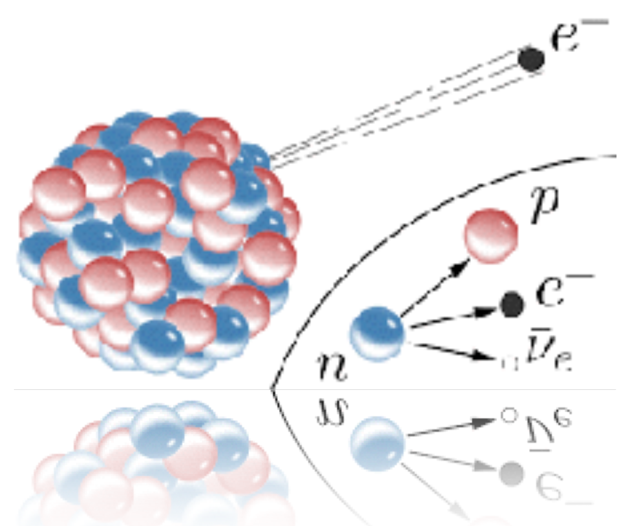
Adam Falkowski

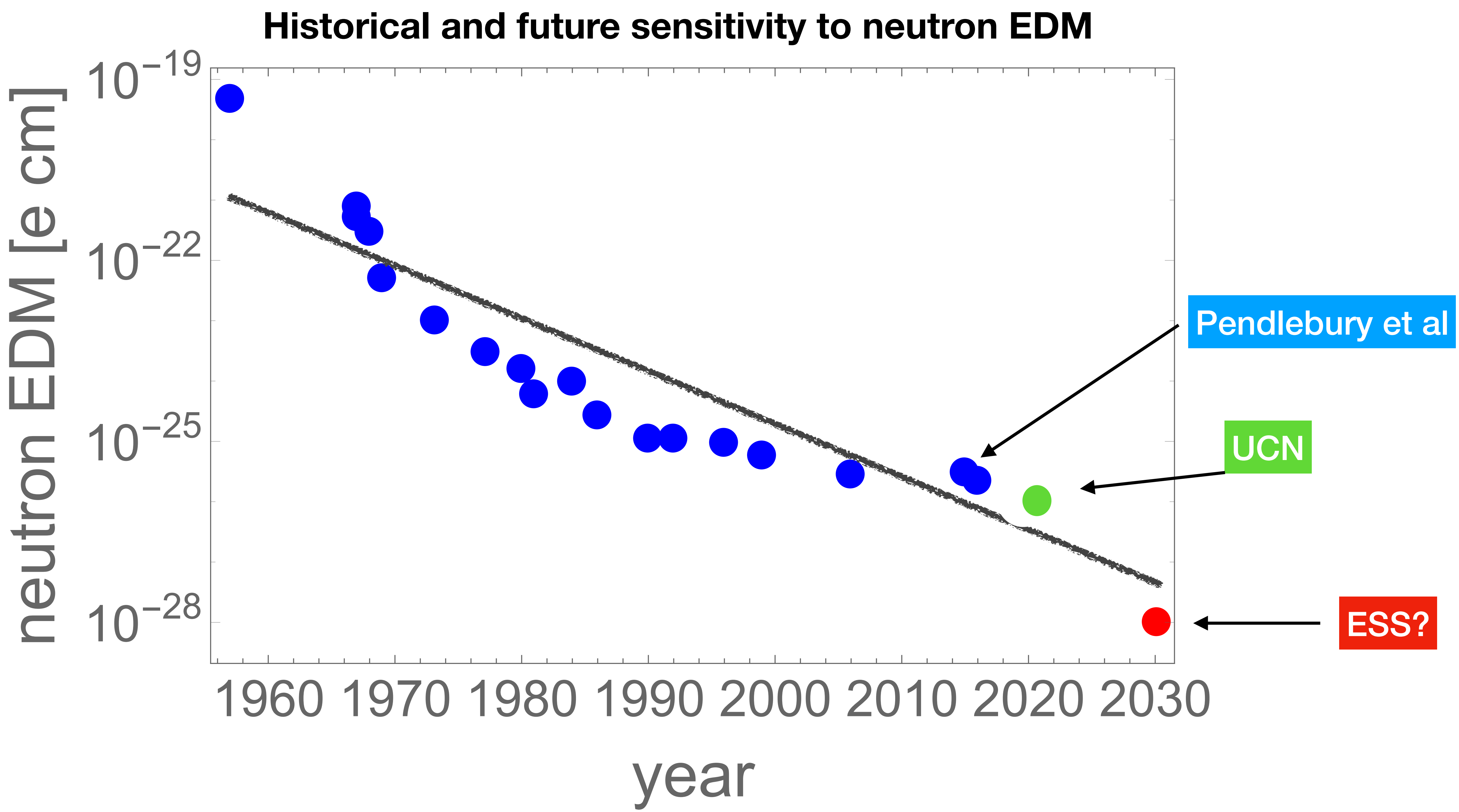
Precision measurements of beta transitions: in search for new physics

ECT* Trento, 09 September 2021



based on [arXiv:2010.13797] with Martin Gonzalez-Alonso and Oscar Naviliat-Cuncic
and a paper to appear with Martin Gonzalez-Alonso, Ajdin Palavric, and Antonio Rodriguez-Sanchez

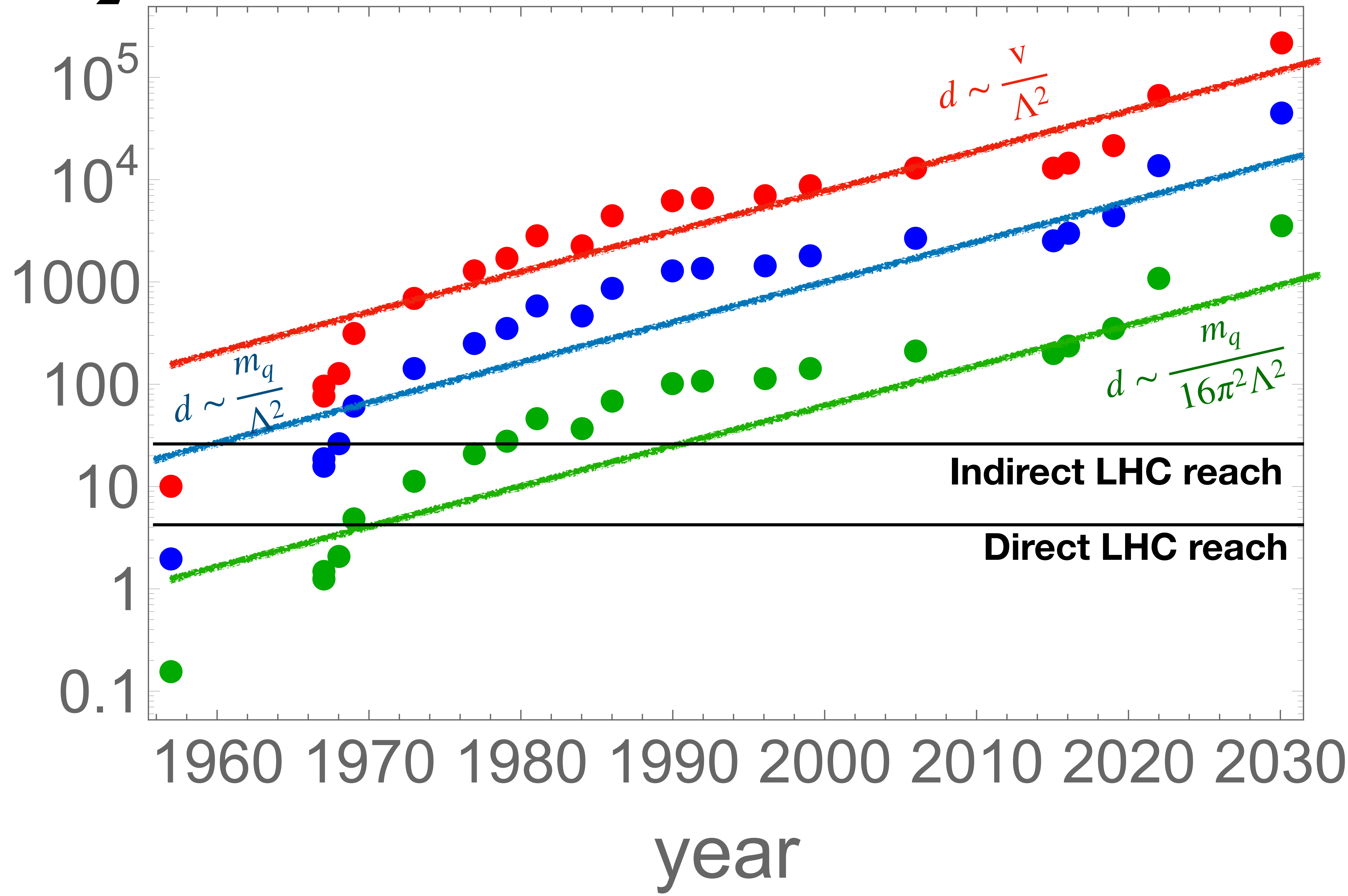
Low-energy frontier



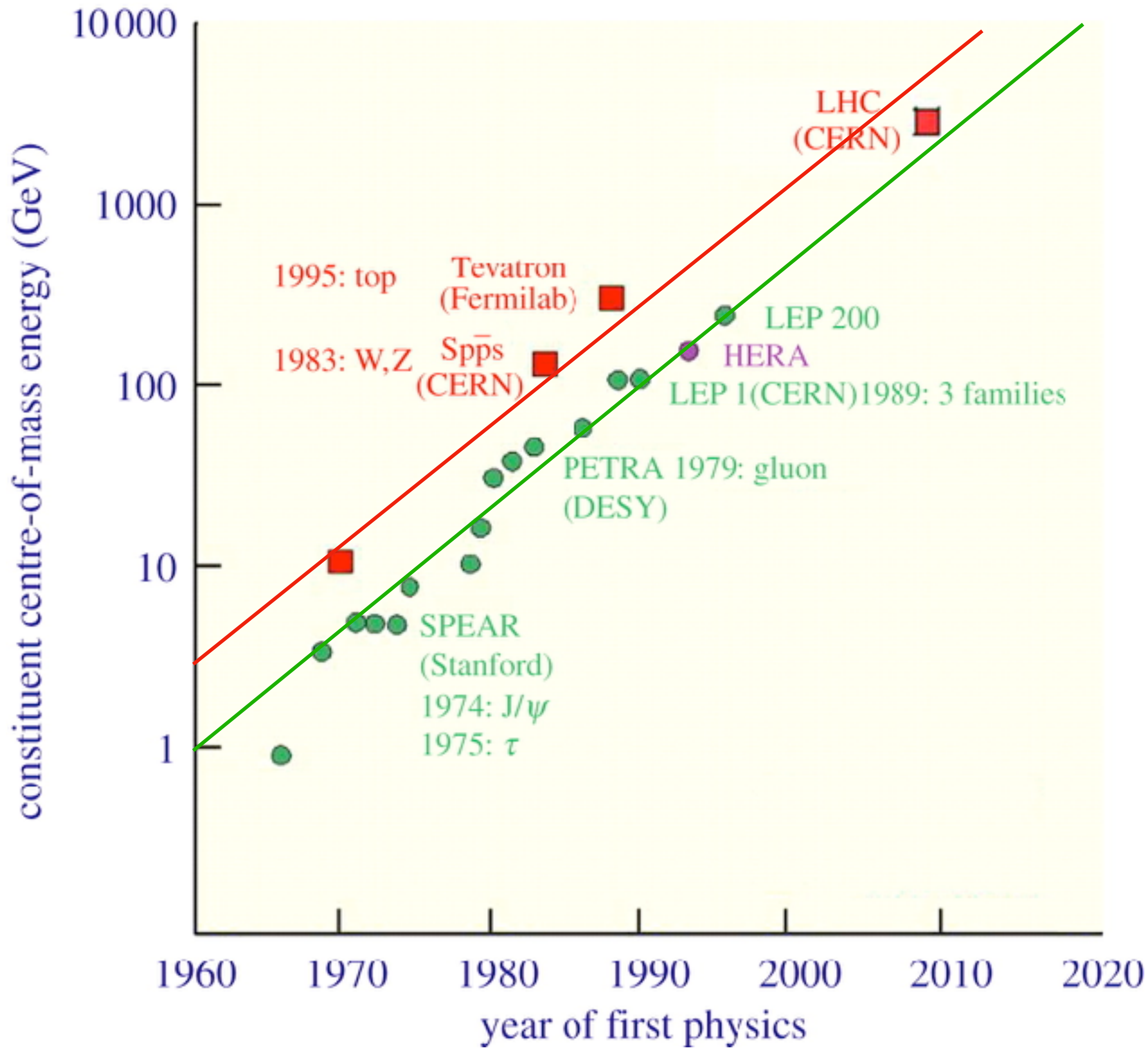
Neutron EDM and a host of other precision measurements is providing complementary information about fundamental interactions and is indirectly probing new particles at a very large energy scales

Low-energy frontier

$$\mathscr{L} = -\frac{i}{2} d_q\, \bar{q}\sigma_{\mu\nu}\gamma_5 q F^{\mu\nu}$$

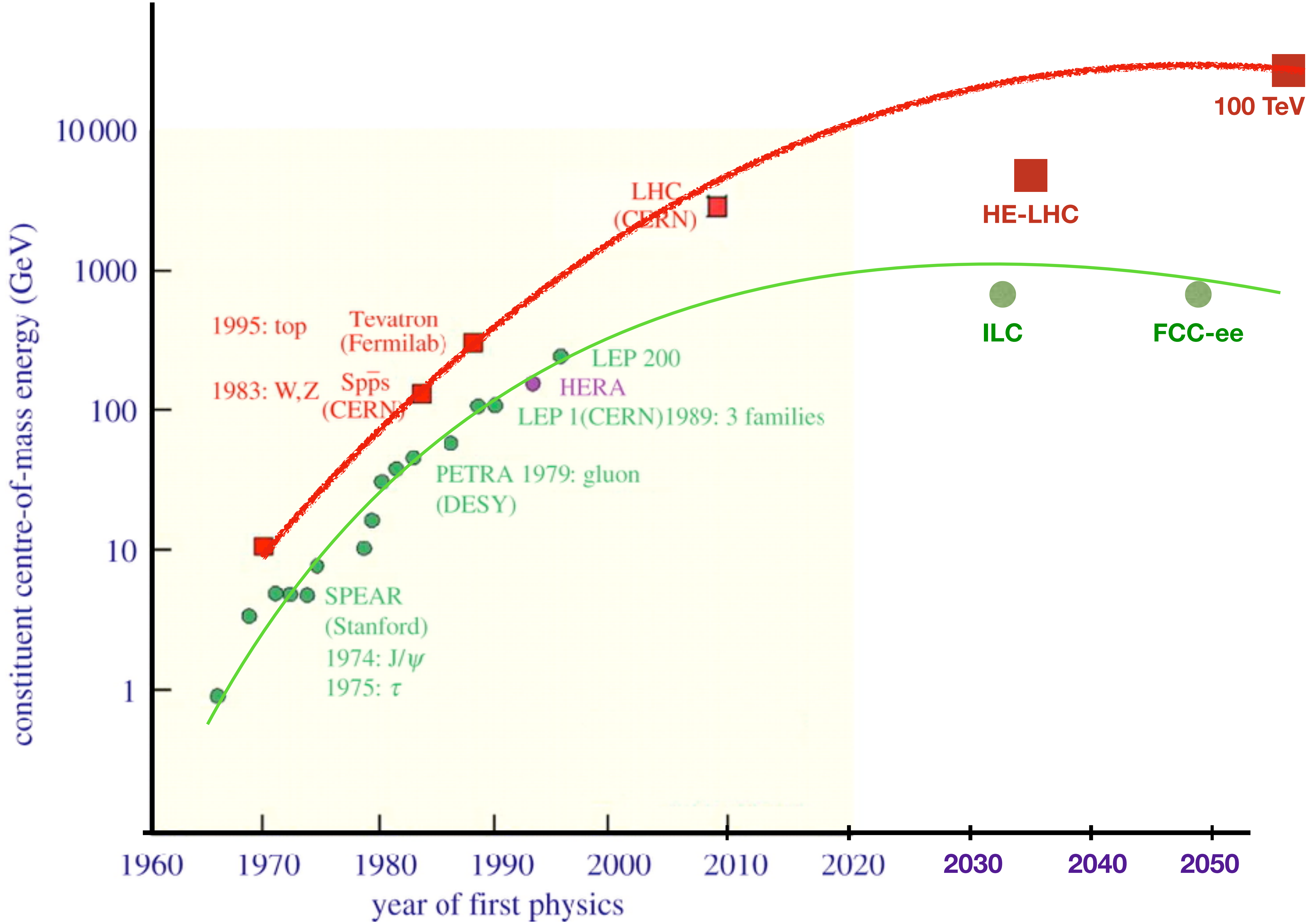


High-energy frontier



Most of what we know about fundamental interactions we learned on the high-energy frontier

High-energy frontier

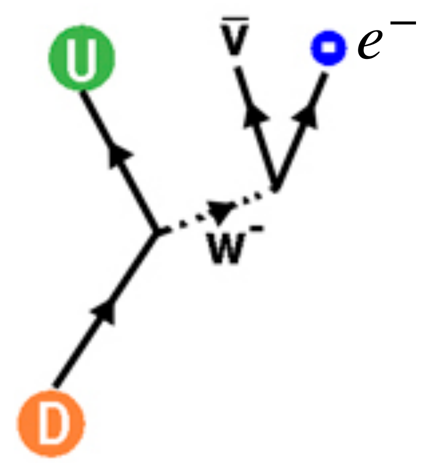


Impressive progress in collider energy, initially an order of magnitude per decade, is clearly flatlining in this century

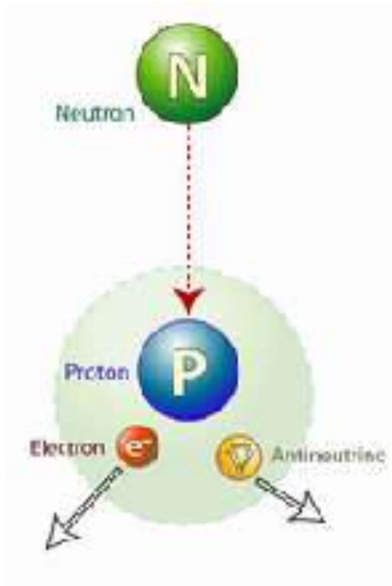
Introduction

Beta decay

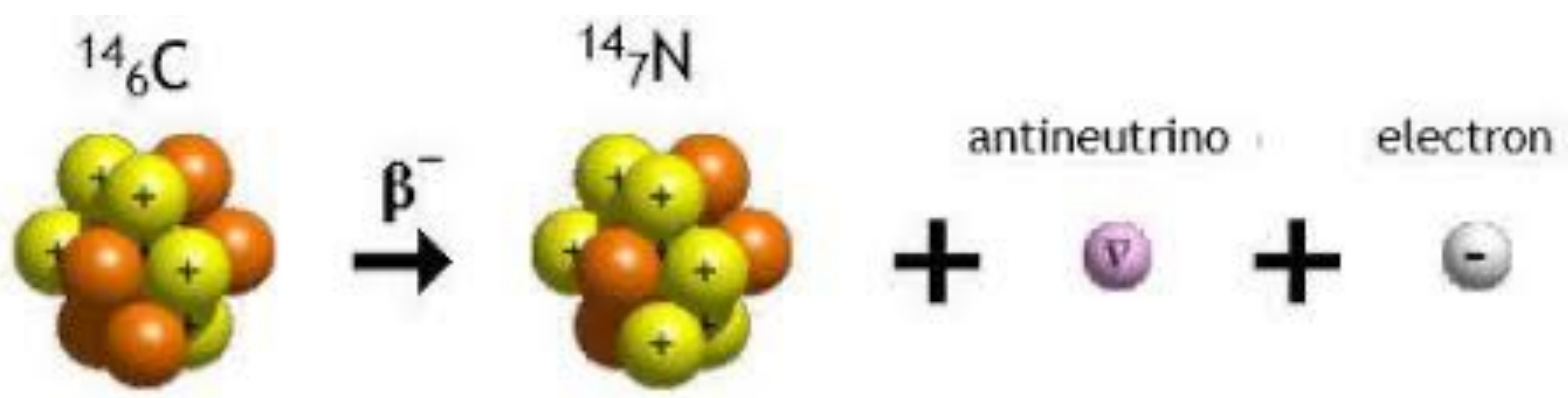
Quark level



Nucleon level



Nuclear level



Beta decay

What has beta decay 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

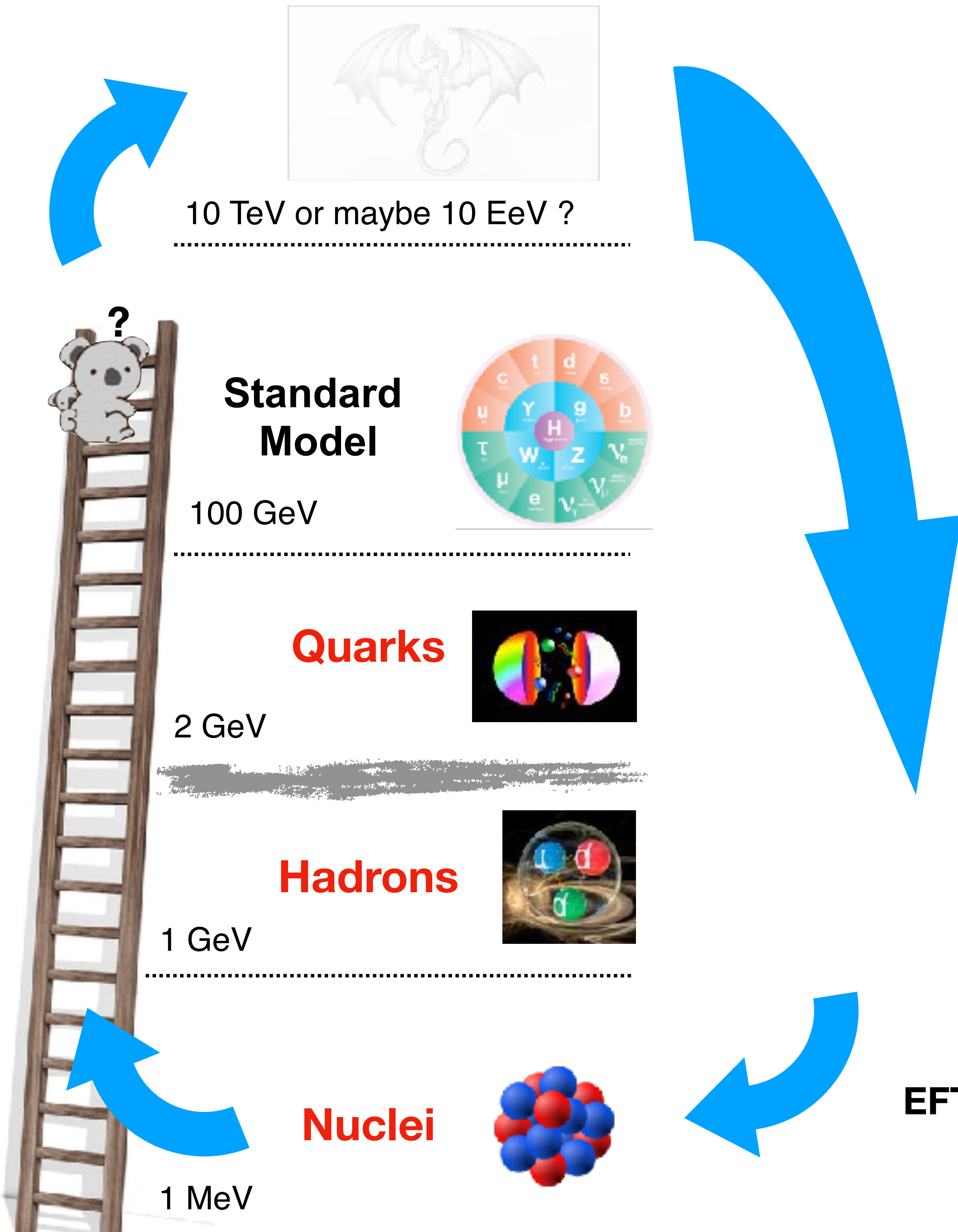
Beta decay

- 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 subleading 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**



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 for nuclear beta transitions

EFT Ladder

Connecting high-energy physics to nuclear physics via a series of effective theories

"Fundamental" BSM model

10 TeV?

EFT for SM particles

100 GeV

EFT for Light Quarks

2 GeV

EFT for Hadrons

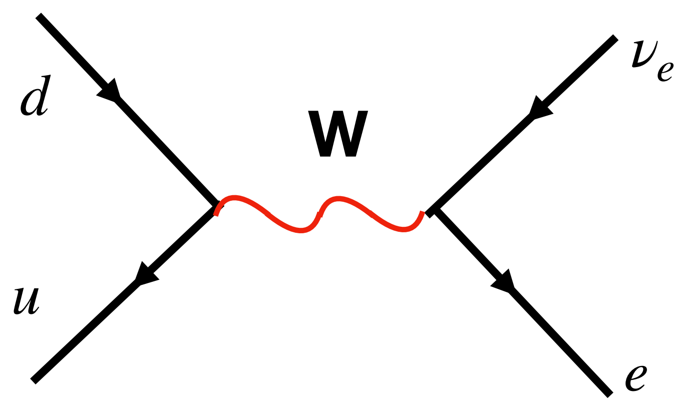
1 GeV

NR EFT for nucleons

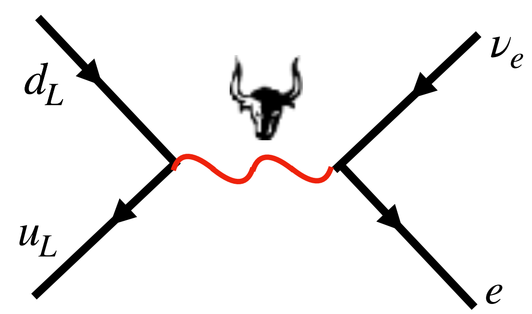
1 MeV

“Fundamental” models

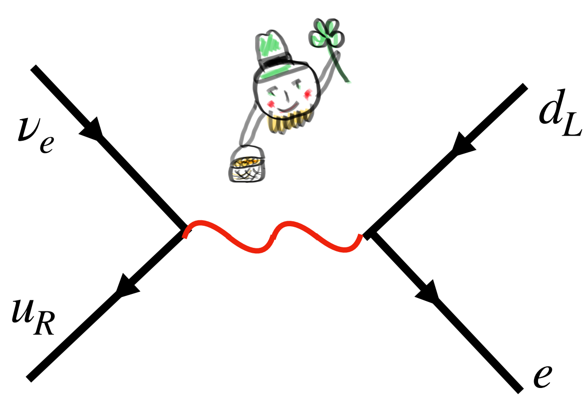
In the SM beta decay is mediated by the W boson



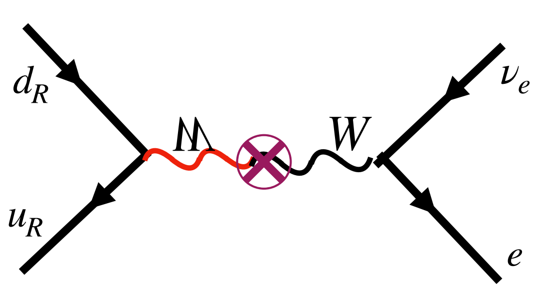
Several high-energy effects may contribute to beta decay



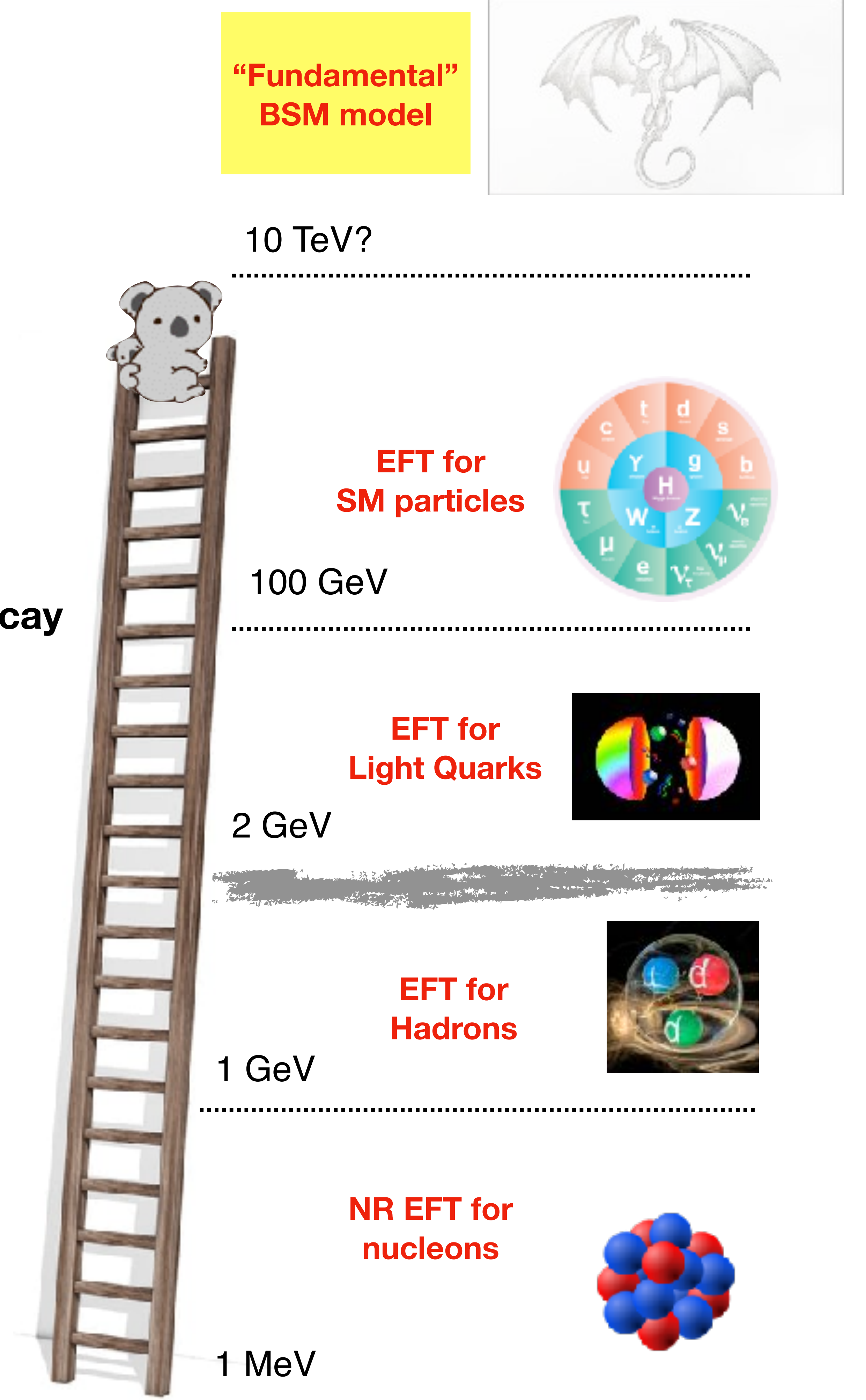
W’



Leptoquark

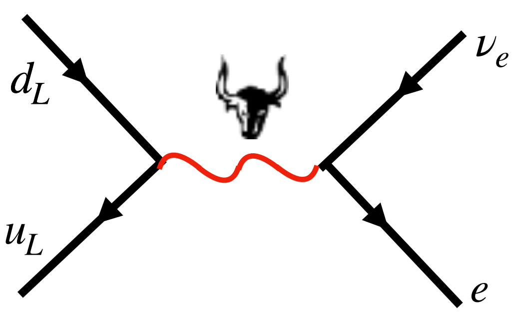


W_L-W_R mixing

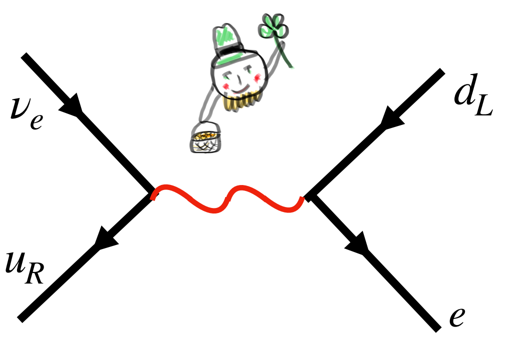


SMEFT at electroweak scale

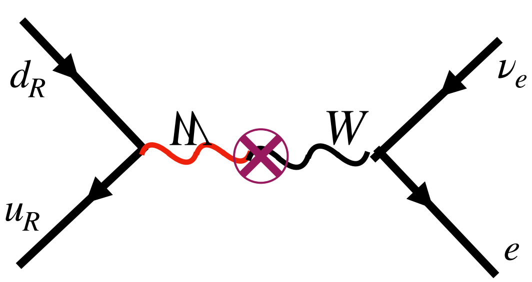
$$\mathscr{L}_{\rm SMEFT} \supset c_{HQ} H^\dagger \sigma^a D_\mu H (\bar{Q}\sigma^a\gamma_\mu Q) + c_{HL} H^\dagger \sigma^a D_\mu H (\bar{L}\sigma^a\gamma_\mu L)$$
$$+ c_{Hud} H^T D_\mu H (\bar{u}_R \gamma_\mu d_R)$$
$$+ c_{LQ} (\bar{Q}\sigma^a\gamma_\mu Q)(\bar{L}\sigma^a\gamma_\mu L) + c'_{LeQu}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



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



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



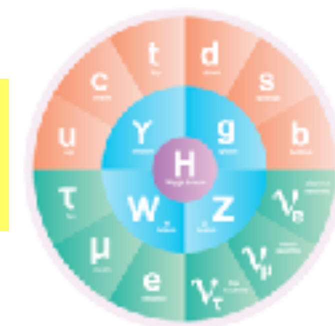
$$c_{Hud} \sim \frac{g_*^2}{M_M^2}$$

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

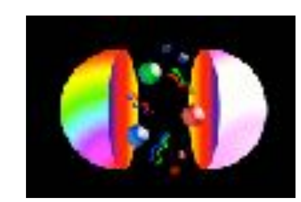
10 TeV?

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

$$
\mathscr{L}_{\rm WEFT} \supset -\frac{V_{ud}}{\mathrm{v}^2}\Big\{ (1+\epsilon_L)\ \bar{e}\gamma_\mu\nu_L \cdot \bar{u}\gamma^\mu(1-\gamma_5)d \qquad \textbf{V-A}
$$

$$
+\epsilon_R\,\bar{e}\gamma_\mu\nu_L \cdot \bar{u}\gamma^\mu(1+\gamma_5)d \qquad \textbf{V+A}
$$

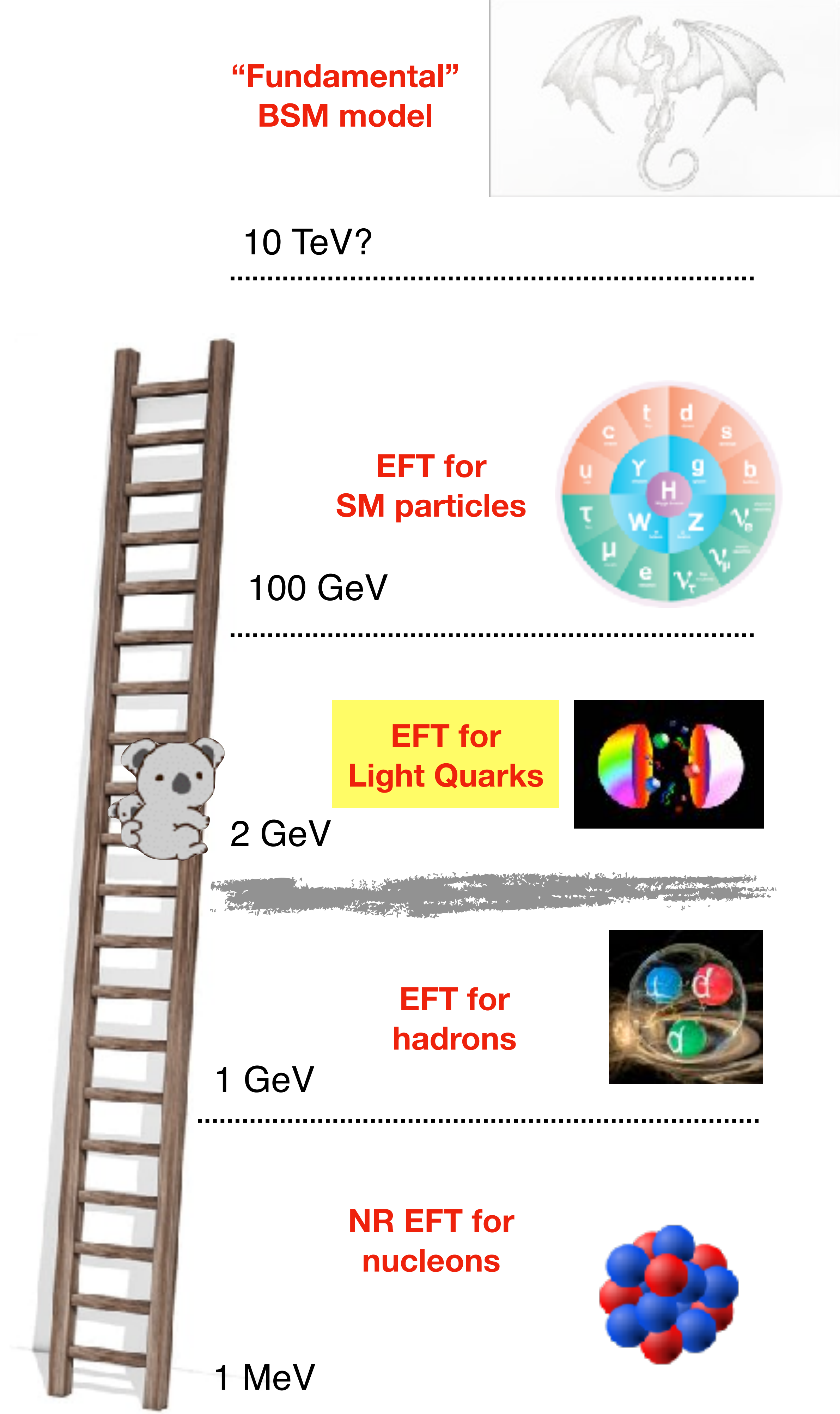
$$
+\epsilon_T\frac{1}{4}\bar{e}\sigma_{\mu\nu}\nu_L \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5)d \qquad \textbf{Tensor}
$$

$$
+\epsilon_S\,\bar{e}\nu_L \cdot \bar{u}d \qquad \textbf{Scalar}
$$

$$
-\epsilon_P\,\bar{e}\nu_L \cdot \bar{u}\gamma_5 d\Big\} \qquad \textbf{Pseudoscalar}
$$

$$
+\mathrm{hc}
$$

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



Translation from SMEFT to WEFT

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

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

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

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

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

$$\epsilon_R/\mathrm{v}^2 = \frac{1}{2V_{ud}}c_{Hud}$$

$$\epsilon_S/\mathrm{v}^2 = -\frac{1}{2V_{ud}}\left(c^*_{LeQu} + V_{ud}c^*_{LedQ}\right)$$

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

$$\epsilon_P/\mathrm{v}^2 = -\frac{1}{2V_{ud}}\left(c^*_{LeQu} - V_{ud}c^*_{LedQ}\right)$$

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

NR EFT for nucleons

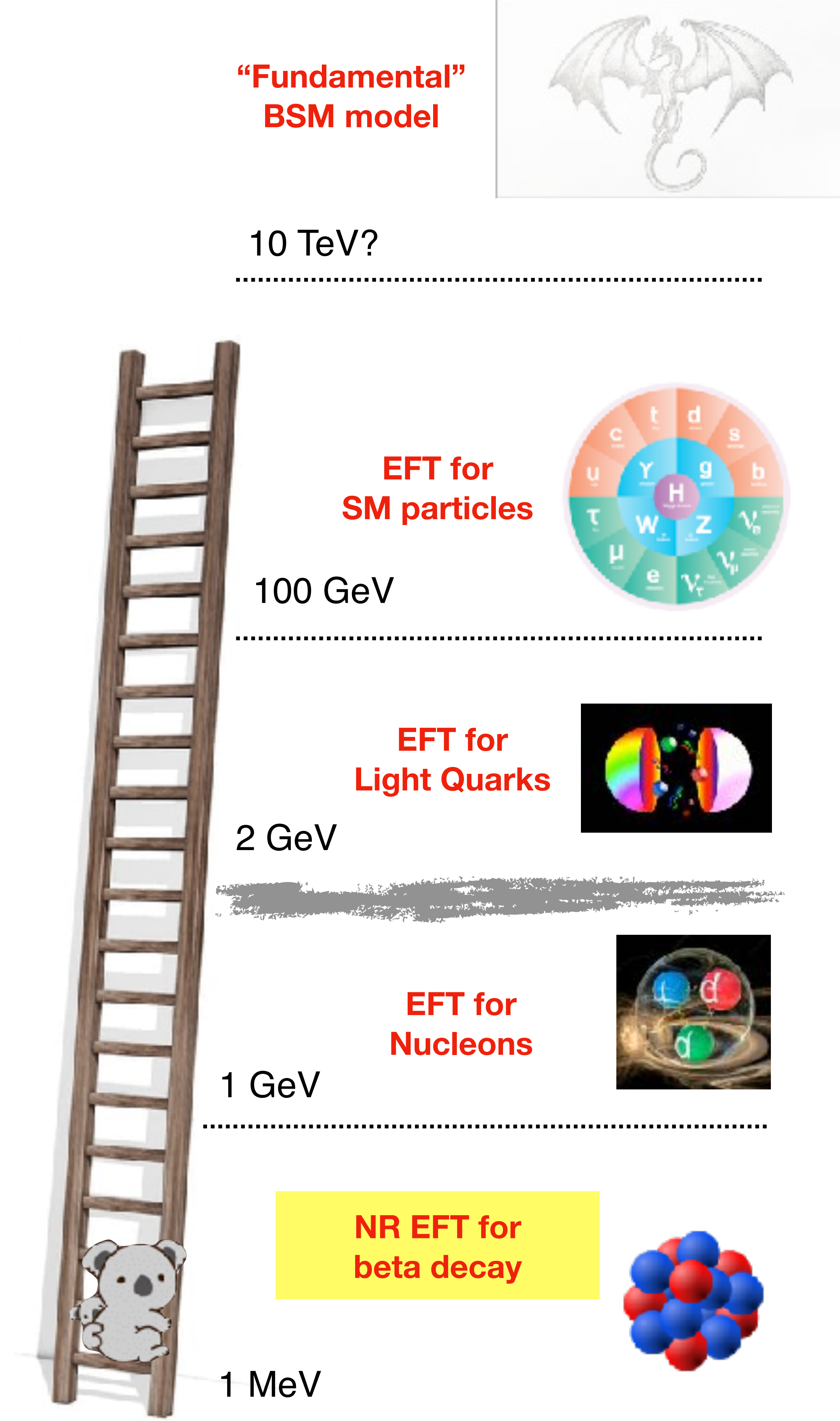
In beta decay, the momentum transfer is much smaller than the nucleon mass, due to approximate isospin symmetry leading to small mass splittings

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:

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



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 $\mathcal{N} \to \mathcal{N}' e^- \bar{\nu}$:

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

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

Fermi matrix element	**Gamow-Teller matrix element**
Calculable from group theory in the isospin limit	**Difficult to calculate from first principles**

NR EFT for nucleons

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

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Matching to quark-level EFT:

Non-zero in the SM

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

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

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

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

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

Note that pseudoscalar interactions do not enter at the leading order

Lattice + theory fix non-perturbative parameters with good precision

$$g_V \approx 1, \qquad g_A = 1.251 \pm 0.033, \qquad g_S = 1.02 \pm 0.10, \qquad g_T = 0.989 \pm 0.034$$

Ademolo, Gatto (1964)

Flag'19 N_f=2+1+1 value

Gupta et al 1806.09006

Matching also includes short-distance radiative corrections

$$\Delta_R^V = 0.02467(22)$$

Seng et al 1807.10197

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

Gorchtein Seng 2106.09185

Summary of the language

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

- We will use the non-relativistic limit of the Lee-Yang effective Lagrangian to describe nuclear beta transitions

- We will be agnostic about its Wilson coefficients, allowing all four of them to be simultaneously present in an arbitrary pattern.

- This way our results are relevant for a broad class of theories, including SM and its extensions

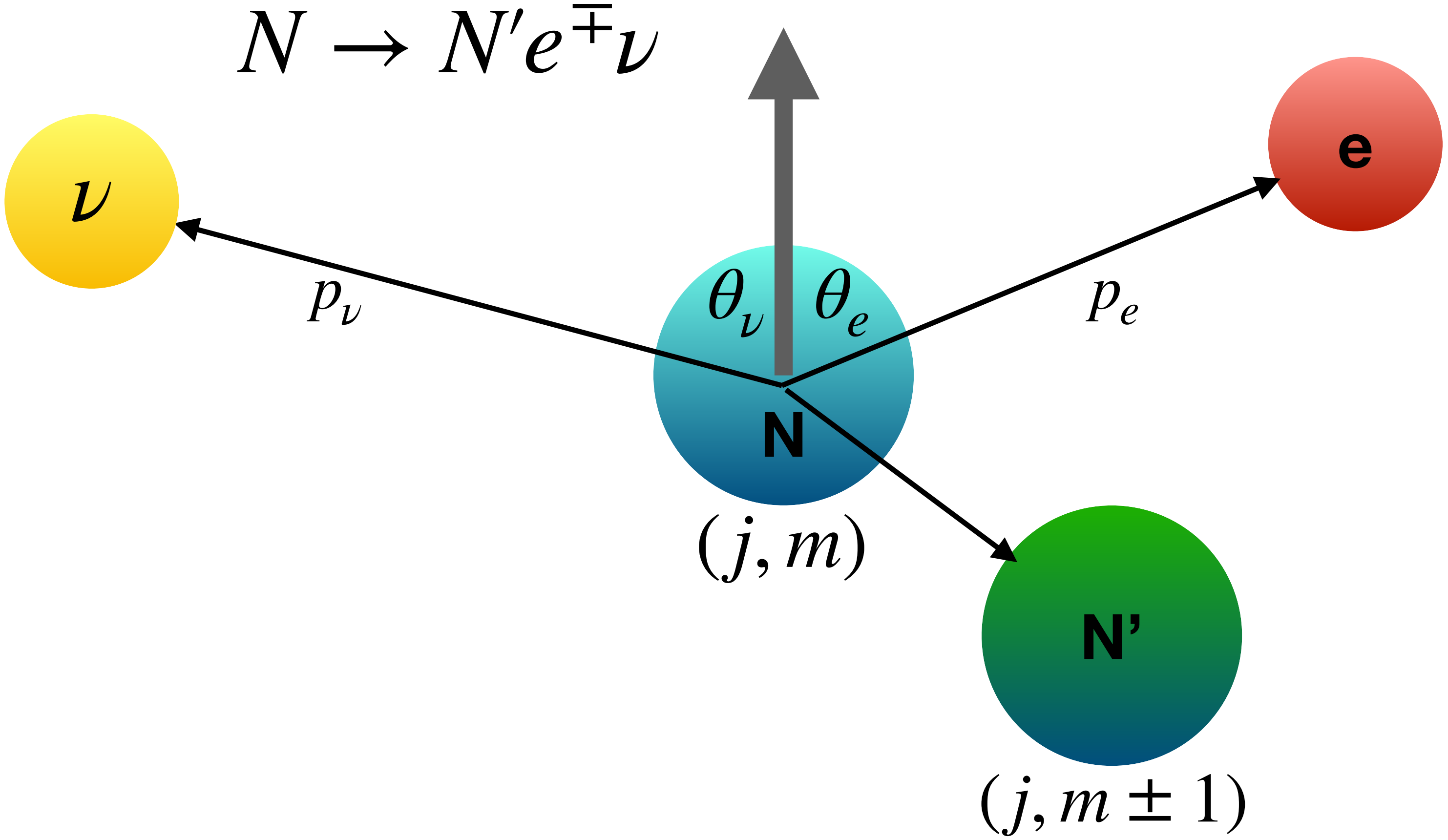
- The goal is produce the likelihood function for the 4 Wilson coefficients, based on the up-to date precision data for allowed nuclear beta transitions

- For the moment we assume, however, that the Wilson coefficients are real (most of our observables are sensitive only to absolute values anyway)

Observables for allowed beta transitions

Observables in beta decay

$$N \to N' e^{\mp} \nu$$



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:

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

No-one talks about it

Violates CP

From effective Lagrangian to observables

Jackson Treiman Wyld (1957)

Fierz term controls the shape of the beta spectrum:

$$b \times X \equiv \pm 2 \left\{ C_V^+ C_S^+ + \rho^2 \frac{(C_V^+)^2}{(C_A^+)^2} \left[C_A^+ C_T^+ \right] \right\}$$

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

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

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

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

Mixing parameter ρ
is related to the ratio of Fermi and GT matrix elements

Normalization:

$$X \equiv (C_V^+)^2 + (C_S^+)^2 + \rho^2 \frac{(C_V^+)^2}{(C_A^+)^2} \left[(C_A^+)^2 + (C_T^+)^2 \right]$$

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

Observables in beta decays

Total decay width Γ:

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

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

Some nuclear idiosyncrasy:

Half-life:

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

Half-life is very transition-dependent because the phase space integral can be vastly different because of different mass splittings

ft :

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

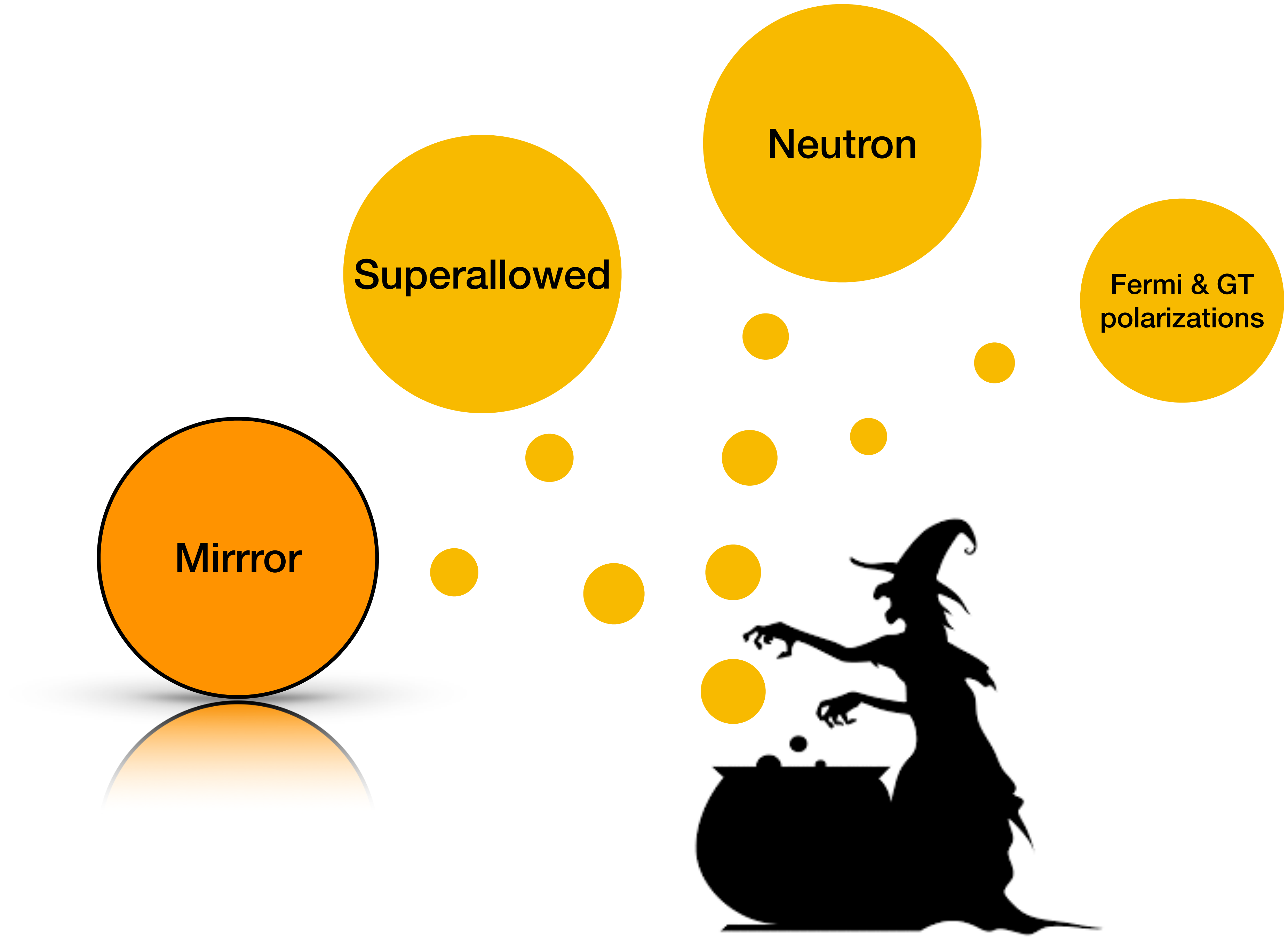
Once one reaches per-mille level measurements, it is convenient to introduce $\mathscr{F}t$ where transition-dependent radiative and nuclear corrections are also divided away

$\mathscr{F}t$:

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

Data for allowed beta transitions

Global BSM fits to beta transitions



Gonzalez-Alonso, Naviliat-Cuncic, Severijns, 1803.08732

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

Superallowed beta decay data

$0^+ \rightarrow 0^+$ 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)

$0^+ \rightarrow 0^+$ beta transitions are pure Fermi

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

$$bX \equiv \pm 2\left\{ C_V^+ C_S^+ + \cancel{\rho^2 \frac{(C_V^+)^2}{(C_A^+)^2}}\left[\cancel{C_A^+ C_T^+}\right]\right\}$$

X and b are the same for all $0^+ \rightarrow 0^+$ 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 should be the same for all superallowed 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]

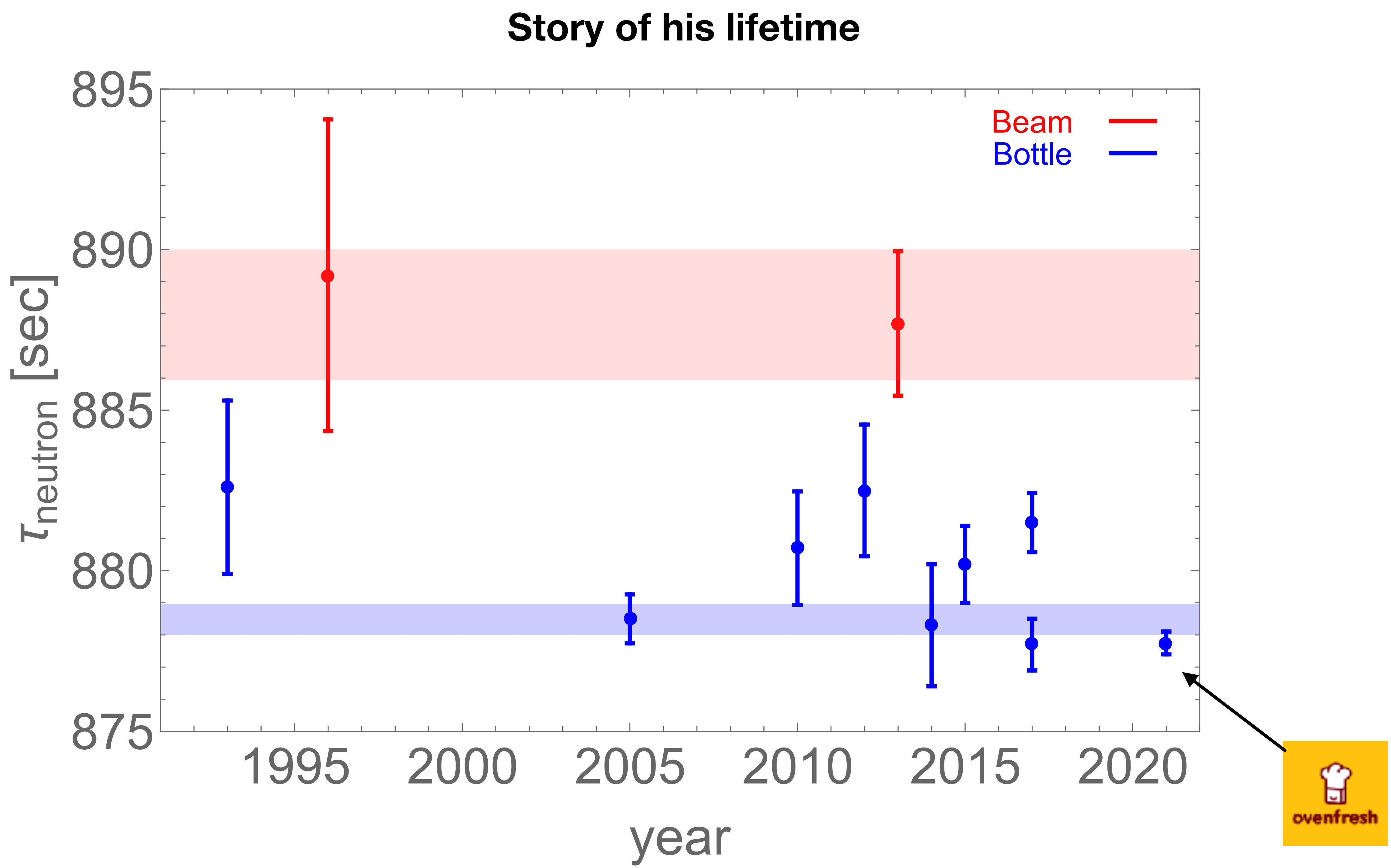
Observable	Value	$\langle m_e/E_e \rangle$	References
τ_n (s)	**878.64(59)** ~~879.75(76)~~	0.655	[52–61]
$\tilde{A}_n$	−0.11958(18)	0.569	[45, 62–66]
$\tilde{B}_n$	0.9805(30)	0.591	[67–70]
λ_{AB}	−1.2686(47)	0.581	[71]
a_n	−0.10426(82)		[46, 72, 73]
$\tilde{a}_n$	~~−0.1090(41)~~	0.695	[74]

-0.1078(20)

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

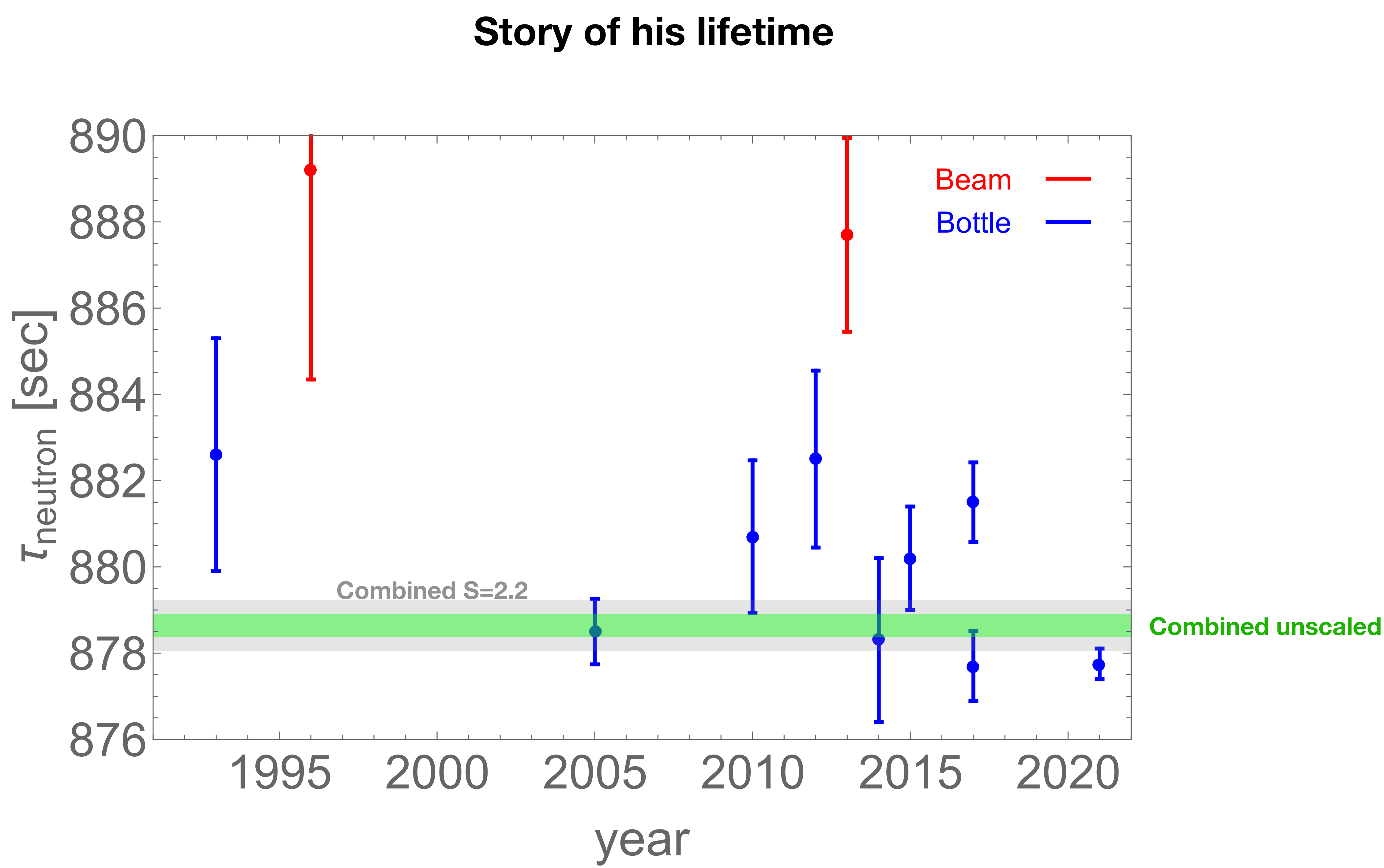
Order per-mille precision !

Neutron lifetime



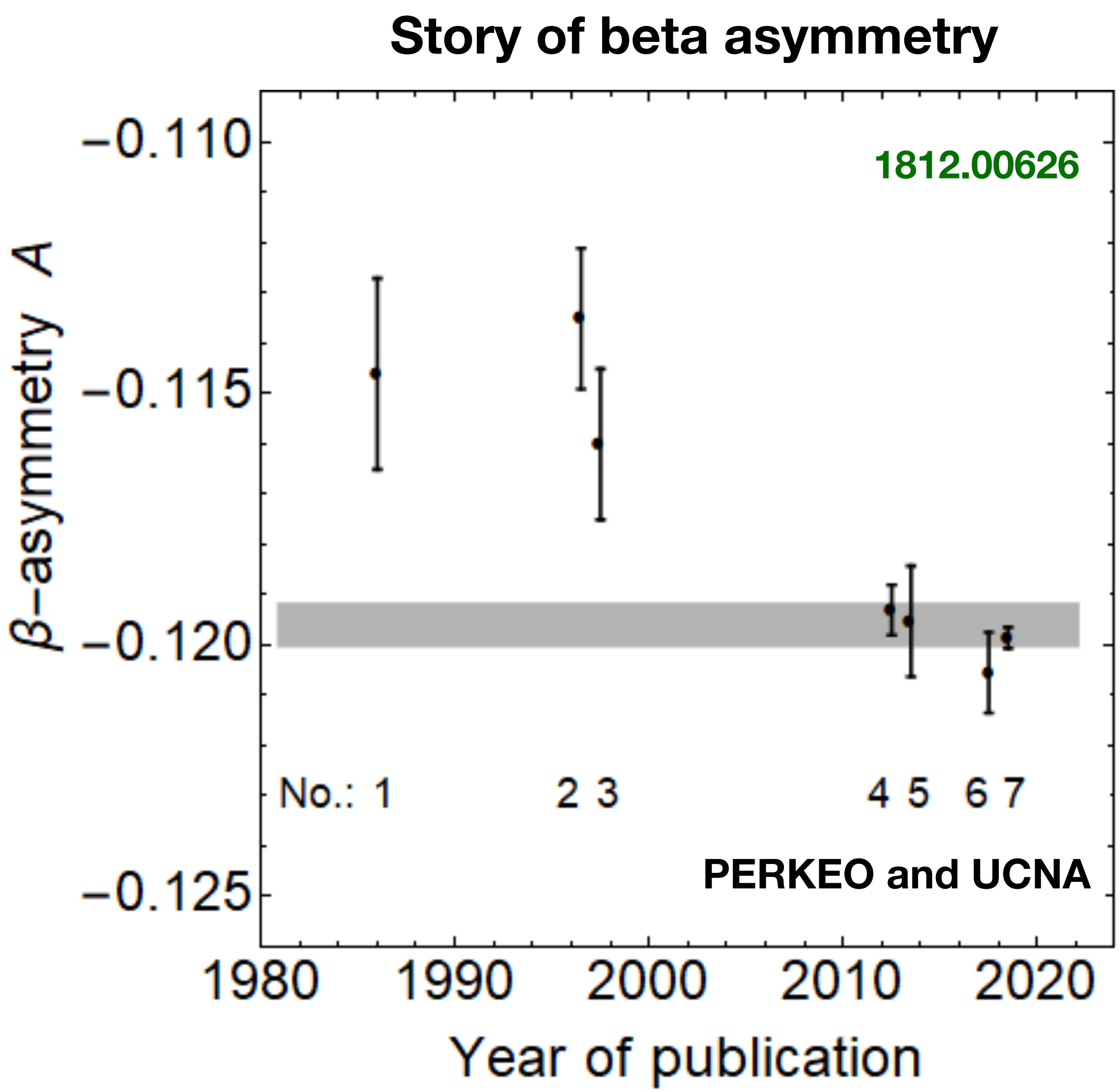
There is a large discrepancy between bottle and beam measurements of the lifetime, but also some inconsistency between different bottle measurements

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 nuclei[1)]

- These are mixed Fermi-Gamow/Teller beta transitions, thus they depend on the mixing parameter ρ

- 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

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

For mirror beta transitions

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

$$bX \equiv \pm 2\sqrt{1-(\alpha Z)^2}\left\{C_V^+C_S^+ + \rho^2\frac{(C_V^+)^2}{(C_A^+)^2}\left[C_A^+C_T^+\right]\right\}$$

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

Since we don't know the mixing parameter ρ apriori, measuring $\mathcal{F}t$ alone does not constrain fundamental parameters. Given the input from superallowed and neutron data, $\mathcal{F}t$ can be considered merely a measurement of the mixing parameter ρ 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]

[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:

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

$$\begin{pmatrix} \mathrm{v}^2 C_V^+ \\ \mathrm{v}^2 C_A^+ \\ \rho_{\mathrm{F}} \\ \rho_{\mathrm{Ne}} \\ \rho_{\mathrm{Na}} \\ \rho_{\mathrm{P}} \\ \rho_{\mathrm{Ar}} \\ \rho_{\mathrm{K}} \end{pmatrix} = \begin{pmatrix} 0.98577(22) \\ -1.25754(39) \\ -1.2958(13) \\ 1.60183(76) \\ -0.7129(11) \\ -0.5383(21) \\ -0.2838(25) \\ 0.5789(20) \end{pmatrix}$$

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

Bonus: $\mathcal{O}(10^{-3})$**-level measurements of mixing ratios** ρ

SM fit

Translation to particle physics parameters

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

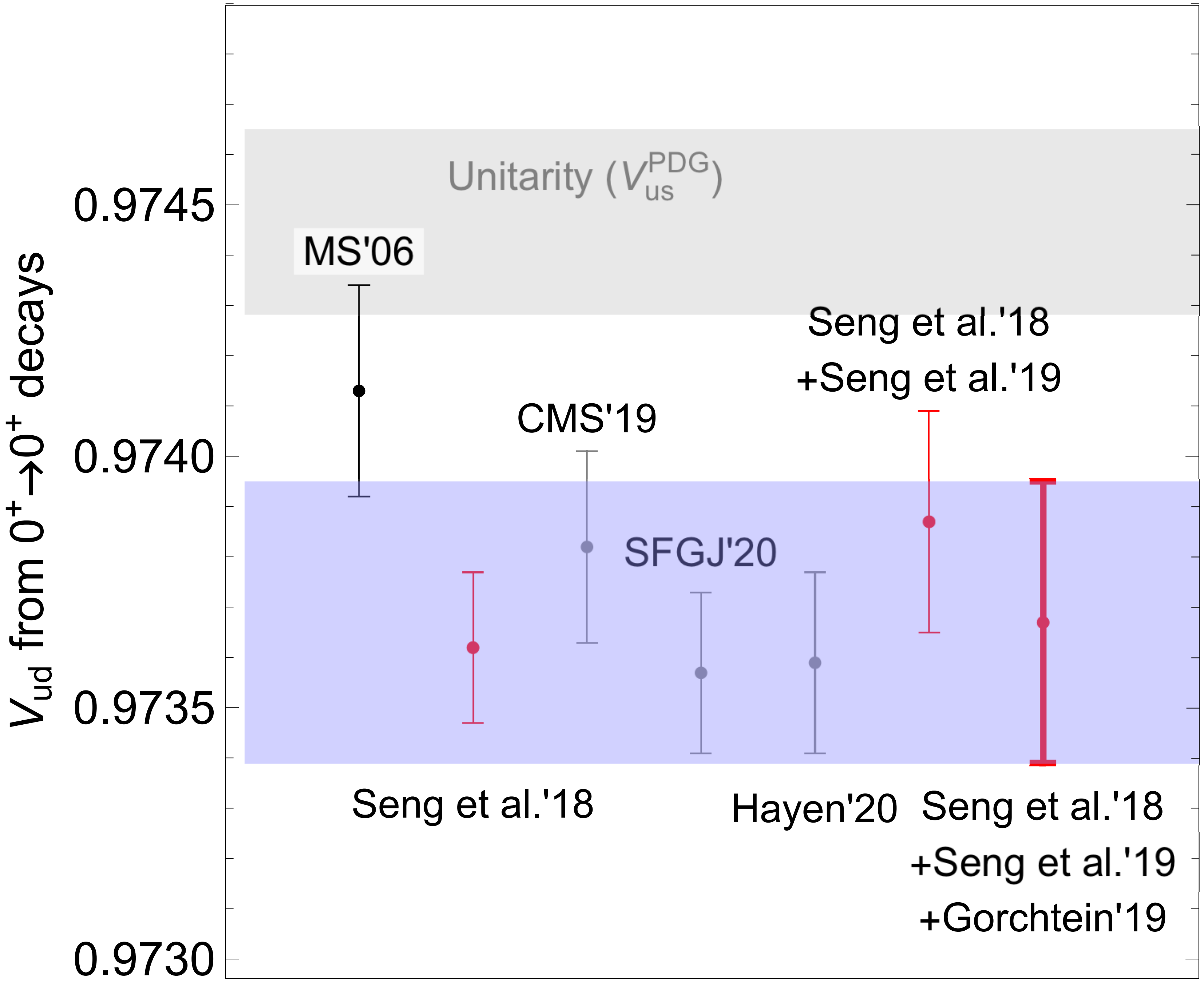
$$C_A^+ = -\frac{V_{ud}}{\mathrm{v}^2} g_A \sqrt{1 + \Delta_R^A}$$

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

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

SM fit

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

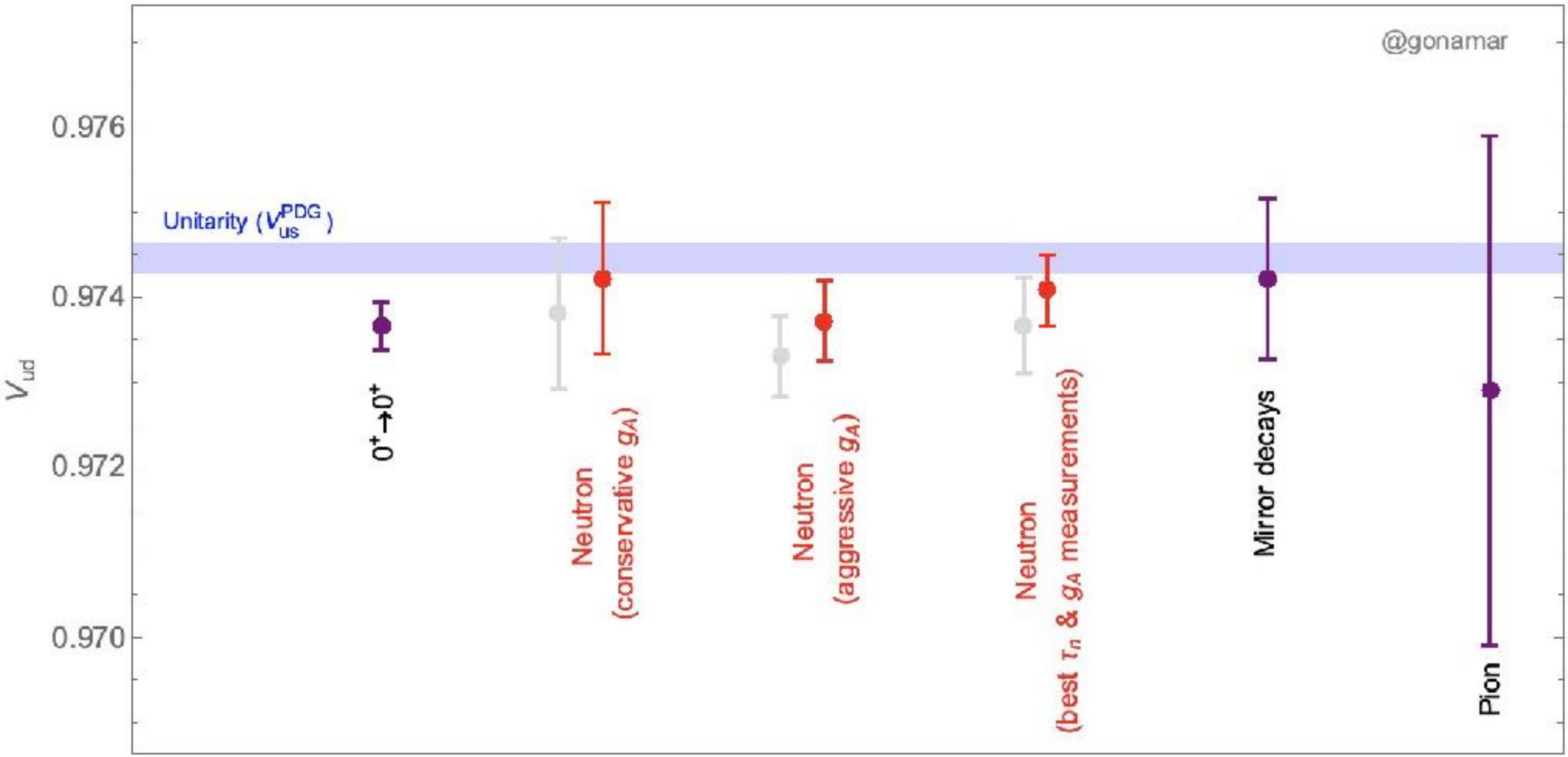


Our value
V_{ud}=0.97382(24)

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

Seng et al 1812.03352   Gorchtein 1812.04229

CKM unitarity problem



Plot from Twitter feed of Martin Gonzalez-Alonso

WEFT 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:

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

$$\mathrm{v}^2 \begin{pmatrix} C_V^+ \\ C_A^+ \\ C_S^+ \\ C_T^+ \end{pmatrix} = \begin{pmatrix} 0.98572(43) \\ -1.25736(56) \\ 0.0001(11) \\ -0.0007(12) \end{pmatrix}$$

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**

Fit also constrains mixing ratios ρ, but not displayed here to reduce clutter

WEFT fit

Translation to particle physics variables

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

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

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

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

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

Polluted CKM element

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

Polluted axial charge

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

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

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'19:

$$g_A = 1.251(33)$$

WEFT fit

Translation to particle physics variables

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

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

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

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

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

$$\hat{g}_A = g_A \frac{1+\epsilon_L-\epsilon_R}{1+\epsilon_L+\epsilon_R} \qquad g_A = 1.251(33)$$

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

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

Rescaled BSM Wilson coefficients

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

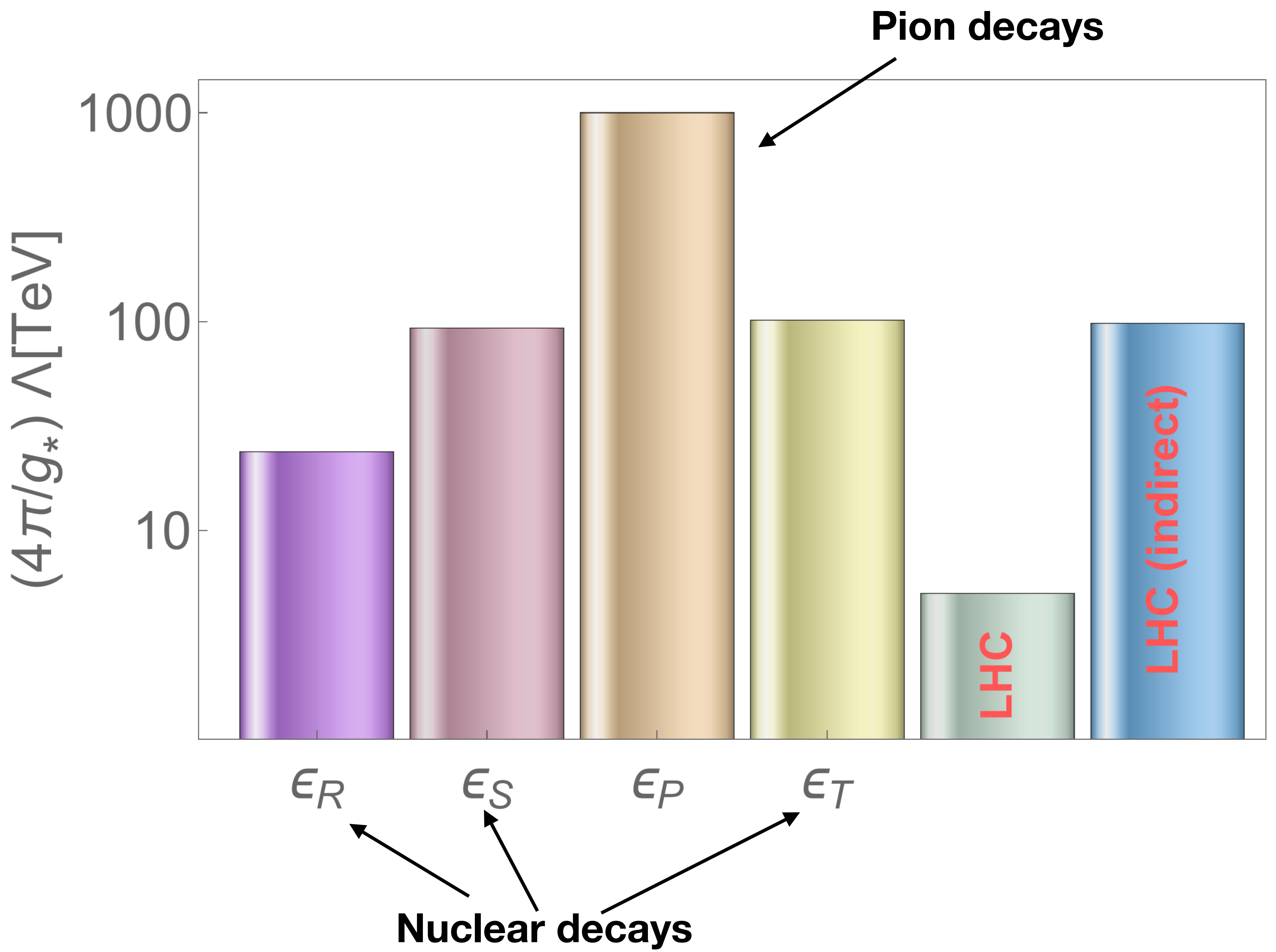
polluted CKM matrix element (in principle, can lead to apparent breakdown of CKM unitarity)

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!

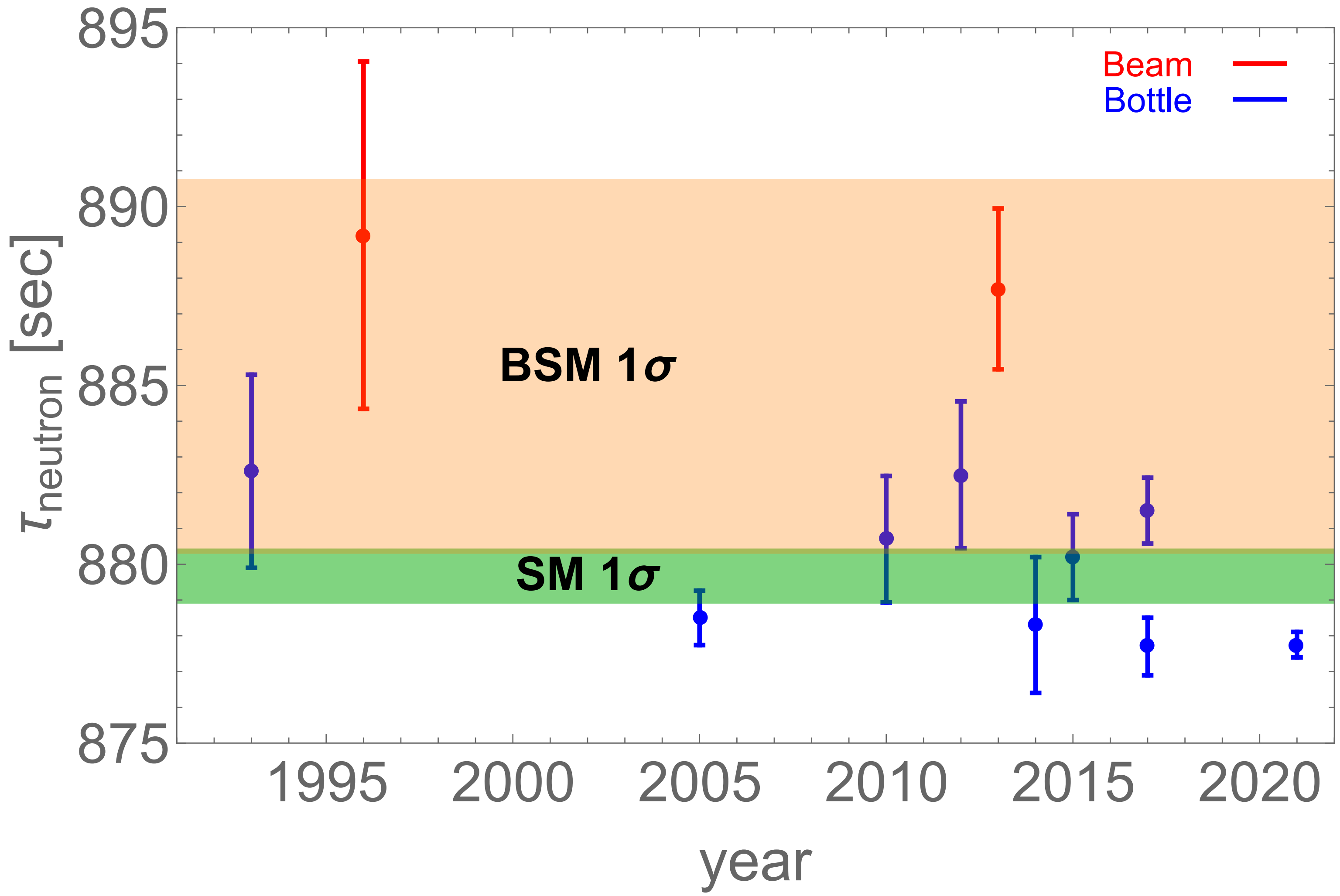
New physics reach of beta decays

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

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!

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

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

The coefficients of the subleading EFT Lagrangian can also be determined from the data!

Example: constraining pseudoscalar interactions

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

$$
\mathrm{v}^2\begin{pmatrix} C_V^+ \\ C_A^+ \\ C_S^+ \\ C_T^+ \\ C_P^+ \end{pmatrix} = \begin{pmatrix} 0.98545(48) \\ -1.25800(75) \\ -0.0004(12) \\ 0.0005(15) \\ -5.2(4.1) \end{pmatrix}
$$

$$
\begin{pmatrix} \epsilon_S \\ \epsilon_T \\ \epsilon_R \\ \epsilon_P \end{pmatrix} = \begin{pmatrix} -0.0004(12) \\ -0.0005(16) \\ -0.008(13) \\ -0.015(12) \end{pmatrix}
$$

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

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

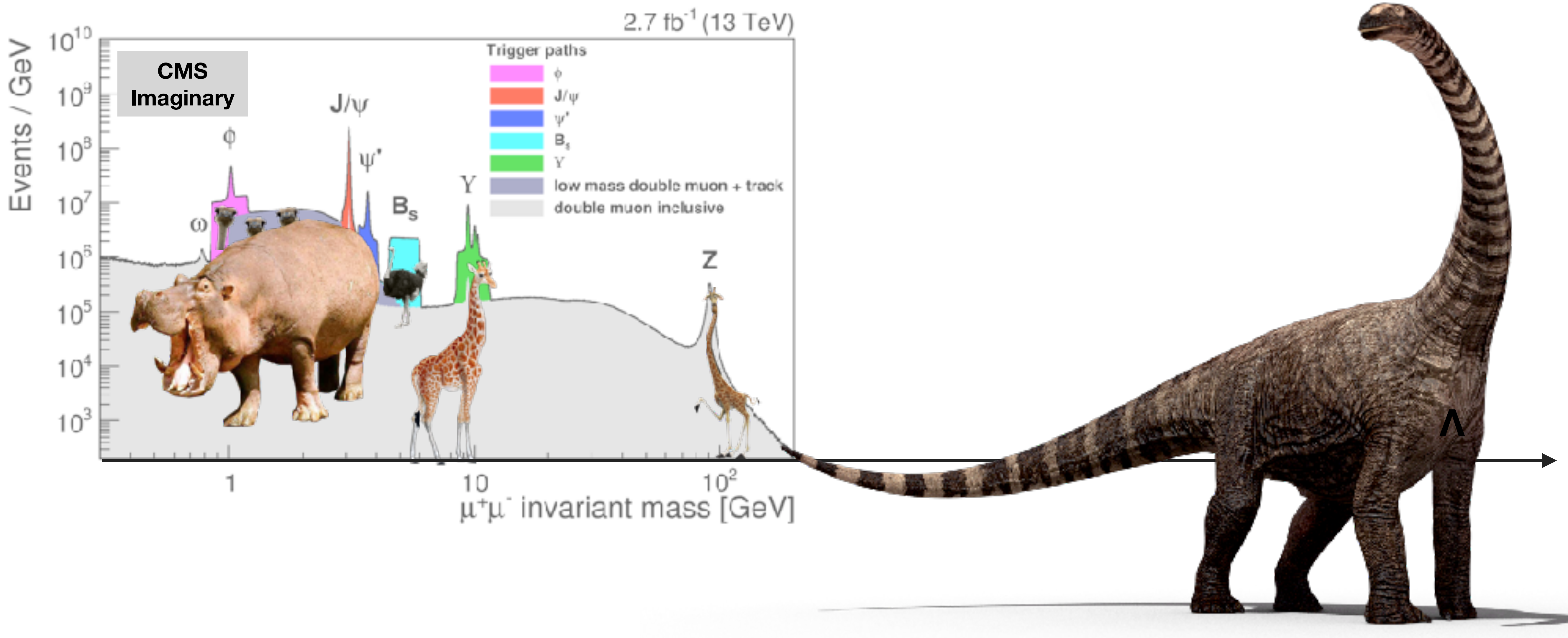
$$
\mathrm{v}^2\begin{pmatrix} C_V^+ \\ C_A^+ \\ C_M \end{pmatrix} = \begin{pmatrix} 0.98569(24) \\ -1.25779(48) \\ 3.82(87) \end{pmatrix}
$$

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

Fantastic Beasts and Where To Find Them



THANK YOU