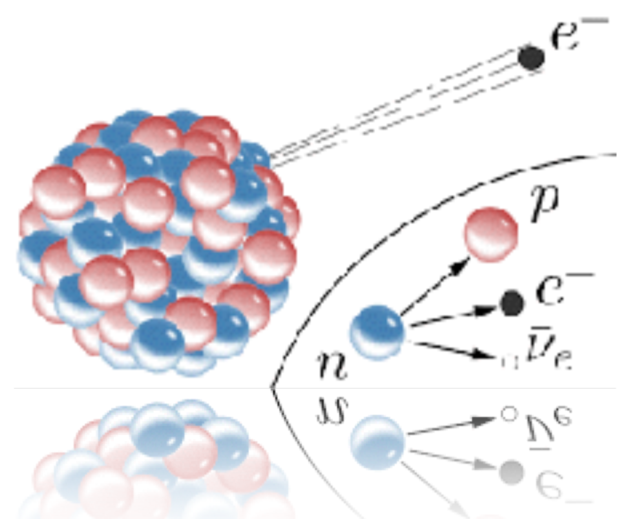
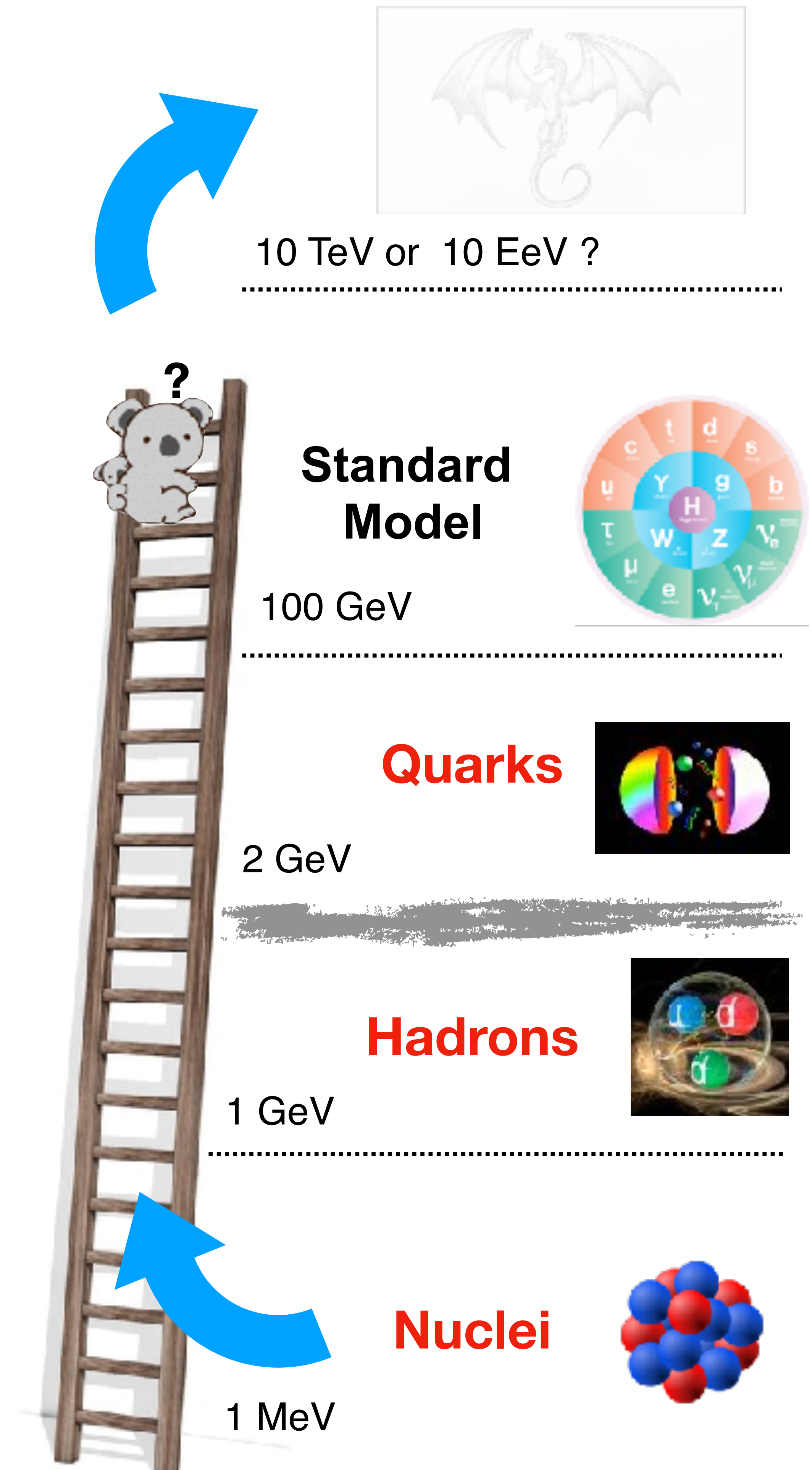
Adam Falkowski

Constraints on new physics from nuclear beta transitions

Free Meson Seminar, Tata Institute for Fundamental Research,
25 February 2021



based on [arXiv:2010.13797] with Martin Gonzalez-Alonso and Oscar Naviliat-Cuncic



Properties of new particles beyond the Standard Model can be related to parameters of the effective Lagrangian describing low-energy interactions between nucleons, electrons, and neutrinos

Effective weak interactions for nucleons

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

All these parameters can be precisely measured in nuclear beta transitions

Language for nuclear beta transitions

Language

- Nuclear beta decays probe different aspects of how first generation quarks and leptons interact with each other

- Possible to perform model-dependent studies using popular benchmark models with heavy particles (SUSY, composite Higgs, extra dimensions) or light particles (axions, dark photons)

- Efficient and model-independent description can be developed under assumption that no non-SM degrees of freedom are produced on-shell in a given experiment. This leads to the universal language of **effective field theories**

EFT Ladder

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

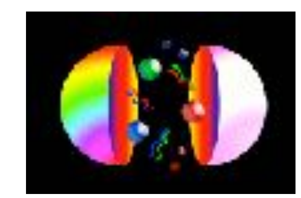
"Fundamental" BSM model

10 TeV?

EFT for SM particles

100 GeV

EFT for Light Quarks



2 GeV

EFT for Nucleons

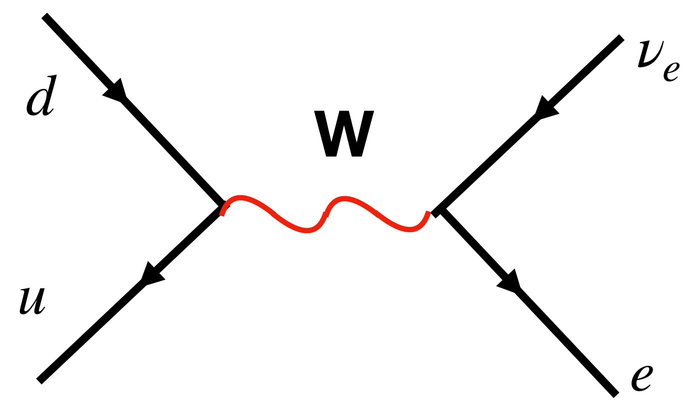
1 GeV

Effective description of nuclear observables

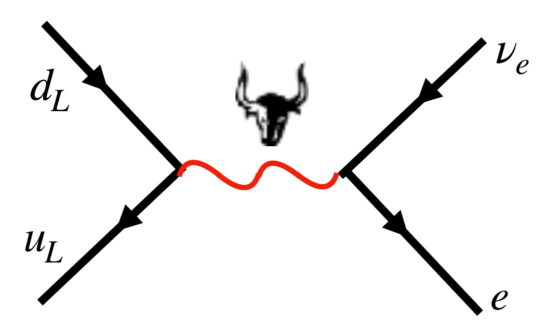
1 MeV

“Fundamental” models

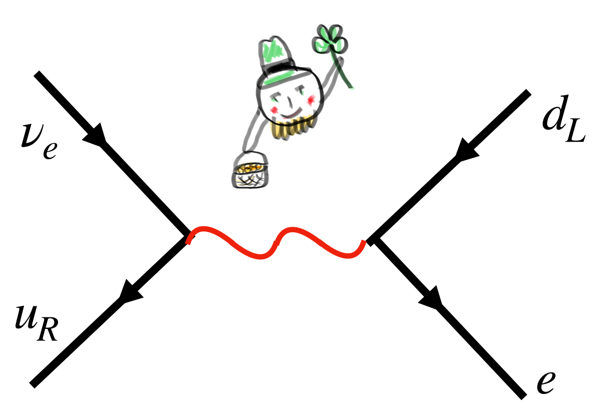
In the SM beta decay is mediated by the W boson



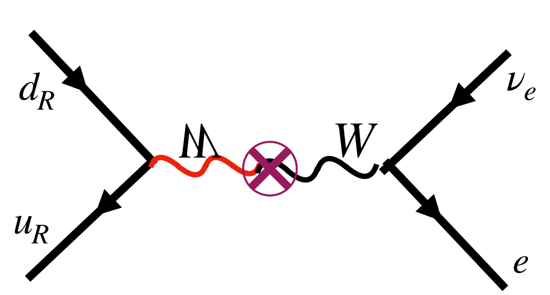
Several high-energy effects may contribute to beta decay



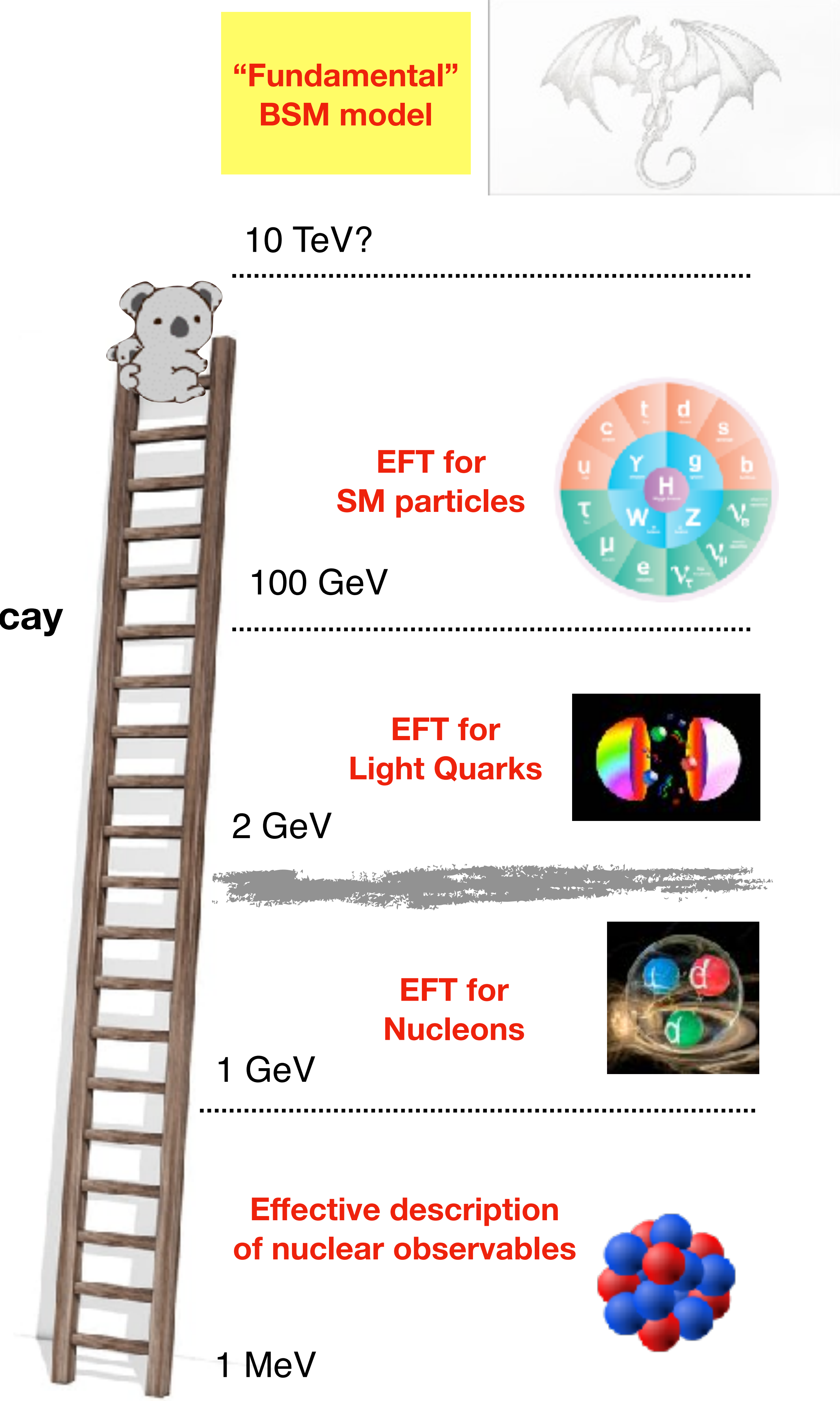
W’



Leptoquark

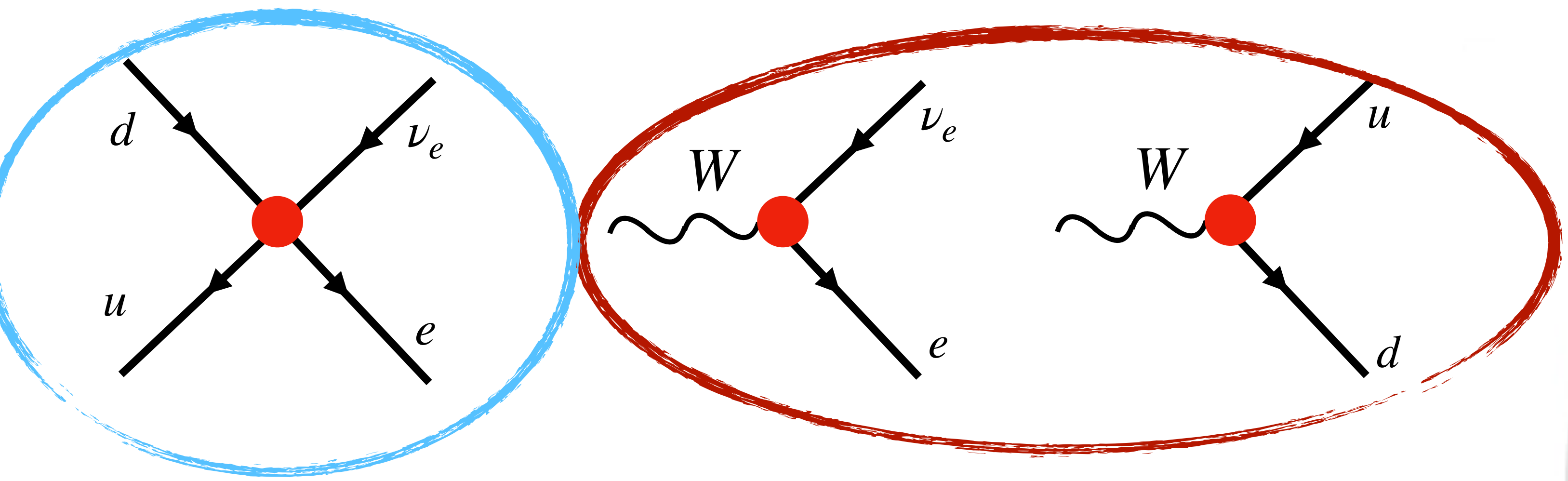


W_L-W_R mixing

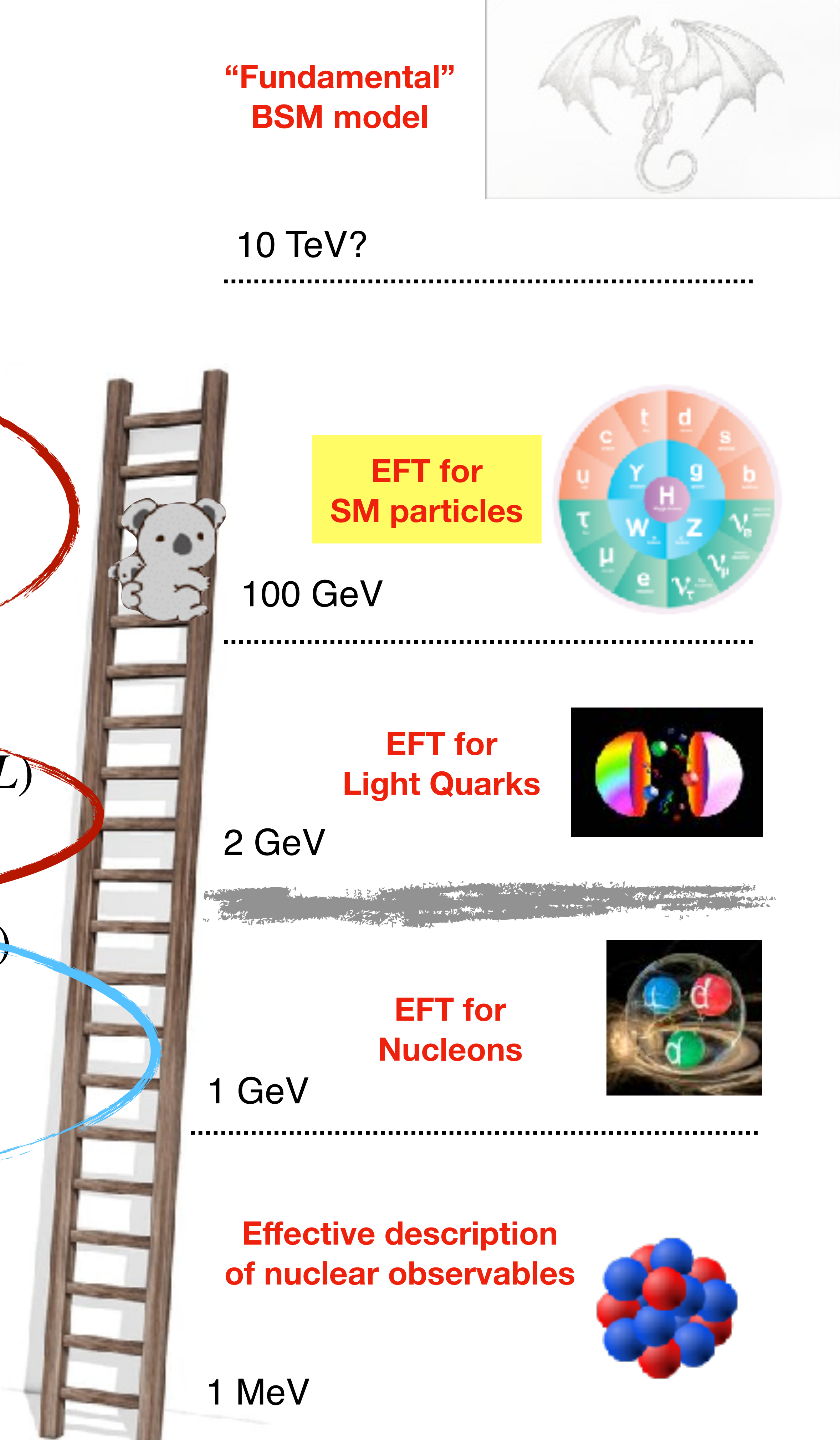


EFT at electroweak scale

At the electroweak scale, these effects can be approximated by gauge invariant operators describing contact 4-fermion interactions or modified W boson couplings to quarks and leptons

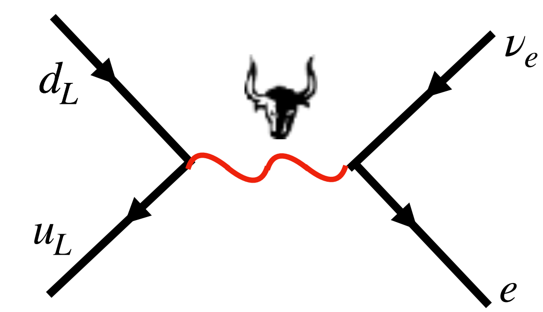


$$
\begin{aligned}
\mathscr{L}_{\rm EFT} \supset\ & c_{HQ} H^\dagger \sigma^a D_\mu H (\bar{Q} \sigma^a \gamma_\mu Q) + c_{HL} H^\dagger \sigma^a D_\mu H (\bar{L} \sigma^a \gamma_\mu L) \\
& + c_{Hud} H^T D_\mu H (\bar{u}_R \gamma_\mu d_R) + \tilde{c}_{Hud} H^T D_\mu H (\bar{\nu}_R \gamma_\mu e_R) \\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

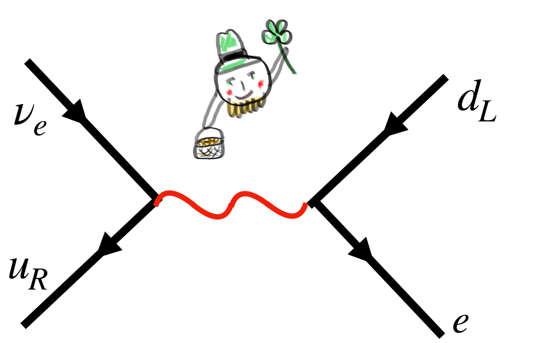


EFT at electroweak scale

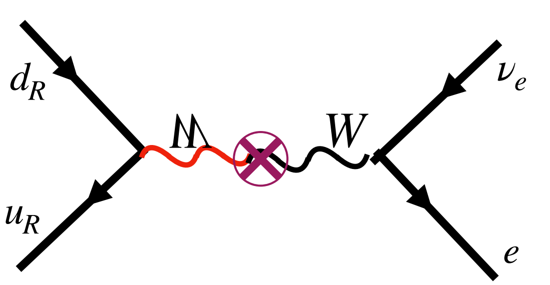
$$\mathscr{L}_{\rm EFT} \supset c_{HQ} H^\dagger \sigma^a D_\mu H (\bar{Q}\sigma^a \gamma_\mu Q) + c_{HL} H^\dagger \sigma^a D_\mu H (\bar{L}\sigma^a \gamma_\mu L)$$
$$+ c_{Hud} H^T D_\mu H (\bar{u}_R \gamma_\mu d_R) + \tilde{c}_{Hud} H^T D_\mu H (\bar{\nu}_R \gamma_\mu e_R)$$
$$+ c_{LQ} (\bar{Q}\sigma^a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



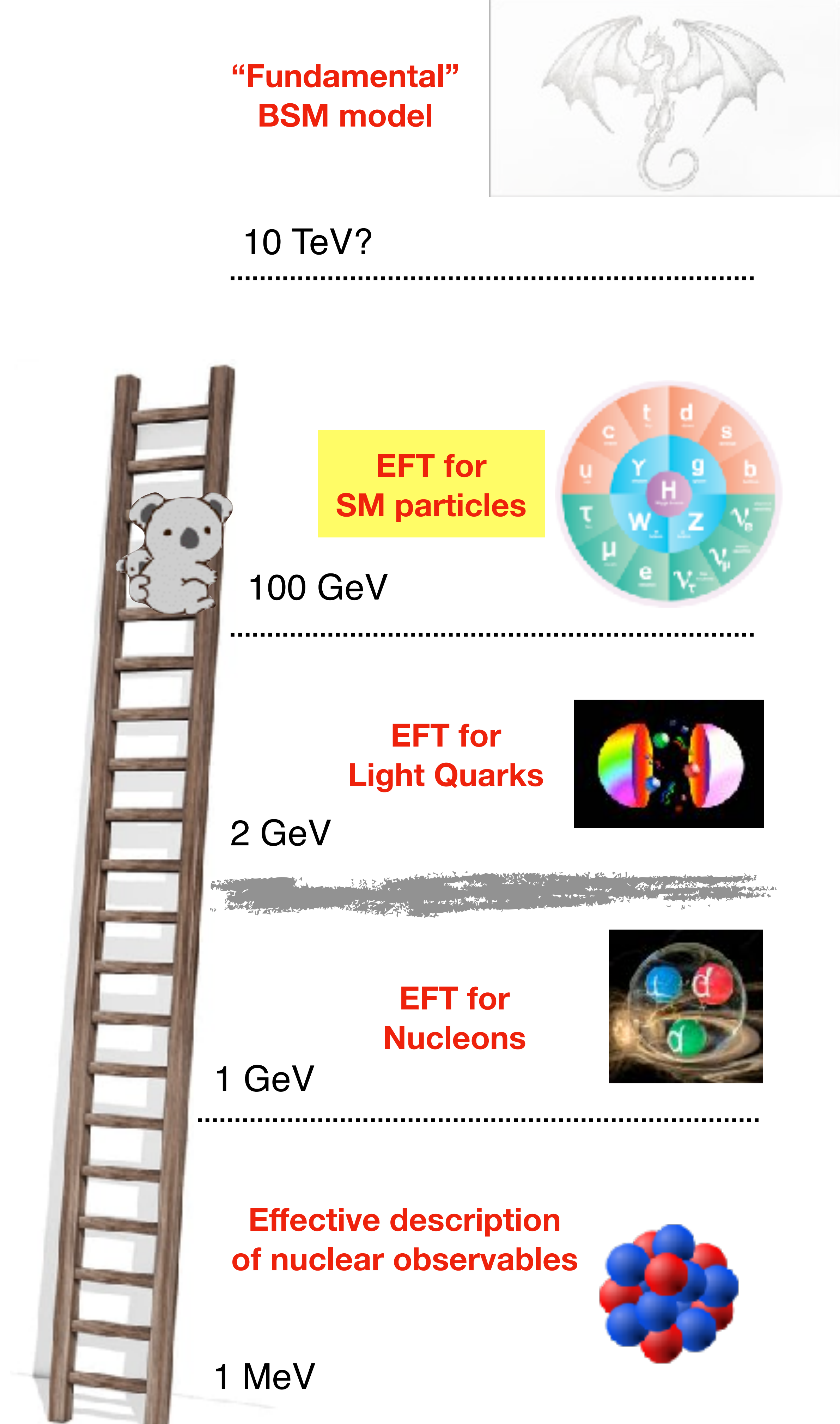
$$c_{LQ} \sim \frac{g_*^2}{M_{W'}^2}$$



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



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



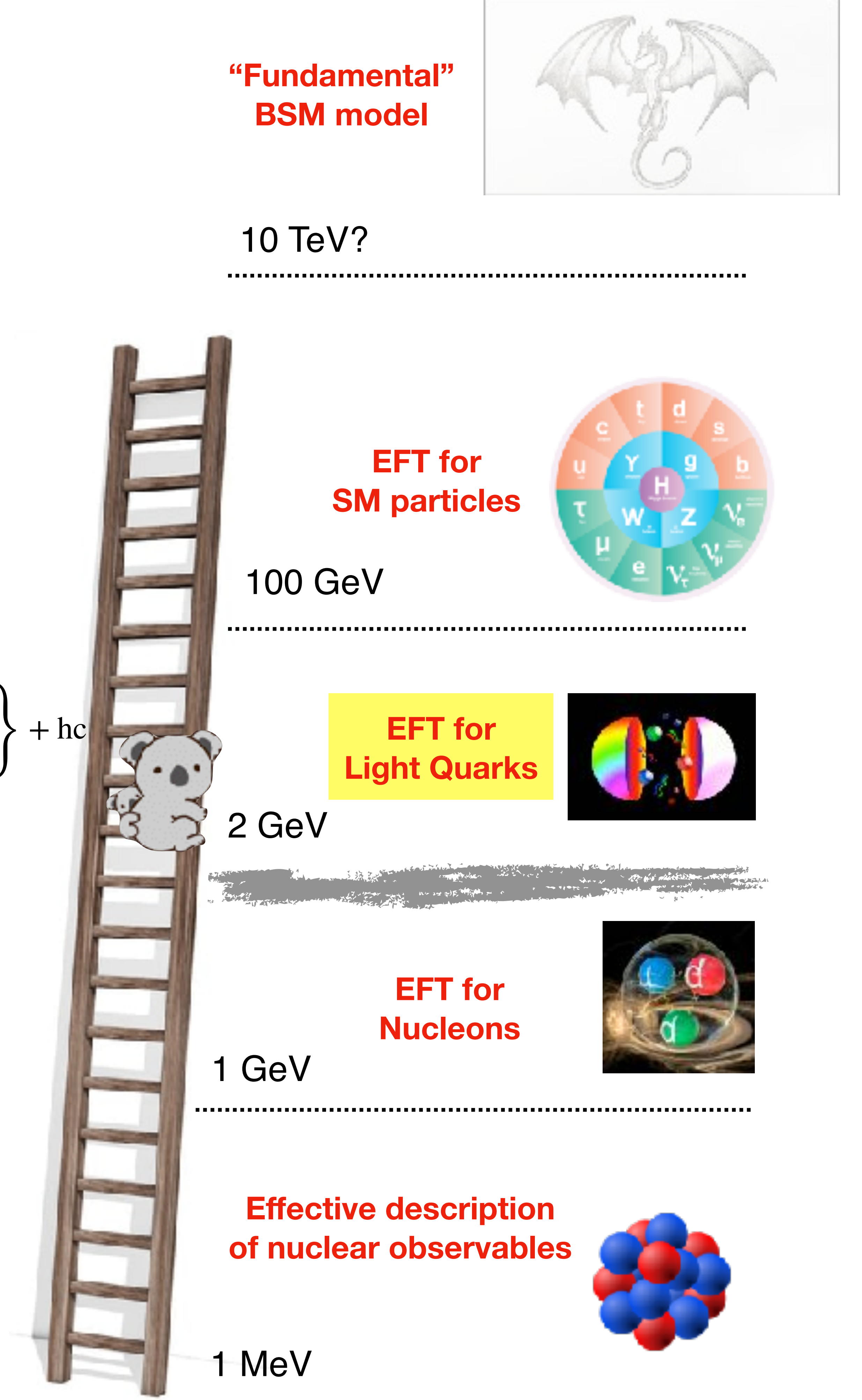
For any "fundamental" model, the Wilson coefficients c_i can be calculated in terms of masses and couplings of new particles at the high-scale

EFT 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

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

Much simplified description, only 10 (in principle complex) parameters at leading order



Translation from low-to-high energy EFT

Assuming lack of right-handed neutrinos, the EFT below the weak scale (WEFT) can be matched to the EFT above the weak scale (SMEFT)

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

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

At the scale mz, WEFT parameters ϵ_X map to dimension-6 operators in the SMEFT

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

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

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

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

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

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

More generally, the low-energy theory can be matched to RSMEFT

Quark level effective Lagrangian

Effective Lagrangian defined at a low scale μ ~ 2 GeV

	Left-handed neutrino	Right-handed neutrino	
	$\mathscr{L} \supset -\frac{V_{ud}}{\mathrm{v}^2}\Big\{ \left(1+\epsilon_L\right)\ \bar{e}\gamma_\mu\nu_L\cdot\bar{u}\gamma^\mu(1-\gamma_5)d$	$+\ \tilde{\epsilon}_L\,\bar{e}\gamma_\mu\nu_R\cdot\bar{u}\gamma^\mu(1-\gamma_5)d$	**V-A**
	$+\epsilon_R\,\bar{e}\gamma_\mu\nu_L\cdot\bar{u}\gamma^\mu(1+\gamma_5)d$	$+\ \tilde{\epsilon}_R\,\bar{e}\gamma_\mu\nu_R\cdot\bar{u}\gamma^\mu(1+\gamma_5)d$	**V+A**
	$+\epsilon_T\frac{1}{4}\bar{e}\sigma_{\mu\nu}\nu_L\cdot\bar{u}\sigma^{\mu\nu}(1-\gamma_5)d$	$+\ \tilde{\epsilon}_T\frac{1}{4}\bar{e}\sigma_{\mu\nu}\nu_R\cdot\bar{u}\sigma^{\mu\nu}(1+\gamma_5)d$	**Tensor**
	$+\epsilon_S\,\bar{e}\nu_L\cdot\bar{u}d$	$+\ \tilde{\epsilon}_S\,\bar{e}(1+\gamma_5)\nu_R\cdot\bar{u}d$	**Scalar**
Pseudo-scalar	$-\epsilon_P\,\bar{e}\nu_L\cdot\bar{u}\gamma_5 d$	$-\ \tilde{\epsilon}_P\bar{e}\nu_R\cdot\bar{u}\gamma_5 d\Big\} + \mathrm{h.c.}$	

CKM element

Normalization scale, set by Fermi constant

$$\mathrm{v} = \frac{1}{\sqrt{\sqrt{2}G_F}} \approx 246\ \mathrm{GeV}$$

The Wilson coefficients of this EFT can be connected, to the Wilson coefficients above the electroweak scale, and consequently to masses and couplings of new heavy particles at the scale M :

$$\epsilon_X, \tilde{\epsilon}_X \sim \mathrm{v}^2 c_i \sim g_*^2\frac{\mathrm{v}^2}{M^2}$$

EFT for nucleons

Below the QCD scale there is no quarks.
The relevant degrees of freedom are instead <u>nucleons</u>

Leading order EFT described by the Lee-Yang Lagrangian

$$
\begin{aligned}
\mathcal{L}_{\mathrm{EFT}} \supset & -\bar{p}\gamma^{\mu}n\left(C_V^{+}\bar{e}\gamma_{\mu}\nu_L + C_V^{-}\bar{e}\gamma_{\mu}\nu_R\right) \\
& -\bar{p}\gamma^{\mu}\gamma_5 n\left(C_A^{+}\bar{e}\gamma_{\mu}\nu_L - C_A^{-}\bar{e}\gamma_{\mu}\nu_R\right) \\
& -\bar{p}n\left(C_S^{+}\bar{e}\nu_L + C_S^{-}\bar{e}\nu_R\right) \\
& -\frac{1}{2}\bar{p}\sigma^{\mu\nu}n\left(C_T^{+}\bar{e}\sigma_{\mu\nu}\nu_L + C_T^{-}\bar{e}\sigma_{\mu\nu}\nu_R\right) \\
& +\bar{p}\gamma_5 n\left(C_P^{+}\bar{e}\nu_L - C_P^{-}\bar{e}\nu_R\right) + \mathrm{hc}
\end{aligned}
$$

T.D. Lee and C.N. Yang (1956)

Again, 10 (in principle complex) parameters
at leading order to describe physics of beta decays

<u>Nuclear physics experiments</u>
measure the Wilson coefficients $C_X^{+/-}$

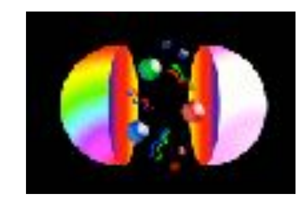
"Fundamental" BSM model

10 TeV?

EFT for SM particles

100 GeV

EFT for Light Quarks



2 GeV

EFT for Nucleons

1 GeV

Effective description of nuclear observables

1 MeV

Translation from nuclear to particle physics

Non-zero in the SM

$$C_V^+ = \frac{V_{ud}}{v^2} g_V \sqrt{1+\Delta_R^V}\left(1+\epsilon_L+\epsilon_R\right) \qquad C_V^- = \frac{V_{ud}}{v^2} g_V \sqrt{1+\Delta_R^V}\left(\tilde{\epsilon}_L+\tilde{\epsilon}_R\right)$$

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

$$C_T^+ = \frac{V_{ud}}{v^2} g_T \epsilon_T \qquad C_T^- = \frac{V_{ud}}{v^2} g_T \tilde{\epsilon}_T$$

$$C_S^+ = \frac{V_{ud}}{v^2} g_S \epsilon_S \qquad C_S^- = \frac{V_{ud}}{v^2} g_S \tilde{\epsilon}_S$$

$$C_P^+ = \frac{V_{ud}}{v^2} g_P \epsilon_P \qquad C_P^- = -\frac{V_{ud}}{v^2} g_P \tilde{\epsilon}_P$$

$$\begin{aligned}
\mathscr{L}_{\rm EFT} \supset & -\bar{p}\gamma^\mu n\left(C_V^+ \bar{e}\gamma_\mu \nu_L \quad + C_V^- \bar{e}\gamma_\mu \nu_R\right) \\
& -\bar{p}\gamma^\mu \gamma_5 n\left(C_A^+ \bar{e}\gamma_\mu \nu_L \quad - C_A^- \bar{e}\gamma_\mu \nu_R\right) \\
& -\bar{p} n\left(C_S^+ \bar{e}\nu_L \quad + C_S^- \bar{e}\nu_R\right) \\
& -\frac{1}{2}\bar{p}\sigma^{\mu\nu} n\left(C_T^+ \bar{e}\sigma_{\mu\nu}\nu_L \quad + C_T^- \bar{e}\sigma_{\mu\nu}\nu_R\right) \\
& +\bar{p}\gamma_5 n\left(C_P^+ \bar{e}\nu_L \quad - C_P^- \bar{e}\nu_R\right) + \text{hc}
\end{aligned}$$

$$\begin{aligned}
\mathscr{L}_{\rm EFT} \supset -\frac{V_{ud}}{v^2}\Big\{ & (1+\epsilon_L)\ \bar{e}\gamma_\mu\nu_L \cdot \bar{u}\gamma^\mu(1-\gamma_5)d \quad + \tilde{\epsilon}_L\,\bar{e}\gamma_\mu\nu_R \cdot \bar{u}\gamma^\mu(1-\gamma_5)d \\
& +\epsilon_R\,\bar{e}\gamma_\mu\nu_L \cdot \bar{u}\gamma^\mu(1+\gamma_5)d \quad + \tilde{\epsilon}_R\,\bar{e}\gamma_\mu\nu_R \cdot \bar{u}\gamma^\mu(1+\gamma_5)d \\
& +\epsilon_T\frac{1}{4}\bar{e}\sigma_{\mu\nu}\nu_L \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5)d \quad + \tilde{\epsilon}_T\frac{1}{4}\bar{e}\sigma_{\mu\nu}\nu_R \cdot \bar{u}\sigma^{\mu\nu}(1+\gamma_5)d \\
& +\epsilon_S\,\bar{e}\nu_L \cdot \bar{u}d \quad + \tilde{\epsilon}_S\,\bar{e}(1+\gamma_5)\nu_R \cdot \bar{u}d \\
& -\epsilon_P\,\bar{e}\nu_L \cdot \bar{u}\gamma_5 d \quad - \tilde{\epsilon}_P\bar{e}\nu_R \cdot \bar{u}\gamma_5 d \Big\} + \text{hc}
\end{aligned}$$

Translation from nuclear to particle physics

Non-zero in the SM

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

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

$$C_T^+ = \frac{V_{ud}}{v^2} g_T \epsilon_T \qquad C_T^- = \frac{V_{ud}}{v^2} g_T \tilde\epsilon_T$$

$$C_S^+ = \frac{V_{ud}}{v^2} g_S \epsilon_S \qquad C_S^- = \frac{V_{ud}}{v^2} g_S \tilde\epsilon_S$$

$$C_P^+ = \frac{V_{ud}}{v^2} g_P \epsilon_P \qquad C_P^- = -\frac{V_{ud}}{v^2} g_P \tilde\epsilon_P$$

Lattice + theory fix these non-perturbative parameters with good precision

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

$g_A = 1.251 \pm 0.033,$ — **Flag'19 N_f=2+1+1 value**

$g_S = 1.02 \pm 0.10,$ — Gupta et al 1806.09006

$g_P = 349 \pm 9,$ — Gonzalez-Alonso et al 1803.08732

$g_T = 0.989 \pm 0.034$ — Gupta et al 1806.09006

Matching includes short-distance (inner) radiative corrections

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

Seng et al 1807.10197

$$\Delta_R^A - \Delta_R^V = 4.07(8)\times 10^{-3}$$

Hayen 2010.07262

Down the rabbit hole

$$
\begin{aligned}
\mathcal{L}_{\rm Fermi} \supset & -C_V^+ \bar{p}\gamma^\mu n \, \bar{e}_L \gamma_\mu \nu_L \\
& -C_A^+ \bar{p}\gamma^\mu \gamma_5 n \, \bar{e}_L \gamma_\mu \nu_L \\
& -C_S^+ \bar{p} n \, \bar{e}_R \nu_L \\
& -\frac{1}{2} C_T^+ \bar{p}\sigma^{\mu\nu} n \, \bar{e}_R \sigma_{\mu\nu} \nu_L \\
& +C_P^+ \bar{p}\gamma_5 n \, \bar{e}_R \nu_L \qquad\qquad + \mathrm{h.c.}
\end{aligned}
$$

This is a relativistic Lagrangian, and may not be most convenient to use for non-relativistic processes

In neutron decay the momentum transfer is much smaller then the nucleon mass, due to the tiny mass splitting between neutron and proton.

It is thus convenient to change variables in the Lagrangian, and use non-relativistic version of the neutron and proton quantum fields

$$
N \to \frac{e^{-i m_N t}}{\sqrt{2}} \left(1 + i \frac{\boldsymbol{\sigma} \cdot \nabla}{2 m_N} \right) \psi_N + \mathcal{O}(\nabla^2), \qquad N = p, n
$$

In these variables, and expanding in powers of ∇, the Lagrangian simplifies

$$
\mathcal{L}_{\rm Fermi}^{\rm NR} \supset -(\bar{\psi}_p \psi_n) \left[C_V^+ \bar{e}_L \nu_L + C_S^+ \bar{e}_R \nu_L \right] - (\bar{\psi}_p \sigma^k \psi_n) \left[C_A^+ \bar{e}_L \sigma^k \nu_L + C_T^+ \bar{e}_R \sigma^k \nu_L \right] + \mathcal{O}(\nabla / m_n)
$$

It is clear that pseudoscalar couplings do not affect beta decay at leading order

Non-relativistic Fermi EFT

$$\mathcal{L}_{\text{Fermi}}^{\text{NR}} \supset -(\bar{\psi}_p \psi_n)\left[C_V^+ \bar{e}_L \nu_L + C_S^+ \bar{e}_R \nu_L\right] - \sum_{k=1}^{3} (\bar{\psi}_p \sigma^k \psi_n)\left[C_A^+ \bar{e}_L \sigma^k \nu_L + C_T^+ \bar{e}_R \sigma^k \nu_L\right] + \mathcal{O}(\nabla/m_n)$$

This Lagrangian can also describe beta decays of nuclei: $N \to N' e^- \bar{\nu}$

$$\mathcal{M} = -\mathcal{M}_F\left[C_V^+(\bar{x}_3 y_4) + C_S^+(y_3 y_4)\right] - \sum_{k=1}^{3} \mathcal{M}_{\text{GT}}^k \left[C_A^+(\bar{x}_3 \sigma^k y_4) + C_T^+(y_3 \sigma^k y_4)\right]$$

where the Fermi and Gamow-Teller matrix elements are

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

Fermi transitions

Calculable from group theory in the isospin limit

Gamow-Teller transitions

Difficult to calculate from first principles

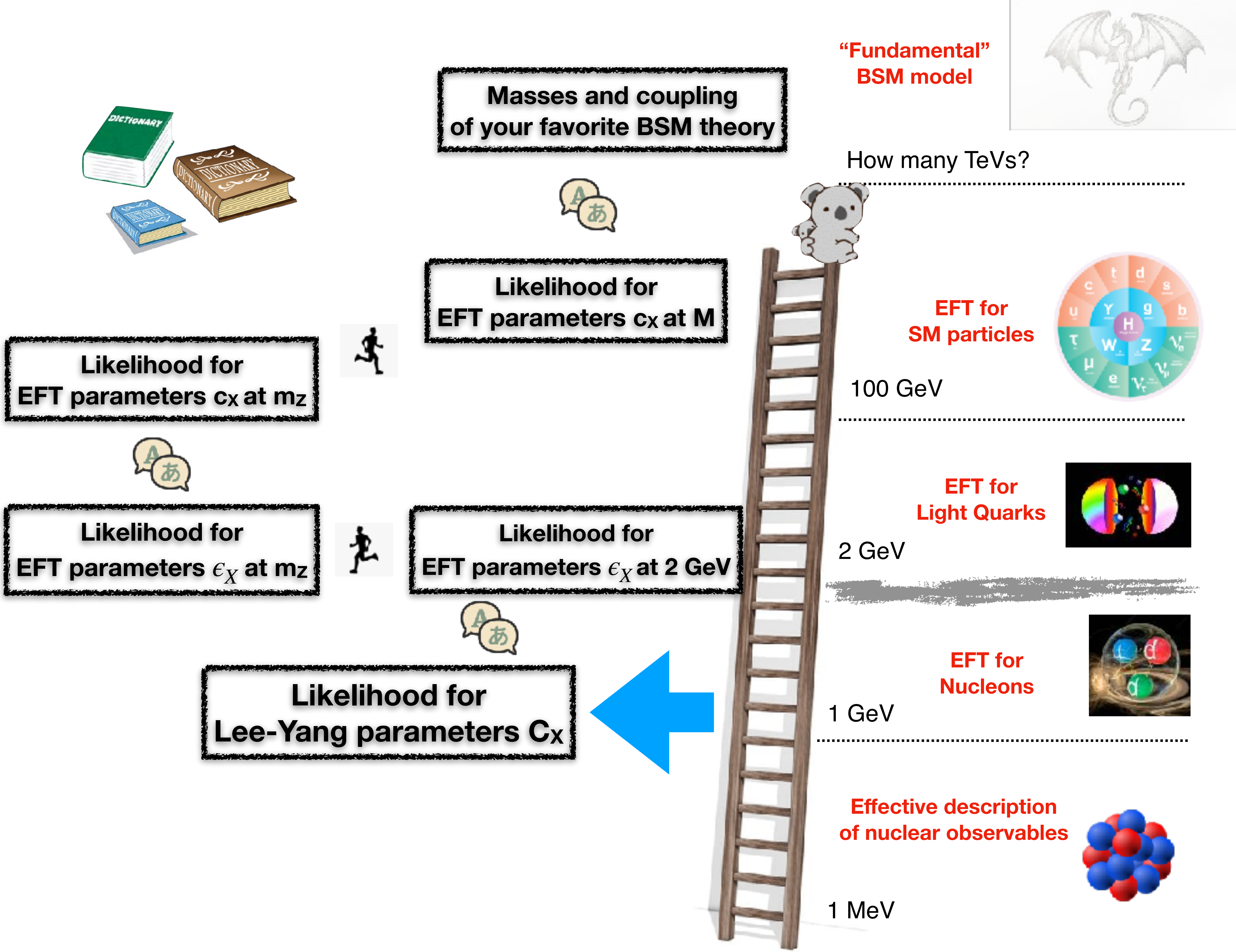
The use of non-relativistic EFT allows one to reduce the problem of calculating amplitudes for allowed beta transitions of nuclei to calculating two nuclear matrix elements

Forbidden transitions correspond to higher order terms in the non-relativistic expansion

Summary of the language

$$
\begin{aligned}
\mathscr{L}_{\rm EFT} \supset & -\bar{p}\gamma^\mu n\left(C_V^+ \bar{e}\gamma_\mu \nu_L \qquad + C_V^- \bar{e}\gamma_\mu \nu_R\right) \\
& -\bar{p}\gamma^\mu \gamma_5 n\left(C_A^+ \bar{e}\gamma_\mu \nu_L \qquad - C_A^- \bar{e}\gamma_\mu \nu_R\right) \\
& -\bar{p} n\left(C_S^+ \bar{e}\nu_L \qquad + C_S^- \bar{e}\nu_R\right) \\
& -\frac{1}{2}\bar{p}\sigma^{\mu\nu} n\left(C_T^+ \bar{e}\sigma_{\mu\nu}\nu_L \qquad + C_T^- \bar{e}\sigma_{\mu\nu}\nu_R\right) + \ldots + \mathrm{hc}
\end{aligned}
$$

- We will use the Lee-Yang effective Lagrangian to describe nuclear beta transitions
- We will be agnostic about its Wilson coefficients, allowing all 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, with or without the right-handed neutrino
- The goal is produce the likelihood function for the 8 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)

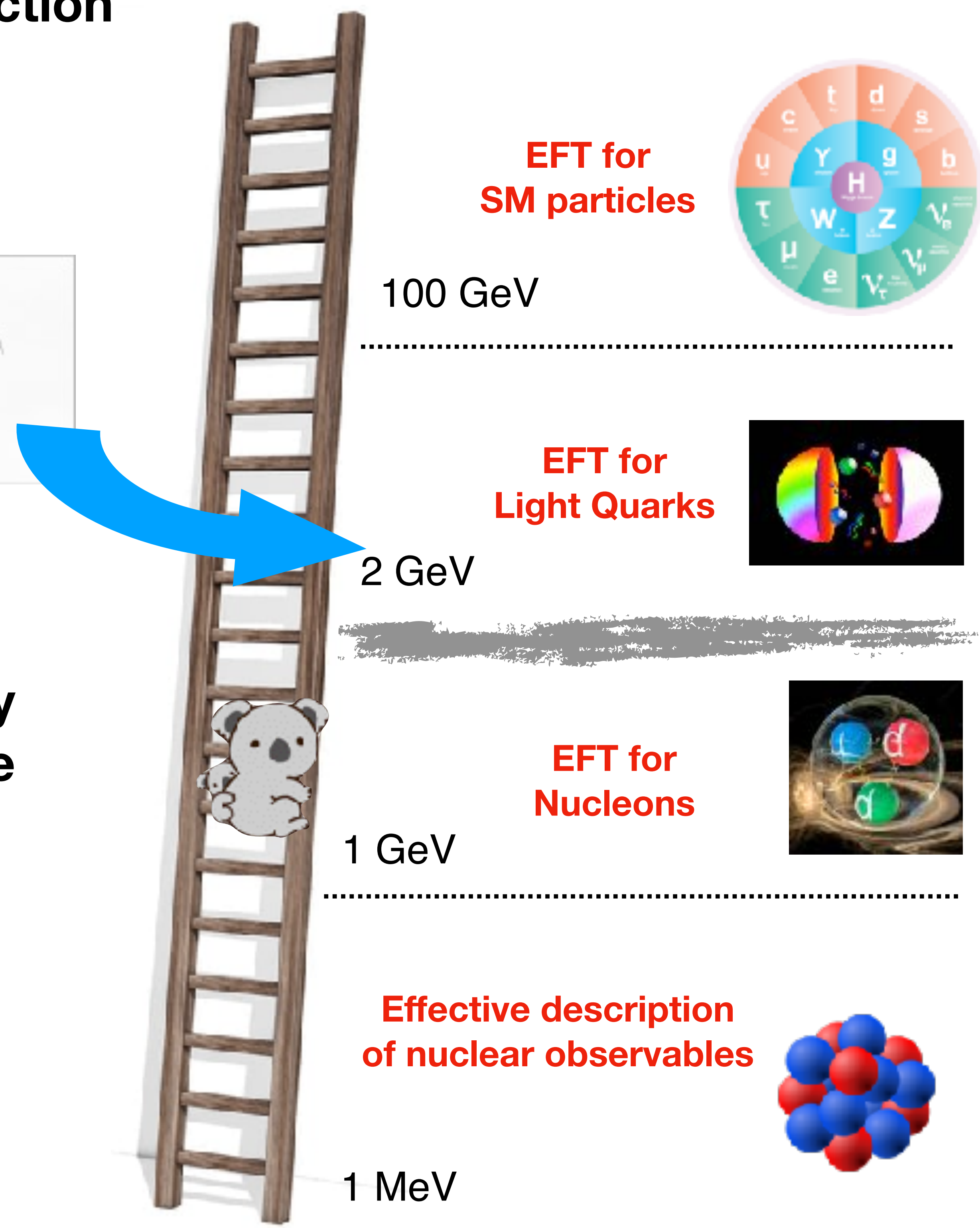


"Fundamental"
BSM model
Masses and coupling
of your favorite BSM theory
How many TeVs?
DICTIONARY
DICTIONARY
DICTIONARY
Likelihood for
EFT parameters c_X at M
EFT for
SM particles
100 GeV
Likelihood for
EFT parameters c_X at m_Z
EFT for
Light Quarks
2 GeV
Likelihood for
EFT parameters ϵ_X at m_Z
Likelihood for
EFT parameters ϵ_X at 2 GeV
EFT for
Nucleons
1 GeV
Likelihood for
Lee-Yang parameters C_X
Effective description
of nuclear observables
1 MeV

Shortcuts

It is not entirely excluded that new physics, is lighter than the electroweak scale and weakly coupled so as to avoid detection

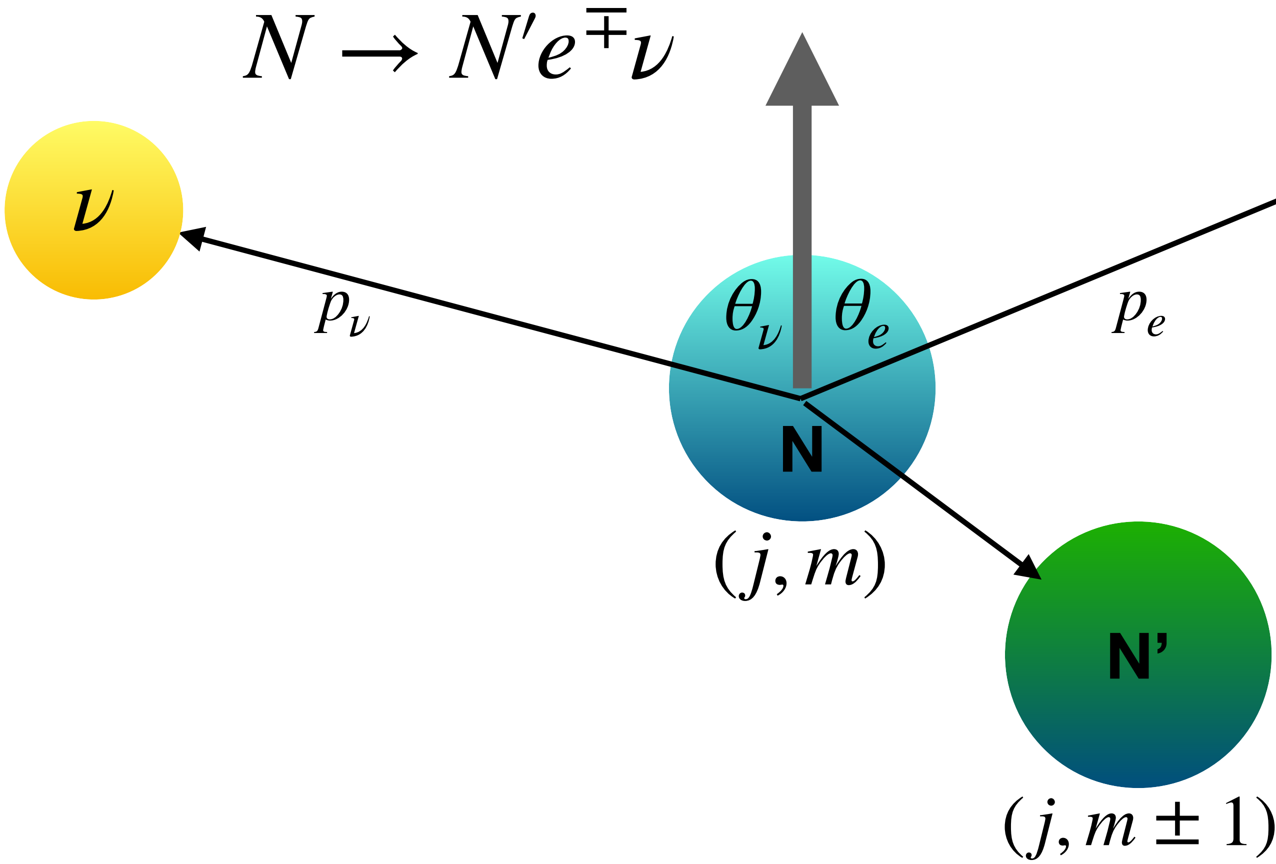
"Fundamental" BSM model



Then new physics may connect directly to the EFT below the electroweak scale

Observables for allowed beta transitions

Observable in beta decays



Electron energy/momentum

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

Neutrino energy

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

From effective Lagrangian to observables

Fermi matrix element given by nucleus isospin numbers

Fierz term

Phase space factor

Decay width:

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

Jackson Treiman Wyld (1957)

Higher-order corrections

Mixing parameter

Non-zero in SM

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

Vanishes in SM

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

Mixing parameter for mixed Fermi-GT transitions

$$\rho = r\frac{C_A^+}{C_V^+}$$

where r is ratio of Fermi and Gamow-Teller matrix elements

For allowed beta decays, no dependence on pseudoscalar Wilson coefficients $C_P^{\pm}$, so these will not be probed by our observables

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

Observable in beta decays

1. Total decay width Γ or lifetime τ or half-life $t_{1/2}$

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

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

Half-life:

$$t_{1/2} \equiv \frac{\log_{10}(2)}{\Gamma} = \frac{\log_{10}(2) 4\pi^3}{\left(1+\delta\right) M_F^2 m_e^5 X \left[1 + b\left\langle \frac{m_e}{E_e}\right\rangle\right] f}$$

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

ft:

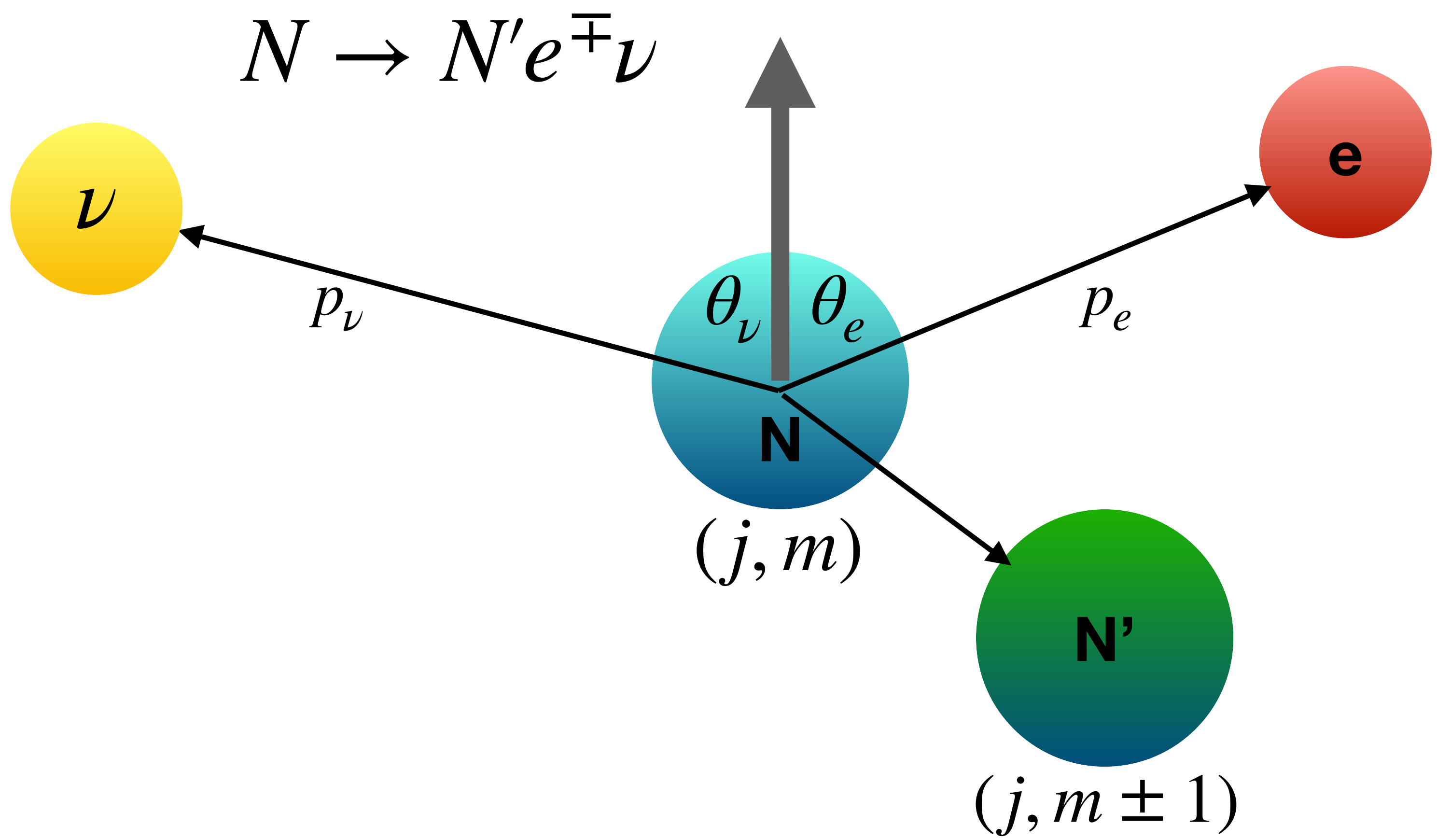
$$ft \equiv \frac{f \log_{10}(2)}{\Gamma} = \frac{4\pi^3 \log_{10}(2)}{\left(1+\delta\right) M_F^2 m_e^5 X \left[1 + b\left\langle \frac{m_e}{E_e}\right\rangle\right]}$$

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

$\mathcal{F}$t:

$$\mathcal{F}t \equiv \frac{\left(1+\delta\right) f \log_{10}(2)}{\Gamma} = \frac{4\pi^3 \log_{10}(2)}{M_F^2 m_e^5 X \left[1 + b\left\langle \frac{m_e}{E_e}\right\rangle\right]}$$

Observable in beta decays



Electron energy/momentum

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

Neutrino energy

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

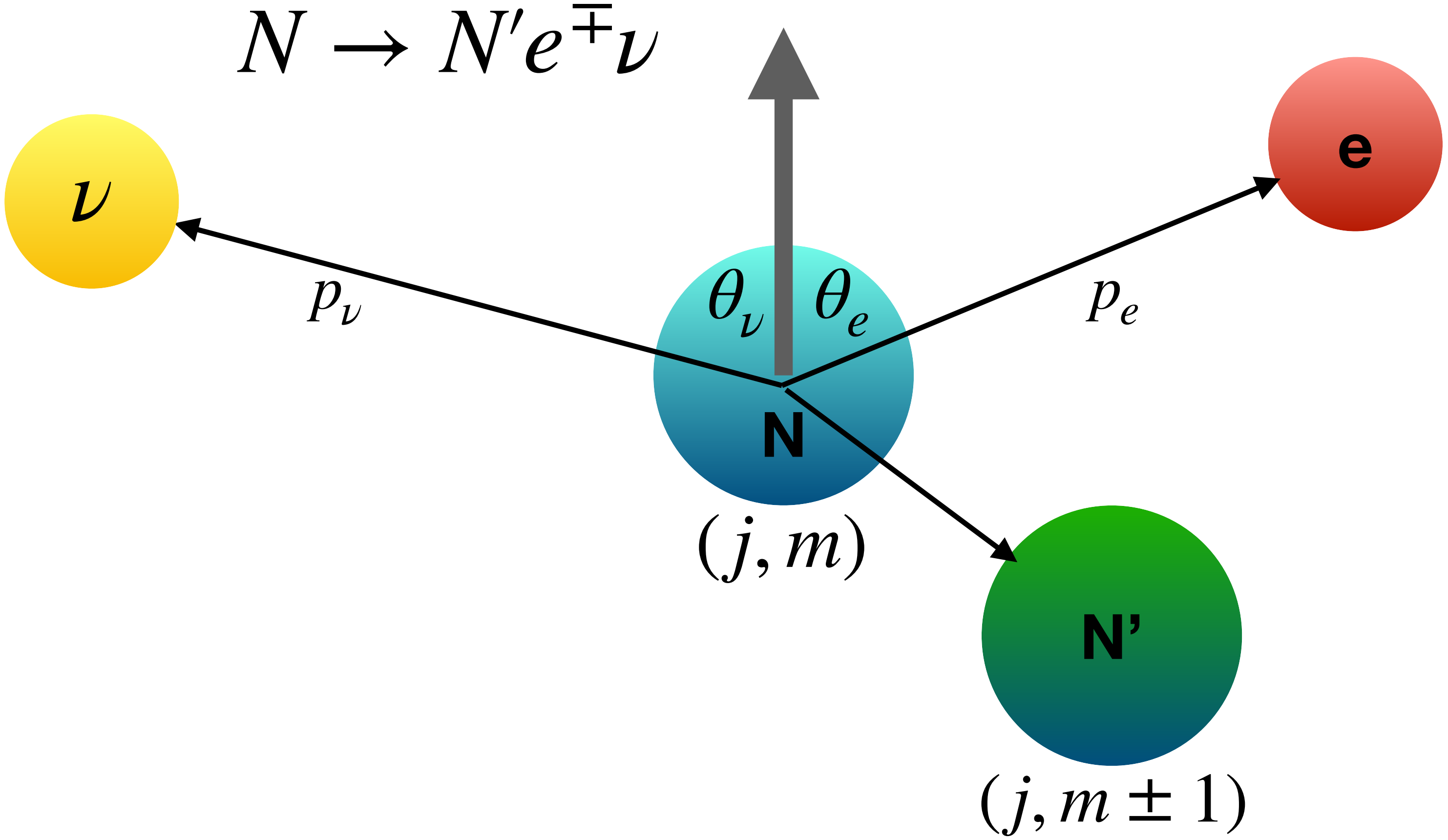
2. β-ν correlation

For unpolarized decays, one can also measure the angular correlation, between the directions of the final-state positron(electron) and (anti)neutrino:

$$\frac{d\Gamma}{dE_e d\Omega_e d\Omega_\nu} = F(E_e)\left[1 + a \frac{\vec{p}_e}{E_e} \cdot \frac{\vec{p}_\nu}{E_\nu}\right]$$

Observable in beta decays

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



Electron energy/momentum

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

Neutrino energy

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

3. β-correlation and ν-correlation

For polarized decays, one can also measure the angular correlation, between the polarization direction and the direction of the final-state positron(electron) or (anti)neutrino:

$$\frac{d\Gamma}{dE_e d\Omega_e d\Omega_\nu} = F(E_e)\left[1 + a\frac{\overrightarrow{p}_e}{E_e}\cdot\frac{\overrightarrow{p}_\nu}{E_\nu} + A\frac{\overrightarrow{p}_e}{E_e}\cdot\frac{\langle\overrightarrow{J}\rangle}{J} + B\frac{\overrightarrow{p}_\nu}{E_\nu}\cdot\frac{\langle\overrightarrow{J}\rangle}{J}\right]$$

From effective Lagrangian to observables

Jackson Treiman Wyld (1957)

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

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

Correlation observable probe other combination of Wilson coefficients:

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

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

$$\tilde{a} \equiv \frac{a}{1 + b\left\langle \frac{m_e}{E_e}\right\rangle}$$

$$\tilde{A} \equiv \frac{A}{1 + b\left\langle \frac{m_e}{E_e}\right\rangle}$$

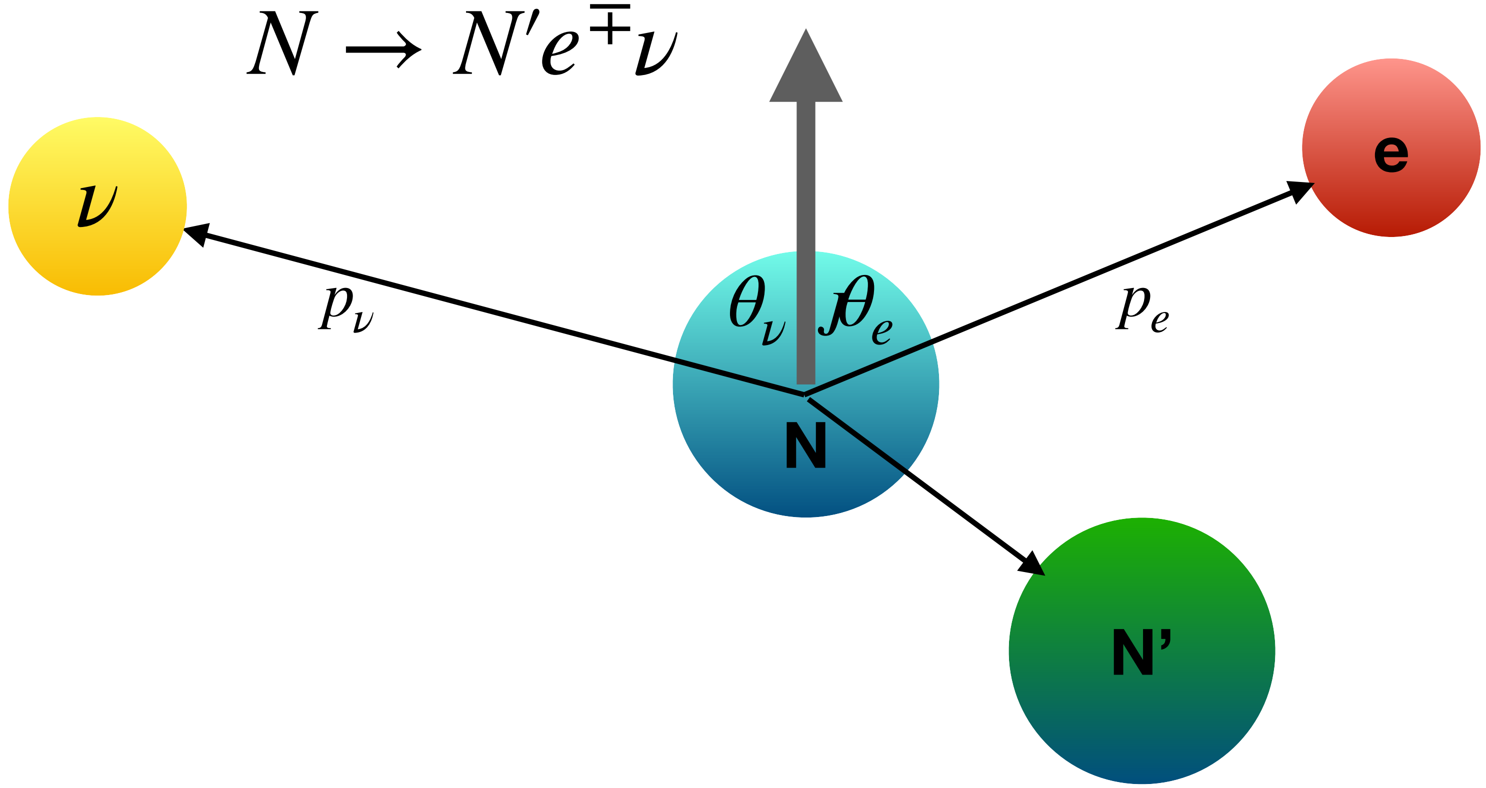
One can also explore the energy E_e dependence of these observables, but this is rarely done in experiment

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

Effective Lagrangian describing allowed nuclear beta decays:

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



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 lifetimes and correlations

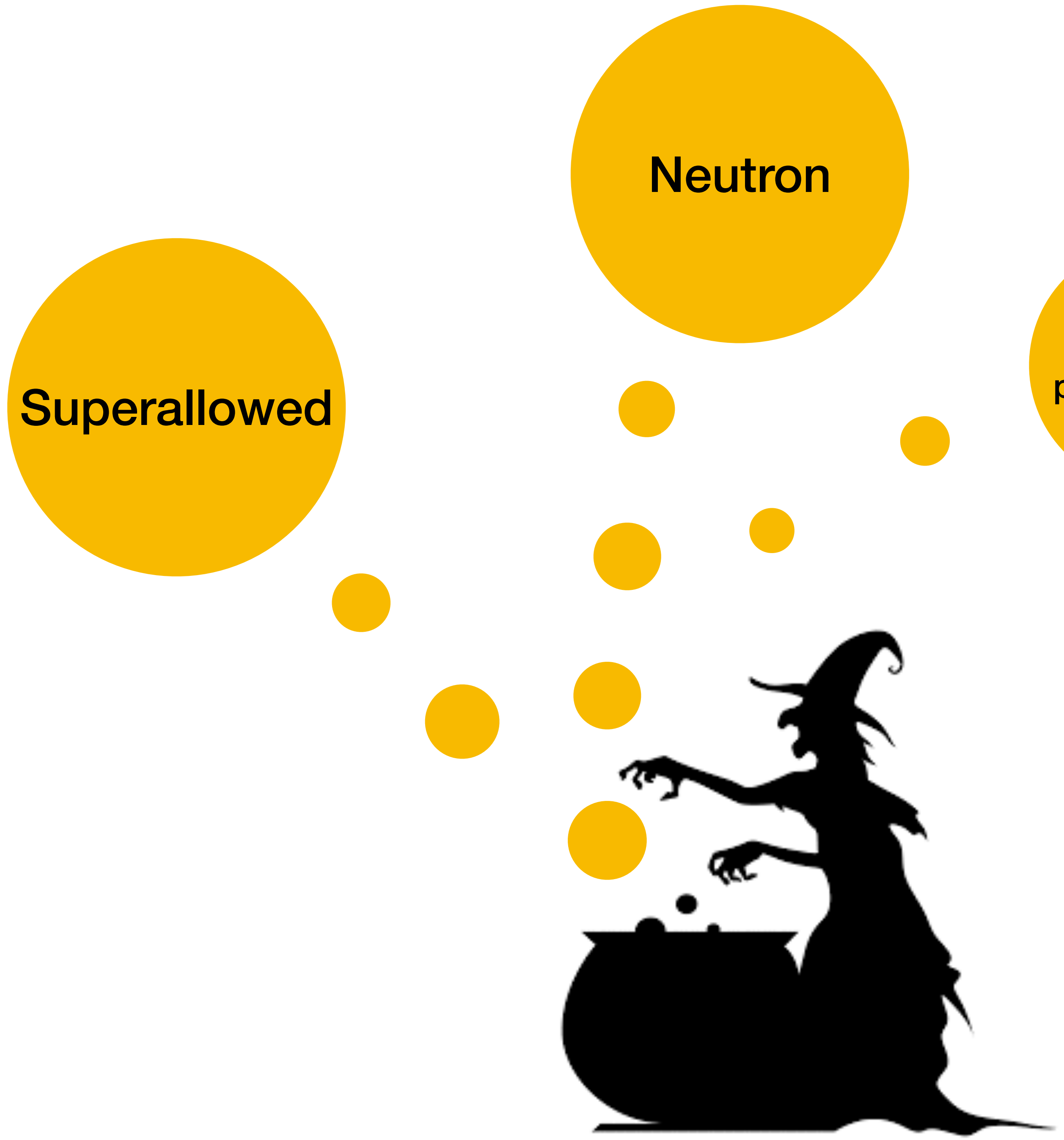
$$\frac{d\Gamma}{dE_e d\Omega_e d\Omega_\nu} = F(E_e)\left\{ 1 + b\frac{m_e}{E_e} + a\frac{\boldsymbol{p}_e \cdot \boldsymbol{p}_\nu}{E_e} + A\frac{\langle \boldsymbol{J} \rangle \cdot \boldsymbol{p}_e}{JE_e} + B\frac{\langle \boldsymbol{J} \rangle \cdot \boldsymbol{p}_\nu}{JE_\nu} \right.$$
$$\left.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

No-one talks about it

Violates CP

Data for allowed beta transitions

Global BSM fits so far



For a review see Gonzalez-Alonso, Naviliat-Cuncic, Severijns, 1803.08732

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)

$$\mathcal{F}t \equiv \frac{(1+\delta)f\log_{10}(2)}{\Gamma} = \frac{4\pi^3\log_{10}(2)}{M_F^2 m_e^5 X\left[1 + b\left\langle \frac{m_e}{E_e}\right\rangle\right]}$$

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

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

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

M_F and X are the same for all $0^+ \rightarrow\ 0^+$ transitions!

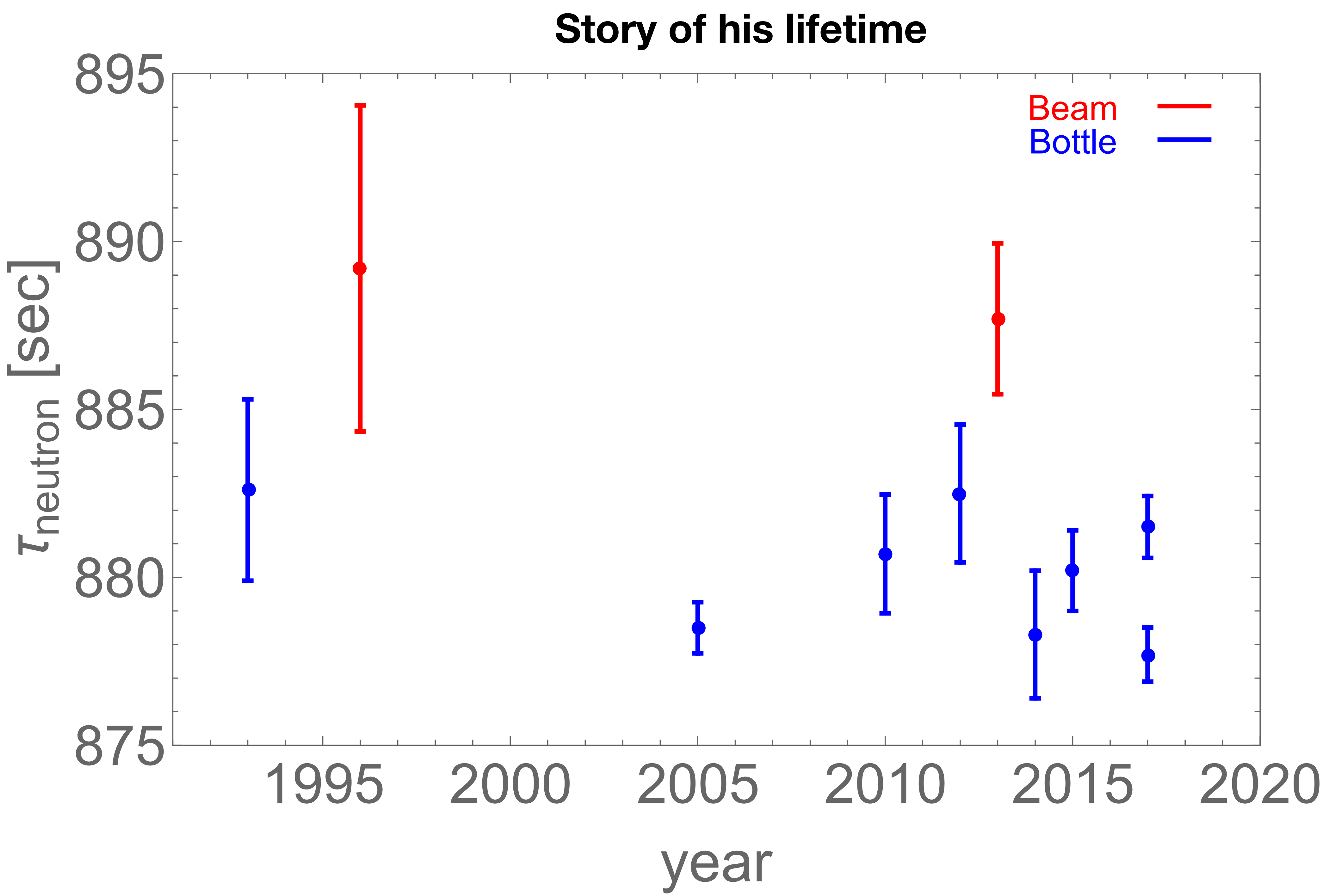
$\mathcal{F}t$ is defined such that it should be the same for all superallowed transitions if the SM gives the complete description of beta decays

Neutron decay data

Observable	Value	$\langle m_e/E_e \rangle$	References
τ_n (s)	$879.75(76)$	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]

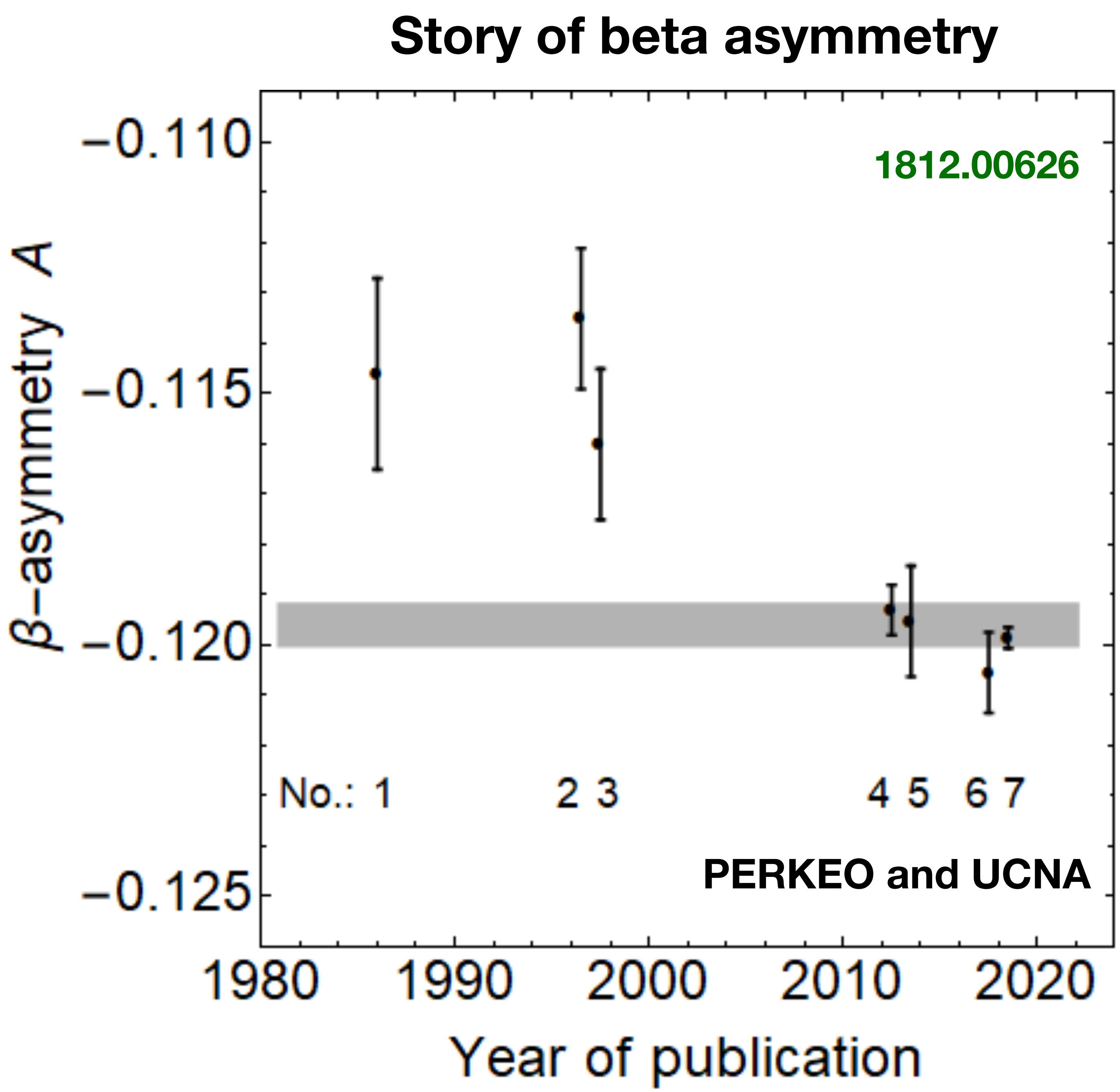
Order per-mille precision !

Neutron lifetime



Because of incompatible measurements from different experiment, uncertainty of the combined lifetime is inflated by the factor S=1.9

Neutron beta asymmetry



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

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

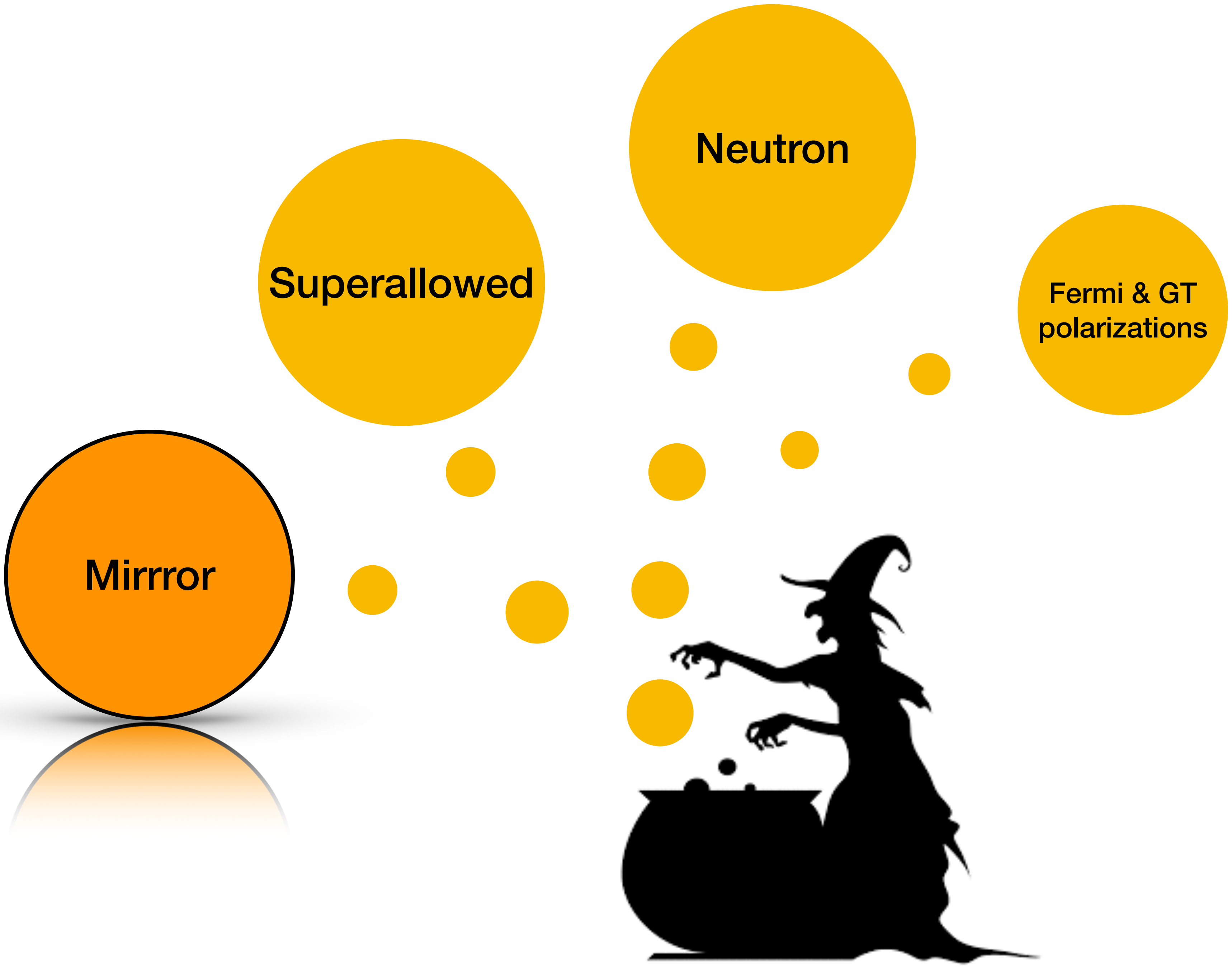
Fivefold error reduction

Fermi & GT polarizations

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

This talk



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

Mirror decays

- Mirror decays are β transitions between isospin half, same spin, and positive parity nuclei[1)]
- These are 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

$$\mathcal{F}t \equiv \frac{(1+\delta)f \log_{10}(2)}{\Gamma} = \frac{4\pi^3 \log_{10}(2)}{M_F^2 m_e^5 X \left[1 + b\left\langle \frac{m_e}{E_e} \right\rangle\right]}$$

For mirror beta transitions

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

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

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 aprior, 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]

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

In the SM limit the Lee-Yang Lagrangian simplifies a lot:

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

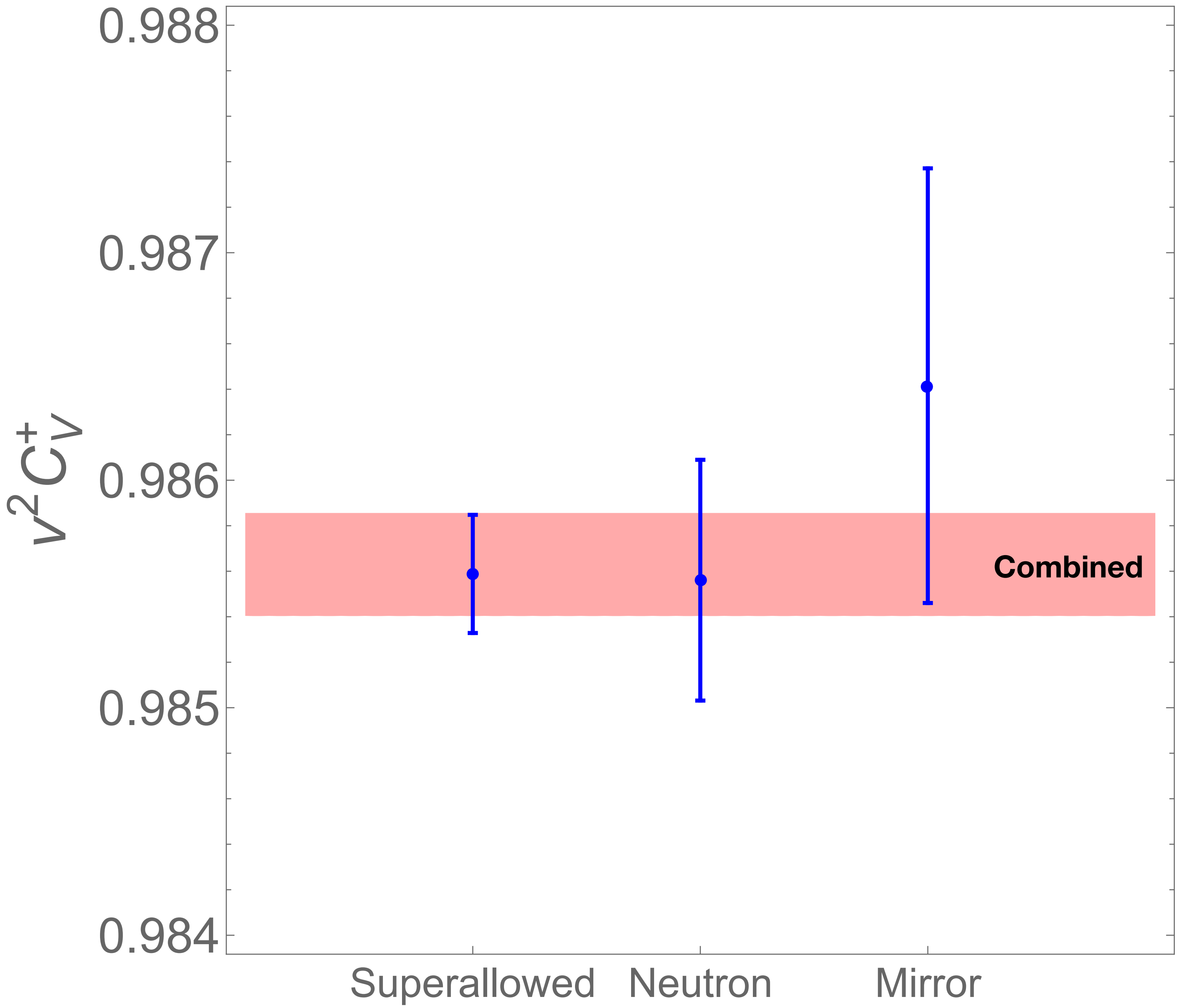
$$
\begin{pmatrix} \mathrm{v}^2 C_V^{+} \\ \mathrm{v}^2 C_A^{+} \\ \rho_{\mathrm{F}} \\ \rho_{\mathrm{Ne}} \\ \rho_{\mathrm{Na}} \\ \rho_{\mathrm{P}} \\ \rho_{\mathrm{Ar}} \\ \rho_{\mathrm{K}} \end{pmatrix} = \begin{pmatrix} 0.98564(23) \\ -1.25700(42) \\ -1.2958(13) \\ 1.60183(76) \\ -0.7129(11) \\ -0.5383(21) \\ -0.2838(25) \\ 0.5789(20) \end{pmatrix}
$$

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

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

SM fit

Currently, superallowed data dominate the constraints on C_V^+ while mirror constraints are a factor of 4 weaker



SM fit

Translation to particle physics variables

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

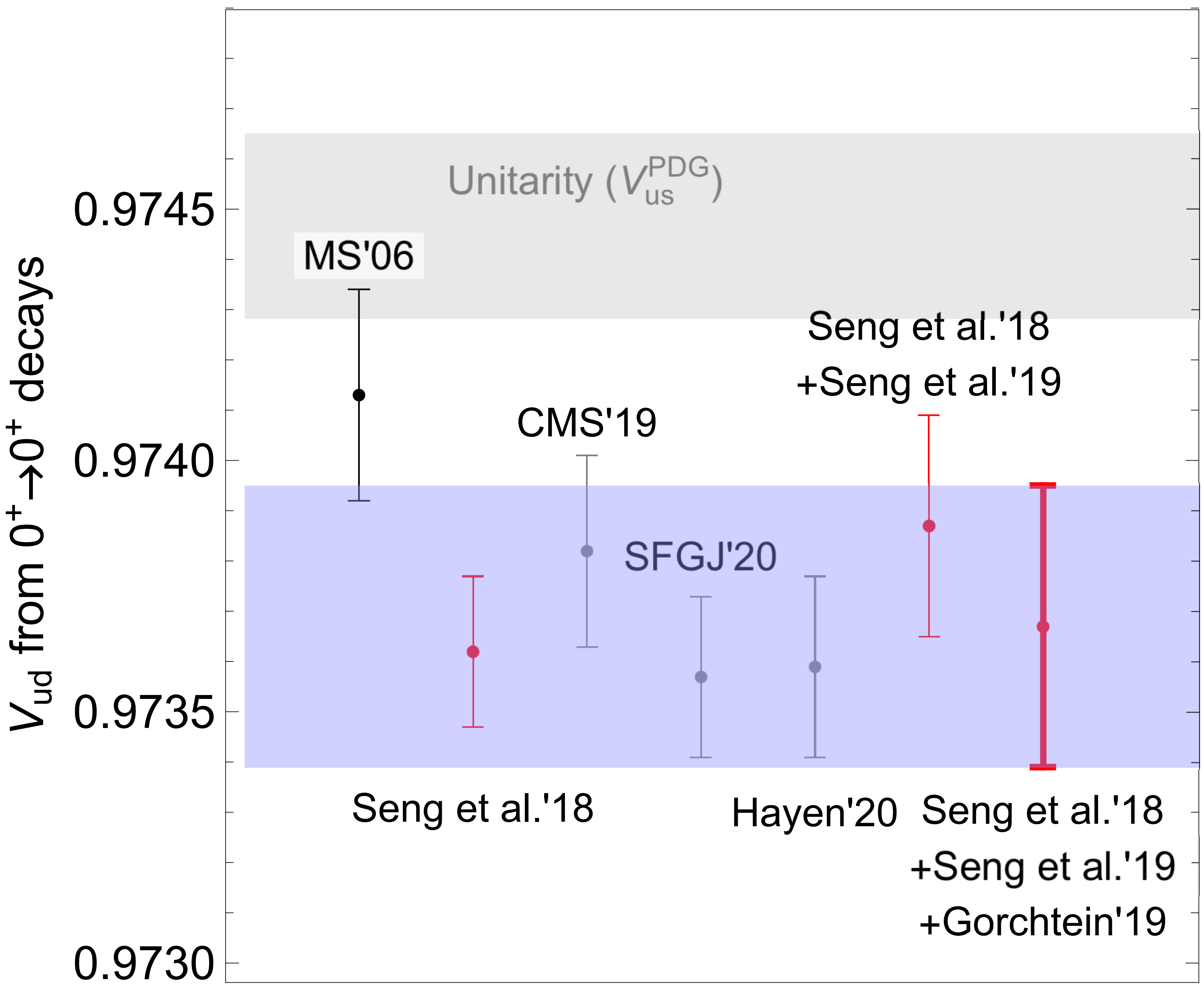
$$C_A^+ = -\frac{V_{ud}}{\mathrm{v}^2} g_A \sqrt{1+\Delta_R^A}$$

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

$$\begin{pmatrix} V_{ud} \\ g_A \end{pmatrix} = \begin{pmatrix} 0.97370(25) \\ 1.27276(45) \end{pmatrix} \qquad \rho = \begin{pmatrix} 1 & -0.27 \\ . & 1 \end{pmatrix}$$

SM fit

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



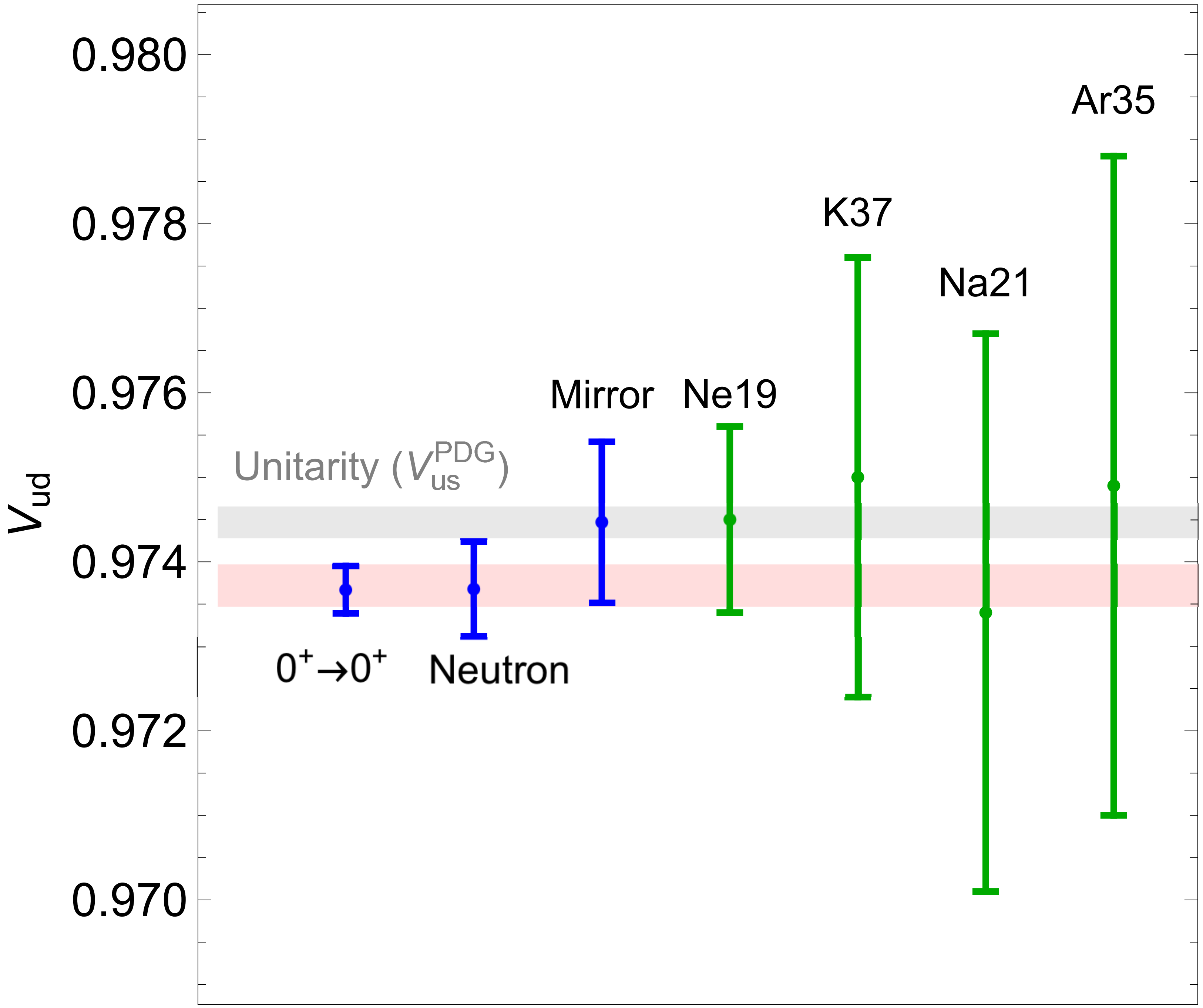
Our value
V_{ud}=0.97370(25)

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

Seng et al 1812.03352

Gorchtein 1812.04229

SM fit



All Combined
V_{ud} = 0.97370(25)

Global update of previous results on V_{ud} determination from mirror decays

Naviliat-Cuncic, Severijns
arXiv: 0809.0994

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 Lee-Yang Lagrangian simplifies:

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

Our observables independent of C_P at leading order

$$
v^2 \begin{pmatrix} C_V^{+} \\ C_A^{+} \\ C_S^{+} \\ C_T^{+} \end{pmatrix} = \begin{pmatrix} 0.98571(41) \\ -1.25707(55) \\ 0.0010(19) \\ 0.0004(12) \end{pmatrix}
$$

Uncertainty on SM parameters increases compared to SM fit

$\mathcal{O}(10^{-3})$ **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

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

Polluted CKM element

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

Polluted axial charge

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

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

Rescaled BSM Wilson coefficients

$$\begin{pmatrix} \hat{V}_{ud} \\ \hat{g}_A \\ \hat{\epsilon}_S \\ \hat{\epsilon}_T \end{pmatrix} = \begin{pmatrix} 0.97377(41) \\ 1.27272(44) \\ 0.0001(10) \\ 0.0005(13) \end{pmatrix}$$

Central values + errors + correlation matrix → full information about the likelihood retained in the Gaussian approximation

Per-mille level constraints on Wilson coefficients, describing scalar and tensor interactions between quarks and leptons. Better than per-mille constraint on the polluted CKM element

Bonus from the lattice

From experiment (fit):

$$\hat{g}_A = 1.27272(44)$$

From lattice (FLAG'19):

$$g_A = 1.251(33)$$

This is the same parameter in the absence of BSM physics, in which case lattice and experiment are in agreement within errors

But this is not the same parameter in the presence of BSM physics!

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

One can treat lattice determination of g_A as another "experimental" input constraining ϵ_R

$$\epsilon_R = -0.009(13)$$

For right-handed BSM currents, only a percent level constraint, due to larger lattice error

Bonus from the lattice

1805.12130

From experiment (fit):

$$\hat{g}_A = 1.27272(44)$$

Smaller error using CalLat'18 result

$$g_A = 1.271(13)$$

This is the same parameter in the absence of BSM physics, in which case lattice and experiment are in agreement within errors

But this is not the same parameter in the presence of BSM physics!

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

One can treat lattice determination of g_A as another "experimental" input constraining ε_R

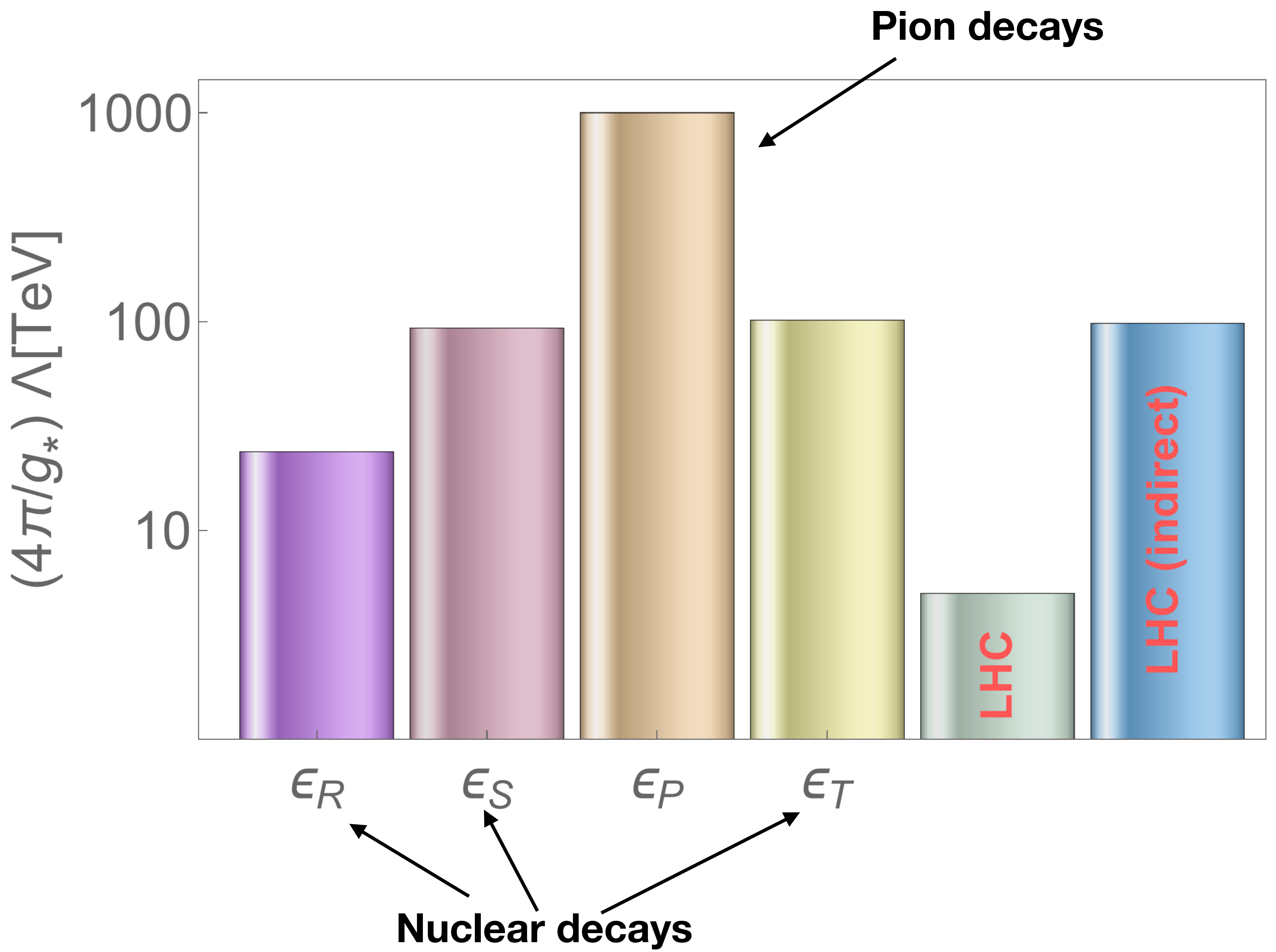
$$\epsilon_R = -0.0007(51)$$

Sub-percent accuracy!

Progress in lattice directly translates to better constraints on right-handed currents!

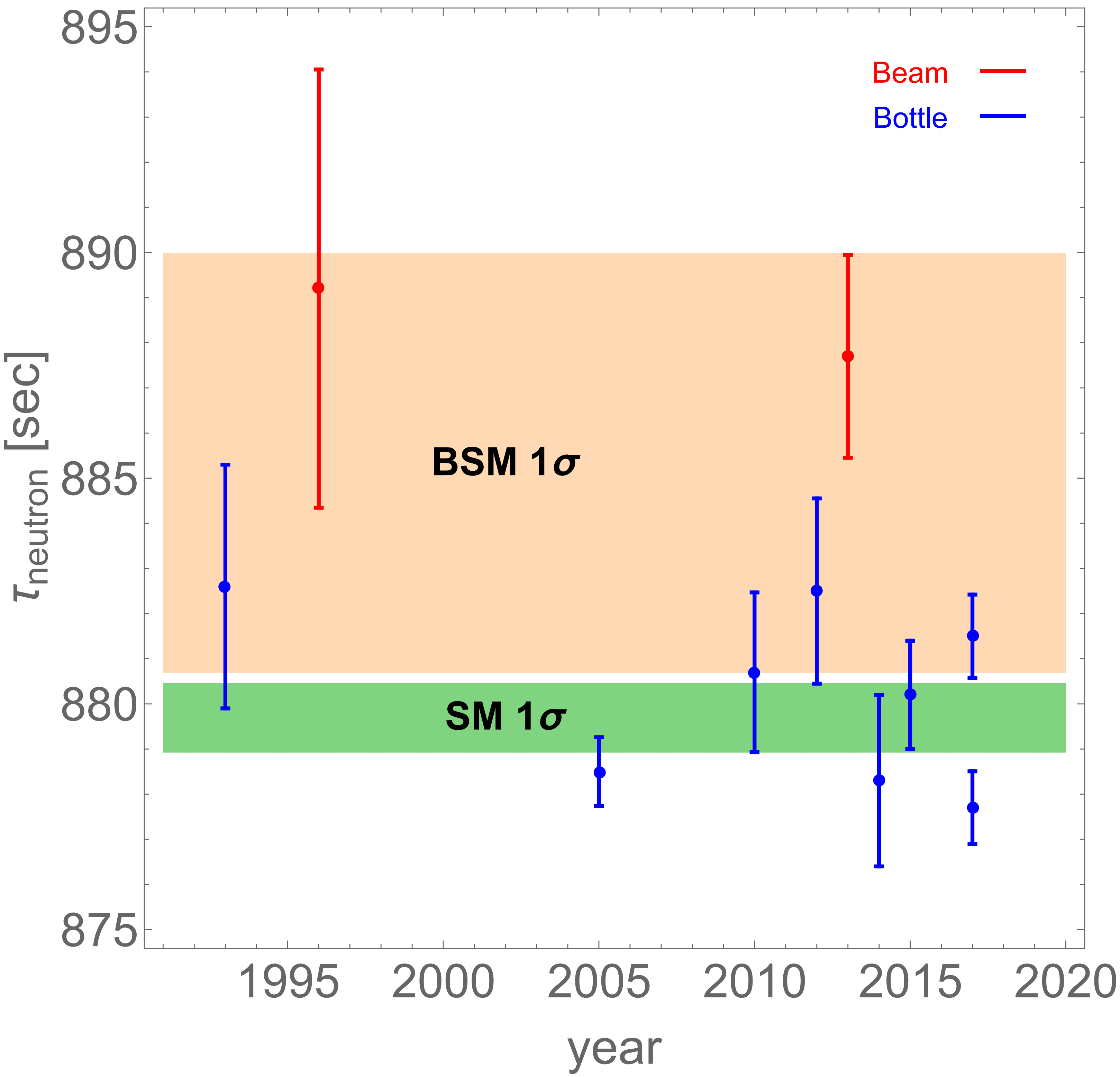
New physics reach of beta decays

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

Lee-Yang fit

Never done previously in this form and generality

Global fit of Lee-Yang Wilson coefficients

Global fit to 8 Wilson coefficients and 6 mixing ratios:

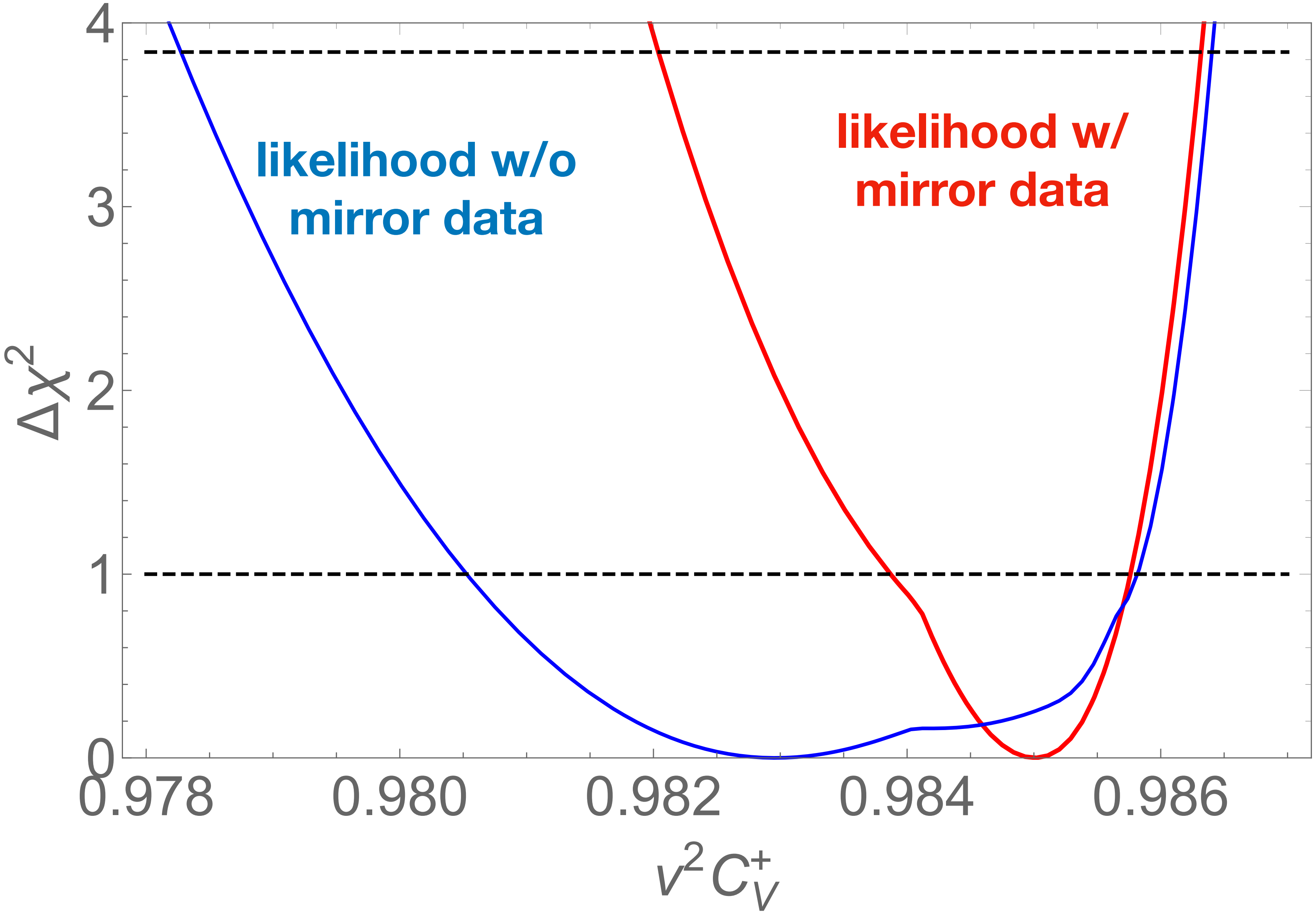
$$
\begin{aligned}
\mathscr{L}_{\text{Lee-Yang}} = & -\bar{p}\gamma^{\mu}n\left(C_V^{+}\bar{e}\gamma_{\mu}\nu_L + C_V^{-}\bar{e}\gamma_{\mu}\nu_R\right) \\
& -\bar{p}\gamma^{\mu}\gamma_5 n\left(C_A^{+}\bar{e}\gamma_{\mu}\nu_L - C_A^{-}\bar{e}\gamma_{\mu}\nu_R\right) \\
& -\frac{1}{2}\bar{p}\sigma^{\mu\nu}n\left(C_T^{+}\bar{e}\sigma_{\mu\nu}\nu_L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

Our observables independent of $C_P^{\pm}$ at leading order

$$
v^2 \begin{pmatrix} C_V^{+} \\ C_A^{+} \\ C_S^{+} \\ C_T^{+} \end{pmatrix} = \begin{pmatrix} 0.98501^{+(75)}_{-(114)} \\ -1.2544^{+(14)}_{-(11)} \\ -0.0007^{+(29)}_{-(14)} \\ -0.0001^{+(33)}_{-(22)} \end{pmatrix}
\qquad
\begin{pmatrix} v^2\,|C_V^{-}| < 0.053 \\ v^2\,|C_A^{-}| < 0.063 \\ v^2\,|C_S^{-}| < 0.050 \\ v^2\,|C_T^{-}| \in [0.072, 0.099] \end{pmatrix}
$$

Global fit of Lee-Yang Wilson coefficients

Example: Cv+ fit $\mathscr{L}_{\mathrm{EFT}} \supset -C_V^+(\bar{p}\gamma^\mu n)(\bar{e}\gamma_\mu \nu_L) + \mathrm{h.c.}$



$$\mathrm{v}^2 C_V^+ = 0.98501^{+(75)}_{-(114)}$$

The effect of mirror data is very significant!

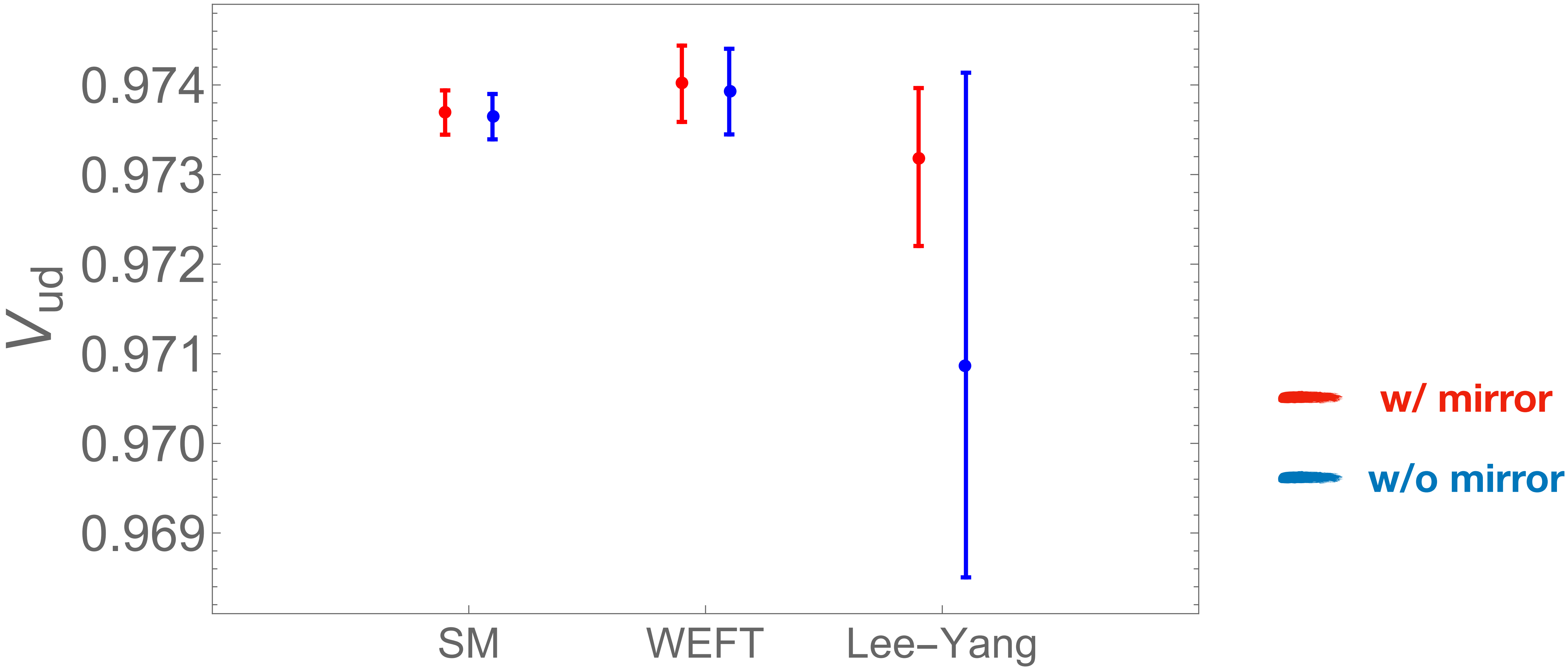
Per-mille level constraints, thanks to the mirror data!

Constraints on V_{ud} matrix element

Constraints on C_{V+} translate into constraints on the (polluted) CKM matrix element V_{ud}

$$C_V^+ = \frac{\tilde{V}_{ud}}{v^2} g_V \sqrt{1 + \Delta_R^V}, \qquad \tilde{V}_{ud} \equiv V_{ud}(1 + \epsilon_L + \epsilon_R)$$

Mirror data bring a factor of 3 improvement on the determination V_{ud} in the general scenario



$$\text{(LY)}: \quad \tilde{V}_{ud} = 0.97317^{+(79)}_{-(97)}$$

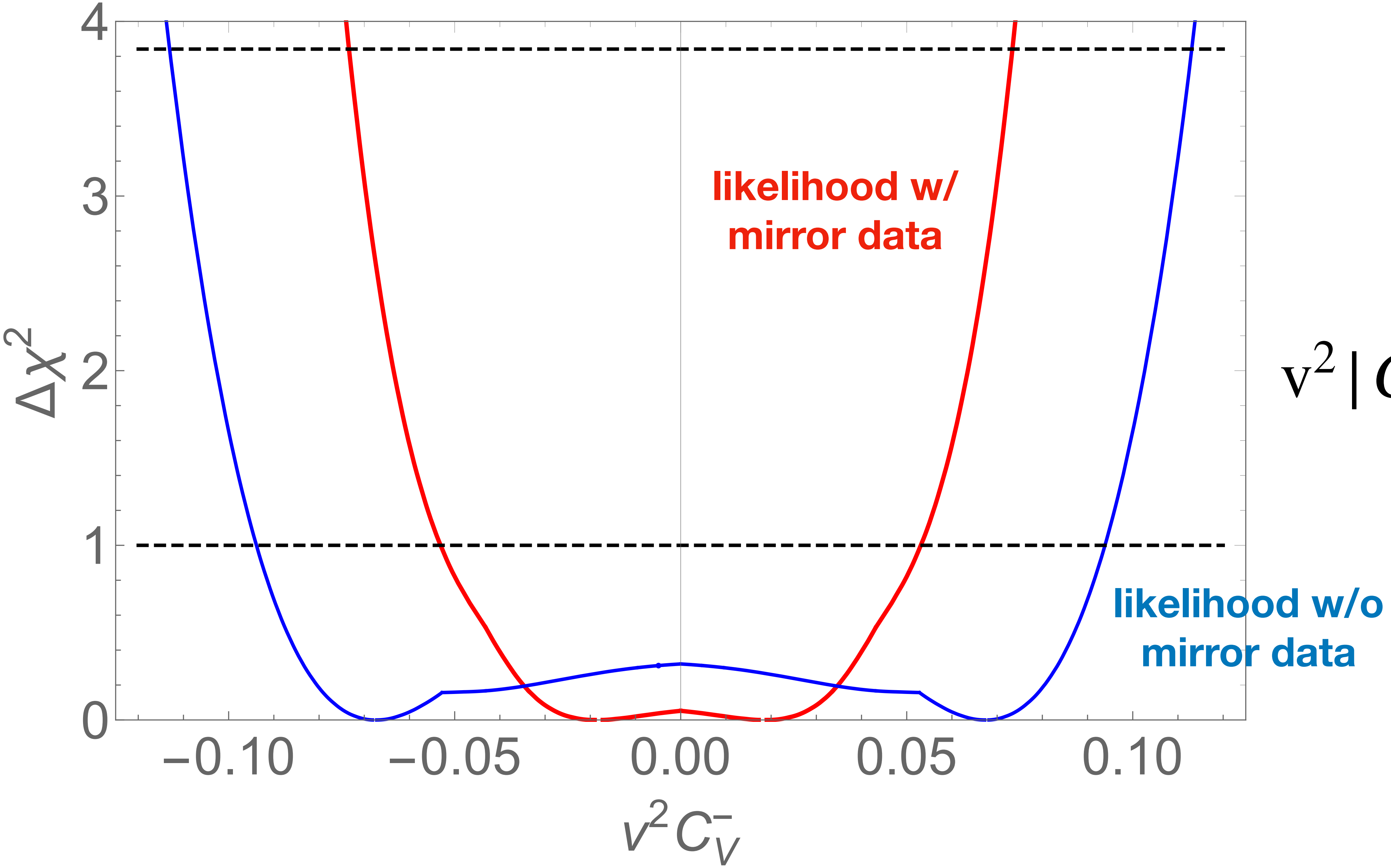
compare with

$$\text{(SM)}: \quad V_{ud} = 0.97370(25)$$

$$\text{(WEFT)}: \quad \tilde{V}_{ud} = 0.97377(41)$$

Global fit of Lee-Yang Wilson coefficients

Example: C_{V-} fit $\mathscr{L}_{\rm EFT} \supset -C_V^-(\bar p \gamma^\mu n)(\bar e \gamma_\mu \nu_R) + {\rm hc}$



$$v^2 |C_V^-| < 0.053$$

Few percent level constraints, thanks to the mirror data!
Constraints are much weaker than for C_{V+} because effects of right-handed neutrinos do not interfere with the SM amplitudes, and thus enter quadratically in C_{V-}.

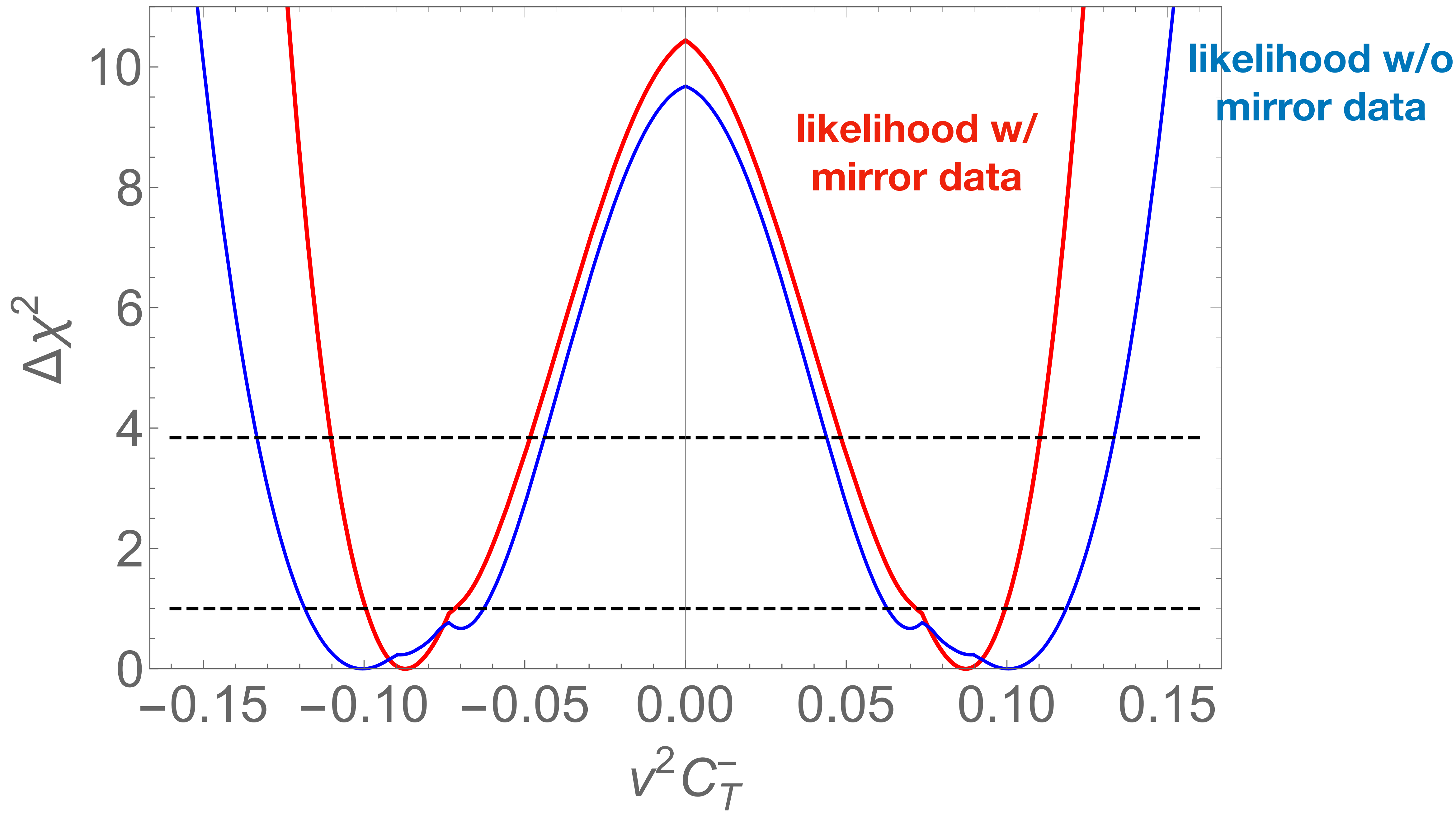
Global fit of Lee-Yang Wilson coefficients

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

Mirror data leads to shrinking of the confidence intervals by an O(2-3) factor for almost all Wilson coefficients, except for C_{S^-}

Global fit of Lee-Yang Wilson coefficients

Tensor anomaly ?



Data show 3.2 sigma preference for new physics,
manifesting as O(0.1) tensor interactions with the right-handed neutrino

Tensor anomaly

- Current data show a preference for tensor contact interactions between the nucleons, electron, and right-handed neutrino
- Inclusion of mirror data slightly increases the significance of the anomaly, from 3.0 to 3.2 sigma
- The anomaly is driven by the neutron data: mostly by the measurement of the β-ν asymmetry by aSPECT, with a smaller contribution from the ν-polarization asymmetry measurements
- This could hint at new physics (leptoquarks?) close to the electroweak scale and coupled to right-handed neutrinos, but it is not clear if a model consistent with all collider constraints can be constructed

Historical anecdote

- Back in the 50s, the central question was whether weak interactions are vector-axial, or scalar tensor. After some initial confusion, the former option was favored, paving the way to the creation of the SM
- But the preference for V-A interactions has never been demonstrated in a completely model-independent fashion. Our analysis does this for the first time (some 60 years too late ;)
- More interestingly, we quantify the magnitude of non-V-A admixtures. Scalar and tensor interactions with left-handed neutrinos are constrained at the per-mille level, while vector, axial, scalar, and tensor interactions with the right-handed neutrino are possible at the 10% level
- Mirror data are essential to lift some of the degeneracies in the large parameter space of the Lee-Yang Lagrangian

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

- We are completing the first comprehensive analysis of allowed beta decay transitions in the general framework of the nucleon-level EFT (Lee-Yang Lagrangian)

- Using the latest available data on superallowed, neutron, Fermi, Gamow-Teller, and mirror decays, we build a global 14-parameter likelihood for the 8 Wilson coefficients of the Lee-Yang Lagrangian affecting allowed beta transitions, together with 6 mixing parameter of mirror nuclei included in the analysis

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

- We obtain stringent constraints on the 8 Lee-Yang Wilson coefficients, without any simplifying assumptions that only a subset of these parameters is present in the Lagrangian

- For this analysis, inclusion of the mirror data is essential to lift approximate degeneracies in the multi-parameter space, so as to improve the constraints by an O(2-3) factor

Future

Cirigliano et al 1907.02164

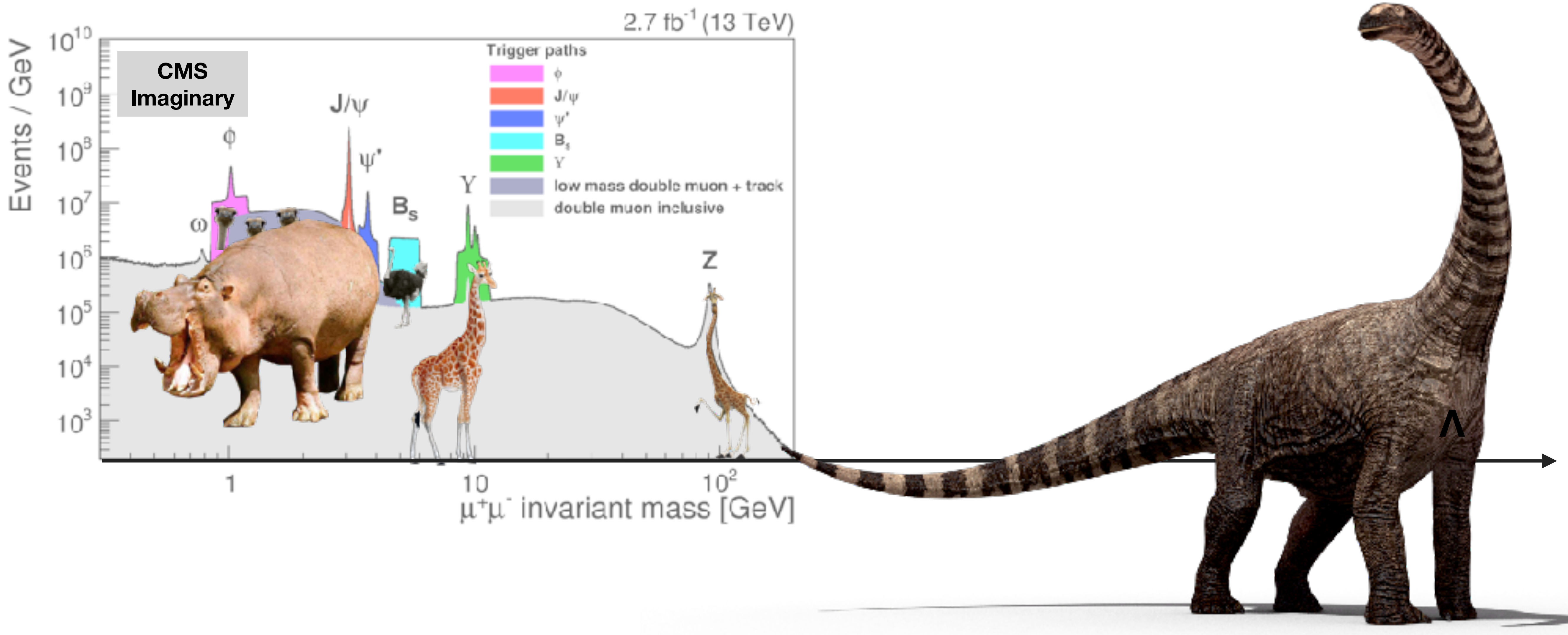
TABLE I. List of nuclear β-decay correlation experiments in search for non-SM physics [a]

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	**Already present tense!**	
$\beta - \nu$	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

Fantastic Beasts and Where To Find Them



THANK YOU

Backup slides

Dimension-6 operators

Warsaw basis

Grządkowski et al.
1008.4884

Bosonic CP-even		Bosonic CP-odd	
O_H	$(H^\dagger H)^3$		
$O_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$		
O_{HD}	$\left\lvert H^\dagger D_\mu H\right\rvert^2$		
O_{HG}	$H^\dagger H\, G^a_{\mu\nu} G^a_{\mu\nu}$	$O_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}^a_{\mu\nu} G^a_{\mu\nu}$
O_{HW}	$H^\dagger H\, W^i_{\mu\nu} W^i_{\mu\nu}$	$O_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}^i_{\mu\nu} W^i_{\mu\nu}$
O_{HB}	$H^\dagger H\, B_{\mu\nu} B_{\mu\nu}$	$O_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B_{\mu\nu}$
O_{HWB}	$H^\dagger \sigma^i H\, W^i_{\mu\nu} B_{\mu\nu}$	$O_{H\widetilde{W}B}$	$H^\dagger \sigma^i H\, \widetilde{W}^i_{\mu\nu} B_{\mu\nu}$
O_W	$\epsilon^{ijk} W^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$	$O_{\widetilde{W}}$	$\epsilon^{ijk} \widetilde{W}^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$
O_G	$f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$	$O_{\widetilde{G}}$	$f^{abc} \widetilde{G}^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$

Table 2.2: Bosonic D=6 operators in the Warsaw basis.

Yukawa	
$[O^\dagger_{eH}]_{IJ}$	$H^\dagger H e^c_I H^\dagger \ell_J$
$[O^\dagger_{uH}]_{IJ}$	$H^\dagger H u^c_I \widetilde{H}^\dagger q_J$
$[O^\dagger_{dH}]_{IJ}$	$H^\dagger H d^c_I H^\dagger q_J$

Vertex	
$[O^{(1)}_{H\ell}]_{IJ}$	$i\bar{\ell}_I \bar{\sigma}_\mu \ell_J H^\dagger \overleftrightarrow{D}_\mu H$
$[O^{(3)}_{H\ell}]_{IJ}$	$i\bar{\ell}_I \sigma^i \bar{\sigma}_\mu \ell_J H^\dagger \sigma^i \overleftrightarrow{D}_\mu H$
$[O_{He}]_{IJ}$	$ie^c_I \sigma_\mu \bar{e}^c_J H^\dagger \overleftrightarrow{D}_\mu H$
$[O^{(1)}_{Hq}]_{IJ}$	$i\bar{q}_I \bar{\sigma}_\mu q_J H^\dagger \overleftrightarrow{D}_\mu H$
$[O^{(3)}_{Hq}]_{IJ}$	$i\bar{q}_I \sigma^i \bar{\sigma}_\mu q_J H^\dagger \sigma^i \overleftrightarrow{D}_\mu H$
$[O_{Hu}]_{IJ}$	$iu^c_I \sigma_\mu \bar{u}^c_J H^\dagger \overleftrightarrow{D}_\mu H$
$[O_{Hd}]_{IJ}$	$id^c_I \sigma_\mu \bar{d}^c_J H^\dagger \overleftrightarrow{D}_\mu H$
$[O_{Hud}]_{IJ}$	$iu^c_I \sigma_\mu \bar{d}^c_J \tilde{H}^\dagger D_\mu H$

Dipole	
$[O^\dagger_{eW}]_{IJ}$	$e^c_I \sigma_{\mu\nu} H^\dagger \sigma^i \ell_J W^i_{\mu\nu}$
$[O^\dagger_{eB}]_{IJ}$	$e^c_I \sigma_{\mu\nu} H^\dagger \ell_J B_{\mu\nu}$
$[O^\dagger_{uG}]_{IJ}$	$u^c_I \sigma_{\mu\nu} T^a \widetilde{H}^\dagger q_J\, G^a_{\mu\nu}$
$[O^\dagger_{uW}]_{IJ}$	$u^c_I \sigma_{\mu\nu} \widetilde{H}^\dagger \sigma^i q_J\, W^i_{\mu\nu}$
$[O^\dagger_{uB}]_{IJ}$	$u^c_I \sigma_{\mu\nu} \widetilde{H}^\dagger q_J\, B_{\mu\nu}$
$[O^\dagger_{dG}]_{IJ}$	$d^c_I \sigma_{\mu\nu} T^a H^\dagger q_J\, G^a_{\mu\nu}$
$[O^\dagger_{dW}]_{IJ}$	$d^c_I \sigma_{\mu\nu} \bar{H}^\dagger \sigma^i q_J\, W^i_{\mu\nu}$
$[O^\dagger_{dB}]_{IJ}$	$d^c_I \sigma_{\mu\nu} H^\dagger q_J\, B_{\mu\nu}$

$(\bar{R}R)(\bar{R}R)$	
O_{ee}	$\eta(e^c\sigma_\mu \bar{e}^c)(e^c\sigma_\mu \bar{e}^c)$
O_{uu}	$\eta(u^c\sigma_\mu \bar{u}^c)(u^c\sigma_\mu \bar{u}^c)$
O_{dd}	$\eta(d^c\sigma_\mu \bar{d}^c)(d^c\sigma_\mu \bar{d}^c)$
O_{eu}	$(e^c\sigma_\mu \bar{e}^c)(u^c\sigma_\mu \bar{u}^c)$
O_{ed}	$(e^c\sigma_\mu \bar{e}^c)(d^c\sigma_\mu \bar{d}^c)$
O_{ud}	$(u^c\sigma_\mu \bar{u}^c)(d^c\sigma_\mu \bar{d}^c)$
O'_{ud}	$(u^c\sigma_\mu T^a \bar{u}^c)(d^c\sigma_\mu T^a \bar{d}^c)$

$(\bar{L}L)(\bar{R}R)$	
$O_{\ell e}$	$(\bar{\ell}\bar{\sigma}_\mu \ell)(e^c\sigma_\mu \bar{e}^c)$
$O_{\ell u}$	$(\bar{\ell}\bar{\sigma}_\mu \ell)(u^c\sigma_\mu \bar{u}^c)$
$O_{\ell d}$	$(\bar{\ell}\bar{\sigma}_\mu \ell)(d^c\sigma_\mu \bar{d}^c)$
O_{eq}	$(e^c\sigma_\mu \bar{e}^c)(\bar{q}\bar{\sigma}_\mu q)$
O_{qu}	$(\bar{q}\bar{\sigma}_\mu q)(u^c\sigma_\mu \bar{u}^c)$
O'_{qu}	$(\bar{q}\bar{\sigma}_\mu T^a q)(u^c\sigma_\mu T^a \bar{u}^c)$
O_{qd}	$(\bar{q}\bar{\sigma}_\mu q)(d^c\sigma_\mu \bar{d}^c)$
O'_{qd}	$(\bar{q}\bar{\sigma}_\mu T^a q)(d^c\sigma_\mu T^a \bar{d}^c)$

$(\bar{L}L)(\bar{L}L)$	
$O_{\ell\ell}$	$\eta(\bar{\ell}\bar{\sigma}_\mu \ell)(\bar{\ell}\bar{\sigma}_\mu \ell)$
O_{qq}	$\eta(\bar{q}\bar{\sigma}_\mu q)(\bar{q}\bar{\sigma}_\mu q)$
O'_{qq}	$\eta(\bar{q}\bar{\sigma}_\mu \sigma^i q)(\bar{q}\bar{\sigma}_\mu \sigma^i q)$
$O_{\ell q}$	$(\bar{\ell}\bar{\sigma}_\mu \ell)(\bar{q}\bar{\sigma}_\mu q)$
$O'_{\ell q}$	$(\bar{\ell}\bar{\sigma}_\mu \sigma^i \ell)(\bar{q}\bar{\sigma}_\mu \sigma^i q)$

$(\bar{L}R)(\bar{L}R)$	
O_{quqd}	$(u^c q^j)\epsilon_{jk}(d^c q^k)$
O'_{quqd}	$(u^c T^a q^j)\epsilon_{jk}(d^c T^a q^k)$
$O_{\ell equ}$	$(e^c \ell^j)\epsilon_{jk}(u^c q^k)$
$O'_{\ell equ}$	$(e^c \bar{\sigma}_{\mu\nu} \ell^j)\epsilon_{jk}(u^c \bar{\sigma}^{\mu\nu} q^k)$
$O_{\ell edq}$	$(\bar{\ell}\bar{e}^c)(d^c q)$

Alonso et al 1312.2014,
Henning et al 1512.03433

Full set has 2499 distinct operators, including flavor structure and CP conjugates

Wilson coefficient of these operators can be connected (now semi-automatically) to fundamental parameters of BSM models like SUSY, composite Higgs, etc.

CP-violating observables in beta decays

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

The triple correlation D is CP-violating

$$D = -2r\sqrt{\frac{J}{J+1}}\frac{\mathrm{Im}\left[C_V^+\bar{C}_A^+ - C_S^+\bar{C}_T^+\right]}{|C_V^+|^2 + |C_S^+|^2 + r^2\left[|C_A^+|^2 + |C_T^+|^2\right]}$$

$$r \equiv \rho C_V^+/C_A^+$$

Back to the quark level Lagrangian:

$$\mathscr{L}_{\mathrm{WEFT}} \supset -\frac{2V_{ud}}{\mathrm{v}^2}\left\{ \begin{array}{l} (1+\epsilon_L)\ \bar{e}_L\gamma_\mu\nu_L\cdot\bar{u}_L\gamma^\mu d_L \\ +\epsilon_R\,\bar{e}_L\gamma_\mu\nu_L\cdot\bar{u}_R\gamma^\mu d_R \\ +\epsilon_T\frac{1}{4}\bar{e}_R\sigma_{\mu\nu}\nu_L\cdot\bar{u}_R\sigma^{\mu\nu}d_L \\ +\epsilon_S\frac{1}{2}\bar{e}_R\nu_L\cdot\bar{u}d \end{array}\right\} + \mathrm{h.c.}$$

$$C_V^+ = \frac{V_{ud}}{\mathrm{v}^2}\sqrt{1+\Delta_R^V}(1+\epsilon_L+\epsilon_R)$$
$$C_A^+ = -\frac{V_{ud}}{\mathrm{v}^2}g_A\sqrt{1+\Delta_R^A}(1+\epsilon_L-\epsilon_R)$$
$$C_T^+ = \frac{V_{ud}}{\mathrm{v}^2}g_T\epsilon_T$$
$$C_S^+ = \frac{V_{ud}}{\mathrm{v}^2}g_S\epsilon_S$$

$$\Rightarrow\quad D = -\frac{4\rho}{1+\rho^2}\sqrt{\frac{J}{J+1}}\mathrm{Im}[\epsilon_R] + \mathcal{O}(\epsilon_X^2)$$

Constraints from D parameter

$$D = -\frac{4\rho}{1+\rho^2}\sqrt{\frac{J}{J+1}}\,\mathrm{Im}[\epsilon_R] + \mathcal{O}(\epsilon_X^2)$$

$$\mathcal{L}_{\rm WEFT} \supset -\frac{2V_{ud}}{\mathrm{v}^2}\epsilon_R\,\bar{e}_L\gamma_\mu\nu_L\cdot\bar{u}_R\gamma^\mu d_R + \mathrm{h.c.}$$

D-parameter probes the CP violating part of the V+A currents in the WEFT Lagrangian

For neutron, the current PDG combination $D_n = (-1.2 \pm 2.0)\times 10^{-4}$

$J_n = 1/2$ $\quad\rho_n \approx -\sqrt{3}g_A \approx -2.2$ $\quad D_n \approx 0.86\,\mathrm{Im}[\epsilon_R]$

This translates into the constraint

$$\boxed{\mathrm{Im}\,\epsilon_R = (-1.4 \pm 2.3)\times 10^{-4}}$$

Up the ladder to the SMEFT:

$$\epsilon_R = \frac{1}{2V_{ud}}c_{Hud}\frac{\mathrm{v}^2}{\Lambda^2} \qquad \Lambda \gtrsim 10\ \mathrm{TeV}\sqrt{|c_{Hud}|}$$