EFT for nuclear β transitions

HEFT 2022, Granada

June 2022

Martín González-Alonso

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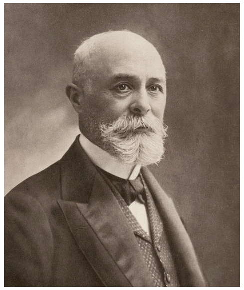
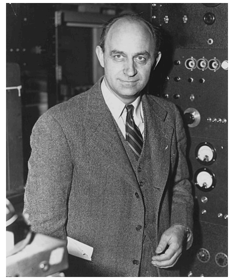
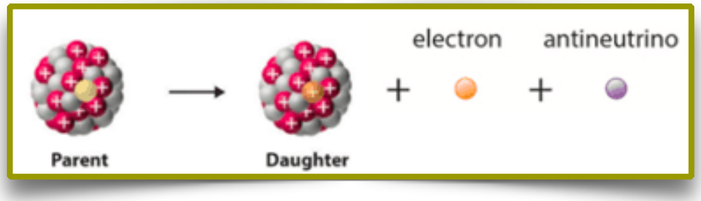
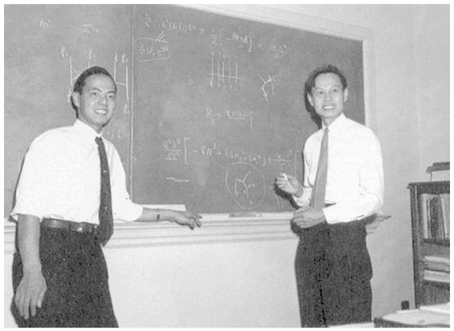
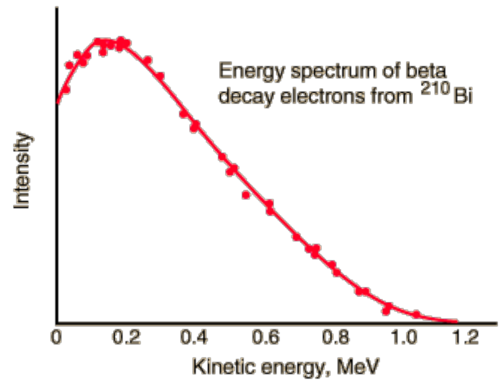
Beta decays: a trove of discoveries

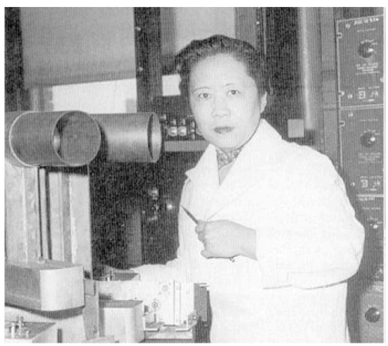


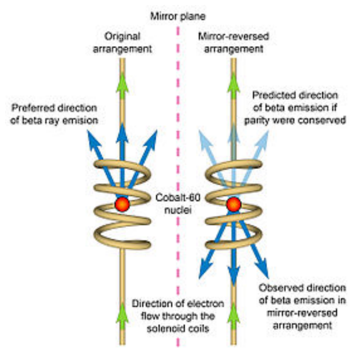


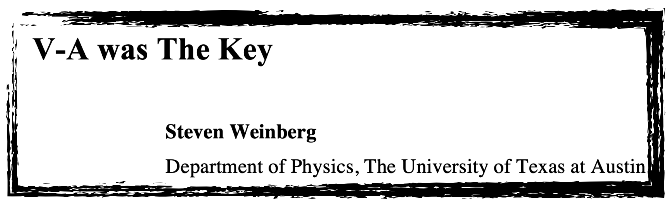












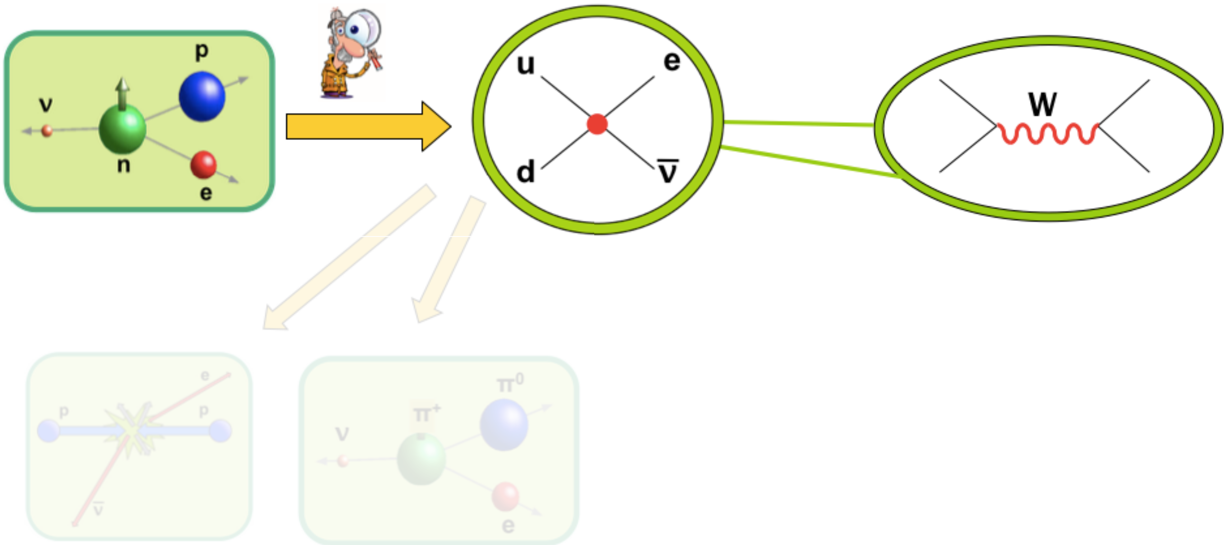
V-A was The Key

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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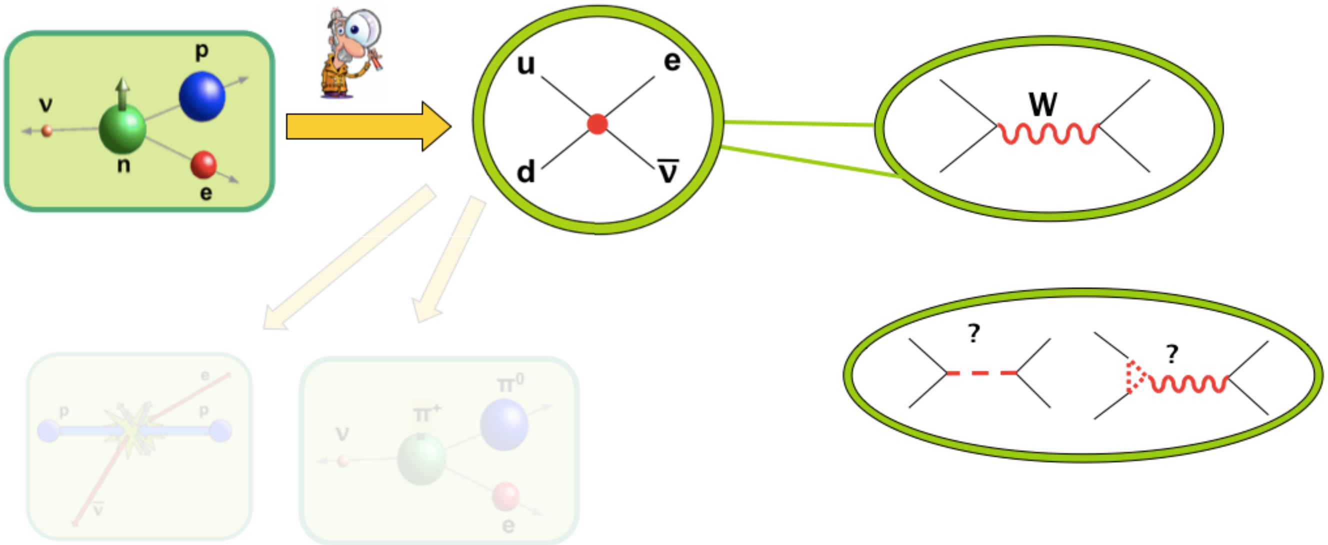

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  - Beta decay = precision field (TH + EXP)
  - We are playing the same old game, but we are looking for a small contribution on top of the dominant V-A interaction.

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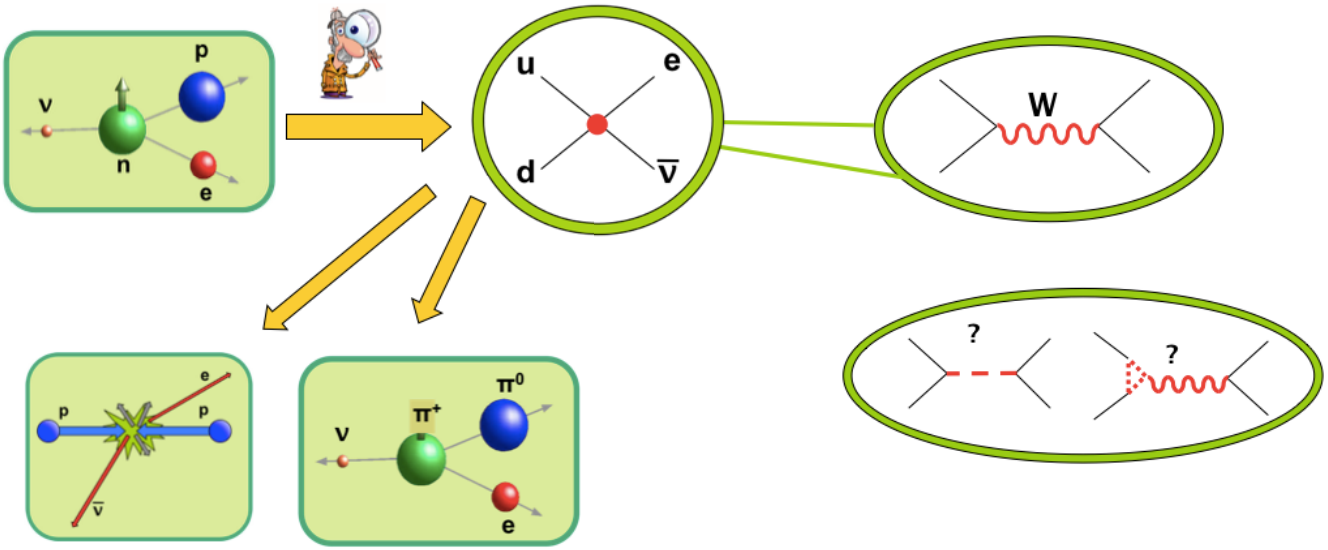

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  - Specific NP model vs. Effective Field Theories
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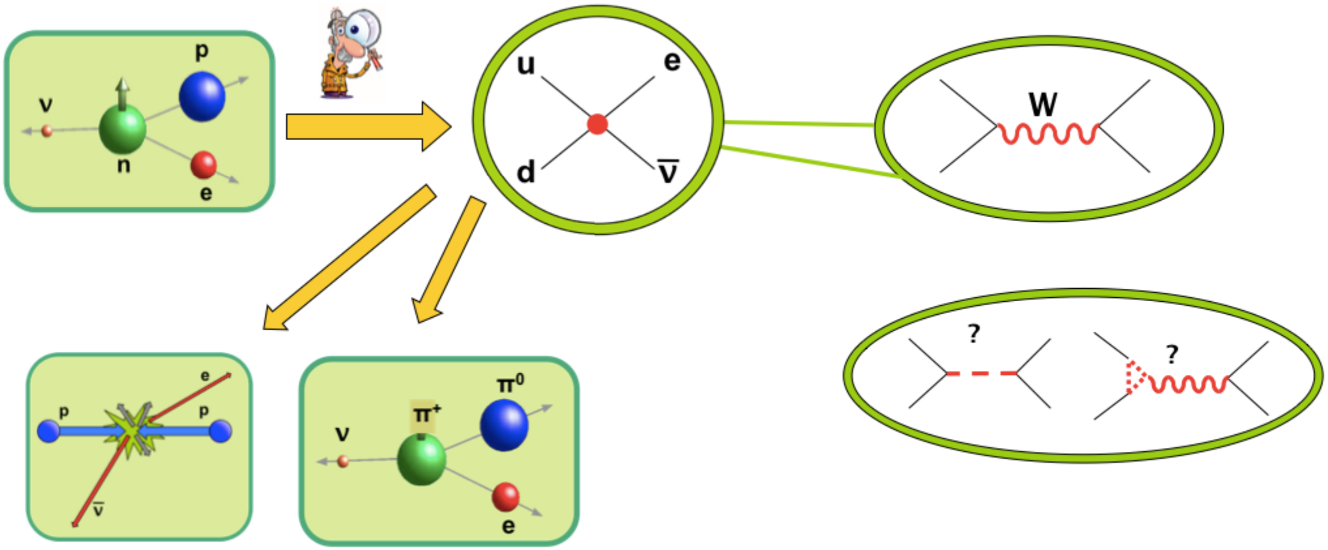

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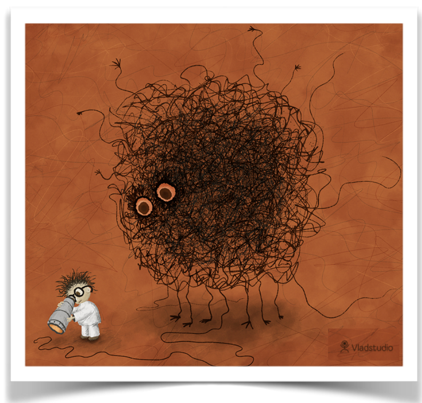
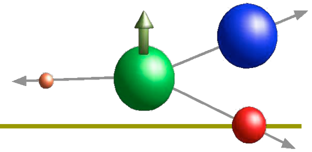


Which EFT?



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

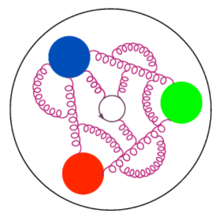
$$
\begin{aligned}
-\mathcal{L}_{n\to pe^-\bar{\nu}_e} = \; & \bar{p}\, n \; (C_S \bar{e}\nu_e - C'_S \bar{e}\gamma_5\nu_e) \\
& + \bar{p}\gamma^\mu n \,(C_V \bar{e}\gamma_\mu \nu_e - C'_V \bar{e}\gamma_\mu\gamma_5\nu_e) \\
& + \frac{1}{2}\bar{p}\sigma^{\mu\nu} n \,(C_T \bar{e}\sigma_{\mu\nu}\nu_e -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

[Lee & Yang'1956]

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

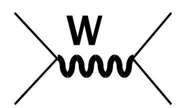
$$
\mathcal{L}_{d\to u\ell^-\bar{\nu}_\ell} = -\frac{4G_F V_{ij}}{\sqrt{2}}\left[\bar{\ell}_L\gamma_\mu\nu\cdot\bar{u}\gamma^\mu d_L \;+\; \sum_{\rho\delta\Gamma}\epsilon^\Gamma_{\rho\delta}\,\bar{\ell}_\rho\Gamma\nu\cdot\bar{u}\Gamma d_\delta\right]
$$

$$
\mathbf{C_i \sim FF \; x \; \varepsilon_i}
$$



- 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]

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

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

For some transitions and observables:

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

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[Lee & Yang'1956]

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

For some transitions and observables:

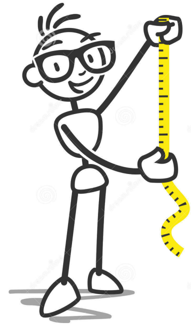
$\mathcal{O} \approx f(C_i)$ + small corrections

High precision measurements

UV meaning of the C coefficients?
(within & beyond the SM)
(hadronization, RC, EFT, ...)

Current data

Precision:
O(0.01 – 1)% !!



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

Fermi or Gamow-Teller
Nuclear decays

Ft (0⁺→0⁺) values

Parent	$\mathcal{F}t$ [s]
^{10}C	3075.7 ± 4.4
^{14}O	3070.2 ± 1.9
^{22}Mg	3076.2 ± 7.0
^{26m}Al	3072.4 ± 1.1
^{26}Si	3075.4 ± 5.7
^{34}Cl	3071.6 ± 1.8
^{34}Ar	3075.1 ± 3.1
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^{46}V	3074.3 ± 2.0
^{50}Mn	3071.1 ± 1.6
^{54}Co	3070.4 ± 2.5
^{62}Ga	3072.4 ± 6.7
^{74}Rb	3077 ± 11

[Hardy-Towner'2020]

Correlation coefficients

Parent	Type	Parameter	Value
^{6}He	GT/β^-	a	$-0.3308(30)^{a)}$
^{32}Ar	F/β^+	$\tilde{a}$	0.9989(65)
^{38m}K	F/β^+	$\tilde{a}$	0.9981(48)
^{60}Co	GT/β^-	$\tilde{A}$	$-1.014(20)$
^{67}Cu	GT/β^-	$\tilde{A}$	0.587(14)
^{114}In	GT/β^-	$\tilde{A}$	$-0.994(14)$
^{14}O/^{10}C	F-GT/β^+	P_F/P_{GT}	0.9996(37)
^{26}Al/^{30}P	F-GT/β^+	P_F/P_{GT}	1.0030 (40)

Neutron data

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

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

Current data (+ TH!!)

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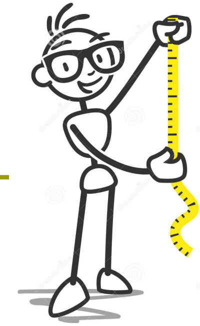
$O(0.01 - 1)\%$!!



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Th: QED + Isospin symmetry breaking corrections

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

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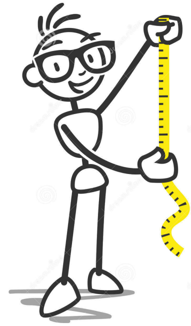

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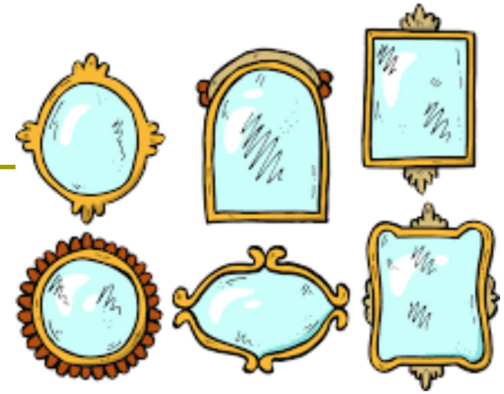
RECENT:
Perkeo-III, PRL122 (2019): A_n
aSPECT, PRC101 (2020): a_n
aCORN, PRC103 (2021): a_n
UCNτ, PRL127 (2021): τ_n

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
[Seng, Gorchtein, & Ramsey-Musolf, PRD100 (2019)]
[Gorchtein, PRL123 (2019)]

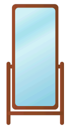
What about mirror beta decays?



- β transitions between isobaric analog states in T = 1/2 isospin doublets (Nuclei with $p \leftrightarrow n$)

$$^{19}\mathrm{Ne} \rightarrow {}^{19}\mathrm{F} \quad e^{+}\,\nu_e$$

10 p ● *9 n* ●



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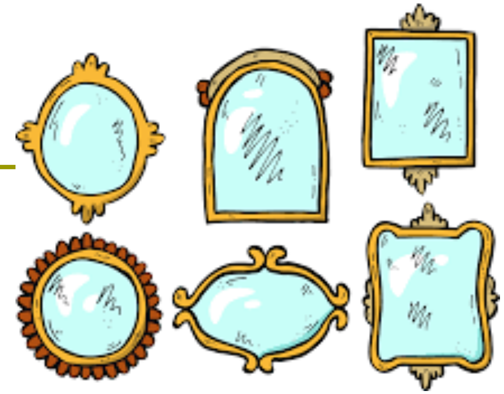

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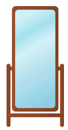

- Many per-mil level determinations of the Ft values! (Exp + Th) [e.g. Severijns et al, PRC78 (2008)]

- M_{GT} / M_F ratio needed:

$$\mathcal{O} \approx f(C_i, M_{GT}/M_F) \approx f(C_i, \rho)$$

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- We need 2 observables per transition (Ft value + correlation);

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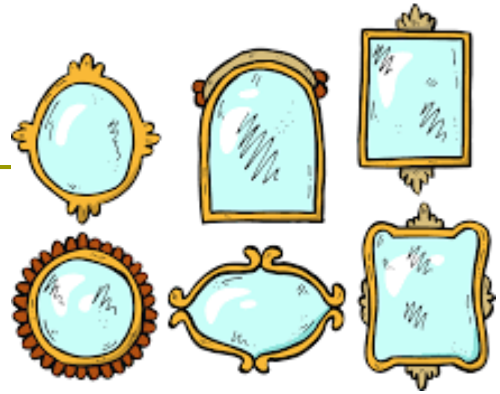

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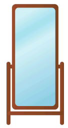

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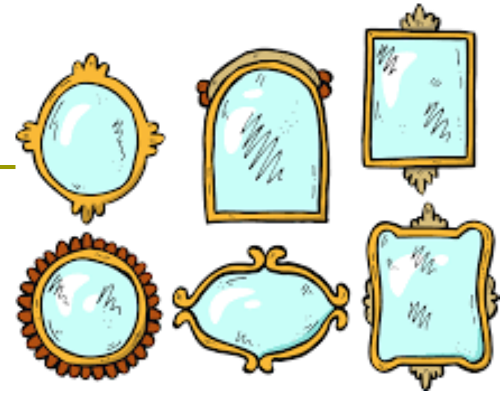

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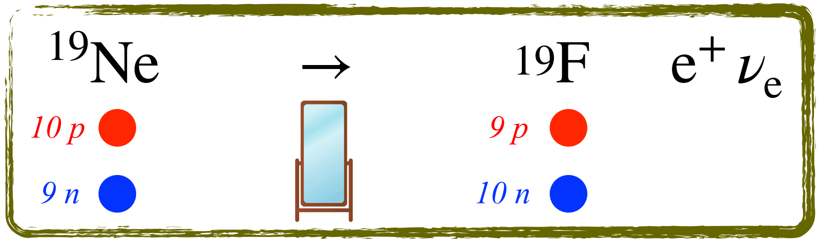

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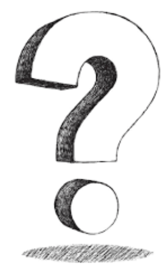
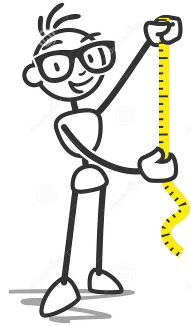
- What about BSM? [Falkowski, MGA, Naviliat-Cuncic, JHEP 04 (2021) 126]



Current data



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^{38}Ca	3077.8 ± 6.2
^{42}Sc	3071.7 ± 2.0
^{46}V	3074.3 ± 2.0
^{50}Mn	3071.1 ± 1.6
^{54}Co	3070.4 ± 2.5
^{62}Ga	3072.4 ± 6.7
^{74}Rb	3077 ± 11

Correlation coefficients

Parent	Type	Parameter	Value
^{6}He	GT/β^-	a	$-0.3308(30)^{a)}$
^{32}Ar	F/β^+	$\tilde{a}$	$0.9989(65)$
^{38m}K	F/β^+	$\tilde{a}$	$0.9981(48)$
^{60}Co	GT/β^-	$\tilde{A}$	$-1.014(20)$
^{67}Cu	GT/β^-	$\tilde{A}$	$0.587(14)$
^{114}In	GT/β^-	$\tilde{A}$	$-0.994(14)$
			$0.9996(37)$
			$1.0030\ (40)$

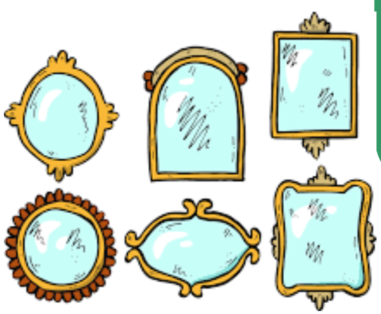
Neutron data

Observable	Value	S factor
τ_n (s)	$879.75(76)$	1.9
$\tilde{A}_n$	$-0.11958(21)$	1.2
$\tilde{B}_n$	$0.9805(30)$	
λ_{AB}	$-1.2686(47)$	
a_n	$-0.10426(82)$	
$\tilde{a}_n$	$-0.1090(41)$	

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

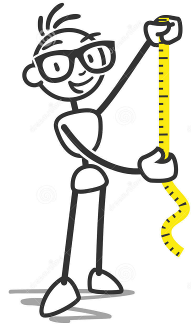
Mirror transitions

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	$4605.4(8.2)$	$\tilde{A} = -0.5707(19)$
		$\tilde{B} = -0.755(24)$



Current data (+ TH!!)

Precision:
O(0.01 – 1)% !!



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

Fermi or Gamow-Teller
Nuclear decays

Ft (0⁺→0⁺) values

Parent	$\mathcal{F}t$ [s]
^{10}C	3075.7 ± 4.4
^{14}O	3070.2 ± 1.9
^{22}Mg	3076.2 ± 7.0
^{26m}Al	3072.4 ± 1.1
^{26}Si	3075.4 ± 5.7
^{34}Cl	3071.6 ± 1.8
^{34}Ar	3075.1 ± 3.1
^{38m}K	3072.9 ± 2.0
^{38}Ca	3077.8 ± 6.2
^{42}Sc	3071.7 ± 2.0
^{46}V	3074.3 ± 2.0
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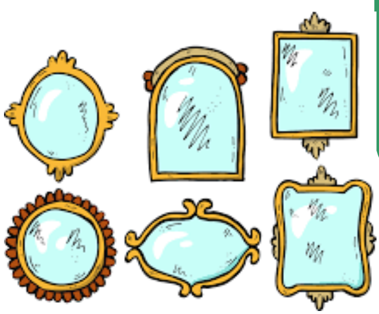


Mirror transitions

RECENT:
Fenker et al., PRL120 (2018): A_{K-37}
Combs et al., 2009.13700: A_{Ne-19}
Hayen, PRD103 (2021): f_A/f_V values
...

Standard Model fit:

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

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

SM fit

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

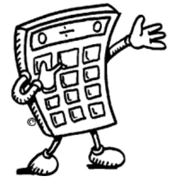
$$\rightarrow C_V^+ = 0.98576(22)\, G_F/\sqrt{2}$$

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

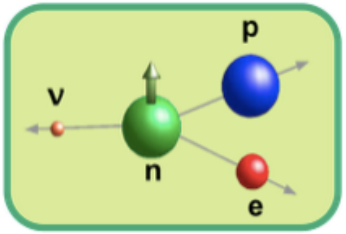
$$\rho \approx -1.2757 \frac{M_{GT}}{M_F}$$

Impressive precision!

SM fit

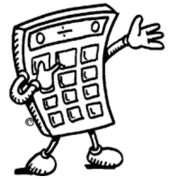


$$\begin{pmatrix} v^2 C_V^+ \\ v^2 C_A^+ \\ \rho_F \\ \rho_{Ne} \\ \rho_{Na} \\ \rho_P \\ \rho_{Ar} \\ \rho_K \end{pmatrix} = \begin{pmatrix} 0.98576(22) \\ -1.25754(39) \\ -1.2955(13) \\ 1.60157(75) \\ -0.7127(11) \\ -0.5380(21) \\ -0.2834(25) \\ 0.5787(20) \end{pmatrix}$$

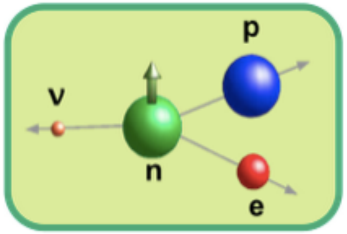


$$\mathscr{L}^{eff}_{n\to pe\nu} = -\, C_V^+ \bar{p}\gamma^\mu n\, \bar{e}\gamma_\mu \nu_L - C_A^+ \bar{p}\gamma^\mu\gamma_5 n\, \bar{e}\gamma_\mu \nu_L$$

SM fit



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



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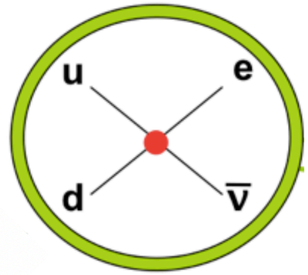
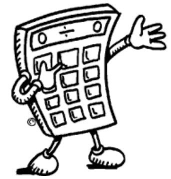


$$\mathcal{L}^{eff}_{d\to ue\nu} = -\frac{V_{ud}}{v^2}\bar{u}\gamma^\mu(1-\gamma_5)d\,\bar{e}\gamma^\mu(1-\gamma_5)\nu_e$$

SM fit



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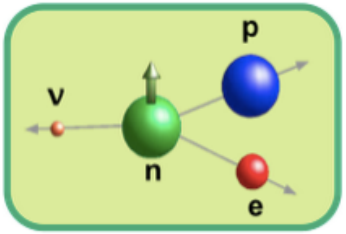

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$$C_V^+ = \frac{V_{ud}}{v^2} g_V \sqrt{1+\Delta_R^V}$$

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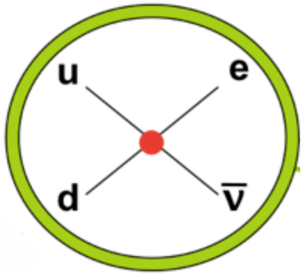

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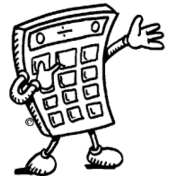
SM fit



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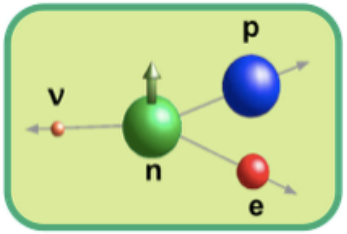
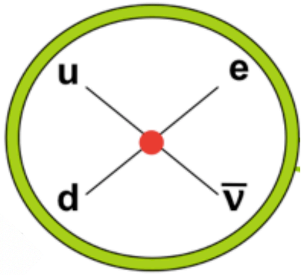
$$V_{ud} = 0.97382(24)$$
$$g_A = 1.27553(45)$$





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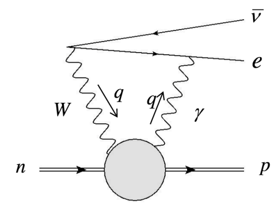
Inner RC:

[Seng et al., PRL121 (2018)]
[Gorchtein & Seng, JHEP10 (2021)]



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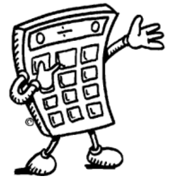

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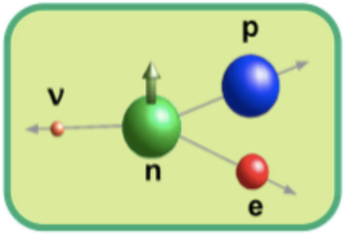

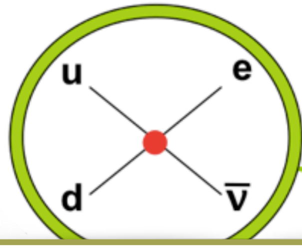

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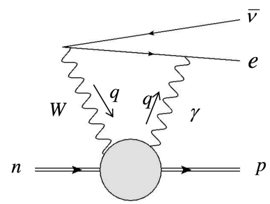

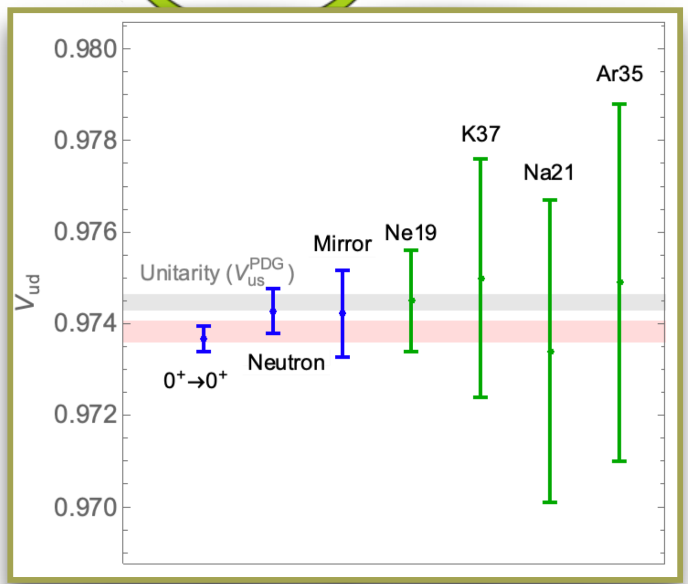

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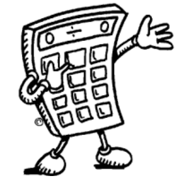

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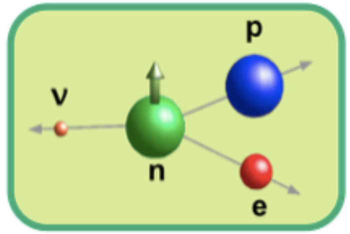

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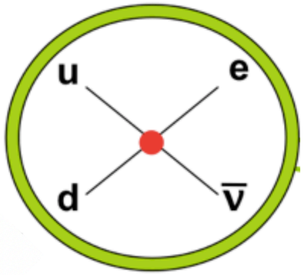

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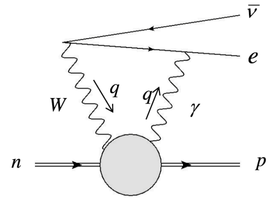
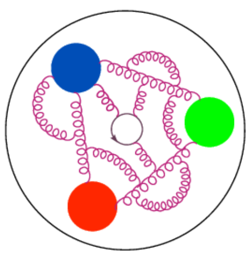




Axial charge

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

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

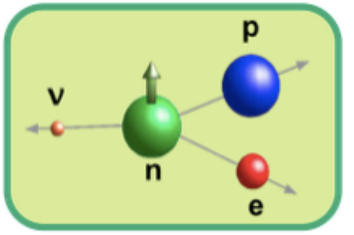
g_A = 1.218(39) PNDME, PRD'18

g_A = 1.246(28) FLAG'21

NEW: missed % level corrections?
Cirigliano et al., 2202.10439

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 ν_L

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

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

BSM x recoil

Good approximation for the EFT with ν_L & ν_R if the couplings with ν_R are not large

SM + small + ~~(small)²~~

EFT with ν_L

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

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

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 ν_L

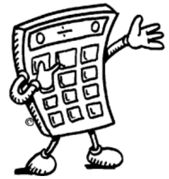
$$\mathcal{L}_{\text{Lee-Yang}} = -\bar{p}\gamma^{\mu} n \left(C_V^{+} \bar{e}\gamma_{\mu}\nu_L + \text{[redacted]} \right) - \bar{p}\gamma^{\mu}\gamma_5 n \left(C_A^{+} \bar{e}\gamma_{\mu}\nu_L - \text{[redacted]} \right)$$
$$- \bar{p}n \left(C_S^{+} \bar{e}\nu_L + \text{[redacted]} \right) - \frac{1}{2}\bar{p}\sigma^{\mu\nu}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

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

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

(+ mixing ratios)

EFT with νL



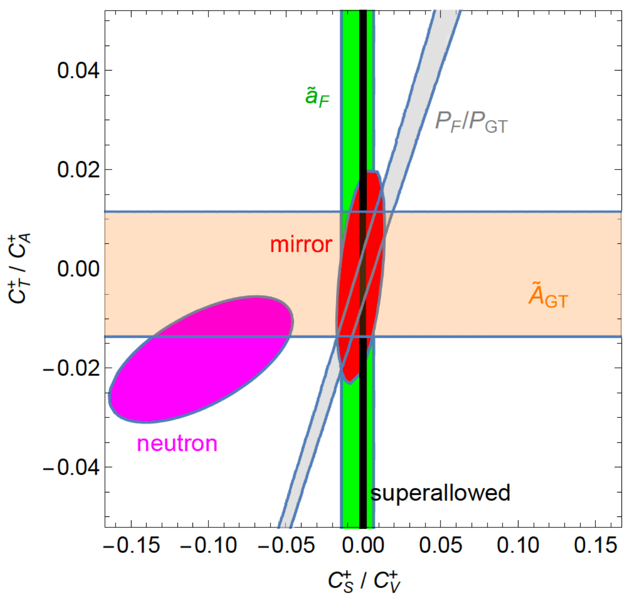
$$\mathcal{L}_{\mathrm{Lee-Yang}} = -\bar{p}\gamma^{\mu}n\left(C_V^{+}\bar{e}\gamma_{\mu}\nu_L + \cancel{C_V^{-}\bar{e}\gamma_{\mu}\nu_R}\right) - \bar{p}\gamma^{\mu}\gamma_5 n\left(C_A^{+}\bar{e}\gamma_{\mu}\nu_L - \cancel{C_A^{-}\bar{e}\gamma_{\mu}\nu_R}\right)$$
$$- \bar{p}n\left(C_S^{+}\bar{e}\nu_L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

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

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

(+ mixing ratios)

Role of mirror transitions?



EFT with ν_L

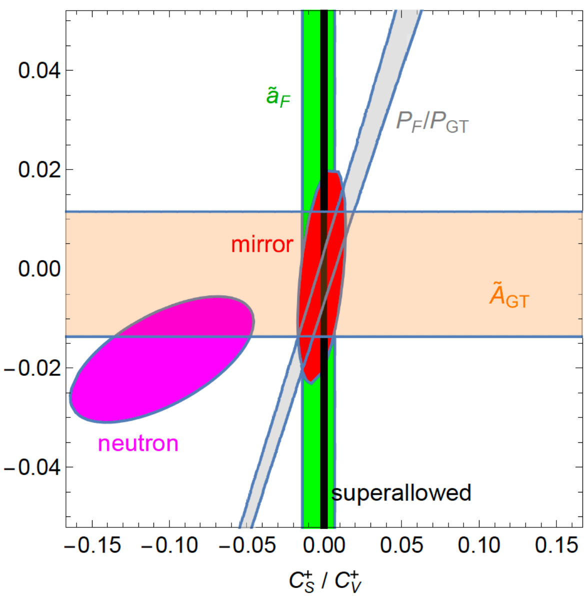
$$\mathcal{L}_{\mathrm{Lee-Yang}} = -\bar{p}\gamma^{\mu}n\left(C_V^{+}\bar{e}\gamma_{\mu}\nu_L + \text{[redacted]}\right) - \bar{p}\gamma^{\mu}\gamma_5 n\left(C_A^{+}\bar{e}\gamma_{\mu}\nu_L - \text{[redacted]}\right)$$
$$- \bar{p}n\left(C_S^{+}\bar{e}\nu_L + \text{[redacted]}\right) - \frac{1}{2}\bar{p}\sigma^{\mu\nu}n\left(C_T^{+}\bar{e}\sigma_{\mu\nu}\nu_L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

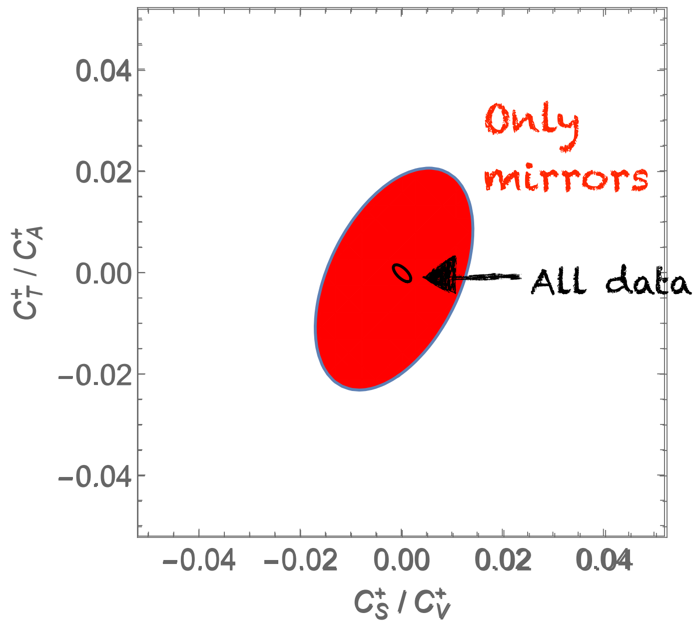
$$v^2\begin{pmatrix} C_V^{+} \\ C_A^{+} \\ C_S^{+} \\ C_T^{+} \end{pmatrix} = \begin{pmatrix} 0.98576(41) \\ -1.25740(54) \\ 0.0002(10) \\ 0.0005(12) \end{pmatrix}$$

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

(+ mixing ratios)

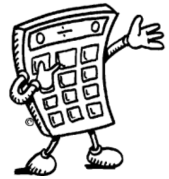
Role of mirror transitions?



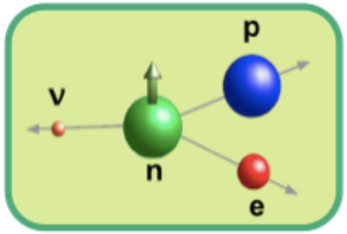


Driven by Ft(0->0), τ_n, A_n!

EFT with ν_L

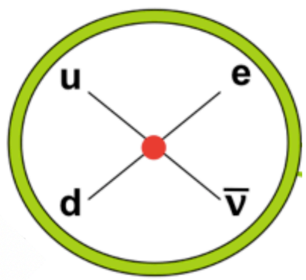


$$v^2 \begin{pmatrix} C_V^+ \\ C_A^+ \\ C_S^+ \\ C_T^+ \end{pmatrix} = \begin{pmatrix} 0.98576(41) \\ -1.25712(55) \\ 0.0002(10) \\ 0.0006(12) \end{pmatrix},$$



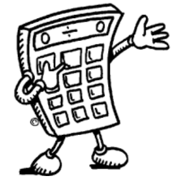
$$\begin{aligned} \mathcal{L} = \; & \bar{p}\, n\, \left(C_S \bar{e}\nu_e - C_S' \bar{e}\gamma_5\nu_e\right) \\ & + \bar{p}\gamma^\mu n \left(C_V \bar{e}\gamma_\mu\nu_e - C_V' \bar{e}\gamma_\mu\gamma_5\nu_e\right) \\ & + \frac{1}{2}\bar{p}\sigma^{\mu\nu} n \left(C_T \bar{e}\sigma_{\mu\nu}\nu_e - C_T'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

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

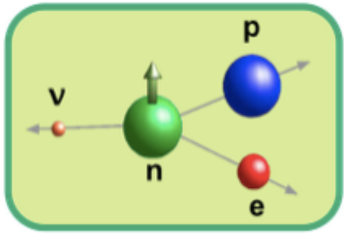


$$\mathcal{L} = -\frac{4G_F V_{ij}}{\sqrt{2}} \Big[\bar{\ell}_L \gamma_\mu \nu \cdot \bar{u}\gamma^\mu d_L + \sum_{\rho\delta\Gamma} \epsilon_{\rho\delta}^{\Gamma}\, \bar{\ell}_\rho \Gamma \nu \cdot \bar{u}\Gamma d_\delta \Big]$$

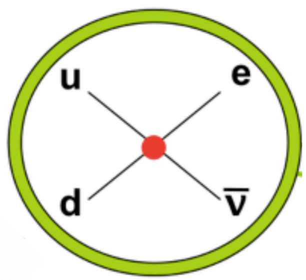
EFT with ν_L



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



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



$\hat{V}_{ud}$

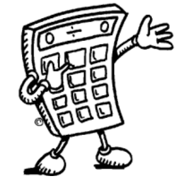
$$C_V^+ = \frac{V_{ud}\left(1 + \epsilon_L + \epsilon_R\right)}{v^2}\sqrt{1 + \Delta_R^V}$$

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

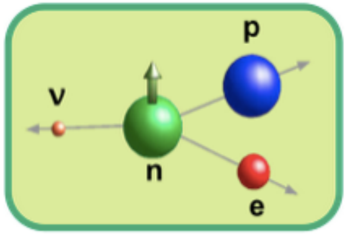
$$C_S^+ \approx \frac{\hat{V}_{ud}}{v^2} g_S \epsilon_S$$

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

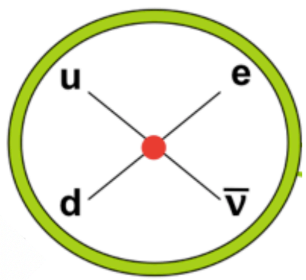
EFT with ν_L



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



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



$\hat{V}_{ud}$

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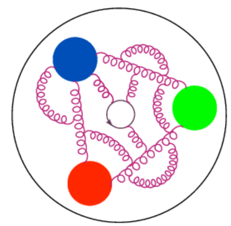
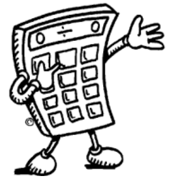
$$C_T^+ \approx \frac{\hat{V}_{ud}}{v^2}\, g_T \epsilon_T$$



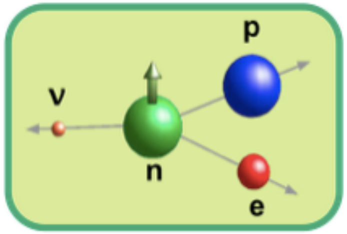
Nucleon charges

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

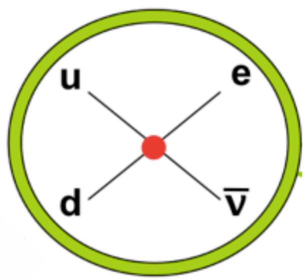
EFT with ν_L



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



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



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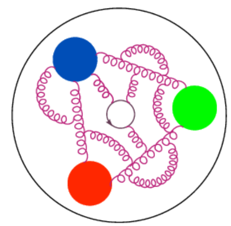
$$C_T^+ \approx \frac{V_{ud}}{v^2} g_T \epsilon_T$$



Nucleon charges

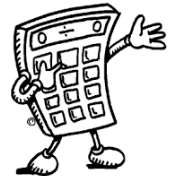
$\langle p | \bar{u} \Gamma d | n \rangle$

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

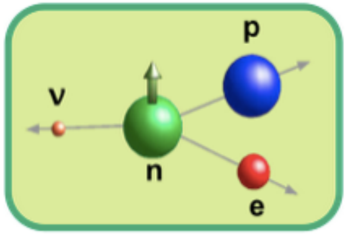
g_A = 1.218(39) PNDME, PRD'18

g_A = 1.246(28) FLAG'21

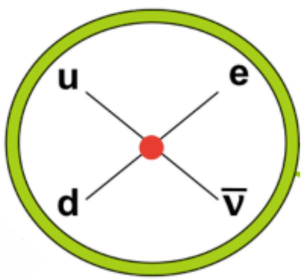
EFT with ν_L



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



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



$\hat{V}_{ud}$

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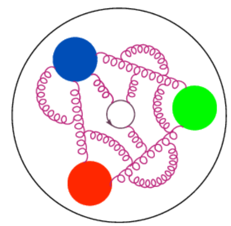
$$C_A^+ \approx -\frac{\hat{V}_{ud}}{v^2}\sqrt{1 + \Delta_R^A}\, g_A \left(1 - 2\,\epsilon_R\right)$$

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

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



Nucleon charges

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

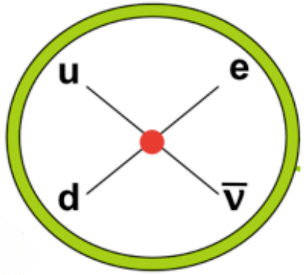
g_S = 1.02(10) FLAG'21* *[PNDME'18]*

g_T = 0.989(34) FLAG'21 *[PNDME'18]*

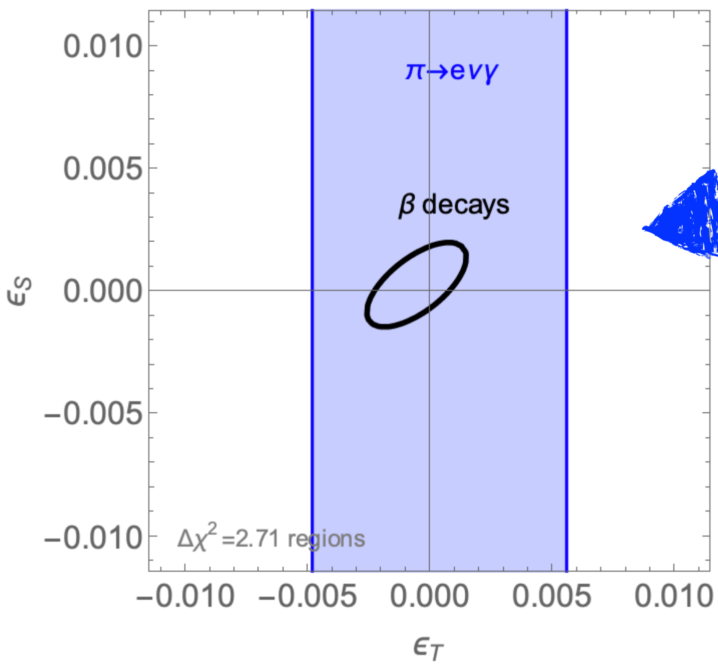
* in perfect agreement with g_S = 1.02(2)
MGA & Camalich, Phys. Rev. Lett. 112 (2014)

EFT with ν_L

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

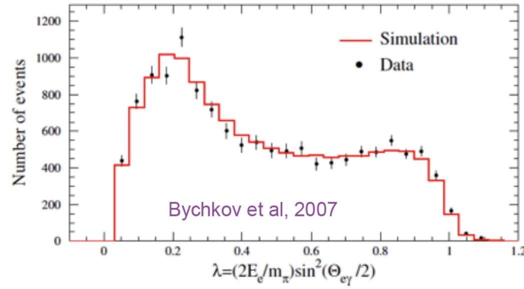


$$\mathcal{L} = -\frac{4G_F V_{ij}}{\sqrt{2}} \left[\bar{\ell}_L \gamma_\mu \nu \cdot \bar{u} \gamma^\mu d_L + \sum_{\rho\delta\Gamma} \epsilon^\Gamma_{\rho\delta} \, \bar{\ell}_\rho \Gamma \nu \cdot \bar{u} \Gamma d_\delta \right]$$



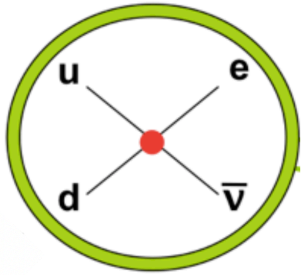
$\pi \to e\nu\gamma$

(PIBETA´2009)



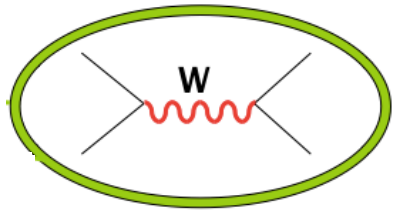
Going to higher energies…

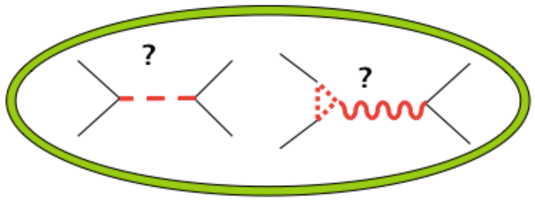
$$\begin{pmatrix} \hat{V}_{ud} \\ \epsilon_R \\ \epsilon_S \\ \epsilon_T \end{pmatrix} = \begin{pmatrix} 0.97382(42) \\ -0.012(12) \\ 0.0002(10) \\ -0.0004(12) \end{pmatrix}$$

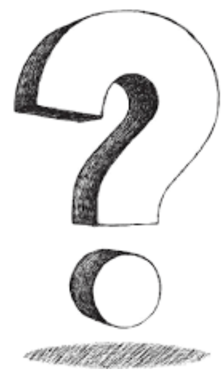


$$\mathcal{L} = -\frac{4G_F V_{ij}}{\sqrt{2}} \Big[\bar{\ell}_L \gamma_\mu \nu \cdot \bar{u} \gamma^\mu d_L + \sum_{\rho\delta\Gamma} \epsilon^{\Gamma}_{\rho\delta} \, \bar{\ell}_\rho \Gamma \nu \cdot \bar{u} \Gamma d_\delta \Big]$$

$\epsilon_i = f(??)$

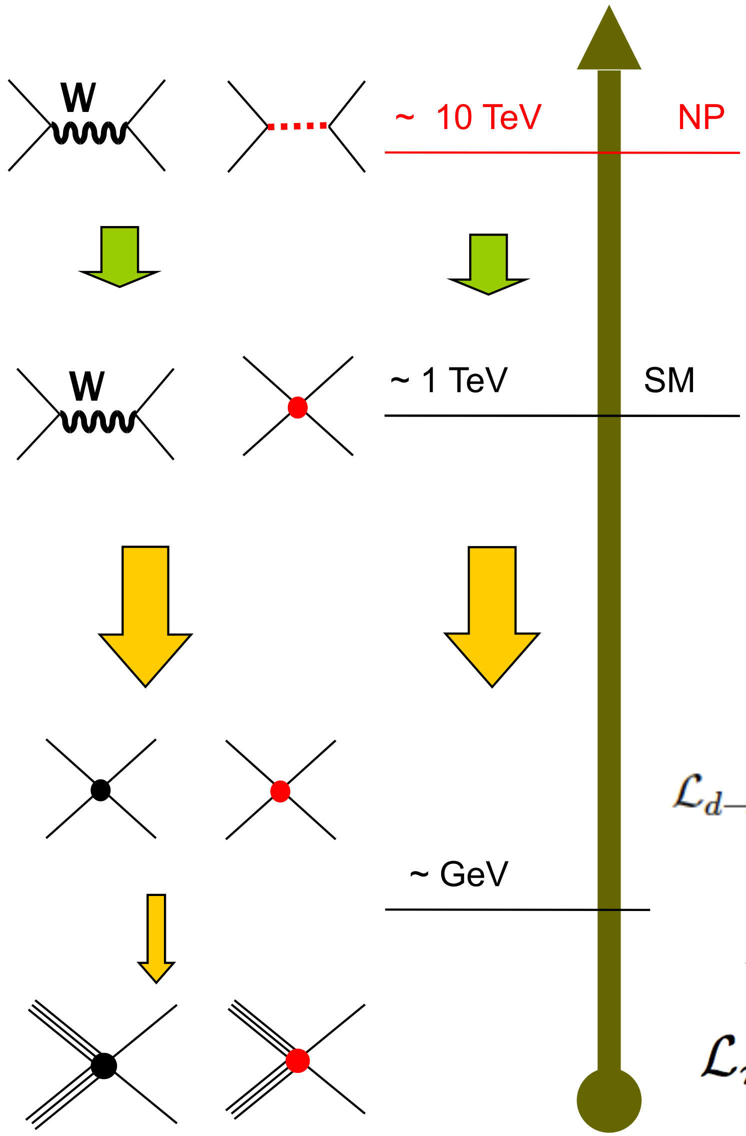






Matching to the SMEFT

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



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

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

"SMEFT"

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

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

$$\varepsilon_i = f(\alpha_j)$$

Matching to the SMEFT

Low-E EFT → ϵ_i ; SMEFT → α_j

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

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

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

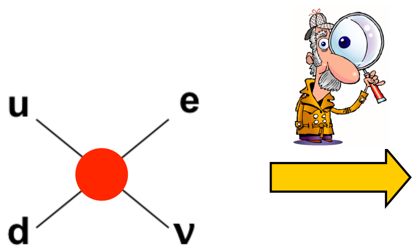
$$V_{1j}\cdot\epsilon^{j\ell}_{L} = 2\,V_{1j}\left[\hat{\alpha}^{(3)}_{\varphi l}\right]_{\ell\ell} + 2\,\left[V\hat{\alpha}^{(3)}_{\varphi q}\right]_{1j} - 2\left[V\hat{\alpha}^{(3)}_{lq}\right]_{\ell\ell 1j} ,$$

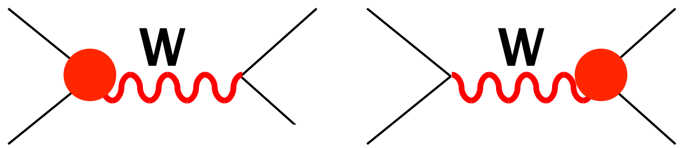
$$V_{1j}\cdot\epsilon^{j}_{R} = -\,[\hat{\alpha}_{\varphi\varphi}]_{1j} ,$$

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

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

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



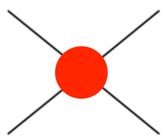


$$O_{\varphi\varphi} = i(\varphi^{T}\epsilon D_{\mu}\varphi)(\overline{u}\gamma^{\mu}d) + \text{h.c.}$$

$$O^{(3)}_{\varphi q} = i(\varphi^{\dagger}D^{\mu}\sigma^{a}\varphi)(\overline{q}\gamma_{\mu}\sigma^{a}q) + \text{h.c.}$$

$$O^{(3)}_{\varphi l} = i(\varphi^{\dagger}D^{\mu}\sigma^{a}\varphi)(\overline{l}\gamma_{\mu}\sigma^{a}l) + \text{h.c.}$$

$$O'_{\varphi\varphi} = i(\varphi^{T}\epsilon D_{\mu}\varphi)(\overline{\nu}\gamma^{\mu}e) + \text{h.c.}$$



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

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

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

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

Matching to the SMEFT

Low-E EFT

SMEFT

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

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

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

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

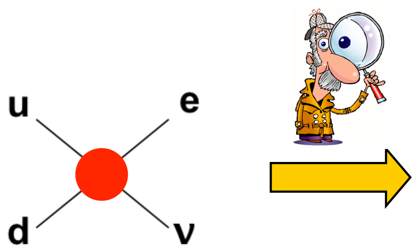
$$V_{1j}\cdot\epsilon^{j}_R = -\,[\hat{\alpha}_{\varphi\varphi}]_{1j}\,,$$

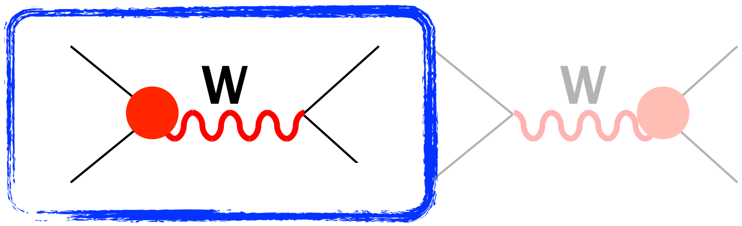
ϵ_R is lepton independent!

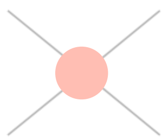
$$V_{1j}\cdot\epsilon^{j\ell}_{s_L} = -\,[\hat{\alpha}_{lq}]^{*}_{\ell\ell j1}\,,$$

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

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







$$O_{\varphi\varphi} = i(\varphi^T\epsilon D_\mu\varphi)(\overline{u}\gamma^\mu d) + \text{h.c.}$$

$$O^{(3)}_{\varphi q} = i(\varphi^\dagger D^\mu\sigma^a\varphi)(\overline{q}\gamma_\mu\sigma^a q) + \text{h.c.}$$

$$O^{(3)}_{\varphi l} = i(\varphi^\dagger D^\mu\sigma^a\varphi)(\overline{l}\gamma_\mu\sigma^a l) + \text{h.c.}$$

$$O'_{\varphi\varphi} = i(\varphi^T\epsilon D_\mu\varphi)(\overline{\nu}\gamma^\mu e) + \text{h.c.}$$

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

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

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

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

Matching to the SMEFT

Low-E EFT → ϵ_i; SMEFT → α_j

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

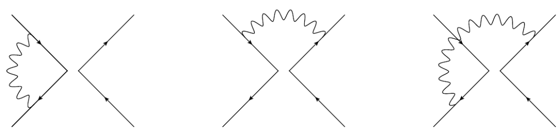
[Cirigliano, MGA, Jenkins'2010; Cirigliano, MGA, Graesser'2012]

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

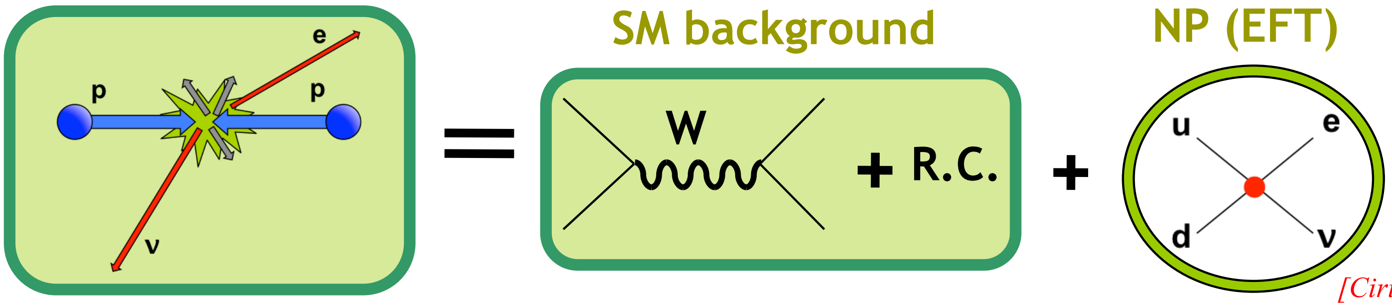
Running (QCD x QED & QCD x EW)
[MGA, Martin Camalich & Mimouni'17]

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

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



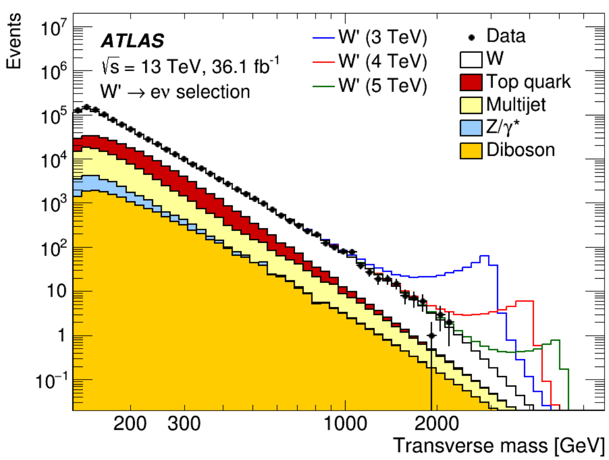
LHC limits on $\varepsilon_{S,T}$

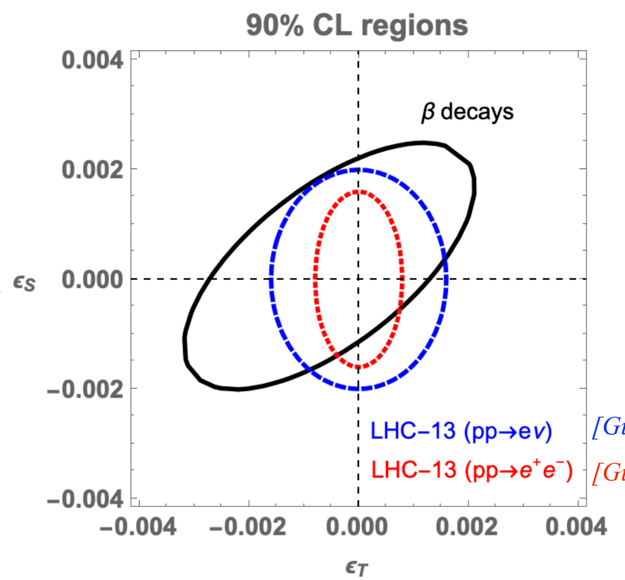


[Cirigliano, MGA & Graesser, JHEP1302 (2013)*]*
[Bhattacharya et al, PRD85 (2012)*]*

$$N_{pp\to e\nu X}\left(m_T^2 > m_{T,cut}^2\right) = \varepsilon \times L \times \sigma_{pp\to e\nu X}\left(m_T^2 > m_{T,cut}^2\right) = \varepsilon \times L \times \left(\sigma_W + \sigma_S\, \varepsilon_S^2 + \sigma_T\, \varepsilon_T^2\right)$$

(Interference w/ SM ~ m/E)





[Gupta et al., 1806.09006]
[Gupta et al., 1806.09006]

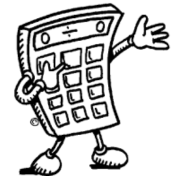
[Falkowski, MGA, Naviliat-Cuncic, JHEP 04 (2021) 126]

EFT with ν_L & ν_R

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

Back to 1956

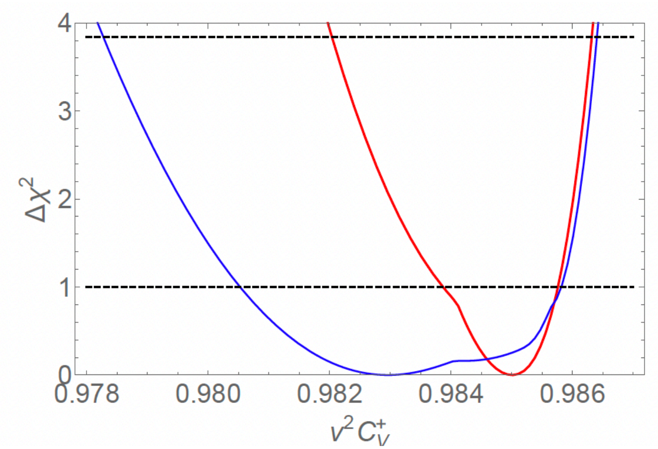
EFT with νL & νR

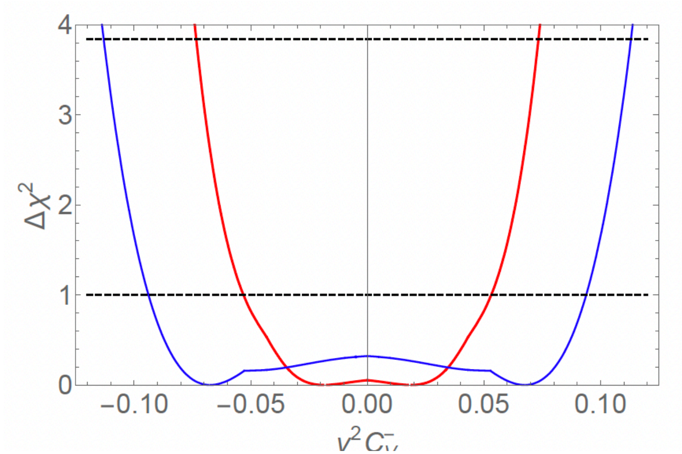


$$\mathcal{L}_{\text{Lee-Yang}} = -\bar{p}\gamma^{\mu}n\left(C_V^{+}\bar{e}\gamma_{\mu}\nu_L + C_V^{-}\bar{e}\gamma_{\mu}\nu_R\right) - \bar{p}\gamma^{\mu}\gamma_5 n\left(C_A^{+}\bar{e}\gamma_{\mu}\nu_L - C_A^{-}\bar{e}\gamma_{\mu}\nu_R\right)$$
$$- \bar{p}n\left(C_S^{+}\bar{e}\nu_L + C_S^{-}\bar{e}\nu_R\right)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

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

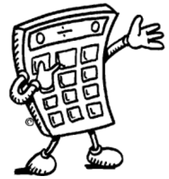
(+ mixing ratios)





Mirrors are very important

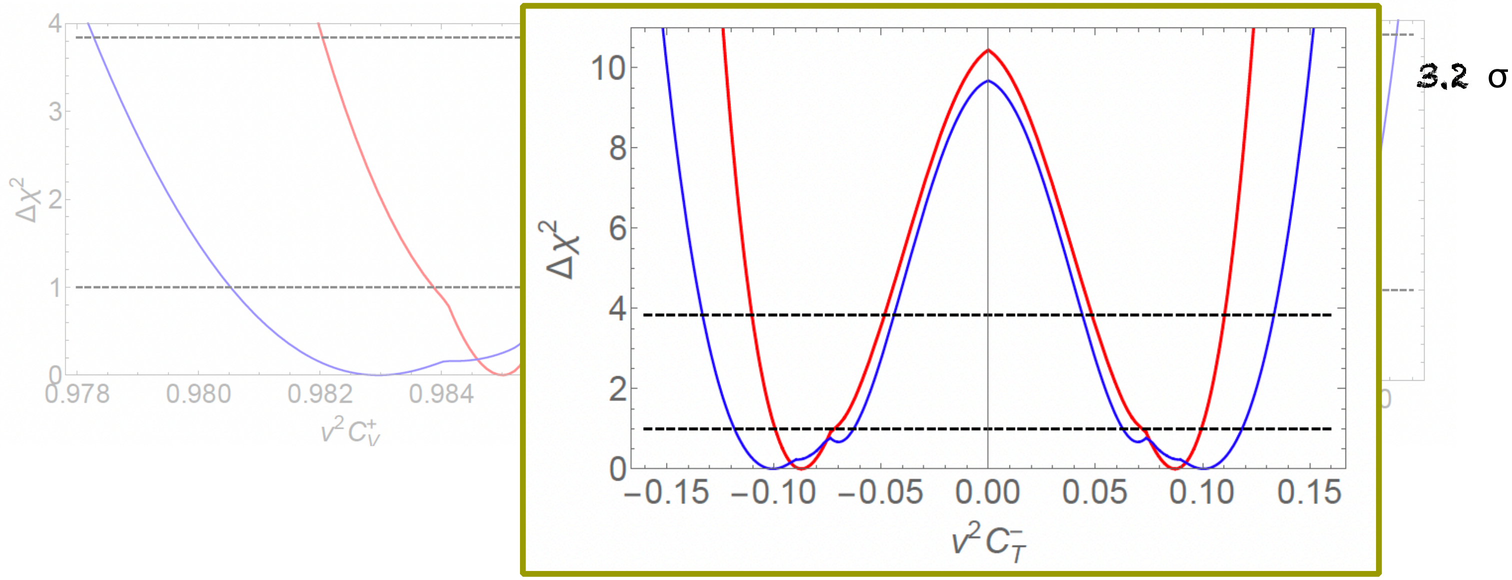
EFT with ν_L & ν_R



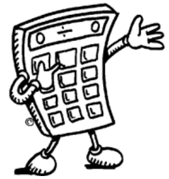
$$\mathcal{L}_{\text{Lee-Yang}} = -\bar{p}\gamma^\mu n\left(C_V^+\bar{e}\gamma_\mu\nu_L + C_V^-\bar{e}\gamma_\mu\nu_R\right) - \bar{p}\gamma^\mu\gamma_5 n\left(C_A^+\bar{e}\gamma_\mu\nu_L - C_A^-\bar{e}\gamma_\mu\nu_R\right)$$
$$- \bar{p}n\left(C_S^+\bar{e}\nu_L + C_S^-\bar{e}\nu_R\right) - \frac{1}{2}\bar{p}\sigma^{\mu\nu}n\left(C_T^+\bar{e}\sigma_{\mu\nu}\nu_L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

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

(+ mixing ratios)



EFT with ν_L & ν_R



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

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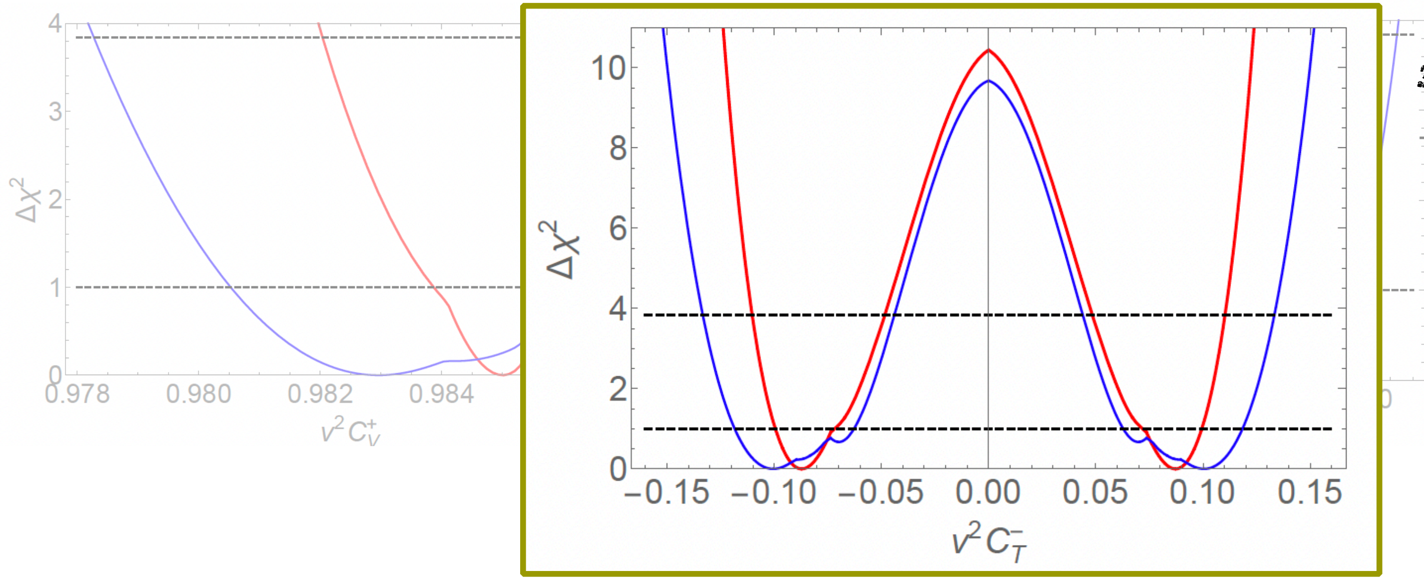
(+ mixing ratios)



3.2 σ

→ 1.8 σ w/o aSPECT'20:

$a_n = -0.10426(82)$

[SM: $-0.10655(13)$]

EFT with ν_L & ν_R

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(+ mixing ratios)

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

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

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

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

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

Beta decays at NLO in recoil

NEW

[Falkowski, MGA, Palavric & Rodríguez-Sánchez, 2112.07688]

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

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

$$+ \boxed{\bar{p}\gamma_5 n\left(C_P^{+}\bar{e}\nu_L\right.} \cancel{- C_P^{-}\bar{e}\nu_R\Big)} + \text{h.c.}$$

Beta decays at NLO in recoil

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[Falkowski, MGA, Palavric & Rodríguez-Sánchez, 2112.07688]

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

- The pseudoscalar contribution is zero at LO in recoil. But: $C_P = 346(9)\ \varepsilon_P$ [MGA & Camalich, PRL 112 (2014)]

Beta decays at NLO in recoil

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\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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Beta decays at NLO in recoil

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$$-\ \bar{p}n\left(C_S^+\bar{e}\nu_L + \cancel{C_S^-\bar{e}\nu_R}\right) - \frac{1}{2}\bar{p}\sigma^{\mu\nu}n\left(C_T^+\bar{e}\sigma_{\mu\nu}\nu_L + \cancel{C_T^-\bar{e}\sigma_{\mu\nu}\nu_R}\right)$$
$$+\ \bar{p}\gamma_5 n\left(C_P^+\bar{e}\nu_L \cancel{- C_P^-\bar{e}\nu_R}\right) + \text{h.c.}$$

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- Linear effects not only in b but also in ξ_b, a, A & B
- First bound on WEFT pseudoscalar interactions from β decays:

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

Beta decays at NLO in recoil

NEW

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

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

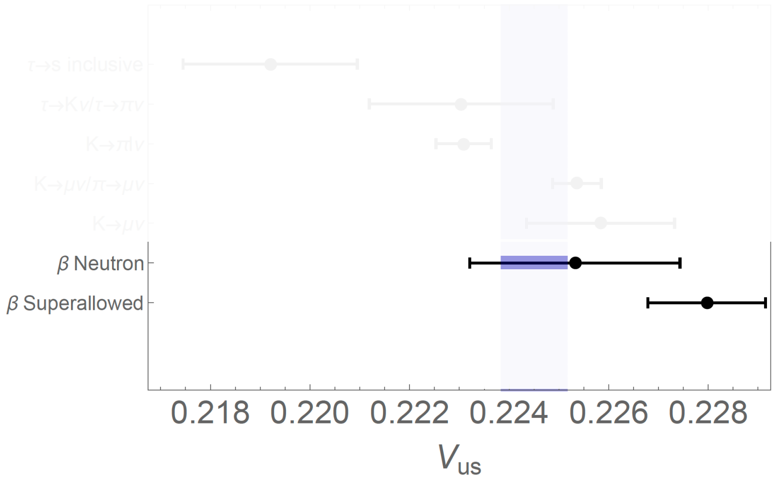
$$\mathcal{L}^{(1)} \supset -C_M^+ \frac{1}{2m_N}\epsilon^{ijk}(\psi_p^\dagger \sigma^j \psi_n)\nabla_i(\bar{e}_L\gamma^k\nu_L) \Longrightarrow C_M^+ = 3.5(1.0)/v^2$$

Beta decays & flavor

NEW

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

- SM limit:



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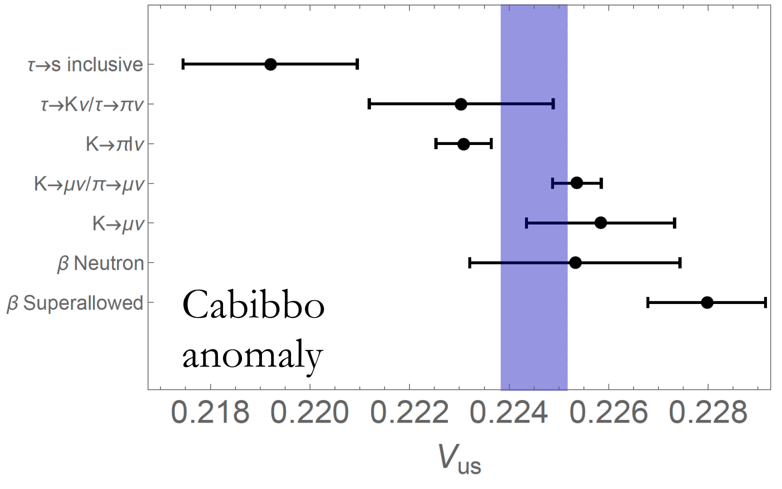

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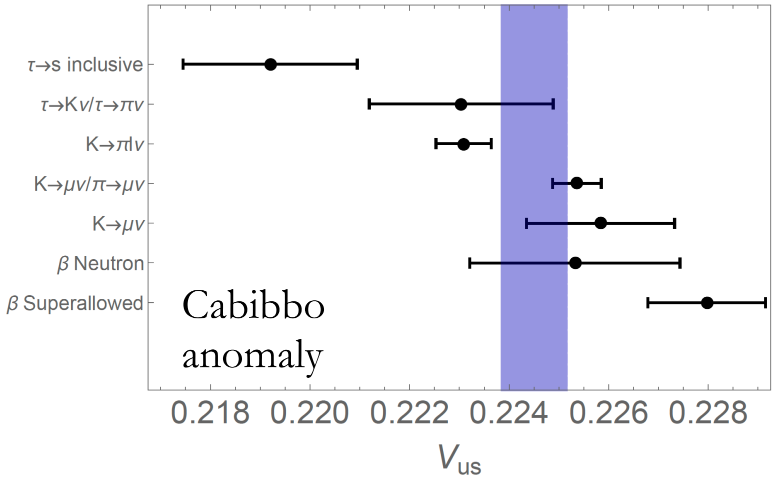
[Cirigliano, Díaz-Calderón, Falkowski, MGA & Rodríguez-Sánchez, JHEP04 (2022) 152]

- SM limit:



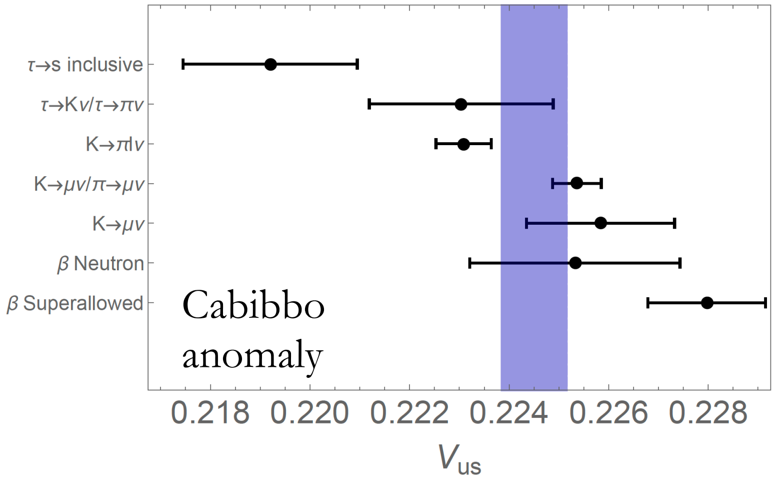
- BSM turned on => These processes do not probe the same quantity:

Beta decays & flavor

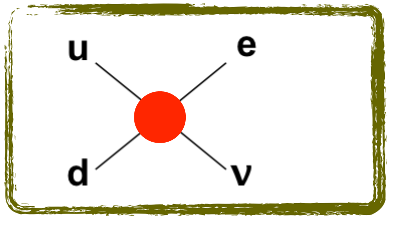
NEW

[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



Beta decays & flavor

NEW

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

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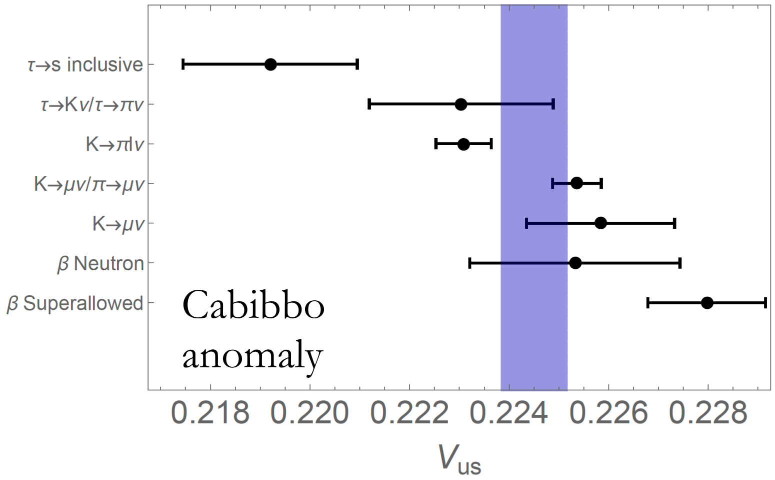
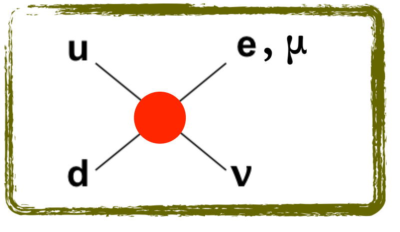


- BSM turned on => These processes do not probe the same quantity:
  - Beta decays → udeν
  - Pion decays → udeν & udμν



Beta decays & flavor

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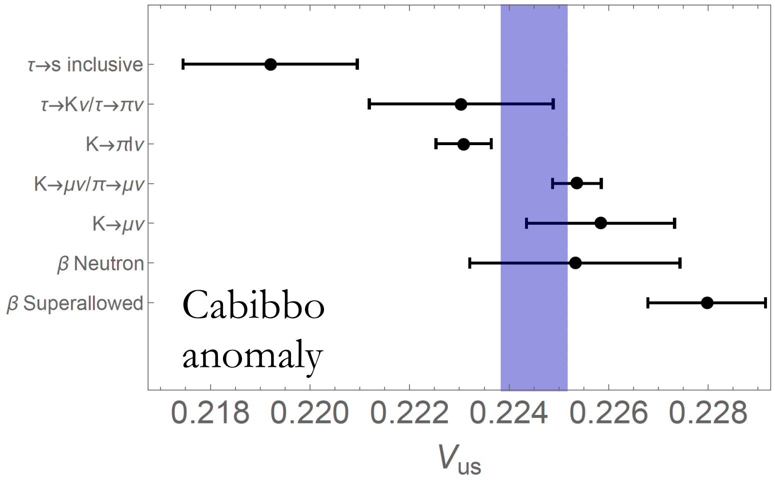

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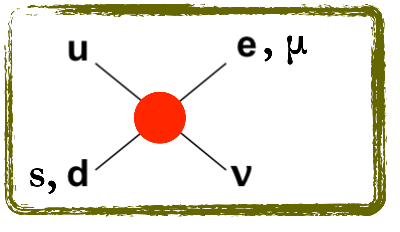
  - Pion decays → udeν & udμν
  - Kaon decays → useν & usμν



Beta decays & flavor

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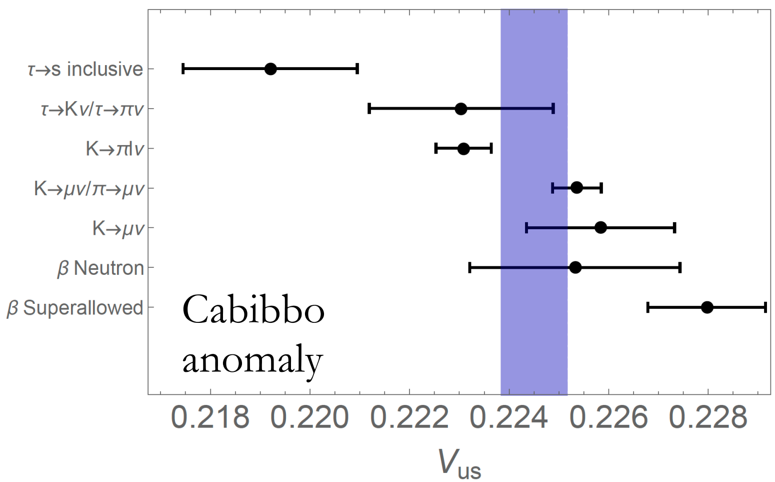

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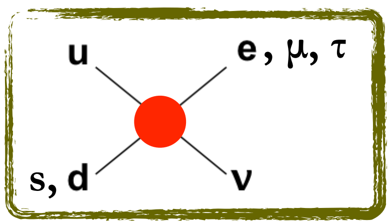
  - Pion decays → udeν & udμν
  - Kaon decays → useν & usμν
  - Tau decays → udτν & usτν



Beta decays & flavor

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

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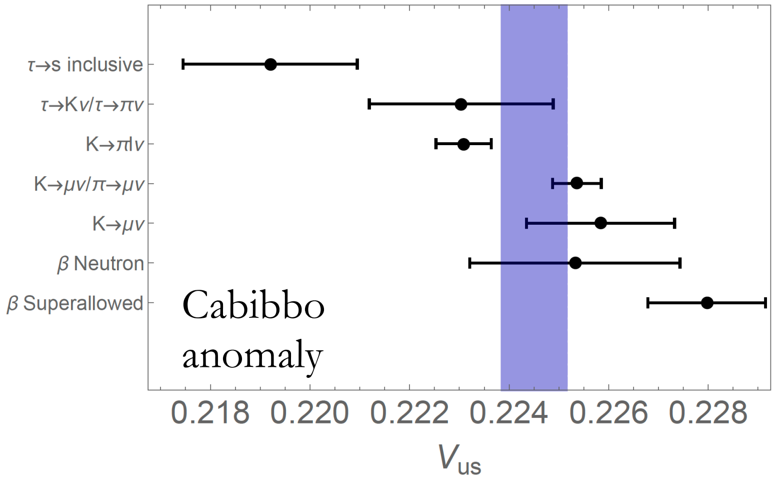

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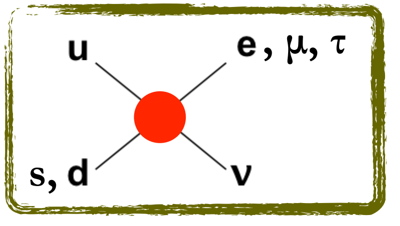

- Cross-correlations due to CKM, FFs, and lepton-universal RH currents (SMEFT)

Beta decays & flavor

NEW

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

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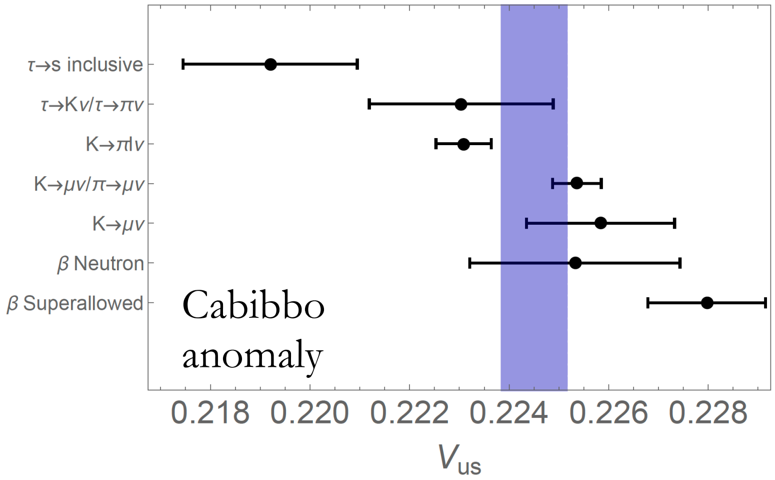

- BSM turned on => These processes do not probe the same quantity:
  - Beta decays ⟶ udeν
  - Pion decays ⟶ udeν & udμν
  - Kaon decays ⟶ useν & usμν
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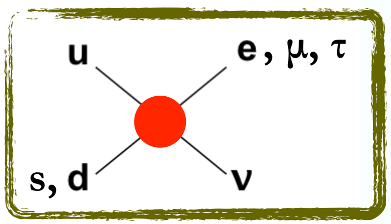

$$\mathscr{L}_{\rm WEFT} \supset -\sum_{D=d,s}\sum_{\ell=e,\mu,\tau}\frac{V_{uD}}{v^2}\Big\{ \left(1+\epsilon_L^{D\ell}\right)\ \bar{\ell}\gamma_\mu P_L \nu_\ell \cdot \bar{u}\gamma^\mu(1-\gamma_5)D + \epsilon_R^{D}\ \bar{\ell}\gamma_\mu P_L \nu_\ell \cdot \bar{u}\gamma^\mu(1+\gamma_5)D + \epsilon_T^{D\ell}\frac{1}{4}\bar{\ell}\sigma_{\mu\nu}P_L\nu_\ell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

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

Beta decays & flavor

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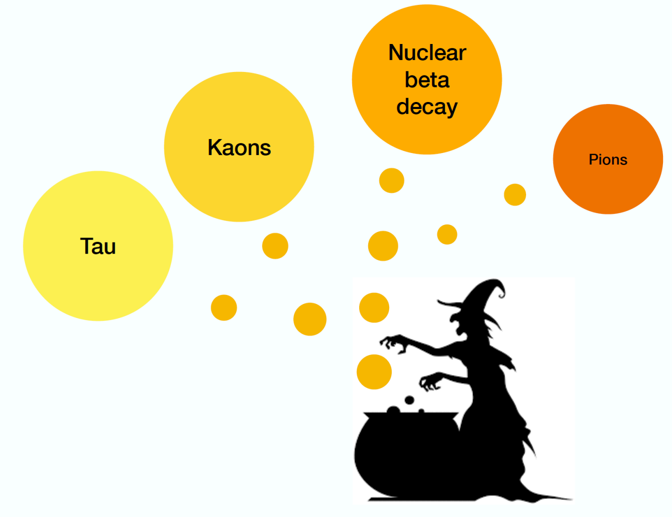

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Beta decays & flavor

NEW

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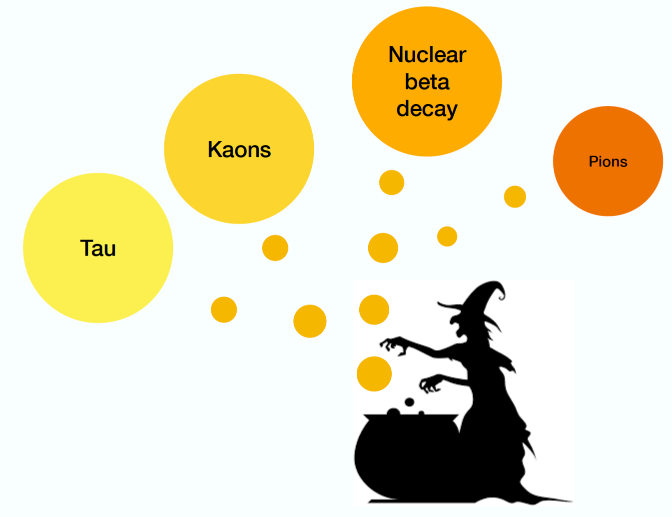


$$\mathcal{L}_{\rm WEFT} \supset -\sum_{D=d,s}\sum_{\ell=e,\mu,\tau} \frac{V_{uD}}{v^2}\Big\{ \left(1+\epsilon_L^{D\ell}\right) \bar\ell\gamma_\mu P_L\nu_\ell\cdot\bar u\gamma^\mu(1-\gamma_5)D$$
$$+\epsilon_R^{D} \bar\ell\gamma_\mu P_L \nu_\ell \cdot \bar u\gamma^\mu(1+\gamma_5)D$$
$$+\epsilon_T^{D\ell}\frac{1}{4}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

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

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

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

- Large correlations!

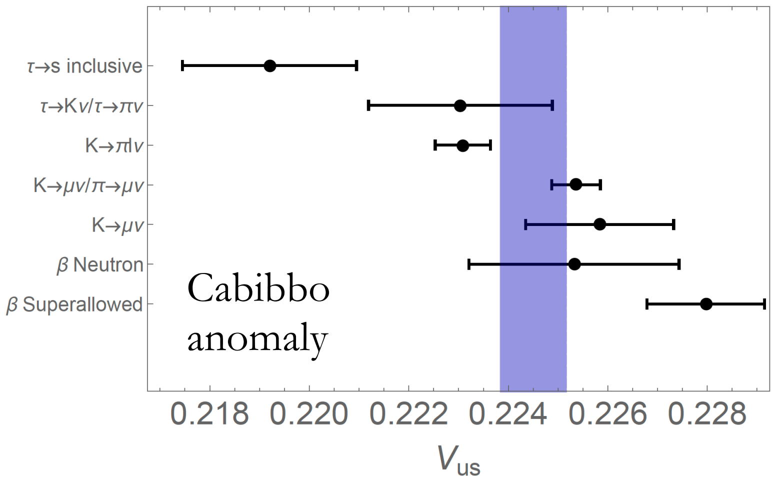
- 3σ preference for NP

Beta decays & flavor

NEW

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

- SM limit:



- 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, ...

Beta decays & flavor

NEW

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

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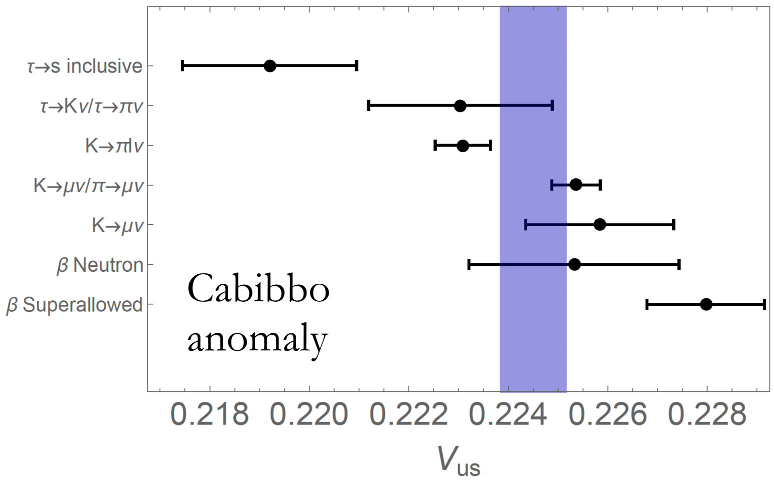

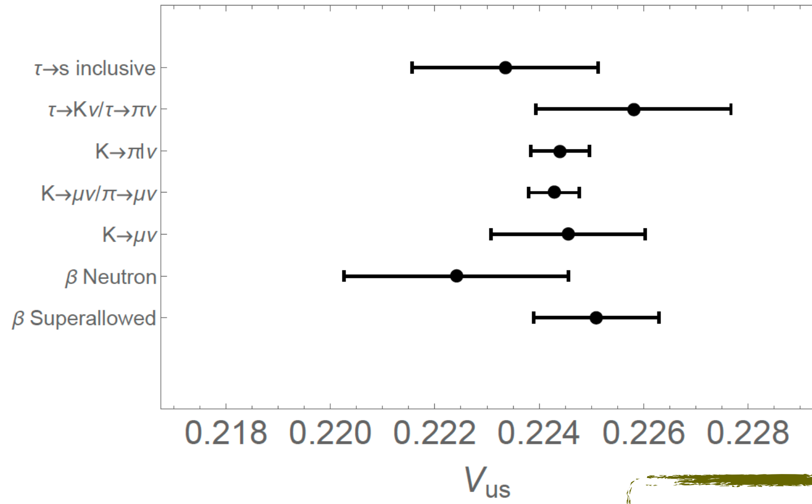

4.4 σ !

$$\epsilon_R^d = -6.8 \times 10^{-4}, \quad \epsilon_R^s = -5.9 \times 10^{-3}, \quad \epsilon_L^{s\tau} = -1.8 \times 10^{-2}.$$

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

	$\epsilon_X^{de} \times 10^3$	$\epsilon_X^{se} \times 10^3$	$\epsilon_X^{d\mu} \times 10^3$	$\epsilon_X^{s\mu} \times 10^3$	$\epsilon_X^{d\tau} \times 10^3$	$\epsilon_X^{s\tau} \times 10^3$
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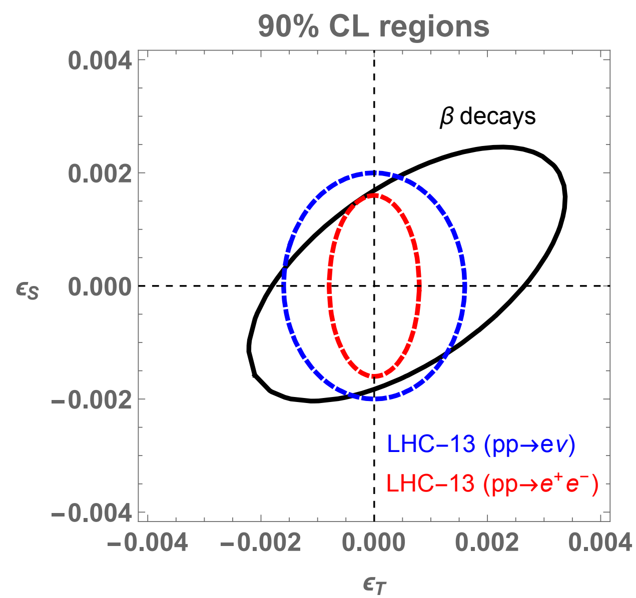
Conclusions

- (Sub) permil-level precision in β decays
- Great laboratory for nuclear, hadronic and particle physics
- Progress in all fronts:
  - Experiments!
  - Lattice QCD;
  - Rad. corrections: SM & EFT RGEs.
  - Inclusion of new data (mirror decays);
  - Full LO fit;
  - First NLO fits;
  - SMEFT: combination with flavor (Cabibbo anomaly), comparison with LHC, LEP, or even neutrino oscillations [Falkowski-MGA-Tabrizi, 2019]

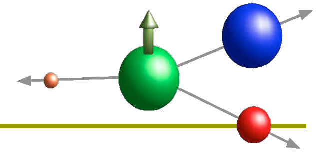
    → β decays are competitive TeV probes;

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



Backup slides

Hadronic EFT



[Lee & Yang'1956]

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

$$
\begin{aligned}
C_X &= (C_X^+ + C_X^-)/2\\
C'_X &= (C_X^+ - C_X^-)/2
\end{aligned}
$$

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

For some transitions and observables:

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

High precision measurements

UV meaning of the C coefficients?
(within & beyond the SM)
(hadronization, RC, EFT, ...)

Hadronic EFT

SM terms

$$-\mathcal{L}_{n\to pe^-\bar\nu_e} = C_V \left(\bar p\gamma^\mu n + \frac{C_A}{C_V}\bar p\gamma^\mu\gamma_5 n\right) \times \bar e\gamma_\mu(1-\gamma_5)\nu_e$$

$$+ C_S\, \bar p\, n \times \bar e(1-\gamma_5)\nu_e + \frac{1}{2}C_T\, \bar p\sigma^{\mu\nu}n \times \bar e\sigma_{\mu\nu}(1-\gamma_5)\nu_e$$

$$- C_P\, \bar p\gamma_5 n \times \bar e(1-\gamma_5)\nu_e + \text{h.c.}$$

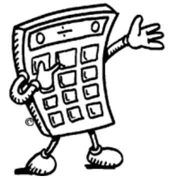
+ terms with RH neutrinos

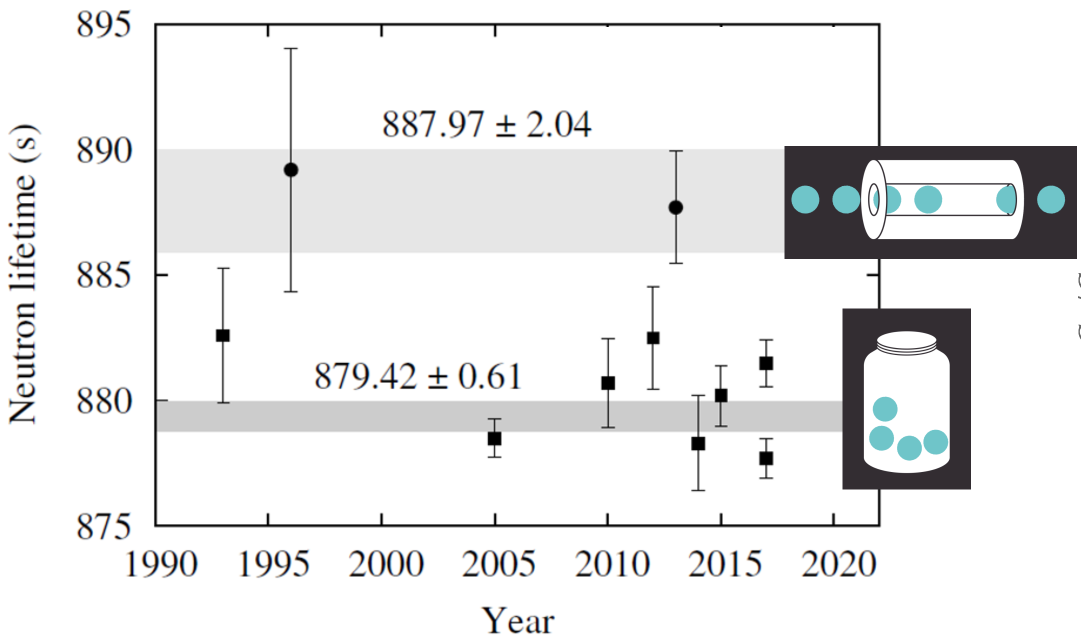
+ terms with ν_μ or ν_τ neutrinos

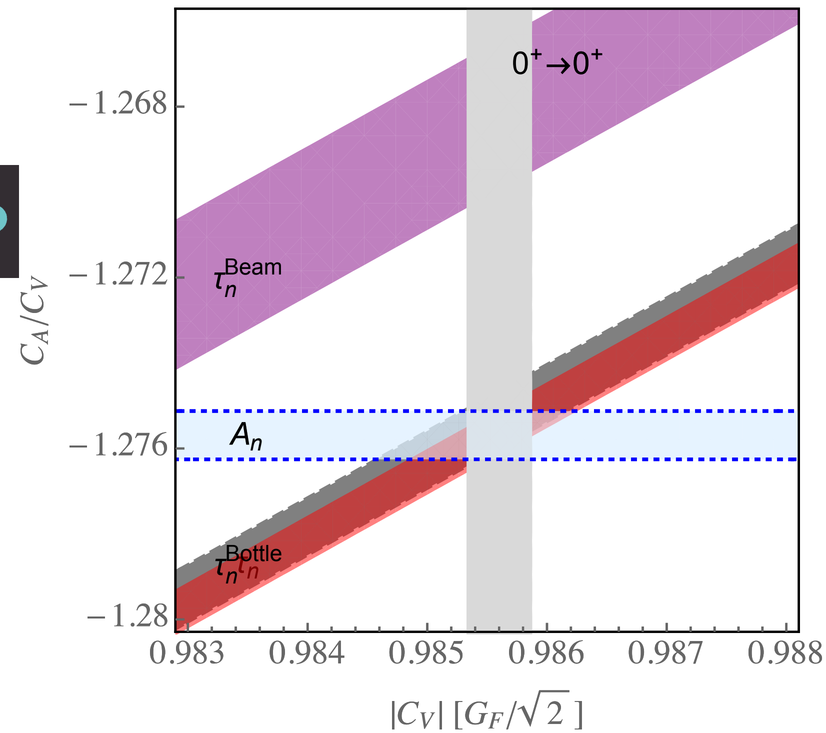
Bounds first derived in [Falkowski-MGA-Tabrizi, JHEP 2019]: 90%CL bound = O(0.01)

[PS: neutrino oscillation experiments are less precise but linearly sensitive]

SM fit







Heavy NP cannot explain the beam vs. bottle tension

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

From hadrons to quarks

Likewise...

[MGA & Martin Camalich, Phys. Rev. Lett. 112 (2014)]

$$\partial_\mu \left(\bar{u}\gamma^\mu\gamma_5 d\right) = i(m_d + m_u)\bar{u}\gamma_5 d \quad \Rightarrow \quad g_P = \frac{M_n + M_p}{m_d + m_u} g_A = 348(11)$$

Implications? It almost compensates the bilinear suppression!

$$\langle p(p_p)|\bar{u}\gamma_5 d|n(p_n)\rangle = g_P(q^2)\bar{u}_p(p_p)\gamma_5 u_n(p_n)$$

$\sim q/M \sim 10^{-3}$

"since the nucleons are treated nonrelativistically, the pseudoscalar couplings are omitted"

[Jackson, Treiman & Wyld, 1957]

The same β decay experiments that set bounds on S & T, are also sensitive to P!

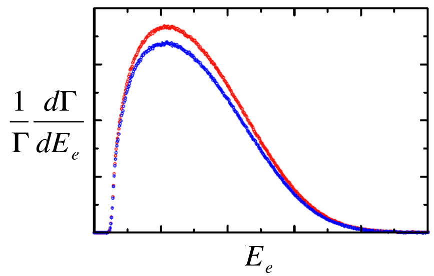
Probing scalar/tensor interactions

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

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

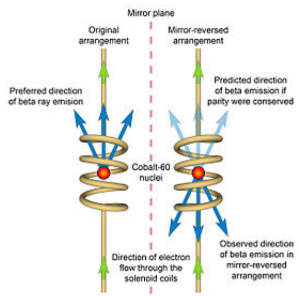
(Fierz term)

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



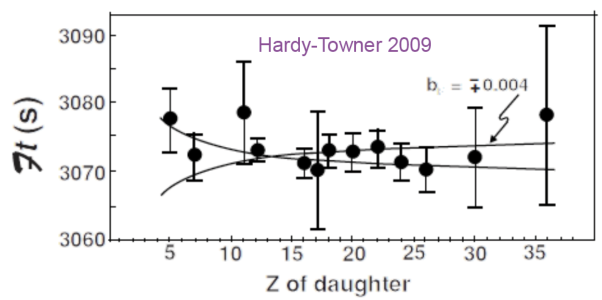
✓ Indirect effect in the asymmetries:

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



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

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



Beta decays at NLO in recoil

[Falkowski, MGA, Palavric & Rodríguez-Sánchez, 2112.07688]

$$\mathcal{L}_{\not\pi\mathrm{EFT}} \supset \mathcal{L}^{(0)} + \mathcal{L}^{(1)} + \mathcal{O}(\boldsymbol{\nabla}^2/m_N^2) + \mathrm{h.c.}\,,$$

$$\mathcal{L}^{(0)} = -(\psi_p^\dagger \psi_n)\Big[C_V^+ \bar{e}_L \gamma^0 \nu_L + C_S^+ \bar{e}_R \nu_L\Big] + (\psi_p^\dagger \sigma^k \psi_n)\Big[C_A^+ \bar{e}_L \gamma^k \nu_L + C_T^+ \bar{e}_R \gamma^0 \gamma^k \nu_L\Big]$$

$$\begin{aligned}\mathcal{L}^{(1)} =& \frac{1}{2m_N}\Big\{ iC_P^+ (\psi_p^\dagger \sigma^k \psi_n)\nabla_k(\bar{e}_R \nu_L) - C_M^+ \epsilon^{ijk} (\psi_p^\dagger \sigma^j \psi_n)\nabla_i(\bar{e}_L \gamma^k \nu_L) \\ & - iC_E^+ (\psi_p^\dagger \sigma^k \psi_n)\nabla_k(\bar{e}_L \gamma^0 \nu_L) - iC_{E'}^+ (\psi_p^\dagger \sigma^k \psi_n)\partial_t(\bar{e}_L \gamma^k \nu_L) \\ & - iC_{T1}^+ (\psi_p^\dagger \psi_n)\nabla_k(\bar{e}_R \gamma^0 \gamma^k \nu_L) + iC_{T2}^+ (\psi_p^\dagger \psi_n)(\bar{e}_R \overleftrightarrow{\partial_t} \nu_L) + 2iC_{T3}^+ (\psi_p^\dagger \sigma^k \psi_n)(\bar{e}_R \overleftrightarrow{\nabla}_k \nu_L) \\ & - iC_{FV}^+ (\psi_p^\dagger \overleftrightarrow{\nabla}_k \psi_n)(\bar{e}_L \gamma^k \nu_L) + iC_{FA}^+ (\psi_p^\dagger \sigma^k \overleftrightarrow{\nabla}_k \psi_n)(\bar{e}_L \gamma^0 \nu_L) + C_{FT}^+ \epsilon^{ijk} (\psi_p^\dagger \sigma^i \overleftrightarrow{\nabla}_j \psi_n)(\bar{e}_R \gamma^0 \gamma^k \nu_L) \Big\},\end{aligned}$$

Beta decays at NLO in recoil

NEW

[Falkowski, MGA, Palavric & Rodríguez-Sánchez, 2112.07688]

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

- The pseudoscalar contribution is zero at LO in recoil. But… $C_P = 346(9)\,\varepsilon_P$ [MGA & Camalich, PRL 112 (2014)]

- Linear effects not only in b but also in ξ_b, a, A & B →

$$\xi_b(E_e) = \frac{m_e}{3m_N}\left[\frac{E_e^{\rm max}}{E_e} - 1\right]\frac{r^2 C_A^{+} C_P^{+}}{(C_V^{+})^2 + r^2 (C_A^{+})^2},$$
$$\Delta a(E_e) = \frac{m_e}{3m_N}\frac{r^2 C_A^{+} C_P^{+}}{(C_V^{+})^2 + r^2 (C_A^{+})^2},$$
$$\Delta A(E_e) = -\frac{m_e}{m_N}\sqrt{\frac{J}{J+1}}\frac{r C_V^{+} C_P^{+}}{(C_V^{+})^2 + r^2 (C_A^{+})^2},$$
$$\Delta B(E_e) = -\frac{m_e}{m_N}\left[\frac{E_e^{\rm max}}{E_e} - 1\right]\sqrt{\frac{J}{J+1}}\frac{r C_V^{+} C_P^{+}}{(C_V^{+})^2 + r^2 (C_A^{+})^2}.$$

- First bound on WEFT pseudoscalar interactions from β decays:

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

PS: The bound on ε_P from pion decays is much stronger

$$|\mathcal{A}(\pi \to \ell\nu)|^2 \sim m_\ell^2\left(1 + \frac{M_{QCD}}{m_\ell}\epsilon_P\right)^2$$