Unleashing the Power of EFT in Neutrino-Nucleus Scattering

Artwork by Sandbox Studio, Chicago with Ana Kova

"DPF-PHENO 2024"

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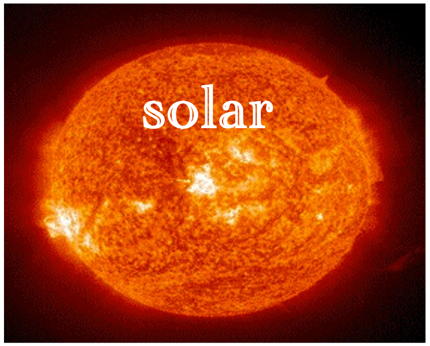
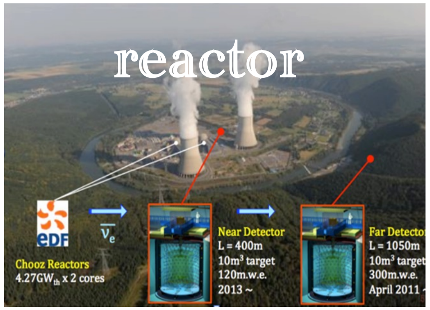
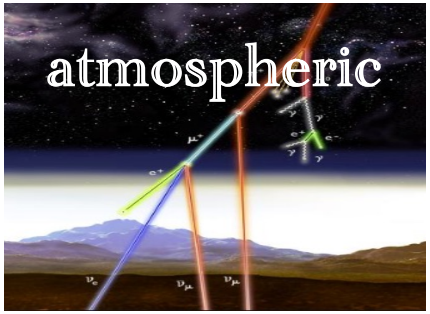
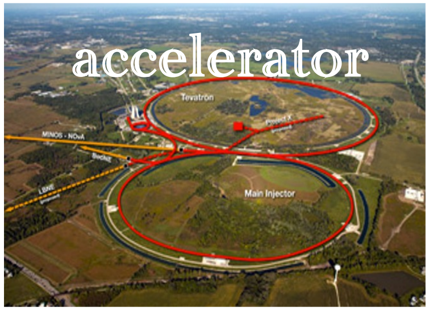
Northwestern University









Precision Measurements at Oscillation Experiments

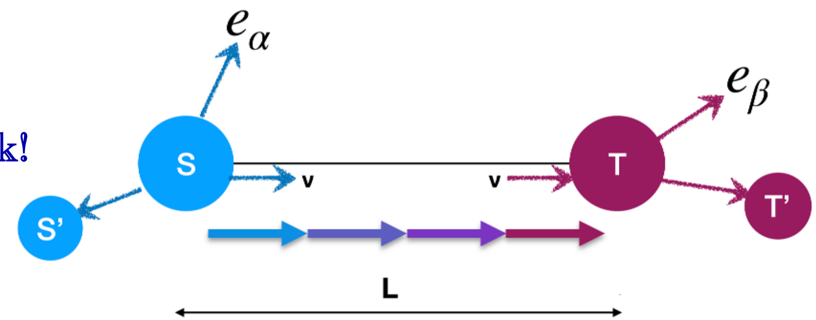
- **Tons of data;**
- **Identify neutrino flavor;**
- **More sensitive to some HE operators;**

Goal:

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

EFT at neutrino experiments

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



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

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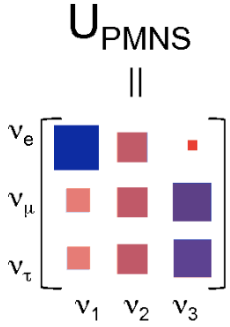

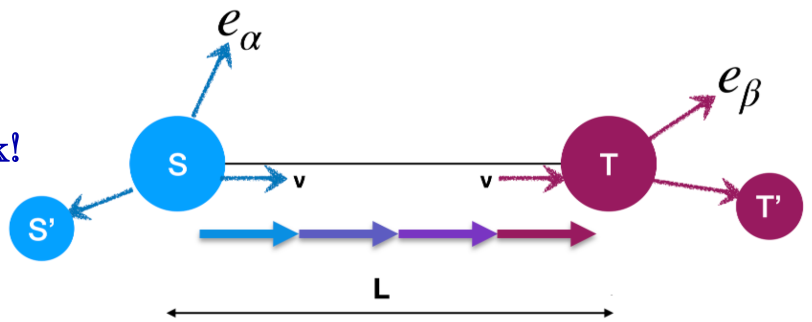

Observable: rate of detected events

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

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

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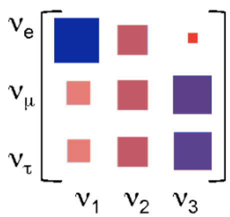
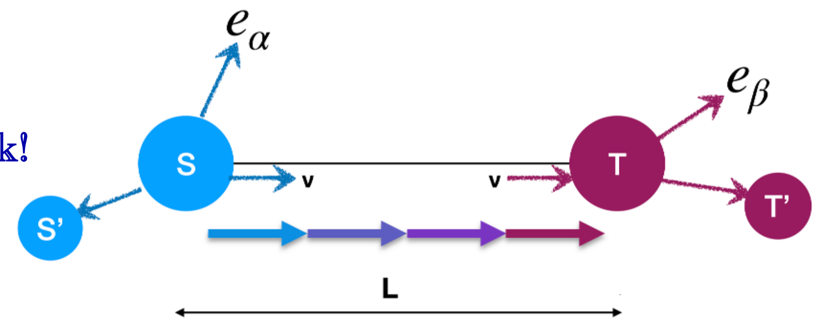
U_{PMNS}

||





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

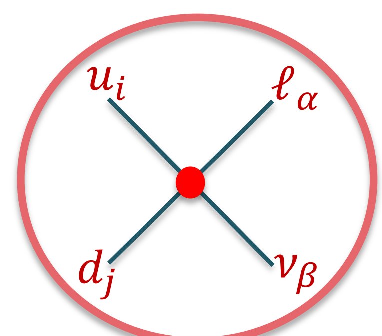
$$\mathcal{M}^P_{\alpha k} = U^*_{\alpha k} A^P_L + \sum_X [\epsilon_X U]^*_{\alpha k} A^P_X$$

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

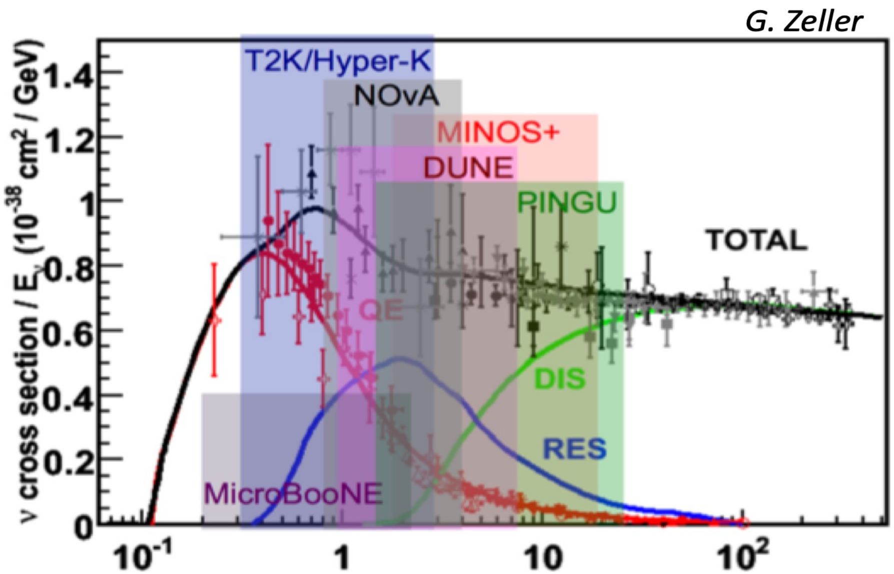
Corrections to fluxes/cross sections

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

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

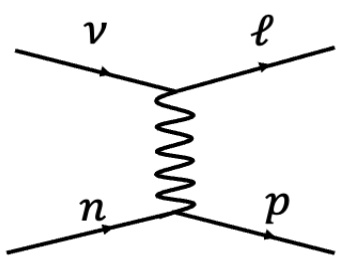


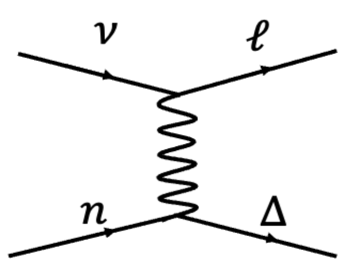
Long Baseline Accelerator Experiments

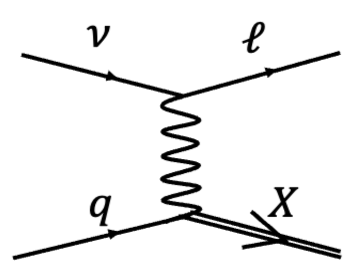


0.1-5 GeV: cross section is much more involved!

Quasi-Elastic Scattering	Resonance Production	Deep Inelastic Scattering







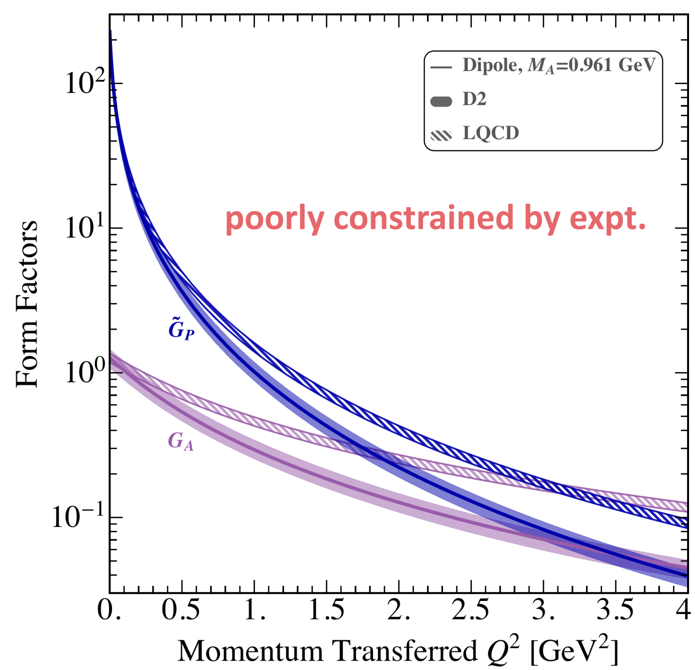
CCQE Hadronic Matrix Elements

Kopp, Rocco, <u>ZT</u>, arXiv: 2401.07902

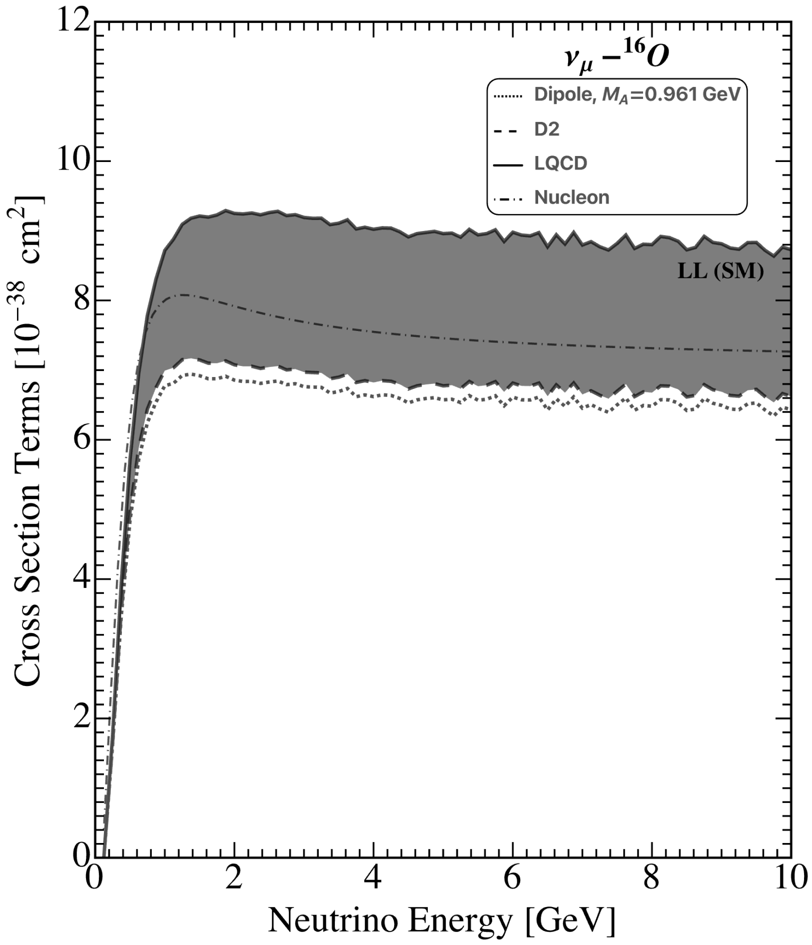
SM-Interactions:

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;

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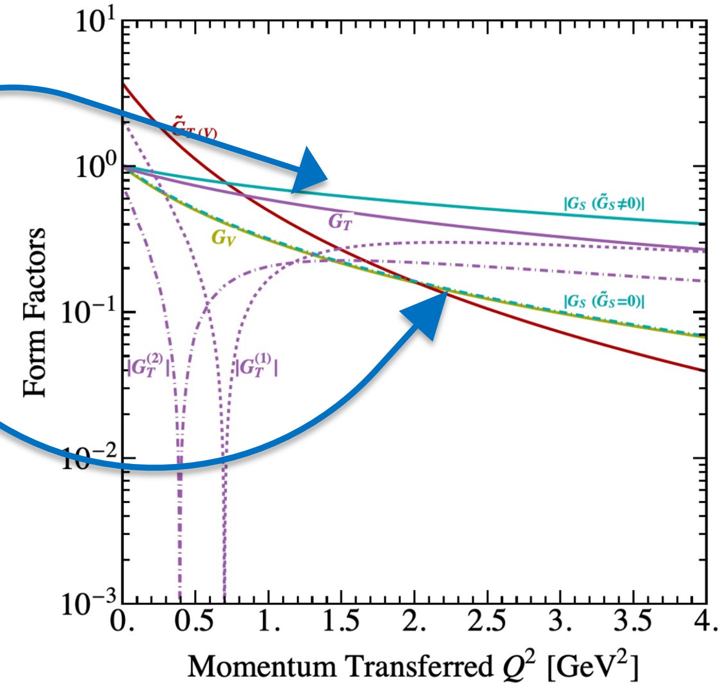

- **Scalar: conservation of the vector current (CVC):**

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

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

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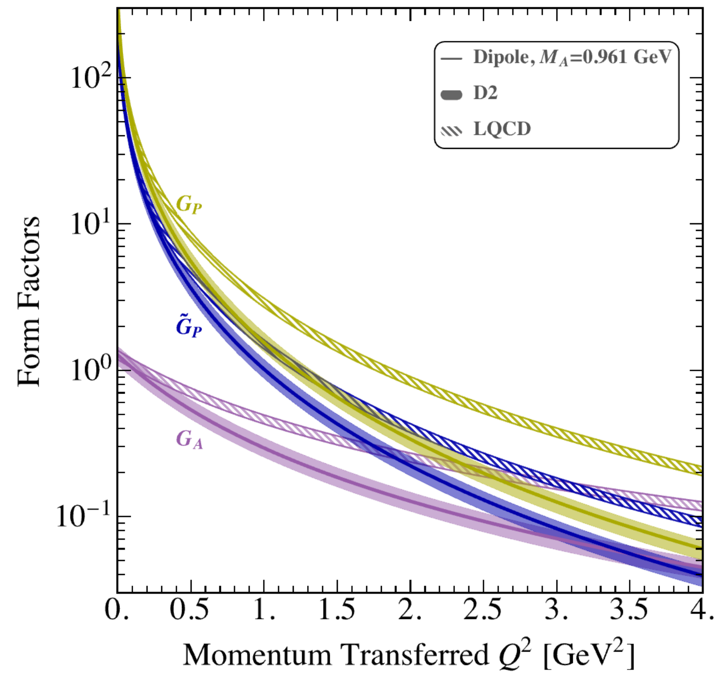
Kopp, Rocco, ZT, arXiv: 2401.07902

- 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:

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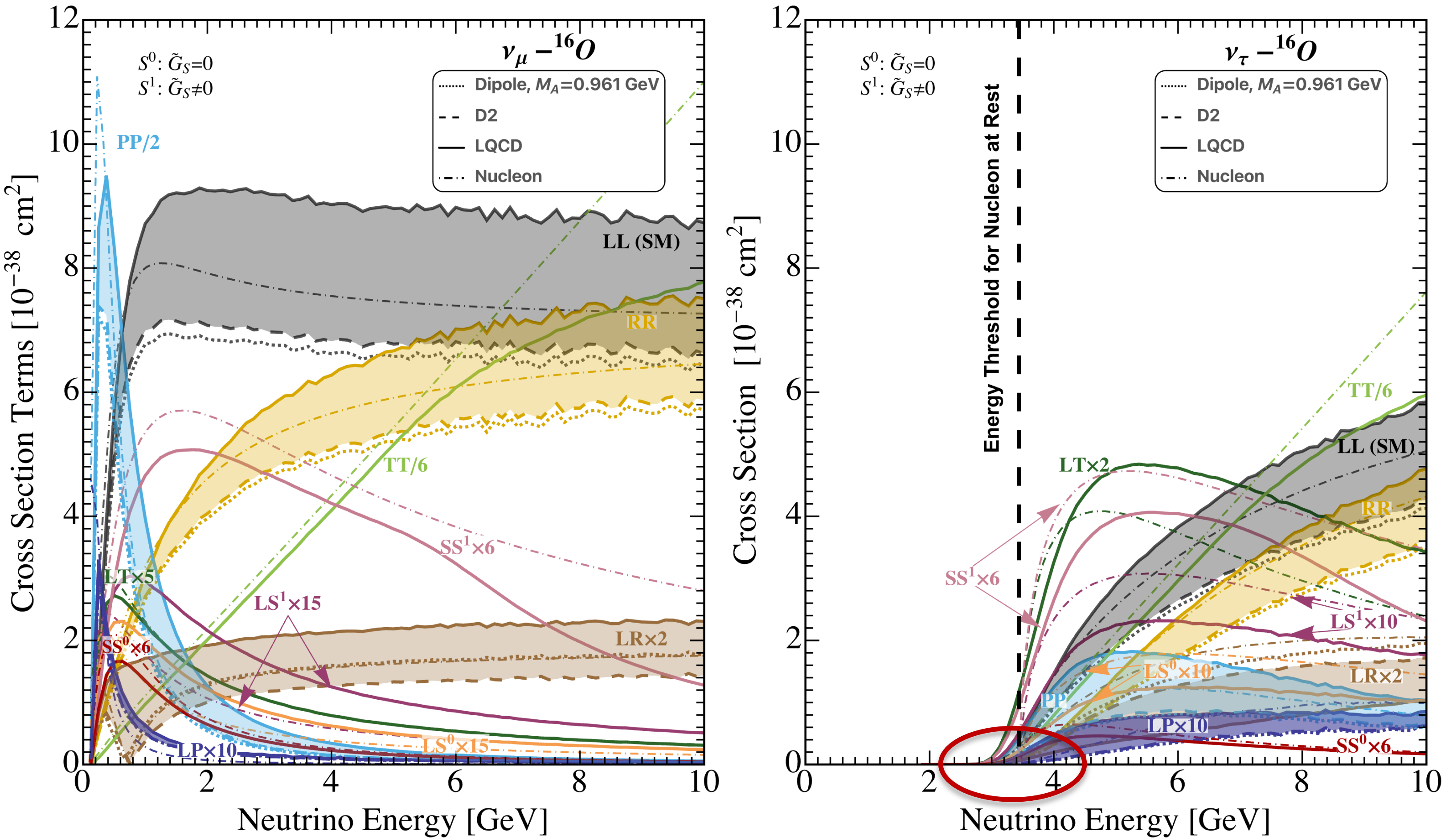


- z-expansion fit to LQCD and D2 data;
- Nuclear effects;
- Comparison with nucleon scattering

How about flux corrections?

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

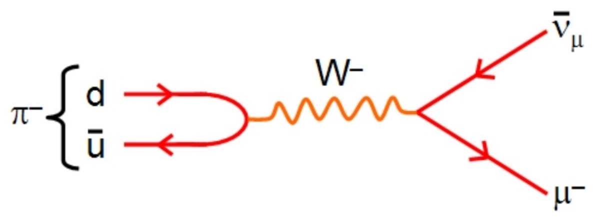
Due to the pseudoscalar nature of the pion, it is sensitive only to axial (ε_L-ε_R) and pseudo-scalar (ε_P) interactions.

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

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

~-27

~700!



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

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

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

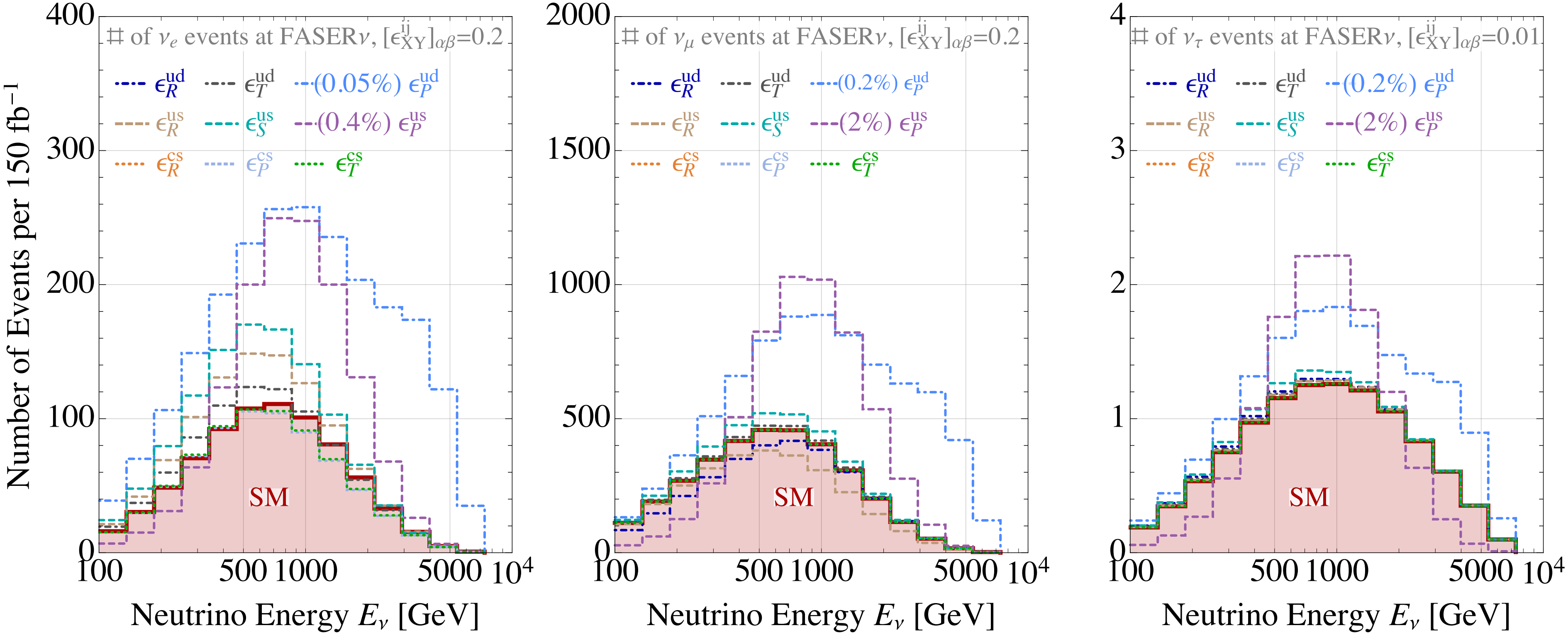
$$\langle 0|\bar{d}\gamma^\mu\gamma_5 u\,|\pi^+(p_\pi)\rangle = i p_\pi^\mu f_\pi$$

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

Huge overall flux normalization for pion decay!

Example: Event Rates at FASERν

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 ν_e, 10% on ν_μ, 15% on ν_τ
- Conservative systematic uncertainties: 30% on ν_e, 40% on ν_μ, 50% on ν_τ

EFT at neutrino experiments

- Observed rate at the experiment: $\boxed{R_{Obs} = 10^4\ \nu_\mu}$

- Uncertainty: $\boxed{\sqrt{R_{obs}} = 10^2\ \nu_\alpha \equiv \Delta R}$

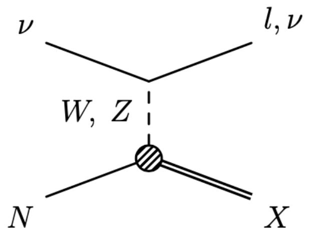
- From theory: $\boxed{R_{Th} = R_{SM}(1 + C\,\epsilon^2) = R_{SM} + \Delta R}$

- Limit on ϵ: $\boxed{C\,\epsilon^2 = \frac{\Delta R}{R_{SM}}}$ $\left\{ \boxed{\begin{array}{c} C = 10^3 \\ \epsilon < \frac{10^2}{10^3 \times 10^4} \sim 3\times10^{-3} \end{array}} \right.$

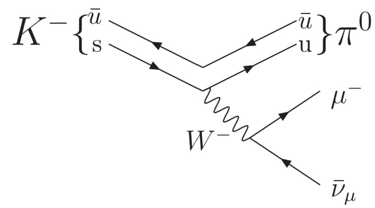
- New Physics Limit: $\boxed{\Lambda \equiv \frac{\mathrm{v}\ [246\ GeV]}{\sqrt{\epsilon}} = 4.5\ \mathrm{TeV}}$

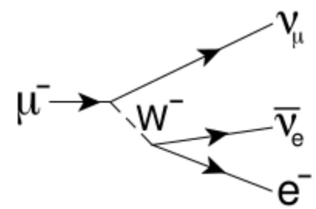
$$C \propto \frac{\sigma_{NP}}{\sigma_{SM}} \text{ or } \frac{\phi_{NP}}{\phi_{SM}}$$

DIS: FASERv



Kaon/Muon decay: ISODAR, KDAR





Solar neutrinos: Borexino

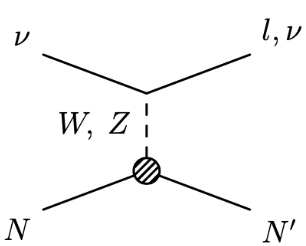
^{7}**Be** $\boxed{{}^7\mathrm{Be} + e^- \to {}^7\mathrm{Li} + \nu_e}$

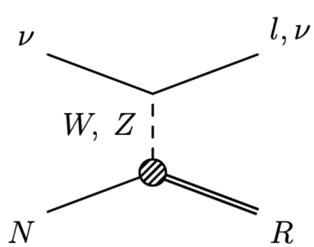
$\boxed{{}^3\mathrm{He} + p \to {}^4\mathrm{He} + e^+ + \nu_e}$ **hep**

(hep)

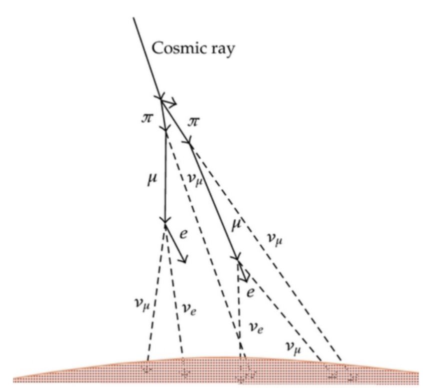
$\boxed{p + e^- + p \to {}^2\mathrm{H} + \nu_e}$ ***pep***

QE, Resonances: MINOS, NOvA, DUNE

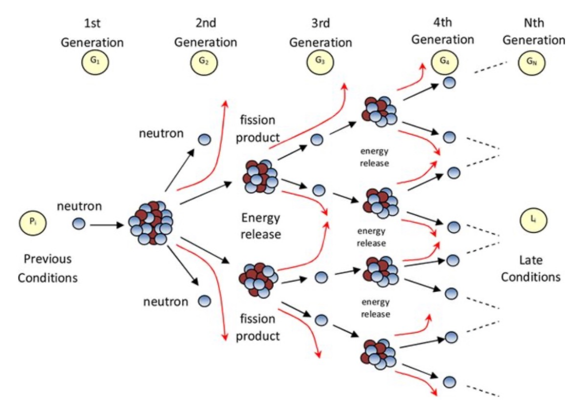




Atmospheric Neutrinos: IceCube

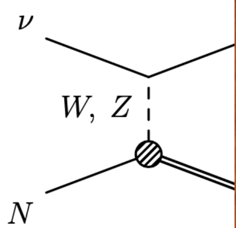


Beta decay and IBD: Reactor Experiments



DIS: FASERν

Solar neutrinos: Borexino



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

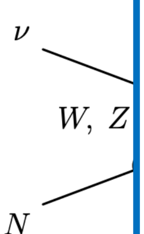
$+ p \to {}^4\mathrm{He} + e^+ + \nu_e$ **hep**

(hep)

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

QE, Resonances:

Beta decay and



- We have the tools to do a global EFT analysis with all neutrino experiments;

- Extracting 10 TeV physics from GeV neutrino experiments!

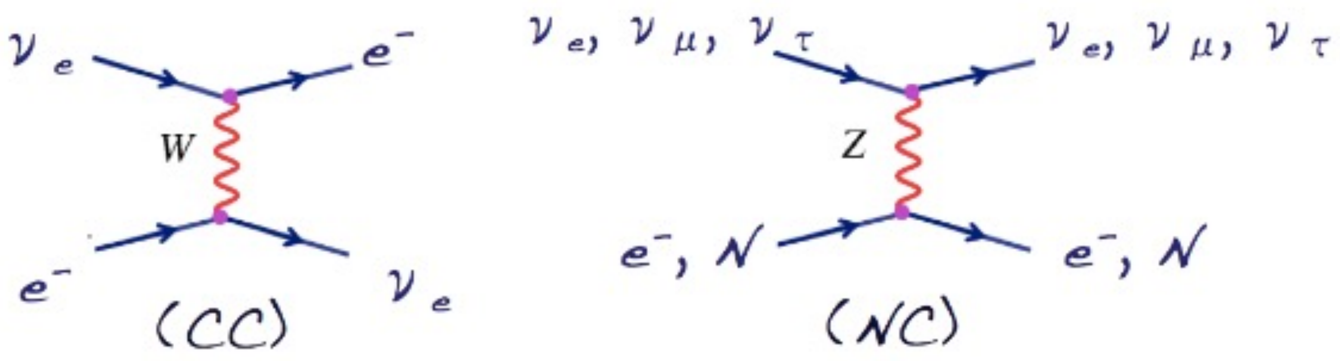
Any Questions?

I'M NOW GOING TO OPEN THE FLOOR TO QUESTIONS.

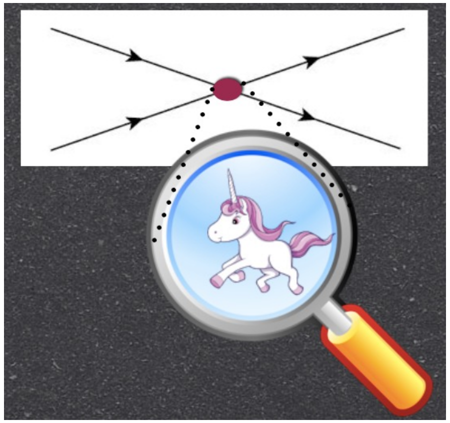
Zahra Tabrizi, NTN fellow, Northwestern U.

Back up Slides

- Coherent CC and NC forward scattering of neutrinos

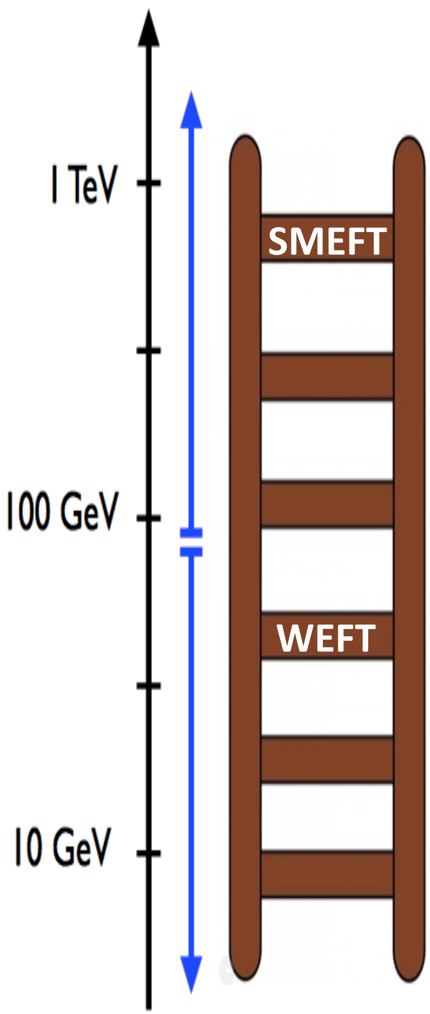


- New 4-fermion interactions



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

EFT ladder



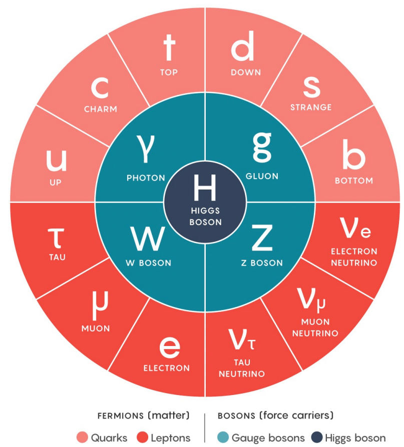
- Colliders
- CLFV

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



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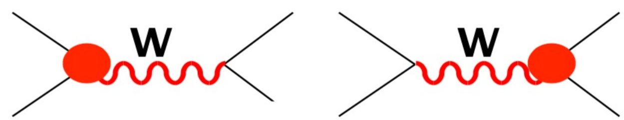
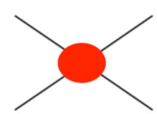
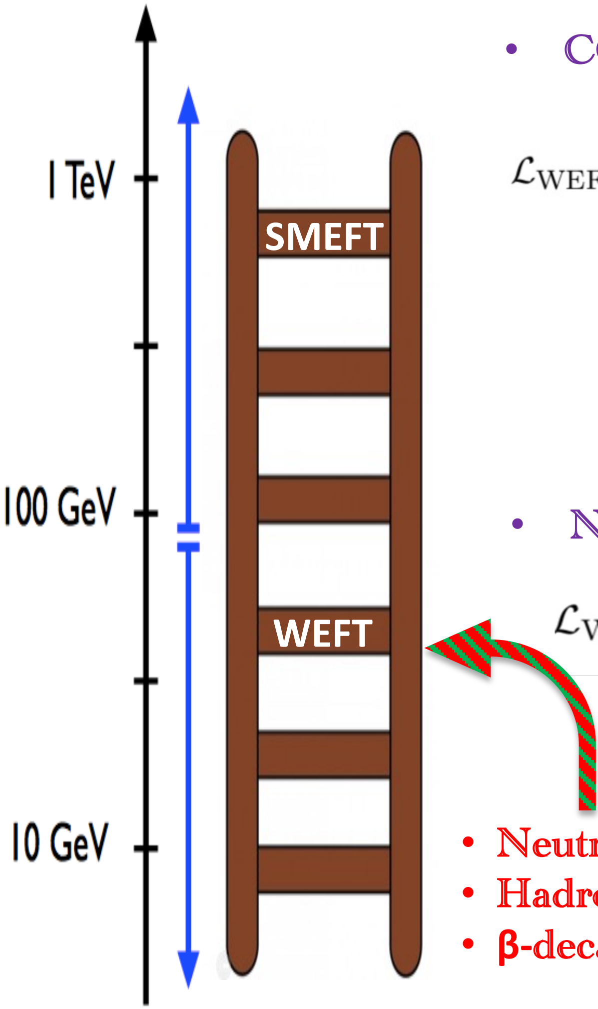




$$O_{lq}^{(3)} = (\bar{l}\gamma^{\mu}\sigma^{a}l)(\bar{q}\gamma_{\mu}\sigma^{a}q)$$
$$O_{qde} = (\bar{l}e)(\bar{d}q) + \text{h.c.}$$
$$O_{lq} = (\bar{l}_{a}e)\epsilon^{ab}(\bar{q}_{b}u) + \text{h.c.}$$
$$O_{lq}^{t} = (\bar{l}_{a}\sigma^{\mu\nu}e)\epsilon^{ab}(\bar{q}_{b}\sigma_{\mu\nu}u) + \text{h.c.}$$

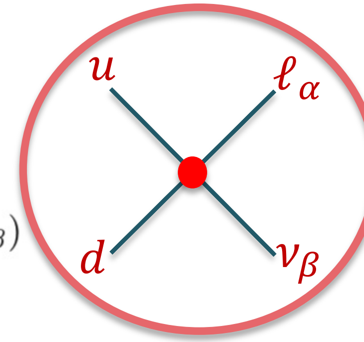
EFT ladder

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



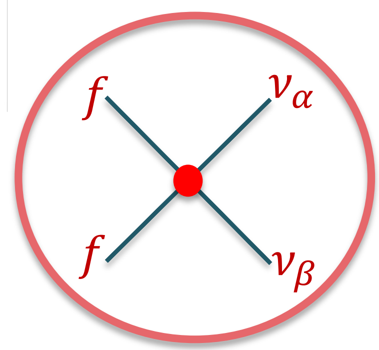
- CC: New left/right handed, (pseudo)scalar and tensor interactions

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



- NC: New left and right handed interactions

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



- Neutrino experiments
- Hadron Decays
- β-decays

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

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

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

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

Hadronic Matrix Elements

Kopp, Rocco, <u>ZT</u>, arXiv: 2401.07902

SM-Interactions:

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

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

Hadronic Matrix Elements

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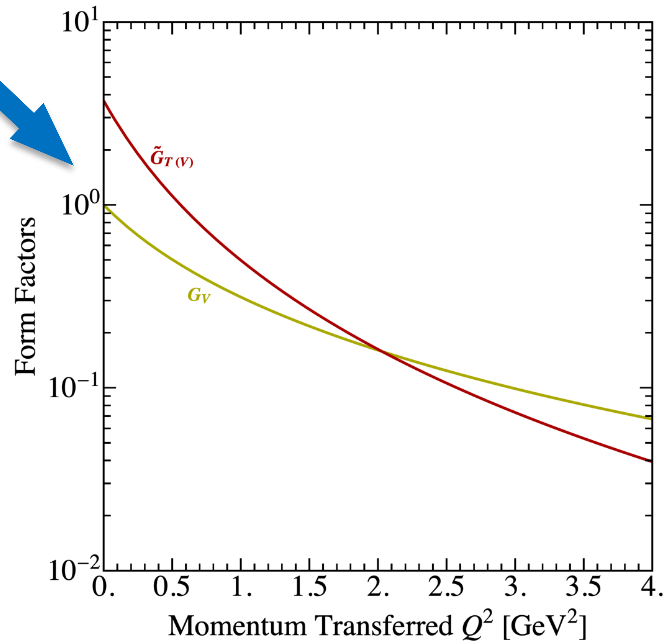
SM-Interactions:

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

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

constrained by eN scattering



Hadronic Matrix Elements

Kopp, Rocco, ZT, arXiv: 2401.07902

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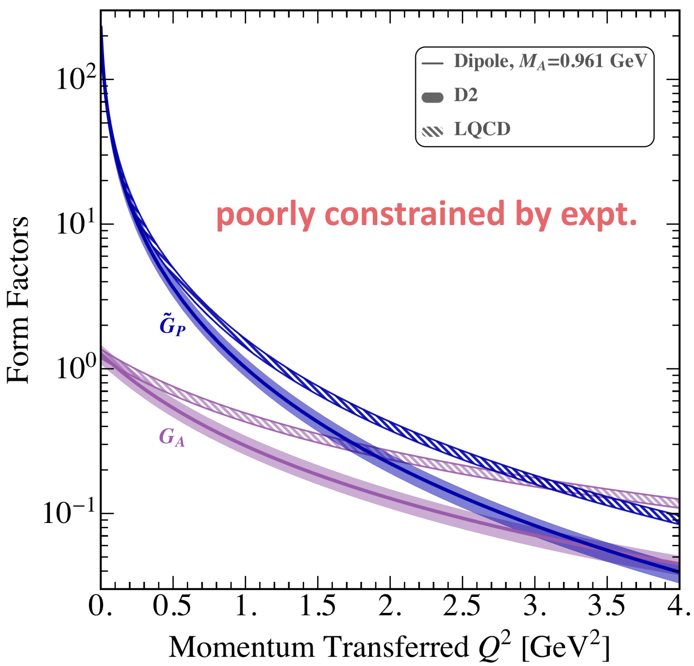
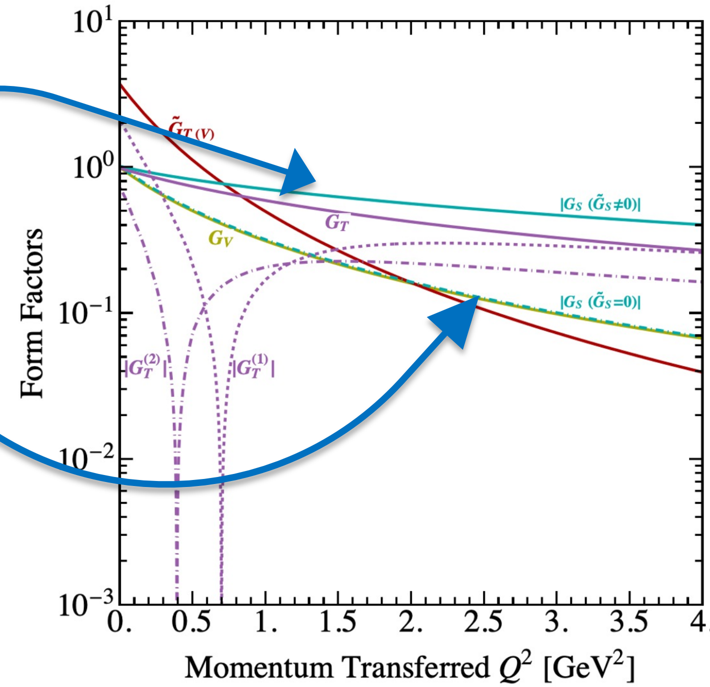


NEW-Interactions:

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

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

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



Kopp, Rocco, <u>ZT</u>, arXiv: 2401.07902

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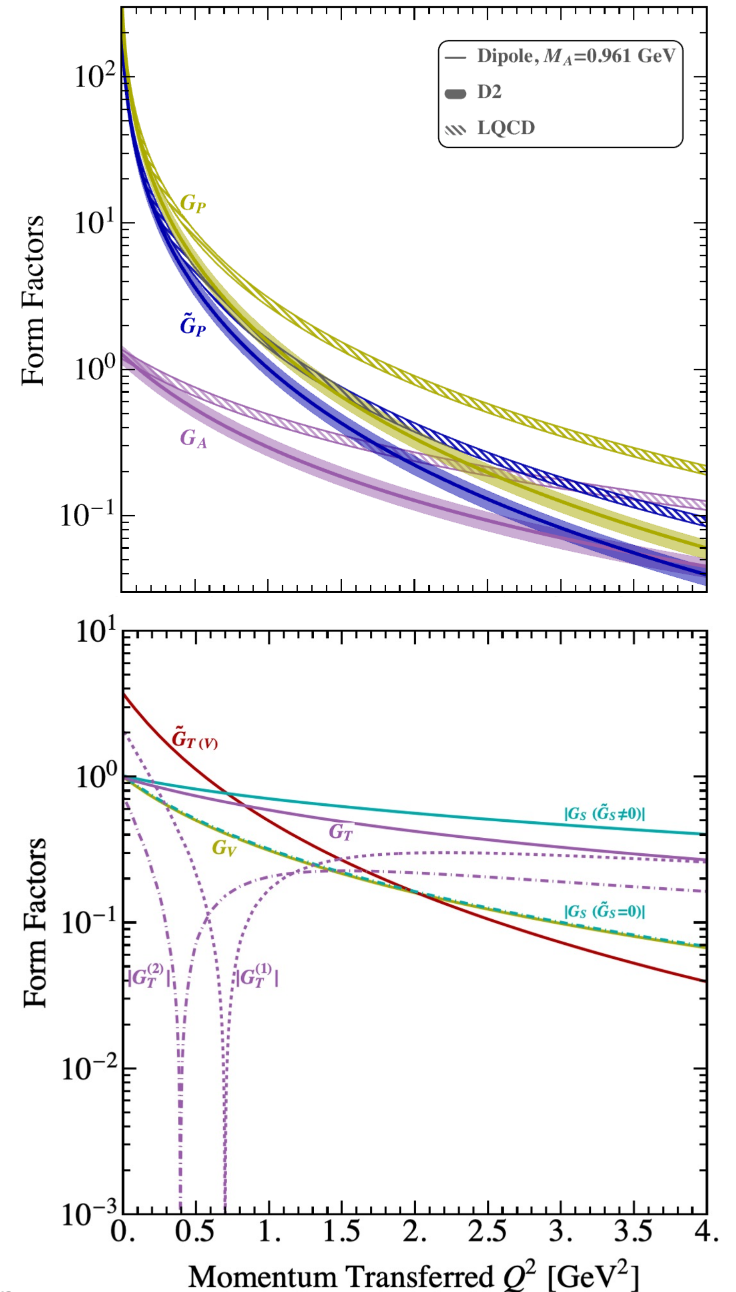
- Pseudo-Scalar: partial conservation of the axial current (PCAC):

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

➢D2: neutrino-deuterium data (shaded band)

➢RQCD Collaboration (hatched band)

Kopp, Rocco, <u>ZT</u>, arXiv: 2401.07902



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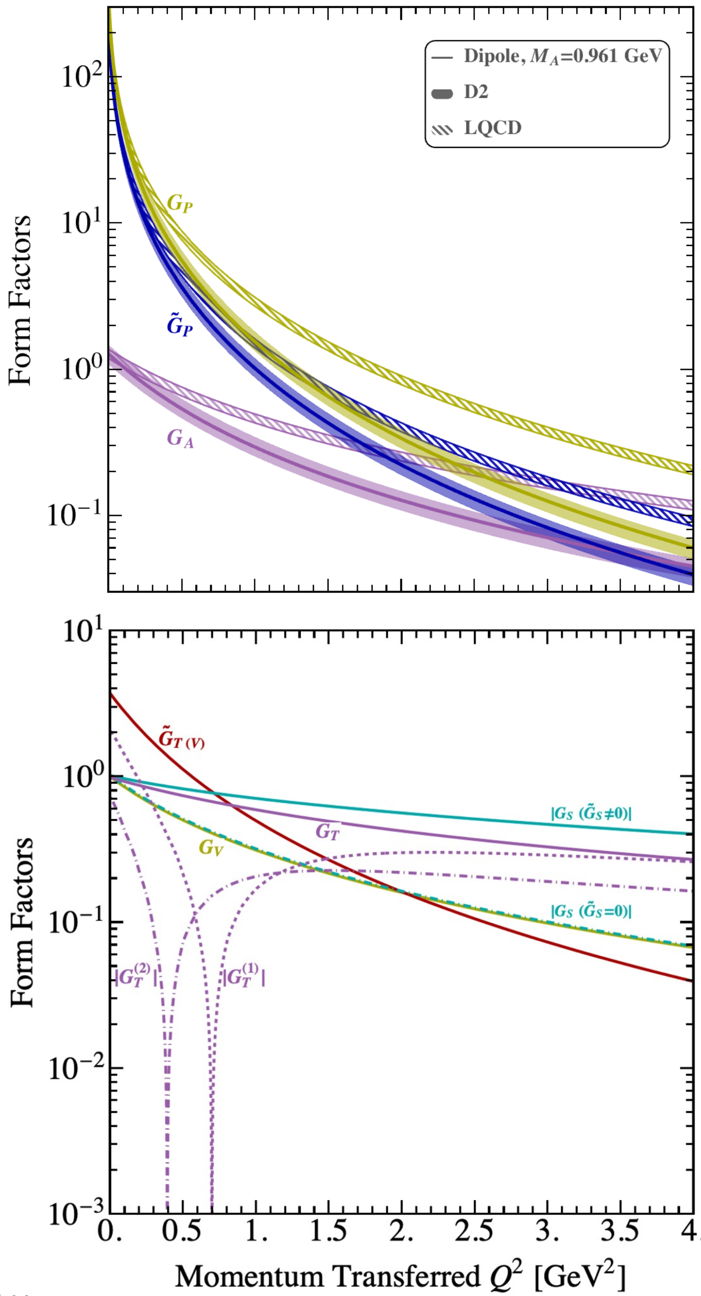
- Tensor: LQCD and theoretical considerations

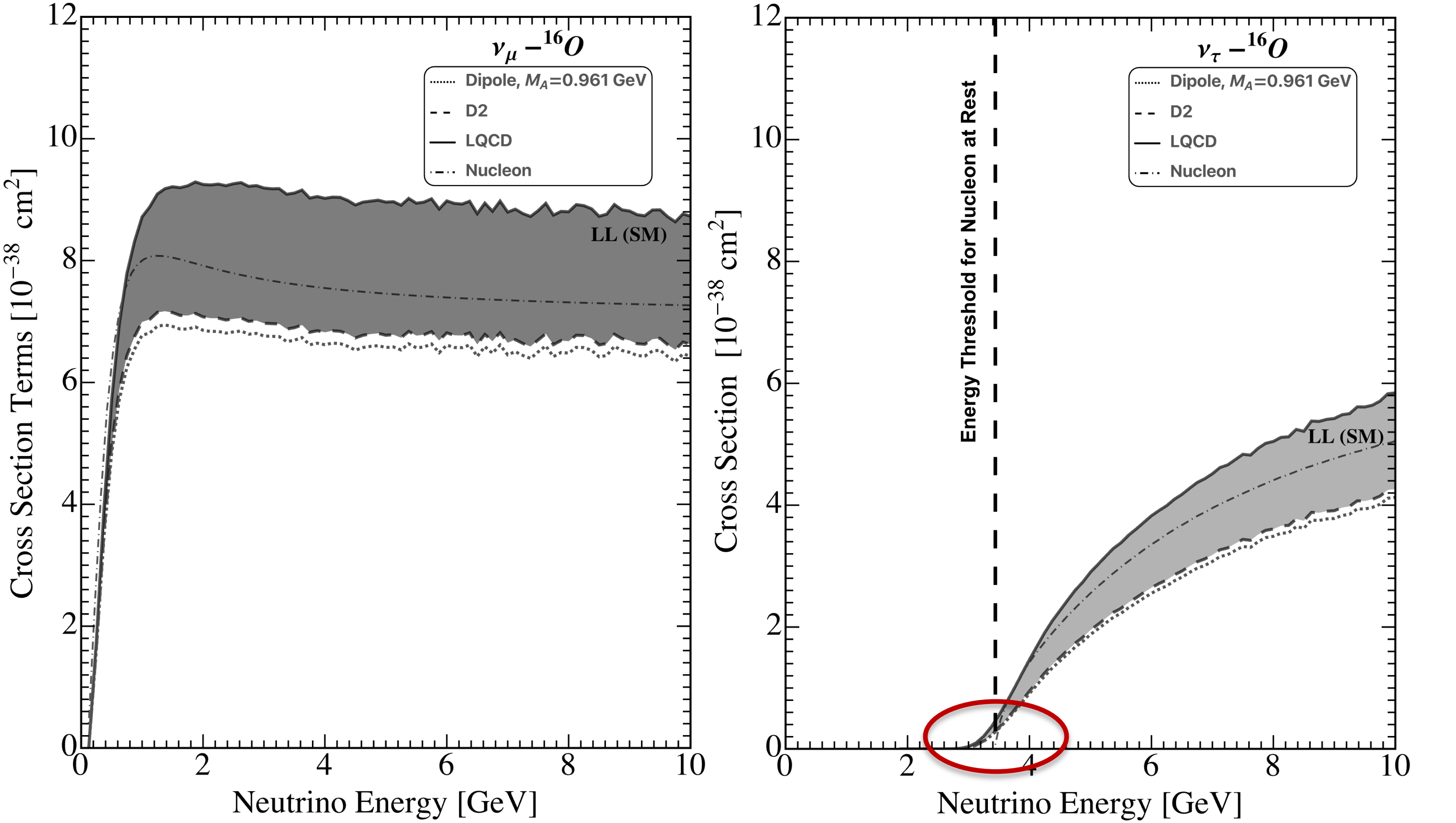
  - **We cannot neglect $\widetilde{G}_S$ anymore!**
  - **Large enhancements for several interactions;**

Kopp, Rocco, <u>ZT</u>, 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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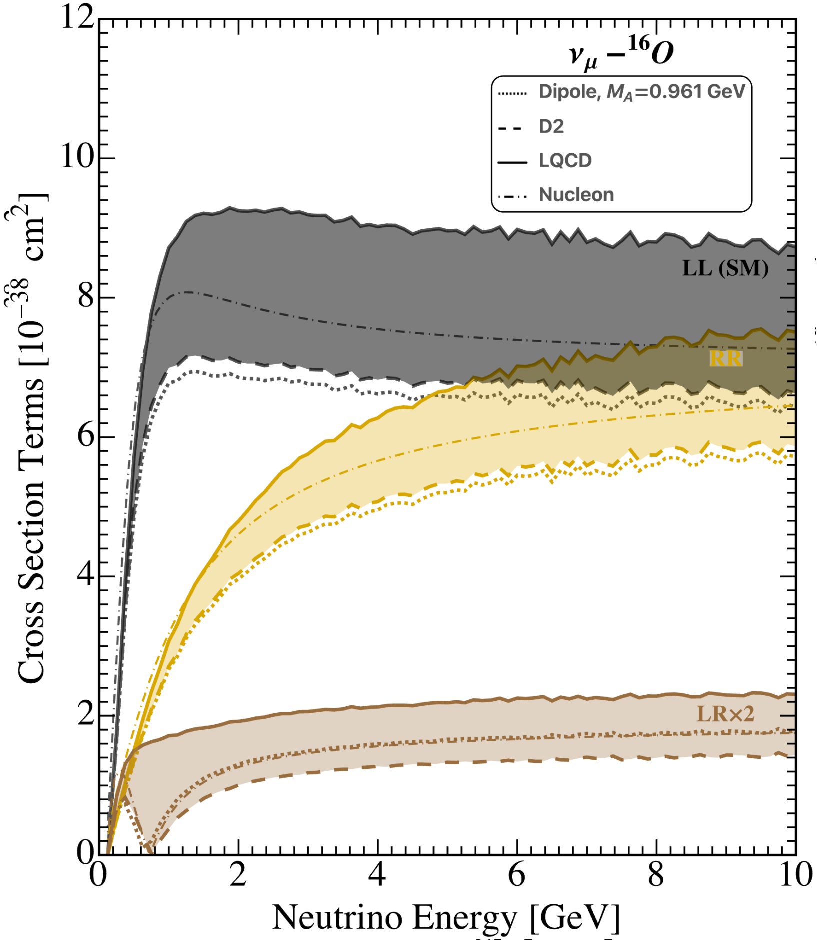
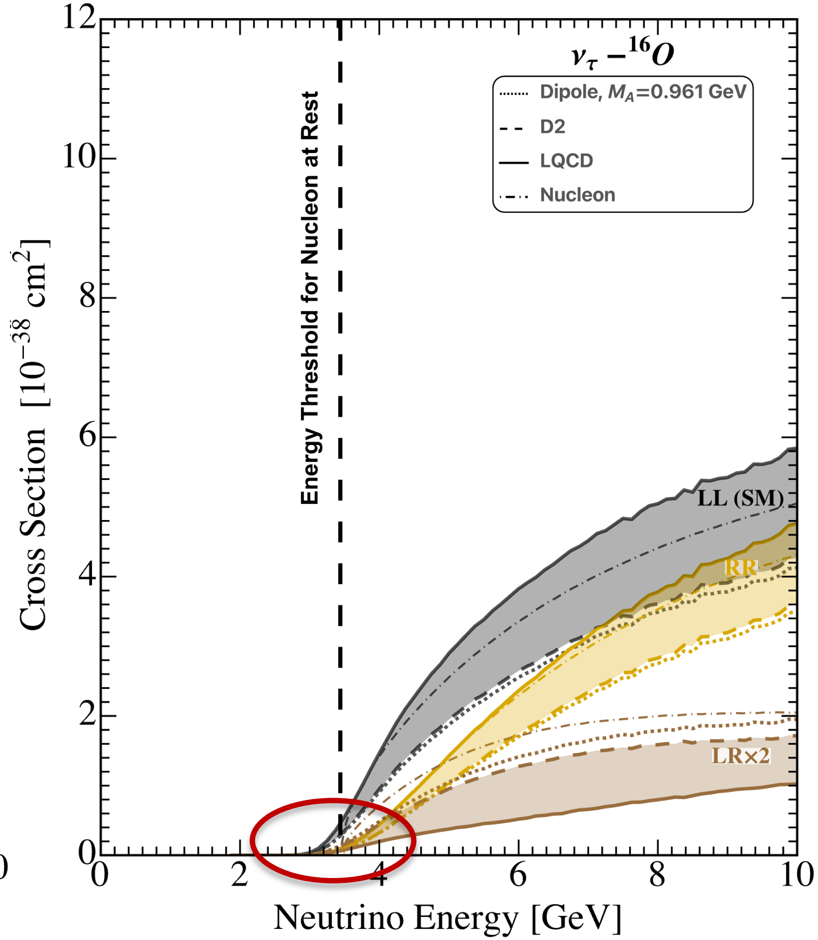
Kopp, Rocco, ZT, arXiv: 2401.07902





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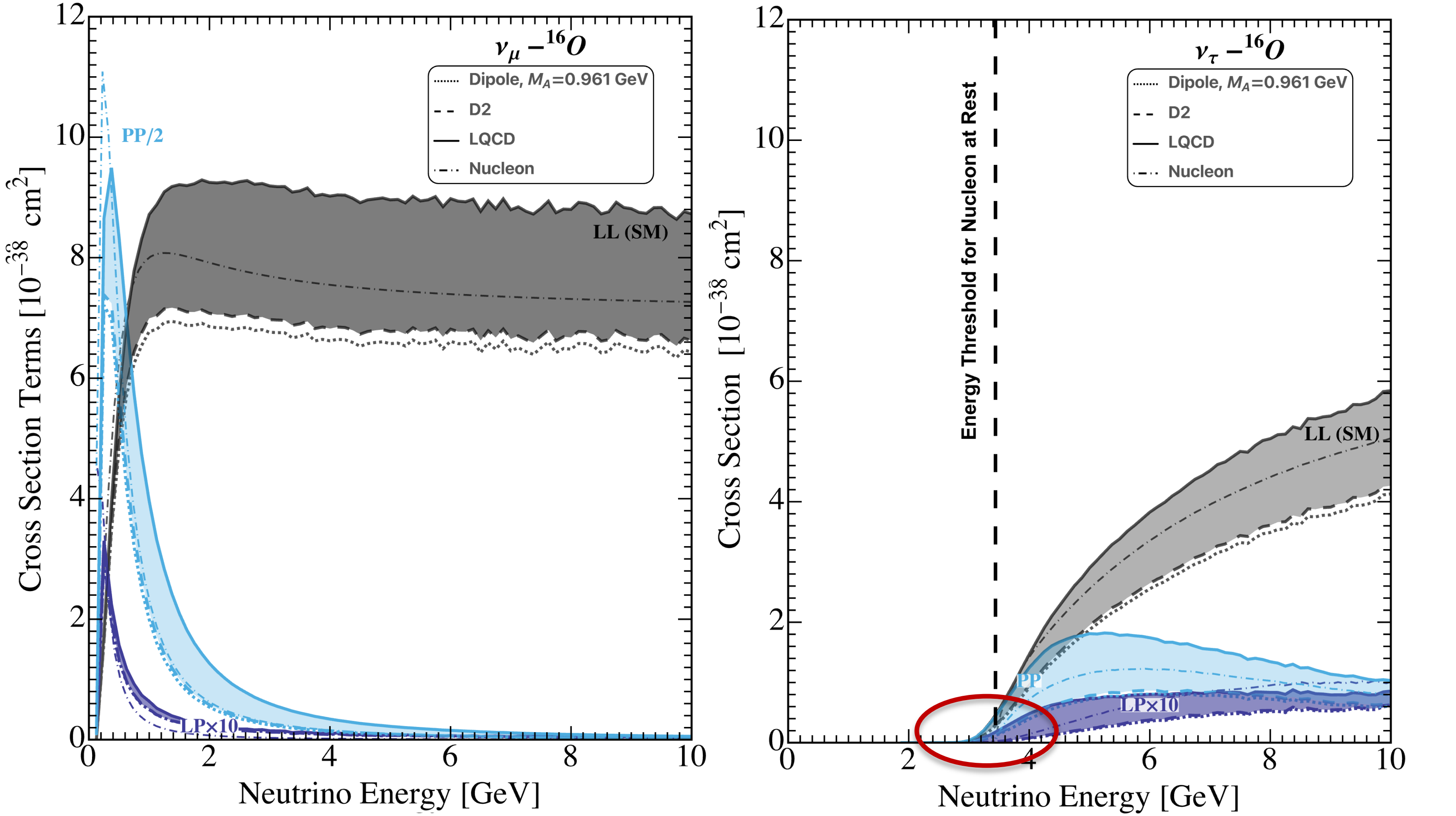

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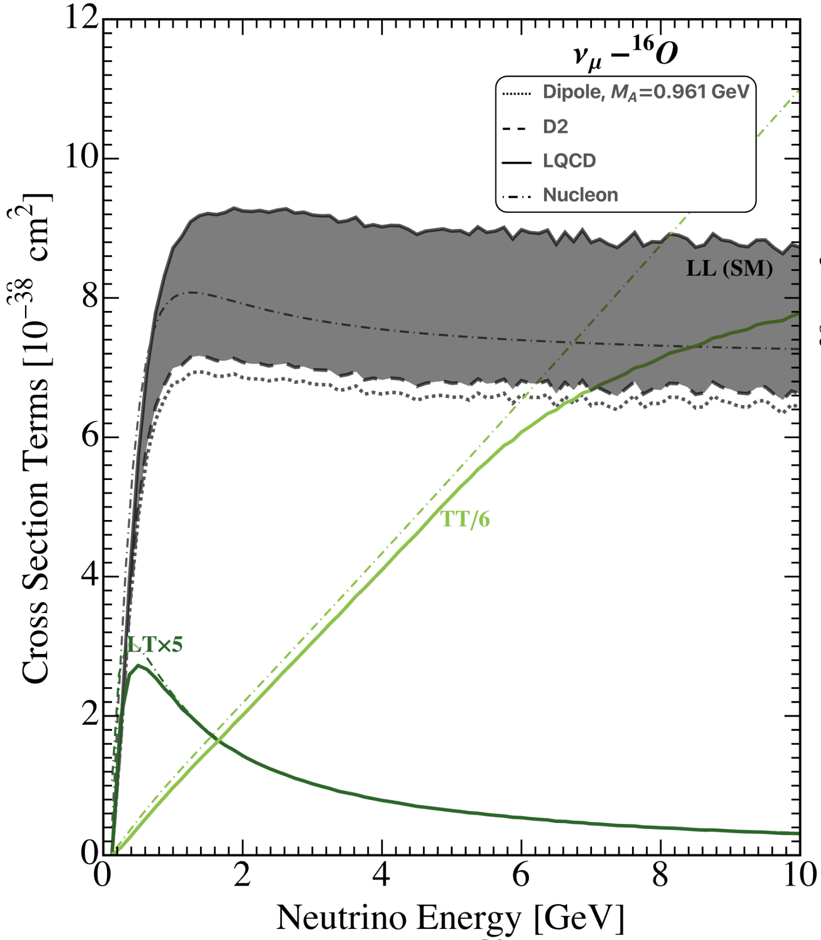

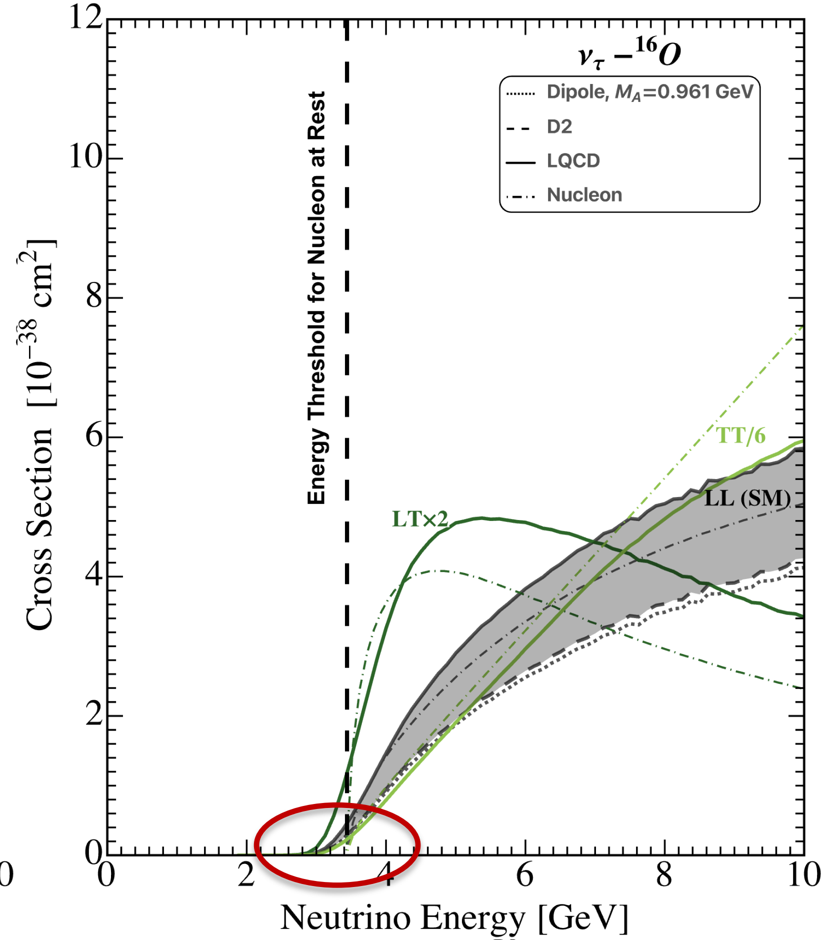

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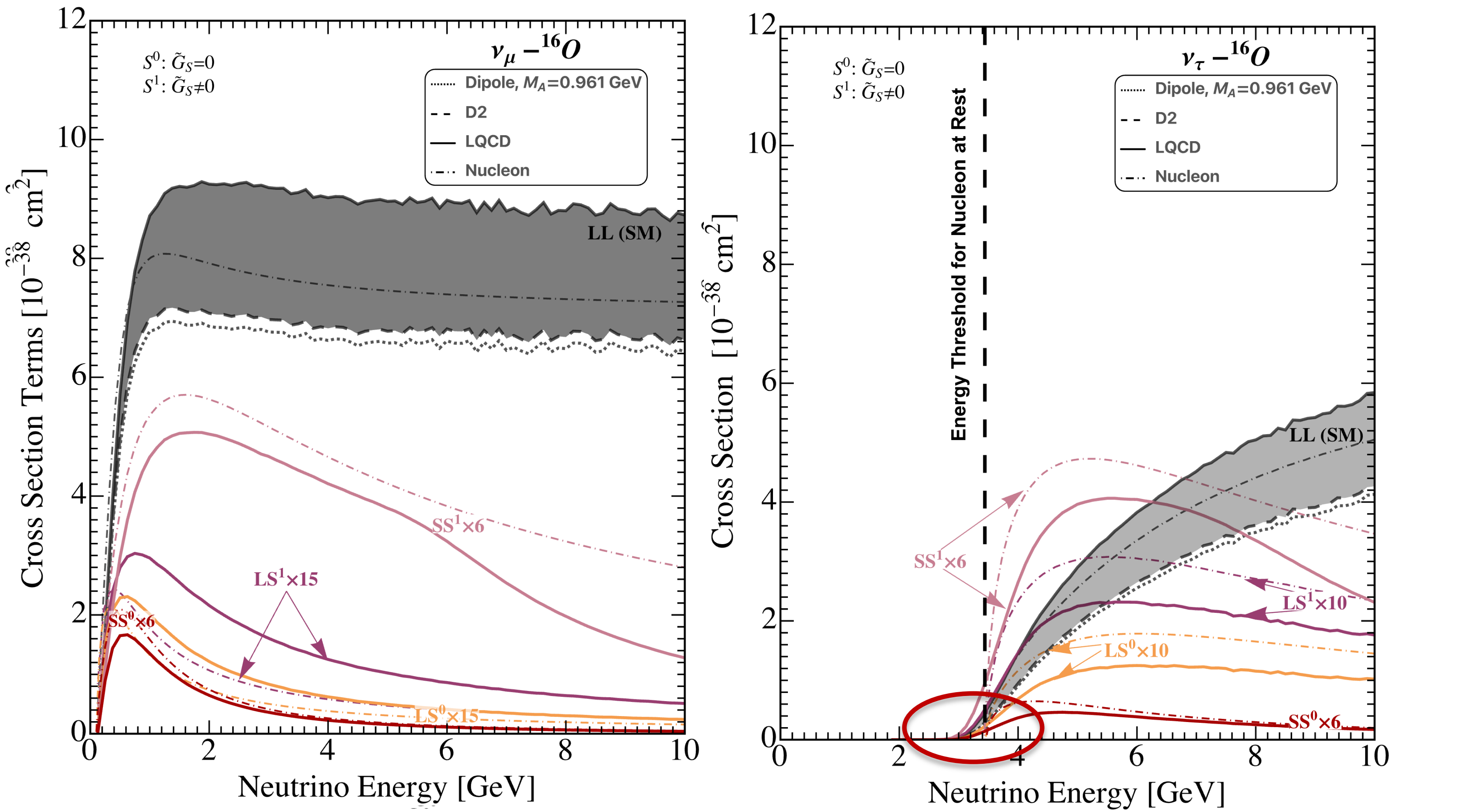

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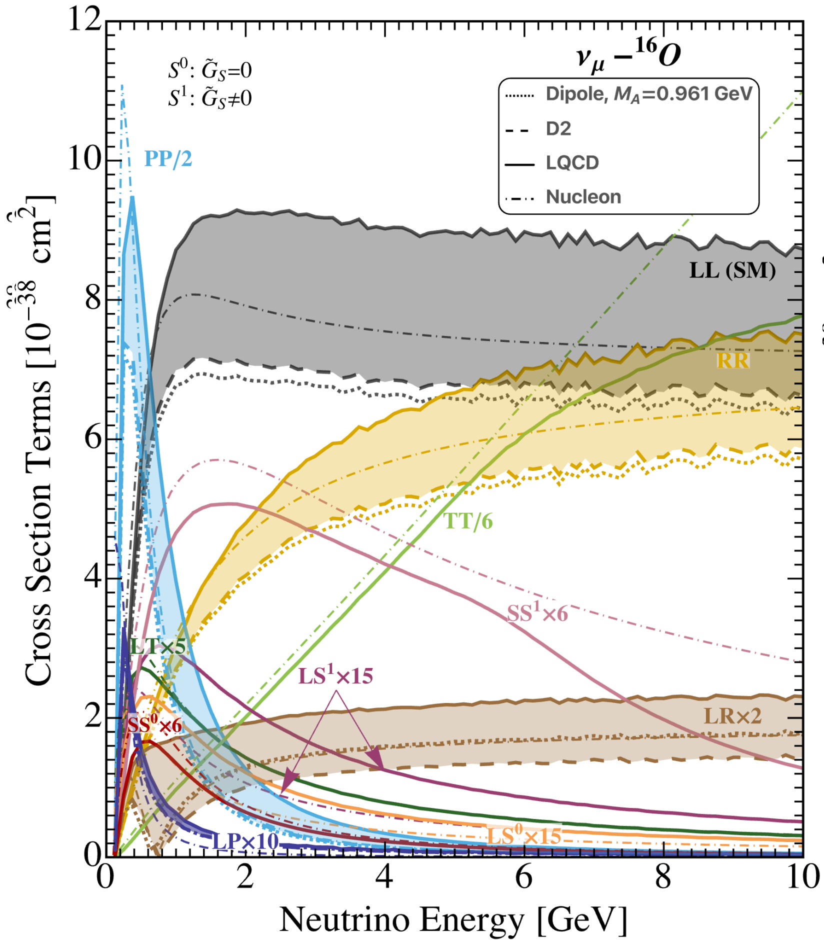

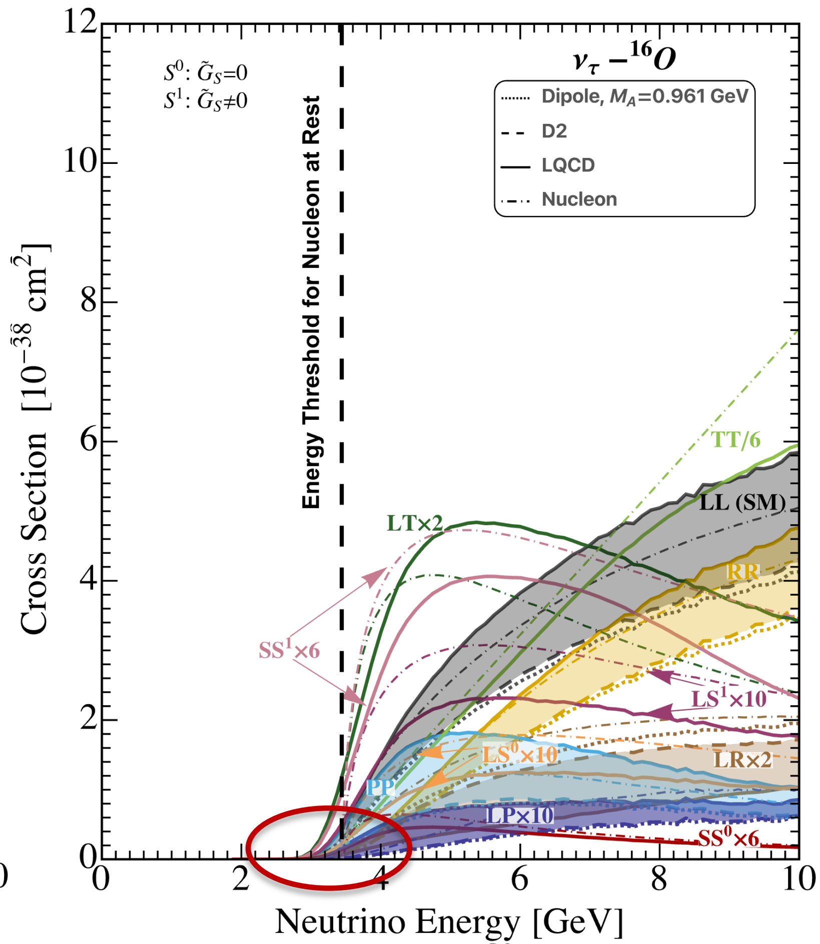

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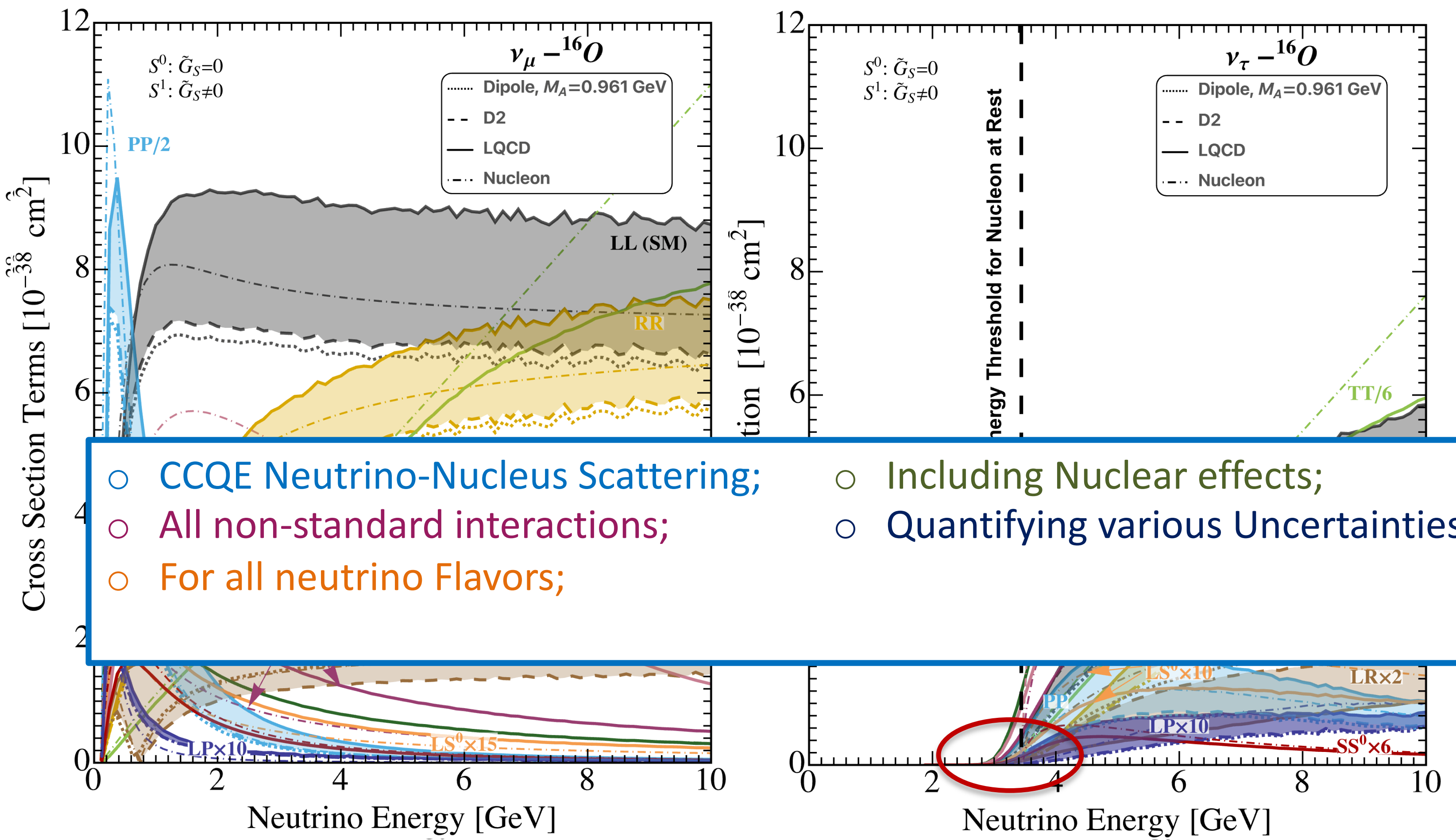

- CCQE Neutrino-Nucleus Scattering;
- All non-standard interactions;
- For all neutrino Flavors;
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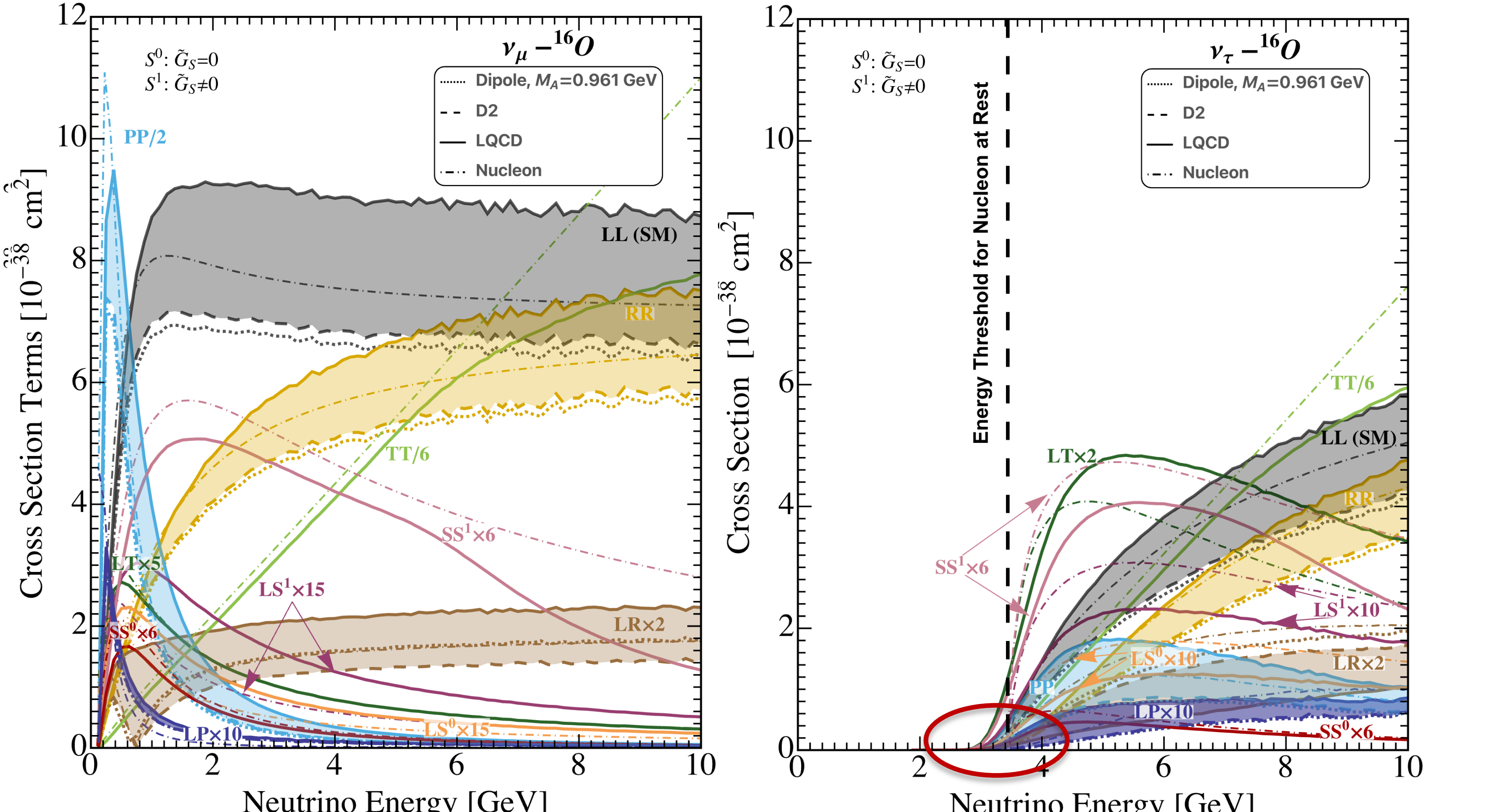
- Quantifying various Uncertainties;

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

Neutrino-Nucleus Cross Sections:

Kopp, Rocco, ZT, arXiv: 2401.07902



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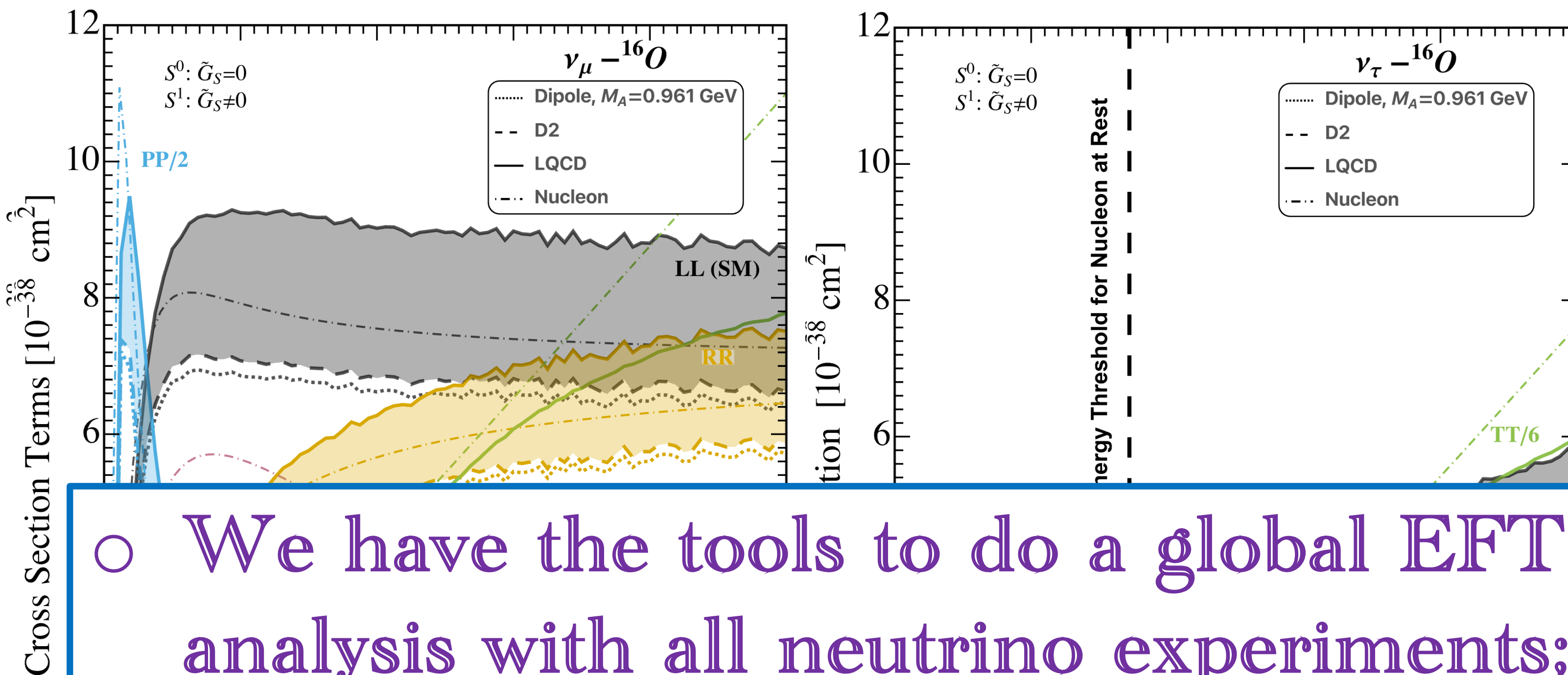


- We have the tools to do a global EFT analysis with all neutrino experiments;
- Extracting 10 TeV physics from GeV neutrino experiments!

Pion decay

Production

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

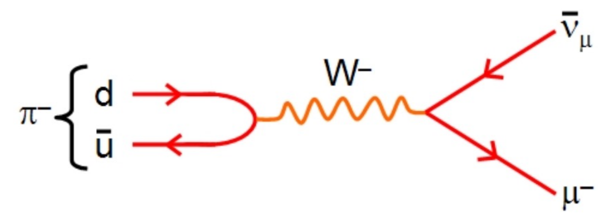
Due to the pseudoscalar nature of the pion, it is sensitive only to axial (ε_L-ε_R) and pseudo-scalar (ε_P) interactions.

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

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

~-27

~700!



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

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

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

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

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

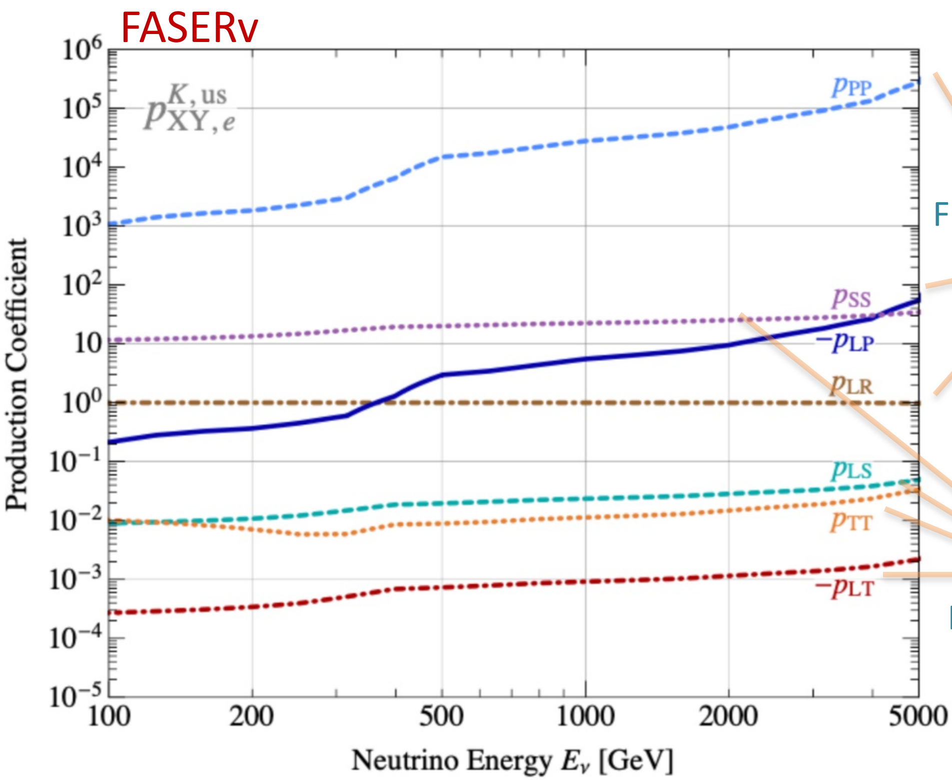
Huge overall flux normalization for pion decay!

kaon decay

Production

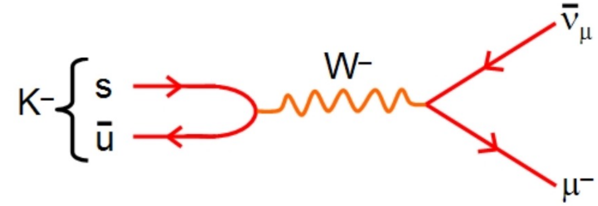
Falkowski, González-Alonso, Kopp, Soreq, ZT, JHEP (2021)

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

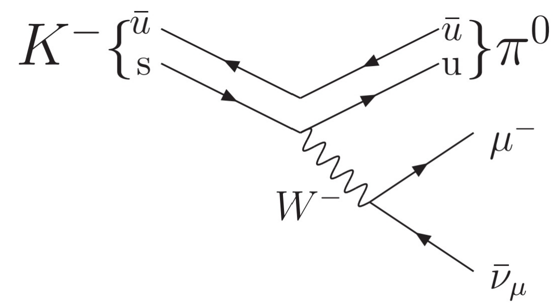


From 2-b decay

From 3-b decay



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



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

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

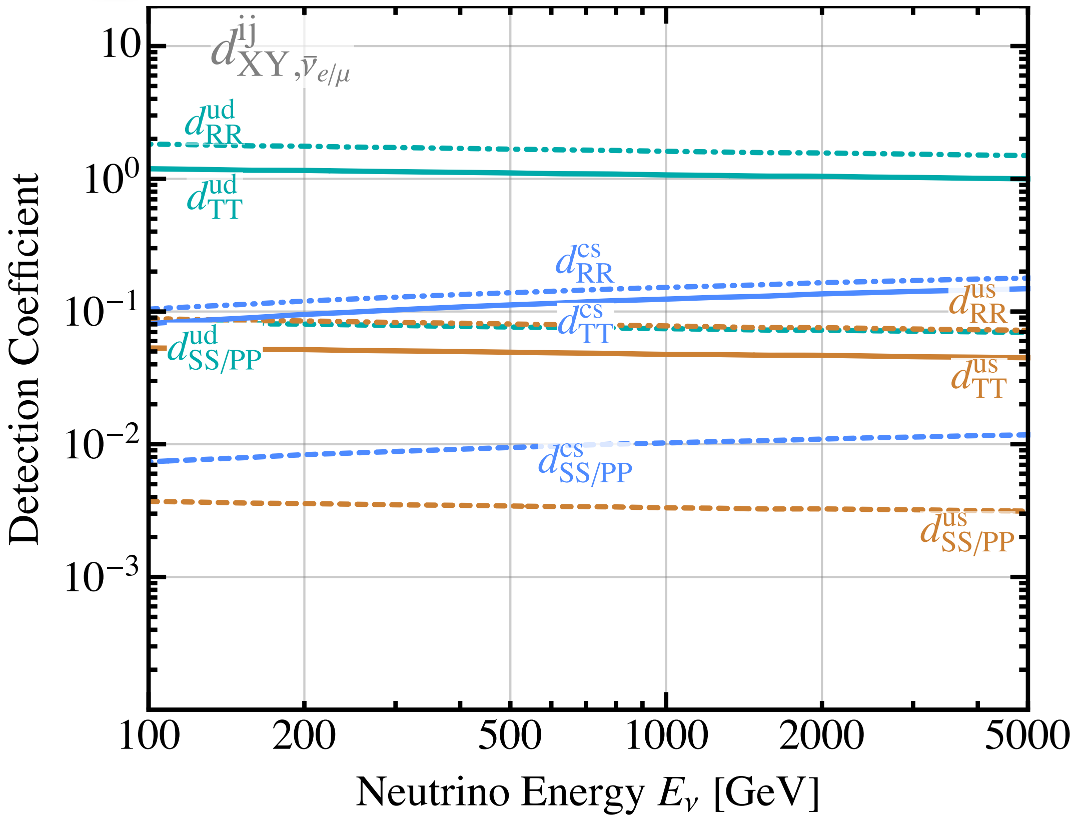
$$\langle \pi^- | \bar{s}\sigma^{\mu\nu} u | K^0 \rangle = i\frac{p_K^\mu p_\pi^\nu - p_\pi^\mu p_K^\nu}{m_K} B_T(q^2)\,,$$

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

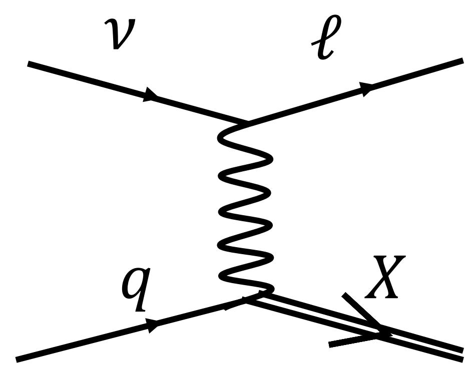
DIS

Detection

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



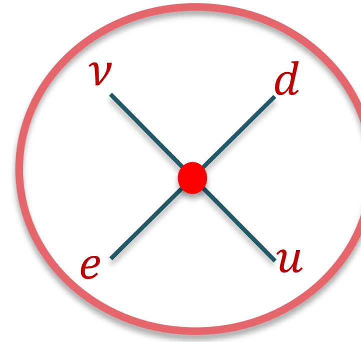
Deep Inelastic Scattering



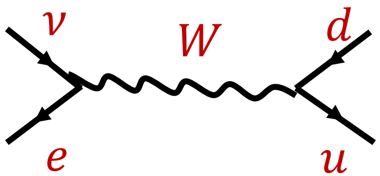
$$\boldsymbol{\sigma^{Total} \sim \sigma^{SM}(1+\varepsilon_X\, d_{XL} + \varepsilon_X{}^2\, d_{XX})}$$

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

Specific New Physics Models

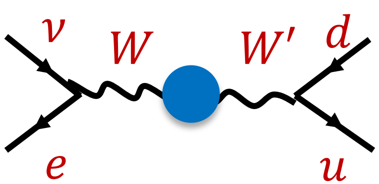


ε_L: **measures deviations of the W boson to quarks and leptons, compared to the SM prediction**



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

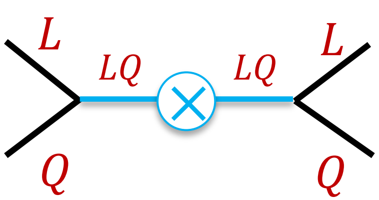
ε_R : **left-right symmetric $SU(3)_C \mathrm{x} SU(2)_L \mathrm{x} SU(2)_R \mathrm{x} U(1)_X$ models introduce new charged vector bosons W' coupling to right-handed quarks**



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

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

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

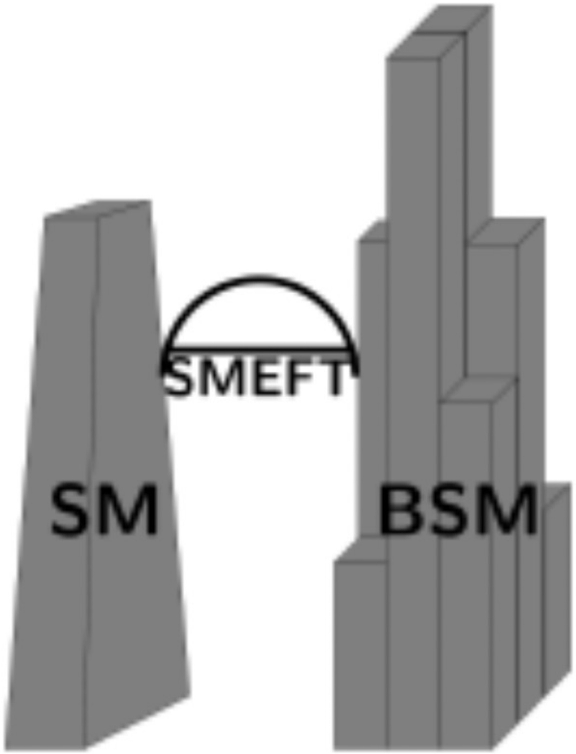


$$(LQ)(LQ)$$

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

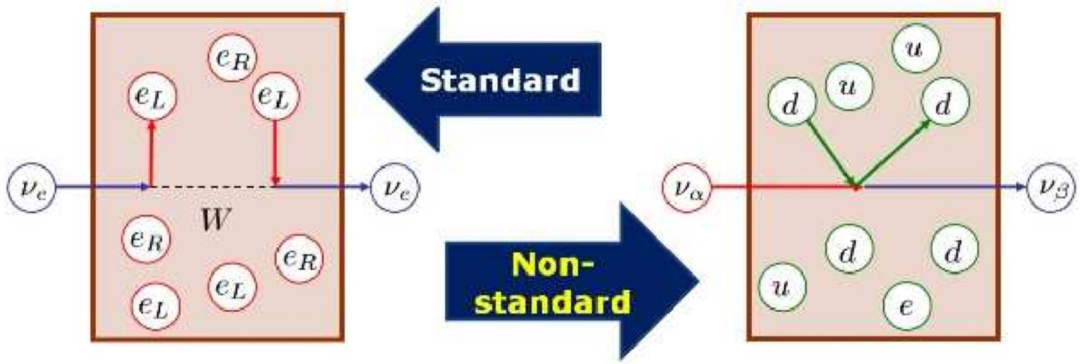
Indirect Searches: Future Directions

- 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

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

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

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- 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.

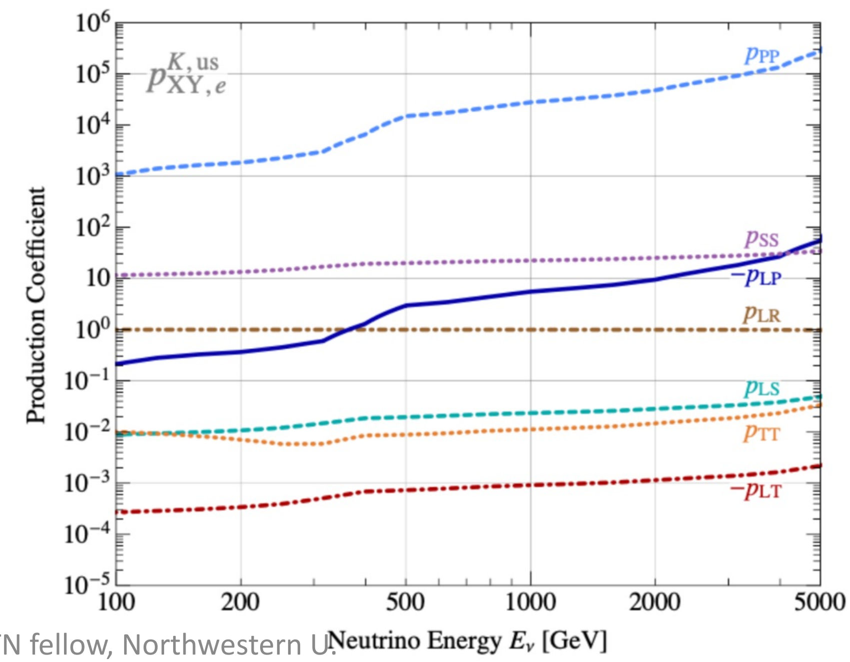
Comparing QM and QFT

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

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

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

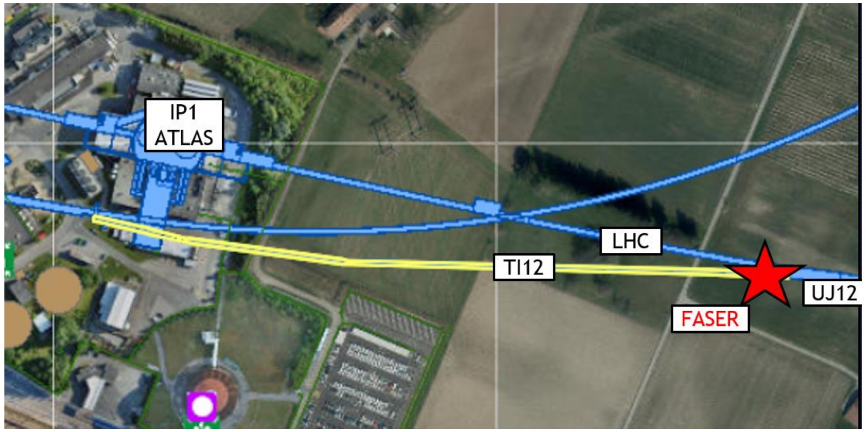


Falkowski, González-Alonso, *ZT*, JHEP (2019)

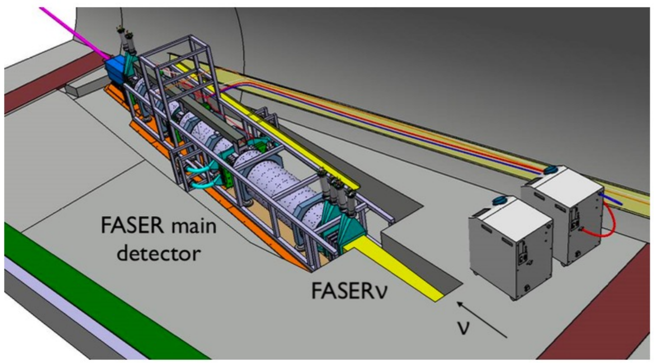
$$p_{XY} \equiv \frac{\int d\Pi_{P'} A^P_X \bar{A}^P_Y}{\int d\Pi_{P'} |A^P_L|^2}, \quad d_{XY} \equiv \frac{\int d\Pi_D A^D_X \bar{A}^D_Y}{\int d\Pi_D |A^D_L|^2}.$$

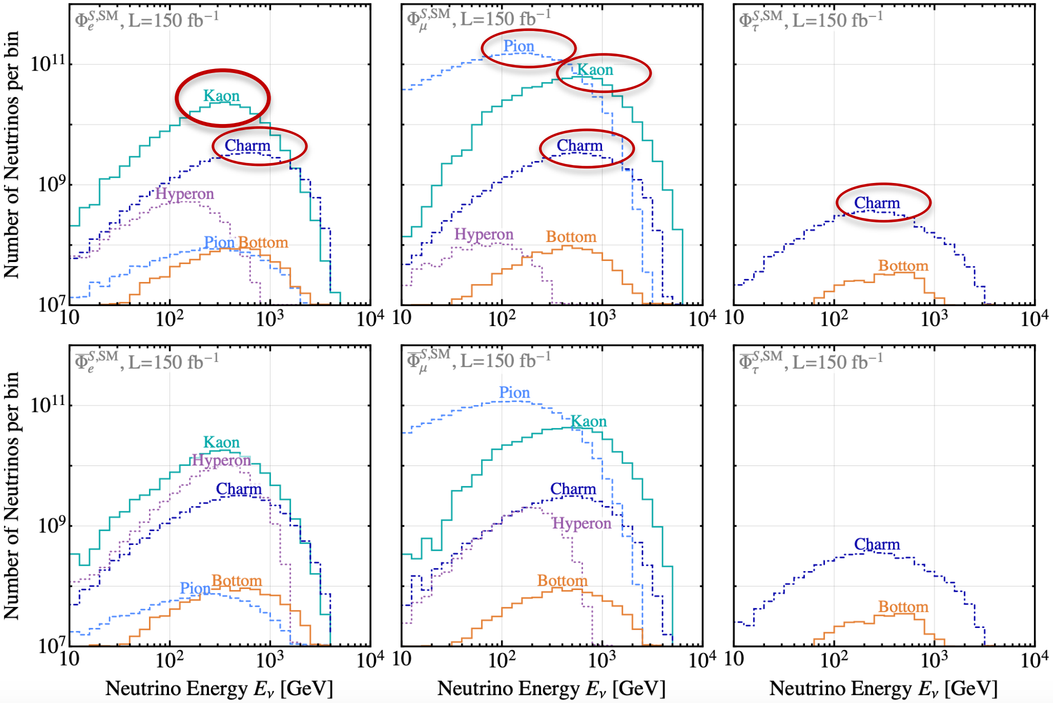
FASERν

- 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)



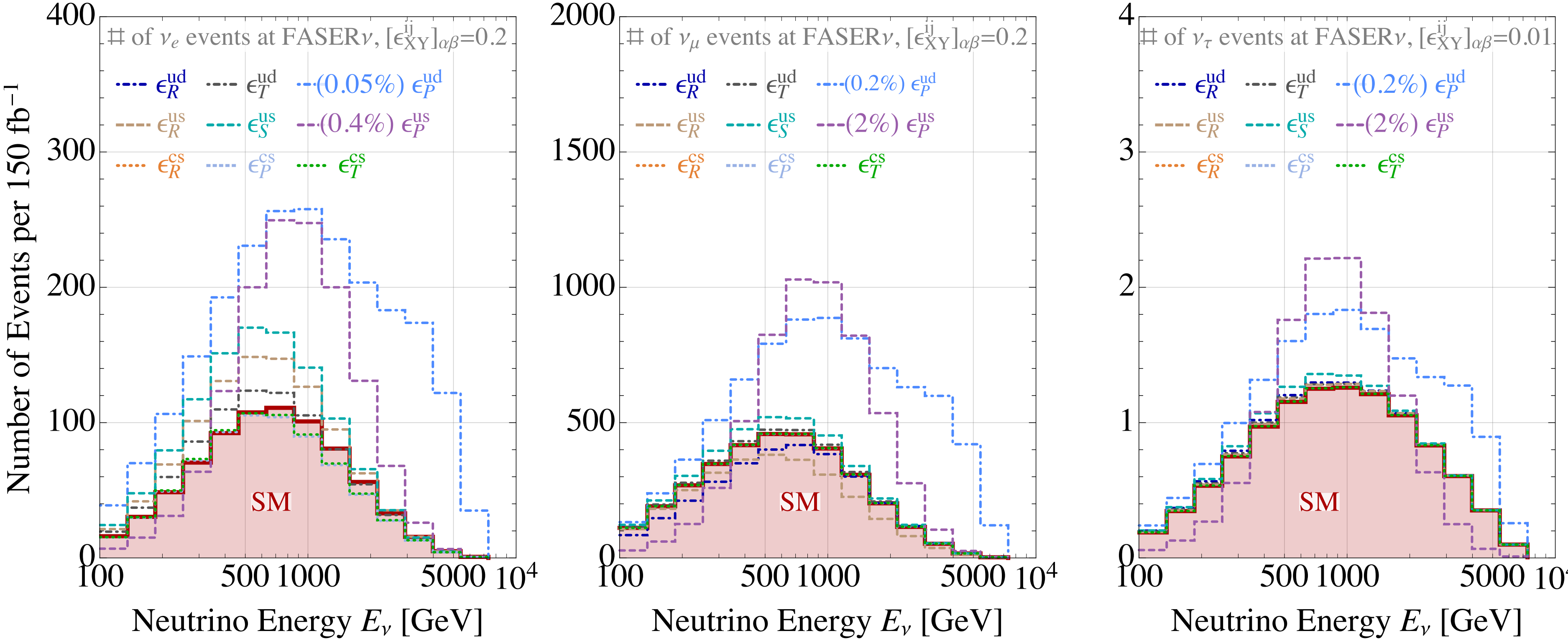


Within the SM:

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

EFT at FASERν

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



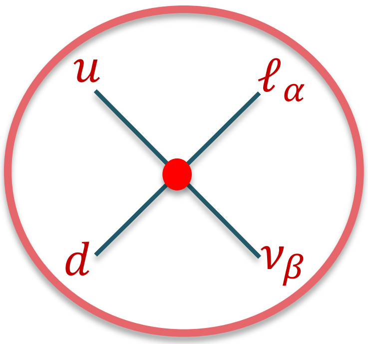
- Results are statistics dominated: ν_e~1000, ν_μ~5000, ν_τ~10
- Optimistic systematic uncertainties: 5% on ν_e, 10% on ν_μ, 15% on ν_τ
- Conservative systematic uncertainties: 30% on ν_e, 40% on ν_μ, 50% on ν_τ

EFT at FASERν

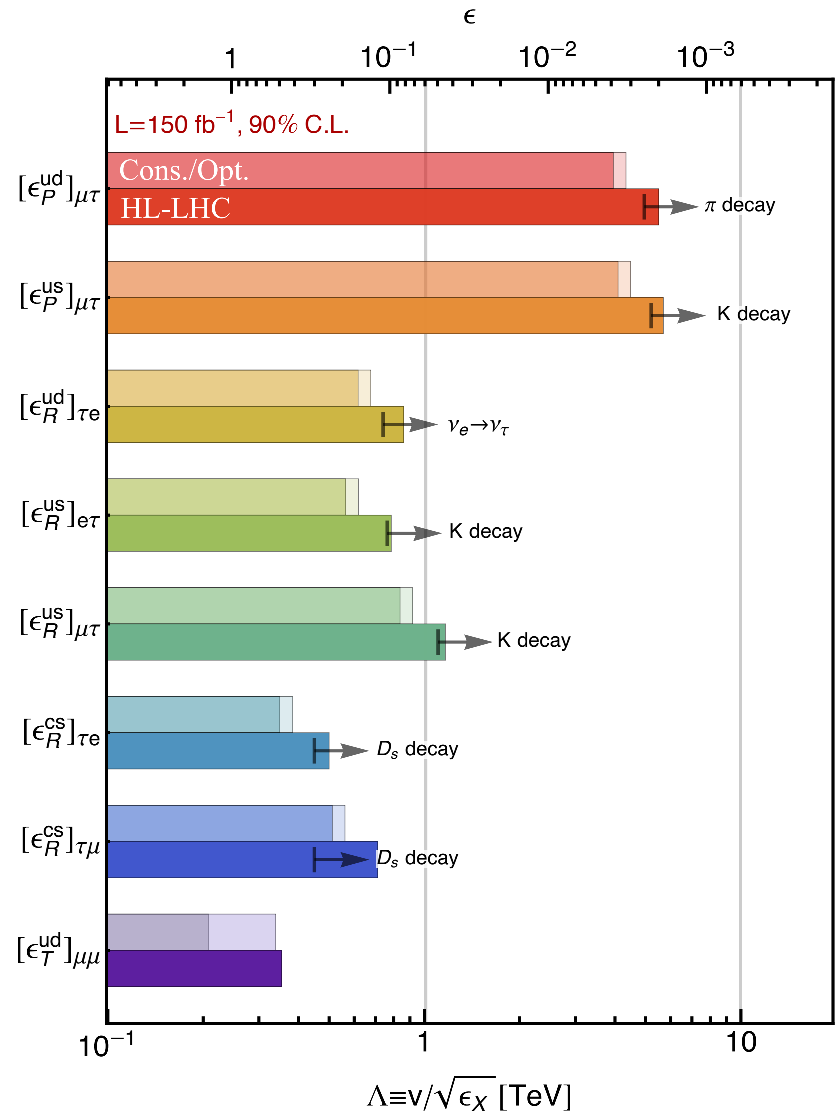
Falkowski, González-Alonso, Kopp, Soreq, ZT, JHEP (2021)

- FASERν: colored bars

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



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



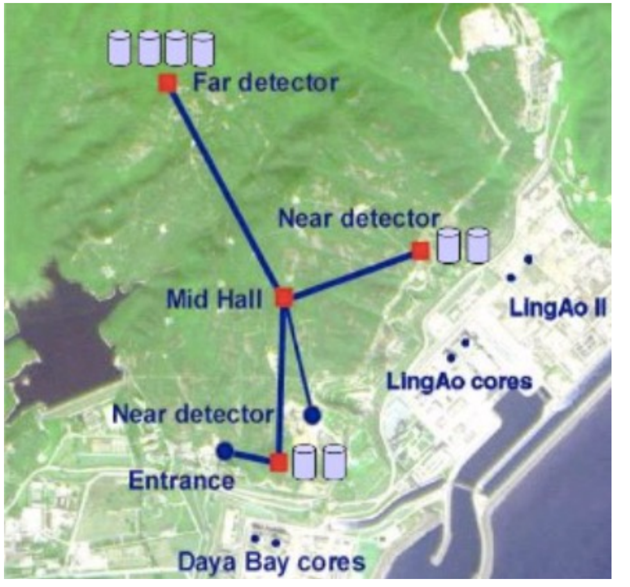
New physics reach at multi-TeV

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 ~ 4 million anti-neutrino events in 1958 days of data taking;

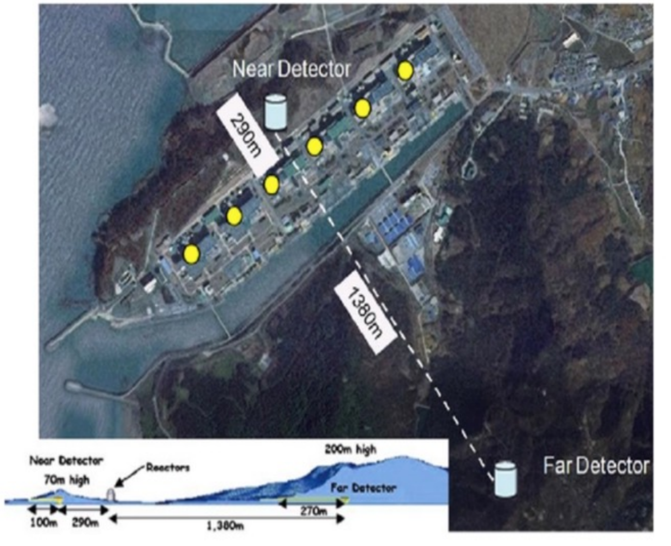
Daya Bay Collaboration, D. Adey et al., (2018)



RENO:

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

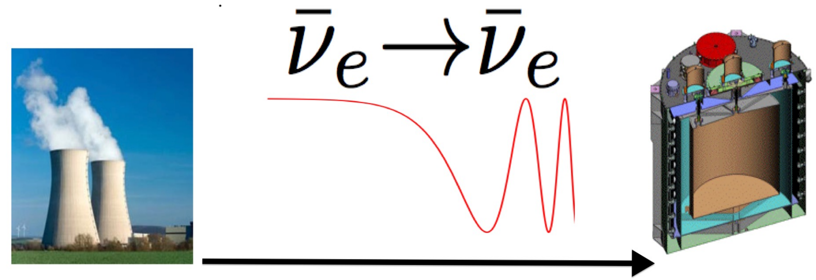
RENO Collaboration, G. Bak et al., (2018)



Inverse Beta Decay

Detection

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



$$p^+ + \bar{\nu}_e \rightarrow e^+ + n^0$$

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

IBD will be sensitive to the scalar and tensor NP!

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

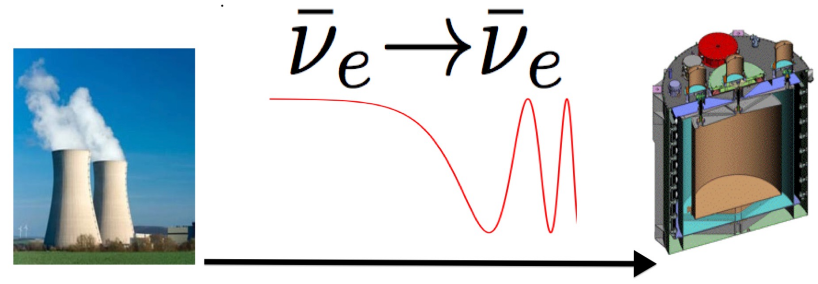
$$g_A = 1.2728 \pm 0.0017, \quad g_S = 1.02 \pm 0.11, \quad g_P = 349 \pm 9, \quad g_T = 0.987 \pm 0.055$$

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

Inverse Beta Decay

Detection

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



$$p^+ + \bar{\nu}_e \rightarrow e^+ + n^0$$

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

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

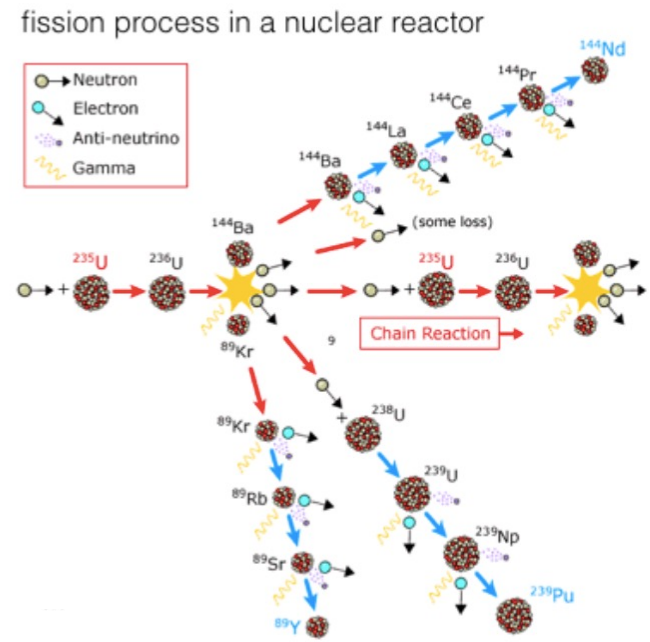
DO NOT depend on neutrino energy!!!

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

Nuclear Beta Decay

Production

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



- 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)

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

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

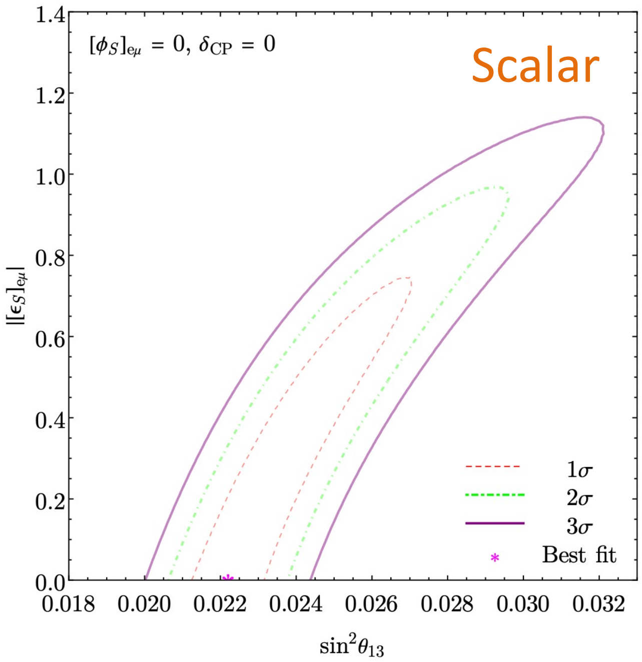
$$f_T(E_\nu) \quad = \quad \frac{\sum_{i=1}^n w_i(\Delta_i - E_\nu)\sqrt{(\Delta_i - E_\nu - m_e)(\Delta_i - E_\nu + m_e)}}{\sum_{i=1}^n w_i\sqrt{(\Delta_i - E_\nu - m_e)(\Delta_i - E_\nu + m_e)}}$$

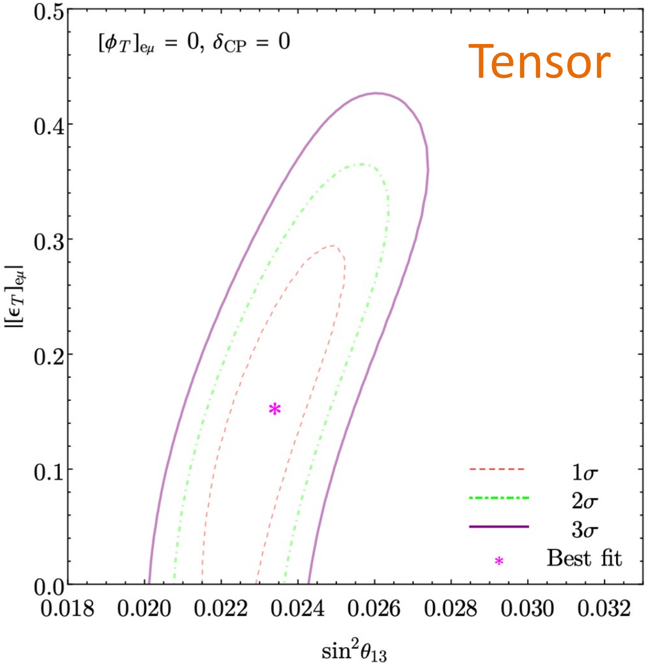
- Reactor experiments will probe tensor and scalar NP!
- They depend on the neutrino energy.

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