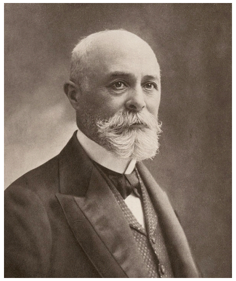
New Physics searches from CP-conserving observables in β decay

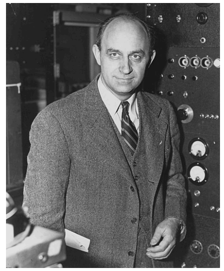
MORA international workshop May 2022

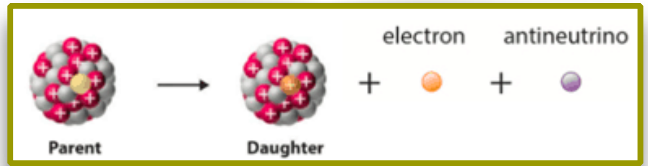
Martín González-Alonso
IFIC, Univ. of Valencia / CSIC

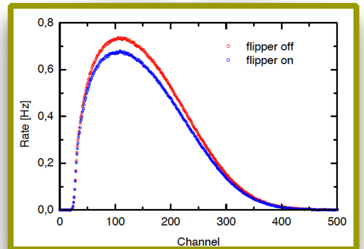
CP-cons. observables in

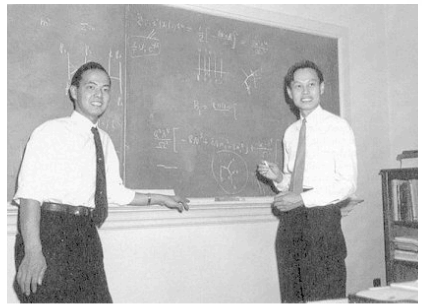
Beta decays: a trove of discoveries

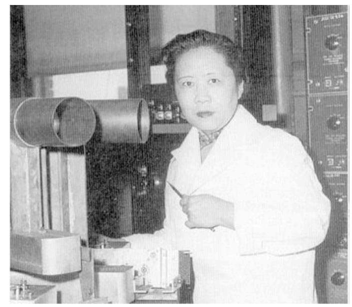




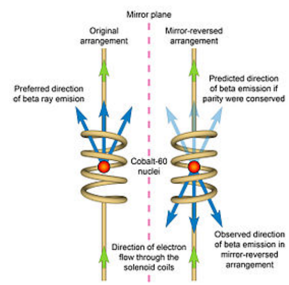








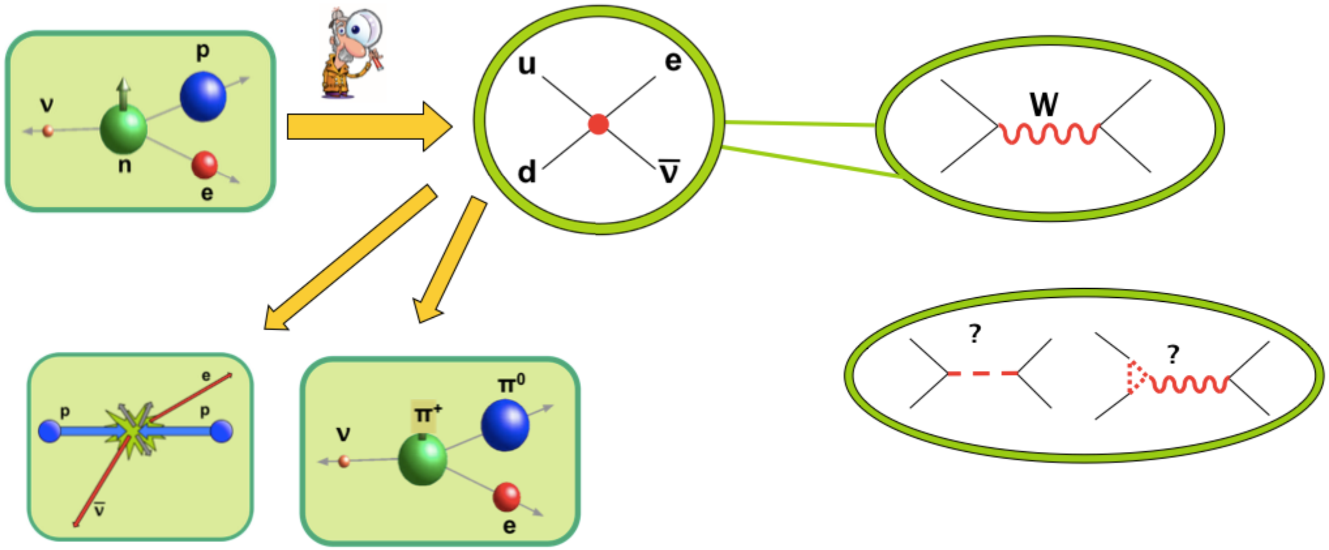
$$
\begin{aligned}
-\mathcal{L}_{n\to pe^-\bar{\nu}_e} \;=\;\; & \bar{p}\, n\;\left(C_S \bar{e}\nu_e - C'_S \bar{e}\gamma_5\nu_e\right) \\
& + \bar{p}\gamma^\mu n\left(C_V \bar{e}\gamma_\mu\nu_e - C'_V \bar{e}\gamma_\mu\gamma_5\nu_e\right) \\
& + \frac{1}{2}\bar{p}\sigma^{\mu\nu} n\left(C_T \bar{e}\sigma_{\mu\nu}\nu_e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



CP-cons. observables in

Beta decays: a trove of discoveries

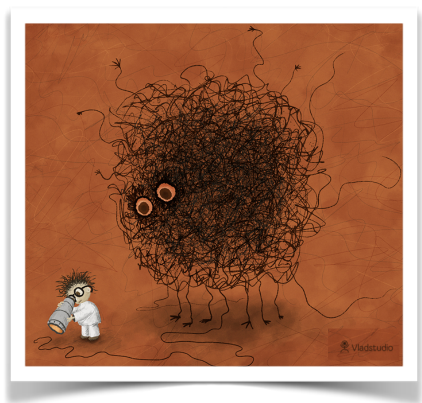
- Then the **EW theory** and the SM came…



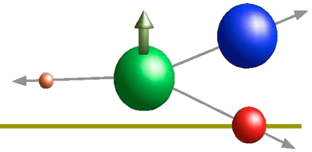
- Next?
  - Beta decay = precision field (TH + EXP)
  - We are playing the same old game, but we are looking for a small contribution on top of the dominant V-A interaction.

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

- Competitive probes?



Comparing experiments



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

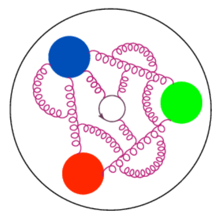
$$
\begin{aligned}
-\mathcal{L}_{n\to pe^-\bar\nu_e} = \; & \bar p\, n\, \left(C_S \bar e \nu_e - C'_S \bar e \gamma_5 \nu_e\right) \\
& + \bar p \gamma^\mu n \left(C_V \bar e \gamma_\mu \nu_e - C'_V \bar e \gamma_\mu \gamma_5 \nu_e\right) \\
& + \frac{1}{2} \bar p \sigma^{\mu\nu} n \left(C_T \bar e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

[Lee & Yang'1956]

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

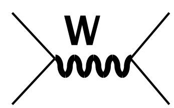
$$
\mathcal{L}_{d\to u\ell^-\bar\nu_\ell} = -\frac{4G_F V_{ij}}{\sqrt{2}} \left[\bar\ell_L \gamma_\mu \nu \cdot \bar u \gamma^\mu d_L \; + \; \sum_{\rho\delta\Gamma} \epsilon^{\Gamma}_{\rho\delta}\, \bar\ell_\rho \Gamma \nu \cdot \bar u \Gamma d_\delta \right]
$$

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



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

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



Hadronic EFT

[Lee & Yang'1956]

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

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

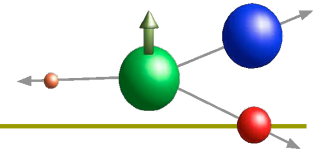
$$d\Gamma \approx f(C_i, M_F, M_{GT})$$

For some transitions and observables:

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

High precision measurements

Hadronic EFT



[Lee & Yang'1956]

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

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

$$C_X = (C_X^+ + C_X^-)/2$$
$$C'_X = (C_X^+ - C_X^-)/2$$

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

For some transitions and observables:

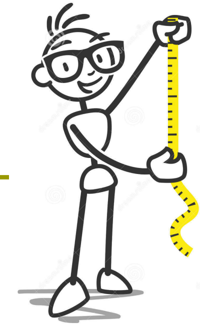
$\mathcal{O} \approx f(C_i)$ + small corrections

High precision measurements

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

Current data (+ 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
^{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	$-0.10426(82)$	
$\tilde{a}_n$	$-0.1078(18)$	

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

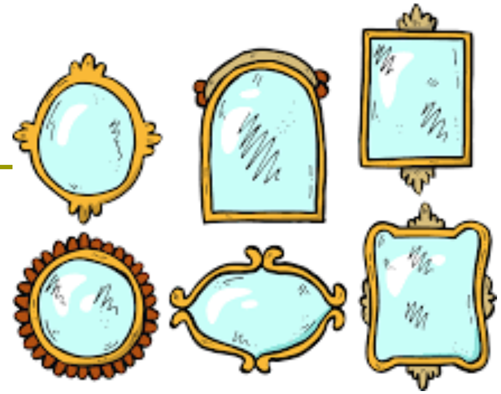
RECENT:
Perkeo-III, PRL122 (2019): A_n
aSPECT, PRC101 (2020): a_n
aCORN, PRC103 (2021): a_n
UCNτ, PRL127 (2021): τ_n

Th: QED + Isospin symmetry breaking corrections

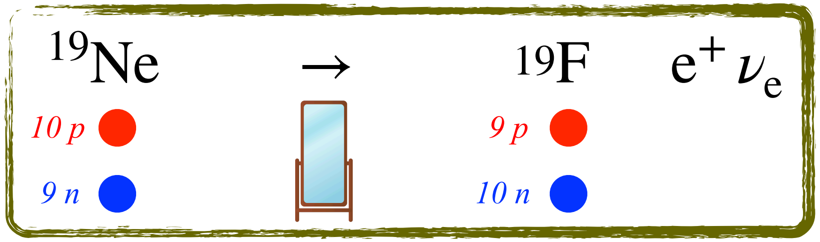
$$\mathcal{F}t_i \equiv ft_i\,(1+\delta_R')\,(1+\delta_{NS}-\delta_C)$$

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 $p \leftrightarrow n$)



- Many per-mil level determinations of the Ft values! (Exp + Th)
  [Severijns et al, PRC78 (2008); Hayen & Severijns, 1906.09870; etc.]

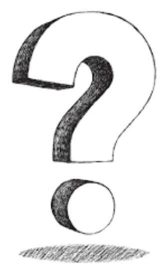
- M_{GT} / M_F ratio needed: $$\mathcal{O} \approx f(C_i, M_{GT}/M_F) \approx f(C_i, \rho)$$

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

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

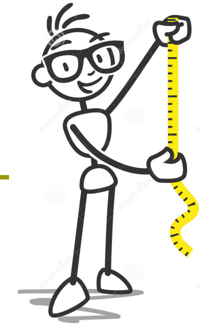
- SM analysis: [Naviliat-Cuncic & Severijns, PRL102 (2009)]
  V_{ud} can be extracted with 0.1% precision!
  Although (*currently*) not competitive, it's a nontrivial crosscheck;

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



Current data (+ TH!!)

Precision: O(0.01 – 1)% !!



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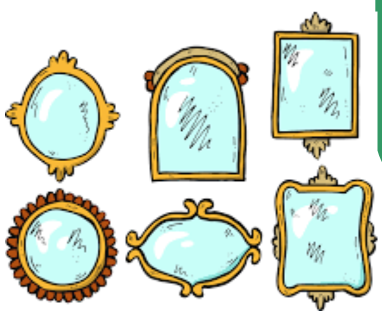
λ_{AB}	−1.2686(47)	
a_n	−0.10426(82)	
$\tilde{a}_n$	−0.1090(41)	

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

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



RECENT:
Fenker et al., PRL120 (2018): A_{K-37}
Combs et al., 2009.13700: A_{Ne-19}
Hayen, 2010.07262: f_A/f_V values
...

Standard Model fit:

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

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

SM fit

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

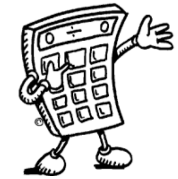
$$\rightarrow C_V^+ = 0.98576(22)\, G_F/\sqrt{2}$$

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

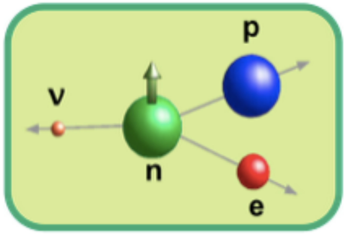
$$\rho \approx -1.2757 \frac{M_{GT}}{M_F}$$

Impressive precision!

SM fit



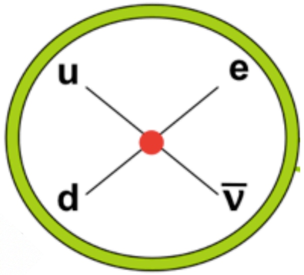
$$\begin{pmatrix} v^2 C_V^+ \\ v^2 C_A^+ \\ \rho_F \\ \rho_{Ne} \\ \rho_{Na} \\ \rho_P \\ \rho_{Ar} \\ \rho_K \end{pmatrix} = \begin{pmatrix} 0.98576(22) \\ -1.25754(39) \\ -1.2955(13) \\ 1.60157(75) \\ -0.[illegible]127(11) \\ -0.[illegible]380(21) \\ -[illegible]34(25) \\ 0.5787(20) \end{pmatrix}$$



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

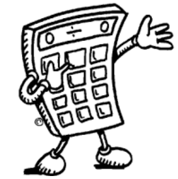
$$C_V^+ = \frac{V_{ud}}{v^2} g_V \sqrt{1+\Delta_R^V}$$

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



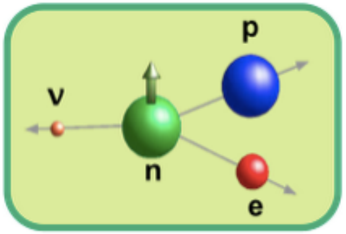
$$\mathscr{L}^{eff}_{d\to ue\nu} = -\frac{V_{ud}}{v^2}\bar{u}\gamma^\mu(1-\gamma_5)d\; \bar{e}\gamma^\mu(1-\gamma_5)\nu_e$$

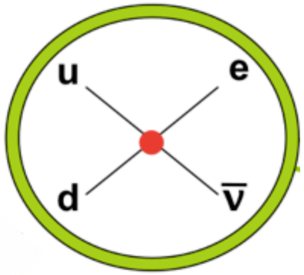
SM fit



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

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

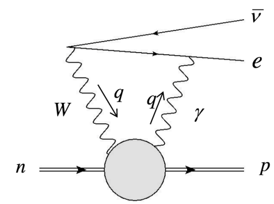




$$C_V^+ = \frac{V_{ud}}{v^2} g_V \sqrt{1 + \Delta_R^V}$$
$$C_A^+ = -\frac{V_{ud}}{v^2} g_A \sqrt{1 + \Delta_R^A}$$

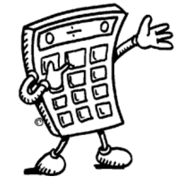
Inner RC:

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



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

SM fit



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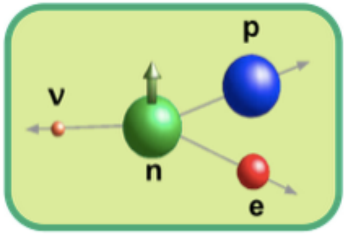

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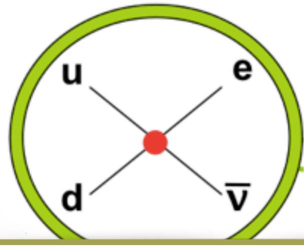

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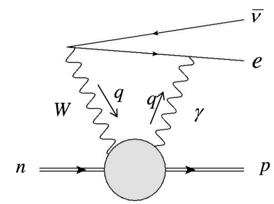

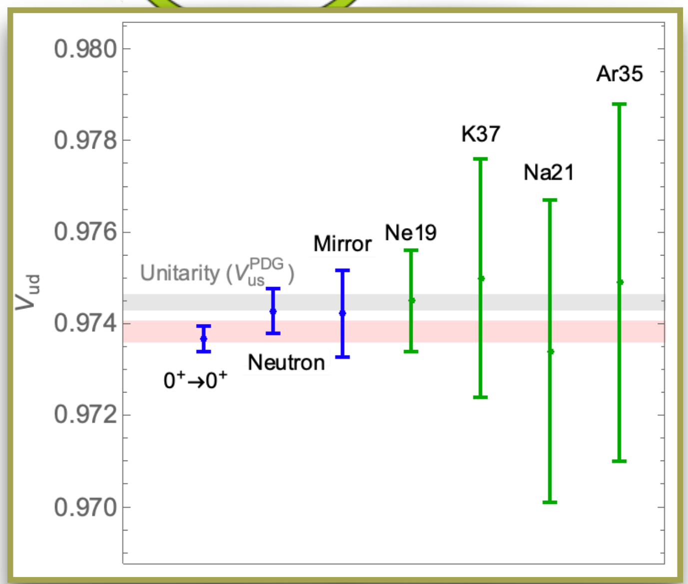

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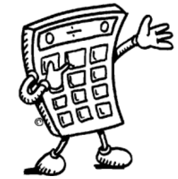
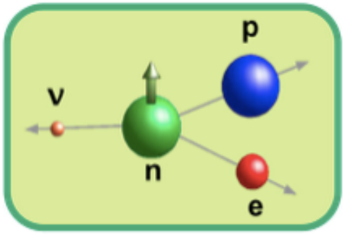


$$\begin{pmatrix} v^2 C_V^+ \\ v^2 C_A^+ \\ \rho_F \\ \rho_{Ne} \\ \rho_{Na} \\ \rho_P \\ \rho_{Ar} \\ \rho_K \end{pmatrix} = \begin{pmatrix} 0.98576(22) \\ -1.25754(39) \\ -1.2955(13) \\ 1.60157(75) \\ -0.\ldots127(11) \\ -0.\ldots380(21) \\ -\ldots34(25) \\ 0.5787(20) \end{pmatrix}$$



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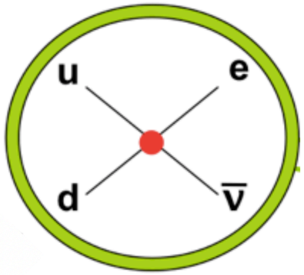

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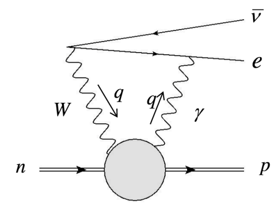
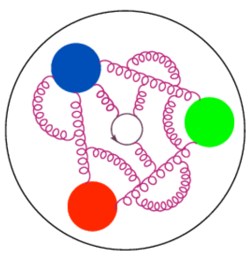




Axial charge

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

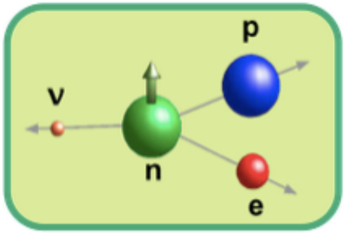
g_A = 1.2642(93) CalLat, Nature'18 + update

g_A = 1.218(39) PNDME, PRD'18

g_A = 1.246(28) FLAG'21

SM fit

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



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

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

EFT with ν_L

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

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

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

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

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

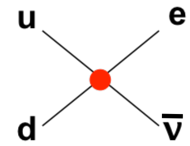
S and T affect the angular distributions and the spectrum!!

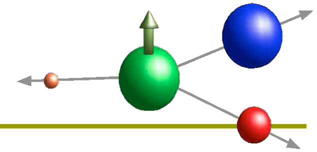
$$\frac{d\Gamma(\mathbf{J})}{dE_e d\Omega_e d\Omega_\nu} \sim \xi(E) \left\{ 1 + a\frac{\mathbf{p}_e \cdot \mathbf{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + A\frac{\mathbf{p}_e}{E_e}\frac{\mathbf{J}}{J} + \left(B + b_B\frac{m_e}{E_e}\right)\frac{\mathbf{p}_\nu}{E_\nu}\frac{\mathbf{J}}{J} \right\}$$

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

Fierz term [1937]

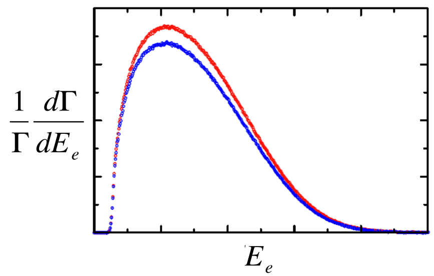
Probing the Fierz term





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

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

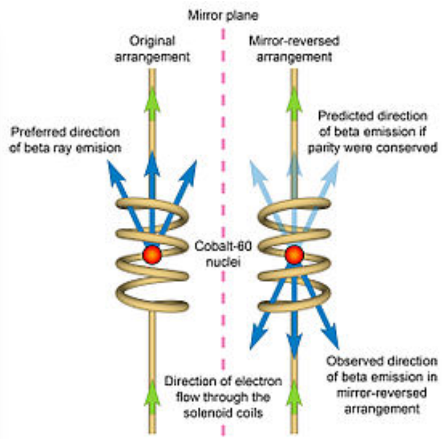


Optimal endpoint: 1-4 MeV
[MGA & Naviliat-Cuncic, PRC94 (2016)]

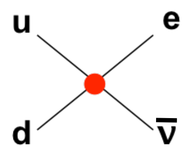
✓ Indirect effect in the asymmetries:

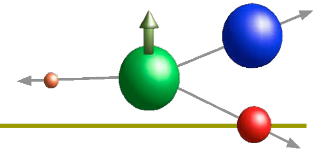
$$\tilde{X} = \frac{X}{1 + b\langle m/E_e\rangle}$$

PS: Not always valid! (proton spectrum)
[MGA & Naviliat-Cuncic, PRC94 (2016)]



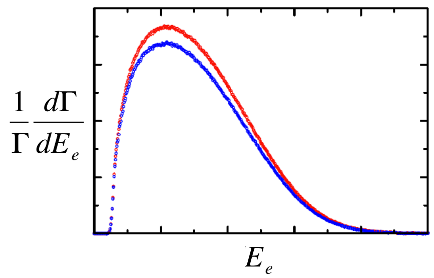
Probing the Fierz term





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

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



Optimal endpoint: 1-4 MeV
[MGA & Naviliat-Cuncic, PRC94 (2016)]

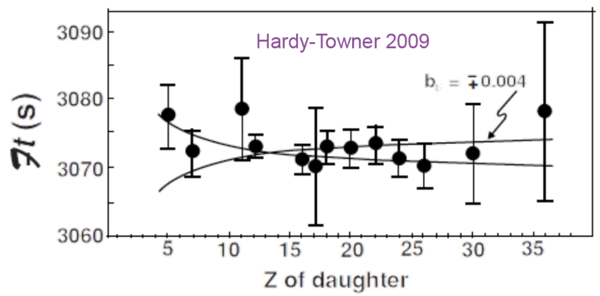
✓ Indirect effect in the asymmetries:

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

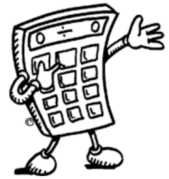
PS: Not always valid! (proton spectrum)
[MGA & Naviliat-Cuncic, PRC94 (2016)]

✓ 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 ν_L



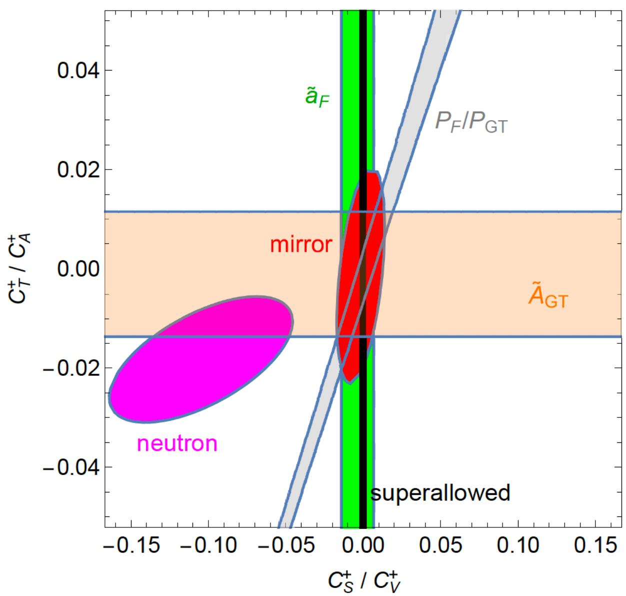
$$\mathcal{L}_{\text{Lee-Yang}} = -\bar{p}\gamma^{\mu}n\left(C_V^{+}\bar{e}\gamma_{\mu}\nu_L + \cancel{C_V^{-}\bar{e}\gamma_{\mu}\nu_R}\right) - \bar{p}\gamma^{\mu}\gamma_5 n\left(C_A^{+}\bar{e}\gamma_{\mu}\nu_L - \cancel{C_A^{-}\bar{e}\gamma_{\mu}\nu_R}\right)$$
$$- \bar{p}n\left(C_S^{+}\bar{e}\nu_L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

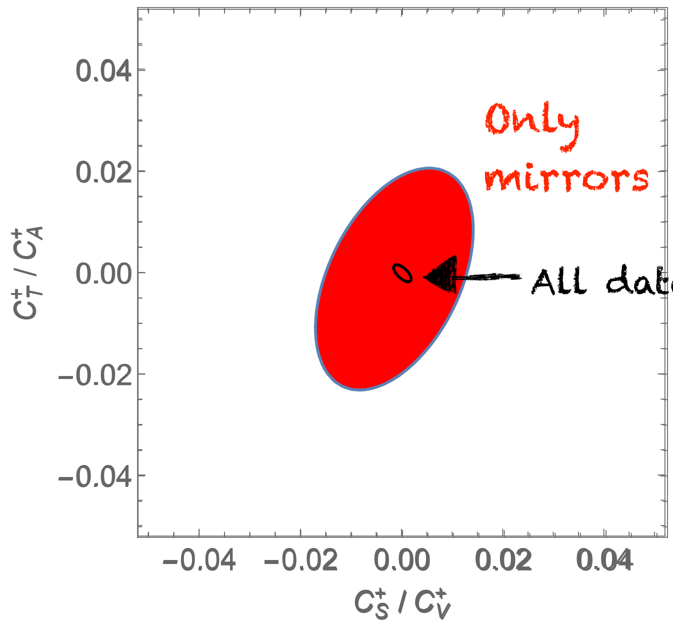
$$v^2\begin{pmatrix} C_V^{+} \\ C_A^{+} \\ C_S^{+} \\ C_T^{+} \end{pmatrix} = \begin{pmatrix} 0.98576(41) \\ -1.25740(54) \\ 0.0002(10) \\ 0.0005(12) \end{pmatrix}$$

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

(+ mixing ratios)

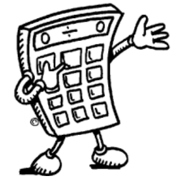
Role of mirror transitions?



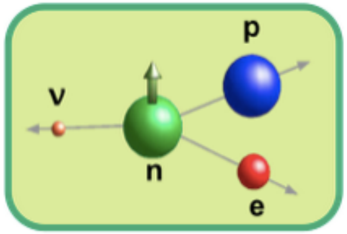


Driven by Ft(0->0), τ_n, A_n!

EFT with ν_L

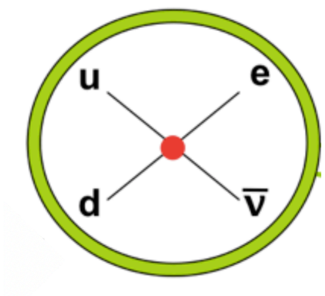


$$v^2 \begin{pmatrix} C_V^+ \\ C_A^+ \\ C_S^+ \\ C_T^+ \end{pmatrix} = \begin{pmatrix} 0.98576(41) \\ -1.25712(55) \\ 0.0002(10) \\ 0.0006(12) \end{pmatrix},$$

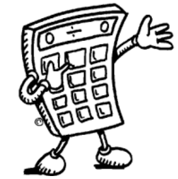


$$\begin{aligned} \mathcal{L} = \; & \bar{p}\, n \; (C_S \bar{e}\nu_e - C'_S \bar{e}\gamma_5\nu_e) \\ & + \bar{p}\gamma^\mu n\, (C_V \bar{e}\gamma_\mu\nu_e - C'_V \bar{e}\gamma_\mu\gamma_5\nu_e) \\ & + \frac{1}{2}\bar{p}\sigma^{\mu\nu} n\, (C_T \bar{e}\sigma_{\mu\nu}\nu_e - C'_T \bar{e}\sigma_{\mu\nu}\gamma_5\nu_e)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

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



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



EFT with ν_L

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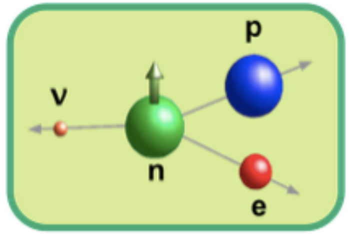


$\hat{V}_{ud}$

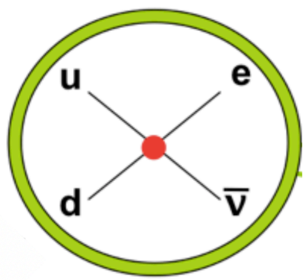
$$C_V^+ = \frac{V_{ud}\left(1+\epsilon_L+\epsilon_R\right)}{v^2}\sqrt{1+\Delta_R^V}$$

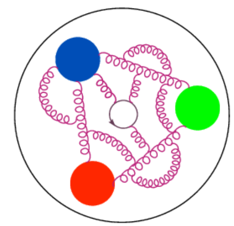
$$C_A^+ \approx -\frac{\hat{V}_{ud}}{v^2}\sqrt{1+\Delta_R^A}\, g_A \left(1-2\,\epsilon_R\right)$$

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

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

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

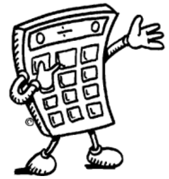




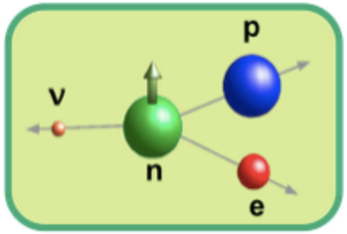
Nucleon charges

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

EFT with ν_L



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



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

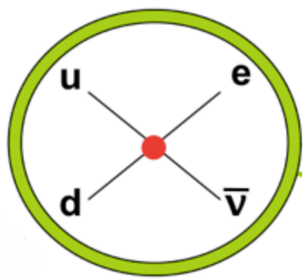
$\hat{V}_{ud}$

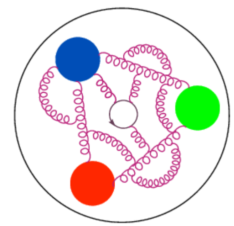
$$C_A^+ \approx -\frac{\hat{V}_{ud}}{v^2}\sqrt{1+\Delta_R^A}\, g_A \left(1-2\,\epsilon_R\right)$$

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

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

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





Nucleon charges

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

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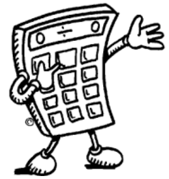
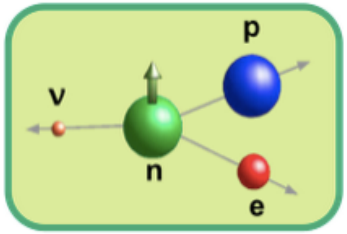
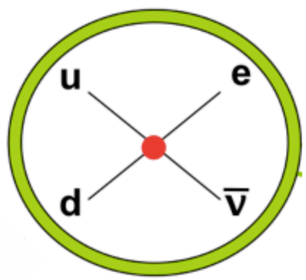
EFT with νL



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



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



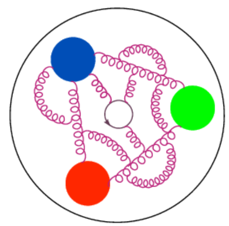
$\hat{V}_{ud}$

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

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

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

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



Nucleon charges

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

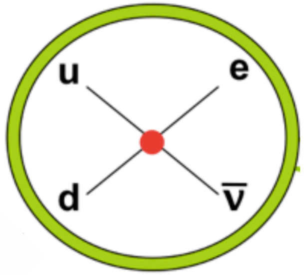
g_S = 1.02(10) FLAG'21* [PNDME'18]

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

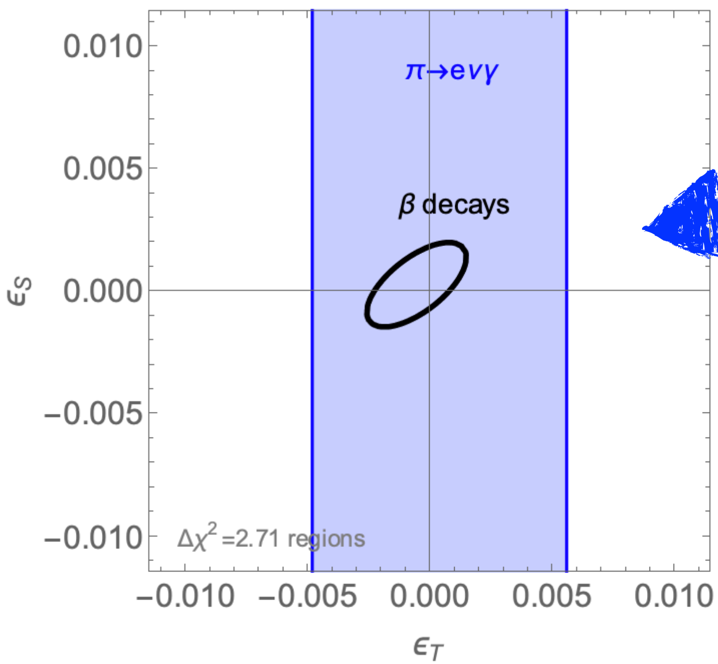
* in perfect agreement with g_S = 1.02(2)
MGA & Camalich, Phys. Rev. Lett. 112 (2014)

EFT with ν_L

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

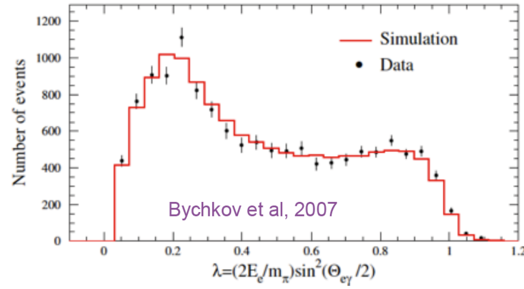


$$\mathcal{L} = -\frac{4G_F V_{ij}}{\sqrt{2}} \Big[\bar{\ell}_L \gamma_\mu \nu \cdot \bar{u} \gamma^\mu d_L + \sum_{\rho\delta\Gamma} \epsilon^{\Gamma}_{\rho\delta} \, \bar{\ell}_\rho \Gamma \nu \cdot \bar{u} \Gamma d_\delta \Big]$$



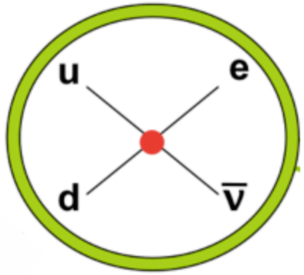
$\pi \to e\nu\gamma$

(PIBETA´2009)



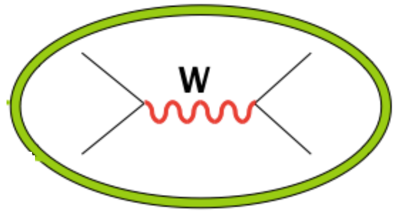
Going to higher energies…

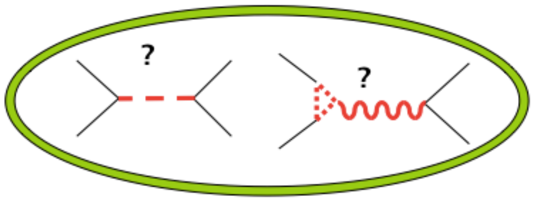
$$\begin{pmatrix}\hat{V}_{ud}\\ \epsilon_R\\ \epsilon_S\\ \epsilon_T\end{pmatrix} = \begin{pmatrix}0.97382(42)\\ -0.012(12)\\ 0.0002(10)\\ -0.0004(12)\end{pmatrix}$$

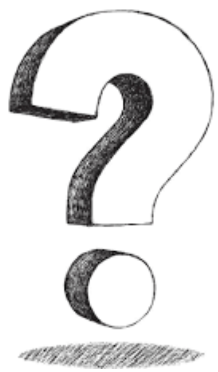


$$\mathcal{L} = -\frac{4G_F V_{ij}}{\sqrt{2}}\Big[\bar{\ell}_L\gamma_\mu\nu\cdot\bar{u}\gamma^\mu d_L + \sum_{\rho\delta\Gamma}\epsilon^{\Gamma}_{\rho\delta}\ \bar{\ell}_\rho\Gamma\nu\cdot\bar{u}\Gamma d_\delta\Big]$$

$\epsilon_i = f(??)$

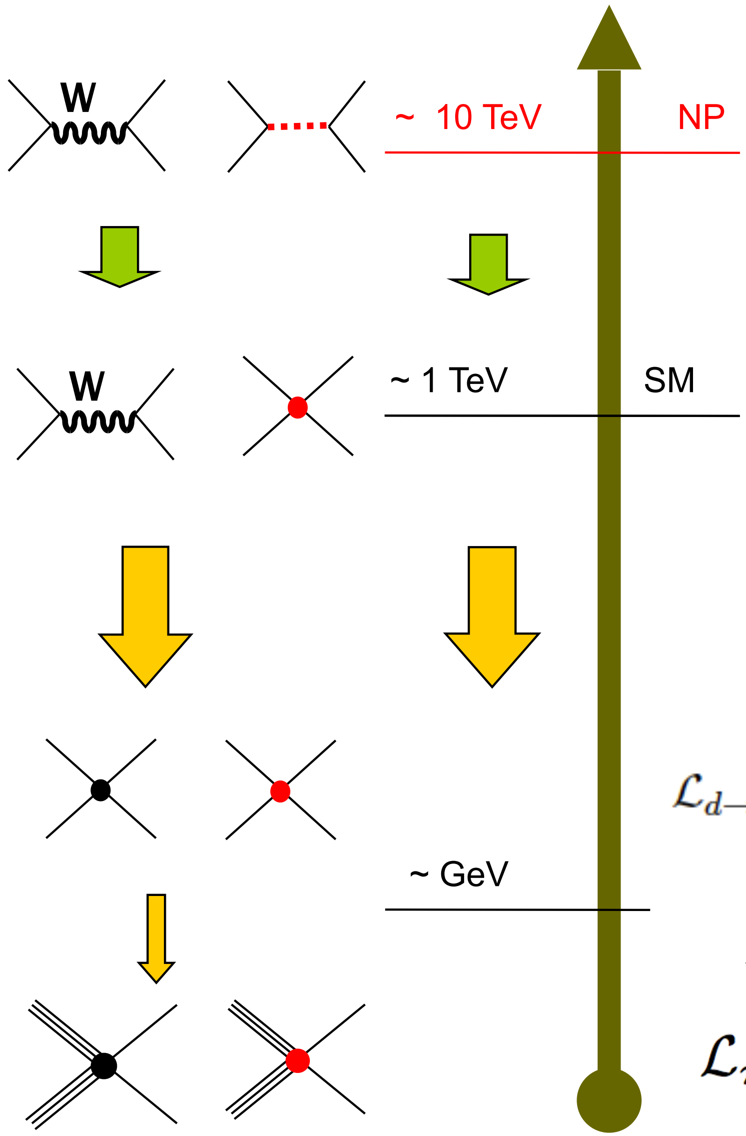






Matching with high-E EFT

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



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

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

"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 with high-E EFT

Low-E EFT → *SMEFT*

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

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

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

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

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

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

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

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

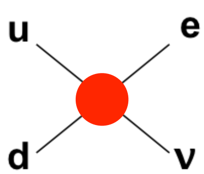
Beta decays sensitive to a few EFT coefficients

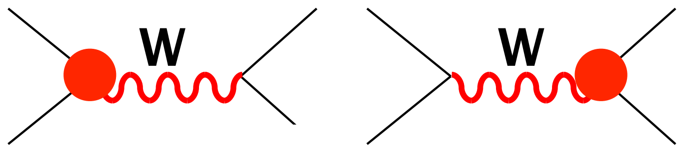
$$O_{\varphi\varphi} = i(\varphi^T\epsilon D_\mu\varphi)(\overline{u}\gamma^\mu d) + \text{h.c.}$$

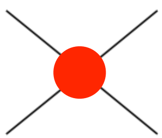
$$O_{\varphi q}^{(3)} = i(\varphi^\dagger D^\mu\sigma^a\varphi)(\overline{q}\gamma_\mu\sigma^a q) + \text{h.c.}$$

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

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







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

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

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

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

Matching with high-E EFT

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]

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

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

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

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

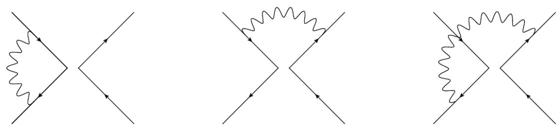
$$V_{1j}\cdot\epsilon^{j\ell}_{s_R} = -\left[V\hat\alpha^{\dagger}_{qde}\right]_{\ell\ell 1j}\,,$$

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

Beta decays sensitive to a few EFT coefficients

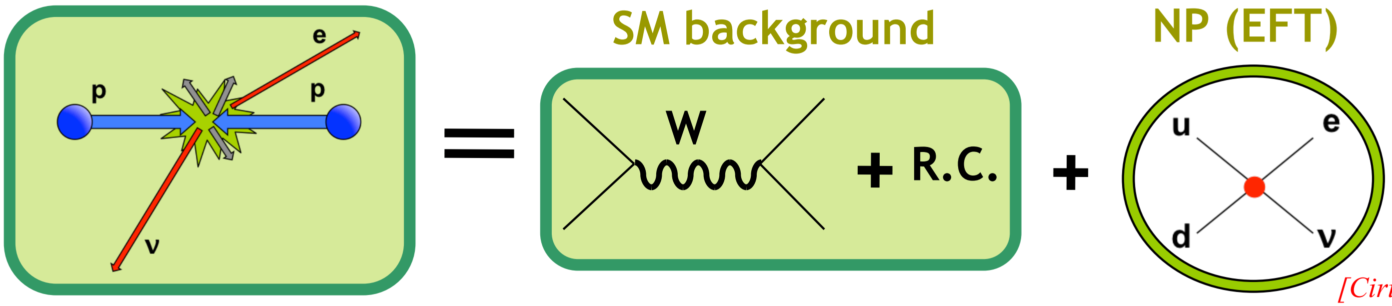
Running (QCD x QED & QCD x EW)
[MGA, Martin Camalich & Mimouni'17]

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



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

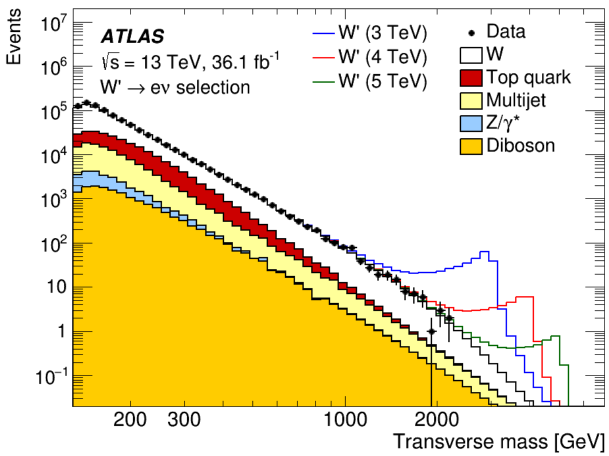
LHC limits on $\varepsilon_{S,T}$

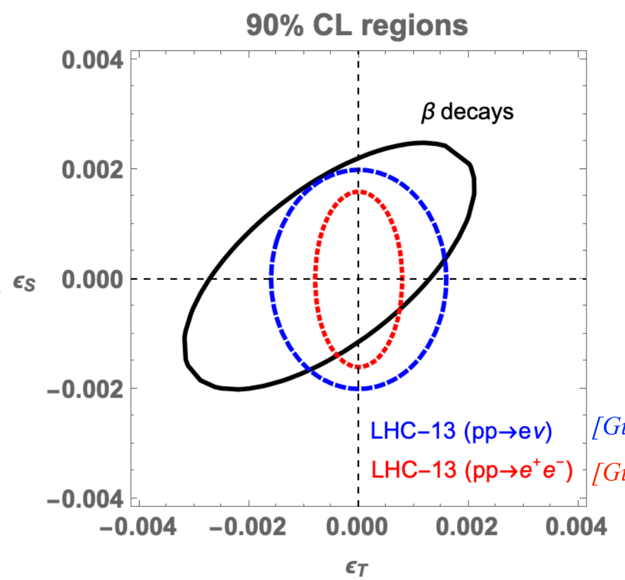


[Cirigliano, MGA & Graesser, JHEP1302 (2013)*]*
[Bhattacharya et al, PRD85 (2012)*]*

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

(Interference w/ SM ~ m/E)





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

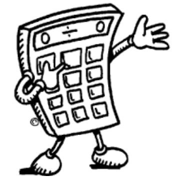
[Falkowski, MGA, Naviliat-Cuncic, JHEP 04 (2021) 126]

EFT with ν_L & ν_R

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

Back to 1956

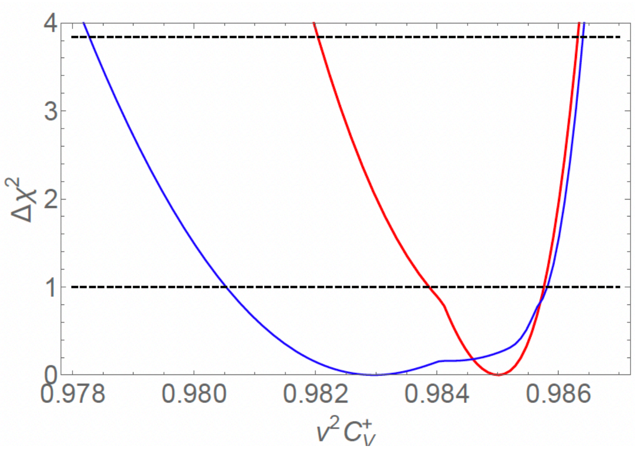
EFT with ν_L & ν_R

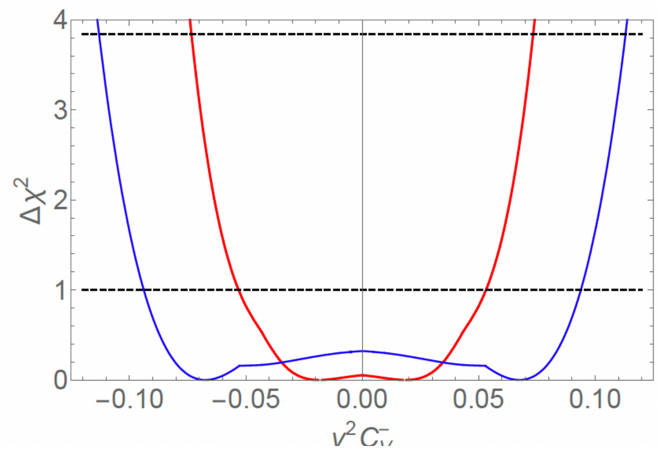


$$\mathcal{L}_{\text{Lee-Yang}} = -\bar{p}\gamma^\mu n \left(C_V^+ \bar{e}\gamma_\mu \nu_L + C_V^- \bar{e}\gamma_\mu \nu_R\right) - \bar{p}\gamma^\mu \gamma_5 n \left(C_A^+ \bar{e}\gamma_\mu \nu_L - C_A^- \bar{e}\gamma_\mu \nu_R\right)$$
$$- \bar{p}n \left(C_S^+ \bar{e}\nu_L + C_S^- \bar{e}\nu_R\right)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

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

(+ mixing ratios)

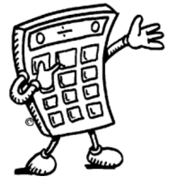




Parameter	C_V^+	C_A^+	C_S^+	C_T^+	C_V^-	C_A^-	C_S^-	C_T^-
Improvement factor	2.8	2.8	1.6	2.3	1.8	1.7	1.0	2.0

Mirrors are very important

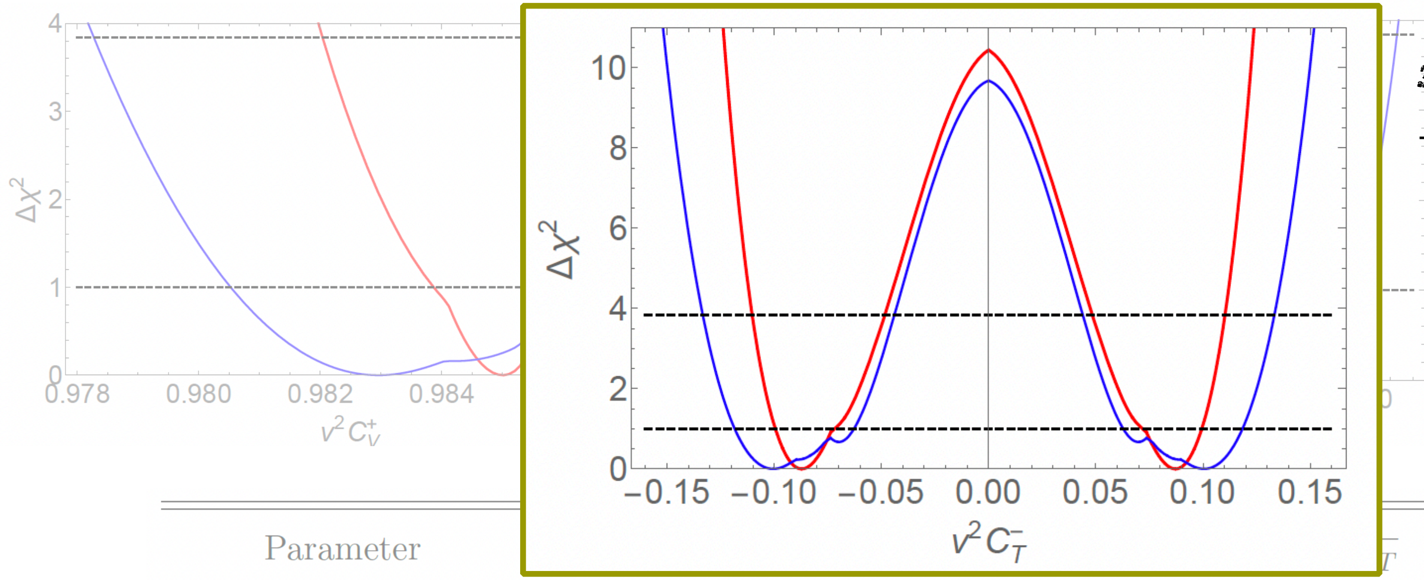
EFT with ν_L & ν_R



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

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

(+ mixing ratios)



3.2 σ

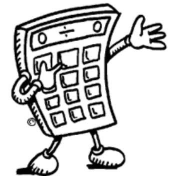
→ 1.8 σ w/o aSPECT'20:

$a_n = -0.10426(82)$

[SM: $-0.10655(13)$]

Parameter								
Improvement factor	2.8	2.8	1.6	2.3	1.8	1.7	1.0	2.0

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)

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

$$C_V^{+} = \frac{V_{ud}}{v^2} g_V \sqrt{1+\Delta_R^V}(1+\epsilon_L+\epsilon_R), \qquad C_V^{-} = \frac{V_{ud}}{v^2} g_V \sqrt{1+\Delta_R^V}(\tilde{\epsilon}_L+\tilde{\epsilon}_R),$$
$$C_A^{+} = -\frac{V_{ud}}{v^2} g_A \sqrt{1+\Delta_R^A}(1+\epsilon_L-\epsilon_R), \qquad C_A^{-} = \frac{V_{ud}}{v^2} g_A \sqrt{1+\Delta_R^A}(\tilde{\epsilon}_L-\tilde{\epsilon}_R),$$
$$C_T^{+} = \frac{V_{ud}}{v^2} g_T \epsilon_T, \qquad C_T^{-} = \frac{V_{ud}}{v^2} g_T \tilde{\epsilon}_T,$$
$$C_S^{+} = \frac{V_{ud}}{v^2} g_S \epsilon_S, \qquad C_S^{-} = \frac{V_{ud}}{v^2} g_S \tilde{\epsilon}_S,$$

Beta decays at NLO in recoil

NEW

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

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

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

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

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

- First (modern) bound on pseudoscalar interactions from β decays:

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

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

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

Beta decays at NLO in recoil

NEW

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

- Weak-Magnetism:

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

- From Ft(0+→0+) + neutron data:

$$v^2 \begin{pmatrix} C_V^+ \\ C_A^+ \\ C_M^+ \end{pmatrix} = \begin{pmatrix} 0.98562(26) \\ -1.25787(52) \\ 3.5(1.0) \end{pmatrix}, \qquad \rho = \begin{pmatrix} 1 & 0.13 & 0.47 \\ & 1 & 0.66 \\ & & 1 \end{pmatrix}$$

- In perfect agreement with the CVC prediction:

$$C_M^{+,\mathrm{CVC}} \approx 4.6/v^2$$

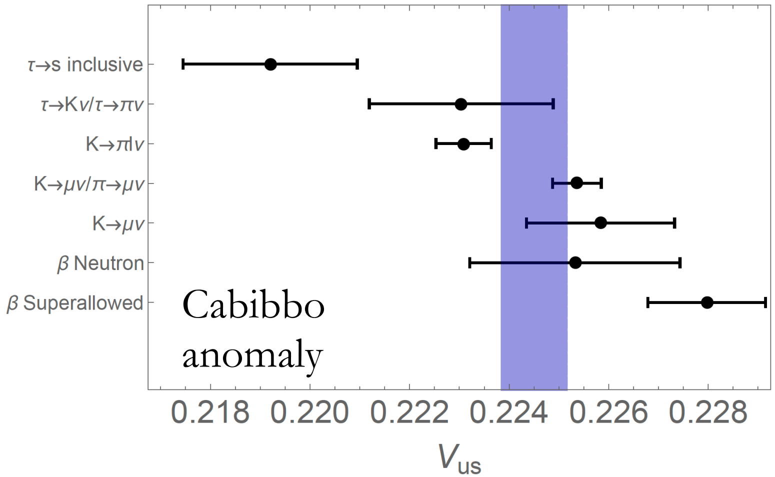
- Improves to ~4σ if mirror decays are added (recoil NME needed with O(1) precision)

Beta decays & flavor

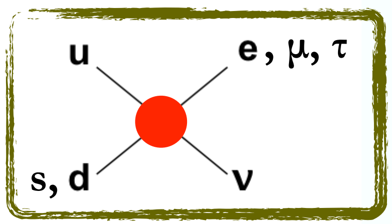
NEW

[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 Wilson Coefficients
  - Pion decays → udeν (pseudoscalar!) & udμν
  - Kaon decays → useν & usμν
  - Tau decays → udτν & usτν



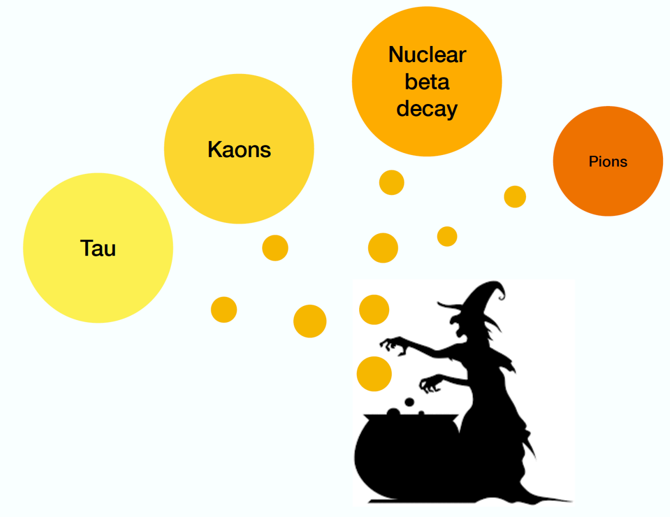
$$\mathscr{L}_{\text{WEFT}} \supset -\sum_{D=d,s}\sum_{\ell=e,\mu,\tau}\frac{V_{uD}}{v^2}\Big\{ \left(1+\epsilon_L^{D\ell}\right)\,\bar{\ell}\gamma_\mu P_L\nu_\ell\cdot\bar{u}\gamma^\mu(1-\gamma_5)D + \epsilon_R^{D}\,\bar{\ell}\gamma_\mu P_L\nu_\ell\cdot\bar{u}\gamma^\mu(1+\gamma_5)D + \epsilon_T^{D\ell}\frac{1}{4}\bar{\ell}\sigma_{\mu\nu}P_L\nu_\ell\cdot\bar{u}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

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

Beta decays & flavor

NEW

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



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

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

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

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

- Large correlations!

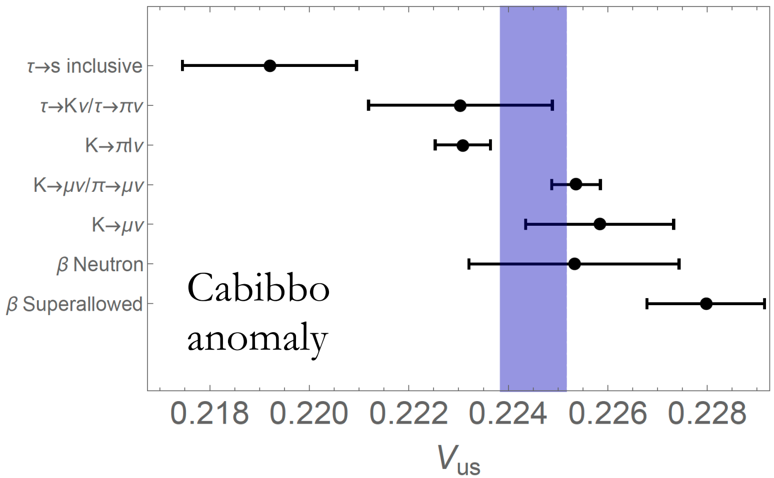
- 3σ preference for NP

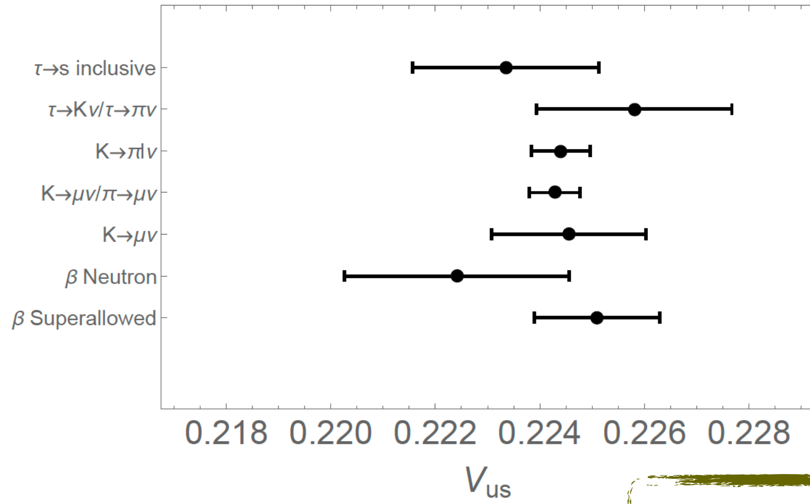
Beta decays & flavor

NEW

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

- SM limit:





4.4 σ !

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

- 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, ...

Conclusions

- (Sub) permil-level precision in CP-cons. observables in β decays

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

- Great laboratory for nuclear, hadronic and particle physics
- Progress in all fronts:
  - Lattice QCD, rad. corrections, experiment, …
  - Pheno: mirror decays, full LO fit, pseudoscalar interaction, nucleon WM, …
  - EFT: matching, RGEs, comparison with flavor (Cabibbo anomaly), LHC, LEP, or even neutrino oscillations! [Falkowski-MGA-Tabrizi, 2019]

    → β decays are competitive TeV probes;