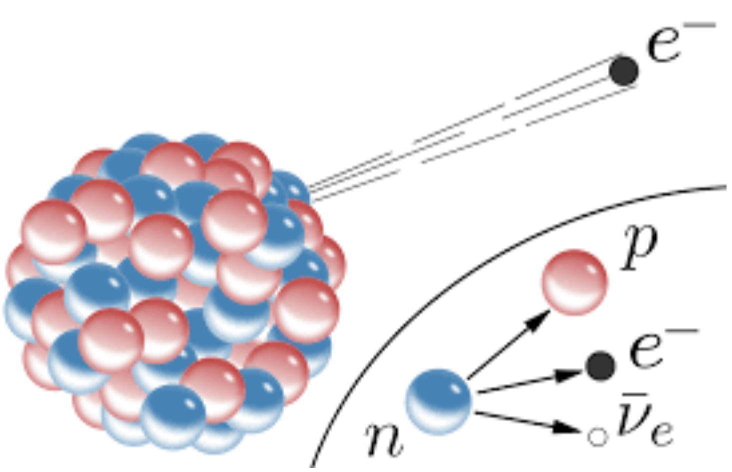
Adam Falkowski

Constraints on new physics from nuclear beta transitions



Oslo, 4 September 2019

Status Report

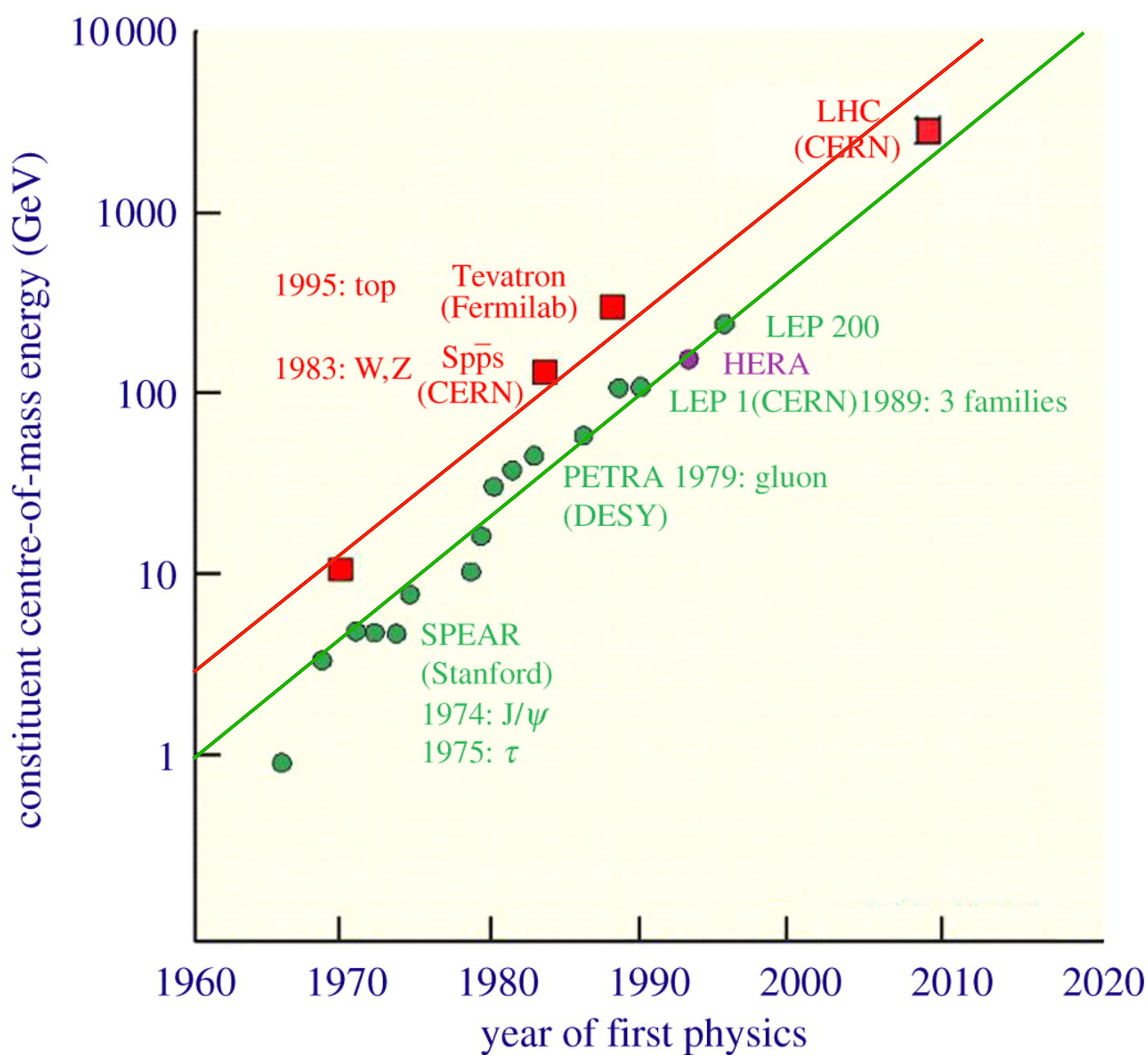
- The Standard Model (SM) has been excessively successful in describing (almost) all collider and low-energy experiments. The discovery of the 125 GeV Higgs boson was the last piece of the puzzle that nicely fell into place. No more free parameters in the SM

- But we know physics beyond the SM exists (neutrino masses, dark matter, inflation, baryon asymmetry). There are also some theoretical hints for new physics (strong CP problem, flavor hierarchies, gauge coupling unifications, naturalness problem)

- At the same time, the current evidences and hints of new physics do not point to one specific model or a class of models. In particular, the naturalness paradigm seems to be a dead end, which means that BSM physics can be at any mass scale, from sub-eV to Planck scales

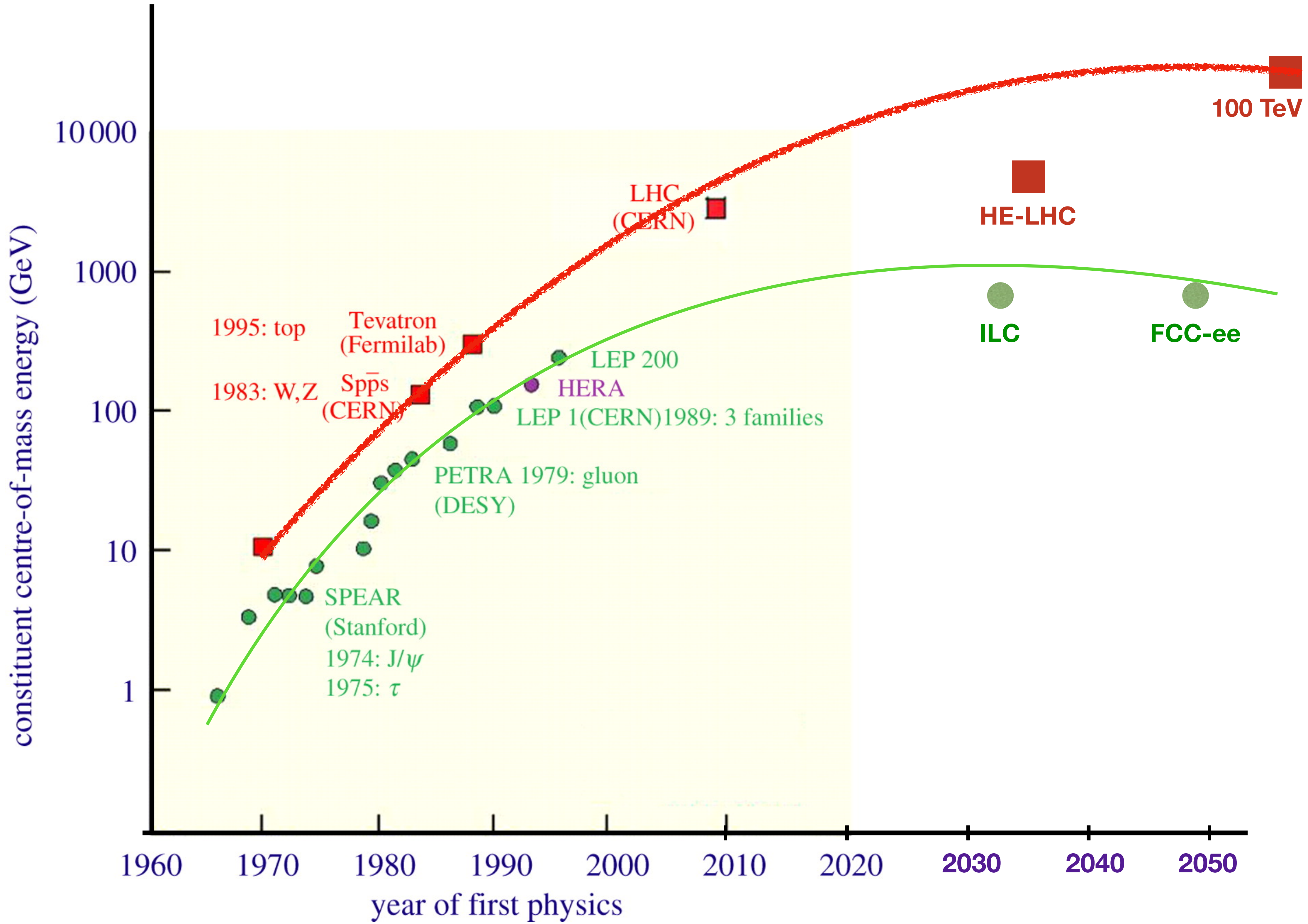
- To make further progress we need a hint from experiment…

High-energy frontier



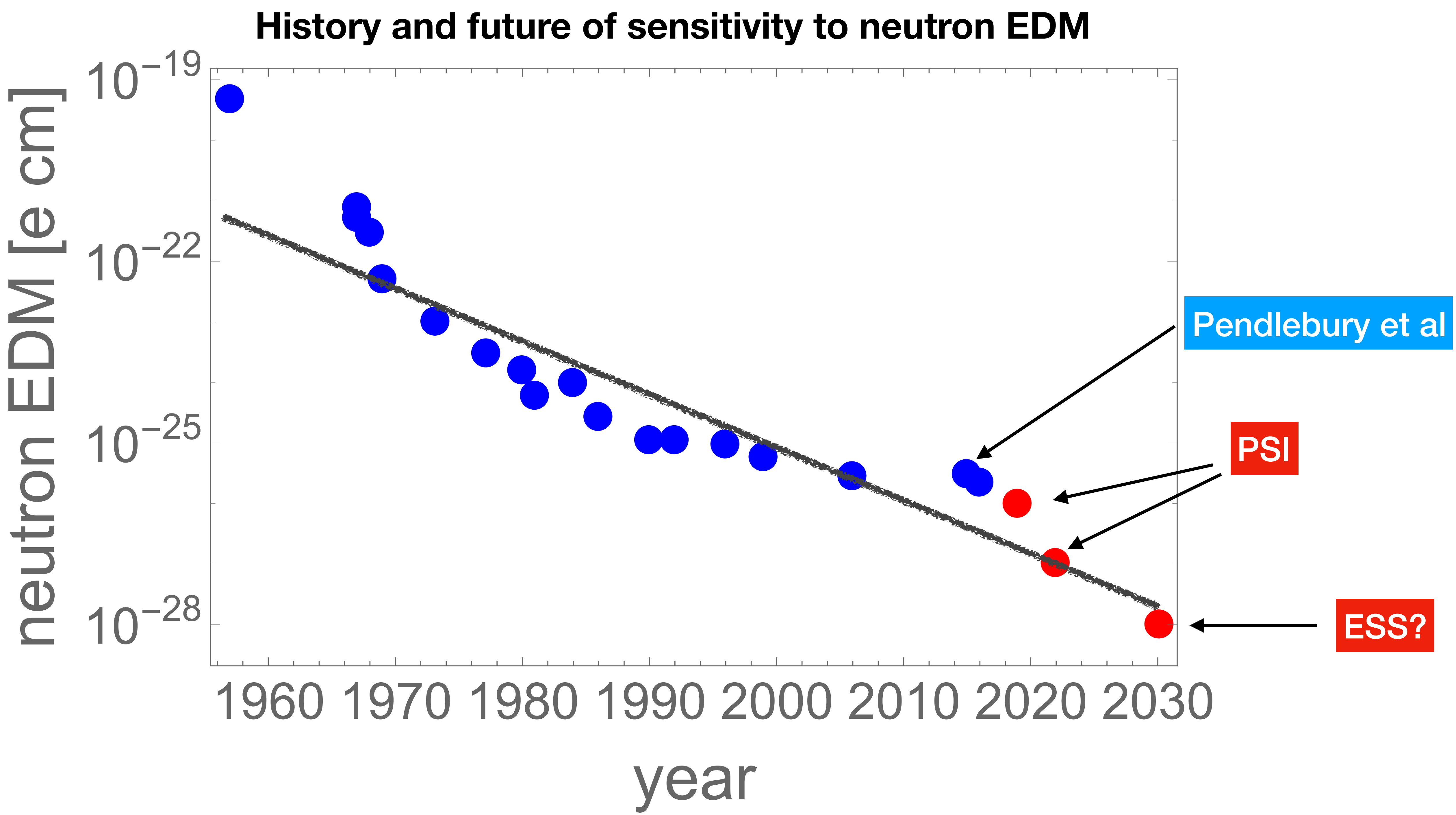
Most of what we know about fundamental interactions we learned on the high-energy frontier

High-energy frontier



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

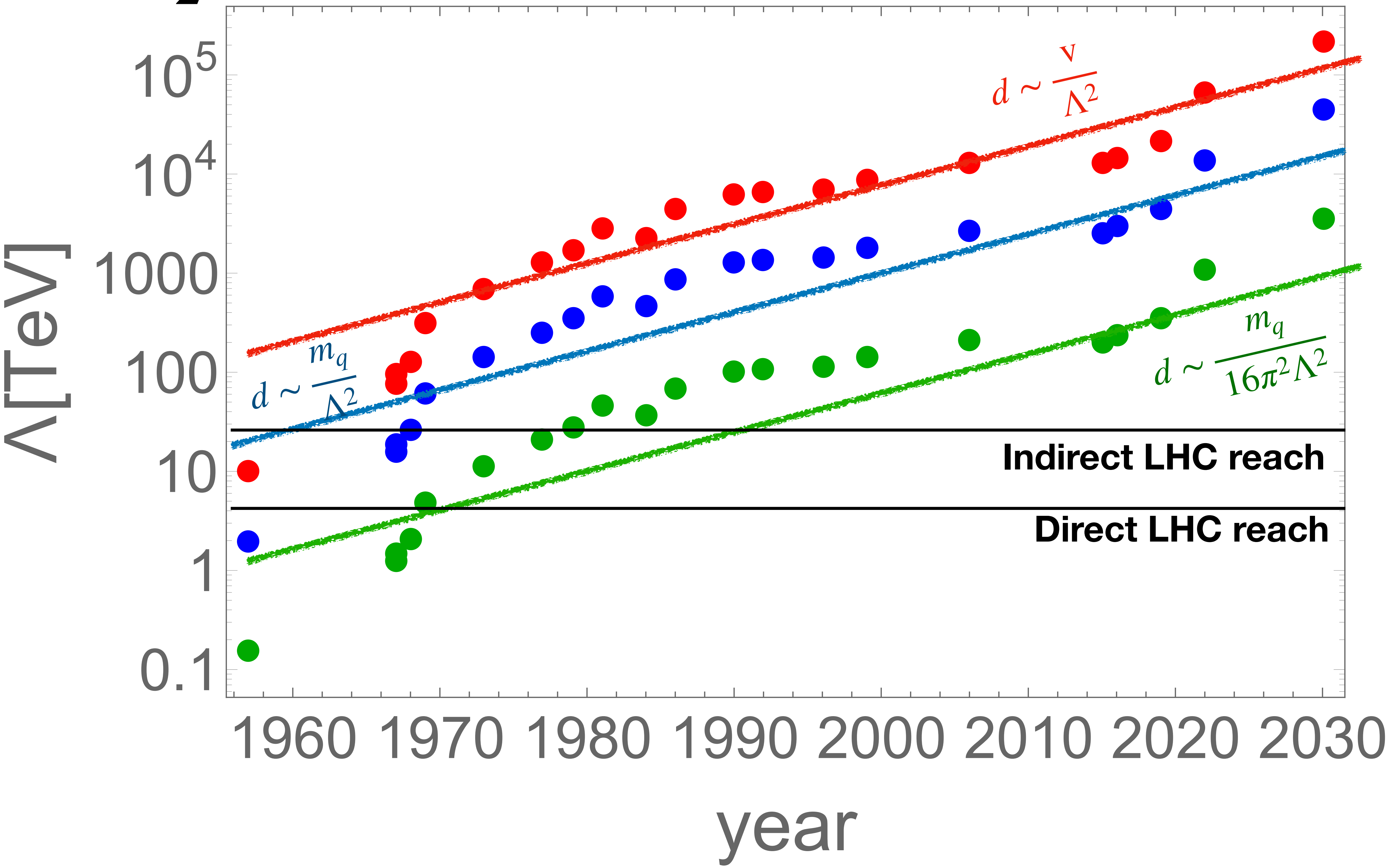
Low-energy frontier



Neutron EDM and a host of other precision measurements is providing complementary information about fundamental interactions

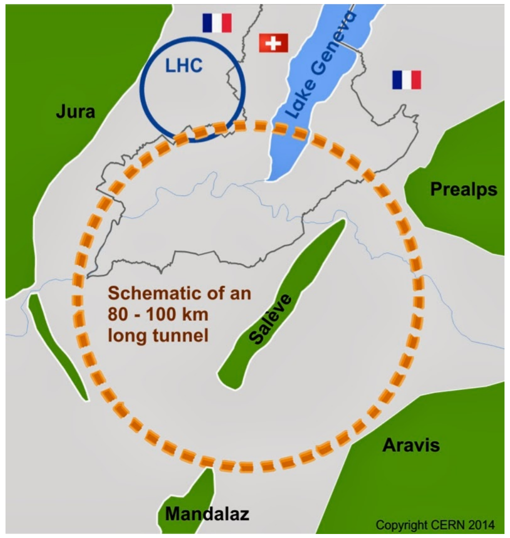
Low-energy frontier

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



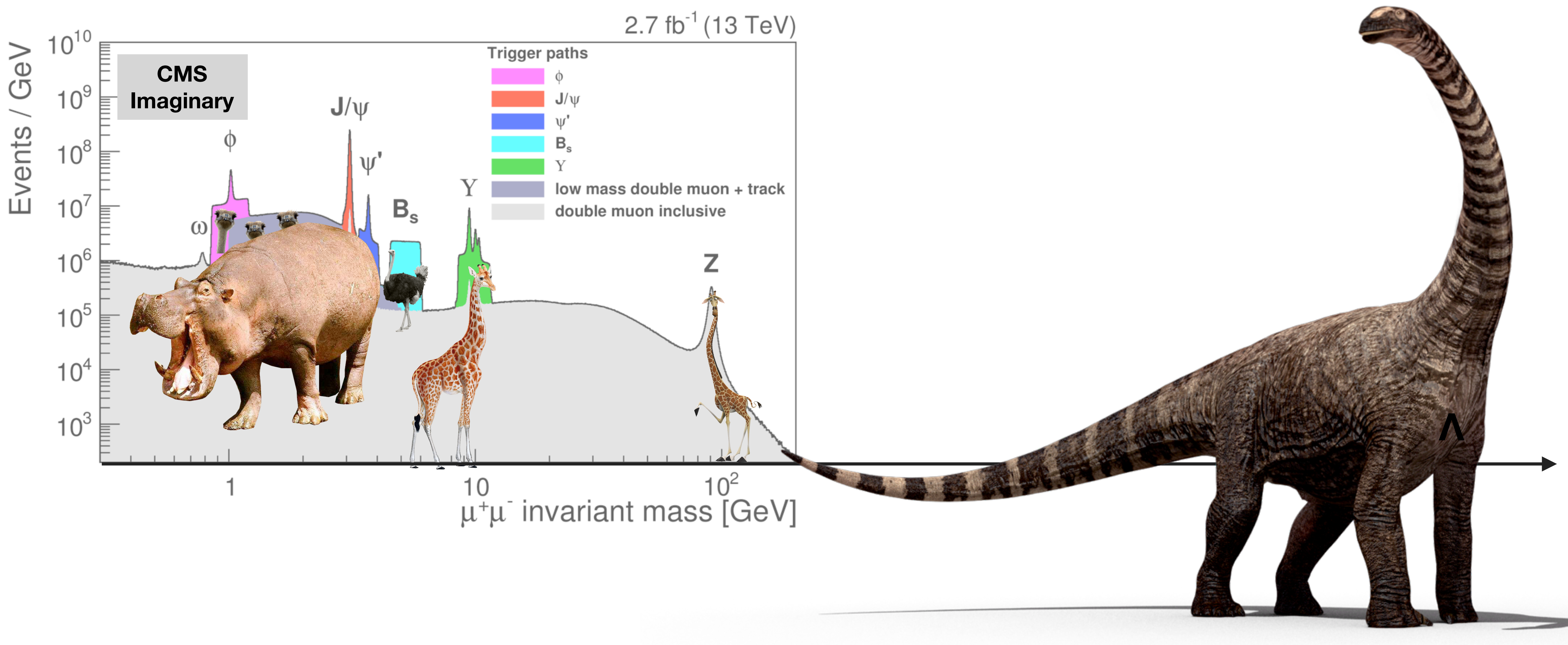
Precision frontier has had a slower pace of progress compared to high-energy colliders, order of magnitude/20 years, however higher scales reached and no sign of flatlining

Future HEP



High-energy frontier

Low-energy frontier



High energy frontier is about finding heads

Low energy frontier is about finding tails

Low-energy frontier

Rare or forbidden processes

E.g.
proton decay,
neutron-antineutron oscillations,
neutron and electron EDM,
charged lepton flavor violation:
$\mu \to e\gamma$, $\tau \to l\gamma$, $B_s \to \mu e$ …

Zero or negligible SM background
Simple interpretation: any signal is unambiguous evidence of new physics

Precision measurements

E.g.
electron or muon MDM,
atomic parity violation,
basically entire flavor physics:
neutral meson mixing, kaon ε'/ε
$\pi \to l\nu$, $B_s \to \mu\mu$, $K \to \pi\nu\nu$, …

Signal appears as a small correction on top of the SM prediction
More difficult interpretation: evidence from new physics requires good understanding of backgrounds (often non-perturbative)

Typically, observables sensitive to new physics scale as

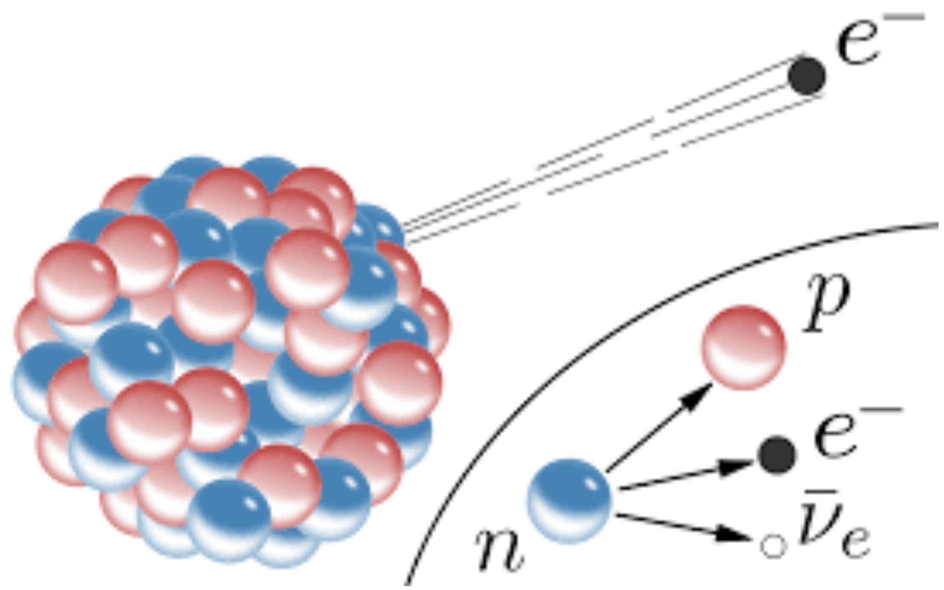
$$\text{Precision} \sim \frac{1}{\Lambda^4}$$

(except for EDMs, where $d \sim \Lambda^{-2}$)

$$\text{Precision} \sim \frac{1}{\Lambda^2}$$

(except when NP does not interfere with SM)

This talk: precision measurements of nuclear beta decays



Nuclear level:

$$N(Z,A) \rightarrow N(Z+1,A) + e^- + \bar{\nu}$$

or

$$N(Z,A) \rightarrow N(Z-1,A) + e^+ + \nu$$

Nucleon level:

$$n \rightarrow p + e^- + \bar{\nu}$$

or

$$p \rightarrow n + e^+ + \nu$$

Fundamental level:

$$d \rightarrow u + e^- + \bar{\nu}$$

or

$$u \rightarrow d + e^+ + \nu$$

Language for nuclear beta transitions

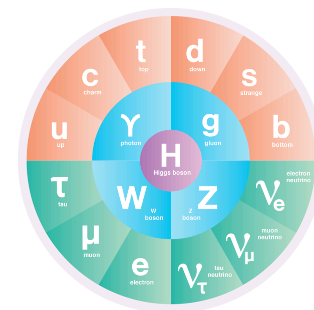
Language

- 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

Energy Scale	Theory	Particles	Expansion Parameter
1 TeV 100 GeV	SMEFT		$\frac{E}{\Lambda}$
10 GeV 1 GeV	WEFT (aka Fermi theory, LEFT, WET)	**γ,g,ν,e,μ,τ + N_f q**	$\frac{E}{m_W}$
100 MeV 10 MeV 1 MeV	NR-WEFT	**γ,ν,e,p,n**	$\frac{E_k}{m_p}$

WEFT = minimal EFT below the weak scale

- For beta decays, the characteristic energy scale is much smaller than the W and Z boson mass. One can describe it using a simpler theory where W and Z bosons (and also Higgs and heavy quarks) are absent

- Central assumption here is that there is no other light degrees of freedom beyond those of the SM

- Then, below m_W, the only degrees of freedom available are leptons, photon, gluons, and 3, 4, or 5 flavors of quark, depending on the energy scale. The local symmetry group is $SU(3)xU(1)_{em}$ rather than the full $SU(3)xSU(2)xU(1)_Y$ of the SM

- The effective theory of these degrees of freedom with this local symmetry is referred to as the WEFT (also known as the Fermi theory, WET, LEFT,…)

Leading order WEFT for beta decays

CKM element

Part relevant for beta decays

$$\mathcal{L}_{WEFT} \supset -\frac{V_{ud}}{2\mathrm{v}^2}\Big[\left(1+\epsilon_L\right)\bar{e}\gamma_\mu(1-\gamma_5)\nu_e\cdot\bar{u}\gamma^\mu(1-\gamma_5)d \qquad \text{"V-A"}$$

$$+\epsilon_R\,\bar{e}\gamma_\mu(1-\gamma_5)\nu_e\cdot\bar{u}\gamma^\mu(1+\gamma_5)d \qquad \text{"V+A"}$$

$$+\bar{e}(1-\gamma_5)\nu_e\cdot\bar{u}\left[\epsilon_S-\epsilon_P\gamma_5\right]d \qquad \text{"(Pseudo)Scalar"}$$

$$+\epsilon_T\,\bar{e}\sigma_{\mu\nu}(1-\gamma_5)\nu_e\cdot\bar{u}\sigma^{\mu\nu}(1-\gamma_5)d\Big] + \mathrm{h.c.}$$

"Tensor"

Normalization scale, by convention set by Fermi constant

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

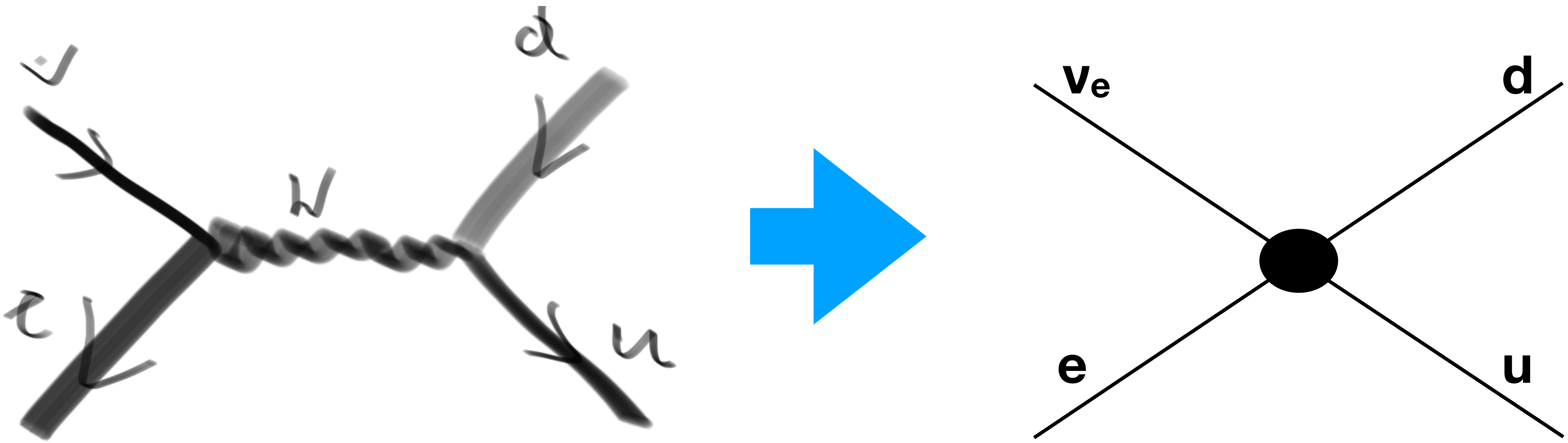
Charged currents with different Lorentz structure

If WEFT Lagrangian is a low-energy approximation of the SM then all ε_X are zero at leading order

Leading order Lagrangian relevant for beta decays parametrized by 5 BSM unknowns ε_X, and one SM (apriori) unknown V_{ud}.
More free parameters at NLO, where Lagrangian contains derivative interactions.

Interpretation of BSM parameters

W exchange in the SM leads to the V-A effective interaction in WEFT

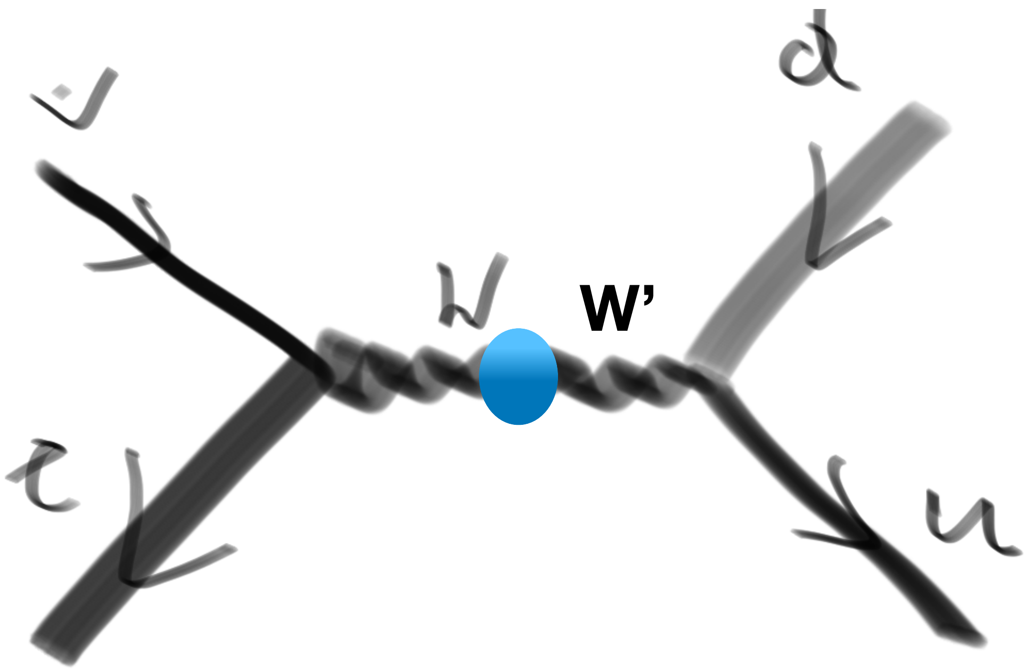


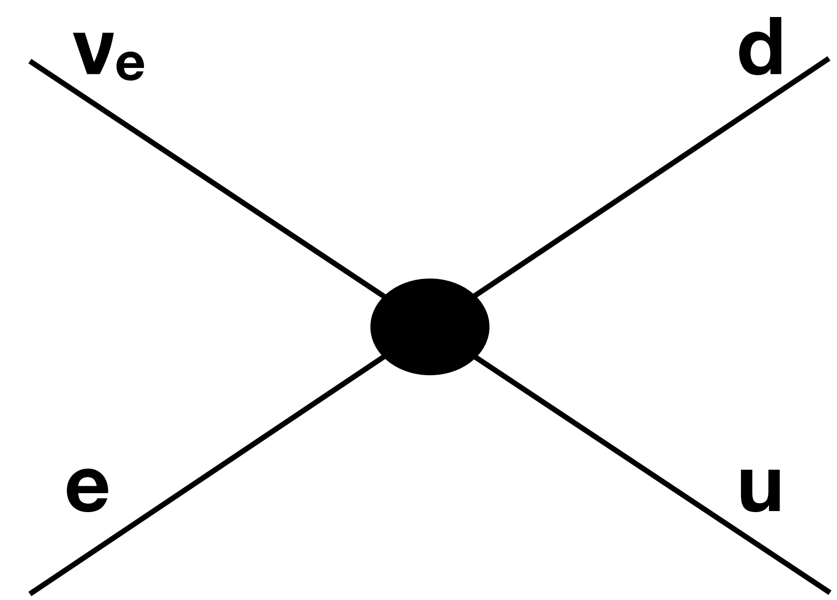
$$-\frac{g^W_{\nu e} g^W_{ud}}{4 m_W^2} V_{ud} \bar{e} \gamma_\mu (1-\gamma_5) \nu_e \cdot \bar{u} \gamma^\mu (1-\gamma_5) d$$

The BSM parameter ε_L measures deviations of the W boson couplings to quarks and leptons, compared to the SM prediction

Interpretation of BSM parameters

E.g. left-right symmetric $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_X$ models introduce new charged vector bosons W' coupling to right-handed quarks



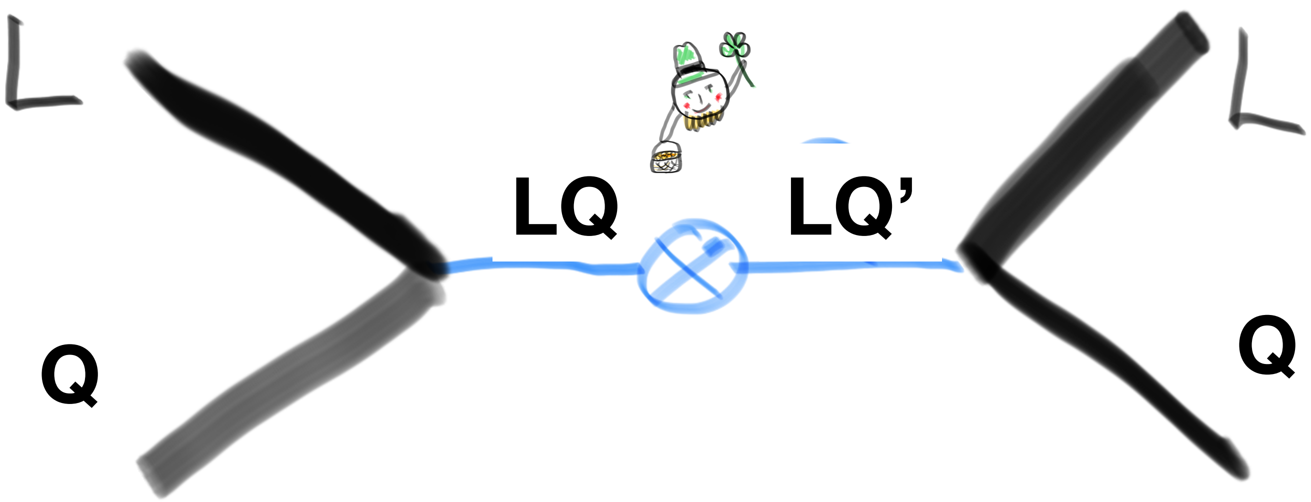


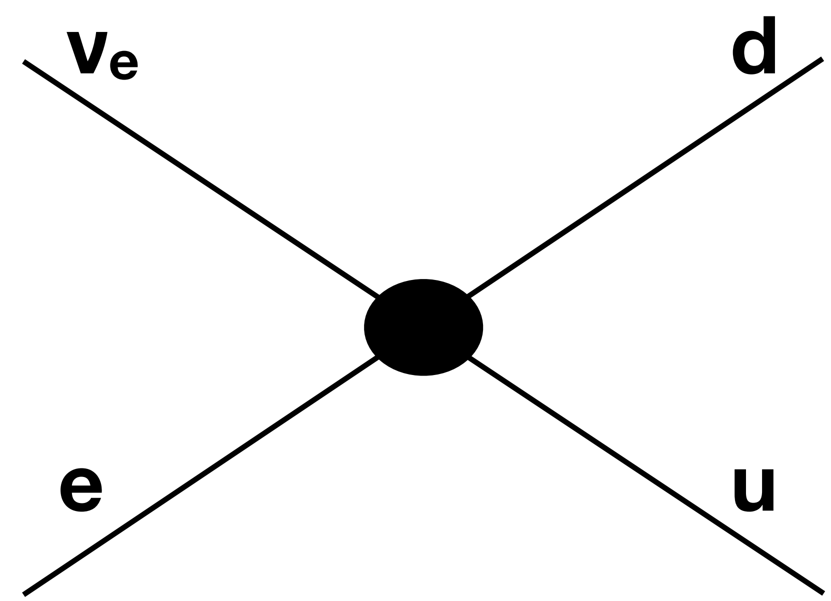
$$\bar{e}\gamma_\mu(1-\gamma_5)\nu_e \cdot \bar{u}\gamma^\mu(1+\gamma_5)d$$

$$\epsilon_R \sim \frac{m_W^2}{m_{W'}^2}$$

Interpretation of BSM parameters

In leptoquark models, new scalar particles couple to both quarks and leptons





$$\epsilon_{S,P,T} \sim \frac{v^2}{m_{LQ}^2}$$

Leading order WEFT for beta decays

Part relevant for beta decays

$$\mathscr{L}_{WEFT} \supset -\frac{V_{ud}}{2\mathrm{v}^2}\Bigg[\Big(1+\epsilon_L\Big)\bar{e}\gamma_\mu(1-\gamma_5)\nu_e \cdot \bar{u}\gamma^\mu(1-\gamma_5)d$$ **"V-A"**

$$+\epsilon_R\,\bar{e}\gamma_\mu(1-\gamma_5)\nu_e \cdot \bar{u}\gamma^\mu(1+\gamma_5)d$$ **"V+A"**

$$+\bar{e}(1-\gamma_5)\nu_e \cdot \bar{u}\Big[\epsilon_S - \epsilon_P\gamma_5\Big]d$$ **"(Pseudo)Scalar"**

$$+\epsilon_T\,\bar{e}\sigma_{\mu\nu}(1-\gamma_5)\nu_e \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5)d\Bigg] + \mathrm{h.c.}$$

"Tensor"

The goal is to determine simultaneously determine V_{ud} and constrain ϵ_X using all available data on nuclear beta transitions

Down the EFT rabbit hole

1. Lee-Yang Lagrangian for nucleons (protons and electrons)

$$\mathscr{L}_{\rm LY} \supset -\frac{V_{ud}}{{\rm v}^2}\Big\{g_V\left[1+\epsilon_L+\epsilon_R\right](\bar{p}\gamma^\mu n)(\bar{e}\gamma_\mu P_L\nu_e) - g_A\left[1+\epsilon_L-\epsilon_R\right](\bar{p}\gamma^\mu\gamma_5 n)(\bar{e}\bar{\gamma}_\mu P_L\nu_e)$$

$$+g_S\epsilon_S(\bar{p}n)(\bar{e}P_L\nu_e) - g_P\epsilon_P(\bar{p}\gamma_5 n)(\bar{e}P_L\nu_e) + \frac{1}{2}g_T\epsilon_T(\bar{p}\sigma^{\mu\nu}n)(\bar{e}\sigma_{\mu\nu}P_L\nu_e)\Big\} + {\rm h.c.}$$

g_X are matrix elements of the corresponding quark bilinear on the nucleon states:

$$g_V \equiv \langle n|\bar{u}\gamma_\mu d|p\rangle, \qquad g_A \equiv \langle n|\bar{u}\gamma_\mu\gamma_5 d|p\rangle, \qquad {\rm etc.}$$

They are called vector, axial, scalar, pseudoscalar, and tensor nucleon charges

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

$$g_V \approx 1, \qquad g_A = 1.251 \pm 0.033, \quad g_S = 1.02 \pm 0.10, \quad g_P = 349 \pm 9, \quad g_T = 0.989 \pm 0.033$$

Down the EFT rabbit hole

2. Leading order non-relativistic Lagrangian for nucleons

For all beta decays, nuclei are non-relativistic (in N rest frame).
Thus we can use non-relativistic approximation for neutron and proton fields.

NR proton and neutron fields

Higher-order in $\frac{\nabla \psi}{2m_p}$

$$\mathscr{L}_{\rm LY}^{\rm NR} = -\frac{V_{ud}}{v^2}(\bar{\psi}_p\psi_n)\left\{\left[1+\epsilon_L+\epsilon_R\right](\bar{e}\gamma^0 P_L\nu_e) + g_S\epsilon_S(\bar{e}P_L\nu_e)\right\}$$
$$+\frac{V_{ud}}{v^2}(\bar{\psi}_p\sigma^k\psi_n)\left\{g_A\left[1+\epsilon_L-\epsilon_R\right](\bar{e}\gamma^0\sigma^k P_L\nu_e) - g_T\epsilon_T(\bar{e}\sigma^k P_L\nu_e)\right\} + \mathrm{h.c.} + \ldots$$

No dependence on pseudoscalar BSM interactions at leading order

At leading order, only two nuclear matrix elements are needed to calculate amplitudes:

$N \to N' e \nu$

$$M_{\rm F} = \langle N' | \bar{\psi}_p \psi_n | N \rangle$$

Fermi transitions
Calculable from group theory

$$M_{\rm GT} = \langle N' | \bar{\psi}_p \sigma^k \psi_n | N \rangle$$

Gamow-Teller transitions
Difficult to calculate

$$\langle j', m', J', M' | \bar{\psi}_p \psi_n | j, m, J, M \rangle \approx \sqrt{j(j+1) - m(m+1)}\,\delta_{jj'}\delta_{m',m+1}\delta_{JJ'}\delta_{MM'}$$

Isospin **Spin**

Down the EFT rabbit hole

3. Simplify and remove redundancies

$$\mathscr{L}_{\rm LY}^{\rm NR} = -\frac{V_{ud}}{v^2}(\bar\psi_p\psi_n)\left\{\left[1+\epsilon_L+\epsilon_R\right](\bar e\gamma^0 P_L\nu_e) + g_S\epsilon_S(\bar e P_L\nu_e)\right\}$$

$$+\frac{V_{ud}}{v^2}(\bar\psi_p\sigma^k\psi_n)\left\{g_A\left[1+\epsilon_L-\epsilon_R\right](\bar e\gamma^0\sigma^k P_L\nu_e) - g_T\epsilon_T(\bar e\sigma^k P_L\nu_e)\right\} + \mathrm{h.c.} + \ldots$$

We can simplify Lagrangian by defining new tilde variables:

$$\tilde V_{ud} \equiv V_{ud}\left(1+\epsilon_L+\epsilon_R\right), \qquad \tilde g_A \equiv g_A\frac{1+\epsilon_L-\epsilon_R}{1+\epsilon_L+\epsilon_R},$$

$$\tilde\epsilon_S \equiv g_S\frac{\epsilon_S}{1+\epsilon_L+\epsilon_R}, \qquad \tilde\epsilon_T \equiv \frac{g_T}{g_A}\frac{\epsilon_T}{1+\epsilon_L-\epsilon_R},$$

$$\mathscr{L}_{\rm LY}^{\rm NR} = -\frac{\tilde V_{ud}}{v^2}(\bar\psi_p\psi_n)\left\{(\bar e\gamma^0 P_L\nu_e) + \tilde\epsilon_S(\bar e P_L\nu_e)\right\}$$

$$+\frac{\tilde V_{ud}\tilde g_A}{v^2}(\bar\psi_p\sigma^k\psi_n)\left\{(\bar e\gamma^0\sigma^k P_L\nu_e) - \tilde\epsilon_T(\bar e\sigma^k P_L\nu_e)\right\} + \mathrm{h.c.} + \ldots$$

This makes clear that nuclear beta transitions at leading order probe:

- 2 “contaminated” SM parameters tilde V_{ud} and tilde g_A,

- 2 BSM parameters tilde ε_S and tilde ε_T.

The goal is to determine all 4 of these parameters simultaneously from all available data on nuclear beta transitions

Allowed beta transitions

Allowed beta decays

- Allowed beta decays are the ones for which Fermi or Gamow-Teller (or both) matrix element is non-zero

- Characterized by relatively short lifetimes. Most of experimental and theoretical efforts is concerned with those

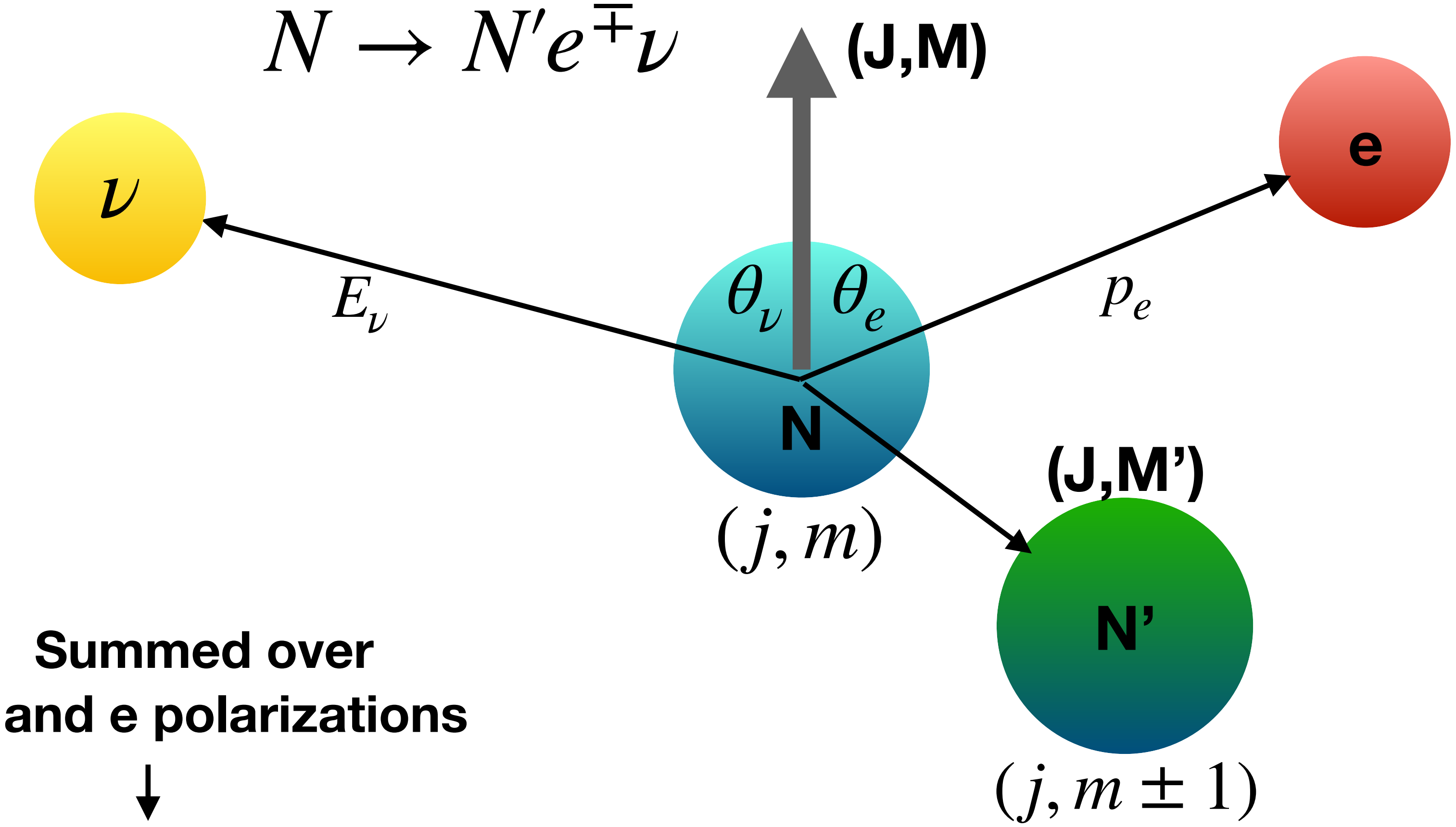
- In the following, I assume parameters ϵ_X are real - no CP violation

- Discussion at leading order in non-relativistic expansion in inverse nucleon mass. NLO corrections are important when precision reaches per-mille level, but they won't be discussed here. There are also non-perturbative Fermi corrections, isospin breaking corrections, nuclear structure corrections, etc. They are numerically important, but again not discussed here

- Discussion at leading order in BSM parameters tilde ϵ_X

Allowed beta decays

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



Electron energy/momentum

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

Neutrino energy

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

Fermi matrix element

$$M_{F_\mp} = \sqrt{j(j+1) - m(m \pm 1)}$$

Fermi-Gamow-Teller mixing

$$\tilde{\rho} = \tilde{g}_A \frac{M_{\rm GT}}{M_{\rm F}}$$

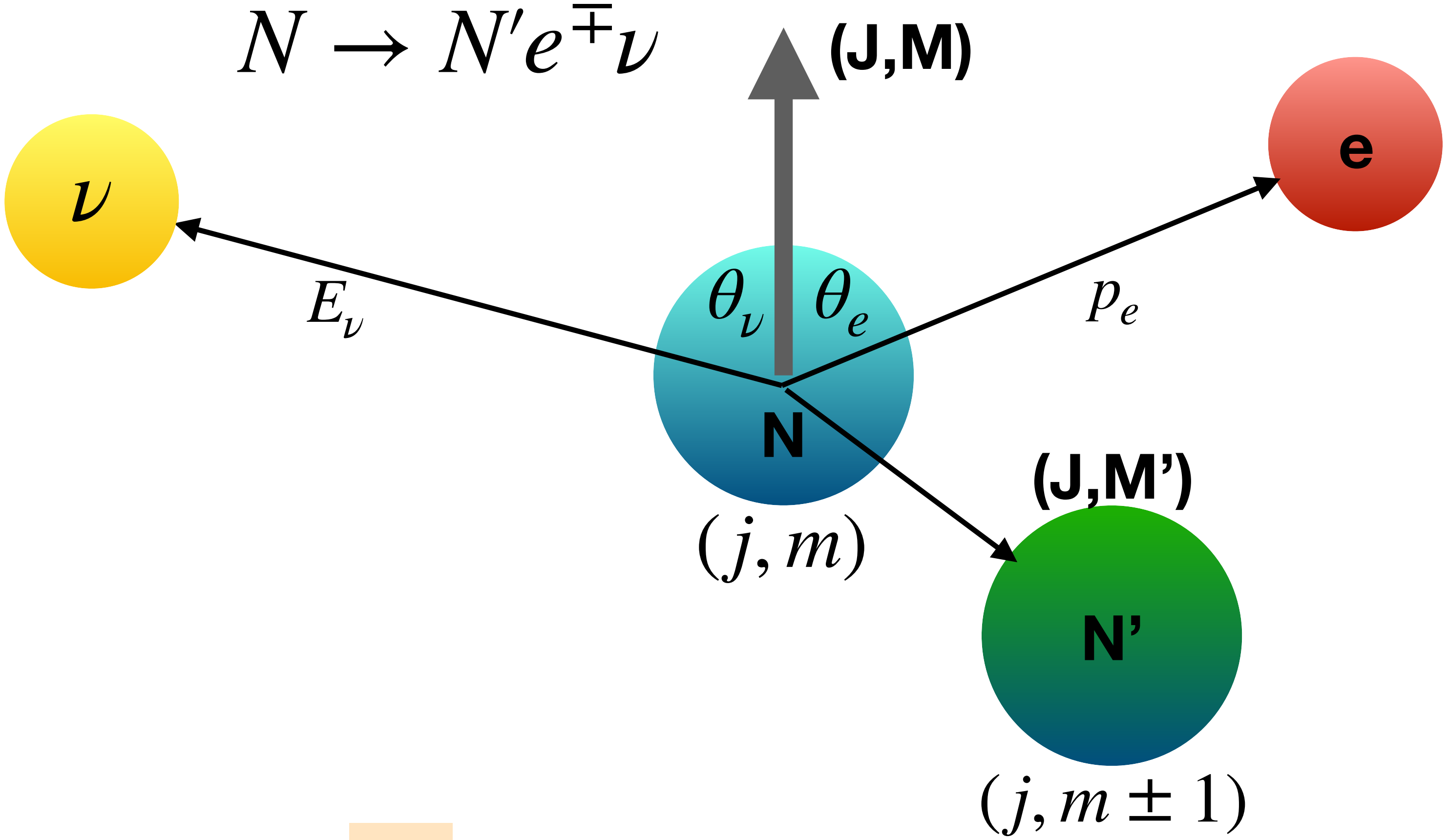
Summed over N' and e polarizations

↓

$$\frac{d\Gamma}{d\Omega_e d\Omega_\nu dE_e} = \frac{\tilde{V}_{ud}^2 M_{F_\mp}^2 E_\nu^2 p_e E_e}{64\pi^5 \mathrm{v}^4} \Bigg\{ (1+\tilde{\rho}^2) \pm 2\left(\tilde{\epsilon}_S - \tilde{\rho}^2 \tilde{\epsilon}_T\right) \frac{m_e}{E_e}$$
$$+ \left(1 - \tilde{\rho}^2 + 2\tilde{\rho}^2 \frac{M^2}{J(J+1)}\right) \cos\theta_e \cos\theta_\nu \frac{p_e}{E_e} + \left(1 - \tilde{\rho}^2 \frac{M^2}{J(J+1)}\right) \sin\theta_e \sin\theta_\nu \cos\phi \frac{p_e}{E_e}$$
$$- M\tilde{\rho}\cos\theta_\nu \left[\frac{2\sqrt{J(J+1)} \mp \tilde{\rho}}{J(J+1)} \pm 2\tilde{\epsilon}_S \frac{1}{\sqrt{J(J+1)}} \frac{m_e}{E_e} + 2\tilde{\epsilon}_T \frac{\tilde{\rho} \mp \sqrt{J(J+1)}}{J(J+1)} \frac{m_e}{E_e} \right]$$
$$- M\tilde{\rho} \frac{2\sqrt{J(J+1)} \pm \tilde{\rho}}{J(J+1)} \cos\theta_e \frac{p_e}{E_e} \Bigg\} + \mathcal{O}(\epsilon_X^2) + \mathcal{O}(m_N^{-1})$$

Allowed beta decays

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



Total rate proportional to the (contaminated) CKM element V_{ud} .

$$\frac{d\Gamma}{d\Omega_e d\Omega_\nu dE_e} = \frac{\tilde{V}_{ud}^2 M_{F_\mp}^2 E_\nu^2 p_e E_e}{64\pi^5 \mathrm{v}^4} \Bigg\{ (1+\tilde{\rho}^2) \pm 2\left(\tilde{\epsilon}_S - \tilde{\rho}^2 \tilde{\epsilon}_T\right) \frac{m_e}{E_e}$$

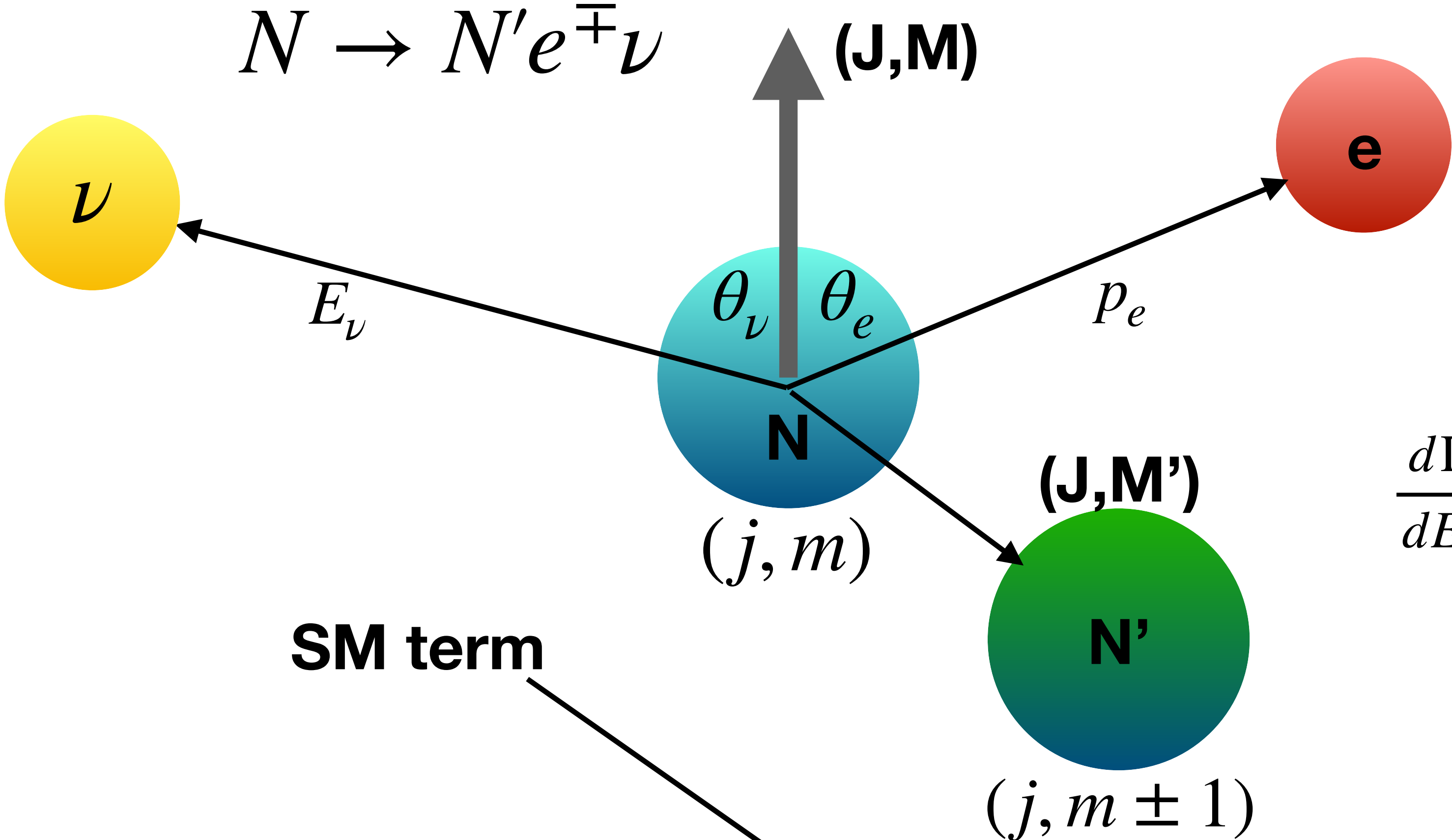
$$+ \left(1 - \tilde{\rho}^2 + 2\tilde{\rho}^2 \frac{M^2}{J(J+1)}\right) \cos\theta_e \cos\theta_\nu \frac{p_e}{E_e} + \left(1 - \tilde{\rho}^2 \frac{M^2}{J(J+1)}\right) \sin\theta_e \sin\theta_\nu \cos\phi \frac{p_e}{E_e}$$

$$- M\tilde{\rho}\cos\theta_\nu \left[\frac{2\sqrt{J(J+1)} \mp \tilde{\rho}}{J(J+1)} \pm 2\tilde{\epsilon}_S \frac{1}{\sqrt{J(J+1)}} \frac{m_e}{E_e} + 2\tilde{\epsilon}_T \frac{\tilde{\rho} \mp \sqrt{J(J+1)}}{J(J+1)} \frac{m_e}{E_e} \right]$$

$$- M\tilde{\rho} \frac{2\sqrt{J(J+1)} \pm \tilde{\rho}}{J(J+1)} \cos\theta_e \frac{p_e}{E_e} \Bigg\} + \mathcal{O}(\epsilon_X^2) + \mathcal{O}(m_N^{-1})$$

Allowed beta decays

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



Lifetime and beta energy spectrum depend on all 4 parameters

$$\frac{d\Gamma}{dE_e} = \frac{\tilde{V}_{ud}^2 M_{F_\mp}^2 E_\nu^2 p_e E_e}{4\pi^3 \mathrm{v}^4}\left\{(1+\tilde{\rho}^2) \pm 2\left(\tilde{\epsilon}_S - \tilde{\rho}^2 \tilde{\epsilon}_T\right)\frac{m_e}{E_e}\right\}$$

$$\tau = \left(\int dE_e \frac{d\Gamma}{dE_e}\right)^{-1}$$

SM term

Fierz term

$$\frac{d\Gamma}{d\Omega_e d\Omega_\nu dE_e} = \frac{\tilde{V}_{ud}^2 M_{F_\mp}^2 E_\nu^2 p_e E_e}{64\pi^5 \mathrm{v}^4}\left\{(1+\tilde{\rho}^2) \pm 2\left(\tilde{\epsilon}_S - \tilde{\rho}^2\tilde{\epsilon}_T\right)\frac{m_e}{E_e}\right.$$

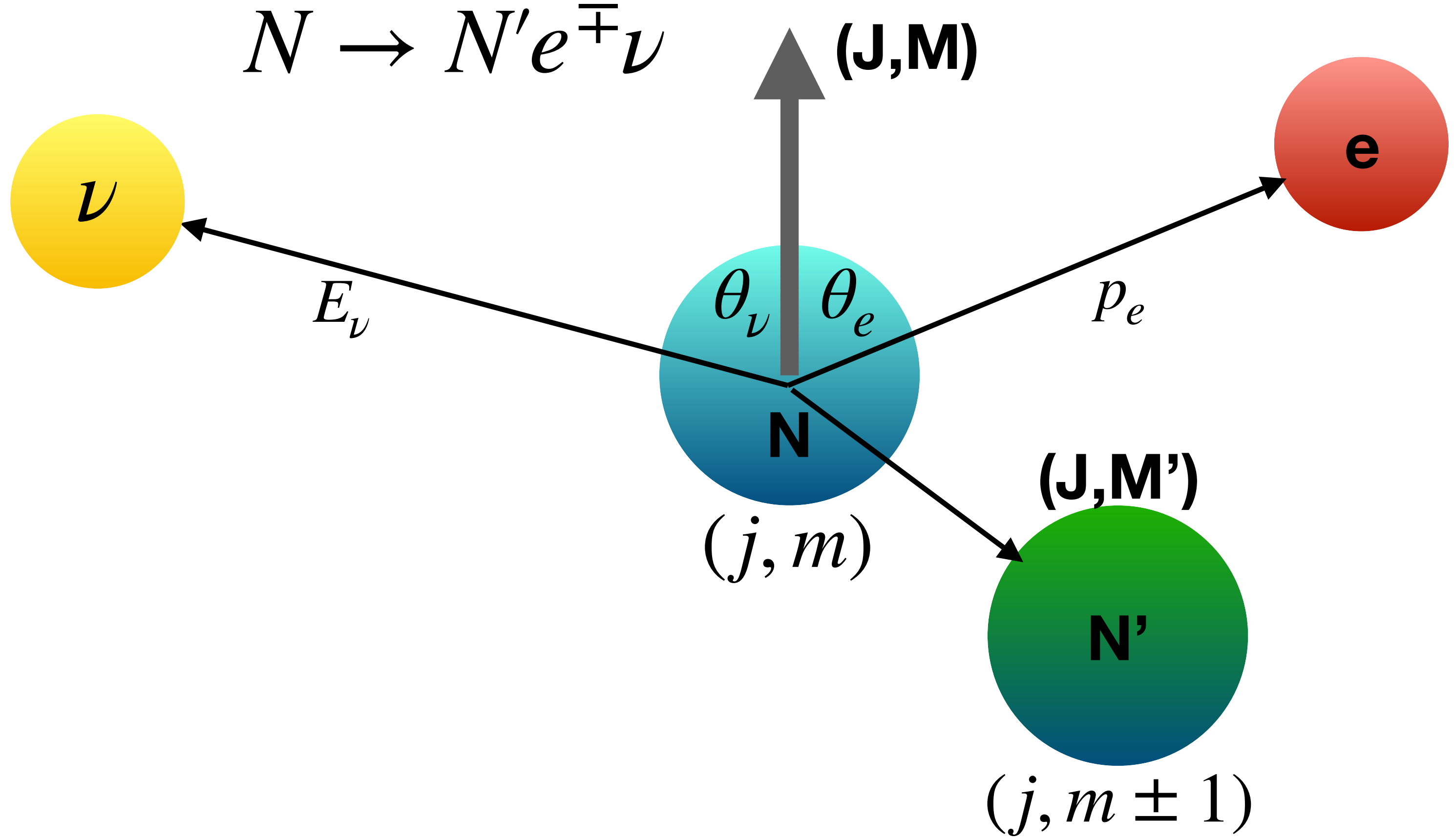
$$+\left(1 - \tilde{\rho}^2 + 2\tilde{\rho}^2 \frac{M^2}{J(J+1)}\right)\cos\theta_e \cos\theta_\nu \frac{p_e}{E_e} + \left(1 - \tilde{\rho}^2 \frac{M^2}{J(J+1)}\right)\sin\theta_e \sin\theta_\nu \cos\phi \frac{p_e}{E_e}$$

$$-M\tilde{\rho}\cos\theta_\nu\left[\frac{2\sqrt{J(J+1)} \mp \tilde{\rho}}{J(J+1)} \pm 2\tilde{\epsilon}_S \frac{1}{\sqrt{J(J+1)}}\frac{m_e}{E_e} + 2\tilde{\epsilon}_T \frac{\tilde{\rho} \mp \sqrt{J(J+1)}}{J(J+1)}\frac{m_e}{E_e}\right]$$

$$\left.-M\tilde{\rho}\frac{2\sqrt{J(J+1)} \pm \tilde{\rho}}{J(J+1)}\cos\theta_e \frac{p_e}{E_e}\right\} + \mathcal{O}(\epsilon_X^2) + \mathcal{O}(m_N^{-1})$$

Allowed beta decays

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



After summing over polarizations of N 2nd line describes asymmetry between electron and neutrino directions

$$a_{\beta\nu} = \frac{1 - \tilde{\rho}^2/3}{1 + \tilde{\rho}^2} + \mathcal{O}(\epsilon_X^2)$$

βν asymmetry directly measures "contaminated" mixing parameter

$$\frac{d\Gamma}{d\Omega_e d\Omega_\nu dE_e} = \frac{\tilde{V}_{ud}^2 M_{F_\mp}^2 E_\nu^2 p_e E_e}{64\pi^5 \mathrm{v}^4} \Bigg\{ (1 + \tilde{\rho}^2) \pm 2\left(\tilde{\epsilon}_S - \tilde{\rho}^2 \tilde{\epsilon}_T\right) \frac{m_e}{E_e}$$

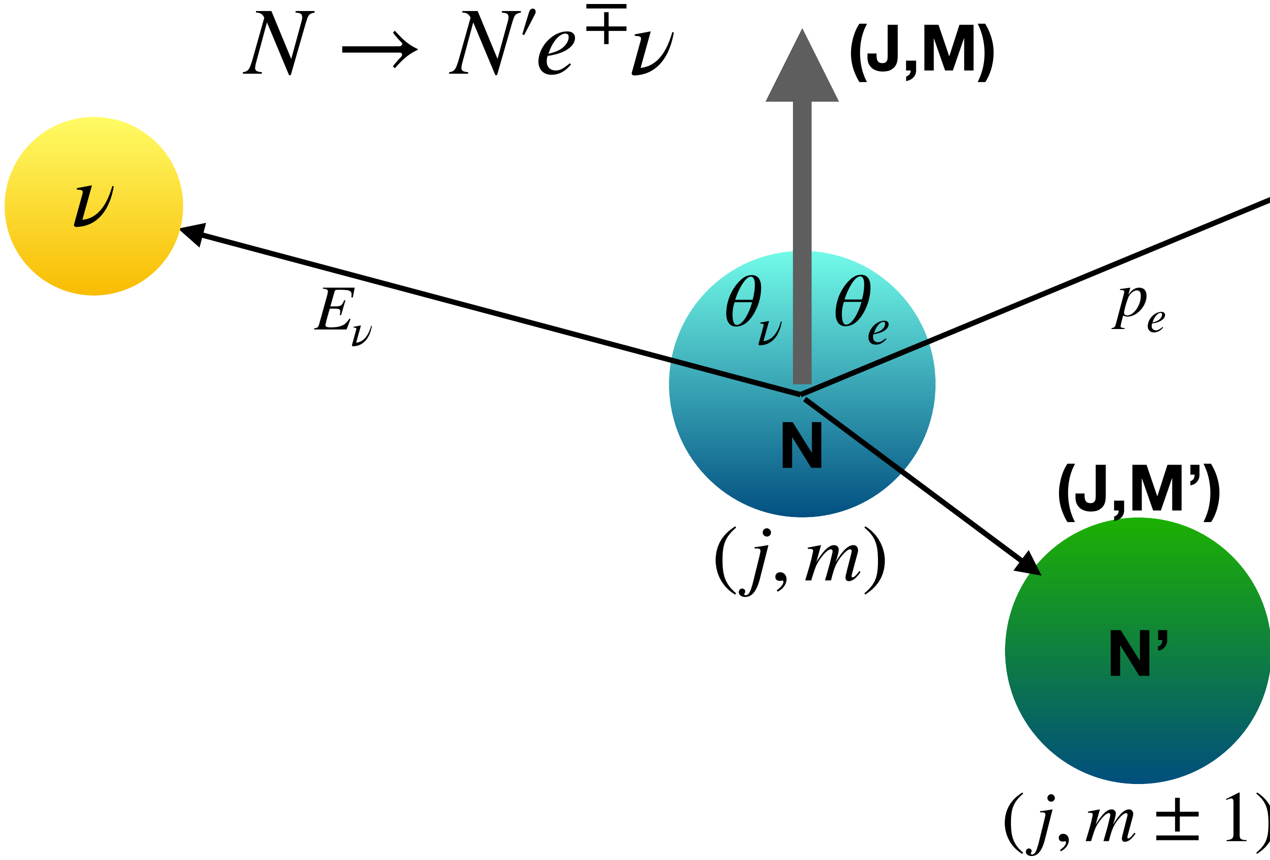
$$+ \left(1 - \tilde{\rho}^2 + 2\tilde{\rho}^2 \frac{M^2}{J(J+1)}\right) \cos\theta_e \cos\theta_\nu \frac{p_e}{E_e} + \left(1 - \tilde{\rho}^2 \frac{M^2}{J(J+1)}\right) \sin\theta_e \sin\theta_\nu \cos\phi \frac{p_e}{E_e}$$

$$- M\tilde{\rho} \cos\theta_\nu \left[\frac{2\sqrt{J(J+1)} \mp \tilde{\rho}}{J(J+1)} \pm 2\tilde{\epsilon}_S \frac{1}{\sqrt{J(J+1)}} \frac{m_e}{E_e} + 2\tilde{\epsilon}_T \frac{\tilde{\rho} \mp \sqrt{J(J+1)}}{J(J+1)} \frac{m_e}{E_e} \right]$$

$$- M\tilde{\rho} \frac{2\sqrt{J(J+1)} \pm \tilde{\rho}}{J(J+1)} \cos\theta_e \frac{p_e}{E_e} \Bigg\} + \mathcal{O}(\epsilon_X^2) + \mathcal{O}(m_N^{-1})$$

Allowed beta decays

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



The last line describes asymmetry between electron and N polarization directions

$$A_\beta = -\tilde{\rho}\,\frac{2\sqrt{J(J+1)} \pm \tilde{\rho}}{J(J+1)(1+\tilde{\rho}^2)} + \mathcal{O}(\epsilon_X^2)$$

β polarization asymmetry directly measures "contaminated" mixing parameter

$$\frac{d\Gamma}{d\Omega_e d\Omega_\nu dE_e} = \frac{\tilde{V}_{ud}^2 M_{F_\mp}^2 E_\nu^2 p_e E_e}{64\pi^5 \mathrm{v}^4}\Bigg\{(1+\tilde{\rho}^2) \pm 2\left(\tilde{\epsilon}_S - \tilde{\rho}^2\tilde{\epsilon}_T\right)\frac{m_e}{E_e}$$

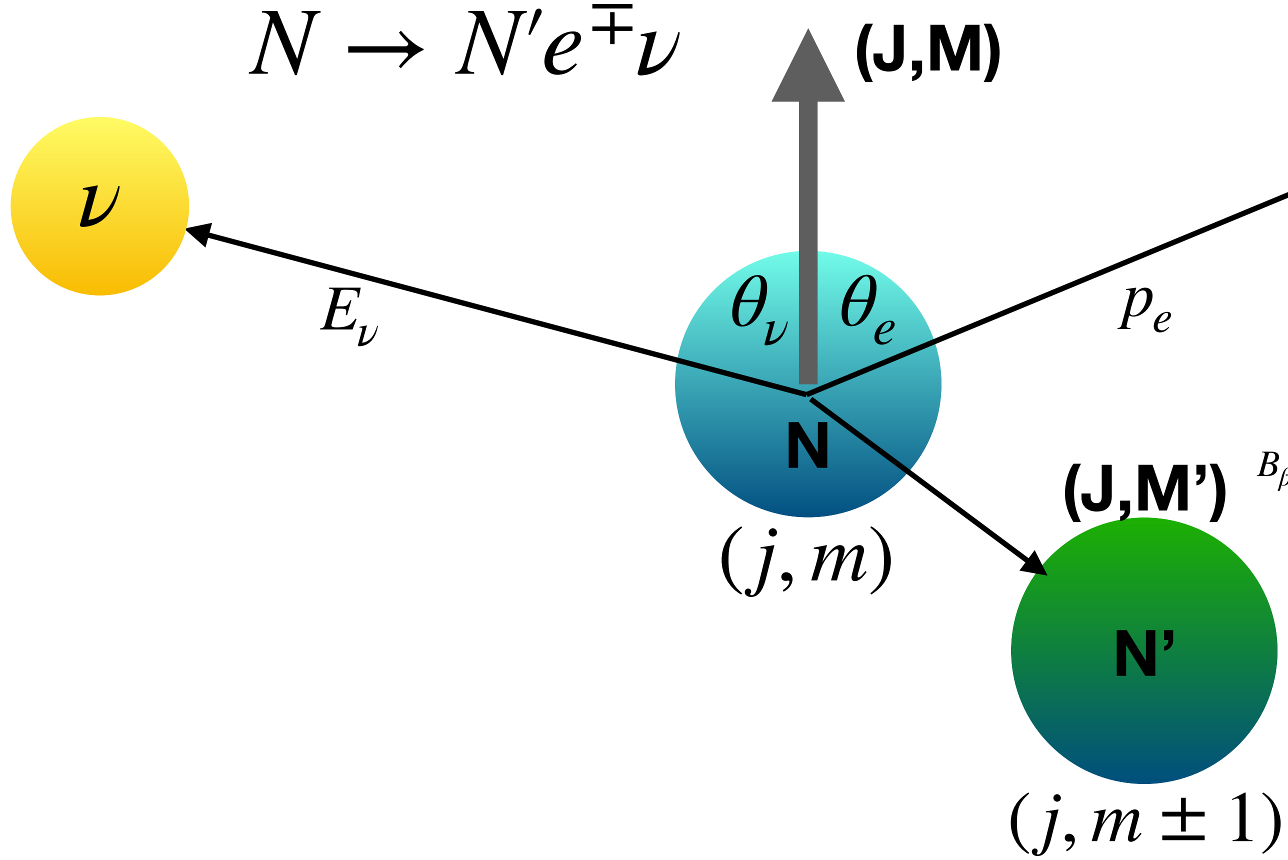
$$+\left(1 - \tilde{\rho}^2 + 2\tilde{\rho}^2\frac{M^2}{J(J+1)}\right)\cos\theta_e\cos\theta_\nu\frac{p_e}{E_e} + \left(1 - \tilde{\rho}^2\frac{M^2}{J(J+1)}\right)\sin\theta_e\sin\theta_\nu\cos\phi\,\frac{p_e}{E_e}$$

$$-M\tilde{\rho}\cos\theta_\nu\left[\frac{2\sqrt{J(J+1)} \mp \tilde{\rho}}{J(J+1)} \pm 2\tilde{\epsilon}_S\frac{1}{\sqrt{J(J+1)}}\frac{m_e}{E_e} + 2\tilde{\epsilon}_T\frac{\tilde{\rho} \mp \sqrt{J(J+1)}}{J(J+1)}\frac{m_e}{E_e}\right]$$

$$-M\tilde{\rho}\frac{2\sqrt{J(J+1)} \pm \tilde{\rho}}{J(J+1)}\cos\theta_e\frac{p_e}{E_e}\Bigg\} + \mathcal{O}(\epsilon_X^2) + \mathcal{O}(m_N^{-1})$$

Allowed beta decays

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



The next-to-last line describes asymmetry between N polarization and neutrino directions

$$B_\beta = -\frac{\tilde{\rho}}{1+\tilde{\rho}^2}\left[\frac{2\sqrt{J(J+1)} \mp \tilde{\rho}}{J(J+1)} \pm 2\tilde{\epsilon}_S \frac{1}{\sqrt{J(J+1)}}\frac{m_e}{E_e} + 2\tilde{\epsilon}_T \frac{\tilde{\rho} \mp \sqrt{J(J+1)}}{J(J+1)}\frac{m_e}{E_e}\right] + \mathcal{O}(\epsilon_X^2$$

ν polarization asymmetry measures combination of "contaminated" mixing parameter and BSM parameters

$$\frac{d\Gamma}{d\Omega_e d\Omega_\nu dE_e} = \frac{\tilde{V}_{ud}^2 M_{F_\mp}^2 E_\nu^2 p_e E_e}{64\pi^5 \mathrm{v}^4}\left\{(1+\tilde{\rho}^2) \pm 2\left(\tilde{\epsilon}_S - \tilde{\rho}^2\tilde{\epsilon}_T\right)\frac{m_e}{E_e}\right.$$

$$+\left(1 - \tilde{\rho}^2 + 2\tilde{\rho}^2\frac{M^2}{J(J+1)}\right)\cos\theta_e\cos\theta_\nu\frac{p_e}{E_e} + \left(1 - \tilde{\rho}^2\frac{M^2}{J(J+1)}\right)\sin\theta_e\sin\theta_\nu\cos\phi\frac{p_e}{E_e}$$

$$-M\tilde{\rho}\cos\theta_\nu\left[\frac{2\sqrt{J(J+1)} \mp \tilde{\rho}}{J(J+1)} \pm 2\tilde{\epsilon}_S\frac{1}{\sqrt{J(J+1)}}\frac{m_e}{E_e} + 2\tilde{\epsilon}_T\frac{\tilde{\rho} \mp \sqrt{J(J+1)}}{J(J+1)}\frac{m_e}{E_e}\right]$$

$$\left.-M\tilde{\rho}\frac{2\sqrt{J(J+1)} \pm \tilde{\rho}}{J(J+1)}\cos\theta_e\frac{p_e}{E_e}\right\} + \mathcal{O}(\epsilon_X^2) + \mathcal{O}(m_N^{-1})$$

Experimental data on allowed beta transitions

Data: Superallowed beta decays

- Superallowed beta decays are β+ transitions between spin zero, isospin one, positive parity nuclei

$$J = 0, \quad j = 1, \quad M_F = \sqrt{2}$$

- Thus mixing parameter vanishes, and all asymmetries are void

$$\tilde{\rho} = 0$$

$$\frac{d\Gamma(0^+ \to 0^+)}{d\Omega_e d\Omega_\nu dE_e} = \frac{\tilde{V}_{ud}^2 E_\nu^2 p_e E_e}{32\pi^5 \mathrm{v}^4} \left\{ 1 - 2\tilde{\epsilon}_S \frac{m_e}{E_e} + \cos(\theta_e - \theta_\nu) \frac{p_e}{E_e} \right\} + \mathcal{O}(\epsilon_X^2) + \mathcal{O}(m_N^{-1})$$

$$\frac{d\Gamma(0^+ \to 0^+)}{dE_e} = \frac{\tilde{V}_{ud}^2 E_\nu^2 p_e E_e}{2\pi^3 \mathrm{v}^4} \left\{ 1 - 2\tilde{\epsilon}_S \frac{m_e}{E_e} \right\} + \mathcal{O}(\epsilon_X^2) + \mathcal{O}(m_N^{-1})$$

Superallowed beta decays

Half-life: $$t^{-1} = \frac{\tilde{V}_{ud}^2}{2\log 2\pi^3 \mathrm{v}^4}\int_{m_e}^{m_N - m_{N'}} dE_e E_\nu^2 p_e E_e \left\{1 - 2\tilde{\epsilon}_S \frac{m_e}{E_e}\right\}$$

To project out the phase space part from lifetime define:

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

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

The product *ft* is universal for all superallowed decays in the SM limit

$$ft = \frac{2\log 2\pi^3 \mathrm{v}^4}{\tilde{V}_{ud}^2 m_e^5}\frac{1}{1 - 2\tilde{\epsilon}_S \langle \frac{m_e}{E_e}\rangle}$$

Many sub-per-mille level measurements of *ft* !

Parent	$\mathcal{F}t$ (s)	$\langle m_e/E_e \rangle$
^{10}C	3078.0 ± 4.5	0.619
^{14}O	3071.4 ± 3.2	0.438
^{22}Mg	3077.9 ± 7.3	0.310
^{26m}Al	3072.9 ± 1.0	0.300
^{34}Cl	3070.7 ± 1.8	0.234
^{34}Ar	3065.6 ± 8.4	0.212
^{38m}K	3071.6 ± 2.0	0.213
^{38}Ca	3076.4 ± 7.2	0.195
^{42}Sc	3072.4 ± 2.3	0.201
^{46}V	3074.1 ± 2.0	0.183
^{50}Mn	3071.2 ± 2.1	0.169
^{54}Co	3069.8 ± 2.6	0.157
^{62}Ga	3071.5 ± 6.7	0.141
^{74}Rb	3076.0 ± 11.0	0.125

From these data one can simultaneously determine:
1. **Via over normalization, "contaminated" tilde V_{ud}**
2. **Via Fierz term, BSM parameter tilde ε_S**

Note: in this slide for simplicity I'm ignoring numerically important effects: Fermi function effects, and radiative corrections. These are taken into account in the fits.

Hardy, Towner 1411.5987
Gonzalez-Alonso et al 1803.08732

Neutron decay

- Neutron decay is a β- transition between spin half, isospin half, positive parity nucleons

$$J = 1/2, \quad j = 1/2, \quad M_F = 1$$

- Mixing parameter is non-zero, however it is perturbatively calculable, in terms of the nucleon axial charge

$$M_{\rm GT} = \langle p \,|\, \bar{\psi}_p \sigma^k \psi_n \,|\, n \rangle$$

$$\tilde{\rho} = -\sqrt{3}\,\tilde{g}_A$$

Neutron decay simultaneously constrains 4 parameters:
- 2 "contaminated" SM parameters tilde V_{ud} and tilde g_A,
- 2 BSM parameters tilde ε_S and tilde ε_T.

Neutron decay data

Wealth of per-mille precision data!

Coefficient	Value	Year / Method	$\langle m_e/E_e \rangle$	Reference
τ_n (s)	882.6 ± 2.7	1993 / Bottle		[198]
	$889.2 \pm 3.0 \pm 3.8$	1996 / Beam		[191]
	$878.5 \pm 0.7 \pm 0.3$	2005 / Bottle		[197]
	$880.7 \pm 1.3 \pm 1.2$	2010 / Bottle		[199]
	$882.5 \pm 1.4 \pm 1.5$	2012 / Bottle		[200]
	$887.7 \pm 1.2 \pm 1.9$	2013 / Beam		[192]
	878.3 ± 1.9	2014 / Bottle		[201]
	880.2 ± 1.2	2015 / Bottle		[202]
	$877.7 \pm 0.7 \pm 0.4$	2017 / Bottle		[189]
	$881.5 \pm 0.7 \pm 0.6$	2017 / Bottle		[203]
	879.75 ± 0.76			Average (S=1.9)
a_n	$-0.1017(51)$	1978		[355]
	$-0.1054(55)$	2002		[356]
	~~$-0.1034(37)$~~			~~Average~~
$\tilde{A}_n$	$-0.1146(19)$	1986	0.581	[377]
	$-0.1160(9)(12)$	1997	0.582	[378]
	$-0.1135(14)$	1997	0.558	[379]
	$-0.11926(31)(42)$	2013	0.559	[190]
	$-0.12015(34)(63)$	2018	0.586	[384]
	~~$-0.11869(99)$~~		~~0.569~~	~~Average (S=2.6)~~
$\tilde{B}_n$	$0.9894(83)$	1995	0.554	[394]
	$0.9801(46)$	1998	0.594	[395]
	$0.9670(120)$	2005	0.600	[396]
	$0.9802(50)$	2007	0.598	[393]
	$0.9805(30)$		0.591	Average

Update '19 aSPECT

$a_n = -0.10430(84)$

Update '18 PERKEO-III

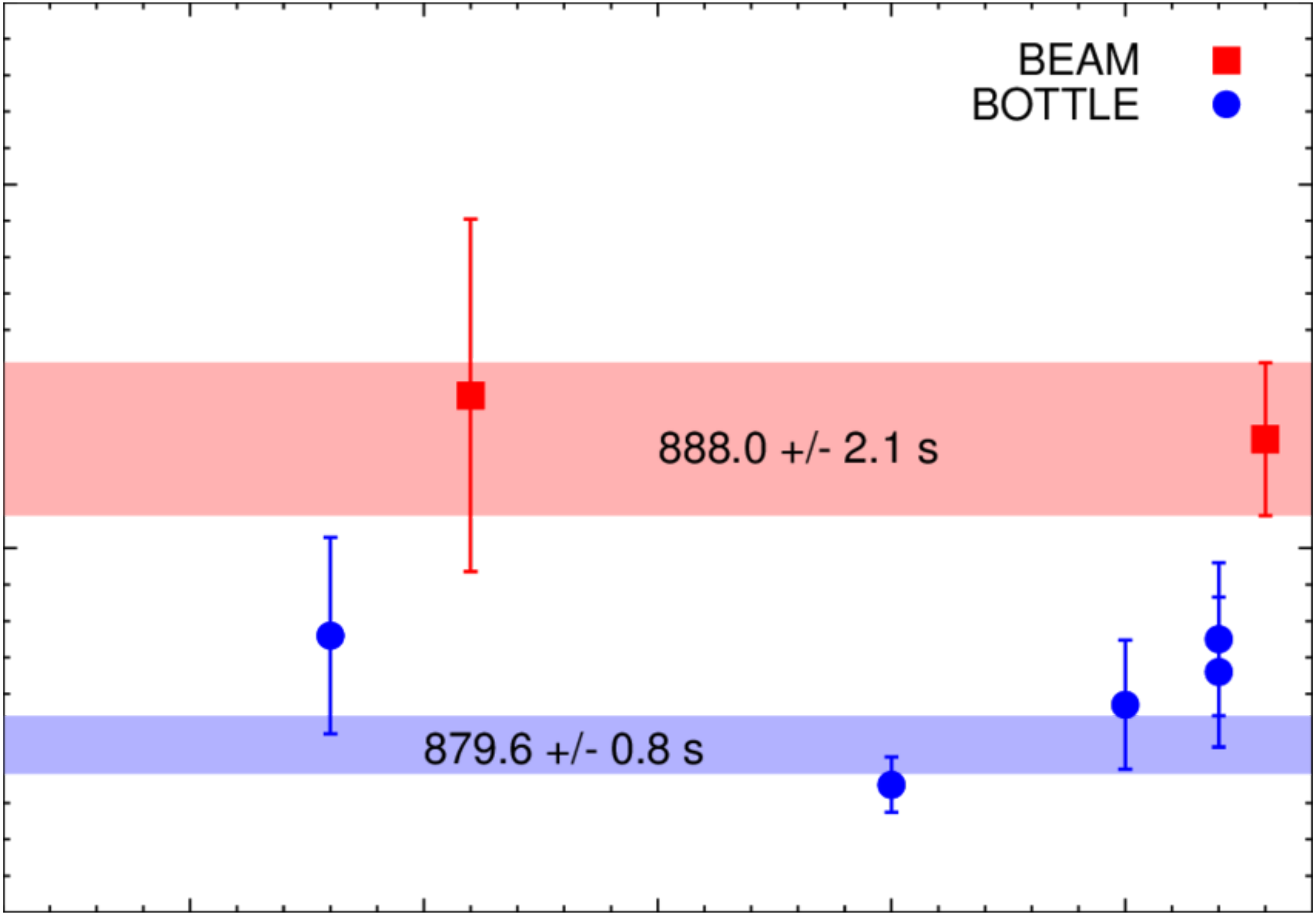
$A_n = -0.11985(21)$

combined:

$A_n = -0.11979(19)$

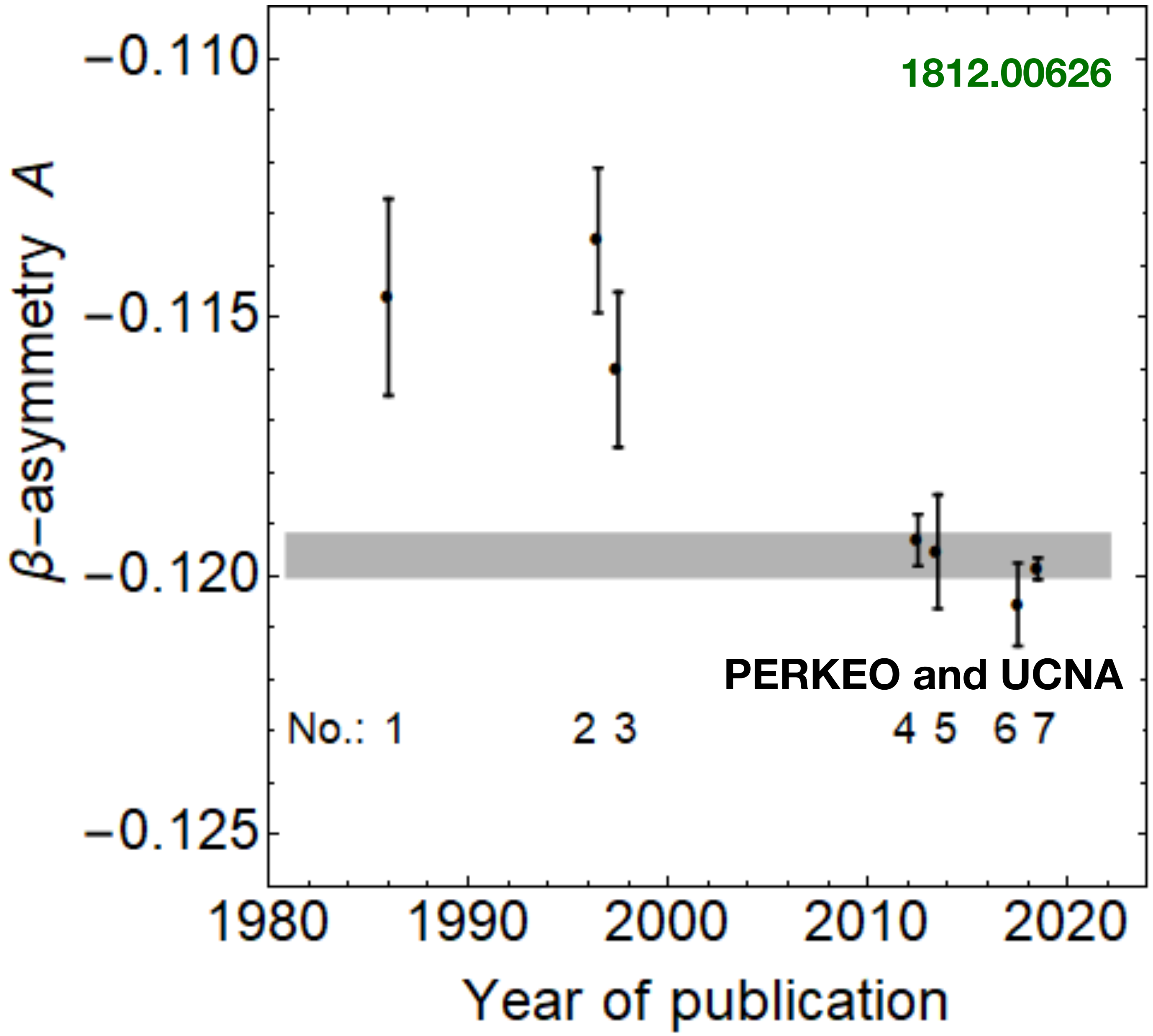
Gonzalez-Alonso et al, 1803.08732

Neutron lifetime: bottle vs beam



Neutron beta polarization asymmetry

Story of beta polarization asymmetry



According to PDG algorithm, it is no longer necessary to scale up the error of A_n

$$A_n = -0.11869(99) \quad \Rightarrow \quad A_n = -0.11979(19)$$

Mirror decays

- Mirror decays are β transitions between isospin half, positive parity nuclei

$$j = 1/2, \quad M_F = 1$$

- Mixing parameter is non-zero,
and currently it cannot be calculated with any decent precision

$$\tilde{\rho} \neq 0$$

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

Formally, neutron decay is also an example of 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

Phalet et al
0807.2201

Half-life:

$$t^{-1} = \int_{m_e}^{m_N - m_{N'}} dE_e \frac{\tilde{V}_{ud}^2 E_\nu^2 p_e E_e}{4 \log 2 \pi^3 \mathrm{v}^4} \left\{ (1+\tilde{\rho}^2) \pm 2 \left(\tilde{\epsilon}_S - \tilde{\rho}^2 \tilde{\epsilon}_T\right) \frac{m_e}{E_e} \right\}$$

$$ft = \frac{4 \log 2 \pi^3 \mathrm{v}^4}{\tilde{V}_{ud}^2 m_e^5} \frac{1}{(1+\tilde{\rho}^2) \pm 2 \left(\tilde{\epsilon}_S - \tilde{\rho}^2 \tilde{\epsilon}_T\right) \langle \frac{m_e}{E_e} \rangle}$$

Now *ft* depends on mixing parameter ρ
It also probes tensor BSM interactions

For mirror decays *ft* is not universal for all nuclei in the SM limit

Measuring *ft* alone does not constrain fundamental parameters. With an input from superallowed and neutron decays, it only constrains the mixing parameter.

More input is needed!

Mirror decays

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

${}^A_J$Decay	Δ [MeV]	$\langle m_e/E_e\rangle$	f_A/f_V	$\mathcal{F}t$ [sec]	asymmetry
${}^{19}_{1/2}$Ne $\to$ F	2.72849 [9]	0.396	1.0012(2)	1721.44(92) [10]	$A_{\beta,0}$=-0.0391(14)
${}^{21}_{3/2}$Na $\to$ Ne	3.035903	0.364	1.0019(4)	4071(4) [11]	$\tilde{a}_{\beta\nu}$=0.5502(60)
${}^{35}_{3/2}$Ar $\to$ Cl	2.780	0.220	0.9930(14)	5688.6(7.2)	$\tilde{A}_\beta$=0.430(22)
${}^{37}_{3/2}$K $\to$ Ar	5.63646	0.214	0.9957(9)	4605.4(8.2) [12]	$\tilde{A}_\beta$=-0.5707(19) [13]

This set of observables simultaneously constrains 7 parameters:

- **1 "contaminated" CKM parameters tilde V_{ud}**
- **2 BSM parameters tilde ε_S and tilde ε_T.**
- **4 distinct mixing parameters tilde ρ**

In an upcoming paper we study for the first time constraints from mirror decay on BSM parameters

AA, Gonzalez-Alonso, Naviliat-Cuncic
In preparation

Global fit to allowed beta transitions

All together

AA, Gonzalez-Alonso, Naviliat-Cuncic
In preparation

Marginalized constraints:

$$\begin{pmatrix} \tilde{V}_{ud} \\ \tilde{g}_A \\ \tilde{\epsilon}_S \\ \tilde{\epsilon}_T \end{pmatrix} = \begin{pmatrix} 0.97420(32) \\ 1.27525(42) \\ 0.0014(11) \\ 0.00097(92) \end{pmatrix} \qquad \rho = \begin{pmatrix} 1 & -0.25 & 0.83 & 0.55 \\ . & 1 & -0.27 & -0.05 \\ . & . & 1 & 0.61 \\ . & . & . & 1 \end{pmatrix}$$

Per-mille level constraints on BSM parameters!
Better than per-mille constraints on SM parameters, even in the presence of BSM!
Mixing ratios for the mirror nuclei also constrained at per-mille level (not displayed)

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

Assuming absence of BSM physics, ϵ_X=0, error on CKM parameter is reduced by half

$$\begin{pmatrix} V_{ud} \\ g_A \end{pmatrix} = \begin{pmatrix} 0.97385(18) \\ 1.27525(42) \end{pmatrix} \qquad \rho = \begin{pmatrix} 1 & -0.13 \\ . & 1 \end{pmatrix}$$

Bonus from the lattice

From experiment (fit):

$$\tilde{g}_A = 1.27525(42)$$

From lattice (FLAG):

$$g_A = 1.251(33)$$

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

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

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

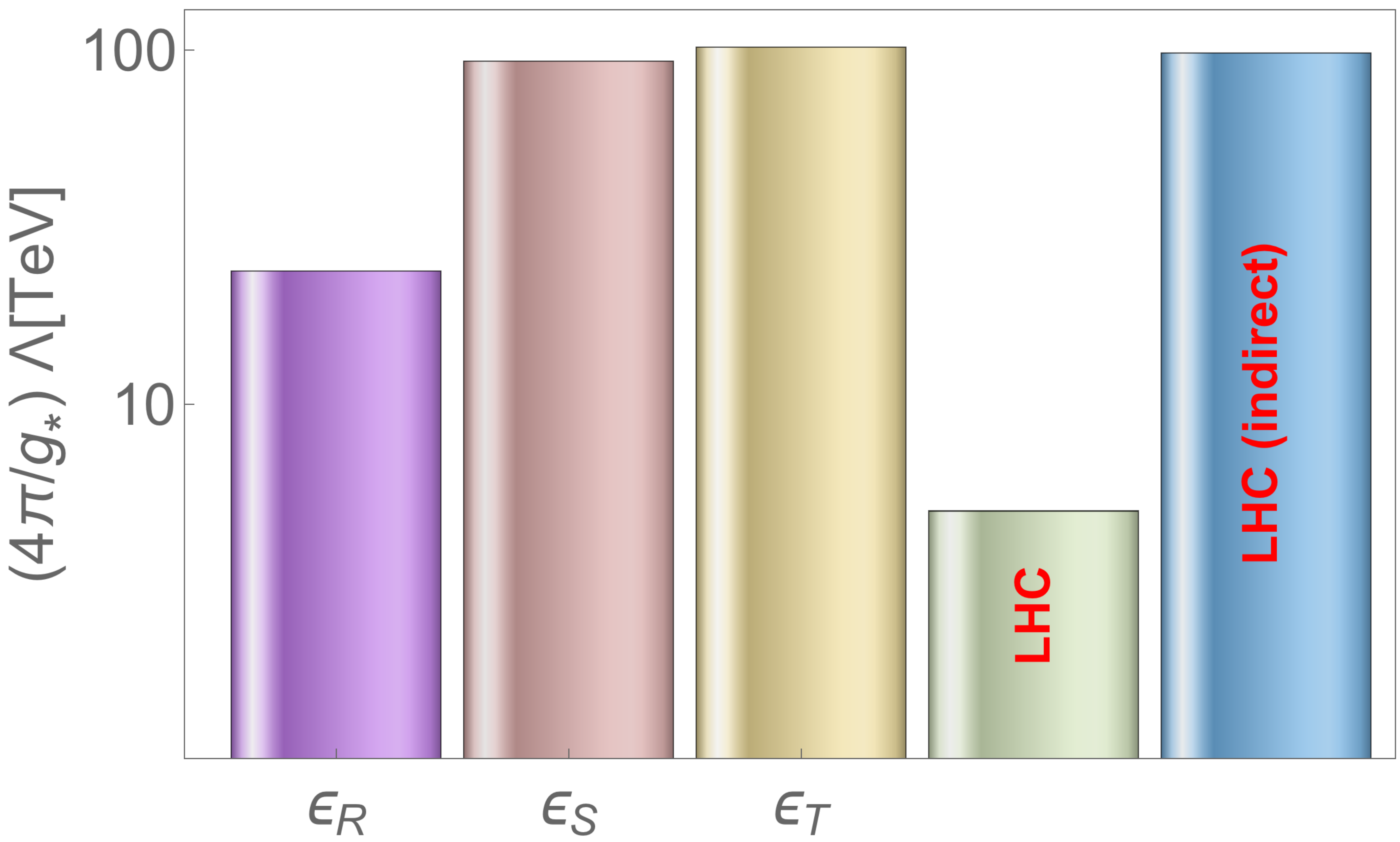
One can treat lattice determination of g_A as another "experimental" input constraining ε_R

$$\epsilon_R = -0.010(17)$$

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

BSM reach of nuclear decays

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



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

Future

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 presence!
$\beta - \nu$	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

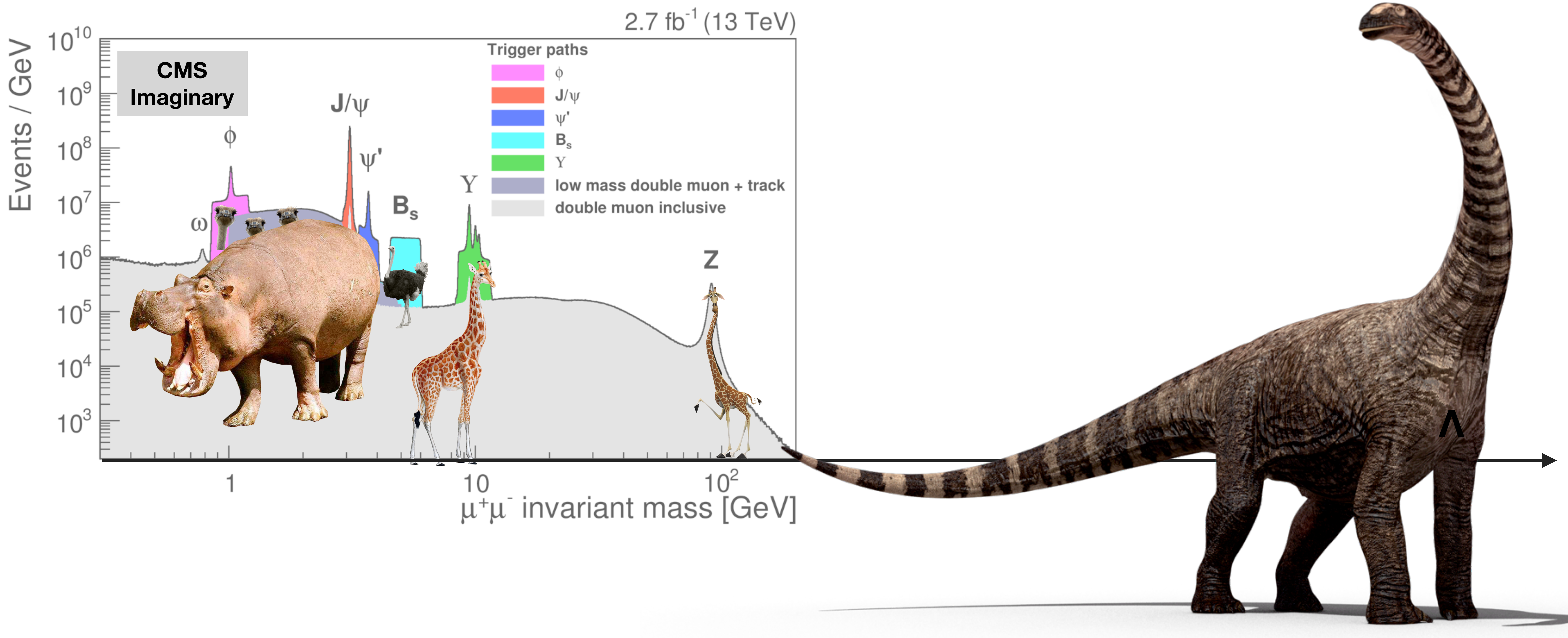
TABLE III. List of nuclear β-decay spectral measurements in search for non-SM physics [a]

Measurement	Transition Type	Nucleus	Institution/Collaboration	Goal
β spectrum	GT	^{114}In	MiniBETA-Krakow-Leuven	0.1 %
β spectrum	GT	^{6}He	LPC-Caen	0.1 %
β spectrum	GT	^{6}He, ^{20}F	NSCL-MSU	0.1 %
β spectrum	GT, F, Mixed	^{6}He, ^{14}O, ^{19}Ne	He6-CRES	0.1 %

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
- Reach for new physics is currently much better than the direct reach of the LHC, and comparable to the indirect one. Also, different Lorentz structures of new physics operators can be resolved
- Expect progress by order of magnitude in the near future

Fantastic Beasts and Where To Find Them



THANK YOU

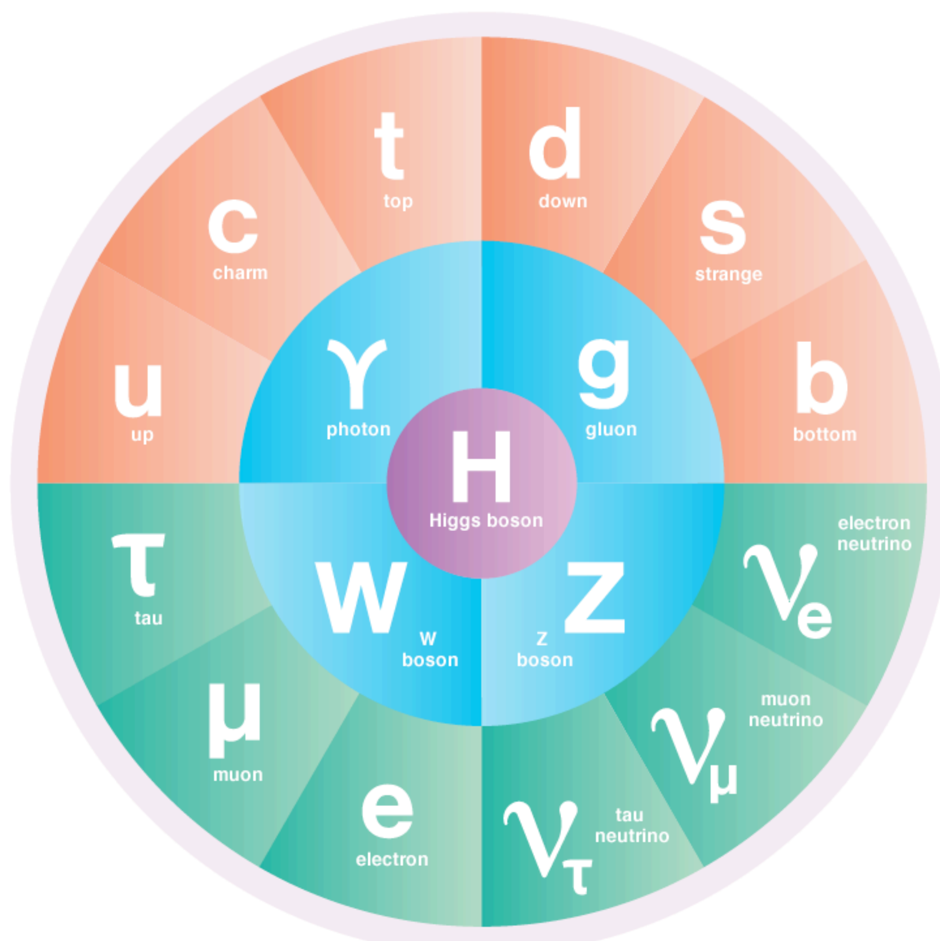
SMEFT - WEFT dictionary

SMEFT = minimal EFT above the weak scale

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \mathscr{L}_{D=5} + \mathscr{L}_{D=6} + \mathscr{L}_{D=7} + \mathscr{L}_{D=8} + \mathscr{L}_{D=9} + \ldots$$

Known SM Lagrangian

Higher-dimensional $SU(3)_C \times SU(2)_L \times U(1)_Y$ invariant interactions added to the SM



SMEFT = minimal EFT above the weak scale

$$\mathscr{L}_{\rm SMEFT} = \mathscr{L}_{\rm SM} + \mathscr{L}_{D=5} + \mathscr{L}_{D=6} + \mathscr{L}_{D=7} + \mathscr{L}_{D=8} + \mathscr{L}_{D=9} + \dots$$

Known SM Lagrangian

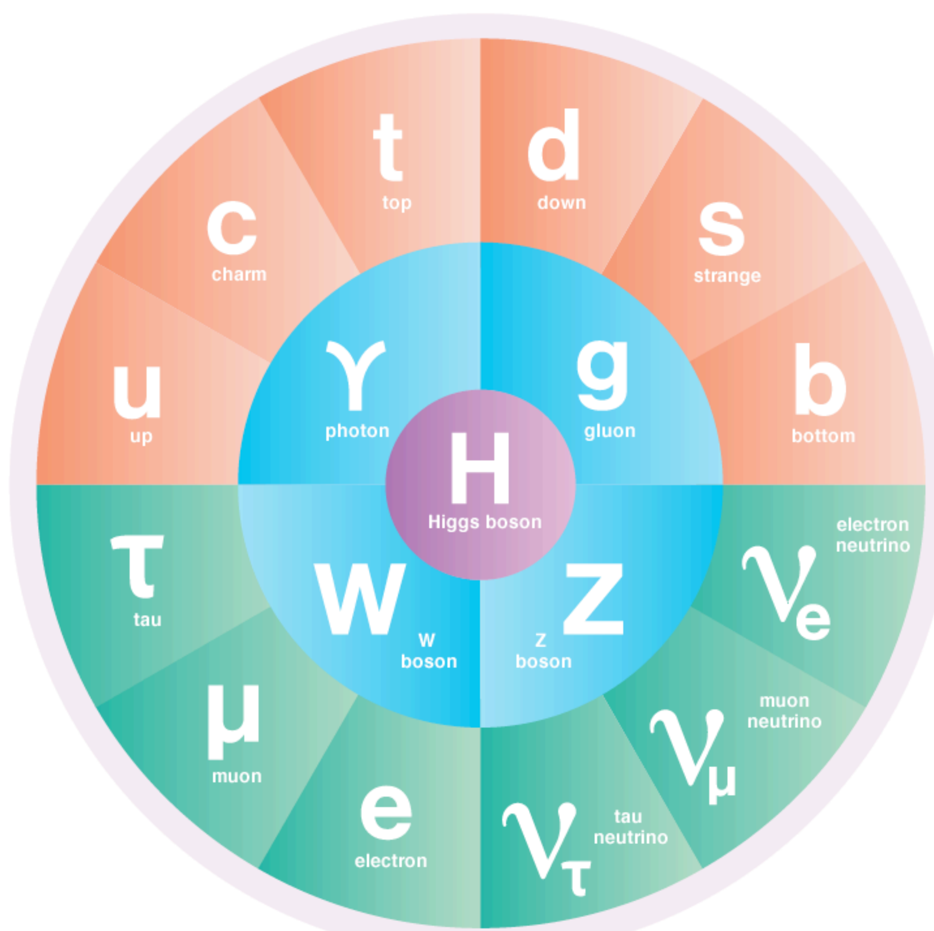
$$\mathscr{L}_{D=5} \supset \frac{1}{\Lambda_L}(HL_i)(HL_j)$$

Scale of new lepton-number violating physics

Provides neutrino masses (we sort of already discovered these terms!)

$$\Lambda_L \sim 10^{15}\ \mathrm{GeV}$$

Irrelevant for other applications than neutrino oscillations



SMEFT = minimal EFT above the weak scale

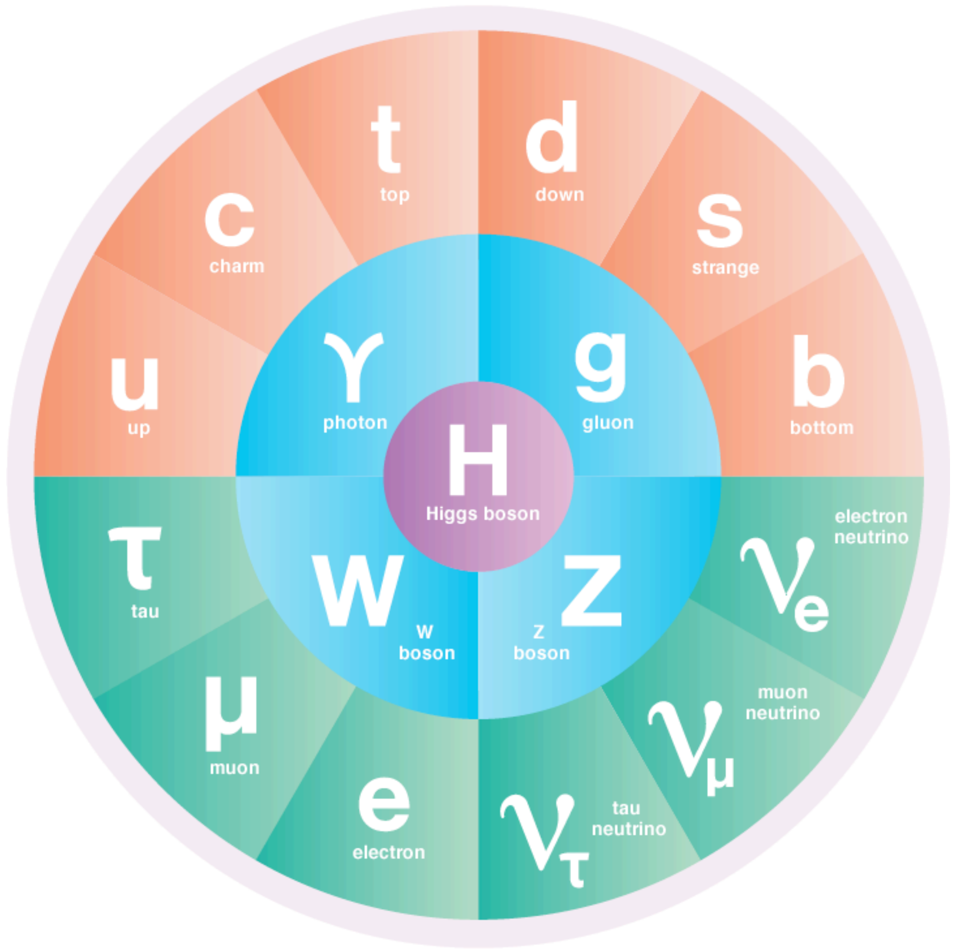
$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{D=5} + \mathcal{L}_{D=6} + \mathcal{L}_{D=7} + \mathcal{L}_{D=8} + \mathcal{L}_{D=9} + \dots$$

Known SM Lagrangian

e.g. 4-fermion operators

$$\mathcal{L}_{D=6} \supset \frac{1}{\Lambda^2} \bar{q}_i \bar{\sigma}^\mu q_j \bar{l}_a \bar{\sigma}_\mu l_b$$

Leading effects for lepton-number conserving observables



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	$f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$	$O_{\widetilde{G}}$	$f^{abc} \widetilde{G}^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$

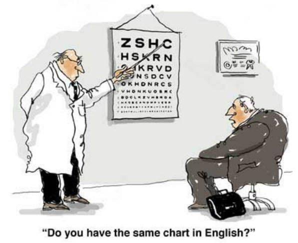


Table 2.2: Bosonic D=6 operators in the Warsaw basis.

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

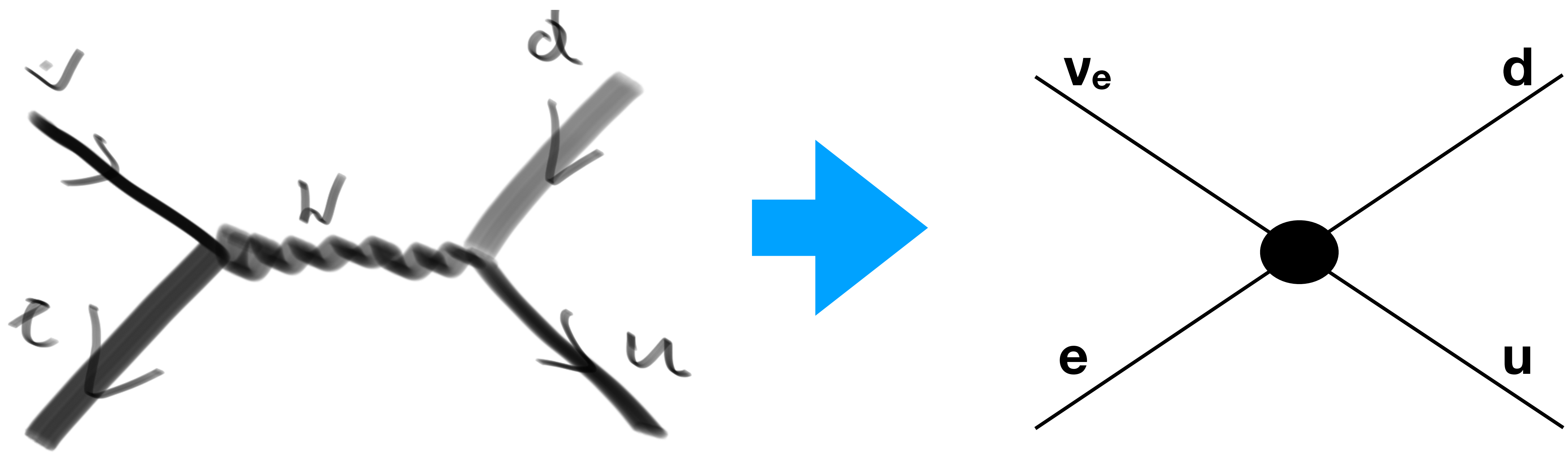
Full set has 2499 distinct operators, including flavor structure and CP conjugates

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

WEFT from SMEFT

In the SMEFT, at the level of dimension-6 operators, two types of effects leading to contact interactions between quarks and leptons at low-energies:

One is via W exchange, much as in the SM



Dimension-6 operators generate W coupling to right-handed quarks, in addition to the usual SM one to left-handed quarks

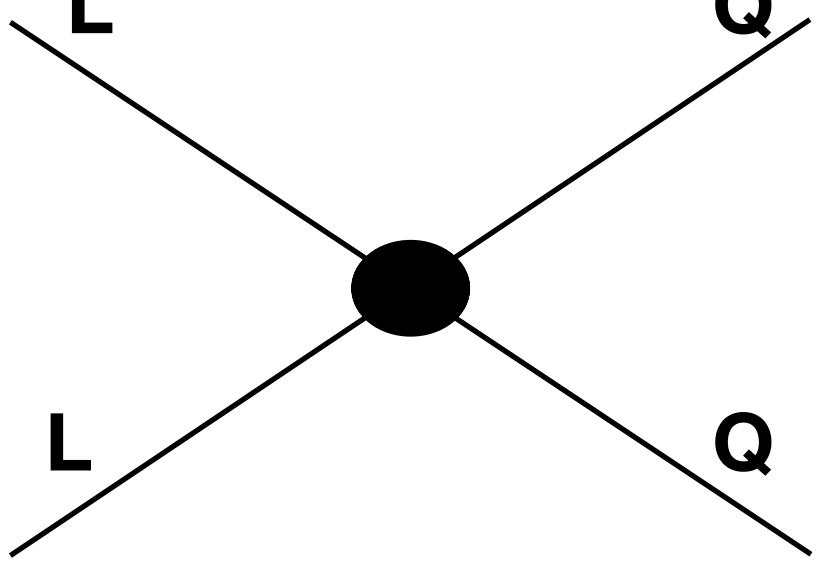
$$\mathscr{L}_{\rm SMEFT} \supset \frac{c_{Hud}}{\Lambda^2}(\tilde{H}^\dagger D_\mu H)(\bar{u}_R \gamma_\mu d_R) + {\rm h.c.} \longrightarrow \delta g_R^{Wq_1} = c_{Hud}\frac{{\rm v}^2}{2\Lambda^2}$$

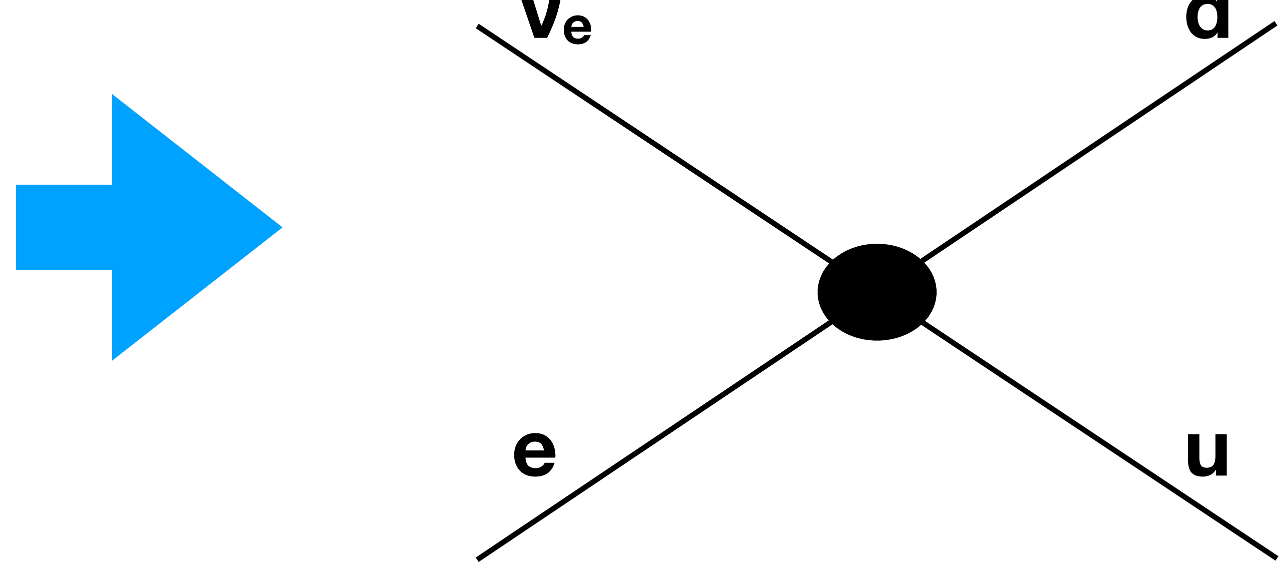
$$\mathscr{L}_{\rm SMEFT} \supset \frac{g_L}{\sqrt{2}} W^{\mu+}\left[\bar{\nu}_e \gamma_\mu (1 + \delta g_L^{We}) e_L + \bar{u}_L \gamma_\mu \left(V_{ud} + \delta g_L^{Wq_1}\right) d_L + \delta g_R^{Wq_1} \bar{u}_R \gamma_\mu d_R\right] + {\rm h.c.}$$

WEFT from SMEFT

In the SMEFT, at the level of dimension-6 operators, two types of effects leading to contact interactions between quarks and leptons at low-energies:

The other is contact 4-fermion interactions in SMEFT





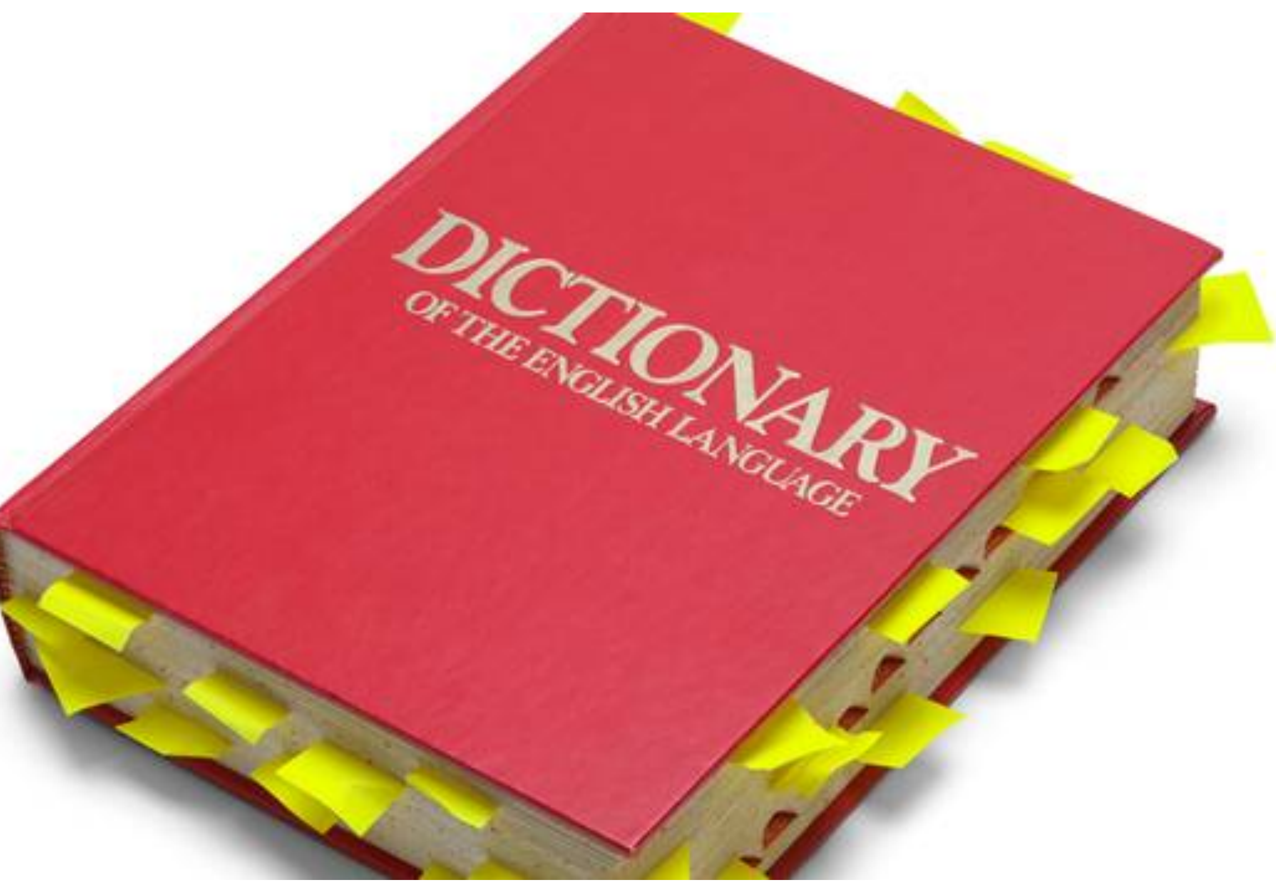
$$\mathscr{L}_{\text{SMEFT}} \supset \frac{1}{\Lambda^2}\left[c_{lq}^{(3)}(\bar{L}\gamma_\mu\sigma^i L)(\bar{Q}\gamma^\mu\sigma^i Q) + c_{lequ}(\bar{L}e)(\bar{Q}u) + c_{ledq}(\bar{L}e)(\bar{d}Q) + c_{lequ}^{(3)}(\bar{L}\sigma_{\mu\nu}e)(\bar{Q}\sigma^{\mu\nu}u)\right]$$

None leads to V-A or V+A currents!
Only left-handed, scalar, pseudoscalar, and tensor ones are generated by these operators

Matching WEFT to SMEFT

The map allows one to connect parameters ε_X measured in beta decays to SMEFT Wilson coefficients (and thus indirectly to fundamental parameters of BSM models)

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



$$\epsilon_L = \delta g_L^{We} - \frac{1}{V_{ud}}[V_{\mathrm{CKM}}]_{Pd}[c_{lq}^{(3)}]_{ee1P} - 2\delta m_W + \frac{1}{V_{ud}}\delta g_L^{Wq_1}$$

$$\epsilon_R = \frac{1}{V_{ud}}\delta g_R^{Wq_1}$$

$$\epsilon_S = -\frac{1}{2V_{ud}}\left([V_{\mathrm{CKM}}]_{Pd}[c_{lequ}]^*_{eeP1} + [c_{ledq}]^*_{ee11}\right)$$

$$\epsilon_P = -\frac{1}{2V_{ud}}\left([V_{\mathrm{CKM}}]_{Pd}[c_{lequ}]^*_{JKP1} - [c_{ledq}]^*_{ee11}\right)$$

$$\epsilon_T = -\frac{2}{V_{ud}}[V_{\mathrm{CKM}}]_{Pd}[c_{lequ}^{(3)}]^*_{eeP1}$$

NR

Non-relativistic fields

$$\psi_\alpha = \frac{1}{\sqrt{2}} e^{imt} \left(N f_\alpha + \bar{N} \bar{f}^\alpha_c \right) , \qquad \psi^c_\alpha = \frac{1}{\sqrt{2}} e^{imt} \left(N f^c_\alpha + \bar{N} \bar{f}^\alpha \right) ,$$

$$\bar{\psi}^\alpha = \frac{1}{\sqrt{2}} e^{-imt} \left(N \bar{f}^\alpha - \bar{N} f^c_\alpha \right) , \qquad \bar{\psi}^\alpha_c = \frac{1}{\sqrt{2}} e^{-imt} \left(N \bar{f}^\alpha_c - \bar{N} f_\alpha \right) ,$$

$$\begin{aligned} N &= \sqrt{\frac{m^2 \left(\sqrt{m^2 - \nabla^2} - m \right)}{-2\nabla^2 \sqrt{m^2 - \nabla^2}}} \left(\sqrt{1 - \frac{\nabla^2}{m^2}} + 1 + i \frac{\vec{\sigma}\vec{\nabla}}{m} \right) , \\ \bar{N} &= \sqrt{\frac{m^2 \left(\sqrt{m^2 - \nabla^2} - m \right)}{-2\nabla^2 \sqrt{m^2 - \nabla^2}}} \left(\sqrt{1 - \frac{\nabla^2}{m^2}} + 1 - i \frac{\vec{\sigma}\vec{\nabla}}{m} \right) . \end{aligned}$$

Pseudoscalar

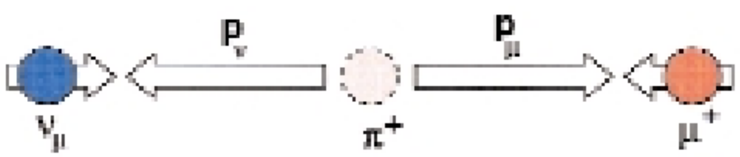
The 5th element

$$\mathcal{L}_{WEFT} \supset -\frac{V_{ud}}{2v^2}\Bigg[\left(1+\epsilon_L^e\right)\bar{e}\gamma_\mu(1-\gamma_5)\nu_e\cdot\bar{u}\gamma^\mu(1-\gamma_5)d$$

$$+\epsilon_R^e\,\bar{e}\gamma_\mu(1-\gamma_5)\nu_e\cdot\bar{u}\gamma^\mu(1+\gamma_5)d$$

$$+\bar{e}(1-\gamma_5)\nu_e\cdot\bar{u}\left[\epsilon_S^e-\epsilon_P^e\gamma_5\right]d$$

$$+\epsilon_T^e\,\bar{e}\sigma_{\mu\nu}(1-\gamma_5)\nu_e\cdot\bar{u}\sigma^{\mu\nu}(1-\gamma_5)d\Bigg]+\mathrm{h.c.}$$



≈ 26

$$\Gamma(\pi\to\mu\nu)=|\tilde{V}_{ud}|^2\frac{f_{\pi^\pm}^2 m_\mu^2(m_{\pi^\pm}^2-m_\mu^2)^2}{16\pi m_{\pi^\pm}^3\tilde{v}^4}\left(1-4\epsilon_R^e-2\frac{m_{\pi^\pm}^2}{m_\mu(m_u+m_d)}\epsilon_P^e\right)$$

But that's fine because pion decays are very sensitive to it thanks to chiral enhancement

LHC

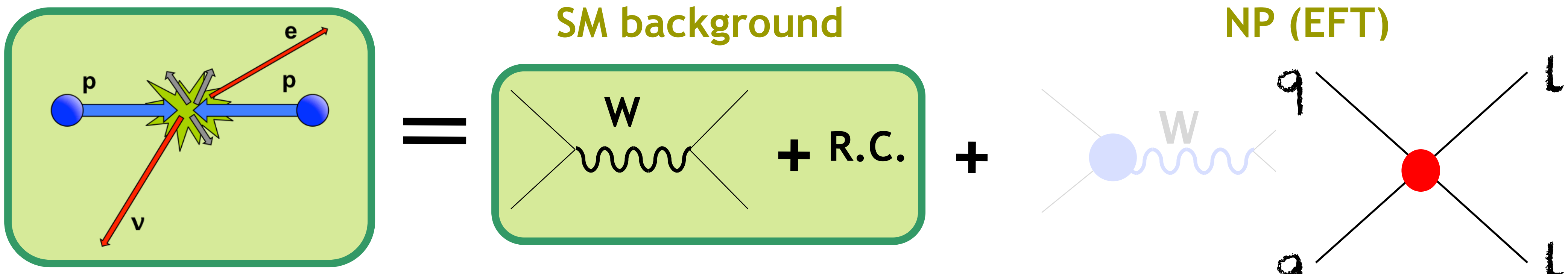
Comparing LHC and low-energy bounds

- In spite of poor O(10%) accuracy, currently LHC has similar sensitivity to chirality conserving eeqq 4-fermion operators as low-energy measurements with per-mille accuracy

- This happens because effects of 4-fermion operators on scattering amplitudes are enhanced by E^2/v^2, where E is the center-of-mass energy of the parton collision. In this case, the superior energy reach of the LHC trumps the inferior accuracy

- Note that the same is not true for the vertex correction δg. These SMEFT deformations are not energy enhanced, and therefore it will be difficult to improve the constraints on δg at the LHC.

Comparing LHC and low-energy bounds



Borrowed from Martin Gonzalez-Alonso

$(ee)(qq)$

	$[c^{(3)}_{\ell q}]_{1111}$	$[c_{\ell q}]_{1111}$	$[c_{\ell u}]_{1111}$	$[c_{\ell d}]_{1111}$	$[c_{eq}]_{1111}$	$[c_{eu}]_{1111}$	$[c_{ed}]_{1111}$
Low-energy	0.45 ± 0.28	1.6 ± 1.0	2.8 ± 2.1	3.6 ± 2.0	-1.8 ± 1.1	-4.0 ± 2.0	-2.7 ± 2.0
$\mathrm{LHC}_{1.5}$	$-0.70^{+0.66}_{-0.74}$	$2.5^{+1.9}_{-2.5}$	$2.9^{+2.4}_{-2.9}$	$-1.6^{+3.4}_{-3.0}$	$1.6^{+1.8}_{-2.2}$	$1.6^{+2.5}_{-1.5}$	$-3.1^{+3.6}_{-3.0}$
$\mathrm{LHC}_{1.0}$	$-0.84^{+0.85}_{-0.92}$	$3.6^{+3.6}_{-3.7}$	$4.4^{+4.4}_{-4.7}$	$-2.4^{+4.8}_{-4.7}$	$2.4^{+3.0}_{-3.2}$	$1.9^{+2.5}_{-1.9}$	$-4.6^{+5.4}_{-4.1}$
$\mathrm{LHC}_{0.7}$	$-1.0^{+1.4}_{-1.5}$	5.9 ± 7.2	7.4 ± 9.0	-3.6 ± 8.7	3.8 ± 5.9	$2.1^{+3.8}_{-2.9}$	-8 ± 10

AA, Gonzalez-Alonso, Mimouni
1706.03783

$(\mu\mu)(qq)$

	$[c^{(3)}_{\ell q}]_{2211}$	$[c_{\ell q}]_{2211}$	$[c_{\ell u}]_{2211}$	$[c_{\ell d}]_{2211}$	$[c_{eq}]_{2211}$	$[c_{eu}]_{2211}$	$[c_{ed}]_{2211}$
Low-energy	-0.2 ± 1.2	4 ± 21	18 ± 19	-20 ± 37	40 ± 390	-20 ± 190	40 ± 390
$\mathrm{LHC}_{1.5}$	$-1.22^{+0.62}_{-0.70}$	1.8 ± 1.3	2.0 ± 1.6	-1.1 ± 2.0	1.1 ± 1.2	$2.5^{+1.8}_{-1.4}$	-2.2 ± 2.0
$\mathrm{LHC}_{1.0}$	$-0.72^{+0.81}_{-0.87}$	$3.2^{+4.0}_{-3.5}$	$3.9^{+4.8}_{-4.4}$	$-2.3^{+4.9}_{-4.7}$	$2.3^{+3.1}_{-3.2}$	$1.6^{+2.3}_{-1.8}$	-4.4 ± 5.3
$\mathrm{LHC}_{0.7}$	$-0.7^{+1.3}_{-1.4}$	$3.2^{+10.3}_{-4.8}$	$4.3^{+12.5}_{-6.4}$	-3.6 ± 9.0	3.8 ± 6.2	$1.6^{+3.4}_{-2.7}$	-8 ± 11

Chirality-violating operators ($\mu = 1$ TeV)

	$[c_{\ell equ}]_{1111}$	$[c_{\ell edq}]_{1111}$	$[c^{(3)}_{\ell equ}]_{1111}$	$[c_{\ell equ}]_{2211}$	$[c_{\ell edq}]_{2211}$	$[c^{(3)}_{\ell equ}]_{2211}$
Low-energy	$(-0.6 \pm 2.4)10^{-4}$	$(0.6 \pm 2.4)10^{-4}$	$(0.4 \pm 1.4)10^{-3}$	$0.014(49)$	$-0.014(49)$	$-0.09(29)$
$\mathrm{LHC}_{1.5}$	0 ± 2.0	0 ± 2.6	0 ± 0.91	0 ± 1.2	0 ± 1.6	0 ± 0.56
$\mathrm{LHC}_{1.0}$	0 ± 2.9	0 ± 3.7	0 ± 1.4	0 ± 2.9	0 ± 3.7	0 ± 1.4
$\mathrm{LHC}_{0.7}$	0 ± 5.3	0 ± 6.6	0 ± 2.6	0 ± 5.5	0 ± 6.9	0 ± 2.6

ATLAS
1606.01736