Direct and Indirect BSM searches at Neutrino Experiments

Neutrino Theory Network Workshop

June 21-23, 2022

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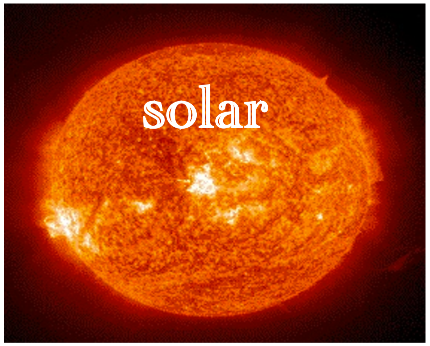
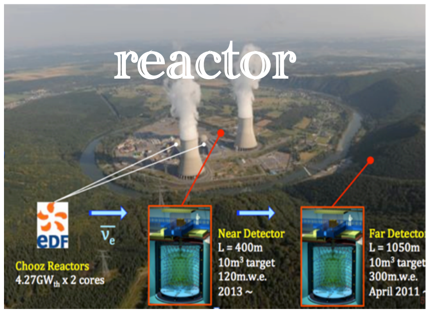
Neutrino Theory Network fellow

Northwestern University

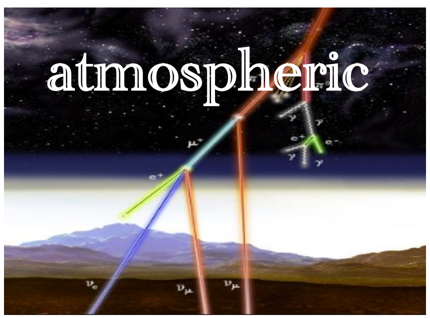
Status of Neutrino Physics in 2022



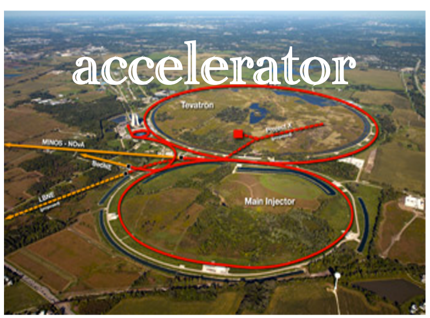
Super-Kamiokande, Borexino, SNO



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:

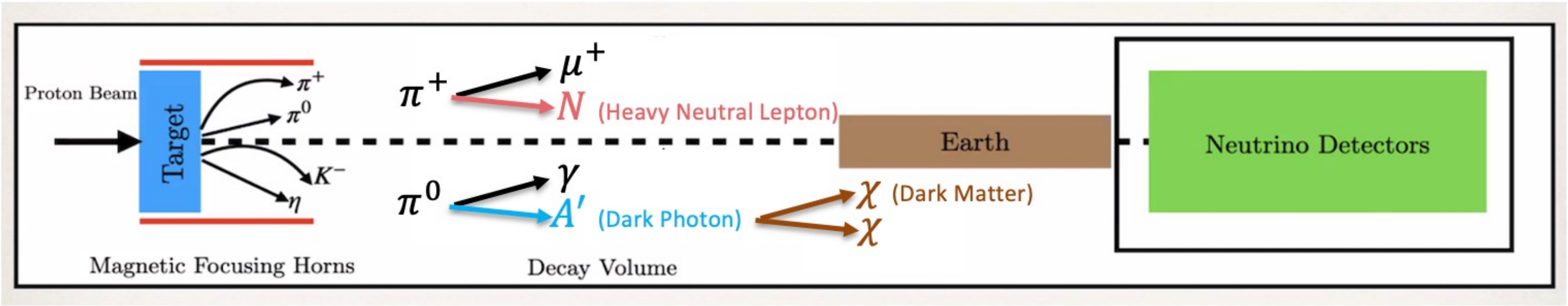
- How can we systematically use different neutrino experiments for BSM searches?

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

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

Neutrino Experiments as Dark Sector factories!

1) Direct Production of New Physics

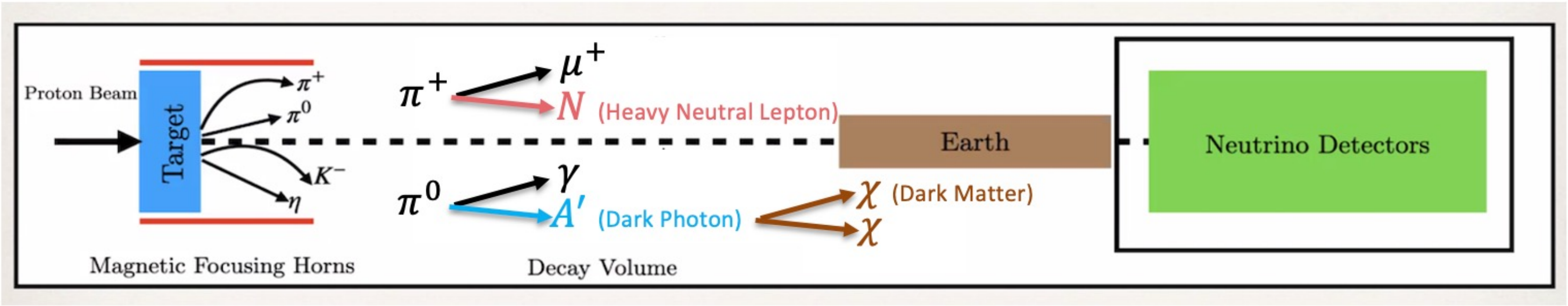


Credit: Kevin Kelly

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

Neutrino Experiments as Dark Sector factories!

1) Direct Production of New Physics

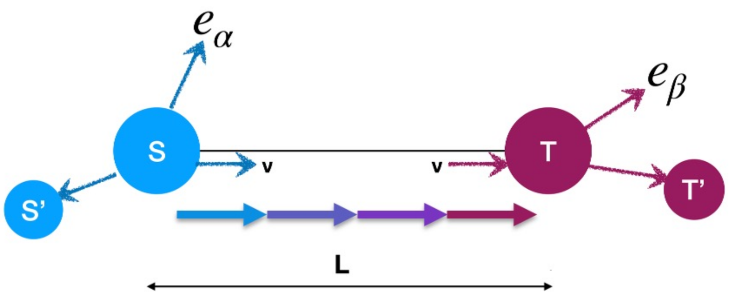


Credit: Kevin Kelly

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

How about "Heavy" New Physics?

2) Affect Neutrino Interactions: Indirect Search



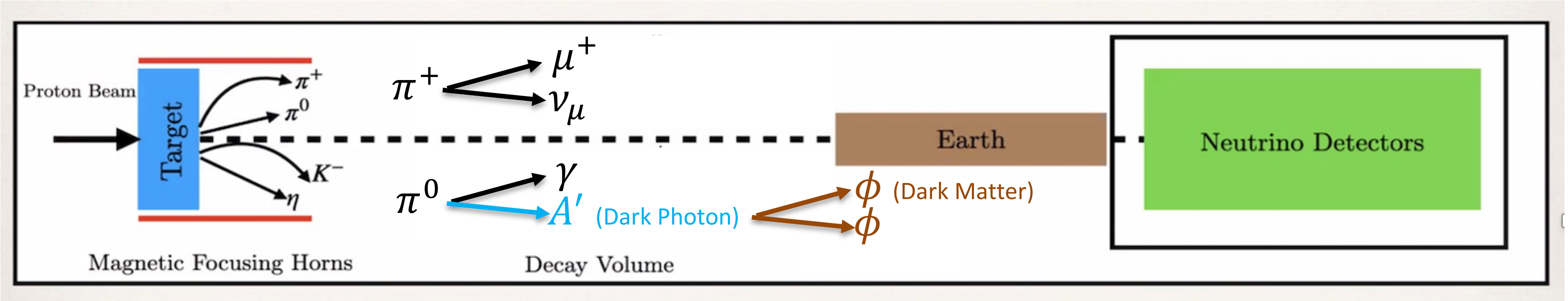
Observable: rate of detected events

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

Outline

- 1) Direct Search of Dark Sectors:
  - Light Dark Matter
  - Axion-Like Particles
- 2) Indirect Search-EFT:
  - Why EFT?
  - EFT at FASERν
  - EFT at DUNE?
- Conclusion

Light Dark Matter

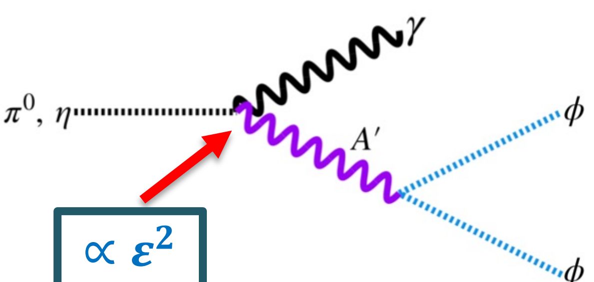


Photons at the target kinetically produce Dark Photons, which decay into dark matter:

$$\mathcal{L} \supset -\frac{\varepsilon}{2} F^{\mu\nu} F'_{\mu\nu} + \frac{M_{A'}^2}{2} A'_\mu A'^\mu + |D_\mu \phi|^2 - M_\phi^2 |\phi|^2$$

$$\boxed{D_\mu = \partial_\mu - i g_D A'_\mu, \quad g_D = \sqrt{4\pi\alpha_D}}$$

DM production

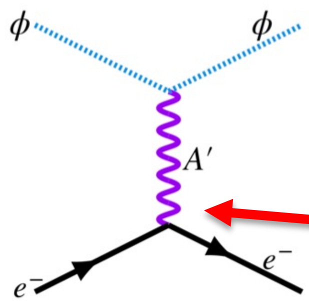


$\boxed{\propto \varepsilon^2}$

De Romeri, Kelly, Machado, PRD (2019)

(also Beam bremsstrahlung and Resonance production)

DM detection

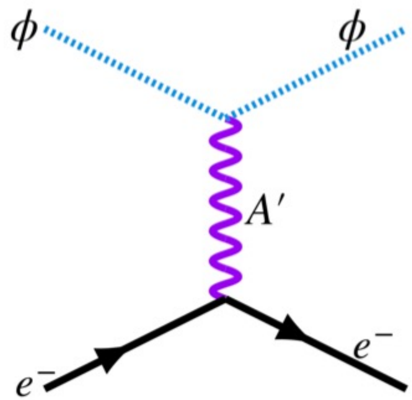


$\boxed{\propto \varepsilon^2}$

$\boxed{\text{DM event rate} \sim \varepsilon^4 \alpha_D}$

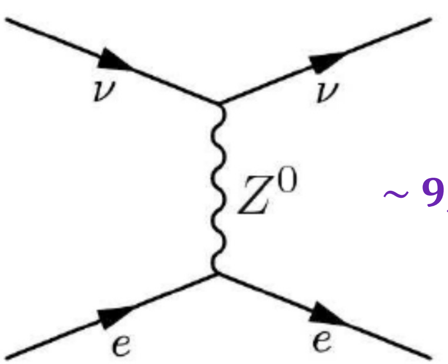
Light Dark Matter

DM signal: elastic scattering on electrons



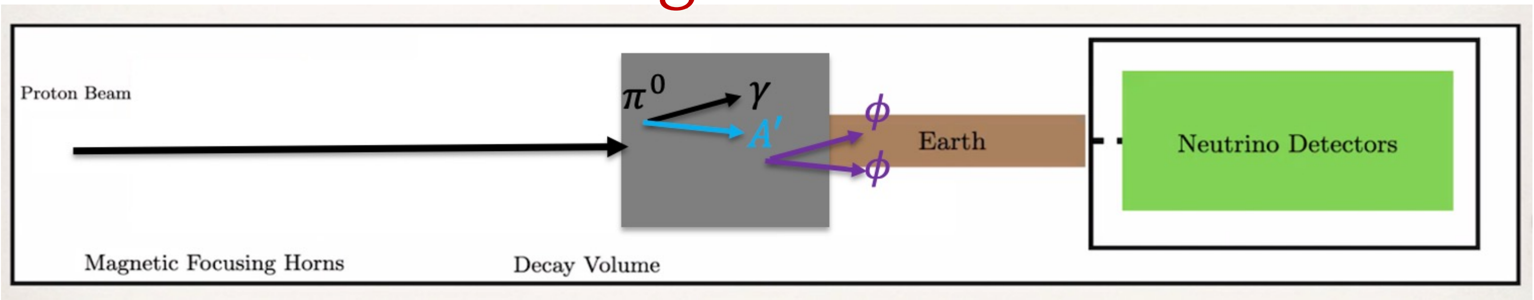
How can we get rid of neutrinos in a neutrino detector?

But so do neutrinos!

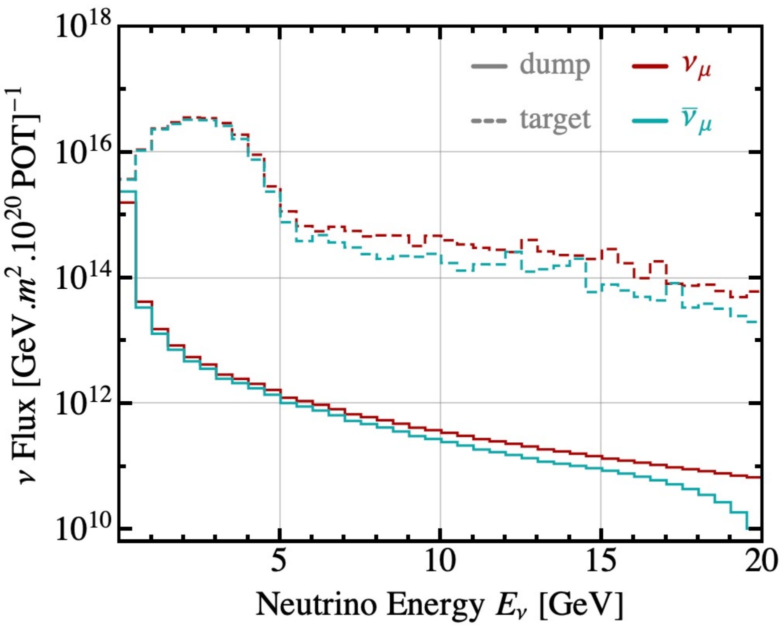


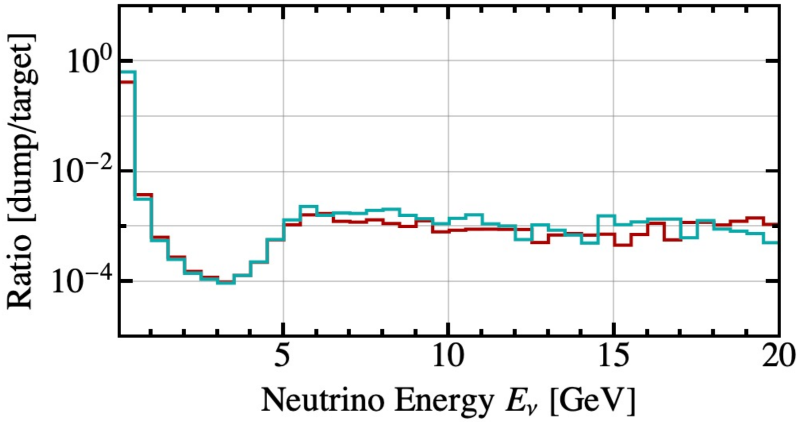
$\sim \mathbf{9,400}\ \boldsymbol{\nu - e}$ events / year!

Light Dark Matter---Target-less DUNE



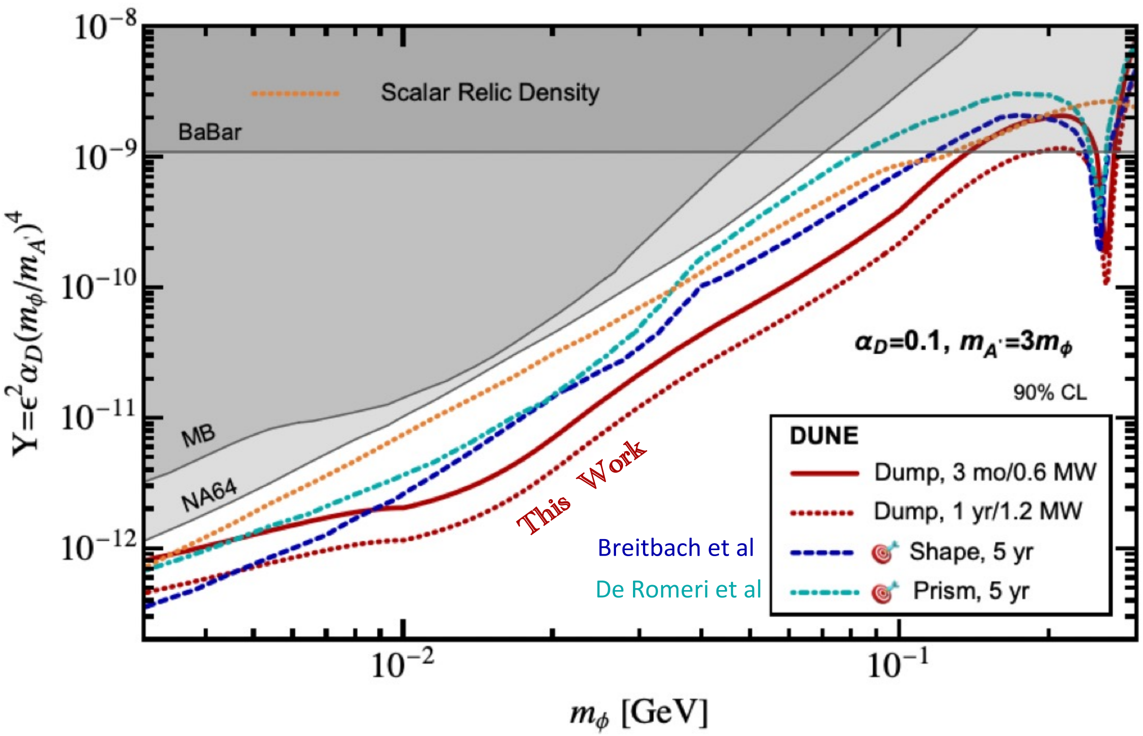
- Impinging protons directly to the dump area;
- Shorter distance between the source point and the detector → more DM signal;
- Charged mesons absorbed in the Al beam dump before decay;
- **The ν flux decreases by 3 orders of magnitude → Only 0.5 ν-e background in 3 mo-0.6 MW!**





Bhattarai, Brdar, Dutta, Jang, Kim, Shoemaker, *ZT*, Thompson, Yu
arXiv: 2206.06380

Light Dark Matter---Target-less DUNE



Bhattarai, Brdar, Dutta, Jang, Kim, Shoemaker, *ZT*, Thompson, Yu
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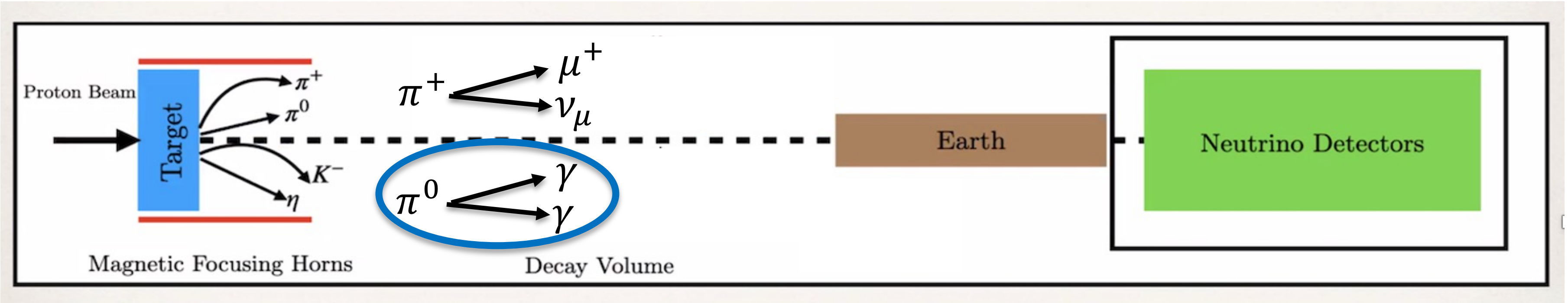
Target-less DUNE can probe the parameter space for thermal relic DM in only 3 months!

ALPs at Neutrino Experiments

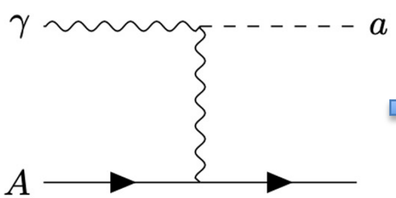


Credit: Kevin Kelly

Using photons to produce ALPs:

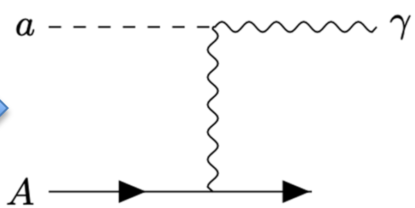
$$\mathcal{L}_{a\gamma\gamma} \supset -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

ALP production

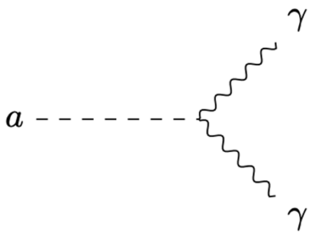


Primakoff scattering

ALP detection

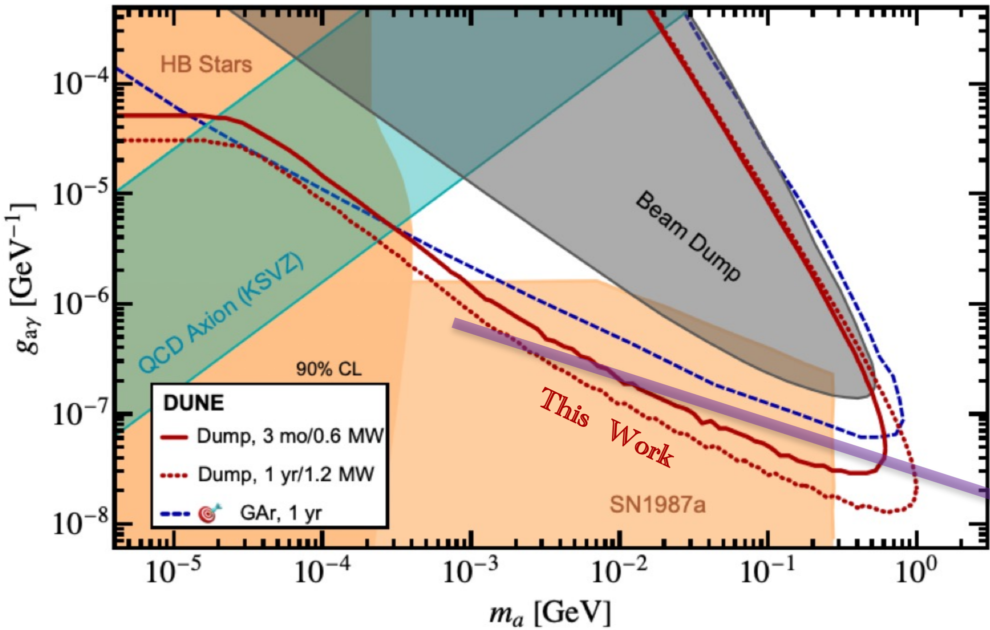


Inverse Primakoff scattering



ALP decay

ALPs at Neutrino Experiments



- The only lab-based constraints!
- Can probe QCD-axion
- 3 months target-less DUNE can do better than 1 yr GAr

Brdar, Dutta, Jang, Kim, Shoemaker, *ZT*, Thompson, Yu
PRL (2021)

Bhattarai, Brdar, Dutta, Jang, Kim, Shoemaker, *ZT*, Thompson, Yu
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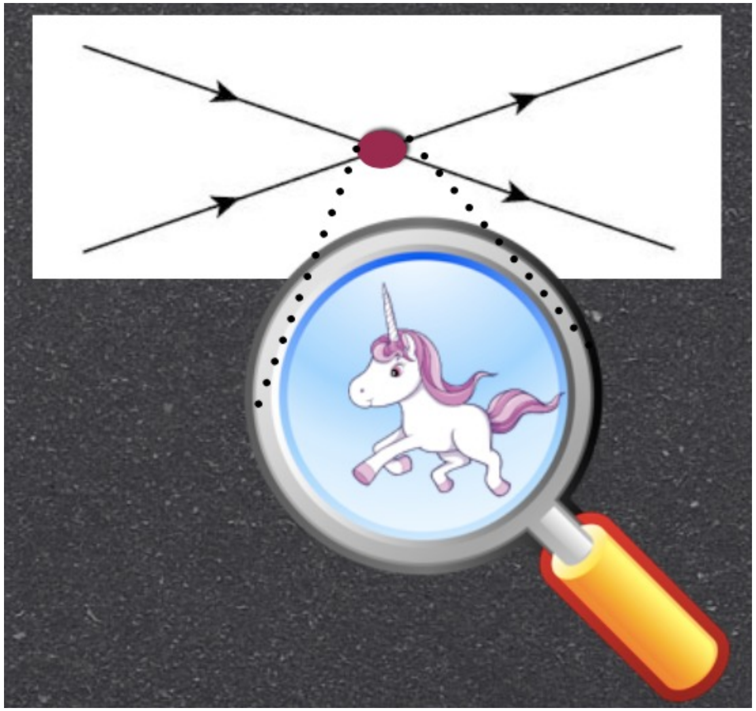
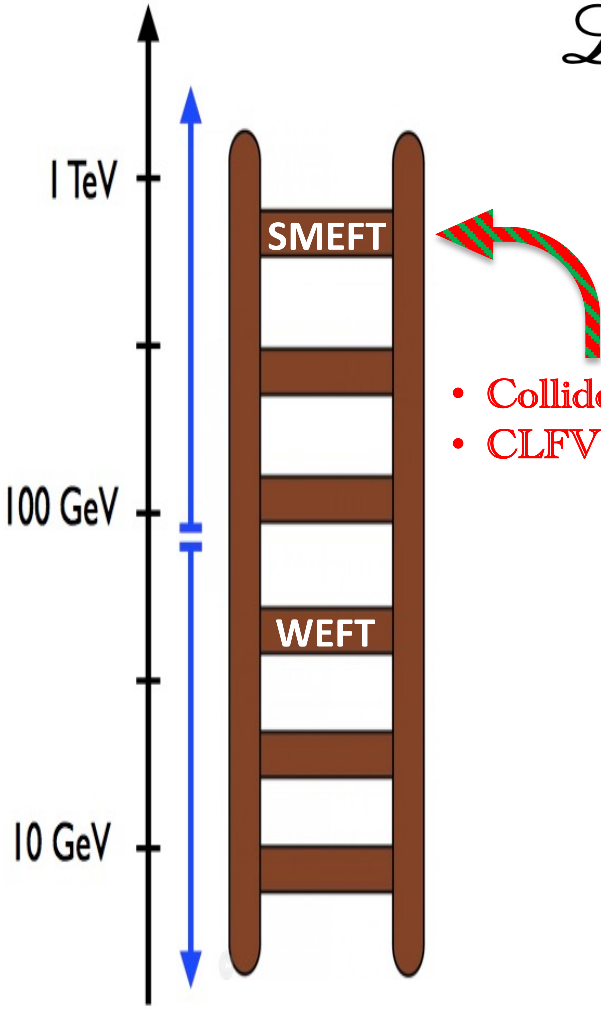


EFT ladder



- Colliders
- CLFV

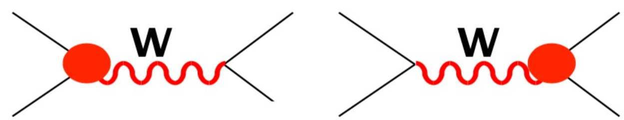
SMEFT: minimal EFT above the weak scale

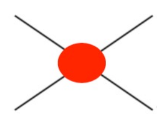
$$\mathscr{L}_{\mathrm{SMEFT}} = \mathscr{L}_{\mathrm{SM}} + \mathscr{L}_{D=5} + \boxed{\mathscr{L}_{D=6}}$$

Known SM Lagrangian

Gives neutrino Masses

+

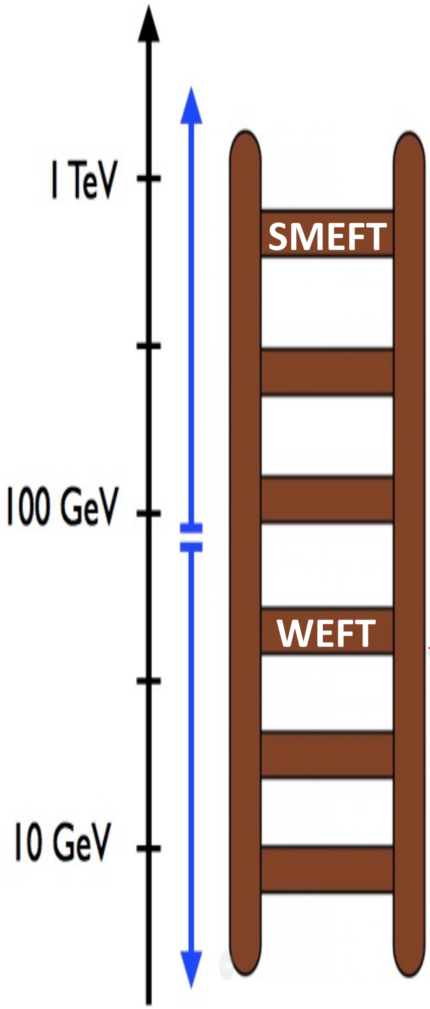




$$O_{lq}^{(3)} = (\bar{l}\gamma^{\mu}\sigma^{a}l)(\bar{q}\gamma_{\mu}\sigma^{a}q)$$
$$O_{qde} = (\bar{l}e)(\bar{d}q) + \mathrm{h.c.}$$
$$O_{lq} = (\bar{l}_a e)\epsilon^{ab}(\bar{q}_b u) + \mathrm{h.c.}$$
$$O_{lq}^{t} = (\bar{l}_a \sigma^{\mu\nu} e)\epsilon^{ab}(\bar{q}_b \sigma_{\mu\nu} u) + \mathrm{h.c.}$$

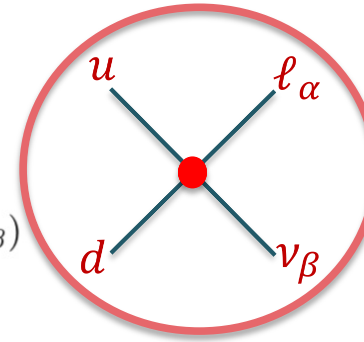
EFT ladder

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



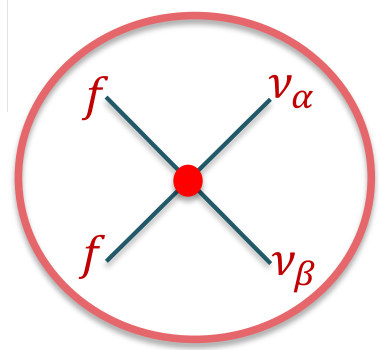
- CC: New left/right handed, (pseudo)scalar and tensor interactions

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



- NC: New left and right handed interactions

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



- Neutrino experiments
- Hadron Decays
- β-decays

Why EFT?

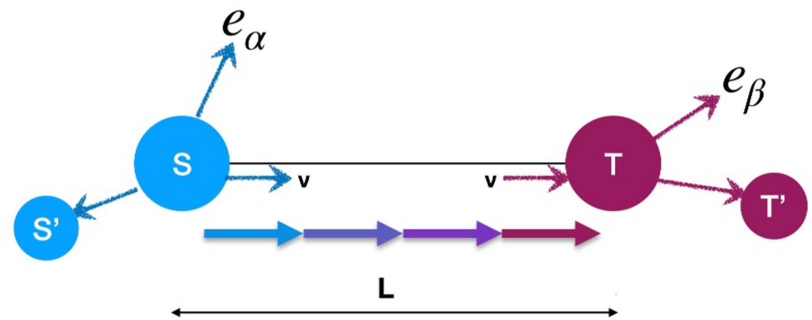
- One consistent framework to probe different aspects of particle interactions;
- Constraints from different low/high experiments can be meaningfully compared;
- Results can be translated into specific new physics models;
- We can probe very heavy particles, often beyond the reach of present colliders, by precisely measuring low-energy observables;

What's the place of neutrino experiments in this program?

EFT at neutrino experiments

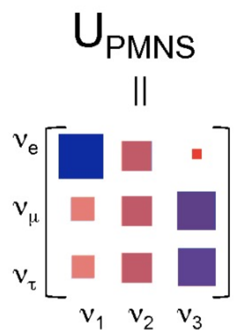
We proposed a systematic approach to neutrino oscillations in the SMEFT framework!

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



Observable: rate of detected events

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



depend on the kinematic and spin variables

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

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

Can the new interactions "enhance" the SM cross section/flux?

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

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

Pion decay

Production

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

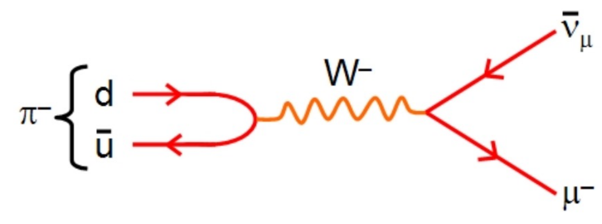
Due to the pseudoscalar nature of the pion, it is sensitive only to axial (ε_L-ε_R) and pseudo-scalar (ε_P) interactions.

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

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

~-27

~700!



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

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

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

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

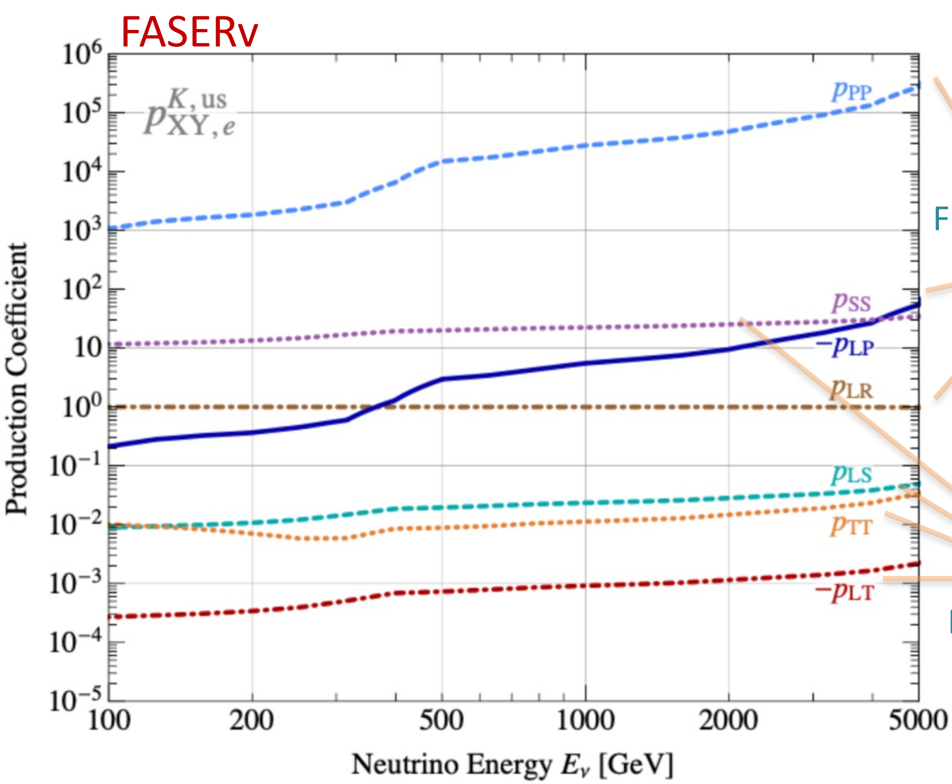
$$\langle 0|\, \bar{d}\gamma_5 u\, |\pi^+(p_\pi)\rangle = -i\frac{m_\pi^2}{m_u+m_d} f_\pi$$

Huge overall flux normalization for pion decay!

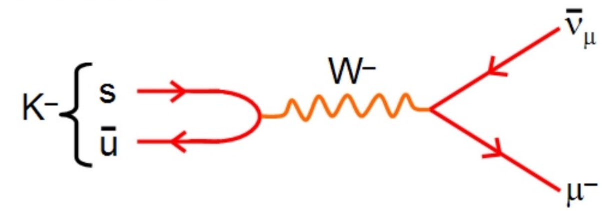
Production

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

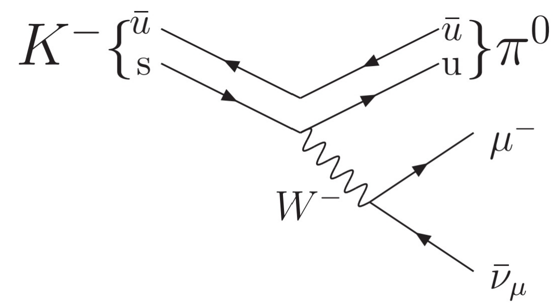
Both 2-body and 3-body kaon decays contribute:



From 2-b decay



K⁻(sū) → μ⁻ + $\bar{\nu}_\mu$



From 3-b decay

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

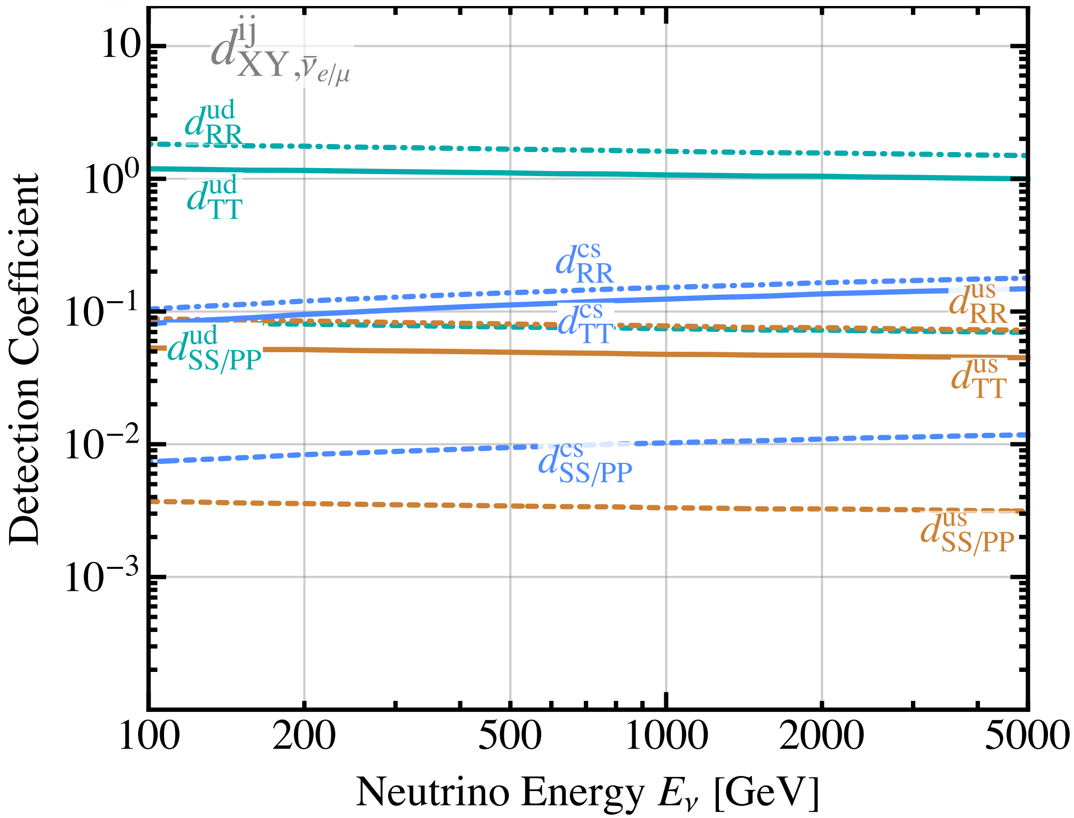
$$\langle \pi^- | \bar{s} u | K^0 \rangle = -\frac{m_K^2 - m_\pi^2}{m_s - m_u} f_0(q^2)\,,$$

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

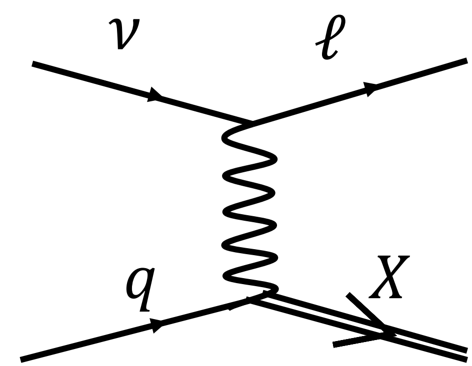
Depends on energy distribution of $K^\pm$, K_L or K_S at each experiments

Detection

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



Deep Inelastic Scattering



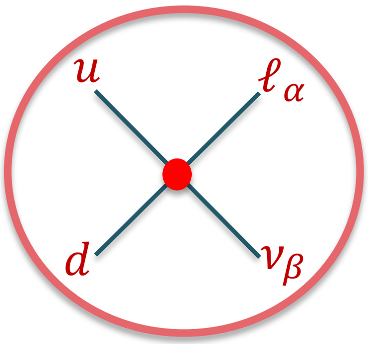
$$\sigma^{Total} \sim \sigma^{SM}(1+\varepsilon_X\, d_{XL} + \varepsilon_X{}^2\, d_{XX})$$

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

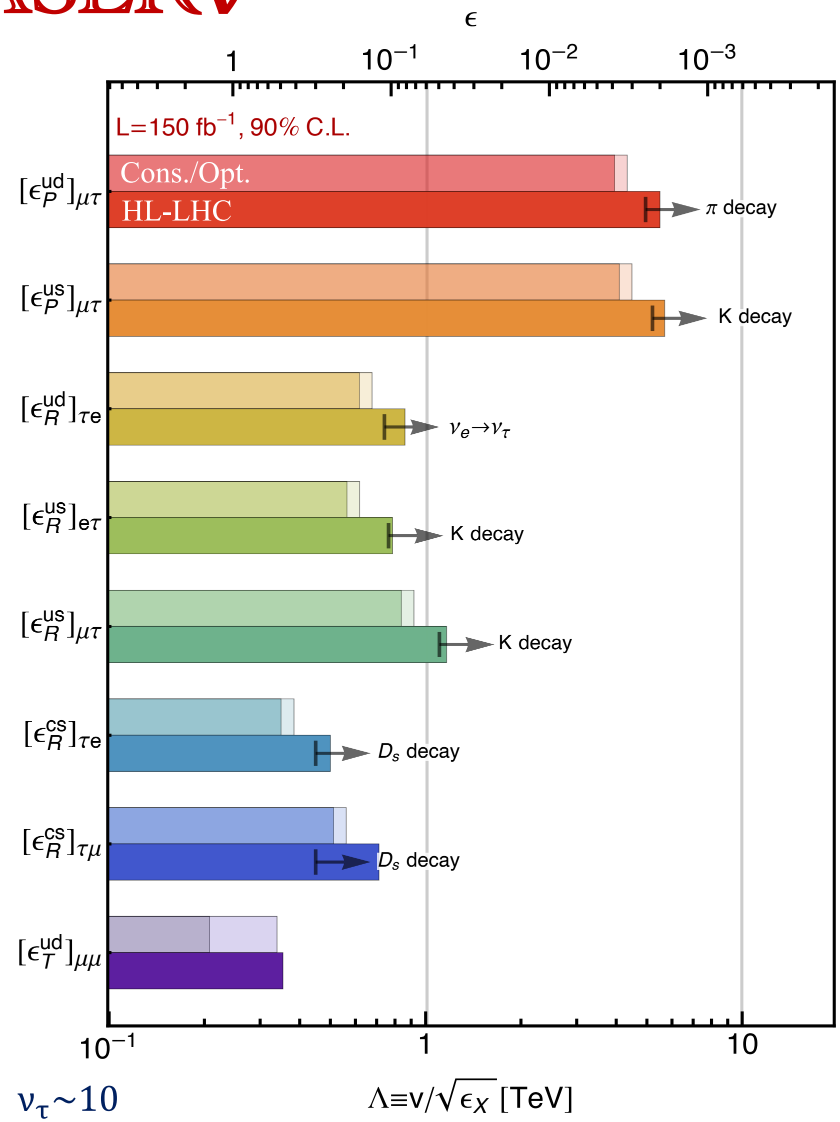
EFT at FASERν

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

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



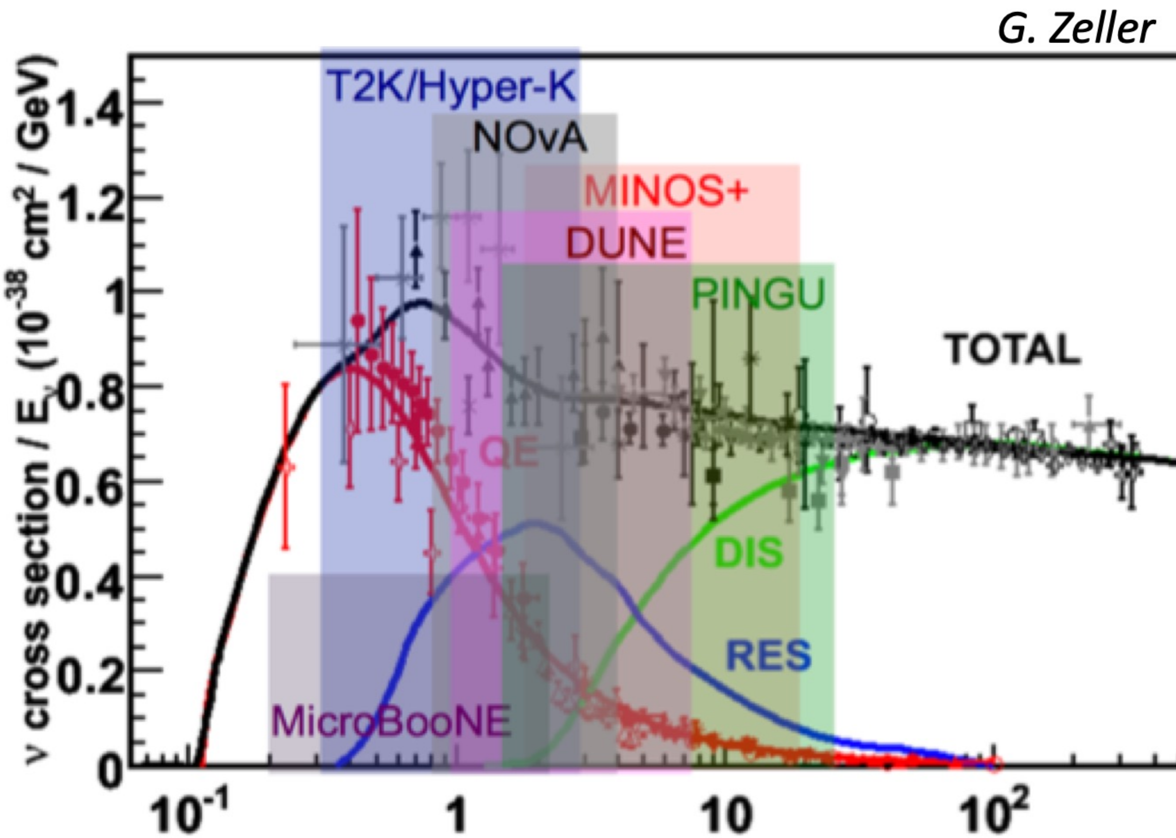
- Neutrino detectors can identify flavor: 81 operators at FASERν
- New physics reach at multi-TeV
- Complementary or dominant constraints



- ➢ Results are 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

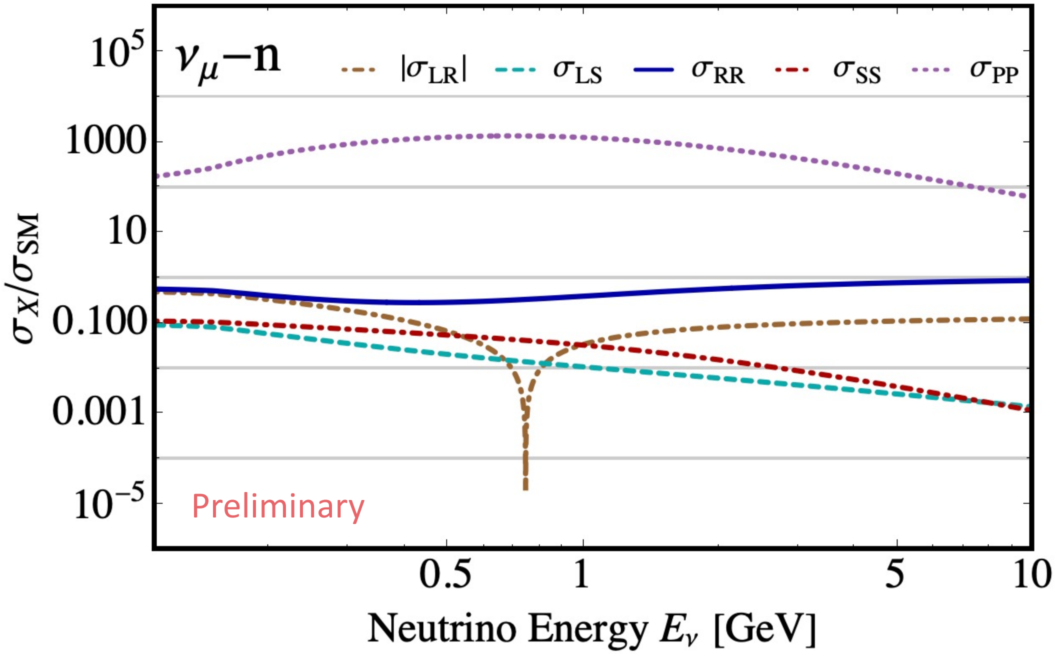
Long Baseline Accelerator Experiments

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



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

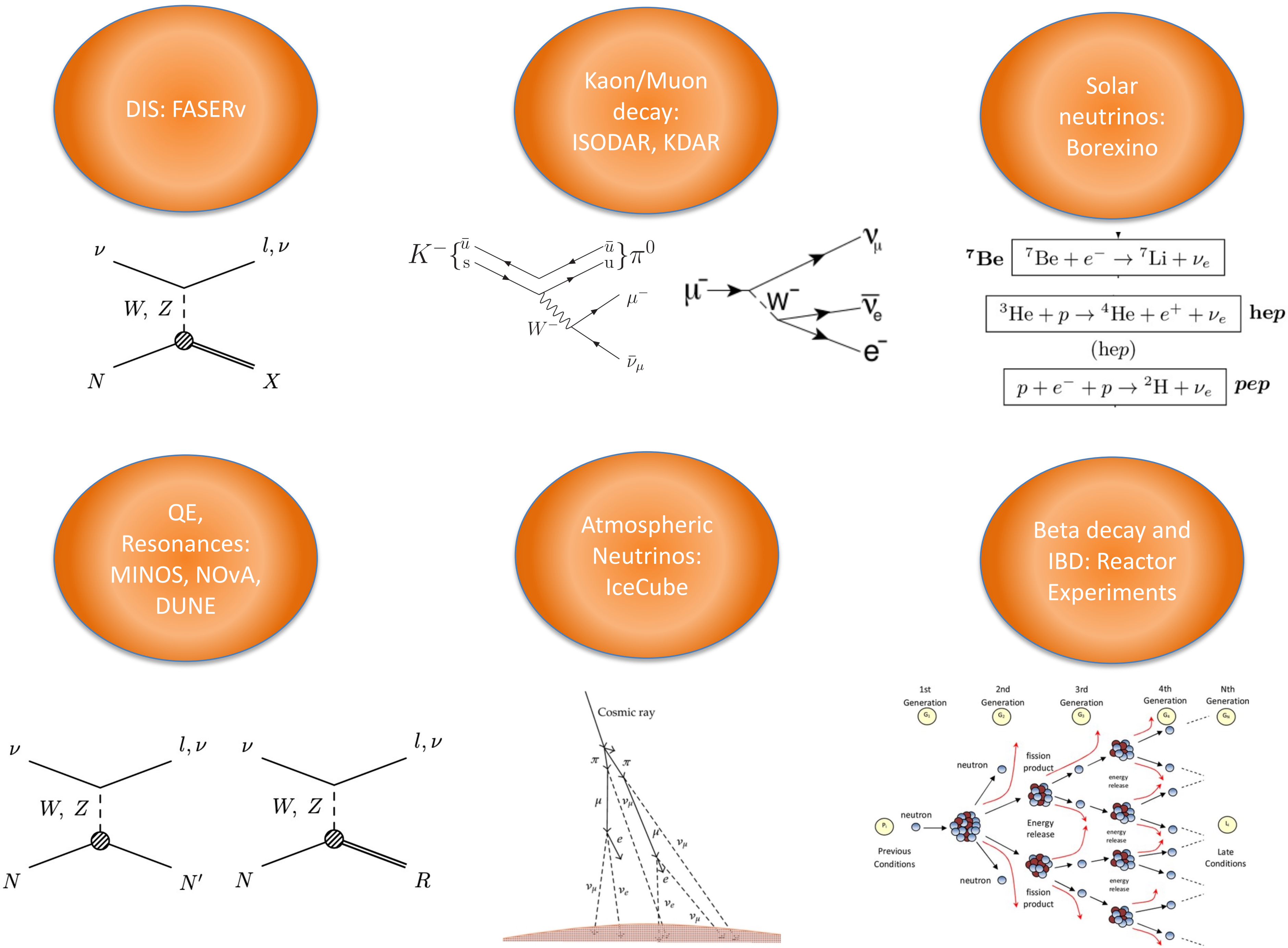
Quasi-Elastic scattering at the nucleon level



- 10^3 times x-section enhancement
- Much higher statistics

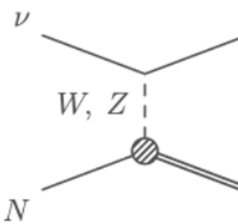
Kopp, Rocco, *ZT*, in preparation

Can neutrino experiments have access to new physics at 100 TeV scale?



DIS: FASERv
Kaon/Muon decay: ISODAR, KDAR
Solar neutrinos: Borexino
QE, Resonances: MINOS, NOvA, DUNE
Atmospheric Neutrinos: IceCube
Beta decay and IBD: Reactor Experiments
ν
l, ν
$W,\ Z$
N
X
$K^- \{^{\bar{u}}_{s}$
$^{\bar{u}}_{u}\} \pi^0$
W^-
μ^-
$\bar{\nu}_\mu$
μ^-
W^-
ν_μ
$\bar{\nu}_e$
e^-
^{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
N'
R
Cosmic ray
π
μ
ν_μ
e
ν_e
1st Generation
2nd Generation
3rd Generation
4th Generation
Nth Generation
neutron
fission product
energy release
Energy release
Previous Conditions
Late Conditions

DIS: FASERν



Solar neutrinos: Borexino

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

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

(hep)

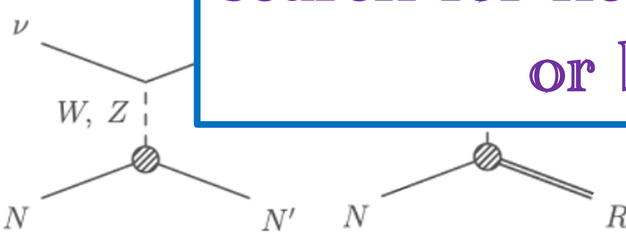
$e^- + p \to {}^2\mathrm{H} + \nu_e$ ***pep***

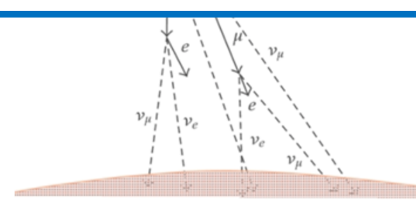
QE, Resonances: MINOS, NOvA DUNE

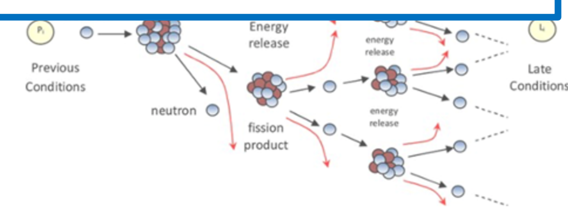
IceCube

eta 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:

- New generation of neutrino experiments are being built to answer many unknowns in the neutrino sectors;

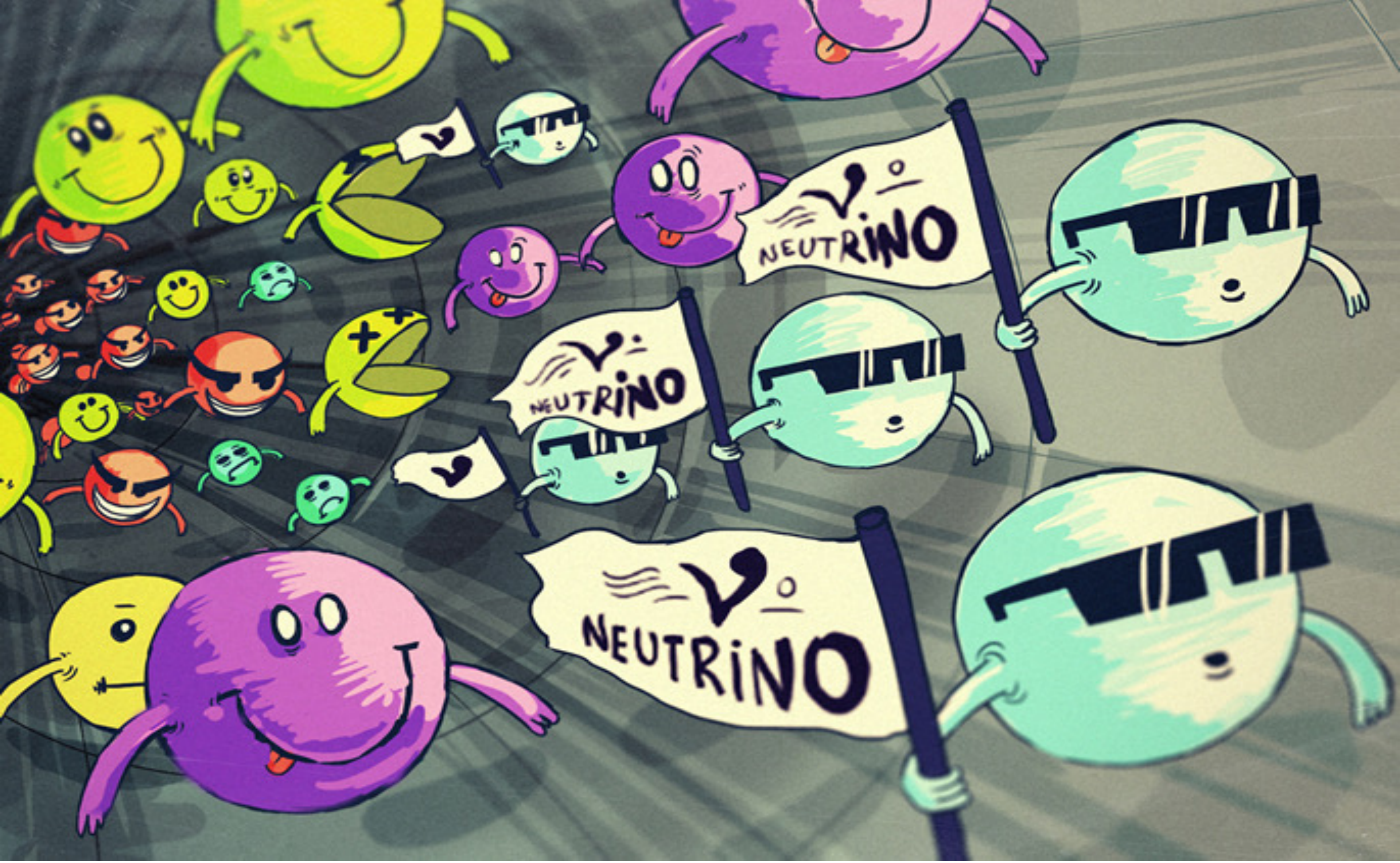
- We can use the near detectors to directly search for dark sector (e.g.: ALPs, light DM, etc.);

- For several BSM models, near detectors give the best constraints;

- We can probe very heavy particles, often beyond the reach of present colliders, by precisely measuring low-energy observables using the EFT formalism;

- 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.

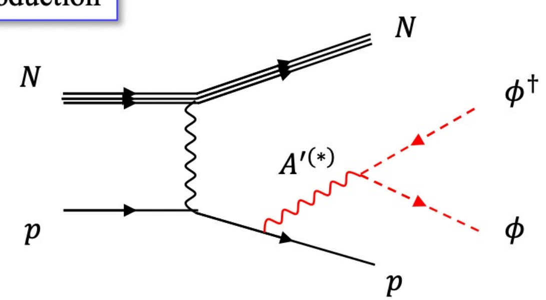


Thanks for your attention

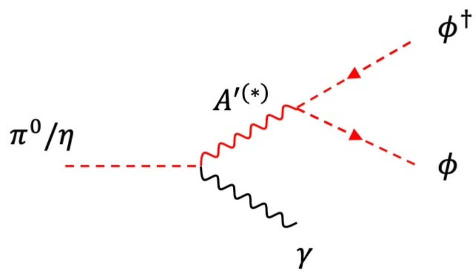
Back up Slides

Production and Detection of Dark Matter

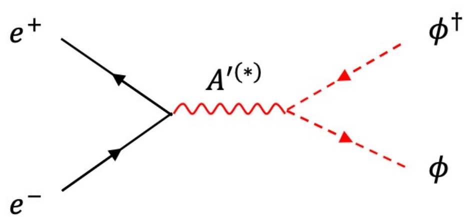
DM production



Beam bremsstrahlung

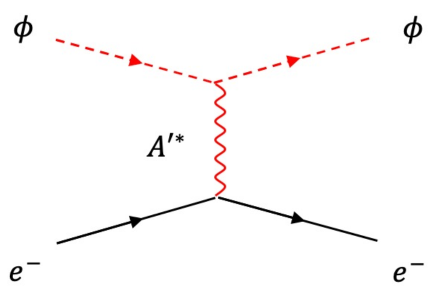


Neutral meson decays



Resonance production

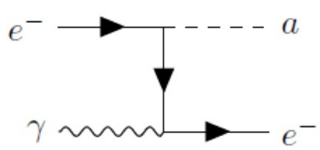
DM detection



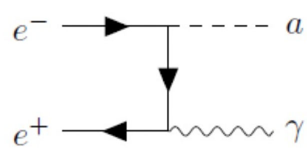
Elastic scattering with an electron

Production and Detection of ALPs

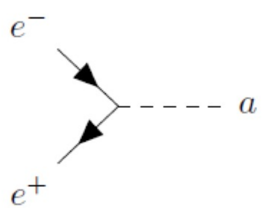
ALP production



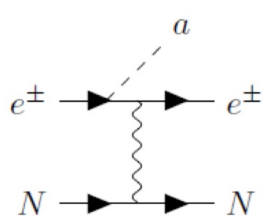
Compton



Associated production

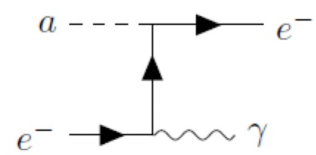


Resonant production

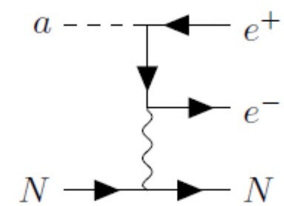


ALP-bremsstrahlung

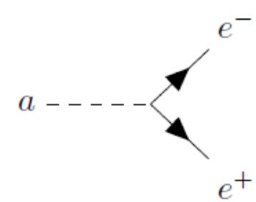
ALP detection



Inverse Compton

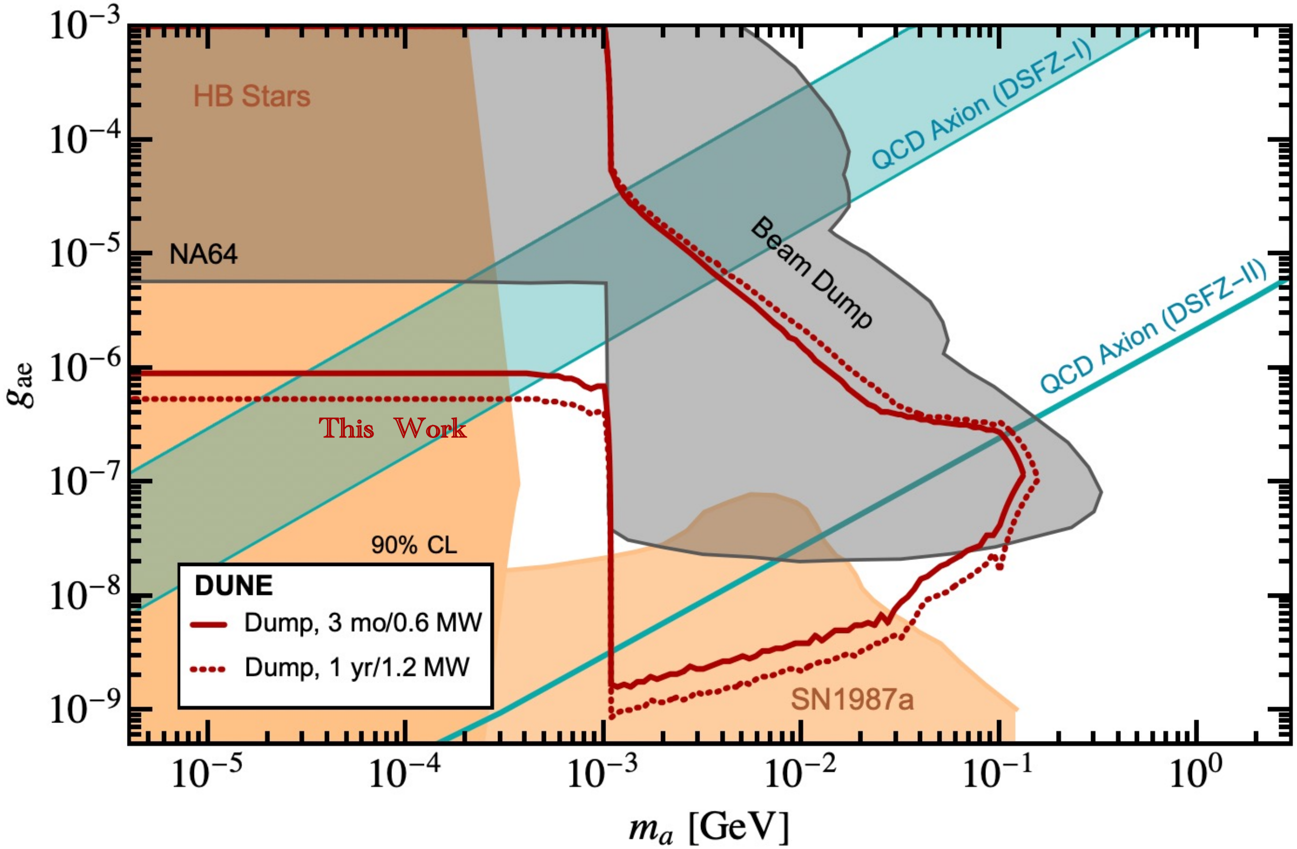


External pair conversion



Di-lepton decay

ALPs at Neutrino Experiments



Bhattarai, Brdar, Dutta, Jang, Kim, Shoemaker, *ZT*, Thompson, Yu
arXiv: 2206.06380

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

WEFT-SMEFT Matching:

SMEFT:

$$
\begin{aligned}
\mathcal{L} \supset\ & \frac{g_{L,0}\, g_{Y,0}}{\sqrt{g_{L,0}^2 + g_{Y,0}^2}} A_\mu \sum_f Q_f (\bar e_I \bar\sigma_\mu e_I + e_I^c \sigma_\mu \bar e_I^c) \\
+\ & \left[\frac{[g_L^{We}]_{IJ}}{\sqrt{2}} W_\mu^+ \bar\nu_I \bar\sigma_\mu e_J + W_\mu^+ \frac{[g_L^{Wq}]_{IJ}}{\sqrt{2}} \bar u_I \bar\sigma_\mu d_J + \frac{[g_R^{Wq}]_{IJ}}{\sqrt{2}} W_\mu^+ u_I^c \sigma_\mu \bar d_J^c + \text{h.c.} \right] \\
+\ & Z_\mu \sum_{f=u,d,e,\nu} [g_L^{Zf}]_{IJ} \bar f_I \bar\sigma_\mu f_J + Z_\mu \sum_{f=u,d,e} [g_R^{Zf}]_{IJ} f_I^c \sigma_\mu \bar f_J^c .
\end{aligned}
$$

+

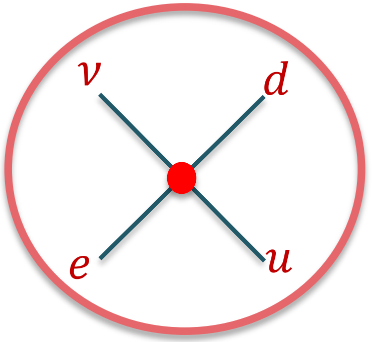
Chirality conserving $(I, J = 1, 2, 3)$	Chirality violating $(I, J = 1, 2, 3)$
$[O_{\ell q}]_{IIJJ} = (\bar\ell_I \bar\sigma_\mu \ell_I)(\bar q_J \bar\sigma^\mu q_J)$	$[O_{\ell equ}]_{IIJJ} = (\bar\ell_I^j \bar e_I^c)\epsilon_{jk}(\bar q_J^k \bar u_J^c)$
$[O_{\ell q}^{(3)}]_{IIJJ} = (\bar\ell_I \bar\sigma_\mu \sigma^i \ell_I)(\bar q_J \bar\sigma^\mu \sigma^i q_J)$	$[O_{\ell equ}^{(3)}]_{IIJJ} = (\bar\ell_I^j \bar\sigma_{\mu\nu} \bar e_I^c)\epsilon_{jk}(\bar q_J^k \bar\sigma_{\mu\nu} \bar u_J^c)$
$[O_{\ell u}]_{IIJJ} = (\bar\ell_I \bar\sigma_\mu \ell_I)(u_J^c \sigma^\mu \bar u_J^c)$	$[O_{\ell edq}]_{IIJJ} = (\bar\ell_I^j \bar e_I^c)(d_J^c q_J^j)$
$[O_{\ell d}]_{IIJJ} = (\bar\ell_I \bar\sigma_\mu \ell_I)(d_J^c \sigma^\mu \bar d_J^c)$	
$[O_{eq}]_{IIJJ} = (e_I^c \sigma_\mu \bar e_I^c)(\bar q_J \bar\sigma^\mu q_J)$	
$[O_{eu}]_{IIJJ} = (e_I^c \sigma_\mu \bar e_I^c)(u_J^c \sigma^\mu \bar u_J^c)$	
$[O_{ed}]_{IIJJ} = (e_I^c \sigma_\mu \bar e_I^c)(d_J^c \sigma^\mu \bar d_J^c)$	

One flavor $(I = 1, 2, 3)$	Two flavors $(I < J = 1, 2, 3)$
$[O_{\ell\ell}]_{IIII} = \frac{1}{2}(\bar\ell_I \bar\sigma_\mu \ell_I)(\bar\ell_I \bar\sigma^\mu \ell_I)$	$[O_{\ell\ell}]_{IIJJ} = (\bar\ell_I \bar\sigma_\mu \ell_I)(\bar\ell_J \bar\sigma^\mu \ell_J)$
	$[O_{\ell\ell}]_{IJJI} = (\bar\ell_I \bar\sigma_\mu \ell_J)(\bar\ell_J \bar\sigma^\mu \ell_I)$
$[O_{\ell e}]_{IIII} = (\bar\ell_I \bar\sigma_\mu \ell_I)(e_I^c \sigma^\mu \bar e_I^c)$	$[O_{\ell e}]_{IIJJ} = (\bar\ell_I \bar\sigma_\mu \ell_I)(e_J^c \sigma^\mu \bar e_J^c)$
	$[O_{\ell e}]_{JJII} = (\bar\ell_J \bar\sigma_\mu \ell_J)(e_I^c \sigma^\mu \bar e_I^c)$
	$[O_{\ell e}]_{IJJI} = (\bar\ell_I \bar\sigma_\mu \ell_J)(e_J^c \sigma^\mu \bar e_I^c)$
$[O_{ee}]_{IIII} = \frac{1}{2}(e_I^c \sigma_\mu \bar e_I^c)(e_I^c \sigma^\mu \bar e_I^c)$	$[O_{ee}]_{IIJJ} = (e_I^c \sigma_\mu \bar e_I^c)(e_J^c \sigma^\mu \bar e_J^c)$

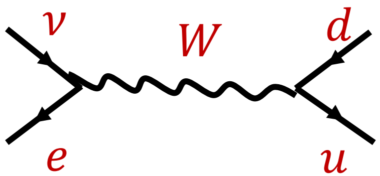
WEFT:

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

Specific New Physics Models

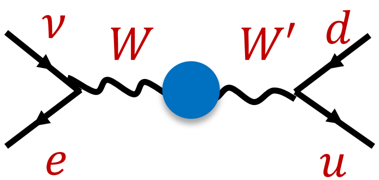


ε_L: **measures deviations of the W boson to quarks and leptons, compared to the SM prediction**



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

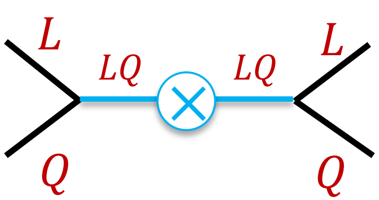
ε_R **: left-right symmetric $SU(3)_C xSU(2)_L xSU(2)_R xU(1)_X$ models introduce new charged vector bosons W' coupling to right-handed quarks**



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

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

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



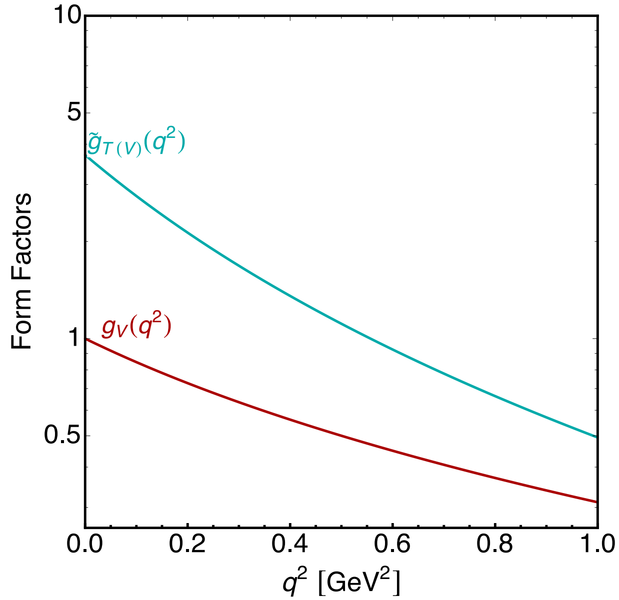
$$(LQ)(LQ)$$

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

QE matrix elements at the nucleon level

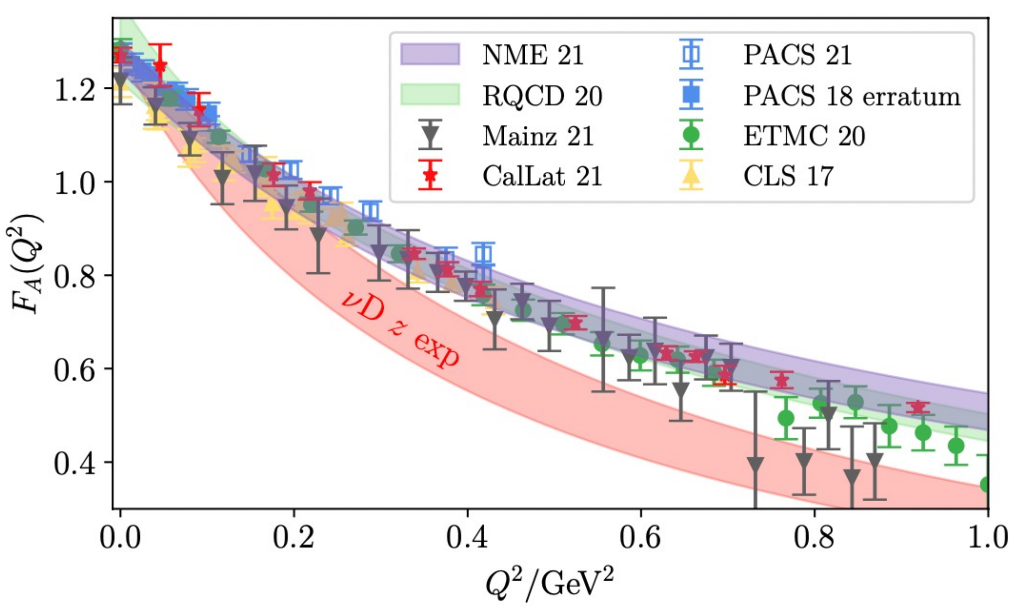
$$\langle p(p_p)|\, \bar{u}\gamma_\mu d\, |n(p_n)\rangle = \bar{u}_p(p_p)\left[g_V(q^2)\,\gamma_\mu - i\,\frac{\tilde{g}_{T(V)}(q^2)}{2M_N}\,\sigma_{\mu\nu}q^\nu + \cancel{\frac{\tilde{g}_S(q^2)}{2M_N}}\,q_\mu\right]u_n(p_n)$$

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



constrained by eN scattering

Kopp, Rocco, *ZT*, in preparation



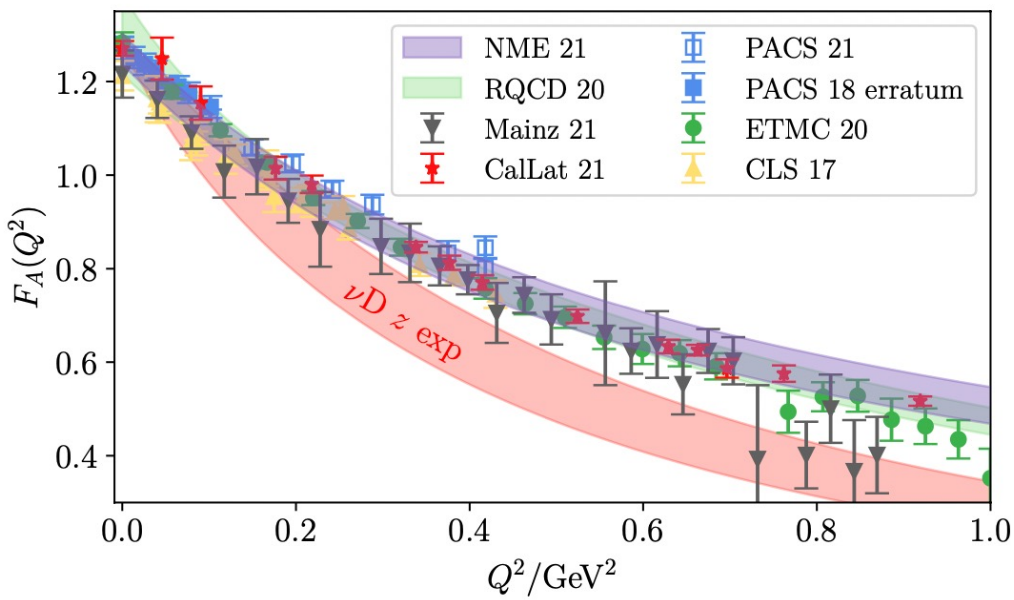
poorly constrained by expt.

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

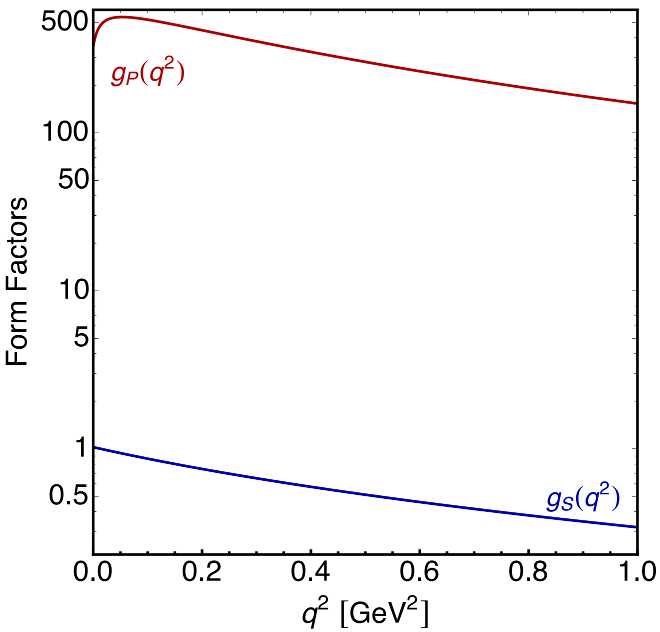
$$
\begin{aligned}
\langle p(p_p)|\,\bar u\, d\,|n(p_n)\rangle &= g_S(q^2)\;\bar u_p(p_p)\,u_n(p_n)\\
\langle p(p_p)|\,\bar u\,\gamma_5\, d\,|n(p_n)\rangle &= g_P(q^2)\;\bar u_p(p_p)\,\gamma_5\,u_n(p_n)\\
\langle p(p_p)|\,\bar u\,\sigma_{\mu\nu}\, d\,|n(p_n)\rangle &= \bar u_p(p_p)\,\Big[g_T(q^2)\,\sigma_{\mu\nu}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

- conservation of the vector current (CVC):

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

- partial conservation of the axial current (PCAC):

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

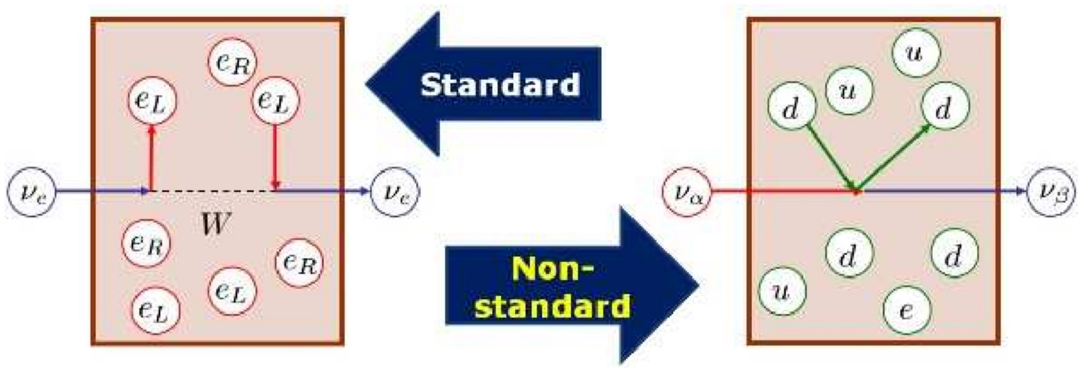


- We need axial form factor for NP as well
- Much larger statistics
- Large pseudo-scalar form factor (no q/M suppression)
- Different energy scale compare to beta decay experiments

Kopp, Rocco, *ZT*, in preparation

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)

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.

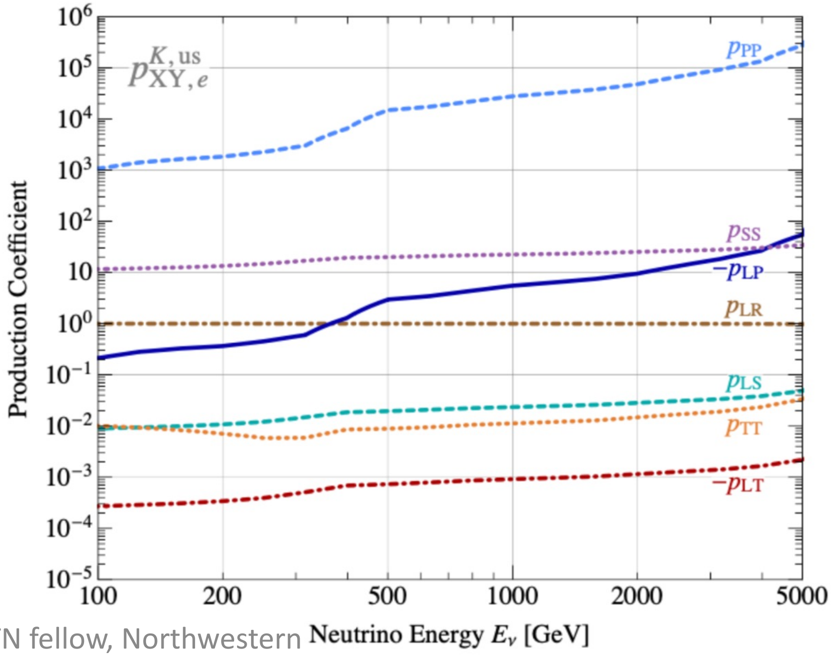
Comparing QM and QFT

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)

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

RESULTS

Turning on one interaction at a time: Right handed

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

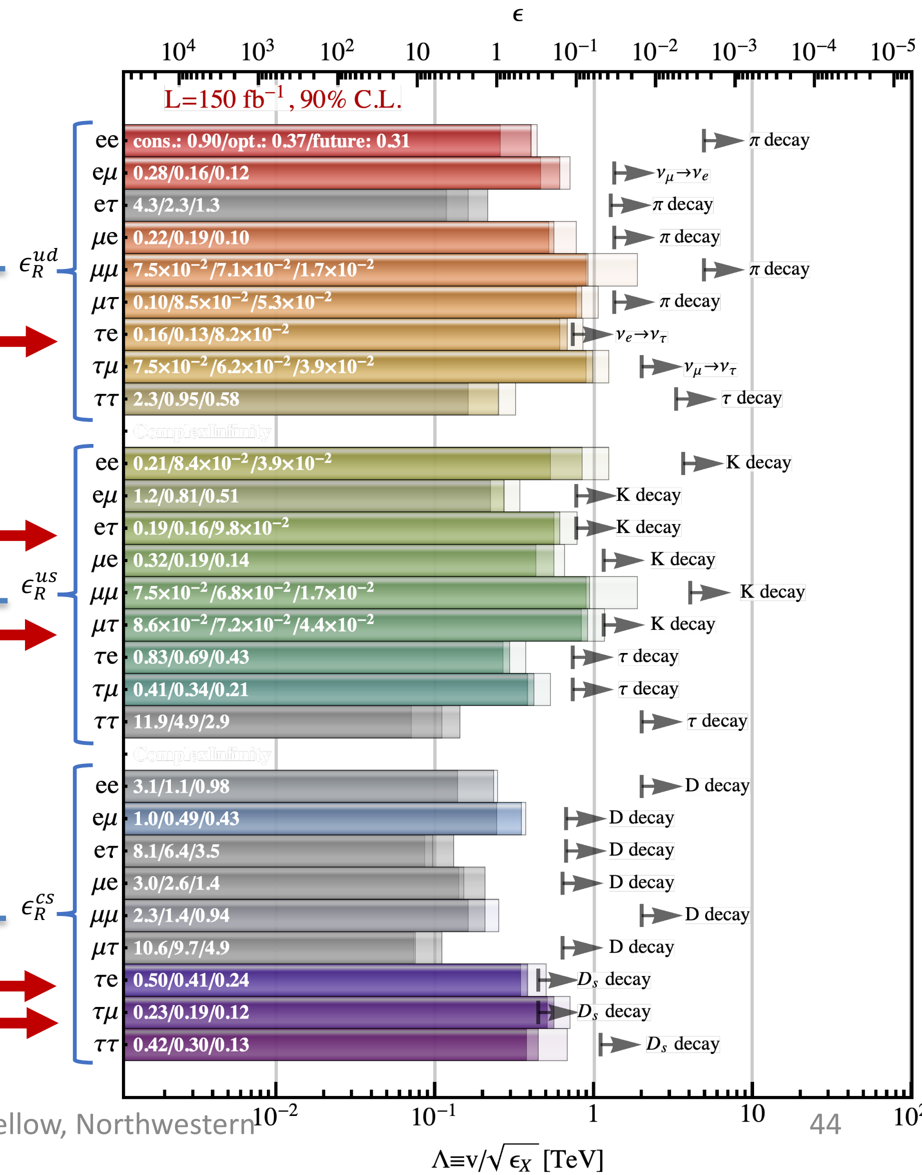
JHEP 10 (2021) 086

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



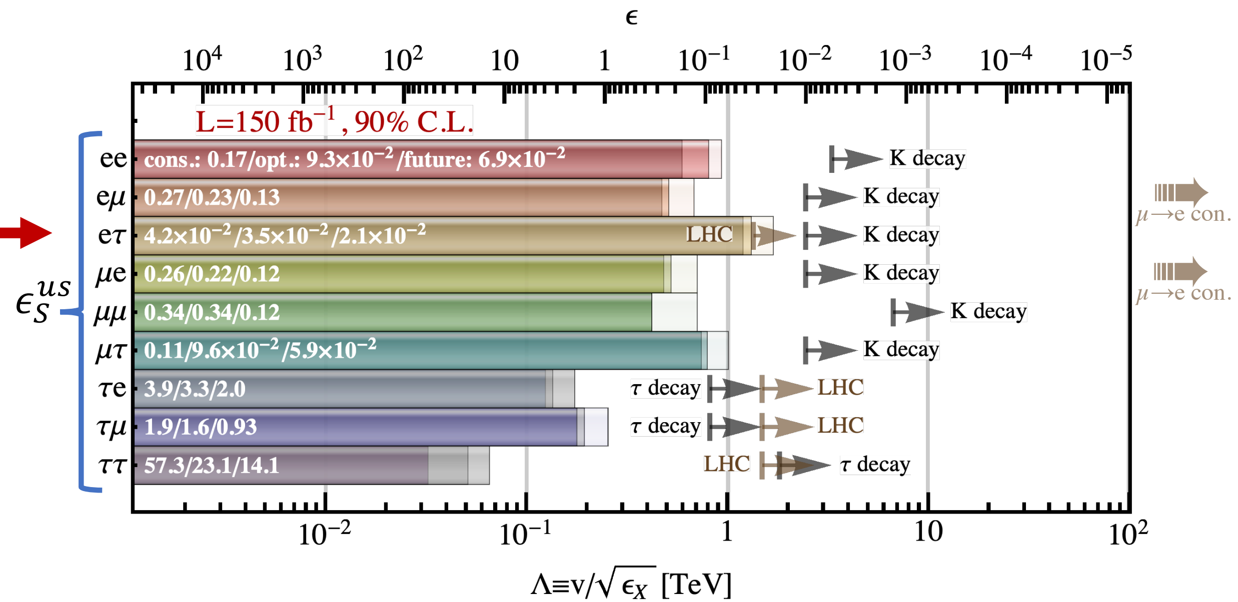
RESULTS

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

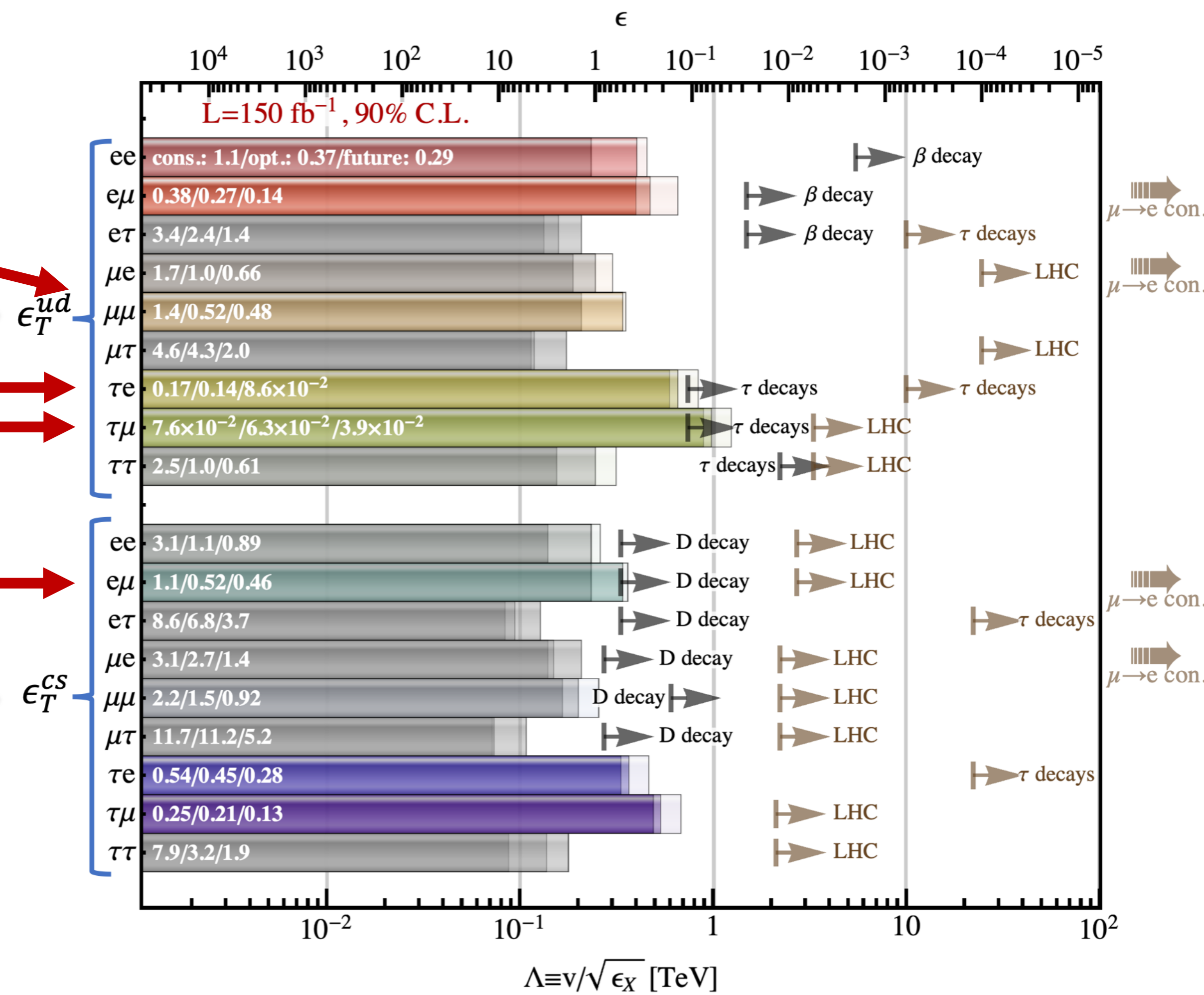
Turning on one interaction at a time: Tensor

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

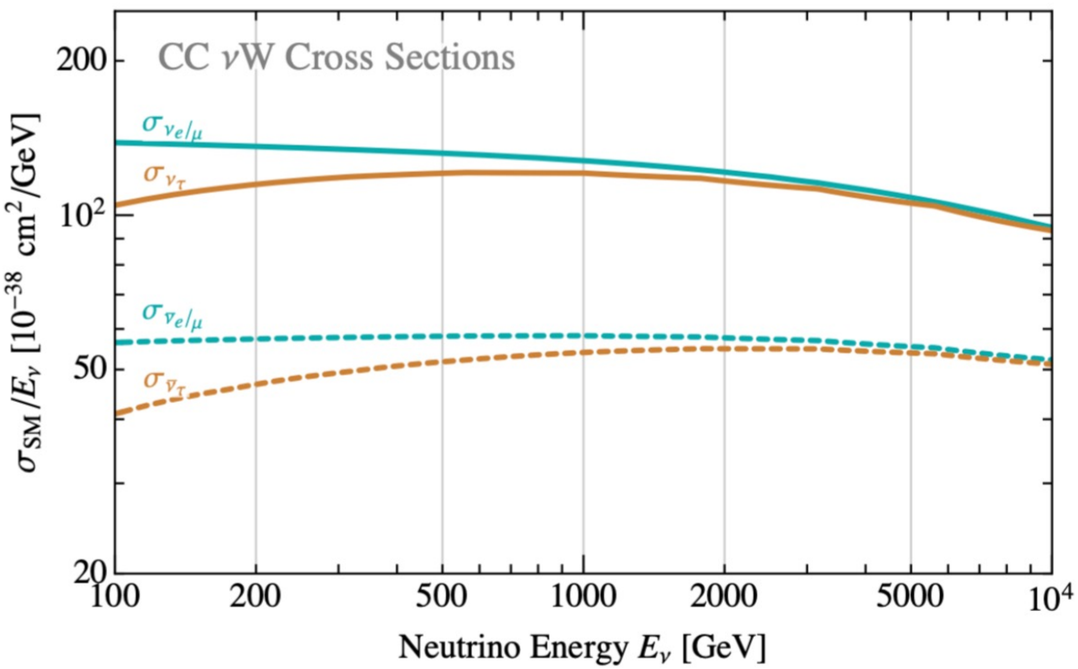
From charm decay and DIS



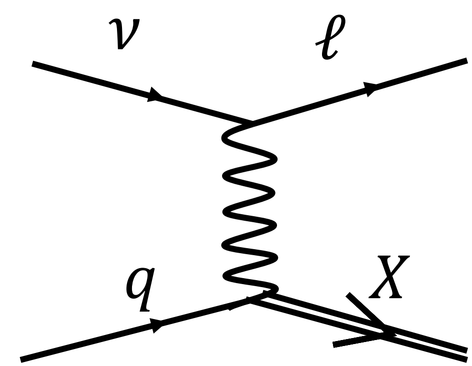
DIS

Detection

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



Deep Inelastic Scattering



DIS detection, easy to include NP

(compared to QE and Resonances)

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].

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
$[\epsilon_P^{ud}]_{ee}$	$\mathbf{4.6 \times 10^{-7}}$	$\mathbf{\Gamma_{\pi\to e\nu}/\Gamma_{\pi\to\mu\nu}}$		
$[\epsilon_P^{ud}]_{e\mu}$	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]