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Constraints on new physics from nuclear beta transitions

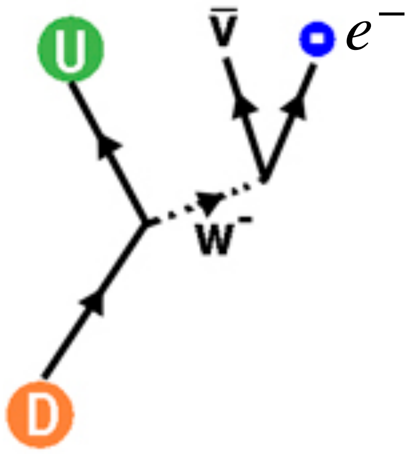
Kraków
20 January 2022

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

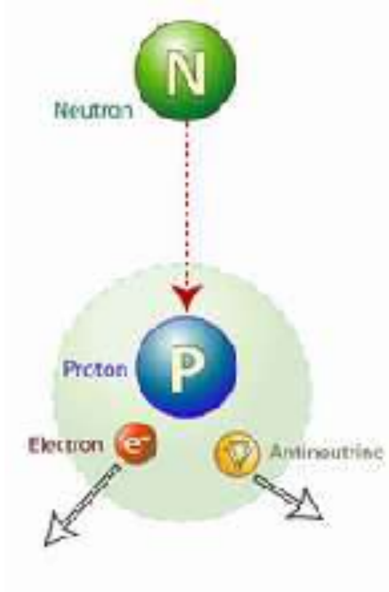
Introduction

Beta decay

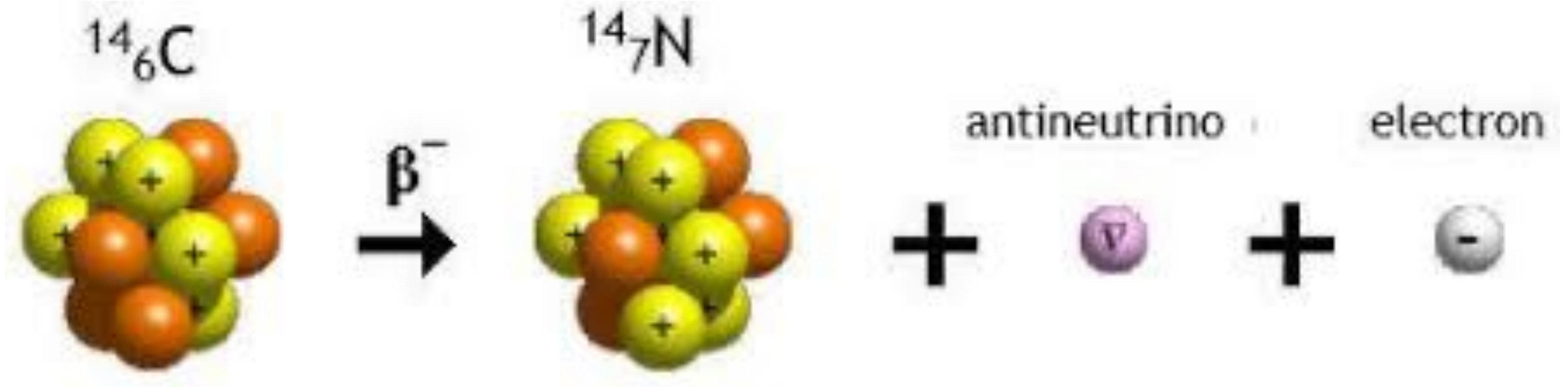
Quark level



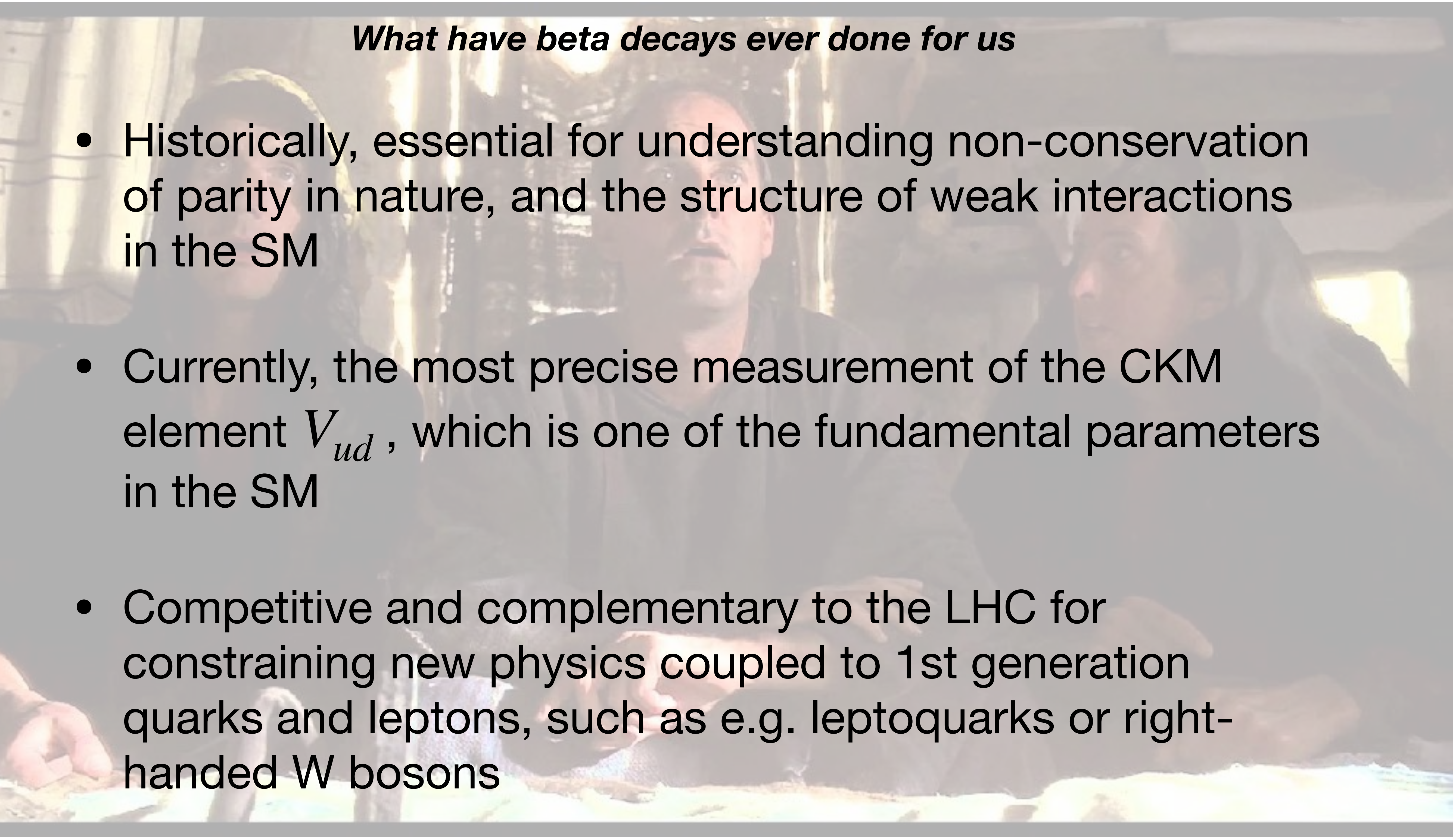
Nucleon level



Nuclear level



Beta decay



What have beta decays ever done for us

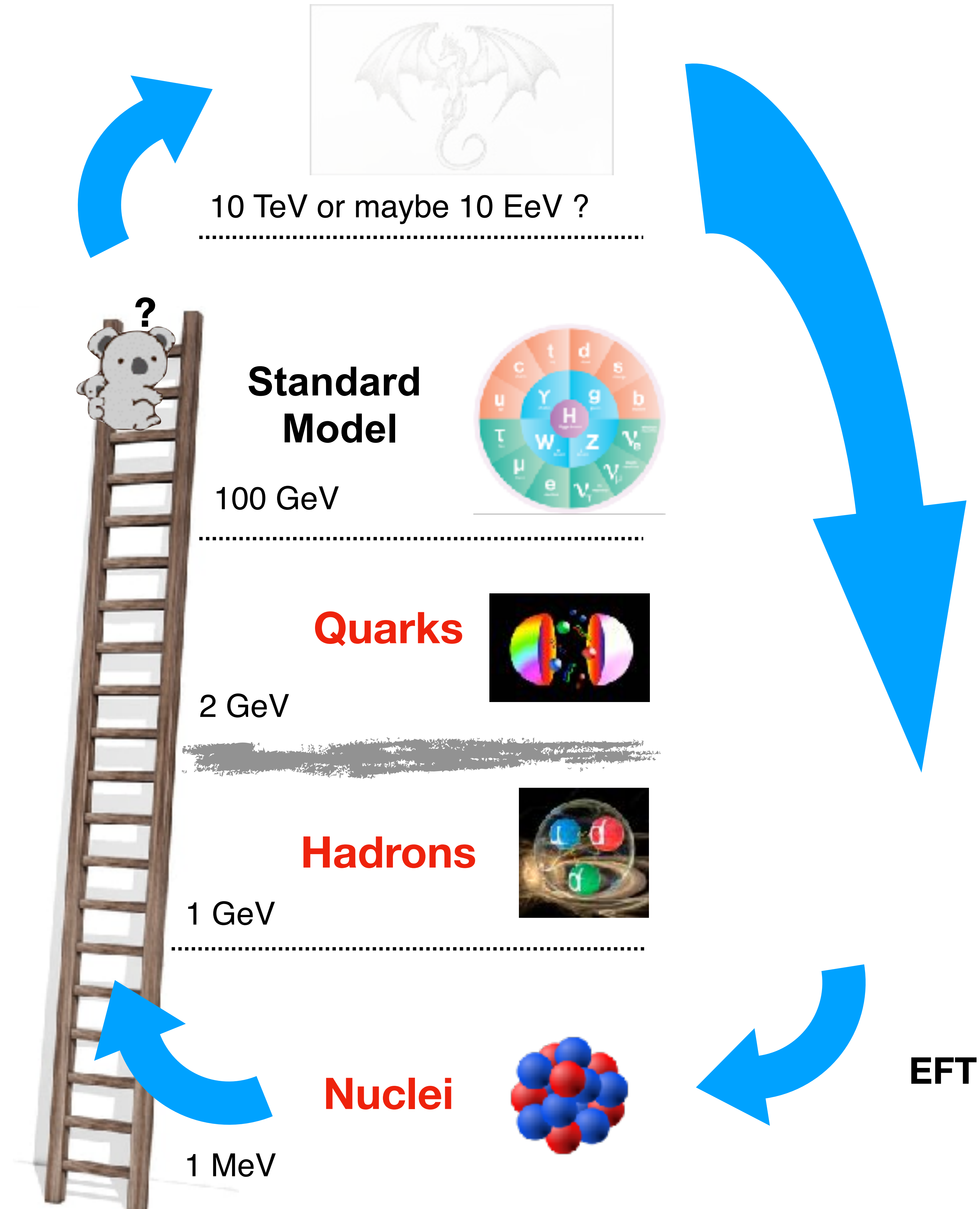
- Historically, essential for understanding non-conservation of parity in nature, and the structure of weak interactions in the SM

- 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

Beta decay

- Nuclear beta decays are a probe of how first generation quarks and leptons interact with each other at low energies
- Formalism has been developed since the 30s of the previous century, basic physics was understood by the end of the 50s, and 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 that used by the high-energy community, and allows one to treat possible beyond-the-SM interactions on the same footing as the SM ones
- Efficient and model-independent description can be developed under assumption that no non-SM degrees of freedom are produced on-shell in beta decays. If that is the case, the physics of beta transitions can be succinctly formulated in the language of **effective field theories**



?

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

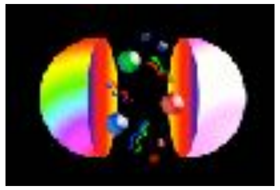
“Fundamental” BSM model

10 TeV?

EFT for SM particles (SMEFT)

100 GeV

EFT for light SM particles (WEFT)



2 GeV

EFT for Hadrons (ChPT etc)

1 GeV

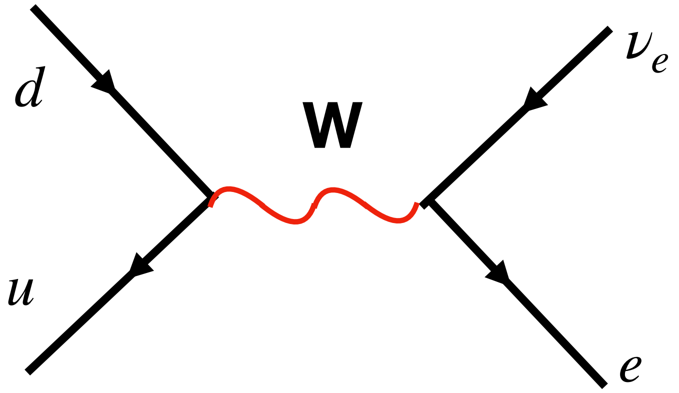
NR EFT for nucleons

1 MeV

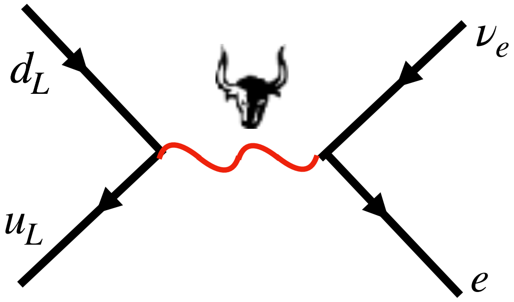
“Fundamental” models

“Fundamental” BSM model

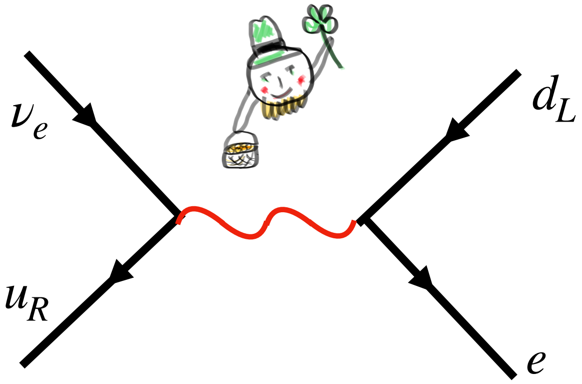
In the SM beta decay is mediated by the W boson



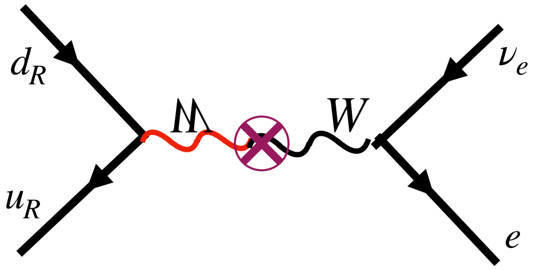
Several high-energy effects may contribute to beta decay



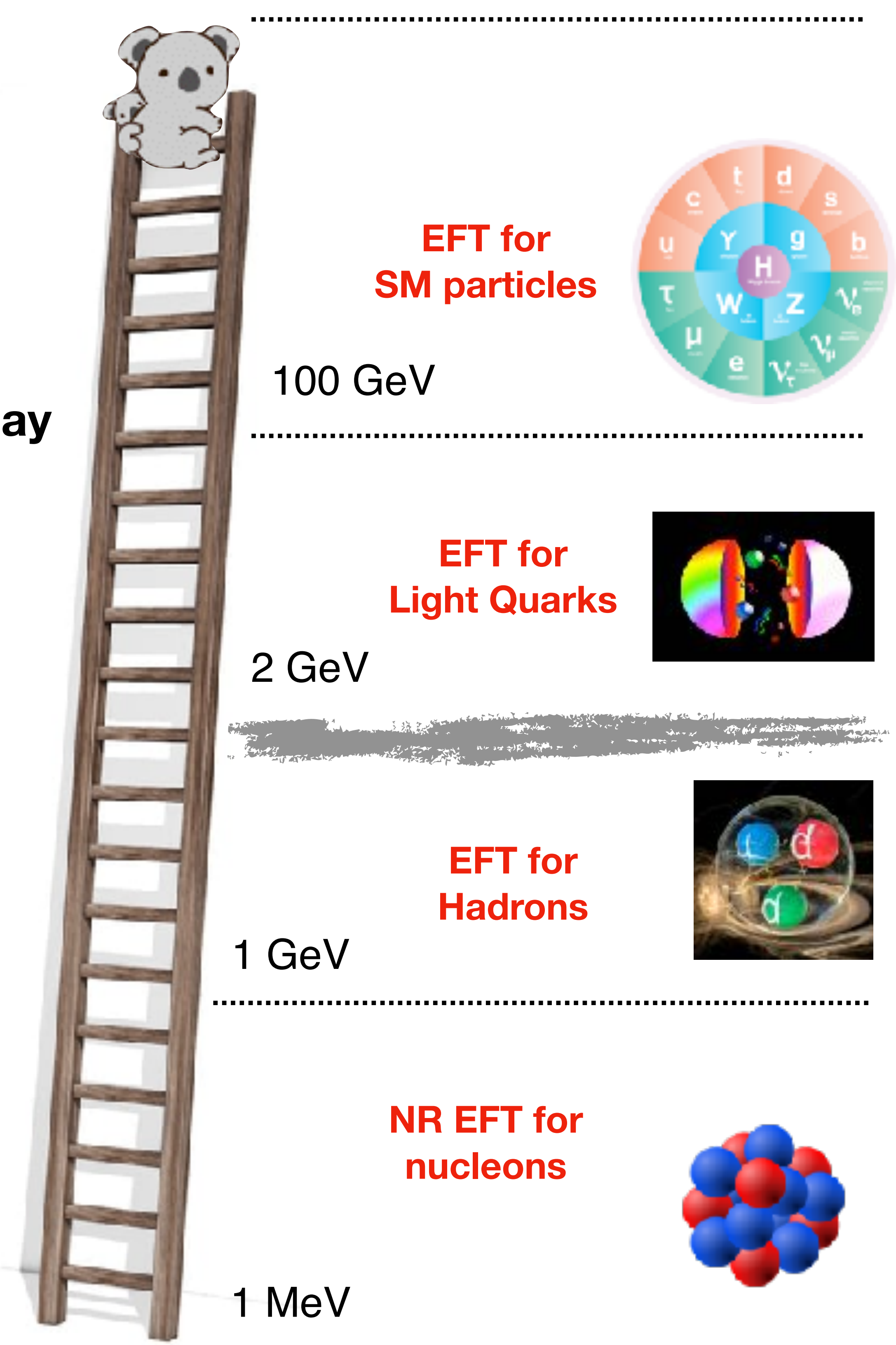
W’



Leptoquark



W_L-W_R mixing



10 TeV?

EFT for SM particles

100 GeV

EFT for Light Quarks

2 GeV

EFT for Hadrons

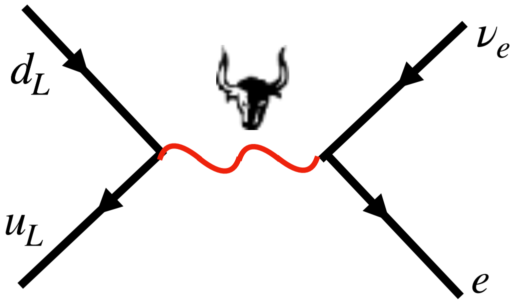
1 GeV

NR EFT for nucleons

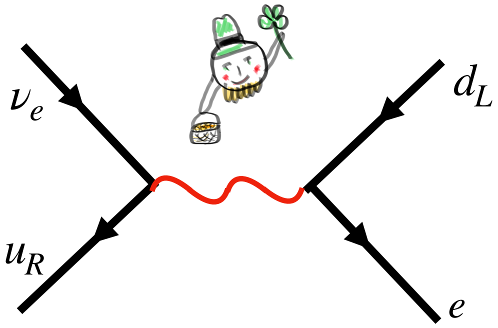
1 MeV

SMEFT at electroweak scale

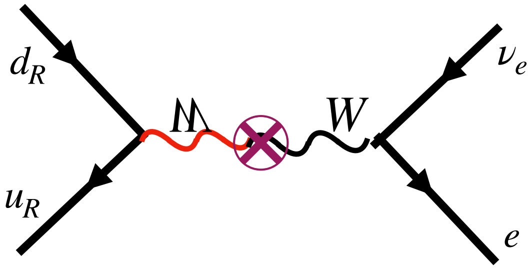
$$
\begin{aligned}
\mathscr{L}_{\rm SMEFT} \supset\ & c_{HQ} H^\dagger \sigma^a D_\mu H (\bar{Q} \sigma^a \gamma_\mu Q) + c_{HL} H^\dagger \sigma^a D_\mu H (\bar{L} \sigma^a \gamma_\mu L) \\
& + c_{Hud} H^T D_\mu H (\bar{u}_R \gamma_\mu d_R) \\
& + c_{LQ} (\bar{Q} \sigma^a \gamma_\mu Q)(\bar{L} \sigma^a \gamma_\mu L) + c'_{LeQu} (\bar{e}_R \sigma_{\mu\nu} L)(\bar{u}_R \sigma_{\mu\nu} Q) \\
& + c_{LeQu} (\bar{e}_R L)(\bar{u}_R Q) + c_{LedQ} (\bar{L} e_R)(\bar{d}_R Q) \\
& + \ldots
\end{aligned}
$$



$$c_{LQ} \sim \frac{g_*^2}{M_{W'}^2}$$

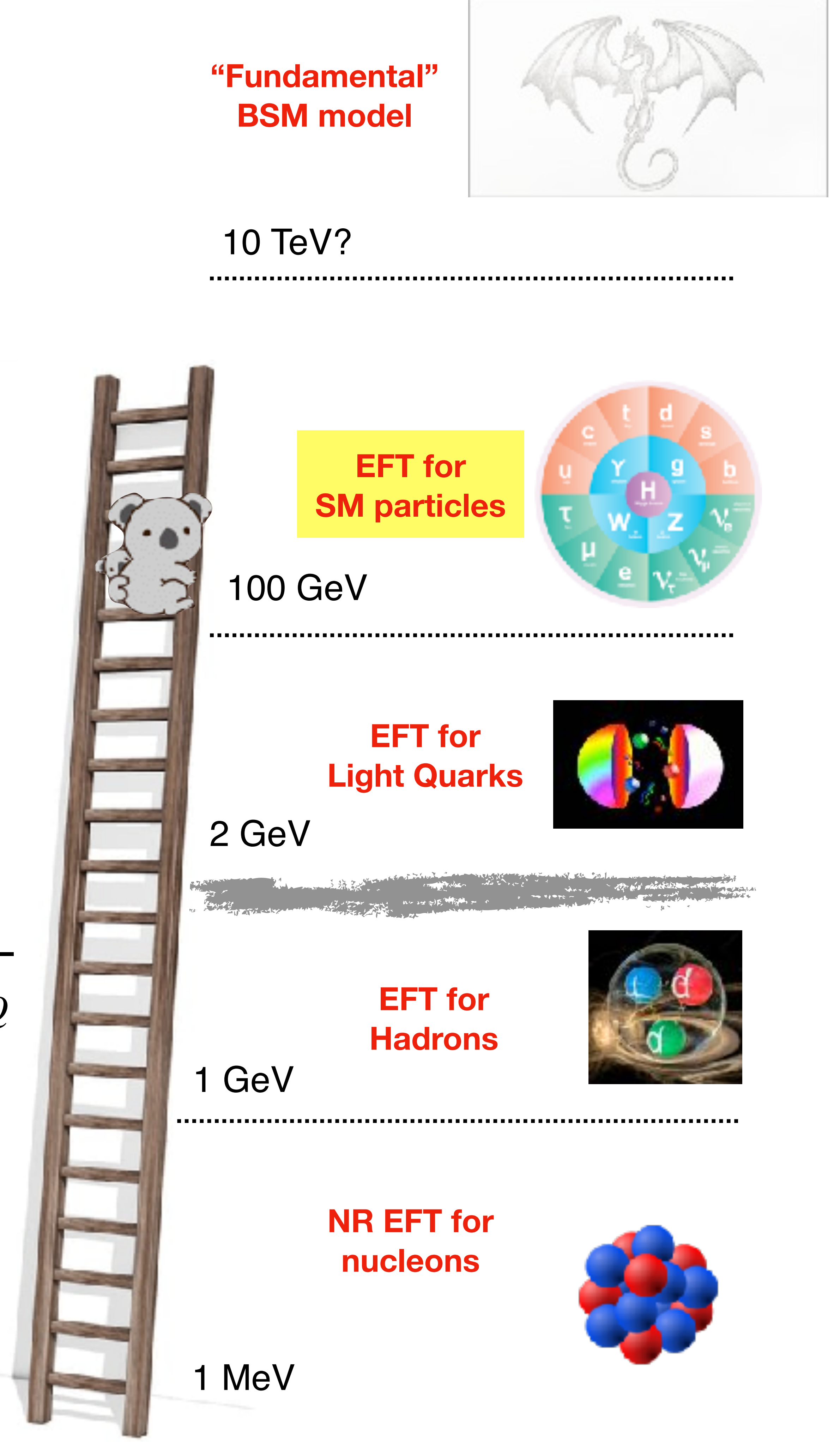


$$c'_{LeQu}, c_{LeQu}, c_{LedQ} \sim \frac{g_*^2}{M_{LQ}^2}$$



$$c_{Hud} \sim \frac{g_*^2}{M_M^2}$$

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

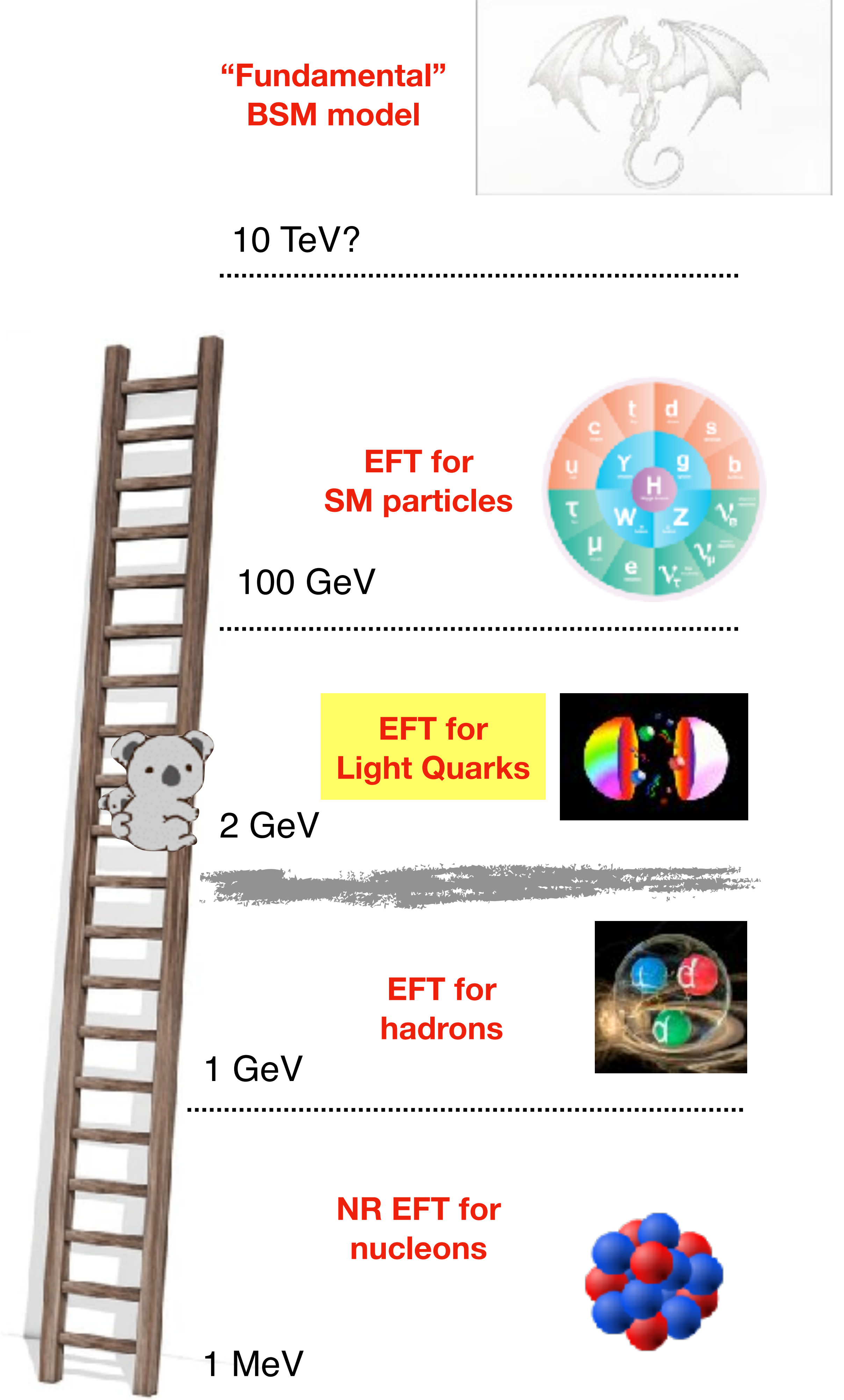
WEFT below electroweak scale

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

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

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 leptons



Translation from SMEFT to WEFT

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

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

$$\begin{aligned}\mathscr{L}_{\rm SMEFT} \supset\ & c_{HQ}H^\dagger\sigma^a D_\mu H(\bar{Q}\sigma^a\gamma_\mu Q) + c_{HL}H^\dagger\sigma^a D_\mu H(\bar{L}\sigma^a\gamma_\mu L) \\ & +c_{Hud}H^T D_\mu H(\bar{u}_R\gamma_\mu d_R) \\ & +c^{(3)}_{LQ}(\bar{Q}\sigma^a\gamma_\mu Q)(\bar{L}\sigma^a\gamma_\mu L) + c^{(3)}_{LeQu}(\bar{e}_R\sigma_{\mu\nu}L)(\bar{u}_R\sigma_{\mu\nu}Q) \\ & +c_{LeQu}(\bar{e}_R L)(\bar{u}_R Q) + c_{LedQ}(\bar{L}e_R)(\bar{d}_R Q)\end{aligned}$$

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

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

$$\epsilon_R = \frac{\mathrm{v}^2}{2V_{ud}}c_{Hud}$$

$$\epsilon_S = -\frac{\mathrm{v}^2}{2V_{ud}}\left(c^*_{LeQu} + V_{ud}c^*_{LedQ}\right)$$

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

$$\epsilon_P = -\frac{\mathrm{v}^2}{2V_{ud}}\left(c^*_{LeQu} - V_{ud}c^*_{LedQ}\right)$$

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

NR EFT for nucleons

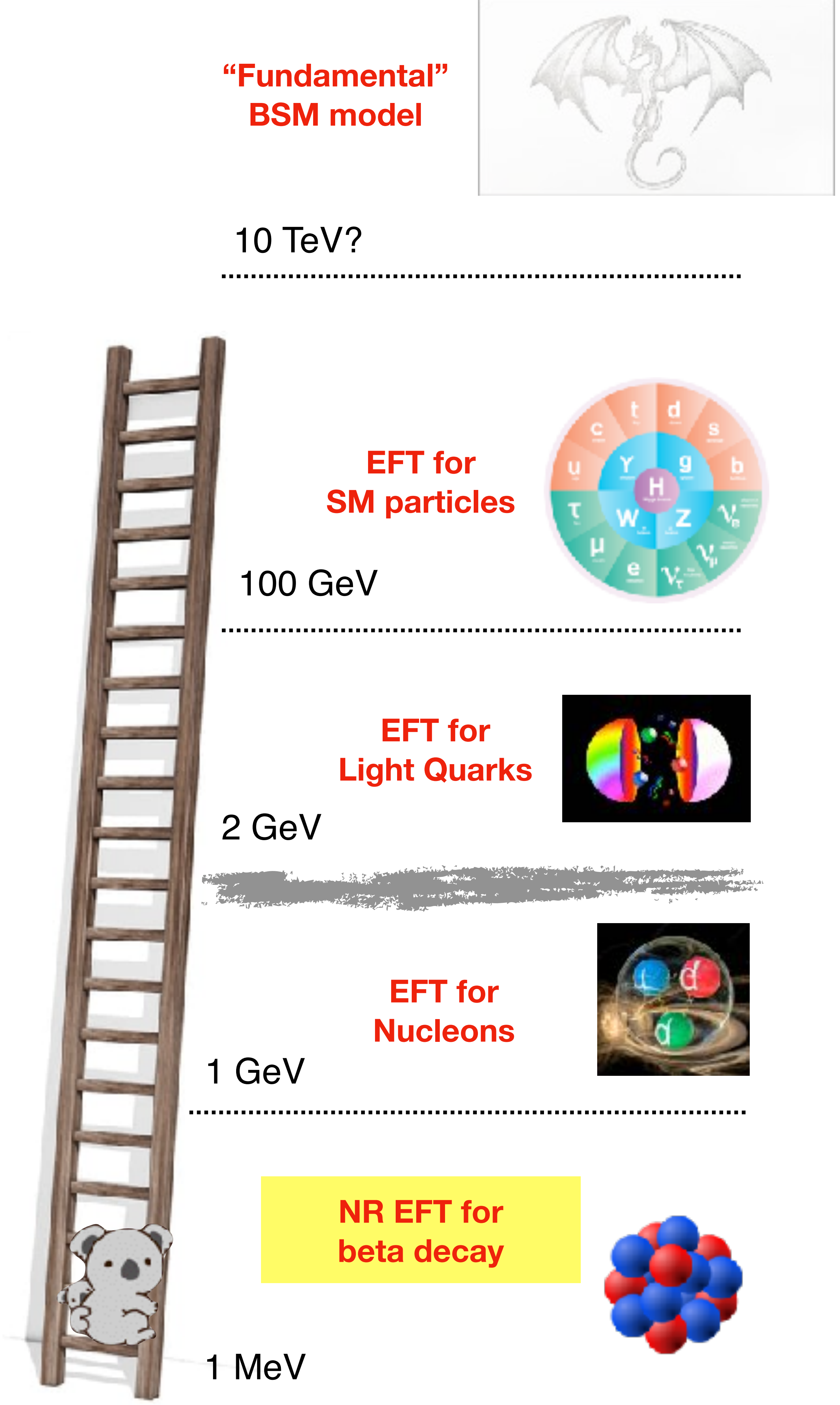
In beta decay, the momentum transfer is much smaller than the nucleon mass, due to approximate isospin symmetry leading to small mass splittings

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

NR 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

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

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 $\mathscr{N} \to \mathscr{N}' e^- \bar{\nu}$ where J=J':

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

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

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

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

Calculable from group theory in the isospin limit

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

Difficult to calculate from first principles

Spin-J generators

NR EFT for nucleons

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

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

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

Matching to quark-level EFT:

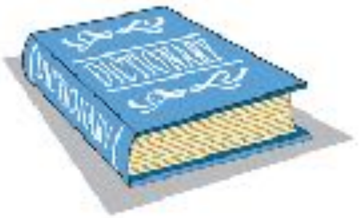
Non-zero in the SM

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

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

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

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



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

Note that pseudoscalar interactions do not enter at the leading order

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

$g_V \approx 1,\quad g_A = 1.246 \pm 0.028,\quad g_S = 1.02 \pm 0.10,\quad g_T = 0.989 \pm 0.034$

Ademolo, Gatto (1964)

Flag'21 N_f=2+1+1 value

Gupta et al 1806.09006

Gorchtein Seng 2106.09185

Matching also includes short-distance radiative corrections

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

$\Delta_R^A - \Delta_R^V = 0.13(12) \times 10^{-3}$

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

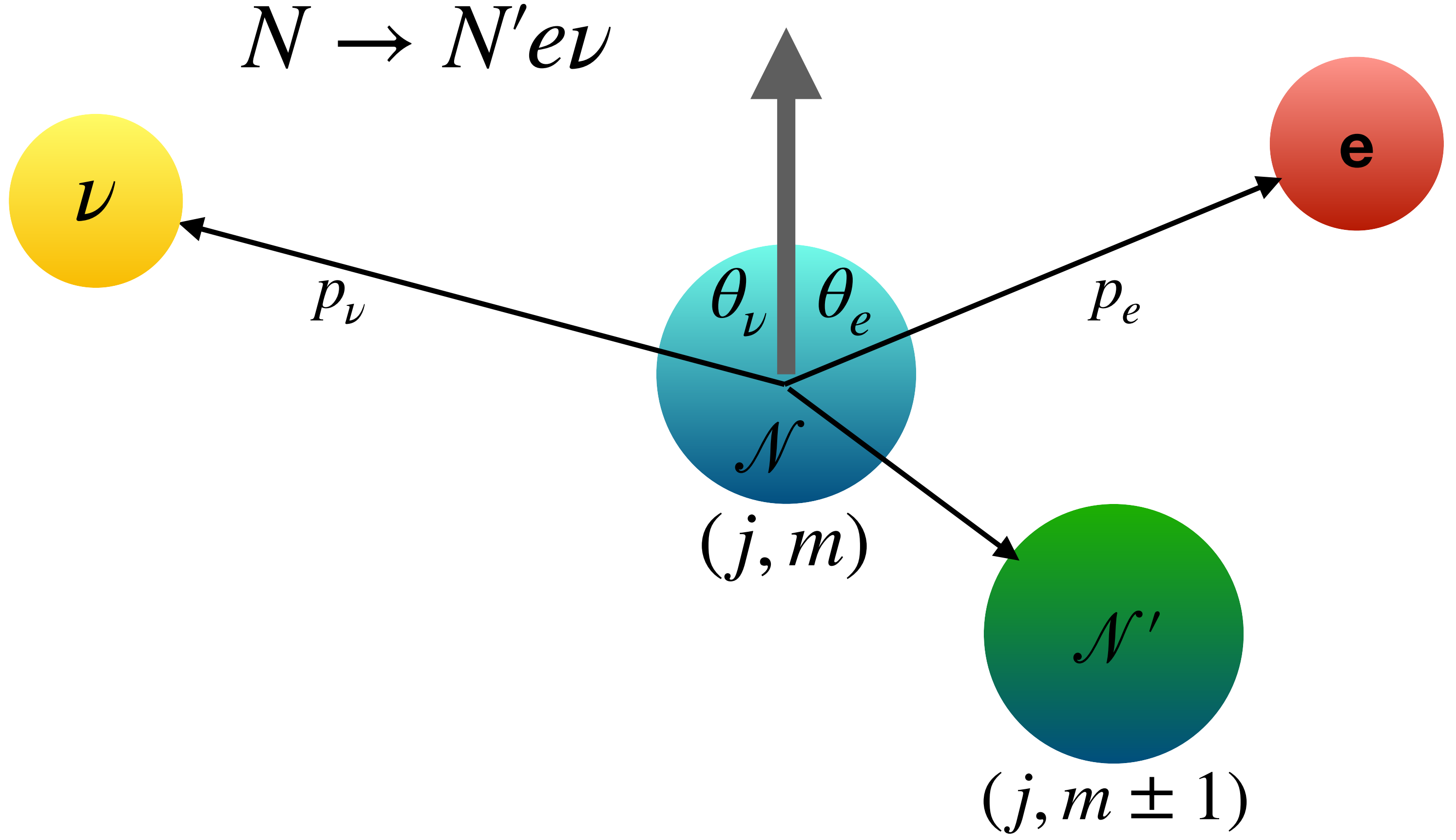
$$\mathscr{L}^{(0)} = -(\psi_p^\dagger \psi_n)\left[\underset{\substack{\Big\uparrow \\ \textbf{Generated by} \\ \textbf{weak interactions} \\ \textbf{in SM}}}{C_V^+} \bar{e}_L \gamma^0 \nu_L + \underset{\substack{\Big\uparrow \\ \textbf{Highly suppressed} \\ \textbf{in SM}}}{C_S^+} \bar{e}_R \nu_L\right]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

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

$$N \to N' e \nu$$



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:

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

No-one talks about it

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

Violates CP
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:

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

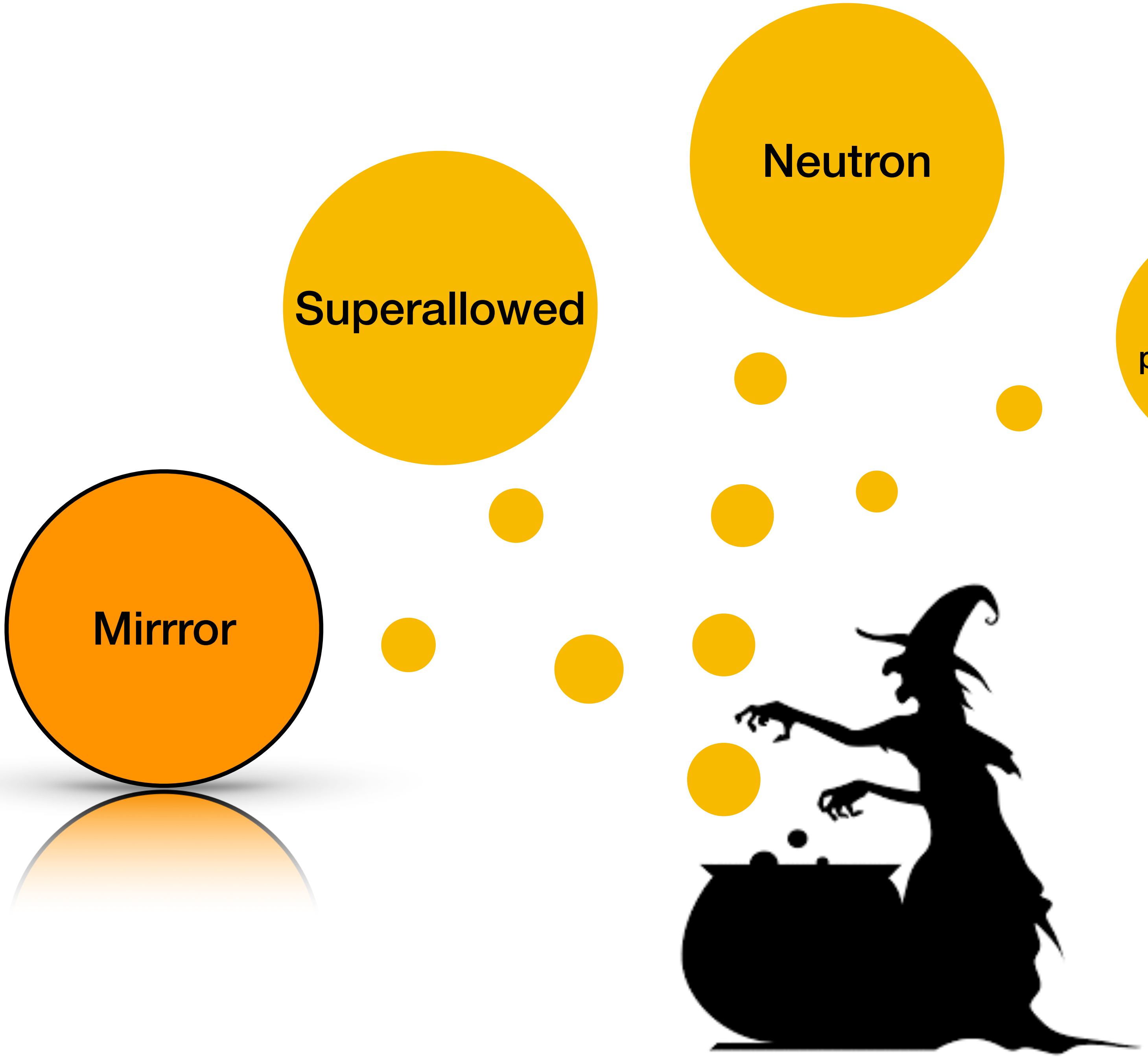
"Big A" parameter controls correlation between nucleus polarization and electron directions:

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

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

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

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

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

Higher-order corrections

Fermi matrix element

Fierz term

Phase space factor

$\delta, \langle m_e/E_e\rangle, f$ 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]

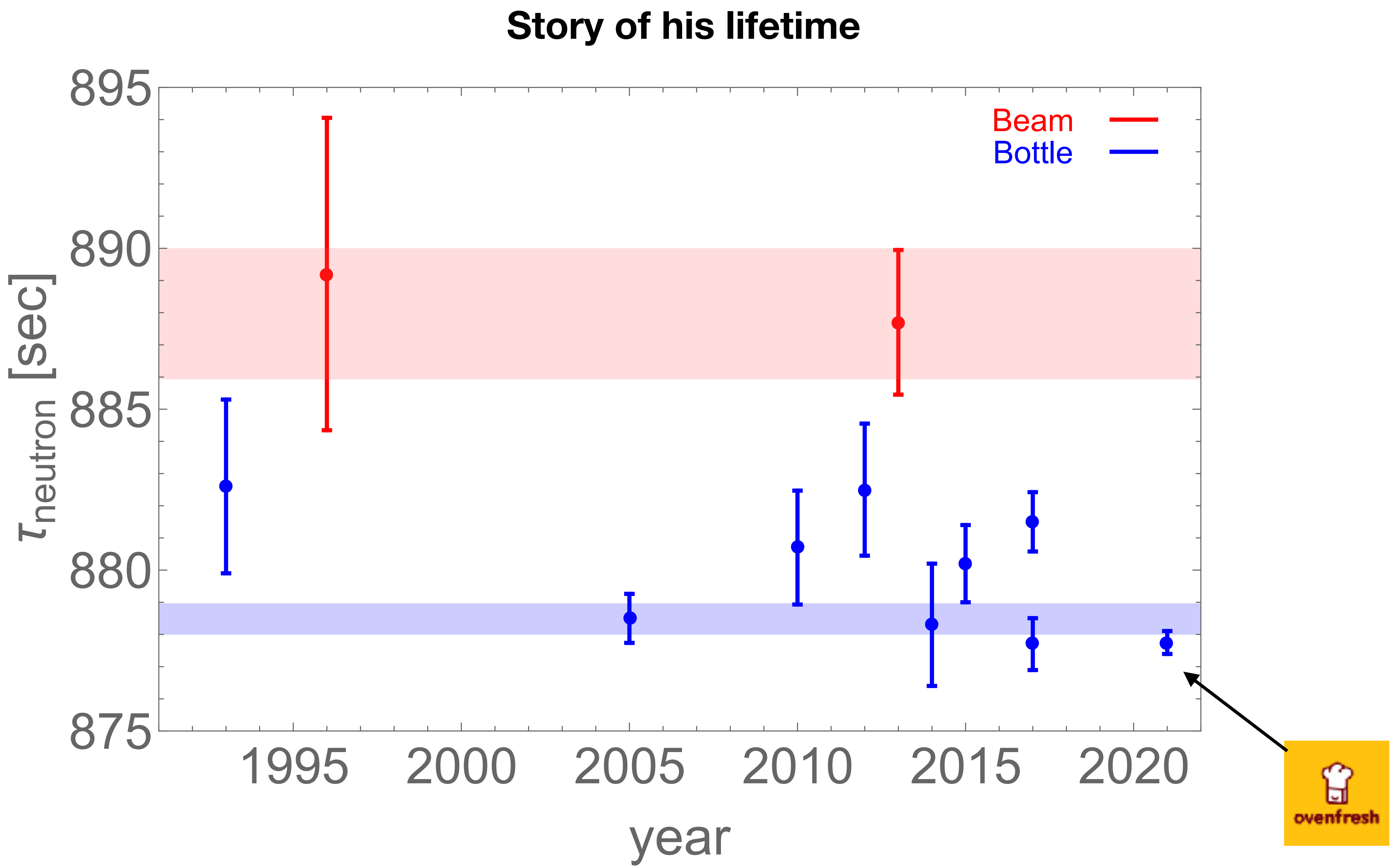
Observable	Value	$\langle m_e/E_e \rangle$	References
τ_n (s)	**878.64(59)** ~~879.75(76)~~	0.655	[52–61]
$\tilde{A}_n$	$-0.11958(18)$	0.569	[45, 62–66]
$\tilde{B}_n$	$0.9805(30)$	0.591	[67–70]
λ_{AB}	$-1.2686(47)$	0.581	[71]
a_n	$-0.10426(82)$		[46, 72, 73]
$\tilde{a}_n$	~~$-0.1090(41)$~~	0.695	[74]

-0.1078(20)

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

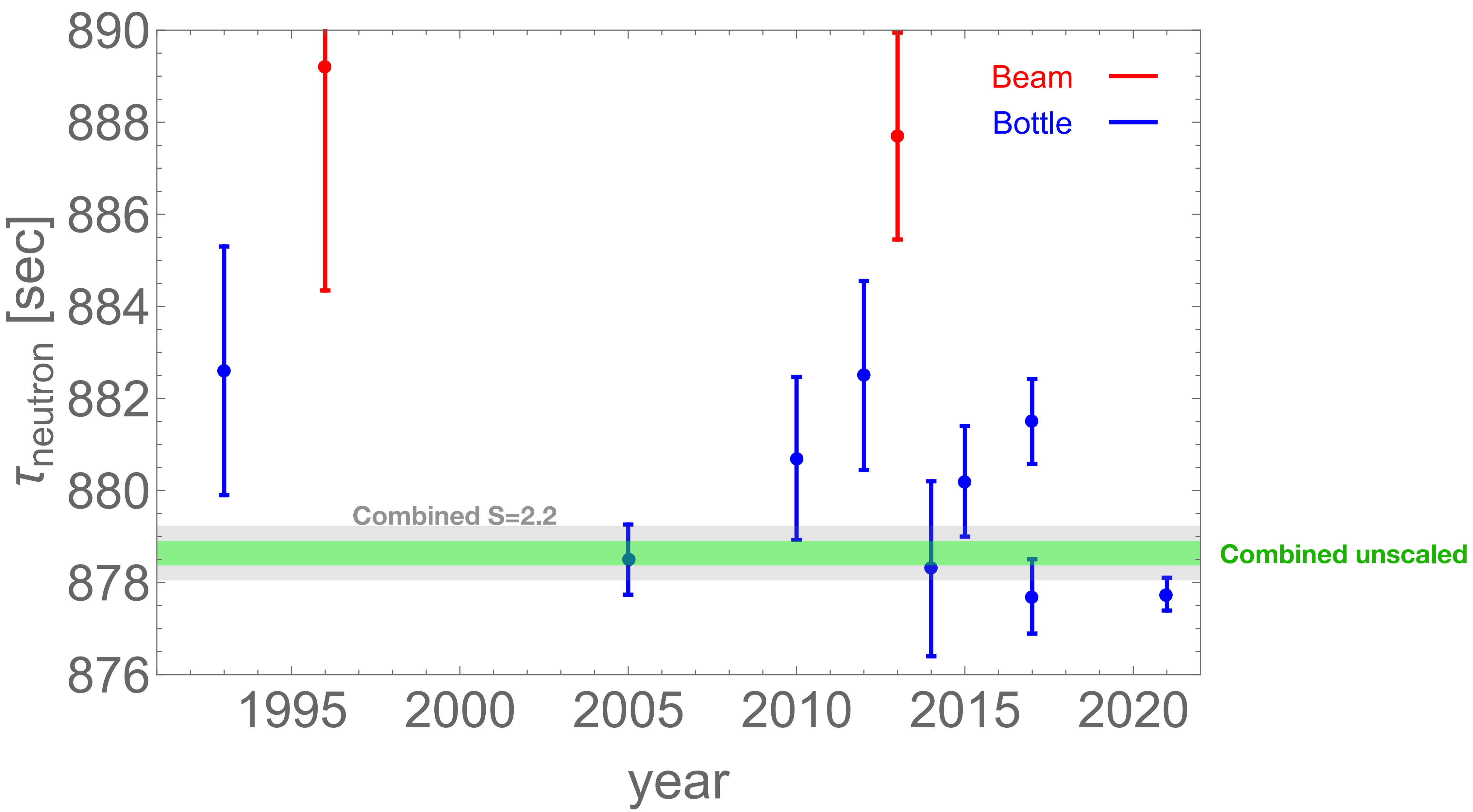
Order per-mille precision !

Neutron lifetime



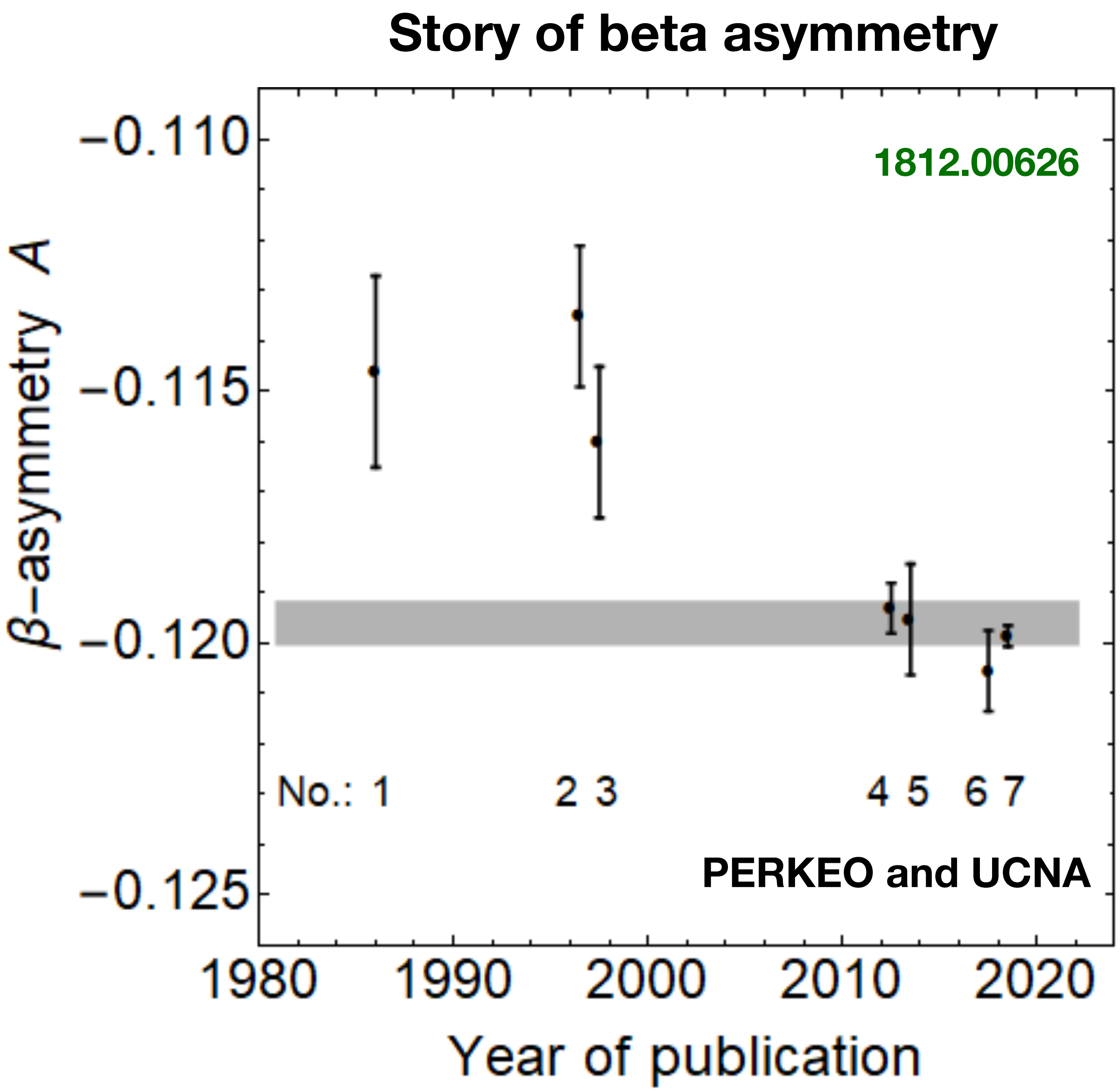
There is a large discrepancy between bottle and beam measurements of the lifetime, but also some inconsistency between different bottle measurements

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	$\mathcal{F}t$ (s)	$\delta\mathcal{F}t$ (%)	ρ	$\delta\rho$ (%)
^{3}H	1135.3 ± 1.5	0.13	-2.0951 ± 0.0020	0.10
^{11}C	3933 ± 16	0.41	0.7456 ± 0.0043	0.58
^{13}N	4682.0 ± 4.9	0.10	0.5573 ± 0.0013	0.23
^{15}O	4402 ± 11	0.25	-0.6281 ± 0.0028	0.45
^{17}F	2300.4 ± 6.2	0.27	-1.2815 ± 0.0035	0.27
^{19}Ne	1718.4 ± 3.2	0.19	1.5933 ± 0.0030	0.19
^{21}Na	4085 ± 12	0.29	-0.7034 ± 0.0032	0.45
^{23}Mg	4725 ± 17	0.36	0.5426 ± 0.0044	0.81
^{25}Al	3721.1 ± 7.0	0.19	-0.7973 ± 0.0027	0.34
^{27}Si	4160 ± 20	0.48	0.6812 ± 0.0053	0.78
^{29}P	4809 ± 19	0.40	-0.5209 ± 0.0048	0.92
^{31}S	4828 ± 33	0.68	0.5167 ± 0.0084	1.63
^{33}Cl	5618 ± 13	0.23	0.3076 ± 0.0042	1.37
^{35}Ar	5688.6 ± 7.2	0.13	-0.2841 ± 0.0025	0.88
^{37}K	4562 ± 28	0.61	0.5874 ± 0.0071	1.21
^{39}Ca	4315 ± 16	0.37	-0.6504 ± 0.0041	0.63
^{41}Sc	2849 ± 11	0.39	-1.0561 ± 0.0053	0.50
^{43}Ti	3701 ± 56	1.51	0.800 ± 0.016	2.00
^{45}V	4382 ± 99	2.26	-0.621 ± 0.025	4.03

Not the latest numbers
For illustration only!

Phalet et al
0807.2201

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

For mirror beta transitions

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

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

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 F*t* 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]

ovenfresh

[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:

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

$$\begin{pmatrix} \mathrm{v}^2 C_V^+ \\ \mathrm{v}^2 C_A^+ \end{pmatrix} = \begin{pmatrix} 0.98577(22) \\ -1.25754(39) \end{pmatrix}$$

$\mathscr{O}(10^{-4})$ 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!**

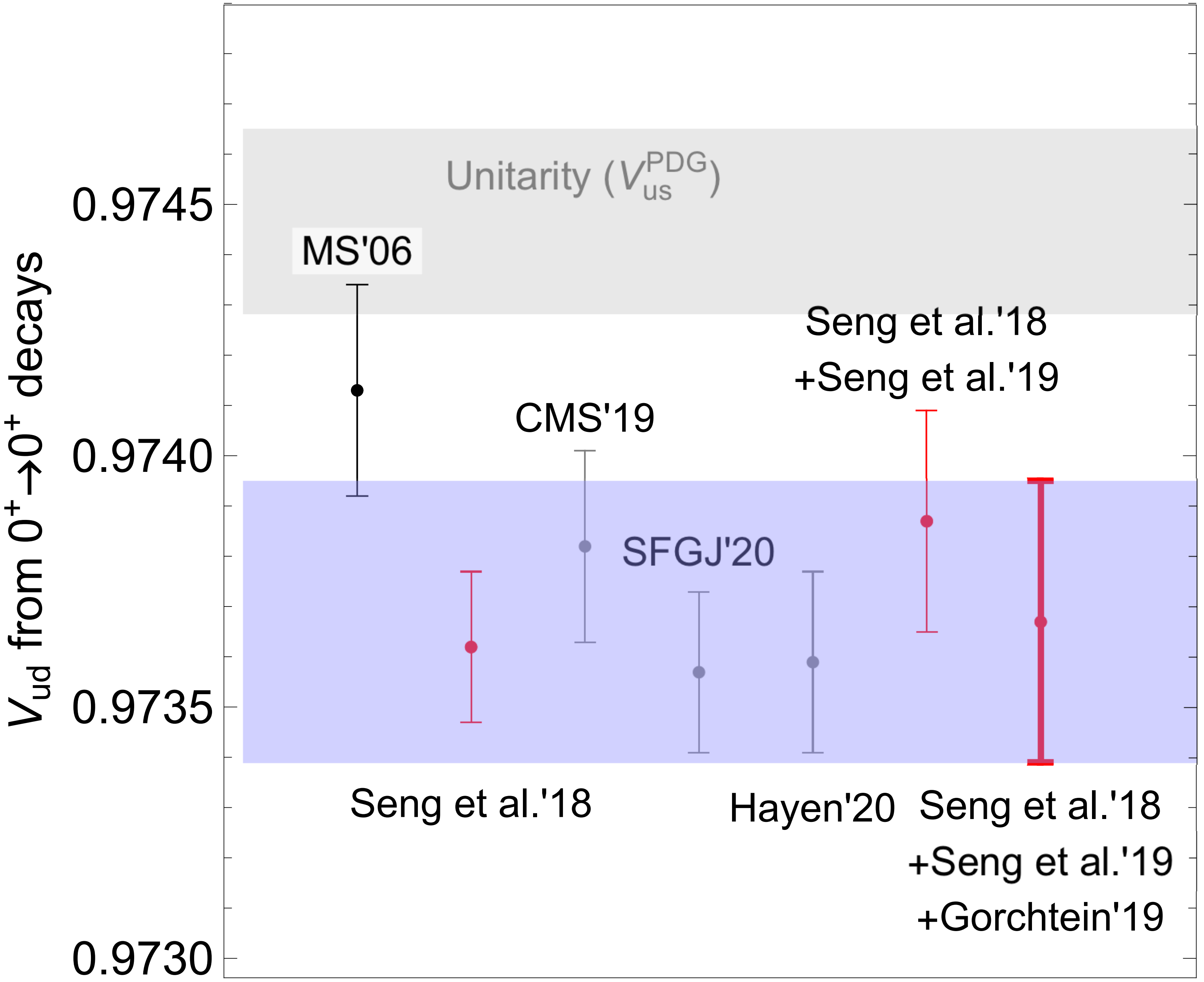
$$\begin{pmatrix} V_{ud} \\ g_A \end{pmatrix} = \begin{pmatrix} 0.97382(24) \\ 1.27562(43) \end{pmatrix} \qquad \rho = \begin{pmatrix} 1 & -0.39 \\ . & 1 \end{pmatrix}$$

Sub-permille precision for the nucleon axial charge!

Experiment is much better than lattice, but only after assuming that SM is true

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)

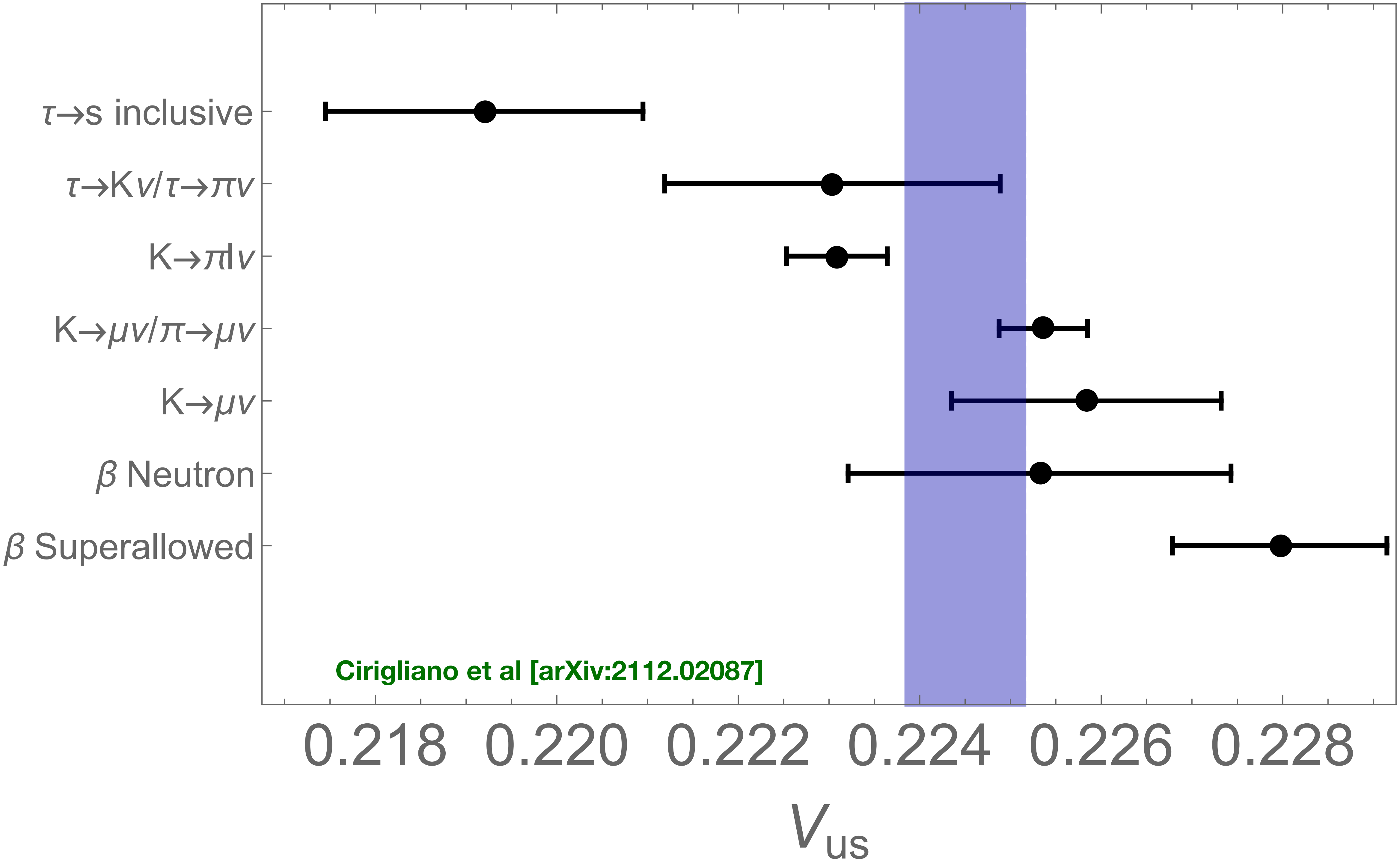
Our error bars are larger, because we take into account additional uncertainties in superallowed decays

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:

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

$$\mathrm{v}^2 \begin{pmatrix} C_V^+ \\ C_A^+ \\ C_S^+ \\ C_T^+ \end{pmatrix} = \begin{pmatrix} 0.98571(43) \\ -1.25735(55) \\ 0.0001(11) \\ -0.0007(12) \end{pmatrix}$$

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

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

$$\hat{V}_{ud} = V_{ud}\left(1+\epsilon_L+\epsilon_R\right)$$

Polluted CKM element

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

$$\hat{g}_A = g_A \frac{1+\epsilon_L-\epsilon_R}{1+\epsilon_L+\epsilon_R}$$

$$g_A = 1.246(28)$$

$$C_T^+ = \frac{V_{ud}}{\mathrm{v}^2} g_T \epsilon_T = \frac{\hat{V}_{ud}}{\mathrm{v}^2} g_T \hat{\epsilon}_T$$

$$\hat{\epsilon}_S = \frac{\epsilon_S}{1+\epsilon_L+\epsilon_R}$$

$$C_S^+ = \frac{V_{ud}}{\mathrm{v}^2} g_S \epsilon_S = \frac{\hat{V}_{ud}}{\mathrm{v}^2} g_S \hat{\epsilon}_S$$

$$\hat{\epsilon}_T = \frac{\epsilon_T}{1+\epsilon_L+\epsilon_R}$$

Rescaled BSM Wilson coefficients

$$\begin{pmatrix} \hat{V}_{ud} \\ \epsilon_R \\ \epsilon_S \\ \epsilon_T \end{pmatrix} = \begin{pmatrix} 0.97362(44) \\ -0.010(13) \\ -0.0001(11) \\ -0.0010(13) \end{pmatrix}$$

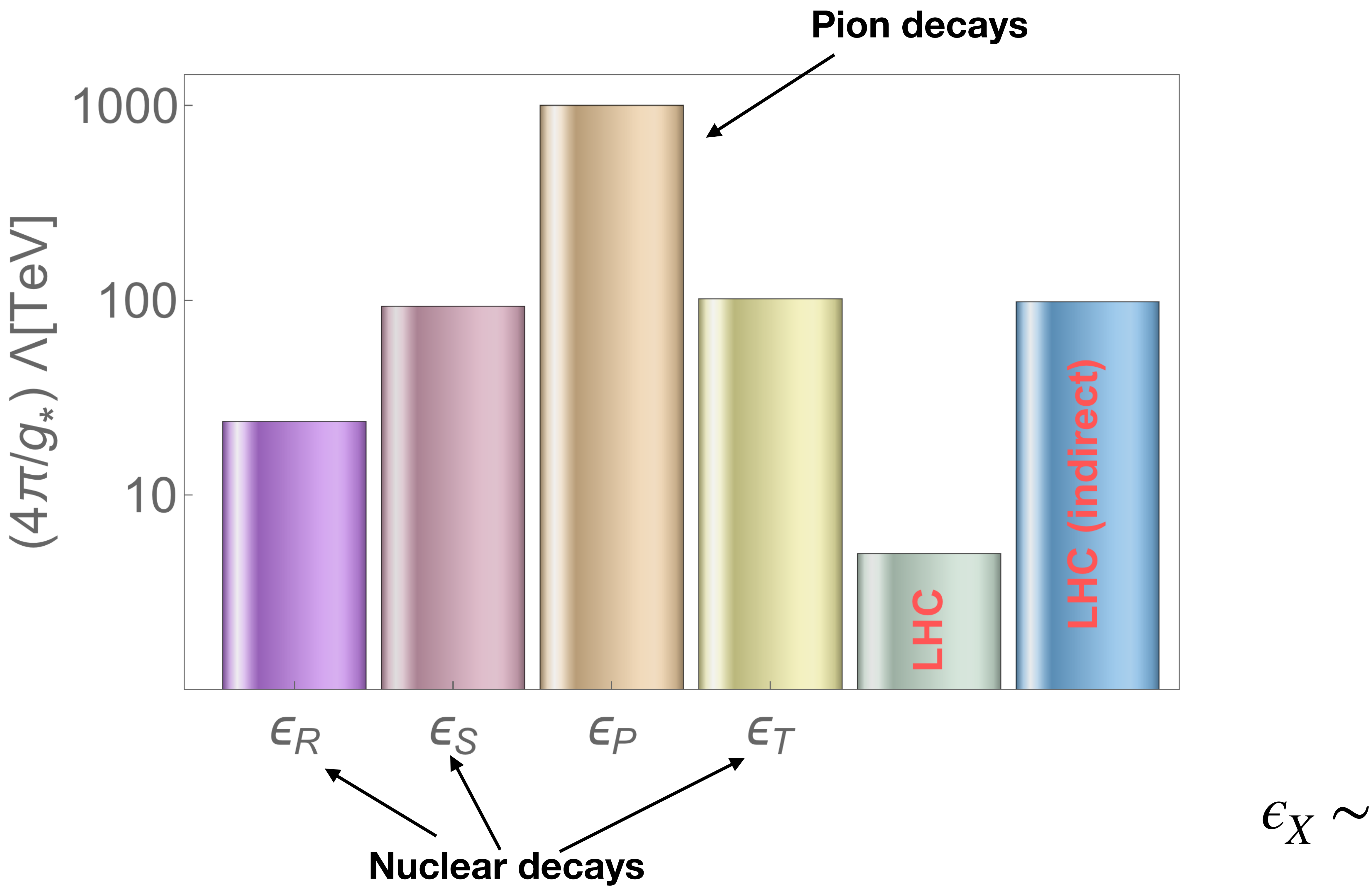
polluted CKM matrix element (in principle, can lead to apparent breakdown of CKM unitarity)

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

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

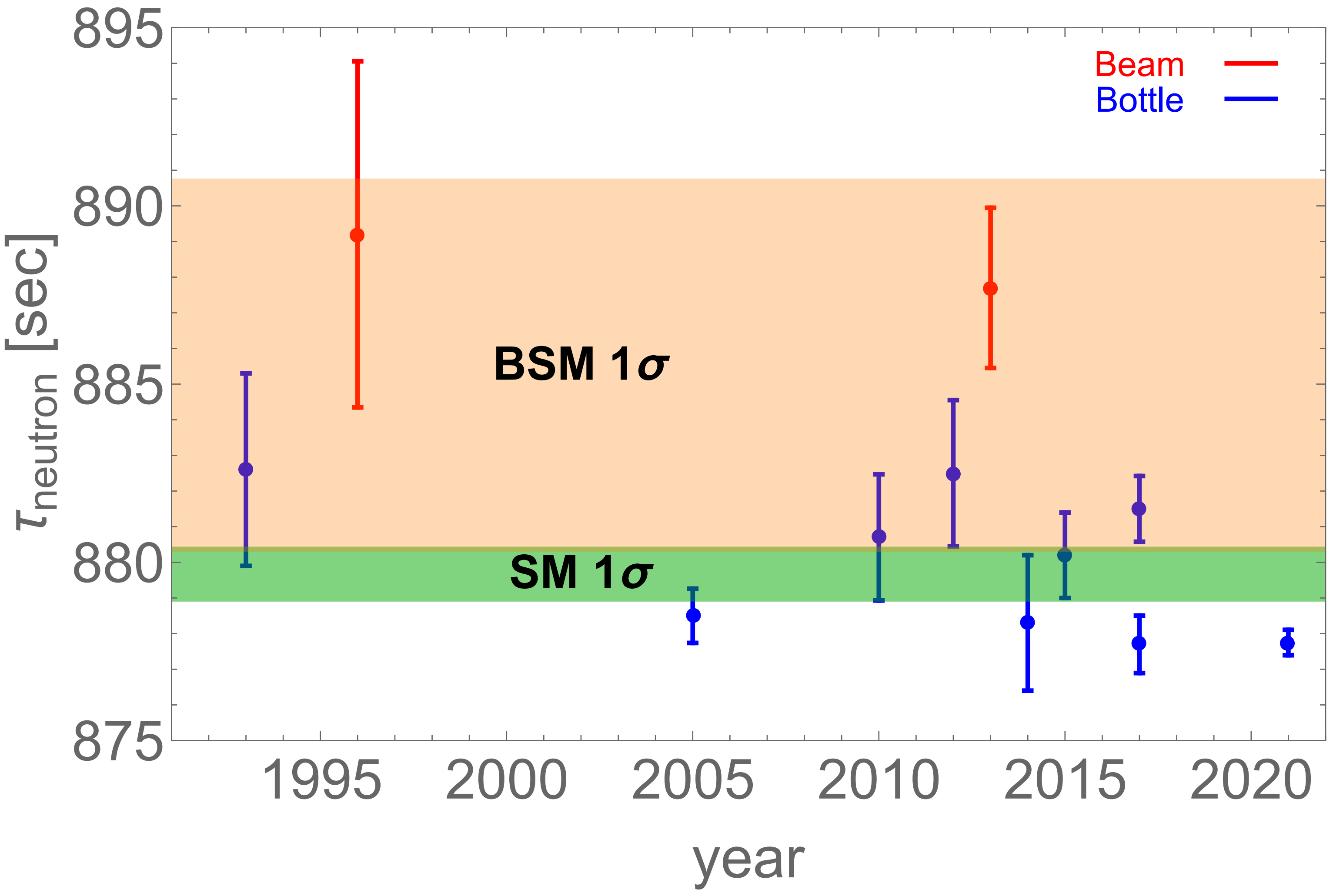
New physics reach of beta decays

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



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

Neutron lifetime: bottle vs beam

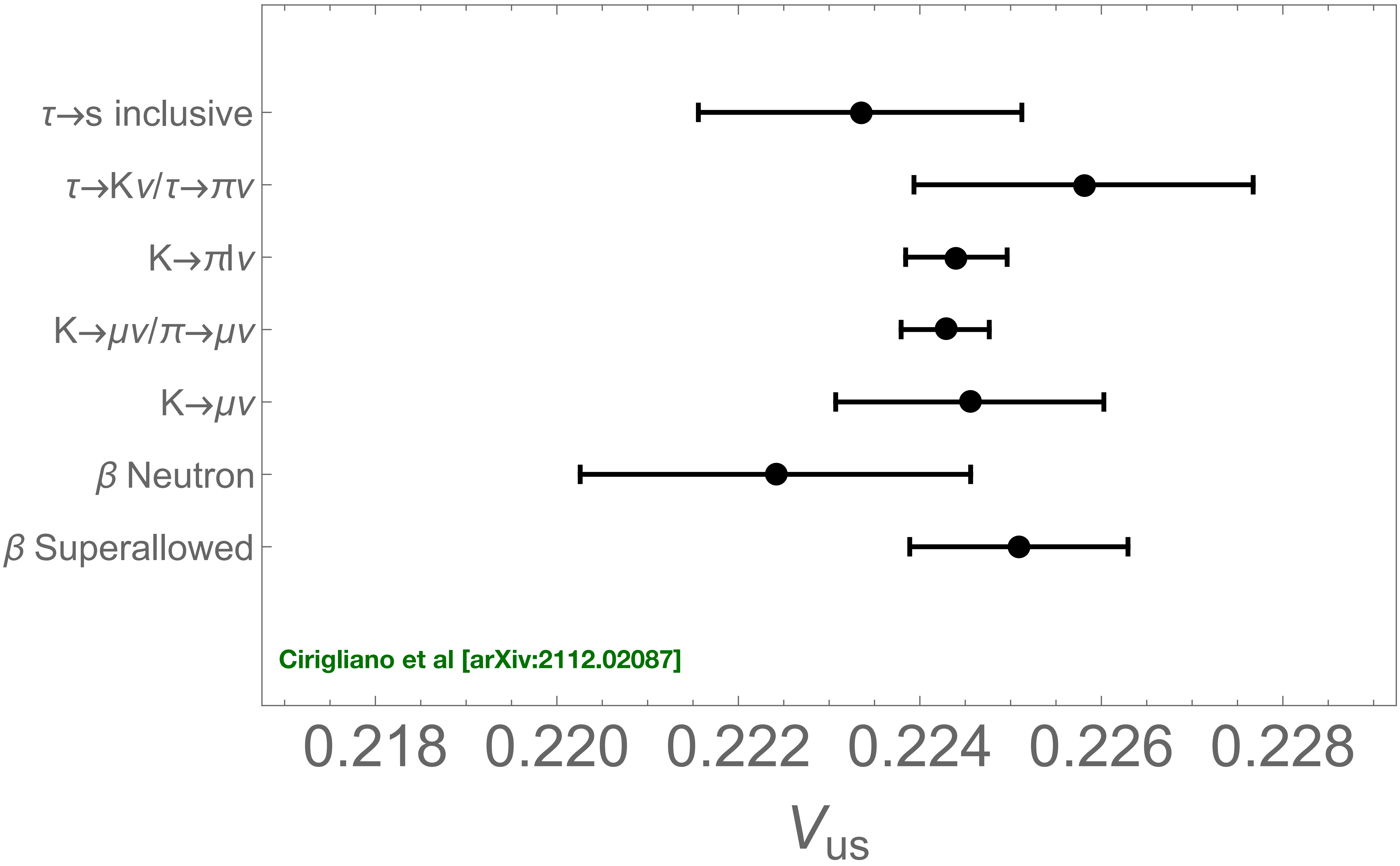


Beyond SM both beam and bottle are consistent with other experiments

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

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

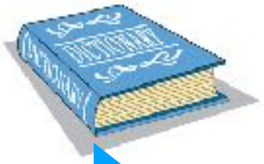
[arXiv:2112.07688] AA, Martin Gonzalez-Alonso, Ajdin Palavrić, Antonio Rodriguez-Sanchez

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

Example: constraining pseudoscalar interactions

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

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



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

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

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

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

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

- Nuclear physics is a treasure trove of data that can be used to constrain new physics beyond the Standard Model

- Thanks to continuing experimental and theoretical progress, accuracy of beta transitions measurements is reaching 0.1% - 0.01% for some observables

- Using the latest available data on superallowed, neutron, Fermi, Gamow-Teller, and mirror decays, we build a global 13-parameter likelihood for the 4 Wilson coefficients of the leading order EFT relevant for beta transitions, together with 6 mixing parameter of mirror nuclei included in the analysis and 3 nuisance parameters to take into account largest errors

- Data from mirror beta transitions are included (almost) for the first time in the BSM context

- After translating to quark-level EFT, we obtain per-mille level constraints for Wilson coefficients describing scalar and tensor interactions (relevant for constraining leptoquarks), and percent level constraints for the Wilson coefficient describing V+A interactions (relevant for constraining right-handed W')

Future

**Cirigliano et al
1907.02164**

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

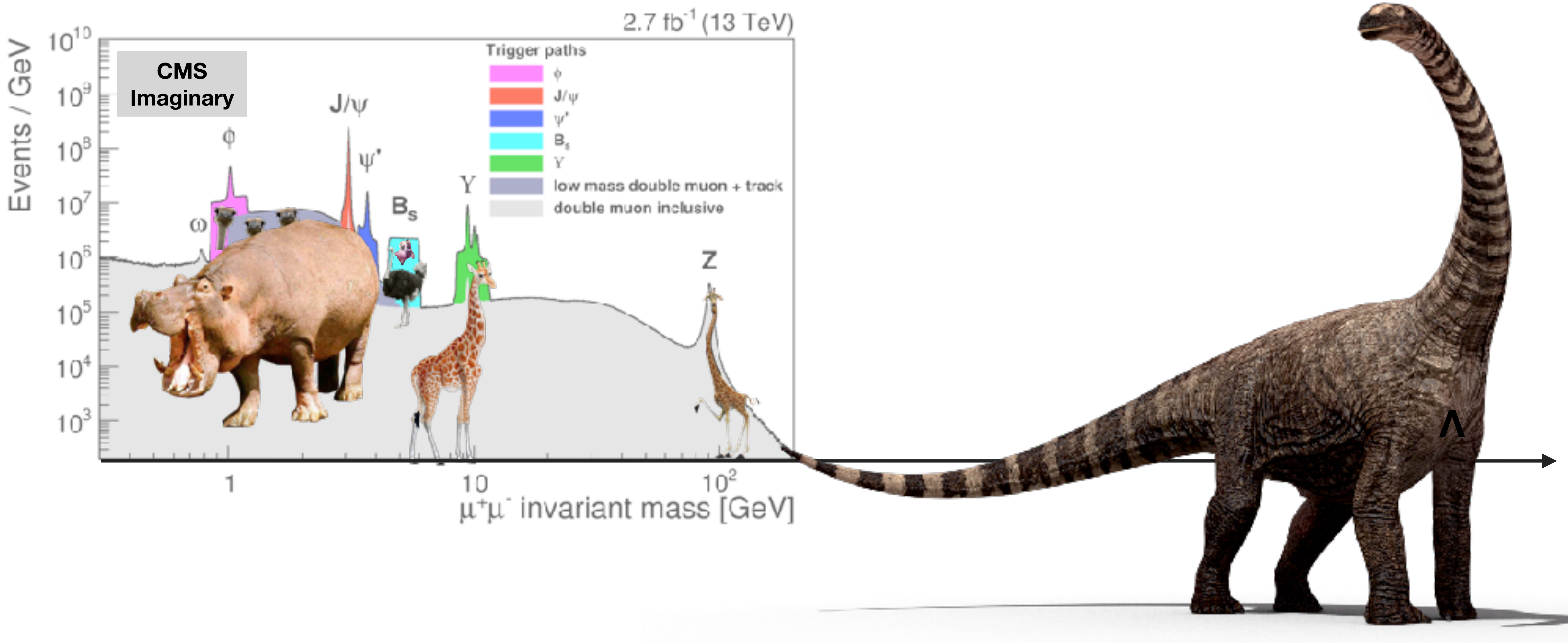
Measurement	Transition Type	Nucleus	Institution/Collaboration	Goal
$\beta - \nu$	F	^{32}Ar	Isolde-CERN	0.1 %
$\beta - \nu$	F	^{38}K	TRINAT-TRIUMF	0.1 %
$\beta - \nu$	GT, Mixed	^{6}He, ^{23}Ne	SARAF	0.1 %
$\beta - \nu$	GT	^{8}B, ^{8}Li	ANL	0.1 %
$\beta - \nu$	F	^{20}Mg, ^{24}Si, ^{28}S, ^{32}Ar, ...	TAMUTRAP-Texas 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