Searches for BSM physics at low energy (theory)

Martín González-Alonso

IFIC, Univ. of Valencia / CSIC

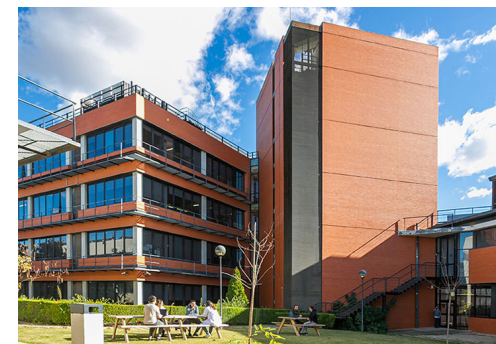EXCELENCIA SEVERO OCHOA

IFIC INSTITUT DE FÍSICA CORPUSCULAR

CSIC

GENERALITAT VALENCIANA Gen-T

Intro: me

- Theoretical physicist at IFIC (Univ. Valencia & CSIC)

- Research interests: BSM searches with precision measurements, interplay of low- and high-E searches (flavor, neutrino, nuclear beta decays, LHC, …), Effective Field Theories, …

- My history with Frascati:
  - 2005: tourist
  - 2007 Spring School (student) [My 1st talk: "Condensates for the light quark V-A correlator"]
  - 2009: 2-month visitor (PhD)
  - 2013-2014: postdoc
  - 2014 Spring School (LOC member)
  - 2024 Spring School (lecturer)

Outline

- Intro: SM → BSM

- Classes of low-energy BSM searches
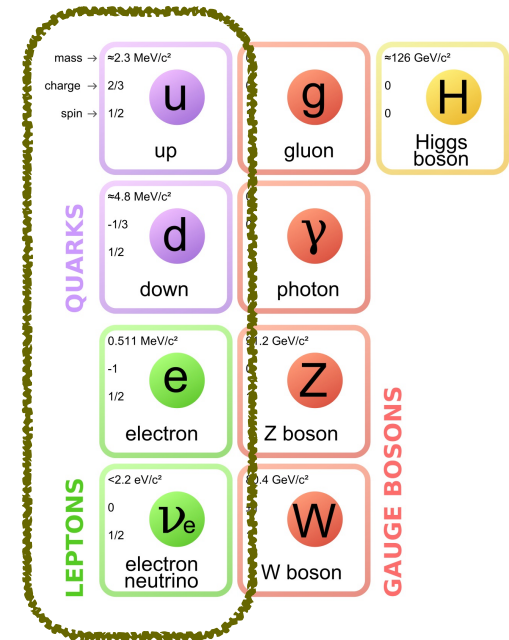
- Effective Field Theories

- EFT Phenomenology
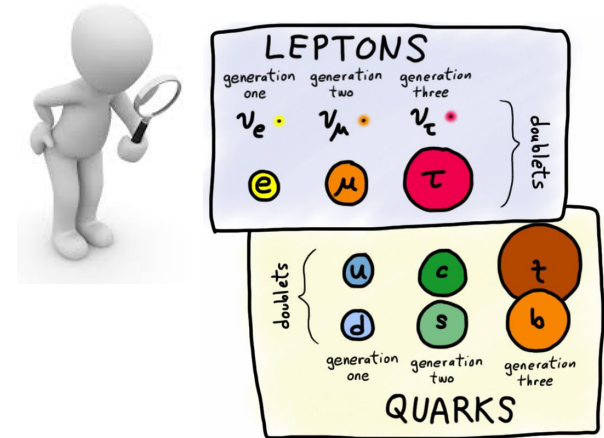
Disclaimer:

- I don't think a technical 1.5h presentation of the subject would be very useful. Instead I'll give a qualitative overview, hopefully conveying some important ideas.

- For technical details, one should resort to written lectures, books, or longer courses. E.g., A. Pich's EW lectures (0705.4264), A. Falkowski SMEFT review (EPJC 83 (2023) 7, 656), MGA-Naviliat-Severijns's β decay review (1803.08732), …

- I don't expect to go over all the slides. Stop me if you get lost.

- I took advantage of these lectures to go outside my strict comfort zone in some points and learn new things. Fun but risky.
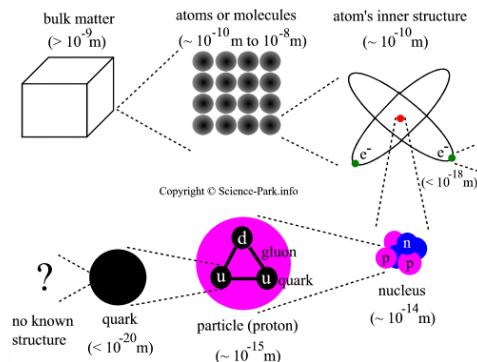
The Standard Model

- The SM is the QFT describing electromagnetic, weak & strong interactions.

- It's the ultimate result of reductionism & unification [electromagnetism ($\rightarrow$ chemistry), radioactivity, nuclear physics, …] Our periodic table.

- ~50 years old, spectacularly confirmed [All particles have been observed (Higgs @CERN, 2012)]

- Whatever [future experiments] find, SM has proven to be valid as an effective theory for E < TeV

x 3 !?

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$
$$+ i \bar{\psi} \slashed{D} \psi + h.c.$$
$$+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$
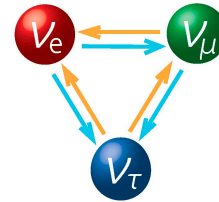$$+ |D_\mu \phi|^2 - V(\phi)$$

The SM is not enough (fortunately for us)

- Neutrinos oscillate → they have a mass!

- What lies under the SM periodic table?
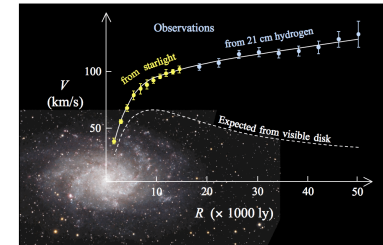

- Dark matter, matter-antimatter asymmetry, strong CP problem, hierarchy problem, dark energy, quantum gravity, cosmological problems, …

- All SM problems are theoretical or astrophysical/cosmological, except for neutrino masses.

- Many BSM theories around (often not very convincing)

- The SM works too well (quite curious crisis).
  We need new hints. Physics = EXP + TH

BSM experimental searches

- One can divide them in high- and low-E searches.
  (my reference: low-E means energies << EW scale)

- High-energy searches ($\rightarrow$ S. Lowette's lecture)
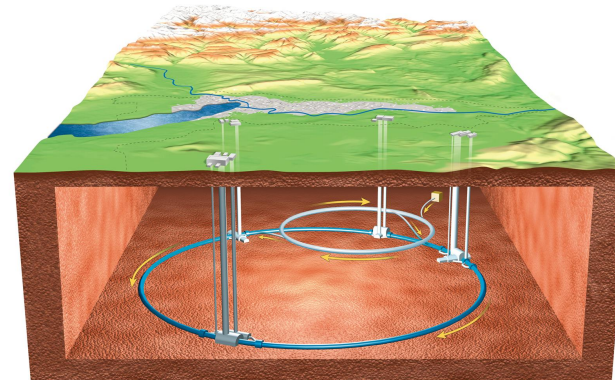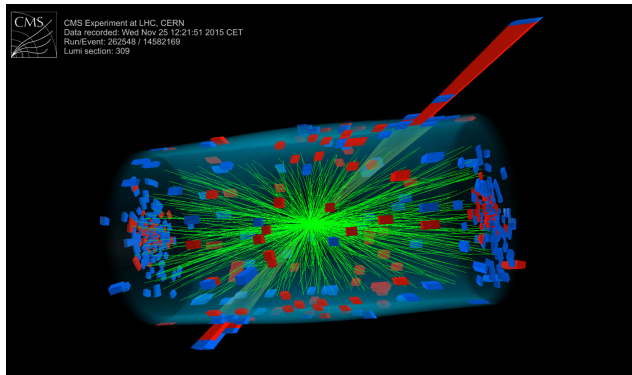
- Low-energy searches

PERKEO III

high

low

BSM searches with low-E processes

- In this lecture: BSM = heavy new physics
  (heavier than the scale of the process → new particles offshell)

QCD >> QED >> EW >> BSM

BSM searches with low-E processes

- In this lecture: BSM = heavy new physics
  (heavier than the scale of the process → new particles offshell)

Q~~C~~D >> QED >> EW >> BSM

Choose leptonic or semileptonic processes

BSM searches with low-E processes

QED >> EW >> BSM. What about QED?

BSM searches with low-E processes

QED >> EW >> BSM. What about QED?

- Solution 1: gargantuan TH+EXP precision (muon g-2)

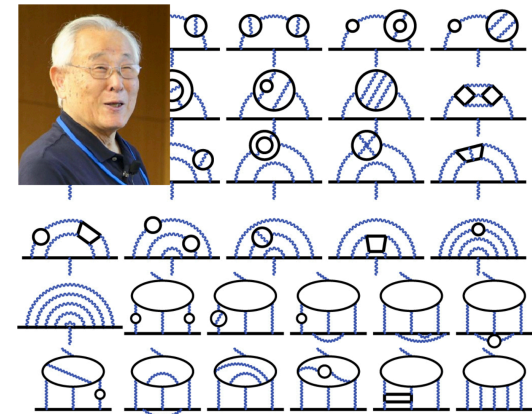Figure Credit: APS/Jorge Cham

$$a_\mu^{\text{Exp}} = 116\,592\,059(22) \times 10^{-11}\ (0.19\,\text{ppm}).$$

BSM searches with low-E processes

QED >> EW >> BSM. What about QED?

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- Solution 2: choose a process with neutrinos ($\nu_i\ f\ \to\ \nu_i\ f$)

scattered
neutrino

ν

ν

Z
boson   nuclear
recoil

$\vec{q}$

secondary
recoils

scintillation

[from COHERENT coll.]

Dinosaur heretic looks
for redemption   p. 1088

Increase inclusion to increase
STEM diversity   p. 1101

Fluorescent or magnetic
cotton fibers   p. 1118

Science

$15
15 SEPTEMBER 2017
sciencemag.org

AAAS

SPOTTING A

GHOST

A compact detector spies
neutrinos scattering from nuclei
pp. 1098 & 1123

[Akimov et al.'17]

[Image credit: Duke U.]

BSM searches with low-E processes

QED >> EW >> BSM. What about QED?

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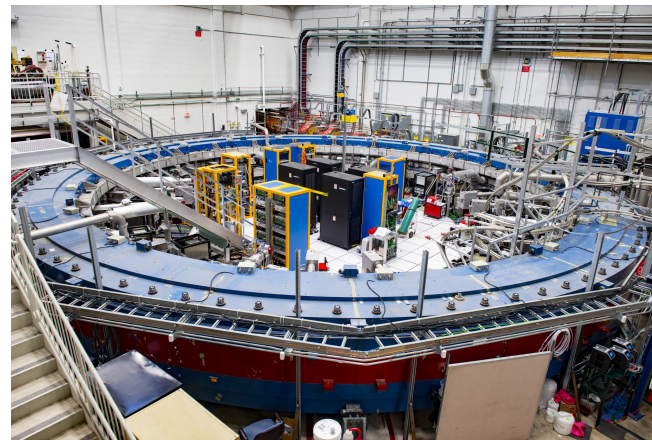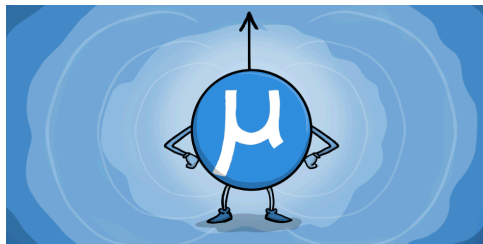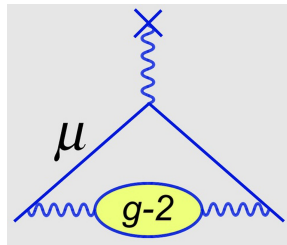- Solution 2: choose a process with neutrinos ($\nu_i\ f\ \to\ \nu_i\ f$)

- Solution 3: choose an observable that violates a QED symmetry

    - Parity! (Atomic PV, PVDIS, Qweak, …)

THE MIRROR DID **NOT** SEEM TO BE OPERATING PROPERLY.
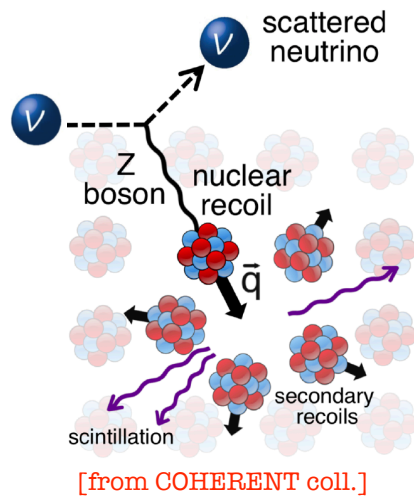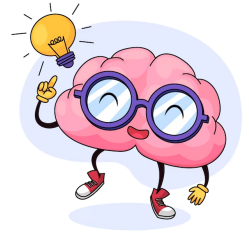
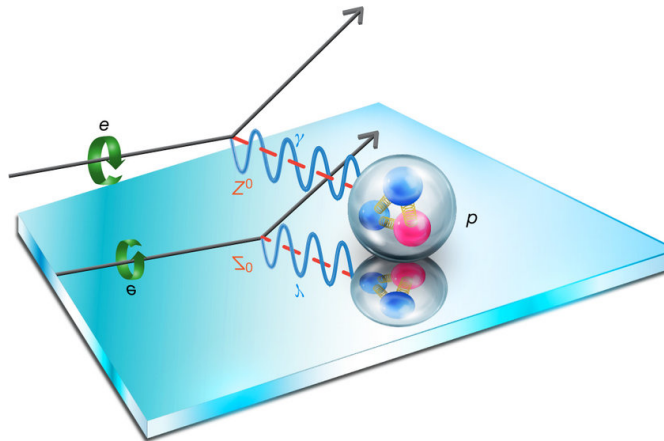| Fields	ψ_1	ψ_2	ψ_3
Quarks	$\begin{pmatrix} u \\ d \end{pmatrix}_L$	u_R	d_R
Leptons	$\begin{pmatrix} \nu_\ell \\ \ell^- \end{pmatrix}_L$	~~ν_R~~	ℓ_R^-

BSM searches with low-E processes

QED >> EW >> BSM. What about QED?

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  - Parity! (Atomic PV, PVDIS, Qweak, ...)
  - Flavor ($f\ f' \to f\ f''$)
    - 1st quark family: $d \to u\ e\ \nu \to$ β decays ($N \to N'\ e\ \nu$)

three generations of matter (fermions)

BSM searches with low-E processes

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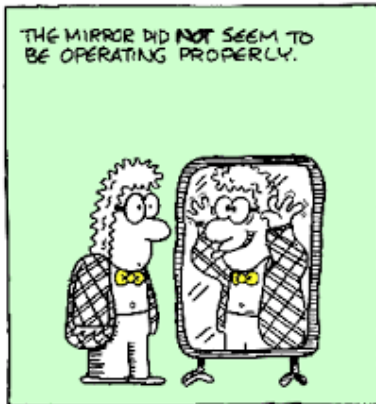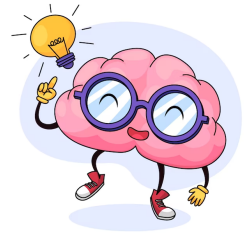
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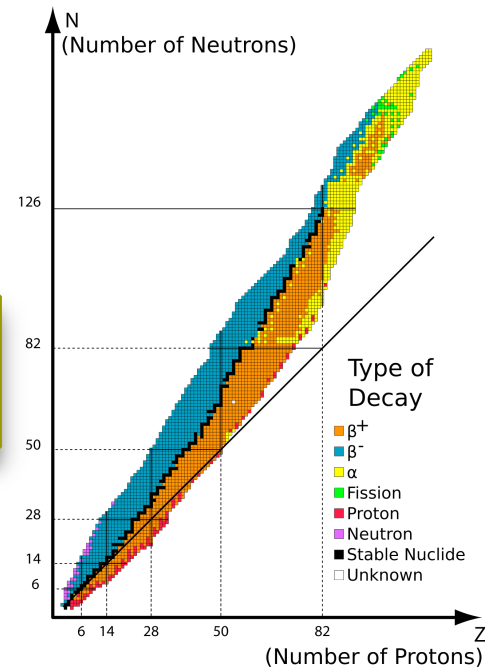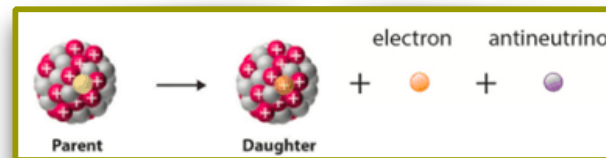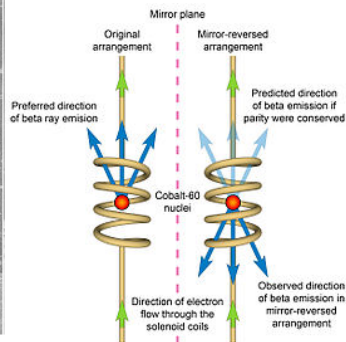
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    - 3 quark families ($d_j \rightarrow u_i\ \ell\ \nu$, $d_j \rightarrow d_i\ \ell^+\ell^-$, …) $\rightarrow$ "flavor physics"

$$
\begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix} \approx
$$

BSM searches with low-E processes

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    - Leptonic (with charged leptons): $\ell \to \ell'\ \nu\bar{\nu}$

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    - Leptonic (with charged leptons): $\ell \to \ell' \, \nu \bar{\nu}$
    - Neutrino oscillations: $\nu_\alpha \to \nu_\beta$

$$\pi^+ \to \mu^+ \bar{\nu}_\mu \qquad \bar{\nu}_e \, p \to n \, e^-$$
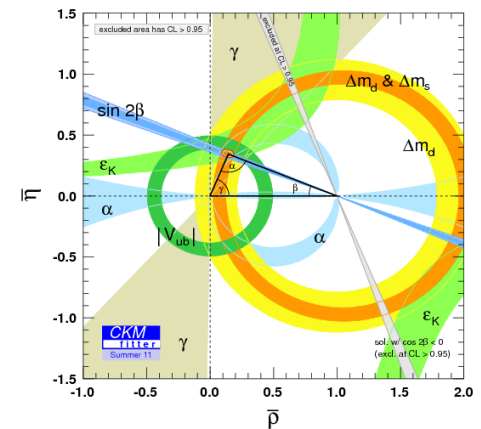
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- Even better $\to$ an observable that violates an EW symmetry: CP (electric dipole moments), B-L (proton decay), cLFV ($\mu\to e\gamma$)

  $\to$ *Either NP is very far (??), or it has a SM-like structure (B, CP, ...).*
  In the 2nd case, precision experiments might find NP first.
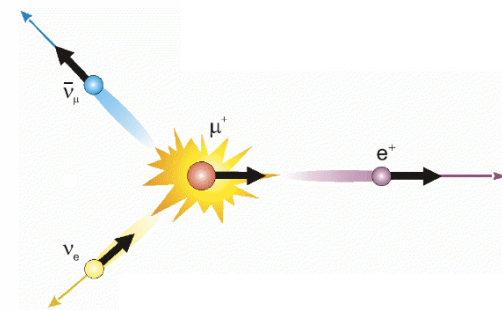
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- Even better → an observable that violates an EW symmetry: CP (electric dipole moments), B-L (proton decay), cLFV (μ→eγ)

→ *Either NP is very far (??), or it has a SM-like structure (B, CP, …).*
In the 2nd case, precision experiments might find NP first.

Precision EXP+TH

Theory?

~ 10 TeV

$$\mathcal{L}_{UV}(x) = \mathcal{L}(\varphi_{SM}, \mathbf{\Phi}_{NP})$$

EW scale   ~ 0.1 TeV

Low-E experiments   << 0.1 TeV

New particles

SM particles

Analysing BSM searches

**Specific
BSM model**

$$\mathcal{L}_{BSM} = \mathcal{L}\left(\phi_{SM}, \Phi_{BSM}\right)$$
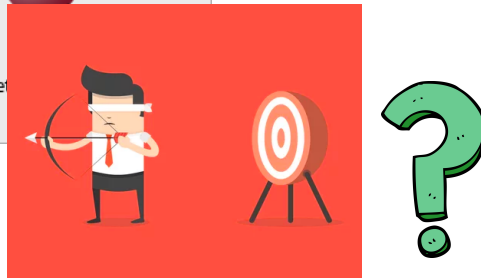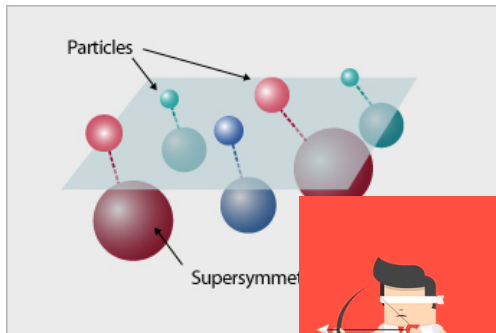
**Effective Field
Theory (EFT)
approach**
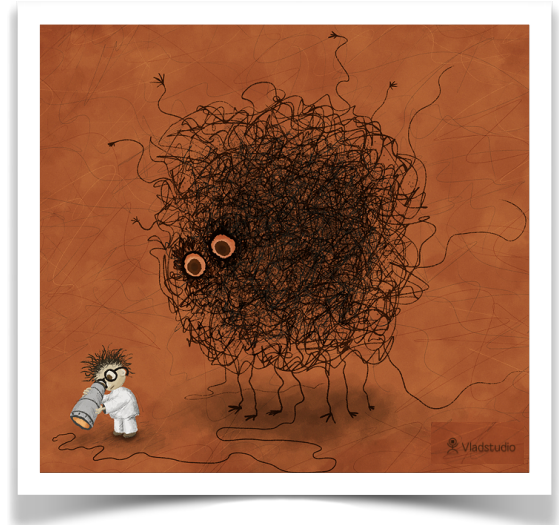
EFT detour
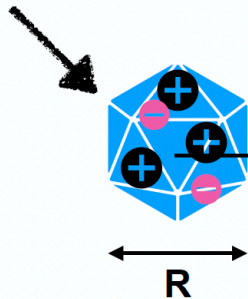
Some distribution of electric charges

Near observer

Far observer

L

r

R

Near observer, L~R, needs to know the position of every charge to describe electric field in her proximity

Far observer, $r \gg R$, can instead use multipole expansion:

$$V(\vec{r}) = \frac{Q}{r} + \frac{\vec{d} \cdot \vec{r}}{r^3} + \frac{Q_{ij} r_i r_j}{r^5} + \cdots$$

$\sim 1/r \quad \sim R/r^2 \quad \sim R^2/r^3$

$d_i \sim R$

$Q_{ij} \sim R^2$

Higher order terms in the multipole expansion are suppressed by powers of the small parameter (R/r). One can truncate the expansion at some order depending on the value of (R/r) and experimental precision

Far observer is able to describe electric field in his vicinity using just a few parameters: the total electric charge Q, the dipole moment $\vec{d}$, eventually the quadrupole moment Q_{ij}, etc....

On the other hand, far observer can only guess the "fundamental" distributions of the charges, as many distinct distributions lead to the same first few moments
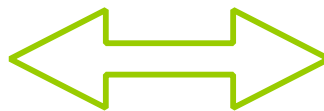
Small distances $\Longleftrightarrow$ **High energies**

EFT detour: QFT example
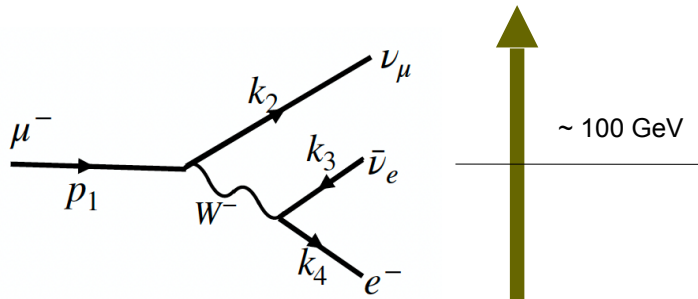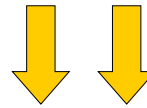
~ 100 GeV $\mathcal{L}_{SM}$ (EW theory)

$$\mathcal{M} = \frac{g_L^2}{2}\bar{u}(k_2)\gamma_\rho P_L u(p_1)\frac{1}{q^2 - m_W^2}\bar{u}(k_4)\gamma_\rho P_L v(k_3)$$

$$q = p_1 - k_2$$

$$q^2 \lesssim m_\mu^2 \ll m_W^2$$

$$\mathcal{M} = -\frac{g_L^2}{2m_W^2}\bar{u}(k_2)\gamma_\rho P_L u(p_1)\bar{u}(k_4)\gamma_\rho P_L v(k_3) + \mathcal{O}(q^2/m_W^4)$$

~ GeV
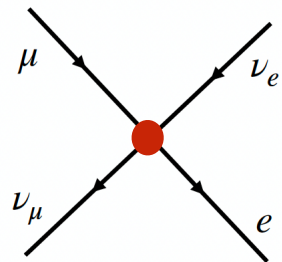
$$\mathcal{L}_{eff} = -\frac{4 G_F}{\sqrt{2}}\bar{e}\,\gamma_\mu(1-\gamma_5)\nu_e \cdot \bar{\nu}_\mu\gamma^\mu(1-\gamma_5)\mu$$

+ higher-dim terms

$$G_F = \frac{g^2}{4\sqrt{2}m_W^2}$$

Wilson coefficient

EFT detour: QFT example
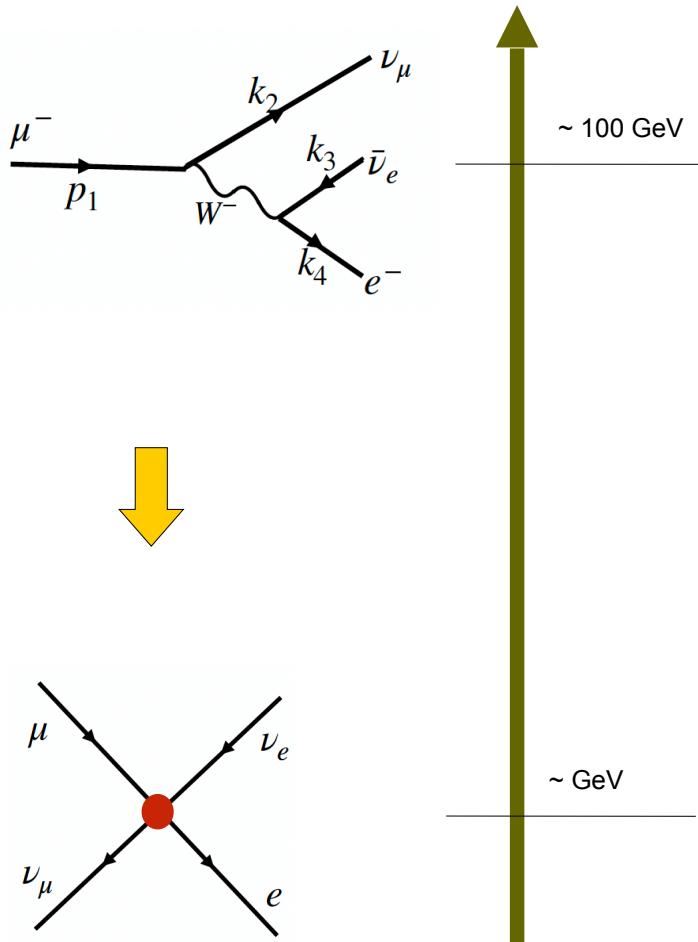
~ 100 GeV

$\mathcal{L}_{SM}$ (EW theory)

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~ GeV

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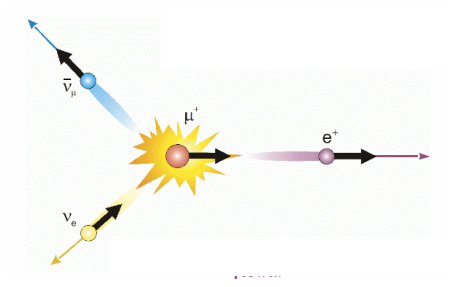
Historically the logic was quite different:
Data → Fermi EFT → SM

$$G_F = \frac{g^2}{4\sqrt{2}m_W^2}$$

Wilson coefficient

EFT detour

Top down

Bottom up

Known theory at
high-E

EFT that includes
high-E effects

EFT at low-E

Known theory at low-E
(or at least symmetries & fields)

Given a set of low-E fields &
symmetries, one builds an
EFT Lagrangian putting all
possible interactions and
following a power counting

M. González-Alonso

EFT at the EW scale: SM → SMEFT
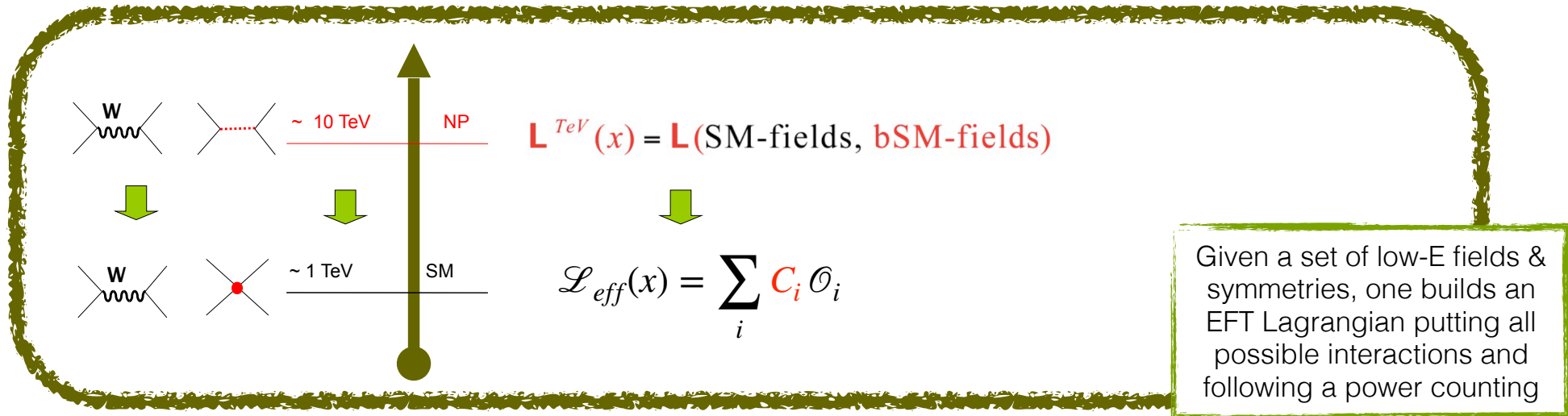
$$L^{TeV}(x) = L(\text{SM-fields, bSM-fields})$$

$$\mathcal{L}_{eff}(x) = \sum_i C_i \, \mathcal{O}_i$$

~ 10 TeV   NP

~ 1 TeV   SM

Given a set of low-E fields & symmetries, one builds an EFT Lagrangian putting all possible interactions and following a power counting

EFT = Model-independent approach ≠ Assumption independent

1. QFT (Lorentz inv.)

2. SM fields + gap:
   NP scale >> EW scale.

3. SU(3)xSU(2)xU(1) gauge symmetry

Building the SMEFT

Building blocks:

$$G_\mu^a \ , \ W_\mu^k \ , \ B_\mu \ , \ q \ , \ u \ , \ d \ , \ \ell \ , \ e \ , \ \varphi$$

Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	Spin
G_μ^a	8	1	0	1
W_μ^k	1	3	0	1
B_μ	1	1	0	1
Q	3	2	1/6	1/2
u	3	1	2/3	1/2
d	3	1	-1/3	1/2
L	1	2	$-1/2$	1/2
e	1	1	-1	1/2
H	1	2	1/2	0

Rules

$$SU(3)c \times SU(2)_L \times U(1)_Y$$

RULES

$$\mathscr{L} = \sum_i C_i \, \mathscr{O}_i \left(\phi_j, D_\mu \phi_k \right)$$

Example: $\quad \mathscr{L} = C \left(\varphi^\dagger \varphi \right)^3$

Building the SMEFT

There are infinite gauge-invariant terms.
But that's OK because there's a well-defined expansion:

- Take an operator (=interaction term) $\mathcal{O}_D$ of dimension D.

- Since $[\mathscr{L}] = E^4 \;\rightarrow\; \mathscr{L} \supset C_D \, \mathcal{O}_D$ where $[C_D] \sim \dfrac{1}{\Lambda^{4-D}}$

- Its contribution to a (dimensionless) amplitude associated to a process with E>>m

$$\mathscr{M} \sim C_D \, E^{D-4} \sim \left(\frac{E}{\Lambda}\right)^{D-4}$$

- Thus, for $E \ll \Lambda$:
  a D=5 term gives a larger contribution than a D=6 one,
  a D=6 term gives a larger contribution than a D=7 one,
  and so on.
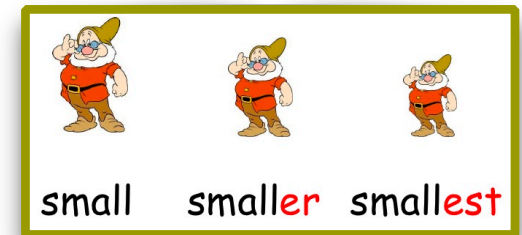
- For a given precision, we only need a finite amount of terms: $\mathscr{L} = \mathscr{L}_{D\leq 4} + \mathscr{L}_5 + \mathscr{L}_6 + \mathscr{L}_7 + \dots$

- This power counting allows us to define SMEFT at the quantum level
  (the SMEFT is renormalizable at a any finite order in the EFT expansion)

Building the SMEFT

$$\mathcal{L} = \mathcal{L}_{D \leq 4} + \mathcal{L}_5 + \mathcal{L}_6 + \mathcal{L}_7 + \ldots$$

$$\sum_i C_6^i \mathcal{O}_6^i$$

Complete (and minimal) set of operators → "Basis"

- Finding a minimal set of operators is a subtle business.
  - It's not just (O_1, O_2) vs (O_1+O_2, O_1-O_2). Operators can be related through integration by parts, Fierz transformation and field redefinitions.
  - Solved recently
    [Grzadkowski et al. 1008.4884; Lehman-Martin 1510.00372; Henning et al. 1512.03433; Li et al. 2201.04639; ...]

- Any physical result will be independent of the basis chosen.
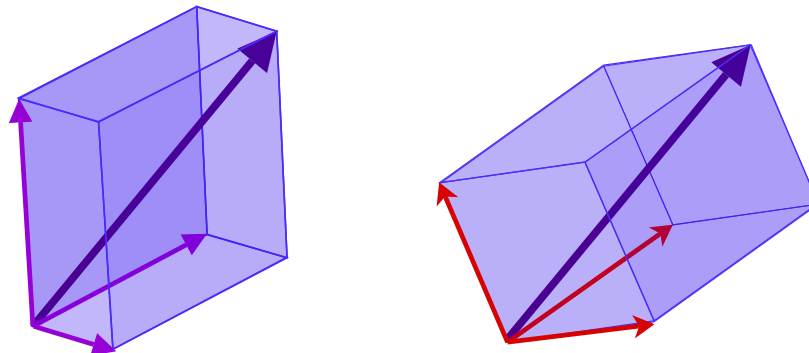
Building the SMEFT
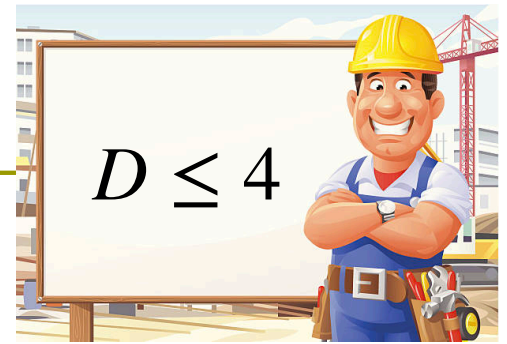
$$\mathscr{L} = \boxed{\mathscr{L}_{D\leq4}} + \mathscr{L}_5 + \mathscr{L}_6 + \mathscr{L}_7 + \dots$$

- At $D \leq 4$ we find the SM

$$\mathscr{L}_{SM} = -\frac{1}{4}G^{a\mu\nu}G^a_{\mu\nu} - \frac{1}{4}W^{k\mu\nu}W^k_{\mu\nu} - \frac{1}{4}B^{\mu\nu}B_{\mu\nu} - \tilde{\theta}\,G^{a\mu\nu}\tilde{G}^a_{\mu\nu}$$

$$+ i\sum_f \bar{f}\,D_\mu\gamma^\mu f$$

$$- \left(\bar{\ell}\,Y_e\,\varphi\,e \;+\; \bar{q}\,\varphi\,Y_d\,d \;+\; \bar{q}\,\tilde{\varphi}\,Y_u\,u\right) + h.c.$$

$$+ \left(D_\mu\varphi\right)^\dagger\left(D^\mu\varphi\right) - \mu^2\left(\varphi^\dagger\varphi\right) - \lambda\left(\varphi^\dagger\varphi\right)^2$$
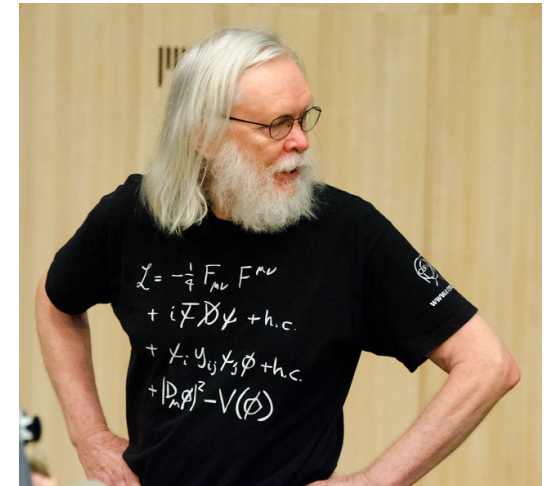
- All coefficients have been measured

    …except the theta term: $\mathscr{L}_{SM} \supset -\,\tilde{\theta}\,G^{a\mu\nu}\tilde{G}^a_{\mu\nu}$

- Interaction size OK except:
    - $\mu = M_h\sqrt{2} \sim 100\,\text{GeV} \ll \Lambda$ (??)
    - EFT predicts: $Y_f \sim \mathcal{O}(1) \;\rightarrow\; m_f \sim v,\;\; V_{ij} \sim \mathcal{O}(1)$
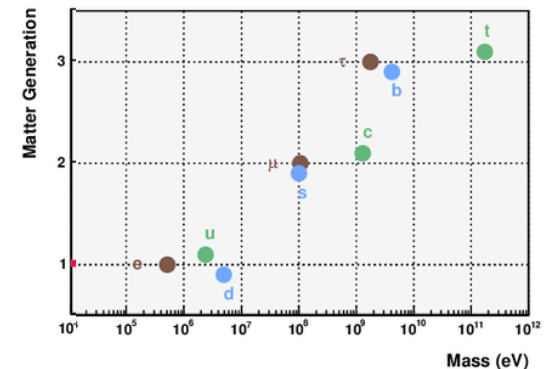
Building the SMEFT
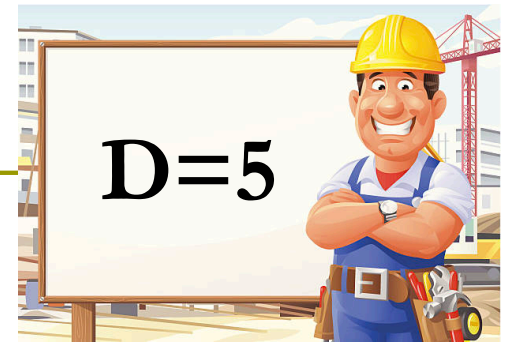
$$\mathscr{L} = \mathscr{L}_{D \leq 4} + \mathscr{L}_5 + \mathscr{L}_6 + \mathscr{L}_7 + \dots$$

- Only one operator (Weinberg'79)

$$\mathscr{L}_5 = \frac{[c_5]_{pr}}{\Lambda} \left(\tilde{\varphi}^\dagger \ell_p \right)^T C \left(\tilde{\varphi}^\dagger \ell_r \right) + h.c.$$

$$\tilde{\varphi} \equiv i \, \sigma_2 \, \varphi = \begin{pmatrix} (\varphi^0)^* \\ -(\varphi^+)^* \end{pmatrix} \rightarrow \frac{1}{\sqrt{2}} \begin{pmatrix} v + H \\ 0 \end{pmatrix}$$

$$\ell \equiv \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$$

- After EWSB generates Majorana masses (for LH neutrinos):

$$\mathscr{L}_M = -\frac{1}{2} m_M \bar{\nu}_L^c \nu_L + h.c. \,, \qquad \nu^c \equiv C \bar{\nu}^T$$

- Perfect! (neutrino oscillations → neutrino masses)
  Great success of the SMEFT approach: corrections to the SM Lagrangian predicted at 1st order in the EFT expansion, are indeed observed!

APPLAUSE
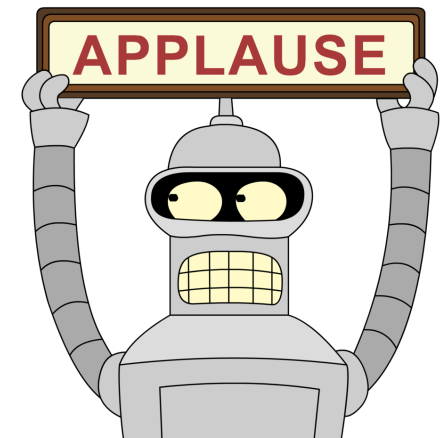
Building the SMEFT
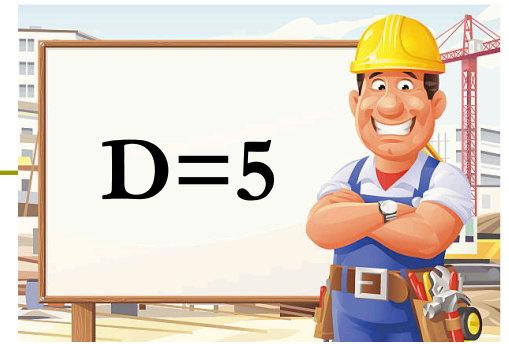
$$\mathscr{L}_5 = \frac{[c_5]_{pr}}{\Lambda} \left(\tilde{\varphi}^\dagger \ell_p \right)^T C \left(\tilde{\varphi}^\dagger \ell_r \right) + h.c. \quad \rightarrow \quad m_\nu \sim 2\, c_5\, v^2/\Lambda$$

- Oscillation data → Δm^2.
  Other experiments (KATRIN!) /observations → bounds on m.
  All in all, m ~ O(0.01) eV. Thus:

$$v^2/\Lambda \sim 0.1 \text{ eV} \quad \rightarrow \quad \Lambda \sim 10^{15} \text{ GeV !!}$$

- The mass gap is certainly OK

- But then higher dimensional effects are
  then extremely suppressed
  (only hope: B-number violation)

  $D = 6 \quad \rightarrow \quad v^2/\Lambda^2 \sim 10^{-26}$!!

Building the SMEFT
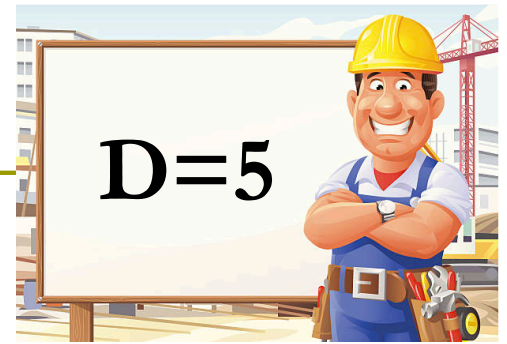
$$\mathcal{L}_5 = \frac{[c_5]_{pr}}{\Lambda} \left(\tilde{\varphi}^\dagger \ell_p\right)^T C \left(\tilde{\varphi}^\dagger \ell_r\right) + h.c. \quad \rightarrow \quad m_\nu \sim 2 c_5 v^2/\Lambda$$

- Tiny neutrino masses point to huge NP scale: $\Lambda \sim 10^{15}$ GeV

- Alternative:
  It's possible (and even natural) that there's more than one NP scale.
  This is not arbitrary since D=5 is "special": it violates B-L

  - A very high scale Λ_L associated to B-L violating physics (D=5, 7, …)

  - A (hopefully) not so high scale, Λ, associated to B-L conserving physics (D=6, 8, …)

  $$\mathcal{L}_{D=5} \sim \frac{1}{\Lambda_L}, \ \mathcal{L}_{D=6} \sim \frac{1}{\Lambda^2}, \ \mathcal{L}_{D=7} \sim \frac{1}{\Lambda_L^3}, \ \mathcal{L}_{D=8} \sim \frac{1}{\Lambda^4}, \ \textbf{and so on}$$

- PS: Outside the SMEFT paradigm there are other explanations for m_ν
  E.g., SM + $\nu_R \rightarrow$ one has D=3 Majorana & D=4 yukawas ($\rightarrow$ Dirac mass).

~ Λ_L NP

~ Λ NP

~ 100 GeV   SM

Building the SMEFT

$$\mathscr{L} = \mathscr{L}_2 + \mathscr{L}_3 + \mathscr{L}_4 + \mathscr{L}_5 + \mathscr{L}_6 + \mathscr{L}_7 + \dots$$

D=6

- First B-L conserving corrections to the SM.

- One finds 63 operators [Grzadkowski et al., 1008.4884]
  Flavor structure → 3045 coefficients

HELP!

	X^3		φ^6 and $\varphi^4 D^2$		$\psi^2 \varphi^3$
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger \varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger \varphi)(\bar{l}_p e_r \varphi)$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\square}$	$(\varphi^\dagger \varphi)\square(\varphi^\dagger \varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p u_r \widetilde{\varphi})$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu \varphi)^\star (\varphi^\dagger D_\mu \varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p d_r \varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

	$X^2 \varphi^2$		$\psi^2 X \varphi$		$\psi^2 \varphi^2 D$
$Q_{\varphi G}$	$\varphi^\dagger \varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$
$Q_{\varphi \widetilde{G}}$	$\varphi^\dagger \varphi\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger \varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{\varphi}\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r)$
$Q_{\varphi \widetilde{W}}$	$\varphi^\dagger \varphi\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{\varphi}\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger \varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi \widetilde{B}}$	$\varphi^\dagger \varphi\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{u}_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r)$
$Q_{\varphi \widetilde{W}B}$	$\varphi^\dagger \tau^I \varphi\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu \varphi)(\bar{u}_p \gamma^\mu d_r)$

Table 2: Dimension-six operators other than the four-fermion ones.

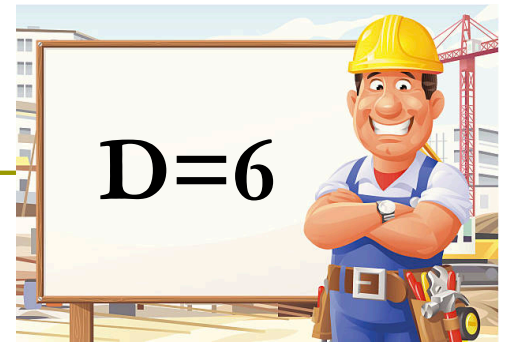|	$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$
Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$

	$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{jk} \left[(d_p^\alpha)^T C u_r^\beta \right] \left[(q_s^{\gamma j})^T C l_t^k \right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{jk} \left[(q_p^{\alpha j})^T C q_r^{\beta k} \right] \left[(u_s^\gamma)^T C e_t \right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{jn}\varepsilon_{km} \left[(q_p^{\alpha j})^T C q_r^{\beta k} \right] \left[(q_s^{\gamma m})^T C l_t^n \right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma} \left[(d_p^\alpha)^T C u_r^\beta \right] \left[(u_s^\gamma)^T C e_t \right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$		

Table 3: Four-fermion operators.

Building the SMEFT

$$\mathscr{L} = \mathscr{L}_2 + \mathscr{L}_3 + \mathscr{L}_4 + \mathscr{L}_5 + \mathscr{L}_6 + \mathscr{L}_7 + \dots$$

- First B-L conserving corrections to the SM.

- One finds 63 operators [Grzadkowski et al., 1008.4884] Flavor structure → 3045 coefficients

$$(\varphi^\dagger i D_\mu \varphi)(l_p \gamma^\mu l_r)$$
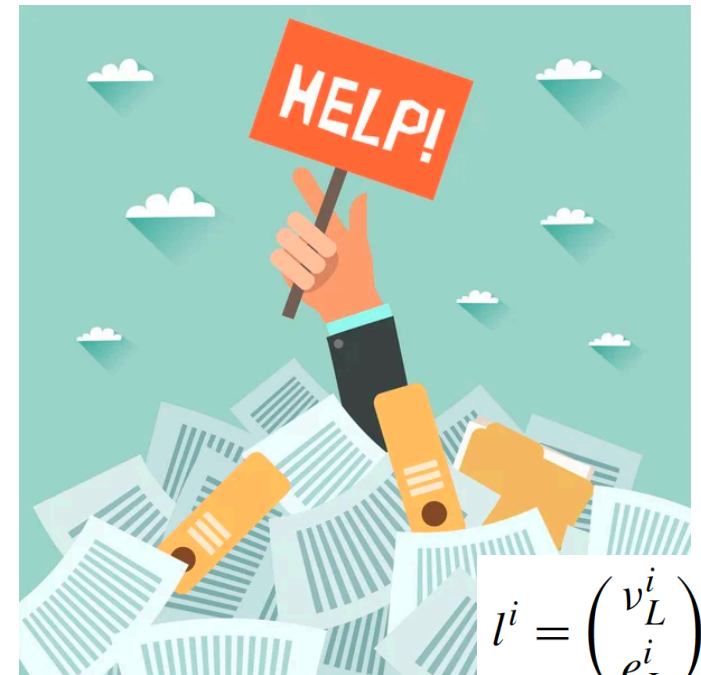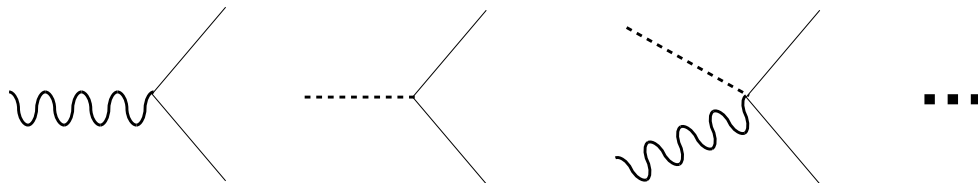
$$l^i = \begin{pmatrix} v_L^i \\ e_L^i \end{pmatrix}$$

$$\varphi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

$$D_\mu = I \partial_\mu - i g_s \frac{\lambda^A}{2} G_\mu^A - i g \frac{\sigma^a}{2} W_\mu^a - i g' Y B_\mu$$

Building the SMEFT

D=6
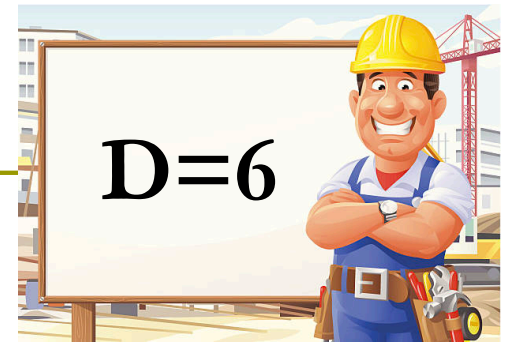
$$\mathscr{L} = \mathscr{L}_2 + \mathscr{L}_3 + \mathscr{L}_4 + \mathscr{L}_5 + \mathscr{L}_6 + \mathscr{L}_7 + \ldots$$

- First B-L conserving corrections to the SM.

- One finds 63 operators [Grzadkowski et al., 1008.4884]
  Flavor structure → 3045 coefficients

$$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$$

...

$$l^i = \begin{pmatrix} v_L^i \\ e_L^i \end{pmatrix}$$

$$\varphi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

$$D_\mu = I\partial_\mu - ig_s \frac{\lambda^A}{2} G_\mu^A - ig\frac{\sigma^a}{2} W_\mu^a - ig'YB_\mu$$

Building the SMEFT
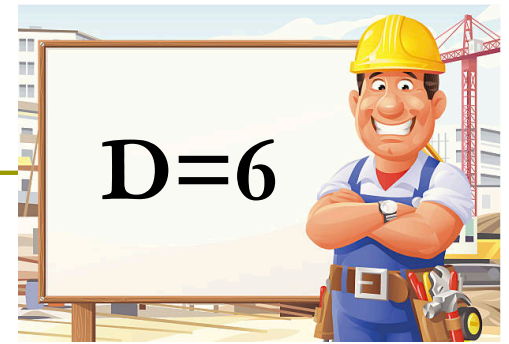
$$\mathscr{L} = \mathscr{L}_2 + \mathscr{L}_3 + \mathscr{L}_4 + \mathscr{L}_5 + \mathscr{L}_6 + \mathscr{L}_7 + \ldots$$

- First B-L conserving corrections to the SM.

- One finds 63 operators [Grzadkowski et al., 1008.4884]
  Flavor structure $\rightarrow$ 3045 coefficients

- Extremely rich phenomenology:
  colliders,
  flavor,
  low-energy searches,
  neutrino physics,
  proton decay,
  CP violation,
  …

- All results compatible with zero $\rightarrow$ Bounds on Λ

$$\left(\mathscr{L} \supset \frac{1}{\Lambda^2}\, \mathscr{O}_6 \right)$$
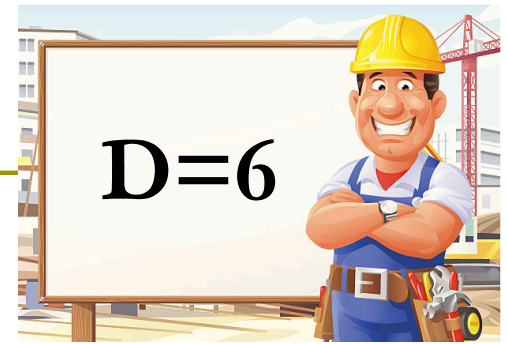
Building the SMEFT

$$\mathscr{L} = \mathscr{L}_2 + \mathscr{L}_3 + \mathscr{L}_4 + \mathscr{L}_5 + \mathscr{L}_6 + \mathscr{L}_7 + \ldots$$

[A. Falkowski, Eur.Phys.J.C 83 (2023) 7, 656]

- First B
- One fir
  Flavor
- Extrem
  collide
  flavor,
  low-en
  neutrin
  proton
  CP vio
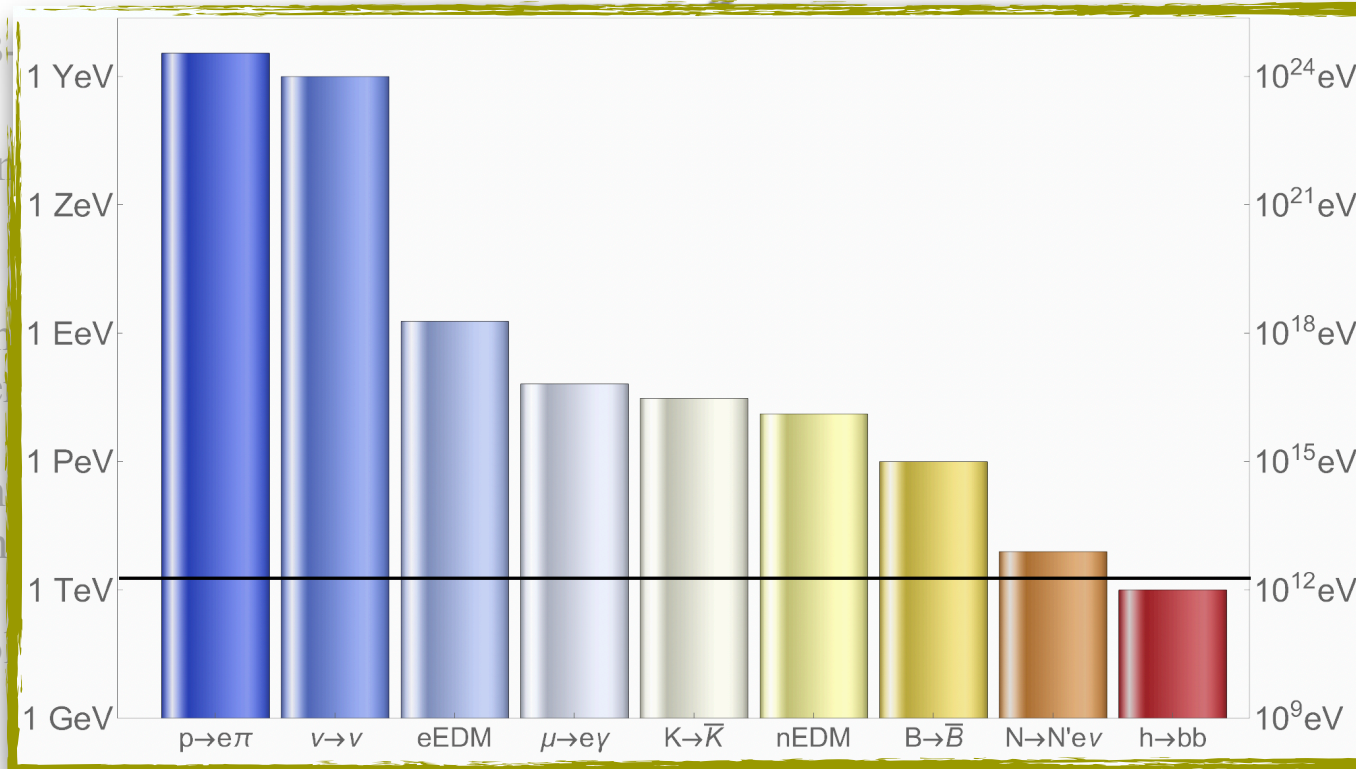
- All results compatible with zero → Bounds on Λ

$$\left(\mathscr{L} \supset \frac{1}{\Lambda^2} \mathscr{O}_6 \right)$$

Building the SMEFT

$$\mathscr{L} = \mathscr{L}_2 + \mathscr{L}_3 + \mathscr{L}_4 + \mathscr{L}_5 + \mathscr{L}_6 + \mathscr{L}_7 + \ldots$$

⦿ At dim-6 is where all the fun starts, but it's also where it ends
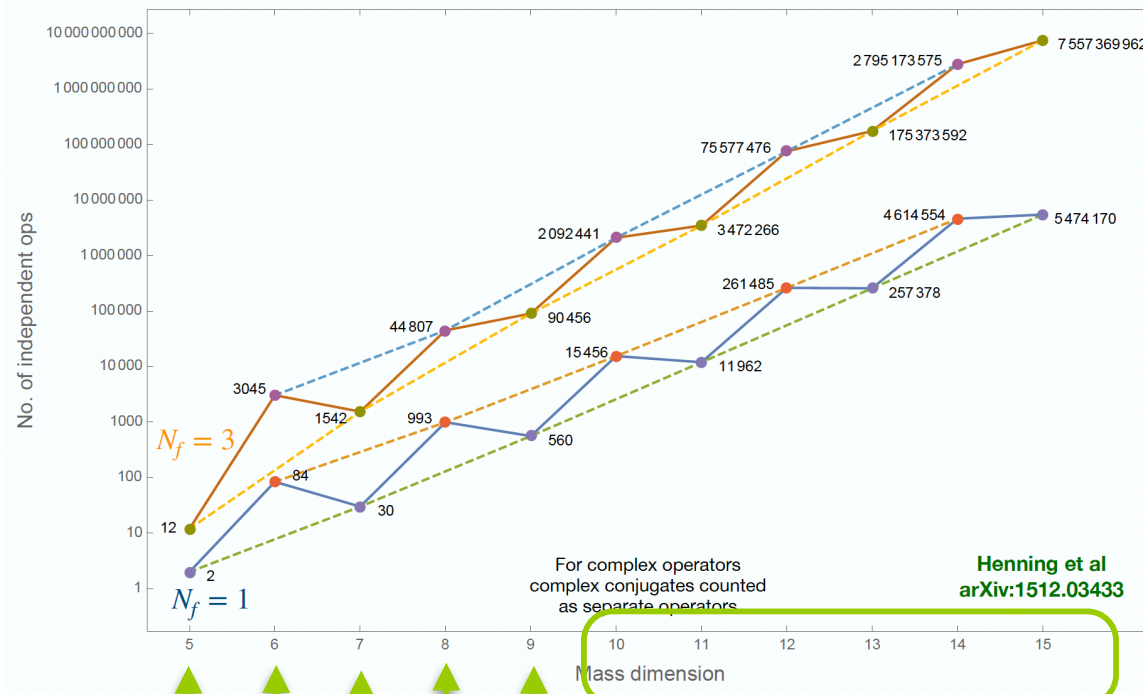
Exponential growth with D

Weinberg'79

Grzadkowski et al.'10

Lehman'14

Li et al.'20

Li et al.'21

Li et al'22 (Code valid at any dimension)

Building the SMEFT

$$\mathcal{L} = \mathcal{L}_2 + \mathcal{L}_3 + \mathcal{L}_4 + \mathcal{L}_5 + \mathcal{L}_6 + \mathcal{L}_7 + \dots$$

- At dim-6 is where all the fun starts, but it's also where it ends
  - Really too many operators
  - For D=7, 9, … the effect is expected to be tiny
  - For D=8, 10, … not easy to imagine situations where terms that are so suppressed (if the EFT works) give measurable effects in observable X whereas all D=6 terms do not give measurable effects in so many other observables.

- A few processes receive their first tree-level correction at D>6:
  light-by-light scattering (dim-8), neutron-antineutron oscillation (dim-9), …
  Depending on the mass gap, they could compete w/ loop effects from lower-dim. operators.
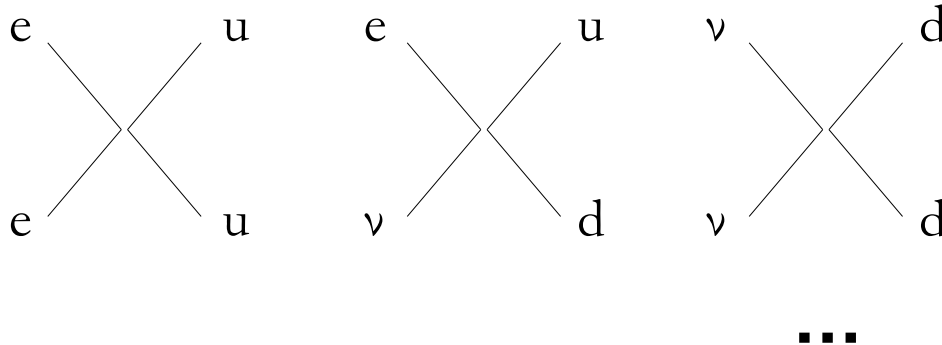
Building the SMEFT

$$\mathcal{L} = \mathcal{L}_2 + \mathcal{L}_3 + \mathcal{L}_4 + \mathcal{L}_5 + \mathcal{L}_6 + \boxed{\mathcal{L}_7 + \ldots}$$

- It's crucial to keep in mind that these operators exist.
  E.g. (dim-6)^2 vs dim-8 contributions (validity of the EFT expansion)

- Let's think in a (non-forbidden) low-E process (E<<v):

$$\mathcal{M} = \mathcal{M}_{SM}\left(1 + c_6\,\mathcal{O}\left(\frac{v^2}{\Lambda^2}\right) + c_8\,\mathcal{O}\left(\frac{v^4}{\Lambda^4}\right) + \ldots \right)$$

$$|\mathcal{M}|^2 = |\mathcal{M}_{SM}|^2\left(1 + c_6\,\mathcal{O}\left(\frac{v^2}{\Lambda^2}\right) + c_6^2\,\mathcal{O}\left(\frac{v^4}{\Lambda^4}\right) + c_8\,\mathcal{O}\left(\frac{v^4}{\Lambda^4}\right) + \ldots \right)$$

- One should *not* include quadratic terms
  (equivalently: results should not depend strongly on quadratic terms)

- The reasoning is the same for E~v or higher energies.

Building the SMEFT

$$\mathcal{L} = \mathcal{L}_{SM} + \text{\textbf{Majorana neutrino masses}} + \sum \frac{c_6^i}{\Lambda^2} \mathcal{O}_6^i + \ldots$$

Down the EFT stairs

Top down

Known theory at
high-E

⬇

EFT at low-E

Bottom up

EFT that includes
high-E effects

SMEFT

⬆

Low-E symmetries & fields

Down the EFT stairs

Top down

Known theory at high-E

⬇

EFT at low-E

SMEFT

Low-energy (~GeV) EFT (LEFT)

Bottom up
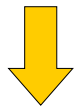
EFT that includes high-E effects

⬆

Low-E symmetries & fields

SMEFT

Down the EFT stairs

Known theory at high-E

SMEFT

SM

Low-energy EFT

EFT at low-E

~ 100 GeV

$$\mathcal{L}_{eff} = \mathcal{L}_{SM}$$

$$G_F = \frac{g^2}{4\sqrt{2}\, m_W^2}$$

$\sim$ GeV
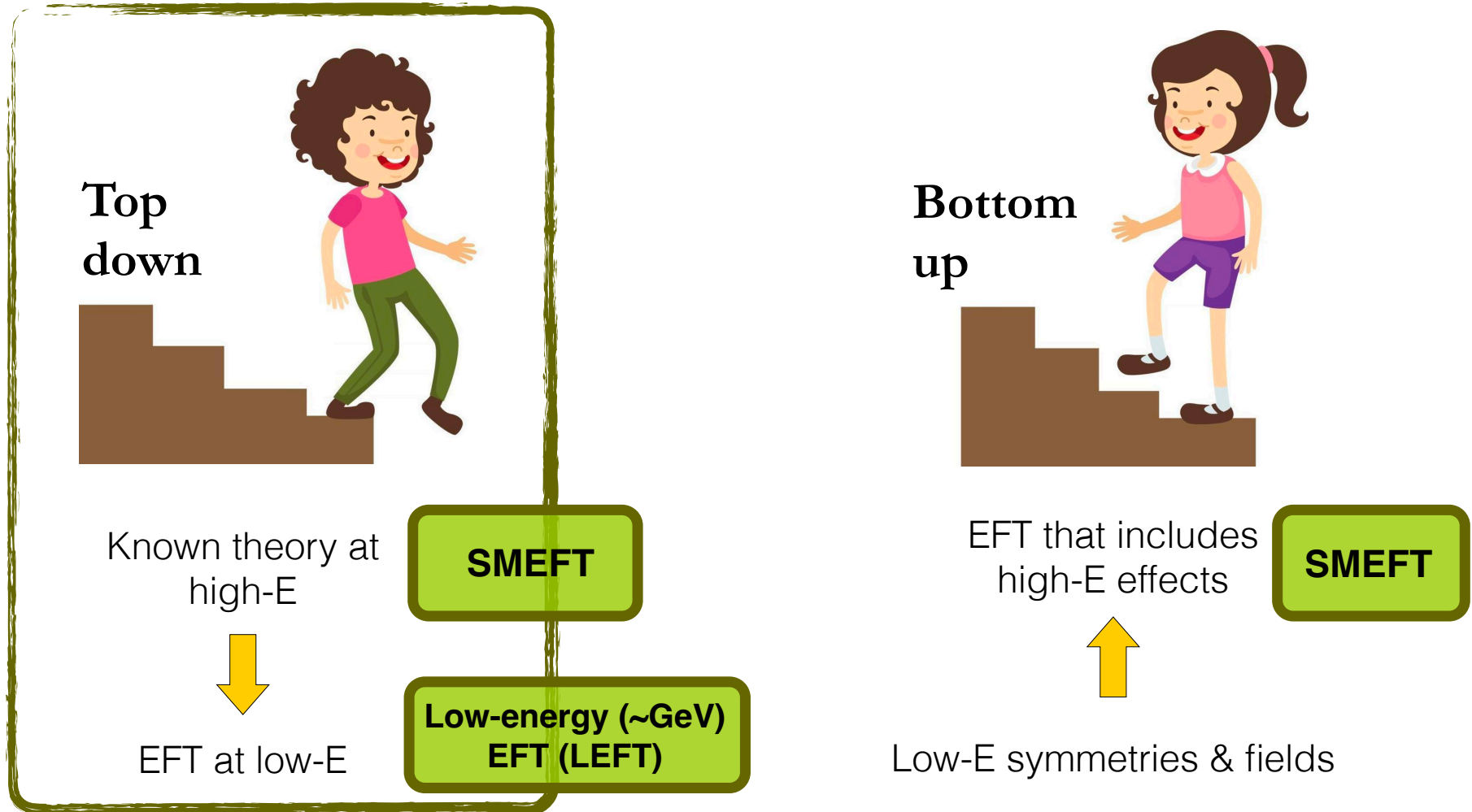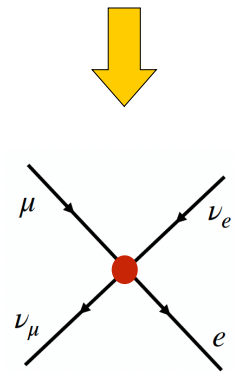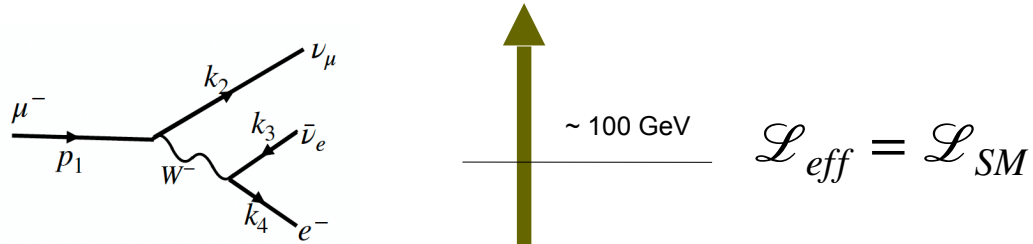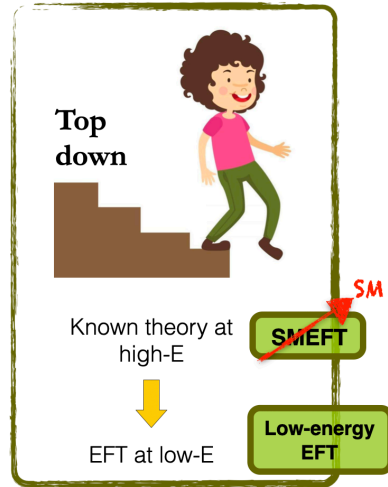
$$\mathcal{L}_{eff} = -\frac{4\,G_F}{\sqrt{2}}\, \bar{e}\,\gamma_\mu\,(1-\gamma_5)\,\nu_e \cdot \bar{\nu}_\mu\,\gamma^\mu\,(1-\gamma_5)\,\mu$$

+ higher-dim terms

Down the EFT stairs

Known theory at high-E

SMEFT

SM

EFT at low-E

Low-energy EFT
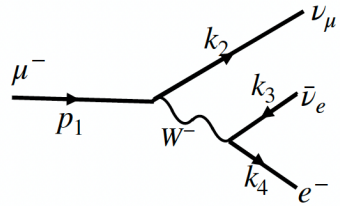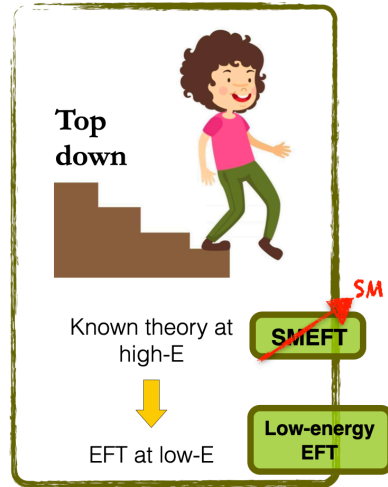
~ 100 GeV

$$\mathscr{L}_{eff} = \mathscr{L}_{SM}$$

$$+ \frac{c_5}{\Lambda} \mathscr{O}_5 + \sum_i \frac{c_6^i}{\Lambda^2} \mathscr{O}_6^i + \dots$$

$$G_F = \frac{g^2}{4\sqrt{2}\, m_W^2} + f\left(\frac{c_6^i}{\Lambda^2}\right)$$

~ GeV
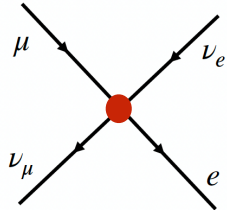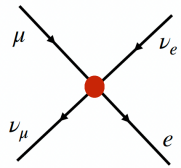
$$\mathscr{L}_{eff} = -\frac{4\,G_F}{\sqrt{2}}\, \bar{e}\, \gamma_\mu (1 - \gamma_5)\, \nu_e \cdot \bar{\nu}_\mu\, \gamma^\mu (1 - \gamma_5)\, \mu$$

+ higher-dim terms

$$+ \frac{4\,\epsilon}{\sqrt{2}}\, \bar{e}\, (1 - \gamma_5)\, \nu_e \cdot \bar{\nu}_\mu\, (1 + \gamma_5)\, \mu$$

$$\epsilon = g\left(\frac{c_6^i}{\Lambda^2}\right)$$

Down the EFT stairs

Known theory at high-E

SMEFT

EFT at low-E

SM

SMEFT

Low-energy EFT

~ 100 GeV

$$\mathscr{L}_{eff} = \mathscr{L}_{SM}$$

$$+ \frac{c_5}{\Lambda} \mathcal{O}_5 + \sum_i \frac{c_6^i}{\Lambda^2} \mathcal{O}_6^i + \ldots$$

The SMEFT has ~3K coefficients, but it generates only one new term to the muon decay low-energy EFT Lagrangian.

- Moreover this term can be neglected in most cases (contributions $\sim m_e/m_\mu$)
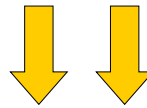
$$G_F = \frac{g^2}{4\sqrt{2}\, m_W^2} + f\left(\frac{c_6^i}{\Lambda^2}\right)$$

$$\mathscr{L}_{eff} = -\frac{4 G_F}{\sqrt{2}} \bar{e}\, \gamma_\mu (1 - \gamma_5)\, \nu_e \cdot \bar{\nu}_\mu \gamma^\mu (1 - \gamma_5)\, \mu$$

+ higher-dim terms

$$+ \frac{4\epsilon}{\sqrt{2}} \bar{e}\, (1 - \gamma_5)\, \nu_e \cdot \bar{\nu}_\mu (1 + \gamma_5)\, \mu$$

$$\epsilon = g\left(\frac{c_6^i}{\Lambda^2}\right)$$

SMEFT → Low-energy EFT

10 TeV	**Dragons**		UV physics
100 GeV	$\gamma,\ g,\ W,\ Z,\ \nu_i,\ e,\ \mu,\ \tau$ **+ u, d, s, c, b, t + h**		
5 GeV	$\gamma,\ g,\ \nu_i,\ e,\ \mu,\ \tau$ **+ u, d, s, c, b**		
2 GeV	$\gamma,\ g,\ \nu_i,\ e,\ \mu,\ \tau$ **+ u, d, s, c**		
1 GeV	$\gamma,\ \nu_i,\ e,\ \mu$ **+ hadrons**		IR physics (data!)
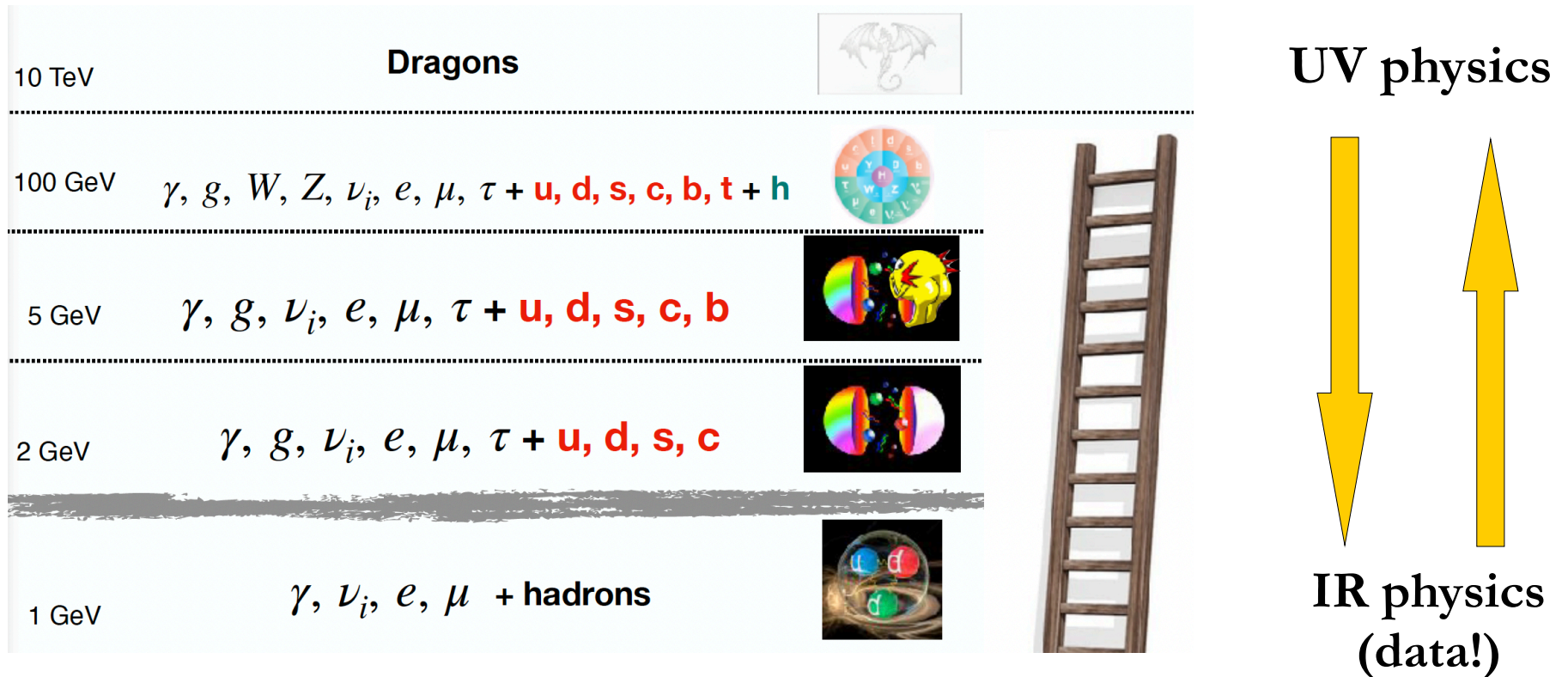
- Various names: LEFT, WEFT, WET, …
  - Variants: LEFT-5, LEFT-4, …

- In any case, the full LEFT (generated by the SMEFT) has of course many many terms. The matching between LEFT & SMEFT is known at 1-loop [Jenkins et al., 1709.04486; Dekens & Stoffer, 1908.05295].

- For concreteness, I'll focus on beta decays ($d \rightarrow u e \bar{\nu}$).

SMEFT → Beta-decay LEFT

$\mathcal{L}(x) = \mathcal{L}$ (SM fields, bSM fields)

~ 10 TeV   NP

$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \sum_i \dfrac{c_6^i}{\Lambda^2} \mathscr{O}_6^i + \dots$

~ 1 TeV   SM

$\mathscr{L}_{\text{WEFT}} \supset -\dfrac{2V_{ud}}{v^2}\Big\{(\bar{u}\gamma^\mu P_L d)(\bar{e}\gamma_\mu P_L \nu_e) + \sum_\Gamma \epsilon_\Gamma (\bar{u}\Gamma d)(\bar{e}\Gamma\nu_e)\Big\} ,$

~ GeV

$\mathcal{L}_{\pi,N,\dots} = \dots$

$\dfrac{\epsilon_\Gamma}{v^2} = f\left(\dfrac{c_6^i}{\Lambda^2}\right) \;\rightarrow\; \epsilon_\Gamma = f\left(c_6^i \dfrac{v^2}{\Lambda^2}\right)$

M. González-Alonso

SMEFT → Beta-decay LEFT

$$\mathcal{L}(x) = \mathcal{L}\,(\text{SM fields, bSM fields})$$

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_i \frac{c_6^i}{\Lambda^2}\,\mathcal{O}_6^i + \dots$$

$$\mathcal{L}_{\text{WEFT}} \supset -\frac{2V_{ud}}{v^2}\Big\{(1+\epsilon_L)(\bar{u}\gamma^\mu P_L d)(\bar{e}\gamma_\mu P_L \nu_e) + \epsilon_R(\bar{u}\gamma^\mu P_R d)(\bar{e}\gamma_\mu P_L \nu_e)$$

$$+ \frac{1}{2}\epsilon_S(\bar{u}d)(\bar{e}P_L\nu_e) - \frac{1}{2}\epsilon_P(\bar{u}\gamma_5 d)(e P_L \nu_e)$$

$$+ \frac{1}{4}\epsilon_T(\bar{u}\sigma^{\mu\nu}P_L d)(\bar{e}\sigma_{\mu\nu}P_L\nu_e) + \text{h.c.}\Big\},$$

$$\epsilon_\Gamma = f\left(c_6^i\frac{v^2}{\Lambda^2}\right)$$

SMEFT → Beta-decay LEFT

$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \sum_i \frac{c_6^i}{\Lambda^2} \mathscr{O}_6^i + \ldots$$

$$\mathscr{L}_{\text{WEFT}} \supset -\frac{2V_{ud}}{v^2}\Big\{(1+\epsilon_L)(\bar{u}\gamma^\mu P_L d)(\bar{e}\gamma_\mu P_L \nu_e) + \epsilon_R(\bar{u}\gamma^\mu P_R d)(\bar{e}\gamma_\mu P_L \nu_e)$$

$$+ \frac{1}{2}\epsilon_S(\bar{u}d)(\bar{e}P_L\nu_e) - \frac{1}{2}\epsilon_P(\bar{u}\gamma_5 d)(eP_L\nu_e)$$

$$+ \frac{1}{4}\epsilon_T(\bar{u}\sigma^{\mu\nu}P_L d)(\bar{e}\sigma_{\mu\nu}P_L\nu_e) + \text{h.c.}\Big\},$$

$$\epsilon_L \approx \frac{v^2}{\Lambda^2 V_{ud}}\left(V_{ud}[c_{Hl}^{(3)}]_{11} + V_{jd}[c_{Hq}^{(3)}]_{1j} - V_{jd}[c_{lq}^{(3)}]_{111j}\right),$$

$$\epsilon_R \approx \frac{v^2}{2\Lambda^2 V_{ud}}[c_{Hud}]_{11}$$

$$\epsilon_S \approx -\frac{v^2}{2\Lambda^2 V_{ud}}\left(V_{jd}[c_{lequ}]^*_{11j1} + [c_{ledq}]^*_{1111}\right),$$

$$\epsilon_P \approx -\frac{v^2}{2\Lambda^2 V_{ud}}\left(V_{jd}[c_{lequ}]^*_{11j1} - [c_{ledq}]^*_{1111}\right),$$

$$\epsilon_T \approx -\frac{2v^2}{\Lambda^2 V_{ud}}V_{jd}[c_{lequ}^{(3)}]^*_{11j1},$$

$$\epsilon_\Gamma = f\left(c_6^i \frac{v^2}{\Lambda^2}\right)$$

SMEFT → Beta-decay LEFT

$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \sum_i \frac{c_6^i}{\Lambda^2} \mathcal{O}_6^i + \dots$$

$$\mathscr{L}_{\text{WEFT}} \supset -\frac{2V_{ud}}{v^2}\Big\{(1+\epsilon_L)(\bar{u}\gamma^\mu P_L d)(\bar{e}\gamma_\mu P_L \nu_e) + \epsilon_R(\bar{u}\gamma^\mu P_R d)(\bar{e}\gamma_\mu P_L \nu_e)$$

$$+ \frac{1}{2}\epsilon_S(\bar{u}d)(\bar{e}P_L\nu_e) - \frac{1}{2}\epsilon_P(\bar{u}\gamma_5 d)(eP_L\nu_e)$$

$$+ \frac{1}{4}\epsilon_T(\bar{u}\sigma^{\mu\nu}P_L d)(\bar{e}\sigma_{\mu\nu}P_L\nu_e) + \text{h.c.}\Big\},$$

$$\epsilon_L \approx \frac{v^2}{\Lambda^2 V_{ud}}\left(V_{ud}[c_{Hl}^{(3)}]_{11} + V_{jd}[c_{Hq}^{(3)}]_{1j} - V_{jd}[c_{lq}^{(3)}]_{111j}\right),$$

$$\epsilon_R \approx \frac{v^2}{2\Lambda^2 V_{ud}}[c_{Hud}]_{11}$$

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$$\epsilon_P \approx -\frac{v^2}{2\Lambda^2 V_{ud}}\left(V_{jd}[c_{lequ}]_{11j1}^* - [c_{ledq}]_{1111}^*\right),$$

$$\epsilon_T \approx -\frac{2v^2}{\Lambda^2 V_{ud}}V_{jd}[c_{lequ}^{(3)}]_{11j1}^*,$$

$$\bar{e}_L\gamma_\mu\nu_L \cdot \bar{u}_R\gamma^\mu d_R \qquad i(\varphi^T\epsilon D_\mu\varphi)(\bar{u}\gamma^\mu d)$$

(V-A) x (V+A)

→ *RH currents are lepton flavor universal!*
(SMEFT prediction)

SMEFT → Beta-decay LEFT

$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \sum_i \frac{c_6^i}{\Lambda^2} \mathcal{O}_6^i + \dots$$

$$\mathscr{L}_{\text{WEFT}} \supset -\frac{2V_{ud}}{v^2}\Big\{(1+\epsilon_L)(\bar{u}\gamma^\mu P_L d)(\bar{e}\gamma_\mu P_L \nu_e) + \epsilon_R(\bar{u}\gamma^\mu P_R d)(\bar{e}\gamma_\mu P_L \nu_e)$$

$$+ \frac{1}{2}\epsilon_S(\bar{u}d)(\bar{e}P_L\nu_e) - \frac{1}{2}\epsilon_P(\bar{u}\gamma_5 d)(eP_L\nu_e)$$

$$+ \frac{1}{4}\epsilon_T(\bar{u}\sigma^{\mu\nu}P_L d)(\bar{e}\sigma_{\mu\nu}P_L\nu_e) + \text{h.c.}\Big\},$$

Reminder:

$$\ell \equiv \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$$

$$q = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$$

$$\epsilon_L \approx \frac{v^2}{\Lambda^2 V_{ud}}\left(V_{ud}[c_{Hl}^{(3)}]_{11} + V_{jd}[c_{Hq}^{(3)}]_{1j} - V_{jd}[c_{lq}^{(3)}]_{111j}\right),$$
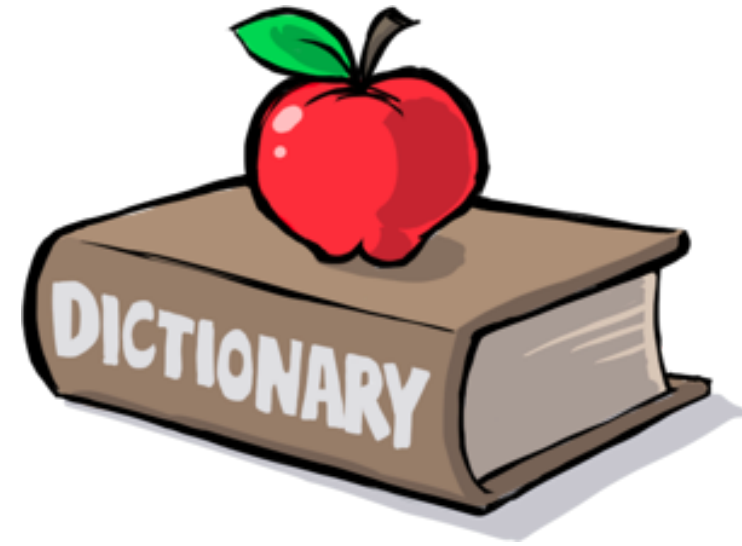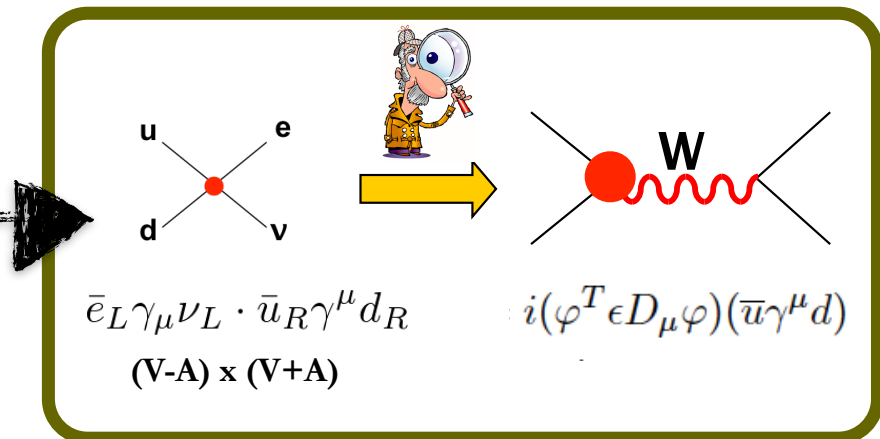
$$\epsilon_R \approx \frac{v^2}{2\Lambda^2 V_{ud}}[c_{Hud}]_{11}$$

$$\epsilon_S \approx -\frac{v^2}{2\Lambda^2 V_{ud}}\left(V_{jd}[c_{lequ}]_{11j1}^* + [c_{ledq}]_{1111}^*\right),$$

$$\epsilon_P \approx -\frac{v^2}{2\Lambda^2 V_{ud}}\left(V_{jd}[c_{lequ}]_{11j1}^* - [c_{ledq}]_{1111}^*\right),$$

$$\epsilon_T \approx -\frac{2v^2}{\Lambda^2 V_{ud}}V_{jd}[c_{lequ}^{(3)}]_{11j1}^*,$$

S, P, T

$$(\bar{\ell}e)(\bar{d}q)$$
$$(\bar{\ell}_a e)\epsilon^{ab}(\bar{q}_b u)$$
$$(\bar{\ell}_a \sigma^{\mu\nu}e)\epsilon^{ab}(\bar{q}_b \sigma_{\mu\nu}u)$$

SMEFT → Beta-decay LEFT

$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \sum_i \frac{c_6^i}{\Lambda^2} \mathcal{O}_6^i + \dots$$

$$\mathscr{L}_{WEFT} \supset -\frac{2V_{ud}}{v^2}\Big\{ (1+\epsilon_L)(\bar{u}\gamma^\mu P_L d)(\bar{e}\gamma_\mu P_L \nu_e) + \epsilon_R(\bar{u}\gamma^\mu P_R d)(\bar{e}\gamma_\mu P_L \nu_e)$$

$$+ \frac{1}{2}\epsilon_S(\bar{u}d)(\bar{e}P_L\nu_e) - \frac{1}{2}\epsilon_P(\bar{u}\gamma_5 d)(\bar{e}P_L\nu_e)$$

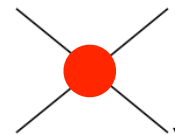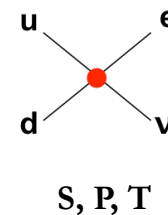$$+ \frac{1}{4}\epsilon_T(\bar{u}\sigma^{\mu\nu}P_L d)(\bar{e}\sigma_{\mu\nu}P_L\nu_e) + \mathrm{h.c.}\Big\}$$

$$\epsilon_L \approx \frac{v^2}{\Lambda^2 V_{ud}}\left(V_{ud}[c_{Hl}^{(3)}]_{11} + V_{jd}[c_{Hq}^{(3)}]_{1j} - V_{jd}[c_{lq}^{(3)}]_{111j} \right),$$

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$$\epsilon_T \approx -\frac{2v^2}{\Lambda^2 V_{ud}}V_{jd}[c_{lequ}^{(3)}]^*_{11j1},$$

(V-A) x (V-A)

$$i(\varphi^\dagger D^\mu \sigma^a \varphi)(\bar{q}\gamma_\mu \sigma^a q)$$

$$i(\varphi^\dagger D^\mu \sigma^a \varphi)(\bar{l}\gamma_\mu \sigma^a l)$$

$$(\bar{l}\gamma^\mu \sigma^a l)(\bar{q}\gamma_\mu \sigma^a q)$$

SMEFT → Beta-decay LEFT

$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \sum_i \frac{c_6^i}{\Lambda^2} \mathcal{O}_6^i + \dots$$

$$\mathscr{L}_{WEFT} \supset -\frac{2V_{ud}}{v^2}\Big\{(1+\epsilon_L)(\bar{u}\gamma^\mu P_L d)(\bar{e}\gamma_\mu P_L \nu_e) + \epsilon_R(\bar{u}\gamma^\mu P_R d)(\bar{e}\gamma_\mu P_L \nu_e)$$

$$+ \frac{1}{2}\epsilon_S(\bar{u}d)(\bar{e}P_L\nu_e) - \frac{1}{2}\epsilon_P(\bar{u}\gamma_5 d)(\bar{e}P_L\nu_e)$$

$$+ \frac{1}{4}\epsilon_T(\bar{u}\sigma^{\mu\nu}P_L d)(\bar{e}\sigma_{\mu\nu}P_L\nu_e) + \text{h.c.}\Big\}$$

(V-A) x (V-A)

$$\epsilon_L \approx \frac{v^2}{\Lambda^2 V_{ud}}\left(V_{ud}[c_{Hl}^{(3)}]_{11} + V_{jd}[c_{Hq}^{(3)}]_{1j} - V_{jd}[c_{lq}^{(3)}]_{111j}\right),$$

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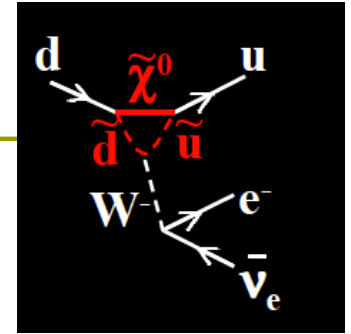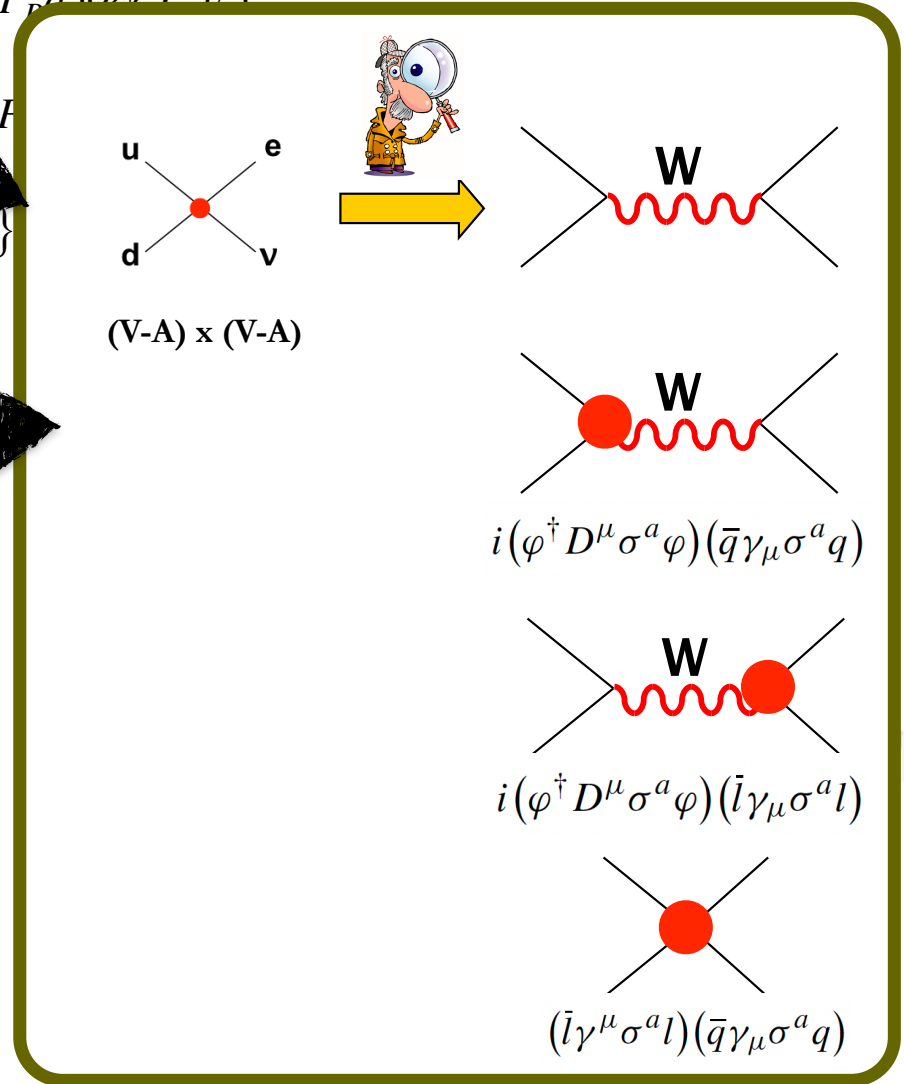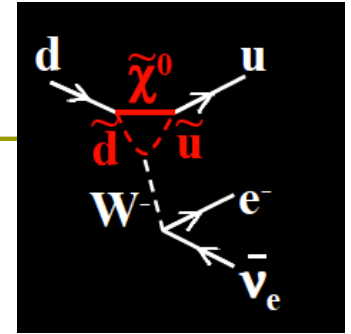$$\epsilon_S \approx -\frac{v^2}{2\Lambda^2 V_{ud}}\left(V_{jd}[c_{lequ}]_{11j1}^* + [c_{ledq}]_{1111}^*\right),$$

$$\epsilon_P \approx -\frac{v^2}{2\Lambda^2 V_{ud}}\left(V_{jd}[c_{lequ}]_{11\dots}^* - [c_{\dots}]_{\dots}^*\right)$$

$$\epsilon_T \approx -\frac{2v^2}{\Lambda^2 V_{ud}}V_{jd}[c_{lequ}^{(3)}]_{11j}^*$$

$$i(\varphi^\dagger D^\mu \sigma^a \varphi)(\bar{q}\gamma_\mu \sigma^a q)$$

$$i(\varphi^\dagger D^\mu \sigma^a \varphi)(\bar{l}\gamma_\mu \sigma^a l)$$

$$(\bar{l}\gamma^\mu \sigma^a l)(\bar{q}\gamma_\mu \sigma^a q)$$

This dictionary shows the interplay between:
- low-E and high-E searches
- CC ($d \to ue\bar{\nu}$) & NC ($ed \to ed$) low-E searches

LEFT from SMEFT

$$\mathcal{L}(x) = \mathcal{L}\,(\text{SM fields, bSM fields})$$

$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \sum_i \frac{c_6^i}{\Lambda^2}\,\mathscr{O}_6^i + \dots$$

$$\mathscr{L}_{\text{WEFT}} \supset -\frac{2V_{ud}}{v^2}\Big\{(\bar{u}\gamma^\mu P_L d)(\bar{e}\gamma_\mu P_L \nu_e) + \sum_\Gamma \epsilon_\Gamma\,(\bar{u}\Gamma d)(\bar{e}\Gamma \nu_e)\Big\}\,,$$

$$\mathcal{L}_{\pi,N,\dots} = \dots$$

$$\epsilon_\Gamma = f\left(\frac{c_6^i}{\Lambda^2}\right)$$

~ 10 TeV   NP

~ 1 TeV   SM

~ GeV

LEFT ~~from~~ *without* SMEFT

~ 100 GeV?   NP

$$\mathcal{L}(x) = \mathcal{L}\left(\text{SM fields, bSM fields}\right)$$

$$\mathscr{L}_{SMEFT} \quad \mathscr{L}_{SM} \; + \; \sum_i \frac{c_6^i}{\Lambda^2} \mathcal{O}_6^i \; + \; \dots$$

$$\mathscr{L}_{\text{WEFT}} \supset -\frac{2V_{ud}}{v^2}\left\{(\bar{u}\gamma^\mu P_L d)(\bar{e}\gamma_\mu P_L \nu_e) + \sum_\Gamma \epsilon_\Gamma (\bar{u}\Gamma d)(\bar{e}\Gamma\nu_e)\right\},$$

$\sim$ GeV
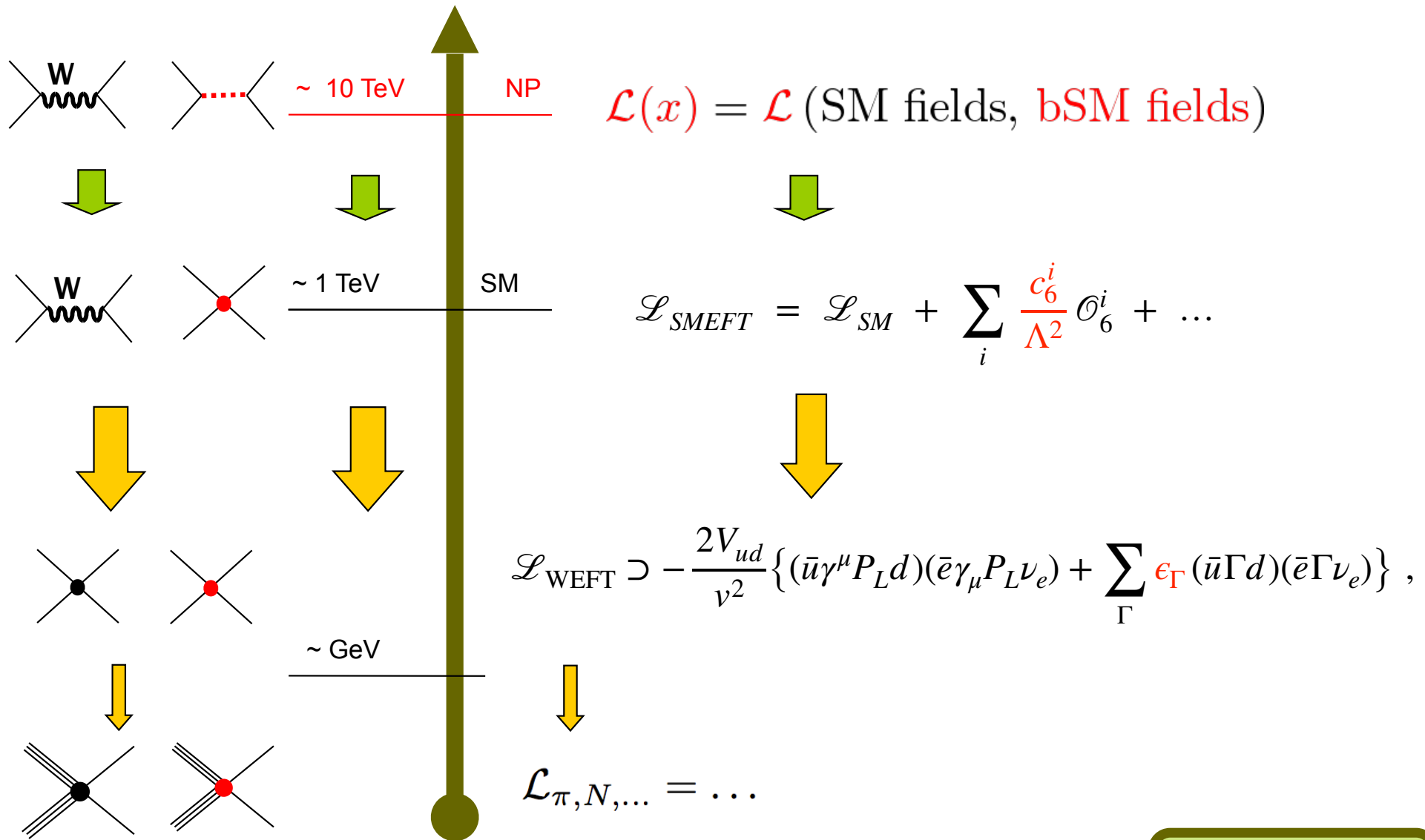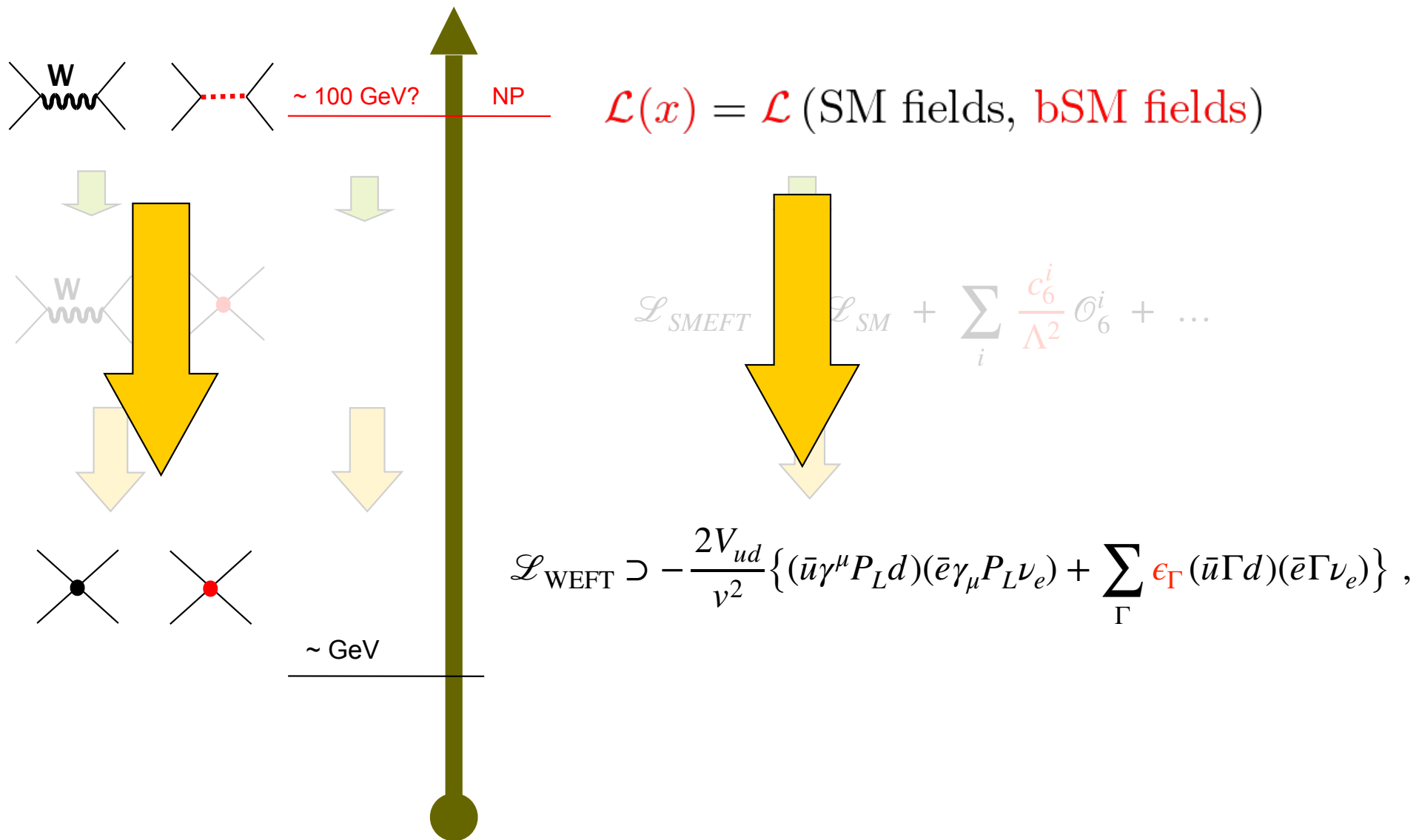
Building the LEFT

LEFT

Building blocks:

$$G_\mu^a \ , \ A_\mu \ , \ q_L^i \ , \ q_R^i \ , \ e_L^i \ , \ e_R^i \ , \ \nu_L^i$$

Rules

$$SU(3)c \times U(1)_{em}$$

RULES

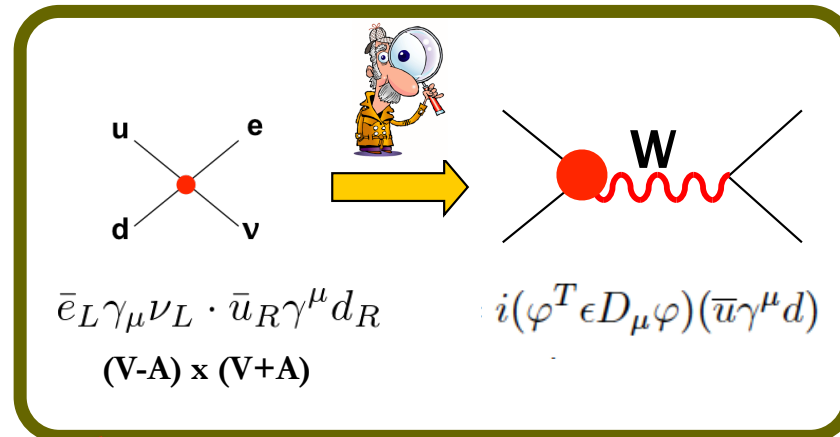$$\mathcal{L} = \mathcal{L}_2 + \mathcal{L}_3 + \mathcal{L}_4 + \mathcal{L}_5 + \mathcal{L}_6 + \mathcal{L}_7 + \ldots$$

[Jenkins et al., 1709.04486]
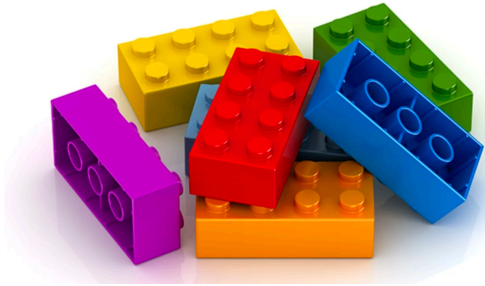
Beta-decay LEFT (not necessarily from SMEFT)

$$\mathscr{L}_{\text{WEFT}} \supset -\frac{2V_{ud}}{v^2}\Big\{(1+\epsilon_L)(\bar{u}\gamma^\mu P_L d)(\bar{e}\gamma_\mu P_L \nu_e) \;+\; \epsilon_R(\bar{u}\gamma^\mu P_R d)(\bar{e}\gamma_\mu P_L \nu_e)$$

$$+\; \frac{1}{2}\epsilon_S(\bar{u}d)(\bar{e}P_L\nu_e) \;-\; \frac{1}{2}\epsilon_P(\bar{u}\gamma_5 d)(eP_L\nu_e)$$

$$+\; \frac{1}{4}\epsilon_T(\bar{u}\sigma^{\mu\nu}P_L d)(\bar{e}\sigma_{\mu\nu}P_L\nu_e) + \text{h.c.}\Big\}\,,$$

No new operators (SMEFT generates them all)*

$$\bar{e}_L\gamma_\mu\nu_L \cdot \bar{u}_R\gamma^\mu d_R$$

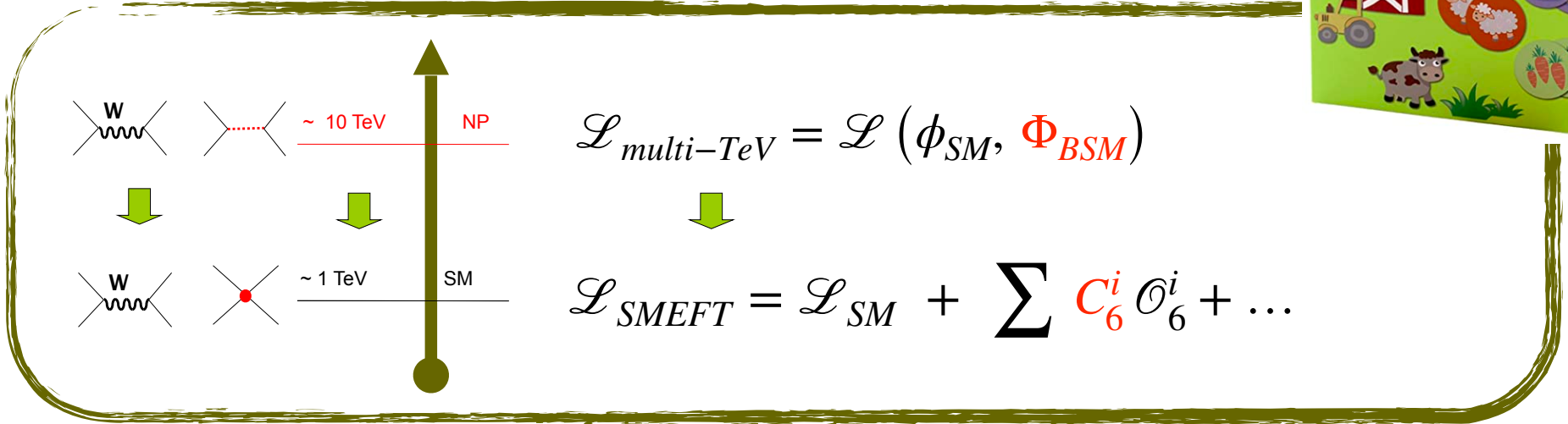(V-A) x (V+A)

$$i(\varphi^T\epsilon D_\mu\varphi)(\bar{u}\gamma^\mu d)$$

Not necessarily true anymore
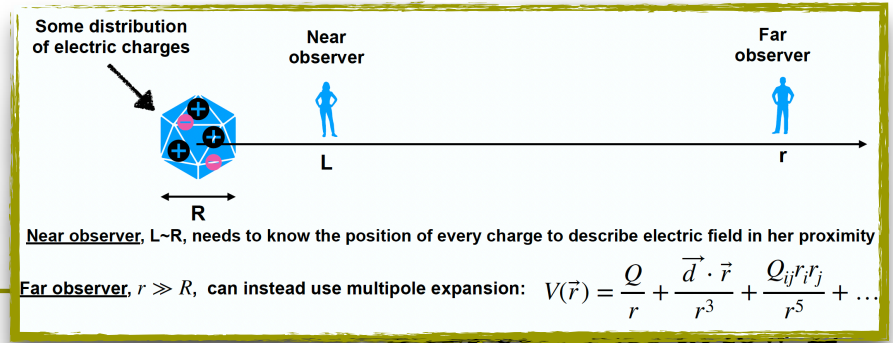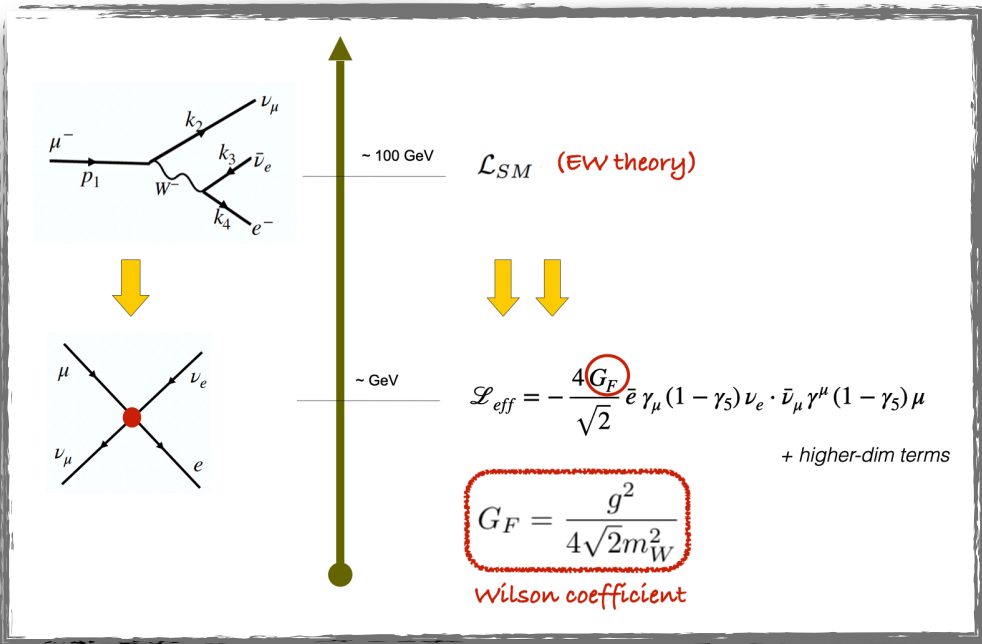
~~RH currents are lepton-flavor universal!~~
(SMEFT prediction)

*Not always the case. E.g., in b → s e⁺e⁻ some structures are forbidden!

[Alonso, Grinstein & Camalich '2014]

Matching to NP models

$$\mathcal{L}_{multi-TeV} = \mathcal{L}\left(\phi_{SM}, \Phi_{BSM}\right)$$

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum C_6^i \, \mathcal{O}_6^i + \dots$$

$$C_6^i = f\left(g_{NP}, M_{NP}\right)$$

~ 10 TeV   NP

~ 1 TeV   SM

~ 100 GeV $\mathcal{L}_{SM}$ (EW theory)

$\sim$ GeV

$$\mathcal{L}_{eff} = -\frac{4 G_F}{\sqrt{2}} \bar{e} \, \gamma_\mu (1-\gamma_5) \, \nu_e \cdot \bar{\nu}_\mu \gamma^\mu (1-\gamma_5) \, \mu$$

+ higher-dim terms

$$G_F = \frac{g^2}{4\sqrt{2} m_W^2}$$

Wilson coefficient

Some distribution of electric charges

Near observer

Far observer

L

r

R

Near observer, L~R, needs to know the position of every charge to describe electric field in her proximity

Far observer, $r \gg R$, can instead use multipole expansion: $V(\vec{r}) = \dfrac{Q}{r} + \dfrac{\vec{d}\cdot\vec{r}}{r^3} + \dfrac{Q_{ij} r_i r_j}{r^5} + \dots$
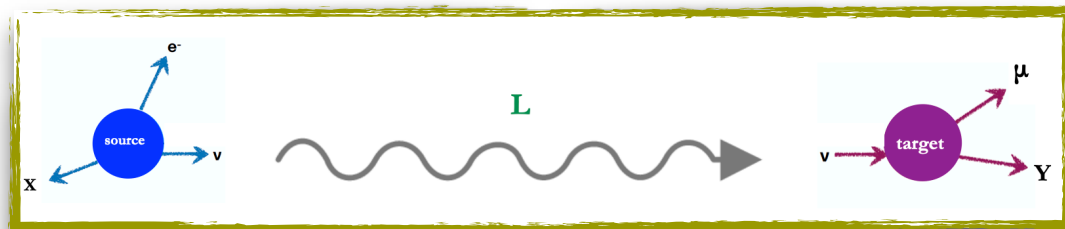
(SM)EFT phenomenology

(SM)EFT phenomenology

- First step: calculate observable X in the (SM)EFT:

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i C_6^i O_6^i + \dots \quad \longrightarrow \quad X = X_{SM} + \sum_i \alpha_i C_6^i + \dots$$

- Sometimes it's trivial.
  Sometimes it's not:

  - New quark currents? Hadrons? Nuclei?

  - "Indirect" BSM effects: $X = X_{SM}(V_{ud}) + 3C_6^{(13)}$
    One can't just take the value of V_{ud} from the PDG.
    More generally: $V_{ud} \rightarrow$ CKM, PMNS, FFs (FLAG), …

  - PDFs, cuts, correlations, FFs, EFT at 1 loop, consistent EFT expansion, …

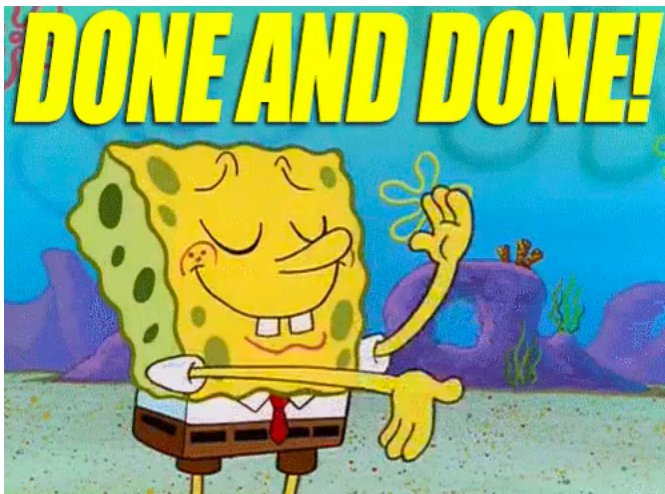 - Was the SM assumed to hold in the experimental analysis?

  - Other complications…

(SM)EFT phenomenology

- First step: calculate observable X in the (SM)EFT:

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i C_6^i O_6^i + \ldots \longrightarrow X = X_{SM} + \sum_i \alpha_i C_6^i + \ldots$$

- Sometimes it's trivial.
  Sometimes it's not.

- But once it's done, it's done.
  (you don't have to do it for each model)
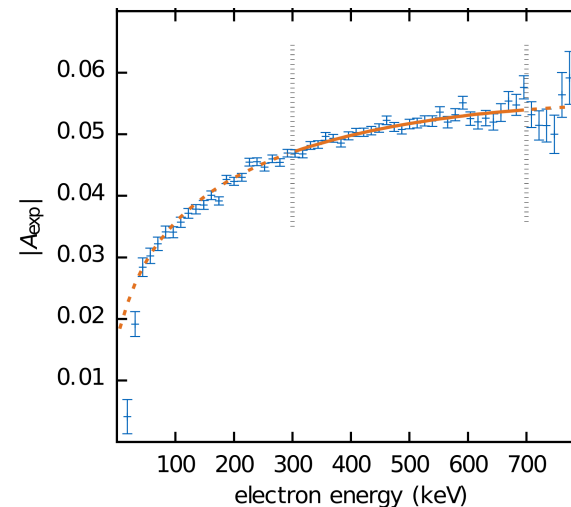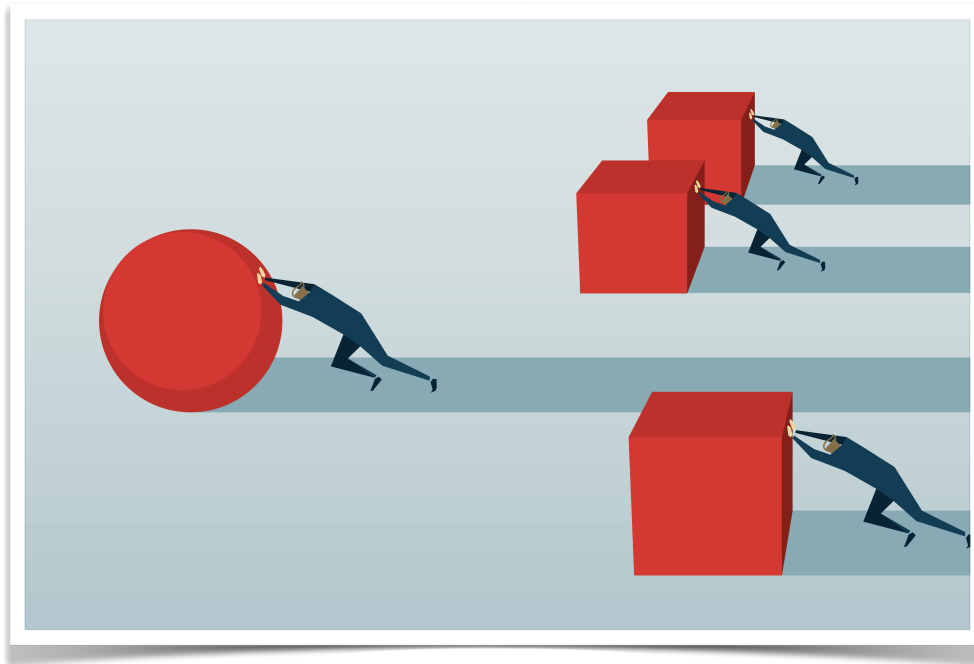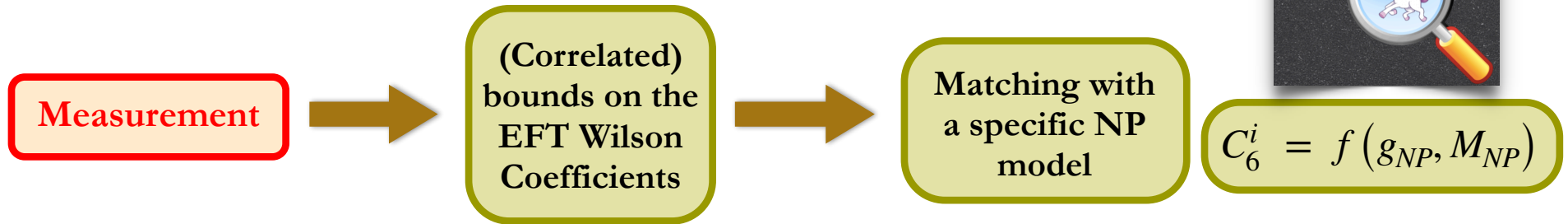
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$$X_j = X_{j,SM} + \sum_i \alpha_{ij} C_6^i + \ldots$$

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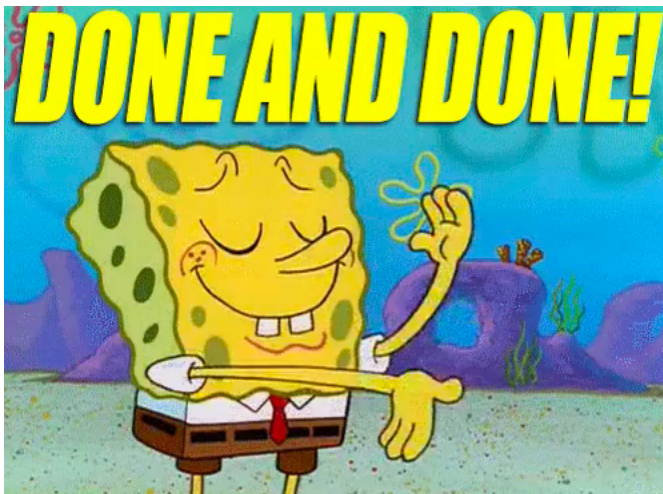
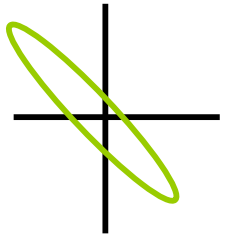This approach gives us a model-indep. parametrization for the observable X

$$\frac{dX}{dE} = \left(\frac{dX}{dE}\right)_{SM} (1 + 2C_6^{13}) + \frac{m_e}{E_e} C_6^4$$

(SM)EFT phenomenology

$$\boxed{\text{Measurement}} \longrightarrow \boxed{\text{(Correlated) bounds on the EFT Wilson Coefficients}} \longrightarrow \boxed{\text{Matching with a specific NP model}} \qquad C_6^i = f\left(g_{NP}, M_{NP}\right)$$
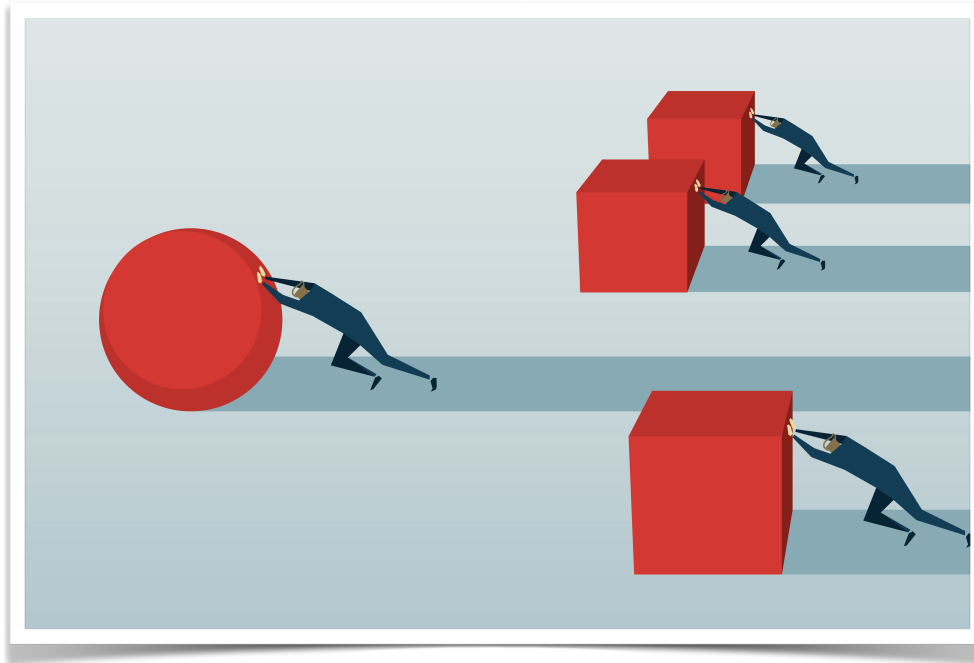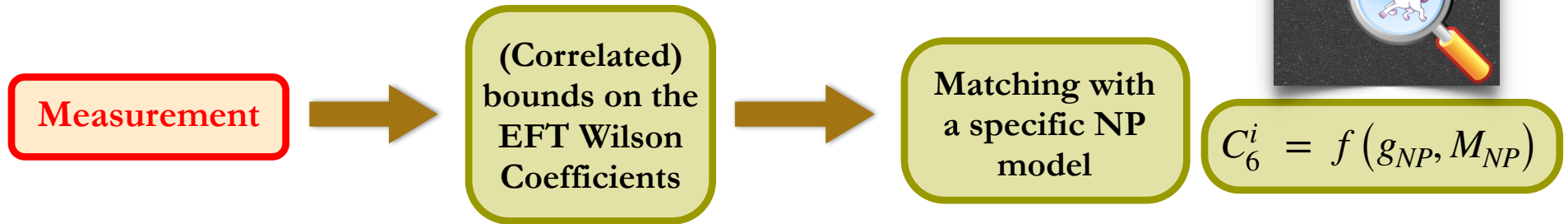

- Useful especially if…

  - Global analysis

  - Final likelihood public (correlation matrix!)

  - Avoid additional assumptions

- Valid also if NP is found!
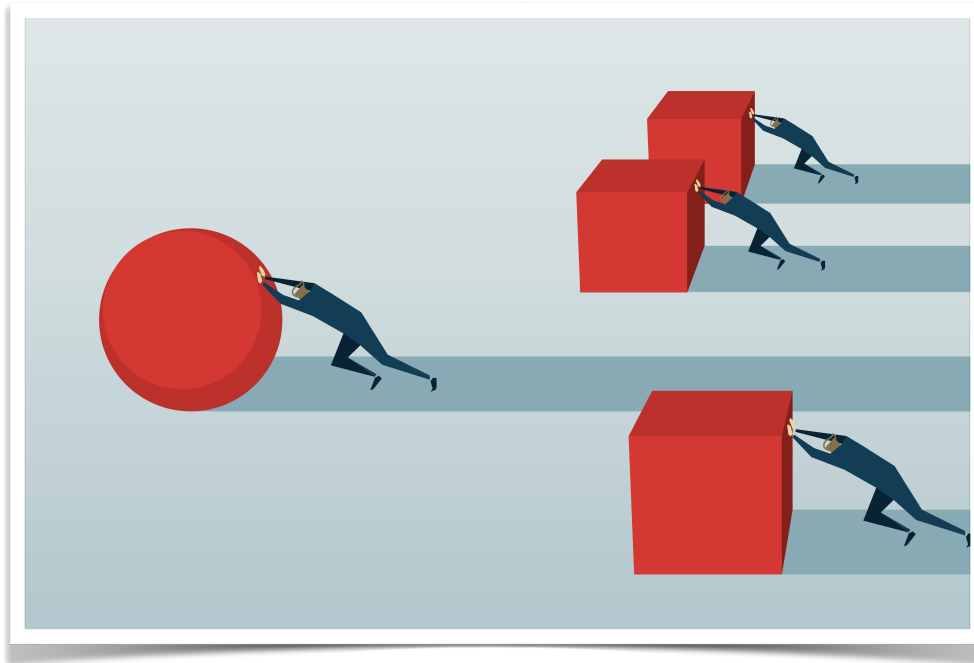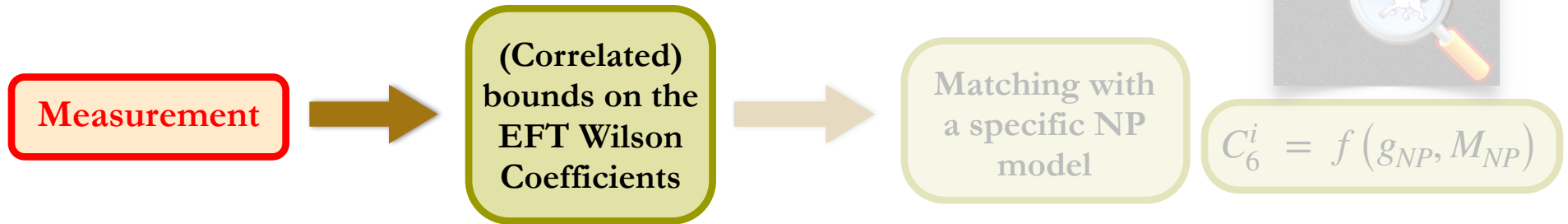
(SM)EFT phenomenology

Measurement → (Correlated) bounds on the EFT Wilson Coefficients → Matching with a specific NP model

$$C_6^i = f\left(g_{NP}, M_{NP}\right)$$

The EFT setup allows us to…

- Obtain results that can be applied to any given model later;

- Assess the interplay between processes (related by symmetries) in a general setup;
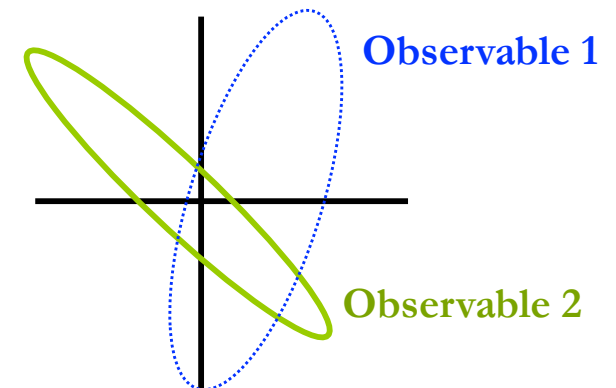
(SM)EFT phenomenology

Measurement $\longrightarrow$ **(Correlated) bounds on the EFT Wilson Coefficients** $\longrightarrow$ Matching with a specific NP model $\qquad C_6^i = f\left(g_{NP}, M_{NP}\right)$

The EFT setup allows us to…

- Obtain results that can be applied to any given model later;

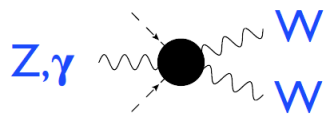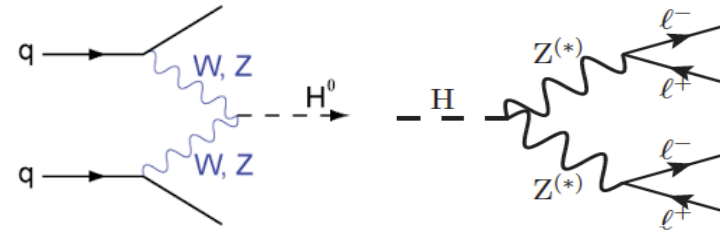- Assess the interplay between processes (related by symmetries) in a general setup;

Comparing different probes

- Choose an operator basis $\{O_1, O_2, \ldots, O_n\}$, *e.g. the Warsaw basis*
  $$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \Sigma\, C_i\, O_i$$

- Calculate the observable you like in the EFT, *e.g.* $O = O_{SM} + 3C_1 - C_6$

- What are the known limits on the Wilson coeff.? *e.g. from LEP... $C_1 = 0.001(3)$, $C_2 = \ldots$, ...*
  More precisely: χ^2 with (*LEP*) measurements gives you central values and error matrix.

- Implications for your observable? *e.g. error matrix* $\rightarrow 3C_1 - C_6 = 0.02(4)$
  - ~ 4% sensitivity (th+exp) to be competitive (or to check a LEP anomaly);
  - If your sensitivity is better than that, you are exploring new SMEFT territory and your measurement should be added to the big fit.
  - A deviation larger than that indicates some wrong assumptions in your EFT!

- Often we have a dataset (instead of a single data point O).
  The same logic applies, but it's often better to look at
  the (C_1, C_6) space $\rightarrow$ example.

Observable 1

Observable 2

Comparing different probes

$$(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$

Z, γ — W, W

$e^+ e^- \to W^+ W^-$ (LEP2)

- LEP−2 (WW)
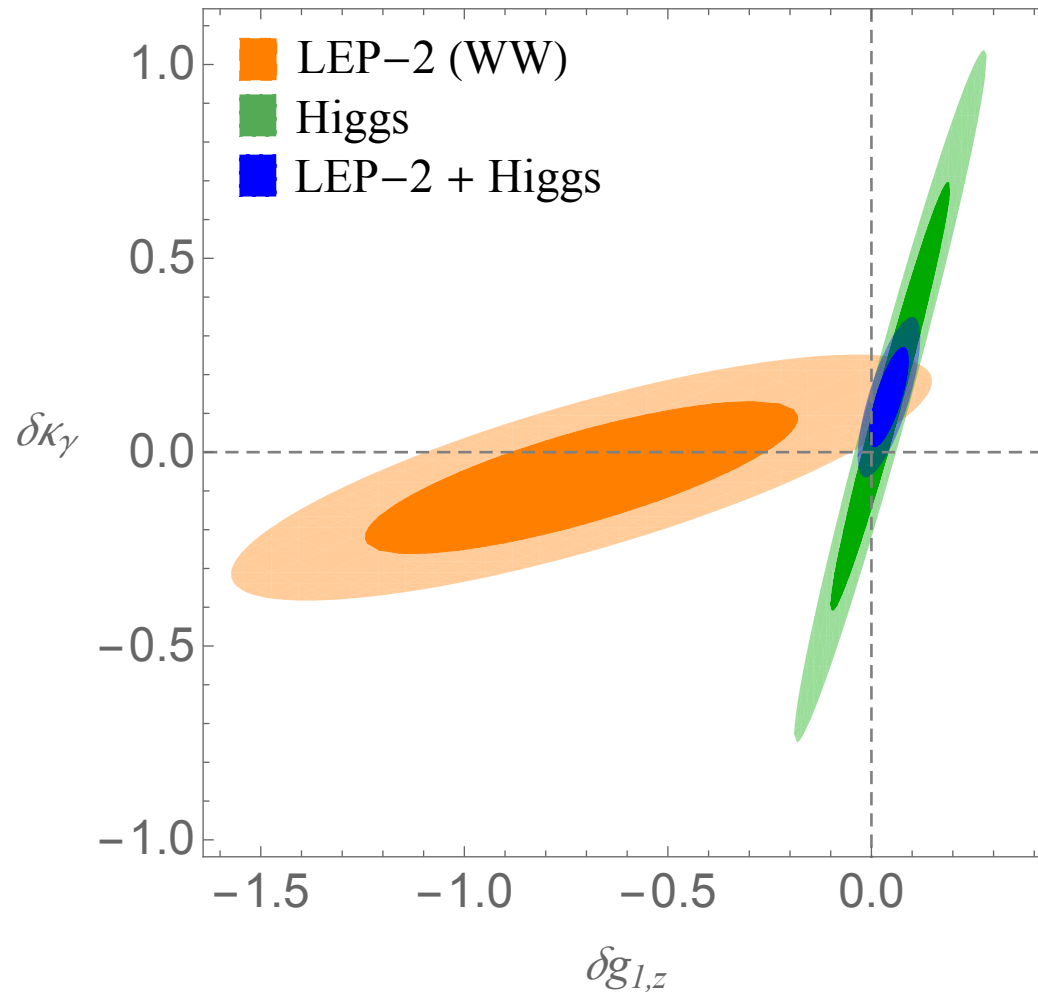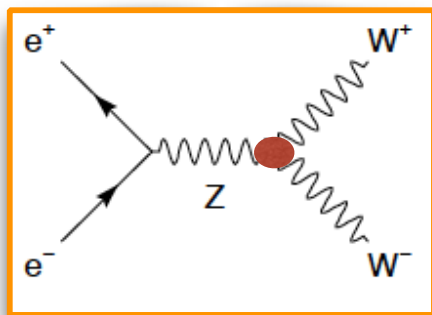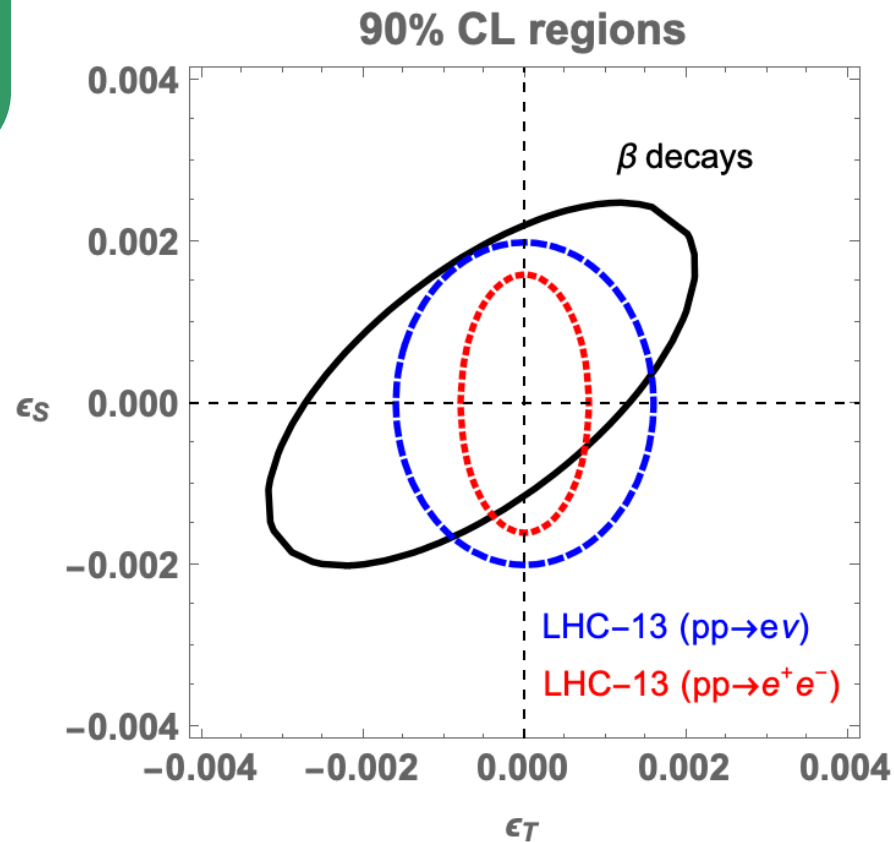- Higgs
- LEP−2 + Higgs

$\delta\kappa_\gamma$

$\delta g_{1,z}$

[Falkowski et al., 1508.00581]

Comparing different probes

90% CL regions

β decays

ϵ_S

LHC−13 (pp→eν)
LHC−13 (pp→e⁺e⁻)

ϵ_T
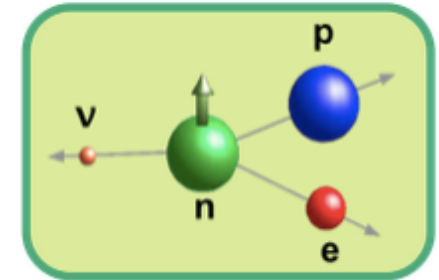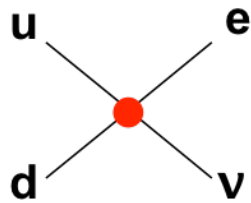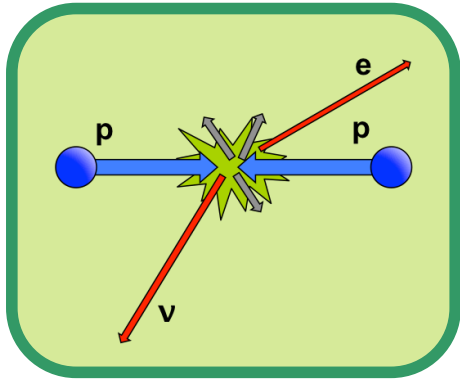
[Falkowski et al, JHEP 04 (2021) 126]

[Gupta et al., PRD98 (2018)]

[Gupta et al., PRD98 (2018)]

[Cirigliano et al.,
1210.4553]

Fitting room: global analyses

Measurement 1

Measurement 2

...

Measurement N

$$\chi^2 = \chi^2(C_6^i)$$

(Correlated) bounds on the EFT Wilson Coefficients

Specific NP model

$$C_6^i = f\left(g_{NP}, M_{NP}\right)$$

EFT fitting room

EWPO fit *in the flavorful SMEFT*

$$O = O_{SM} + O\,(c_1, c_2, ..., c_{80}) \rightarrow \chi^2 = \chi^2\,(c_i)$$

- 264 experimental input
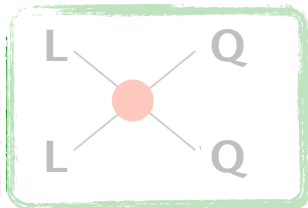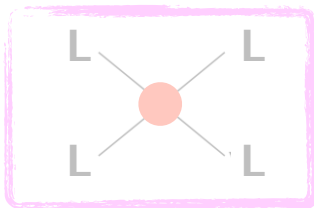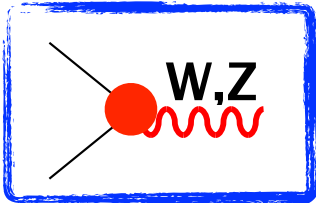 - Z- & W-pole data
  - $[e^+e^- \rightarrow l^+l^-, qq]$
  - Low-energy processes:
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    - neutrino scattering
    - PV in atoms and in scattering
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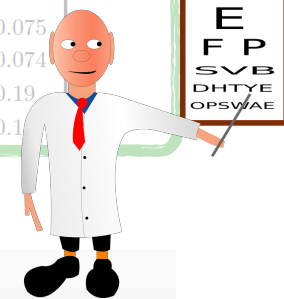
- They constrain 61 combinations of Wilson Coefficients [Higgs / Warsaw basis]

W, Z

$$
\begin{pmatrix}
\delta g_L^{We} \\
\delta g_L^{W\mu} \\
\delta g_L^{W\tau} \\
\delta g_L^{Ze} \\
\delta g_L^{Z\mu} \\
\delta g_L^{Z\tau} \\
\delta g_R^{Ze} \\
\delta g_R^{Z\mu} \\
\delta g_R^{Z\tau} \\
\delta g_L^{Zu} \\
\delta g_L^{Zc} \\
\delta g_L^{Zt} \\
\delta g_R^{Zu} \\
\delta g_R^{Zc} \\
\delta g_L^{Zd} \\
\delta g_L^{Zs} \\
\delta g_L^{Zb} \\
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\delta g_R^{Zb} \\
\end{pmatrix}
=
\begin{pmatrix}
-1.00 \pm 0.64 \\
-1.36 \pm 0.59 \\
1.95 \pm 0.79 \\
-0.023 \pm 0.028 \\
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-0.15 \pm 0.36 \\
-0.3 \pm 3.8 \\
1.4 \pm 5.1 \\
-0.35 \pm 0.53 \\
-0.9 \pm 4.4 \\
0.9 \pm 2.8 \\
0.33 \pm 0.17 \\
3 \pm 16 \\
3.4 \pm 4.9 \\
2.30 \pm 0.88 \\
\end{pmatrix}
\times 10^{-2},
$$

$$
\begin{pmatrix}
[c_{\ell\ell}]_{1111} \\
[c_{\ell e}]_{1111} \\
[c_{ee}]_{1111} \\
[c_{\ell\ell}]_{1221} \\
[c_{\ell\ell}]_{1122} \\
[c_{\ell e}]_{1122} \\
[c_{\ell e}]_{2211} \\
[c_{ee}]_{1122} \\
[c_{\ell\ell}]_{1331} \\
[c_{\ell\ell}]_{1133} \\
[c_{\ell e}]_{1133} \\
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[c_{ee}]_{1133} \\
[\hat{c}_{\ell\ell}]_{2222} \\
\end{pmatrix}
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1.7 \pm 7.2 \\
-1 \pm 12 \\
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$$

$$
\begin{pmatrix}
[c_{\ell q}^{(3)}]_{1111} \\
[\hat{c}_{eq}]_{1111} \\
[\hat{c}_{\ell u}]_{1111} \\
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[\hat{c}_{ed}]_{1111} \\
[c_{\ell q}^{(3)}]_{1122} \\
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[c_{\ell u}]_{2211} \\
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-1.4 \pm 10 \\
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18 \pm 20 \\
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15 \pm 12 \\
25 \pm 34 \\
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-0.080 \pm 0.075 \\
-0.079 \pm 0.074 \\
-0.02 \pm 0.19 \\
-0.02 \pm 0.1
\end{pmatrix}
\times 10^{-2}
$$

L L
L L

L Q
L Q

E
F P
S V B
D H T Y E
O P S W A E

EWPO fit in the flavorful SMEFT

$$O = O_{SM} + O\left(c_1, c_2, ..., c_{80}\right) \rightarrow \chi^2 = \chi^2\left(c_i\right)$$

- 264 experimental input
  - Z- & W-pole data
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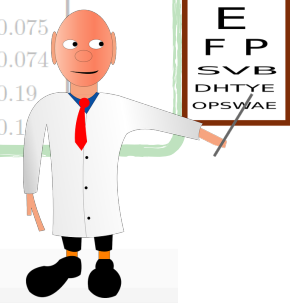   - PV in atoms and in scattering
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W,Z

L — L
L — L

L — Q
L — Q

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[c_{\ell q}^{(3)}]_{2211} \\
[c_{\ell q}]_{2211} \\
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[\hat{c}_{eq}]_{2211} \\
[c_{\ell e q u}]_{1111} \\
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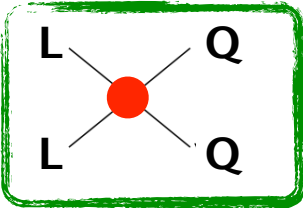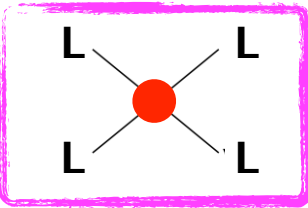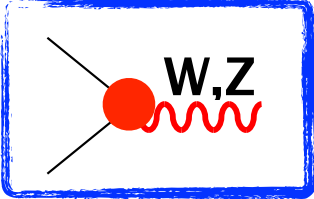 - Z- & W-pole data
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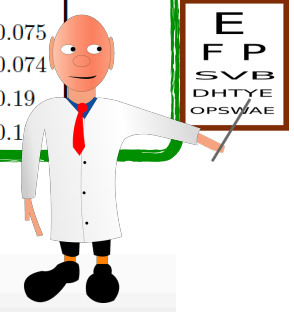
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\begin{pmatrix}
[c_{\ell q}^{(3)}]_{1111} \\
[\hat{c}_{eq}]_{1111} \\
[\hat{c}_{\ell u}]_{1111} \\
[\hat{c}_{\ell d}]_{1111} \\
[\hat{c}_{eu}]_{1111} \\
[\hat{c}_{ed}]_{1111} \\
[\hat{c}_{\ell q}^{(3)}]_{1122} \\
[c_{\ell u}]_{1122} \\
[\hat{c}_{\ell d}]_{1122} \\
[c_{eq}]_{1122} \\
[c_{eu}]_{1122} \\
[\hat{c}_{ed}]_{1122} \\
[\hat{c}_{\ell q}^{(3)}]_{1133} \\
[c_{\ell d}]_{1133} \\
[c_{eq}]_{1133} \\
[c_{ed}]_{1133} \\
[c_{\ell q}^{(3)}]_{2211} \\
[c_{\ell q}]_{2211} \\
[c_{\ell u}]_{2211} \\
[c_{\ell d}]_{2211} \\
[\hat{c}_{eq}]_{2211} \\
[c_{\ell equ}]_{1111} \\
[c_{\ell edq}]_{1111} \\
[c_{\ell equ}^{(3)}]_{1111} \\
\epsilon_P^{d\mu}(2\ \text{GeV})
\end{pmatrix}
=
\begin{pmatrix}
-2.2 \pm 3.2 \\
100 \pm 180 \\
-5 \pm 11 \\
-5 \pm 23 \\
-1 \pm 12 \\
-4 \pm 21 \\
-61 \pm 32 \\
2.4 \pm 8.0 \\
-310 \pm 130 \\
-21 \pm 28 \\
-87 \pm 46 \\
270 \pm 140 \\
-8.6 \pm 8.0 \\
-1.4 \pm 10 \\
-3.2 \pm 5.1 \\
18 \pm 20 \\
-1.2 \pm 3.9 \\
1.3 \pm 7.6 \\
15 \pm 12 \\
25 \pm 34 \\
4 \pm 41 \\
-0.080 \pm 0.075 \\
-0.079 \pm 0.074 \\
-0.02 \pm 0.19 \\
-0.02 \pm 0.1
\end{pmatrix}
\times 10^{-2}
$$

W,Z

L   L
L   L

L   Q
L   Q

E
F P
S V B
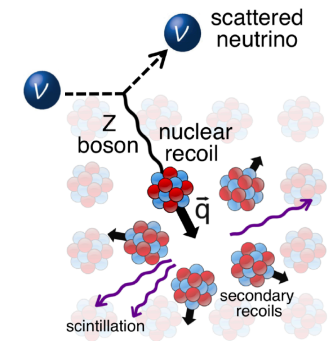D H T Y E
O P S W A E

A new low-energy observable:

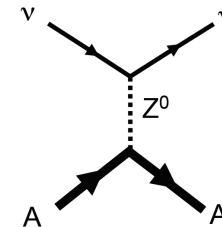## the COHERENT experiment

EFT analysis of NP at COHERENT

[from Scholberg's talk at IPA18]

[from COHERENT coll.]

$\pi^+ \to \mu^+ \, \nu_\mu$ (prompt)

$\quad \hookrightarrow \mu^+ \to e^+ \, \bar{\nu}_\mu \, \nu_e$ (delayed)
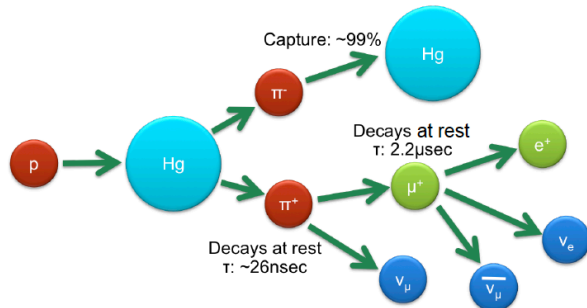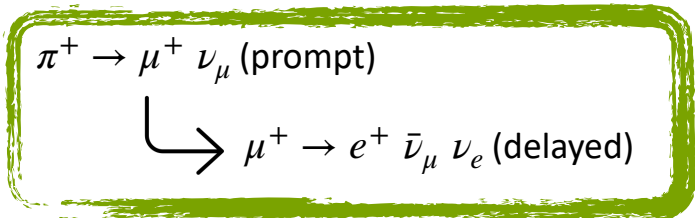
- COHERENT observed for the first time CEvNS (Coherent Elastic Neutrino-Nucleus Scattering): $\nu N \to \nu N$

- It occurs for E_ν small enough so that the neutrino does not resolve the nucleus $\to$ CEvNS cross section enhanced by N^2.
  Theoretically known since the 70's [Freedman'74; Kopeliovich & Frankfurt'74]

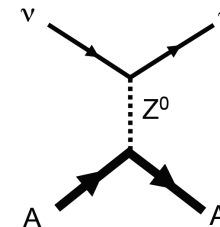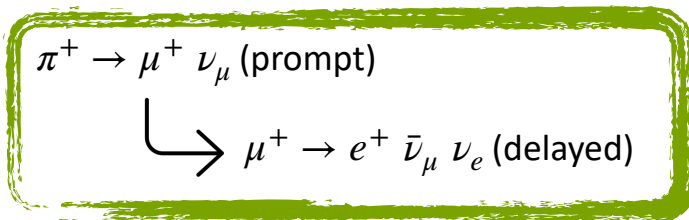- Extremely challenging experimentally (very small nuclear recoil)

EFT analysis of NP at COHERENT

[from Scholberg's talk at IPA18]

[from COHERENT coll.]

$\pi^+ \to \mu^+ \, \nu_\mu$ (prompt)

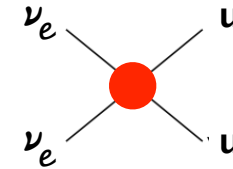$\quad \hookrightarrow \mu^+ \to e^+ \, \bar{\nu}_\mu \, \nu_e$ (delayed)
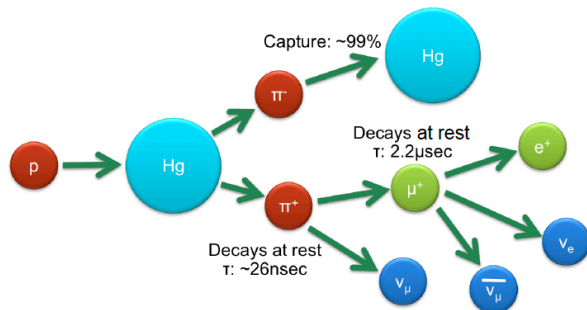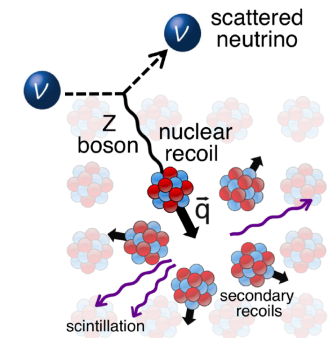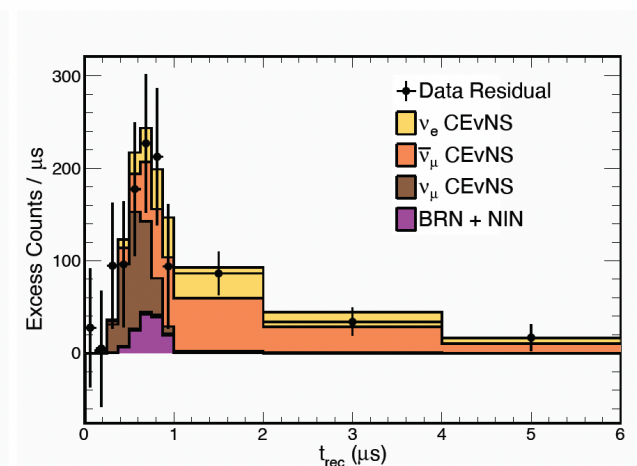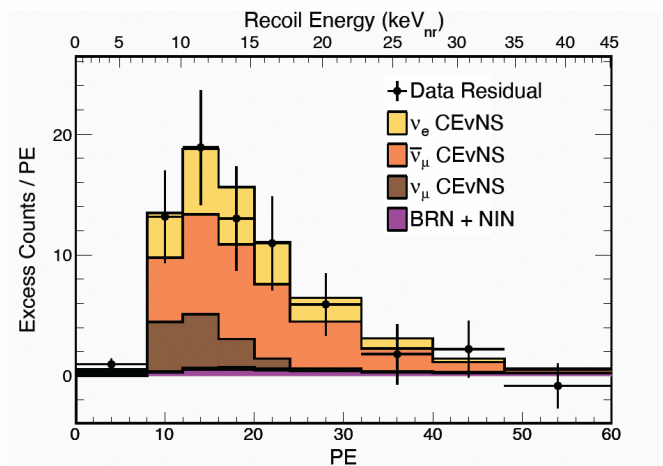
EFT analysis of NP at COHERENT

- COHERENT data (LAr + CsI, recoil & time distribution: <u>664 data, 13 nuisance parameters</u>) give:

$$0.68\,\epsilon_{ee}^{dd} + 0.61\,\epsilon_{ee}^{uu} - 0.30\,\epsilon_{\mu\mu}^{dd} - 0.27\,\epsilon_{\mu\mu}^{uu} = 0.037(42)$$
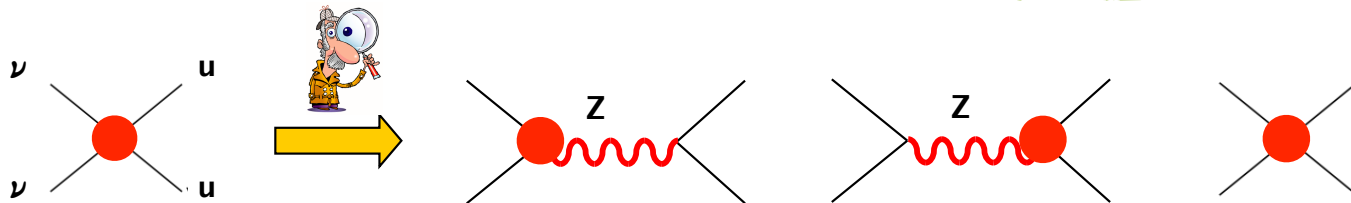
$$0.30\,\epsilon_{ee}^{dd} + 0.27\,\epsilon_{ee}^{uu} + 0.68\,\epsilon_{\mu\mu}^{dd} + 0.61\,\epsilon_{\mu\mu}^{uu} = -0.004(13)$$

$$\epsilon_u = \delta g_L^{Zu} + \delta g_R^{Zu} + \left(1 - \frac{8s_\theta^2}{3}\right)\delta g_L^{Z\nu} - \frac{1}{2}\left(c_{lq}^{(1)} + c_{lq}^{(3)} + c_{lu}\right)$$
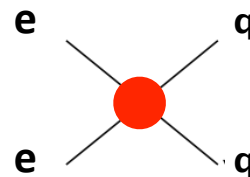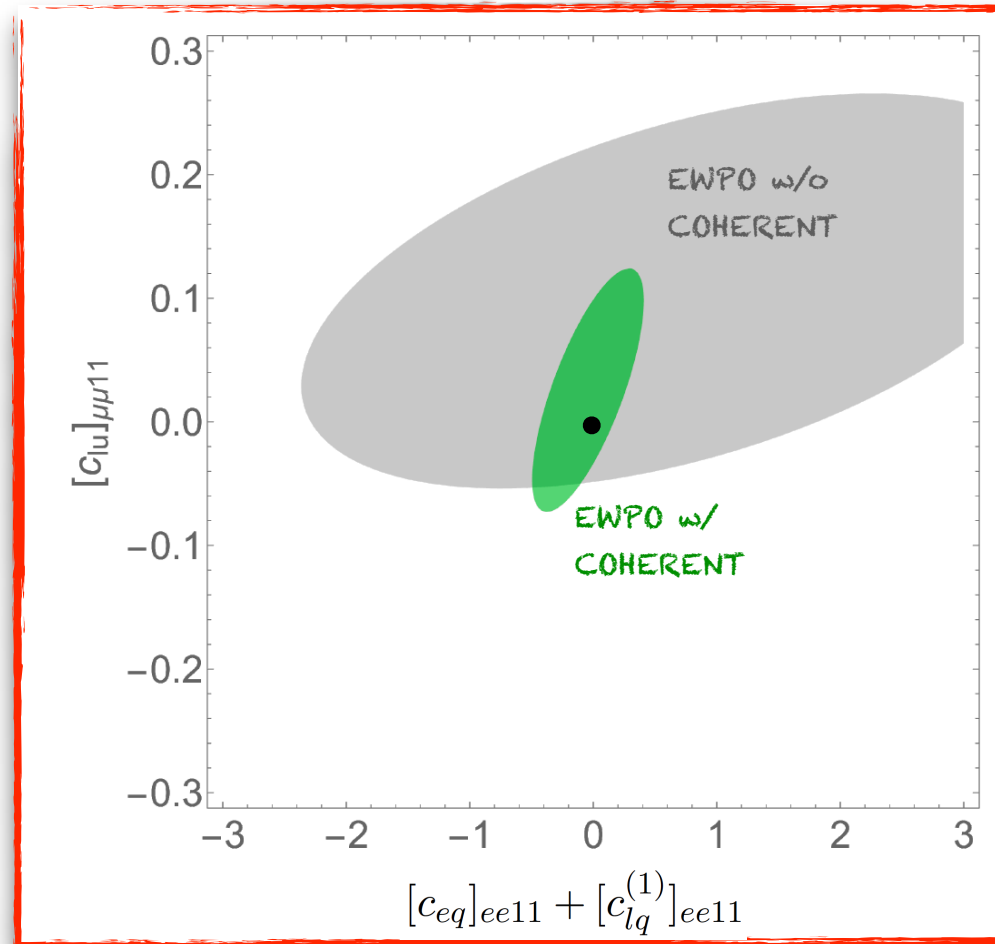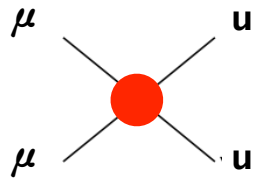
$$\epsilon_d = \delta g_L^{Zd} + \delta g_R^{Zd} - \left(1 - \frac{4s_\theta^2}{3}\right)\delta g_L^{Z\nu} - \frac{1}{2}\left(c_{lq}^{(1)} - c_{lq}^{(3)} + c_{ld}\right)$$
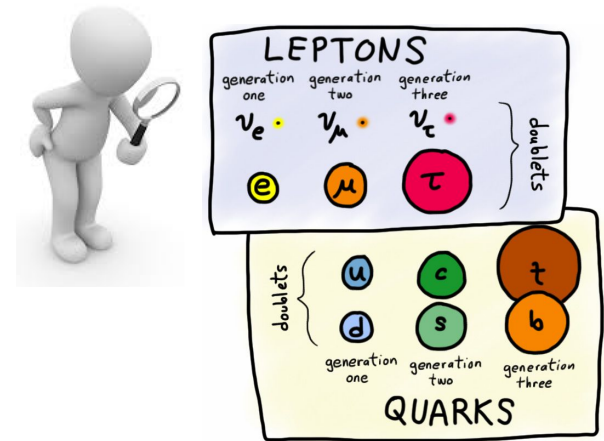
WEFT/SMEFT
Matching

- Is COHERENT probing a new region in the SMEFT parameter space?
  These operators are constrained by many EWPO: LEP1, LEP2, APV, … → Global fit needed!

COHERENT in the SMEFT

~~Outline~~ → Summary

- Intro: SM → BSM

- Classes of low-energy BSM searches
  → *Plenty of activity!*

- Effective Field Theories
  → *A natural theory setup to study low-E probes with minimal assumptions (plenty of theory activity)*

- EFT Phenomenology
  → *Efficient & model-independent (plenty of theory activity)*
  → *Forbidden processes probe huge scales*
  → *Precision low-E measurements probe TeV scales (interplay with high-E!)*

EFT!!