Precision Tests of the Standard Model with Beta Decays

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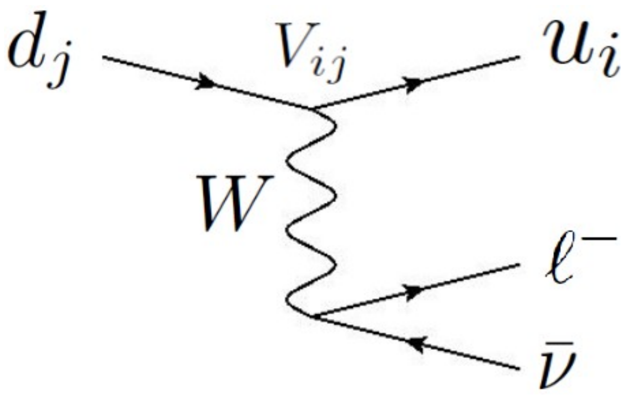
Charged weak decay: Decay of **strong interaction bound states** through the emission of a **W-boson**

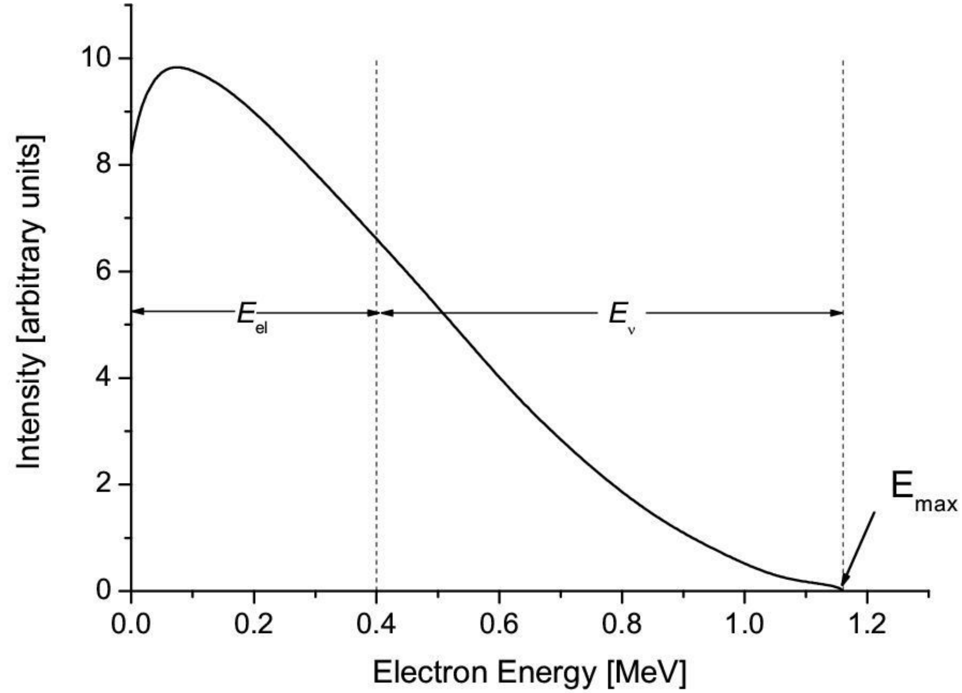


Beta decay:

$$\phi_i \rightarrow \phi_f + e + \nu_e$$

Charged weak decay had been crucial in shaping the **Standard Model**!

1930: **Neutrino** postulated to explain the **continuous beta decay spectrum**

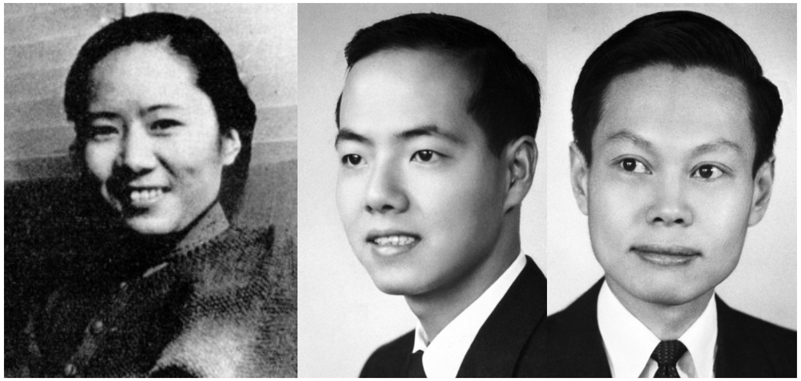


> Namely [there is] the possibility that there could exist in the nuclei electrically neutral particles that I wish to call neutrons, which have spin ½ and obey the exclusion principle, and additionally differ from light quanta in that they do not travel with the velocity of light: The mass of the neutron must be of

Statements in Pauli's letter (1930), translated by *Physics Today*

Charged weak decay had been crucial in shaping the **Standard Model**!

1956: First discovery of **parity violation** in ^{60}**Co decay correlation**



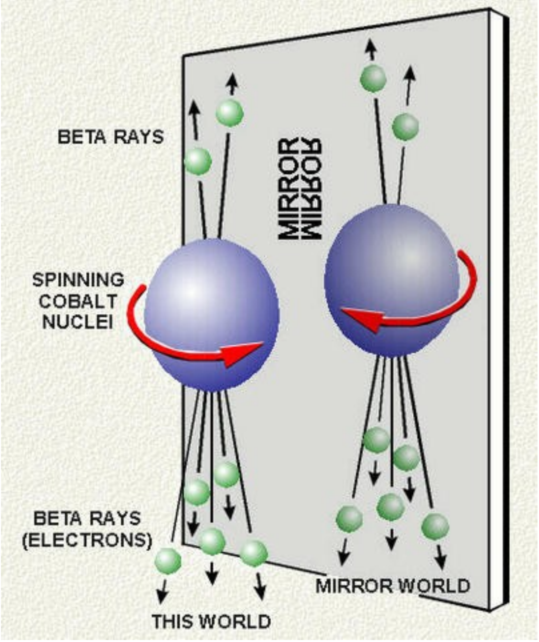
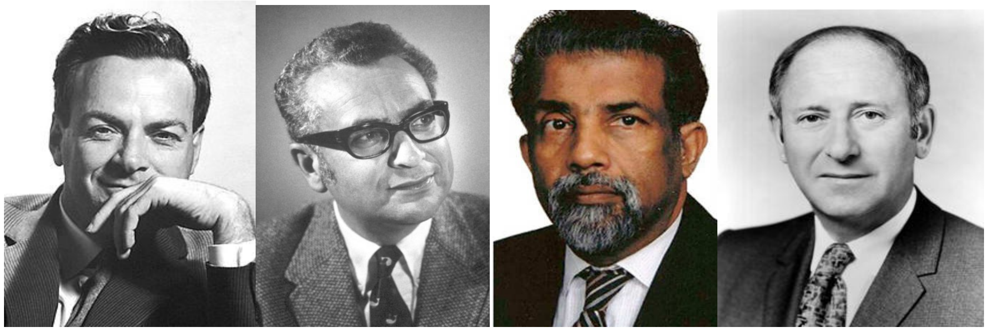


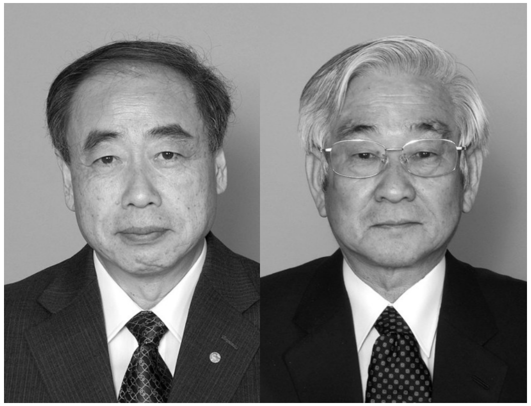
Image credit: NIST

1957: Postulation of the **V-A structure** in the charged weak interaction



Charged weak decay had been crucial in shaping the **Standard Model**!

1963: A **2*2 mixing matrix** proposed to explain the strength of **strangeness-changing weak decays**



1973: Extended to **3*3 matrix** to incorporate **CP-violation**

$$\psi_{d,f} = \begin{pmatrix} d \\ s \\ b \end{pmatrix}_f = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_m$$

The CKM matrix

Now that we have the Standard Model...

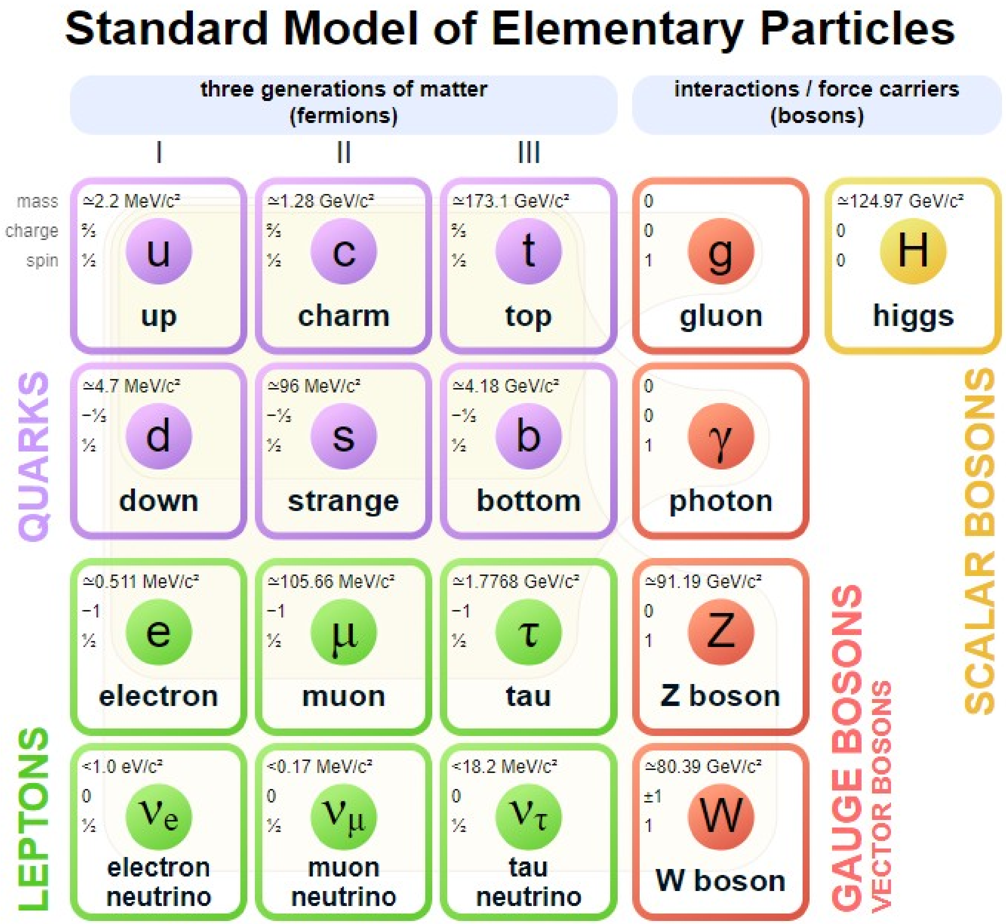
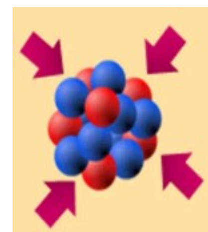
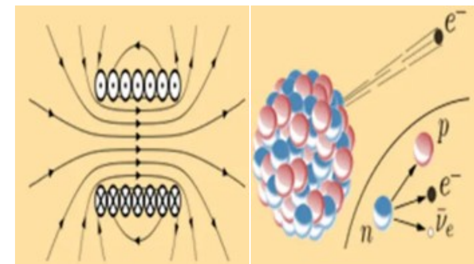


Image credit: Wikipedia





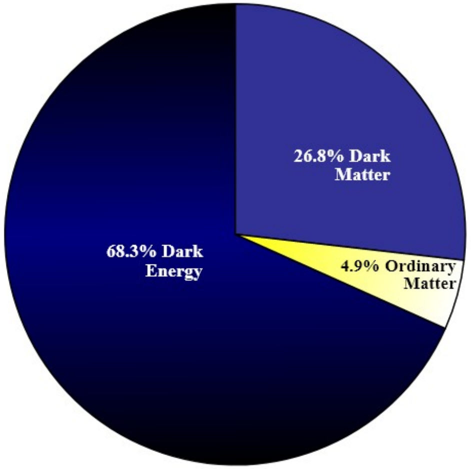
$SU(3)_C$ x $SU(2)_L$ x $U(1)_Y$

Strong (QCD)

Electroweak

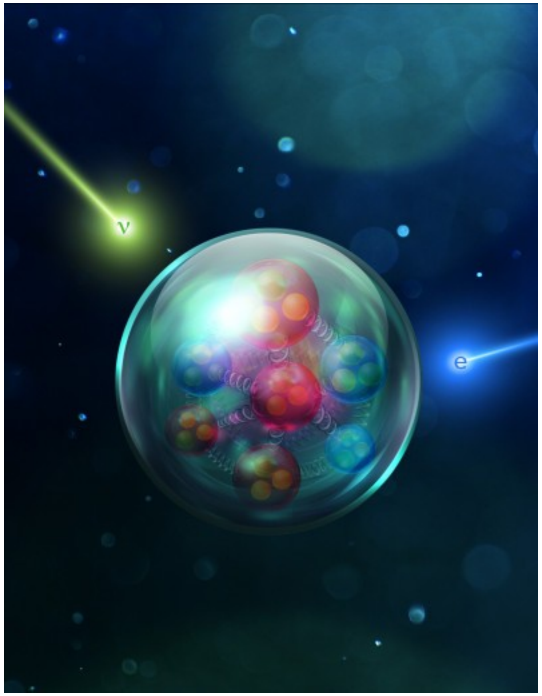
...which we know is incomplete and requires
physics beyond the Standard Model (BSM) !

Image credit: Wikipedia

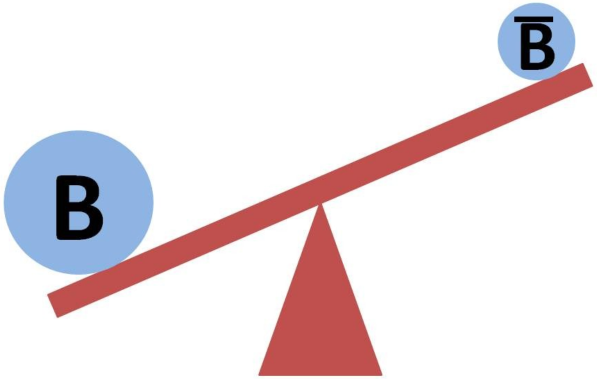


What is the origin of dark energy and dark matter?

Image credit: Jefferson Lab

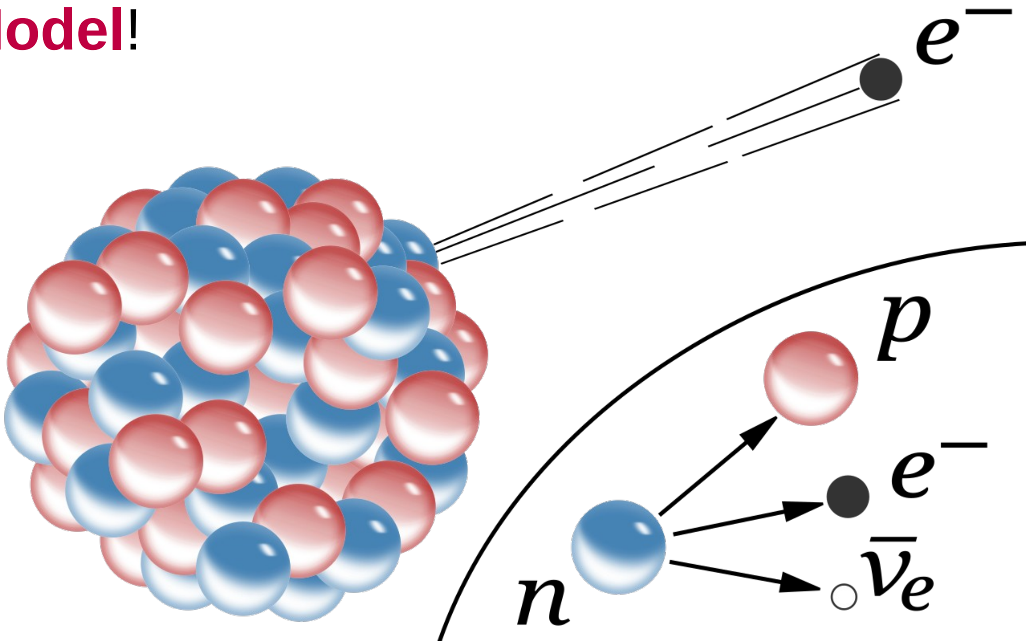


What is the nature of the neutrino mass?



Why is there much more matter than antimatter in the observed universe?

Beta decay provides a perfect avenue for **precision tests of the Standard Model**!



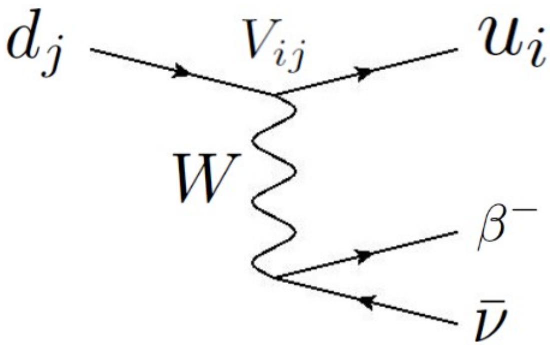
Compare experimental results of:

(1) Decay lifetime

(2) Decay correlations

with Standard Model predictions to search for **traces of new physics**!

Beta decay lifetime and V_{ud}



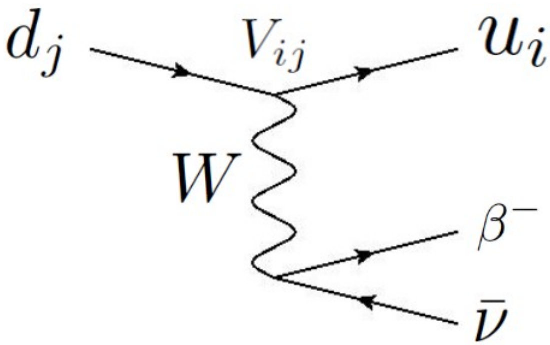
Testing CKM unitarity from charged weak decays:

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} V_{ud}^* & V_{cd}^* & V_{td}^* \\ V_{us}^* & V_{cs}^* & V_{ts}^* \\ V_{ub}^* & V_{cb}^* & V_{tb}^* \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

"First-row CKM unitarity"

$$|V_{ud}|^2 + |V_{us}|^2 + |\cancel{V_{ub}}|^2 = 1$$

$\sim 10^{-5}$



Testing CKM unitarity from charged weak decays:

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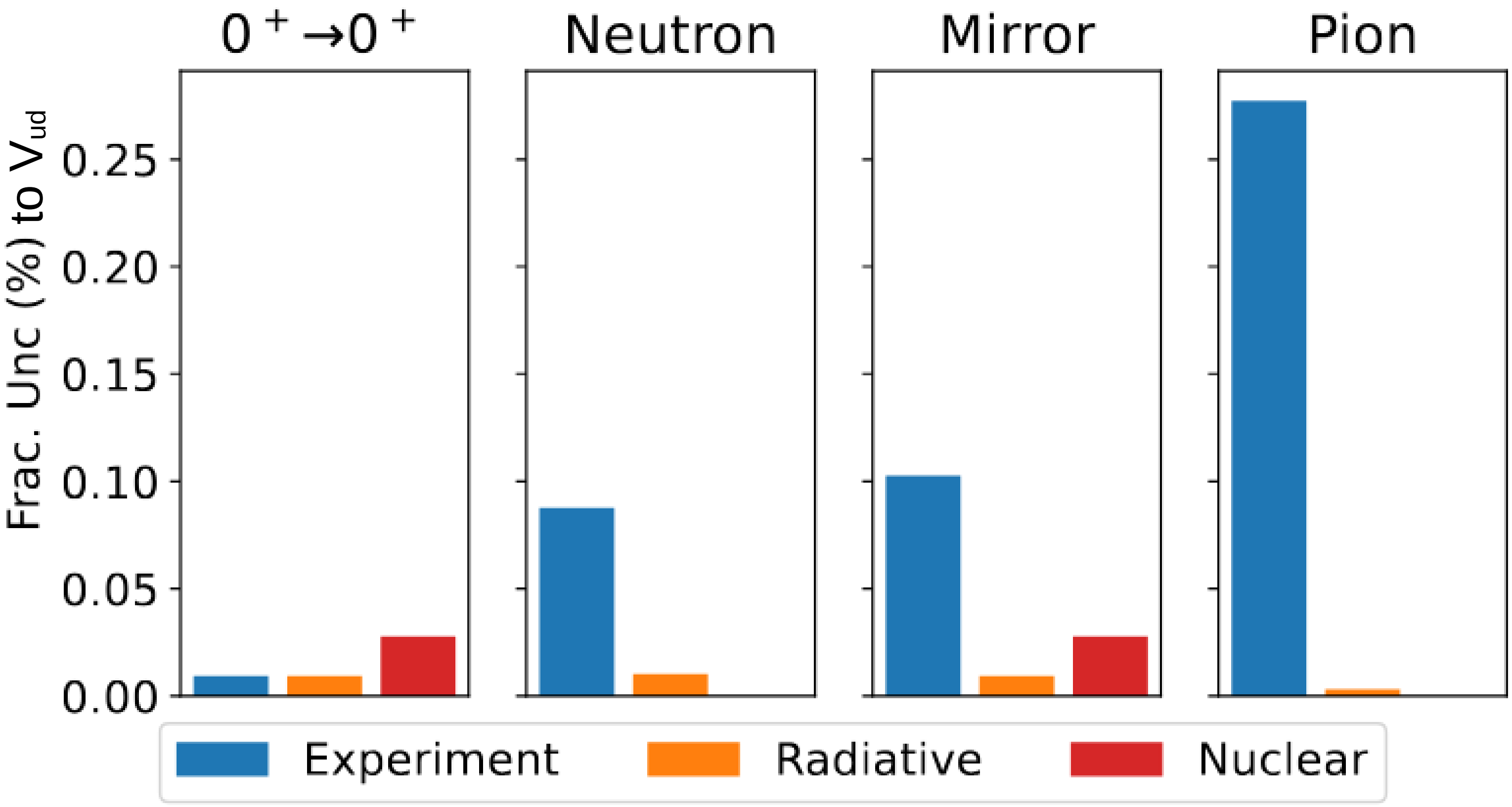
Can be tested at **0.01%** level! Probes new physics at the scale:

$$\left(\frac{v_{\mathrm{H}}}{\Lambda_{\mathrm{BSM}}}\right)^2 \sim 0.01\% \quad \Longrightarrow \quad \Lambda_{\mathrm{BSM}} \sim 20\ \mathrm{TeV}$$

Competitive to high-energy experiments!

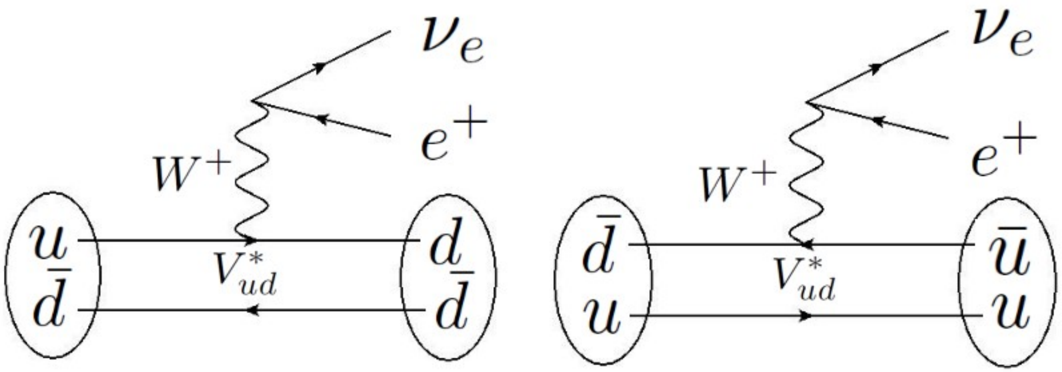
Primary channels for V_{ud} extraction:



Brodeur et al., 2301.03975

(1) Pion beta decay (π_{e3})

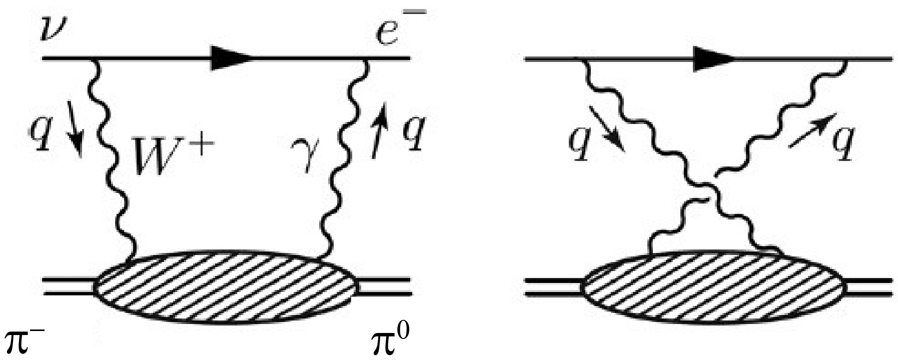
$$\pi^+ \to \pi^0 + e^+ + \nu_e$$



Pure Fermi transition + lightest hadron

→ **Theoretically cleanest**

Theory Input: "Radiative corrections"



Involves **non-perturbative** hadron physics

Chiral Perturbation Theory: 0.1% precision

Cirigliano, Knecht, Neufeld and Pichl, EPJC 2003

Lattice QCD: 0.01% precision

Feng, Gorchtein, Jin, Ma and CYS, 2020 PRL

Bottleneck: The π_{e3} branching ratio

$$\mathrm{BR}(\pi_{e3}) = 1.036(6) \times 10^{-8}$$

Pocanic et al (PIBETA), 2004 PRL

$$|V_{ud}|_{\pi} = 0.9740(28)_{\mathrm{exp}}(1)_{\mathrm{th}}$$

PIONEER

Future experiment: PIONEER at Paul Scherrer Institute (PSI)

Phase I : > yr 2029

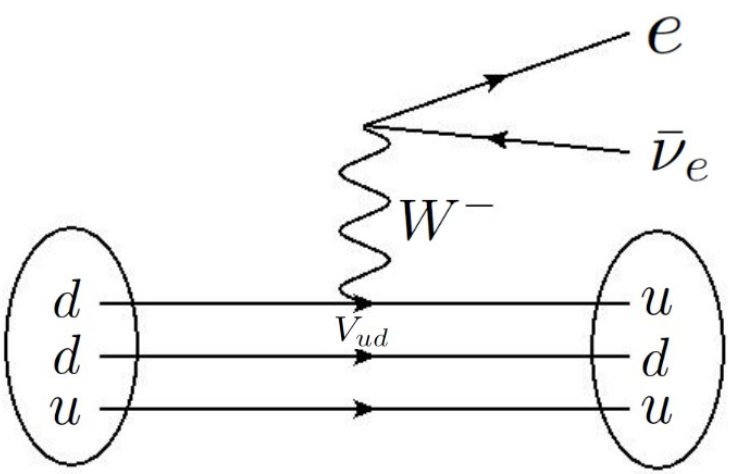
Phase II : Improve BR(π_{e3}) precision by a factor 3

Phase III: Improve BR(π_{e3}) precision by a factor 10

PIONEER, 2203.01981; 2504.06375

(2) Neutron beta decay

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

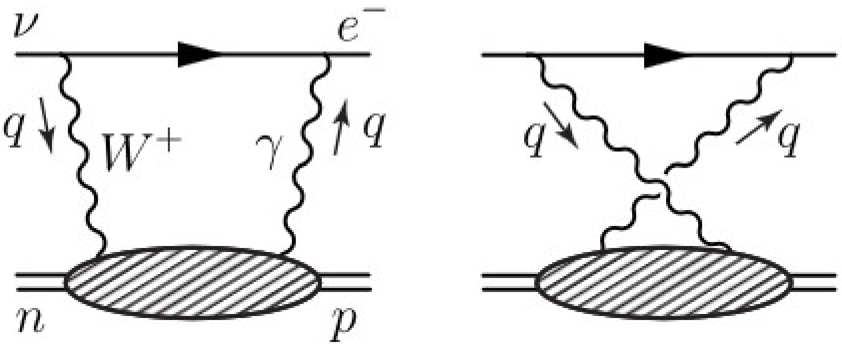


Mixed (Fermi + Gamow-Teller) transition:
Needs measurements of both

(i) Decay lifetime

(ii) Axial coupling strength

Single-nucleon radiative corrections:



Hadron model *Marciano and Sirlin, 2006 PRL*

Big change

Dispersion relation *CYS, Gorchtein, Patel and Ramsey-Musolf, 2018 PRL*

0.01% precision

Consistent

Lattice QCD *Ma, Feng, Gorchtein, Jin, Liu,CYS, Wand and Zhang, 2024 PRL*

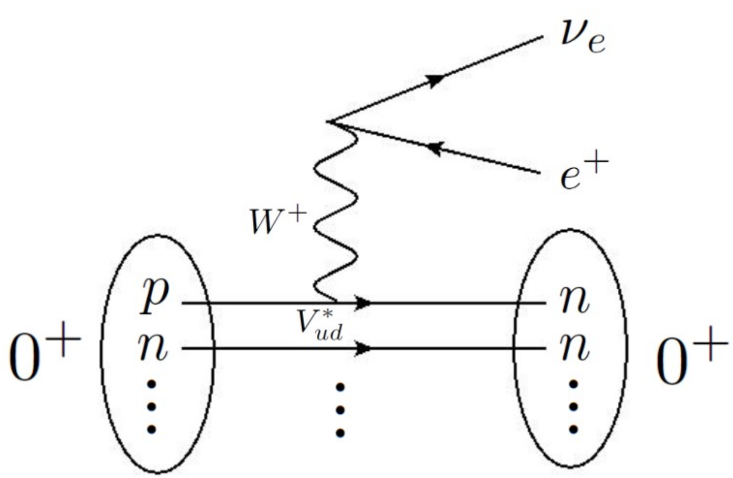
$$|V_{ud}|_n^{\mathrm{PDG-av}} = 0.97433(28)_{\tau_n}(82)_\lambda(10)_{\mathrm{RC}}$$

Gorchtein and CYS, 2023 Universe

Bottleneck: Neutron **lifetime** and **axial coupling**

(3) "Superallowed" nuclear beta decay

$$i(0^+) \to f(0^+) + e^+ + \nu_e$$



$T_z = -1$
$^{10}_{6}\text{C} \to ^{10}_{5}\text{B}$
$^{14}_{8}\text{O} \to ^{14}_{7}\text{N}$
$^{18}_{10}\text{Ne} \to ^{18}_{9}\text{F}$
$^{22}_{12}\text{Mg} \to ^{22}_{11}\text{Na}$
$^{26}_{14}\text{Si} \to ^{26}_{13}\text{Al}$
$^{30}_{16}\text{S} \to ^{30}_{15}\text{P}$
$^{34}_{18}\text{Ar} \to ^{34}_{17}\text{Cl}$
$^{38}_{20}\text{Ca} \to ^{38}_{19}\text{K}$
$^{42}_{22}\text{Ti} \to ^{42}_{21}\text{Sc}$
$^{46}_{24}\text{Cr} \to ^{46}_{23}\text{V}$
$^{50}_{26}\text{Fe} \to ^{50}_{25}\text{Mn}$
$^{54}_{28}\text{Ni} \to ^{54}_{27}\text{Co}$

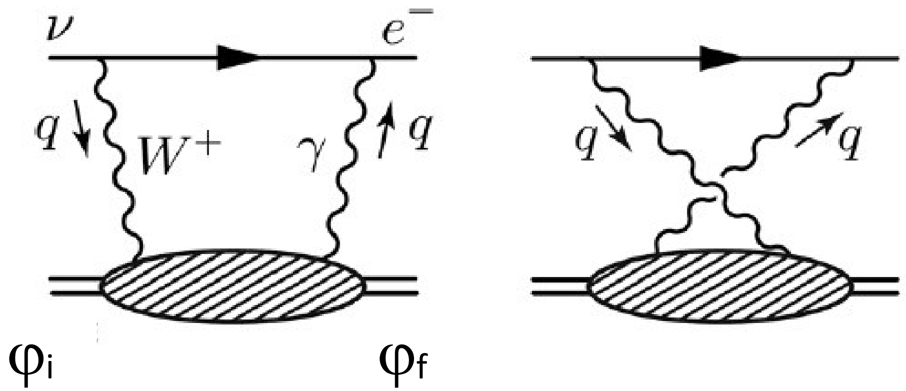
$T_z = 0$
$^{26m}_{13}\text{Al} \to ^{26}_{12}\text{Mg}$
$^{34}_{17}\text{Cl} \to ^{34}_{16}\text{S}$
$^{38m}_{19}\text{K} \to ^{38}_{18}\text{Ar}$
$^{42}_{21}\text{Sc} \to ^{42}_{20}\text{Ca}$
$^{46}_{23}\text{V} \to ^{46}_{22}\text{Ti}$
$^{50}_{25}\text{Mn} \to ^{50}_{24}\text{Cr}$
$^{54}_{27}\text{Co} \to ^{54}_{26}\text{Fe}$
$^{62}_{31}\text{Ga} \to ^{62}_{30}\text{Zn}$
$^{66}_{33}\text{As} \to ^{66}_{32}\text{Ge}$
$^{70}_{35}\text{Br} \to ^{70}_{34}\text{Se}$
$^{74}_{37}\text{Rb} \to ^{74}_{36}\text{Kr}$

- Pure **Fermi** transition
- **23** measured transitions, **15** with lifetime precision better than **0.23%**

Hardy and Towner, 2020 PRC

Bottleneck: Nucleus-dependent **theory inputs**

(1) Radiative corrections:



(2) Isospin-symmetry-breaking corrections:

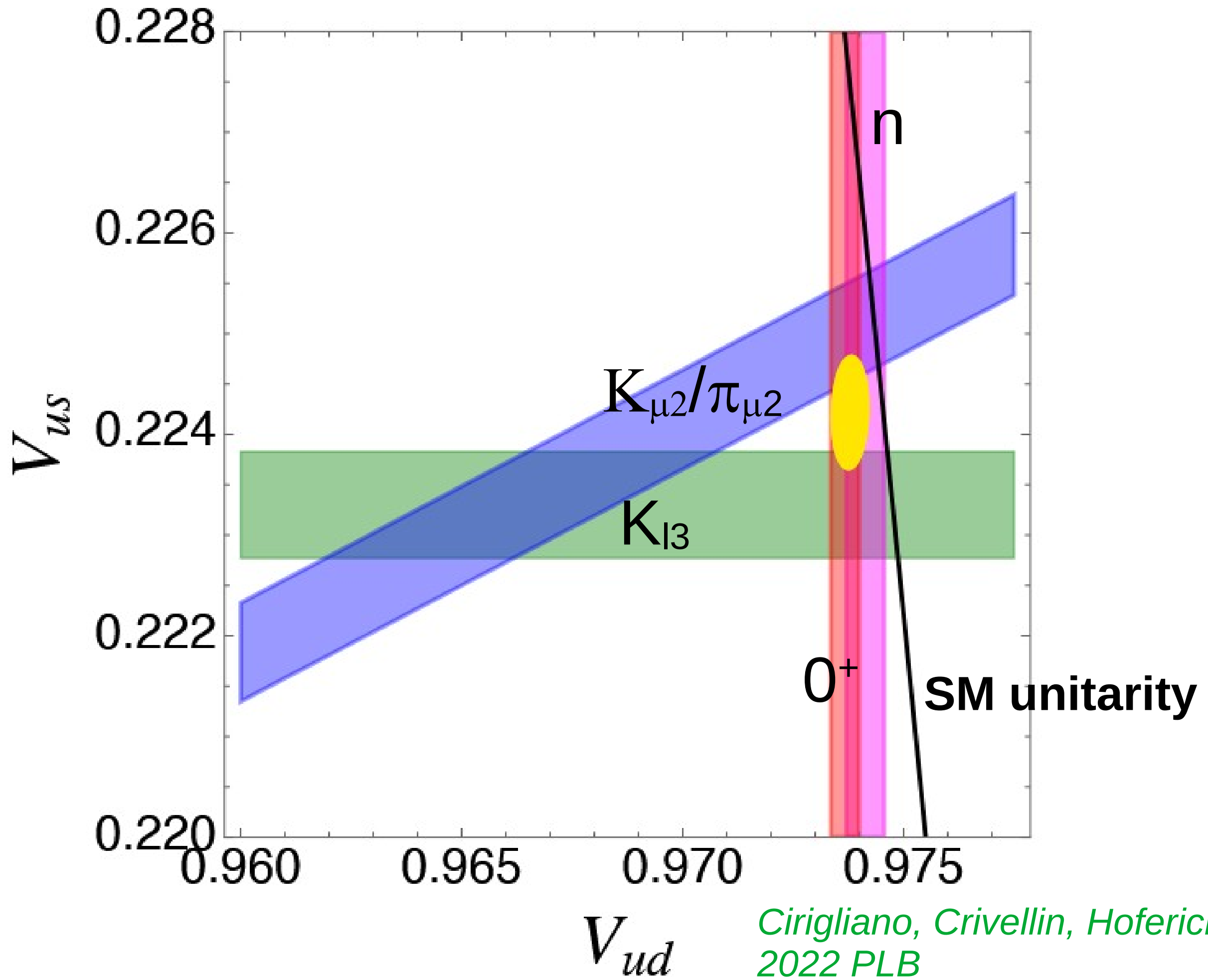
$$|\langle f|\tau_+|i\rangle|^2 = 2\,(1-\delta_C)$$

Averaging over 15 superallowed transitions:

$$|V_{ud}|^{avg}_{0^+} = 0.97367(11)_{\exp}(13)_{\Delta^V_R}(27)_{NS}$$

PDG 2024

Current status of V_{ud} and V_{us}

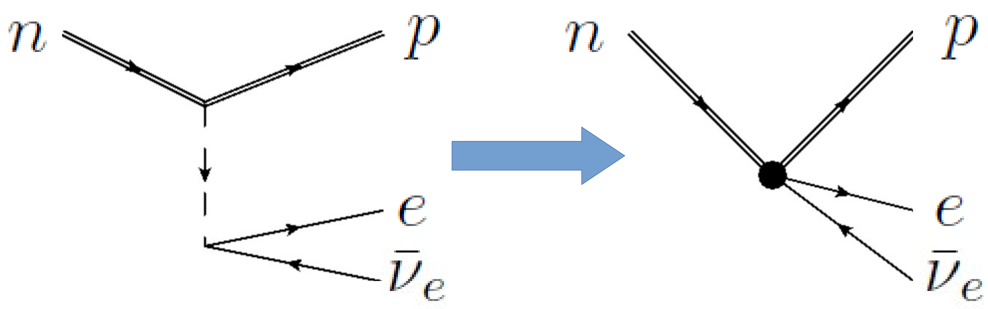


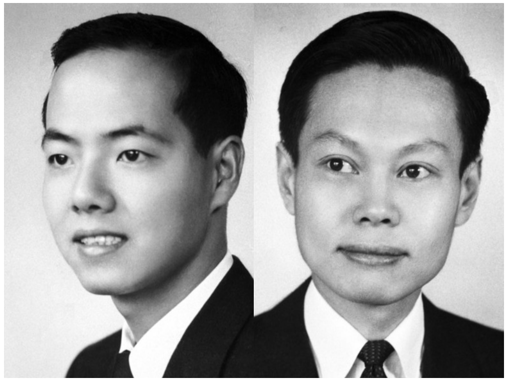
Cirigliano, Crivellin, Hoferichter and Moulson, 2022 PLB

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = -0.00148(53)$$

Unitarity deficit ~3σ, "Cabibbo angle anomaly"

BSM interpretation, assuming new physics are **heavy:**



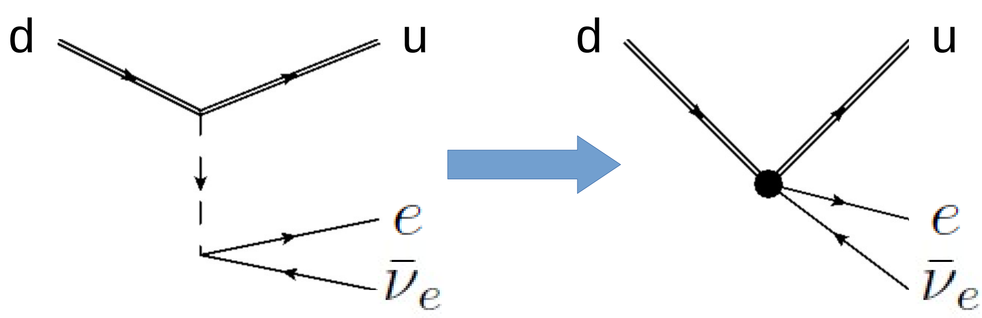


MeV-scale effective Lagrangian:

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

Lee and Yang, 1956 PR

GeV-scale effective Lagrangian:

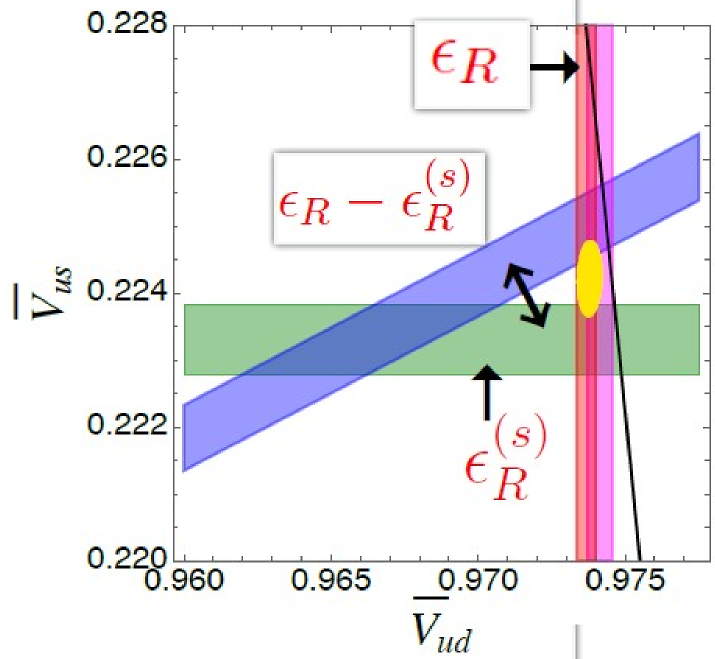


$$
\begin{aligned}
\mathcal{L}_{\rm CC} \;=\; & -\frac{G_F^{(0)} V_{ud}}{\sqrt{2}} \times \Big[\left(\delta^{ab} + \epsilon_L^{ab}\right) \; \bar{e}_a \gamma_\mu (1-\gamma_5) \nu_b \cdot \bar{u} \gamma^\mu (1-\gamma_5) d \\
& + \; \epsilon_R^{ab} \; \bar{e}_a \gamma_\mu (1-\gamma_5) \nu_b \cdot \bar{u} \gamma^\mu (1+\gamma_5) d \\
& + \; \epsilon_S^{ab} \; \bar{e}_a (1-\gamma_5) \nu_b \cdot \bar{u} d \\
& - \; \epsilon_P^{ab} \; \bar{e}_a (1-\gamma_5) \nu_b \cdot \bar{u} \gamma_5 d \\
& + \; \epsilon_T^{ab} \; \bar{e}_a \sigma_{\mu\nu} (1-\gamma_5) \nu_b \cdot \bar{u} \sigma^{\mu\nu} (1-\gamma_5) d \Big] + \text{h.c.}
\end{aligned}
$$

$\varepsilon_i \sim (v/\Lambda)^2$

Cabibbo angle anomaly favors a non-zero **BSM right-handed current**:

$$|\bar{V}_{ud}|^2_{0^+\to 0^+} = |V_{ud}|^2\left(1+2\,\epsilon_R\right)$$
$$|\bar{V}_{ud}|^2_{n\to pe\bar{\nu}} = |V_{ud}|^2\left(1+2\,\epsilon_R\right)$$
$$|\bar{V}_{us}|^2_{Ke3} = |V_{us}|^2\left(1+2\,\epsilon_R^{(s)}\right)$$
$$|\bar{V}_{ud}|^2_{\pi e3} = |V_{ud}|^2\left(1+2\,\epsilon_R\right)$$
$$|\bar{V}_{us}|^2_{K\mu 2} = |V_{us}|^2\left(1-2\,\epsilon_R^{(s)}\right)$$
$$|\bar{V}_{ud}|^2_{\pi\mu 2} = |V_{ud}|^2\left(1-2\,\epsilon_R\right)$$



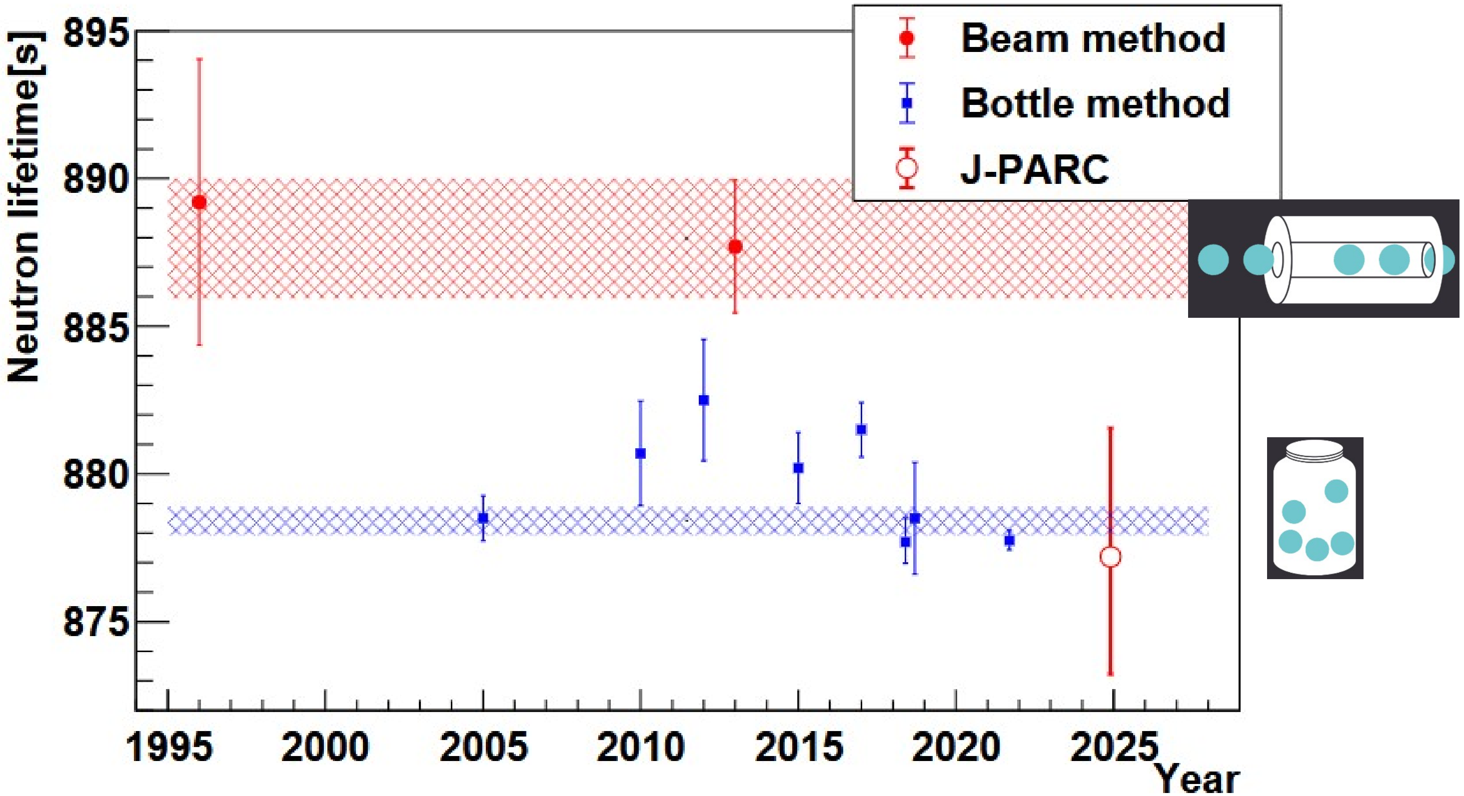
$$\epsilon_R = -0.69(27)\times 10^{-3}$$
$$\epsilon_R^{(s)} - \epsilon_R = -3.9(1.6)\times 10^{-3}$$

$\Lambda_R \sim$ 5-10 TeV

Cirigliano, Dekens, de Vries, Mereghetti and Tong, 2024 JHEP

...but **NOT** all the anomalies can be explained in this way!

E.g. "Neutron lifetime puzzle":



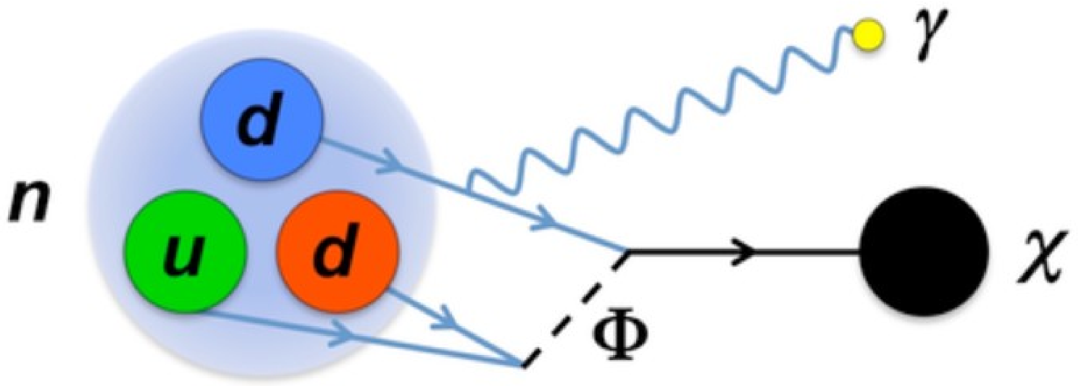
JPARC, 2412.19519

PDG: $\tau_n = 878.4(5)\ \mathrm{s}$ (bottle only)

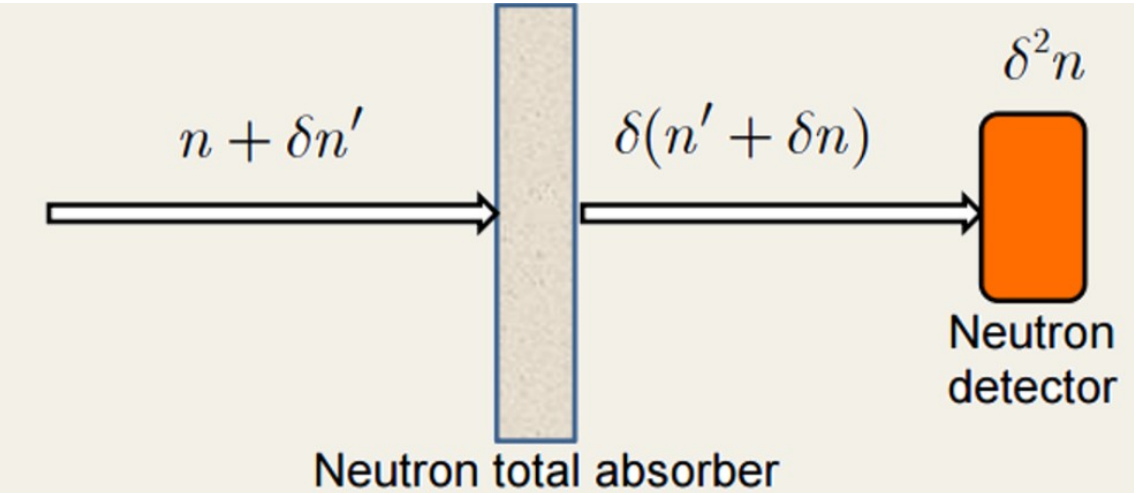
BSM explanation must involve new **LIGHT** particles!

Examples of proposed explanations:

Dark decay mode: *Fornal and Grinstein, 2018 PRL*



n – n' (mirror) oscillation: *Berezhiani, 2019 EPJC*



… and so on.

Some ongoing/future **neutron lifetime** experiments:

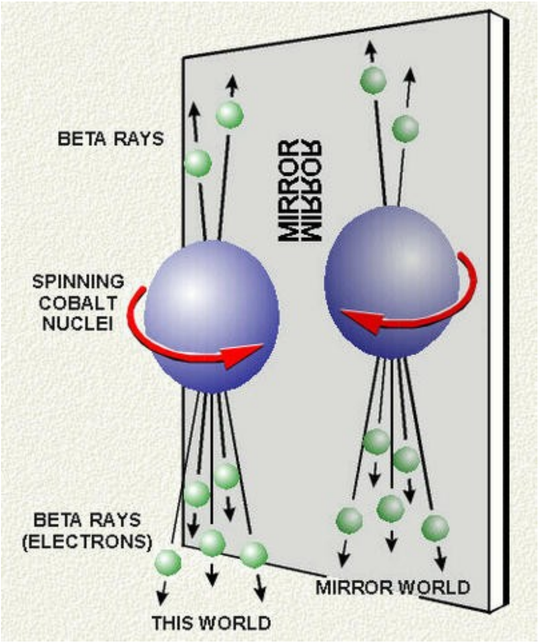
Experiment	Method	Projected precision
UCNτ+	Bottle	0.1 s
BL2	Beam	1 s
BL3	Beam	0.3 s
UCNProBe	Bottle + Beam (detect e)	1-2 s

⋮

Beta decay correlations

Differential decay rate:

$$d\Gamma \propto 1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + \hat{\sigma} \cdot \left[A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + \ldots \right]$$



First evidence of parity violation comes from the measurement of **A** in ^{60}Co decay

Decay correlations probe the **most general** weak interaction couplings: *Jackson, Treiman and Wyld, 1957 PR*

$$\xi = |M_F|^2(|C_S|^2+|C_V|^2+|C_S'|^2+|C_V'|^2)+|M_{GT}|^2(|C_T|^2+|C_A|^2+|C_T'|^2+|C_A'|^2),$$

$$a\xi = |M_F|^2(-|C_S|^2+|C_V|^2-|C_S'|^2+|C_V'|^2)+\frac{|M_{GT}|^2}{3}(|C_T|^2-|C_A|^2+|C_T'|^2-|C_A'|^2),$$

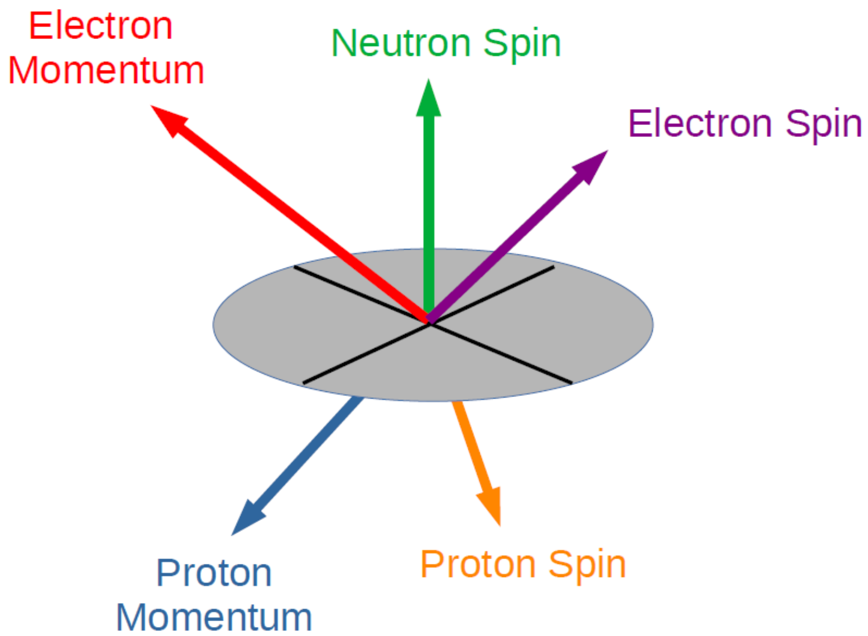
$$b\xi = \pm 2\,\mathrm{Re}[|M_F|^2(C_S C_V^*+C_S' C_V'^*)+|M_{GT}|^2(C_T C_A^*+C_T' C_A'^*)],$$

$$c\xi = |M_{GT}|^2\Lambda_{J'J}(|C_T|^2-|C_A|^2+|C_T'|^2-|C_A'|^2),$$

$$A\xi = 2\,\mathrm{Re}\Big[\pm|M_{GT}|^2\lambda_{J'J}(C_T C_T'^*-C_A C_A'^*) + \delta_{J'J}|M_F||M_{GT}|\left(\frac{J}{J+1}\right)^{\frac{1}{2}}(C_S C_T'^*+C_S' C_T^*-C_V C_A'^*-C_V' C_A^*)\Big]$$

$$B\xi = 2\,\mathrm{Re}\Big\{|M_{GT}|^2\lambda_{J'J}\Big[\frac{m}{E_e}(C_T C_A'^*+C_T' C_A^*)\pm(C_T C_T'^*+C_A C_A'^*)\Big]-\delta_{J'J}|M_F||M_{GT}|\left(\frac{J}{J+1}\right)^{\frac{1}{2}} \times\Big[(C_S C_T'^*+C_S' C_T^*+C_V C_A'^*+C_V' C_A^*)\pm\frac{m}{E_e}(C_S C_A'^*+C_S' C_A^*+C_V C_T'^*+C_V' C_T^*)\Big]\Big\}$$

Free neutron decay $n \to p e \bar{\nu}_e$,

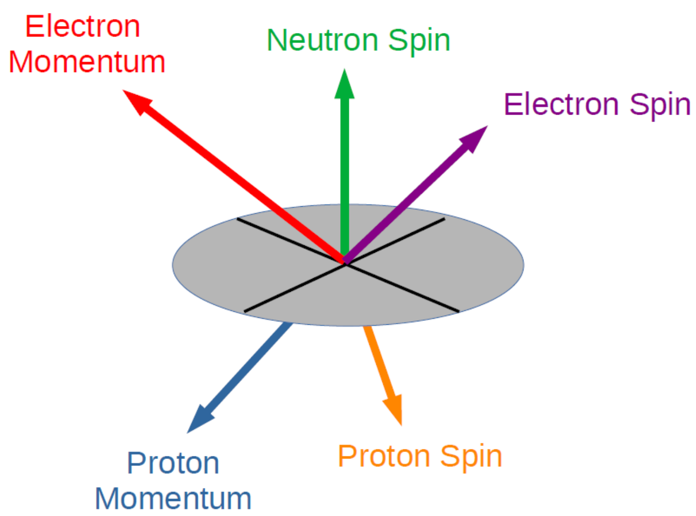


Standard Model weak current:

$$\langle p | J^{\mu}_{W} | n \rangle \propto \bar{u}_p \gamma^{\mu} (g_V + g_A \gamma_5) u_n$$

Vector coupling | Axial coupling

Standard Model prediction of neutron decay correlations:



$$a = \frac{1-\lambda^2}{1+3\lambda^2} \approx -0.10$$

$$b = 0$$

$$A = -\frac{2\lambda(\lambda+1)}{1+3\lambda^2} \approx -0.12$$

$$\lambda \equiv \frac{g_A}{g_V} \approx -1.27$$

Measurements of the beta decay correlations determines the fundamental parameter λ !

Comparison with **lattice QCD** result may probe new physics!

$$N_f = 2+1+1 \quad : \quad |g_A^{\rm QCD}| = 1.263(10)$$
$$N_f = 2+1 \quad : \quad |g_A^{\rm QCD}| = 1.265(20)$$

2024 FLAG review

$$\lambda = g_A^{\rm QCD}\left(1 + \delta_{\rm RC}^{(\lambda)} - 2{\rm Re}(\epsilon_R)\right)$$

BSM right-handed current

nature › letters › article

Letter | Published: 30 May 2018

A per-cent-level determination of the nucleon axial coupling from quantum chromodynamics

C. C. Chang, A. N. Nicholson, E. Rinaldi, E. Berkowitz, N. Garron, D. A. Brantley, H. Monge-Camacho, C. J. Monahan, C. Bouchard, M. A. Clark, B. Joó, T. Kurth, K. Orginos, P. Vranas & A. Walker-Loud

Nature **558**, 91–94 (2018) | Cite this article

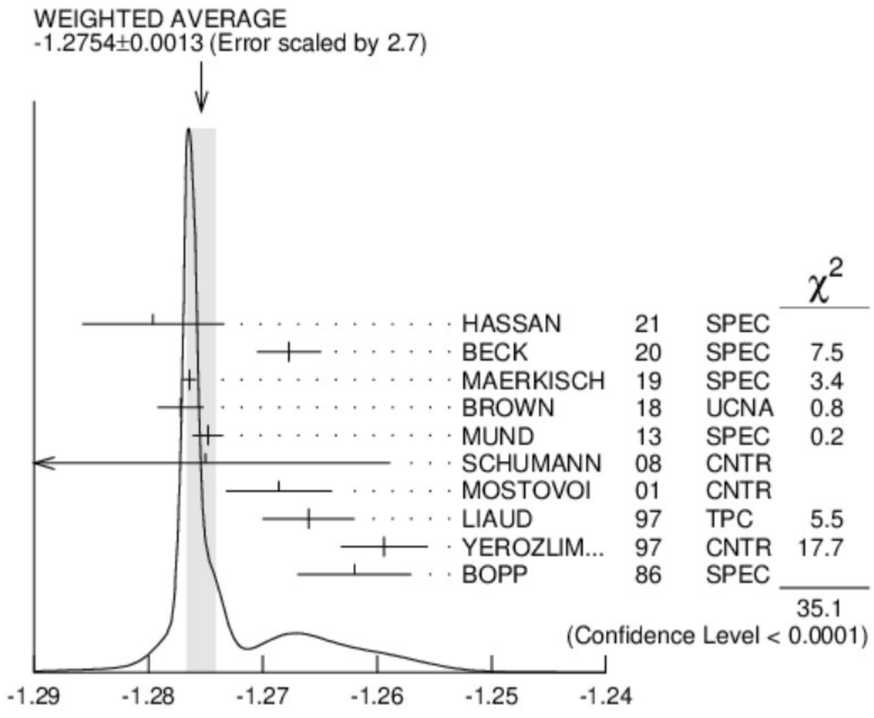
California Lattice Collaboration

“λ - discrepancy”

λ obtained from different decay correlations disagree (~3.5σ)!

$$\lambda_A = -1.27641(56)$$ *PERKEO-III, 2019 PRL*

$$\lambda_a = -1.2668(27)$$ *aSPECT, 2024 PRL*

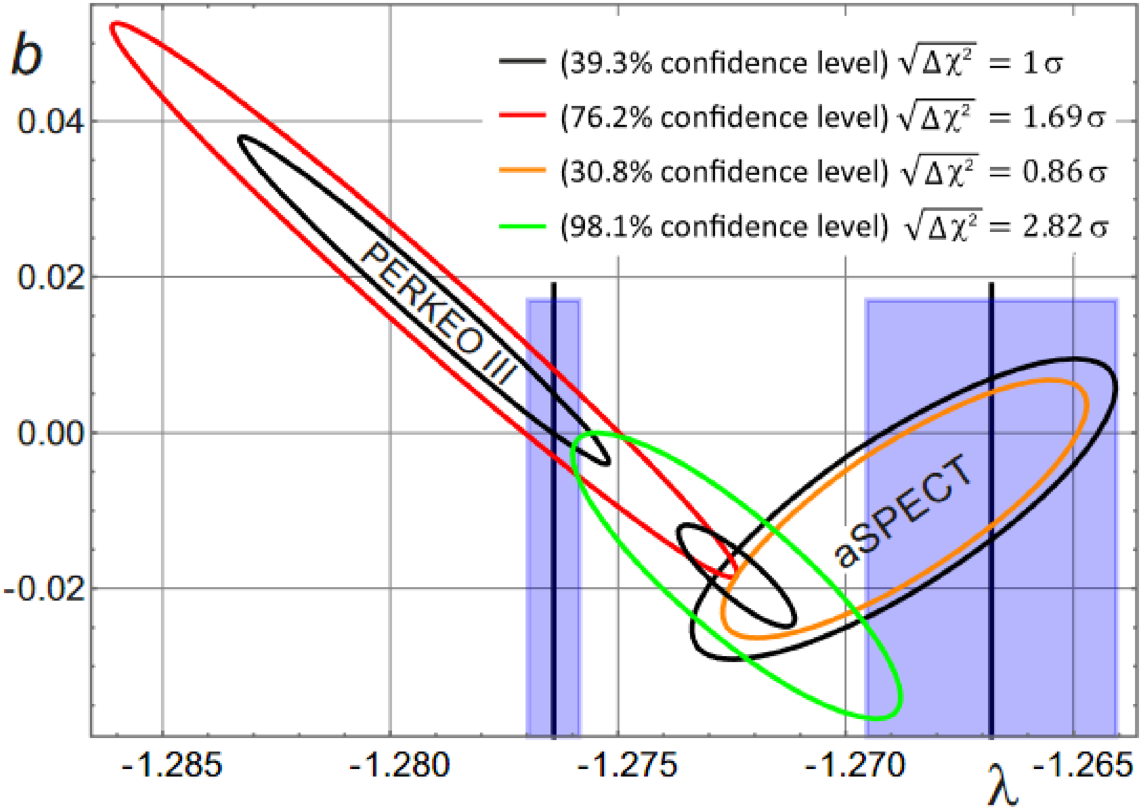


$\lambda \equiv g_A / g_V$

$$\lambda_{\rm PDG} = -1.2754(13)$$
$$S = 2.7$$

PDG 2024

“λ - discrepancy”



aSPECT, 2024 PRL

Incompatible with upper limits of Fierz term by individual experiment!

PERKEO-III, 2020 PRL

$\lambda_a - \lambda_A = \mathcal{O}(C_{\rm BSM}^2)$ assuming heavy new physics

Signature of **light new physics**?

Some ongoing/future **neutron correlation** experiments:

Experiment	Correlation	Projected precision
Nab	a	0.1%
	b	3 $\times 10^{-3}$ (abs)
UCNA+	A	0.2%
PERC	a	0.1%
	A	0.01%
	b	$\sim 10^{-3}$ (abs)

⋮

Summary

- Beta decays of pion, neutron and nuclei provide sensitive probe for new physics
- Decay lifetime determines V_{ud}; beta decay correlations probe most general EFT coupling
- ~3σ tension in the first-row CKM unitarity favors right-handed current
- Discrepancies in neutron lifetime and λ-measurement suggest possible light new physics
- Upcoming experiments on beta decay lifetimes and correlations may further improve the discovery potential for new physics