



# Unleashing the Power of EFT in Neutrino-Nucleus Scattering

Artwork by Sandbox Studio, Chicago with Ana Kova

“Collider, Dark Matter, and Neutrino Physics 2024”

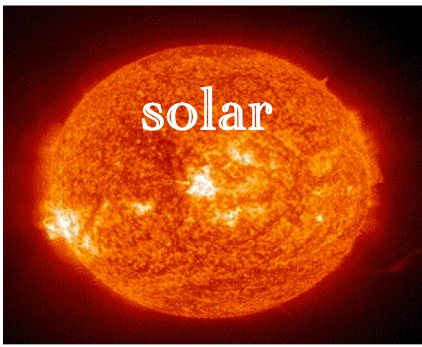
May 23-26, 2024

Zahra Tabrizi

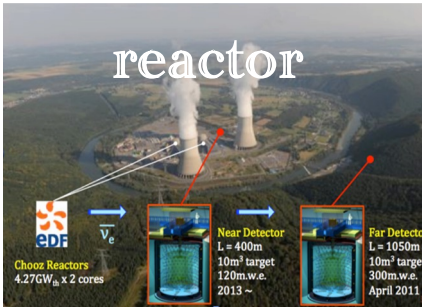
Neutrino Theory Network fellow



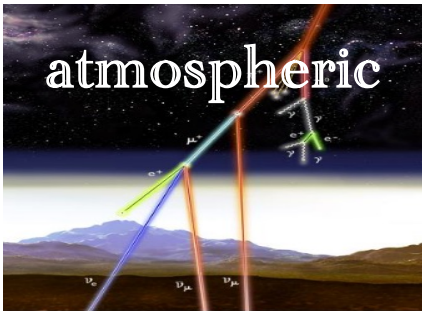
Northwestern  
University



# Precision Measurements at Oscillation Experiments

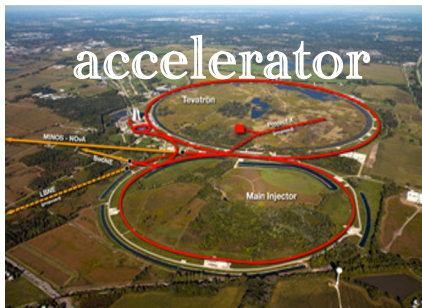


- Tons of data;
- Identify neutrino flavor;
- More sensitive to some HE operators;



## Goal:

A systematic analysis of NP using neutrino experiments;  
Connecting the results to other precision experiments;



# Goal:

- Going beyond the oscillation physics to answer other questions in particle physics;
- Fully leveraging the potential of these multi-billion dollar experiments to search for exotic particles;

- 
- 1) Direct Search of New Physics
  - 2) Indirect Search: EFT (This Talk)

# EFT ladder

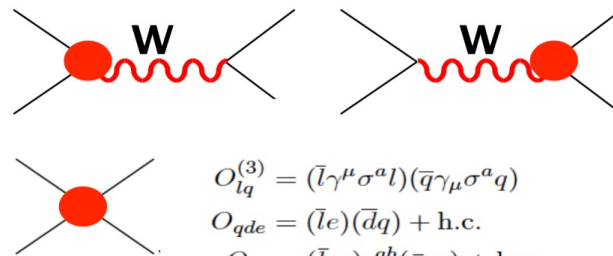
SMEFT: minimal EFT above the weak scale

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

Known SM  
Lagrangian

Gives neutrino  
Masses

- Colliders
- CLFV

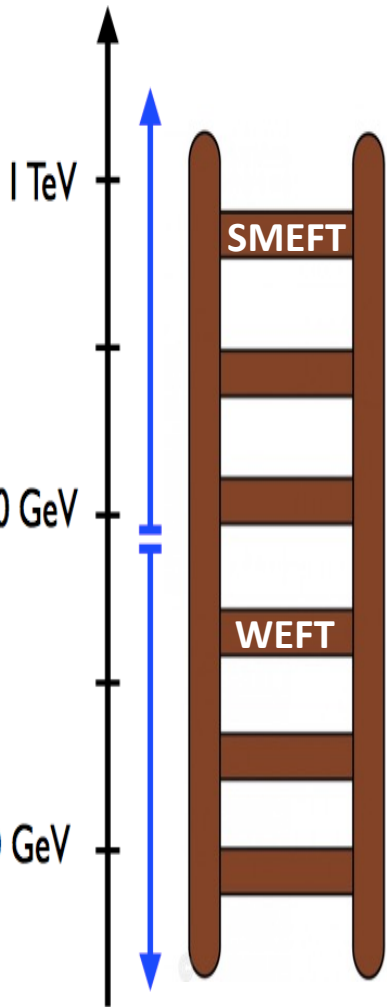


$$O_{lq}^{(3)} = (\bar{l}\gamma^\mu \sigma^a l)(\bar{q}\gamma_\mu \sigma^a q)$$

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

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

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

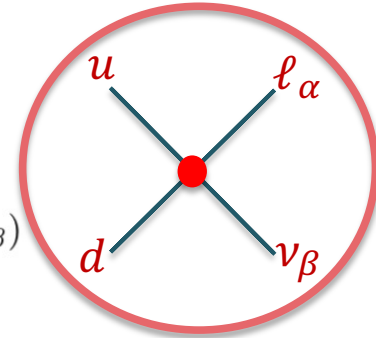


# EFT ladder

WEFT: Effective Lagrangian defined at a low scale  $\mu \sim 2 \text{ GeV}$

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

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

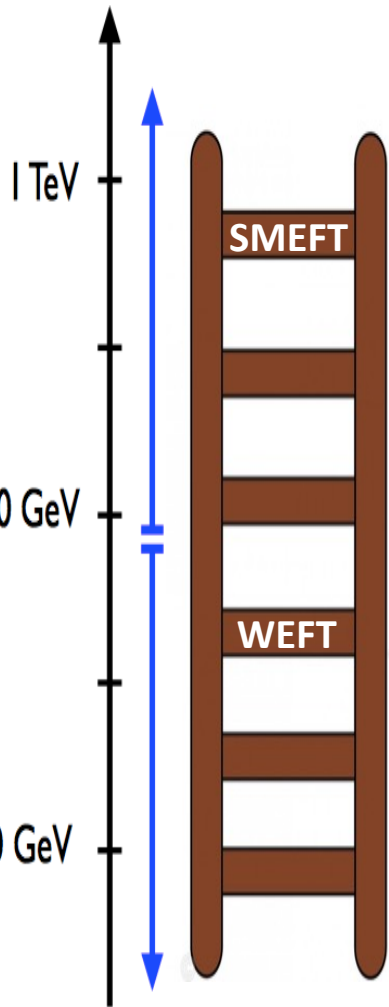
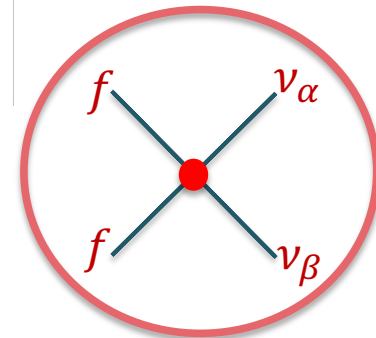


- NC: New left and right handed interactions

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

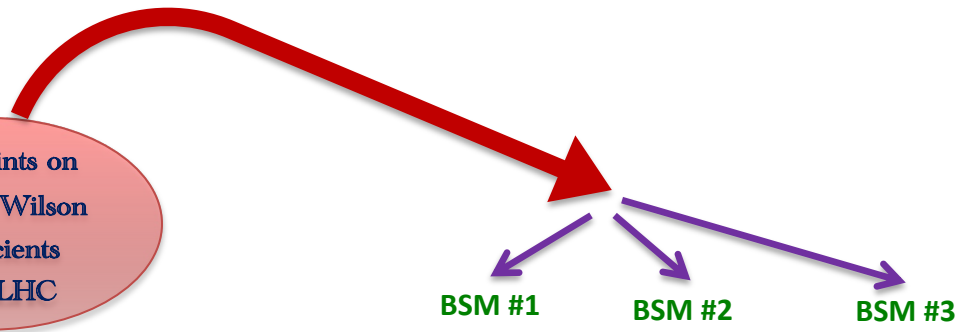
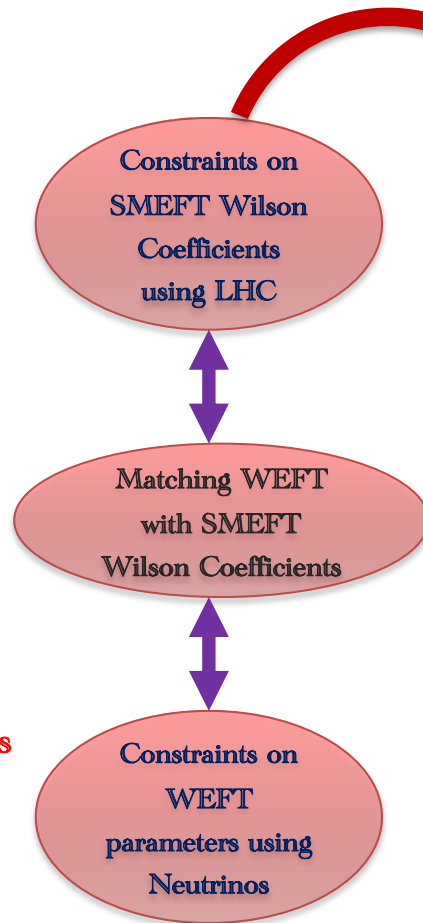
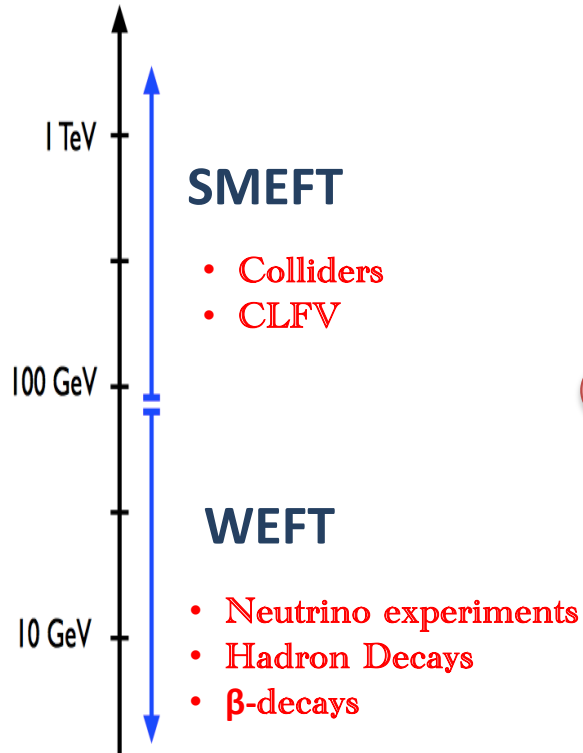


- Neutrino experiments
- Hadron Decays
- $\beta$ -decays



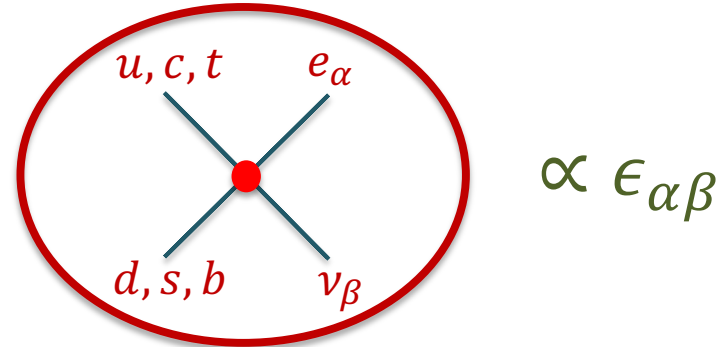
# EFT Workflow:

EFT Energy Scale



*Translation to specific benchmark models*

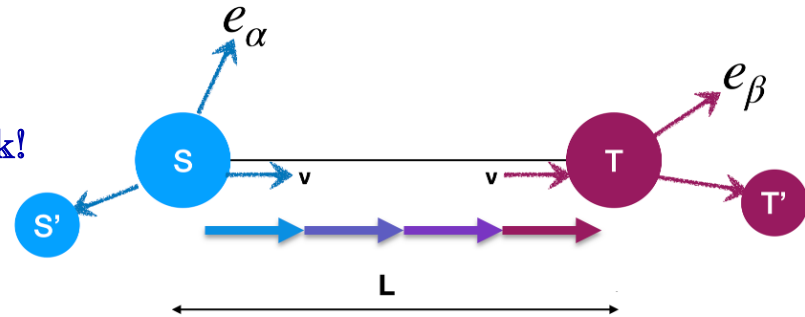
Probing heavy particles by precisely measuring low-energy observables



# EFT at neutrino experiments

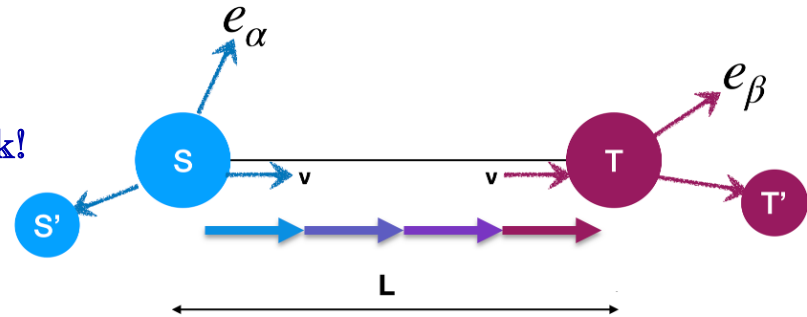
We have proposed a systematic approach to neutrino oscillations in the SMEFT framework!

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



# EFT at neutrino experiments

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

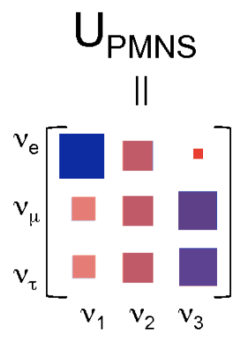


Observable: rate of detected events

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

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

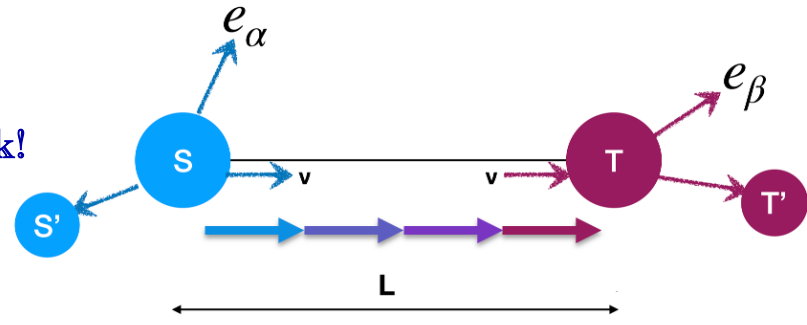
Falkowski, González-Alonso, ZT, JHEP (2020)





# EFT at neutrino experiments

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



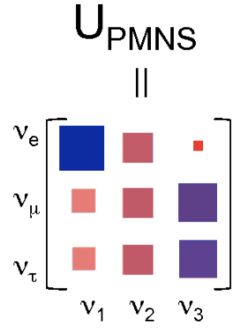
Observable: rate of detected events

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

CC EFT

NC EFT

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



depend on the kinematic and spin variables

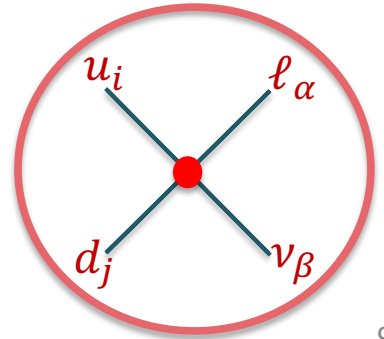
$$\mathcal{M}_{\alpha k}^P = U_{\alpha k}^* A_L^P + \sum_X [\epsilon_X U]_{\alpha k}^* A_X^P$$

$$\mathcal{M}_{\beta k}^D = U_{\beta k} A_L^D + \sum_X [\epsilon_X U]_{\beta k} A_X^D$$

Corrections to fluxes/cross sections

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

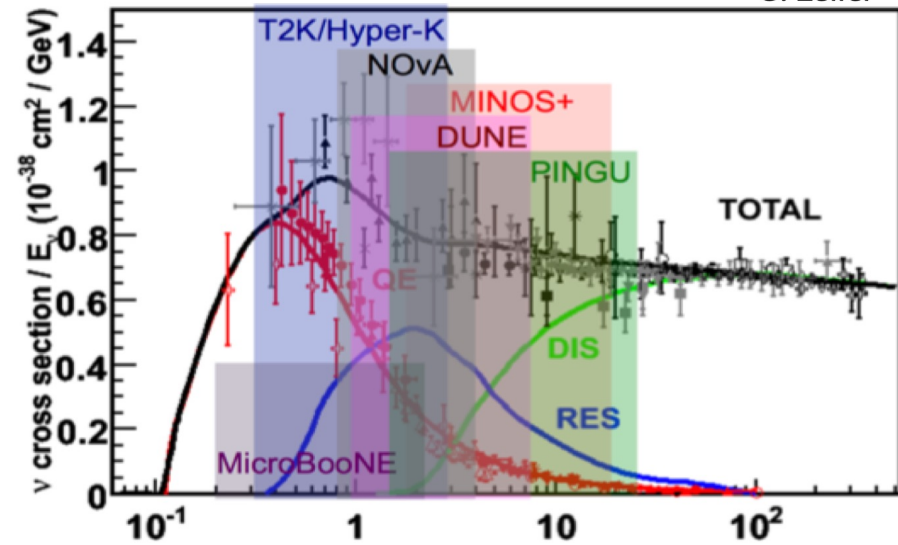
$$\phi^{\text{Total}} = \phi^{\text{SM}} + \epsilon_X \phi^{\text{Int}} + \epsilon_X^2 \phi^{\text{NP}} \sim \phi^{\text{SM}} (1 + \epsilon_X p_{XL} + \epsilon_X^2 p_{XX})$$



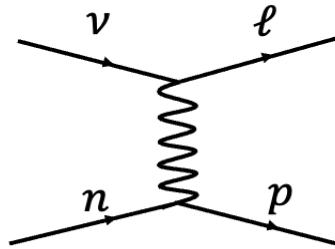
# Long Baseline Accelerator Experiments

G. Zeller

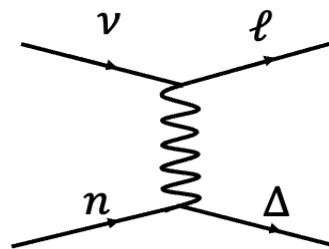
0.1-5 GeV: cross section is much more involved!



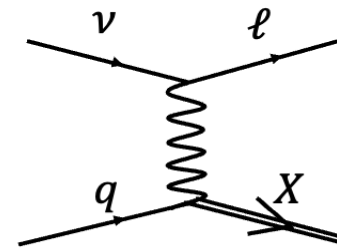
**Quasi-Elastic Scattering**



**Resonance Production**



**Deep Inelastic Scattering**



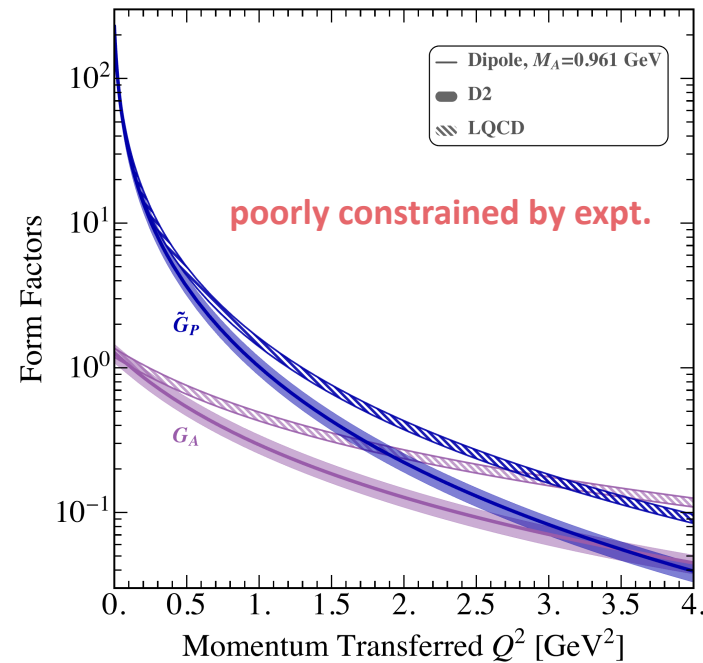
# CCQE Hadronic Matrix Elements

Kopp, Rocco, ZT, arXiv: 2401.07902

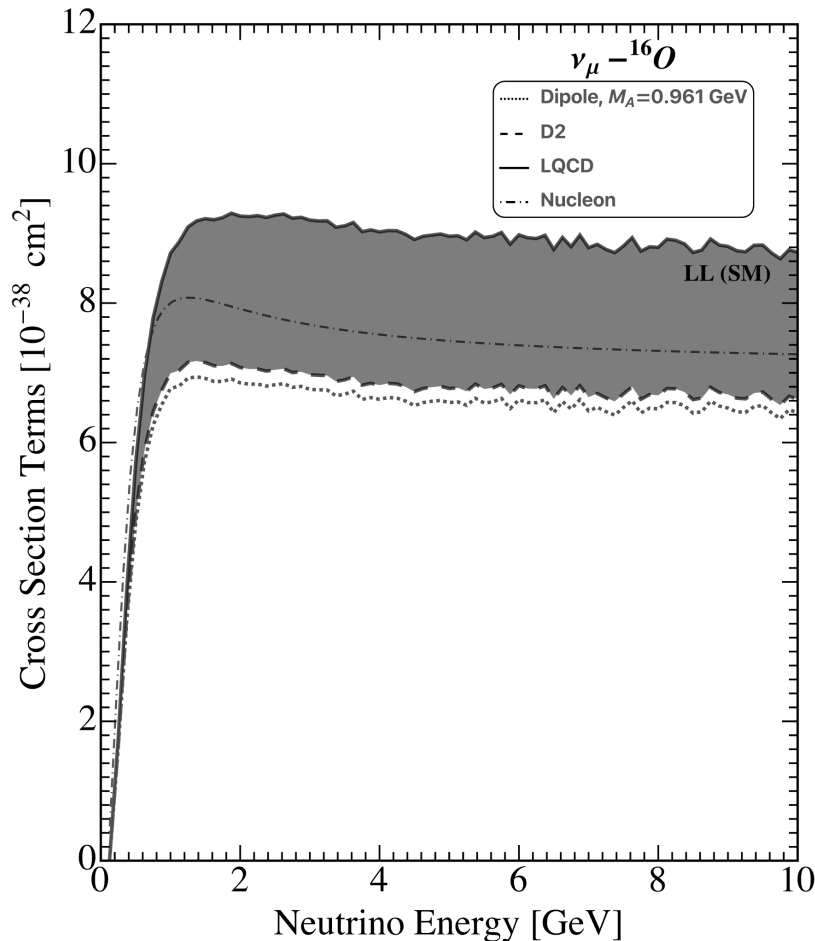
## SM-Interactions:

Vector Current: Form Factors well understood (constrained by eN scattering)

Axial Current:



# CCQE Neutrino-Nucleus Cross Sections



Kopp, Rocco, [ZT](#), arXiv: 2401.07902

- z-expansion fit to LQCD and D2 data;
- Nuclear effects;
- Comparison with nucleon scattering

**Large uncertainties from  
form factors!**

# NEW-Interactions:

Kopp, Rocco, ZT, arXiv: 2401.07902

- We add new scalar, pseudo-scalar and tensor currents;
- Interference with the SM;
- New Cross Section Contributions;

# NEW-Interactions:

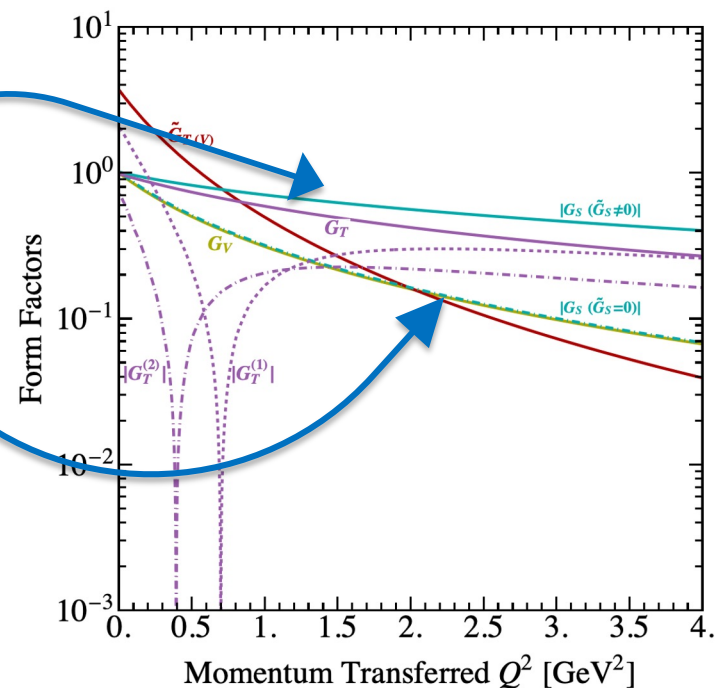
Kopp, Rocco, ZT, arXiv: 2401.07902

- We add new scalar, pseudo-scalar and tensor currents;
- Interference with the SM;
- New Cross Section Contributions;

- **Scalar: conservation of the vector current (CVC):**

$$G_S(Q^2) = -\frac{\delta M_N^{QCD}}{\delta m_q} G_V(Q^2) + \frac{Q^2/2M_N}{\delta m_q} \tilde{G}_S(Q^2)$$

- We cannot neglect  $\tilde{G}_S$  (second class current ) anymore!



# NEW-Interactions:

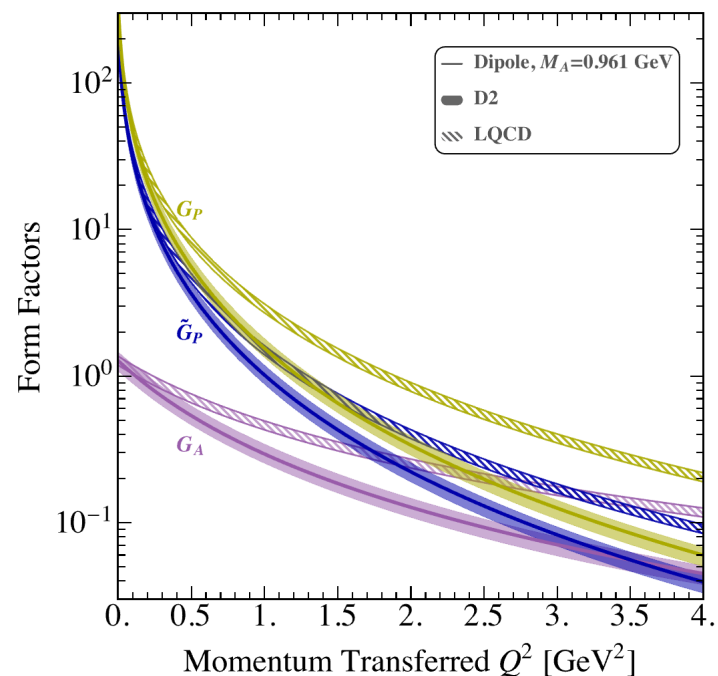
Kopp, Rocco, ZT, arXiv: 2401.07902

- We add new scalar, pseudo-scalar and tensor currents;
- Interference with the SM;
- New Cross Section Contributions;
- **Pseudo-Scalar: partial conservation of the axial current (PCAC)**

$$G_P(Q^2) = \frac{M_N}{m_q} G_A(Q^2) + \frac{Q^2/2M_N}{2m_q} \tilde{G}_P(Q^2)$$

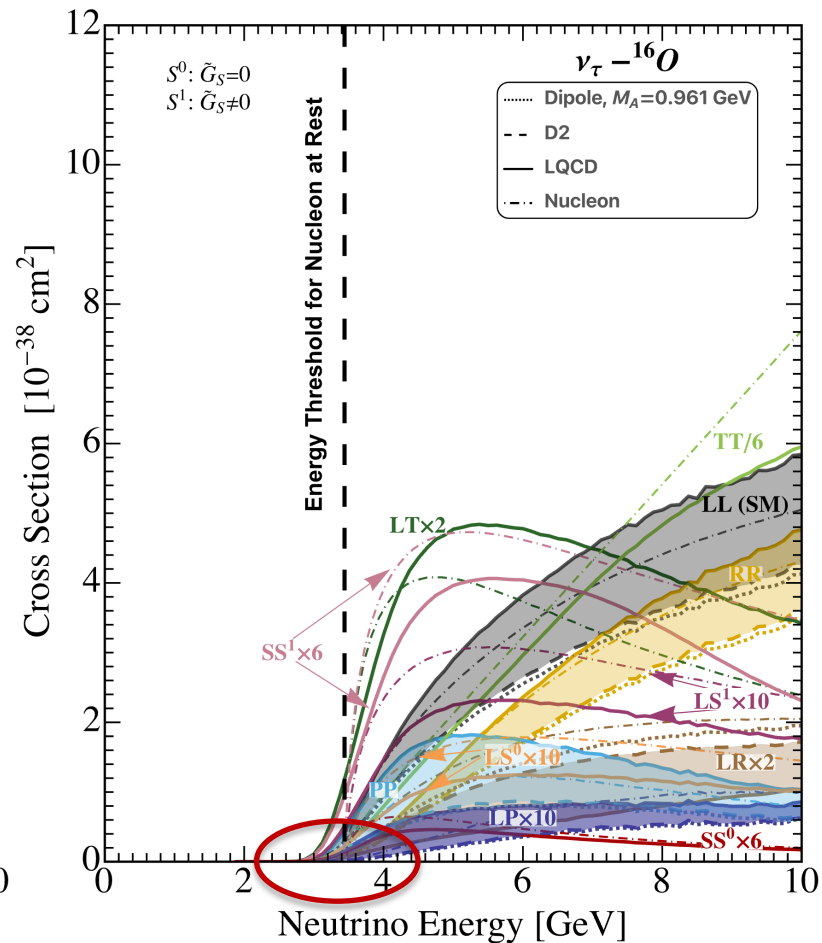
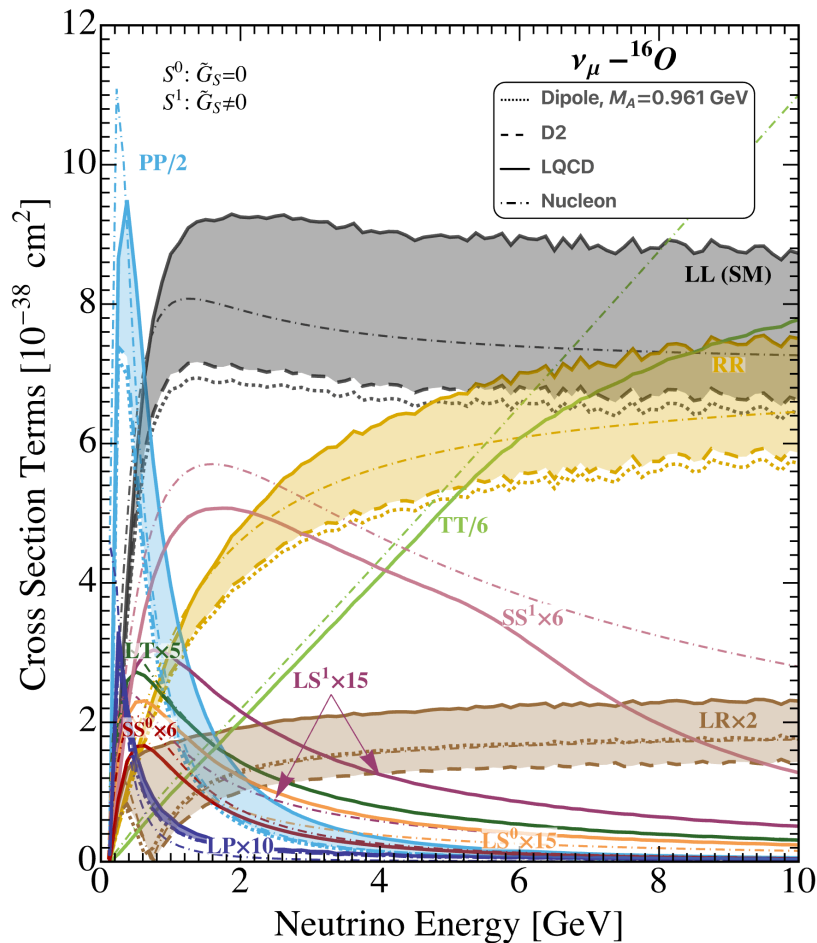
➤ D2: neutrino-deuterium data (shaded band)

➤ RQCD Collaboration (hatched band)



# CCQE Neutrino-Nucleus Cross Sections:

Kopp, Rocco, ZT, arXiv: 2401.07902



- z-expansion fit to LQCD and D2 data;
- Nuclear effects;
- Comparison with nucleon scattering



# How about flux corrections?

## Pion decay

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

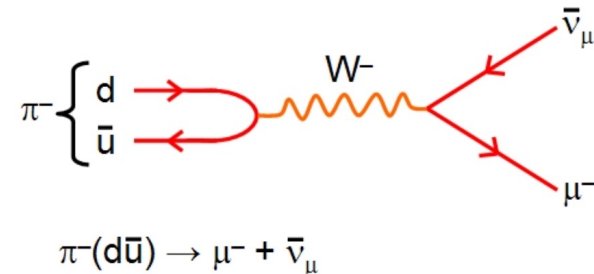
Due to the pseudoscalar nature of the pion, it is sensitive only to axial ( $\epsilon_L$ - $\epsilon_R$ ) and pseudo-scalar ( $\epsilon_P$ ) interactions.

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

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

~700!

~-27



- Larger  $p_{XY} \Rightarrow$  smaller  $\epsilon$ !

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

Huge overall flux  
normalization for pion  
decay!

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

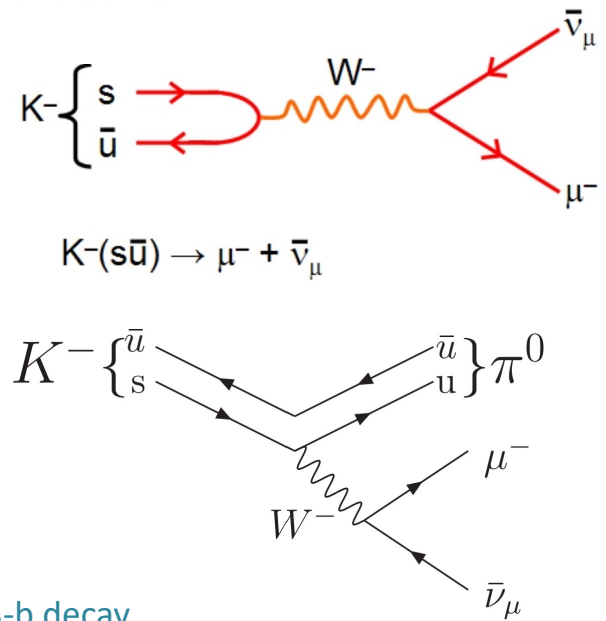
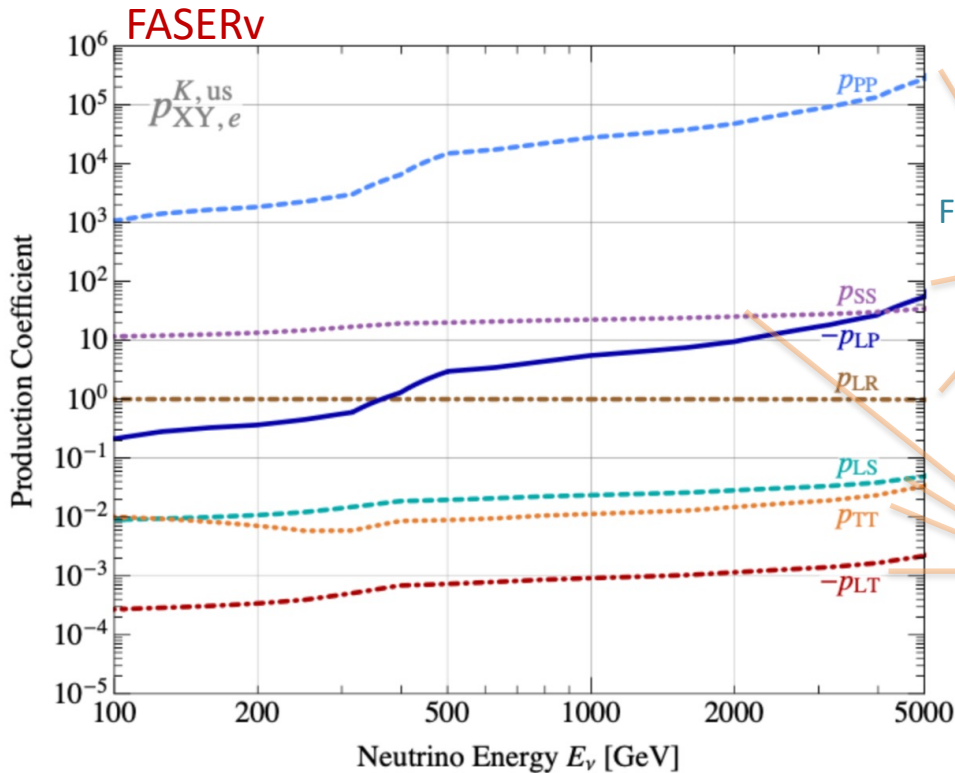
$$\langle 0 | \bar{d} \gamma_5 u | \pi^+(p_\pi) \rangle = -i \frac{m_\pi^2}{m_u + m_d} f_\pi$$

kaon decay

# Production

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

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



From 2-b decay

From 3-b decay

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

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

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

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

# EFT at neutrino experiments

- Observed rate at the experiment:

$$R_{Obs} = 10^4 \nu_\mu$$

- Uncertainty:

$$\sqrt{R_{Obs}} = 10^2 \nu_\alpha \equiv \Delta R$$

- From theory:

$$R_{Th} = R_{SM}(1 + C \epsilon^2) = R_{SM} + \Delta R$$

- Limit on  $\epsilon$ :

$$C \epsilon^2 = \frac{\Delta R}{R_{SM}}$$



$$\epsilon < \frac{C = 10^3}{10^2} \frac{10^2}{10^3 \times 10^4} \sim 3 \times 10^{-3}$$

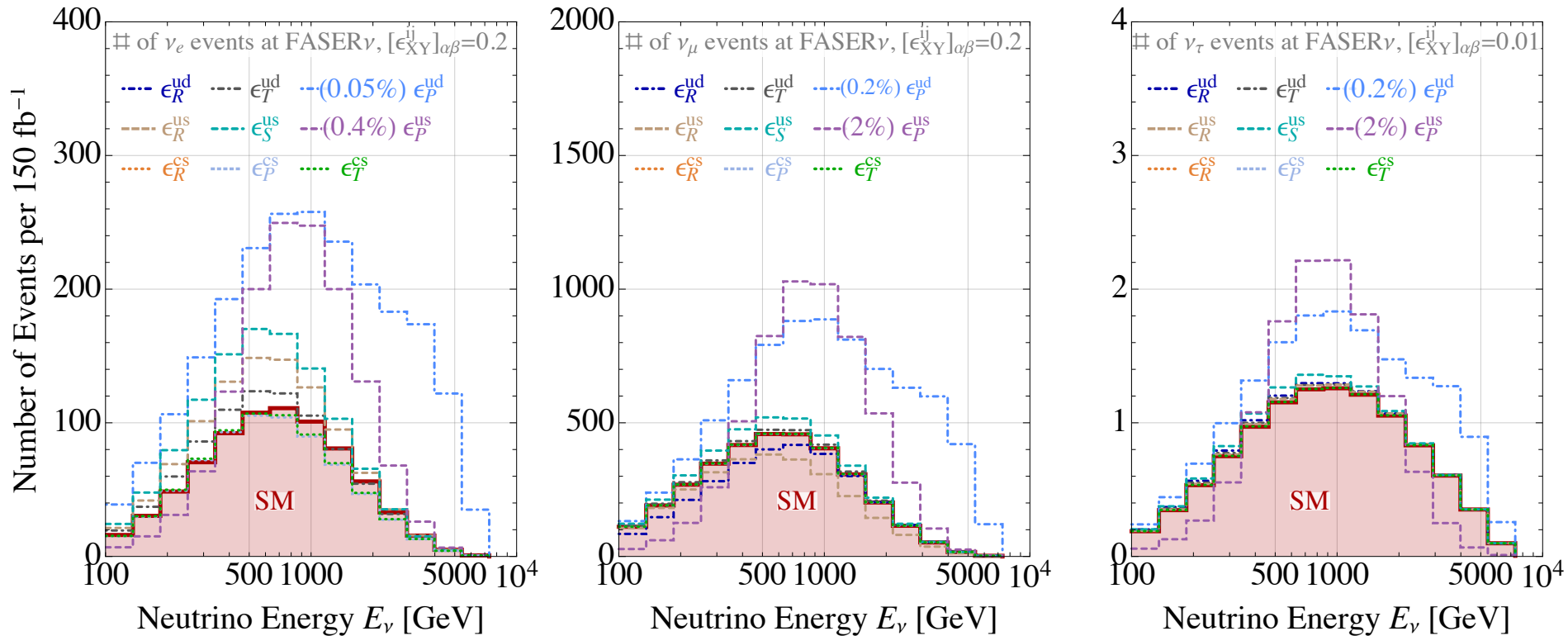
- New Physics Limit:

$$\Lambda \equiv \frac{v [246 \text{ GeV}]}{\sqrt{\epsilon}} = 4.5 \text{ TeV}$$

$$C \propto \frac{\sigma_{NP}}{\sigma_{SM}} \text{ or } \frac{\phi_{NP}}{\phi_{SM}}$$

# Example: Event Rates at FASER $\nu$

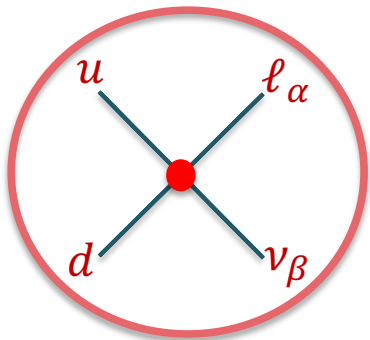
Falkowski, González-Alonso, Kopp, Soreq, ZT, JHEP (2021)



- Results are statistics dominated:  $\nu_e \sim 1000$ ,  $\nu_\mu \sim 5000$ ,  $\nu_\tau \sim 10$
- Optimistic systematic uncertainties: 5% on  $\nu_e$ , 10% on  $\nu_\mu$ , 15% on  $\nu_\tau$
- Conservative systematic uncertainties: 30% on  $\nu_e$ , 40% on  $\nu_\mu$ , 50% on  $\nu_\tau$

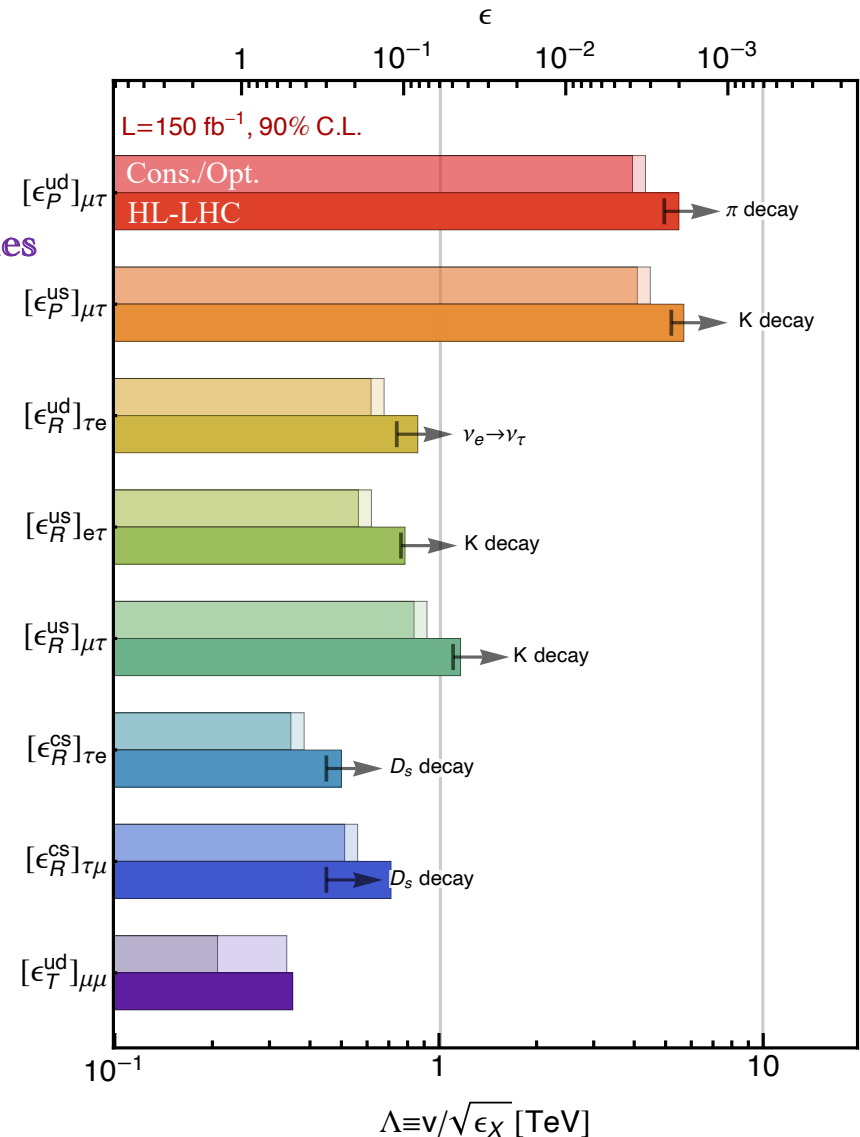
# EFT at FASER $\nu$

- FASER $\nu$ : colored bars
- Top: Conservative/Optimistic flux uncertainties
- Bottom: High luminosity LHC

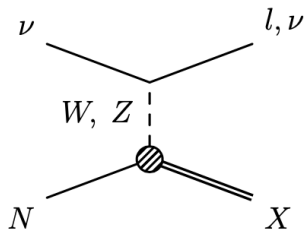


- Neutrino detectors can identify flavor: 81 operators at FASER $\nu$
- New physics reach at multi-TeV
- Complementary or dominant constraints

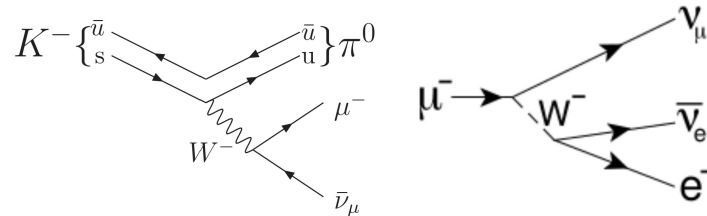
Falkowski, González-Alonso, Kopp, Soreq, ZT, JHEP (2021)



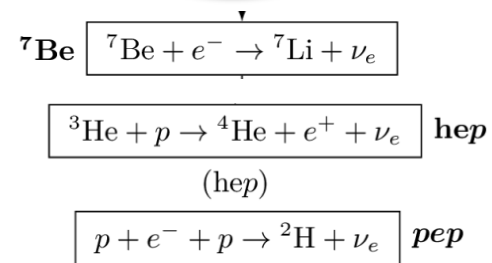
DIS: FASERv



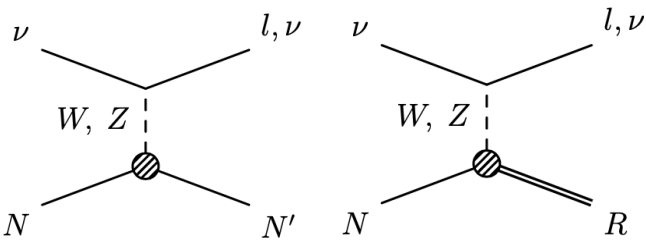
Kaon/Muon decay:  
ISODAR, KDAR



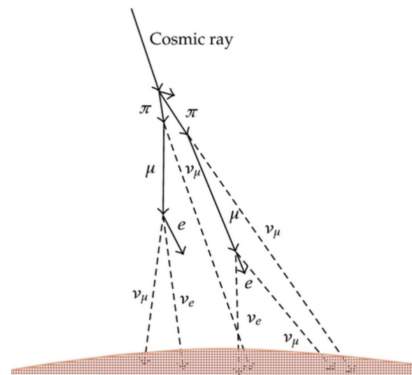
Solar neutrinos:  
Borexino



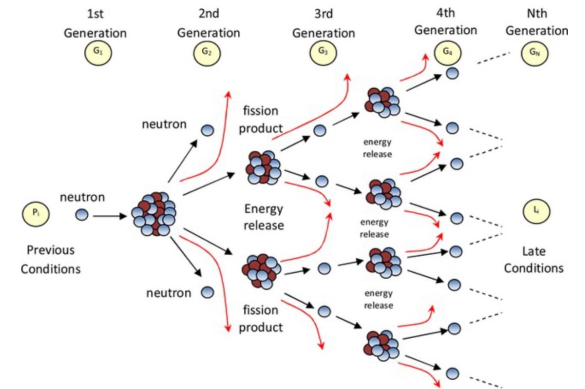
QE,  
Resonances:  
MINOS, NOvA,  
DUNE



Atmospheric  
Neutrinos:  
IceCube

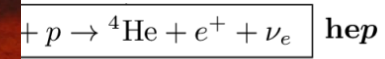
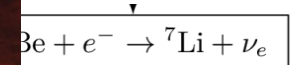


Beta decay and  
IBD: Reactor  
Experiments

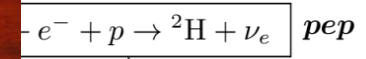


DIS: FASERV

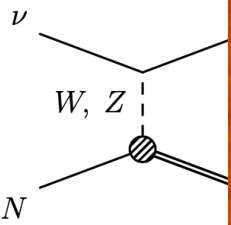
Solar neutrinos:  
Borexino



(hep)



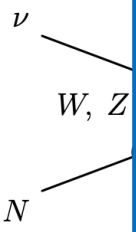
Beta decay and



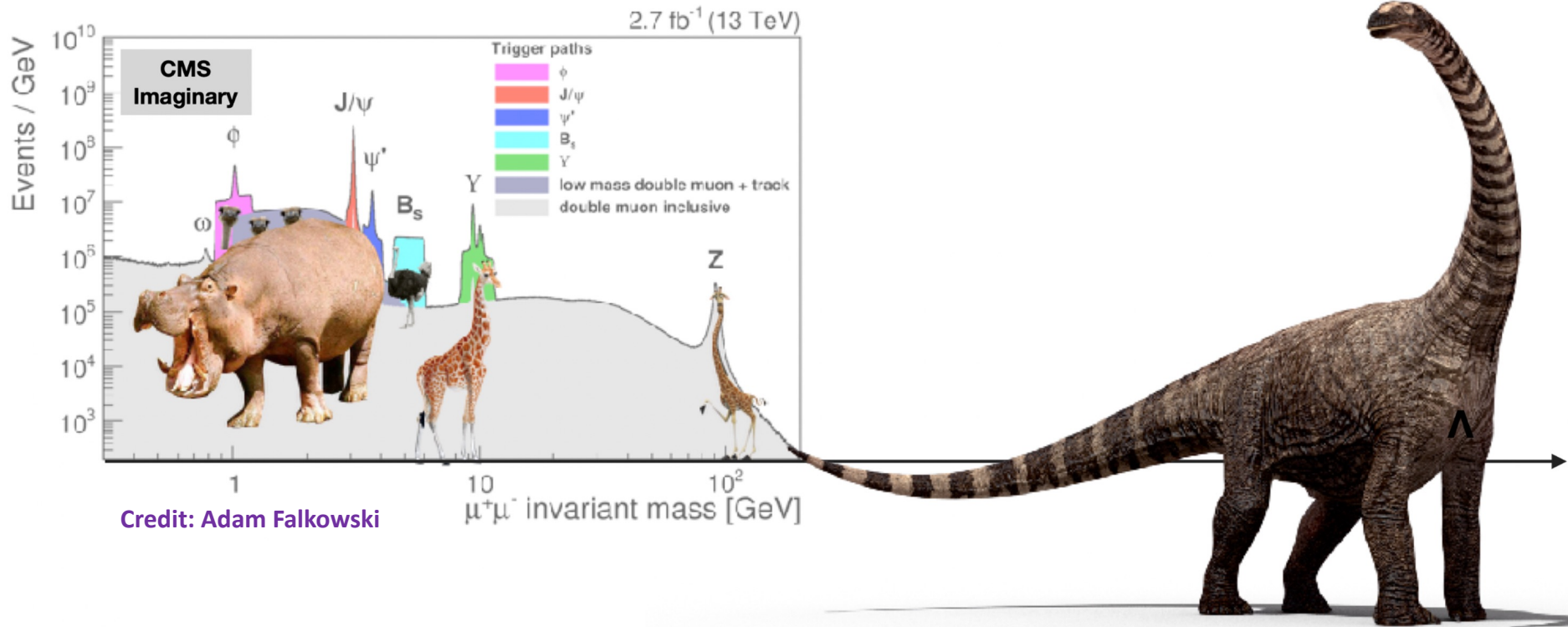
QE,  
Resonances:

Neutrinos:

- We have the tools to do a global EFT analysis with all neutrino experiments;
- Extracting 10's TeV physics from GeV neutrino experiments!



# Fantastic Beasts and How to Find Them With Neutrino Detectors





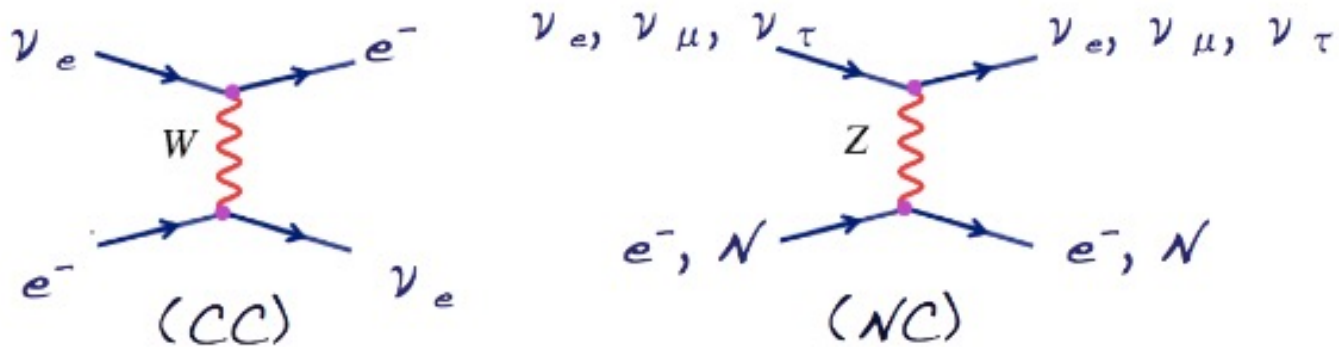
# Any Questions?



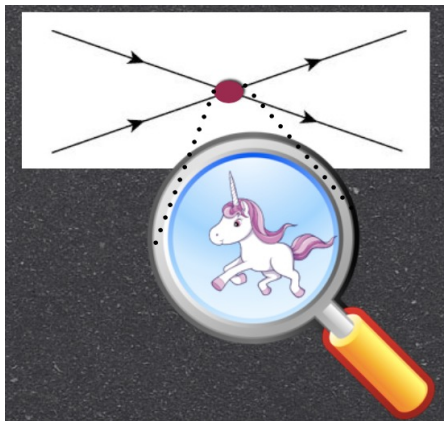
i'm now GOING TO OPEN THE FLOOR TO QUESTIONS.

# Back up Slides

- 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

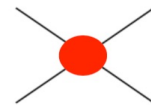
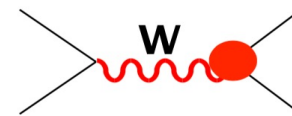
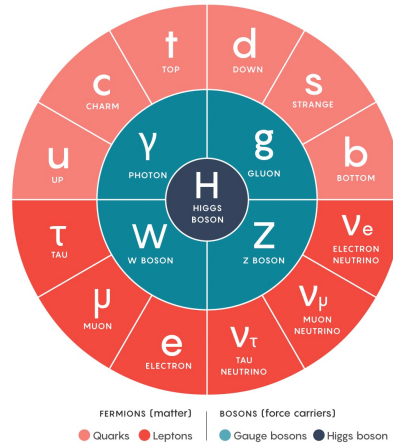
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$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{D=5} + \mathcal{L}_{D=6}$$

Known SM  
Lagrangian

Gives neutrino  
Masses

- Colliders
- CLFV

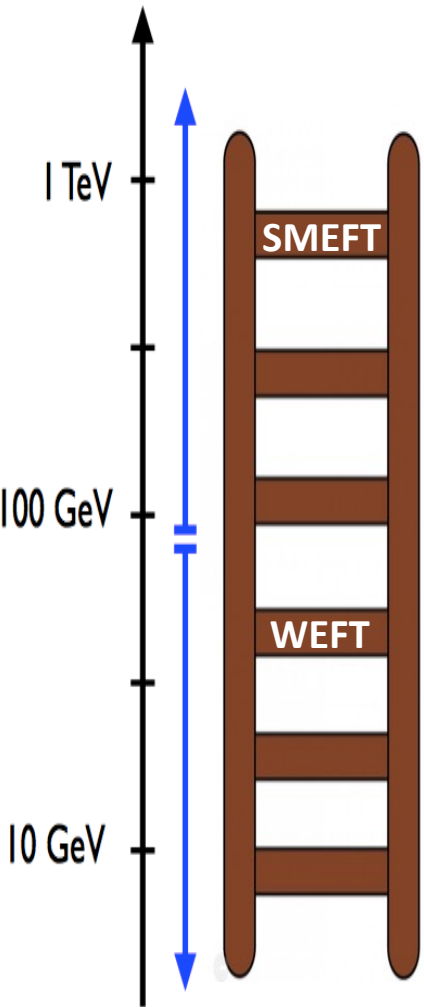


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$$O_{qde} = (\bar{l}e)(\bar{d}q) + \text{h.c.}$$

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

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

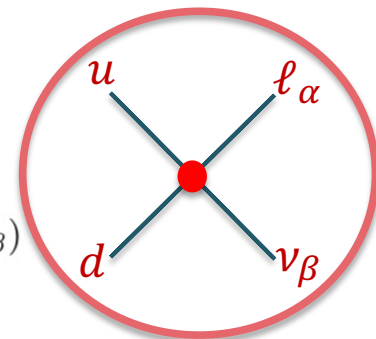


# EFT ladder

WEFT: Effective Lagrangian defined at a low scale  $\mu \sim 2 \text{ GeV}$

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

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

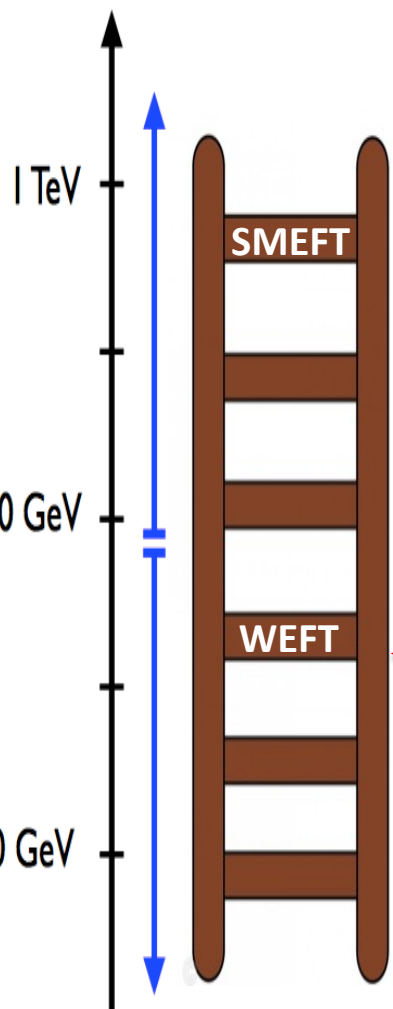
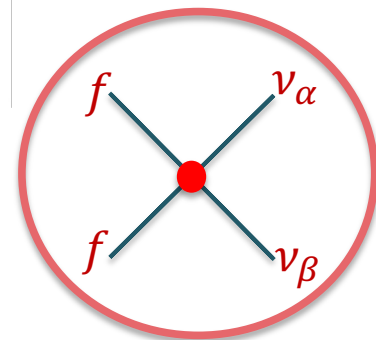


- NC: New left and right handed interactions

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



- Neutrino experiments
- Hadron Decays
- $\beta$ -decays



At the scale  $m_Z$  WEFT parameters  $\epsilon_X$  map to dim-6 operators in SMEFT

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

Falkowski, González-Alonso, [ZL](#), JHEP (2019)



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

# Hadronic Matrix Elements

Kopp, Rocco, ZT, arXiv: 2401.07902

## SM-Interactions:

**Vector:**  $\langle p(p_p) | \bar{q}_u \gamma_\mu q_d | n(p_n) \rangle = \bar{u}_p(p_p) \left[ G_V(Q^2) \gamma_\mu + i \frac{\tilde{G}_{T(V)}(Q^2)}{2M_N} \sigma_{\mu\nu} q^\nu - \frac{\tilde{G}_S(Q^2)}{2M_N} q_\mu \right] u_n(p_n)$

**Axial:**  $\langle p(p_p) | \bar{q}_u \gamma_\mu \gamma_5 q_d | n(p_n) \rangle = \bar{u}_p(p_p) \left[ G_A(Q^2) \gamma_\mu \gamma_5 + i \frac{\tilde{G}_{T(A)}(Q^2)}{2M_N} \sigma_{\mu\nu} q^\nu \gamma_5 - \frac{\tilde{G}_P(Q^2)}{2M_N} q_\mu \gamma_5 \right] u_n(p_n)$

# Hadronic Matrix Elements

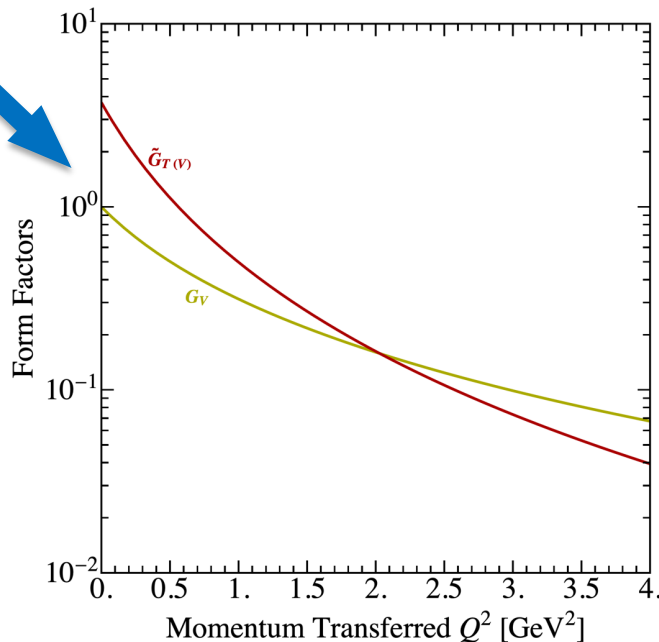
Kopp, Rocco, ZT, arXiv: 2401.07902

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constrained by eN scattering





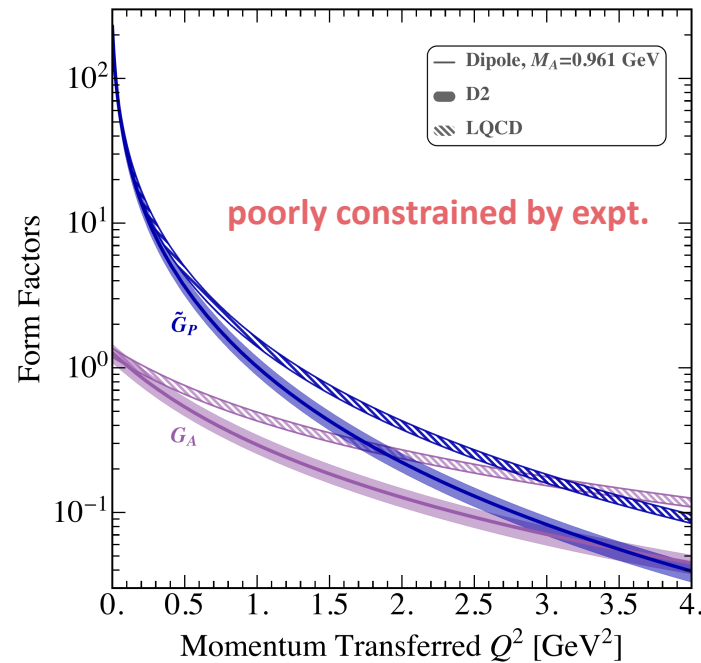
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Kopp, Rocco, ZT, arXiv: 2401.07902

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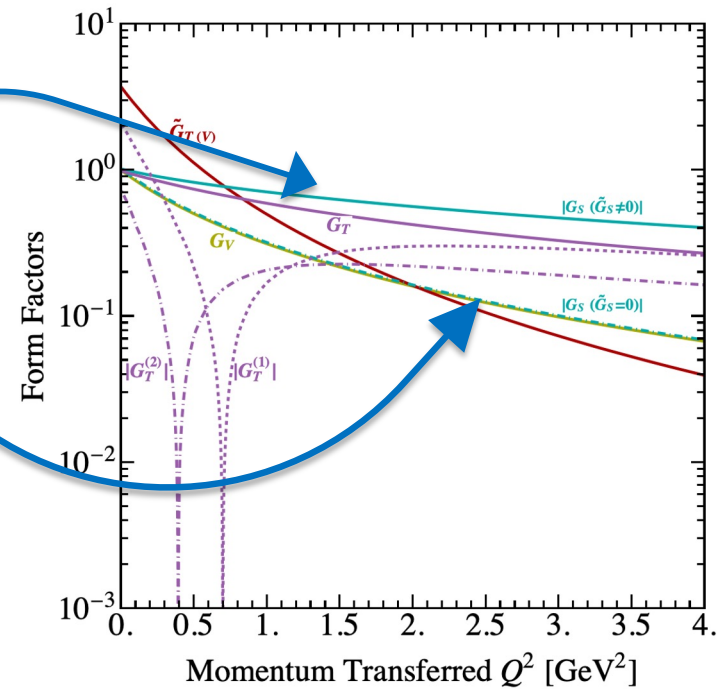


## NEW-Interactions:

- Scalar: conservation of the vector current (CVC):

$$G_S(Q^2) = -\frac{\delta M_N^{QCD}}{\delta m_q} G_V(Q^2) + \frac{Q^2/2M_N}{\delta m_q} \tilde{G}_S(Q^2)$$

- We cannot neglect  $\tilde{G}_S$  anymore!



Kopp, Rocco, ZT, arXiv: 2401.07902

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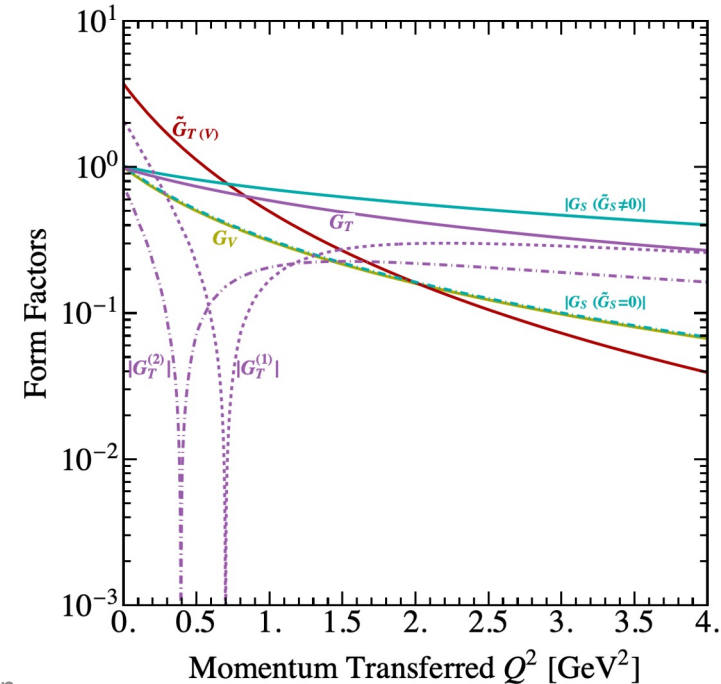
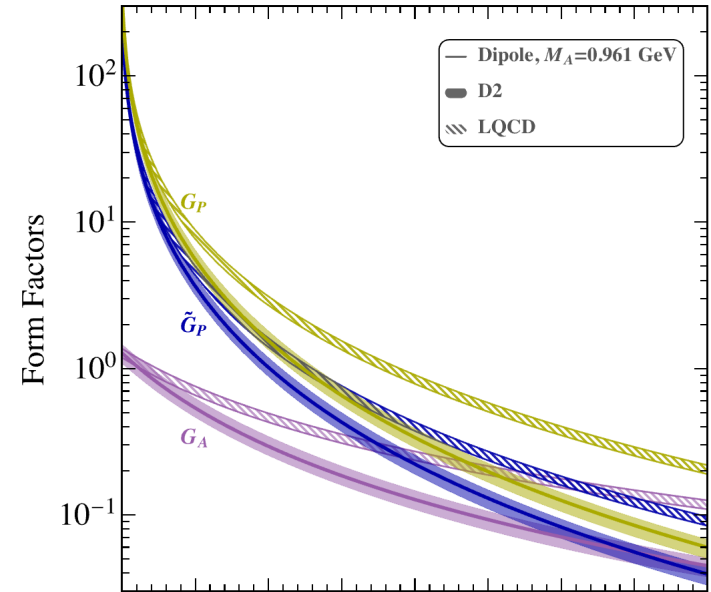
- Pseudo-Scalar: partial conservation of the axial current (PCAC):

$$G_P(Q^2) = \frac{M_N}{m_q} G_A(Q^2) + \frac{Q^2/2M_N}{2m_q} \tilde{G}_P(Q^2) \sim 350$$

➤ D2: neutrino-deuterium data (shaded band)

➤ RQCD Collaboration (hatched band)

Kopp, Rocco, ZT, arXiv: 2401.07902



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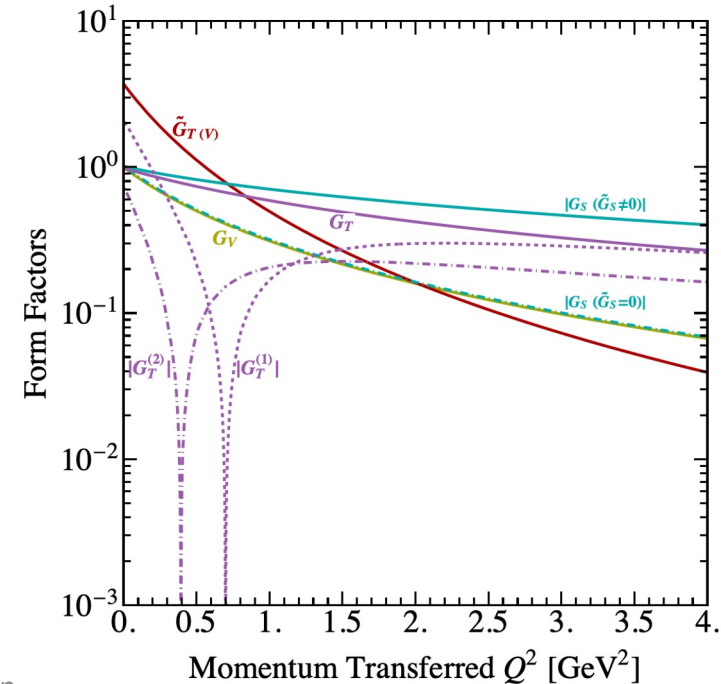
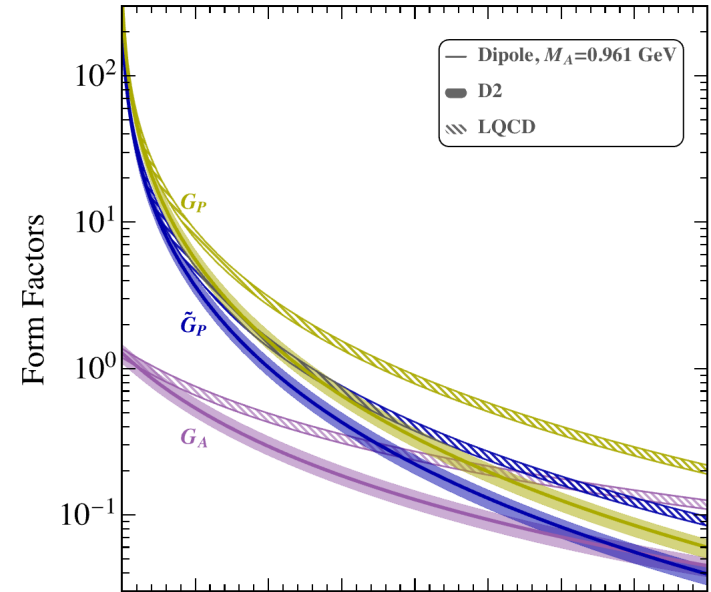
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- Tensor: LQCD and theoretical considerations

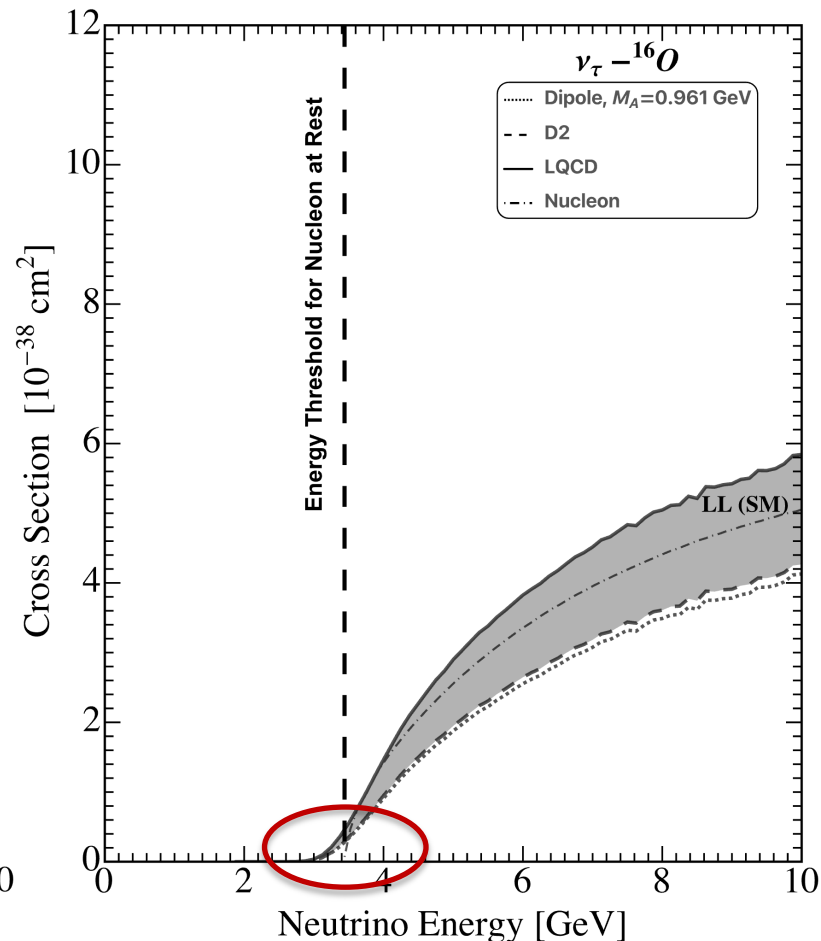
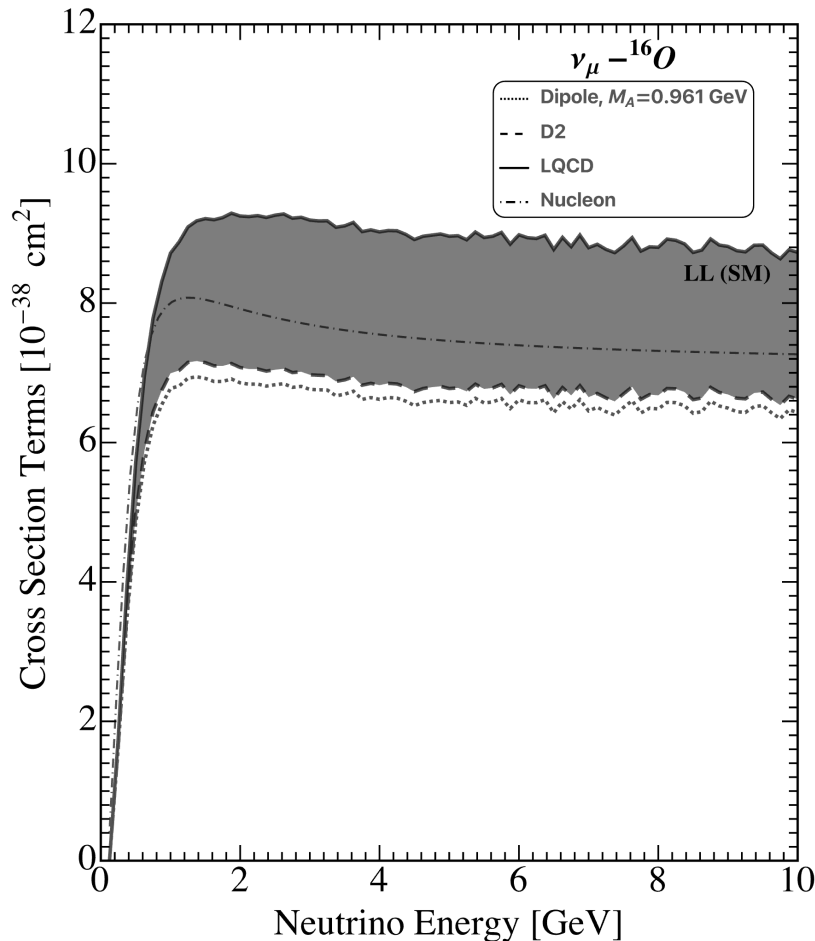
- We cannot neglect  $\tilde{G}_S$  anymore!
- Large enhancements for several interactions;

Kopp, Rocco, ZT, arXiv: 2401.07902



# Neutrino-Nucleus Cross Sections:

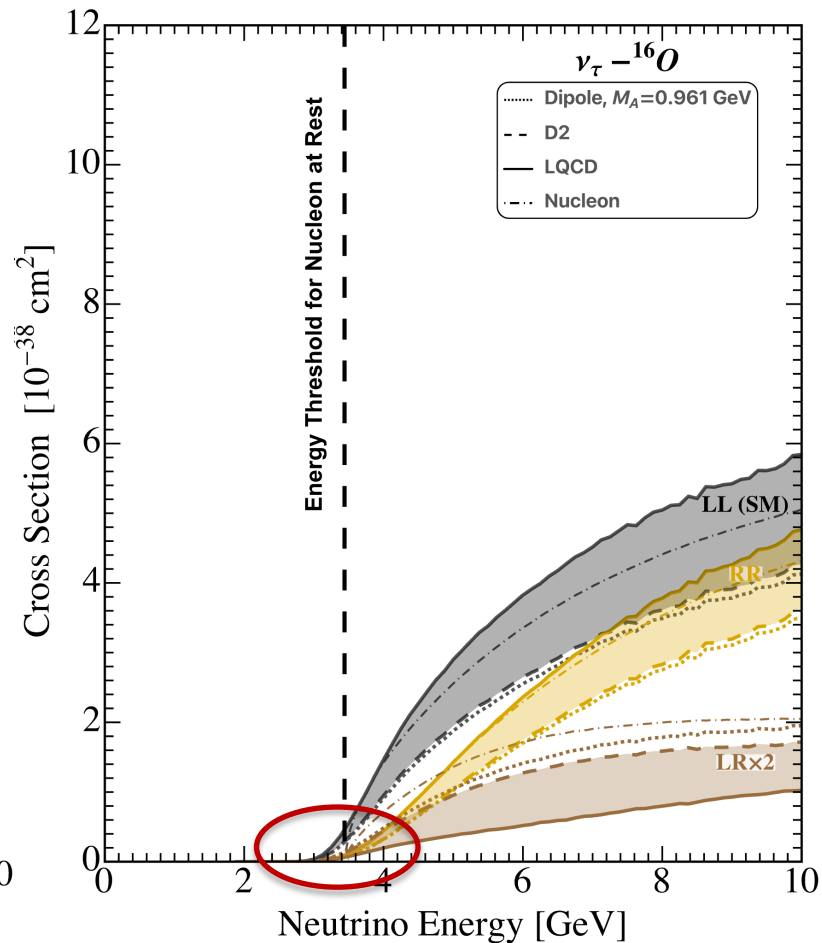
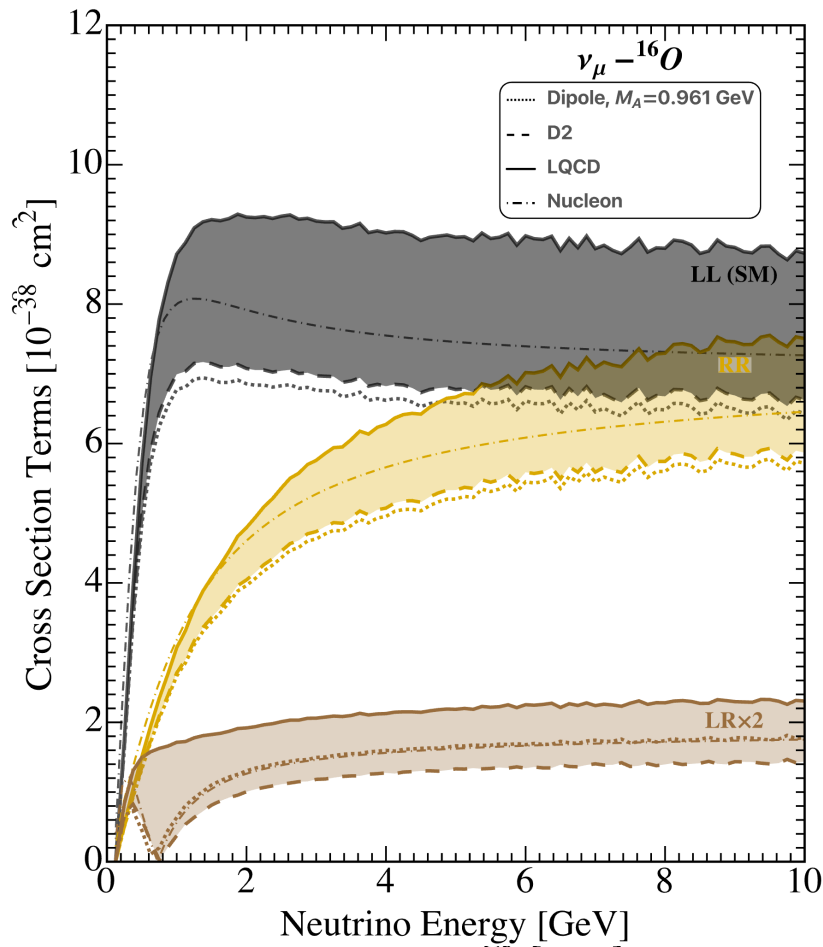
Kopp, Rocco, ZT, arXiv: 2401.07902



- z-expansion fit to LQCD and D2 data;
- Nuclear effects;
- Comparison with nucleon scattering

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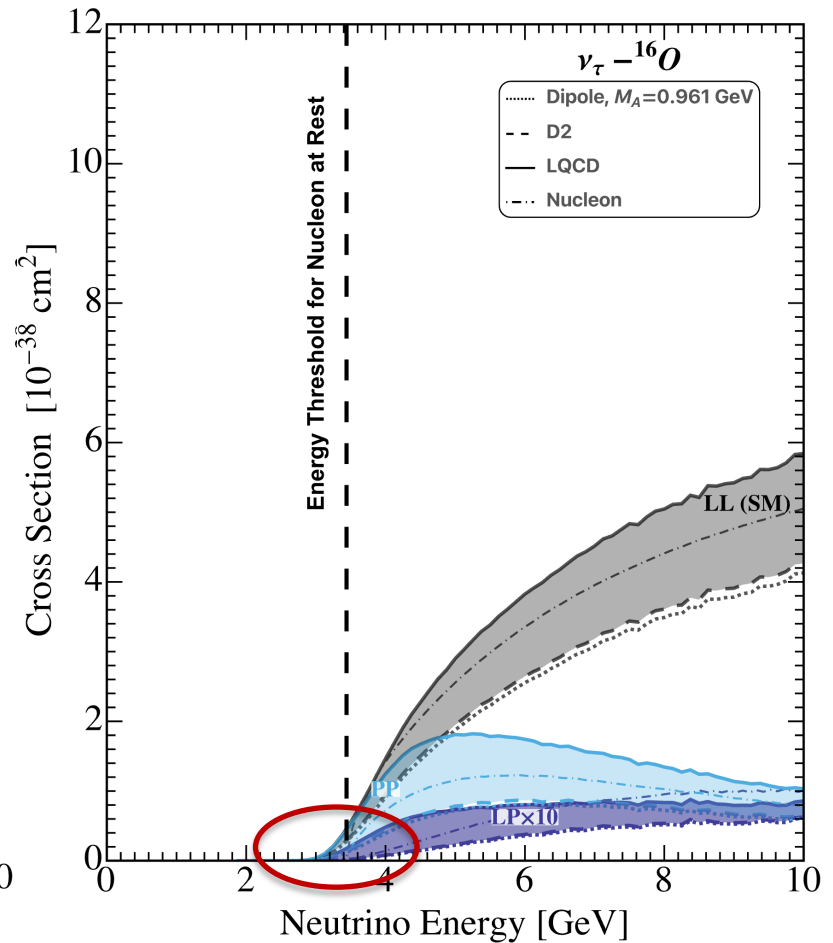
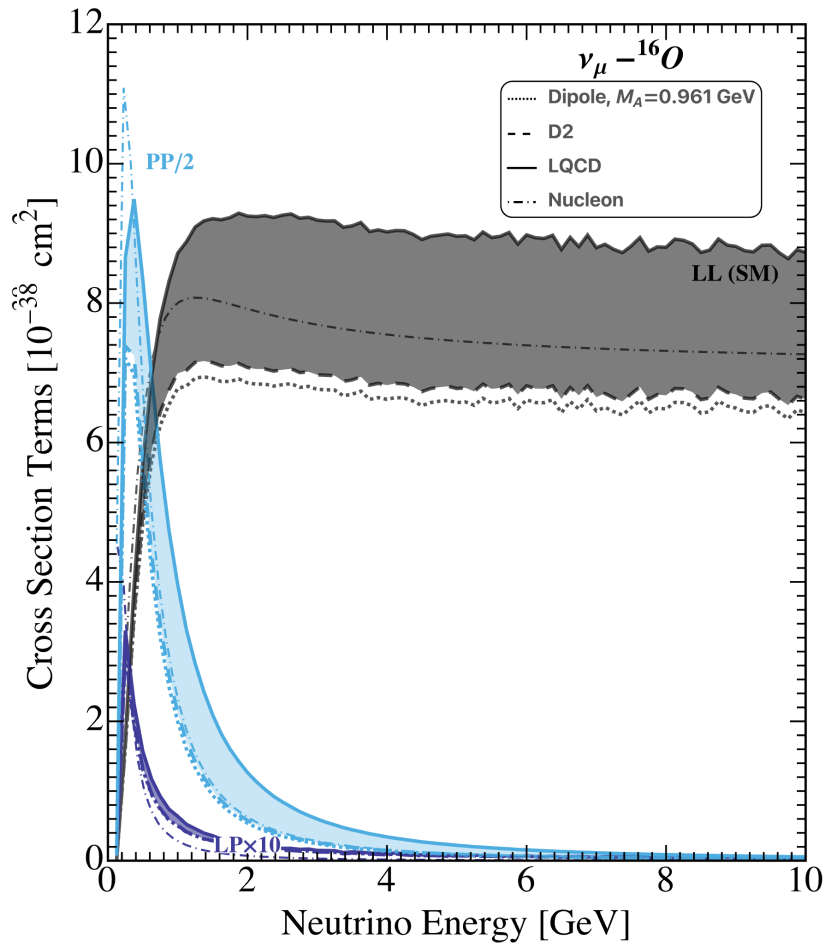
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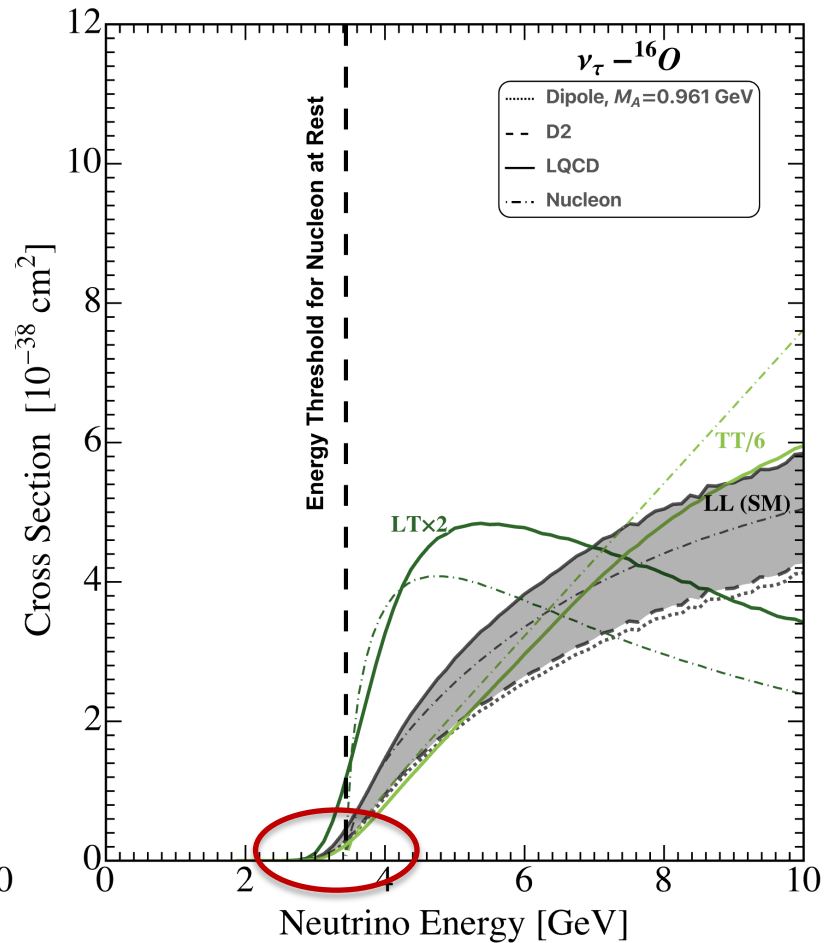
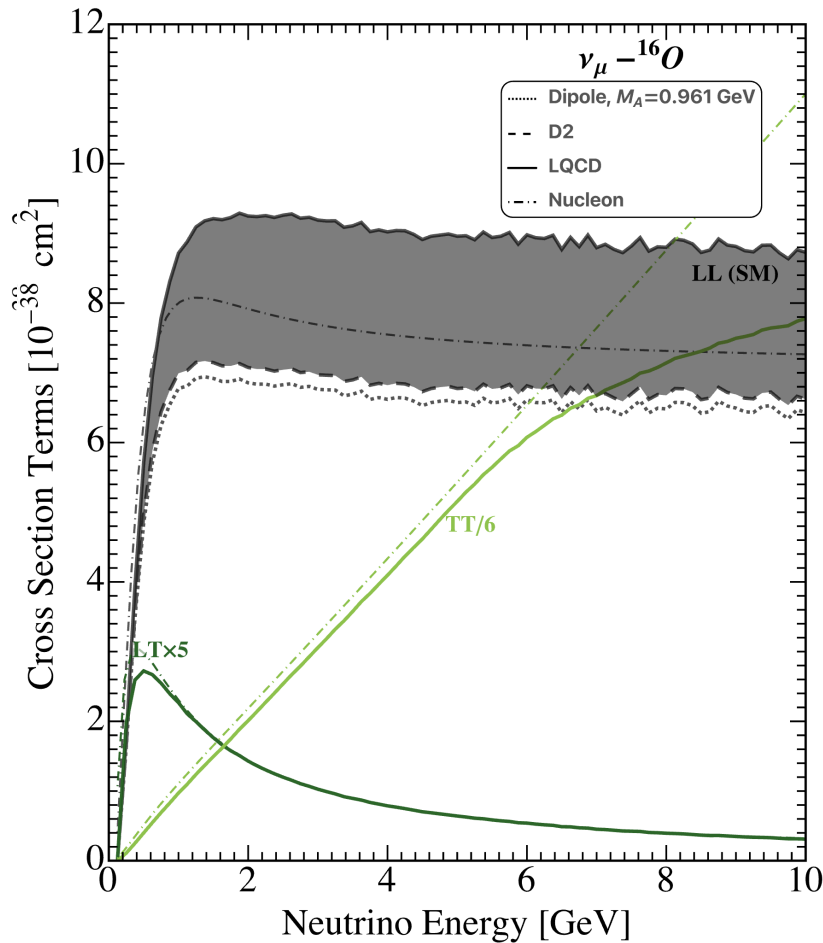
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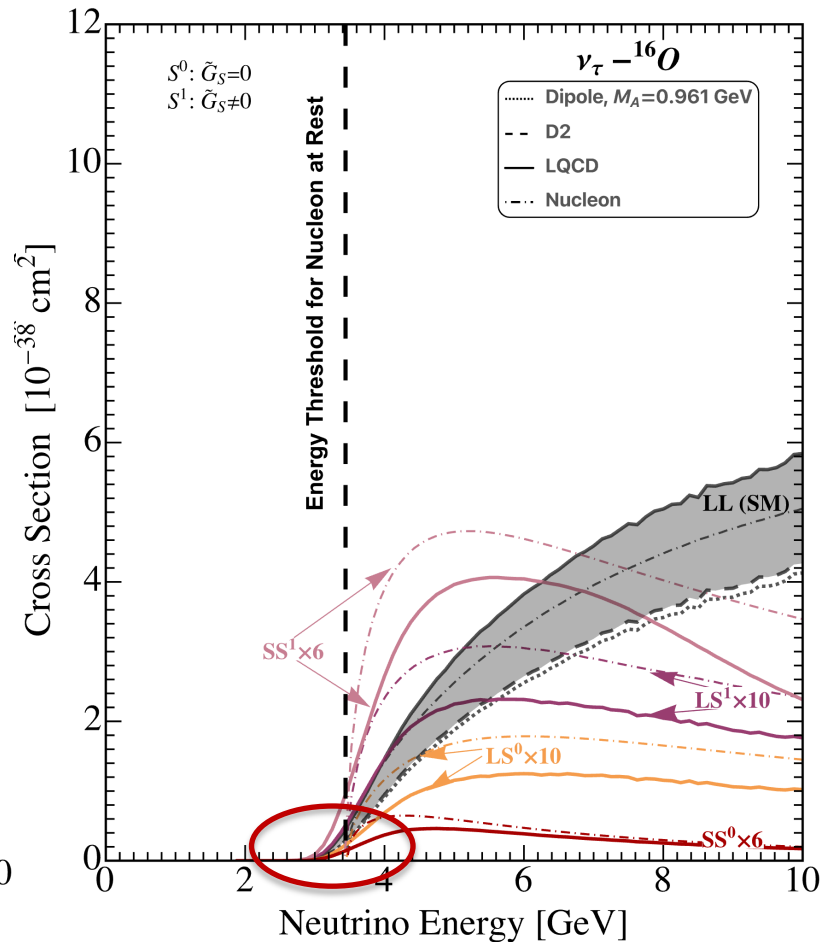
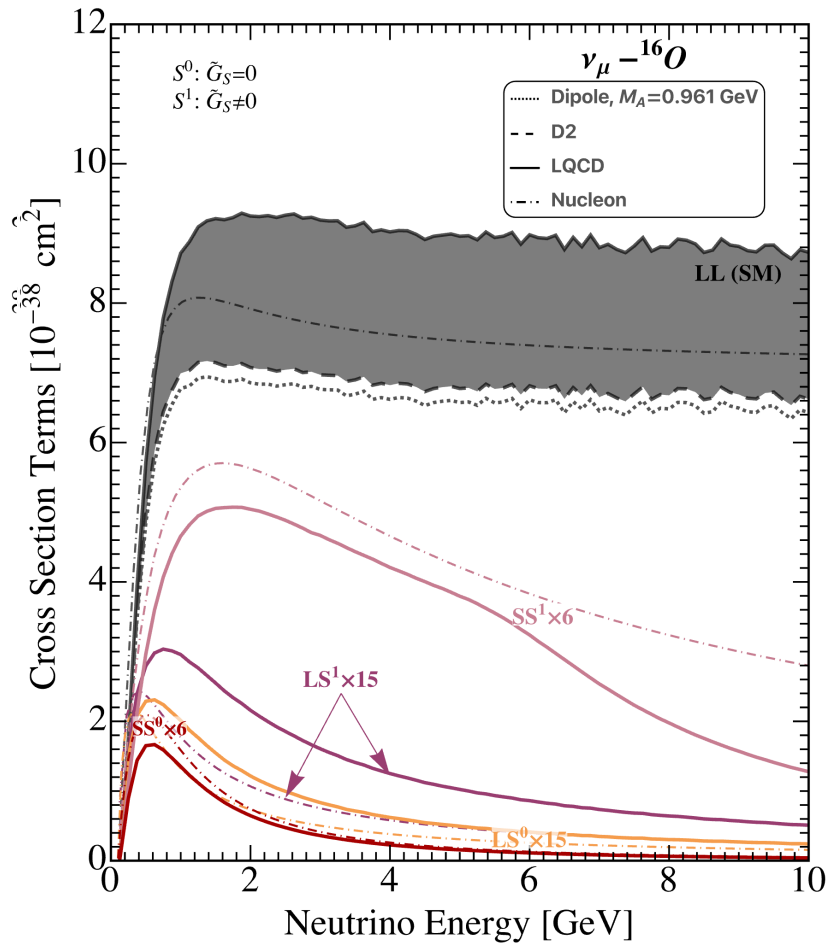


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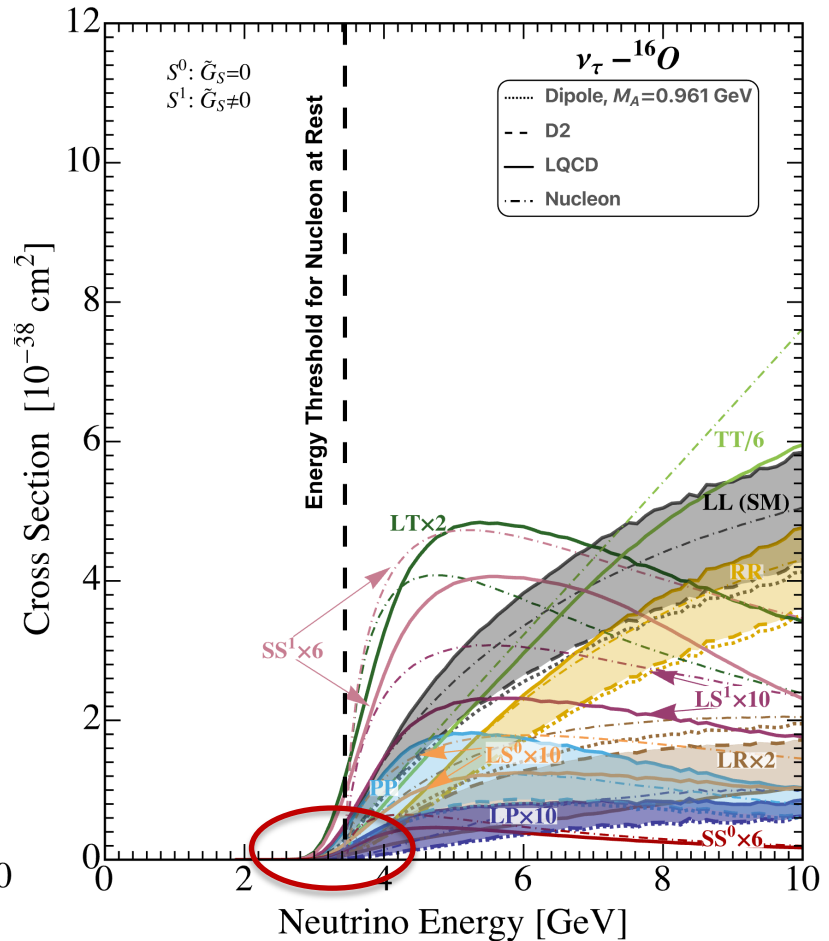
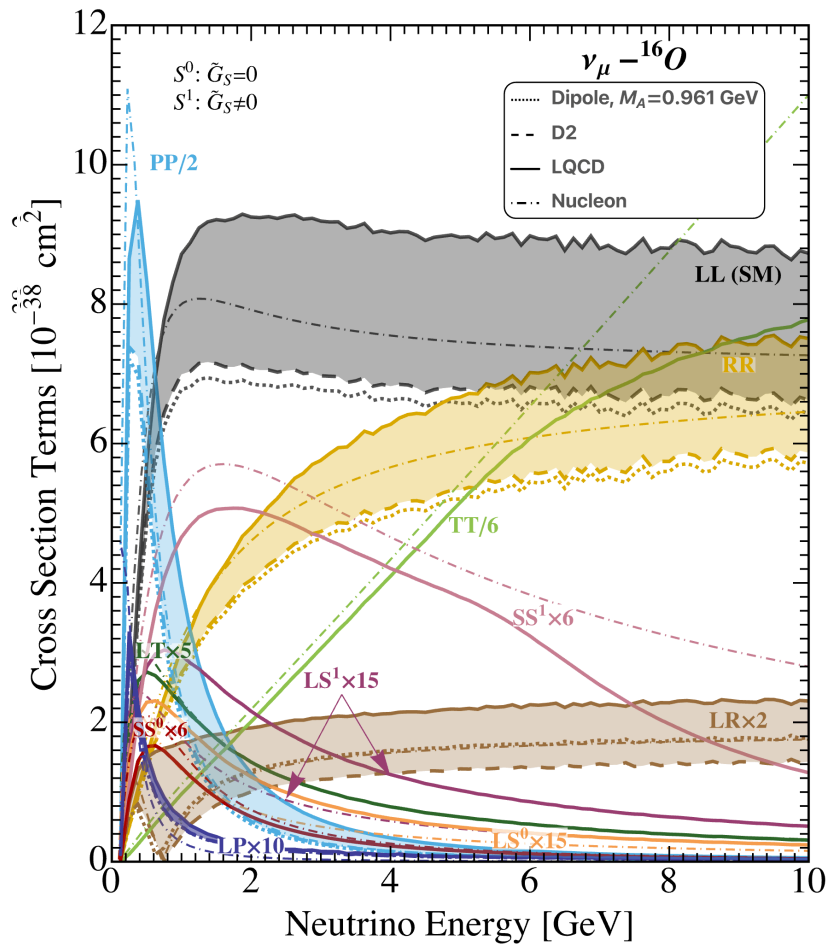
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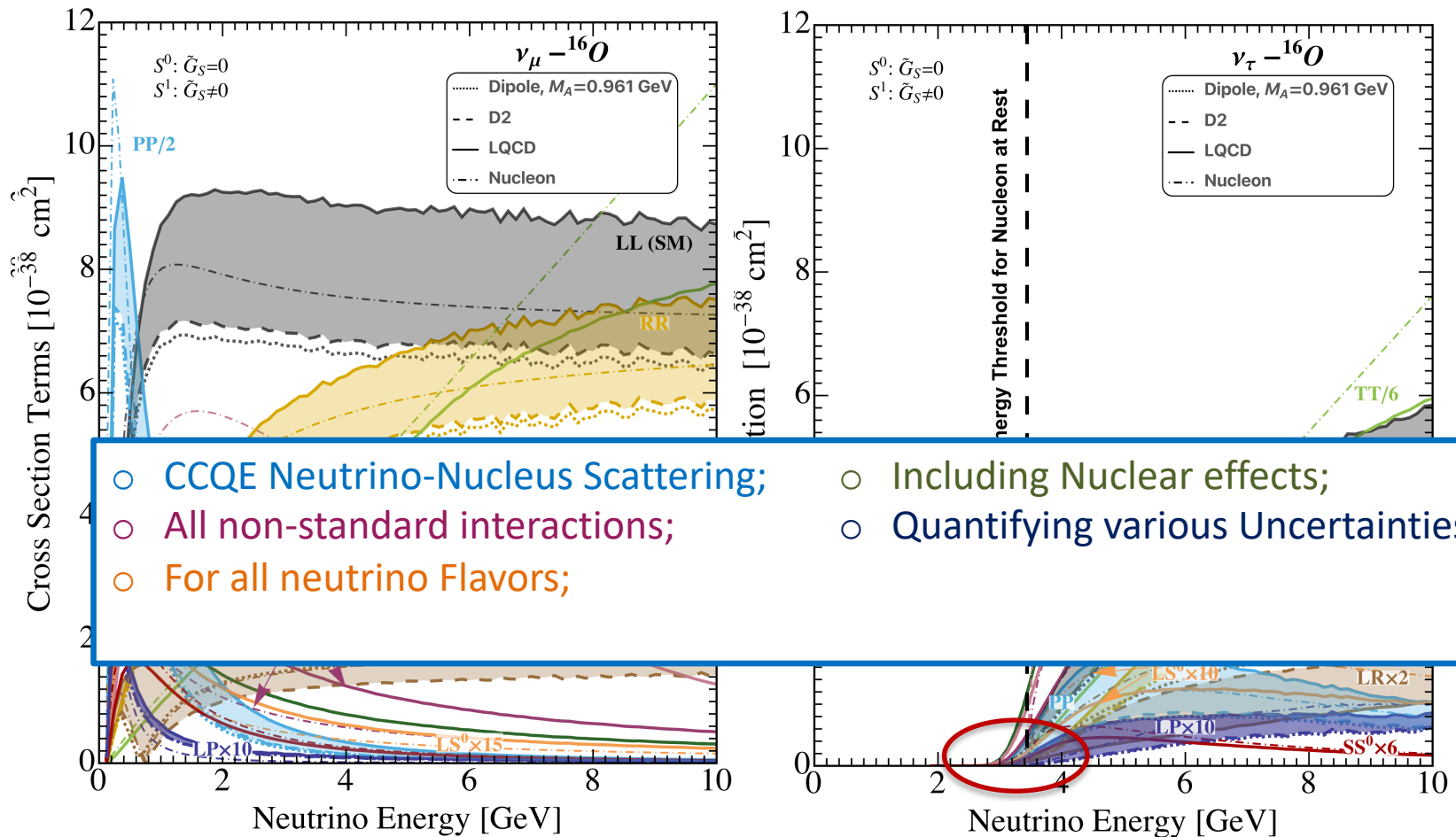
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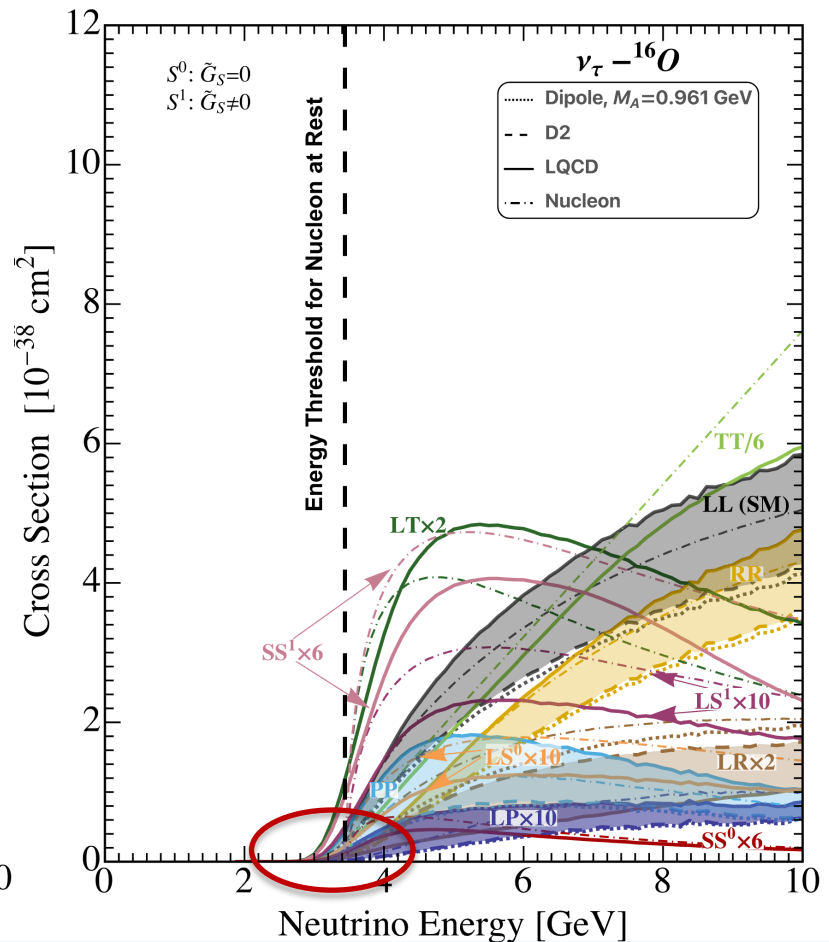
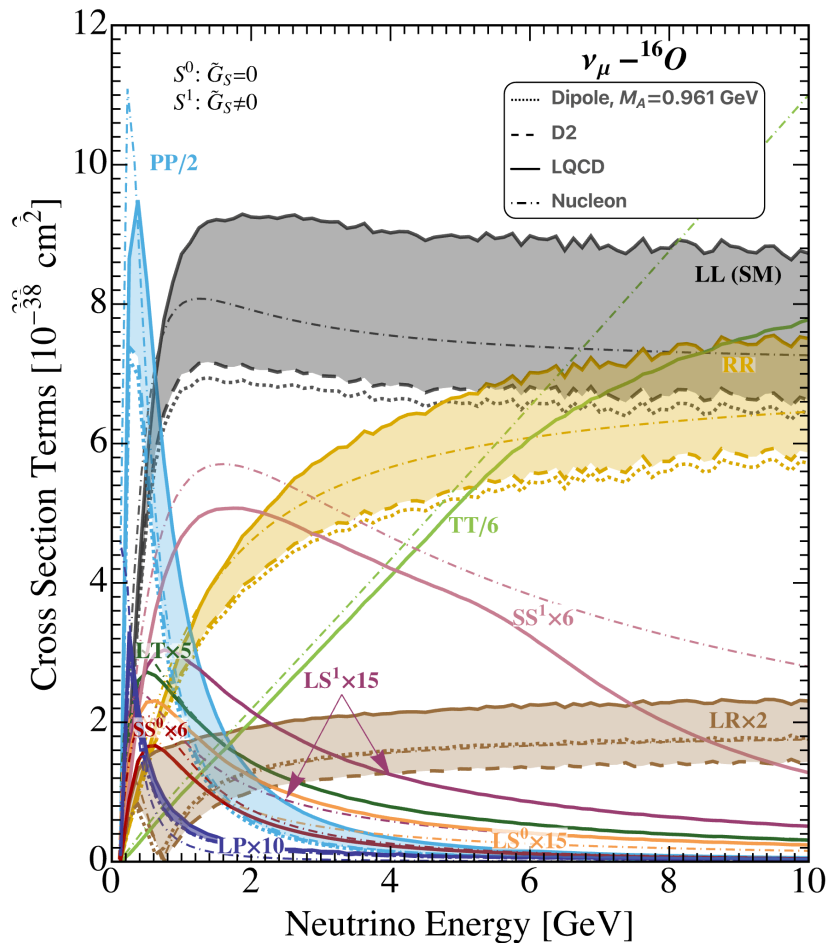
Kopp, Rocco, ZT, arXiv: 2401.07902



○ We have the tools to do a global EFT analysis with all neutrino ex

# Neutrino-Nucleus Cross Sections:

Kopp, Rocco, ZT, arXiv: 2401.07902

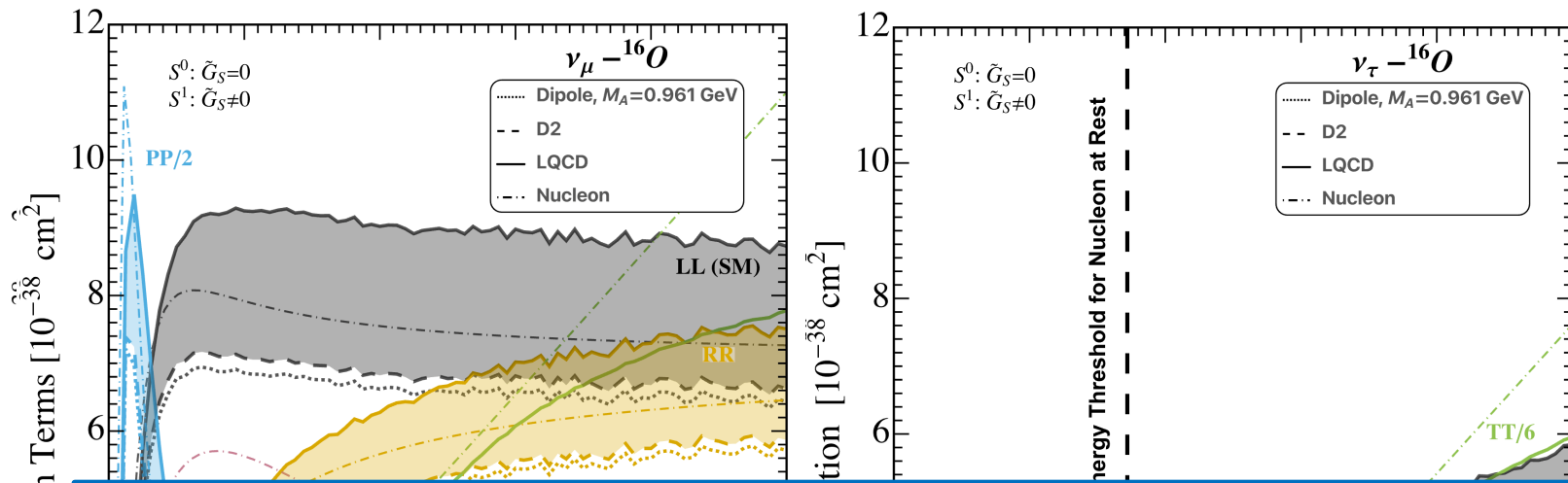


- CCQE Neutrino-Nucleus Scattering;
- All non-standard interactions;
- For all neutrino Flavors;

- Including Nuclear effects;
- Quantifying various Uncertainties;

# Neutrino-Nucleus Cross Sections:

Kopp, Rocco, [ZT](#), arXiv: 2401.07902



- We have the tools to do a global EFT analysis with all neutrino experiments;
- Extracting 10 TeV physics from GeV neutrino experiments!

# Pion decay

# Production

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

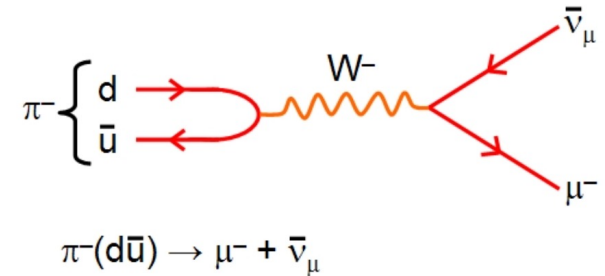
Due to the pseudoscalar nature of the pion, it is sensitive only to axial ( $\epsilon_L$ - $\epsilon_R$ ) and pseudo-scalar ( $\epsilon_P$ ) interactions.

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

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

~700!

~-27



- Larger  $p_{XY} \Rightarrow$  smaller  $\epsilon!$

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

Huge overall flux  
normalization for pion  
decay!

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

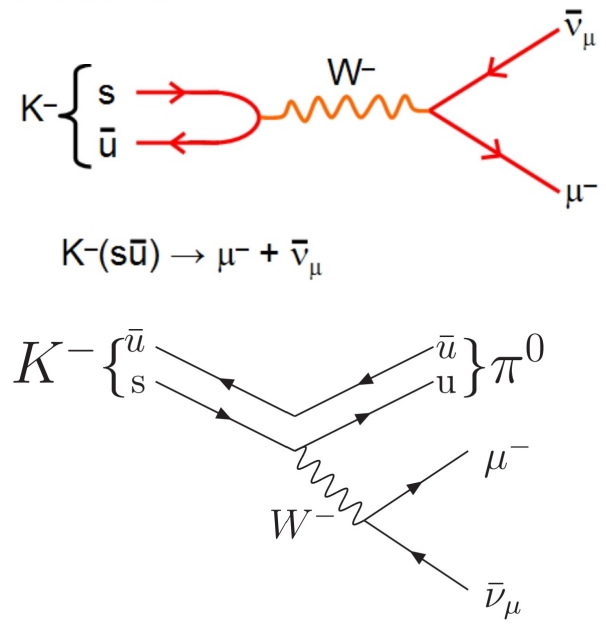
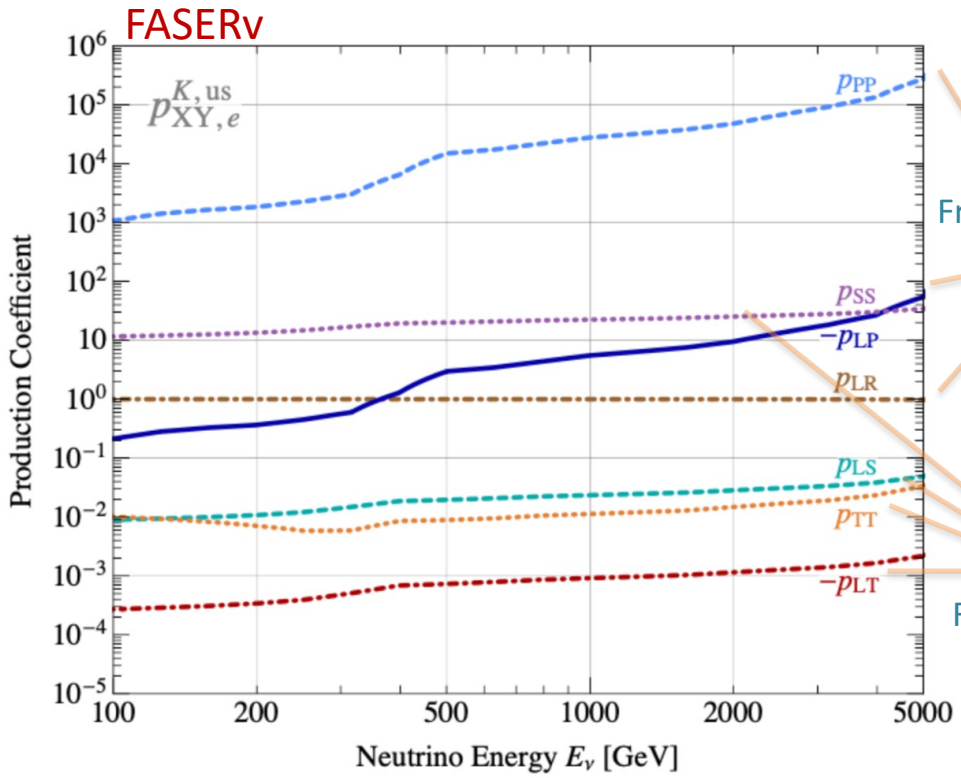
$$\langle 0 | \bar{d} \gamma_5 u | \pi^+(p_\pi) \rangle = -i \frac{m_\pi^2}{m_u + m_d} f_\pi$$

kaon decay

# Production

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

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



From 2-b decay

From 3-b decay

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

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

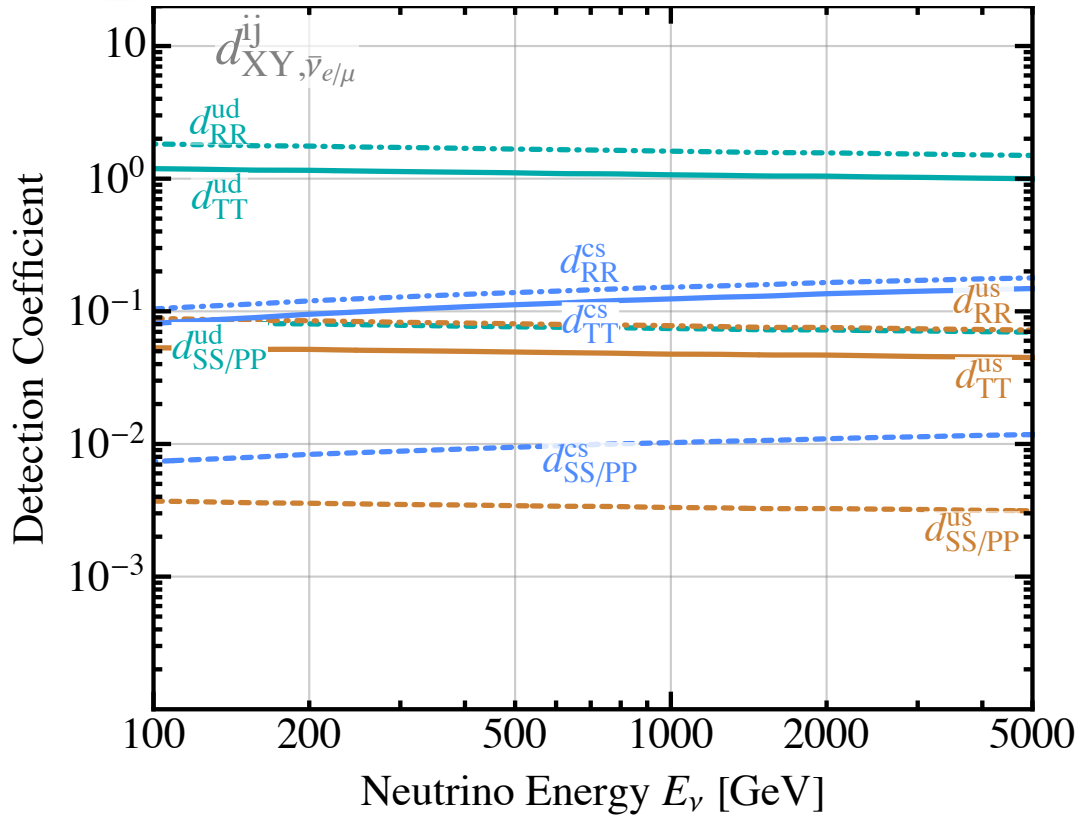
$$\langle \pi^- | \bar{s} u | K^0 \rangle = -\frac{m_K^2 - m_\pi^2}{m_s - m_u} f_0(q^2),$$

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

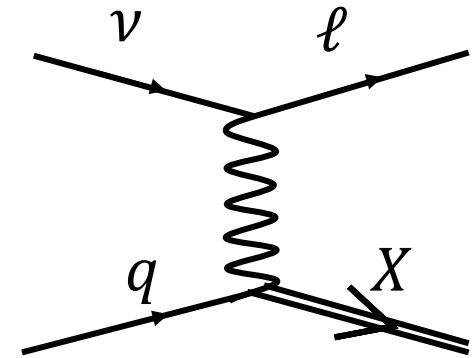
# Detection

DIS

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



Deep Inelastic Scattering

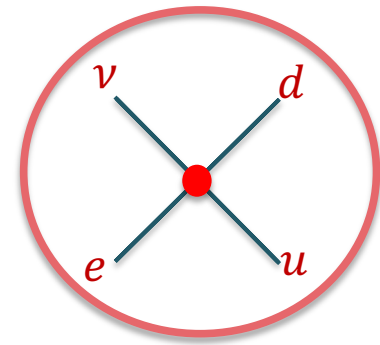


$$\sigma^{Total} \sim \sigma^{SM} (1 + \epsilon_X d_{XL} + \epsilon_X^2 d_{XX})$$

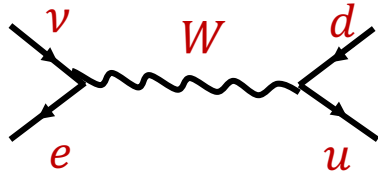
$\epsilon_X^2$  is more important than  $\epsilon_X$ !



# Specific New Physics Models

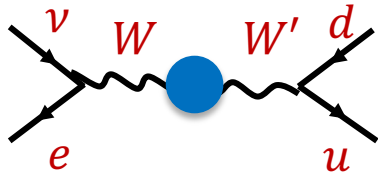


$\epsilon_L$ : measures deviations of the W boson to quarks and leptons, compared to the SM prediction



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

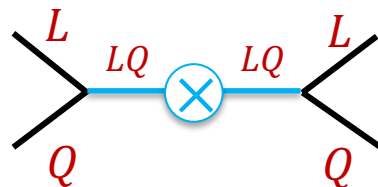
$\epsilon_R$ : left-right symmetric  $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_X$  models introduce new charged vector bosons  $W'$  coupling to right-handed quarks



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

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

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

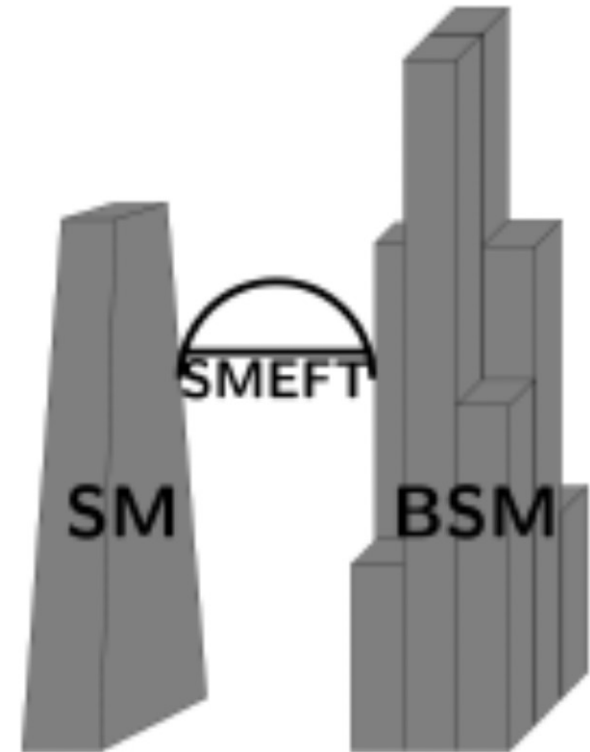


$$(LQ)(LQ)$$

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

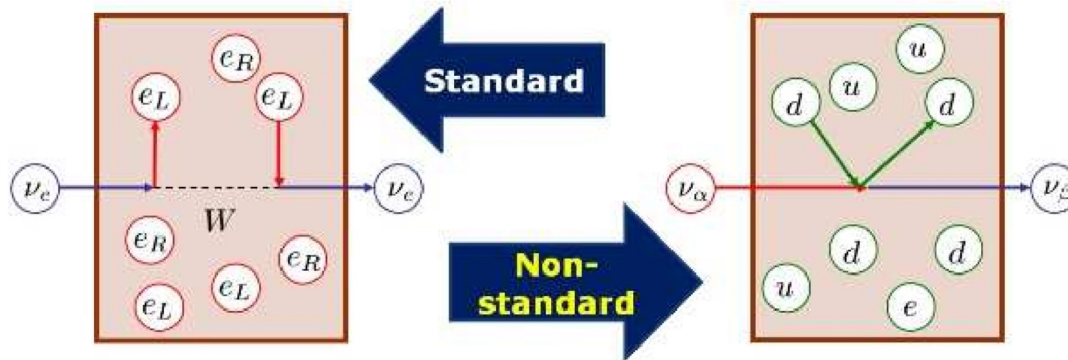
# Indirect Searches: Future Directions

- EFT global fit in neutrino oscillation experiments;
- Extraction of oscillation parameters in presence of general new physics;
- Preparing a public software package and implementing the EFT results: e.g. GLOBES-EFT;
- Comparison between the sensitivity of oscillation and other low/high energy experiments;



# QM-NSI Description

Neutrinos are not pure flavor states:



Standard NSI approach

NSI parameters

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

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

Rotation of flavor states at the source

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

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

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

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

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?

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- 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)

$$\epsilon_{\alpha\beta}^s = \sum_X p_{XL}[\epsilon_X]_{\alpha\beta}^*, \quad \epsilon_{\beta\alpha}^d = \sum_X d_{XL}[\epsilon_X]_{\alpha\beta}$$

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
$\nu_e$ produced in beta decay	$\epsilon_{e\beta}^s = [\epsilon_L]_{e\beta}^* - [\epsilon_R]_{e\beta}^* - \frac{g_T}{g_A} \frac{m_e}{f_T(E_\nu)} [\epsilon_T]_{e\beta}^*$
$\nu_e$ detected in inverse beta decay	$\epsilon_{\beta e}^d = [\epsilon_L]_{e\beta} + \frac{1-3g_A^2}{1+3g_A^2} [\epsilon_R]_{e\beta} - \frac{m_e}{E_\nu - \Delta} \left( \frac{g_S}{1+3g_A^2} [\epsilon_S]_{e\beta} - \frac{3g_A g_T}{1+3g_A^2} [\epsilon_T]_{e\beta} \right)$
$\nu_\mu$ produced in pion decay	$\epsilon_{\mu\beta}^s = [\epsilon_L]_{\mu\beta}^* - [\epsilon_R]_{\mu\beta}^* - \frac{m_\pi^2}{m_\mu(m_u + m_d)} [\epsilon_P]_{\mu\beta}^*$

- 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

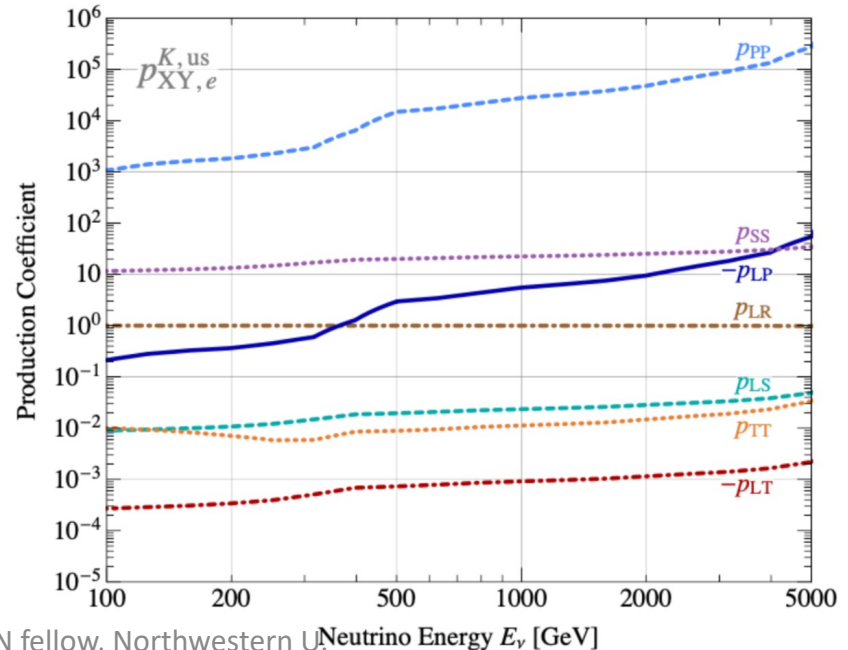
$$p_{XL}p_{YL}^* = p_{XY}, \quad d_{XL}d_{YL}^* = d_{XY}$$

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, ZI, JHEP (2019)

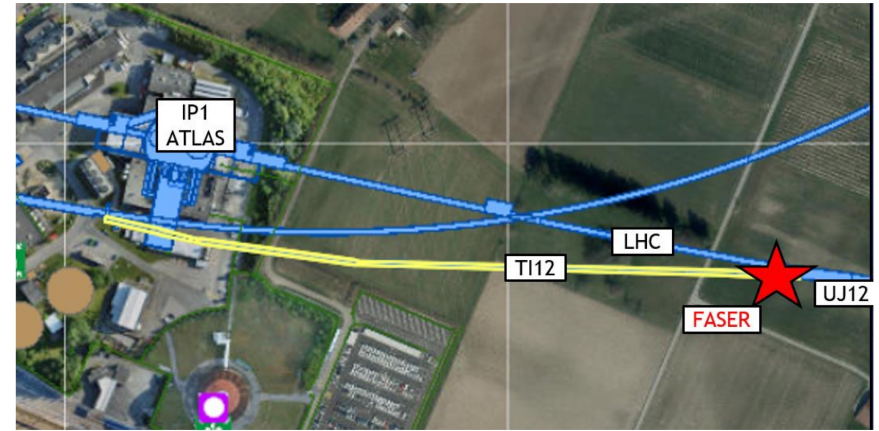
$$p_{XY} \equiv \frac{\int d\Pi_{P'} A_X^P \bar{A}_Y^P}{\int d\Pi_{P'} |A_L^P|^2}, \quad d_{XY} \equiv \frac{\int d\Pi_D A_X^D \bar{A}_Y^D}{\int d\Pi_D |A_L^D|^2}$$



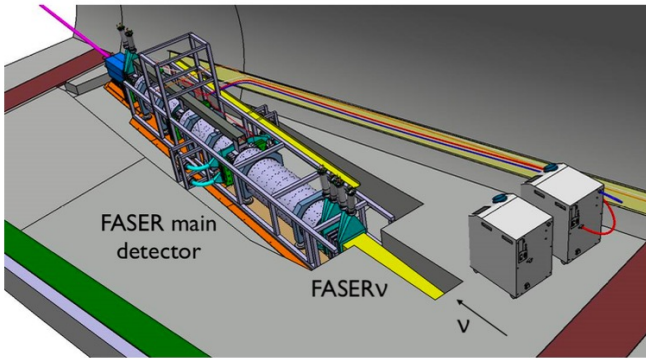


# FASER $\nu$

- 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;

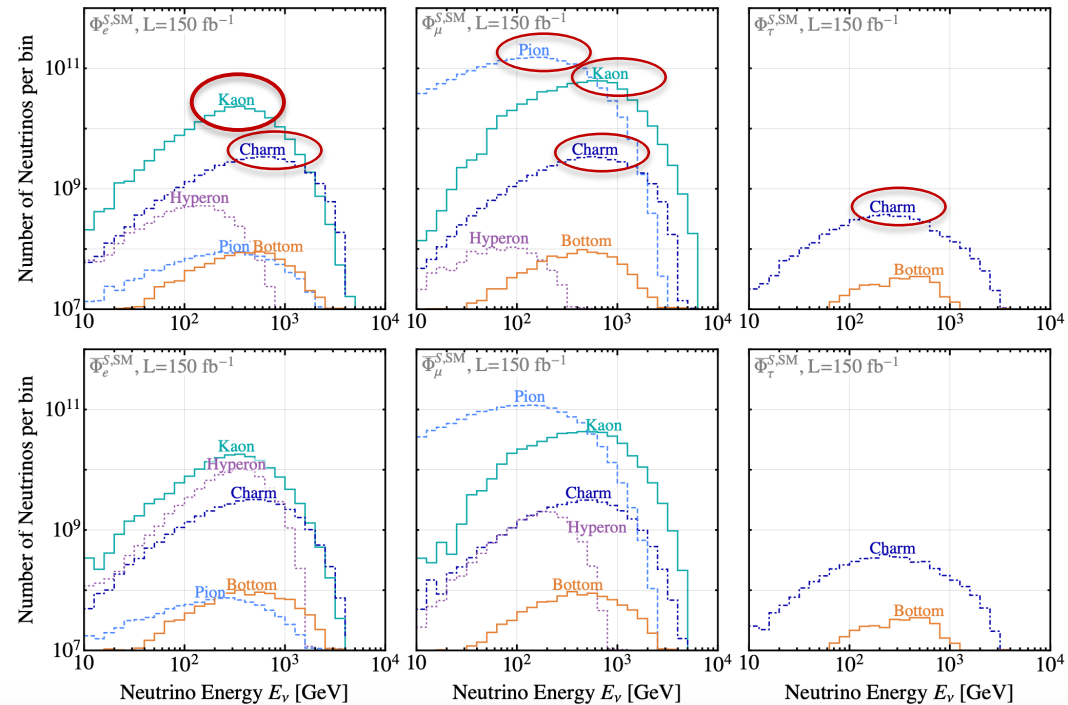


Falkowski, González-Alonso, Kopp, Soreq, ZT, JHEP (2021)



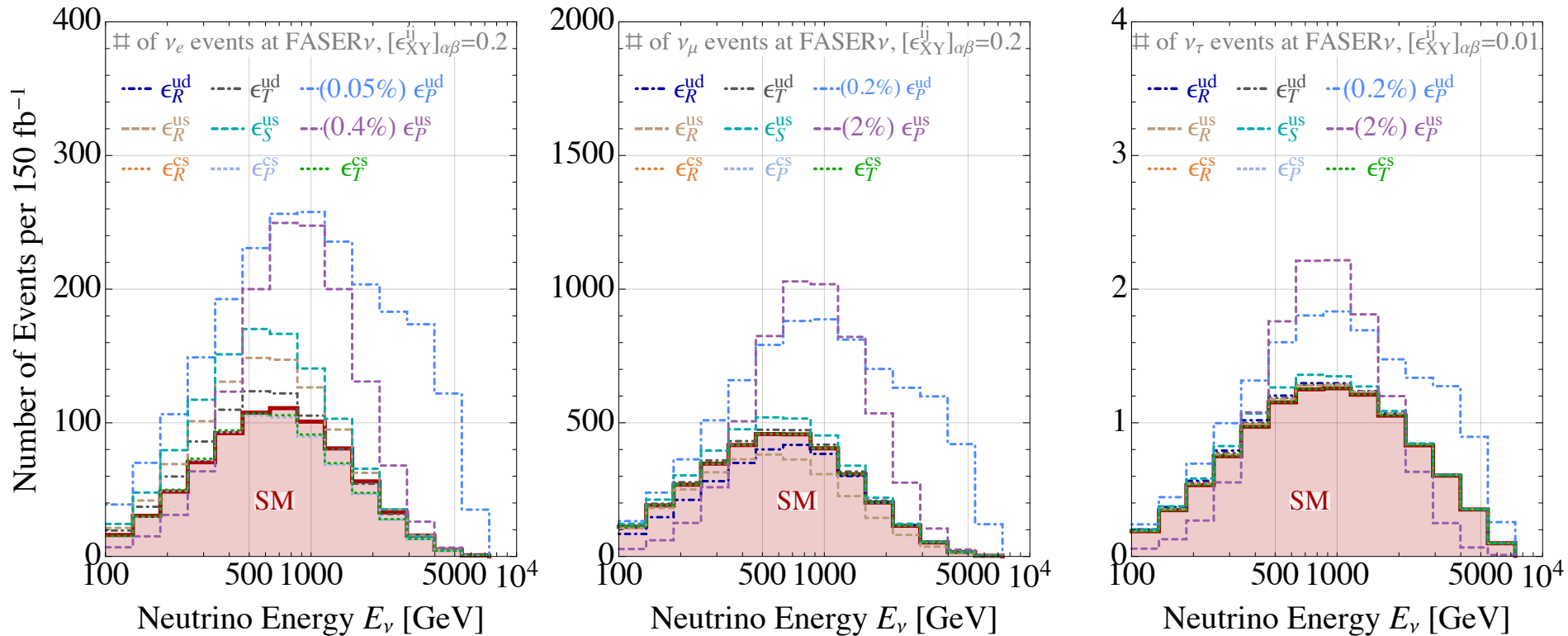
Within the SM:

$$\nu_e \sim 1000, \quad \nu_\mu \sim 5000, \quad \nu_\tau \sim 10$$



# EFT at FASER $\nu$

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

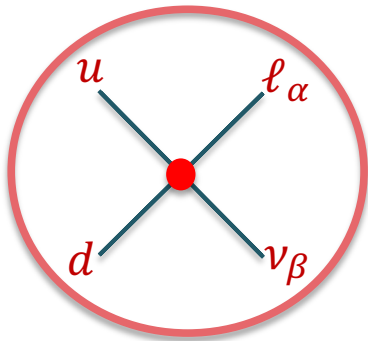


- Results are statistics dominated:  $\nu_e \sim 1000$ ,  $\nu_\mu \sim 5000$ ,  $\nu_\tau \sim 10$
- Optimistic systematic uncertainties: 5% on  $\nu_e$ , 10% on  $\nu_\mu$ , 15% on  $\nu_\tau$
- Conservative systematic uncertainties: 30% on  $\nu_e$ , 40% on  $\nu_\mu$ , 50% on  $\nu_\tau$

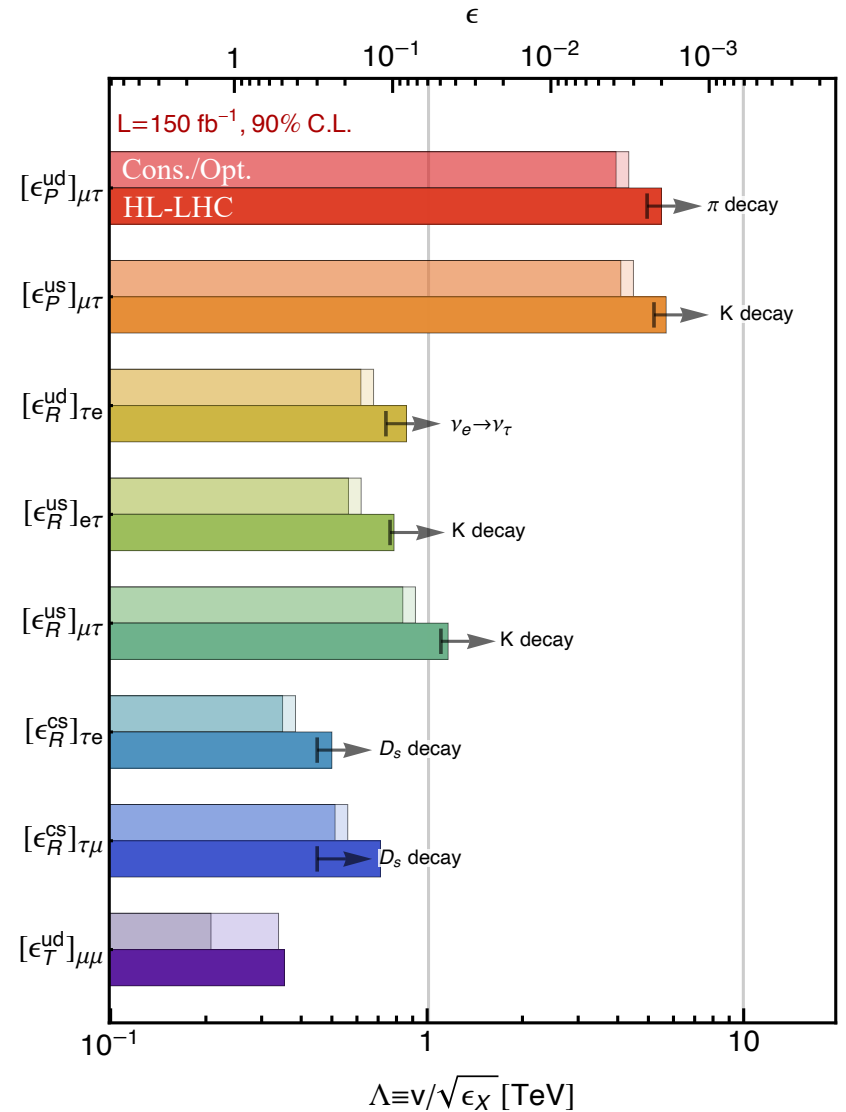
# EFT at FASER $\nu$

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

- FASER $\nu$ : colored bars
- Top: Conservative/Optimistic flux uncertainties
- Bottom: High luminosity LHC



- No SM Oscillation;
- Access to all Flavors;
- Low statistics;
- But large Flux Enhancements;



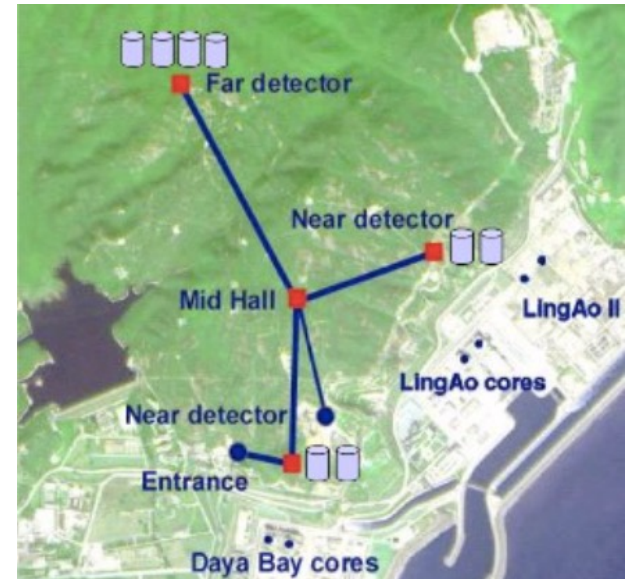
New physics reach at multi-TeV

# 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  $\sim 4$  million anti-neutrino events in 1958 days of data taking;

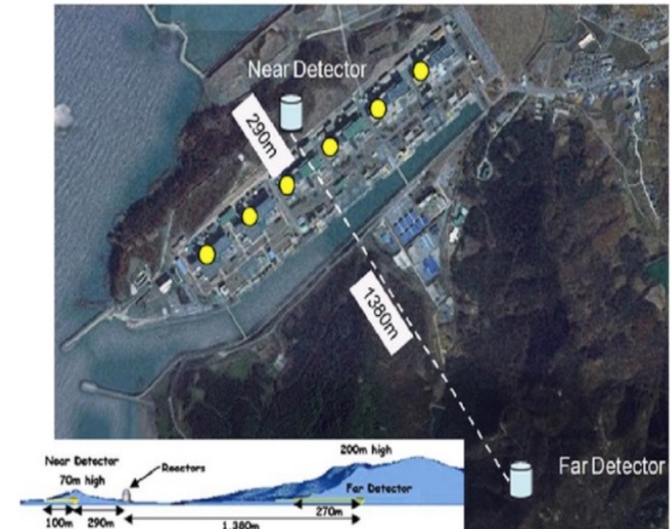
Daya Bay Collaboration, D. Adey et al., (2018)



## RENO:

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

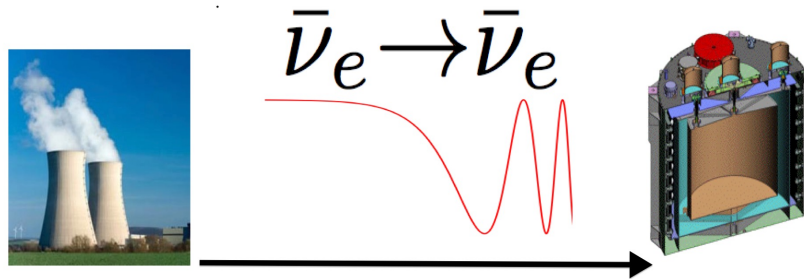
RENO Collaboration, G. Bak et al., (2018)



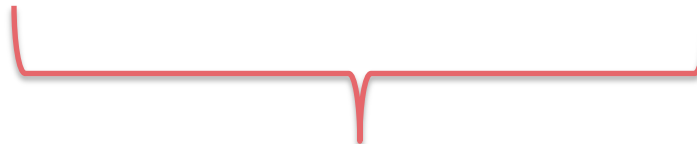
Inverse  
Beta  
Decay

# Detection

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



$$d_{LL} = 1, \quad d_{RL} = \frac{1 - 3g_A^2}{1 + 3g_A^2}, \quad d_{SL} = d_{SR} = -\frac{g_S}{1 + 3g_A^2} \frac{m_e}{E_\nu - \Delta}, \quad d_{TL} = -d_{TR} = \frac{3g_A g_T}{1 + 3g_A^2} \frac{m_e}{E_\nu - \Delta}$$



depend on neutrino energy

$$\Delta \equiv m_n - m_p \approx 1.29 \text{ MeV}$$

IBD will be sensitive to the  
scalar and tensor NP!

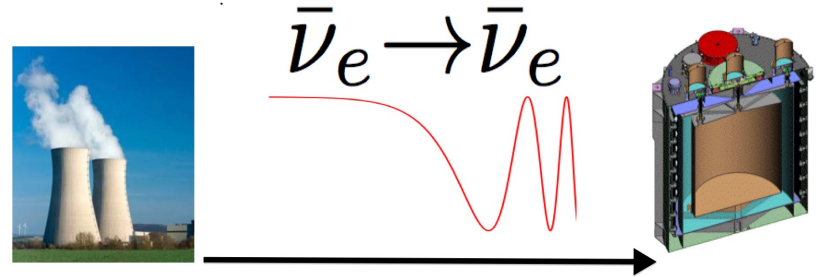
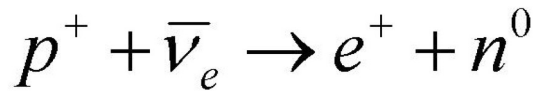
$$g_A = 1.2728 \pm 0.0017, \quad g_S = 1.02 \pm 0.11, \quad g_P = 349 \pm 9, \quad g_T = 0.987 \pm 0.055.$$

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

Inverse  
Beta  
Decay

Detection

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



$$d_{LL} = 1, \quad d_{RL} = \frac{1 - 3g_A^2}{1 + 3g_A^2}, \quad d_{SL} = d_{SR} = -\frac{g_S}{1 + 3g_A^2} \frac{m_e}{E_\nu - \Delta}, \quad d_{TL} = -d_{TR} = \frac{3g_A g_T}{1 + 3g_A^2} \frac{m_e}{E_\nu - \Delta}$$

$$d_{RR} = 1, \quad d_{SS} = \frac{g_S^2}{1 + 3g_A^2}, \quad d_{TT} = \frac{3g_T^2}{1 + 3g_A^2}$$

DO NOT depend on neutrino energy!!!

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

# Nuclear Beta Decay

## Production

- Hundreds of different beta decay processes;
- Assumption: Everything above 1.8 MeV is Gamow-Teller

A. C. Hayes et al, *Ann. Rev. Nucl. Part. Sci.* (2016)

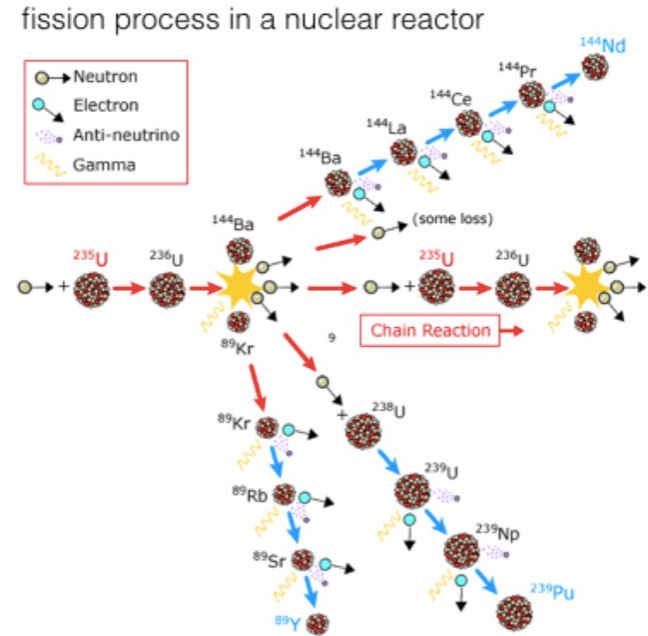
$$p_{LL} = -p_{RL} = 1, \quad p_{TL} = -p_{TR} = -\frac{g_T}{g_A} \frac{m_e}{f_T(E_\nu)}$$

$$p_{RR} = 1, \quad p_{TT} = \frac{g_T^2}{g_A^2}$$

$$f_T(E_\nu) = \frac{\sum_{i=1}^n w_i (\Delta_i - E_\nu) \sqrt{(\Delta_i - E_\nu - m_e)(\Delta_i - E_\nu + m_e)}}{\sum_{i=1}^n w_i \sqrt{(\Delta_i - E_\nu - m_e)(\Delta_i - E_\nu + m_e)}}$$

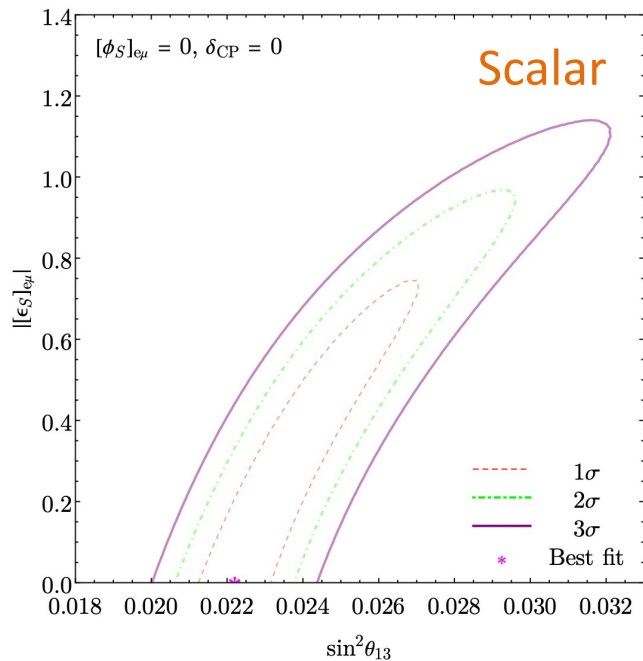
- Reactor experiments will probe tensor and scalar NP!
- They depend on the neutrino energy.

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

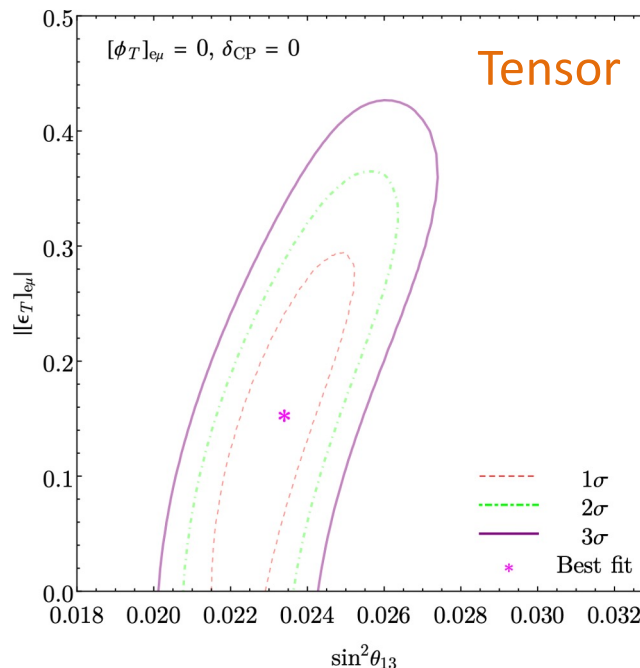


# EFT and Oscillation: Reactor Experiments

Daya Bay Collaboration:  
arXiv:2401.02901



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



- SM Oscillation;
- Access to one Flavors;
- Very High statistics;
- But EFT-Oscillation degeneracy;

• Combining with other experiments will increase the sensitivity