# β decays as probes for fundamental physics

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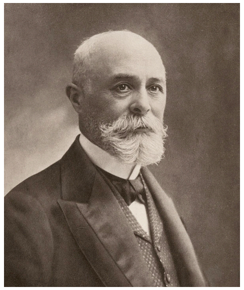
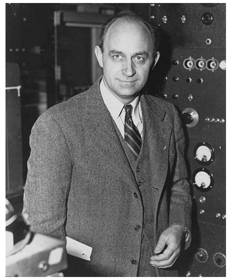
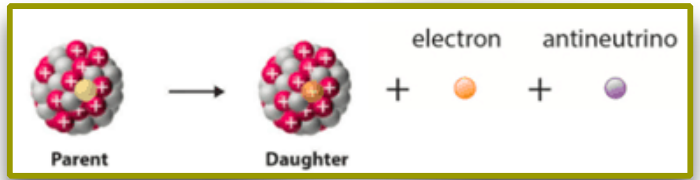
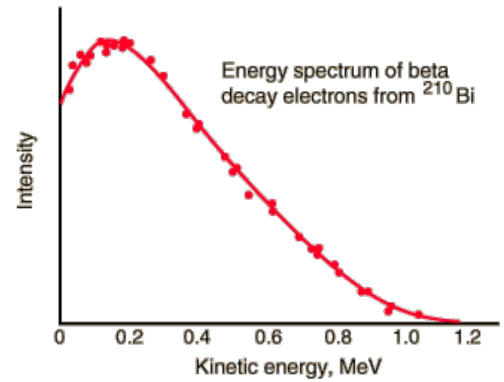
# Beta decays: a trove of discoveries

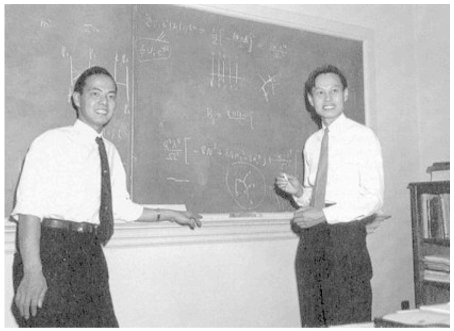


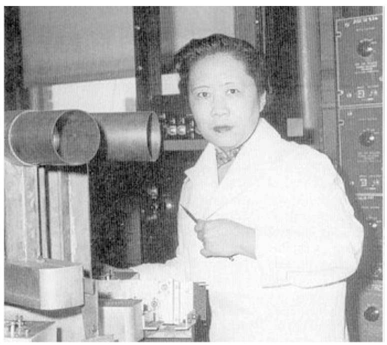


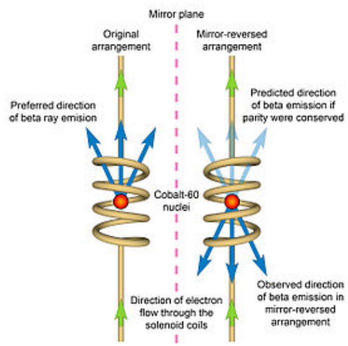


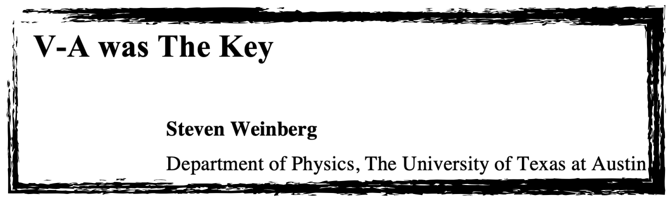











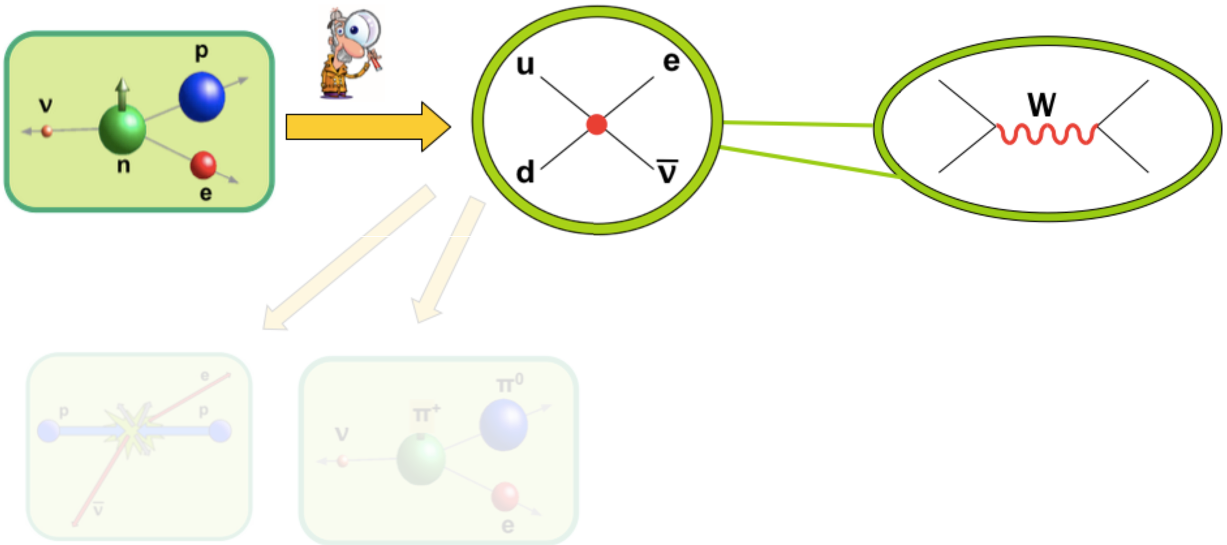
**V-A was The Key**

**Steven Weinberg**

Department of Physics, The University of Texas at Austin

# Beta decays: a trove of discoveries

- Then the **EW theory** and the SM came…

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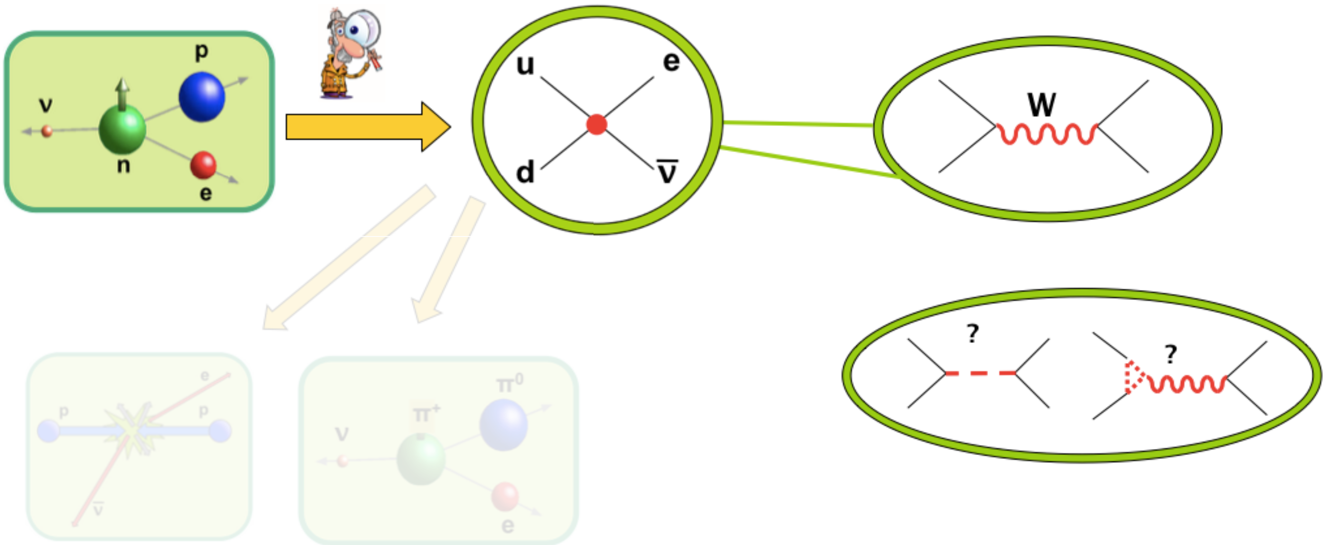


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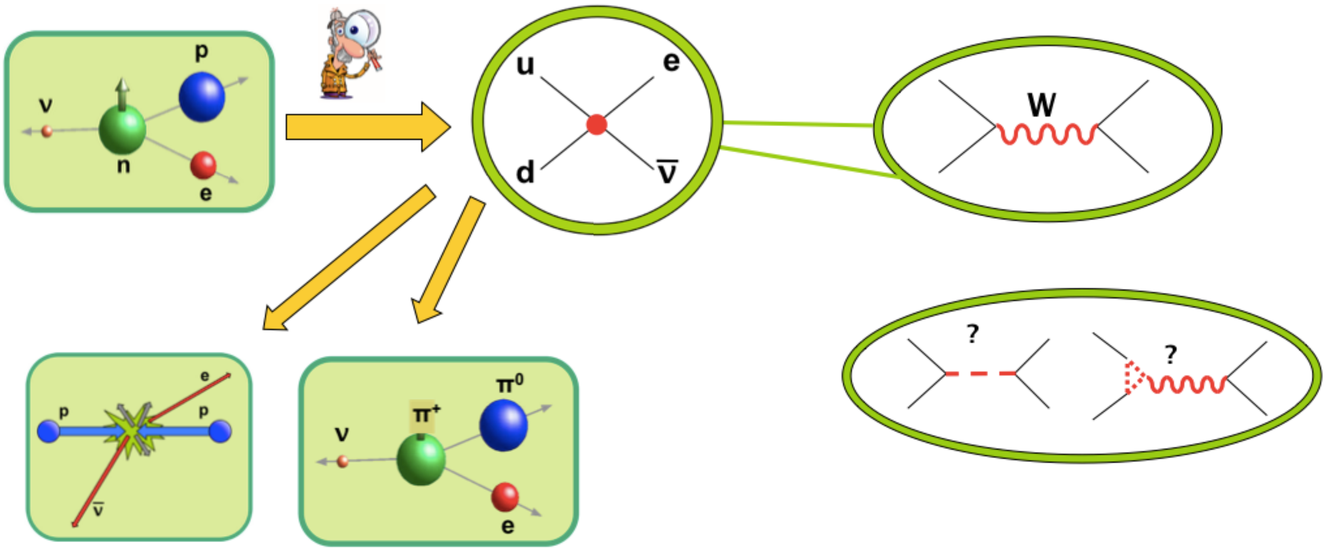


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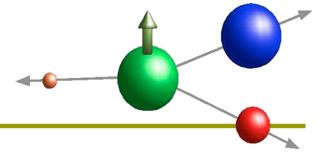
- Theoretical framework?
  - Specific NP model vs. Effective Field Theories ("the same old approach" reloaded)

# Which EFT?



- How to compare different nuclear beta decays?
  - ➔ Effective Lagrangian at the **hadron** level!

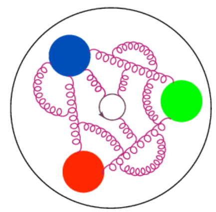
$$
\begin{aligned}
-\mathcal{L}_{n\to pe^-\bar{\nu}_e} \;=\;& \bar{p}\, n\; (C_S \bar{e}\nu_e - C'_S \bar{e}\gamma_5\nu_e) \\
&+ \bar{p}\gamma^\mu n\, (C_V \bar{e}\gamma_\mu\nu_e - C'_V \bar{e}\gamma_\mu\gamma_5\nu_e) \\
&+ \frac{1}{2}\bar{p}\sigma^{\mu\nu} n\, (C_T \bar{e}\sigma_{\mu\nu}\nu_e - C'_T \bar{e}\sigma_{\mu\nu}\gamma_5\nu_e) \\
&- \bar{p}\gamma^\mu\gamma_5 n\, (C_A \bar{e}\gamma_\mu\gamma_5\nu_e - C'_A \bar{e}\gamma_\mu\nu_e) \\
&+ \bar{p}\gamma_5 n\; (C_P \bar{e}\gamma_5\nu_e - C'_P \bar{e}\nu_e) + \text{h.c.}
\end{aligned}
$$

*[Lee & Yang'1956]*

- How to compare with e.g. pion decays?
  - ➔ Effective Lagrangian at the **quark** level!

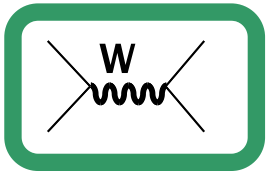
$$
\mathcal{L}_{d\to u\ell^-\bar{\nu}_\ell} = -\frac{4G_F V_{ij}}{\sqrt{2}}\left[\bar{\ell}_L\gamma_\mu\nu\cdot\bar{u}\gamma^\mu d_L \;+\; \sum_{\rho\delta\Gamma}\epsilon^{\Gamma}_{\rho\delta}\,\bar{\ell}_\rho\Gamma\nu\cdot\bar{u}\Gamma d_\delta\right]
$$

$$
\boxed{C_i \sim \mathrm{FF} \times \varepsilon_i}
$$



- How to compare with LHC experiments?
  - ➔ Effective Lagrangian at the **quark** level at the EW scale!

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



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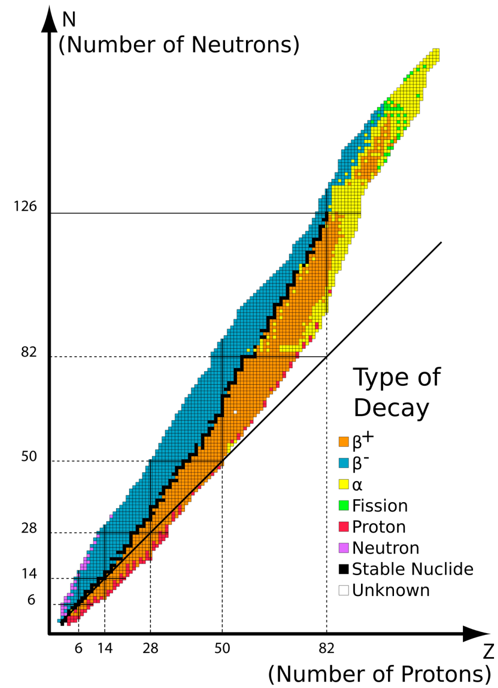
[Lee & Yang'1956]

$$\begin{aligned}\mathcal{L}_{\text{Lee}-\text{Yang}} &= -\bar{p}\gamma^{\mu}n\left(C_V^{+}\bar{e}\gamma_{\mu}\nu_L + C_V^{-}\bar{e}\gamma_{\mu}\nu_R\right) - \bar{p}\gamma^{\mu}\gamma_5 n\left(C_A^{+}\bar{e}\gamma_{\mu}\nu_L - C_A^{-}\bar{e}\gamma_{\mu}\nu_R\right)\\ &- \bar{p}n\left(C_S^{+}\bar{e}\nu_L + C_S^{-}\bar{e}\nu_R\right) - \frac{1}{2}\bar{p}\sigma^{\mu\nu}n\left(C_T^{+}\bar{e}\sigma_{\mu\nu}\nu_L + C_T^{-}\bar{e}\sigma_{\mu\nu}\nu_R\right)\\ &+ \bar{p}\gamma_5 n\left(C_P^{+}\bar{e}\nu_L - C_P^{-}\bar{e}\nu_R\right) + \text{h.c.}\end{aligned}$$

$$d\Gamma \approx f(C_i, M_F, M_{GT})$$

For some transitions and observables:

$$\mathcal{O} \approx f(C_i)$$



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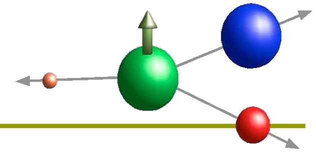

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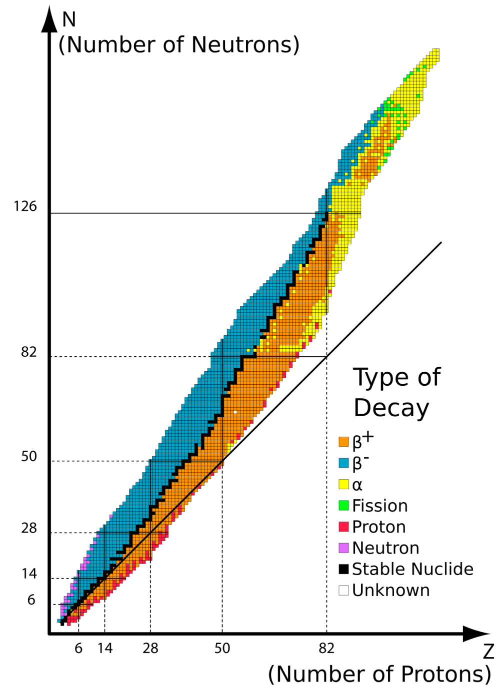
$$d\Gamma \approx f(C_i, M_F, M_{GT})$$

For some transitions and observables:

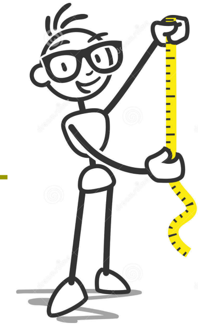
$\mathcal{O} \approx f(C_i)$ + small corrections

High precision measurements



# Current data

Precision:
O(0.01 – 1)% !!



[Falkowski, MGA, Naviliat-Cuncic, JHEP 04 (2021)
+ some updates

Fermi or Gamow-Teller
Nuclear decays

## $\mathcal{F}t$ ($0^+ \to 0^+$) values

| Parent | $\mathcal{F}t$ [s] |
|---|---|
| $^{10}$C | $3075.7 \pm 4.4$ |
| $^{14}$O | $3070.2 \pm 1.9$ |
| $^{22}$Mg | $3076.2 \pm 7.0$ |
| $^{26m}$Al | $3072.4 \pm 1.1$ |
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| $^{74}$Rb | $3077 \pm 11$ |

*[Hardy-Towner'2020]*

## Correlation coefficients

| Parent | Type | Parameter | Value |
|---|---|---|---|
| $^{6}$He | GT/$\beta^-$ | $a$ | $-0.3308(30)^{a)}$ |
| $^{32}$Ar | F/$\beta^+$ | $\tilde{a}$ | 0.9989(65) |
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| $^{14}$O/$^{10}$C | F-GT/$\beta^+$ | $P_F/P_{GT}$ | 0.9996(37) |
| $^{26}$Al/$^{30}$P | F-GT/$\beta^+$ | $P_F/P_{GT}$ | 1.0030 (40) |

## Neutron data

| Observable | Value | S factor |
|---|---|---|
| $\tau_n$ (s) | 878.64(59) | 2.2 |
| $\tilde{A}_n$ | $-0.11958(21)$ | 1.2 |
| $\tilde{B}_n$ | 0.9805(30) | |
| $\lambda_{AB}$ | $-1.2686(47)$ | |
| $a_n$ | $-0.10426(82)$ | |
| $\tilde{a}_n$ | $-0.1078(18)$ | |

$S = (\chi^2_{min}/dof)^{1/2}$

**Latest data:**
Perkeo-III, PRL122 (2019): $A_n$
aSPECT, PRC101 (2020): $a_n$
aCORN, PRC103 (2021): $a_n$
UCN$\tau$, PRL127 (2021): $\tau_n$
UCN$\tau$ (2409.05560)*: $\tau_n$

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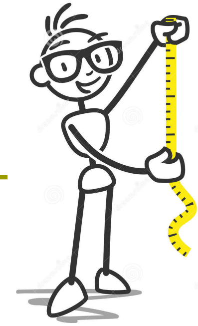

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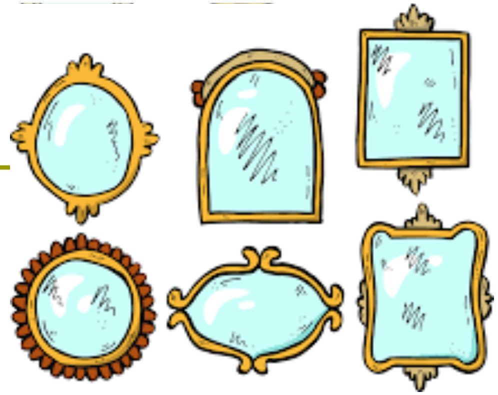
Th: QED + Isospin symmetry breaking corrections

$$\mathcal{F}t_i \equiv ft_i\,(1+\delta'_R)(1+\delta_{NS}-\delta_C)$$

Recent: nuclear structure-dep. corrections (NOW DOMINANT ERROR)
[Seng, Gorchtein, & Ramsey-Musolf, PRD100 (2019)] [Gorchtein, PRL123 (2019)]
[Also: Cirigliano et al. (PRL133, 2024), Gennari et al. (2405.19281), ...]

# What about mirror beta decays?



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*10 p* / *9 n* → *9 p* / *10 n*

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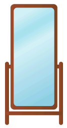

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- Many per-mil level determinations of the Ft values! (Exp + Th)
  [e.g. Severijns et al, PRC78 (2008)]

- $M_{GT}$ / $M_F$ ratio needed: $\mathcal{O} \approx f\left(C_i, \frac{M_{GT}}{M_F}\right) \approx f(C_i, \rho)$

$$\rho = \frac{C_A^{+}}{C_V^{+}}\frac{M_{GT}}{M_F}$$ (1 + corrections)

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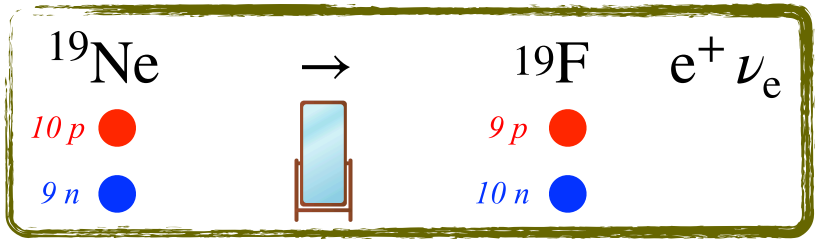


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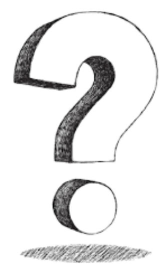
- What about BSM? [Falkowski, MGA, Naviliat-Cuncic, JHEP 04 (2021) 126]



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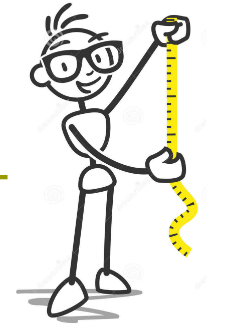

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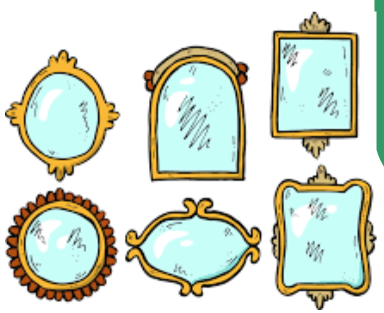
| $\lambda_{AB}$ | $-1.2686(47)$ | |
| $a_n$ | $-0.10426(82)$ | |
| $\tilde{a}_n$ | $-0.1090(41)$ | |

$S = (\chi^2_{min}/dof)^{1/2}$

| Parent | $\mathcal{F}t$ [s] | Correlation |
|---|---|---|
| $^{17}$F | 2292.4(2.7) | $\tilde{A} = 0.960(82)$ |
| $^{19}$Ne | 1721.44(92) | $\tilde{A}_0 = -0.0391(14)$ |
| | | $\tilde{A}_0 = -0.03875(91)$ |
| $^{21}$Na | 4071(4) | $\tilde{a} = 0.5502(60)$ |
| $^{29}$P | 4764.6(7.9) | $\tilde{A} = 0.681(86)$ |
| $^{35}$Ar | 5688.6(7.2) | $\tilde{A} = 0.$ $\tilde{A} = 0.430(22)$ |
| $^{37}$K | 4605.4(8.2) | $\tilde{A} = -0.5707(19)$ |
| | | $\tilde{B} = -0.755(24)$ |



Mirror transitions

**Latest data:**

Fenker et al., PRL120 (2018): $A_{K\text{-}37}$

Combs et al., 2009.13700: $A_{Ne\text{-}19}$

Hayen, PRD103 (2021): $f_A/f_V$ values

Severijns et al., PRC107 (2023)*

...

*it appeared after our work

# Standard Model fit:

$$\mathcal{L}_{\mathrm{Lee-Yang}} = -\bar{p}\gamma^{\mu} n \left( C_V^{+} \bar{e}\gamma_{\mu}\nu_L + \cancel{C_V^{-} \bar{e}\gamma_{\mu}\nu_R} \right) - \bar{p}\gamma^{\mu}\gamma_5 n \left( C_A^{+} \bar{e}\gamma_{\mu}\nu_L - \cancel{C_A^{-} \bar{e}\gamma_{\mu}\nu_R} \right)$$
$$\cancel{- \bar{p} n \left( C_S^{+} \bar{e}\nu_L + C_S^{-} \bar{e}\nu_R \right) - \frac{1}{2}\bar{p}\sigma^{\mu\nu} n \left( C_T^{+} \bar{e}\sigma_{\mu\nu}\nu_L + C_T^{-} \bar{e}\sigma_{\mu\nu}\nu_R \right)}$$
$$\cancel{+ \bar{p}\gamma_5 n \left( C_P^{+} \bar{e}\nu_L - C_P^{-} \bar{e}\nu_R \right)} + \mathrm{h.c.}$$

*[Falkowski, MGA, Naviliat-Cuncic, JHEP 04 (2021) 126*
*+ updates]*

# SM fit

$$\boxed{\begin{pmatrix} v^2 C_V^+ \\ v^2 C_A^+ \\ \rho_{\mathrm{F}} \\ \rho_{\mathrm{Ne}} \\ \rho_{\mathrm{Na}} \\ \rho_{\mathrm{P}} \\ \rho_{\mathrm{Ar}} \\ \rho_{\mathrm{K}} \end{pmatrix} = \begin{pmatrix} 0.98576(22) \\ -1.25754(39) \\ -1.2955(13) \\ 1.60157(75) \\ -0.7127(11) \\ -0.5380(21) \\ -0.2834(25) \\ 0.5787(20) \end{pmatrix}}$$

$$\rightarrow C_V^+ = 0.98576(22)\, G_F/\sqrt{2}$$

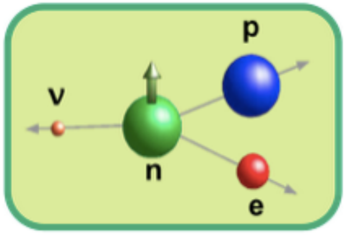
$$\textit{Correlation matrix} = \begin{pmatrix} 1. & -0.27 & 0.36 & -0.63 & 0.41 & 0.26 & 0.33 & -0.23 \\ - & 1. & -0.1 & 0.17 & -0.11 & -0.07 & -0.09 & 0.06 \\ - & - & 1. & -0.23 & 0.15 & 0.09 & 0.12 & -0.08 \\ - & - & - & 1. & -0.26 & -0.17 & -0.21 & 0.15 \\ - & - & - & - & 1. & 0.11 & 0.14 & -0.1 \\ - & - & - & - & - & 1. & 0.09 & -0.06 \\ - & - & - & - & - & - & 1. & -0.08 \\ - & - & - & - & - & - & - & 1. \end{pmatrix}$$

$$\rho \approx -1.2757 \frac{M_{GT}}{M_F}$$

Impressive precision!

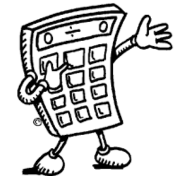
# SM fit

$$\begin{pmatrix} v^2 C_V^+ \\ v^2 C_A^+ \\ \rho_{\mathrm{F}} \\ \rho_{\mathrm{Ne}} \\ \rho_{\mathrm{Na}} \\ \rho_{\mathrm{P}} \\ \rho_{\mathrm{Ar}} \\ \rho_{\mathrm{K}} \end{pmatrix} = \begin{pmatrix} 0.98576(22) \\ -1.25754(39) \\ -1.2955(13) \\ 1.60157(75) \\ -0.7127(11) \\ -0.5380(21) \\ -0.2834(25) \\ 0.5787(20) \end{pmatrix}$$

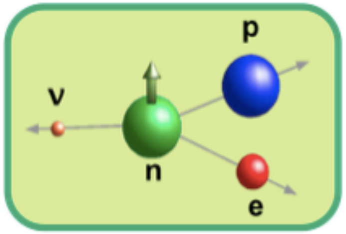



$$\mathscr{L}^{eff}_{n\to pe\nu} = -\, C_V^+ \bar{p}\gamma^\mu n \bar{e}\gamma_\mu \nu_L - C_A^+ \bar{p}\gamma^\mu\gamma_5 n \bar{e}\gamma_\mu \nu_L$$

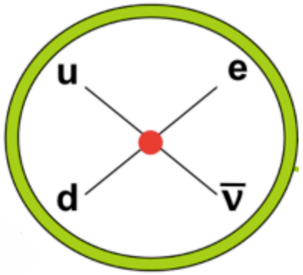
# SM fit



$$\begin{pmatrix} v^2 C_V^+ \\ v^2 C_A^+ \\ \rho_{\mathrm{F}} \\ \rho_{\mathrm{Ne}} \\ \rho_{\mathrm{Na}} \\ \rho_{\mathrm{P}} \\ \rho_{\mathrm{Ar}} \\ \rho_{\mathrm{K}} \end{pmatrix} = \begin{pmatrix} 0.98576(22) \\ -1.25754(39) \\ -1.2955(13) \\ 1.60157(75) \\ -0.\text{[illegible]}127(11) \\ -0.\text{[illegible]}380(21) \\ -\text{[illegible]}34(25) \\ 0.5787(20) \end{pmatrix}$$

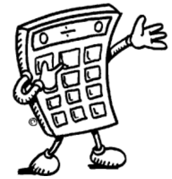



$$\mathscr{L}^{eff}_{n\to pe\nu} = -\, C_V^+ \bar{p}\gamma^\mu n \bar{e}\gamma_\mu \nu_L - C_A^+ \bar{p}\gamma^\mu\gamma_5 n \bar{e}\gamma_\mu \nu_L$$

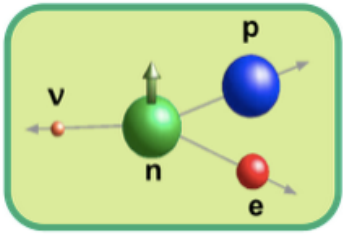



$$\mathscr{L}^{eff}_{d\to ue\nu} = -\frac{V_{ud}}{v^2}\bar{u}\gamma^\mu(1-\gamma_5)d\,\bar{e}\gamma^\mu(1-\gamma_5)\nu_e$$

# SM fit



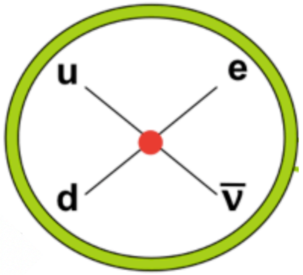
$$\begin{pmatrix} v^2 C_V^+ \\ v^2 C_A^+ \\ \rho_{\mathrm{F}} \\ \rho_{\mathrm{Ne}} \\ \rho_{\mathrm{Na}} \\ \rho_{\mathrm{P}} \\ \rho_{\mathrm{Ar}} \\ \rho_{\mathrm{K}} \end{pmatrix} = \begin{pmatrix} 0.98576(22) \\ -1.25754(39) \\ -1.2955(13) \\ 1.60157(75) \\ -0.\ldots127(11) \\ -0.\ldots380(21) \\ -\ldots534(25) \\ 0.5787(20) \end{pmatrix}$$




$$\mathcal{L}^{eff}_{n\to pe\nu} = -\,C_V^+ \bar{p}\gamma^\mu n\, \bar{e}\gamma_\mu \nu_L - C_A^+ \bar{p}\gamma^\mu \gamma_5 n\, \bar{e}\gamma_\mu \nu_L$$

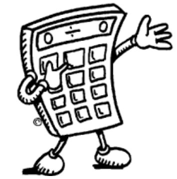
$$C_V^+ = \frac{V_{ud}}{v^2} g_V \sqrt{1+\Delta_R^V}$$

$$C_A^+ = -\frac{V_{ud}}{v^2} g_A \sqrt{1+\Delta_R^A}$$



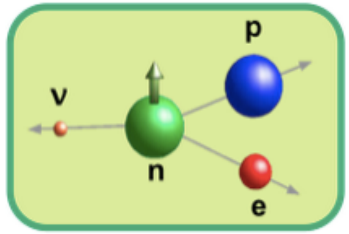

$$\mathcal{L}^{eff}_{d\to ue\nu} = -\frac{V_{ud}}{v^2} \bar{u}\gamma^\mu (1-\gamma_5) d\, \bar{e}\gamma^\mu (1-\gamma_5)\nu_e$$

# SM fit



$$\begin{pmatrix} v^2 C_V^+ \\ v^2 C_A^+ \\ \rho_{\rm F} \\ \rho_{\rm Ne} \\ \rho_{\rm Na} \\ \rho_{\rm P} \\ \rho_{\rm Ar} \\ \rho_{\rm K} \end{pmatrix} = \begin{pmatrix} 0.98576(22) \\ -1.25754(39) \\ -1.2955(13) \\ 1.60157(75) \\ -0\text{[illegible]}127(11) \\ -0\text{[illegible]}380(21) \\ -\text{[illegible]}34(25) \\ 0.5787(20) \end{pmatrix}$$

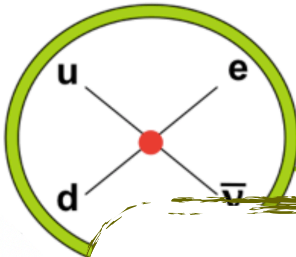
$$V_{ud} = 0.97382(24)$$



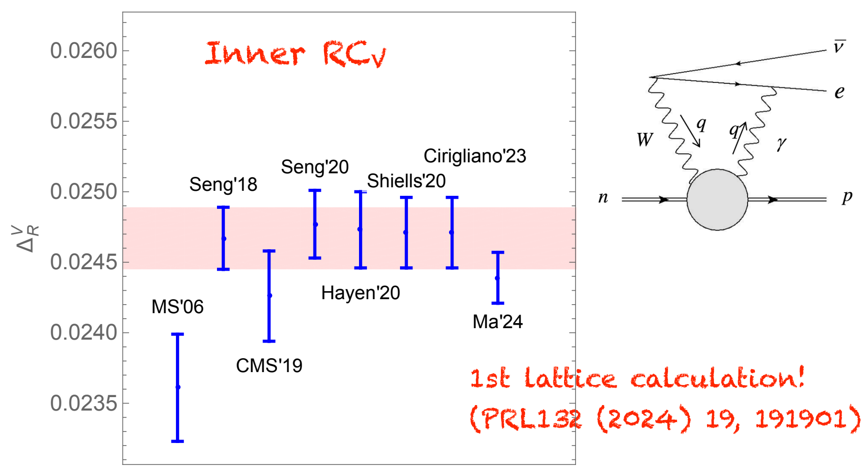

$$\mathscr{L}^{eff}_{n\to pe\nu} = -\,C_V^+ \bar{p}\gamma^\mu n \bar{e}\gamma_\mu \nu_L - C_A^+ \bar{p}\gamma^\mu\gamma_5 n \bar{e}\gamma_\mu \nu_L$$

$$C_V^+ = \frac{V_{ud}}{v^2} g_V \sqrt{1+\Delta_R^V}$$

$$C_A^+ = -\frac{V_{ud}}{v^2} g_A \sqrt{1+\Delta_R^A}$$

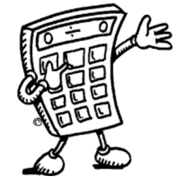



$$\mathscr{L}^{eff}_{d\to ue\nu} = -\frac{V_{ud}}{v^2}\bar{u}\gamma^\mu(1-\gamma_5)d\,\bar{e}\gamma^\mu(1-\gamma_5)\nu_e$$



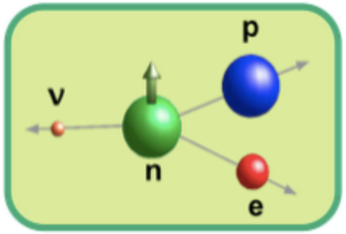

1st lattice calculation!
(PRL132 (2024) 19, 191901)

# SM fit



$$\begin{pmatrix} v^2 C_V^+ \\ v^2 C_A^+ \\ \rho_{\rm F} \\ \rho_{\rm Ne} \\ \rho_{\rm Na} \\ \rho_{\rm P} \\ \rho_{\rm Ar} \\ \rho_{\rm K} \end{pmatrix} = \begin{pmatrix} 0.98576(22) \\ -1.25754(39) \\ -1.2955(13) \\ 1.60157(75) \\ -0.\ldots127(11) \\ -0.\ldots380(21) \\ -\ldots34(25) \\ 0.5787(20) \end{pmatrix}$$

$$V_{ud} = 0.97382(24)$$

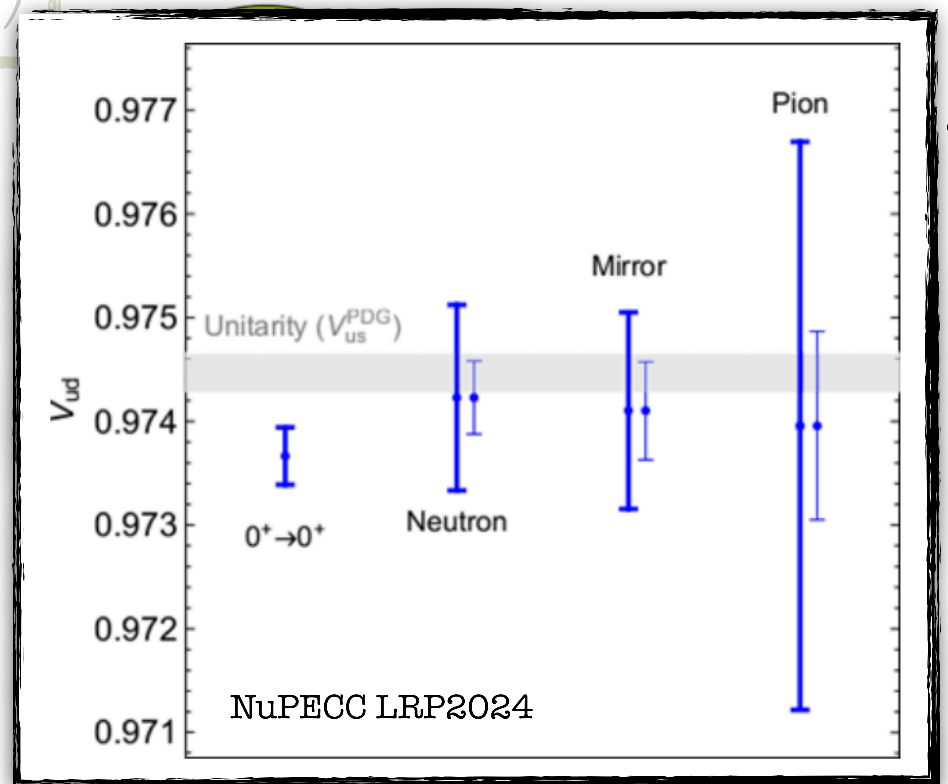



$$\mathscr{L}^{eff}_{n\to pev} = - C_V^+ \bar{p}\gamma^\mu n \bar{e}\gamma_\mu \nu_L - C_A^+ \bar{p}\gamma^\mu\gamma_5 n \bar{e}\gamma_\mu \nu_L$$

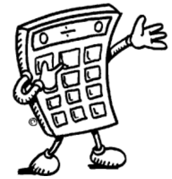
$$C_V^+ = \frac{V_{ud}}{v^2} g_V \sqrt{1+\Delta_R^V}$$

$$C_A^+ = -\frac{V_{ud}}{v^2} g_A \sqrt{1+\Delta_R^A}$$

$\bar{e}\gamma^\mu(1-\gamma_5)\nu_e$



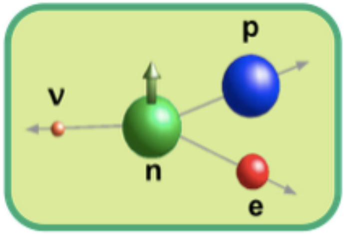
# SM fit



$$\begin{pmatrix} v^2 C_V^+ \\ v^2 C_A^+ \\ \rho_F \\ \rho_{Ne} \\ \rho_{Na} \\ \rho_P \\ \rho_{Ar} \\ \rho_K \end{pmatrix} = \begin{pmatrix} 0.98576(22) \\ -1.25754(39) \\ -1.2955(13) \\ 1.60157(75) \\ -0.\ldots127(11) \\ -0.\ldots380(21) \\ -\ldots34(25) \\ 0.5787(20) \end{pmatrix}$$

$$V_{ud} = 0.97382(24)$$

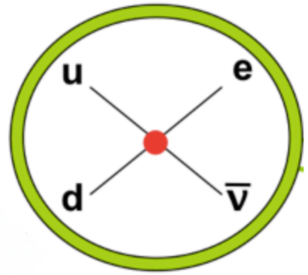
$$g_A^{PDG} = g_A \sqrt{\frac{1+\Delta_R^A}{1+\Delta_R^V}} = 1.27572(42)$$




$$\mathcal{L}^{eff}_{n\to pe\nu} = -\, C_V^+ \bar{p}\gamma^\mu n \bar{e}\gamma_\mu \nu_L - C_A^+ \bar{p}\gamma^\mu \gamma_5 n \bar{e}\gamma_\mu \nu_L$$

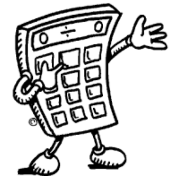
$$C_V^+ = \frac{V_{ud}}{v^2} g_V \sqrt{1+\Delta_R^V}$$

$$C_A^+ = -\frac{V_{ud}}{v^2} g_A \sqrt{1+\Delta_R^A}$$




$$\mathcal{L}^{eff}_{d\to ue\nu} = -\frac{V_{ud}}{v^2} \bar{u}\gamma^\mu (1-\gamma_5) d\, \bar{e}\gamma^\mu (1-\gamma_5)\nu_e$$

# SM fit



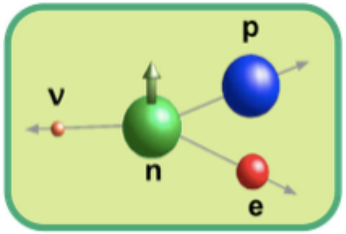
$$\begin{pmatrix} v^2 C_V^+ \\ v^2 C_A^+ \\ \rho_F \\ \rho_{Ne} \\ \rho_{Na} \\ \rho_P \\ \rho_{Ar} \\ \rho_K \end{pmatrix} = \begin{pmatrix} 0.98576(22) \\ -1.25754(39) \\ -1.2955(13) \\ 1.60157(75) \\ -0\cdots127(11) \\ -0\cdots380(21) \\ -\cdots34(25) \\ 0.5787(20) \end{pmatrix}$$

$$V_{ud} = 0.97382(24)$$

$$g_A^{PDG} = g_A \sqrt{\frac{1+\Delta_R^A}{1+\Delta_R^V}} = 1.27572(42)$$

2% correction! $\rightarrow g_A = 1.2507(74)$

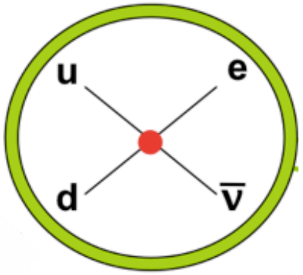
[Cirigliano et al, PRL'22]



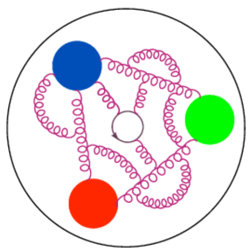

$$\mathcal{L}^{eff}_{n\to pe\nu} = -\, C_V^+ \bar{p}\gamma^\mu n \bar{e}\gamma_\mu \nu_L - C_A^+ \bar{p}\gamma^\mu\gamma_5 n \bar{e}\gamma_\mu \nu_L$$

$$C_V^+ = \frac{V_{ud}}{v^2} g_V \sqrt{1+\Delta_R^V}$$

$$C_A^+ = -\frac{V_{ud}}{v^2} g_A \sqrt{1+\Delta_R^A}$$




$$\mathcal{L}^{eff}_{d\to ue\nu} = -\frac{V_{ud}}{v^2} \bar{u}\gamma^\mu(1-\gamma_5)d\, \bar{e}\gamma^\mu(1-\gamma_5)\nu_e$$



## *Axial charge*

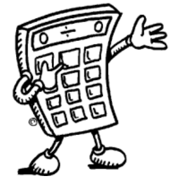
$$\langle p | \bar{u}\gamma_\mu\gamma_5 d | n \rangle$$

$g_A$ = 1.2642(93) CalLat, Nature'18 + update

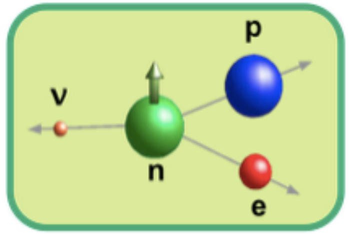
$g_A$ = 1.2460(280) FLAG'21

NEW: $g_A$ = 1.2630(100) FLAG'24

# SM fit



$$\begin{pmatrix} v^2 C_V^+ \\ v^2 C_A^+ \\ \rho_{\rm F} \\ \rho_{\rm Ne} \\ \rho_{\rm Na} \\ \rho_{\rm P} \\ \rho_{\rm Ar} \\ \rho_{\rm K} \end{pmatrix} = \begin{pmatrix} 0.98564(23) \\ -1.25700(44) \\ -1.2958(13) \\ 1.60183(76) \\ -0.7129(11) \\ -0.5383(21) \\ -0.2838(25) \\ 0.5789(20) \end{pmatrix}$$




$$\rho \approx -1.2753 \frac{M_{GT}}{M_F}$$

*[Falkowski, MGA, Naviliat-Cuncic, JHEP 04 (2021) 126*
*+ updates]*

# EFT with $\nu_L$

"Weak EFT" (WEFT)
[e.g. from SMEFT]

$$
\begin{aligned}
\mathcal{L}_{\mathrm{Lee-Yang}} = & -\bar{p}\gamma^{\mu} n \left(C_V^{+} \bar{e}\gamma_{\mu}\nu_L + \cancel{C_V^{-} \bar{e}\gamma_{\mu}\nu_R}\right) - \bar{p}\gamma^{\mu}\gamma_5 n \left(C_A^{+} \bar{e}\gamma_{\mu}\nu_L - \cancel{C_A^{-} \bar{e}\gamma_{\mu}\nu_R}\right) \\
& - \bar{p} n \left(C_S^{+} \bar{e}\nu_L + \cancel{C_S^{-} \bar{e}\nu_R}\right) - \frac{1}{2}\bar{p}\sigma^{\mu\nu} n \left(C_T^{+} \bar{e}\sigma_{\mu\nu}\nu_L + \cancel{C_T^{-} \bar{e}\sigma_{\mu\nu}\nu_R}\right) \\
& + \cancel{\bar{p}\gamma_5 n \left(C_P^{+}\right.} \bar{e}\nu_L - \cancel{C_P^{-} \bar{e}\nu_R}\Big) + \mathrm{h.c.}
\end{aligned}
$$

*BSM x recoil*

Good approximation for the EFT with $\nu_L$ & $\nu_R$ if the couplings with $\nu_R$ are not large

*SM + small + ~~(small)²~~*

# EFT with $\nu_L$

$$\mathcal{L}_{\text{Lee-Yang}} = -\bar{p}\gamma^\mu n \left( C_V^+ \bar{e}\gamma_\mu \nu_L + \cancel{C_V^- \bar{e}\gamma_\mu \nu_R} \right) - \bar{p}\gamma^\mu \gamma_5 n \left( C_A^+ \bar{e}\gamma_\mu \nu_L - \cancel{C_A^- \bar{e}\gamma_\mu \nu_R} \right)$$

$$- \bar{p} n \left( C_S^+ \bar{e}\nu_L + \cancel{C_S^- \bar{e}\nu_R} \right) - \frac{1}{2}\bar{p}\sigma^{\mu\nu} n \left( C_T^+ \bar{e}\sigma_{\mu\nu}\nu_L + \cancel{C_T^- \bar{e}\sigma_{\mu\nu}\nu_R} \right)$$

**S and T affect the angular distributions, the spectrum & the width!!**

$$\frac{d\Gamma(\mathbf{J})}{dE_e d\Omega_e d\Omega_\nu} \sim \xi(E) \left\{ 1 + a\frac{\mathbf{p}_e \cdot \mathbf{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + A\frac{\mathbf{p}_e}{E_e}\frac{\mathbf{J}}{J} + (B + b_B \frac{m_e}{E_e})\frac{\mathbf{p}_\nu}{E_\nu}\frac{\mathbf{J}}{J} \right\}$$

$$b_{(B)} = \# \, C_S^+ + \# \, C_T^+$$

Fierz term [1937]

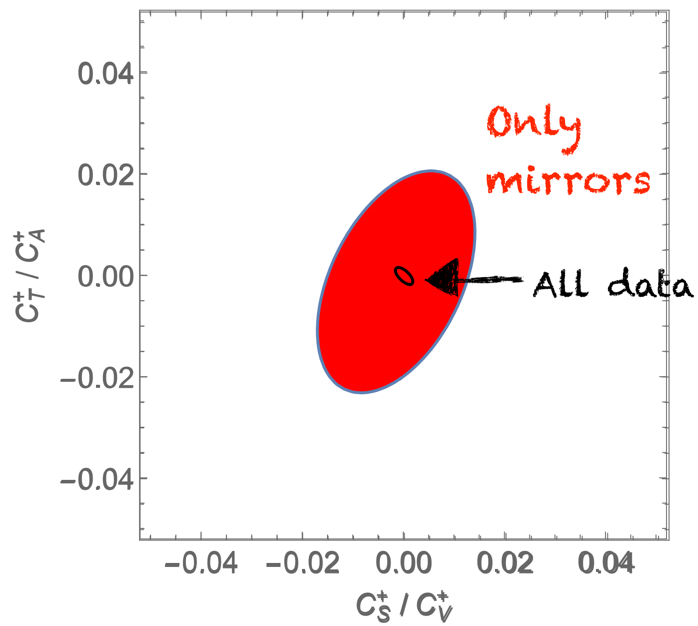
# EFT with $\nu_L$

$$\mathcal{L}_{\text{Lee-Yang}} = -\bar{p}\gamma^\mu n\left(C_V^+\bar{e}\gamma_\mu\nu_L + \cancel{C_V^-\bar{e}\gamma_\mu\nu_R}\right) - \bar{p}\gamma^\mu\gamma_5 n\left(C_A^+\bar{e}\gamma_\mu\nu_L - \cancel{C_A^-\bar{e}\gamma_\mu\nu_R}\right)$$
$$- \bar{p}n\left(C_S^+\bar{e}\nu_L + \cancel{C_S^-\bar{e}\nu_R}\right) - \frac{1}{2}\bar{p}\sigma^{\mu\nu}n\left(C_T^+\bar{e}\sigma_{\mu\nu}\nu_L + \cancel{C_T^-\bar{e}\sigma_{\mu\nu}\nu_R}\right)$$

$$\boxed{v^2\begin{pmatrix} C_V^+ \\ C_A^+ \\ C_S^+ \\ C_T^+ \end{pmatrix} = \begin{pmatrix} 0.98576(41) \\ -1.25740(54) \\ 0.0002(10) \\ 0.0005(12) \end{pmatrix}}$$

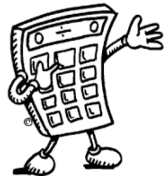
$$\rho = \begin{pmatrix} 1. & -0.63 & 0.81 & 0.71 \\ - & 1. & -0.51 & -0.7 \\ - & - & 1. & 0.65 \\ - & - & - & 1. \end{pmatrix}$$

(+ mixing ratios)

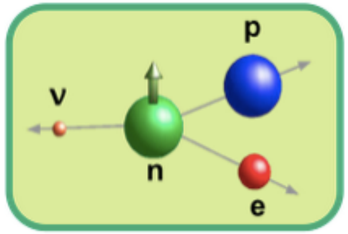



Driven by
Ft(0->0), $\tau_n$, $A_n$!

# EFT with $\nu_L$

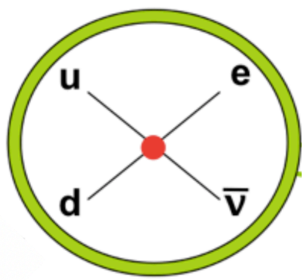


$$v^2 \begin{pmatrix} C_V^+ \\ C_A^+ \\ C_S^+ \\ C_T^+ \end{pmatrix} = \begin{pmatrix} 0.98576(41) \\ -1.25712(55) \\ 0.0002(10) \\ 0.0006(12) \end{pmatrix},$$



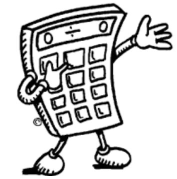

$$\begin{aligned} \mathcal{L} = & \ \bar{p}\, n \ (C_S \bar{e}\nu_e - C_S' \bar{e}\gamma_5\nu_e) \\ & + \bar{p}\gamma^\mu n\,(C_V \bar{e}\gamma_\mu\nu_e - C_V'\bar{e}\gamma_\mu\gamma_5\nu_e) \\ & + \frac{1}{2}\bar{p}\sigma^{\mu\nu} n\,(C_T\bar{e}\sigma_{\mu\nu}\nu_e - C_T'\bar{e}\sigma_{\mu\nu}\gamma_5\nu_e) \\ & - \bar{p}\gamma^\mu\gamma_5 n\,(C_A\bar{e}\gamma_\mu\gamma_5\nu_e - C_A'\bar{e}\gamma_\mu\nu_e) \\ & + \bar{p}\gamma_5 n \ (C_P\bar{e}\gamma_5\nu_e - C_P'\bar{e}\nu_e) + \text{h.c.} \end{aligned}$$

$$C_i^+ = f(\epsilon_i)$$

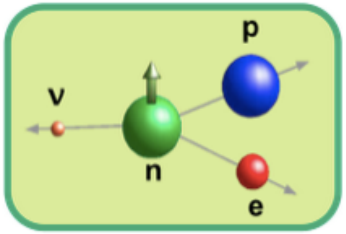



$$\mathcal{L} = -\frac{4G_F V_{ij}}{\sqrt{2}} \left[ \bar{\ell}_L \gamma_\mu \nu \cdot \bar{u}\gamma^\mu d_L + \sum_{\rho\delta\Gamma} \epsilon^\Gamma_{\rho\delta}\, \bar{\ell}_\rho \Gamma \nu \cdot \bar{u}\Gamma d_\delta \right]$$

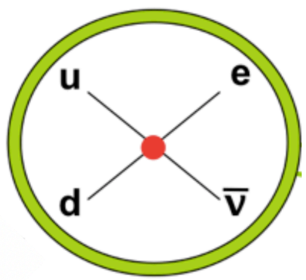
# EFT with $\nu_L$



$$v^2 \begin{pmatrix} C_V^+ \\ C_A^+ \\ C_S^+ \\ C_T^+ \end{pmatrix} = \begin{pmatrix} 0.98576(41) \\ -1.25712(55) \\ 0.0002(10) \\ 0.0006(12) \end{pmatrix},$$




$$\begin{pmatrix} \hat{V}_{ud} \\ \epsilon_R \\ \epsilon_S \\ \epsilon_T \end{pmatrix} = \begin{pmatrix} 0.97382(42) \\ ??? \\ ??? \\ ??? \end{pmatrix}$$




$\hat{V}_{ud}$

$$C_V^+ = \frac{V_{ud}\left(1+\epsilon_L+\epsilon_R\right)}{v^2}\sqrt{1+\Delta_R^V}$$

$$C_A^+ \approx -\frac{\hat{V}_{ud}}{v^2}\sqrt{1+\Delta_R^A}\, g_A\left(1-2\,\epsilon_R\right)$$

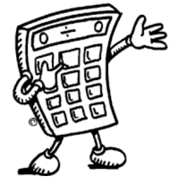
$$C_S^+ \approx \frac{\hat{V}_{ud}}{v^2} g_S \epsilon_S$$

$$C_T^+ \approx \frac{V_{ud}}{v^2} g_T \epsilon_T$$

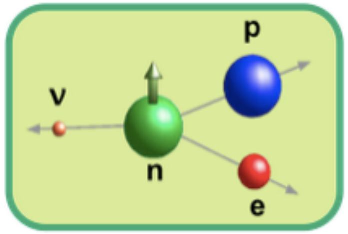
PS: Combining with s→ulν one can access the NP contamination of $\hat{V}_{ud}$ ("CKM unitarity test")

[e.g. Cirigliano, Díaz-Calderón, Falkowski, MGA & Rodríguez-Sánchez, JHEP'22]

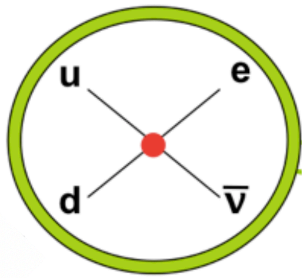
# EFT with $\nu_L$



$$v^2 \begin{pmatrix} C_V^+ \\ C_A^+ \\ C_S^+ \\ C_T^+ \end{pmatrix} = \begin{pmatrix} 0.98576(41) \\ -1.25712(55) \\ 0.0002(10) \\ 0.0006(12) \end{pmatrix},$$




$$\begin{pmatrix} \hat{V}_{ud} \\ \epsilon_R \\ \epsilon_S \\ \epsilon_T \end{pmatrix} = \begin{pmatrix} 0.97382(42) \\ ??? \\ ??? \\ ??? \end{pmatrix}$$




$\hat{V}_{ud}$

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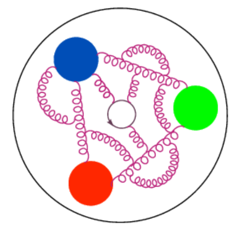
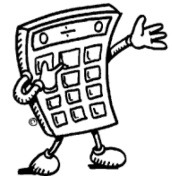


***Nucleon charges***

$\langle p \,|\, \bar{u}\Gamma d \,|\, n\rangle$

# EFT with $\nu_L$



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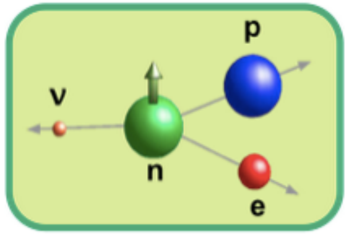
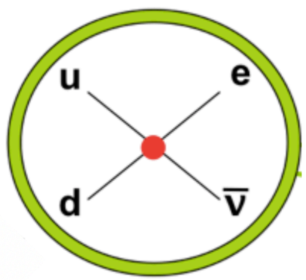



$$\begin{pmatrix} \hat{V}_{ud} \\ \epsilon_R \\ \epsilon_S \\ \epsilon_T \end{pmatrix} = \begin{pmatrix} 0.97382(42) \\ -0.012(12) \\ 0.0002(10) \\ -0.0004(12) \end{pmatrix}$$

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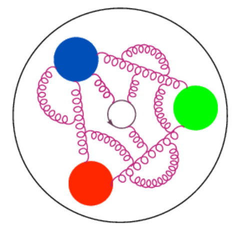


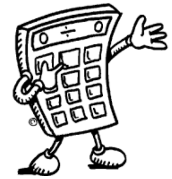
***Nucleon charges***

$\langle p \,|\, \bar{u}\Gamma d \,|\, n \rangle$

FLAG'21

[Falkowski, MGA, Naviliat-Cuncic, JHEP'21; Cirigliano, Díaz-Calderón, Falkowski, MGA & Rodríguez-Sánchez, JHEP'22]

# EFT with $\nu_L$



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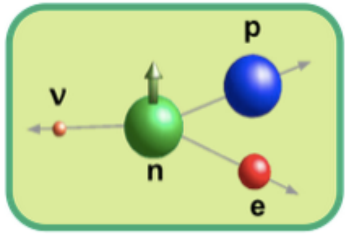


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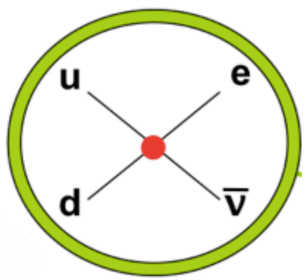


UPDATE with new RC & FLAG'24:

$\varepsilon_R = 0.005(5)$

$\hat{V}_{ud}$

$$C_V^+ = \frac{V_{ud}\left(1+\epsilon_L+\epsilon_R\right)}{v^2}\sqrt{1+\Delta_R^V}$$

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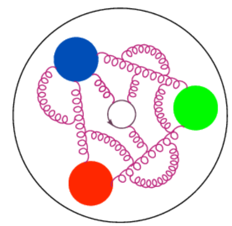


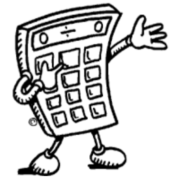
***Nucleon charges***

$$\langle p \,|\, \bar{u}\Gamma d \,|\, n \rangle$$

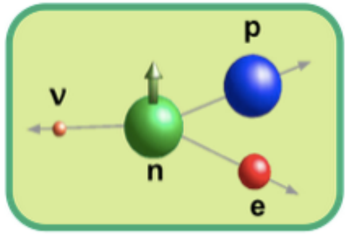
FLAG'21

[Falkowski, MGA, Naviliat-Cuncic, JHEP'21; Cirigliano, Díaz-Calderón, Falkowski, MGA & Rodríguez-Sánchez, JHEP'22]

# EFT with νL



$$v^2 \begin{pmatrix} C_V^+ \\ C_A^+ \\ C_S^+ \\ C_T^+ \end{pmatrix} = \begin{pmatrix} 0.98576(41) \\ -1.25712(55) \\ 0.0002(10) \\ 0.0006(12) \end{pmatrix},$$




$\hat{V}_{ud}$

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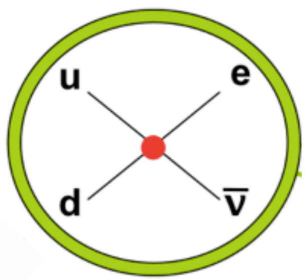
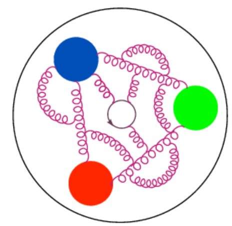
$$\begin{pmatrix} \hat{V}_{ud} \\ \epsilon_R \\ \epsilon_S \\ \epsilon_T \end{pmatrix} = \begin{pmatrix} 0.97382(42) \\ -0.012(12) \\ 0.0002(10) \\ -0.0004(12) \end{pmatrix}$$



***Nucleon charges***

$\langle p\,|\,\bar{u}\Gamma d\,|\,n\rangle$

FLAG'21

UPDATE with new RC & FLAG'24:

$\varepsilon_R$ = 0.005(5)

3.5x improvement in 8 years!

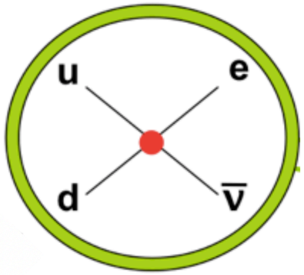
$\varepsilon_R$ = −0.013(17)

[MGA & J. Martín-Camalich'16]

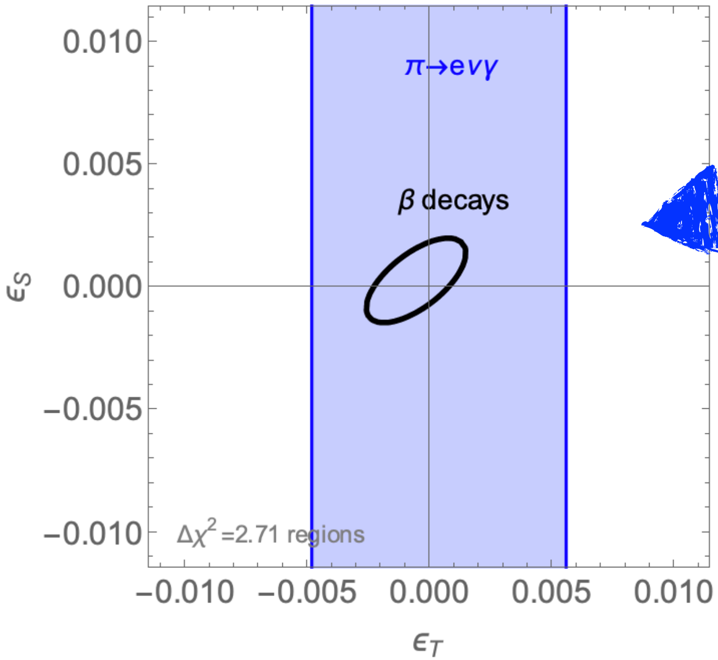
[Falkowski, MGA, Naviliat-Cuncic, JHEP'21; Cirigliano, Díaz-Calderón, Falkowski, MGA & Rodríguez-Sánchez, JHEP'22]

# EFT with $\nu_L$

$$\begin{pmatrix} \hat{V}_{ud} \\ \epsilon_R \\ \epsilon_S \\ \epsilon_T \end{pmatrix} = \begin{pmatrix} 0.97382(42) \\ -0.012(12) \\ 0.0002(10) \\ -0.0004(12) \end{pmatrix}$$

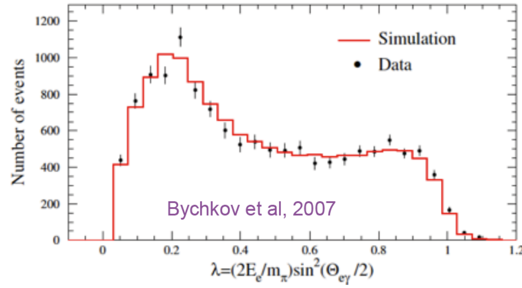



$$\mathcal{L} = -\frac{4G_F V_{ij}}{\sqrt{2}} \Big[ \bar{\ell}_L \gamma_\mu \nu \cdot \bar{u} \gamma^\mu d_L + \sum_{\rho\delta\Gamma} \epsilon^\Gamma_{\rho\delta} \, \bar{\ell}_\rho \Gamma \nu \cdot \bar{u} \Gamma d_\delta \Big]$$



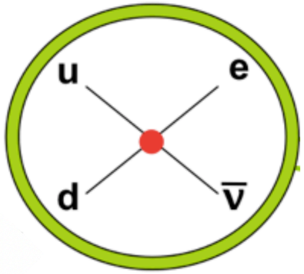

$\pi \to e\nu\gamma$

(PIBETA´2009)



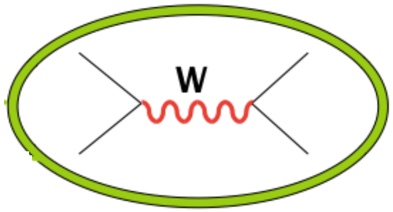
# Going to higher energies…

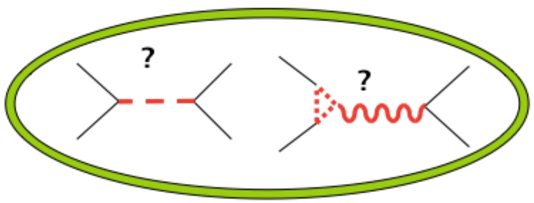
$$\begin{pmatrix} \hat{V}_{ud} \\ \epsilon_R \\ \epsilon_S \\ \epsilon_T \end{pmatrix} = \begin{pmatrix} 0.97382(42) \\ -0.012(12) \\ 0.0002(10) \\ -0.0004(12) \end{pmatrix}$$




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

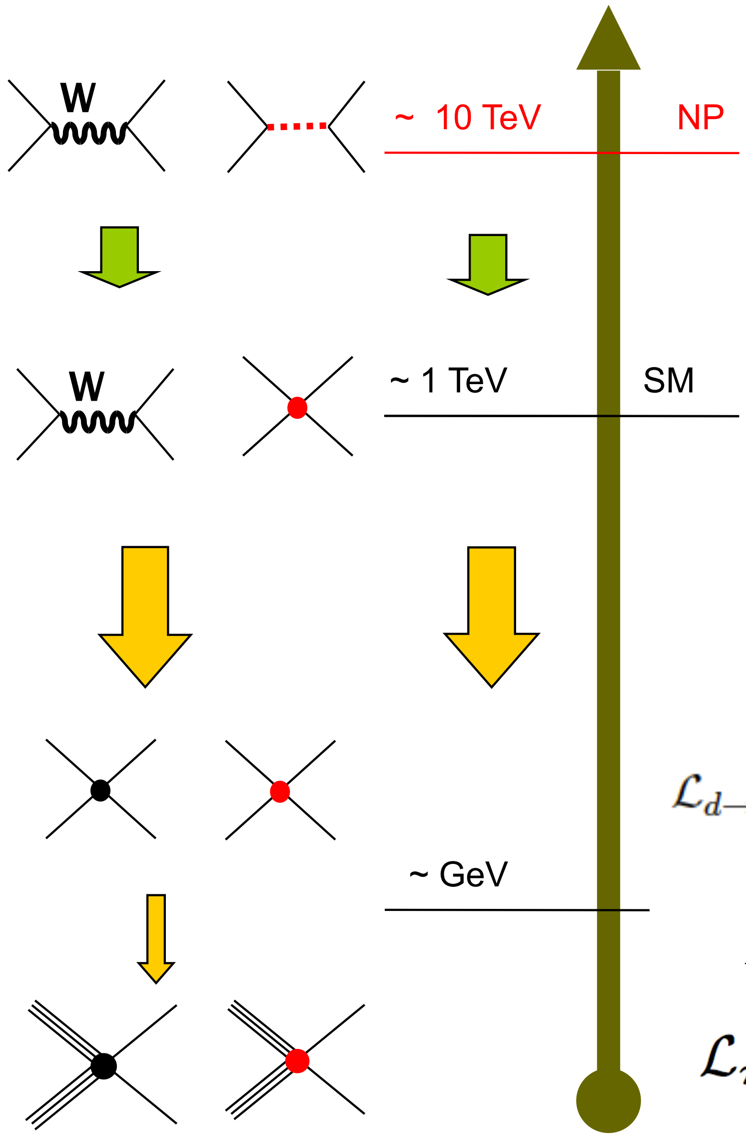
$\epsilon_i = f(??)$




# Matching to the SMEFT

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




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

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

"SMEFT"

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

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

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

# Matching to the SMEFT

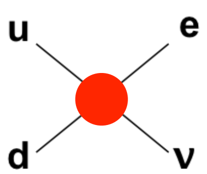
Low-E EFT SMEFT

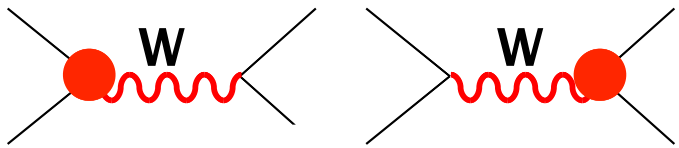
$$\boxed{[\epsilon_i = f(\alpha_j)]_{\mu=M_Z}}$$

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

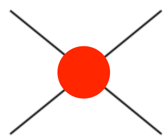
$$\frac{\delta G_F}{G_F} = 2\,[\hat{\alpha}^{(3)}_{\varphi l}]_{11+22} - [\hat{\alpha}^{(1)}_{ll}]_{1221} - 2[\hat{\alpha}^{(3)}_{ll}]_{1122-\frac{1}{2}(1221)}\,,$$
$$V_{1j}\cdot\epsilon_L^{j\ell} = 2\,V_{1j}\left[\hat{\alpha}^{(3)}_{\varphi l}\right]_{\ell\ell} + 2\,[V\hat{\alpha}^{(3)}_{\varphi q}]_{1j} - 2\left[V\hat{\alpha}^{(3)}_{lq}\right]_{\ell\ell 1j}\,,$$
$$V_{1j}\cdot\epsilon_R^{j} = -\,[\hat{\alpha}_{\varphi\varphi}]_{1j}\,,$$
$$V_{1j}\cdot\epsilon_{s_L}^{j\ell} = -\,[\hat{\alpha}_{lq}]^*_{\ell\ell j1}\,,$$
$$V_{1j}\cdot\epsilon_{s_R}^{j\ell} = -\left[V\hat{\alpha}^{\dagger}_{qde}\right]_{\ell\ell 1j}\,,$$
$$V_{1j}\cdot\epsilon_T^{j\ell} = -\,[\hat{\alpha}^t_{lq}]^*_{\ell\ell j1}\,, \qquad \hat{\alpha} = \alpha\frac{v^2}{\Lambda^2}$$

Beta decays sensitive to a few EFT coefficients at tree-level




$$O_{\varphi\varphi} = i(\varphi^T\epsilon D_\mu\varphi)(\overline{u}\gamma^\mu d) + \text{h.c.}$$
$$O^{(3)}_{\varphi q} = i(\varphi^\dagger D^\mu\sigma^a\varphi)(\overline{q}\gamma_\mu\sigma^a q) + \text{h.c.}$$
$$O^{(3)}_{\varphi l} = i(\varphi^\dagger D^\mu\sigma^a\varphi)(\overline{l}\gamma_\mu\sigma^a l) + \text{h.c.}$$
$$O'_{\varphi\varphi} = i(\varphi^T\epsilon D_\mu\varphi)(\overline{\nu}\gamma^\mu e) + \text{h.c.}$$



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

# Matching to the SMEFT

*Low-E EFT* *SMEFT*

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

$$\frac{\delta G_F}{G_F} = 2\,[\hat\alpha^{(3)}_{\varphi l}]_{11+22} - [\hat\alpha^{(1)}_{ll}]_{1221} - 2[\hat\alpha^{(3)}_{ll}]_{1122-\frac{1}{2}(1221)}\,,$$

$$V_{1j}\cdot\epsilon_L^{j\ell} = 2\,V_{1j}\left[\hat\alpha^{(3)}_{\varphi l}\right]_{\ell\ell} + 2\,\left[V\hat\alpha^{(3)}_{\varphi q}\right]_{1j} - 2\,\left[V\hat\alpha^{(3)}_{lq}\right]_{\ell\ell 1j}\,,$$

$$V_{1j}\cdot\epsilon_R^{j} = -\,[\hat\alpha_{\varphi\varphi}]_{1j}\,,$$

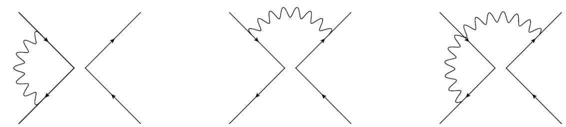
$$V_{1j}\cdot\epsilon_{s_L}^{j\ell} = -\,[\hat\alpha_{lq}]^*_{\ell\ell j1}\,,$$

$$V_{1j}\cdot\epsilon_{s_R}^{j\ell} = -\,\left[V\hat\alpha^{\dagger}_{qde}\right]_{\ell\ell 1j}\,,$$

$$V_{1j}\cdot\epsilon_{T}^{j\ell} = -\,[\hat\alpha^{t}_{lq}]^*_{\ell\ell j1}\,, \qquad \hat\alpha = \alpha\frac{v^2}{\Lambda^2}$$

Beta decays sensitive to a many EFT coefficients at loop-level

[Dawid, Cirigliano & Dekens, JHEP'24]



**Running:**

- 1-loop SMEFT / WEFT RGEs known [Jenkins et al'13, Aebischer et al'17, Jenkins et al.'17, MGA et al.'17 ...]
- Multi-loop QCD RGE effects important for S, P, T operators [MGA, Martin Camalich & Mimouni'17]

$$\begin{pmatrix}\epsilon_L\\ \epsilon_R\\ \epsilon_S\\ \epsilon_P\\ \epsilon_T\end{pmatrix}_{(\mu=2\text{ GeV})} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0\\ 0 & 1.0046 & 0 & 0 & 0\\ 0 & 0 & 1.72 & 2.46\times10^{-6} & -0.0242\\ 0 & 0 & 2.46\times10^{-6} & 1.72 & -0.0242\\ 0 & 0 & -2.17\times10^{-4} & -2.17\times10^{-4} & 0.825\end{pmatrix}\begin{pmatrix}\epsilon_L\\ \epsilon_R\\ \epsilon_S\\ \epsilon_P\\ \epsilon_T\end{pmatrix}_{(\mu=Z)}$$

$$\begin{pmatrix} w_{ledq}\\ w_{\ell equ}\\ w^{(3)}_{\ell equ}\end{pmatrix}_{(\mu=m_Z)} = \begin{pmatrix} 1.19 & 0. & 0.\\ 0. & 1.20 & -0.185\\ 0. & -0.00381 & 0.959\end{pmatrix}\begin{pmatrix} w_{ledq}\\ w_{\ell equ}\\ w^{(3)}_{\ell equ}\end{pmatrix}_{(\mu=1\text{ TeV})}$$

# Matching to the SMEFT

Low-E EFT

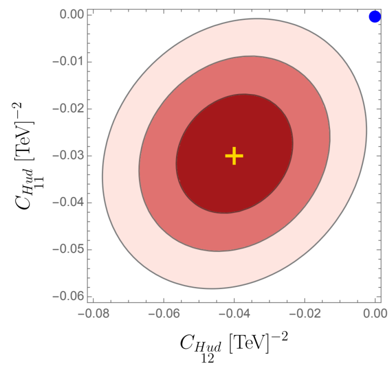
SMEFT

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

- Comparison & combination with EWPO, NC processes, LHC data, etc.

- The CKM unitarity test is particularly interesting (tensions; only effect in the U(3)⁵ limit; very precise)

  [See also Cirigliano, Jenkins & MGA, NPB'10; Crivellin, Hoferichter & Manzari, PRL'21, Breso-Pla, Falkowski, MGA & Monsalvez-Pozo, JHEP'23; Dawid, Cirigliano & Dekens, JHEP'24; ...]




$$Q_{Hud} = i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r) + \text{h.c.}$$

[Cirigliano, Dekens, de Vries & Mereghetti, JHEP'24]

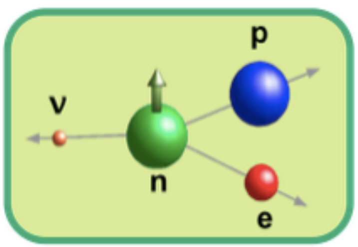
| | $[c^{(3)}_{\ell q}]_{1111}$ |
|---|---|
| CHARM | $-80 \pm 180$ |
| APV | $27 \pm 19$ |
| QWEAK | $7.0 \pm 12$ |
| PVDIS | $-8 \pm 12$ |
| SAMPLE | $-8 \pm 45$ |
| $d_j \to u \ell \nu$ | $\mathbf{0.38 \pm 0.28}$ |
| LEP-2 | $3.5 \pm 2.2$ |

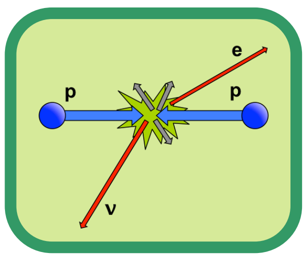
$$\mathcal{O}^{(3)}_{\ell q} = (\bar{\ell}\gamma_\mu \tau^I \ell)(\bar{q}\gamma^\mu \tau^I q)$$

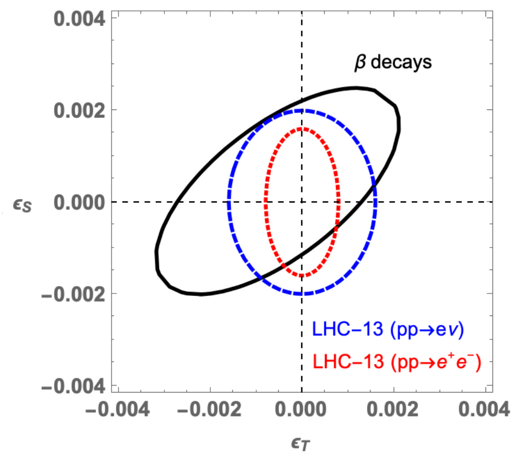
[Falkowski, MGA & Mimouni, JHEP'17]

- Scalar & tensor udeν interactions: β decays vs LHC DY

  [Cirigliano, MGA & Graesser'13]
  [See also de Blas et al'13, Greljo-Marzocca'17, Allwincher et al.'22, ...]



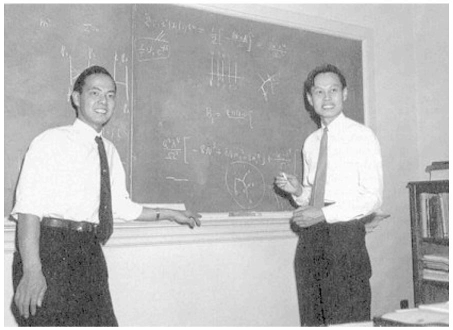

[Falkowski et al, JHEP'21]

[Gupta et al., PRD'18]

[Falkowski, MGA, Naviliat-Cuncic, JHEP 04 (2021) 126]

# EFT with $\nu_L$ & $\nu_R$

$$\mathcal{L}_{\text{Lee-Yang}} = -\bar{p}\gamma^\mu n \left(C_V^+ \bar{e}\gamma_\mu \nu_L + C_V^- \bar{e}\gamma_\mu \nu_R\right) - \bar{p}\gamma^\mu \gamma_5 n \left(C_A^+ \bar{e}\gamma_\mu \nu_L - C_A^- \bar{e}\gamma_\mu \nu_R\right)$$
$$- \bar{p}n \left(C_S^+ \bar{e}\nu_L + C_S^- \bar{e}\nu_R\right) - \frac{1}{2}\bar{p}\sigma^{\mu\nu} n \left(C_T^+ \bar{e}\sigma_{\mu\nu}\nu_L + C_T^- \bar{e}\sigma_{\mu\nu}\nu_R\right)$$



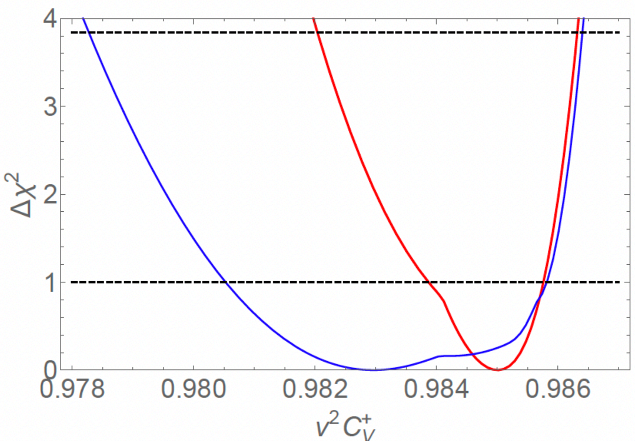
Back to 1956

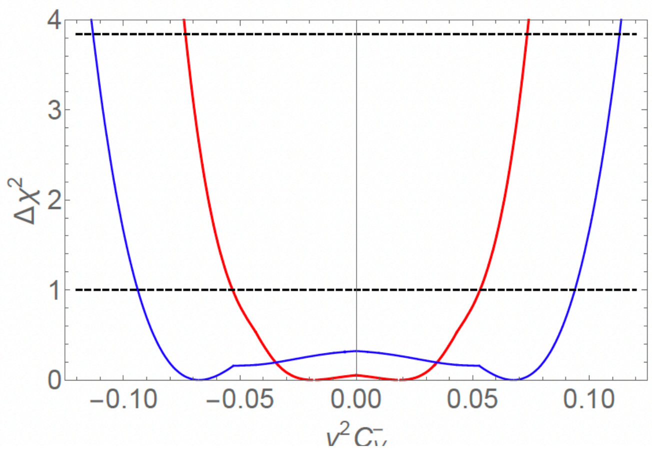
# EFT with $\nu_L$ & $\nu_R$

$$\mathcal{L}_{\text{Lee-Yang}} = -\bar{p}\gamma^{\mu}n\left(C_V^+\bar{e}\gamma_\mu\nu_L + C_V^-\bar{e}\gamma_\mu\nu_R\right) - \bar{p}\gamma^{\mu}\gamma_5 n\left(C_A^+\bar{e}\gamma_\mu\nu_L - C_A^-\bar{e}\gamma_\mu\nu_R\right)$$
$$- \bar{p}n\left(C_S^+\bar{e}\nu_L + C_S^-\bar{e}\nu_R\right) - \frac{1}{2}\bar{p}\sigma^{\mu\nu}n\left(C_T^+\bar{e}\sigma_{\mu\nu}\nu_L + C_T^-\bar{e}\sigma_{\mu\nu}\nu_R\right)$$

$$\boxed{v^2\begin{pmatrix} C_V^+ \\ C_A^+ \\ C_S^+ \\ C_T^+ \end{pmatrix} = \begin{pmatrix} 0.98501^{(+75)}_{(-114)} \\ -1.2544^{(+14)}_{(-11)} \\ -0.0007^{(+29)}_{(-14)} \\ -0.0010^{(+33)}_{(-22)} \end{pmatrix}, \qquad \begin{pmatrix} v^2|C_V^-| < 0.053 \\ v^2|C_A^-| < 0.063 \\ v^2|C_S^-| < 0.050 \\ v^2|C_T^-| \in [0.072, 0.099] \end{pmatrix}}$$

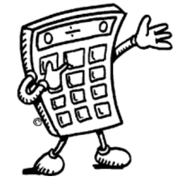
(+ mixing ratios)




Mirrors are very important

# EFT with νL & νR

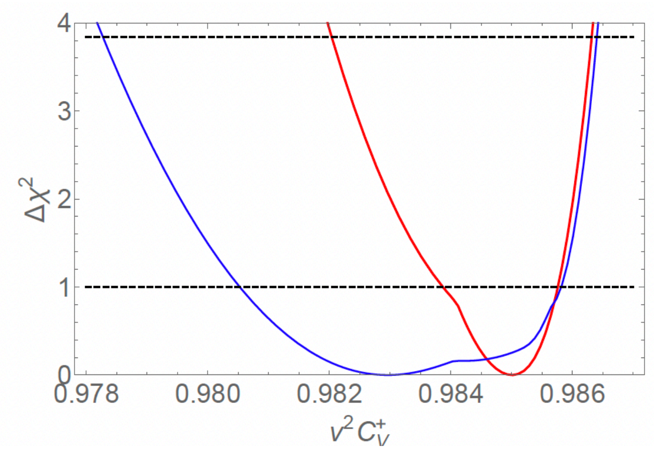


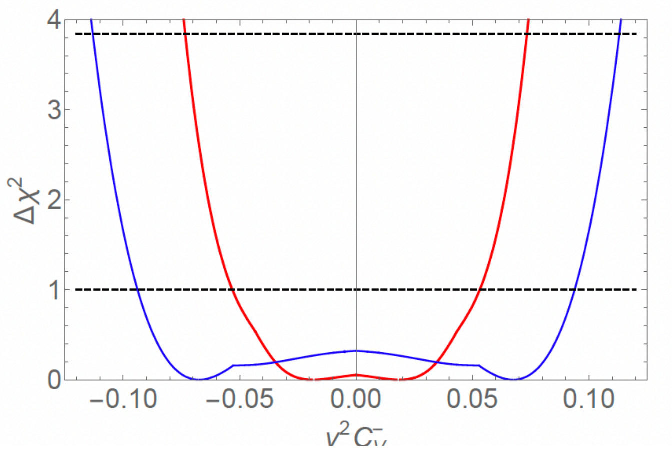
$$\mathcal{L}_{\text{Lee-Yang}} = -\bar{p}\gamma^\mu n\left(C_V^+ \bar{e}\gamma_\mu \nu_L + C_V^- \bar{e}\gamma_\mu \nu_R\right) - \bar{p}\gamma^\mu\gamma_5 n\left(C_A^+ \bar{e}\gamma_\mu \nu_L - C_A^- \bar{e}\gamma_\mu \nu_R\right)$$
$$- \bar{p}n\left(C_S^+ \bar{e}\nu_L + C_S^- \bar{e}\nu_R\right) - \frac{1}{2}\bar{p}\sigma^{\mu\nu} n\left(C_T^+ \bar{e}\sigma_{\mu\nu}\nu_L + C_T^- \bar{e}\sigma_{\mu\nu}\nu_R\right)$$

$$v^2\begin{pmatrix} C_V^+ \\ C_A^+ \\ C_S^+ \\ C_T^+ \end{pmatrix} = \begin{pmatrix} 0.98501^{(+75)}_{(-114)} \\ -1.2544^{(+14)}_{(-11)} \\ -0.0007^{(+29)}_{(-14)} \\ -0.0010^{(+33)}_{(-22)} \end{pmatrix}, \qquad \begin{pmatrix} v^2|C_V^-| < 0.053 \\ v^2|C_A^-| < 0.063 \\ v^2|C_S^-| < 0.050 \\ v^2|C_T^-| \in [0.072, 0.099] \end{pmatrix}$$

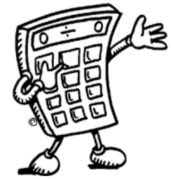
(+ mixing ratios)

3.2 σ → 1.8 σ w/o aSPECT'20



# EFT with νL & νR



$$\mathcal{L}_{\mathrm{Lee-Yang}} = -\bar{p}\gamma^{\mu}n\left(C_V^+\bar{e}\gamma_\mu\nu_L + C_V^-\bar{e}\gamma_\mu\nu_R\right) - \bar{p}\gamma^{\mu}\gamma_5 n\left(C_A^+\bar{e}\gamma_\mu\nu_L - C_A^-\bar{e}\gamma_\mu\nu_R\right) - \bar{p}n\left(C_S^+\bar{e}\nu_L + C_S^-\bar{e}\nu_R\right) - \frac{1}{2}\bar{p}\sigma^{\mu\nu}n\left(C_T^+\bar{e}\sigma_{\mu\nu}\nu_L + C_T^-\bar{e}\sigma_{\mu\nu}\nu_R\right)$$

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$\hat{V}_{ud}, \epsilon_i, \tilde{\epsilon}_i$ (νWEFT)

$$C_V^+ = \frac{V_{ud}}{v^2} g_V \sqrt{1+\Delta_R^V}\,(1+\epsilon_L+\epsilon_R), \qquad C_V^- = \frac{V_{ud}}{v^2} g_V \sqrt{1+\Delta_R^V}\,(\tilde{\epsilon}_L+\tilde{\epsilon}_R),$$

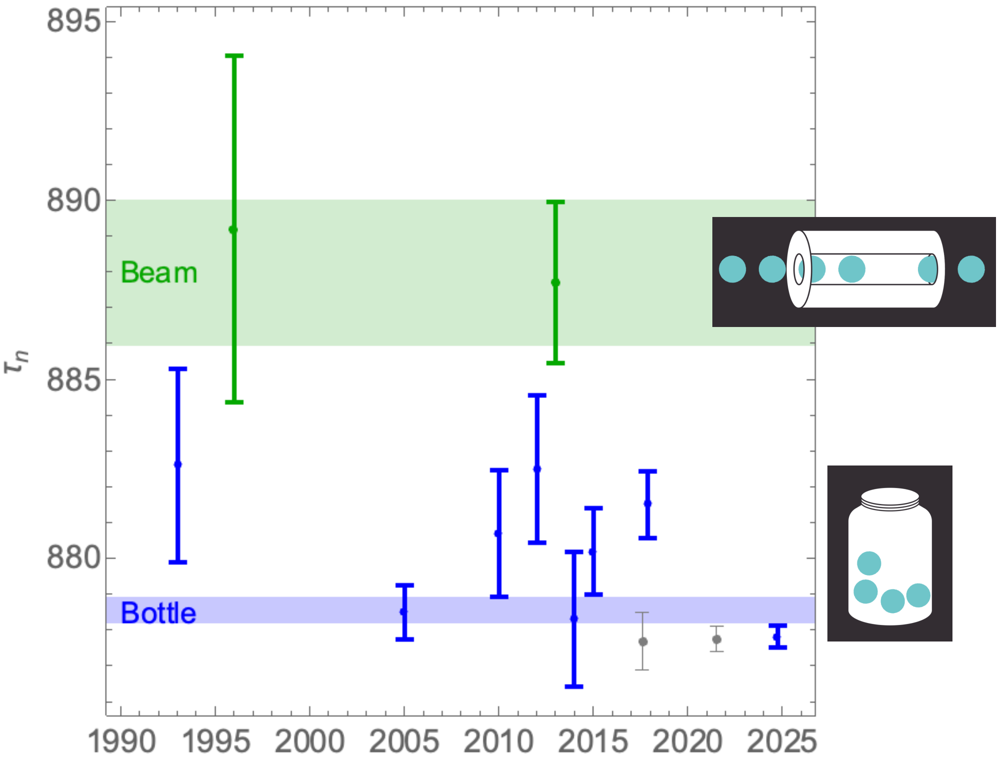
$$C_A^+ = -\frac{V_{ud}}{v^2} g_A \sqrt{1+\Delta_R^A}\,(1+\epsilon_L-\epsilon_R), \qquad C_A^- = \frac{V_{ud}}{v^2} g_A \sqrt{1+\Delta_R^A}\,(\tilde{\epsilon}_L-\tilde{\epsilon}_R),$$

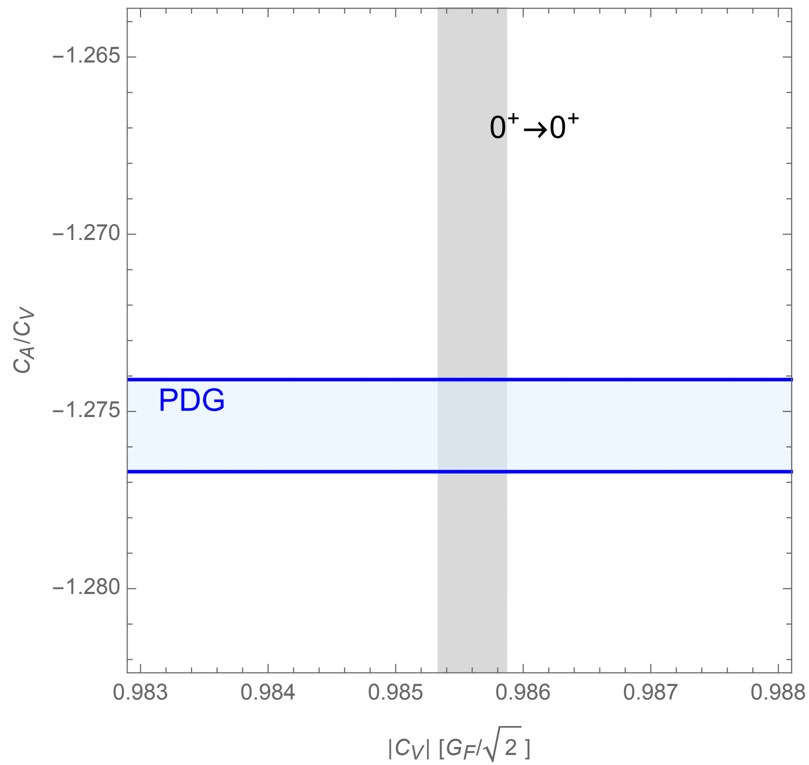
$$C_T^+ = \frac{V_{ud}}{v^2} g_T \epsilon_T, \qquad C_T^- = \frac{V_{ud}}{v^2} g_T \tilde{\epsilon}_T,$$

$$C_S^+ = \frac{V_{ud}}{v^2} g_S \epsilon_S, \qquad C_S^- = \frac{V_{ud}}{v^2} g_S \tilde{\epsilon}_S,$$

νSMEFT / model

# $\tau_n$ "anomaly"



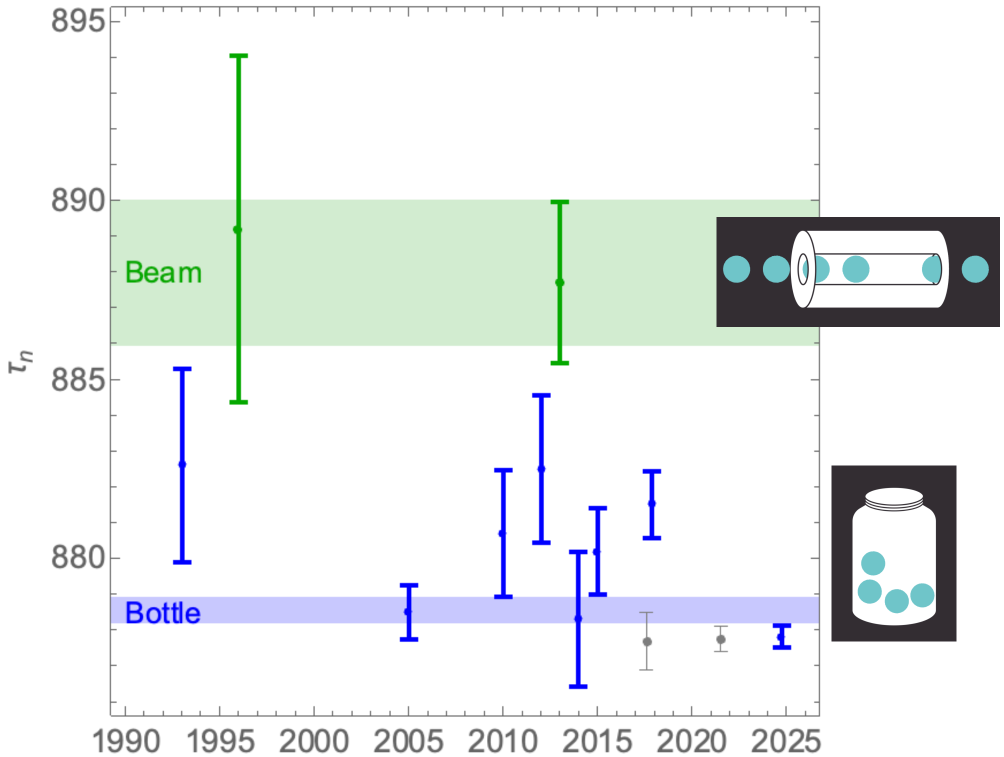



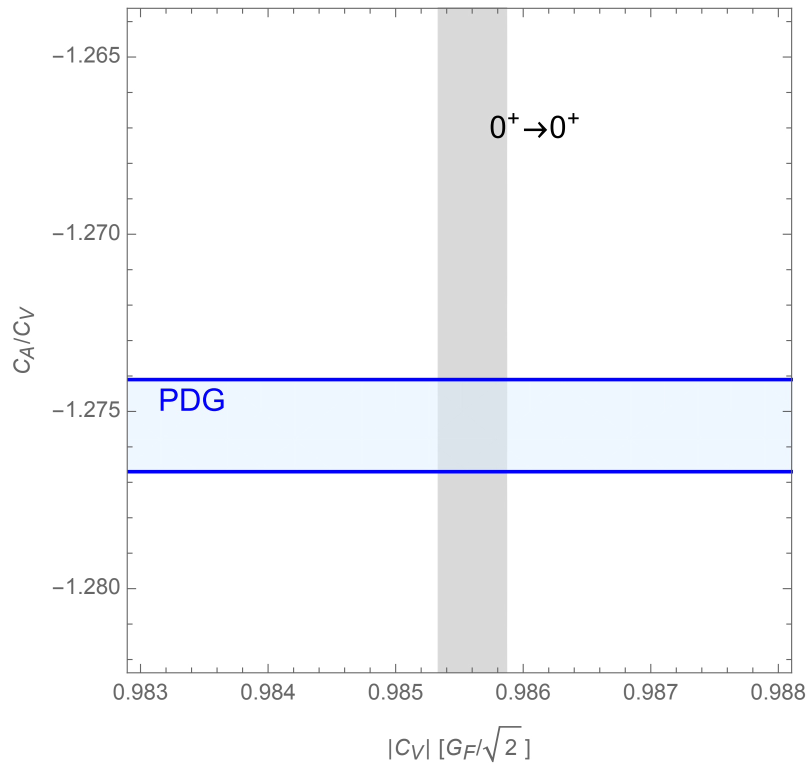

Heavy NP cannot explain the beam vs. bottle tension

PS: 3.7σ between the last 2 bottle points...

$$\tau_n \sim |C_V|^2 \left(1 + 3\left(\frac{C_A}{C_V}\right)^2\right)$$

# $\tau_n$ "anomaly"




Heavy NP cannot explain the beam vs. bottle tension

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What about a dark decay?

[Fornal & Grinstein, PRL120 (2018)]

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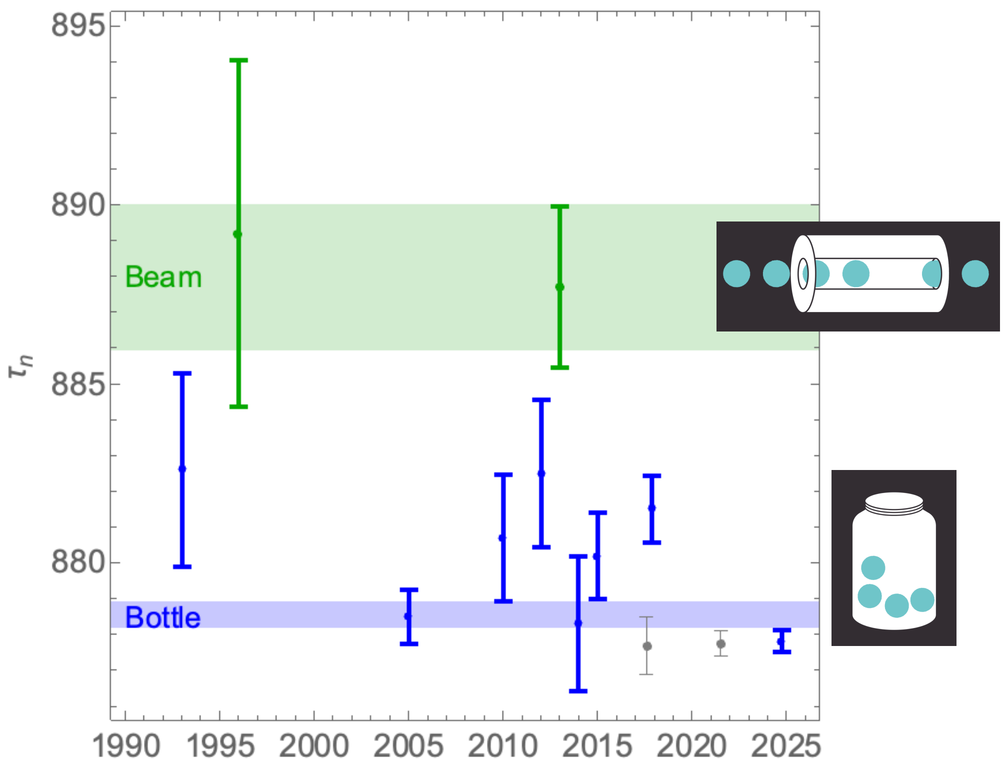


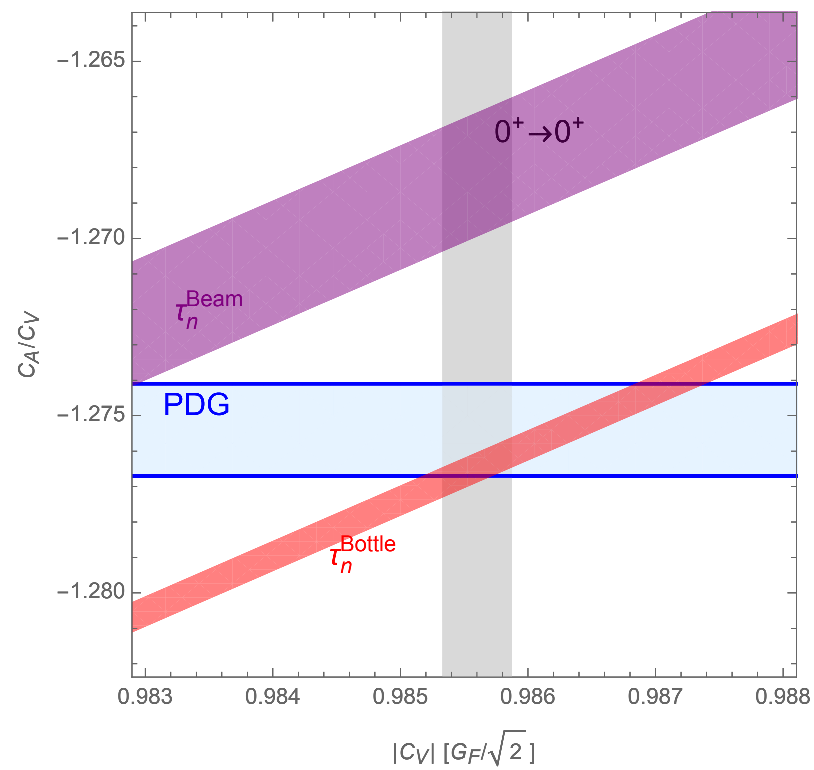


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A dark channel doesn't work either

[Dubbers et al, PLB791 (2019); Czarnecki-Marciano-Sirlin, PRL120 (2018)]

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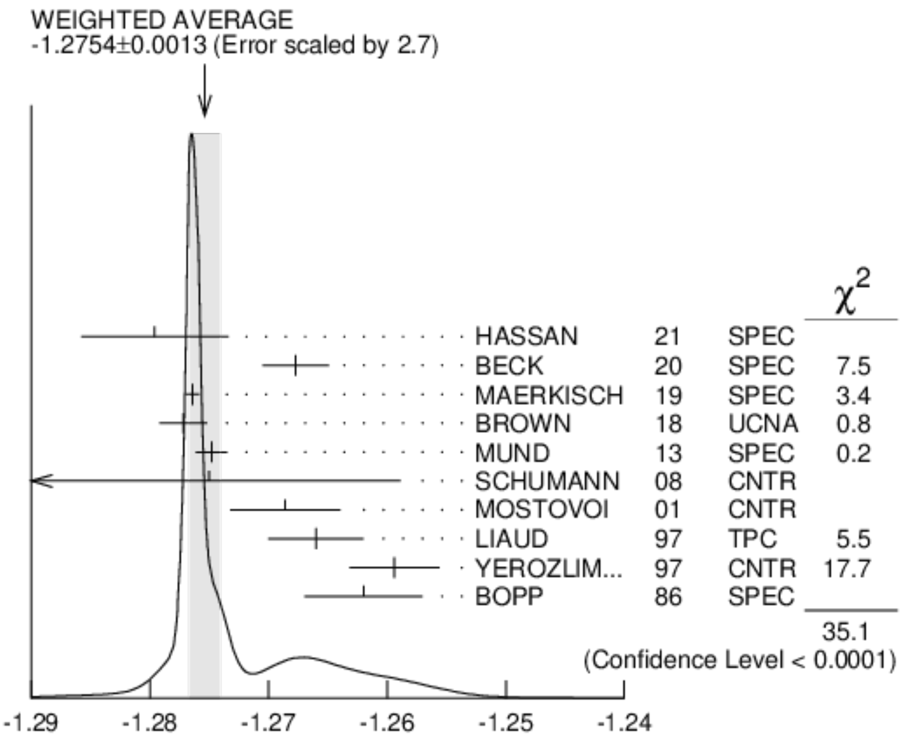


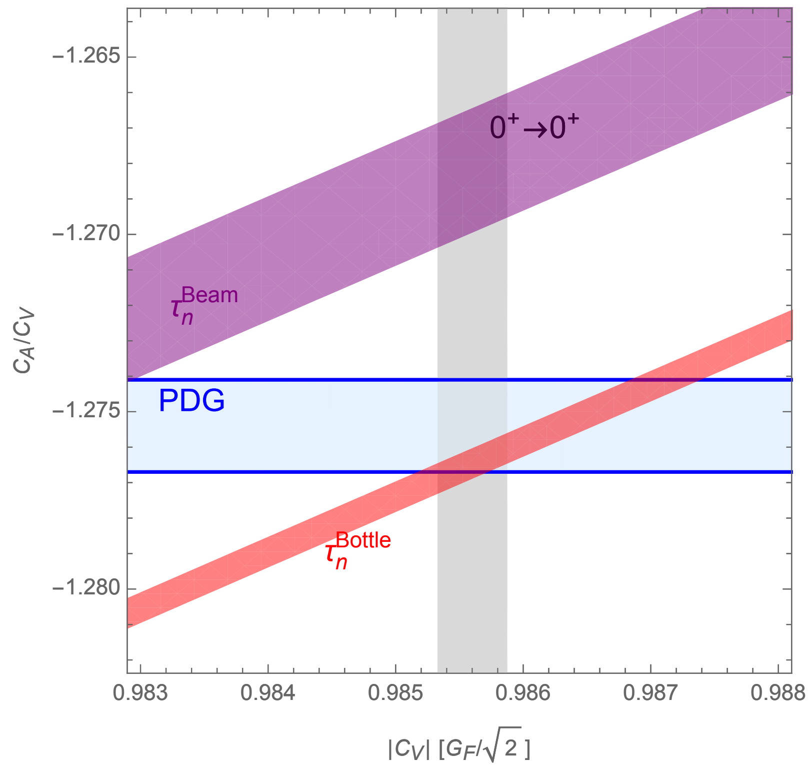


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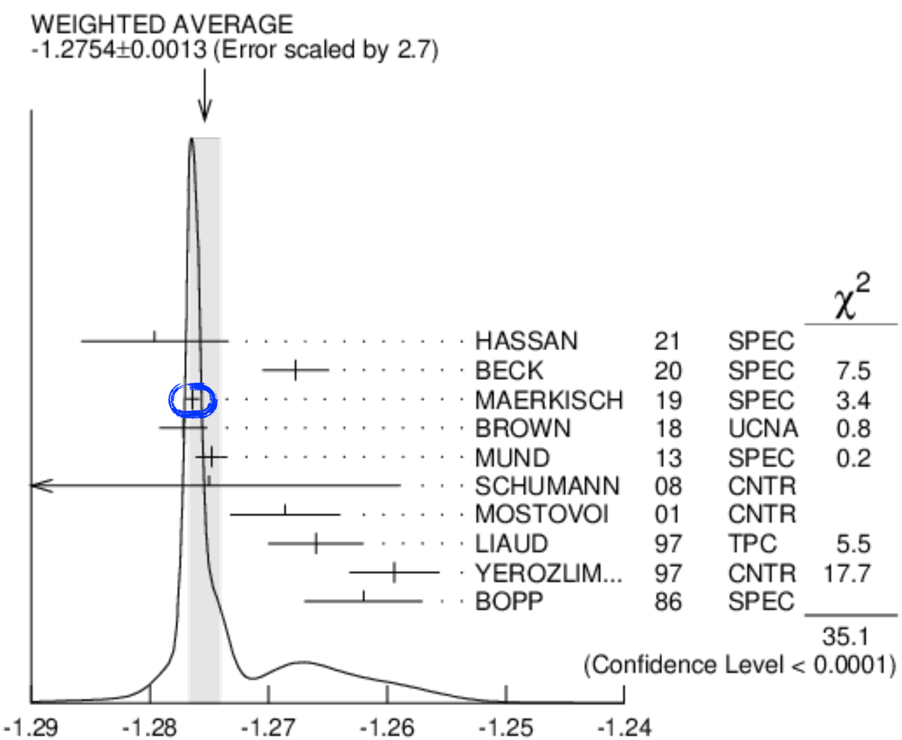


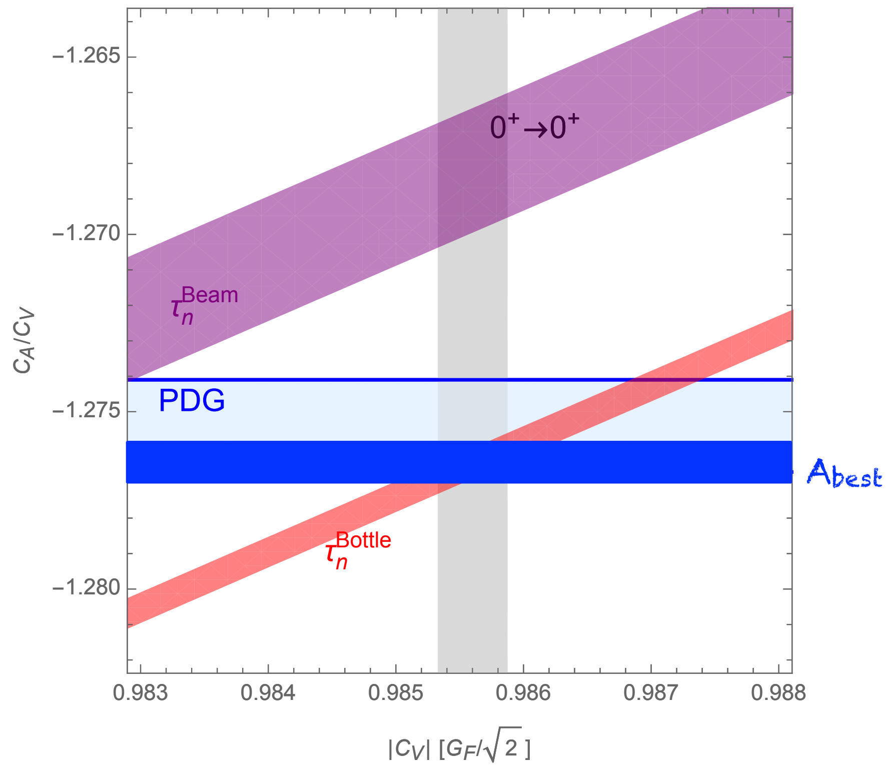


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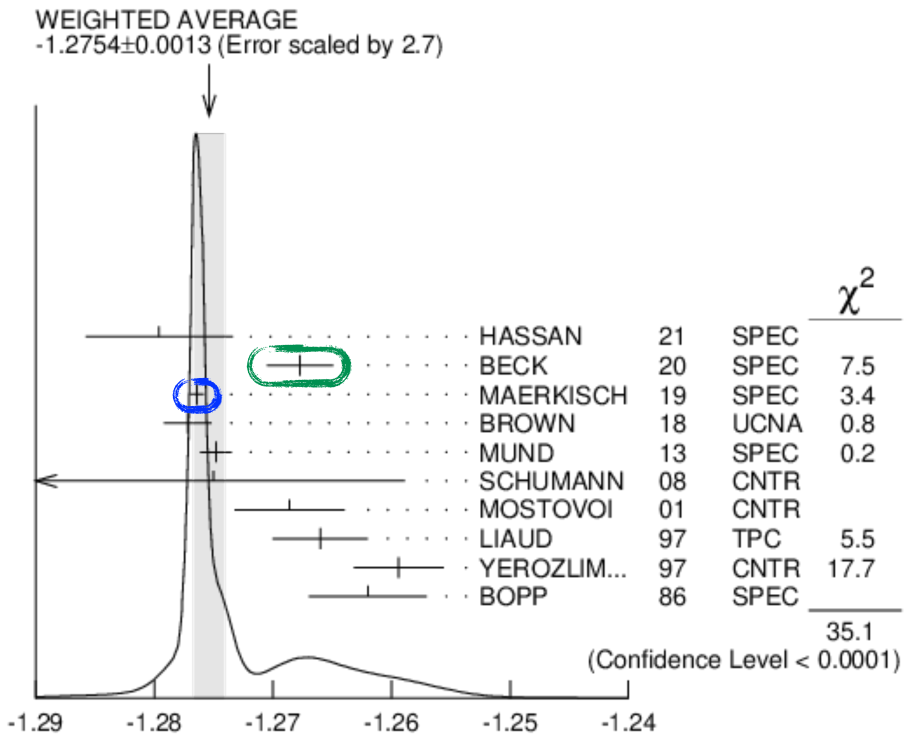


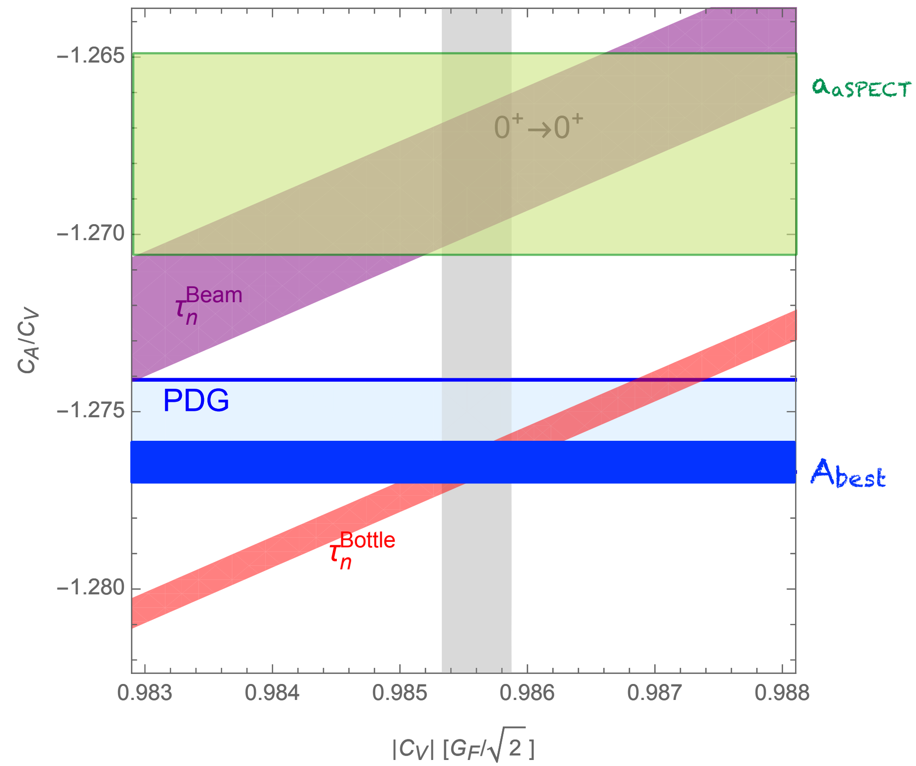


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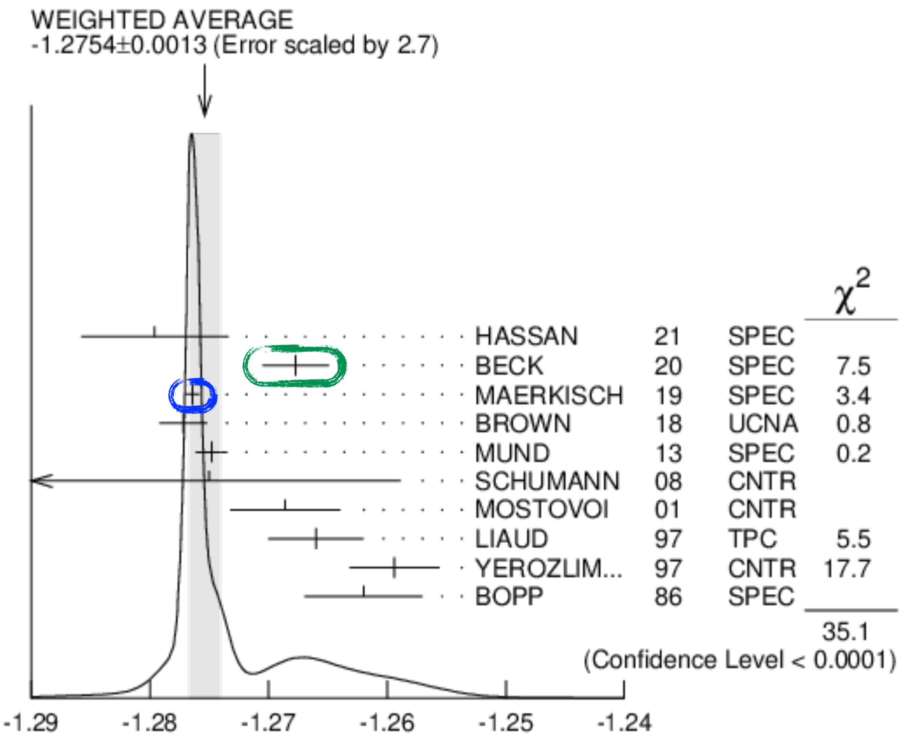
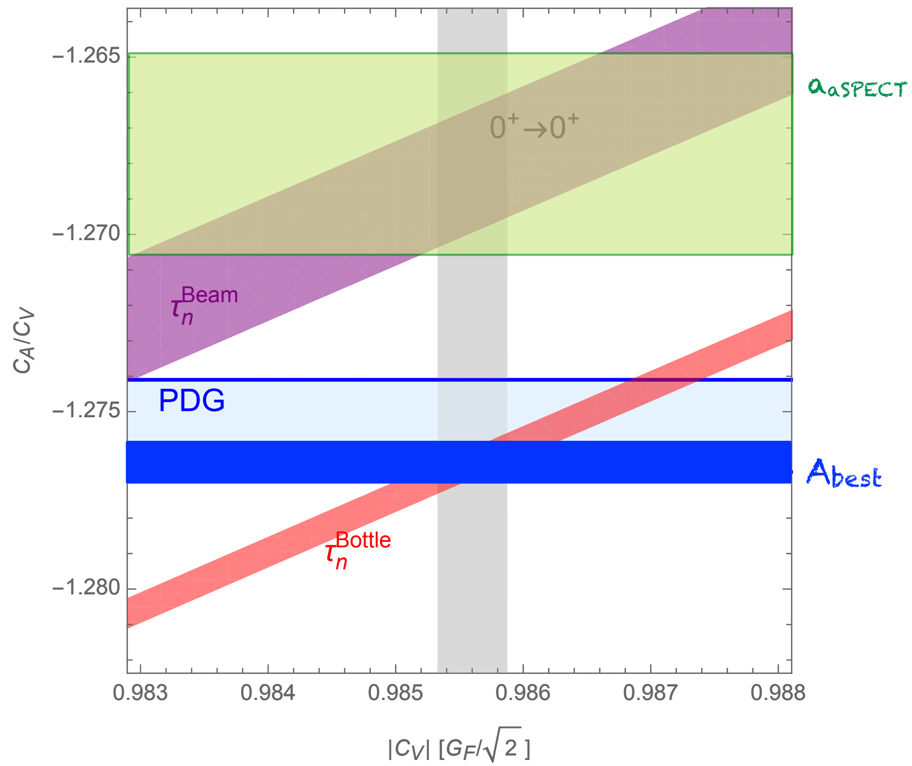



A dark channel doesn't work either
[Dubbers et al, PLB791 (2019);
Czarnecki-Marciano-Sirlin, PRL120 (2018)]

PS: SM + BSM would alter this...

[e.g. Falkowski, MGA, Naviliat-Cuncic, JHEP'21]

$$\tau_n \sim |C_V|^2 \left(1 + 3\left(\frac{C_A}{C_V}\right)^2\right)$$

# And so much more…

- EFT at NLO in recoil [Falkowski, MGA, Palavric & Rodríguez-Sánchez, JHEP'24]
  - First bound on pseudoscalar interactions from β decays:

$$v^2 \begin{pmatrix} C_V^+ \\ C_A^+ \\ C_S^+ \\ C_T^+ \\ C_P^+ \end{pmatrix} = \begin{pmatrix} 0.98540(48) \\ -1.25822(81) \\ -0.0006(12) \\ 0.0009(16) \\ -6.4(4.3) \end{pmatrix} \Rightarrow \begin{pmatrix} \hat{V}_{ud} \\ \epsilon_S \\ \epsilon_T \\ \epsilon_R \\ \epsilon_P \end{pmatrix} = \begin{pmatrix} 0.97351(48) \\ -0.0005(12) \\ 0.0009(17) \\ -0.010(11) \\ -0.018(13) \end{pmatrix}$$

$$C_P = \frac{M_n + M_p}{m_u + m_d}\epsilon_P = 346(9)\epsilon_P$$

[MGA & Camalich, PRL'14]

  - Many more operators appear at NLO in recoil. E.g. weak-magnetism:

$$\mathcal{L}^{(1)} \supset -\frac{C_{WM}^+}{2m_N}\left[\bar{e}\gamma_\mu \nu_L\right]\partial_\nu\left[\bar{p}\sigma^{\mu\nu}n\right] \Rightarrow C_M^+ = 3.5(1.0)/v^2$$

First extraction of nucleon weak-magnetism from data!
[OK with CVC prediction: ~4.6]

- CPV in β decay [Falkowski & Rodríguez-Sánchez, EPJC'22]
  - Interplay with EDMs (huge fine tunning)
  - FSI effects give you access to CP-conserving NP! (ongoing exp. efforts, e.g. MORA)

$$\frac{d\Gamma}{dE_e d\Omega_e d\Omega_\nu} = F(E_e)\left\{1 + \ldots + D\,\frac{\langle \boldsymbol{J}\rangle \cdot (\boldsymbol{p}_e \times \boldsymbol{p}_\nu)}{J E_e E_\nu}\right\}$$

- Operators with $\nu_\mu$ & $\nu_\tau$ (→ interplay with neutrino oscillations) [Falkowski, MGA, Tabrizi, JHEP'19]

- …

# Conclusions

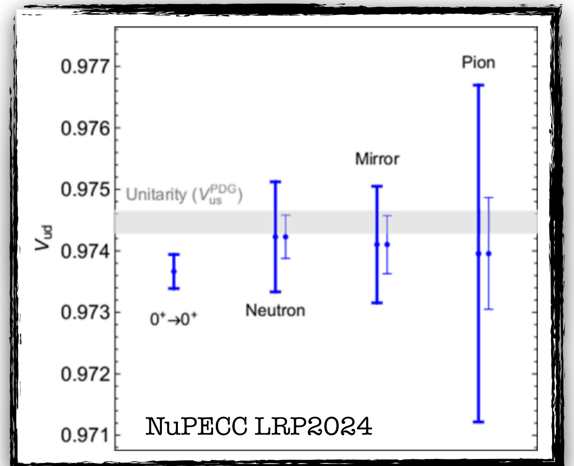
$$\begin{pmatrix} \hat{V}_{ud} \\ \epsilon_R \\ \epsilon_S \\ \epsilon_T \end{pmatrix} = \begin{pmatrix} 0.97377(41) \\ -0.010(13) \\ 0.0001(10) \\ 0.0005(13) \end{pmatrix}$$

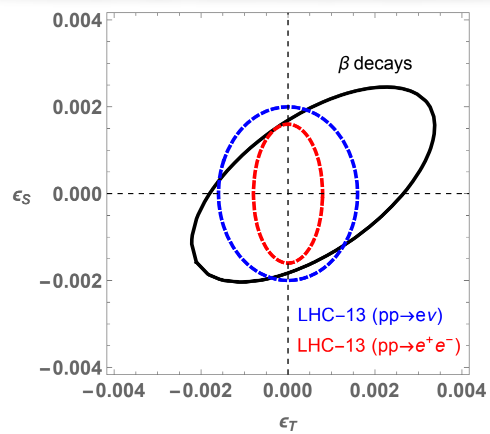
- (Sub) permil-level precision in β decays (exp + th)
  → some internal tensions lead to inflated errors…

- Great laboratory for nuclear, hadronic and particle physics

- Progress in many fronts:

    - Experiments!
    - Lattice QCD;
    - Rad. corrections.
    - Nuclear-structure dependent corrections.
    - Inclusion of new data (mirror decays);
    - WEFT, SMEFT, RH ν, RGEs, recoil effects, LHC, …



# Backup slides

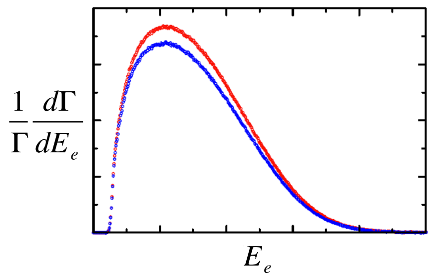
# Probing scalar/tensor interactions

$$\frac{d\Gamma(\mathbf{J})}{dE_e d\Omega_e d\Omega_\nu} \sim \xi(E)\left\{1 + a\frac{\mathbf{p}_e \cdot \mathbf{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + A\frac{\mathbf{p}_e}{E_e}\frac{\mathbf{J}}{J} + (B + b_B\frac{m_e}{E_e})\frac{\mathbf{p}_\nu}{E_\nu}\frac{\mathbf{J}}{J}\right\}$$

$$b_{(B)} = \#\, C_S^+ + \#\, C_T^+$$

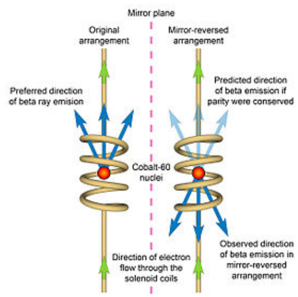
(Fierz term)

✓ Direct effect in the spectrum:
(or in an asymmetry)



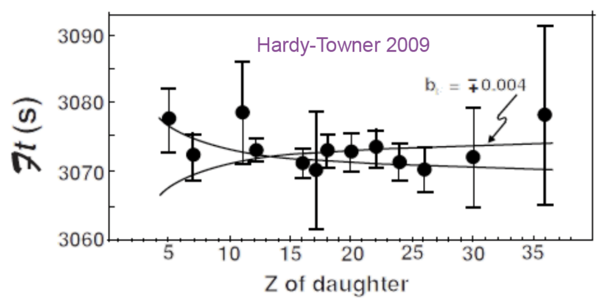

✓ Indirect effect in the asymmetries:

$$\tilde{X} = \frac{X}{1 + b\langle m/E_e\rangle}$$

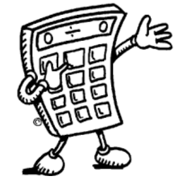



✓ Indirect effect in the Ft-values & neutron lifetime:

$$\delta\tau_n, \delta\mathcal{F}t \sim -b\,\langle\frac{m_e}{E_e}\rangle$$



# EFT with $\nu_L$

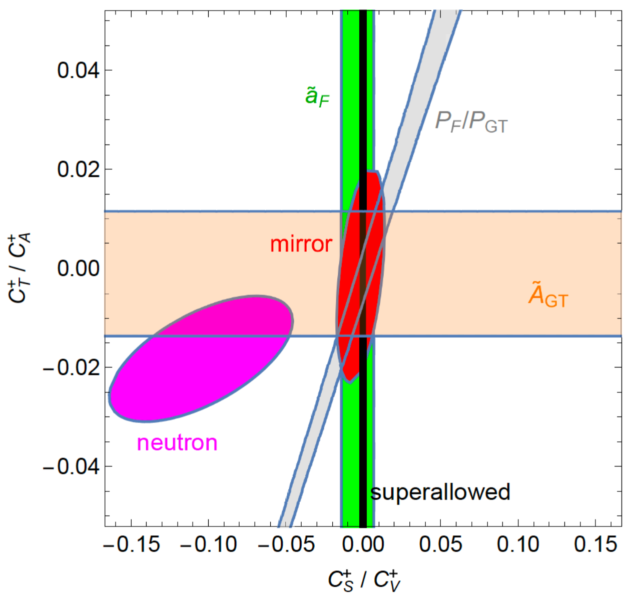


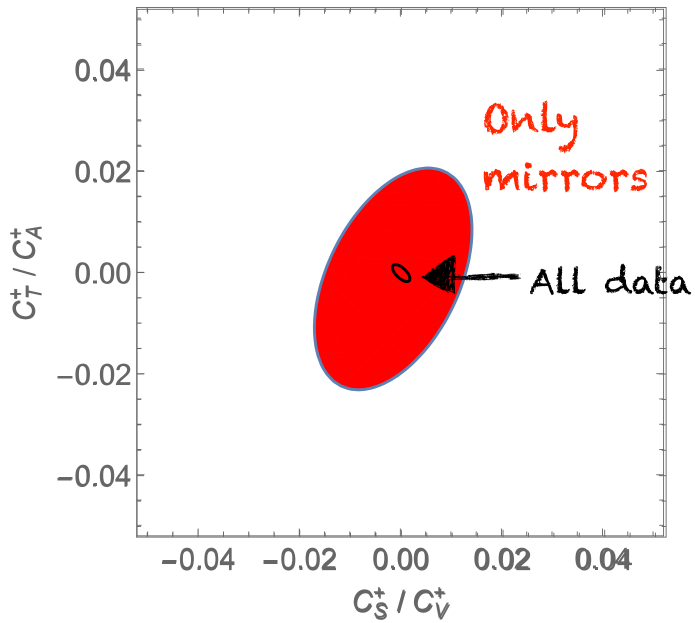
$$\mathcal{L}_{\mathrm{Lee-Yang}} = -\bar p \gamma^\mu n \left(C_V^+ \bar e \gamma_\mu \nu_L + \cancel{C_V^- \bar e \gamma_\mu \nu_R}\right) - \bar p \gamma^\mu \gamma_5 n \left(C_A^+ \bar e \gamma_\mu \nu_L - \cancel{C_A^- \bar e \gamma_\mu \nu_R}\right)$$
$$- \bar p n \left(C_S^+ \bar e \nu_L + \cancel{C_S^- \bar e \nu_R}\right) - \frac{1}{2} \bar p \sigma^{\mu\nu} n \left(C_T^+ \bar e \sigma_{\mu\nu} \nu_L + \cancel{C_T^- \bar e \sigma_{\mu\nu} \nu_R}\right)$$

$$\boxed{v^2 \begin{pmatrix} C_V^+ \\ C_A^+ \\ C_S^+ \\ C_T^+ \end{pmatrix} = \begin{pmatrix} 0.98576(41) \\ -1.25740(54) \\ 0.0002(10) \\ 0.0005(12) \end{pmatrix}}$$

$$\rho = \begin{pmatrix} 1. & -0.63 & 0.81 & 0.71 \\ - & 1. & -0.51 & -0.7 \\ - & - & 1. & 0.65 \\ - & - & - & 1. \end{pmatrix}$$

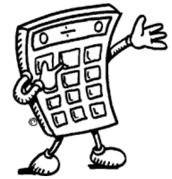
(+ mixing ratios)




Driven by Ft(0->0), $\tau_n$, $A_n$!

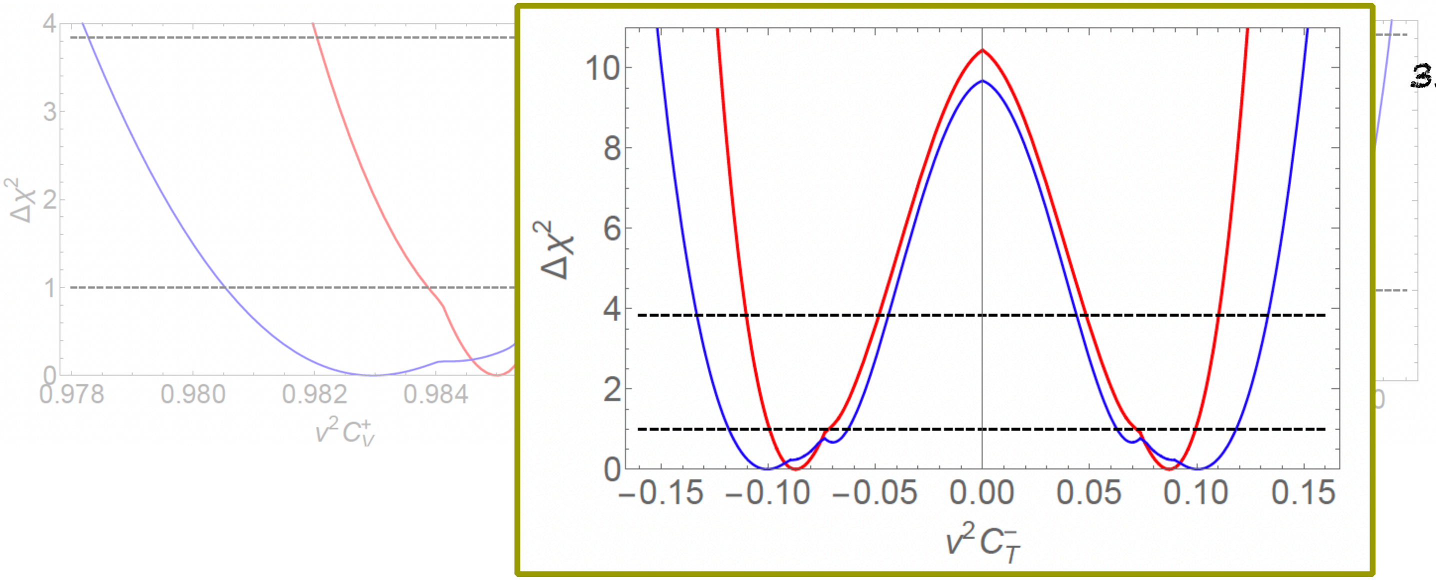
# EFT with νL & νR



$$\mathcal{L}_{\text{Lee-Yang}} = -\bar{p}\gamma^\mu n\left(C_V^+\bar{e}\gamma_\mu\nu_L + C_V^-\bar{e}\gamma_\mu\nu_R\right) - \bar{p}\gamma^\mu\gamma_5 n\left(C_A^+\bar{e}\gamma_\mu\nu_L - C_A^-\bar{e}\gamma_\mu\nu_R\right)$$
$$- \bar{p}n\left(C_S^+\bar{e}\nu_L + C_S^-\bar{e}\nu_R\right) - \frac{1}{2}\bar{p}\sigma^{\mu\nu}n\left(C_T^+\bar{e}\sigma_{\mu\nu}\nu_L + C_T^-\bar{e}\sigma_{\mu\nu}\nu_R\right)$$

$$\boxed{v^2\begin{pmatrix} C_V^+ \\ C_A^+ \\ C_S^+ \\ C_T^+ \end{pmatrix} = \begin{pmatrix} 0.98501^{(+75)}_{(-114)} \\ -1.2544^{(+14)}_{(-11)} \\ -0.0007^{(+29)}_{(-14)} \\ -0.0010^{(+33)}_{(-22)} \end{pmatrix}, \quad \begin{pmatrix} v^2|C_V^-| < 0.053 \\ v^2|C_A^-| < 0.063 \\ v^2|C_S^-| < 0.050 \\ v^2|C_T^-| \in [0.072, 0.099] \end{pmatrix}}$$

(+ mixing ratios)

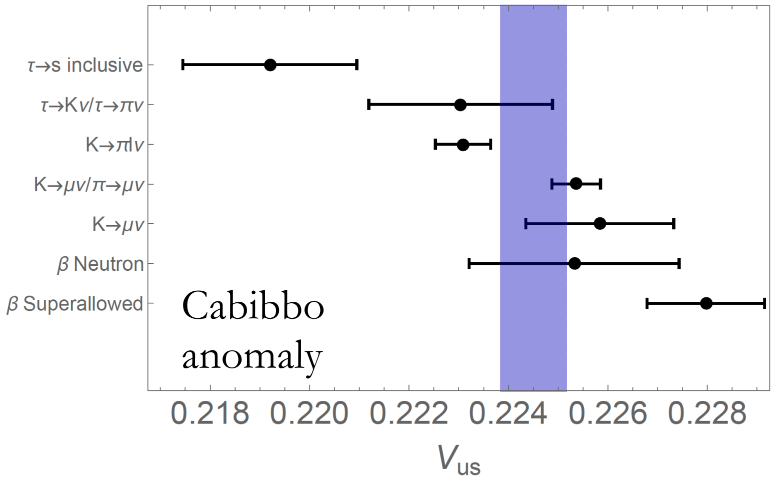



3.2 σ

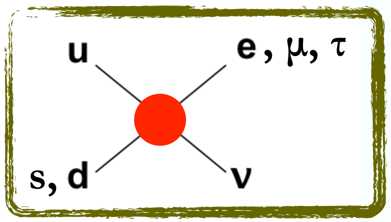
# Beta decays & flavor

[Cirigliano, Díaz-Calderón, Falkowski, MGA & Rodríguez-Sánchez, JHEP04 (2022) 152]

- SM limit:




- BSM turned on => These processes do not probe the same quantity:
  - Beta decays → udeν
  - Pion decays → udeν & udμν
  - Kaon decays → useν & usμν
  - Tau decays → udτν & usτν




$$\mathscr{L}_{\rm WEFT} \supset -\sum_{D=d,s}\sum_{\ell=e,\mu,\tau}\frac{V_{uD}}{v^2}\Big\{\left(1+\epsilon_L^{D\ell}\right)\ \bar{\ell}\gamma_\mu P_L\nu_\ell\cdot\bar{u}\gamma^\mu(1-\gamma_5)D + \epsilon_R^{D}\,\bar{\ell}\gamma_\mu P_L\nu_\ell\cdot\bar{u}\gamma^\mu(1+\gamma_5)D + \epsilon_T^{D\ell}\frac{1}{4}\bar{\ell}\sigma_{\mu\nu}P_L\nu_\ell\cdot\bar{u}\sigma^{\mu\nu}(1-\gamma_5)D + \epsilon_S^{D\ell}\,\bar{\ell}P_L\nu_\ell\cdot\bar{u}D - \epsilon_P^{D\ell}\,\bar{\ell}P_L\nu_\ell\cdot\bar{u}\gamma_5 D\Big\} + \text{hc}$$

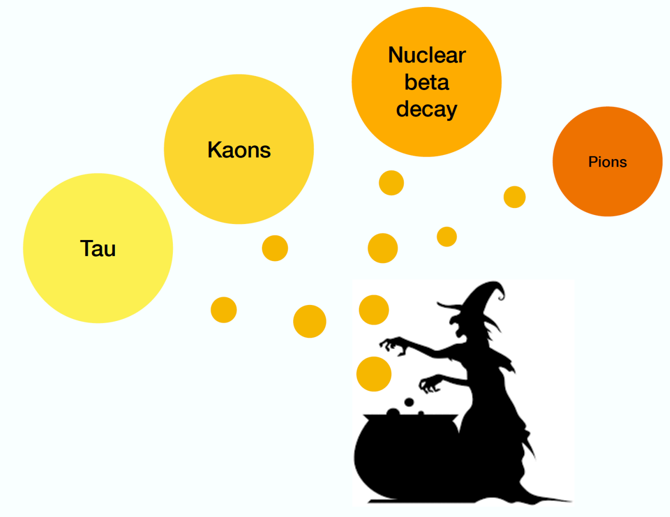
- Cross-correlations due to CKM, FFs, and lepton-universal RH currents (SMEFT)

* **NEW**: Lattice calculation! ETMC, PRL132 (2024): $R_{us}^{(\tau)}/V_{us}^2 = 3.407(22)_{th} \xrightarrow{\text{exp}} V_{us} = 0.2189(7)_{th}(18)_{exp}$
in perfect agreement with the OPE-based extraction plotted above: $V_{us} = 0.2184(11)_{th}(18)_{exp}$

$$R_{us}^{(\tau)} = \frac{\Gamma(\tau\mapsto X_{us}\nu_\tau)}{\Gamma(\tau\mapsto e\bar{\nu}_e\nu_\tau)}$$

# Beta decays & flavor

*[Cirigliano, Díaz-Calderón, Falkowski, MGA & Rodríguez-Sánchez, JHEP04 (2022) 152]*




$$\mathscr{L}_{\mathrm{WEFT}} \supset -\sum_{D=d,s}\sum_{\ell=e,\mu,\tau}\frac{V_{uD}}{v^2}\Big\{ \left(1+\epsilon_L^{D\ell}\right)\bar{\ell}\gamma_\mu P_L \nu_\ell \cdot \bar{u}\gamma^\mu(1-\gamma_5)D + \epsilon_R^{D}\,\bar{\ell}\gamma_\mu P_L\nu_\ell\cdot\bar{u}\gamma^\mu(1+\gamma_5)D + \epsilon_T^{D\ell}\frac{1}{4}\bar{\ell}\sigma_{\mu\nu}P_L\nu_\ell\cdot\bar{u}\sigma^{\mu\nu}(1-\gamma_5)D + \epsilon_S^{D\ell}\,\bar{\ell}P_L\nu_\ell\cdot\bar{u}D - \epsilon_P^{D\ell}\,\bar{\ell}P_L\nu_\ell\cdot\bar{u}\gamma_5 D\Big\} + \mathrm{hc}$$

$$\begin{pmatrix} \hat{V}_{us} \equiv V_{us}\left(1+\epsilon_L^{se}+\epsilon_R^{s}\right) \\ \epsilon_L^{dse} \equiv \epsilon_L^{de} + \frac{\hat{V}_{us}^2}{1-\hat{V}_{us}^2}\epsilon_L^{se} \\ \epsilon_R^{d} \\ \epsilon_S^{de} \\ \epsilon_P^{de} \\ \hat{\epsilon}_T^{de} \\ \epsilon_L^{s\mu/e} \\ \epsilon_R^{s} \\ \epsilon_P^{se} \\ \epsilon_L^{d\mu/e} - \epsilon_P^{d\mu}\frac{m_{\pi^\pm}^2}{m_\mu(m_u+m_d)} \\ \epsilon_S^{s\mu} \\ \epsilon_P^{s\mu} \\ \hat{\epsilon}_T^{s\mu} \\ \epsilon_L^{d\tau/e} \\ \epsilon_P^{d\tau} \\ \hat{\epsilon}_T^{d\tau} \\ \epsilon_L^{s\tau/e} - \epsilon_P^{s\tau}\frac{m_{K^\pm}^2}{m_\tau(m_u+m_s)} \\ \epsilon_L^{s\tau/e} + 0.08(1)\epsilon_S^{s\tau} - 0.38\epsilon_P^{s\tau} + 0.40(13)\hat{\epsilon}_T^{s\tau} \end{pmatrix} = \begin{pmatrix} 0.22306(56) \\ 2.2(8.6) \\ -3.3(8.2) \\ 3.0(9.9) \\ 1.3(3.4) \\ -0.4(1.1) \\ 0.8(2.2) \\ 0.2(5.0) \\ -0.3(2.0) \\ -0.5(1.8) \\ -2.6(4.4) \\ -0.6(4.1) \\ 0.2(2.2) \\ 0.1(1.9) \\ 9.2(8.6) \\ 1.9(4.5) \\ 0.0(1.0) \\ -0.7(5.2) \end{pmatrix} \times 10^\wedge \begin{pmatrix} 0 \\ -3 \\ -3 \\ -4 \\ -6 \\ -3 \\ -3 \\ -2 \\ -5 \\ -2 \\ -4 \\ -3 \\ -2 \\ -2 \\ -3 \\ -2 \\ -1 \\ -2 \end{pmatrix}$$

$$\epsilon_L^{D\ell/e} \equiv \epsilon_L^{D\ell} - \epsilon_L^{De}$$

**Most complete information to date about CC interactions between light quarks & leptons**

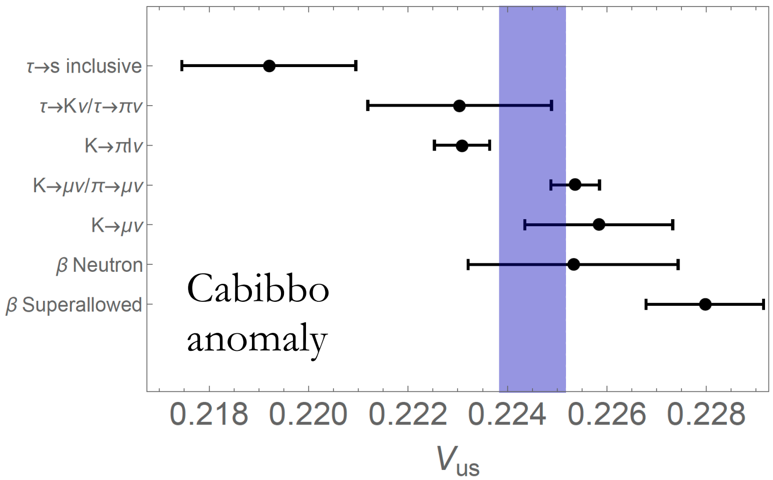
- Large correlations!

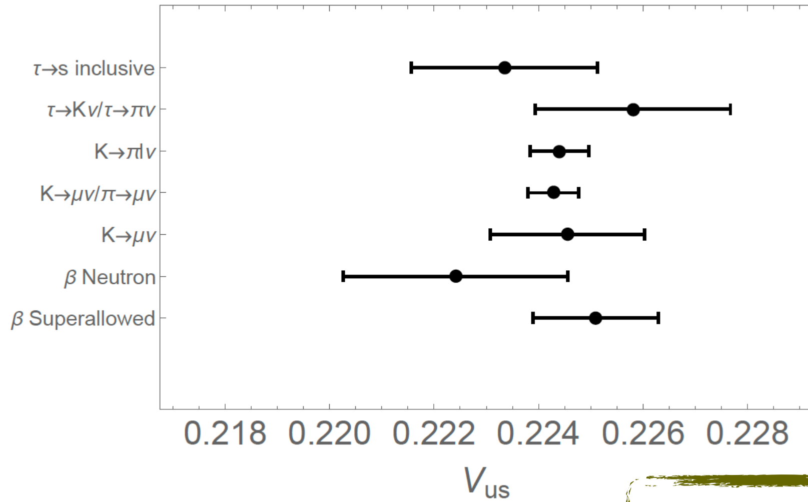
- 3σ preference for NP

# Beta decays & flavor

[Cirigliano, Díaz-Calderón, Falkowski, MGA & Rodríguez-Sánchez, JHEP04 (2022) 152]

- SM limit:




4.4 σ !

$$\boxed{\begin{aligned} \epsilon_R^d &= -6.8\times 10^{-4}, \\ \epsilon_R^s &= -5.9\times 10^{-3}, \\ \epsilon_L^{s\tau} &= -1.8\times 10^{-2}. \end{aligned}}$$

- 1 operator at a time: [10^-3 units]

| | $\epsilon_X^{de}\times 10^3$ | $\epsilon_X^{se}\times 10^3$ | $\epsilon_X^{d\mu}\times 10^3$ | $\epsilon_X^{s\mu}\times 10^3$ | $\epsilon_X^{d\tau}\times 10^3$ | $\epsilon_X^{s\tau}\times 10^3$ |
|---|---|---|---|---|---|---|
| $L$ | -0.79(25) | -0.6(1.2) | 0.40(87) | 0.5(1.2) | 5.0(2.5) | -18.2(6.2) |
| $R$ | -0.62(25) | -5.2(1.7) | -0.62(25) | -5.2(1.7) | -0.62(25) | -5.2(1.7) |
| $S$ | 1.40(65) | -1.6(3.2) | x | -0.51(43) | -6(16) | -270(100) |
| $P$ | 0.00018(17) | -0.00044(36) | -0.015(32) | -0.032(64) | 1.7(2.5) | 10.4(5.5) |
| $\hat{T}$ | 0.29(82) | 0.035(70) | x | 2(18) | 28(10) | -55(27) |

- Models:

Belfatto et al 1906.02714 Kirk 2008.03261 Belfatto Berezhiani 2103.05549 Branco et al 2103.13409, ...