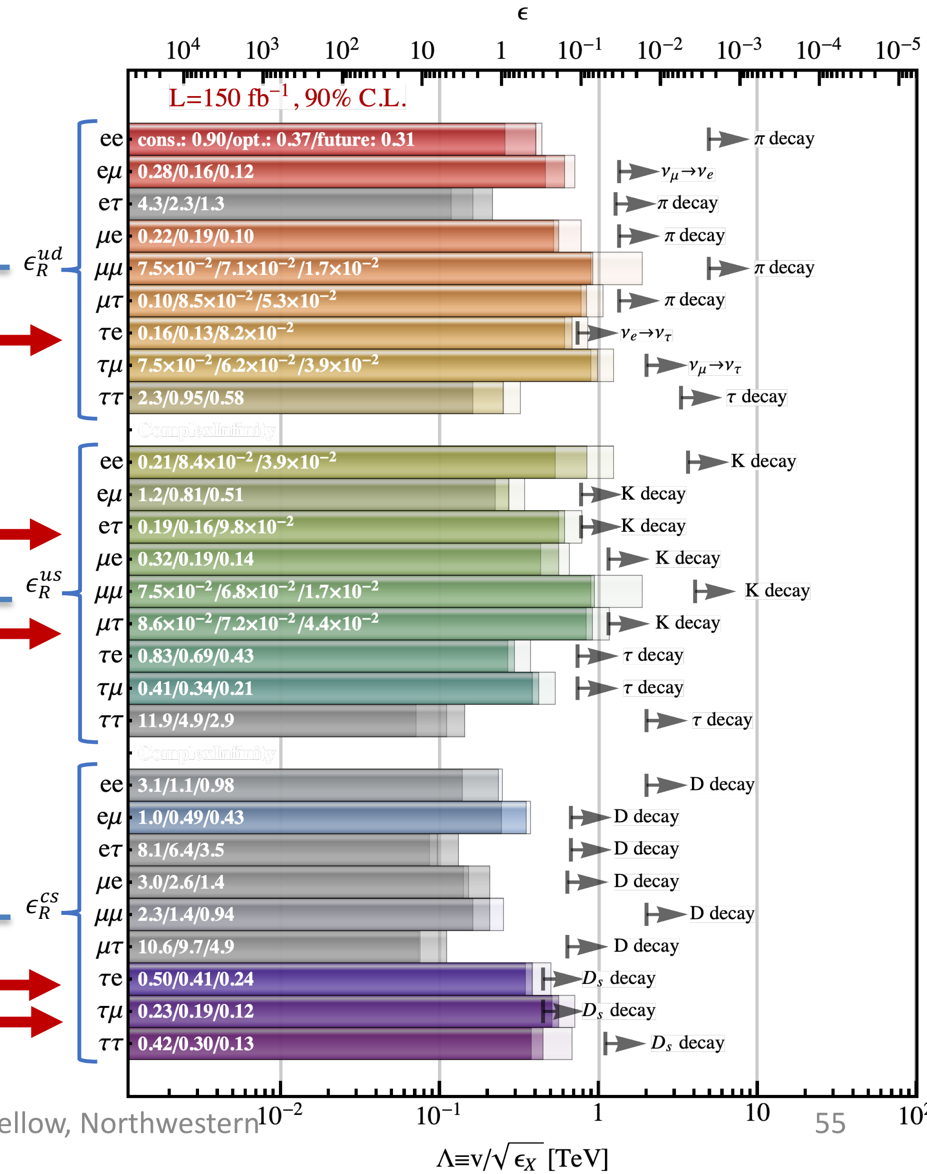
A. Falkowski, M. González-Alonso, J. Kopp, Y. Soreq, **ZT**
JHEP 10 (2021) 086

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

From pion decay and DIS

From kaon decay and DIS

From charm decay and DIS



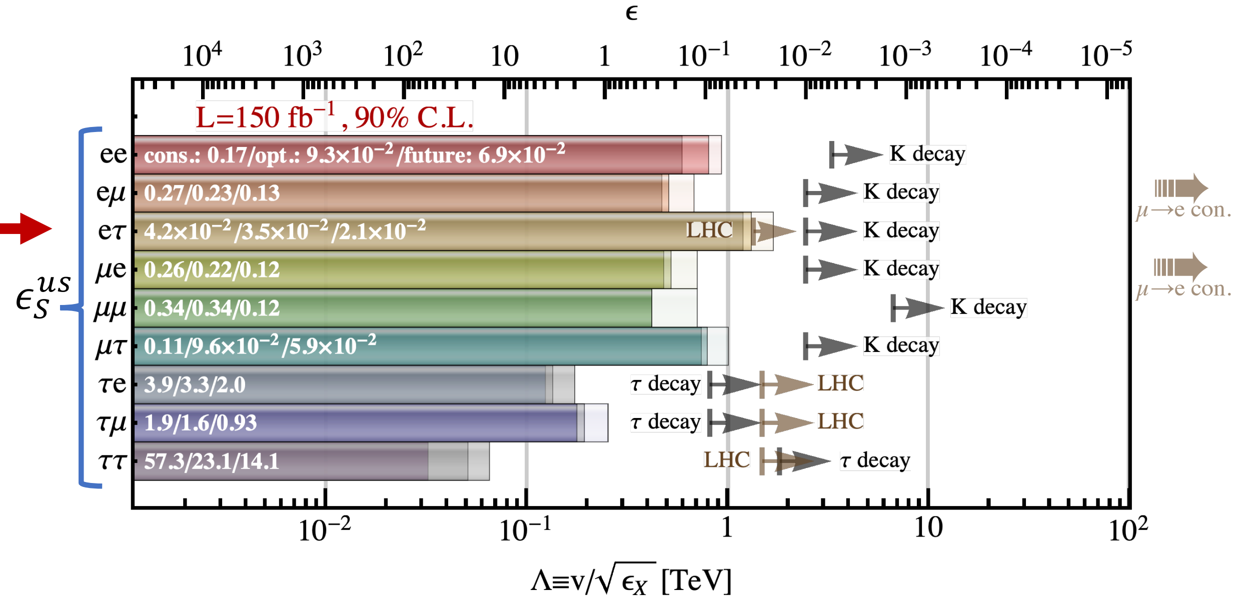
RESULTS

Turning on one interaction at a time: Scalar

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

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

From kaon decay



RESULTS

Turning on one interaction at a time: Tensor

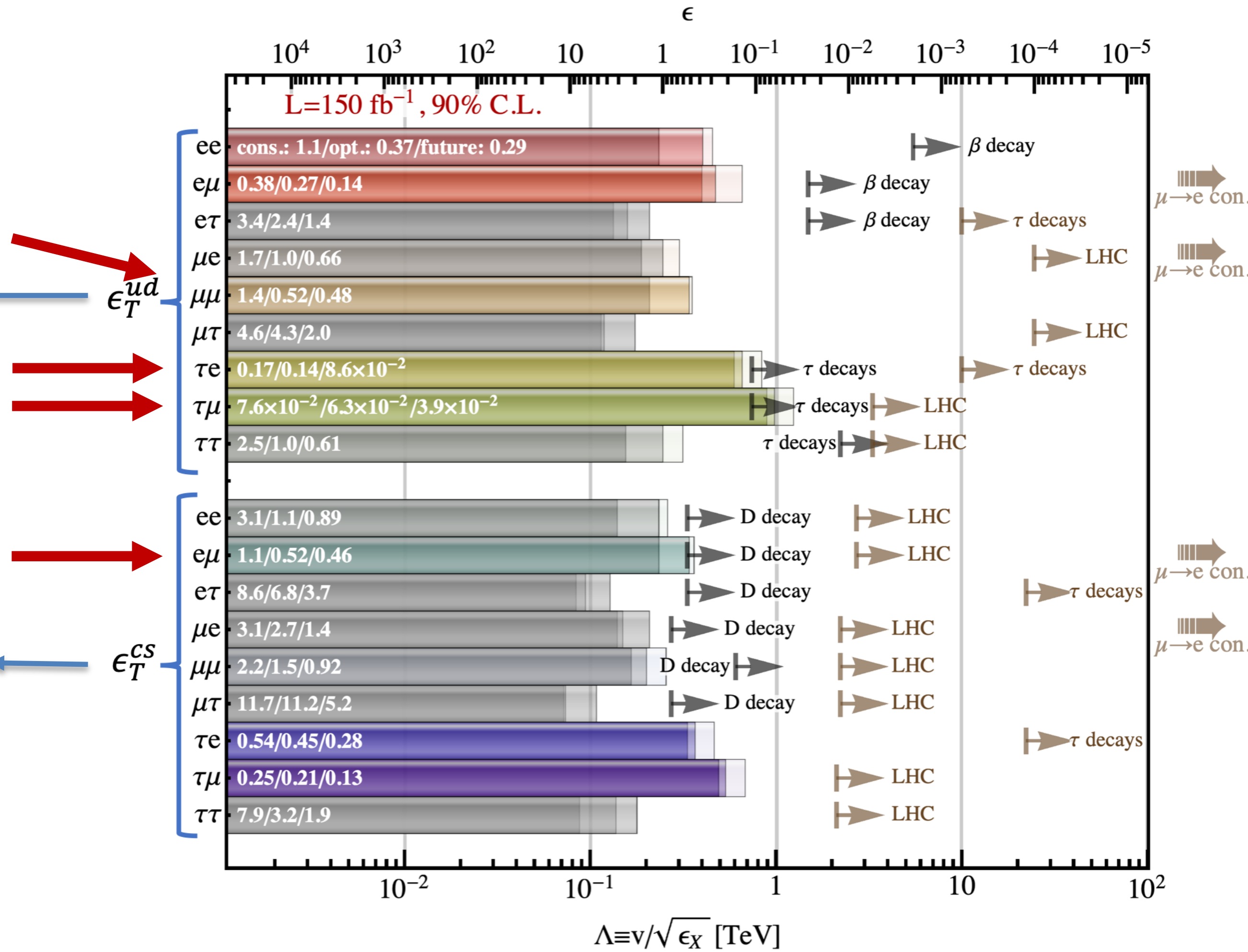
A. Falkowski, M. González-Alonso, J. Kopp, Y. Soreq, ZT

JHEP 10 (2021) 086

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

From DIS

From charm decay and DIS



EFT at FASERν

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

FASERν   Flavor Experiments   Colliders

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

Low energy:
- Independent of the underlying high-energy theory

High-Energy:
- SMEFT is the underlying theory
- Bounds are less robust

Bounds shown in bold face have been calculated in this work

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