Constraints on EFT from neutrino oscillations

BNL high energy theory seminar **Jan 2021**

Martín González-Alonso
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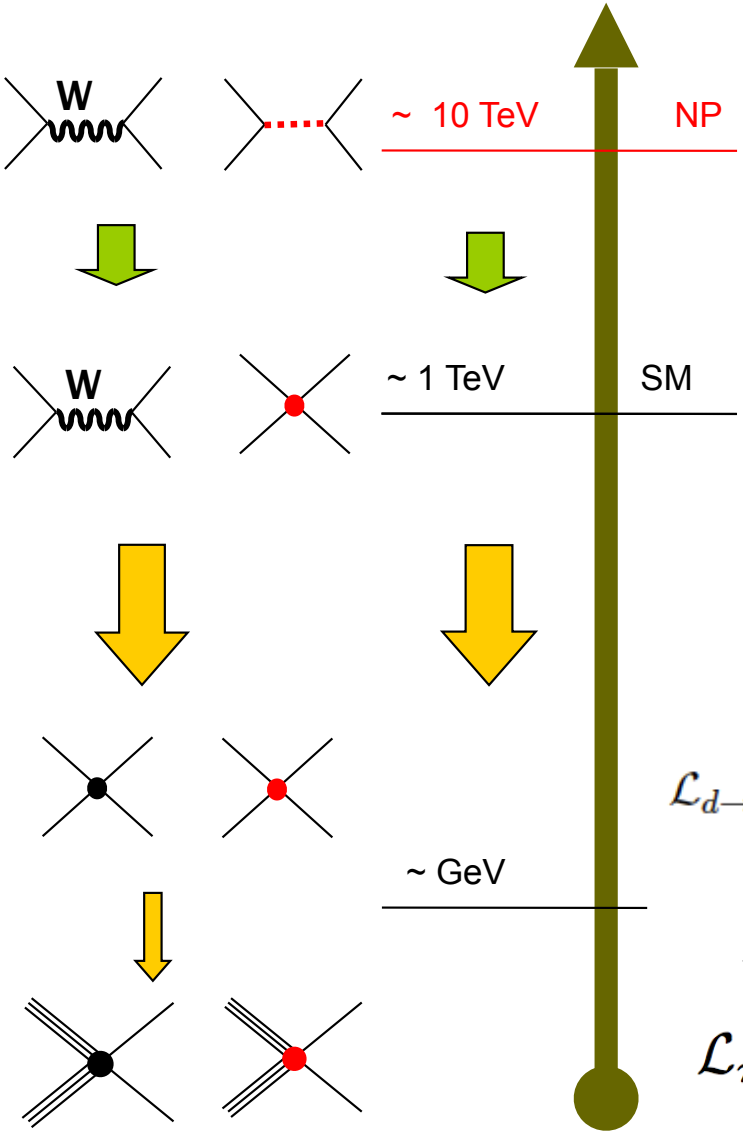
Outline

- Introduction
- Oscillations in QFT/EFT in the presence of NSIs
  [A. Falkowski, MGA, & Z. Tabrizi, JHEP 11 (2020) 048]
- Pheno application: reactors;
  [A. Falkowski, MGA, & Z. Tabrizi, JHEP 05 (2019) 173]
- Conclusions

Introduction



$$\mathcal{L}(x) = \mathcal{L}\,(\text{SM fields, bSM fields})$$

$$\mathcal{L}_{eff.} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\sum \alpha_i\,\mathcal{O}_i$$

Standard Model EFT

[Buchmuller & Wyler'86, Leung et al.'86, Grzadkowksi et al., 10, Jenkins et al'13, ...]

$$\mathcal{L}_{d\to u\ell^-\bar{\nu}_\ell} = -\frac{4G_F V_{ij}}{\sqrt{2}}\left[\bar{\ell}_L\gamma_\mu\nu\cdot\bar{u}\gamma^\mu d_L + \sum_{\rho\delta\Gamma}\epsilon^\Gamma_{\rho\delta}\,\bar{\ell}_\rho\Gamma\nu\cdot\bar{u}\Gamma d_\delta\right]$$

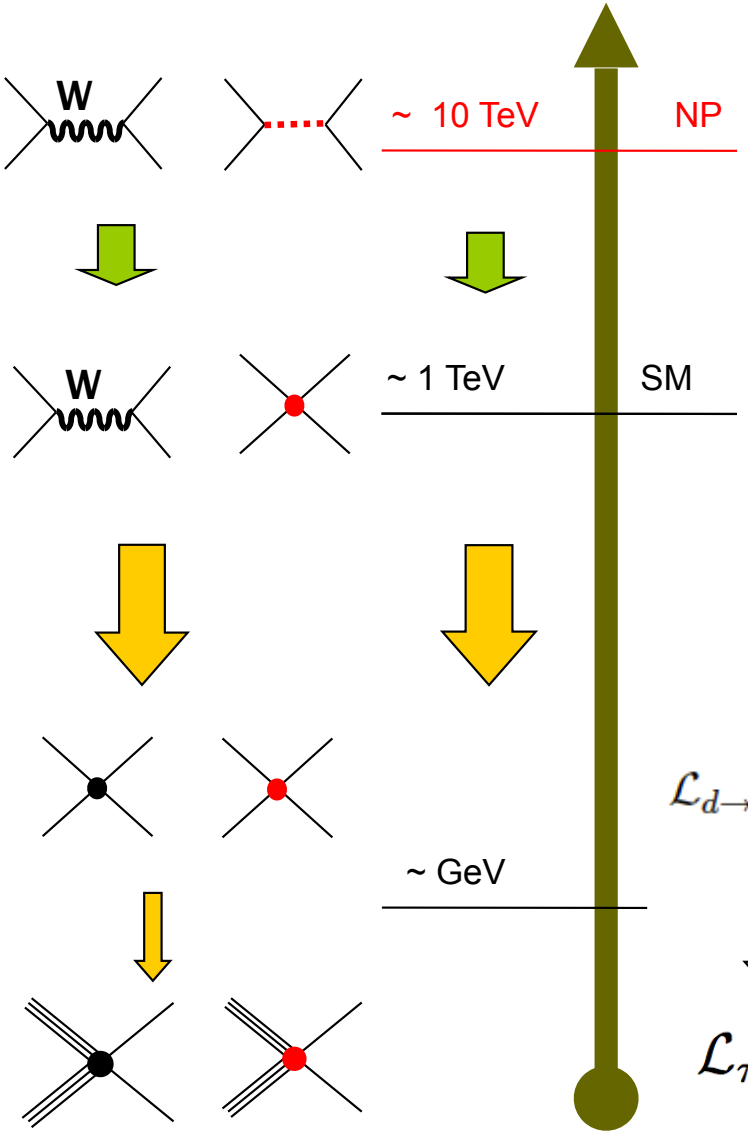
Low-energy EFT

[Cirigliano et al'09, Aebischer al.'15, Jenkins et al'18, ...]

$$\mathcal{L}_{\pi,N,\ldots} = \ldots$$

Introduction

Not assumption independent!
[e.g. no light new states]



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Introduction

Low-energy precision measurement... NP implications?

Data

(+ SM prediction)

(Correlated) bounds on the Wilson coefficients of the low-energy EFT

(Correlated) bounds on the Wilson coefficients of the high-energy EFT (SMEFT)

NP model #1

$$\frac{\alpha_i}{\Lambda^2} = f_i(g_{NP}, M_{NP})$$

NP model #2

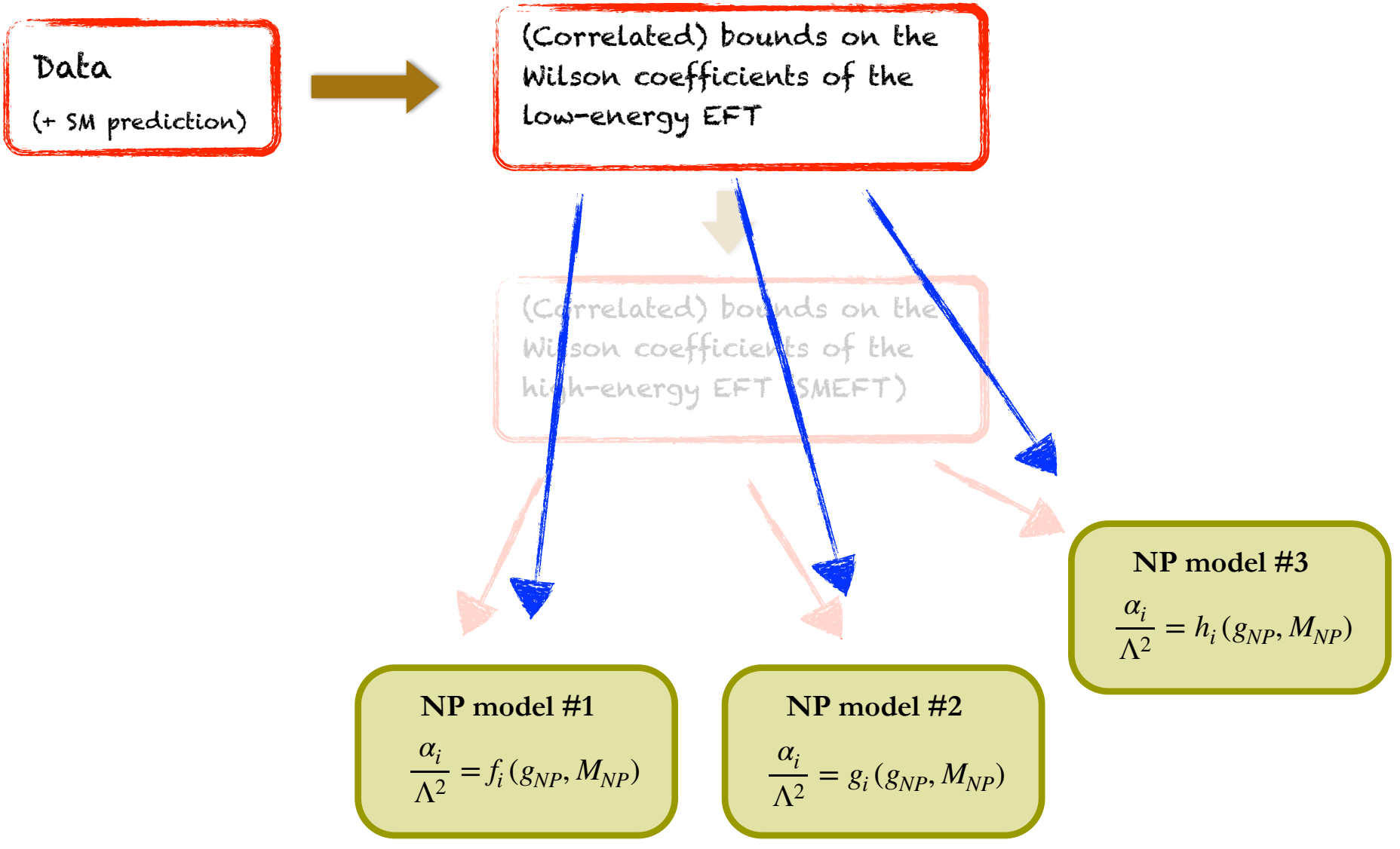
$$\frac{\alpha_i}{\Lambda^2} = g_i(g_{NP}, M_{NP})$$

NP model #3

$$\frac{\alpha_i}{\Lambda^2} = h_i(g_{NP}, M_{NP})$$

Introduction

Low-energy precision measurement... NP implications?



Introduction

Low-energy precision measurement... NP implications?

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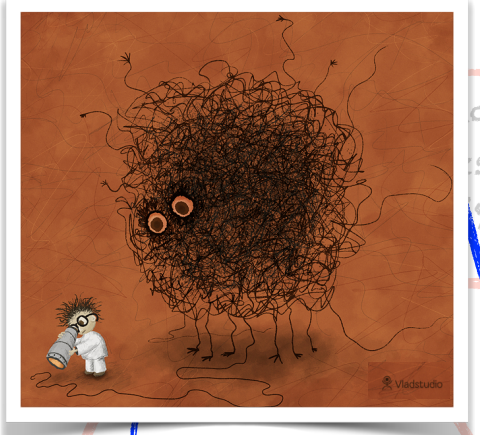
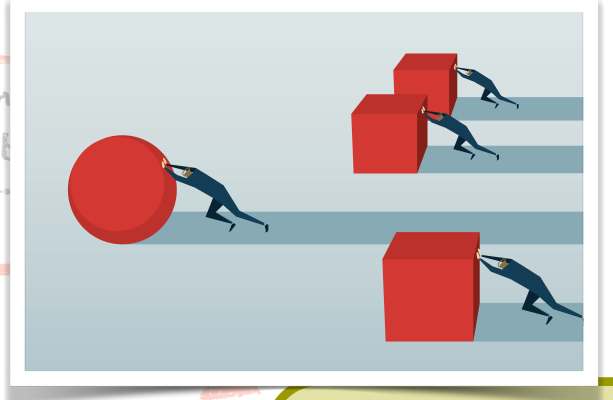
(Correlated) bounds on the Wilson coefficients of the low-energy EFT

Pros:

- Agnostic approach;
- Comparison between probes, under general assumptions;
- Efficiency: analysis done once and for all!





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(+ SM prediction)

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(Correlated) bounds on the Wilson coefficients of the high-energy EFT (SMEFT)

Can we analyze neutrino oscillation data in this EFT approach?

Of course... but with some peculiarities...

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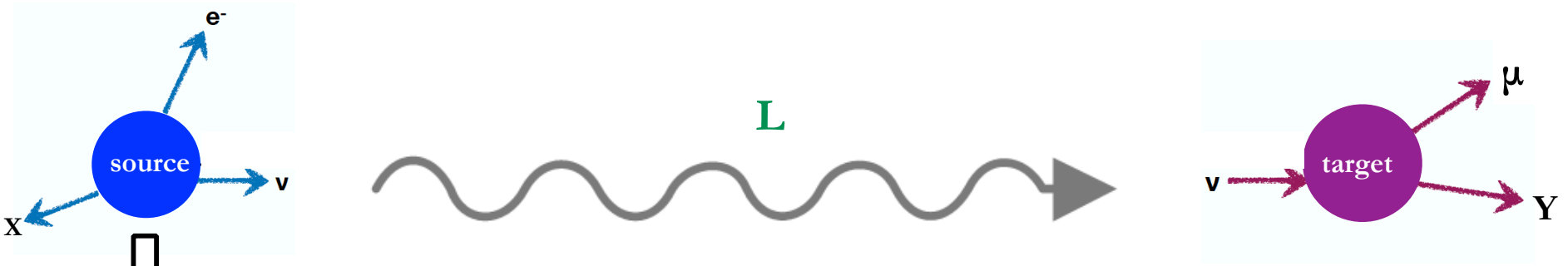
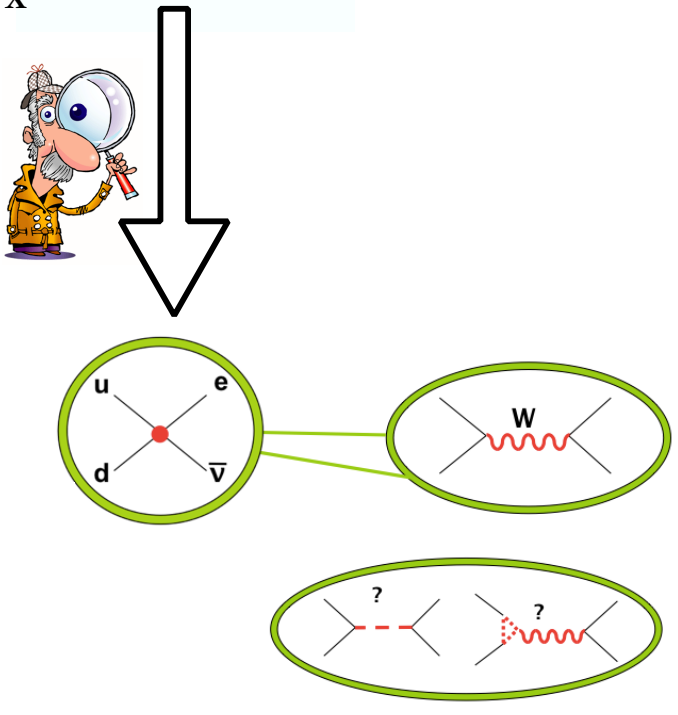
- This talk: I'll focus on charged current interactions (no matter effects).





[Same in detection]

In the SM: $O = O(\theta_i, \Delta m^2)$

Beyond the SM: $O = O(\theta_i, \Delta m^2, \varepsilon_j)$

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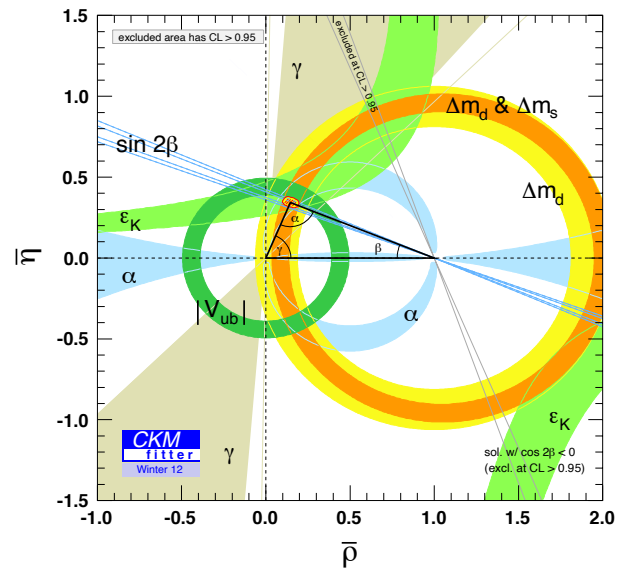
- (High) precision & consistency → nontrivial constraint on NP;

	Normal Ord
	bfp $\pm 1\sigma$
$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$
$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$
$\sin^2\theta_{23}$	$0.580^{+0.017}_{-0.021}$
$\theta_{23}/^\circ$	$49.6^{+1.0}_{-1.2}$
$\sin^2\theta_{13}$	$0.02241^{+0.00065}_{-0.00065}$
$\theta_{13}/^\circ$	$8.61^{+0.13}_{-0.13}$
$\delta_{CP}/^\circ$	215^{+40}_{-29}
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.39^{+0.21}_{-0.20}$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.525^{+0.033}_{-0.032}$

[I.Esteban, M.C. Gonzalez-Garcia, A.Hernandez-Cabezudo, M. Maltoni, T.Schwetz JHEP 01 (2019) 106]



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- The main question I want to address here is:
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  i.e. how can I derive $O = O(\theta_i, \Delta m^2, \varepsilon_j)$? [where ε_j are Lagrangian parameters]

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  - Only *afterwards* one can assess whether the bounds are competitive.
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In other words: how are oscillations affected by a charged Higgs? A leptoquark? Which part of their parameter space is ruled out by current oscillation data?

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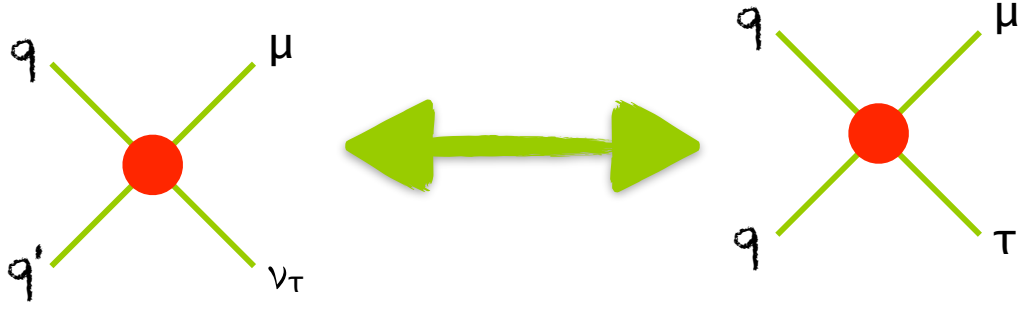
- NB: in simple theory setups the bounds are unlikely to be competitive (competition from hadron decays & CLFV);



Traditional ~~NSI~~ SM-QM approach

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\rm PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

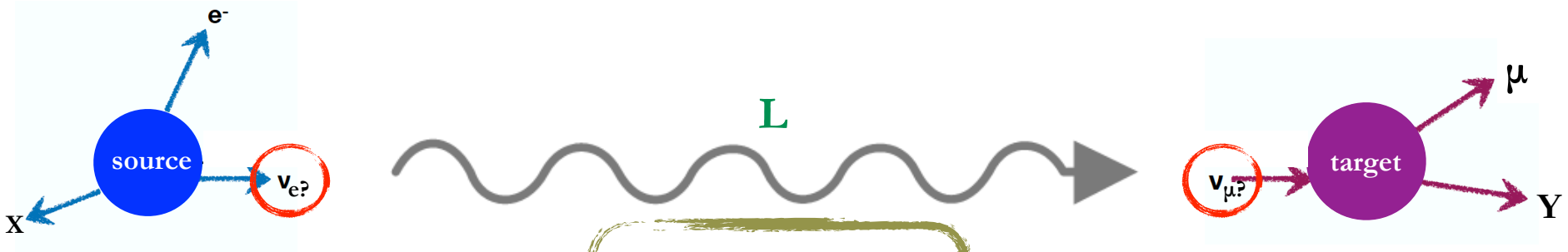
$$|\nu_i(L)\rangle = e^{-im_i^2 L/2E}|\nu_i(0)\rangle$$

$$P_{\nu_\alpha \to \nu_\beta} = |\langle \nu_\beta(L)|\nu_\alpha\rangle|^2 \longleftarrow f\,(U_{ij}\,,\,\Delta m^2)$$

$$R_{\alpha\beta} \equiv \frac{dN_{\alpha\beta}}{dt dE_\nu} = \phi_\alpha^{SM}(E_\nu) P_{\alpha\beta}(E_\nu) \sigma_\beta^{SM}(E_\nu)$$

[Grossman'95, Gonzalez-Garcia et al.'01, Ohlsson'13, Farzan & Tortola'17, ...]

Traditional NSI-QM approach



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

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→ P is not universal anymore;
→ CC NSI give L-dependent effects;

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Normalization:

$$N_\alpha^s = \sqrt{[(1+\epsilon^s)(1+\epsilon^{s\,\dagger})]_{\alpha\alpha}}$$

$$N_\beta^s = \sqrt{[(1+\epsilon^{d\,\dagger})(1+\epsilon^d)]_{\beta\beta}}$$

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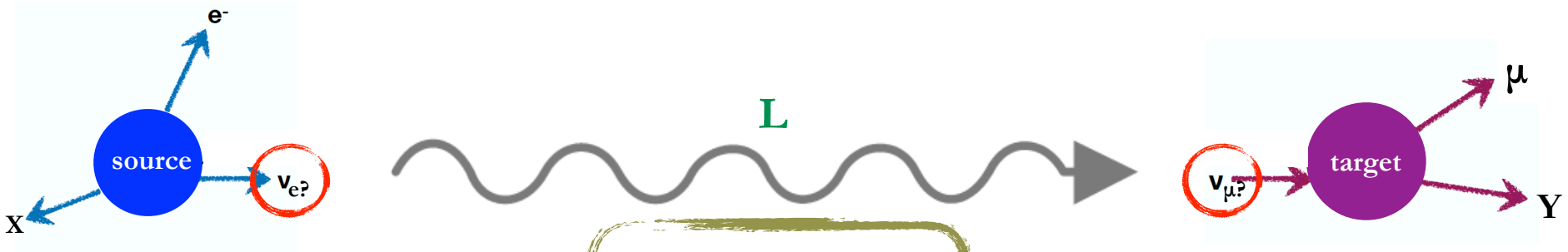

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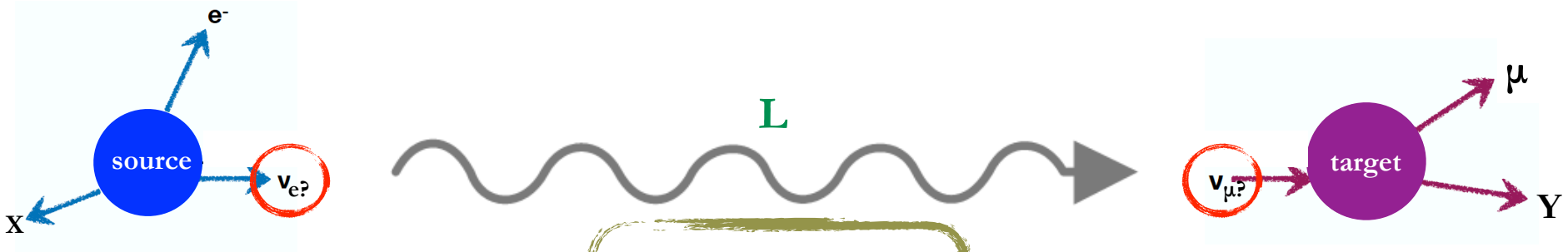

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$$= \phi_\alpha^{SM}\sigma_\beta^{SM}\sum_{k,l} e^{-i\frac{L\Delta m_{kl}^2}{2E_\nu}}[x_s]_{\alpha k}[x_s]^*_{\alpha l}[x_d]_{\beta k}[x_d]^*_{\beta l}$$

$$x_{s(d)} \equiv (1+\epsilon^{s(d)})^{(T)}U^{(*)}$$

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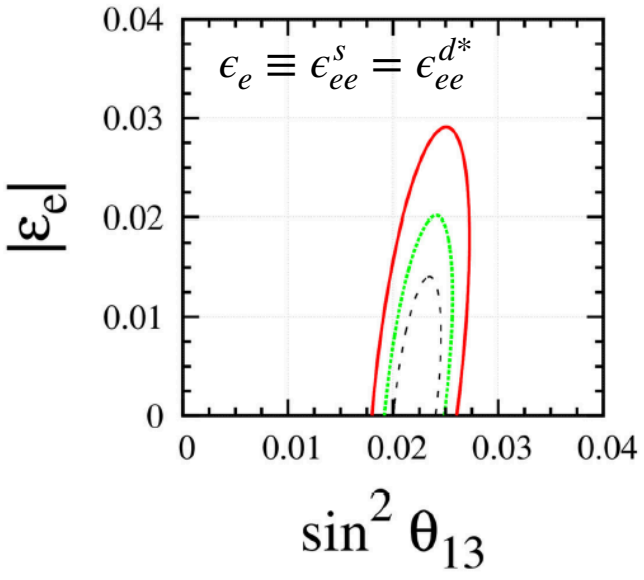
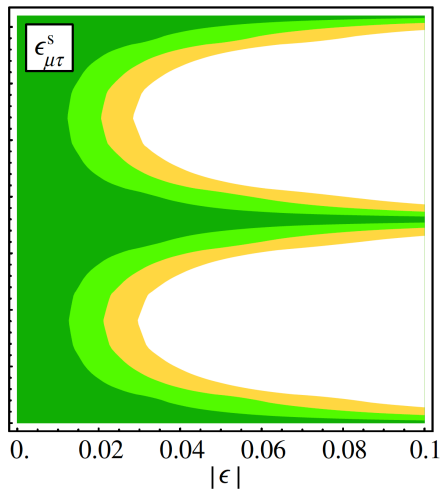
Traditional NSI-QM approach

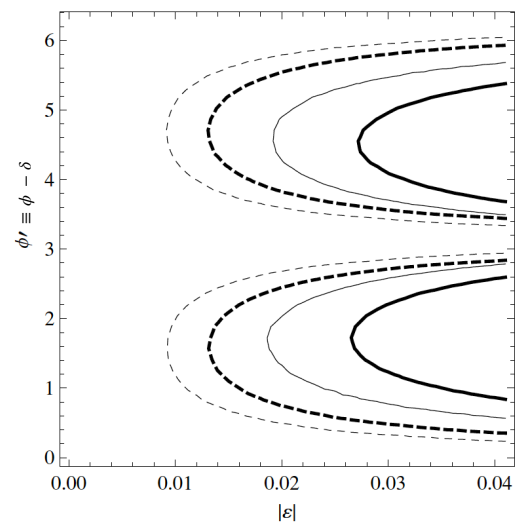
- Oscillation data → combined fit of "SM" (angles + masses) + NSI parameters



[Daya Bay data]
Agarwalla et al'15]



[Discovery reach - NOvA data,
Kopp et al'07]



[Daya Bay data]
Leitner et al'11]

$$\epsilon = |\epsilon| e^{i\phi} \equiv \epsilon^s_{e\mu} = \epsilon^s_{e\tau}$$

$$\epsilon^d = 0$$

PS: Implicit assumption: NSI are energy-independent

Traditional NSI-QM approach

- But...

$$\varepsilon^s, \varepsilon^d = f(?)$$

- NSI parameters are process-dependent!
  - Comparison of NSI parameters for 2 different production processes?
  - Comparison of NSI with other non-oscillation searches? (CLFV, colliders, ...)
  - Meaning of these NSI in terms of fundamental BSM parameters? (couplings, masses, ...)

- Also: are production & detection NSI completely unrelated and free? Are they energy independent?

Traditional NSI-QM approach

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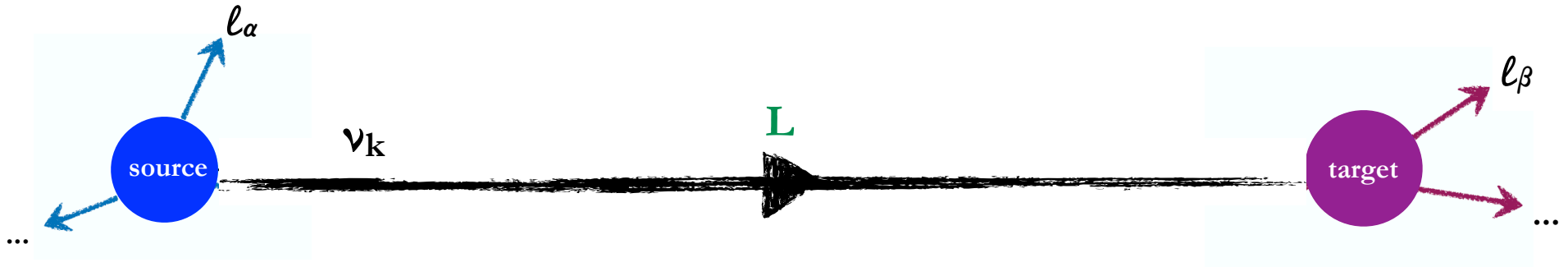
- Also: are production & detection NSI completely unrelated and free? Are they energy independent?

- Conclusion:
  we need to match NSI to a Lagrangian → QFT approach needed

See e.g.
Giunti et al. [hep-ph/9305276]
Akhmedov Kopp [arXiv:1001.4815]
Kobach et al. [arXiv:1711.07491]

Oscillations in QFT

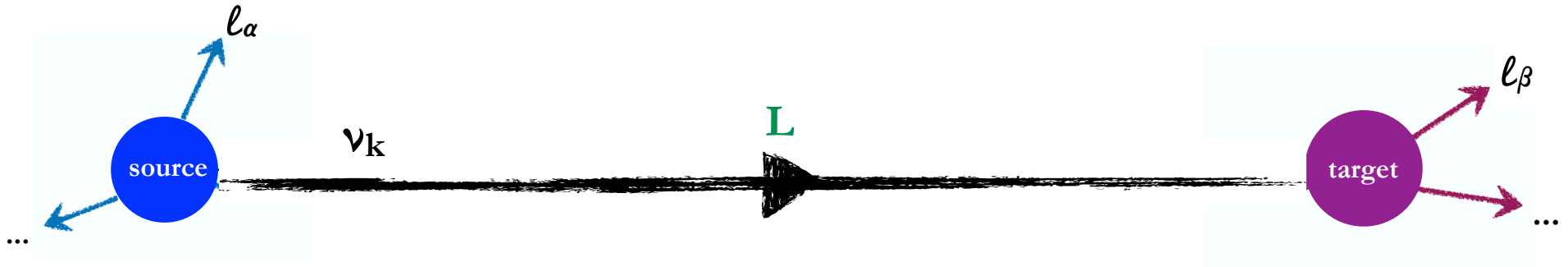


$$R_{\alpha\beta} \equiv \frac{dN_{\alpha\beta}}{dt dE_\nu} = \ \ldots \ = \frac{\kappa}{E_\nu} \sum_{k,l} e^{-i\frac{L\Delta m^2_{kl}}{2E_\nu}} \int d\Pi_{P'} \mathcal{M}^P_{\alpha k} \bar{\mathcal{M}}^P_{\alpha l} \int d\Pi_D \mathcal{M}^D_{\beta k} \bar{\mathcal{M}}^D_{\beta l}$$

Validity:

$$E_\nu \gg m_k$$
$$E_\nu \gg |m_k^2 - m_l^2| \sigma_i$$
$$\ldots$$

Oscillations in QFT



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Geometric factor

$\kappa = N_S N_T / (32\pi L^2 m_S m_T)$

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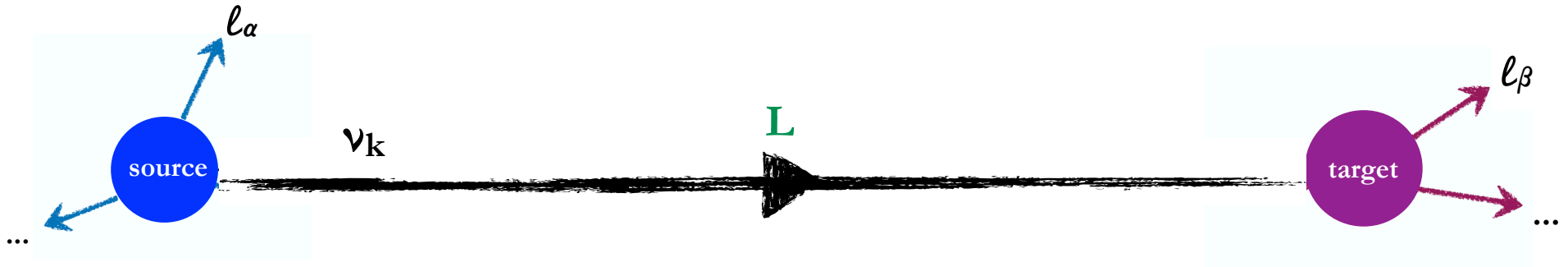
Oscillations in QFT



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Geometric factor

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Oscillation factor

$\Delta m^2_{kl} \equiv m^2_k - m^2_l$

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$E_\nu \gg m_k$

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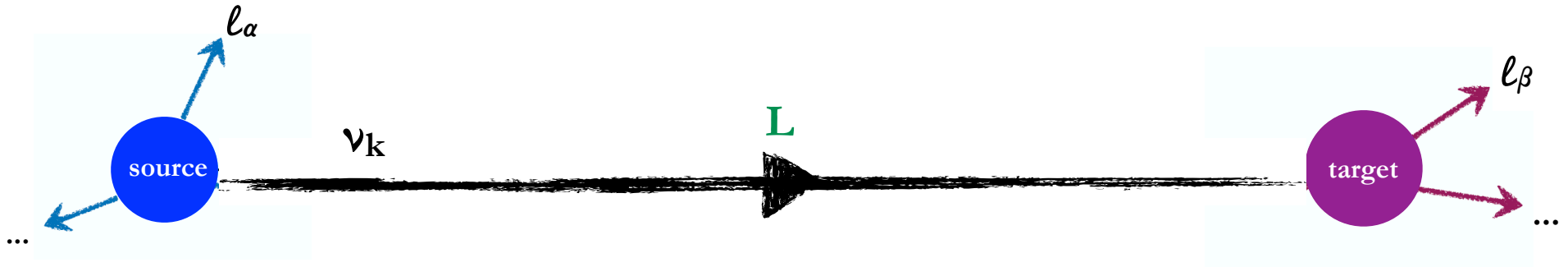
...

Oscillations in QFT



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Geometric factor

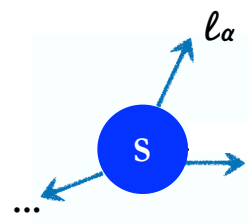
$\kappa = N_S N_T / (32\pi L^2 m_S m_T)$

Oscillation factor

$\Delta m^2_{kl} \equiv m^2_k - m^2_l$

Production
(w/o integration over E_ν)

$\mathcal{M}^P_{\alpha k} \equiv \mathcal{M}(S \to X_\alpha \nu_k)$



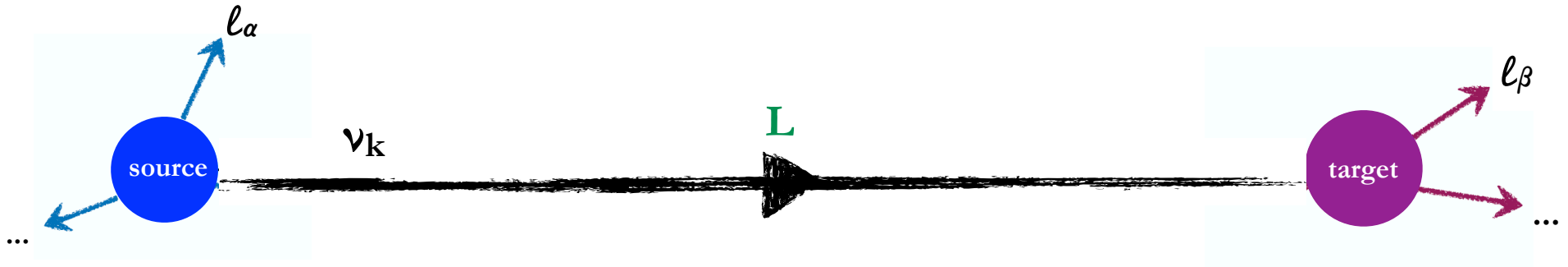
Validity:

$E_\nu \gg m_k$

$E_\nu \gg |m^2_k - m^2_l| \sigma_i$

...

Oscillations in QFT



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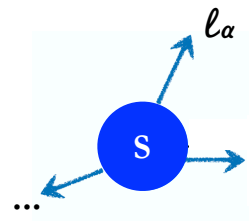

Phase space integrals: $d\Pi \equiv \frac{d^3k_1}{(2\pi)^3 2E_1} \cdots \frac{d^3k_n}{(2\pi)^3 2E_n} (2\pi)^4 \delta^4(\mathcal{P} - \sum k_i)$

$d\Pi_P \equiv d\Pi_{P'} dE_\nu$

Validity:

$E_\nu \gg m_k$

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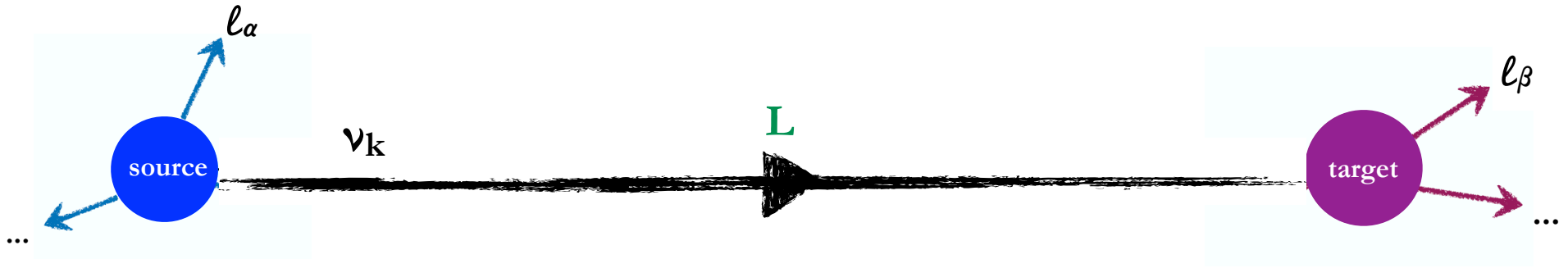
...

Oscillations in QFT



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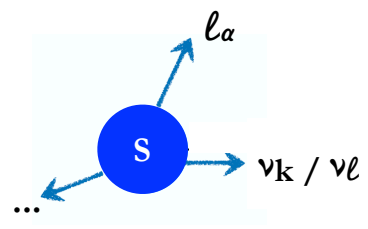
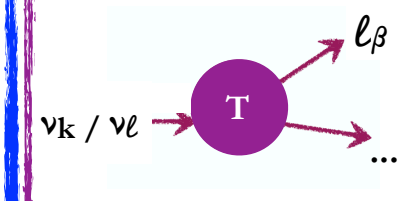


Detection

$\mathcal{M}^D_{\beta k} \equiv \mathcal{M}(\nu_k T \to Y_\beta)$



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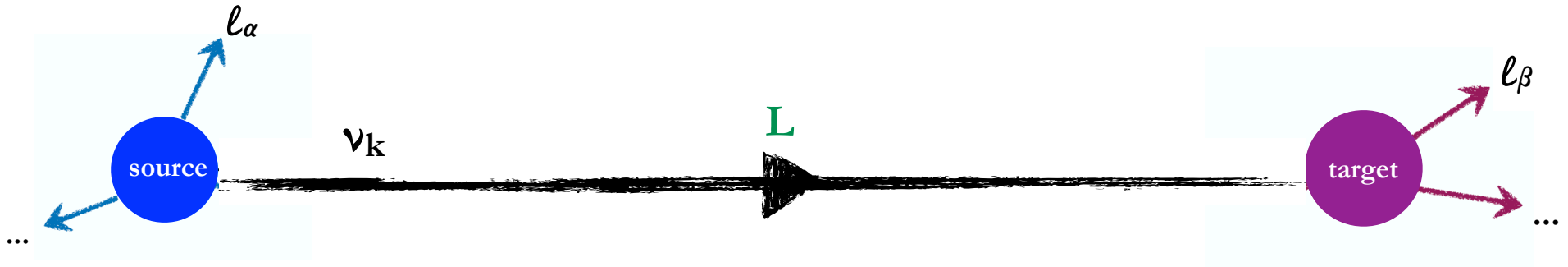
...

Oscillations in QFT: "oscillation probability"



$$P(\nu_\alpha \to \nu_\beta) \equiv \frac{R_{\alpha\beta}}{\phi_\alpha \sigma_\beta} = \frac{\sum_{k,l} e^{-i\frac{L\Delta m^2_{kl}}{2E_\nu}} \int d\Pi_{P'} \mathcal{M}^P_{\alpha k} \bar{\mathcal{M}}^P_{\alpha l} \int d\Pi_D \mathcal{M}^D_{\beta k} \bar{\mathcal{M}}^D_{\beta l}}{\int d\Pi_{P'} \sum_k |\mathcal{M}^P_{\alpha k}|^2 \int d\Pi_D \sum_l |\mathcal{M}^D_{\beta l}|^2}$$

Flux x cross-section
(including NP)

$$\Phi_\alpha \sigma_\beta = \frac{\kappa}{E_\nu} \int d\Pi_{P'} \sum_k |\mathcal{M}^P_{\alpha k}|^2 \int d\Pi_D \sum_l |\mathcal{M}^D_{\beta l}|^2$$

PS: The dependence on M^P & M^D does not reduce to PMNS factors in general, but includes also NP and hadronic effects.

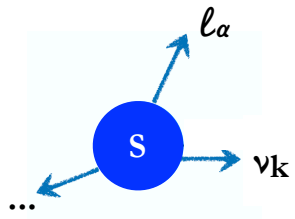
→ P is not universal anymore;

→ CC NSI give L-dependent effects (not just flux & σ);

Oscillations in QFT

$$R_{\alpha\beta} = \frac{\kappa}{E_\nu} \sum_{k,l} e^{-i\frac{L\Delta m^2_{kl}}{2E_\nu}} \int d\Pi_{P'} \mathcal{M}^P_{\alpha k} \bar{\mathcal{M}}^P_{\alpha l} \int d\Pi_D \mathcal{M}^D_{\beta k} \bar{\mathcal{M}}^D_{\beta l}$$

- The rest is "straightforward": calculate the production and detection amplitudes.



$$\mathcal{M}^D_{\beta k} \equiv \mathcal{M}(\nu_k T \to Y_\beta)$$
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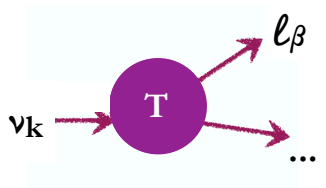


- We need to specify a Lagrangian to calculate the amplitude;

- Comparing QFT & QM rates we can derive the expression for the NSI parameters in terms of fundamental BSM quantities.

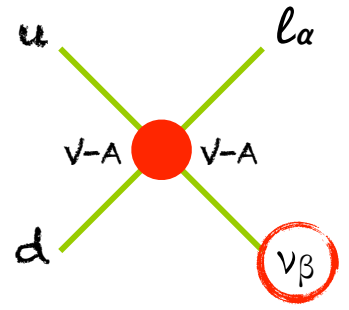
$$\varepsilon^s, \varepsilon^d = f(\,?\,)$$

Oscillations in QFT → SM-**like** case

Low-energy effective Lagrangian:

$$\mathcal{L} \supset -\frac{2V_{ud}}{v^2} \quad [\mathbf{1} + \epsilon_L]_{\alpha\beta} \, (\bar{u}\gamma^\mu P_L d)(\bar{\ell}_\alpha \gamma_\mu P_L \nu_\beta)$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\text{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



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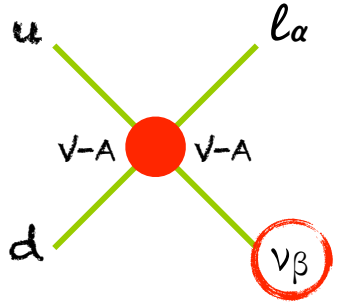

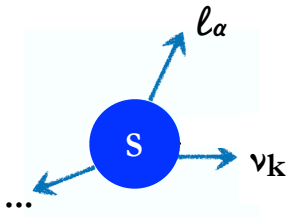

$$\mathcal{M}(S \to X_\alpha \nu_k) = [(1+\epsilon_L)U]^*_{\alpha k} A_L^P$$

It does not depend on k

$$\mathcal{M}(\nu_k T \to Y_\beta) = [(1+\epsilon_L)U]_{\alpha k} A_L^D$$

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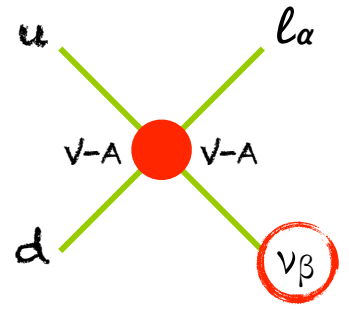

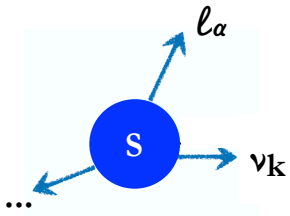

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X_L

"Non-unitary mixing matrix"

[Antusch et al'06, Blennow et al'16, ...]

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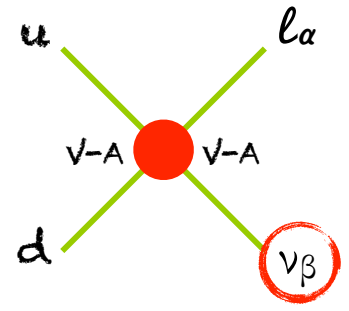

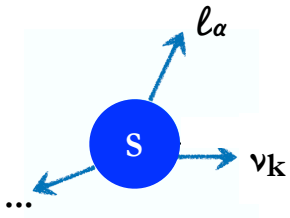

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[Antusch et al'06, Blennow et al'16, ...]

$$\Rightarrow \quad R^{V-A}_{\alpha\beta} = \Phi^{\rm SM}_\alpha \sigma^{\rm SM}_\beta \sum_{k,l} e^{-i\frac{L\Delta m^2_{kl}}{2E_\nu}} [x_L]^*_{\alpha k}[x_L]_{\alpha l}[x_L]_{\beta k}[x_L]^*_{\beta l}$$

$$\Phi^{\rm SM}_\alpha = \frac{N_S \int d\Pi_{P'} |A_L^P|^2}{8 m_S \pi L^2}$$

$$\sigma^{\rm SM}_\beta = \frac{N_T \int d\Pi_D |A_L^D|^2}{4 E_\nu m_T}$$

Oscillations in QFT → SM-**like** case

Low-energy effective Lagrangian:

$$\mathcal{L} \supset -\frac{2V_{ud}}{v^2}\,[\mathbf{1}+\epsilon_L]_{\alpha\beta}\,(\bar{u}\gamma^\mu P_L d)(\bar{\ell}_\alpha\gamma_\mu P_L \nu_\beta)$$

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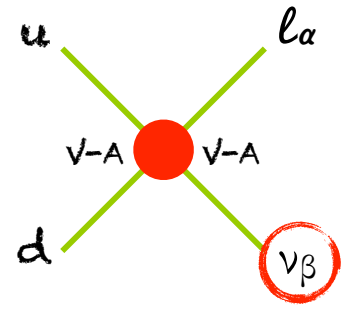

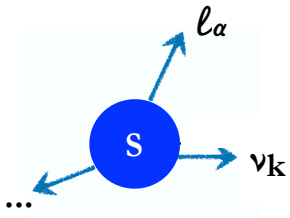

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Comparing with QM-NSI:

$$\epsilon^s_{\alpha\beta} = [\epsilon_L]^*_{\alpha\beta}$$

$$\epsilon^d_{\beta\alpha} = [\epsilon_L]_{\alpha\beta}$$

[Blennow et al'16]

$$\Phi^{\rm SM}_\alpha = \frac{N_S \int d\Pi_{P'} |A_L^P|^2}{8 m_S \pi L^2}$$

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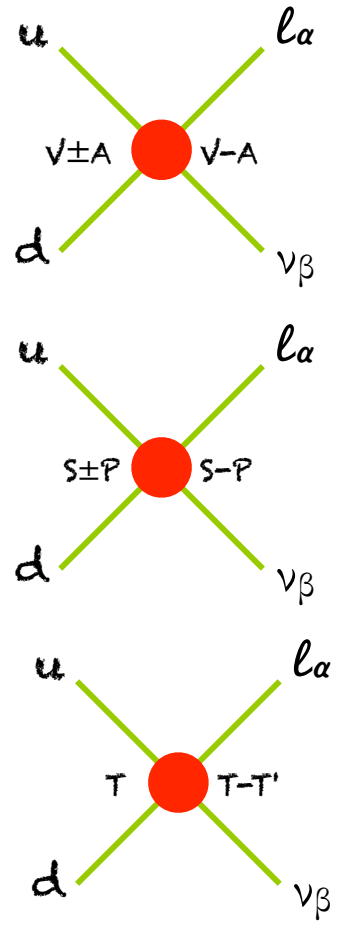
Oscillations in QFT → EFT

Low-energy effective Lagrangian:

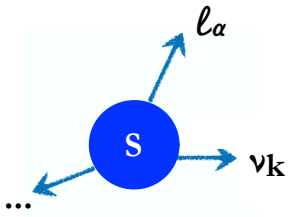
$$\mathcal{L} \supset -\frac{2V_{ud}}{v^2}\Big\{ [\mathbf{1}+\epsilon_L]_{\alpha\beta}\,(\bar{u}\gamma^\mu P_L d)(\bar{\ell}_\alpha\gamma_\mu P_L\nu_\beta)$$
$$+ [\epsilon_R]_{\alpha\beta}(\bar{u}\gamma^\mu P_R d)(\bar{\ell}_\alpha\gamma_\mu P_L\nu_\beta)$$
$$+ \frac{1}{2}[\epsilon_S]_{\alpha\beta}(\bar{u}d)(\bar{\ell}_\alpha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



$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U_{\text{PMNS}}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

NP models: W', charged scalar, LQ, ...

Oscillations in QFT → EFT



$$\mathcal{M}(S \to X_\alpha \nu_k) = U^*_{\alpha k} A^P_L + \sum_X [\epsilon_X U]^*_{\alpha k} A^P_X$$

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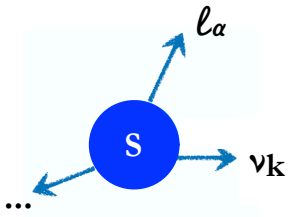
Oscillations in QFT → EFT



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$$R_{\alpha\beta} = \Phi^{\rm SM}_\alpha \sigma^{\rm SM}_\beta \sum_{k,l} e^{-i\frac{L\Delta m^2_{kl}}{2E_\nu}} \left[U^*_{\alpha k} U_{\alpha l} + p_{XL} (\epsilon_X U)^*_{\alpha k} U_{\alpha l} + p^*_{XL} U^*_{\alpha k} (\epsilon_X U)_{\alpha l} + p_{XY} (\epsilon_X U)^*_{\alpha k} (\epsilon_Y U)_{\alpha l}\right]$$
$$\times \left[U_{\beta k} U^*_{\beta l} + d_{XL} (\epsilon_X U)_{\beta k} U^*_{\beta l} + d^*_{XL} U_{\beta k} (\epsilon_X U)^*_{\beta l} + d_{XY} (\epsilon_X U)_{\beta k} (\epsilon_Y U)^*_{\beta l}\right]$$

$$p_{XY} \equiv \frac{\int d\Pi_{P'} A^P_X \bar{A}^P_Y}{\int d\Pi_{P'} |A^P_L|^2}$$

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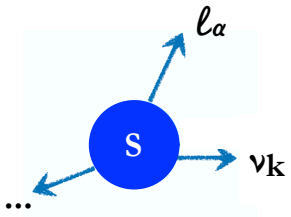
Oscillations in QFT → EFT



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NOTE: Linear sensitivity to offdiagonal Wilson coefficients (unique)

$$p_{XY} \equiv \frac{\int d\Pi_{P'} A^P_X \bar{A}^P_Y}{\int d\Pi_{P'} |A^P_L|^2}$$

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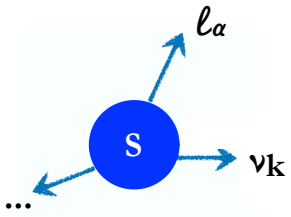
Oscillations in QFT → EFT



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$$R_{\alpha\beta} = \Phi^{\rm SM}_\alpha \sigma^{\rm SM}_\beta \sum_{k,l} e^{-i\frac{L\Delta m^2_{kl}}{2E_\nu}} [U^*_{\alpha k} U_{\alpha l} + p_{XL}(\epsilon_X U)^*_{\alpha k} U_{\alpha l} + p^*_{XL} U^*_{\alpha k} (\epsilon_X U)_{\alpha l} + p_{XY} (\epsilon_X U)^*_{\alpha k} (\epsilon_Y U)_{\alpha l}]$$
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NOTE: Linear sensitivity to offdiagonal Wilson coefficients (unique)

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QM-NSI approach:

$$R^{\rm NSI}_{\alpha\beta} = \phi^{SM}_\alpha \sigma^{SM}_\beta \sum_{k,l} e^{-i\frac{L\Delta m^2_{kl}}{2E_\nu}} [(1+\epsilon^s)U^*]_{\alpha k} [(1+\epsilon^s)^* U]_{\alpha l} [(1+\epsilon^d)^T U]_{\beta k} [(1+\epsilon^d)^T U]^*_{\beta l}$$

EFT / NSI matching

$$R^{\rm EFT}_{\alpha\beta} = R_0 + c_X\,\epsilon_X + \mathcal{O}(\epsilon^2) \quad \text{vs.} \quad R^{\rm NSI}_{\alpha\beta} = R_0 + c^{s,d}\,\epsilon^{s,d} + \mathcal{O}(\epsilon^2)$$

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

We see that in a reactor experiment:

- one "can't" have NP only in production
- the assumption of equal magnitude and non-opposite phases is also not "natural"
- the E-dependence needed for S & T was never taken into account in the NSI literature

[e.g. Leitner et al., JHEP 12 (2011) 001; Li & Zhou, Nucl. Phys. B888 (2014) 137-153; Agarwalla et al., JHEP 07 (2015) 060; ...]

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However, beyond linear order, there's no matching!!!
The NSI-QM approach itself fails <u>in general.</u>
[PS: bounds of O(1) are common...]

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But it does not fail in every case.

Condition:

$$p_{XL}p^*_{YL} = p_{XY}$$
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Examples:

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Recap: main results so far

- Oscillation observable calculated in QFT in the presence of (heavy) CC NP

$$R_{\alpha\beta} = \Phi_\alpha^{\rm SM}\sigma_\beta^{\rm SM}\sum_{k,l} e^{-i\frac{L\Delta m^2_{kl}}{2E_\nu}}\left[U^*_{\alpha k}U_{\alpha l} + p_{XL}(\epsilon_X U)^*_{\alpha k}U_{\alpha l} + p^*_{XL}U^*_{\alpha k}(\epsilon_X U)_{\alpha l} + p_{XY}(\epsilon_X U)^*_{\alpha k}(\epsilon_Y U)_{\alpha l}\right]$$
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- Validity of the traditional NSI-QM approach analyzed

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

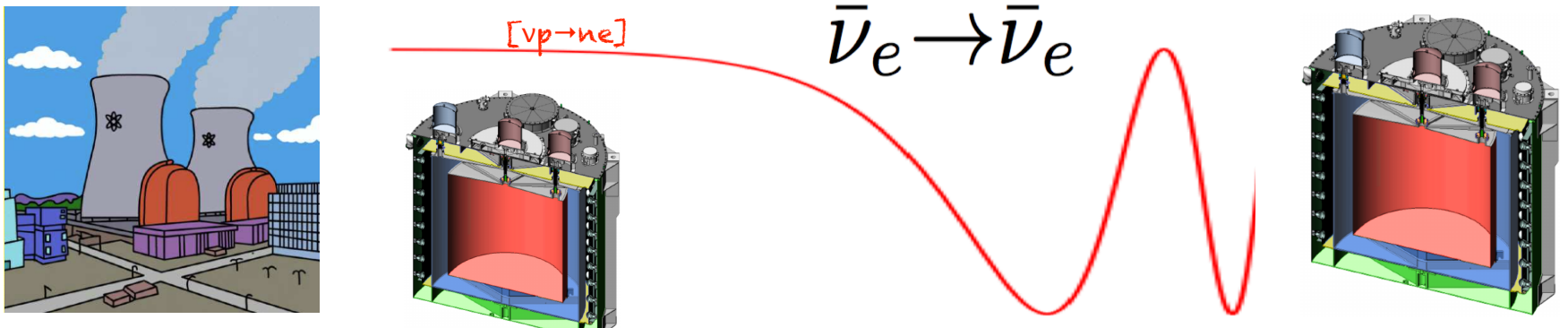
  - Matching with EFT Wilson coefficients
  - Consistency condition for that matching (& the QM-NSI approach itself) to be valid to all orders in NP parameters.
  - Useful for previous (CC) NSI works:
    - To understand the UV meaning & validity;
    - To compare between oscillation experiments & with non-osc. ones;
    - I can run, match & run...

Phenomenology

- Now we can do pheno in any given model or EFT setup
  - Implications for that model / SMEFT?
  - Interplay with other oscillation experiments, and with other probes (CLFV?).

- Example: short-baseline reactor experiments in the (SM)EFT.

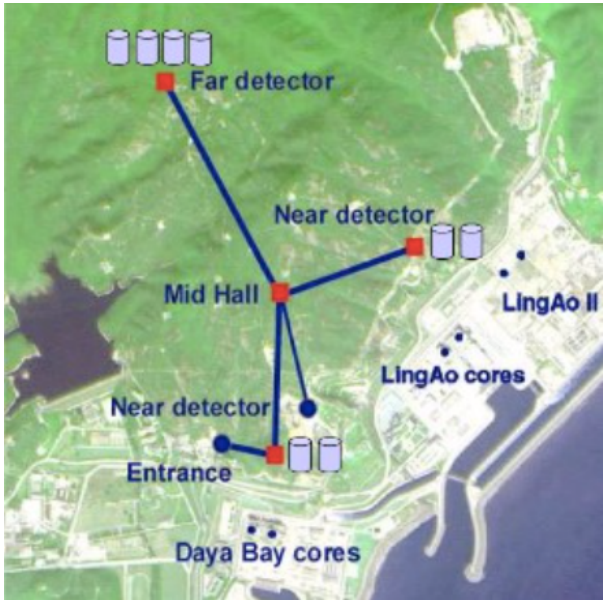
[A. Falkowski, MGA, & Z. Tabrizi, JHEP'19]



$N \to N' e^+ \bar{\nu}_e$

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

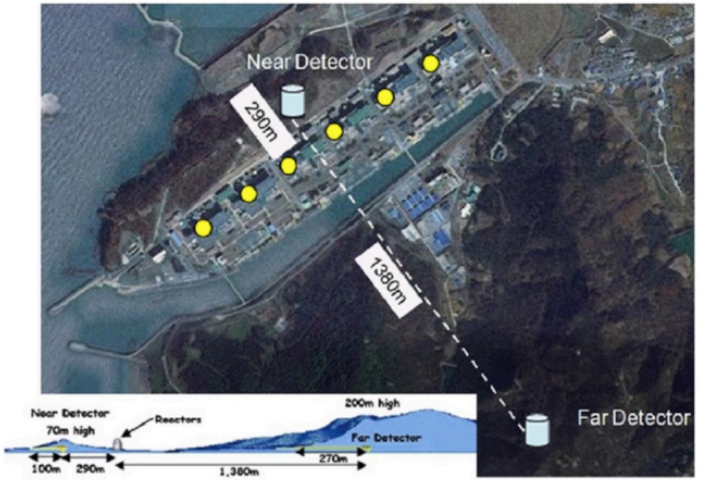
Short-baseline reactor exp.



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

Daya Bay Collaboration, D. Adey et al., arXiv:1809.02261



RENO:

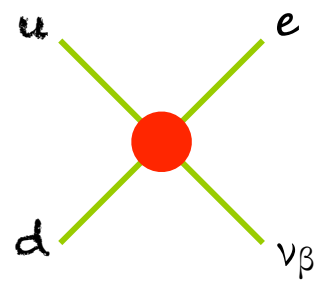
- 6 reactor cores;
- 2 near and far anti-neutrino detectors located at 367 m and 1440 m;
- Has observed ~ 1M anti-neutrino events in 2200 days of data taking

RENO Collaboration, G. Bak et al., arXiv:1806.00248.

[slide borrowed from Z. Tabrizi]

What kind of New Physics are we probing?

- No access to NC NSI (negligible matter effects): ννqq
- Only CC NSI



$\bar{\nu}_e \to \bar{\nu}_e$

$$R_{ee} = \Phi_e^{\rm SM}\sigma_e^{\rm SM}\sum_{k,l} e^{-i\frac{L\Delta m^2_{kl}}{2E_\nu}}\left[U^*_{ek}U_{el} + p^*_{XL}(\epsilon_X U)^*_{ek}U_{el} + p_{XL}U^*_{ek}(\epsilon_X U)_{el} + p^*_{XY}(\epsilon_X U)^*_{ek}(\epsilon_Y U)_{el}\right]^*$$
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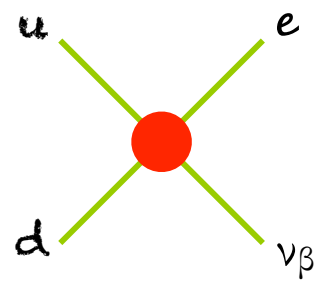

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$f(V_{ud}, g_A)$

One can't just take them from the PDG!
The effect can be dramatic: $[\epsilon_{L,R}]_{ee}$ have no effect at all in neutrino experiments!

$$V_{ud}\left(1 + [\epsilon_L]_{ee} + [\epsilon_R]_{ee}\right) \ , \qquad g_A\,\mathrm{Re}\,\frac{1 + [\epsilon_L]_{ee} - [\epsilon_R]_{ee}}{1 + [\epsilon_L]_{ee} + [\epsilon_R]_{ee}}$$

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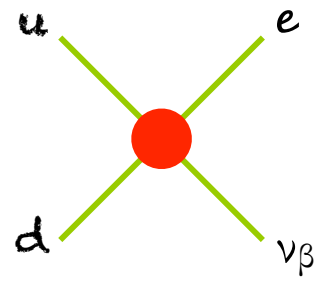

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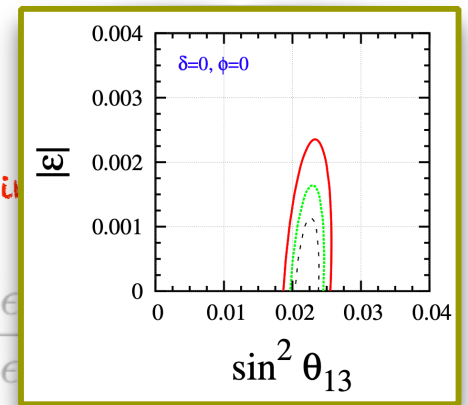

[Agarwalla et al., JHEP'2015]

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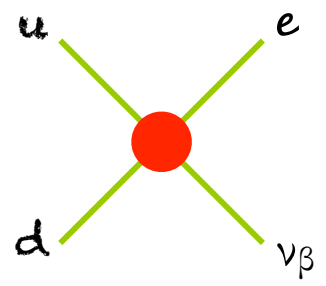

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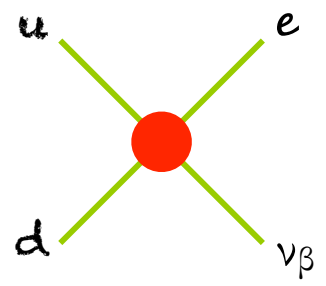

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Cancels in
FD bin to ND bin ratios
(fixed E_ν)

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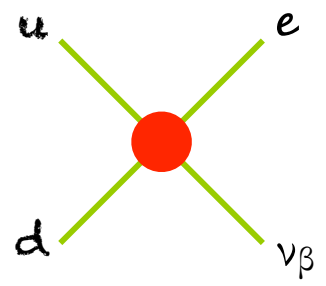

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$$R_{ee} = \Phi_e^{\rm SM}\sigma_e^{\rm SM}\sum_{k,l} e^{-i\frac{L\Delta m^2_{kl}}{2E_\nu}}\left[U^*_{ek}U_{el} + p^*_{XL}(\epsilon_X U)^*_{ek}U_{el} + p_{XL}U^*_{ek}(\epsilon_X U)_{el} + \cancel{p^*_{XY}(\epsilon_X U)^*_{ek}(\epsilon_Y U)_{el}}\right]^*$$
$$\times\left[U_{ek}U^*_{el} + d^*_{XL}(\epsilon_X U)_{ek}U^*_{el} + d_{XL}U_{ek}(\epsilon_X U)^*_{el} + \cancel{d_{XY}(\epsilon_X U)_{ek}(\epsilon_Y U)^*_{el}}\right]$$

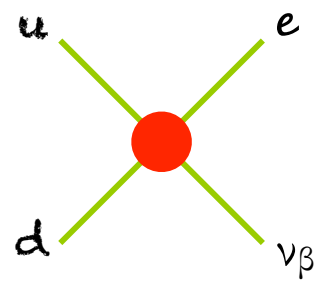
Linear approx (from now on)

$$= \cancel{\Phi_e\sigma_e}\, P(\bar\nu_e \to \bar\nu_e)$$

Cancels in
FD bin to ND bin ratios
(fixed E_ν)

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

What kind of New Physics are we probing?



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Only sensitive to flavor offdiagonal coefficients

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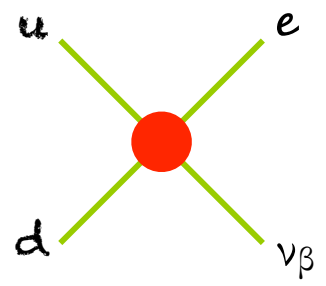

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$$= \cancel{\Phi_e\sigma_e}\, P(\bar\nu_e \to \bar\nu_e)$$

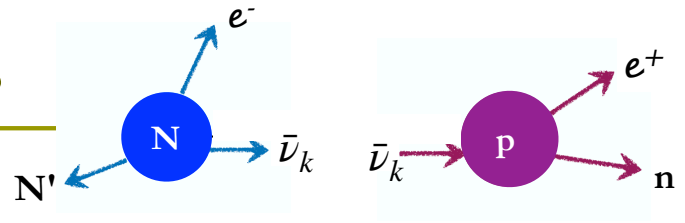
Only sensitive to flavor offdiagonal coefficients

Cancels in FD bin to ND bin ratios (fixed E_ν)

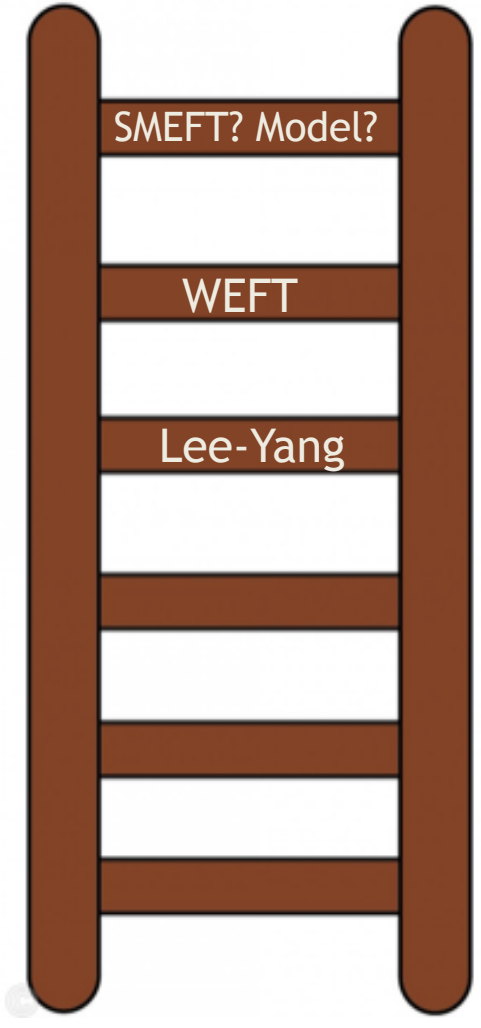
Let's calculate them...

$$p_{XL} \equiv \frac{\int d\Pi_{P'} A_X^P \bar{A}_L^P}{\int d\Pi_{P'} |A_L^P|^2}, \qquad d_{XL} \equiv \frac{\int d\Pi_D A_X^D \bar{A}_L^D}{\int d\Pi_D |A_L^D|^2}.$$

Production & detection amplitudes

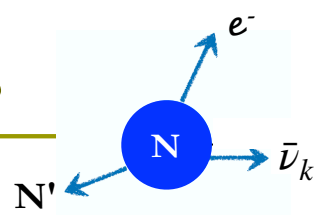


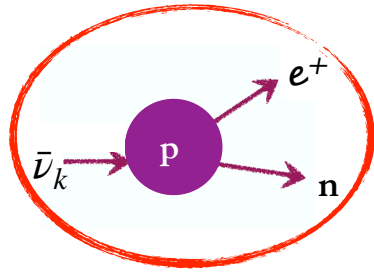
"EFT ladder"



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

Production & detection amplitudes





"EFT ladder"

$$\mathscr{M}(\nu_k p \to e\, n) = U_{\beta k} A_L^D + \sum_X [\epsilon_X U]_{\beta k} A_X^D$$

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

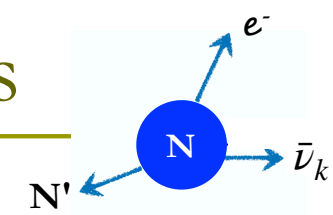
Hadronic charges:

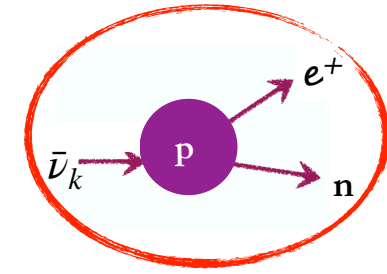
$$g_A = 1.251(33), \quad g_S = 1.02(11), \quad g_P = 349(9), \quad g_T = 0.989(34)\,.$$

E.g. $\langle p|\bar{u}\gamma_\mu\gamma_5 d|n\rangle$

[MGA & Camalich, PRL'14;
[PNDME coll., PRL '15;
CalLat coll., Nature'18;
...]

Production & detection amplitudes





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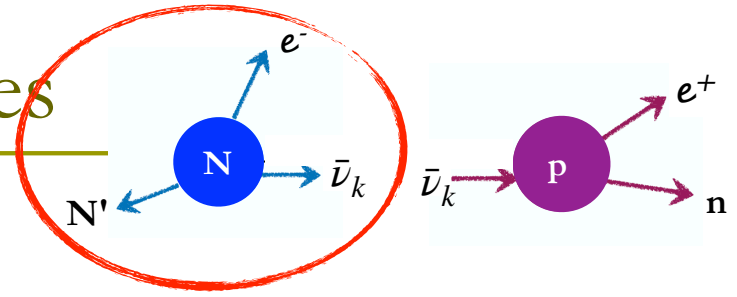
We find

Dependence on E_ν !

$$d_L \equiv 1, \quad d_R = -\frac{3g_A^2-1}{3g_A^2+1}, \quad d_S = -\frac{g_S}{3g_A^2+1}\frac{m_e}{E_\nu-\Delta}, \quad d_T = \frac{3g_A g_T}{3g_A^2+1}\frac{m_e}{E_\nu-\Delta}, \quad d_P = 0$$

$\Delta \equiv m_n - m_p$

Production & detection amplitudes



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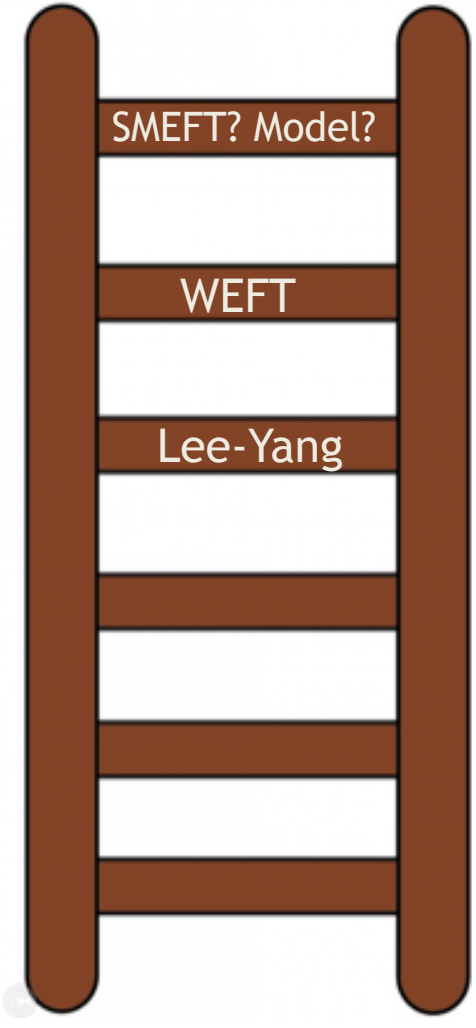

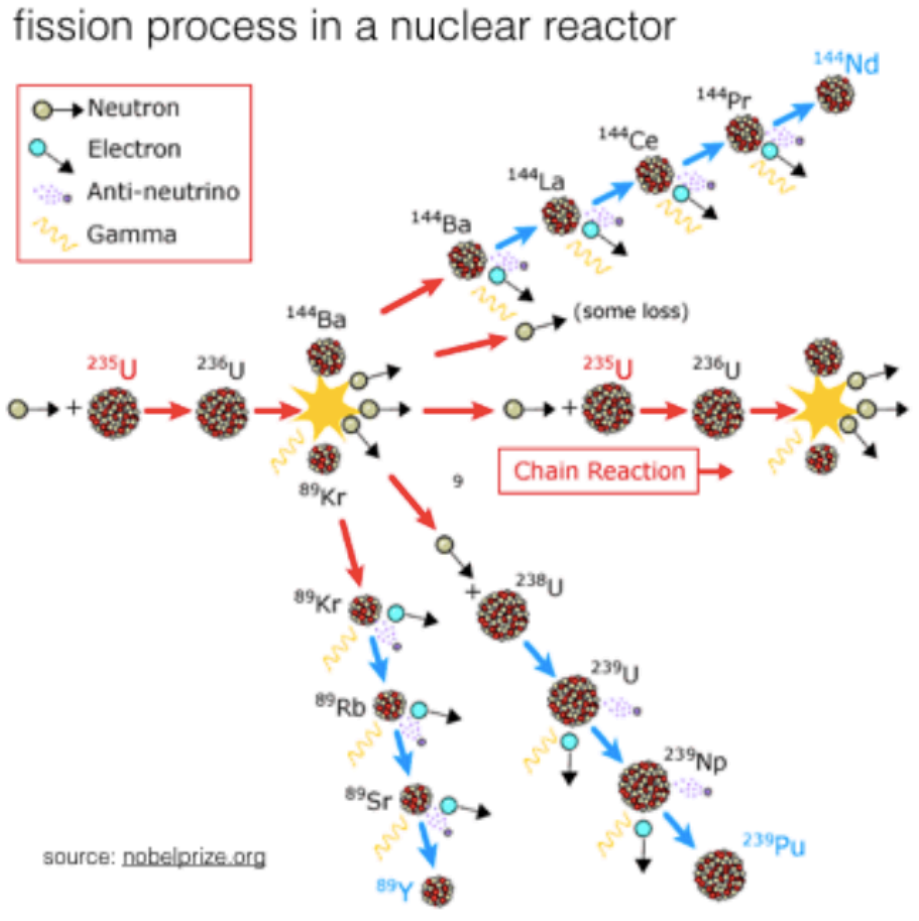

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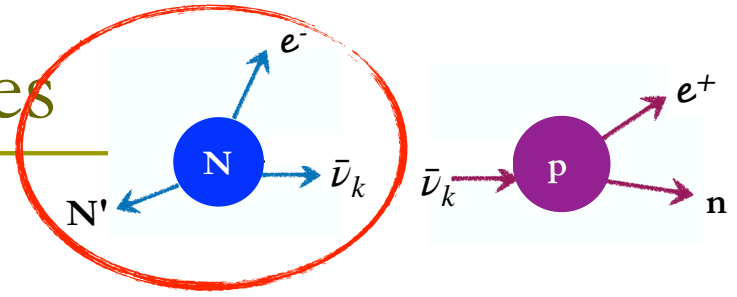

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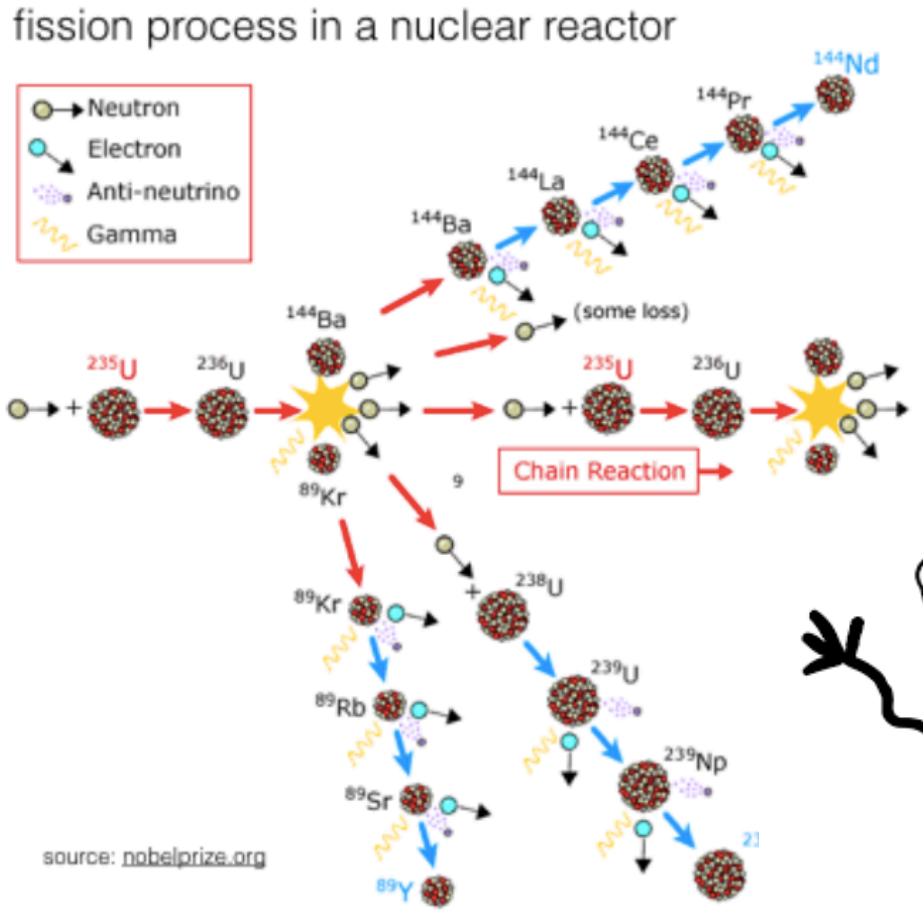

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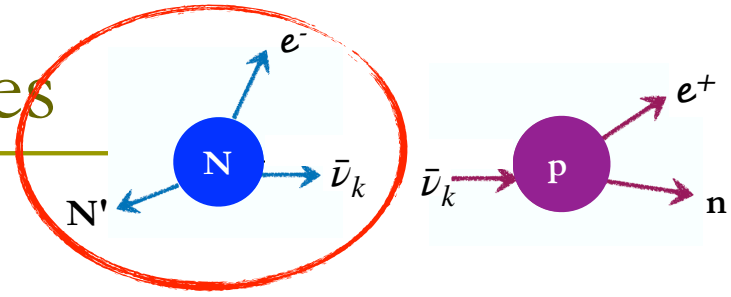

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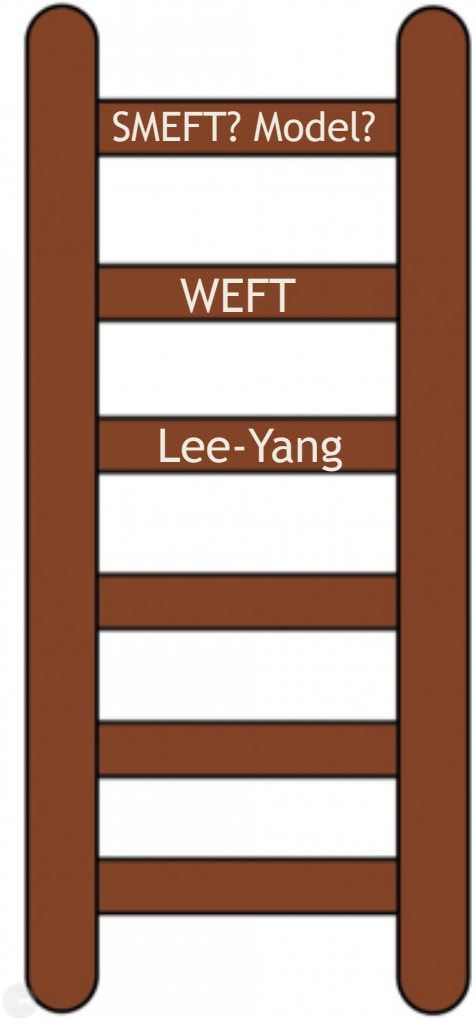

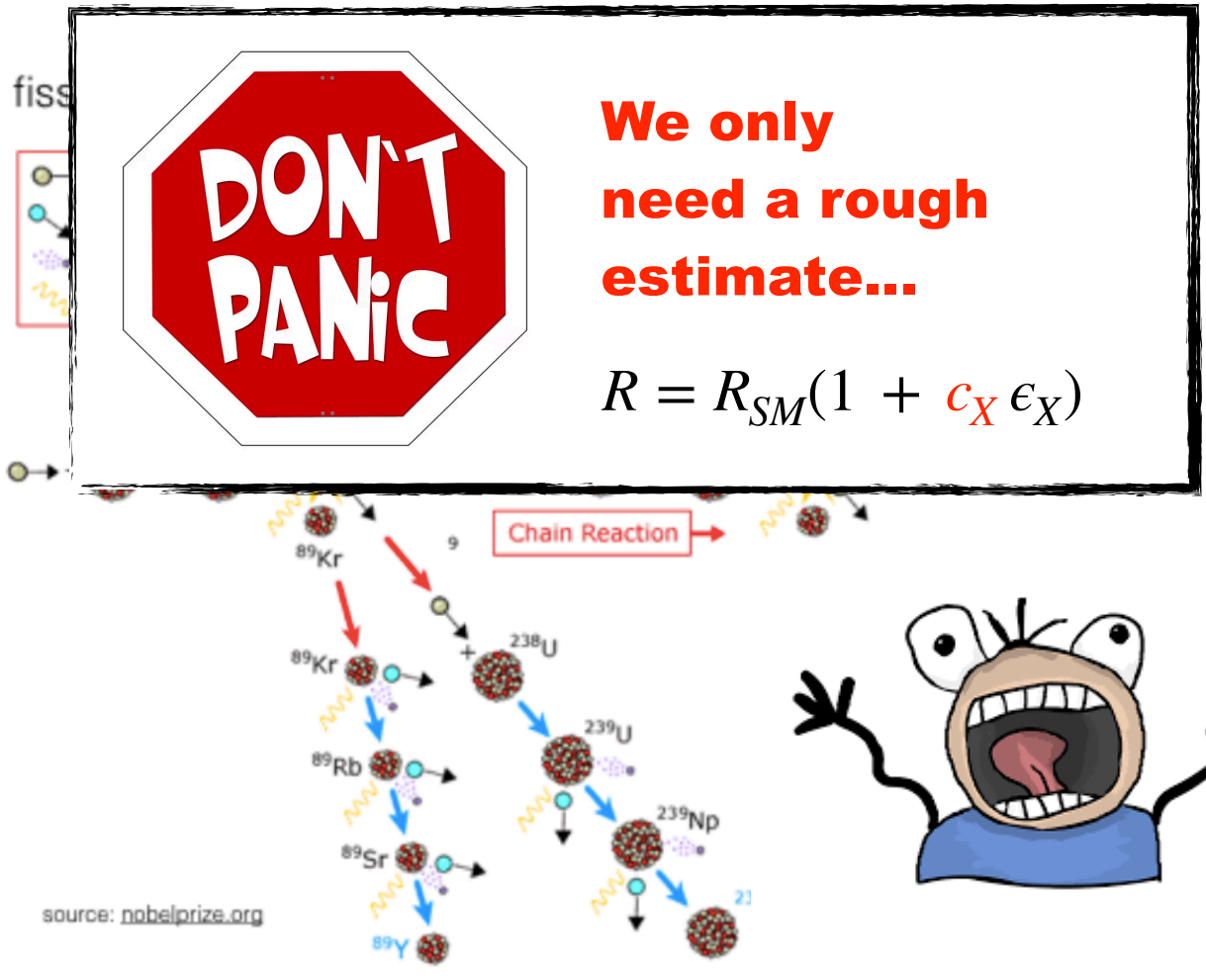

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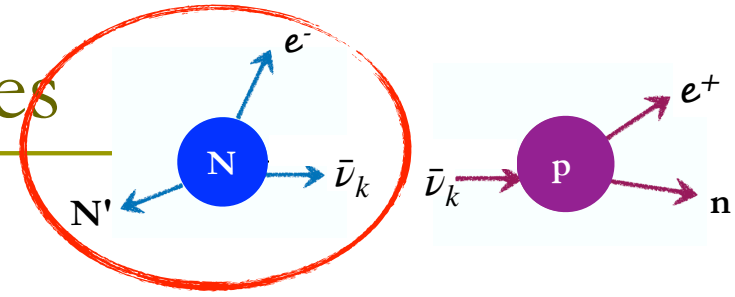


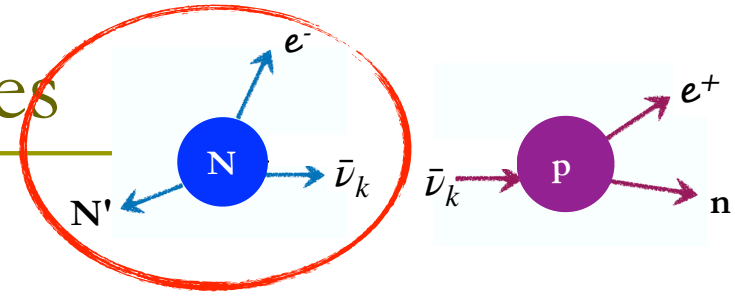
"EFT ladder"

$$\mathscr{L}_{\mathrm{NRLY}} \supset -\frac{V_{ud}}{v^2}(\bar{\psi}_p\psi_n)\left\{\left[\mathbf{1}+\epsilon_L+\epsilon_R\right]_{\alpha\beta}(\bar{\ell}_\alpha\gamma^0 P_L\nu_\beta)+g_S[\epsilon_S]_{\alpha\beta}(\bar{\ell}_\alpha P_L\nu_\beta)\right\}$$
$$+\frac{V_{ud}}{v^2}(\bar{\psi}_p\Sigma^k\psi_n)\left\{g_A\left[\mathbf{1}+\epsilon_L-\epsilon_R\right]_{\alpha\beta}(\bar{\ell}_\alpha\gamma^0\Sigma^k P_L\nu_\beta)-g_T[\hat{\epsilon}_T]_{\alpha\beta}(\bar{\ell}_\alpha\Sigma^k P_L\nu_\beta)\right\}$$

Nuclear matrix elements:

$$M_{\mathrm{F}} \equiv \langle N'|\bar{\psi}_p\psi_n|N\rangle \quad \rightarrow \text{V, S}$$
$$M^k_{\mathrm{GT}} \equiv \langle N'|\bar{\psi}_p\sigma^k\psi_n|N\rangle \quad \rightarrow \text{A, T}$$

Production & detection amplitudes



"EFT ladder"

Good news:
Most of the decays are allowed GT
[Hayes & Vogel, 2016]

$$\mathscr{L}_{\rm NRLY} \supset -\frac{V_{ud}}{v^2}(\bar{\psi}_p\psi_n)\{[\mathbf{1}+\epsilon_L+\epsilon_R]_{\alpha\beta}(\bar{\ell}_\alpha\gamma^0 P_L\nu_\beta)+g_S[\epsilon_S]_{\alpha\beta}(\bar{\ell}_\alpha P_L\nu_\beta)\}$$
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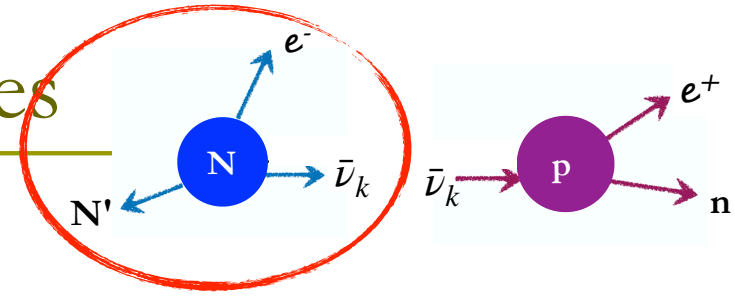
Production & detection amplitudes



$$p_{XL} \equiv \frac{\int d\Pi_{P'} A_X^P \bar{A}_L^P}{\int d\Pi_{P'} |A_L^P|^2}$$

"EFT ladder"

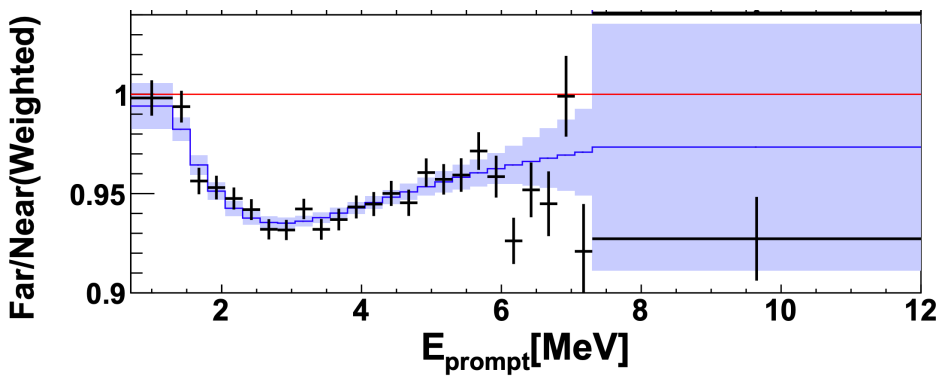
$$f_T(E_\nu) = F(w_i, \Delta M_i; E_\nu)$$
$$\approx F(w(\Delta M; \mu = 1.7\,\mathrm{MeV}, \sigma = 2.5\,\mathrm{MeV}); \mathrm{E}_\nu)$$

[King & Perkins'58, Davis et al'79, Vogel'07]

$$p_L \equiv 1, \qquad p_R = -1, \qquad p_S \approx 0, \qquad p_P \approx 0, \qquad p_T = -\frac{g_T}{g_A}\frac{m_e}{f_T(E_\nu)}$$

Short-baseline reactor exp.

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



$\theta_{13} = 0.0856(29)$

[DayaBay'18, ~4M neutrino events!]

[PS: no anomaly in far/near ratios]

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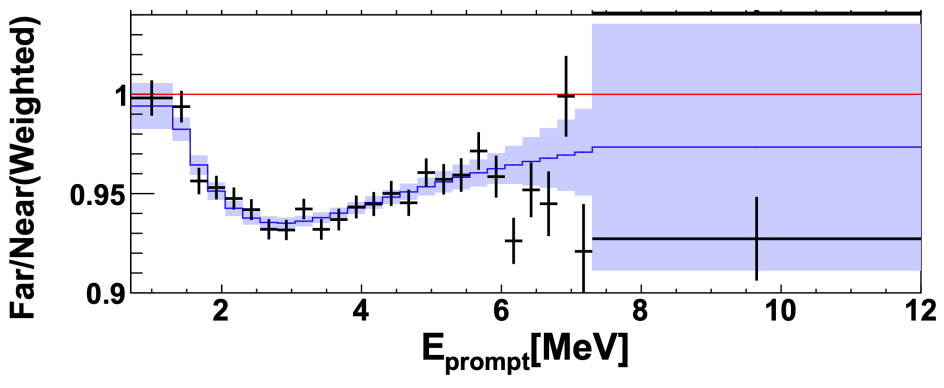
- UV-meaning of the good agreement with the SM?



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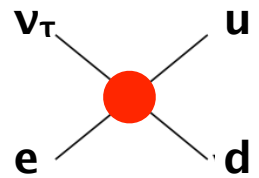


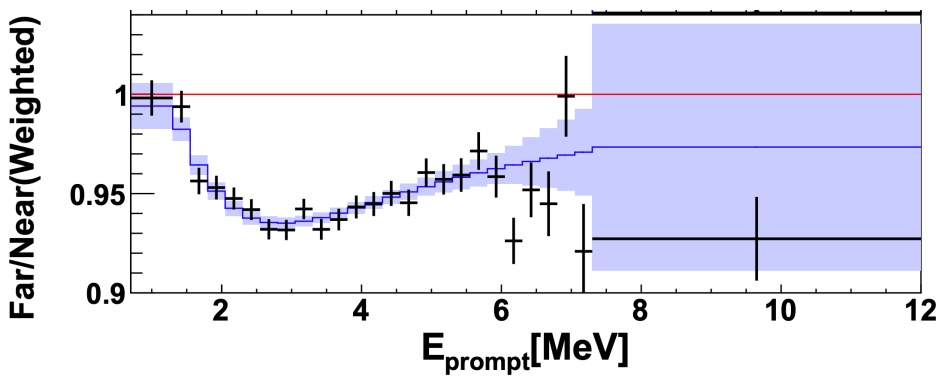
$$P_{\bar{\nu}_e \to \bar{\nu}_e}(L, E_\nu) = 1 - \sin^2\left(\frac{\Delta m^2_{31} L}{4E_\nu}\right)\sin^2\left(2\hat{\theta}_{13}\right)$$

- UV-meaning of the good agreement with the SM?
  - V-A & Re(V+A) gets hidden in θ_{13};

$$\hat{\theta}_{13} = \theta_{13} + \mathrm{Re}\,[L] - \frac{3g_A^2}{3g_A^2+1}\mathrm{Re}\,[R]$$

$$[L] \equiv e^{i\delta_{\rm CP}}\left(s_{23}[\epsilon_L]_{e\mu} + c_{23}[\epsilon_L]_{e\tau}\right)$$

$$[R] \equiv e^{i\delta_{\rm CP}}\left(s_{23}[\epsilon_R]_{e\mu} + c_{23}[\epsilon_R]_{e\tau}\right)$$



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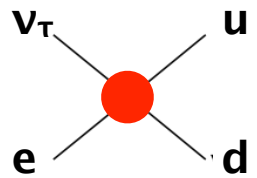

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$$+\sin\left(\frac{\Delta m^2_{31}L}{2E_\nu}\right)\sin(2\hat{\theta}_{13})\left(\gamma_R+\beta_D\frac{m_e}{E_\nu-\Delta}-\beta_P\frac{m_e}{f_T(E_\nu)}\right)$$

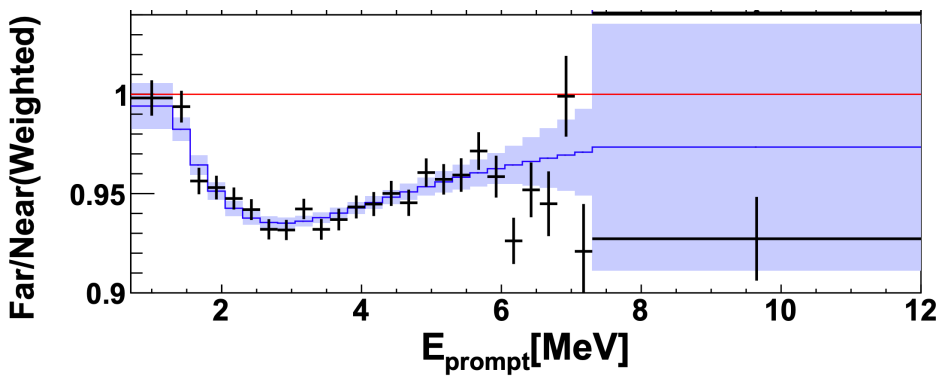
CPV piece (changes sign for ν)

- UV-meaning of the good agreement with the SM?
  - V-A & Re(V+A) gets hidden in θ_{13};
  - S, T and Im(V+A) can be probed

$$\hat{\theta}_{13} = \theta_{13} + \mathrm{Re}\,[L] - \frac{3g_A^2}{3g_A^2+1}\mathrm{Re}\,[R]$$

$$[L] \equiv e^{i\delta_{\rm CP}}\left(s_{23}[\epsilon_L]_{e\mu} + c_{23}[\epsilon_L]_{e\tau}\right)$$
$$[R] \equiv e^{i\delta_{\rm CP}}\left(s_{23}[\epsilon_R]_{e\mu} + c_{23}[\epsilon_R]_{e\tau}\right)$$
$$[S] \equiv e^{i\delta_{\rm CP}}\left(s_{23}[\epsilon_S]_{e\mu} + c_{23}[\epsilon_S]_{e\tau}\right)$$
$$[T] \equiv e^{i\delta_{\rm CP}}\left(s_{23}[\epsilon_T]_{e\mu} + c_{23}[\epsilon_T]_{e\tau}\right)$$

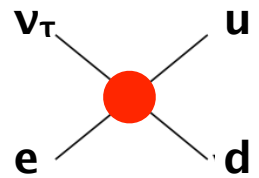
$$\alpha_D = \frac{g_S}{3g_A^2+1}\mathrm{Re}\,[S] - \frac{3g_Ag_T}{3g_A^2+1}\mathrm{Re}\,[T]\,, \qquad \alpha_P = \frac{g_T}{g_A}\mathrm{Re}\,[T]$$
$$\beta_D = \frac{g_S}{3g_A^2+1}\mathrm{Im}\,[S] - \frac{3g_Ag_T}{3g_A^2+1}\mathrm{Im}\,[T]\,, \qquad \beta_P = \frac{g_T}{g_A}\mathrm{Im}\,[T]$$
$$\gamma_R = -\frac{2}{3g_A^2+1}\mathrm{Im}\,[R]$$



$\hat{\theta}_{13} = 0.0856(29)$

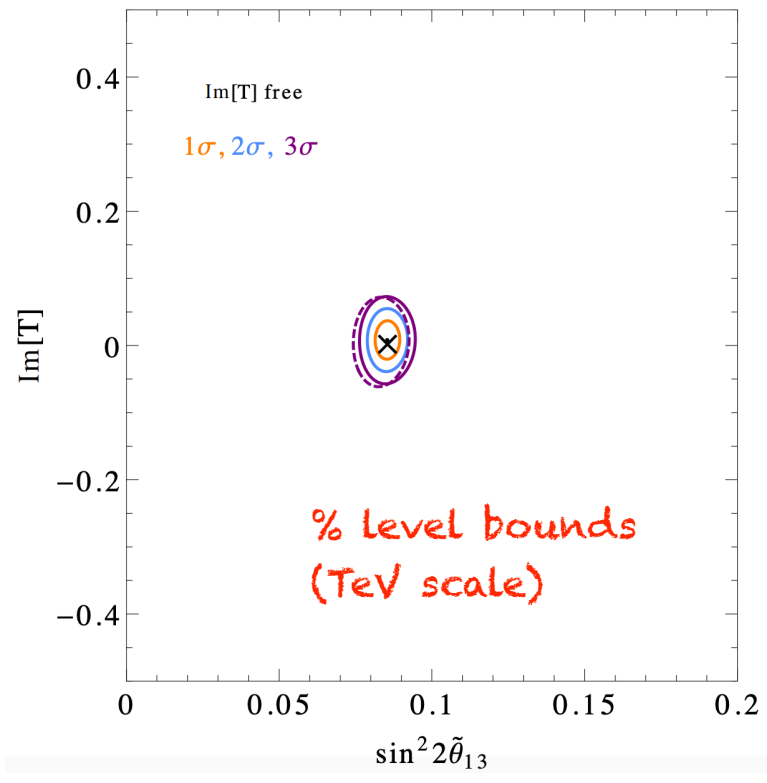
[DayaBay'18, ~4M neutrino events!]

Short-baseline reactor exp.



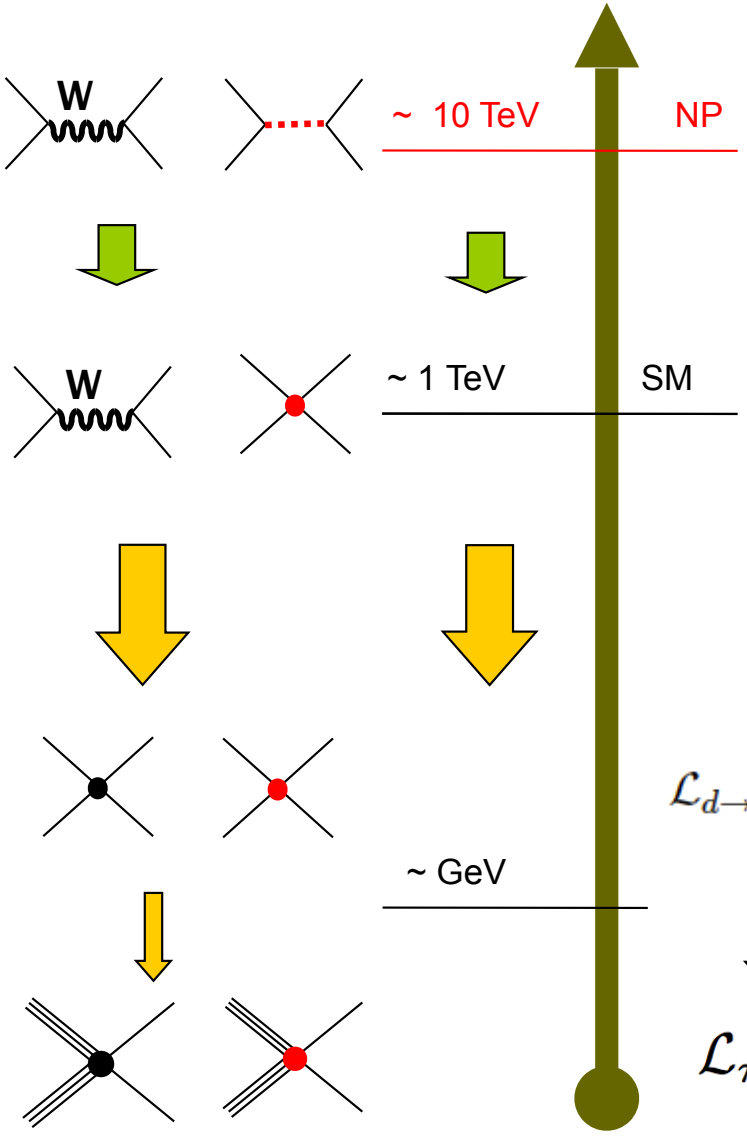
$$P_{\bar{\nu}_e \to \bar{\nu}_e}(L, E_\nu) = 1 - \sin^2\left(\frac{\Delta m^2_{31} L}{4E_\nu}\right)\sin^2\left(2\hat{\theta}_{13} - \alpha_D \frac{m_e}{E_\nu - \Delta} - \alpha_P \frac{m_e}{f_T(E_\nu)}\right)$$
$$+ \sin\left(\frac{\Delta m^2_{31} L}{2E_\nu}\right)\sin(2\hat{\theta}_{13})\left(\gamma_R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

$$[T] \equiv e^{i\delta_{\rm CP}}\left(s_{23}[\epsilon_T]_{e\mu} + c_{23}[\epsilon_T]_{e\tau}\right)$$



Matching with SMEFT

$$\frac{d\,\vec{\epsilon}(\mu)}{d\log\mu} = \left(\frac{\alpha(\mu)}{2\pi}\gamma_{\rm ew} + \frac{\alpha_s(\mu)}{2\pi}\gamma_s\right)\vec{\epsilon}(\mu),$$



$$\mathcal{L}(x) = \mathcal{L}\,(\text{SM fields, bSM fields})$$

$$\mathcal{L}_{eff.} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\sum \alpha_i\,\mathcal{O}_i$$

$$\mathcal{L}_{d\to u\ell^-\bar{\nu}_\ell} = -\frac{4G_F V_{ij}}{\sqrt{2}}\left[\bar{\ell}_L\gamma_\mu\nu\cdot\bar{u}\gamma^\mu d_L + \sum_{\rho\delta\Gamma}\epsilon^\Gamma_{\rho\delta}\,\bar{\ell}_\rho\Gamma\nu\cdot\bar{u}\Gamma d_\delta\right]$$

$$\mathcal{L}_{\pi,N,\ldots} = \ldots$$

$$\boxed{\varepsilon_i = f(\alpha_j)}$$

Matching with SMEFT

Low-E EFT *SMEFT*

$$[\epsilon_i = f(\alpha_j)]_{\mu=M_Z}$$

[Cirigliano, MGA, Jenkins'2010; Cirigliano, MGA, Graesser'2012]

All interactions generated at D=6:

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\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)\\
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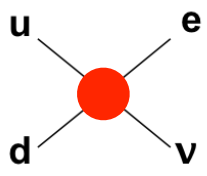

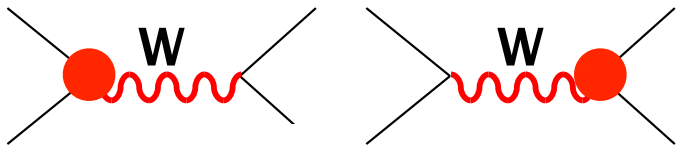

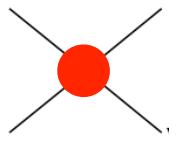

$$
\begin{aligned}
O^{(3)}_{lq} &= (\bar{l}\gamma^\mu\sigma^a l)(\bar{q}\gamma_\mu\sigma^a q)\\
O_{qde} &= (\bar{l}e)(\bar{d}q) + \text{h.c.}\\
O_{lq} &= (\bar{l}_a e)\epsilon^{ab}(\bar{q}_b u) + \text{h.c.}\\
O^t_{lq} &= (\bar{l}_a\sigma^{\mu\nu}e)\epsilon^{ab}(\bar{q}_b\sigma_{\mu\nu}u) + \text{h.c.}
\end{aligned}
$$

$$
\begin{aligned}
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Low-E EFT

SMEFT

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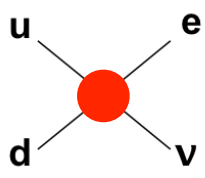
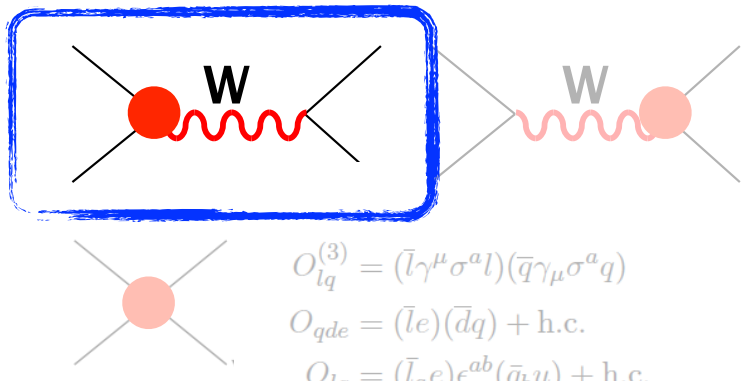
RH interactions are lepton-flavor independent & diagonal!





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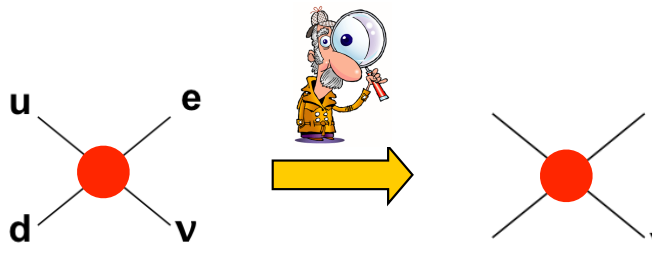
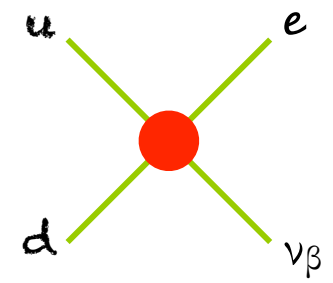


$$(\bar{u}\sigma^{\mu\nu}P_L d)(\bar{\ell}_\alpha\sigma_{\mu\nu}P_L\nu_\beta)$$

$$(\bar{\ell}^m_\alpha\sigma_{\mu\nu}e_1)\epsilon_{mn}(\bar{q}^n_1\sigma^{\mu\nu}u_1)$$

Bounds on this operator from non-oscillation data?

Non-oscillation constraints on $[\varepsilon_{S,T}]_{e\mu,e\tau}$



Additional assumptions needed:

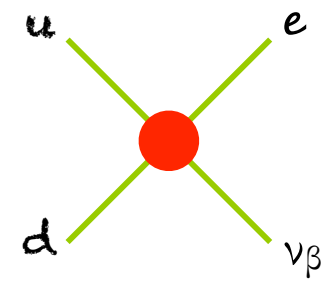
only one (quadratic!) operator, SMEFT, dim-8 operators neglected, ...

- Beta decays: $|[\epsilon_S]_{e\alpha}| \leq 6.4 \times 10^{-2}$, $|[\epsilon_T]_{e\alpha}| \leq 4.4 \times 10^{-2}$
- CKM unitarity: $|[\epsilon_S]_{e\alpha}| \leq 2.0 \times 10^{-2}$
- Pion decay: $|[\epsilon_P]_{e\alpha}|_{\mu=2\,\mathrm{GeV}} \leq 7.5 \times 10^{-6} \longrightarrow \left|[\epsilon_T]_{e\alpha} + 3 \times 10^{-4}[\epsilon_S]_{e\alpha}\right|_{\mu=2\,\mathrm{GeV}} \leq 1.0 \times 10^{-3}$

(Running from Mz)

[MGA, Camalich & Mimouni'17]

Non-oscillation constraints on $[\varepsilon_{S,T}]_{e\mu,e\tau}$



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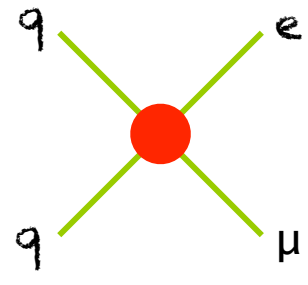
  $\left|[\hat{\epsilon}_T]_{e\alpha} - 4 \times 10^{-2}[\epsilon_S]_{e\alpha}\right|_{\mu=2\,\mathrm{GeV}} \leq 7.0 \times 10^{-5}$ (Running from 1 TeV)

  [MGA, Camalich & Mimouni'17]
- LHC Drell Yan: $\left(\sum_\alpha |[\epsilon_S]_{e\alpha}|^2\right)^{1/2} \lesssim 2 \times 10^{-3}$, $\left(\sum_\alpha |[\epsilon_T]_{e\alpha}|^2\right)^{1/2} \lesssim 2 \times 10^{-3}$
  [Gupta et al.'08]
- μ → e conversion: $\left|[\epsilon_S]_{e\mu}\right| \lesssim 3 \times 10^{-6}$
- τ → e π π: $\left|[\epsilon_S]_{e\tau}\right| \lesssim 4 \times 10^{-4}$



Summary

- Oscillation observables calculated in QFT in the presence of (heavy) CC NP

$$R_{\alpha\beta} = \Phi_\alpha^{\rm SM}\sigma_\beta^{\rm SM}\sum_{k,l} e^{-i\frac{L\Delta m^2_{kl}}{2E_\nu}}\left[U^*_{\alpha k}U_{\alpha l} + p_{XL}(\epsilon_X U)^*_{\alpha k}U_{\alpha l} + p^*_{XL}U^*_{\alpha k}(\epsilon_X U)_{\alpha l} + p_{XY}(\epsilon_X U)^*_{\alpha k}(\epsilon_Y U)_{\alpha l}\right]$$
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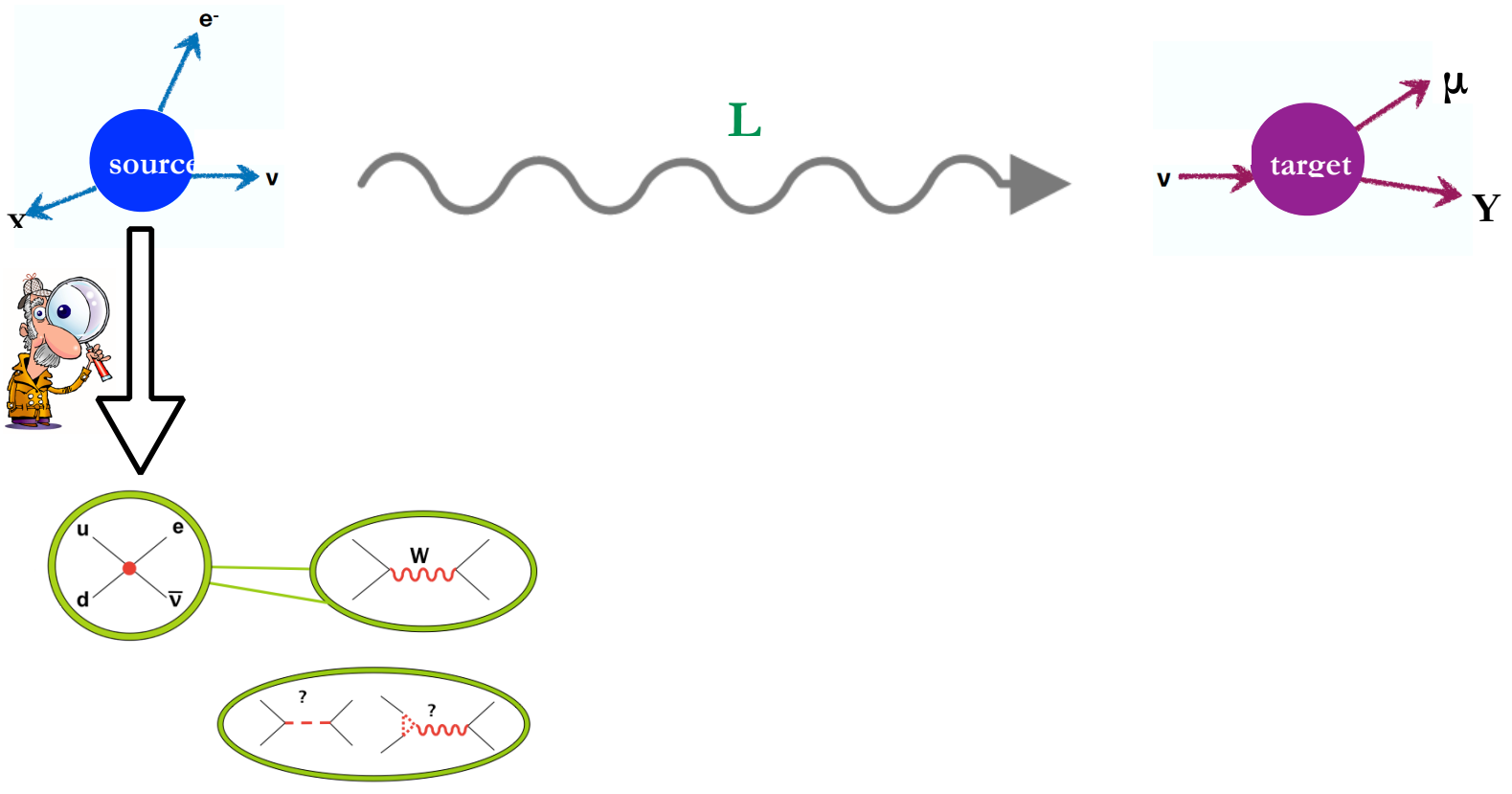

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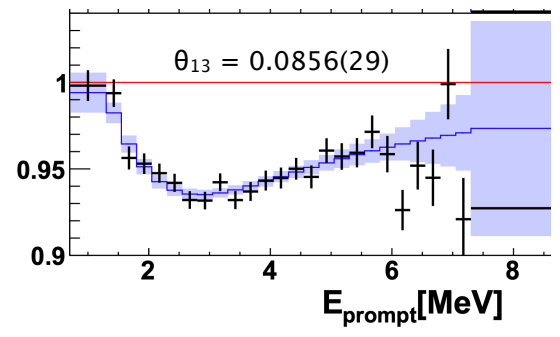
  - We identify the NP probed;
  - We obtained (~%-level) NP bounds;
  - Application of the SMEFT setup;



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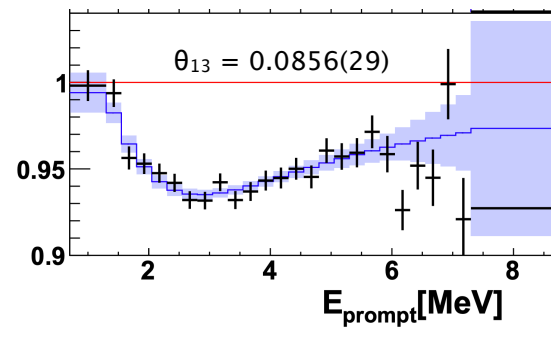

- "Zero-distance" neutrino experiments can also be analyzed with this approach, with their own peculiarities (angles and mixing gone, only quadratic NSI, …). Example: FASERν.
  [A. Falkowski, MGA, J. Kopp, Y. Soreq & Z. Tabrizi, to appear]

Credit: Sandbox Studio, Chicago

Thanks!