Adam Falkowski

Constraints on new physics from nuclear beta transitions

DESY Hamburg
15 June 2023

based on [arXiv:2010.13797] with Martin Gonzalez-Alonso, Oscar Naviliat-Cuncic
and on [arXiv:2112.07688] with Martin Gonzalez-Alonso, Ajdin Palavrić, Antonio Rodriguez-Sanchez
also featuring [arXiv:2112.02087] with Vincenzo Cirigliano, David Diaz, Martin Gonzalez-Alonso, and Antonio Rodriguez-Sanchez

Plan

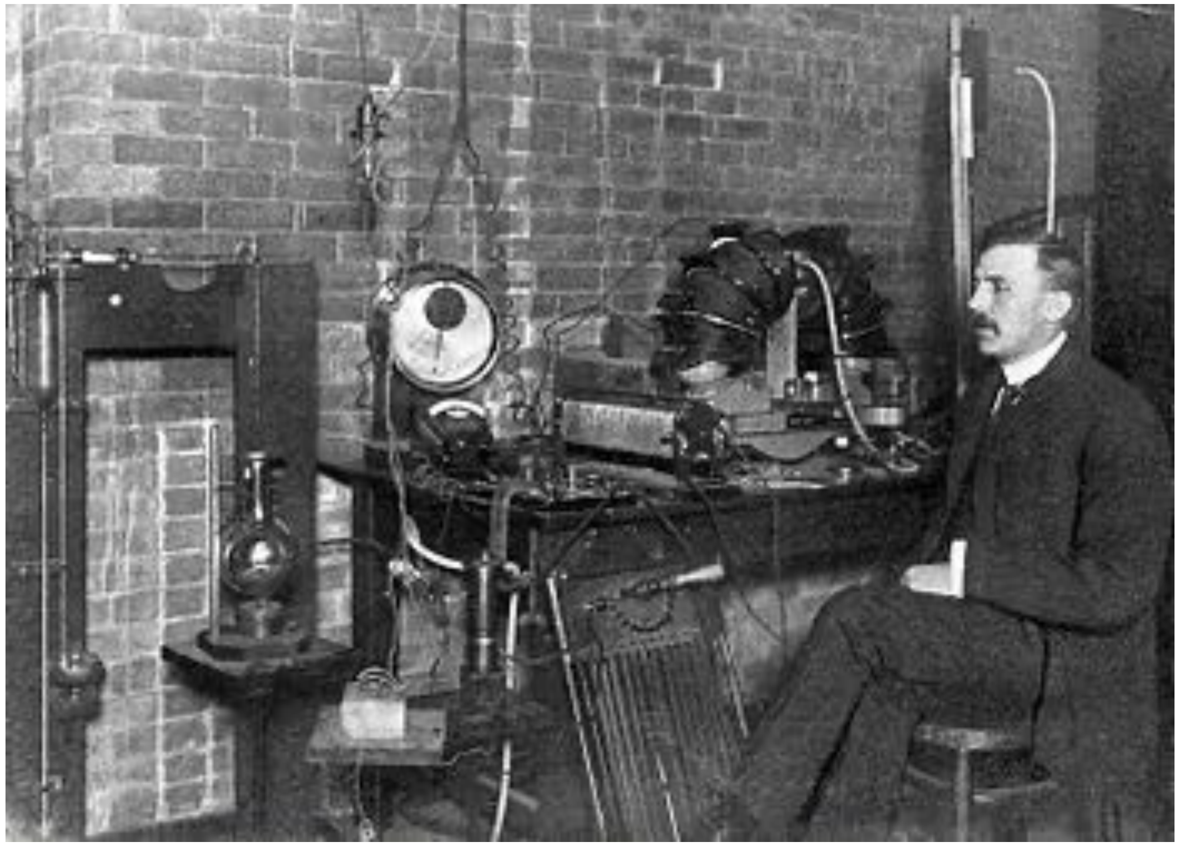
- Rapid historical introduction to beta decay
- EFT approach: from electroweak to nuclear scale
- Observables in beta decay
- Experimental results in beta decay
- Constraints on low-energy EFTs, SM, and SMEFT

Historical Introduction

History

Discovery of radioactivity of uranium in 1896 by Henri Becquerel

History



In 1899 Ernest Rutherford shows that uranium emits at least two different types of radiation: α and β decay

In 1900 Becquerel demonstrated that the β particle is the electron

In 1914 James Chadwick found spectrum of β-decay to be continuous

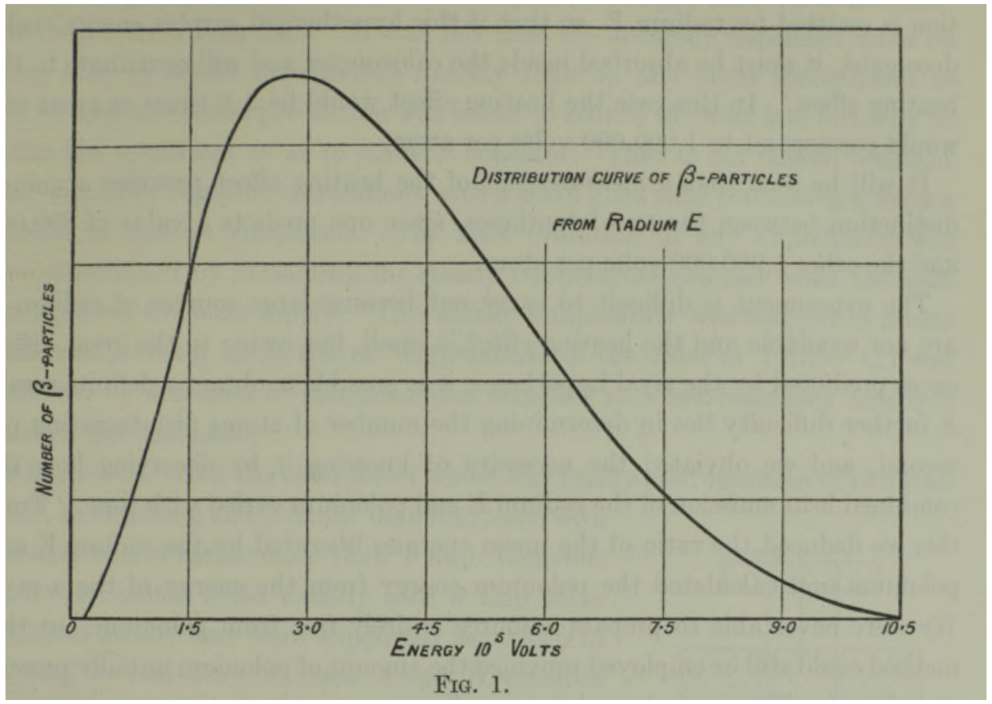
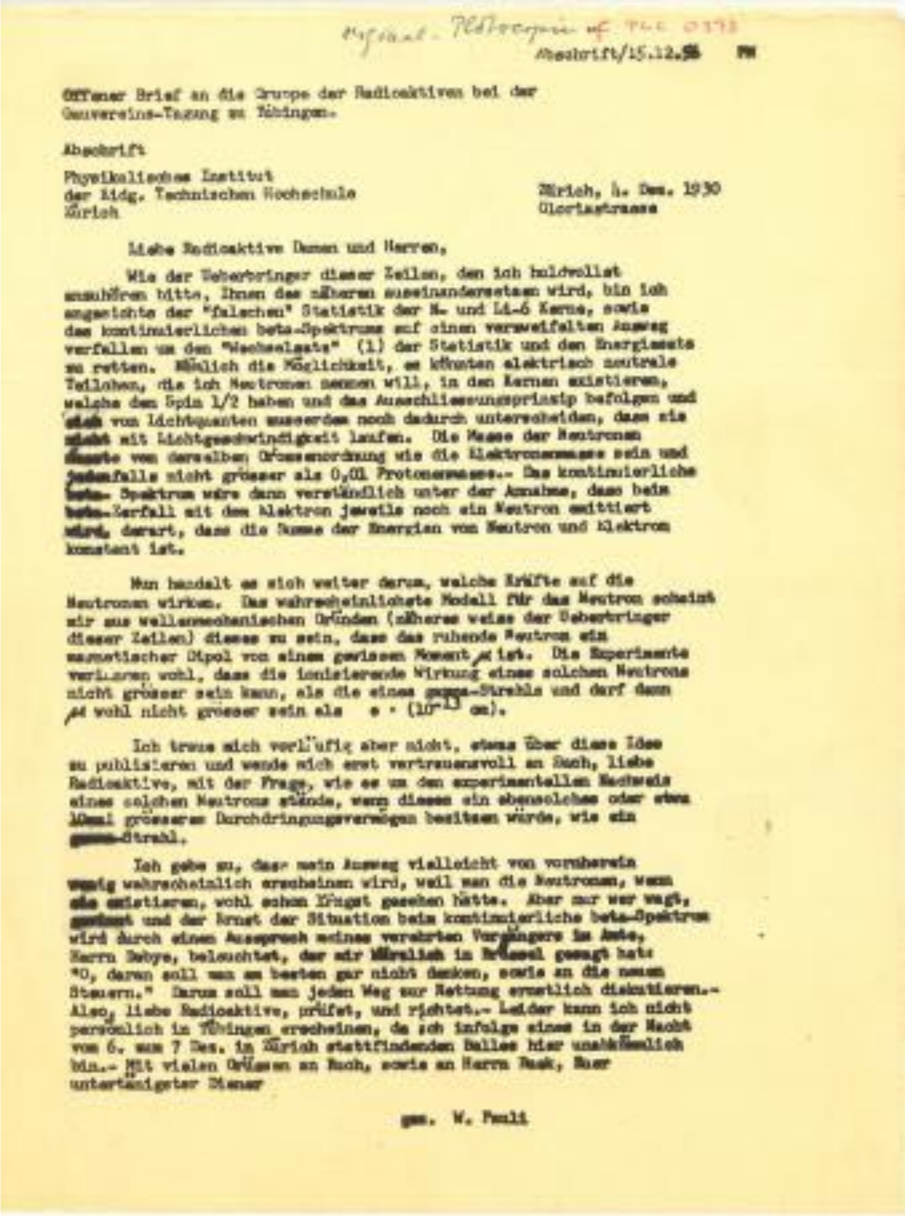


FIG. 1.

Many years of confusion follow, until the 1927 publication of β-decay spectrum in ^{210}Bi by Ellis and Wooster

History



Original - Photocopie of PLC 0393

Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

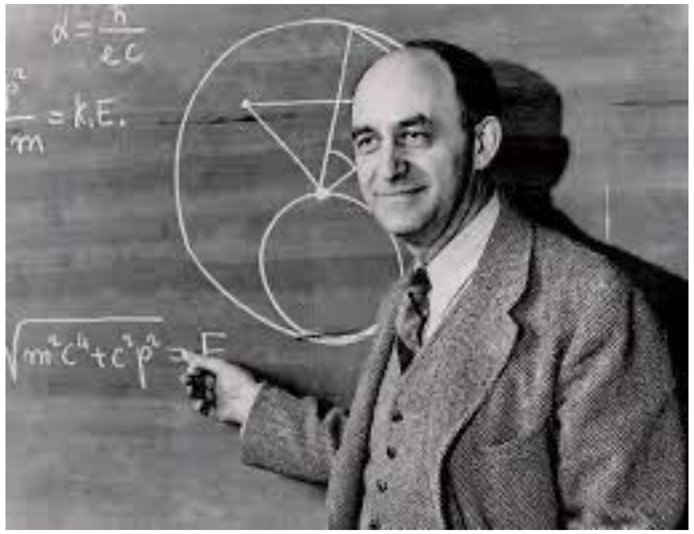
Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann, als die eines gamma-Strahls und darf dann μ wohl nicht grösser sein als $e \cdot (10^{-13}$ cm).

Ich traue mich vorläufig aber nicht, etwas über diese Idee zu publizieren und wende mich erst vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa 10mal grösseres Durchdringungsvermögen besitzen würde, wie ein gamma-Strahl.

Ich gebe zu, dass mein Ausweg vielleicht von vornherein wenig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt, gewinnt und der Ernst der Situation beim kontinuierliche beta-Spektrum wird durch einen Ausspruch meines verehrten Vorgängers im Amte, Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt hat: "O, daran soll man am besten gar nicht denken, sowie an die neuen Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren.- Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich nicht persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht vom 6. zum 7 Dez. in Zürich stattfindenden Balles hier unabkömmlich bin.- Mit vielen Grüssen an Euch, sowie an Herrn Back, Euer untertänigster Diener

gez. W. Pauli

"Liebe radioactive Damen und Herren"
1930 letter by Wolfgang Pauli proposing that a neutral and weakly interacting spin 1/2 particle is emitted along with electron in beta decay



In 1933 Enrico Fermi proposes a theory of β-decay

$$\mathscr{L} \supset -G_F(\bar{p}\gamma^\mu n)(\bar{e}\gamma_\mu \nu_e)$$

This is generalized in 1936 by George Gamow to include axial couplings

History

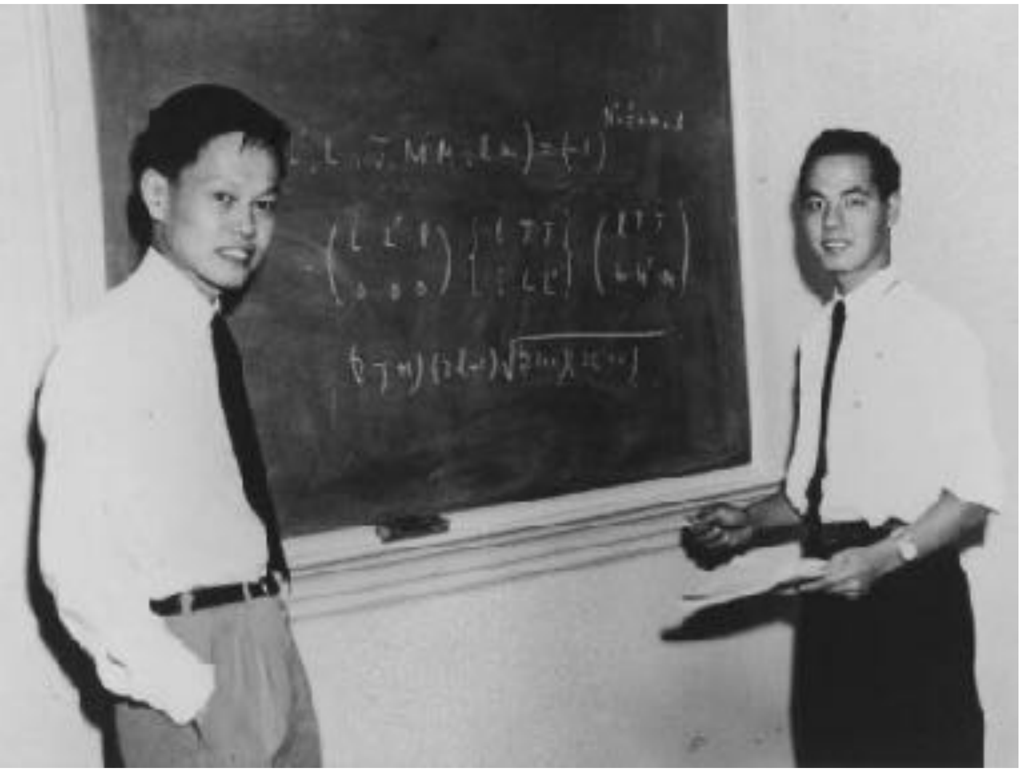
In 1932 James Chadwick studied the reaction

$$^{9}\mathrm{Be} + {}^{4}\mathrm{He} \to {}^{12}C + n$$

He demonstrated the new particle
has roughly the same mass as the proton.
The neutron turns out to be the simplest system
experiencing β decay

In 1934 Fréderic and Irène Joliot-Curie
discover β^{+} decay of ^{30}P
where emitted particle is the positron
rather than the electron

History



In 1956 Chen-Ning Yang and Tsung-Dao Lee publish
"Question of Parity Conservation in Weak Interactions
where they point out that there is
no proof of parity conservation in beta decay
and propose experimental tests

Bombshell drops in 1957, when the experiment of
Chien-Shiung Wu discovers parity violation
in beta decay of $^{60}\mathrm{Co}$

History

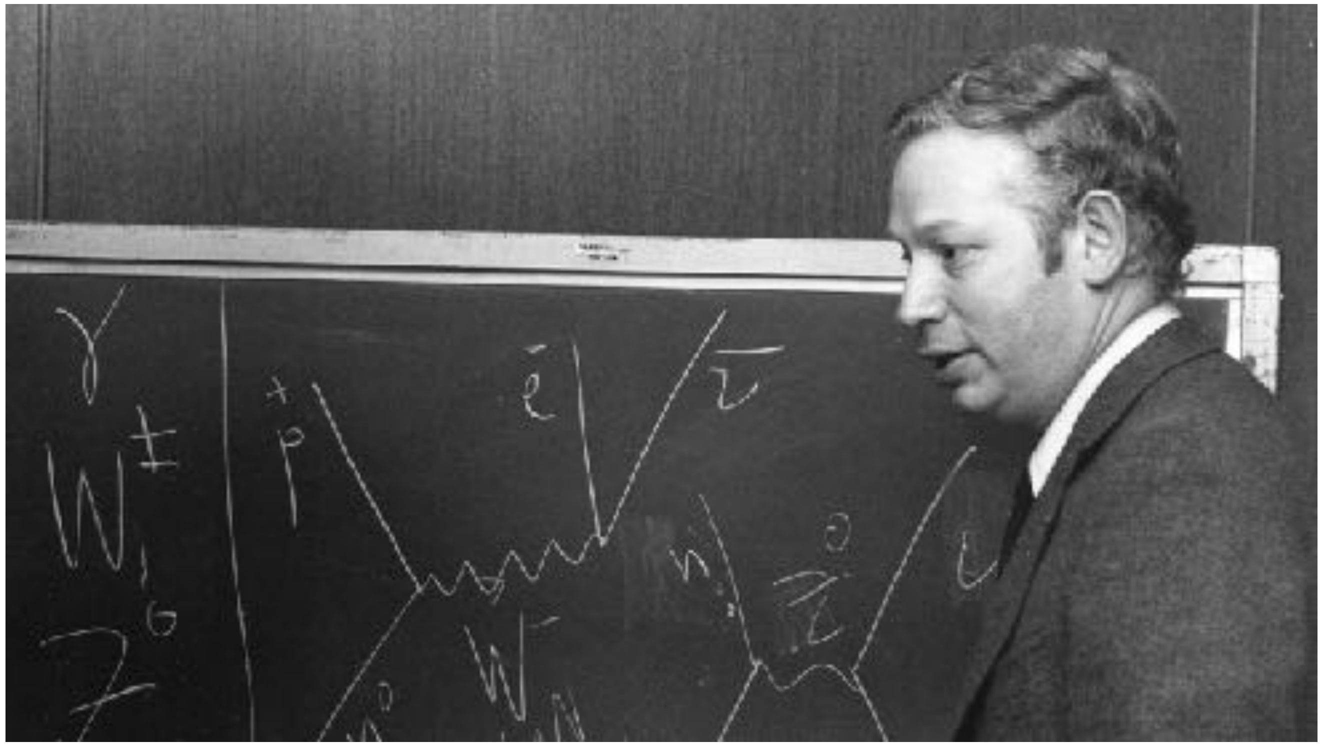
In the 1956 paper, Lee and Yang write down the general effective Lagrangian governing beta decay

$$
\begin{aligned}
H_{\text{int}} = &(\psi_p{}^\dagger\gamma_4\psi_n)(C_S\psi_e{}^\dagger\gamma_4\psi_\nu + C_S{}'\psi_e{}^\dagger\gamma_4\gamma_5\psi_\nu)\\
&+(\psi_p{}^\dagger\gamma_4\gamma_\mu\psi_n)(C_V\psi_e{}^\dagger\gamma_4\gamma_\mu\psi_\nu + C_V{}'\psi_e{}^\dagger\gamma_4\gamma_\mu\gamma_5\psi_\nu)\\
&+\tfrac{1}{2}(\psi_p{}^\dagger\gamma_4\sigma_{\lambda\mu}\psi_n)(C_T\psi_e{}^\dagger\gamma_4\sigma_{\lambda\mu}\psi_\nu\\
&+C_T{}'\psi_e{}^\dagger\gamma_4\sigma_{\lambda\mu}\gamma_5\psi_\nu)+(\psi_p{}^\dagger\gamma_4\gamma_\mu\gamma_5\psi_n)\\
&\times(-C_A\psi_e{}^\dagger\gamma_4\gamma_\mu\gamma_5\psi_\nu - C_A{}'\psi_e{}^\dagger\gamma_4\gamma_\mu\psi_\nu)\\
&+(\psi_p{}^\dagger\gamma_4\gamma_5\psi_n)(C_P\psi_e{}^\dagger\gamma_4\gamma_5\psi_\nu + C_P{}'\psi_e{}^\dagger\gamma_4\psi_\nu), \quad (
\end{aligned}
$$

In 1957, Robert Marshak and George Sudarshan and then Richard Feynman and Murray Gell-Mann identify the V-A structure of weak interactions, corresponding to $C_V = C_V'$ and $C_A = C_A'$ in the Lee-Yang Lagrangian, with other Wilson coefficients set to zero

History

In 1967 Weinberg writes
"A model of leptons"
where the fundamental carrier of
(charged-current) weak interactions
is introduced.
Subsequently, the V-A structure
governing beta decay is explained
via exchange of the W boson
between left-handed quarks and leptons



The rest is the Standard Model...

Summary of history

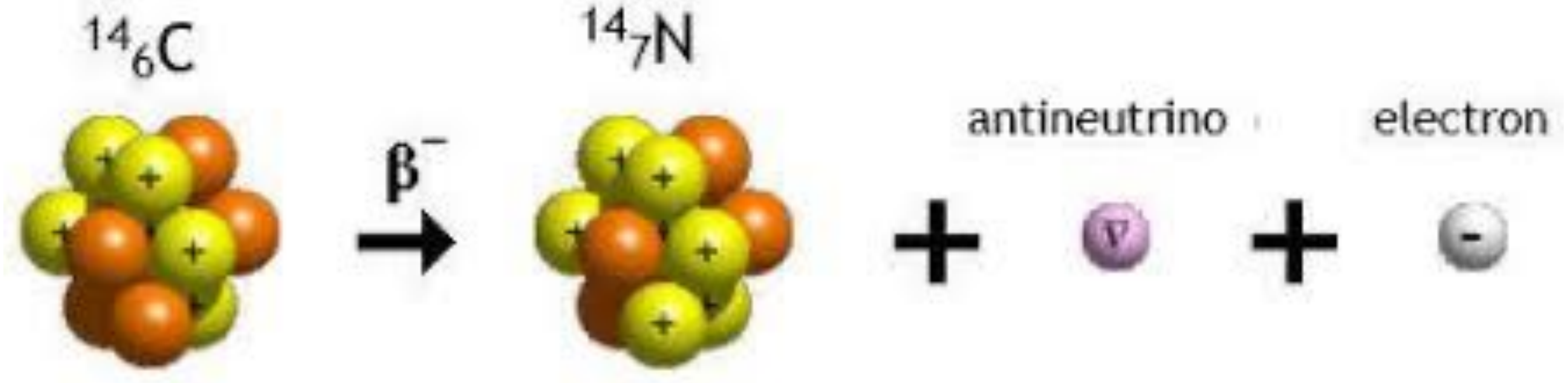
- Formalism of beta decay has been developed since the 30s of the previous century, and basic physics was understood by the end of the 50s. Sub-leading SM effects relevant for present-day experiments were worked out by mid-70s.

- In this talk I will use a somewhat different language, which connects better to the one used by the high-energy community, and allows one to treat possible beyond-the-SM interactions on the same footing as the SM ones. This langue is the effective field theory.

Scales in beta decay

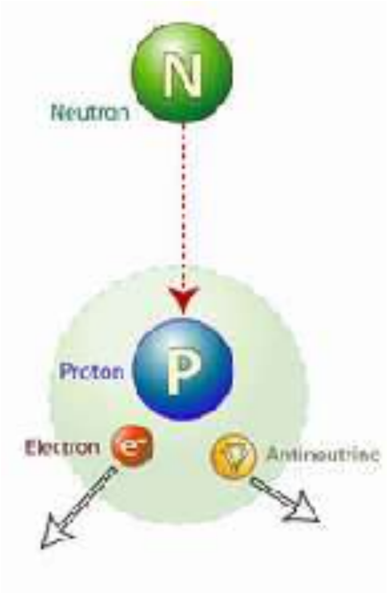
Nuclear level

$E \sim 10$ MeV



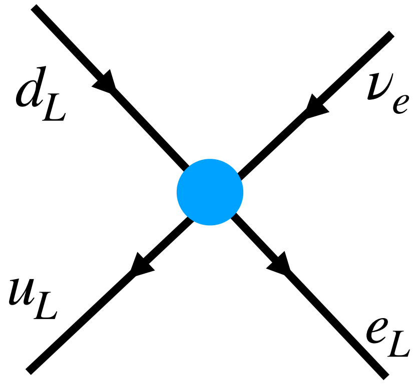
Nucleon level

$E \sim 1$ GeV



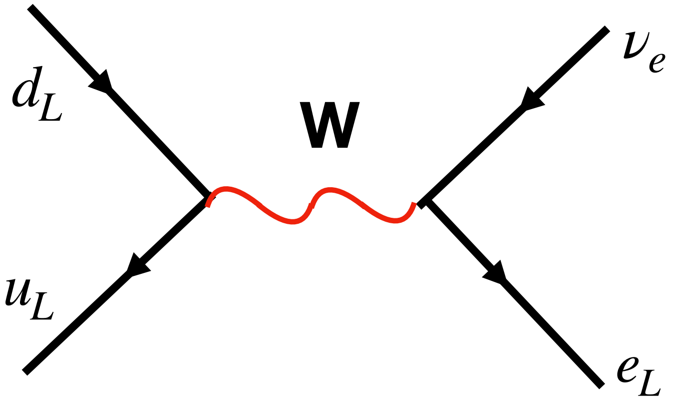
Quark level

$E \gtrsim 2$ GeV



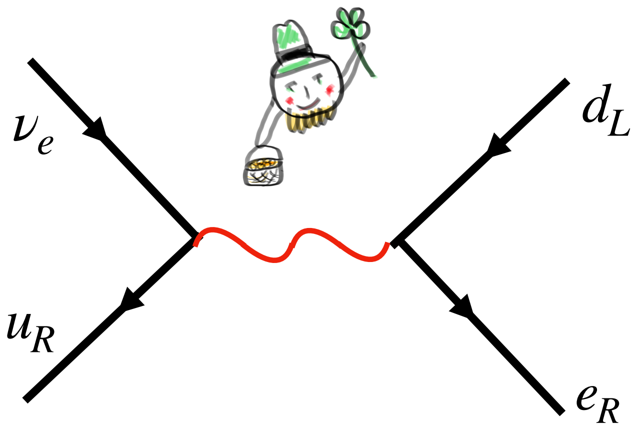
SM level

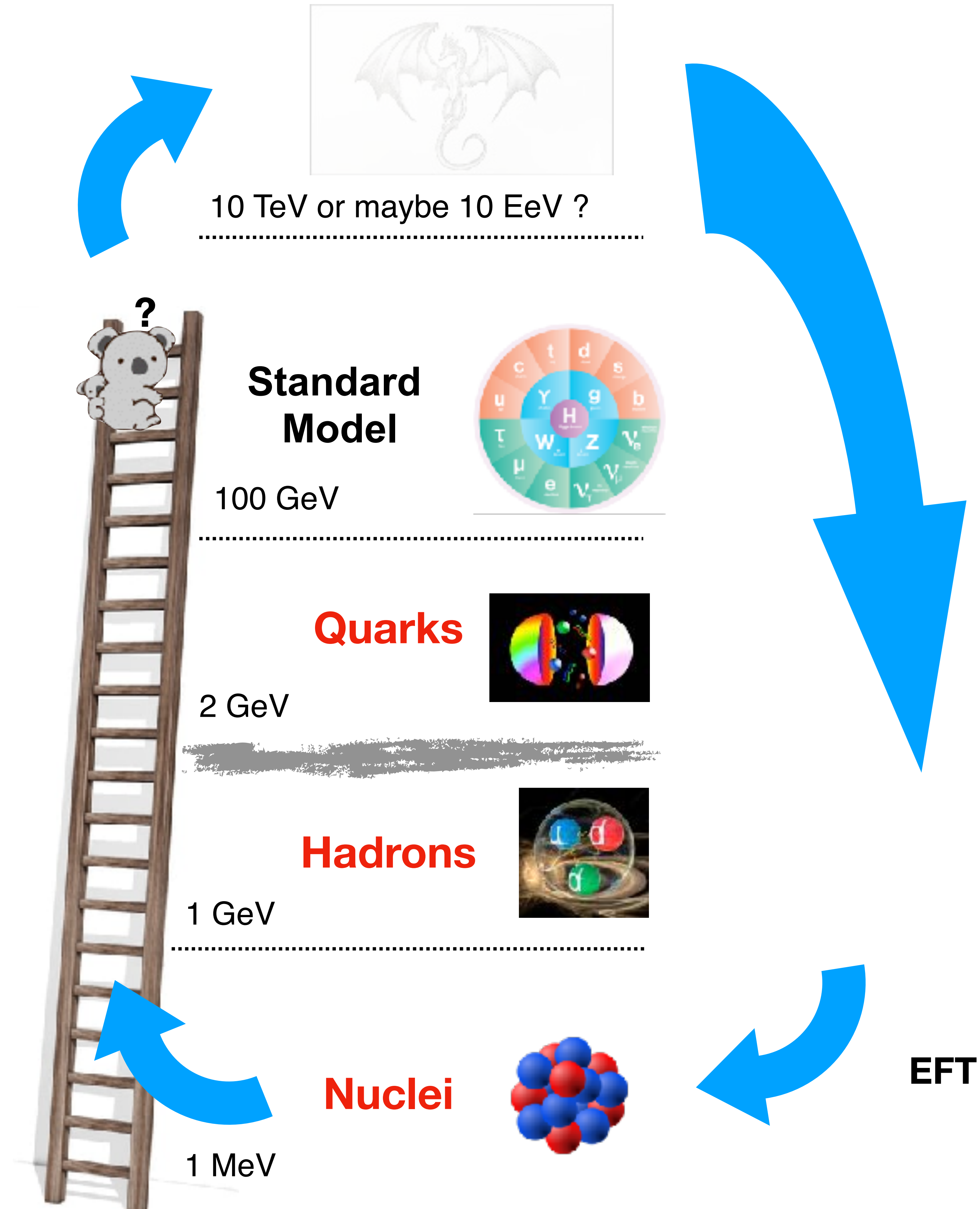
$E \gtrsim 100$ GeV



BSM level

$E \gtrsim 10^N$ TeV





10 TeV or maybe 10 EeV ?

Standard Model

100 GeV

Quarks

2 GeV

Hadrons

1 GeV

Nuclei

1 MeV

Properties of new particles beyond the Standard Model can be related to parameters of the effective Lagrangian describing low-energy interactions between SM particles

EFT for beta decay

EFT parameters can be precisely measured in nuclear beta transitions

Language of EFT

EFT Ladder

Connecting high- and low-energy physics via a series of effective theories

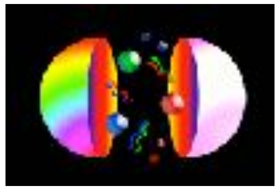
“Fundamental” BSM model

10 TeV?

EFT for SM particles (SMEFT)

100 GeV

EFT for light SM particles (WEFT)



2 GeV

EFT for Hadrons (ChPT etc)

1 GeV

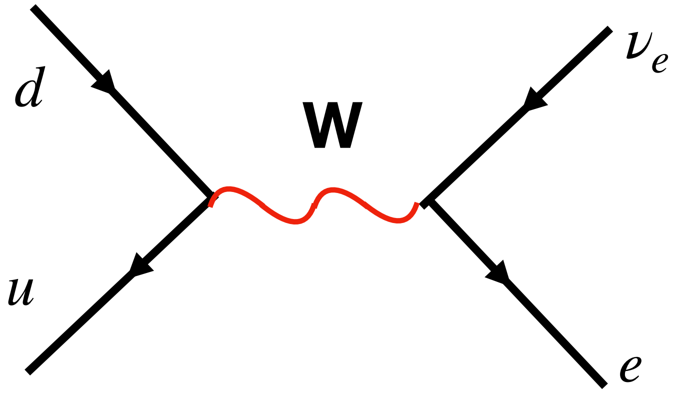
NR EFT for nucleons

1 MeV

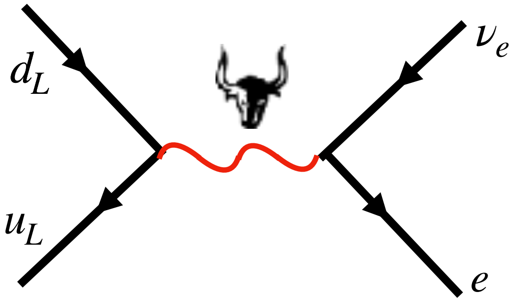
“Fundamental” models

“Fundamental” BSM model

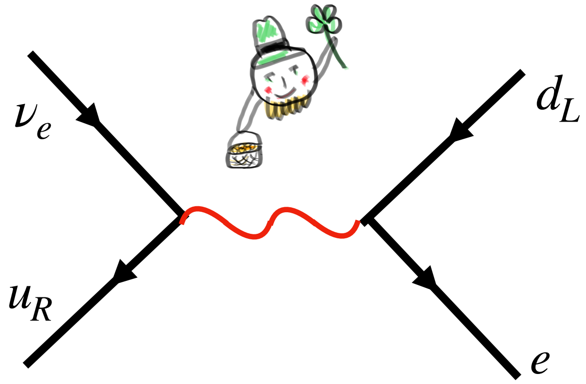
In the SM beta decay is mediated by the W boson



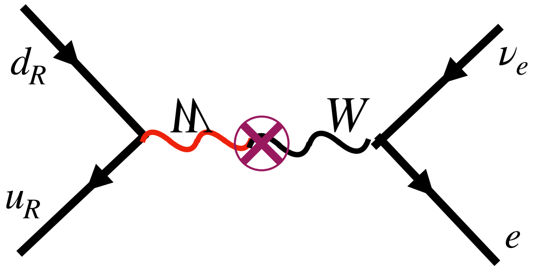
Several high-energy effects may contribute to beta decay



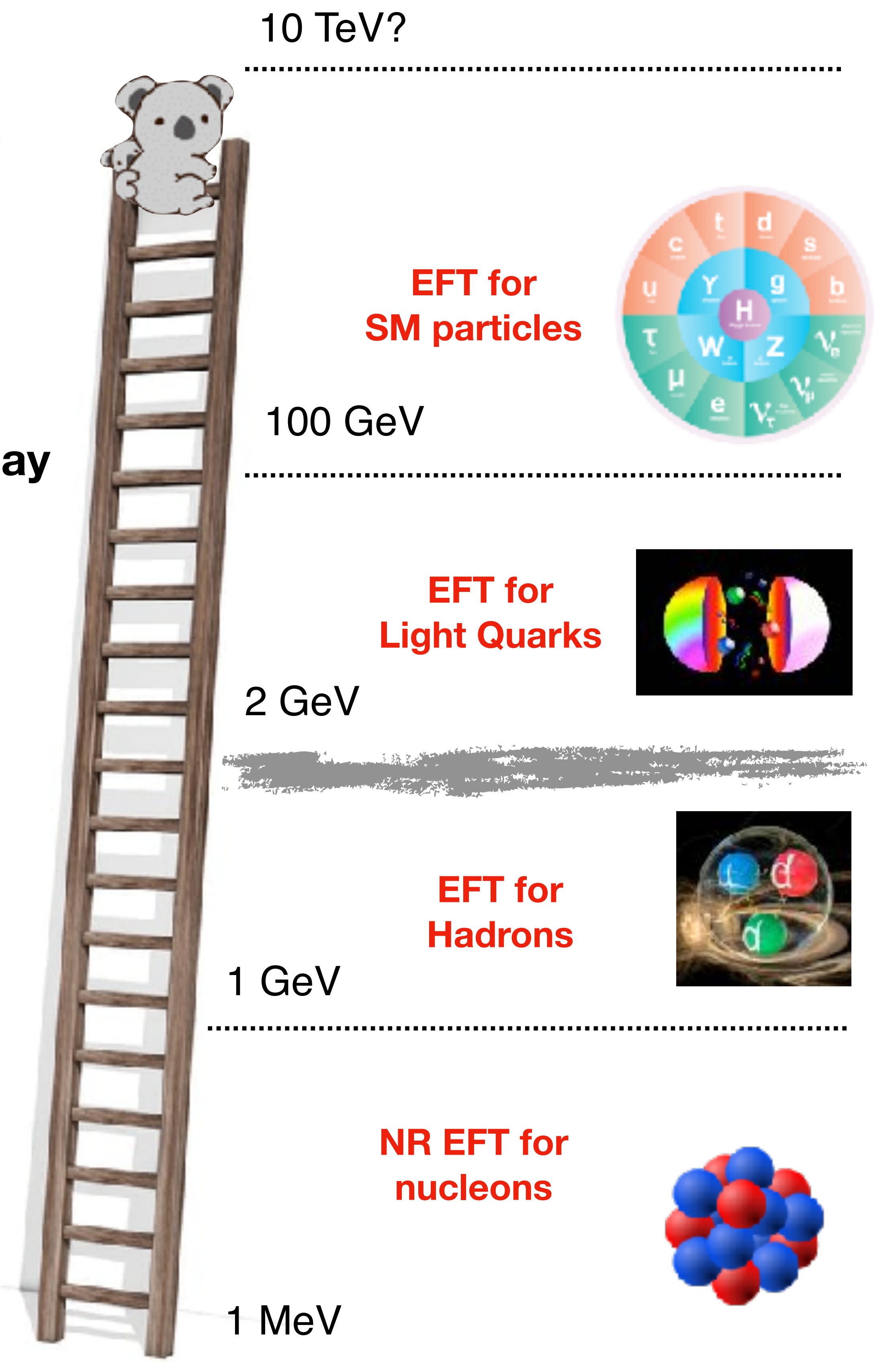
W’



Leptoquark



W_L-W_R mixing



10 TeV?

EFT for SM particles

100 GeV

EFT for Light Quarks

2 GeV

EFT for Hadrons

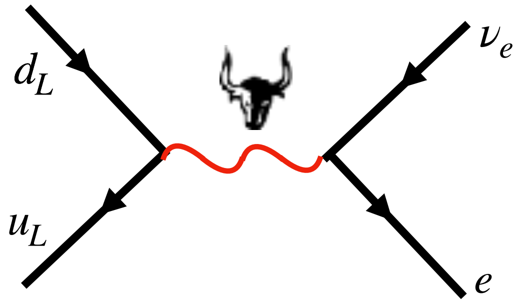
1 GeV

NR EFT for nucleons

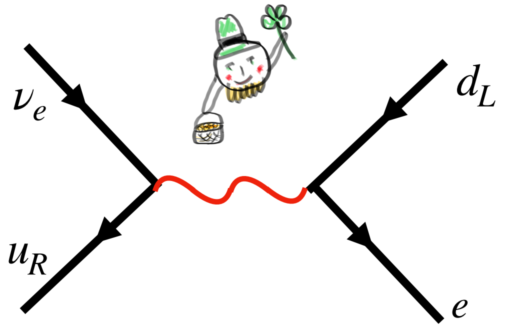
1 MeV

SMEFT at electroweak scale

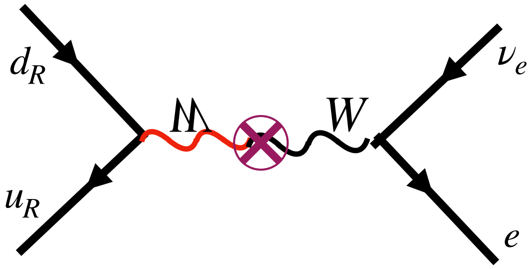
$$\begin{aligned}\mathscr{L}_{\rm SMEFT} \supset\; & C^{(3)}_{Hq} H^\dagger \sigma^a D_\mu H(\bar{Q}\sigma^a\gamma_\mu Q) + C_{Hl} H^\dagger \sigma^a D_\mu H(\bar{L}\sigma^a\gamma_\mu L) \\ & + C_{Hud} H^T D_\mu H(\bar{u}_R\gamma_\mu d_R) \\ & + C^{(3)}_{lq}(\bar{Q}\sigma^a\gamma_\mu Q)(\bar{L}\sigma^a\gamma_\mu L) + C^{(3)}_{lequ}(\bar{e}_R\sigma_{\mu\nu}L)(\bar{u}_R\sigma_{\mu\nu}Q) \\ & + C^{(1)}_{lequ}(\bar{e}_R L)(\bar{u}_R Q) + C_{ledq}(\bar{L}e_R)(\bar{d}_R Q) \\ & + \dots\end{aligned}$$



$$\rightarrow \quad C^{(3)}_{lq} \sim \frac{g_*^2}{M^2_{W'}}$$



$$\rightarrow \quad C^{(3)}_{lequ}, C^{(1)}_{LeQu}, C_{ledq} \sim \frac{g_*^2}{M^2_{LQ}}$$

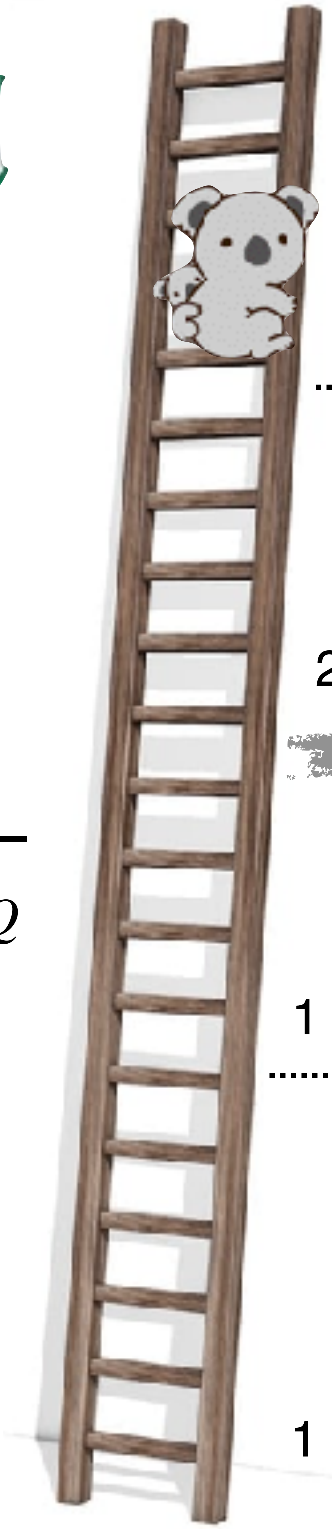


$$\rightarrow \quad C_{Hud} \sim \frac{g_*^2}{M^2_M}$$

For any "fundamental" model, the Wilson coefficients c_i can be calculated in terms of masses and couplings of new particles at the high-scale

"Fundamental" BSM model

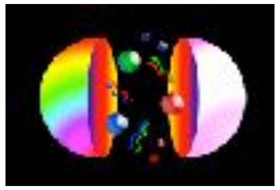
10 TeV?



EFT for SM particles

100 GeV

EFT for Light Quarks



2 GeV

EFT for Hadrons

1 GeV

NR EFT for nucleons

1 MeV

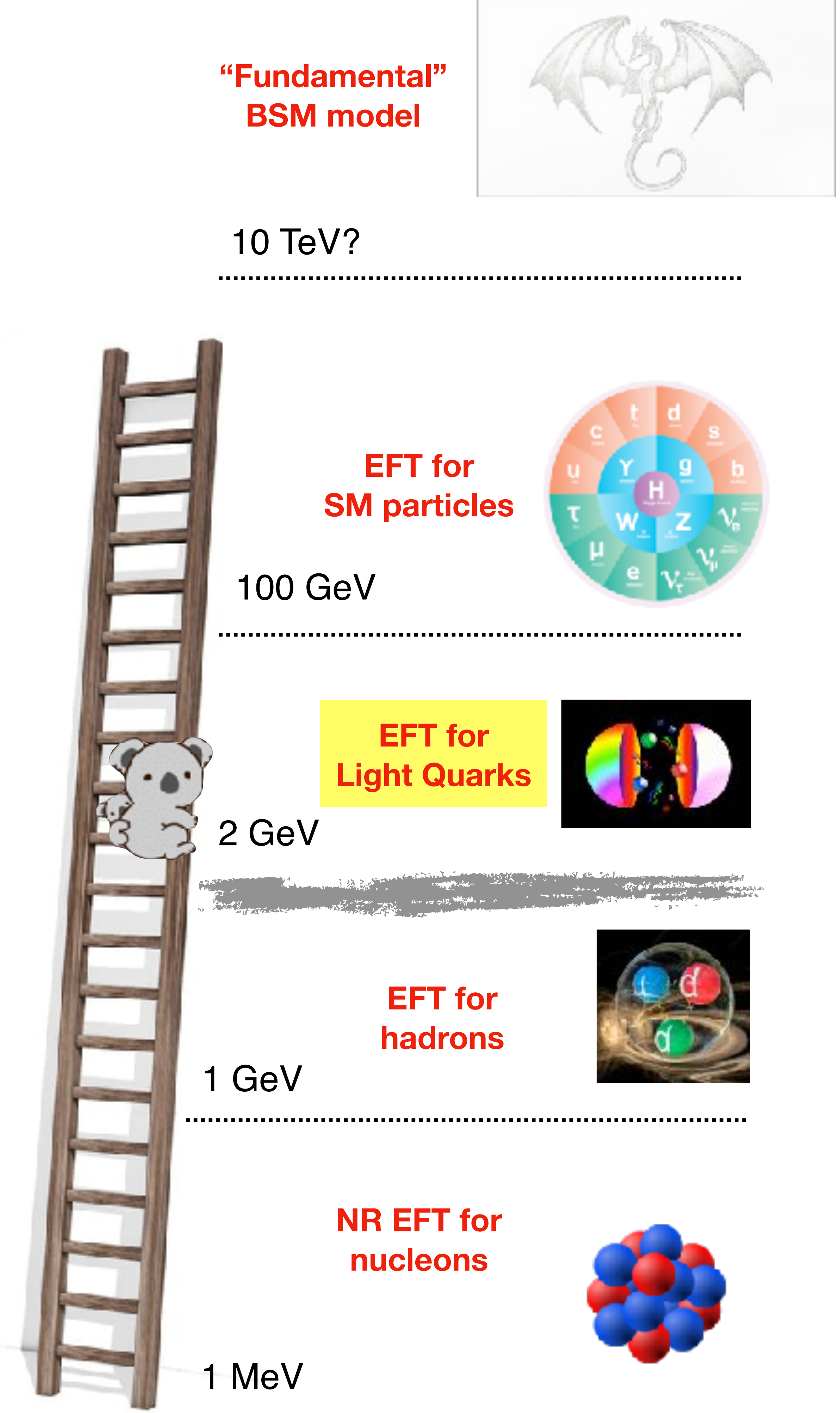
WEFT below electroweak scale

Below the electroweak scale, there is no W, thus all leading effects relevant for beta decays are described contact 4-fermion interactions, whether in SM or beyond the SM

$$\begin{array}{ll}
\mathcal{L}_{\mathrm{WEFT}} \supset -\frac{V_{ud}}{\mathrm{v}^2}\Big\{ \; (1+\epsilon_L) \;\; \bar{e}\gamma_\mu\nu_L \cdot \bar{u}\gamma^\mu(1-\gamma_5)d & \textbf{V-A} \\
\quad + \epsilon_R\, \bar{e}\gamma_\mu\nu_L \cdot \bar{u}\gamma^\mu(1+\gamma_5)d & \textbf{V+A} \\
\quad + \epsilon_T \frac{1}{4}\bar{e}\sigma_{\mu\nu}\nu_L \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5)d & \textbf{Tensor} \\
\quad + \epsilon_S\, \bar{e}\nu_L \cdot \bar{u}d & \textbf{Scalar} \\
\quad - \epsilon_P\, \bar{e}\nu_L \cdot \bar{u}\gamma_5 d \Big\} & \textbf{Pseudoscalar} \\
+\mathrm{hc} &
\end{array}$$

Much simplified description, only 5 (in principle complex) parameters at leading order

Physics beyond the SM characterised by 5 parameters ϵ_X describing effects of heavier non-standard particles (W', W_R, leptoquarks) coupled to light quarks and lepton



Translation from SMEFT to WEFT

The EFT below the weak scale (WEFT)
can be matched to the EFT above the weak scale (SMEFT)

$$\mathscr{L}_{\text{WEFT}} \supset -\frac{V_{ud}}{\text{v}^2}\Big\{ (1+\epsilon_L)\ \bar{e}\gamma_\mu\nu_L\cdot\bar{u}\gamma^\mu(1-\gamma_5)d + \epsilon_R\,\bar{e}\gamma_\mu\nu_L\cdot\bar{u}\gamma^\mu(1+\gamma_5)d + \epsilon_T\frac{1}{4}\bar{e}\sigma_{\mu\nu}\nu_L\cdot\bar{u}\sigma^{\mu\nu}(1-\gamma_5)d + \epsilon_S\,\bar{e}\nu_L\cdot\bar{u}d - \epsilon_P\,\bar{e}\nu_L\cdot\bar{u}\gamma_5 d \Big\}$$

$$\mathscr{L}_{\text{SMEFT}} \supset C^{(3)}_{Hq}H^\dagger\sigma^a D_\mu H(\bar{Q}\sigma^a\gamma_\mu Q) + C_{Hl}H^\dagger\sigma^a D_\mu H(\bar{L}\sigma^a\gamma_\mu L) + C_{Hud}H^T D_\mu H(\bar{u}_R\gamma_\mu d_R) + C^{(3)}_{lq}(\bar{Q}\sigma^a\gamma_\mu Q)(\bar{L}\sigma^a\gamma_\mu L) + C^{(3)}_{lequ}(\bar{e}_R\sigma_{\mu\nu}L)(\bar{u}_R\sigma_{\mu\nu}Q) + C^{(1)}_{lequ}(\bar{e}_R L)(\bar{u}_R Q) + C_{ledq}(\bar{L}e_R)(\bar{d}_R Q) + \ldots$$

At the scale m_Z WEFT parameters ϵ_X map to dimension-6 operators in SMEFT:

$$\epsilon_L = -C^{(3)}_{lq} + \left[\frac{1}{V_{ud}}\delta g_L^{Wq_1} + \delta g_L^{We} - 2\delta m_W\right]$$

$$\epsilon_R = \frac{1}{2V_{ud}}C_{Hud}$$

$$\epsilon_S = -\frac{1}{2V_{ud}}\left(C^{(1)}_{lequ}{}^* + V_{ud}C^*_{ledq}\right)$$

$$\epsilon_T = -\frac{2}{V_{ud}}C^{(3)*}_{LeQu}$$

$$\epsilon_P = -\frac{1}{2V_{ud}}\left(C^{(3)}_{lequ}{}^* - V_{ud}C^*_{ledq}\right)$$

Known RG running equations can translate it to Wilson coefficients ϵ_X at a low scale μ ~ 2 GeV

NR EFT for nucleons

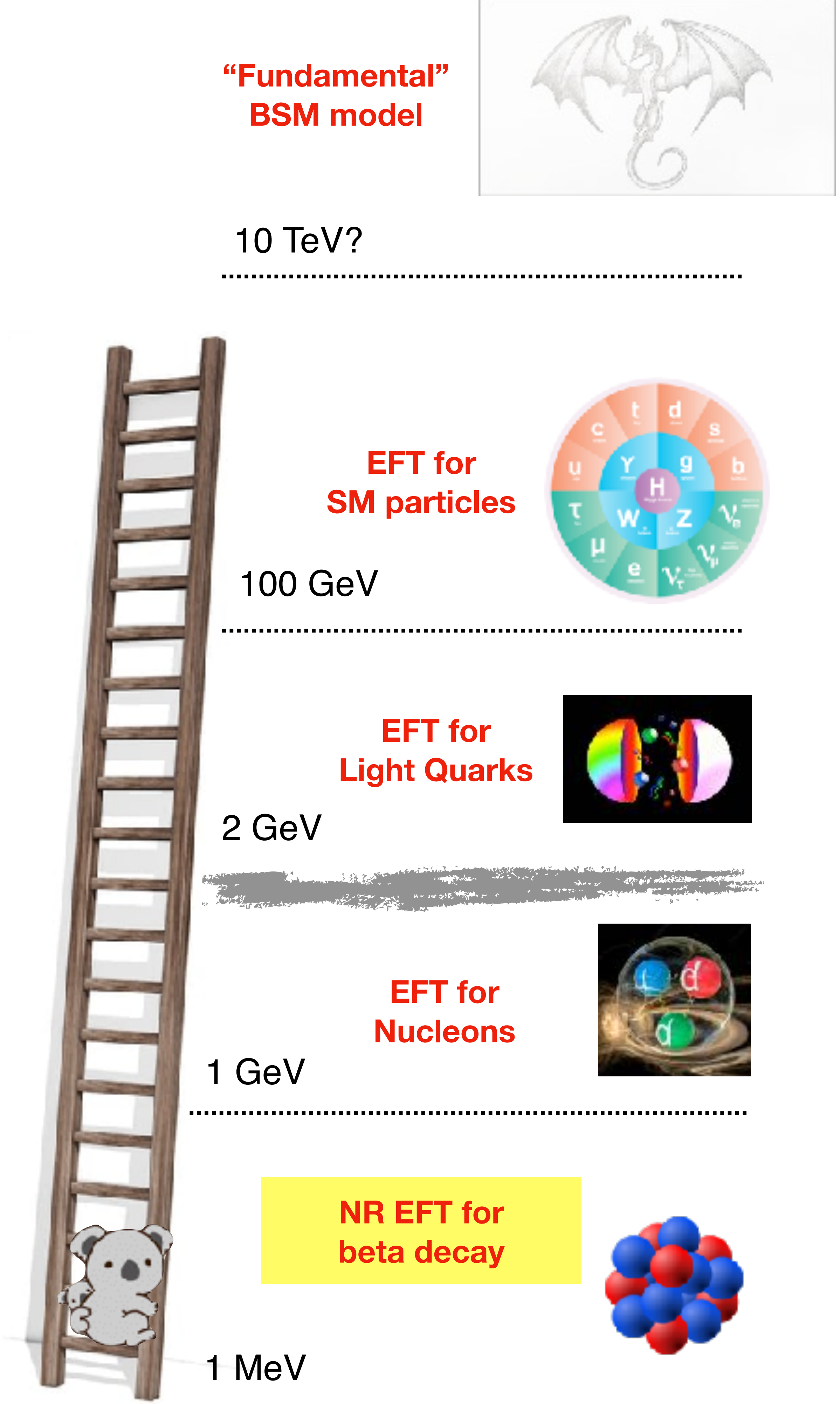
In beta decay, the momentum transfer is much smaller than the nucleon mass, due to approximate isospin symmetry leading to small mass splittings

Appropriate EFT is non-relativistic!

Lagrangian can be organised into expansion in ∇ / m_N , that is expansion in 3-momenta of the particles taking part in beta decay

Expansion parameter:

$$\epsilon \sim \frac{p}{m_N} \sim \frac{1 - 10 \text{ MeV}}{1 \text{ GeV}} \sim 0.01 - 0.001$$



“Fundamental” BSM model

10 TeV?

EFT for SM particles

100 GeV

EFT for Light Quarks

2 GeV

EFT for Nucleons

1 GeV

NR EFT for beta decay

1 MeV

EFT for nucleons

$$\mathscr{L}_{\mathrm{NR-EFT}} = \mathscr{L}^{(0)} + \mathscr{L}^{(1)} + \mathcal{O}(\nabla^2/m_N^2) + \mathrm{h.c.}$$

The most general leading (0-derivative) term in this expansion is

$$\mathscr{L}^{(0)} = -(\psi_p^\dagger \psi_n)\left[C_V^+ \bar{e}_L \gamma^0 \nu_L + C_S^+ \bar{e}_R \nu_L\right] + \sum_{k=1}^{3} (\psi_p^\dagger \sigma^k \psi_n)\left[C_A^+ \bar{e}_L \gamma^k \nu_L + C_T^+ \bar{e}_R \gamma^0 \gamma^k \nu_L\right]$$

where $\psi_{p.n}$ are non-relativistic fields describing proton and neutron

This can be obtained from the WEFT Lagrangian in two steps:

1. Match relativistic WEFT Lagrangian to relativistic nucleon (Lee-Yang) Lagrangian:

$$\begin{aligned}\mathscr{L}_{\mathrm{WEFT}} \supset -\frac{V_{ud}}{\mathrm{v}^2}\Big\{ & \left(1+\epsilon_L\right)\ \bar{e}\gamma_\mu \nu_L \cdot \bar{u}\gamma^\mu(1-\gamma_5)d \\ & +\epsilon_R\, \bar{e}\gamma_\mu \nu_L \cdot \bar{u}\gamma^\mu(1+\gamma_5)d \\ & +\epsilon_T \frac{1}{4}\bar{e}\sigma_{\mu\nu}\nu_L \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5)d \\ & +\epsilon_S\, \bar{e}\nu_L \cdot \bar{u}d \\ & -\epsilon_P\, \bar{e}\nu_L \cdot \bar{u}\gamma_5 d \Big\} \\ & +\mathrm{hc}\end{aligned}$$

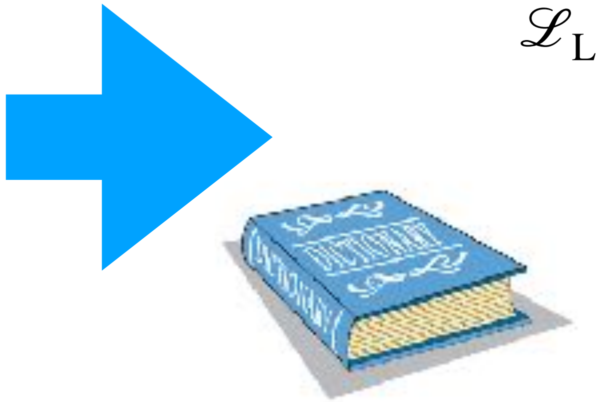
⇒

$$\begin{aligned}\mathscr{L}_{\mathrm{Lee-Yang}} \supset & -C_V^+ \bar{e}\gamma_\mu \nu_L \cdot \bar{p}\gamma^\mu n \\ & -C_A^+ \bar{e}\gamma_\mu \nu_L \cdot \bar{p}\gamma^\mu \gamma_5 n \\ & -\frac{1}{2}C_T^+ \bar{e}\sigma_{\mu\nu}\nu_L \cdot \bar{p}\sigma^{\mu\nu} n \\ & -C_S^+\, \bar{e}\nu_L \cdot \bar{p}n \\ & +C_P^+\, \bar{e}\nu_L \cdot \bar{p}\gamma_5 n \\ & +\mathrm{hc}\end{aligned}$$

$C_X^+ = C_X + C_X'$ **in the original LY Lagrangian**

EFT for nucleons

$$\begin{aligned}\mathcal{L}_{\rm WEFT} \supset -\frac{V_{ud}}{\mathrm{v}^2}\Big\{ & (1+\epsilon_L)\ \bar e\gamma_\mu\nu_L\cdot\bar u\gamma^\mu(1-\gamma_5)d \\ & +\epsilon_R\,\bar e\gamma_\mu\nu_L\cdot\bar u\gamma^\mu(1+\gamma_5)d \\ & +\epsilon_T\frac{1}{4}\bar e\sigma_{\mu\nu}\nu_L\cdot\bar u\sigma^{\mu\nu}(1-\gamma_5)d \\ & +\epsilon_S\,\bar e\nu_L\cdot\bar u d \\ & -\epsilon_P\,\bar e\nu_L\cdot\bar u\gamma_5 d\Big\} \\ +\mathrm{hc} & \end{aligned}$$



$$\begin{aligned}\mathcal{L}_{\rm Lee-Yang} \supset & -C_V^+\bar e\gamma_\mu\nu_L\cdot\bar p\gamma^\mu n \\ & -C_A^+\bar e\gamma_\mu\nu_L\cdot\bar p\gamma^\mu\gamma_5 n \\ & -\frac{1}{2}C_T^+\bar e\sigma_{\mu\nu}\nu_L\cdot\bar p\sigma^{\mu\nu}n \\ & -C_S^+\,\bar e\nu_L\cdot\bar p n \\ & +C_P^+\,\bar e\nu_L\cdot\bar p\gamma_5 n \\ +\mathrm{hc} & \end{aligned}$$

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

$$C_A^+ = -\frac{V_{ud}}{\mathrm{v}^2}g_A\sqrt{1+\Delta_R^A}\left(1+\epsilon_L-\epsilon_R\right)$$

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

$$C_S^+ = \frac{V_{ud}}{\mathrm{v}^2}g_S\epsilon_S$$

$$C_P^+ = \frac{V_{ud}}{\mathrm{v}^2}g_P\epsilon_P$$

Non-zero in the SM

Non-perturbative parameters in matching fixed by lattice+theory with good precision

$g_V \approx 1,$ Ademolo, Gatto (1964)

$g_A = 1.246 \pm 0.028,$ **Flag'21 N_f=2+1+1 value**

$g_S = 1.02 \pm 0.10,$ $g_T = 0.989 \pm 0.034$ Gupta et al 1806.09006

$g_P = 349 \pm 9$ Gonzalez-Alonso Martin-Camalich, 1309.4434

Matching also includes short-distance radiative corrections

$\Delta_R^V = 0.02467(22)$ **Seng et al 1807.10197**

$\Delta_R^A - \Delta_R^V = 0.036(8)$ **Cirigliano et al 2202.10439**

NR EFT for nucleons

$$
\begin{aligned}
\mathcal{L}_{\text{Lee-Yang}} \supset & -C_V^+ \bar{e}\gamma_\mu \nu_L \cdot \bar{p}\gamma^\mu n \\
& -C_A^+ \bar{e}\gamma_\mu \nu_L \cdot \bar{p}\gamma^\mu \gamma_5 n \\
& -\frac{1}{2} C_T^+ \bar{e}\sigma_{\mu\nu} \nu_L \cdot \bar{p}\sigma^{\mu\nu} n \\
& -C_S^+ \, \bar{e}\nu_L \cdot \bar{p}n \\
& +C_P^+ \, \bar{e}\nu_L \cdot \bar{p}\gamma_5 n \\
+\mathrm{hc}
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{L}^{(0)} = & -(\psi_p^\dagger \psi_n)\Big[C_V^+ \bar{e}_L \gamma^0 \nu_L + C_S^+ \bar{e}_R \nu_L\Big] \\
& + \sum_{k=1}^{3} (\psi_p^\dagger \sigma^k \psi_n)\Big[C_A^+ \bar{e}_L \gamma^k \nu_L + C_T^+ \bar{e}_R \gamma^0 \gamma^k \nu_L\Big] \\
& +\mathrm{hc}
\end{aligned}
$$

This is obtained by a change of variables:

$$
N_L \to \frac{e^{-i m_N t}}{\sqrt{2}} \left(1 + i \frac{\boldsymbol{\sigma} \cdot \nabla}{2 m_N}\right) \psi_N
$$

$$
N_R \to \frac{e^{-i m_N t}}{\sqrt{2}} \left(1 - i \frac{\boldsymbol{\sigma} \cdot \nabla}{2 m_N}\right) \psi_N
$$

In the NR EFT the expansion parameter is $\nabla / m_N \sim 10^{-2} - 10^{-3}$

NR EFT for nucleons

$$\mathcal{L}_{\rm NR-EFT} = \mathcal{L}^{(0)} + \mathcal{L}^{(1)} + \mathcal{O}(\nabla^2/m_N^2) + \mathrm{h.c.}$$

$$\mathcal{L}^{(0)} = -(\psi_p^\dagger \psi_n)\left[C_V^+ \bar{e}_L \gamma^0 \nu_L + C_S^+ \bar{e}_R \nu_L\right] + \sum_{k=1}^{3} (\psi_p^\dagger \sigma^k \psi_n)\left[C_A^+ \bar{e}_L \gamma^k \nu_L + C_T^+ \bar{e}_R \gamma^0 \gamma^k \nu_L\right]$$

Greatly simplified description:

- only 4 Lagrangian parameters relevant for beta decay at the leading order

- only two different bilinears of the nucleon fields, thus there is only two different nuclear matrix elements entering into the decay amplitude

Amplitude for the beta decay process $\mathcal{N} \to \mathcal{N}' e^- \bar{\nu}$ where J=J':

$$\mathcal{M} = -\mathcal{M}_F\left[C_V^+ \bar{u}(p_e)\gamma^0 v_L(p_\nu) + C_S^+ \bar{u}(p_e) v_L(p_\nu)\right] + \sum_{k=1}^{3} \mathcal{M}_{\rm GT}^k \left[C_A^+ \bar{u}(p_e)\gamma^k v_L(p_\nu) + C_T^+ u(p_e)\gamma^0\gamma^k v_L(p_\nu)\right]$$

$$\mathcal{M}_{\rm F} \equiv \langle \mathcal{N}' | \bar{\psi}_p \psi_n | \mathcal{N} \rangle \qquad \mathcal{M}_{\rm GT}^k \equiv \langle \mathcal{N}' | \bar{\psi}_p \sigma^k \psi_n | \mathcal{N} \rangle$$

Fermi matrix element **Gamow-Teller matrix element**

$$\mathcal{M}_F = 2m_{\mathcal{N}} M_F \delta_{J_z'}^{J_z}$$

Calculable from group theory in the isospin limit

$$\mathcal{M}_{GT}^k = 2m_{\mathcal{N}} M_F \frac{r}{\sqrt{J(J+1)}} [T^k]_{J_z'}^{J_z}$$

Difficult to calculate from first principles

Spin-J generators

Summary of EFT language

$$\mathscr{L}_{\mathrm{NR-EFT}} = \mathscr{L}^{(0)} + \mathscr{L}^{(1)} + \mathcal{O}(\nabla^2/m_N^2) + \mathrm{h.c.}$$

Assumption: the only light degrees of freedom at the scales $\lesssim 1\ \mathrm{GeV}$ are those of the SM

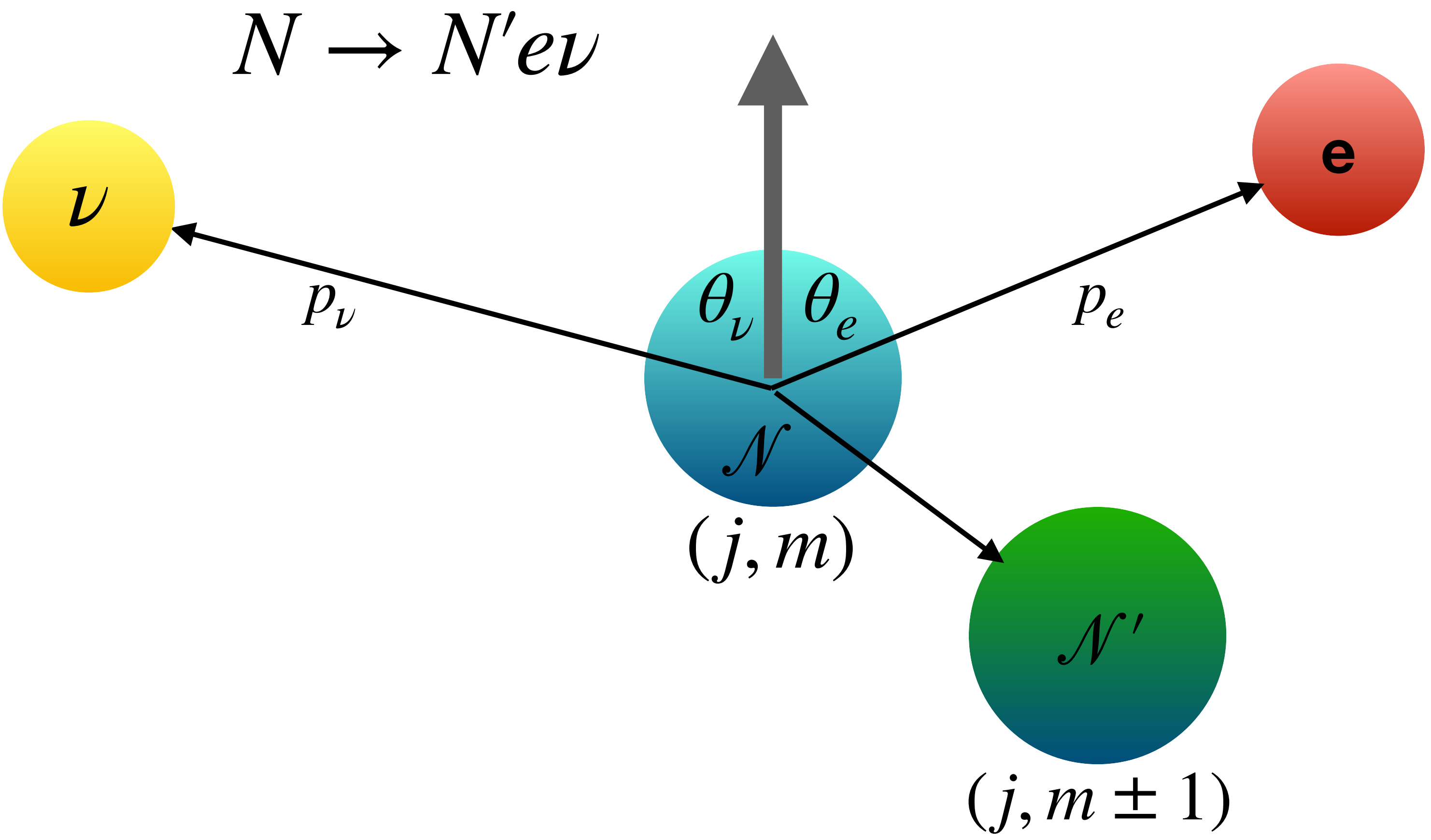
Then the most general leading (0-derivative) term in the EFT expansion is

$$\mathscr{L}^{(0)} = -(\psi_p^\dagger \psi_n)\Big[\underset{\substack{\uparrow\\ \textbf{Generated by}\\ \textbf{weak interactions}\\ \textbf{in SM}}}{C_V^+}\bar{e}_L\gamma^0\nu_L + \underset{\substack{\uparrow\\ \textbf{Highly suppressed}\\ \textbf{in SM}}}{C_S^+}\bar{e}_R\nu_L\Big] + \sum_{k=1}^{3}(\psi_p^\dagger\sigma^k\psi_n)\Big[\underset{\substack{\uparrow\\ \textbf{Generated by}\\ \textbf{weak interactions}\\ \textbf{in SM}}}{C_A^+}\bar{e}_L\gamma^k\nu_L + \underset{\substack{\uparrow\\ \textbf{Not generated}\\ \textbf{in SM}}}{C_T^+}\bar{e}_R\gamma^0\gamma^k\nu_L\Big]$$

The goal of beta decay studies is to measure these 4 parameters of the EFT Lagrangian as precisely as possible, in a model-independent way, and without theoretical biases

Observables for allowed beta transitions

Observables in beta decay



Electron energy/momentum

$$E_e = \sqrt{p_e^2 + m_e^2}$$

Neutrino energy

$$E_\nu = p_\nu = m_N - m_{N'} - E_e$$

Information about the Wilson coefficients can be accessed by measuring (differential) decay width:

$$\frac{d\Gamma}{dE_e d\Omega_e d\Omega_\nu} = F(E_e)\Bigg\{ 1 + b\frac{m_e}{E_e} + a\frac{\boldsymbol{p}_e\cdot\boldsymbol{p}_\nu}{E_eE_\nu} + A\frac{\langle \boldsymbol{J}\rangle\cdot\boldsymbol{p}_e}{JE_e} + B\frac{\langle \boldsymbol{J}\rangle\cdot\boldsymbol{p}_\nu}{JE_\nu}$$
$$+c\frac{\boldsymbol{p}_e\cdot\boldsymbol{p}_\nu - 3(\boldsymbol{p}_e\cdot\boldsymbol{j})(\boldsymbol{p}_\nu\cdot\boldsymbol{j})}{3E_eE_\nu}\left[\frac{J(J+1)-3(\langle\boldsymbol{J}\rangle\cdot\boldsymbol{j})^2}{J(2J-1)}\right] + D\frac{\langle\boldsymbol{J}\rangle\cdot(\boldsymbol{p}_e\times\boldsymbol{p}_\nu)}{JE_eE_\nu}\Bigg\}$$

No-one talks about it

Here, width already summed over polarizations of N' and e

Violates T
I won't discuss it today

From effective Lagrangian to observables

Jackson Treiman Wyld (1957)

Total decay width Γ:

$$\Gamma = (1+\delta)\frac{M_F^2 m_e^5}{4\pi^3} X \left[1 + b\left\langle \frac{m_e}{E_e}\right\rangle\right] f$$

Higher-order corrections

Fermi matrix element

Fierz term

Phase space factor

$$f \equiv \int_{m_e}^{m_N - m_{N'}} dE_e \frac{E_\nu^2 p_e E_e}{m_e^5}\phi(E_e)$$

$$\langle m_e/E_e\rangle \equiv \int_{m_e}^{m_N - m_{N'}} dE_e \frac{E_\nu^2 p_e}{m_e^4}\phi(E_e)$$

Fermi function

$$X \equiv (C_V^+)^2 + (C_S^+)^2 + r^2\left[(C_A^+)^2 + (C_T^+)^2\right]$$

Nuclear-dependent ratio of Fermi and GT matrix elements (equivalent to mixing parameter $\rho = rC_A^+/C_V^+$)

Fierz term controls the shape of the beta spectrum:

$$b \times X \equiv \pm 2\left\{ C_V^+ C_S^+ + r^2 C_A^+ C_T^+ \right\}$$

"Little a" parameter controls correlation between electron and neutrino directions:

$$a \times X = (C_V^+)^2 - (C_S^+)^2 - \frac{r^2}{3}\left[(C_A^+)^2 - (C_T^+)^2\right]$$

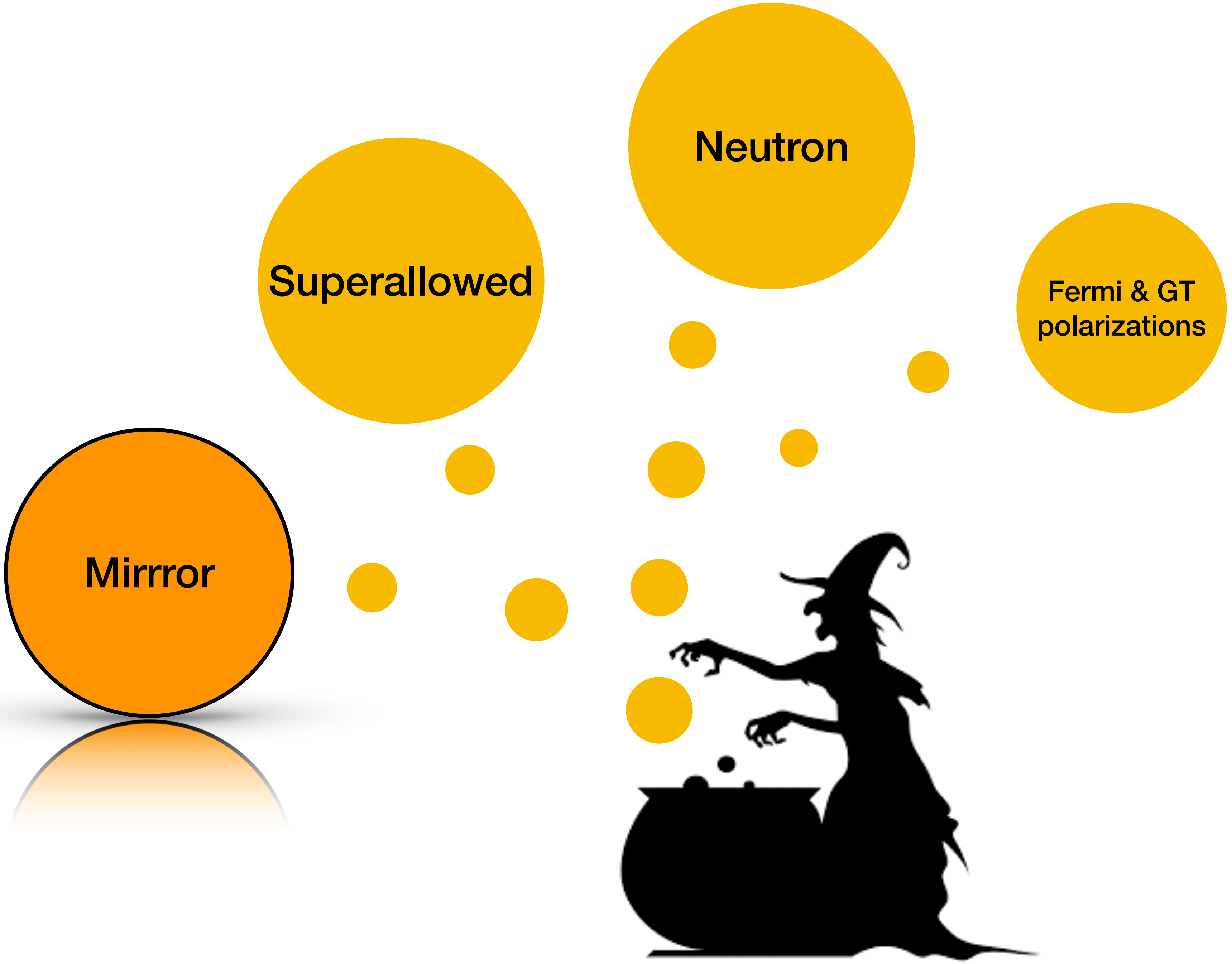
"Big A" parameter controls correlation between nucleus polarization and electron directions:

$$A \times X = -2r\sqrt{\frac{J}{J+1}}\left\{ C_V^+ C_A^+ - C_S^+ C_T^+ \right\} \mp \frac{r^2}{J+1}\left\{ (C_A^+)^2 - (C_T^+)^2 \right\}$$

In addition, one needs to include nuclear structure, isospin breaking weak magnetism, and radiative corrections, which are small but may be significant for most precisely measured observables

Data for
allowed beta transitions

Global BSM fits to beta transitions



Neutron

Superallowed

Fermi & GT polarizations

Mirrror

Gonzalez-Alonso, Naviliat-Cuncic, Severijns, 1803.08732

AA, Martin Gonzalez-Alonso, Oscar Naviliat-Cuncic, 2010.13797

Superallowed beta decay data

0+ → 0+ beta transitions

Parent	$\mathcal{F}t$ [s]	$\langle m_e/E_e \rangle$
^{10}C	3075.7 ± 4.4	0.619
^{14}O	3070.2 ± 1.9	0.438
^{22}Mg	3076.2 ± 7.0	0.308
^{26m}Al	3072.4 ± 1.1	0.300
^{26}Si	3075.4 ± 5.7	0.264
^{34}Cl	3071.6 ± 1.8	0.234
^{34}Ar	3075.1 ± 3.1	0.212
^{38m}K	3072.9 ± 2.0	0.213
^{38}Ca	3077.8 ± 6.2	0.195
^{42}Sc	3071.7 ± 2.0	0.201
^{46}V	3074.3 ± 2.0	0.183
^{50}Mn	3071.1 ± 1.6	0.169
^{54}Co	3070.4 ± 2.5	0.157
^{62}Ga	3072.4 ± 6.7	0.142
^{74}Rb	3077 ± 11	0.125

Latest compilation Hardy, Towner (2020)

0+ → 0+ beta transitions are pure Fermi

$$X \equiv (C_V^+)^2 + (C_S^+)^2 + \xcancel{\frac{f_A}{f_V}} r^2 \overset{\sim}{\Big[} \xcancel{(C_A^+)^2} \xcancel{+} \xcancel{(C_T^+)^2 \Big]}$$

$$bX \equiv \pm 2 \Big\{ C_V^+ C_S^+ + \xcancel{r^2} \xcancel{\Big[C_A^+ C_T^+ \Big]} \xcancel{\Big\}}$$

$$\Gamma = (1+{\color{red}\delta}) \frac{M_F^2 m_e^5}{4\pi^3} X \left[1 + b {\color{red}\left\langle \frac{m_e}{E_e} \right\rangle} \right] {\color{red}f}$$

Higher-order corrections

Fermi matrix element

Fierz term

Phase space factor

$\delta, \langle m_e/E_e \rangle, f$ are transition dependent, but

M_F, X and b are the same for all 0+ → 0+ transitions!

$$\mathscr{F}t \equiv \frac{(1+\delta) f \log 2}{\Gamma} = \frac{4\pi^3 \log 2}{M_F^2 m_e^5 X \left[1 + b \left\langle \frac{m_e}{E_e} \right\rangle \right]}$$

Universal

Transition dependent

$\mathscr{F}t$ is defined such that it is the same for all $0^+ \to 0^+$ transitions if the SM gives the complete description of beta decays

Neutron decay data

New average of neutron lifetime including recent measurement by UCNτ experiment [arXiv:2106.10375]

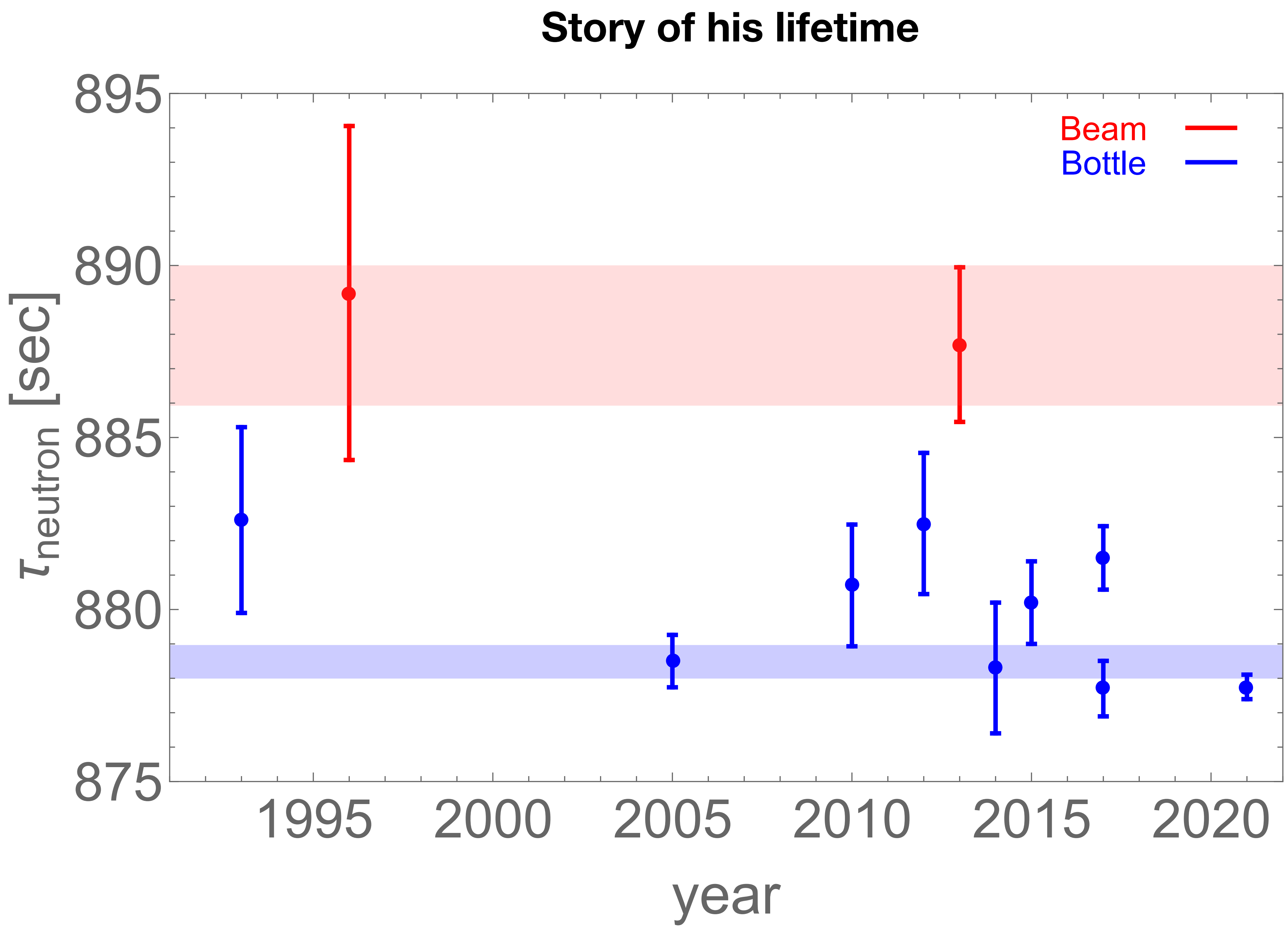
Observable	Value	$\langle m_e/E_e \rangle$	References
τ_n (s)	**878.64(59)** ~~879.75(76)~~	0.655	[52–61]
$\tilde{A}_n$	$-0.11958(18)$	0.569	[45, 62–66]
$\tilde{B}_n$	$0.9805(30)$	0.591	[67–70]
λ_{AB}	$-1.2686(47)$	0.581	[71]
a_n	$-0.10426(82)$		[46, 72, 73]
$\tilde{a}_n$	~~$-0.1090(41)$~~	0.695	[74]

-0.1078(20)

Updated value of $\tilde{a}_n$ from the aCORN experiment [arXiv:2012.14379]

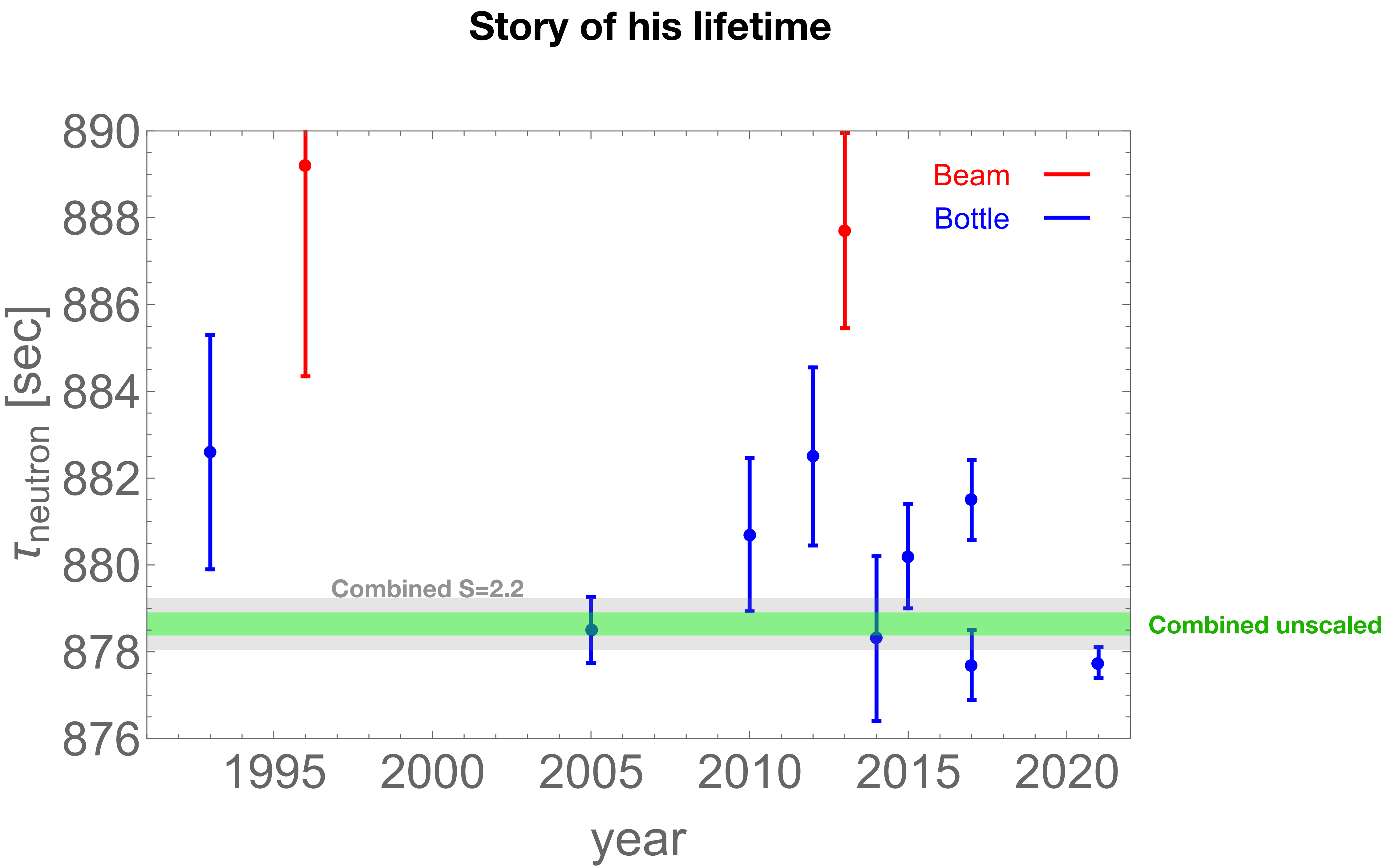
Order per-mille precision !

Neutron lifetime



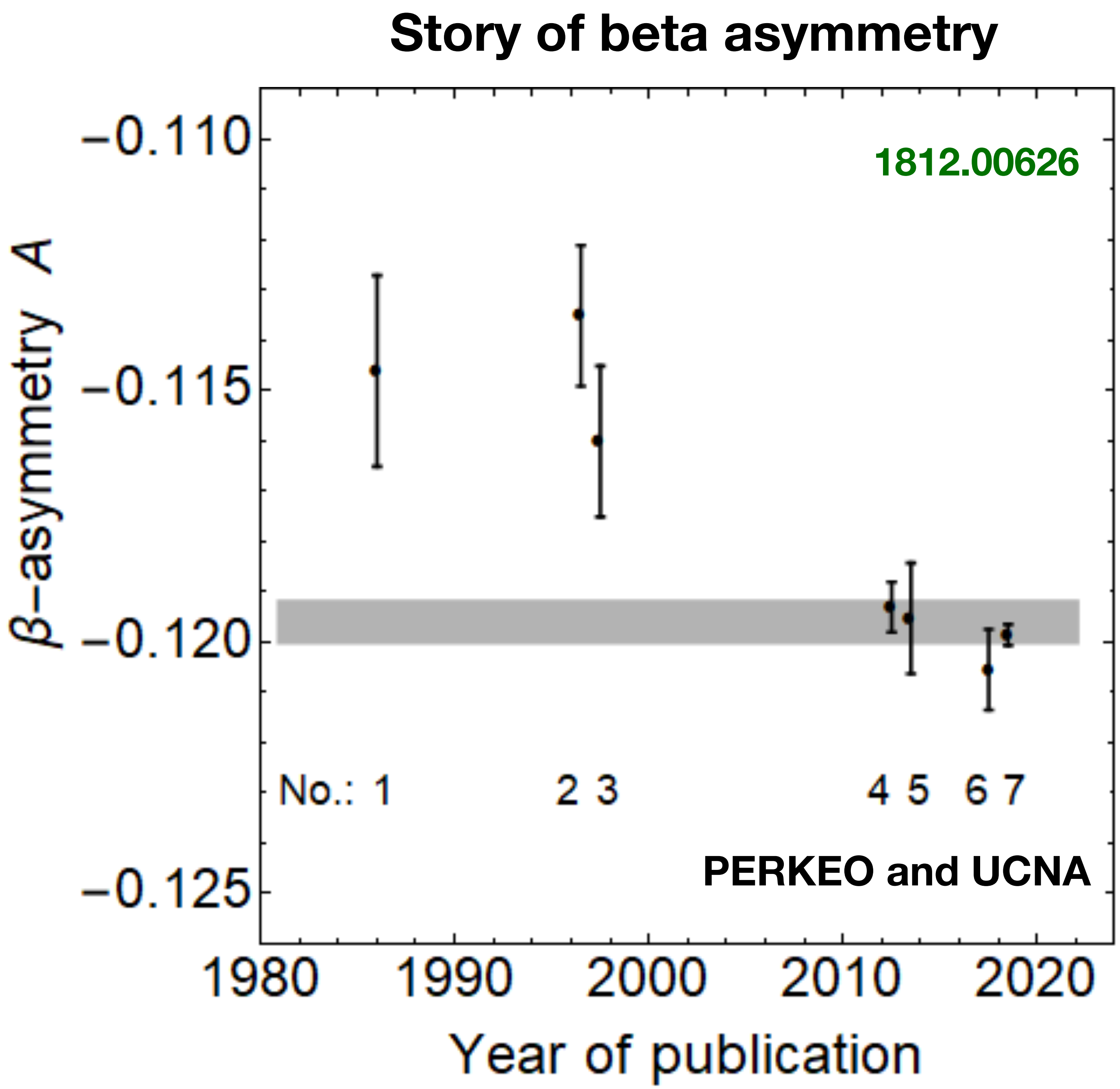
There is a large discrepancy between bottle and beam measurements of the lifetime, but also some inconsistency between different bottle measurements

Neutron lifetime



Because of incompatible measurements from different experiment, uncertainty of the combined lifetime is inflated by the factor S=2.2

Neutron beta asymmetry

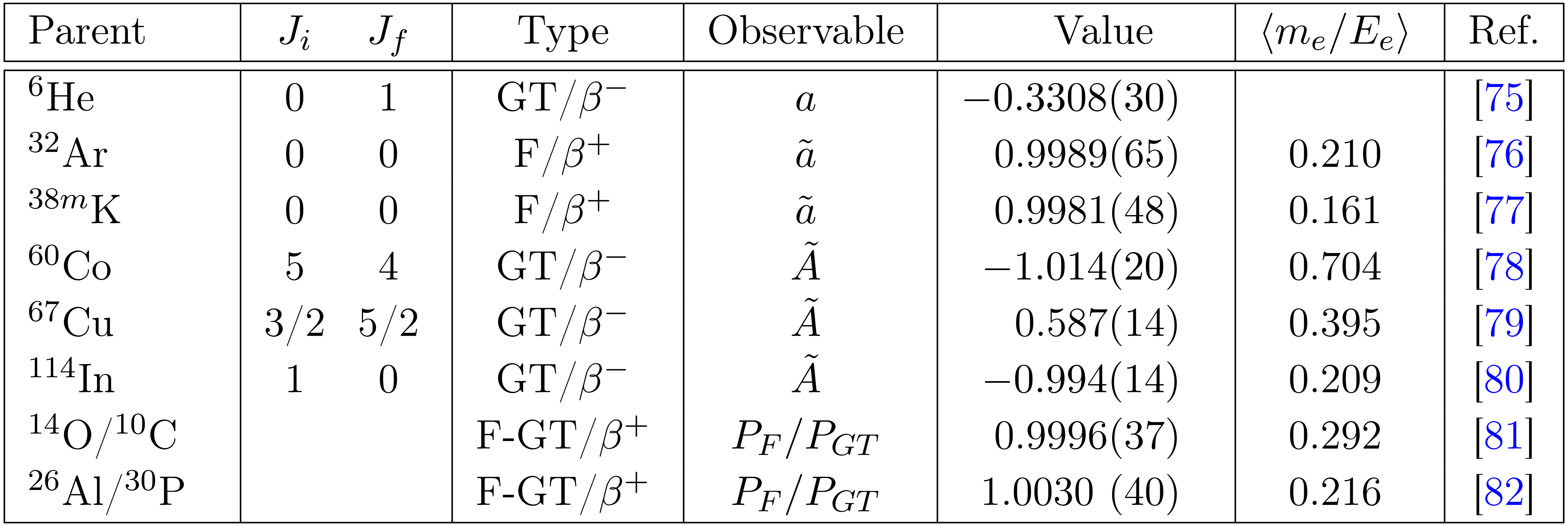


According to PDG algorithm, one should no longer blow up the error of A_n

$$A_n = -0.11869(99) \quad \Rightarrow \quad A_n = -0.11958(18)$$

Fivefold error reduction

Various and Sundry



Parent	J_i	J_f	Type	Observable	Value	$\langle m_e/E_e \rangle$	Ref.
^{6}He	0	1	GT/β^-	a	$-0.3308(30)$		[75]
^{32}Ar	0	0	F/β^+	$\tilde{a}$	0.9989(65)	0.210	[76]
^{38m}K	0	0	F/β^+	$\tilde{a}$	0.9981(48)	0.161	[77]
^{60}Co	5	4	GT/β^-	$\tilde{A}$	$-1.014(20)$	0.704	[78]
^{67}Cu	3/2	5/2	GT/β^-	$\tilde{A}$	0.587(14)	0.395	[79]
^{114}In	1	0	GT/β^-	$\tilde{A}$	$-0.994(14)$	0.209	[80]
^{14}O/^{10}C			F-GT/β^+	P_F/P_{GT}	0.9996(37)	0.292	[81]
^{26}Al/^{30}P			F-GT/β^+	P_F/P_{GT}	1.0030 (40)	0.216	[82]

Various percent-level precision beta-decay asymmetry measurements

Mirror decays

- Mirror decays are β transitions between isospin half, same spin, and positive parity nuclei1)

- These are mixed Fermi-Gamow/Teller beta transitions, thus they depend on the nuclear-dependent parameter r

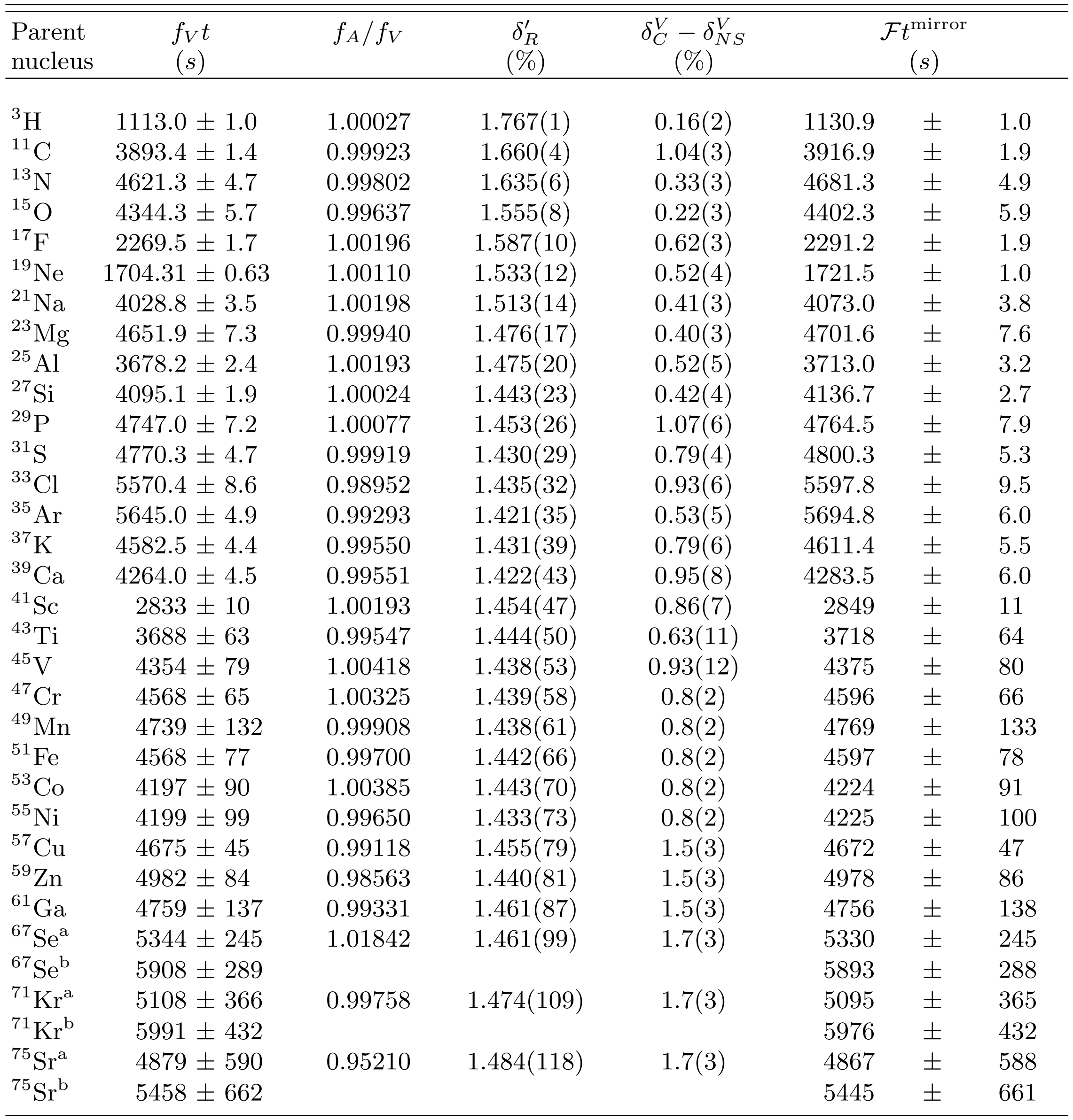
- The mixing parameter is distinct for different nuclei, and currently cannot be calculated from first principles with any decent precision

- Otherwise good theoretical control of nuclear structure and isospin breaking corrections, as is necessary for precision measurements

1) Formally, neutron decay can also be considered a mirror decay, but it's rarely put in the same basket

Mirror decays

Many per-mille level measurements!



Parent nucleus	$f_V t$ (s)	f_A/f_V	δ'_R (%)	$\delta_C^V - \delta_{NS}^V$ (%)	$\mathcal{F}t^{\mathrm{mirror}}$ (s)
^{3}H	1113.0 ± 1.0	1.00027	1.767(1)	0.16(2)	1130.9 ± 1.0
^{11}C	3893.4 ± 1.4	0.99923	1.660(4)	1.04(3)	3916.9 ± 1.9
^{13}N	4621.3 ± 4.7	0.99802	1.635(6)	0.33(3)	4681.3 ± 4.9
^{15}O	4344.3 ± 5.7	0.99637	1.555(8)	0.22(3)	4402.3 ± 5.9
^{17}F	2269.5 ± 1.7	1.00196	1.587(10)	0.62(3)	2291.2 ± 1.9
^{19}Ne	1704.31 ± 0.63	1.00110	1.533(12)	0.52(4)	1721.5 ± 1.0
^{21}Na	4028.8 ± 3.5	1.00198	1.513(14)	0.41(3)	4073.0 ± 3.8
^{23}Mg	4651.9 ± 7.3	0.99940	1.476(17)	0.40(3)	4701.6 ± 7.6
^{25}Al	3678.2 ± 2.4	1.00193	1.475(20)	0.52(5)	3713.0 ± 3.2
^{27}Si	4095.1 ± 1.9	1.00024	1.443(23)	0.42(4)	4136.7 ± 2.7
^{29}P	4747.0 ± 7.2	1.00077	1.453(26)	1.07(6)	4764.5 ± 7.9
^{31}S	4770.3 ± 4.7	0.99919	1.430(29)	0.79(4)	4800.3 ± 5.3
^{33}Cl	5570.4 ± 8.6	0.98952	1.435(32)	0.93(6)	5597.8 ± 9.5
^{35}Ar	5645.0 ± 4.9	0.99293	1.421(35)	0.53(5)	5694.8 ± 6.0
^{37}K	4582.5 ± 4.4	0.99550	1.431(39)	0.79(6)	4611.4 ± 5.5
^{39}Ca	4264.0 ± 4.5	0.99551	1.422(43)	0.95(8)	4283.5 ± 6.0
^{41}Sc	2833 ± 10	1.00193	1.454(47)	0.86(7)	2849 ± 11
^{43}Ti	3688 ± 63	0.99547	1.444(50)	0.63(11)	3718 ± 64
^{45}V	4354 ± 79	1.00418	1.438(53)	0.93(12)	4375 ± 80
^{47}Cr	4568 ± 65	1.00325	1.439(58)	0.8(2)	4596 ± 66
^{49}Mn	4739 ± 132	0.99908	1.438(61)	0.8(2)	4769 ± 133
^{51}Fe	4568 ± 77	0.99700	1.442(66)	0.8(2)	4597 ± 78
^{53}Co	4197 ± 90	1.00385	1.443(70)	0.8(2)	4224 ± 91
^{55}Ni	4199 ± 99	0.99650	1.433(73)	0.8(2)	4225 ± 100
^{57}Cu	4675 ± 45	0.99118	1.455(79)	1.5(3)	4672 ± 47
^{59}Zn	4982 ± 84	0.98563	1.440(81)	1.5(3)	4978 ± 86
^{61}Ga	4759 ± 137	0.99331	1.461(87)	1.5(3)	4756 ± 138
^{67}Se$^{\mathrm{a}}$	5344 ± 245	1.01842	1.461(99)	1.7(3)	5330 ± 245
^{67}Se$^{\mathrm{b}}$	5908 ± 289				5893 ± 288
^{71}Kr$^{\mathrm{a}}$	5108 ± 366	0.99758	1.474(109)	1.7(3)	5095 ± 365
^{71}Kr$^{\mathrm{b}}$	5991 ± 432				5976 ± 432
^{75}Sr$^{\mathrm{a}}$	4879 ± 590	0.95210	1.484(118)	1.7(3)	4867 ± 588
^{75}Sr$^{\mathrm{b}}$	5458 ± 662				5445 ± 661

Bodek et al
2109.08895

$$\mathscr{F}t \equiv \frac{(1+\delta)f\,\log 2}{\Gamma} = \frac{4\pi^3 \log 2}{M_F^2 m_e^5 X\left[1 + b\left\langle \frac{m_e}{E_e}\right\rangle\right]}$$

For mirror beta transitions

$$X \equiv (C_V^+)^2 + (C_S^+)^2 + \frac{f_A}{f_V} r^2 \tilde{\Big[}(C_A^+)^2 + (C_T^+)^2\Big]$$

$$bX \equiv \pm 2\left\{ C_V^+ C_S^+ + r^2\Big[C_A^+ C_T^+\Big]\right\}$$

Ratio *r* of Fermi and Gamow-Teller matrix elements is different for different nuclei, therefore even in the SM limit $\mathscr{F}t$ is different for different mirror transitions!

Since we don't know the parameter r apriori, measuring $\mathscr{F}t$ alone cannot constrain fundamental parameters Given the input from superallowed and neutron data, $\mathscr{F}t$ can be considered merely a measurement of the mixing parameter r in the SM context

More input is needed to constrain the EFT parameters!

Mirror decays

There is a smaller set of mirror decays for which not only Ft but also some asymmetry is measured with reasonable precision

Parent	Spin	Δ [MeV]	$\langle m_e/E_e \rangle$	f_A/f_V	$\mathcal{F}t$ [s]	Correlation
^{17}F	5/2	2.24947(25)	0.447	1.0007(1)	2292.4(2.7) [47]	$\tilde{A} = 0.960(82)$ [12, 48]
^{19}Ne	1/2	2.72849(16)	0.386	1.0012(2)	1721.44(92) [44]	$\tilde{A}_0 = -0.0391(14)$ [49]
						$\tilde{A}_0 = -0.03871(91)$ [42]
^{21}Na	3/2	3.035920(18)	0.355	1.0019(4)	4071(4) [45]	$\tilde{a} = 0.5502(60)$ [39]
^{29}P	1/2	4.4312(4)	0.258	0.9992(1)	4764.6(7.9) [50]	$\tilde{A} = 0.681(86)$ [51]
^{35}Ar	3/2	5.4552(7)	0.215	0.9930(14)	5688.6(7.2) [13]	$\tilde{A} = 0.430(22)$ [14, 52, 53]
^{37}K	3/2	5.63647(23)	0.209	0.9957(9)	4605.4(8.2) [43]	$\tilde{A} = -0.5707(19)$ [38]
						$\tilde{B} = -0.755(24)$ [41]

[30] Brodeur et al (2016), [31] Severijns et al (1989), [27] Rebeiro et al (2019),
[7] Calaprice et al (1975), [33] Combs et al (2020), [28] Karthein et al. (2019),
[11] Vetter et al (2008), [34] Long et al (2020), [9] Mason et al (1990),
[10] Converse et al (1993), [26] Shidling et al (2014), [12] Fenker et al. (2017),
[23] Melconian et al (2007);
f_A/f_V values from Hayen and Severijns, arXiv:1906.09870

Global fit results

SM fit

Done in the previous literature by many groups, we only provide an (important) update

SM fit

In the SM limit the effective Lagrangian simplifies a lot:

$$\mathscr{L} = -(\psi_p^\dagger \psi_n)\left[C_V^+ \bar{e}_L \gamma^0 \nu_L + \cancel{C_S^+} \bar{e}_R \nu_L\right] + \sum_{k=1}^{3} (\psi_p^\dagger \sigma^k \psi_n)\left[C_A^+ \bar{e}_L \gamma^k \nu_L + \cancel{C_T^+} \bar{e}_R \gamma^0 \gamma^k \nu_L\right]$$

$$\begin{pmatrix} \mathrm{v}^2 C_V^+ \\ \mathrm{v}^2 C_A^+ \end{pmatrix} = \begin{pmatrix} 0.98576(22) \\ -1.25754(39) \end{pmatrix}$$

$\mathcal{O}(10^{-4})$ accuracy for measurements of SM-induced Wilson coefficients!

SM fit

Translation to particle physics parameters

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

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

➡

$\mathcal{O}(10^{-4})$ **accuracy for measuring**
one SM parameter V_{ud}
and one QCD parameter g_A

$\mathcal{O}(10^{-4})$ **precision for this CKM element!**

$$\begin{pmatrix} V_{ud} \\ g_A \end{pmatrix} = \begin{pmatrix} 0.97382(24) \\ 1.2536(47) \end{pmatrix} \qquad \rho = \begin{pmatrix} 1 & -0.03 \\ . & 1 \end{pmatrix}$$

cf. $g_A = 1.246(28)$ **from the lattice**

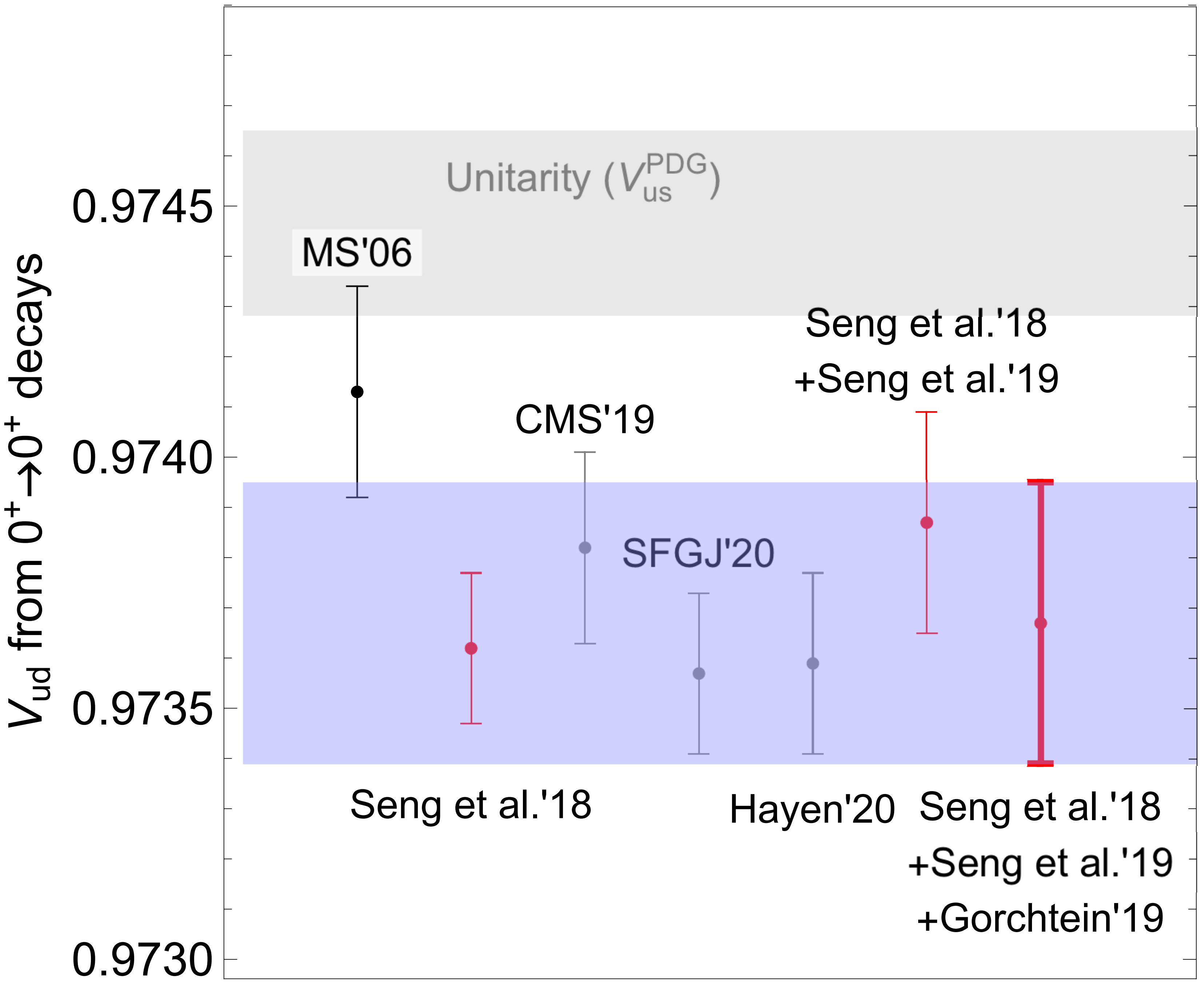
Per-mille precision for the nucleon axial charge!
Experiment factor of six better than lattice (assuming that SM is true)

nb. experimental precision dropped since [arXiv:2010.13797]
because of new calculation of $\Delta_R^V - \Delta_R^A$

Cirigliano et al
2202.10439

SM fit

Comparison of determination of V_{ud} from superallowed beta decays, with different values of inner radiative corrections in the literature



Our value
V_{ud}=0.97382(24)

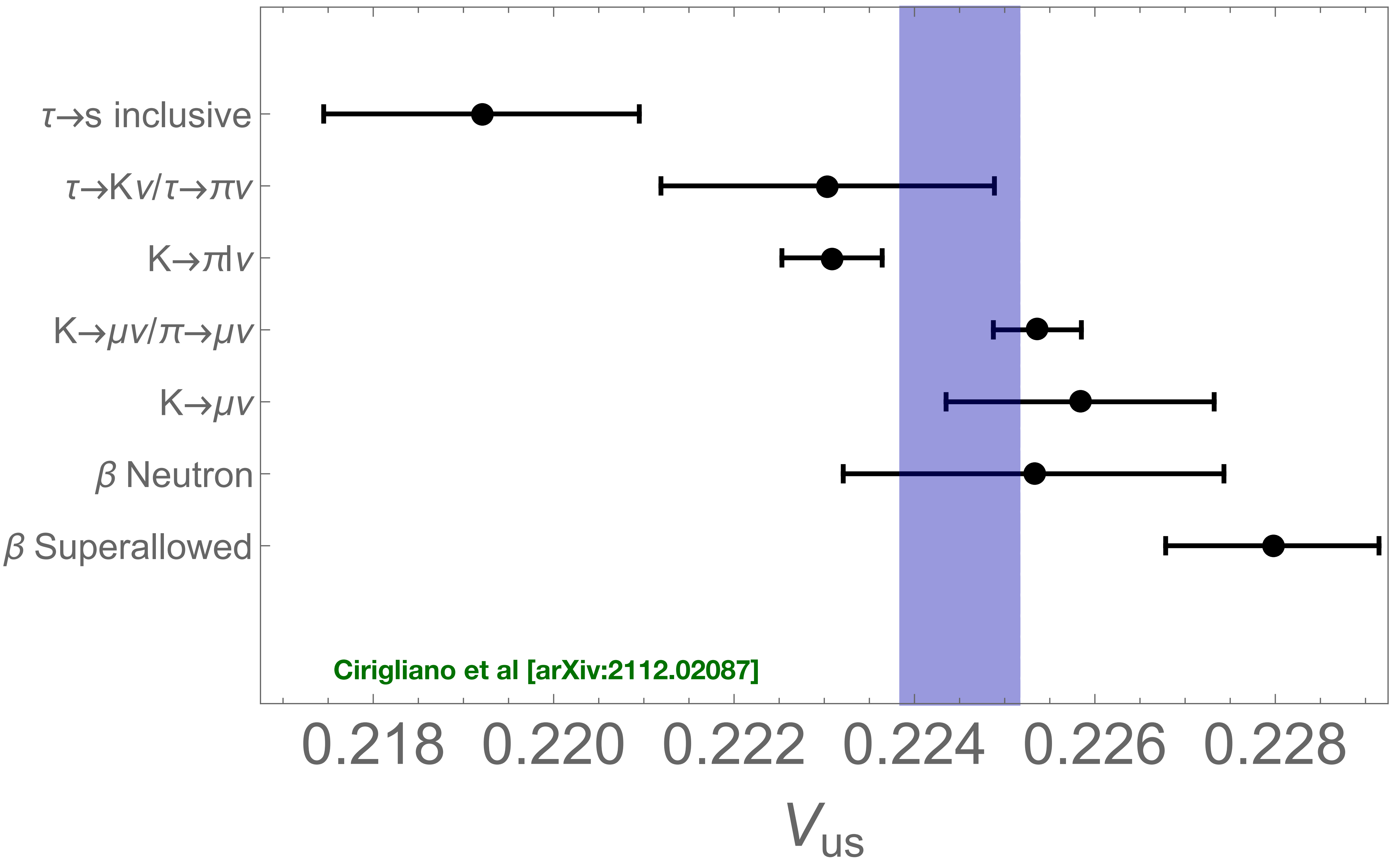
Our error bars are larger, because we take into account additional uncertainties in superallowed decays

Seng et al
1812.03352

Gorchtein
1812.04229

Bigger picture: Cabibbo anomaly

Seng et al 1807.10197
Grossman et al 1911.07821
Coutinho et al 1912.08823
...



BSM fit

Done previously by Gonzalez-Alonso et al in 1803.08732, but many important experimental updates since

WEFT fit

In the absence of right-handed neutrinos, the effective Lagrangian simplifies:

$$\mathscr{L}^{(0)} = -(\psi_p^\dagger \psi_n)\left[C_V^+ \bar{e}_L \gamma^0 \nu_L + C_S^+ \bar{e}_R \nu_L\right] + \sum_{k=1}^{3} (\psi_p^\dagger \sigma^k \psi_n)\left[C_A^+ \bar{e}_L \gamma^k \nu_L + C_T^+ \bar{e}_R \gamma^0 \gamma^k \nu_L\right]$$

$$\mathrm{v}^2 \begin{pmatrix} C_V^+ \\ C_A^+ \\ C_S^+ \\ C_T^+ \end{pmatrix} = \begin{pmatrix} 0.98576(41) \\ -1.25739(54) \\ 0.0002(10) \\ -0.0005(12) \end{pmatrix}$$

Uncertainty on SM parameters slightly increases compared to SM fit but remains impressively sub-permille

$\mathcal{O}(10^{-3})$ **constraints on BSM parameters, no slightest hint of new physics**

WEFT fit

Translation to particle physics variables

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

Polluted CKM element

$$C_A^+ = -\frac{V_{ud}}{\mathrm{v}^2} g_A \sqrt{1+\Delta_R^A}\left(1+\epsilon_L-\epsilon_R\right) \qquad = -\frac{\hat{V}_{ud}}{\mathrm{v}^2} \hat{g}_A \sqrt{1+\Delta_R^A} \qquad \hat{g}_A = g_A \frac{1+\epsilon_L-\epsilon_R}{1+\epsilon_L+\epsilon_R}$$

Polluted axial charge

$$C_T^+ = \frac{V_{ud}}{\mathrm{v}^2} g_T \epsilon_T \qquad = \frac{\hat{V}_{ud}}{\mathrm{v}^2} g_T \hat{\epsilon}_T \qquad \hat{\epsilon}_S = \frac{\epsilon_S}{1+\epsilon_L+\epsilon_R}$$

$$C_S^+ = \frac{V_{ud}}{\mathrm{v}^2} g_S \epsilon_S \qquad = \frac{\hat{V}_{ud}}{\mathrm{v}^2} g_S \hat{\epsilon}_S \qquad \hat{\epsilon}_T = \frac{\epsilon_T}{1+\epsilon_L+\epsilon_R}$$

Rescaled BSM
Wilson coefficients

In SM, measuring C_A^+ translates to measuring axial charge g_A
However, beyond SM it translates into "polluted" axial charge

Approximately,

$$\hat{g}_A \equiv g_A \frac{1+\epsilon_L-\epsilon_R}{1+\epsilon_L+\epsilon_R} \approx g_A\left(1-2\epsilon_R\right)$$

In order to disentangle $\hat{g}_A$ from g_A we need lattice information about the latter:

From FLAG'21:

$$g_A = 1.246(28)$$

WEFT fit

Translation to particle physics variables

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

Polluted CKM element

$$C_A^+ = -\frac{V_{ud}}{\mathrm{v}^2} g_A \sqrt{1+\Delta_R^A}\left(1+\epsilon_L-\epsilon_R\right) = -\frac{\hat{V}_{ud}}{\mathrm{v}^2} \hat{g}_A \sqrt{1+\Delta_R^A} \qquad \hat{g}_A = g_A \frac{1+\epsilon_L-\epsilon_R}{1+\epsilon_L+\epsilon_R} \qquad g_A = 1.246(28)$$

$$C_T^+ = \frac{V_{ud}}{\mathrm{v}^2} g_T \epsilon_T = \frac{\hat{V}_{ud}}{\mathrm{v}^2} g_T \hat{\epsilon}_T \qquad \hat{\epsilon}_S = \frac{\epsilon_S}{1+\epsilon_L+\epsilon_R}$$

$$C_S^+ = \frac{V_{ud}}{\mathrm{v}^2} g_S \epsilon_S = \frac{\hat{V}_{ud}}{\mathrm{v}^2} g_S \hat{\epsilon}_S \qquad \hat{\epsilon}_T = \frac{\epsilon_T}{1+\epsilon_L+\epsilon_R}$$

Rescaled BSM Wilson coefficients

$$\begin{pmatrix} \hat{V}_{ud} \\ \epsilon_S \\ \epsilon_T \\ \epsilon_R \end{pmatrix} = \begin{pmatrix} 0.97365(42) \\ 0.0001(10) \\ -0.0009(12) \\ -0.003(12) \end{pmatrix}$$

polluted CKM matrix element (in principle, can lead to apparent breakdown of CKM unitarity)

per-mille constraints for scalar and tenors non-standard interactions!

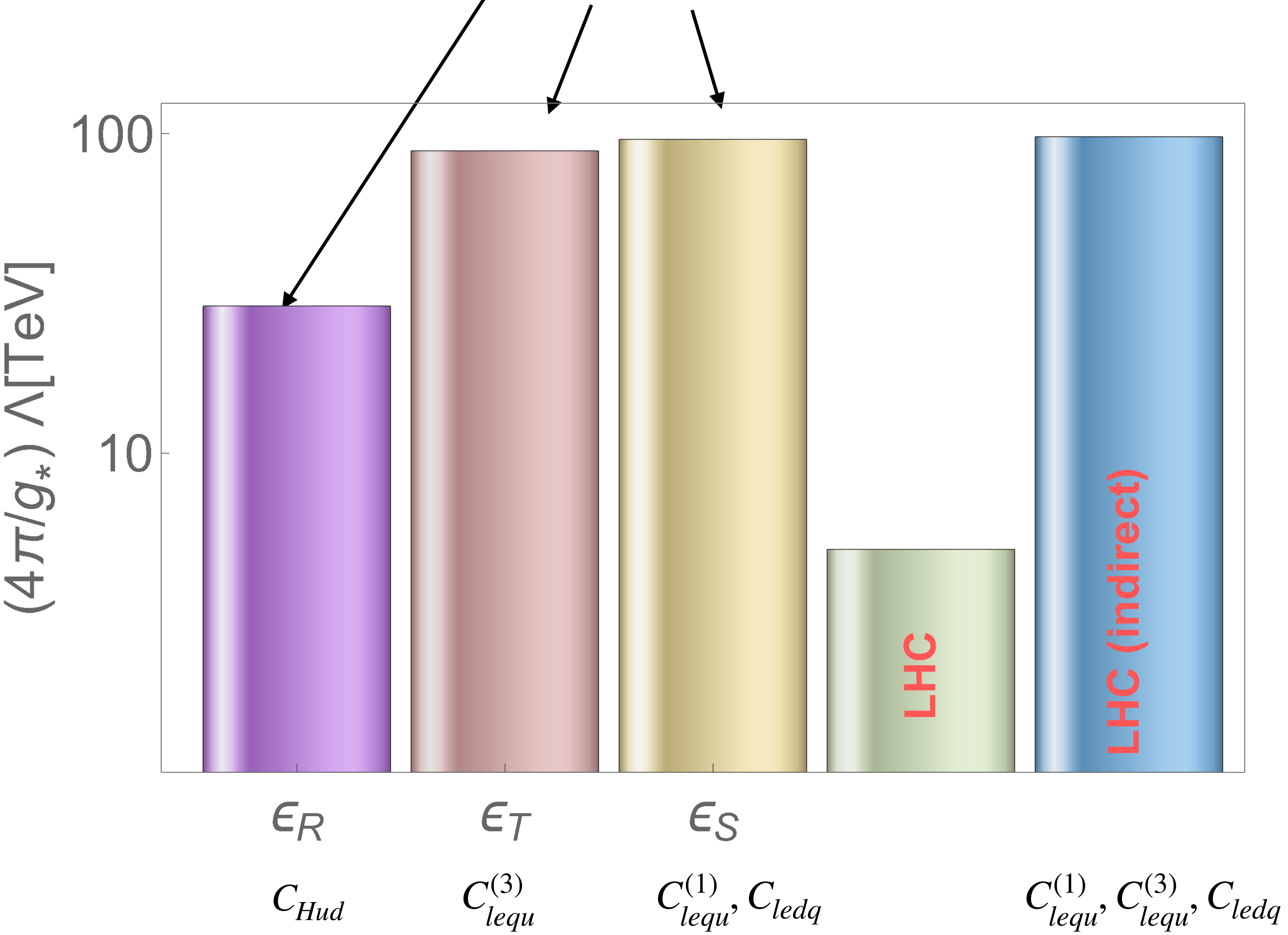
only percent-level constraints for right-handed non-standard interactions, because of reliance on lattice input

$$\rho = \begin{pmatrix} 1. & 0.78 & 0.69 & 0.01 \\ 0.78 & 1. & 0.64 & 0.01 \\ 0.69 & 0.64 & 1. & 0. \\ 0.01 & 0.01 & 0. & 1. \end{pmatrix}$$

New physics reach of beta decays

Probe of new particles well above the direct LHC reach, and comparable to indirect LHC reach via high-energy Drell-Yan processes

Nuclear decays

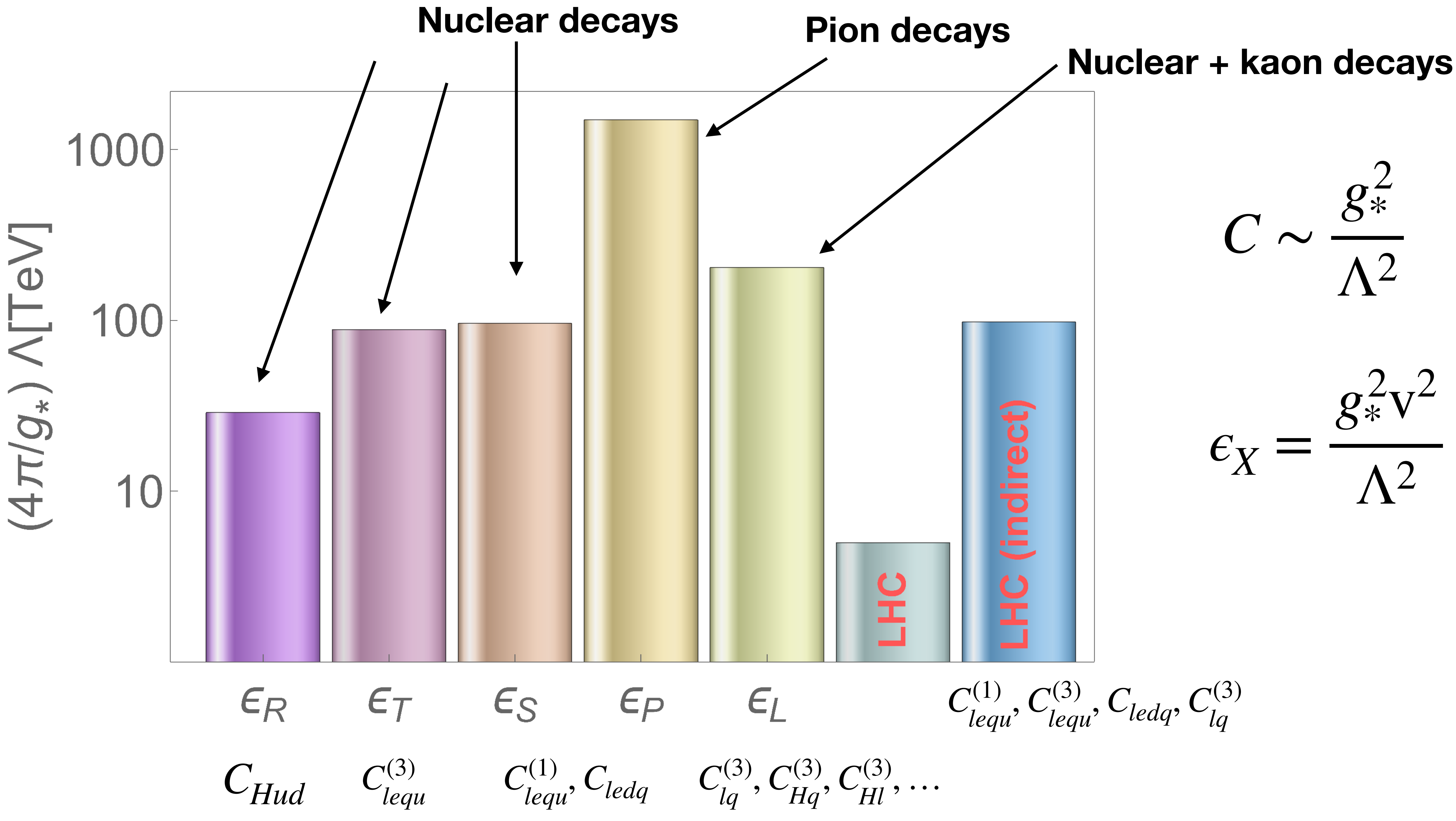


$$C \sim \frac{g_*^2}{\Lambda^2}$$

$$\epsilon_X = \frac{g_*^2 \mathrm{v}^2}{\Lambda^2}$$

New physics reach of beta decays

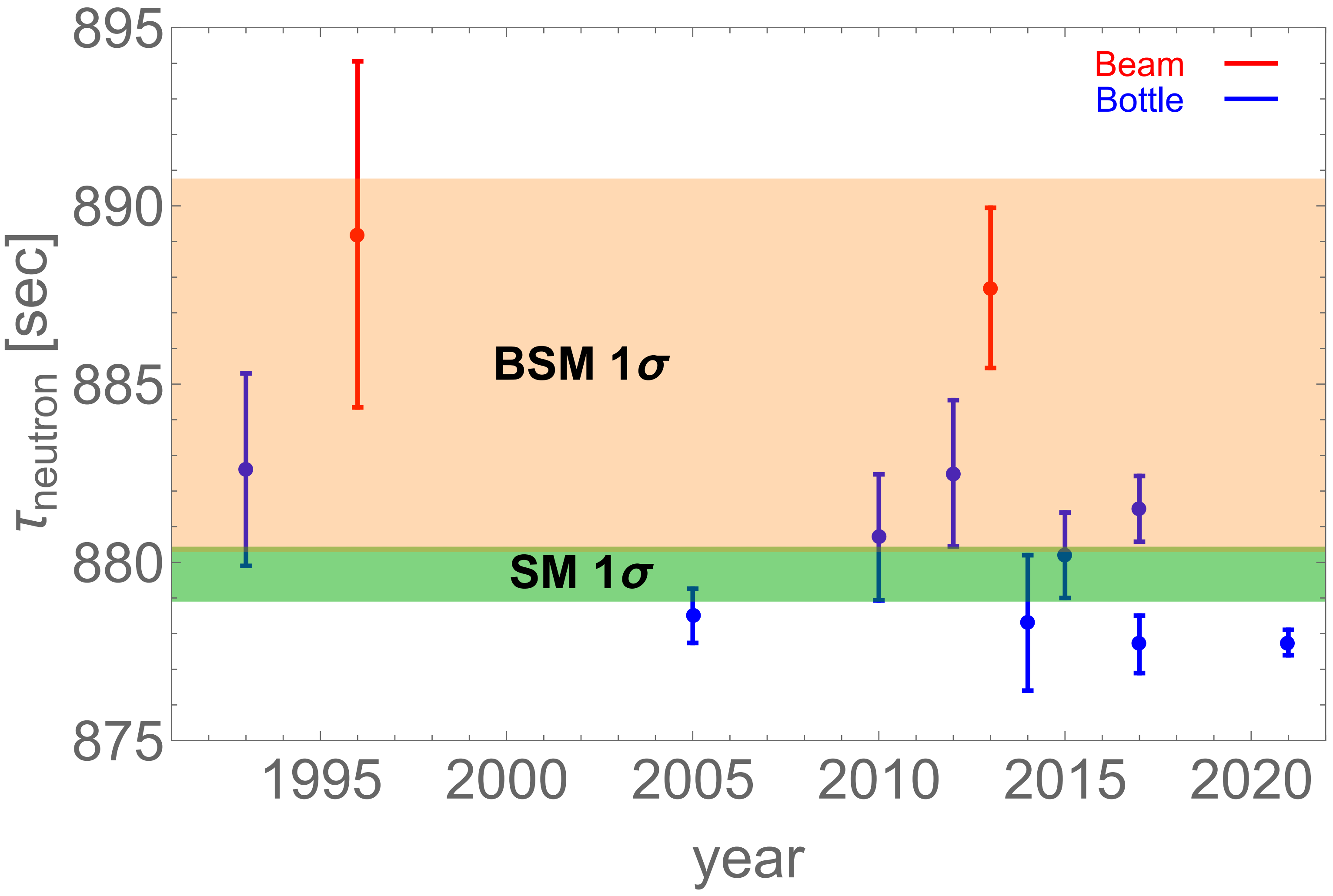
Probe of new particles well above the direct LHC reach,
and comparable or better to indirect LHC reach via high-energy Drell-Yan processes



$$C \sim \frac{g_*^2}{\Lambda^2}$$

$$\epsilon_X = \frac{g_*^2 \mathrm{v}^2}{\Lambda^2}$$

Neutron lifetime: bottle vs beam

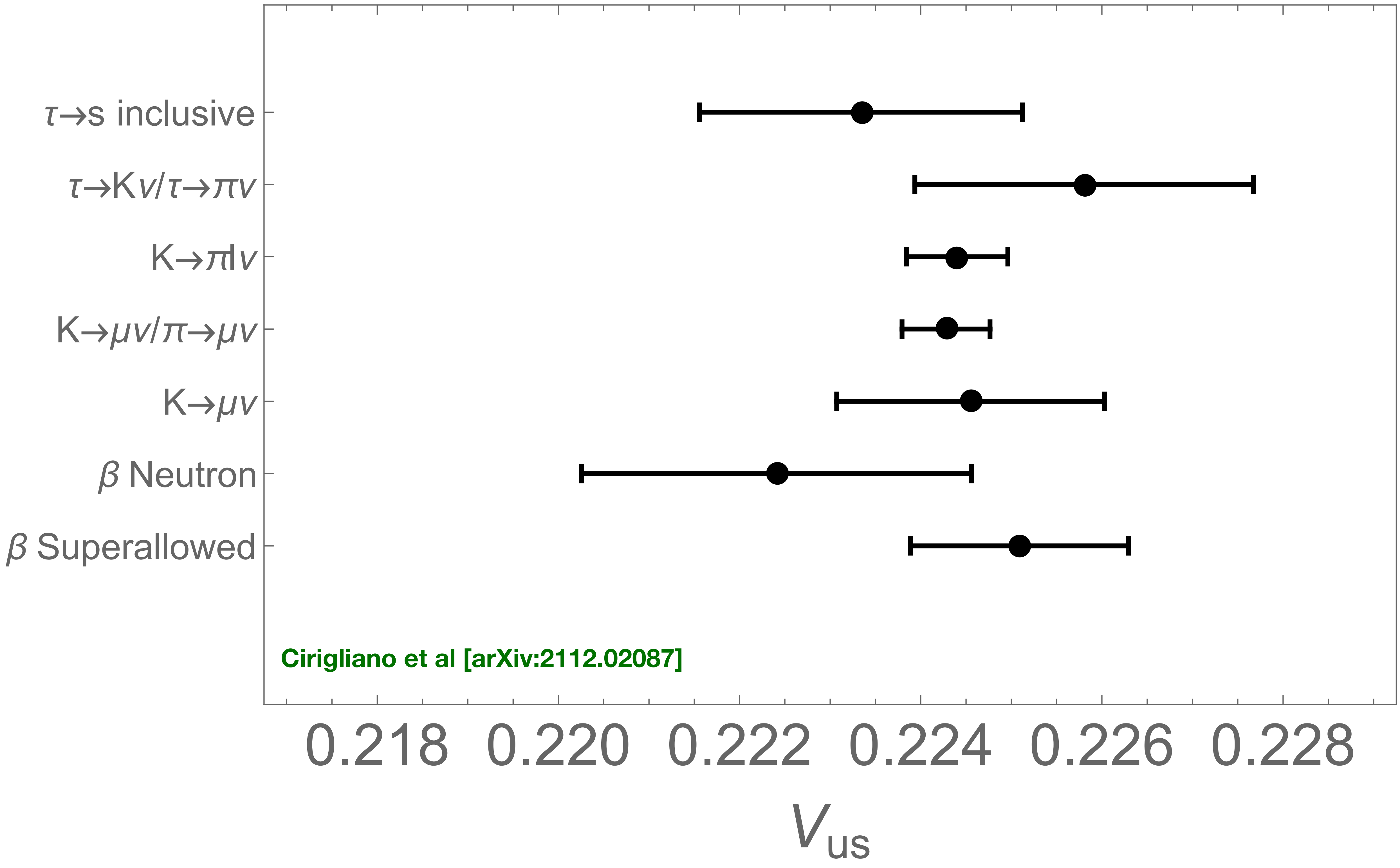


Beyond SM both beam and bottle are consistent with other experiments

Within SM, other experiments point to bottle result being correct

Czarnecki et al
1802.01804

Resolved Cabibbo anomaly in the presence of new physics



Going further

$$\mathscr{L}_{\mathrm{NR-EFT}} = \mathscr{L}^{(0)} + \mathscr{L}^{(1)} + \mathcal{O}(\nabla^2/m_N^2) + \mathrm{h.c.}$$

The most general leading (0-derivative) term in this expansion is

$$\mathscr{L}^{(0)} = -(\psi_p^\dagger \psi_n)\Big[C_V^+ \bar{e}_L \gamma^0 \nu_L + C_S^+ \bar{e}_R \nu_L\Big] + \sum_{k=1}^{3} (\psi_p^\dagger \sigma^k \psi_n)\Big[C_A^+ \bar{e}_L \gamma^k \nu_L + C_T^+ \bar{e}_R \gamma^0 \gamma^k \nu_L\Big]$$

EFTs are systematically improvable, and nothing prevents us to going to the next order in the EFT expansions

The most general subleading (1-derivative) term in this expansion is

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

[arXiv:2112.07688] AA, Martin Gonzalez-Alonso, Ajdin Palavrić, Antonio Rodriguez-Sanchez

The coefficients of the sub-leading EFT Lagrangian can also be determined from the data!

Example: constraining pseudoscalar interactions

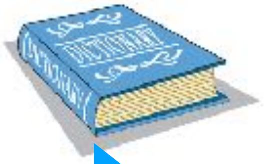
$$\mathscr{L}^{(1)} = \frac{1}{2m_N}\Big\{ iC_P^+(\psi_p^\dagger\sigma^k\psi_n)\nabla_k\big(\bar{e}_R\nu_L\big) - C_M^+\epsilon^{ijk}(\psi_p^\dagger\sigma^j\psi_n)\nabla_i\big(\bar{e}_L\gamma^k\nu_L\big)$$

$$-iC_E^+(\psi_p^\dagger\sigma^k\psi_n)\nabla_k\big(\bar{e}_L\gamma^0\nu_L\big) - iC_{E'}^+(\psi_p^\dagger\sigma^k\psi_n)\partial_t\big(\bar{e}_L\gamma^k\nu_L\big)$$

$$-iC_{T1}^+(\psi_p^\dagger\psi_n)\nabla_k\big(\bar{e}_R\gamma^0\gamma^k\nu_L\big) + iC_{T2}^+(\psi_p^\dagger\psi_n)(\bar{e}_R\overleftrightarrow{\partial}_t\nu_L) + 2iC_{T3}^+(\psi_p^\dagger\sigma^k\psi_n)(\bar{e}_R\overleftrightarrow{\nabla}_k\nu_L)$$

$$-iC_{FV}^+(\psi_p^\dagger\overleftrightarrow{\nabla}_k\psi_n)(\bar{e}_L\gamma^k\nu_L) + iC_{FA}^+(\psi_p^\dagger\sigma^k\overleftrightarrow{\nabla}_k\psi_n)(\bar{e}_L\gamma^0\nu_L) + C_{FT}^+\epsilon^{ijk}(\psi_p^\dagger\sigma^i\overleftrightarrow{\nabla}_j\psi_n)(\bar{e}_R\gamma^0\gamma^k\nu_L)\Big\}$$

$$\mathrm{v}^2\begin{pmatrix} C_V^+ \\ C_A^+ \\ C_S^+ \\ C_T^+ \\ C_P^+ \end{pmatrix} = \begin{pmatrix} 0.98540(48) \\ -1.25822(81) \\ -0.0006(12) \\ 0.0009(16) \\ -6.4(4.3) \end{pmatrix}$$



$$\begin{pmatrix} \hat{V}_{ud} \\ \epsilon_S \\ \epsilon_T \\ \epsilon_R \\ \epsilon_P \end{pmatrix} = \begin{pmatrix} 0.97351(48) \\ -0.0005(12) \\ 0.0009(17) \\ -0.010(11) \\ -0.018(13) \end{pmatrix}$$

The sensitivity of beta decay to pseudoscalar interactions is the same as the sensitivity to the V+A interactions, even though the former enters at the subleading level

Example: constraining universal nucleon's weak magnetism

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

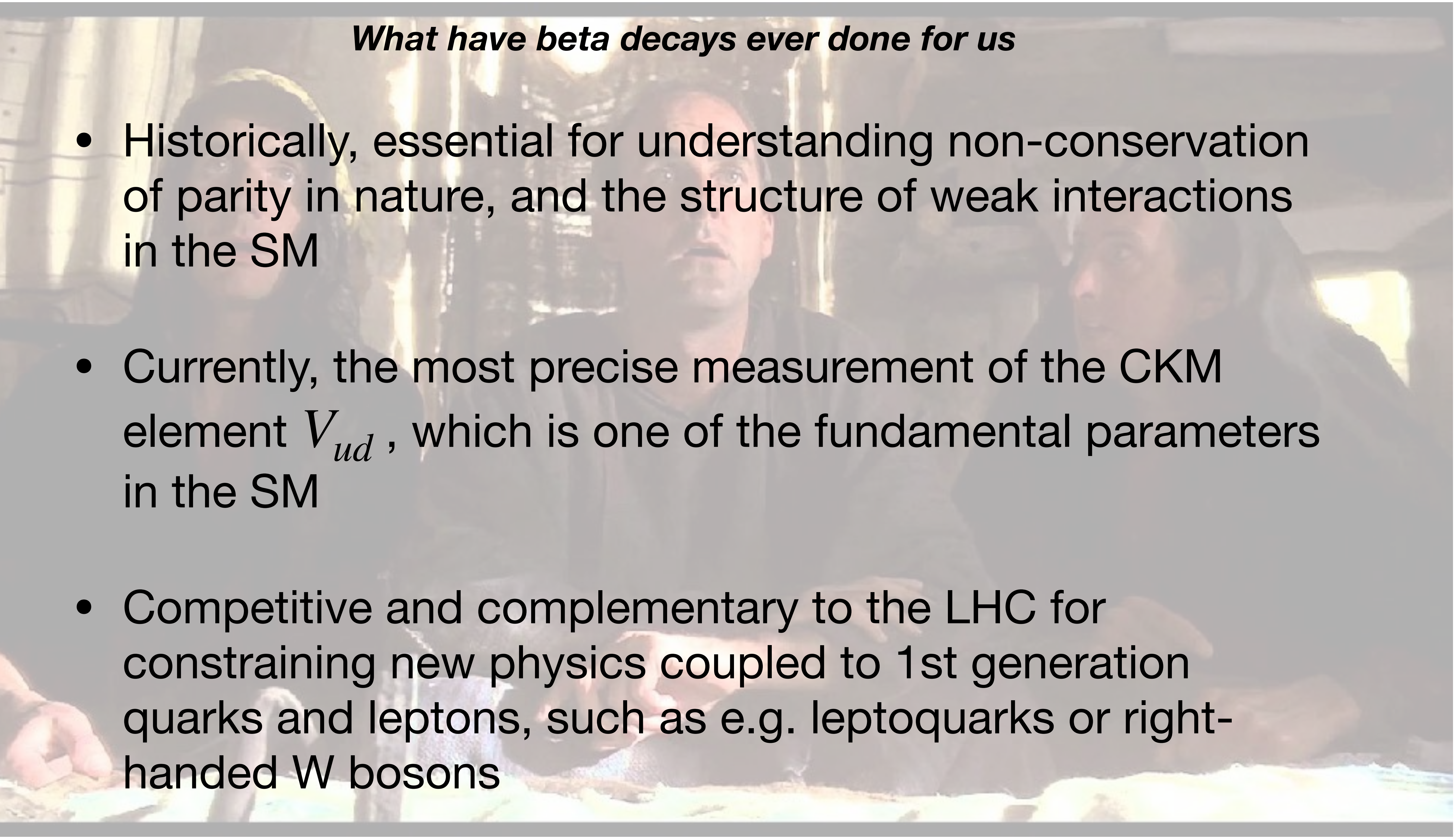
$$\mathrm{v}^2\begin{pmatrix} C_V^+ \\ C_A^+ \\ C_M^+ \end{pmatrix} = \begin{pmatrix} 0.98562(26) \\ -1.25787(52) \\ 3.5(1.0) \end{pmatrix}$$

In the SM, isospin symmetry predicts C_M in terms of magnetic moments of the proton and neutron

$$C_M^{\mathrm{SM}} = \frac{\mu_p - \mu_n}{\mu_N}C_V^+ \approx \frac{4.6}{\mathrm{v}^2}$$

4 sigma detection of weak magnetism of nucleons just from the data, without relying on isospin symmetry (CVC hypothesis).
Result perfectly agrees with the prediction from isospin symmetry

Summary



What have beta decays ever done for us

- Historically, essential for understanding non-conservation of parity in nature, and the structure of weak interactions in the SM

- Currently, the most precise measurement of the CKM element V_{ud} , which is one of the fundamental parameters in the SM

- Competitive and complementary to the LHC for constraining new physics coupled to 1st generation quarks and leptons, such as e.g. leptoquarks or right-handed W bosons

Future

Cirigliano et al
1907.02164

TABLE I. List of nuclear β-decay correlation experiments in search for non-SM physics [a]

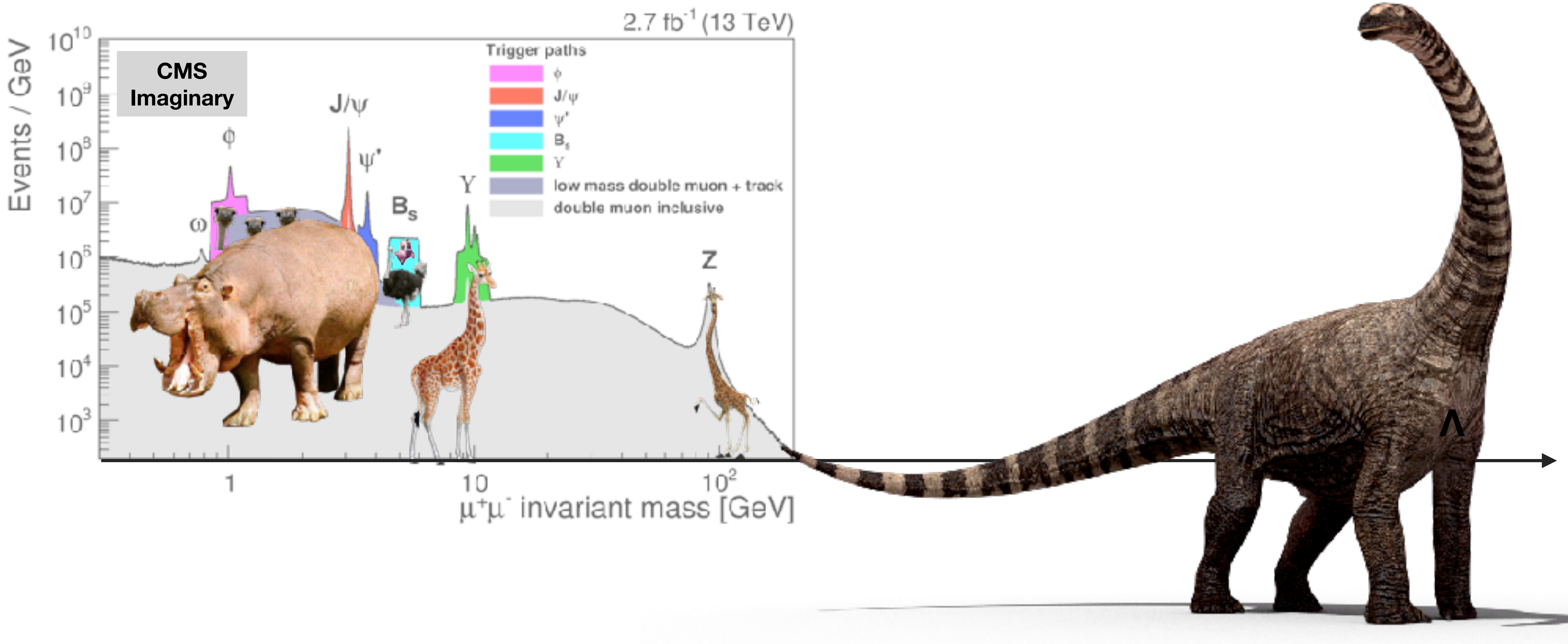
Measurement	Transition Type	Nucleus	Institution/Collaboration	Goal
$\beta - \nu$	F	^{32}Ar	Isolde-CERN	0.1 %
$\beta - \nu$	F	^{38}K	TRINAT-TRIUMF	0.1 %
$\beta - \nu$	GT, Mixed	^{6}He, ^{23}Ne	SARAF	0.1 %
$\beta - \nu$	GT	^{8}B, ^{8}Li	ANL	0.1 %
$\beta - \nu$	F	^{20}Mg, ^{24}Si, ^{28}S, ^{32}Ar, ...	TAMUTRAP-Texas A&M	0.1 %
$\beta - \nu$	Mixed	^{11}C, ^{13}N, ^{15}O, ^{17}F	Notre Dame	0.5 %
β & recoil asymmetry	Mixed	^{37}K	TRINAT-TRIUMF	0.1 %

TABLE II. Summary of planned neutron correlation and beta spectroscopy experiments

Measurable	Experiment	Lab	Method	Status	Sensitivity (projected)	Target Date
$\beta - \nu$	aCORN[22]	NIST	electron-proton coinc.	running complete	1%	N/A
$\beta - \nu$	aSPECT[23]	ILL	proton spectra	running complete		
$\beta - \nu$	Nab[20]	SNS	proton TOF	construction	0.12%	2022
β asymmetry	PERC[21]	FRMII	beta detection	construction	0.05%	commissioning 2020
11 correlations	BRAND[29]	ILL/ESS	various	R&D	0.1%	commissioning 2025
b	Nab[20]	SNS	Si detectors	construction	0.3%	2022
b	NOMOS[30]	FRM II	β magnetic spectr.	construction	0.1%	2020

Already present tense!

Fantastic Beasts and Where To Find Them



THANK YOU