EFT with Neutrinos

Neutrinos as a Portal to New Physics and Astrophysics

9 March 2022

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Neutrino Theory Network (NTN) fellow

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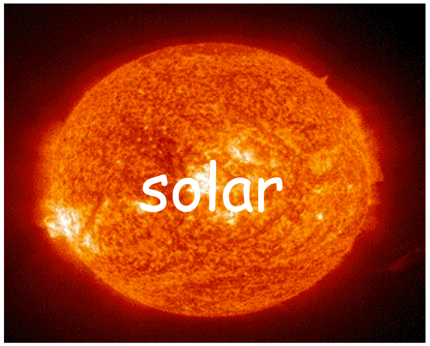
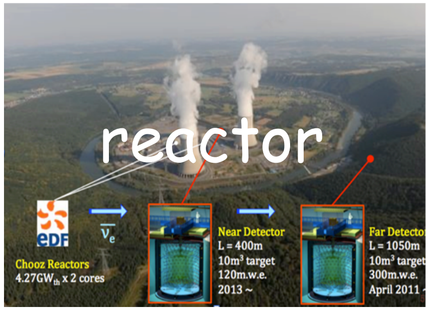
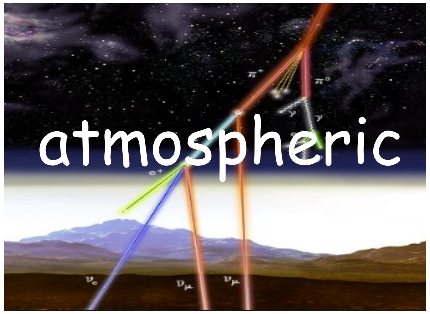
Status of Neutrino Physics in 2022



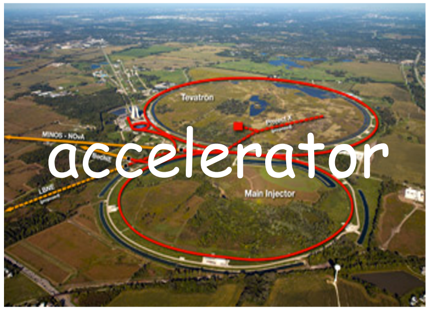
Super-Kamiokande, Borexino, SNO



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:

$$\Delta m^2_{21}\ @\ 3\%$$

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

Future: DUNE, T2HK , JUNO

- Increase the precision
- CP-phase
- Mass hierarchy

Also:
Mass scale? Dirac or Majorana?
Sterile?

Questions:

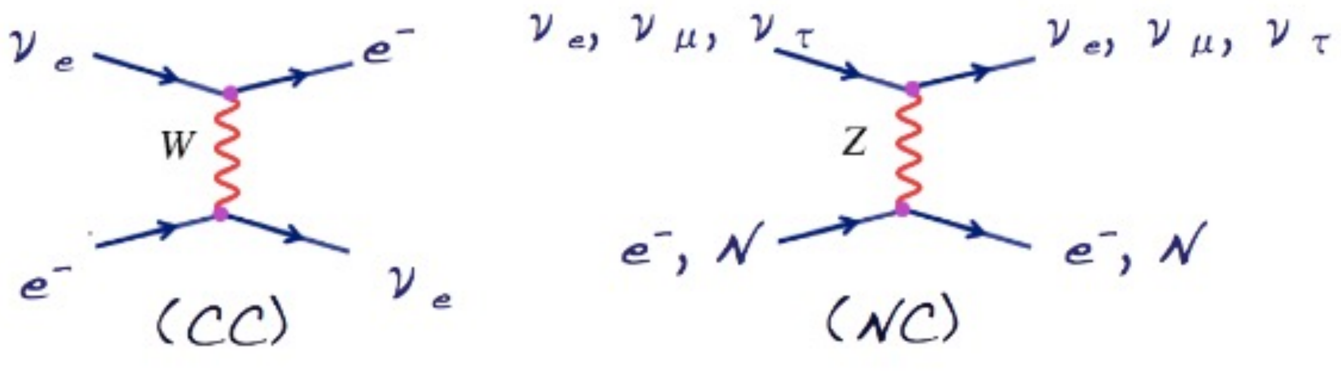
- How can we systematically use different neutrino experiments for BSM searches?

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

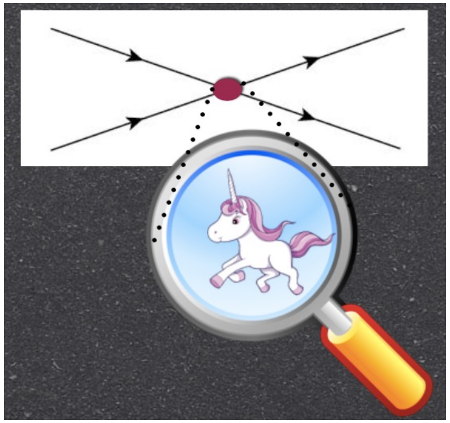
- Can neutrino experiments probe reasonable new physics beyond the reach of high energy colliders?

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

- Coherent CC and NC forward scattering of neutrinos

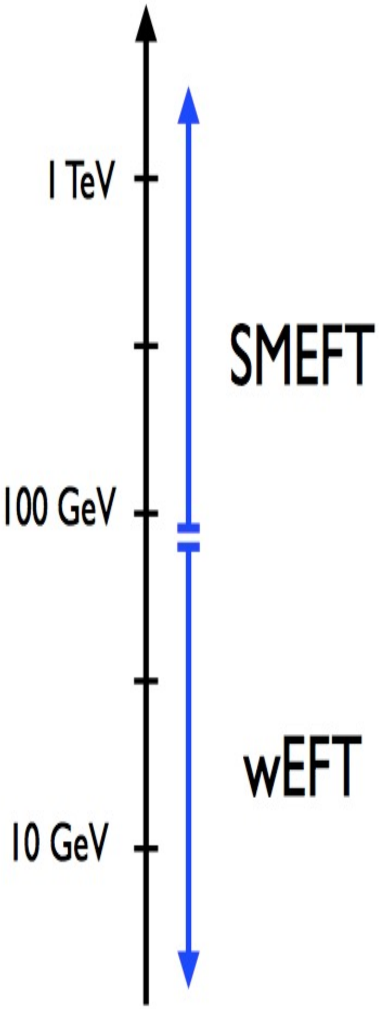


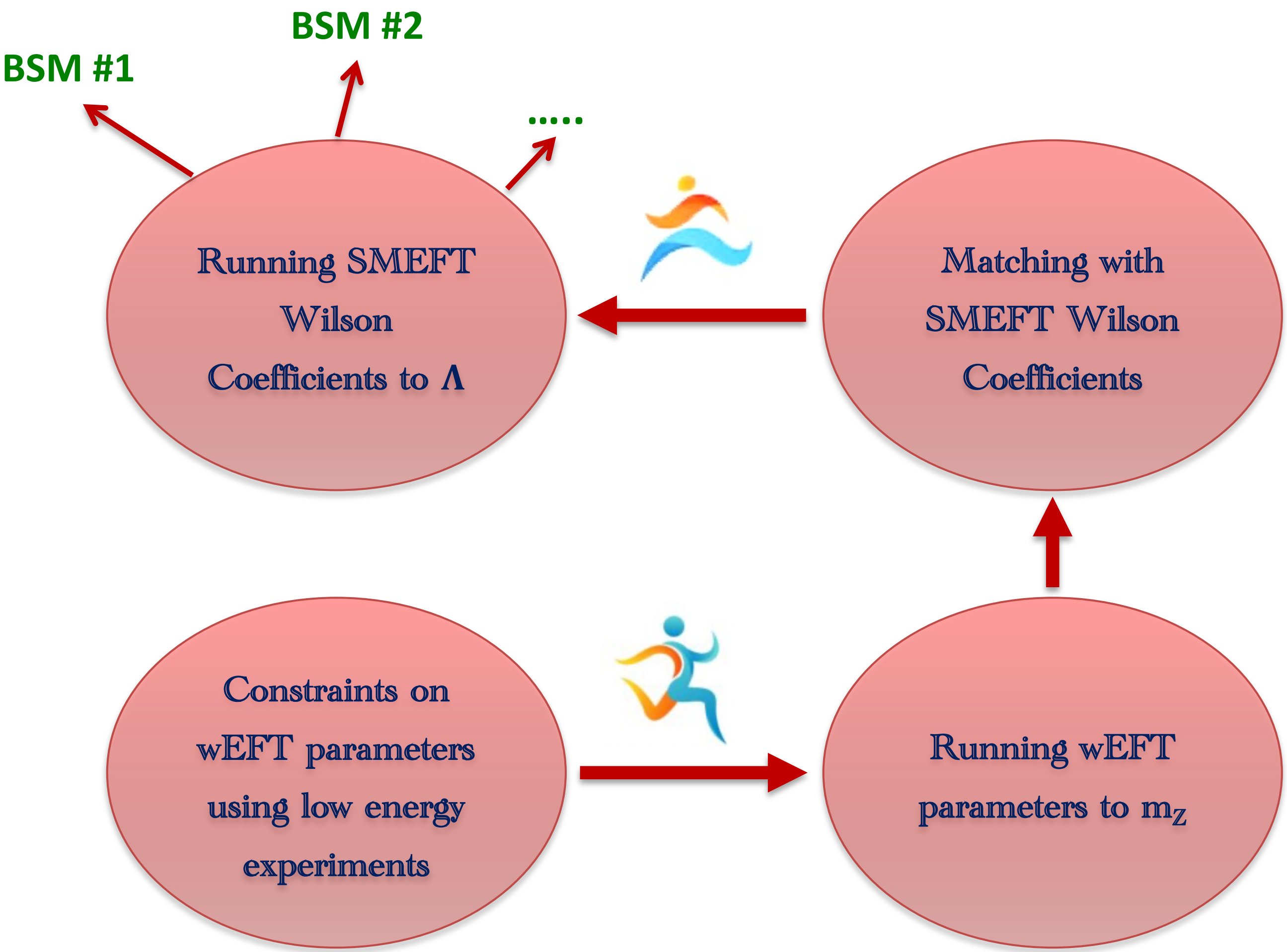
- New 4-fermion interactions



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

Workflow





Running SMEFT Wilson Coefficients to Λ

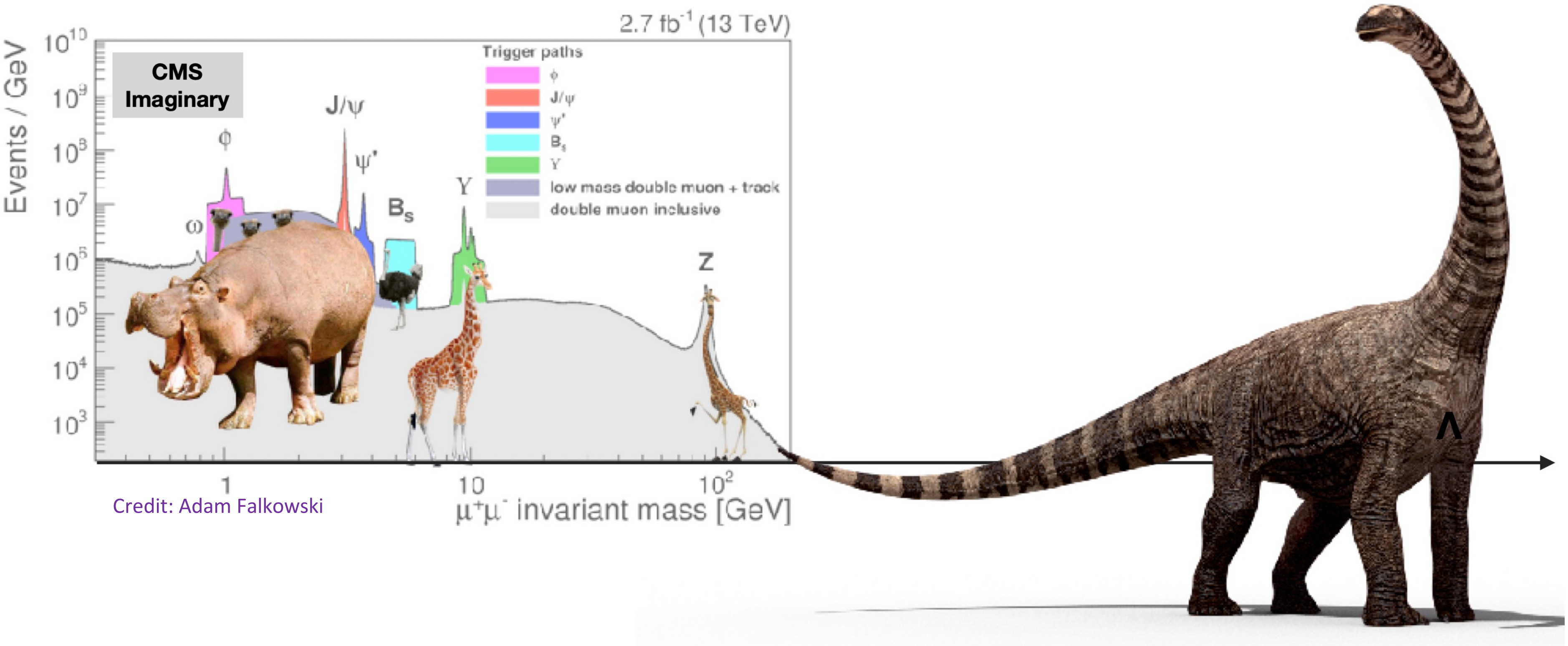
Matching with SMEFT Wilson Coefficients

Constraints on wEFT parameters using low energy experiments

Running wEFT parameters to m_Z

By measuring the wEFT parameters at $E \ll m_Z$ we can get constraints on higher dimensional SMEFT interactions

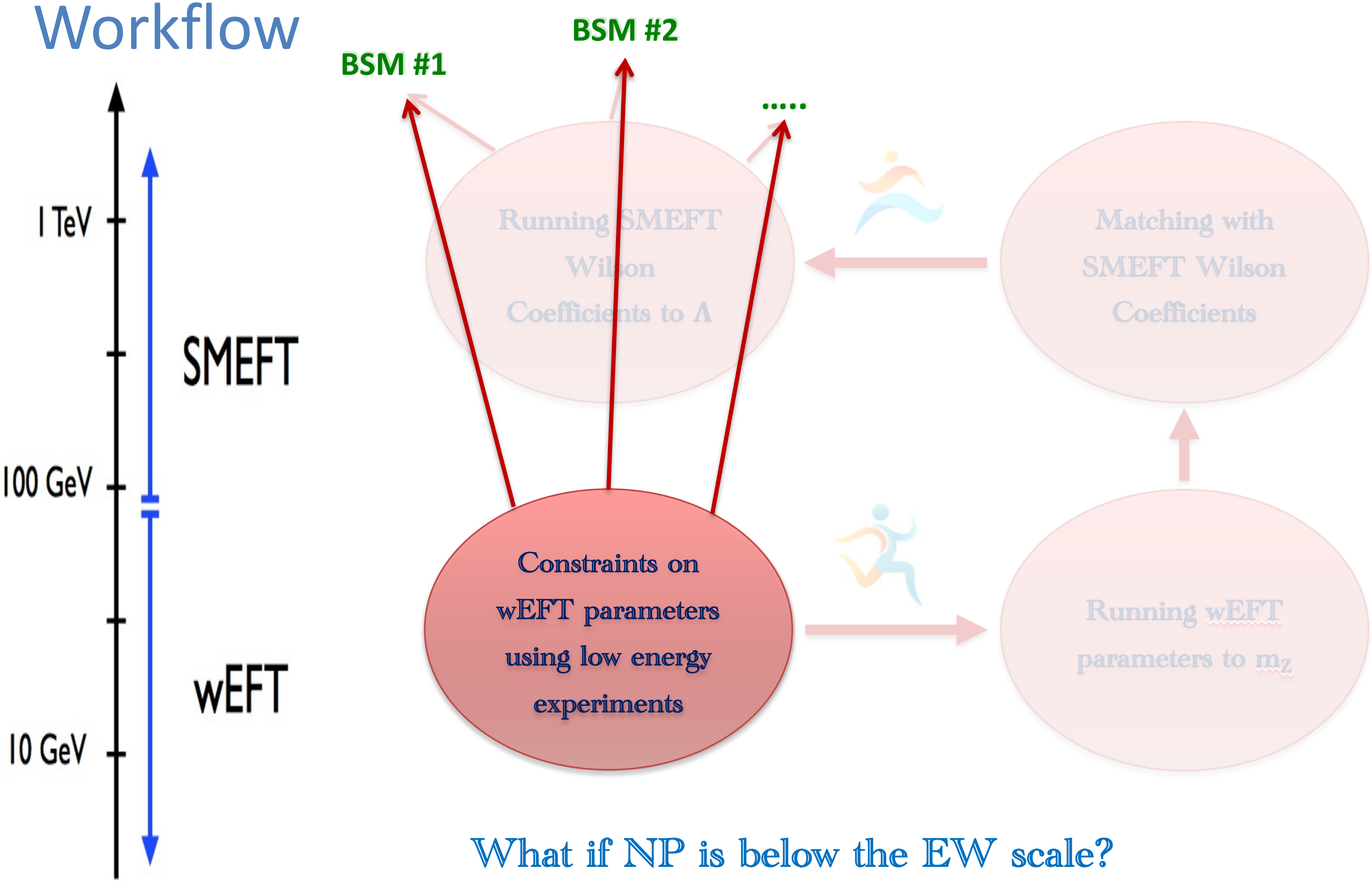
Fantastic Beasts and Where To Find Them



Credit: Adam Falkowski

- It is likely the new degrees of freedom beyond the SM may not be directly available at LHC or even future colliders.
- However, even if it’s not possible to see the head, perhaps we can see the tail?

Workflow



BSM #1

BSM #2

.....

1 TeV

100 GeV

10 GeV

SMEFT

wEFT

Running SMEFT Wilson Coefficients to Λ

Matching with SMEFT Wilson Coefficients

Constraints on wEFT parameters using low energy experiments

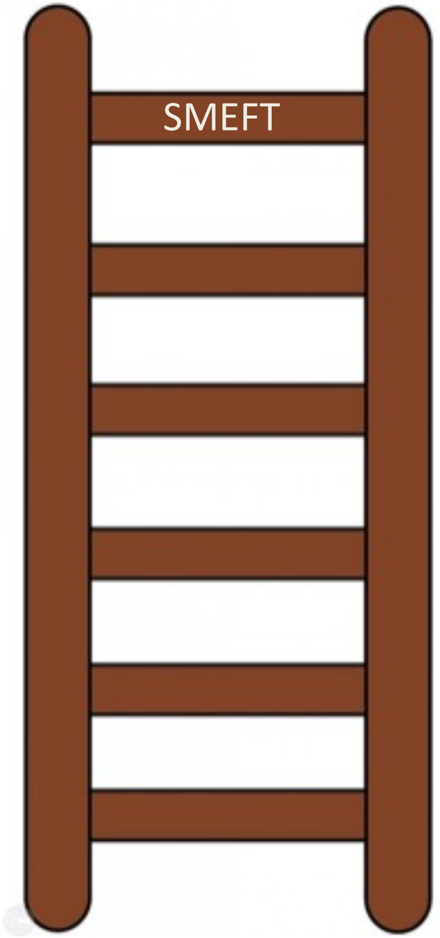
Running wEFT parameters to m_Z

What if NP is below the EW scale?

wEFT is a consistent EFT in its own!

EFT ladder

SMEFT: minimal EFT above the weak scale

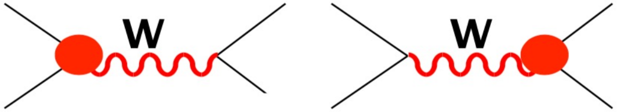


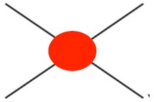
$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \mathscr{L}_{D=5} + \boxed{\mathscr{L}_{D=6}}$$

Known SM Lagrangian

Gives neutrino Masses

+





$$O_{lq}^{(3)} = (\bar{l}\gamma^{\mu}\sigma^{a}l)(\bar{q}\gamma_{\mu}\sigma^{a}q)$$

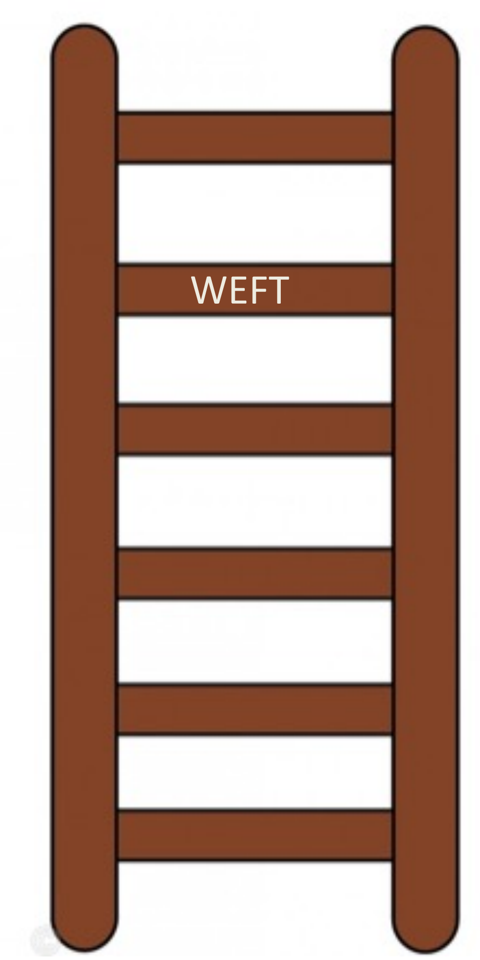
$$O_{qde} = (\bar{l}e)(\bar{d}q) + \text{h.c.}$$

$$O_{lq} = (\bar{l}_{a}e)\epsilon^{ab}(\bar{q}_{b}u) + \text{h.c.}$$

$$O_{lq}^{t} = (\bar{l}_{a}\sigma^{\mu\nu}e)\epsilon^{ab}(\bar{q}_{b}\sigma_{\mu\nu}u) + \text{h.c.}$$

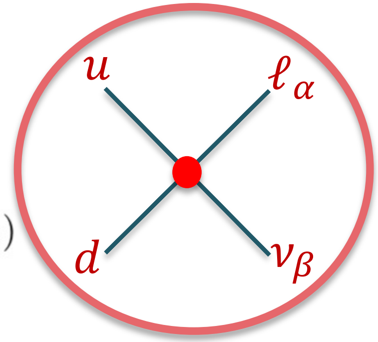
EFT ladder

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



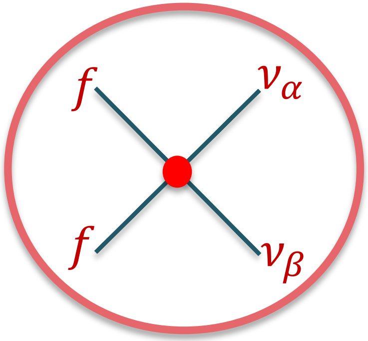
- CC: New left/right handed, (pseudo)scalar and tensor interactions

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



- NC: New left and right handed interactions

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



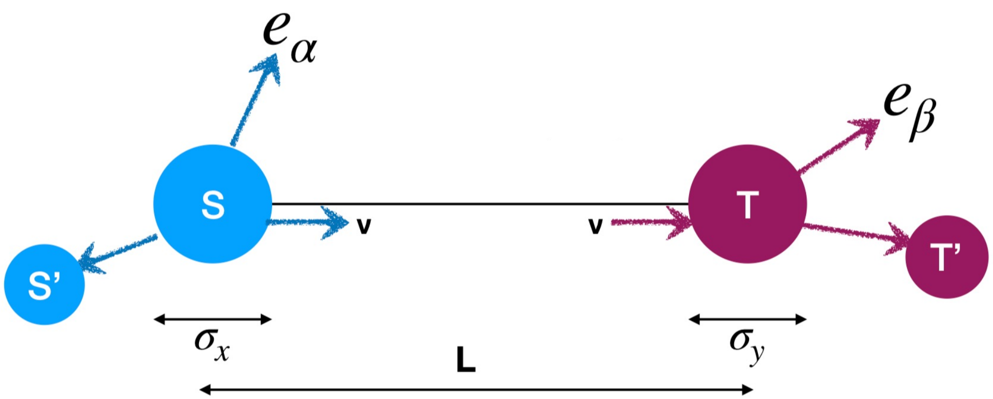
At the scale m_Z WEFT parameters ϵ_X map to dim-6 operators in SMEFT

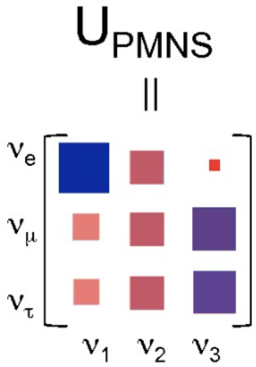
$$
\begin{aligned}
[\epsilon_L]_{\alpha\beta} &\approx \frac{v^2}{\Lambda^2 V_{ud}} \left(V_{ud}[c^{(3)}_{Hl}]_{\alpha\beta} + V_{jd}[c^{(3)}_{Hq}]_{1j}\delta_{\alpha\beta} - V_{jd}[c^{(3)}_{lq}]_{\alpha\beta 1j} \right) \\
[\epsilon_R]_{\alpha\beta} &\approx \frac{v^2}{2\Lambda^2 V_{ud}} [c_{Hud}]_{11}\delta_{\alpha\beta}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

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

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

EFT at neutrino experiments





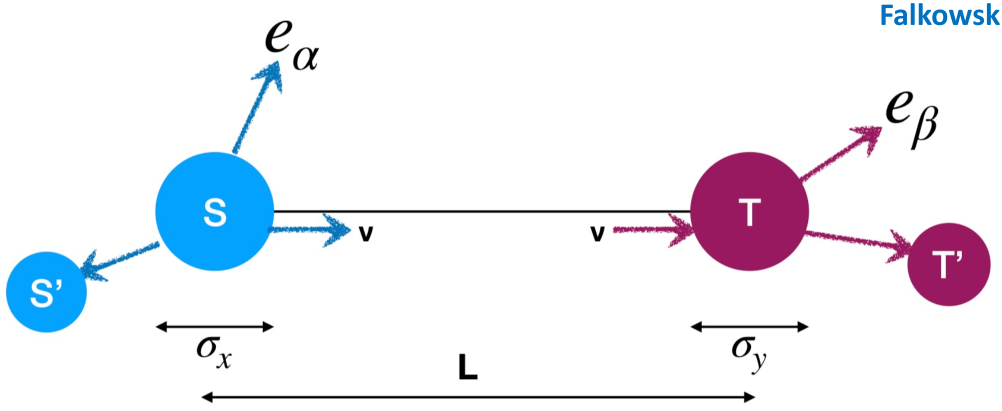
Observable: rate of detected events

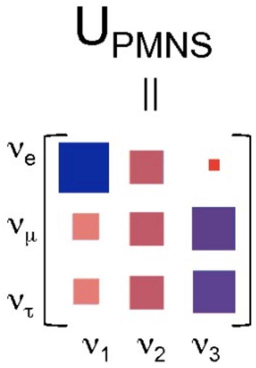
~(flux)×(det. cross section)×(oscillation)

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

EFT at neutrino experiments

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





Observable: rate of detected events

$$\sim\underbrace{(\text{flux})\times(\text{det. cross section})}_{\boxed{\text{CC EFT}}}\times\underbrace{(\text{oscillation})}_{\text{NC EFT}}$$

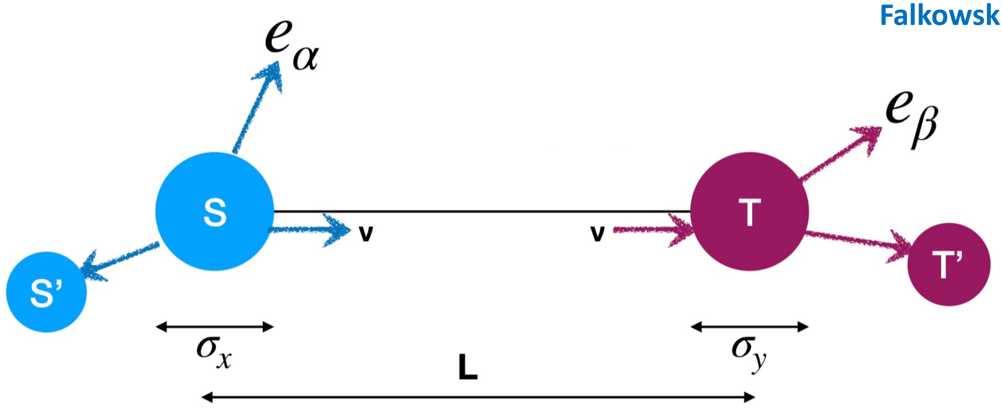
$$\begin{aligned}-\frac{2V_{ud}}{v^2}\Bigg[&\big[1+\epsilon_L\big]_{\alpha\beta}\,\bar e_\alpha\gamma_\mu P_L\nu_\beta\cdot\bar u_L\gamma^\mu d_L\\ &+\big[\epsilon_R\big]_{\alpha\beta}\,\bar e_\alpha\gamma_\mu P_L\nu_\beta\cdot\bar u_R\gamma^\mu d_R\\ &+\frac{1}{2}\bar e_\alpha P_L\nu_\beta\cdot\bar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

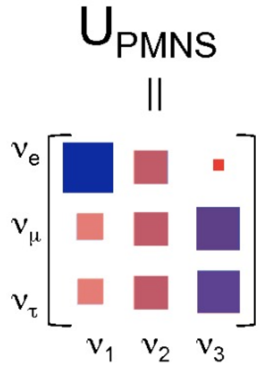
$$\boxed{\begin{aligned}\mathcal{M}^P_{\alpha k}&=U^*_{\alpha k}A^P_L+\sum_X[\epsilon_X U]^*_{\alpha k}A^P_X\\ \mathcal{M}^D_{\beta k}&=U_{\beta k}A^D_L+\sum_X[\epsilon_X U]_{\beta k}A^D_X\end{aligned}}$$

depend on the kinematic and spin variables

EFT at neutrino experiments

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





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

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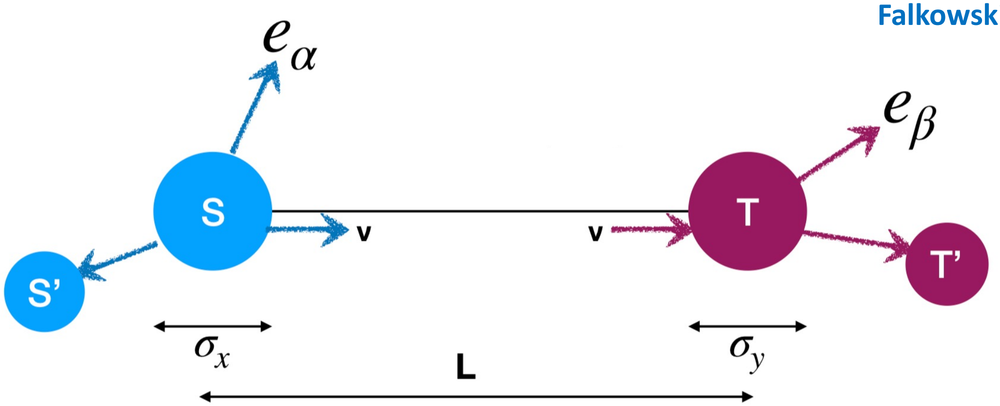
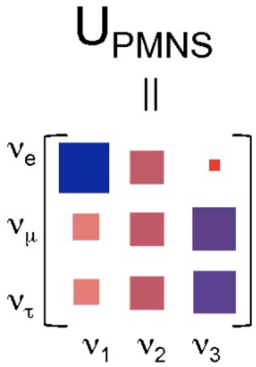
EFT at neutrino experiments

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





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$$\times\left[U_{\beta k}U^*_{\beta l} + d_{XL}(\epsilon_X U)_{\beta k}U^*_{\beta l} + d^*_{XL}U_{\beta k}(\epsilon_X U)^*_{\beta l} + d_{XX}(\epsilon_X U)_{\beta k}(\epsilon_X U)^*_{\beta l}\right]$$

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Pion decay

EFT at Production

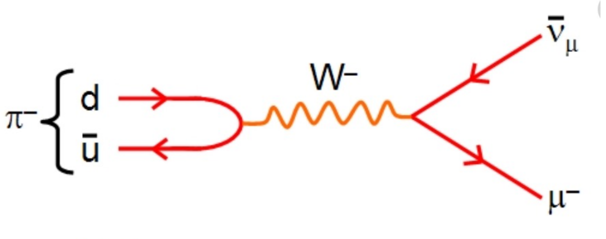
Falkowski, González-Alonso, *<u>ZT</u>*, JHEP (2020)

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!

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

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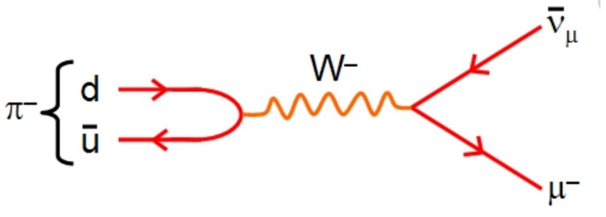
~700!



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

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

kaon decay

EFT at Production

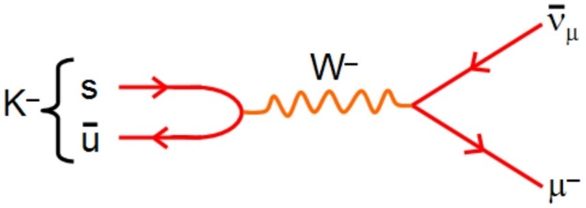
Falkowski, González-Alonso, Kopp, Soreq, *ZT*, JHEP (2021)

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

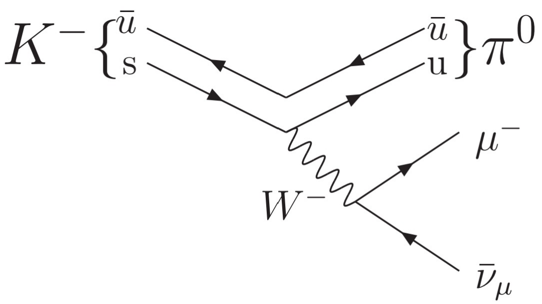
$$p^{S,jk}_{XY,\alpha} \equiv \frac{\int dE_S \frac{\phi_S(E_S)}{E_S} \sum_i \beta_i^S(E_S) \int d\Pi_{P_i'} A^{S_i,jk}_{X,\alpha} A^{S_i,jk*}_{Y,\alpha}}{\int dE_S \frac{\phi_S(E_S)}{E_S} \sum_{i'j'k'} \beta_{i'}^S(E_S) \int d\Pi_{P_{i'}'} |A^{S_i,j'k'}_{L,\alpha}|^2}$$

Energy distribution of K±, K_L or K_S

Depends on the experimental details



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



kaon
decay

EFT at Production

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

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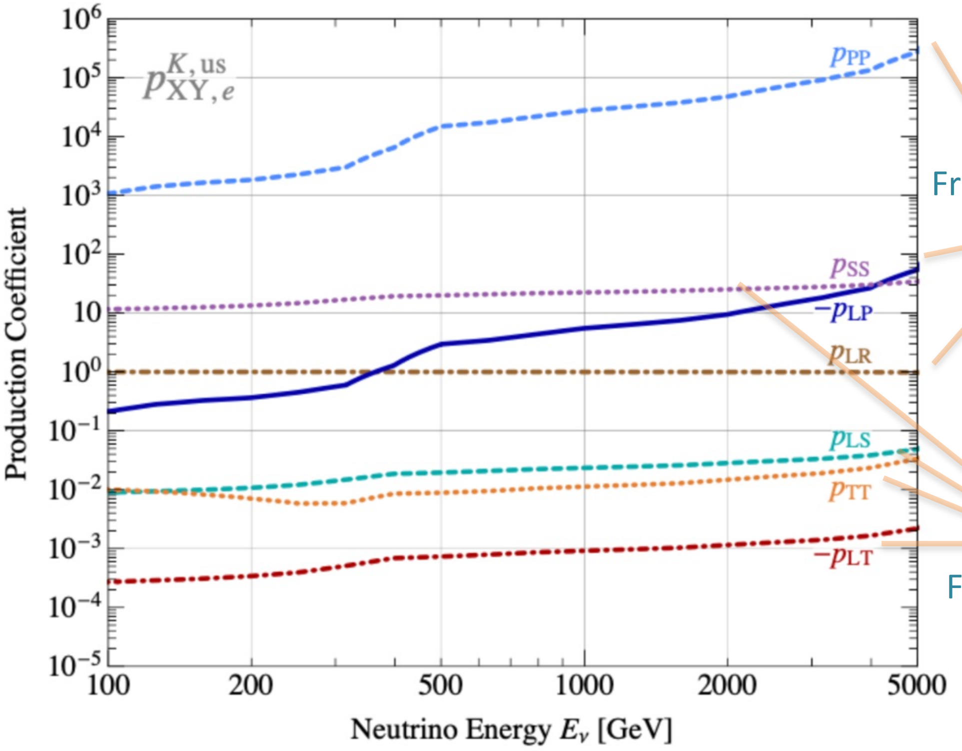
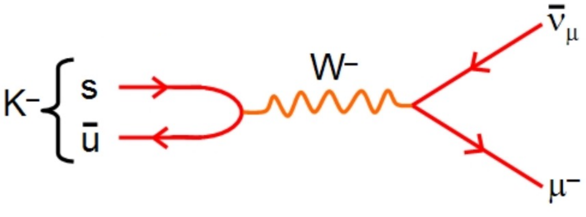
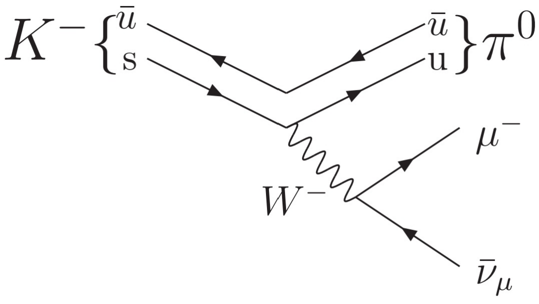


From 2-b decay

From 3-b decay



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



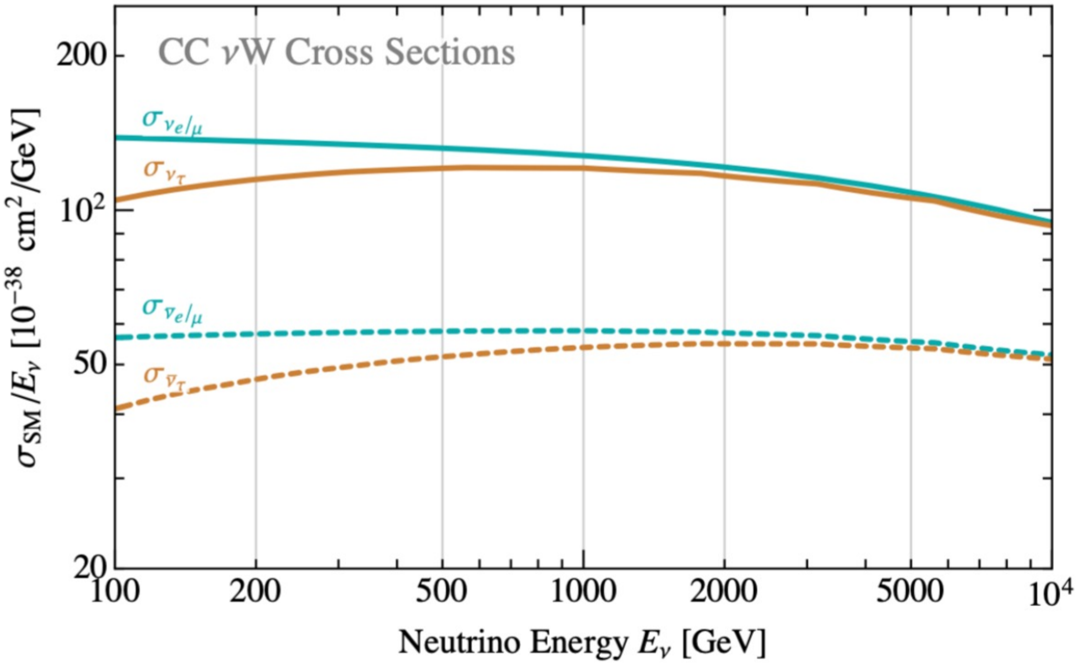
$$\boxed{\phi^{Total} \sim \phi^{SM}(1+\varepsilon_X\, p_{XL} + \varepsilon_X{}^2\, p_{XX})}$$

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

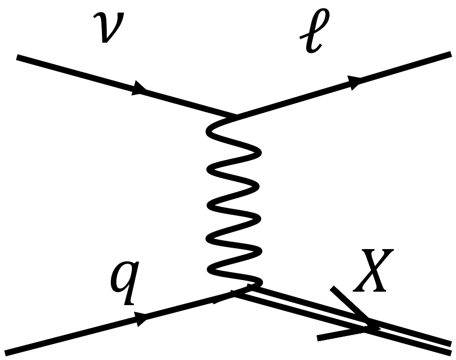
DIS

EFT at Detection

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



Deep Inelastic Scattering



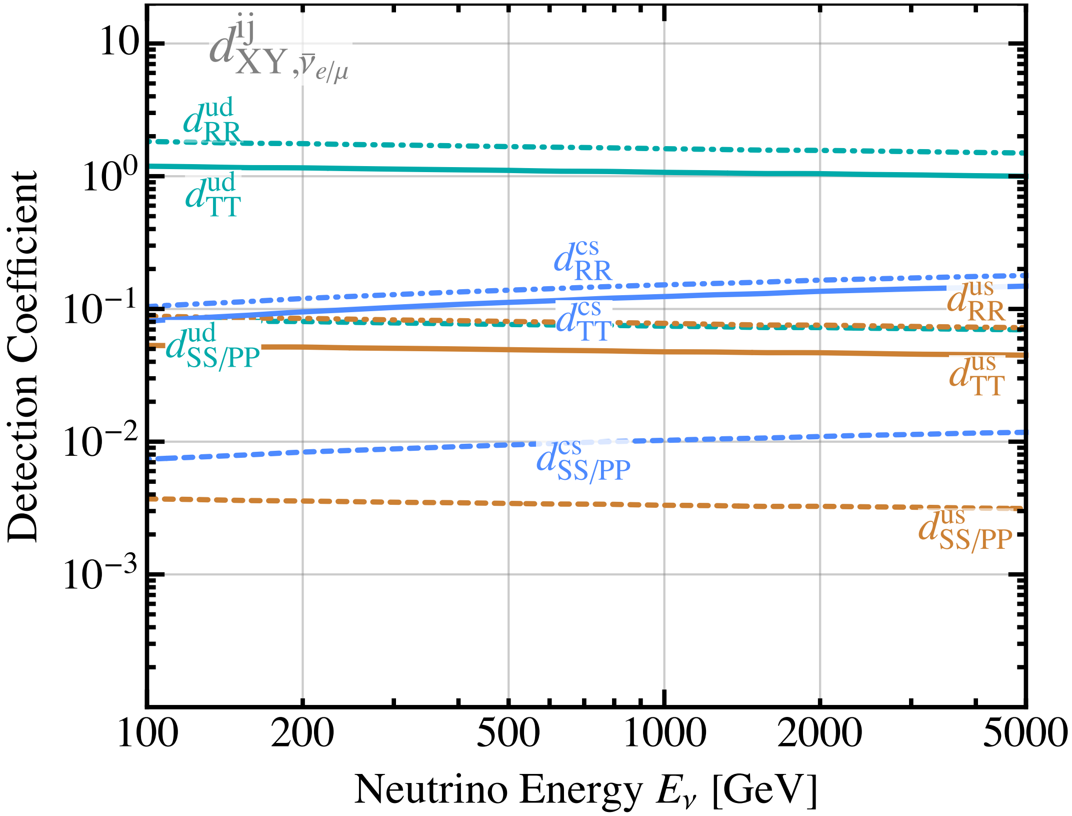
DIS detection, easy to include NP

(compared to QE and Resonances)

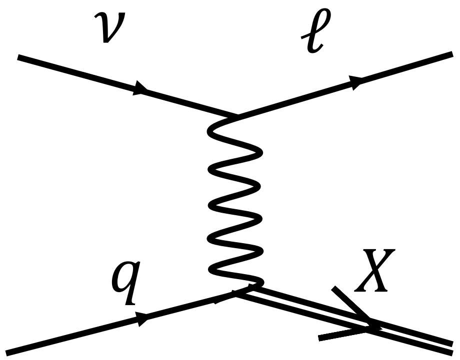
DIS

EFT at Detection

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



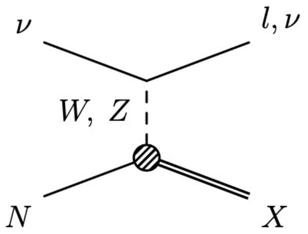
Deep Inelastic Scattering



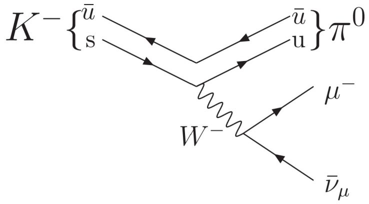
$$\boxed{\sigma^{Total} \sim \sigma^{SM}(1+\varepsilon_X\, d_{XL} + \varepsilon_X{}^2\, d_{XX})}$$

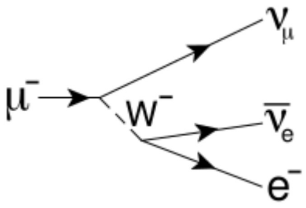
$\varepsilon_X{}^2$ is more important than ε_X!

DIS: FASERν



Kaon/Muon
decay:
ISODAR, KDAR





Solar
neutrinos:
Borexino

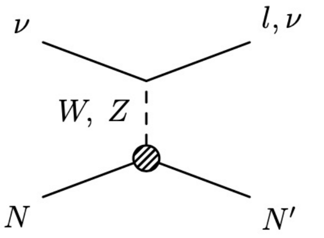
^{7}Be $\;{}^7\mathrm{Be} + e^- \to {}^7\mathrm{Li} + \nu_e$

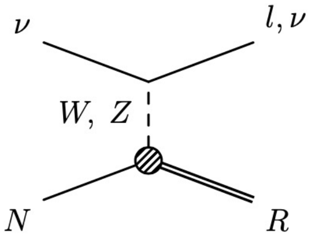
${}^3\mathrm{He} + p \to {}^4\mathrm{He} + e^+ + \nu_e$ **hep**

(hep)

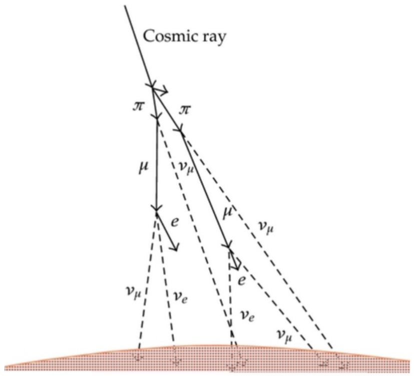
$p + e^- + p \to {}^2\mathrm{H} + \nu_e$ ***pep***

QE,
Resonances:
MINOS, NOvA,
DUNE

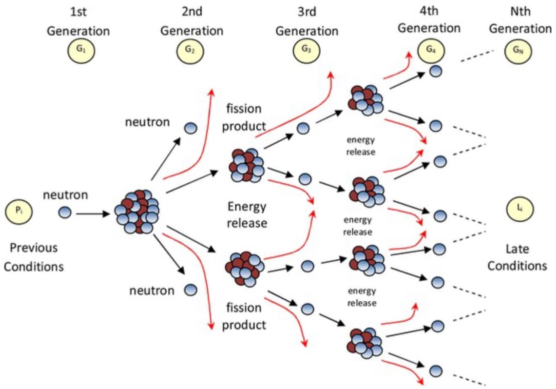




Atmospheric
Neutrinos:
IceCube



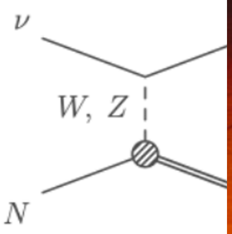
Beta decay and
IBD: Reactor
Experiments



DIS: FASERν

Kaon/Muon decay:

Solar neutrinos: Borexino



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

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

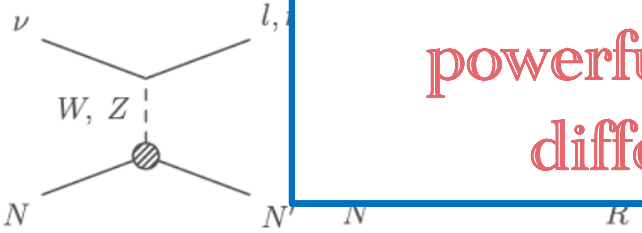
(hep)

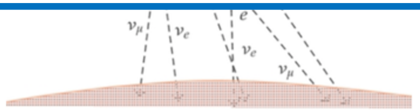
$+ e^- + p \rightarrow {}^2\mathrm{H} + \nu_e$ ***pep***

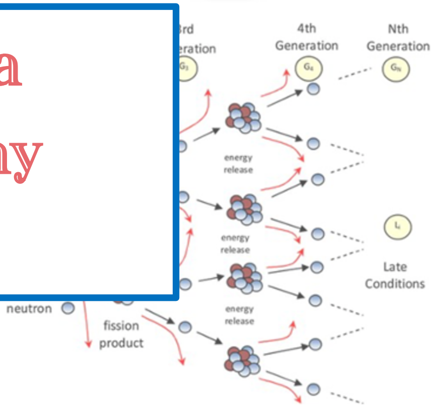
QE, Resonances MINOS, NOν DUNE

Beta decay and IBD: Reactor Experiments

Neutrino experiments give us a powerful tool to search for many different new interactions!

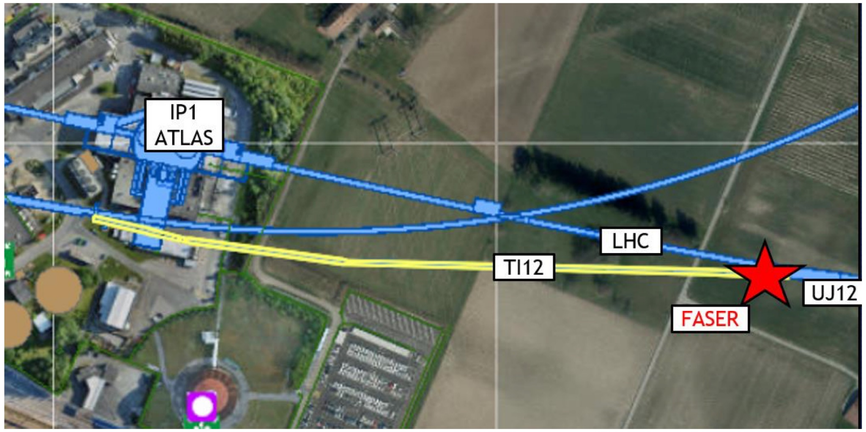


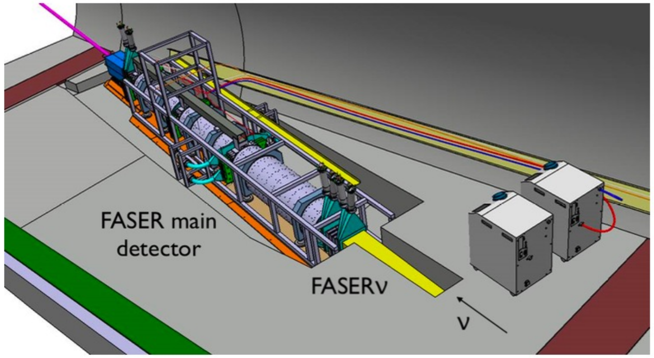


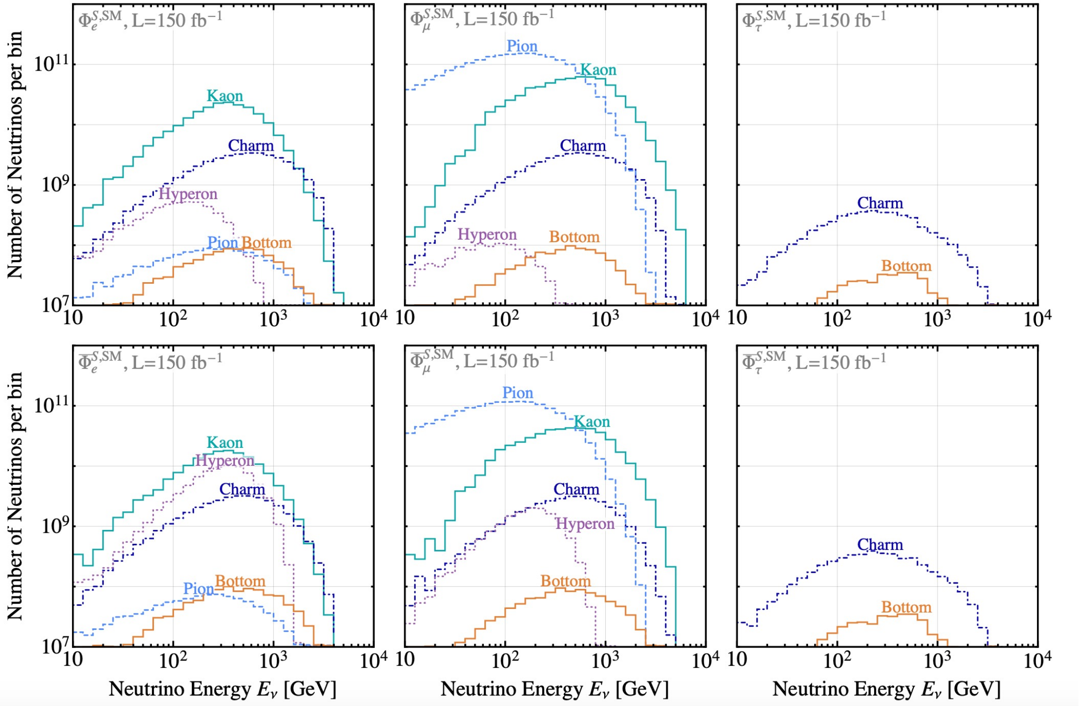


EFT at FASERν

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

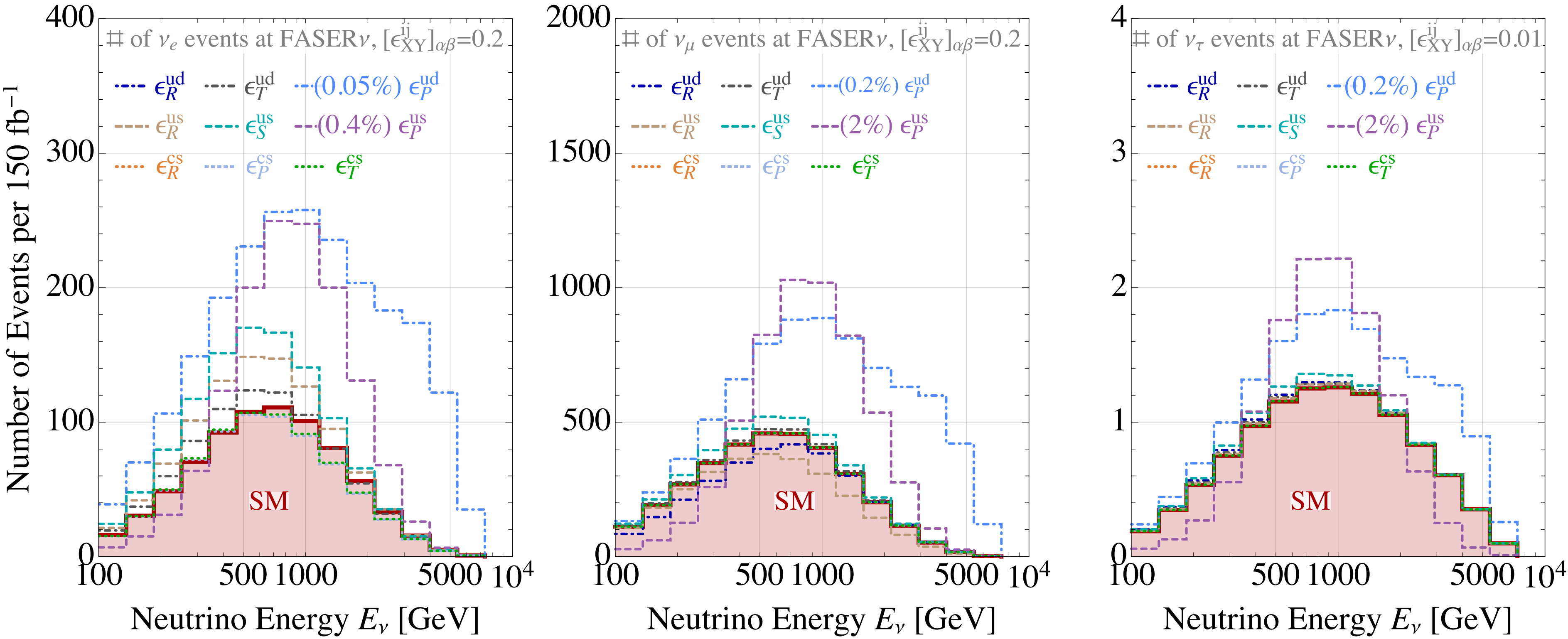






EFT at FASERν

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

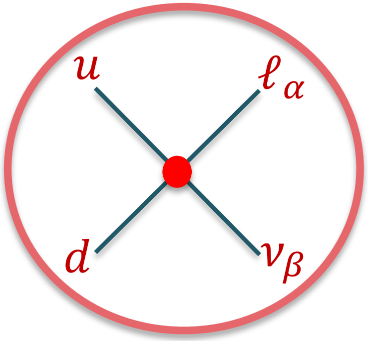


EFT at FASERν

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

- FASERν: colored bars

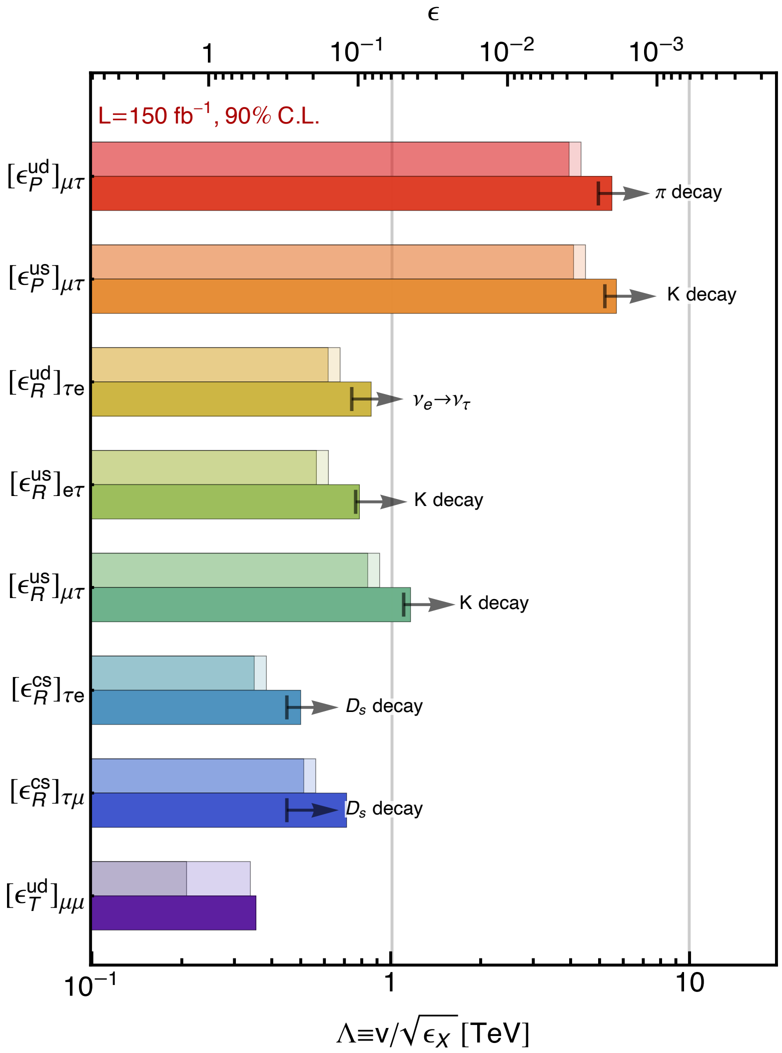
- Top: Pessimistic/Optimistic flux uncertainties
- Bottom: High luminosity LHC



- Neutrino detectors can identify flavor: 81 operators at FASERν

- New physics reach at multi-TeV

- Complementary or dominant constraints



EFT at FASERν

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

- FASERν: colored bars

- Low Energy WEFT:

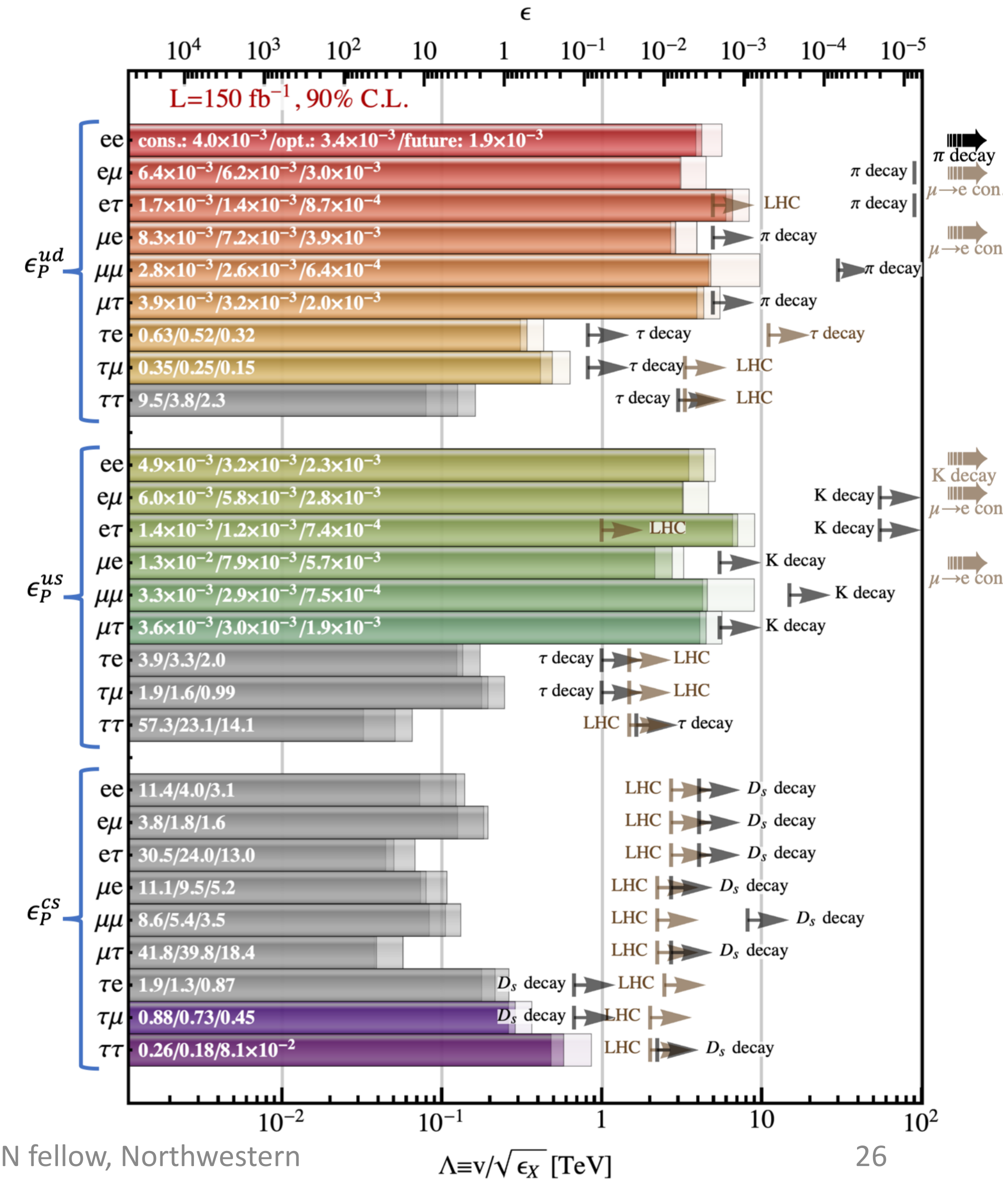
(Independent of the underlying high-energy theory)

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

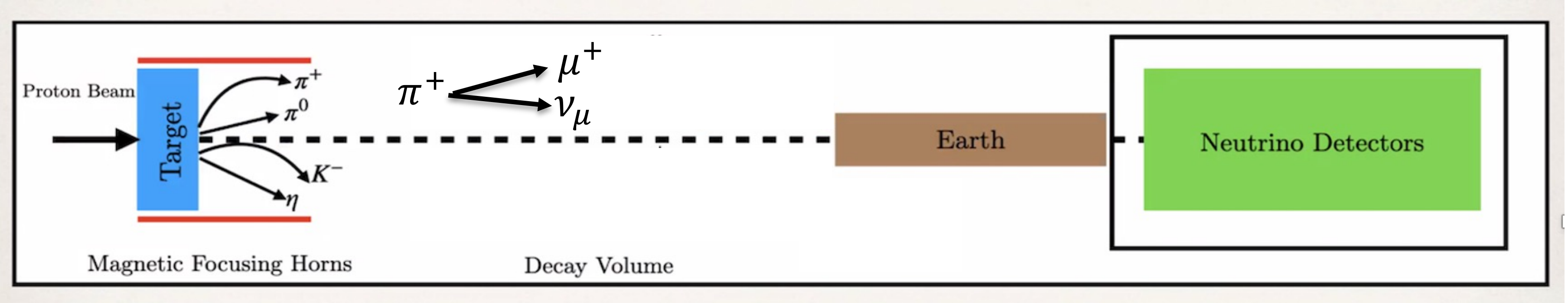
- High Energy SMEFT:

(Bounds are less robust)

  - ✓ LHC
  - ✓ CLFV



Accelerator Neutrino Experiments

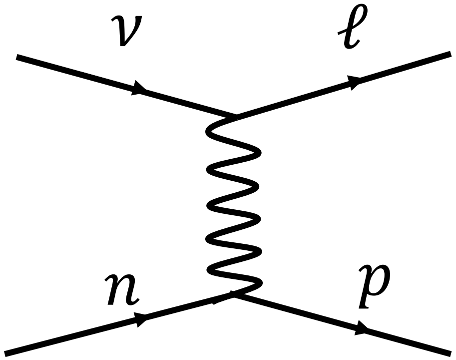


Credit: Kevin Kelly

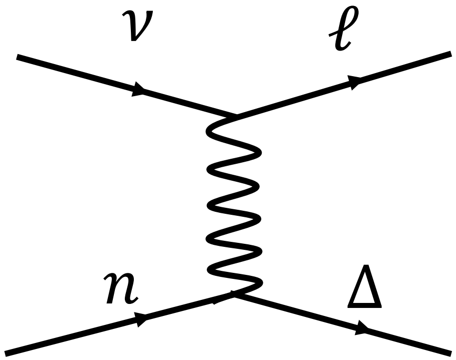
High beam luminosity + Large fiducial mass → Ideal to investigate (rare) neutrino interactions

0.5-5 GeV energy range: QE, resonances, DIS

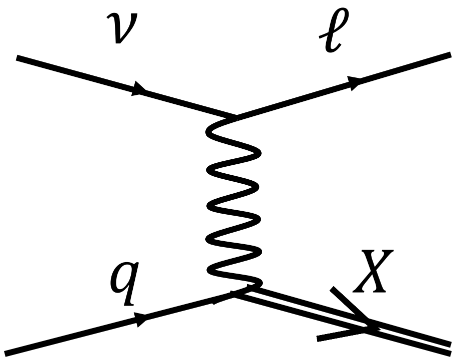
Quasi-Elastic Scattering



Resonance Production



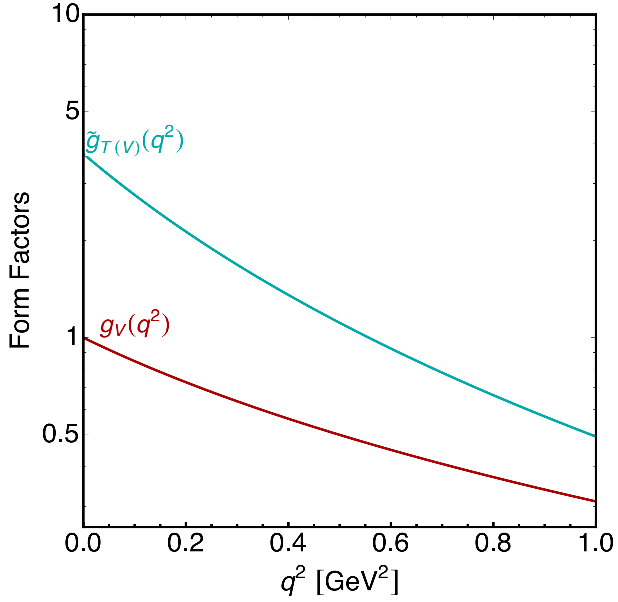
Deep Inelastic Scattering



QE matrix elements at the nucleon level

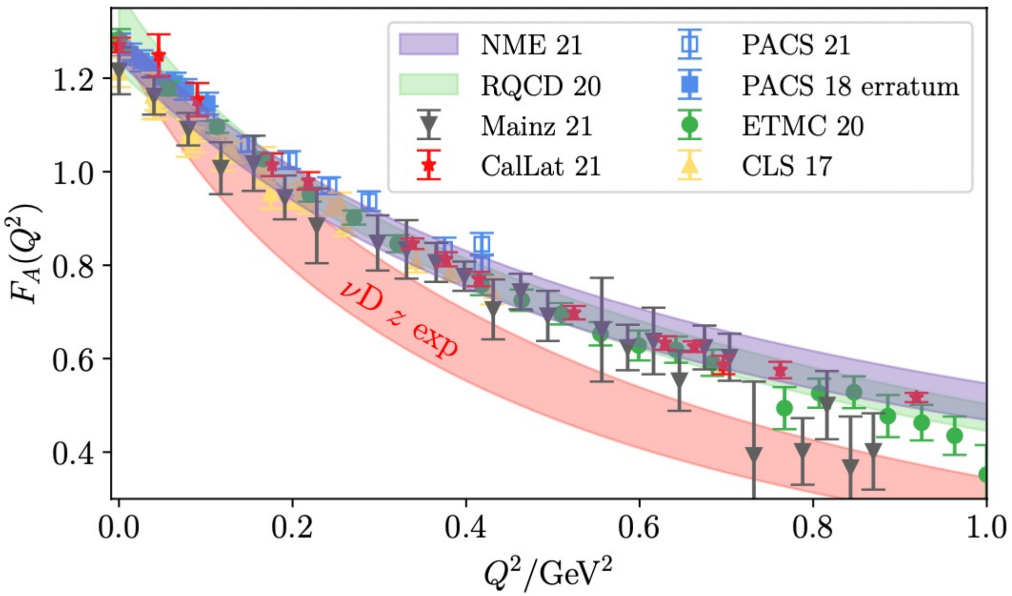
$$\langle p(p_p)|\,\bar{u}\gamma_\mu d\,|n(p_n)\rangle \;=\; \bar{u}_p(p_p)\left[g_V(q^2)\,\gamma_\mu - i\,\frac{\tilde{g}_{T(V)}(q^2)}{2M_N}\,\sigma_{\mu\nu}q^\nu + \cancel{\frac{\tilde{g}_S(q^2)}{2M_N}}\,q_\mu\right]u_n(p_n)$$

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



constrained by eN scattering

Kopp, Rocco, *ZT*, in preparation



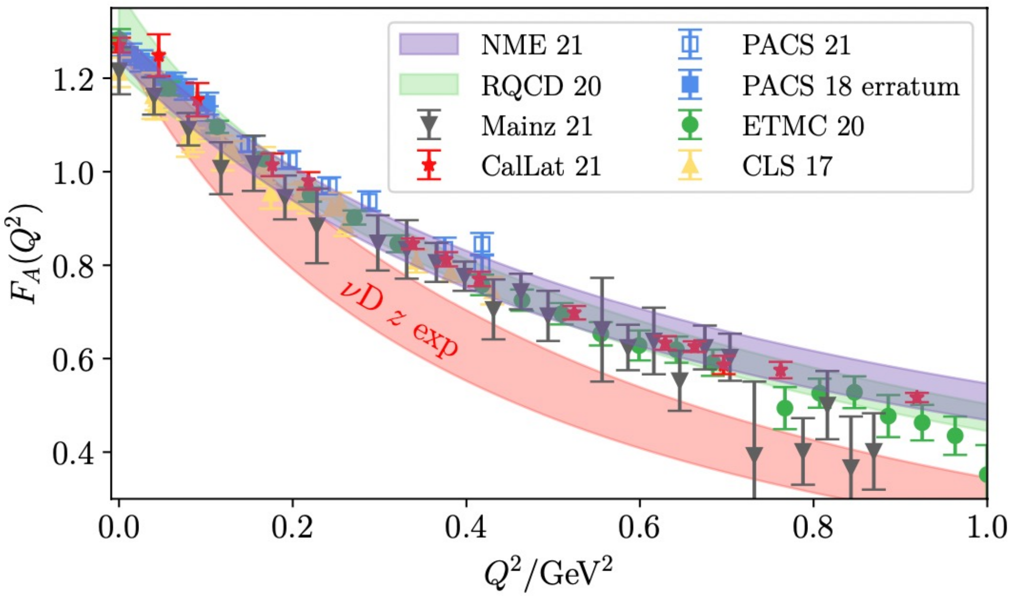
poorly constrained by expt.

Meyer et al, 2201.01839

QE matrix elements at the nucleon level

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

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



poorly constrained by expt.

Meyer et al, 2201.01839

QE matrix elements at the nucleon level

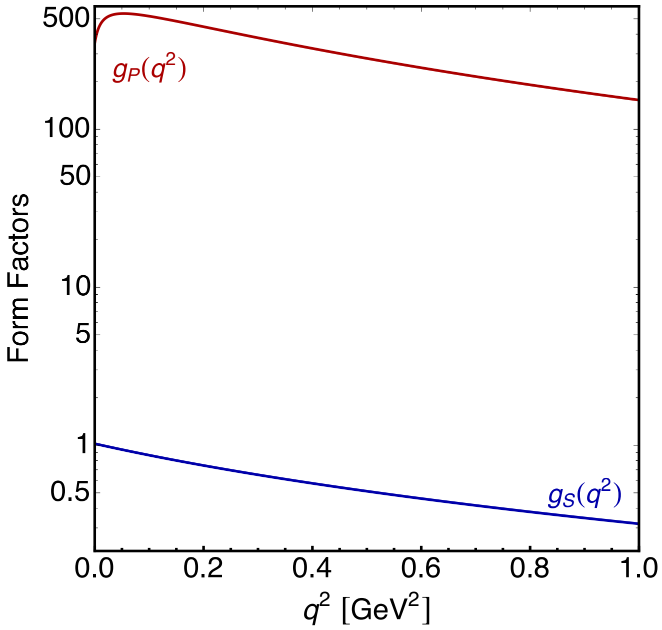
$$
\begin{aligned}
\langle p(p_p)|\, \bar u\, d\, |n(p_n)\rangle &= g_S(q^2)\; \bar u_p(p_p)\, u_n(p_n) \\
\langle p(p_p)|\, \bar u\, \gamma_5\, d\, |n(p_n)\rangle &= g_P(q^2)\; \bar u_p(p_p)\, \gamma_5\, u_n(p_n) \\
\langle p(p_p)|\, \bar u\, \sigma_{\mu\nu}\, d\, |n(p_n)\rangle &= \bar u_p(p_p)\, \Big[g_T(q^2)\,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

- conservation of the vector current (CVC):

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

- partial conservation of the axial current (PCAC):

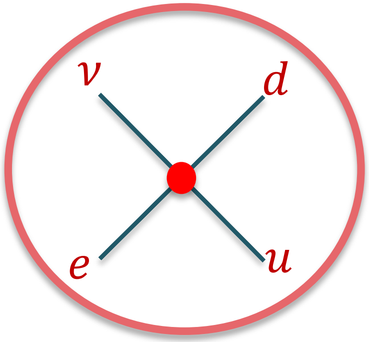
$$g_P(q^2) = \frac{\overline{M}_N}{\overline{m}_q} g_A(q^2) + \frac{q^2/2\overline{M}_N}{(2\overline{m}_q)} \tilde g_P(q^2)$$



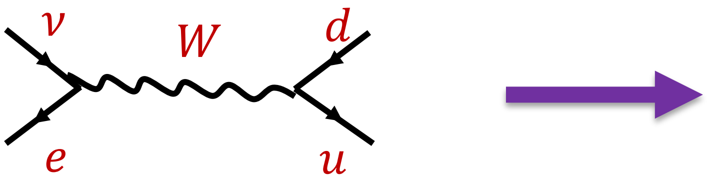
- We need axial form factor for NP as well
- Much larger statistics
- Large pseudo-scalar form factor (no q/M suppression)
- Different energy scale compare to beta decay experiments

Kopp, Rocco, *ZT*, in preparation

Specific New Physics Models

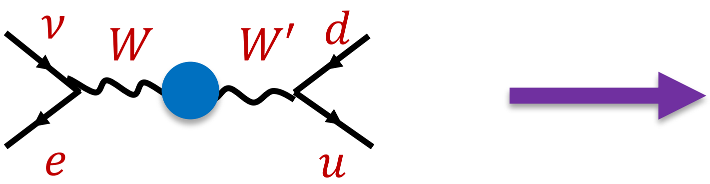


ε_L: measures deviations of the W boson to quarks and leptons, compared to the SM prediction



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

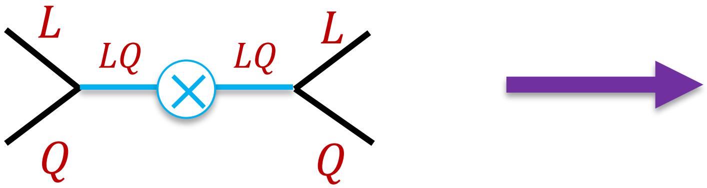
ε_R : left-right symmetric $SU(3)_C xSU(2)_L xSU(2)_R xU(1)_X$ models introduce new charged vector bosons W’ coupling to right-handed quarks



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

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

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

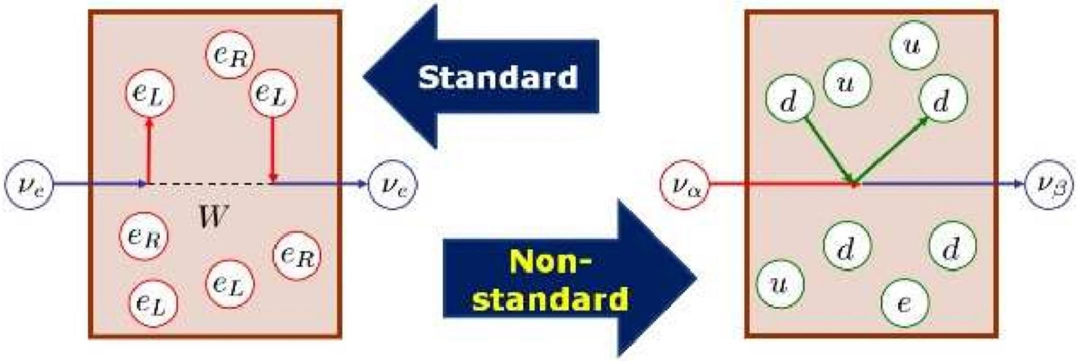


$$(LQ)(LQ)$$

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

QM-NSI Description

Neutrinos are not pure flavor states:



Standard NSI approach

NSI parameters

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

Rotation of flavor states at the source

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

Rotation of flavor states at the detector

Normalization

QM-NSI Description

Neutrinos are not pure flavor states:

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

Observable: **rate of detected events**

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

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

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

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

QM-NSI Description

- Can one “validate” QM-NSI approach from the QFT results?
- If yes, relation between NSI parameters and Lagrangian (EFT) parameters?
- Does the matching hold at all orders in perturbation?

QM-NSI Description

- Can one "validate" QM-NSI approach from the QFT results? Yes…
- If yes, relation between NSI parameters and Lagrangian (EFT) parameters?
- Does the matching hold at all orders in perturbation? No…

Observable is the same, we can match the two

(only at the linear level)

$$\boxed{\epsilon^s_{\alpha\beta} = \sum_X p_{XL} [\epsilon_X]^*_{\alpha\beta}, \quad \epsilon^d_{\beta\alpha} = \sum_X d_{XL} [\epsilon_X]_{\alpha\beta}}$$

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

Comparing QM and QFT

Only at the linear order:

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

Neutrino Process	NSI Matching with EFT
ν_e produced in beta decay	$\epsilon^s_{e\beta} = [\epsilon_L]^*_{e\beta} - [\epsilon_R]^*_{e\beta} - \frac{g_T}{g_A}\frac{m_e}{f_T(E_\nu)}[\epsilon_T]^*_{e\beta}$
ν_e detected in inverse beta decay	$\epsilon^d_{\beta e} = [\epsilon_L]_{e\beta} + \frac{1-3g_A^2}{1+3g_A^2}[\epsilon_R]_{e\beta} - \frac{m_e}{E_\nu-\Delta}\left(\frac{g_S}{1+3g_A^2}[\epsilon_S]_{e\beta} - \frac{3g_A g_T}{1+3g_A^2}[\epsilon_T]_{e\beta}\right)$
ν_μ produced in pion decay	$\epsilon^s_{\mu\beta} = [\epsilon_L]^*_{\mu\beta} - [\epsilon_R]^*_{\mu\beta} - \frac{m_\pi^2}{m_\mu(m_u+m_d)}[\epsilon_P]^*_{\mu\beta}$

- Different NP interactions appear at the source or detection simultaneously
- Some of the p_{XL}/d_{XL} coefficients depend on the neutrino energy
- There are chiral enhancements in some cases

These correlations, energy dependence etc. cannot be seen in the traditional QM approach.

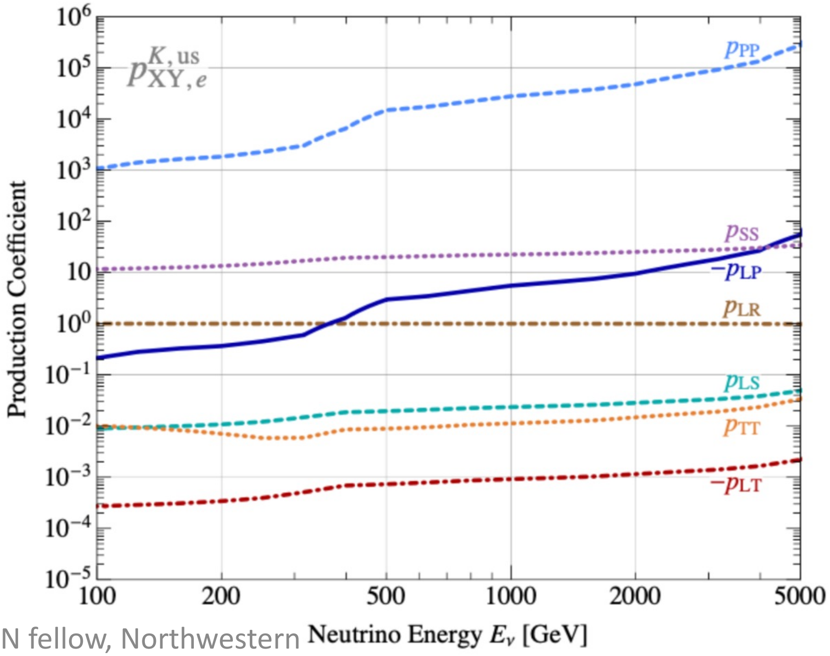
Comparing QM and QFT

Beyond the linear order in new physics parameters, the NSI formula matches the (correct) one derived in the EFT
only if the consistency condition is satisfied

$$p_{XL}p^*_{YL} = p_{XY}, \quad d_{XL}d^*_{YL} = d_{XY}$$

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

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



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

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

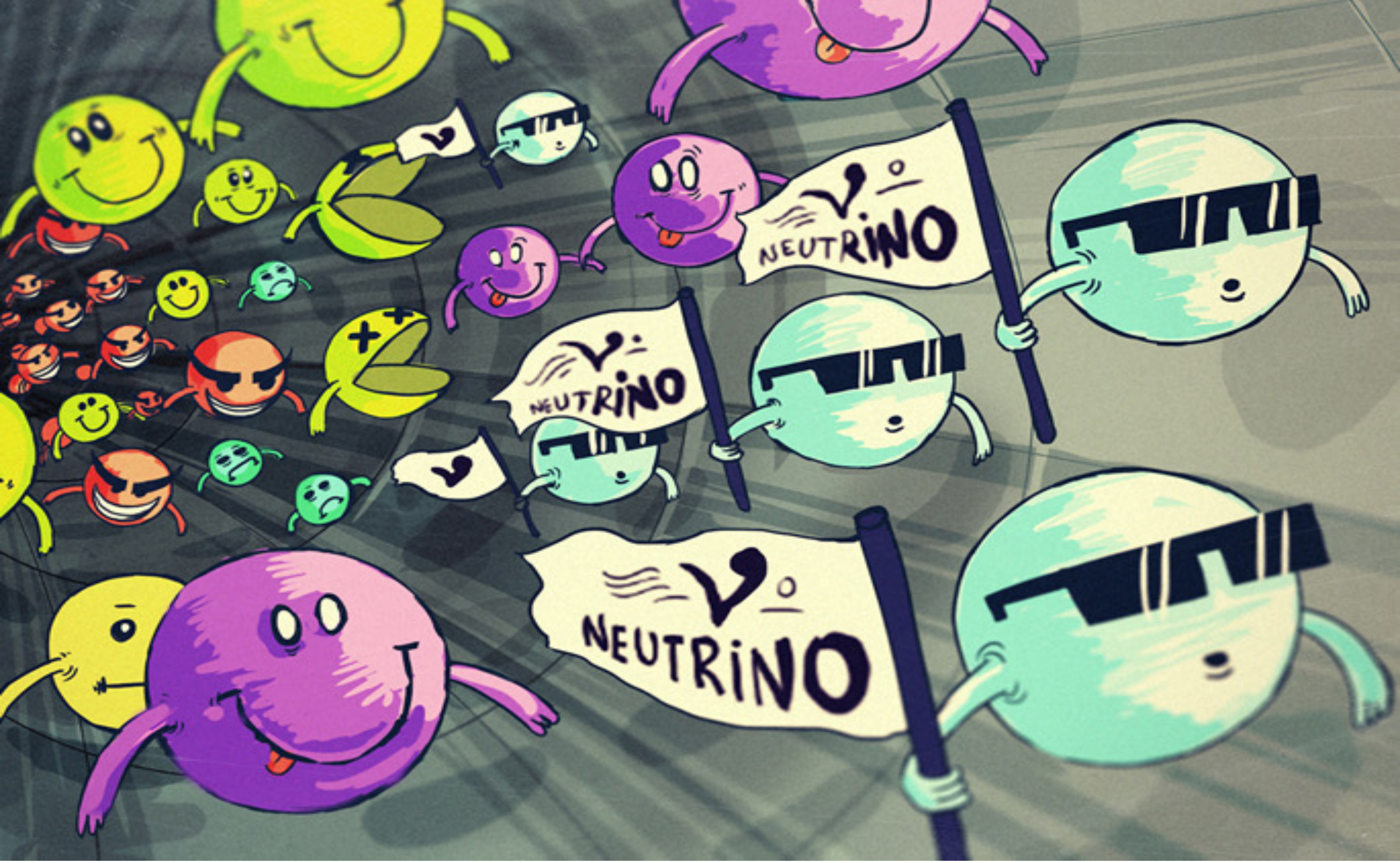
Conclusion:

- 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.



Thanks for your attention

Back up Slides

WEFT Power Counting

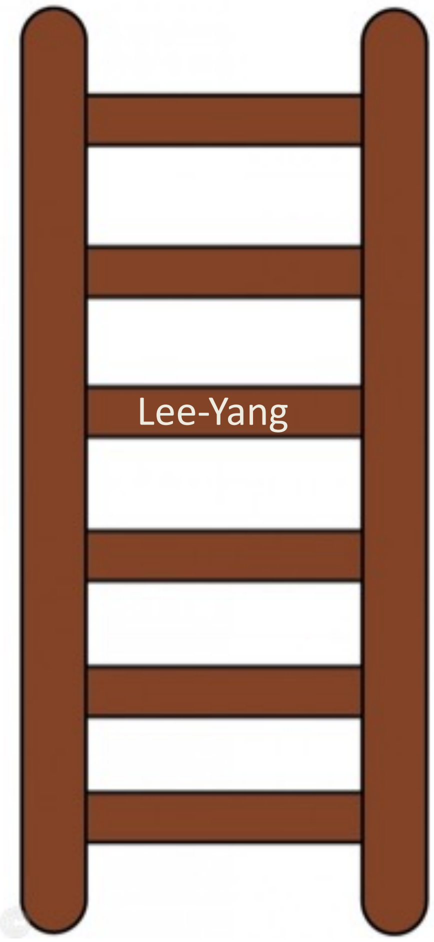
- Dim-6: $\frac{\Delta R}{R_{SM}} = c\ \epsilon_X^2$
- Dim-7: Cannot interfere with the SM amplitudes, suppressed!

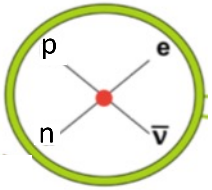
Liao et al, *JHEP* 08 (2020) 162

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

EFT ladder

$E \ll m_Z$





- At the energy scale of reactor neutrino experiments the relevant degrees of freedom are not quarks, but nucleons and nuclei. Matching this EFT to the WEFT Lagrangian we obtain the Lee-Yang Lagrangian:

$$
\begin{aligned}
\mathcal{L}_{\rm LY} \quad \supset \quad & -\frac{V_{ud}}{v^2}\{g_V\,[\mathbf{1}+\epsilon_L+\epsilon_R]_{\alpha\beta}\,(\bar{p}\gamma^\mu n)(\bar{\ell}_\alpha\gamma_\mu P_L\nu_\beta) \\
& \qquad - g_A\,[\mathbf{1}+\epsilon_L-\epsilon_R]_{\alpha\beta}\,(\bar{p}\gamma^\mu\gamma_5 n)(\bar{\ell}_\alpha\gamma_\mu P_L\nu_\beta) \\
& \qquad + g_S[\epsilon_S]_{\alpha\beta}(\bar{p}n)(\bar{\ell}_\alpha P_L\nu_\beta) - g_P[\epsilon_P]_{\alpha\beta}(\bar{p}\gamma_5 n)(\bar{\ell}_\alpha P_L\nu_\beta) \\
& \qquad + \frac{1}{2}g_T[\hat{\epsilon}_T]_{\alpha\beta}(\bar{p}\sigma^{\mu\nu}P_L n)(\bar{\ell}_\alpha\sigma_{\mu\nu}P_L\nu_\beta) + \text{h.c.}\},
\end{aligned}
$$

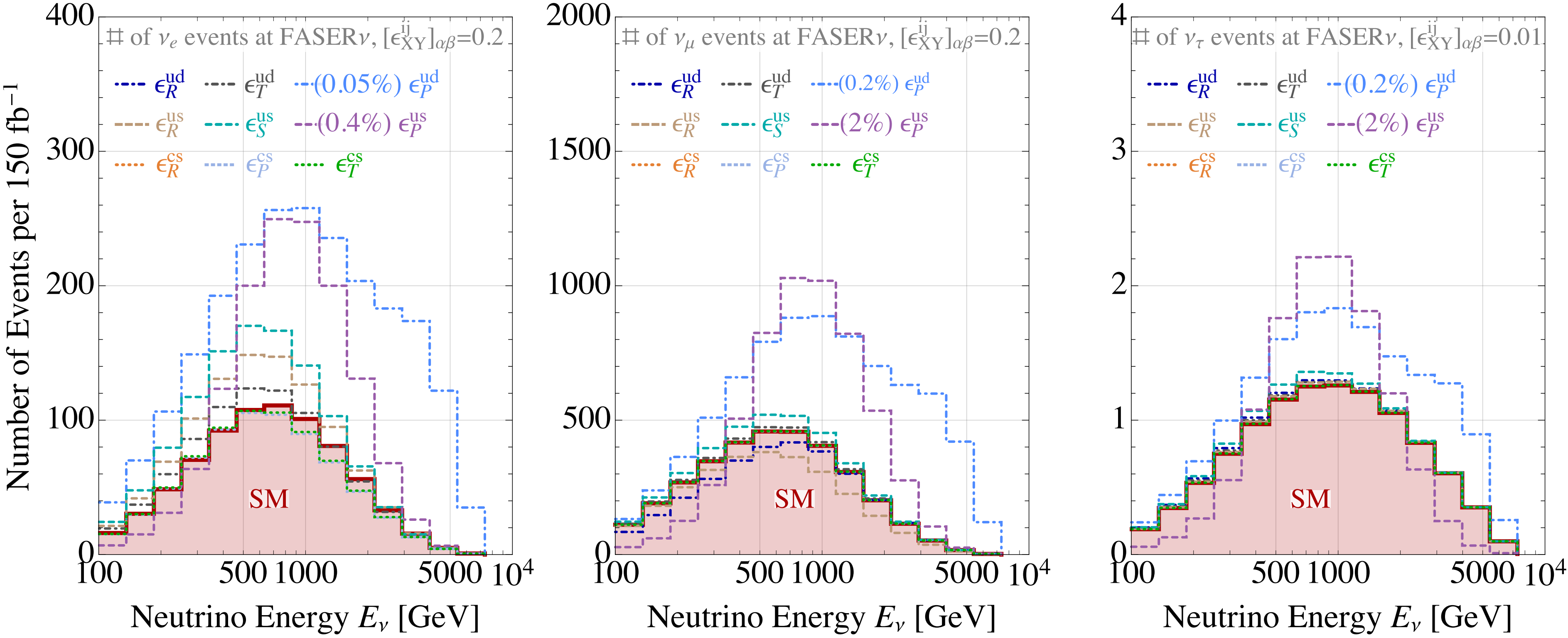
- Lattice+theory fix the non-perturbative parameters with good precision

$$g_A = 1.2728 \pm 0.0017, \quad g_S = 1.02 \pm 0.11, \quad g_P = 349 \pm 9, \quad g_T = 0.987 \pm 0.055$$

- T. Bhattacharya et al, Phys. Rev. D94 (2016), no. 5 054508
- M. Gonzalez-Alonso and J. Martin Camalich, Phys. Rev. Lett. 112 (2014), no. 4 042501
- M. Gonzalez-Alonso et al, Prog. Part. Nucl. Phys. 104 (2019) 165–223

EFT at FASERν

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



RESULTS

Turning on one interaction at a time: Right handed

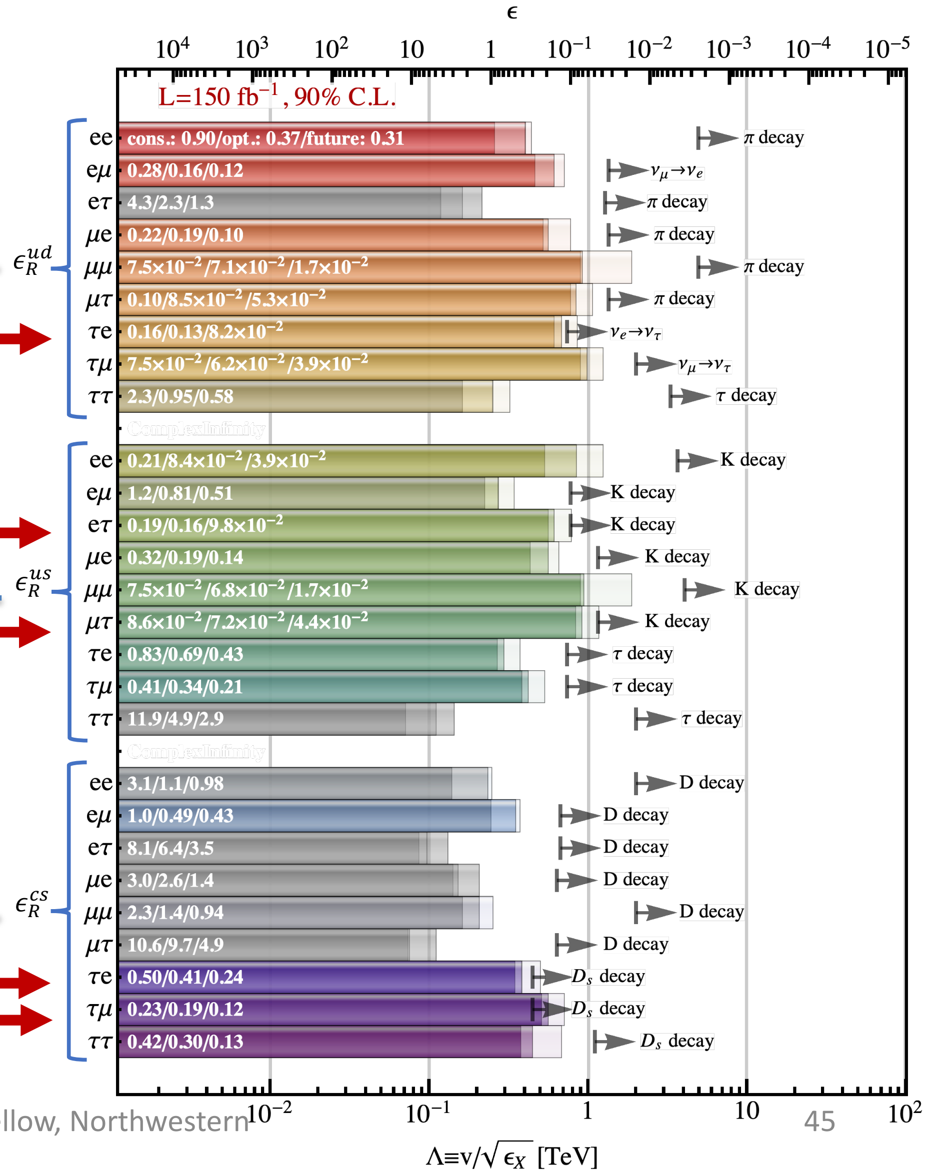
A. Falkowski, M. González-Alonso, J. Kopp, Y. Soreq, **ZT**
JHEP 10 (2021) 086

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



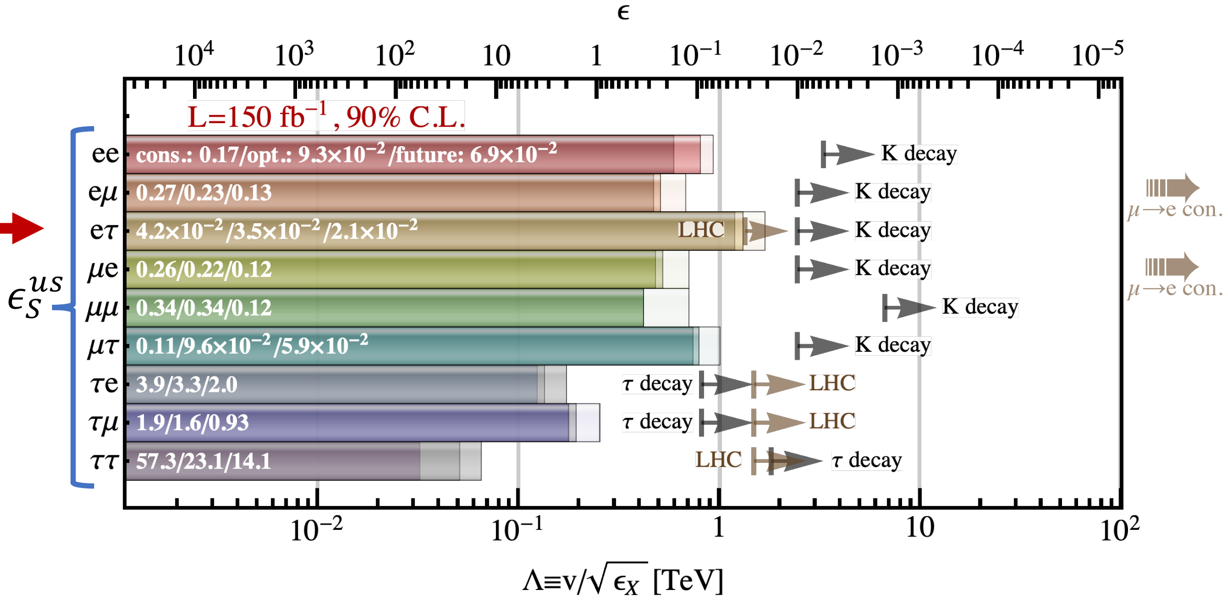
RESULTS

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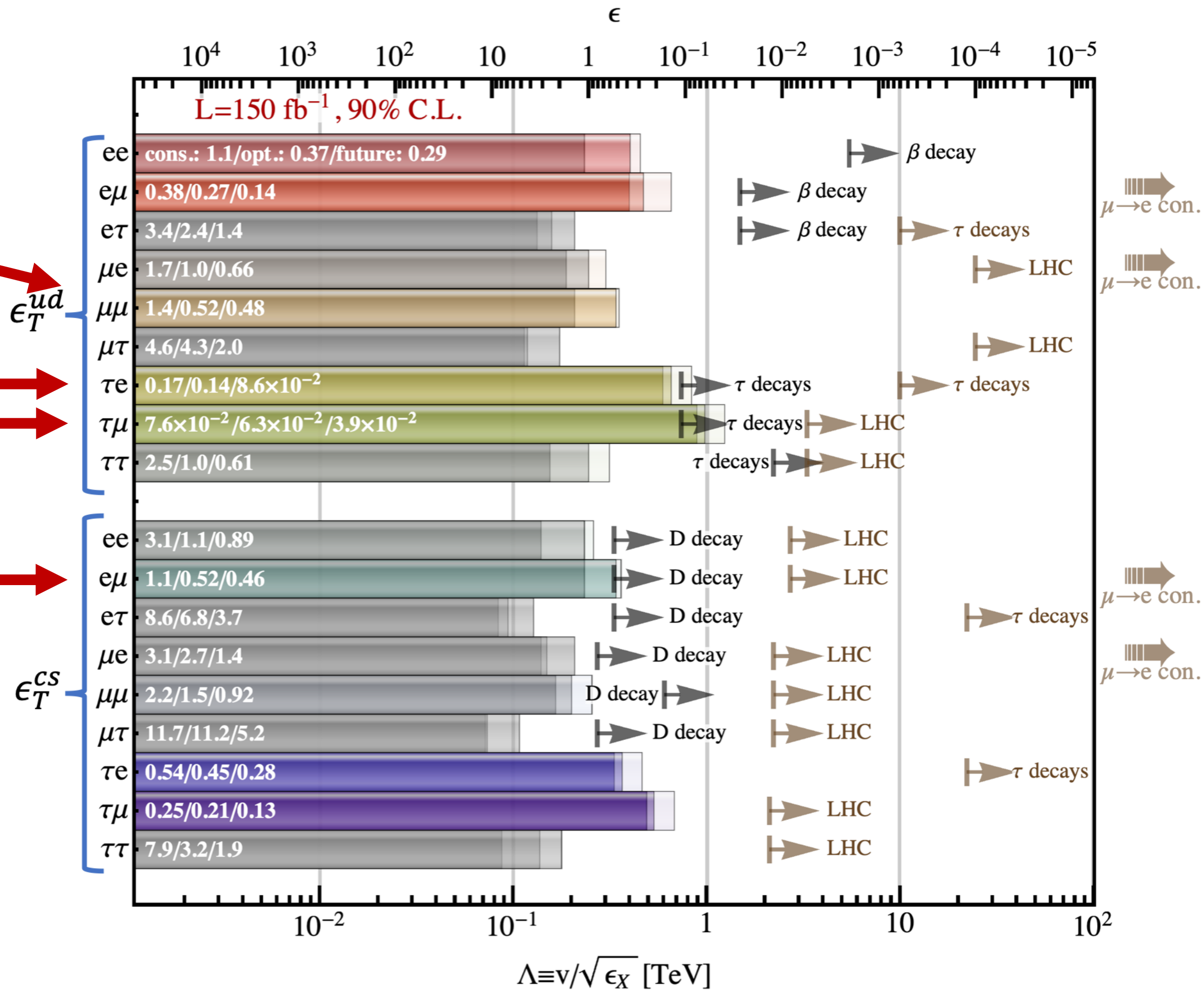
Optimistic (5%, 10%, 15%) and Pessimistic (30%, 40%, 50%), uncertainties on electron muon and tau neutrinos

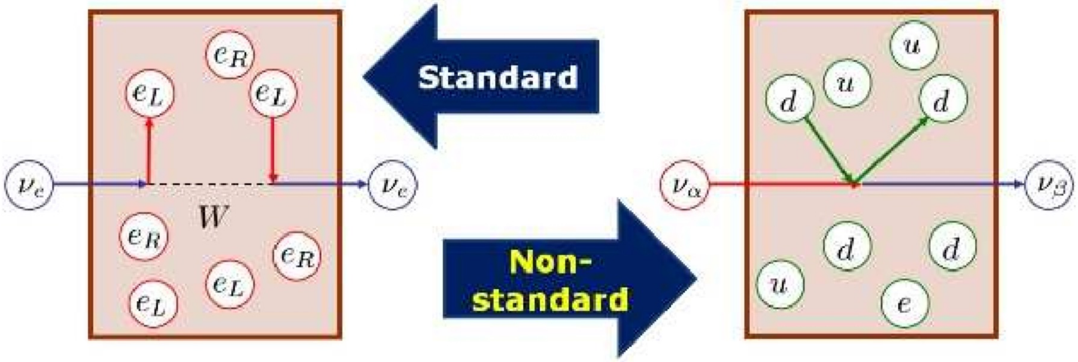
From DIS

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?
- Does the matching hold at all orders in perturbation?

QFT vs QM-NSI

- Can one “validate” QM-NSI approach from the QFT results? Yes…
- If yes, relation between NSI parameters and Lagrangian (EFT) parameters?
- Does the matching hold at all orders in perturbation? No…

Observable is the same, we can match the two

(only at the linear level)

$$\epsilon^s_{\alpha\beta} = \sum_X p_{XL}[\epsilon_X]^*_{\alpha\beta}, \quad \epsilon^d_{\beta\alpha} = \sum_X d_{XL}[\epsilon_X]_{\alpha\beta}$$

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Comparing QM and QFT

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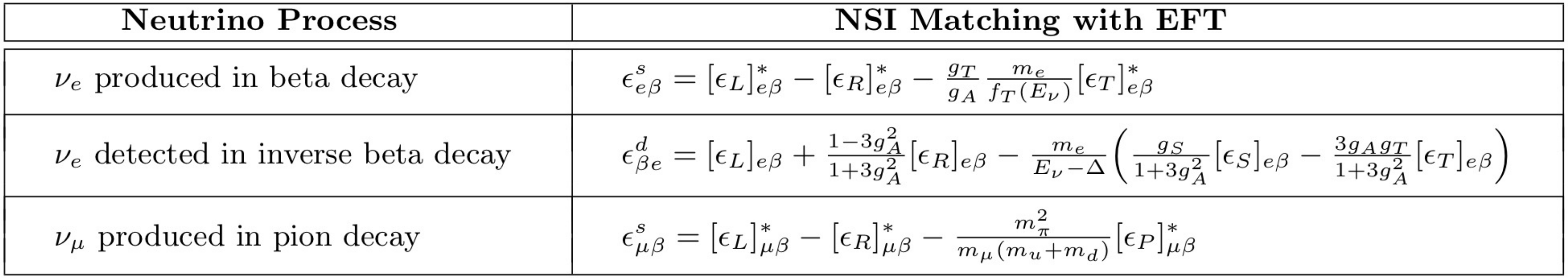
At the linear order we have:



Neutrino Process	NSI Matching with EFT
ν_e produced in beta decay	$\epsilon^s_{e\beta} = [\epsilon_L]^*_{e\beta} - [\epsilon_R]^*_{e\beta} - \frac{g_T}{g_A}\frac{m_e}{f_T(E_\nu)}[\epsilon_T]^*_{e\beta}$
ν_e detected in inverse beta decay	$\epsilon^d_{\beta e} = [\epsilon_L]_{e\beta} + \frac{1-3g_A^2}{1+3g_A^2}[\epsilon_R]_{e\beta} - \frac{m_e}{E_\nu - \Delta}\left(\frac{g_S}{1+3g_A^2}[\epsilon_S]_{e\beta} - \frac{3g_A g_T}{1+3g_A^2}[\epsilon_T]_{e\beta}\right)$
ν_μ produced in pion decay	$\epsilon^s_{\mu\beta} = [\epsilon_L]^*_{\mu\beta} - [\epsilon_R]^*_{\mu\beta} - \frac{m_\pi^2}{m_\mu(m_u+m_d)}[\epsilon_P]^*_{\mu\beta}$

- Different NP interactions appear at the source or detection simultaneously.
- Some of the p/d coefficients depend on the neutrino energy.
- There are chiral enhancements in some cases.

These correlations, energy dependence etc. cannot be seen in the traditional QM approach.

Comparing QM and QFT

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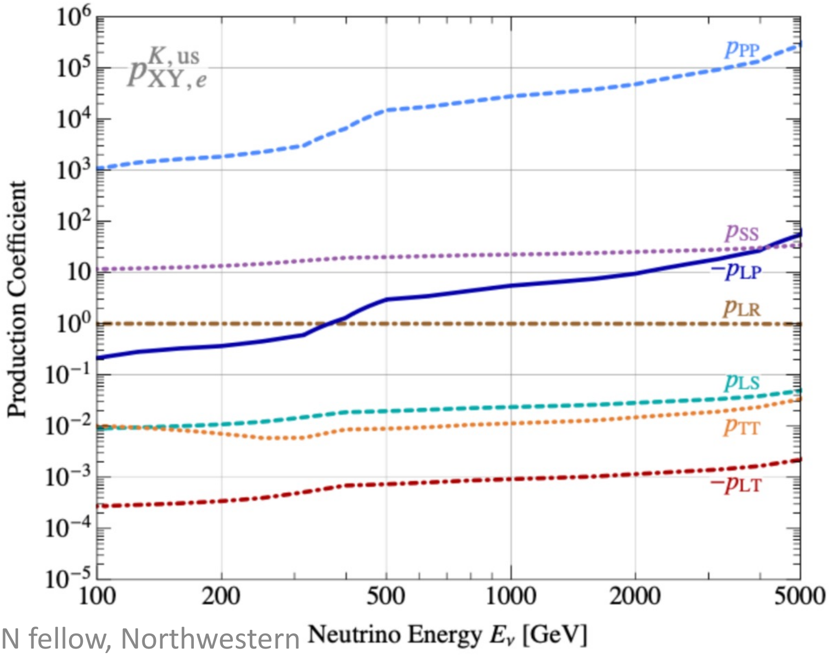
Beyond the linear order in new physics parameters, the NSI formula matches the (correct) one derived in the EFT only if the consistency condition is satisfied

$$p_{XL}p^*_{YL} = p_{XY}, \quad d_{XL}d^*_{YL} = d_{XY}$$

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

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

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



EFT at FASERν

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Neutrino experiments:

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

Low energy:

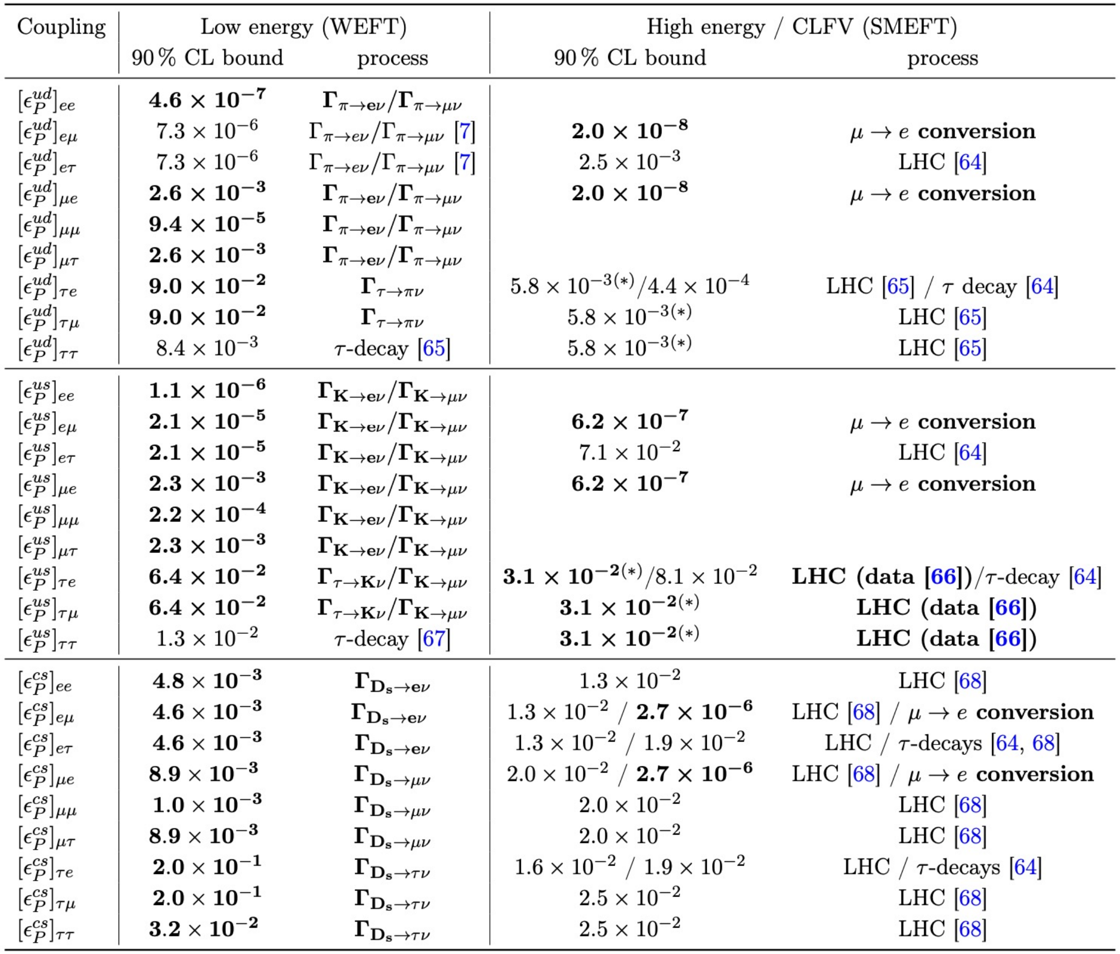
- Independent of the underlying high-energy theory

High-Energy:

- SMEFT is the underlying theory
- Bounds are less robust

Bounds shown in bold face have been calculated in this work

FASERν Flavor Experiments Colliders



Coupling	Low energy (WEFT)		High energy / CLFV (SMEFT)	
	90 % CL bound	process	90 % CL bound	process
$[\epsilon_P^{ud}]_{ee}$	$\mathbf{4.6 \times 10^{-7}}$	$\mathbf{\Gamma_{\pi \to e\nu}/\Gamma_{\pi \to \mu\nu}}$		
$[\epsilon_P^{ud}]_{e\mu}$	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]