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Some Recent Progress in EFT

26 November 2025

Talk at Journée P2I, IJClab

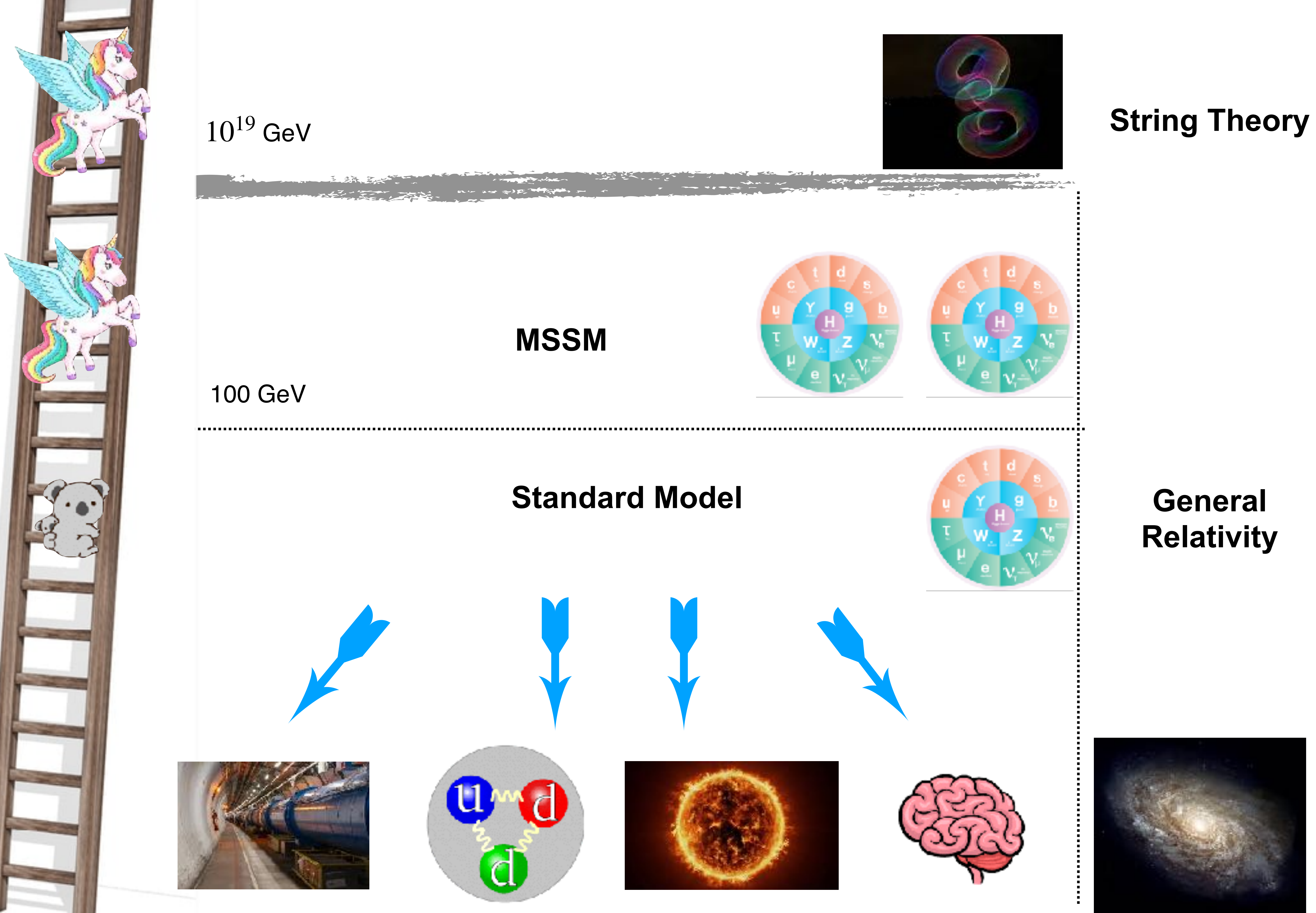
Plan

1. Philosophical introduction
2. EFT for high-energy physics at the TeV scale
3. EFT for gravitational physics

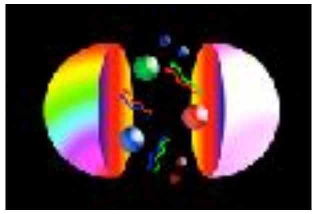
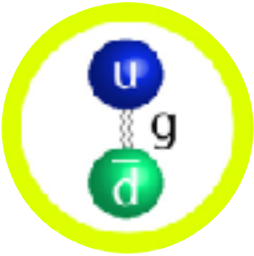
Part 1

Brief Philosophy of EFT

Reductionist picture of particle physics



EFT picture of particle physics

UV	100 TeV ?	**Dragons**	
SMEFT	100 GeV	$\gamma, g, W, Z, \nu_i, e, \mu, \tau$ + u, d, s, c, b, t + h	
WEFT5	5 GeV	$\gamma, g, \nu_i, e, \mu, \tau$ + u, d, s, c, b	
WEFT4	2 GeV	$\gamma, g, \nu_i, e, \mu, \tau$ + u, d, s, c	
ChRT	1 GeV	γ, ν_i, e, μ + hadrons	
ChPT	100 MeV	$\gamma, \nu_i, e, \mu, \pi, K, p^{(*)}$	
QED+	1 MeV	$\gamma, \nu_i, e, p^{(*)}$	
EH+	0.01 eV	$\gamma, \nu_i, p^{(*)}, e^{(*)}$ $\gamma, p^{(*)}, e^{(*)}$	

EFT picture of particle physics

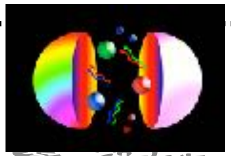
UV

10^{19} GeV — **More Dragons** 

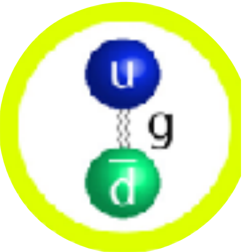
100 TeV ? — **Dragons** 

GRSMEFT — 100 GeV — $h_2, h_0, \gamma, g, W, Z, \nu_i, e, \mu, \tau,$ **u, d, s, c, b, t** 

GRWEFT5 — 5 GeV — $h_2, \gamma, g, \nu_i, e, \mu, \tau,$ **u, d, s, c, b** 

GRWEFT4 — 2 GeV — $h_2, \gamma, g, \nu_i, e, \mu, \tau,$ **u, d, s, c** 

GRChRT — 1 GeV — $h_2, \gamma, \nu_i, e, \mu$ **+ hadrons** 

GRChPT — 100 MeV — $h_2, \gamma, \nu_i, e, \mu, \pi, K, p^{(*)}$ 

GRQED — 1 MeV — $h_2, \gamma, \nu_i, e, p^{(*)}$ 

GREH+ — 0.01 eV — $h_2, \gamma, \nu_i, p^{(*)}, e^{(*)}$ / $h_2, \gamma, p^{(*)}, e^{(*)}$ 

Many particular applications of EFT

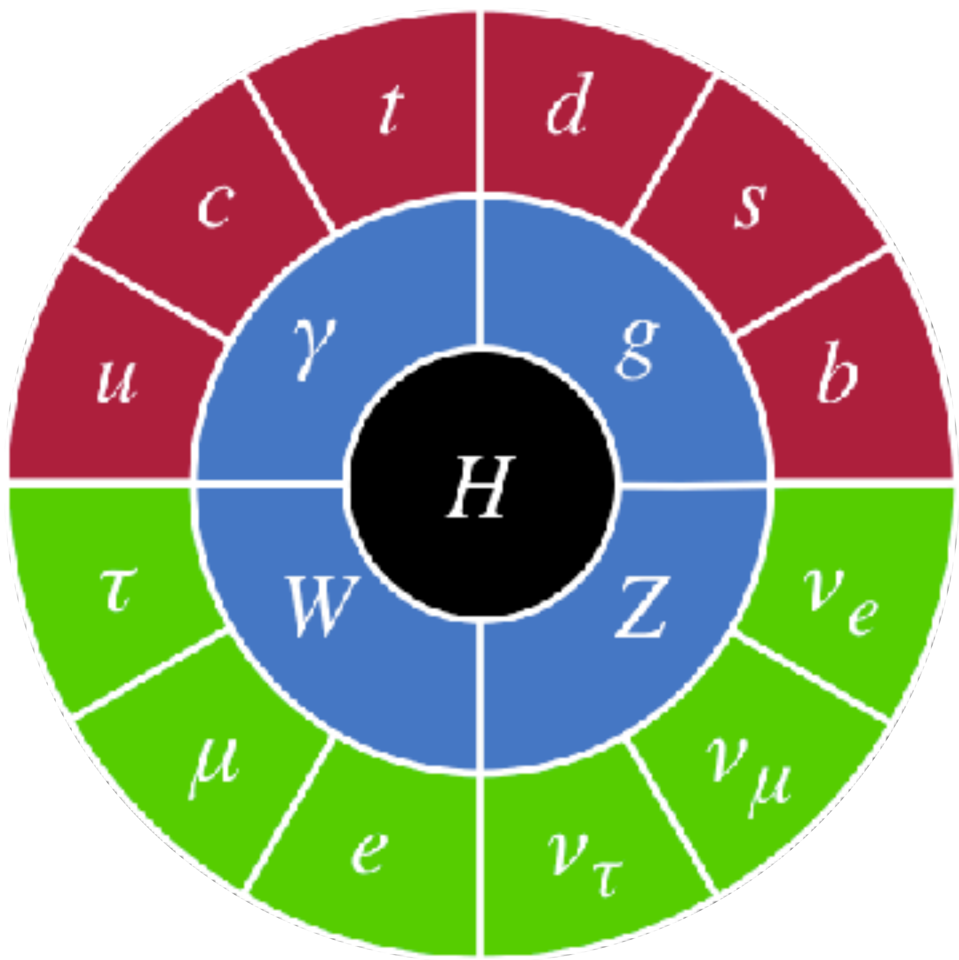
- EFT of the SM particles (SMEFT): [Eur.Phys.J.C 83 (2023) 7, 656]
- EFT for low-energy QCD (χPT): [1804.05664]
- EFT for heavy mesons (HQEFT): [hep-ph/9411275]
- EFT for nuclear forces: [1902.03141]
- EFT for inflation: [0907.5424]
- EFT for large scale structure: [2212.08488]
- EFT for hydrodynamics: [1805.09331]
- EFT for superconductors: [hep-th/9210046]
- EFT for binary inspirals: [hep-ph/07101129]
- EFT for neurons, etc.

Part 2

SMEFT,
or the effective theory
above the electroweak scale

SMEFT

SMEFT is an effective theory for these degrees of freedom:



incorporating certain physical assumptions:

1. **Usual relativistic QFT: locality, unitarity, Poincaré symmetry**
2. **Mass gap: absence of non-SM degrees of freedom at or below the electroweak scale**
3. **Gauge symmetry: local $SU(3)_C \times SU(2)_W \times U(1)_Y$ symmetry strictly respected by all interactions and spontaneously broken to $SU(3)_C \times U(1)_{\rm em}$ by a VEV of the Higgs field**

When this assumption removed → HEFT

SMEFT power counting

We can organize the SMEFT Lagrangian in a dimensional expansion:

$$\mathscr{L}_{\rm SMEFT} = \mathscr{L}_{D=2} + \mathscr{L}_{D=3} + \mathscr{L}_{D=4} + \mathscr{L}_{D=5} + \mathscr{L}_{D=6} + \mathscr{L}_{D=7} + \mathscr{L}_{D=8} + \dots$$

Each $\mathscr{L}_D$ is a linear combination of SU(3)xSU(2)xU(1) invariant interaction terms (operators) where D is the sum of canonical dimensions of all the fields entering the interaction

Since Lagrangian has mass dimension $[\mathscr{L}] = 4$, by dimensional analysis the couplings (Wilson coefficients) of interactions in $\mathscr{L}_D$ have mass dimension $[C_D] = 4 - D$

Standard SMEFT power counting: $C_D \sim \dfrac{c_D}{\Lambda^{D-4}}$ where $c_D \sim 1$,

and Λ is identified with the mass scale of the UV completion of the SMEFT,

In the spirit of EFT, each $\mathscr{L}_D$ should include a <u>complete</u> and <u>non-redundant</u> set of interactions

Dimensional analysis: $$\mathscr{M} \sim C_D E^{D-4} \sim c_D \left(\frac{E}{\Lambda}\right)^{D-4}$$

SMEFT at dimension 2

$$\mathscr{L}_{\mathrm{SMEFT}} = \mathscr{L}_{D=2} + \mathscr{L}_{D=3} + \mathscr{L}_{D=4} + \mathscr{L}_{D=5} + \mathscr{L}_{D=6} + \mathscr{L}_{D=7} + \mathscr{L}_{D=8} + \ldots$$

Only a single D=2 operator can be constructed from the SM fields:

$$\mathscr{L}_{D=2} = \mu_H^2 H^\dagger H$$

Philosophy of EFT: $\mu_H \sim \Lambda \gtrsim 3\ \mathrm{TeV}$

Experiment: $\mu_H \sim 100\ \mathrm{GeV}$

Unsolved mystery why $\mu_H^2 \ll \Lambda^2$,
which is called the hierarchy problem

From the point of view of EFT, the hierarchy problem is a breakdown of dimensional analysis

No D=3 operator can be constructed from the SM fields:

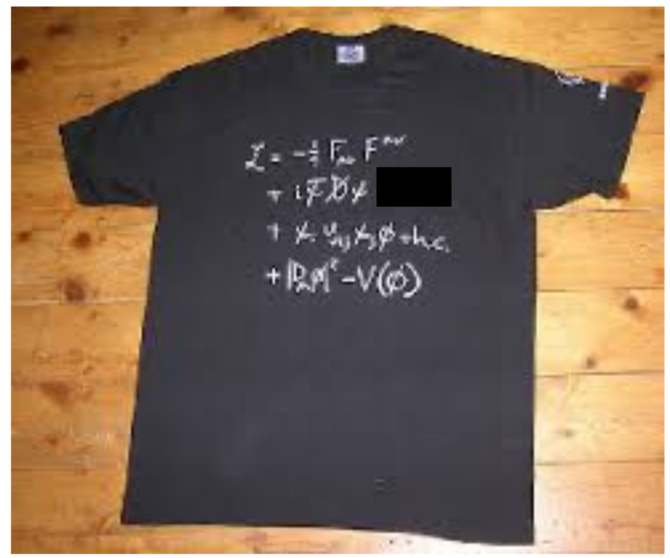
$$\mathscr{L}_{D=3} = 0$$

However, D=3 exist in other EFTs , e.g. in $\nu\mathrm{SMEFT}$

SMEFT at dimension 4

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{D=2} + \mathscr{L}_{D=3} + \mathscr{L}_{D=4} + \mathscr{L}_{D=5} + \mathscr{L}_{D=6} + \mathscr{L}_{D=7} + \mathscr{L}_{D=8} + \dots$$

D=4 is special because it doesn't contain an explicit scale (marginal interactions)



Experiment: all these interactions at D=4 above have been observed (except for θ angle)

Standard SMEFT power counting works OK for y_t, λ, but the full Yukawa matrices contain clear structures, hinting at additional selection rules.
For θ the EFT power counting fails completely

SMEFT at dimension-5

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{D=2} + \mathscr{L}_{D=4} + \mathscr{L}_{D=5} + \mathscr{L}_{D=6} + \mathscr{L}_{D=7} + \mathscr{L}_{D=8} + \ldots$$

Weinberg (1979)
Phys. Rev. Lett. 43, 1566

$$H \to \begin{pmatrix} 0 \\ \mathrm{v}/\sqrt{2} \end{pmatrix}$$

$$\mathscr{L}_{D=5} = (LH)C(LH) + \text{h.c.} \to \frac{1}{2} \sum_{J,K=e,\mu,\tau} \mathrm{v}^2 C_{JK}(\nu_J \nu_K) + \text{h.c.}$$

A huge success of the SMEFT paradigm:
corrections to the SM Lagrangian predicted at the next order in the EFT expansion, are indeed the first physics beyond the SM observed in experiment!

It follows that the dimension-5 Wilson coefficient is of order $C \sim \dfrac{1}{\Lambda}$ with $\Lambda \sim 10^{15}$ **GeV**

SMEFT paradigm points to an existence of a large scale in physics, independent of the Planck scale !

But does is mean that $\mathscr{L}_{D=6} \sim \dfrac{1}{\Lambda^2}$**,** $\mathscr{L}_{D=7} \sim \dfrac{1}{\Lambda^3}$**, and so on ???**

SMEFT at dimension-6

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{D=2} + \mathscr{L}_{D=4} + \mathscr{L}_{D=5} + \mathscr{L}_{D=6} + \mathscr{L}_{D=7} + \mathscr{L}_{D=8} + \ldots$$

Grządkowski et al
arXiv:1008.4884

At dimension-6 all hell breaks loose

$$\begin{aligned}
\mathscr{L}_{D=6} = {} & C_H (H^\dagger H)^3 + C_{H\Box}(H^\dagger H)\Box(H^\dagger H) + C_{HD}|H^\dagger D_\mu H|^2 \\
& + C_{HWB} H^\dagger \sigma^k H\, W^k_{\mu\nu} B_{\mu\nu} + C_{HG} H^\dagger H\, G^a_{\mu\nu} G^a_{\mu\nu} + C_{HW} H^\dagger H\, W^k_{\mu\nu} W^k_{\mu\nu} + C_{HB} H^\dagger H\, B_{\mu\nu} B_{\mu\nu} \\
& + C_W \epsilon^{klm} W^k_{\mu\nu} W^l_{\nu\rho} W^m_{\rho\mu} + C_G f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu} \\
& + C_{H\widetilde{G}} H^\dagger H\, \widetilde{G}^a_{\mu\nu} G^a_{\mu\nu} + C_{H\widetilde{W}} H^\dagger H\, \widetilde{W}^k_{\mu\nu} W^k_{\mu\nu} + C_{H\widetilde{B}} H^\dagger H\, \widetilde{B}_{\mu\nu} B_{\mu\nu} + C_{H\widetilde{W}B} H^\dagger \sigma^k H\, \widetilde{W}^k_{\mu\nu} B_{\mu\nu} \\
& + C_{\widetilde{W}} \epsilon^{klm} \widetilde{W}^k_{\mu\nu} W^l_{\nu\rho} W^m_{\rho\mu} + C_{\widetilde{G}} f^{abc} \widetilde{G}^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu} \\
& + H^\dagger H(\bar{L} H C_{eH} \bar{E}^c) + H^\dagger H(\bar{Q} \tilde{H} C_{uH} \bar{U}^c) + H^\dagger H(\bar{Q} H C_{dH} \bar{D}^c) \\
& + iH^\dagger \overleftrightarrow{D}_\mu H(\bar{L} C^{(1)}_{Hl} \bar{\sigma}^\mu L) + iH^\dagger \sigma^k \overleftrightarrow{D}_\mu H(\bar{L} C^{(3)}_{Hl} \bar{\sigma}^\mu \sigma^k L) + iH^\dagger \overleftrightarrow{D}_\mu H(E^c C_{He} \sigma^\mu \bar{E}^c) \\
& + iH^\dagger \overleftrightarrow{D}_\mu H(\bar{Q} C^{(1)}_{Hq} \bar{\sigma}^\mu Q) + iH^\dagger \sigma^k \overleftrightarrow{D}_\mu H(\bar{Q} C^{(3)}_{Hq} \bar{\sigma}^\mu \sigma^k Q) + iH^\dagger \overleftrightarrow{D}_\mu H(U^c C_{Hu} \sigma^\mu \bar{U}^c) \\
& + iH^\dagger \overleftrightarrow{D}_\mu H(D^c C_{Hd} \sigma^\mu \bar{D}^c) + \Big\{ i\tilde{H}^\dagger D_\mu H(U^c C_{Hud} \sigma^\mu \bar{D}^c) \\
& + (\bar{Q} \sigma^k \tilde{H} C_{uW} \bar{\sigma}^{\mu\nu} \bar{U}^c) W^k_{\mu\nu} + (\bar{Q} \tilde{H} C_{uB} \bar{\sigma}^{\mu\nu} \bar{U}^c) B_{\mu\nu} + (\bar{Q} \tilde{H} C_{uG} T^a \bar{\sigma}^{\mu\nu} \bar{U}^c) G^a_{\mu\nu} \\
& + (\bar{Q} \sigma^k H C_{dW} \bar{\sigma}^{\mu\nu} \bar{D}^c) W^k_{\mu\nu} + (\bar{Q} H C_{dB} \bar{\sigma}^{\mu\nu} \bar{D}^c) B_{\mu\nu} + (\bar{Q} H C_{dG} T^a \bar{\sigma}^{\mu\nu} \bar{D}^c) G^a_{\mu\nu} \\
& + (\bar{L} \sigma^k H C_{eW} \bar{\sigma}^{\mu\nu} \bar{E}^c) W^k_{\mu\nu} + (\bar{L} H C_{eB} \bar{\sigma}^{\mu\nu} \bar{E}^c) B_{\mu\nu} + \mathrm{h.c.} \Big\} + \mathscr{L}^{4-\text{fermion}}_{D=6}
\end{aligned}$$

SMEFT at dimension-6

4-fermion operators

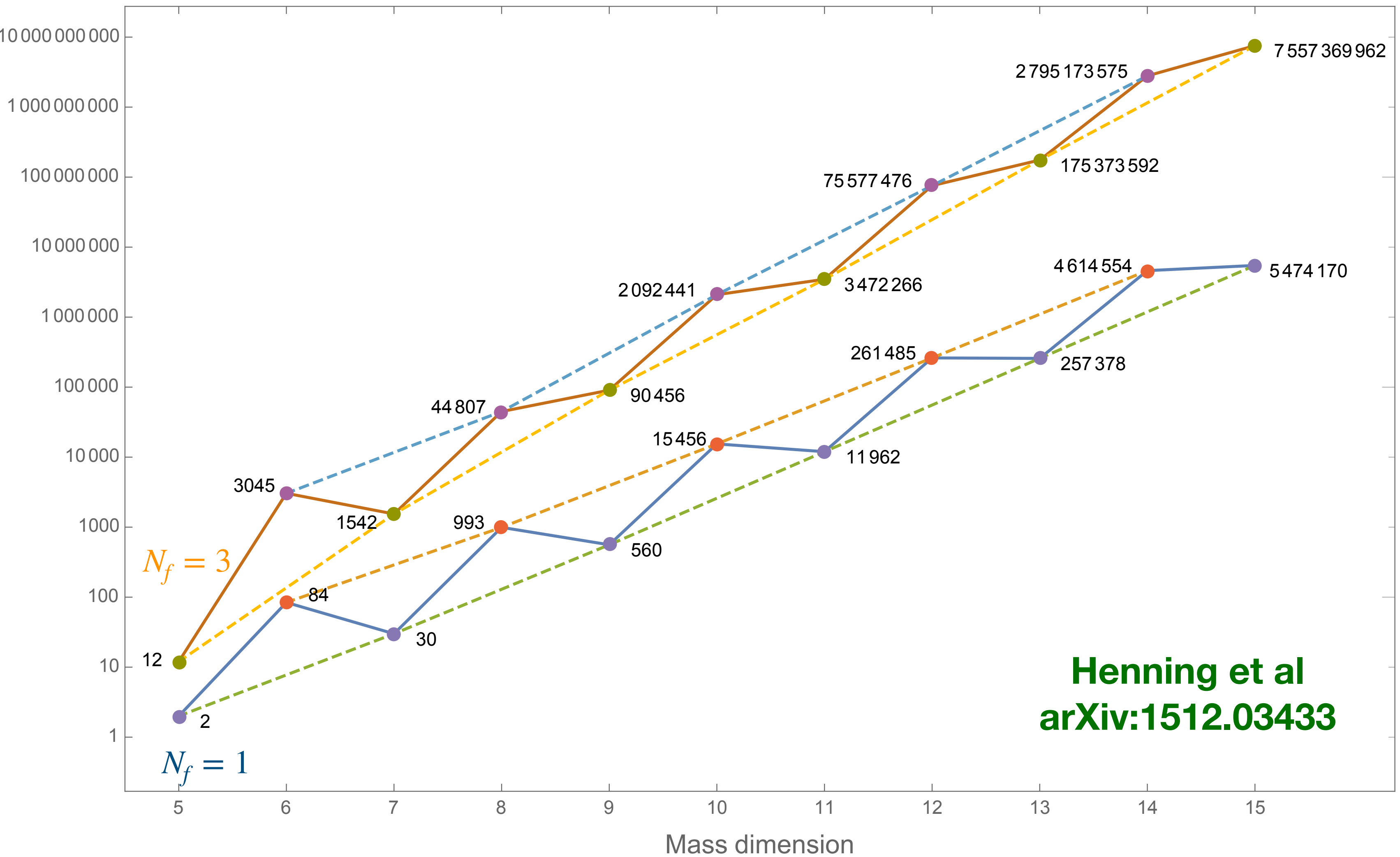
$$
\begin{aligned}
\mathscr{L}_{D=6}^{4-\text{fermion}} = {} & (\bar{L}\bar{\sigma}^{\mu}L)C_{ll}(\bar{L}\bar{\sigma}_{\mu}L) + (E^{c}\sigma_{\mu}\bar{E}^{c})C_{ee}(E^{c}\sigma_{\mu}\bar{E}^{c}) + (\bar{L}\bar{\sigma}^{\mu}L)C_{le}(E^{c}\sigma_{\mu}\bar{E}^{c}) \\
& + (\bar{L}\bar{\sigma}^{\mu}L)C_{lq}^{(1)}(\bar{Q}\bar{\sigma}_{\mu}Q) + (\bar{L}\bar{\sigma}^{\mu}\sigma^{k}L)C_{lq}^{(3)}(\bar{Q}\bar{\sigma}_{\mu}\sigma^{k}Q) \\
& + (E^{c}\sigma_{\mu}\bar{E}^{c})C_{eu}(U^{c}\sigma_{\mu}\bar{U}^{c}) + (E^{c}\sigma_{\mu}\bar{E}^{c})C_{ed}(D^{c}\sigma_{\mu}\bar{D}^{c}) \\
& + (\bar{L}\bar{\sigma}^{\mu}L)C_{lu}(U^{c}\sigma_{\mu}\bar{U}^{c}) + (\bar{L}\bar{\sigma}^{\mu}L)C_{ld}(D^{c}\sigma_{\mu}\bar{D}^{c}) + (E^{c}\sigma_{\mu}\bar{E}^{c})C_{eq}(Q\bar{\sigma}_{\mu}Q) \\
& + \left\{ (\bar{L}\bar{E}^{c})C_{ledq}(D^{c}Q) + \epsilon^{kl}(\bar{L}^{k}\bar{E}^{c})C_{lequ}^{(1)}(\bar{Q}^{l}\bar{U}^{c}) + \epsilon^{kl}(\bar{L}^{k}\bar{\sigma}^{\mu\nu}\bar{E}^{c})C_{lequ}^{(3)}(\bar{Q}^{l}\bar{\sigma}^{\mu\nu}\bar{U}^{c}) + \text{h.c.} \right\} \\
& + (\bar{Q}\bar{\sigma}^{\mu}Q)C_{qq}^{(1)}(\bar{Q}\bar{\sigma}_{\mu}Q) + (\bar{Q}\bar{\sigma}^{\mu}\sigma^{k}Q)C_{qq}^{(3)}(\bar{Q}\bar{\sigma}_{\mu}\sigma^{k}Q) \\
& + (U^{c}\sigma_{\mu}\bar{U}^{c})C_{uu}(U^{c}\sigma_{\mu}\bar{U}^{c}) + (D^{c}\sigma_{\mu}\bar{D}^{c})C_{dd}(D^{c}\sigma_{\mu}\bar{D}^{c}) \\
& + (U^{c}\sigma_{\mu}\bar{U}^{c})C_{ud}^{(1)}(D^{c}\sigma_{\mu}\bar{D}^{c}) + (U^{c}\sigma_{\mu}T^{a}\bar{U}^{c})C_{ud}^{(8)}(D^{c}\sigma_{\mu}T^{a}\bar{D}^{c}) \\
& + (Q^{c}\sigma_{\mu}\bar{Q}^{c})C_{qu}^{(1)}(U^{c}\sigma_{\mu}\bar{U}^{c}) + (Q^{c}\sigma_{\mu}T^{a}\bar{Q}^{c})C_{qu}^{(8)}(U^{c}\sigma_{\mu}T^{a}\bar{U}^{c})] \\
& + (Q^{c}\sigma_{\mu}\bar{Q}^{c})C_{qd}^{(1)}(D^{c}\sigma_{\mu}\bar{D}^{c}) + (Q^{c}\sigma_{\mu}T^{a}\bar{Q}^{c})C_{qd}^{(8)}(D^{c}\sigma_{\mu}T^{a}\bar{D}^{c}) \\
& + \left\{ \epsilon^{kl}(\bar{Q}^{k}\bar{U}^{c})C_{quqd}^{(1)}(\bar{Q}^{l}\bar{D}^{c}) + \epsilon^{kl}(\bar{Q}^{k}T^{a}\bar{U}^{c})C_{quqd}^{(1)}(\bar{Q}^{l}T^{a}\bar{D}^{c}) + \text{h.c.} \right\} \\
& + \left\{ (D^{c}U^{c})C_{duq}(\bar{Q}\bar{L}) + (QQ)C_{qqu}(\bar{U}^{c}\bar{E}^{c}) + (QQ)C_{qqq}(QL) + (D^{c}U^{c})C_{duu}(U^{c}E^{c}) + \text{h.c.} \right\}.
\end{aligned}
$$




$|H|^2 B_{\mu\nu}\widetilde{B}_{\mu\nu}$
$|H|^2 G^a_{\mu\nu}\widetilde{G}^a_{\mu\nu}$
$|H|^2 W^a_{\mu\nu}\widetilde{W}^a_{\mu\nu}$
$|H|^2 W^a_{\mu\nu}W^a_{\mu\nu}$
$|H|^2 B_{\mu\nu}B_{\mu\nu}$
$G^a_{\mu\nu}G^a_{\nu\rho}\widetilde{G}^a_{\rho\mu}$
$|H|^6$
$|H|^2 G^a_{\mu\nu}G^a_{\mu\nu}$

SMEFT at higher dimensions

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{D=2} + \mathscr{L}_{D=4} + \mathscr{L}_{D=5} + \mathscr{L}_{D=6} + \mathscr{L}_{D=7} + \mathscr{L}_{D=8} + \ldots$$



Exponential growth of the number of operators with the canonical dimension D

SMEFT at dimension-5:

Weinberg (1979)
Phys. Rev. Lett. 43, 1566

SMEFT at dimension-6:

Grządkowski et al
arXiv: 1008.4884

SMEFT at dimension-7:

Lehman
arXiv: 1410.4193

SMEFT at dimension-8:

Li et al
arXiv: 2005.00008

SMEFT at dimension-9:

Li et al
arXiv: 2012.09188

SMEFT at dimension-10,11,12:

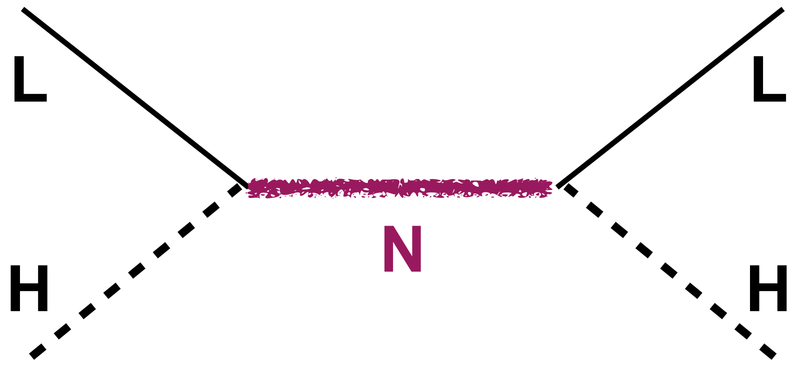
Harlander, Kempkens, Schaaf
arXiv: 2305.06832

Code to generate a basis at arbitrary dimension in SMEFT: Li et al arXiv:2201.04639

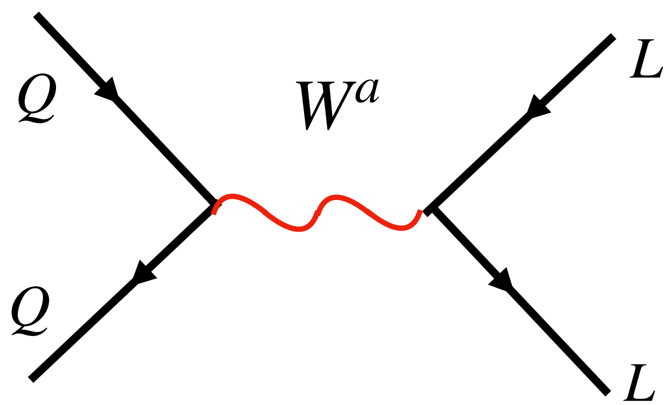
Meaning of SMEFT Wilson coefficients

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

Wilson coefficients of operators with $D \geq 5$ encode information about masses and couplings and quantum numbers of heavy particles at the scale above the SMEFT cutoff



$$\mathscr{L}_{D=5} \supset \frac{Y_N^2}{M_N}(LH)(LH)$$



$$\mathscr{L}_{D=6} \supset \frac{g_*^2}{M_W^2}(\bar{Q}\sigma^a\gamma_\mu Q)(\bar{L}\sigma^a\gamma_\mu L)$$

Complete dictionary at tree level Criado et al arXiv: 1711.10391

At one loop level Guedes, Olgoso arXiv: 2412.14253

From operators to observables

(roughly) four kinds of effects

SMEFT operators with D>4

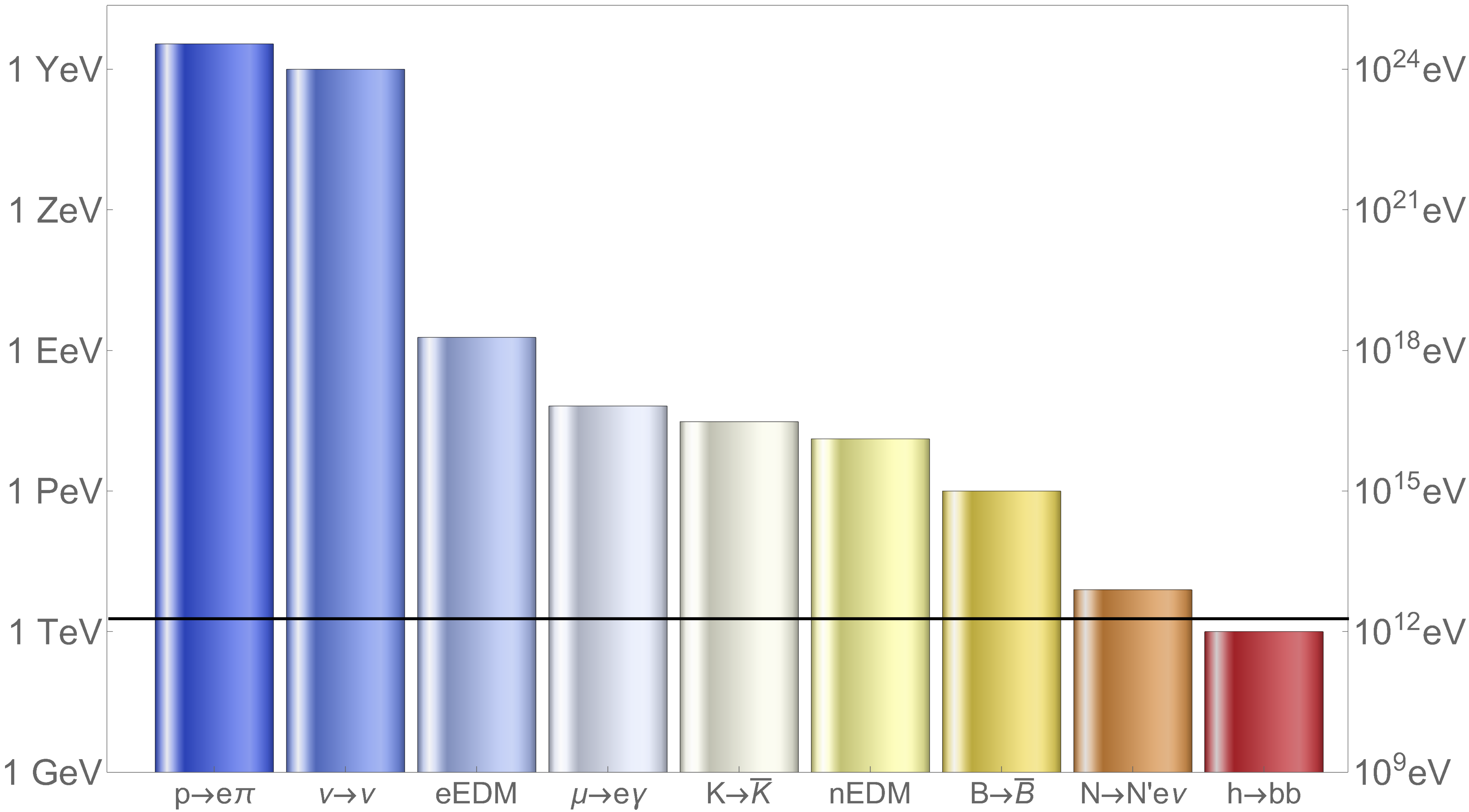
New contributions to SM particles' masses

New Lorentz structures for vertices present in SM Lagrangian

Corrections to strength of SM interactions

New vertices not present in SM Lagrangian (often leading to breaking of SM global and discrete symmetries)

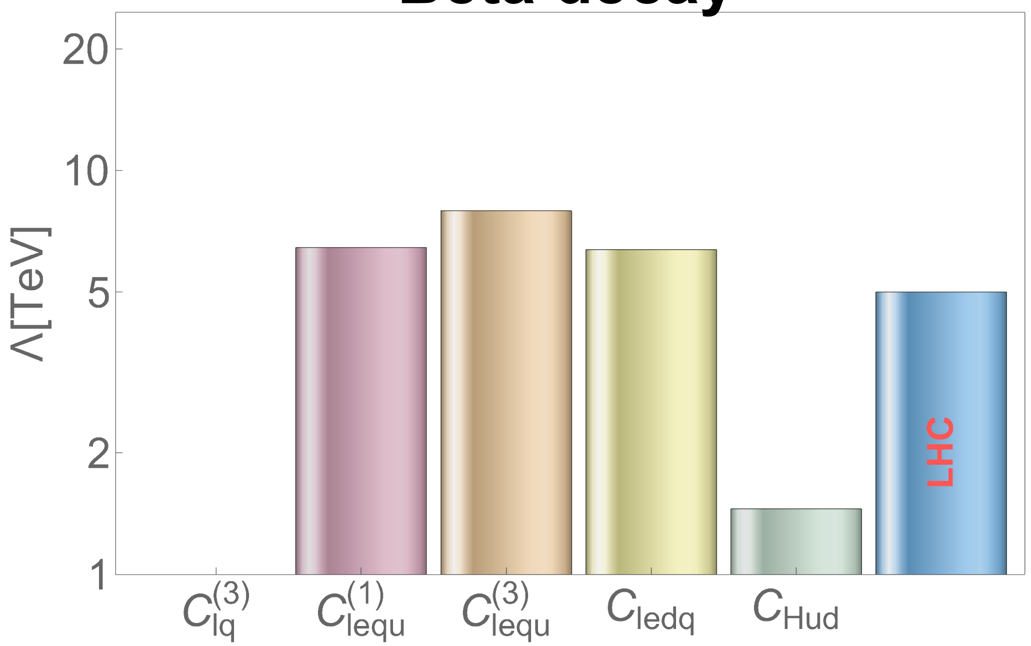
Experimental contraints on SMEFT



Experimental contraints on SMEFT

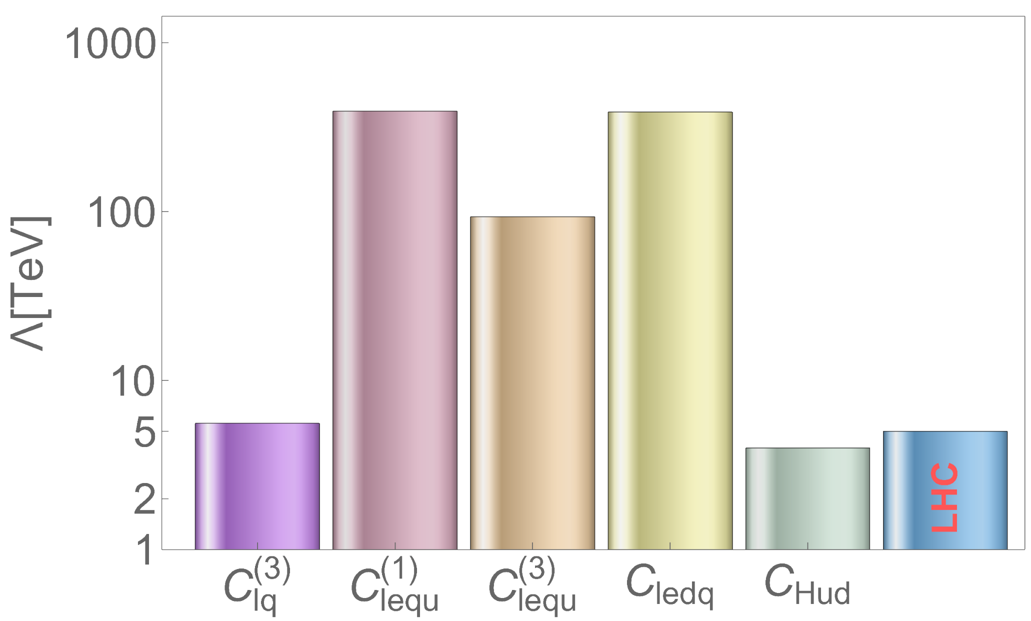
$$
\begin{aligned}
\mathscr{L}_{\rm SMEFT} \supset\ & C_{Hq}^{(3)} H^\dagger \sigma^a D_\mu H (\bar{Q}\sigma^a\gamma_\mu Q) + C_{Hl} H^\dagger \sigma^a D_\mu H (\bar{L}\sigma^a \gamma_\mu L) \\
& + C_{Hud} H^T D_\mu H (\bar{u}_R \gamma_\mu d_R) \\
& + C_{lq}^{(3)} (\bar{Q}\sigma^a\gamma_\mu Q)(\bar{L}\sigma^a\gamma_\mu L) + C_{lequ}^{(3)} (\bar{e}_R \sigma_{\mu\nu} L)(\bar{u}_R \sigma_{\mu\nu} Q) \\
& + C_{lequ}^{(1)} (\bar{e}_R L)(\bar{u}_R Q) + C_{ledq} (\bar{L} e_R)(\bar{d}_R Q) \\
& + \ldots
\end{aligned}
$$

Beta decay



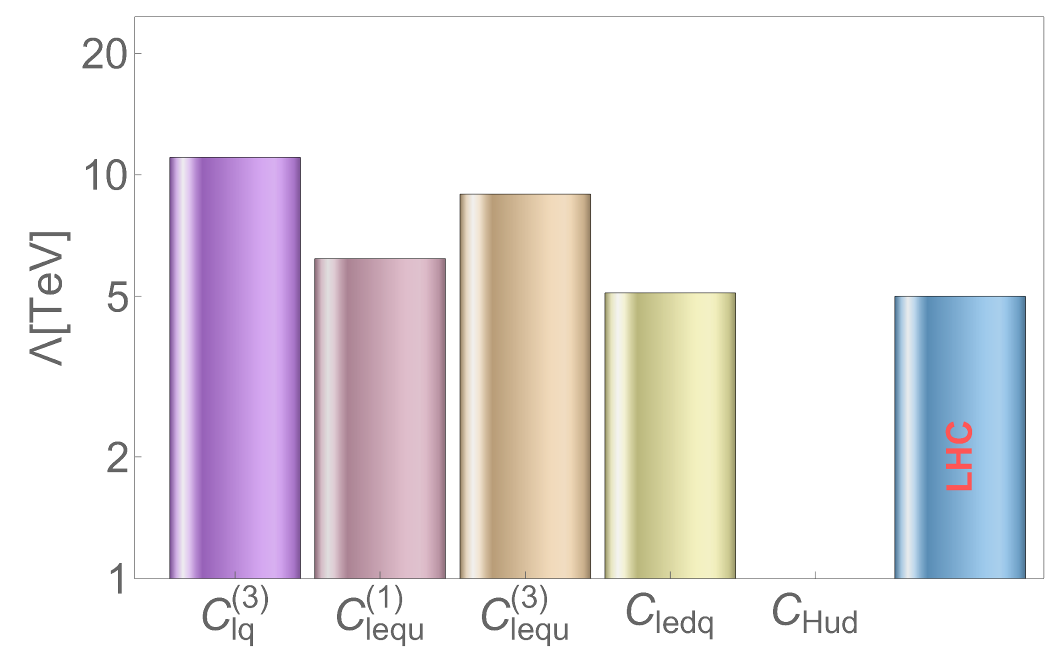
AA. Gonzalez-Alonso, Naviliat-Cuncic
[arXiv:2010.13797]

Beta + meson decay



Cirigliano, Diaz-Calderon, AA, Gonzalez-Alonso, Rodriguez-Sanchez
[arXiv:2112.02087]

CMS Drell-Yan



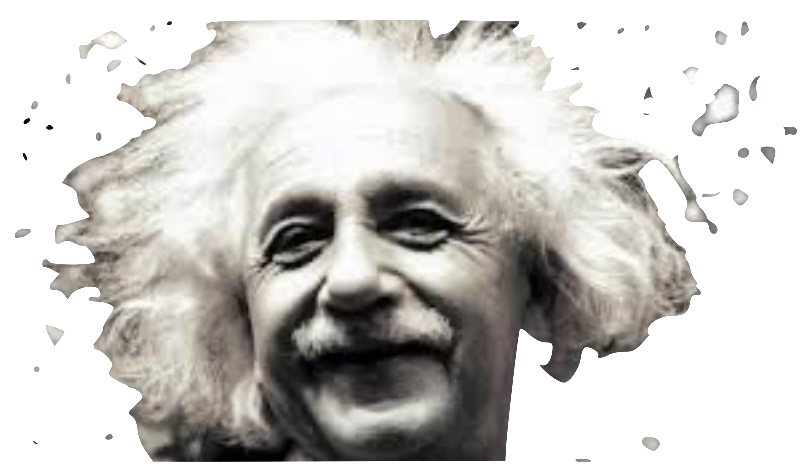
CMS
2103.02708

Frontiers for SMEFT

- **Comprehensive global fits** — e.g. 65 Wilson coefficients simultaneously fit in 2301.07036
- **More observables** — e.g. neutrino observables in 2301.07036 and 2411.00090
- **Automation tools** — e.g. MatchmakerEFT or Matchete for matching EFT to UV models
- **RG running beyond one loop** — e.g. two-loop running of Higgs-gluon coupling in 2510.14680
- **Matching beyond tree level** — e.g. complete 1-loop dictionary in 2412.14253
- **Phenomenology beyond dimension 6** — e.g. impact on Drell-Yan in in 2412.14162
- **Validity, truncation, theory uncertainties** — e.g. impact of EFT truncation for LHC searches in 2507.15954
- **Positivity relations for Wilson coefficients** — e.g. constraints on dimension-8 running in 2309.16611

Part 3

Gravitational EFTs, or quantum gravity for dummies



GREFT

Let's build an EFT out of $g_{\mu\nu}$ according to the usual rules

$$\mathscr{L}_{\rm GREFT} = \sqrt{-g}\left\{ \underset{\sim \Lambda^2}{\mathscr{L}_{D=2}} + \underset{\sim \Lambda^0}{\mathscr{L}_{D=4}} + \underset{\sim \Lambda^{-2}}{\mathscr{L}_{D=6}} + \underset{\sim \Lambda^{-4}}{\mathscr{L}_{D=8}} + \dots \right\}$$

At the next-to-leading order the only possible invariant under GC transformations is

$$\mathscr{L}_{D=2} = \frac{1}{2} M_{\rm Pl}^2 R$$

$$M_{\rm Pl} \equiv (8\pi G)^{-1/2} = 2.44 \times 10^{18}\ {\rm GeV}$$

At this point we have recovered the Einstein-Hilbert Lagrangian for general relativity!

GREFT

Going to higher orders

$$\mathscr{L}_{\text{GREFT}} = \sqrt{-g}\left\{ \frac{1}{2}M_{\text{Pl}}^2 R + \cancel{\mathscr{L}_{D=4}} + \underset{\sim \Lambda^{-2}}{\mathscr{L}_{D=6}} + \underset{\sim \Lambda^{-4}}{\mathscr{L}_{D=8}} + \ldots \right\}$$

$$\mathscr{L}_{D=4} = 0$$

$$\mathscr{L}_{D=6} = \frac{1}{6}\left\{ C_3 R_{\mu\nu\alpha\beta} R_{\alpha\beta\rho\sigma} R_{\rho\sigma\mu\nu} + \widetilde{C}_3 R_{\mu\nu\alpha\beta} R_{\alpha\beta\rho\sigma} \tilde{R}_{\rho\sigma\mu\nu} \right\}$$

$$\mathscr{L}_{D=8} = \frac{1}{8}\left\{ C_{4,1}(R_{\mu\nu\alpha\beta}R_{\mu\nu\alpha\beta})^2 + C_{4,2}(R_{\mu\nu\alpha\beta}\tilde{R}_{\mu\nu\alpha\beta})^2 + \widetilde{C}_4 (R_{\mu\nu\alpha\beta}R_{\mu\nu\alpha\beta})(R_{\mu\nu\alpha\beta}\tilde{R}_{\mu\nu\alpha\beta}) \right\}$$

We do not know what is the UV completion of GREFT
so we do not know the numerical value coefficients C_3 and $\widetilde{C}_3$, $C_{4,1}$, $C_{4,2}$, $\widetilde{C}_4$
At this point, they parametrize our ignorance about nature.
Maybe one day we will measure them experimentally,
and that will give us a hint about the underlying, more fundamental theory of gravity

GREFT

$$\mathscr{L}_{\text{GREFT}} = \sqrt{-g}\left\{ \frac{1}{2}M_{\text{Pl}}^2 R + \underset{\sim \Lambda^{-2}}{\mathscr{L}_{D=6}} + \underset{\sim \Lambda^{-4}}{\mathscr{L}_{D=8}} + \ldots \right\}$$

- We have built a consistent quantum theory of gravity (at least for small fluctuations around flat spacetime) called GREFT

- It is an EFT organized as an expansion in $1/\Lambda$, where $\Lambda \lesssim M_{\text{Pl}}$

- GREFT contains general relativity (GR) as its leading term

- The only price to pay is that we have to include an infinite series of higher order interactions, suppressed by M_{Pl} or a lower scale Λ (if we do not, they will need to be added anyway as counterterms due to loop divergences). This is a problem if we want to predict processes where momentum exchange is of order M_{Pl} or larger. This is however not a problem if we restrict to low-energy effects (basically all currently observable ones)

- It is arguably the best EFT ever, because its validity range is the largest of known EFTs, spanning from very low-energies all the way to the Planck scale, $H_0 \ll E \ll M_{\text{Pl}}$

GREFT

The Wilson coefficient C_3 and $C_{4,k}$ can be generated by string UV completions.
In that case, their magnitude is set by the string scale

Otherwise, for mass m, spin S and charge Q particle minimally coupled to gravity:

$$C_3^{(S)} = \frac{(-)^{2S+1}}{16\pi^2}\frac{(2S+1)}{2520m^2}, \quad \tilde{C}_3 = 0$$

Bern, Kosmopoulos, Zhiboedov
[arXiv:2103.12728]

$$C_{4,1}^{(0)} = \frac{1}{16\pi^2}\frac{11}{37800m^4} \quad C_{4,1}^{(1/2)} = \frac{1}{16\pi^2}\frac{47}{151200m^4} \quad C_{4,1}^{(1)} = \frac{1}{16\pi^2}\frac{1}{350m^4} \quad C_{4,1}^{(3/2)} = \frac{1}{16\pi^2}\frac{1217}{75600m^4} \quad C_{4,1}^{(2)} = \frac{1}{16\pi^2}\frac{1009}{3780m^4}$$

$$C_{4,2}^{(0)} = \frac{1}{16\pi^2}\frac{1}{37800m^4} \quad C_{4,2}^{(1/2)} = \frac{1}{16\pi^2}\frac{127}{151200m^4} \quad C_{4,2}^{(1)} = \frac{1}{16\pi^2}\frac{13}{6300m^4} \quad C_{4,2}^{(3/2)} = \frac{1}{16\pi^2}\frac{1297}{75600m^4} \quad C_{4,2}^{(2)} = \frac{1}{16\pi^2}\frac{251}{945m^4}$$

For non-minimally coupled particles see :

Alviani, AA
[arXiv::2408.03439]

Positivity: $C_{4,1} > 0, \qquad C_{4,2} > 0$

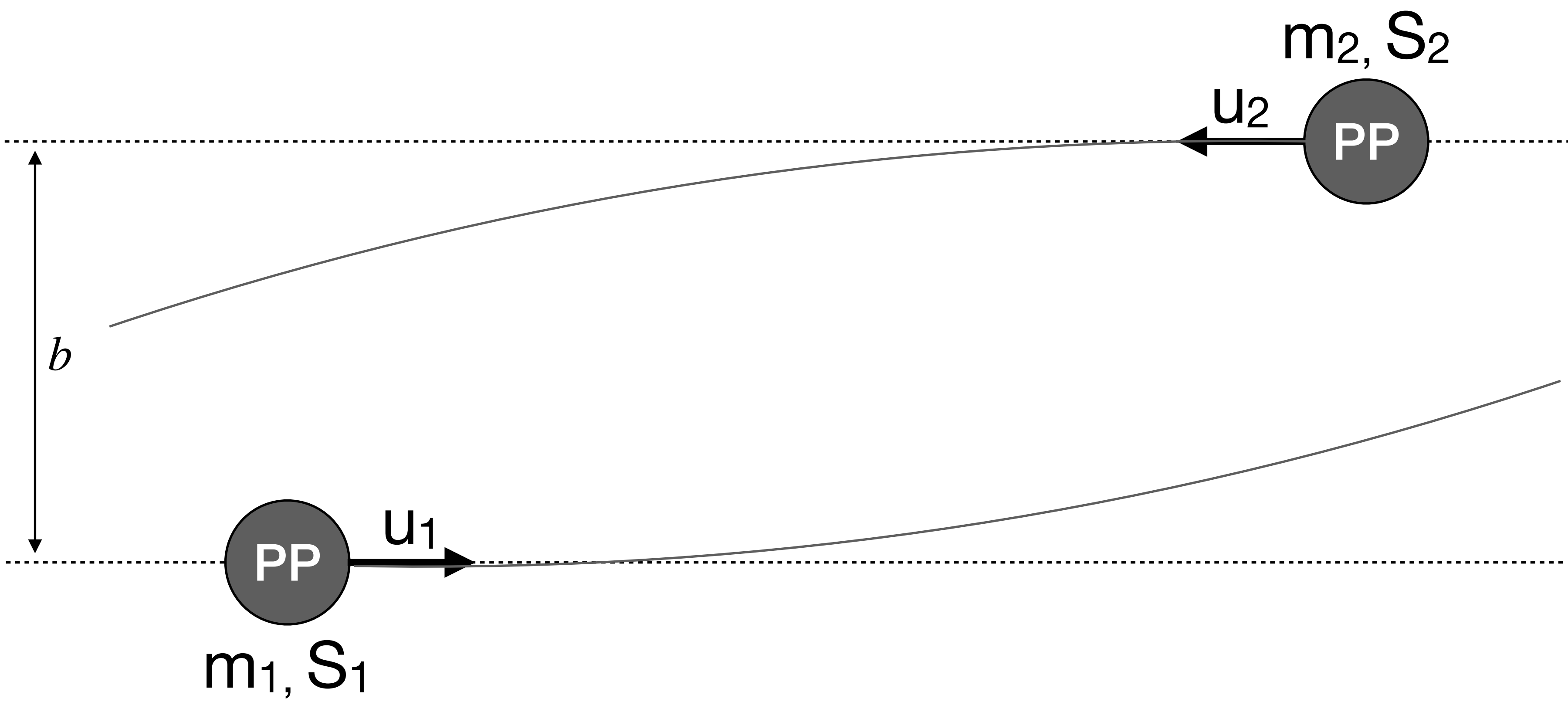
Bellazzini, Cheung, Remmen
[arXiv:1509.00851]

Higher-order corrections to GR are not an abstract irrelevant concept

For example, integrating out the lightest neutrino will generate these operators suppressed by the scale m_{ν_1} which can be very low for all we know.

GREFT

Application to classical gravitational processes



Black holes can be represented by point particles, whose interactions are those of a spin-S particle minimally coupled to gravity

Arkani-Hamed, Huang, O'Connell
arXiv:1906.10100

In particular,

$$\mathscr{L} \supset \sqrt{-g}\left\{ \frac{1}{2} M_{\mathrm{Pl}}^2 R + \frac{1}{2} \partial_\mu \Phi \partial^\mu \Phi \right\}$$

describes gravitational interactions of a Schwarzschild black hole

KMOC formalism

$$\mathcal{R}_h \equiv {}_{\text{out}}\langle\psi|h^{\mu\nu}(x)|\psi\rangle_{\text{out}}\epsilon^{-}_{\mu\nu}$$

Kosower, Maybee, O'Connell
[arXiv:1811.10950]

Cristofoli, R. Gonzo, D. A. Kosower, D. O'Connell
[arXiv:2107.10193]

$$|\psi\rangle_{\text{out}} = S|\psi\rangle_{\text{in}} \quad \Rightarrow \quad \mathcal{R}_h = {}_{\text{in}}\langle\psi|S^\dagger h^{\mu\nu}(x)S|\psi\rangle_{\text{in}}\epsilon^{-}_{\mu\nu}$$

$$|\psi\rangle_{\text{in}} = \Pi_{i=1,2}[\int d\Phi(p_i)f_i(p_i)e^{ip_ib_i}]|p_1p_2\rangle_{\text{in}}$$

The radiation observables depends on an amplitude-like object

$$h_{\mu\nu} \sim \int d\Phi_k\, a_{\text{in}}(k)\, e^{-ikx} + \text{h.c} \quad \Rightarrow \quad \mathcal{R}_h \supset {}_{\text{in}}\langle\psi|S^\dagger a_{\text{in}}(k)S|\psi\rangle_{\text{in}} \equiv \text{Exp}_k$$

"generalized amplitude"

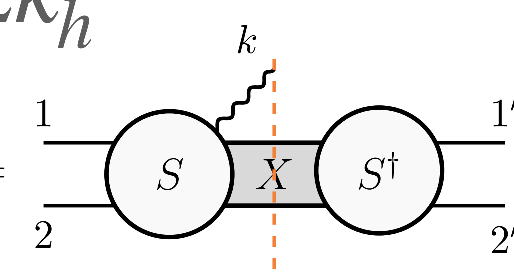
Caron-Huot, Giroux, Hannesdottir, Mizera
arXiv:2310.12199

distinct from ordinary S matrix elements

$${}_{\text{out}}\langle\psi'|\psi\rangle_{\text{in}} = {}_{\text{in}}\langle\psi'|S^\dagger|\psi\rangle_{\text{in}}$$

It can be related to usual S matrix elements for the 2-to-3 process $12 \to 12k_h$

$${}_{\text{in}}\langle\psi|S^\dagger a_{\text{in}}(k)S|\psi\rangle_{\text{in}} = \int d\Phi_X \;\; {}_{\text{in}}\langle\psi|S^\dagger|X\rangle_{\text{in}} \; {}_{\text{in}}\langle X|a_{\text{in}}(k)S|\psi\rangle_{\text{in}} = \int d\Phi_X \;\; {}_{\text{in}}\langle\psi|S^\dagger|X\rangle_{\text{in}} \; {}_{\text{in}}\langle Xk|S|\psi\rangle_{\text{in}}$$

$\text{Exp}_k =$ 

Scalar-tensor EFT

Application to another gravitational EFT featuring also a massless scalar ϕ

$$\mathscr{L} \supset \sqrt{-g}\left[\frac{M_{\rm Pl}^2}{2}R + \frac{\phi}{\Lambda}\left(\alpha\mathscr{G} + \tilde{\alpha}R\tilde{R}\right) + \frac{1}{2}\partial^\mu\phi\partial_\mu\phi\right]$$

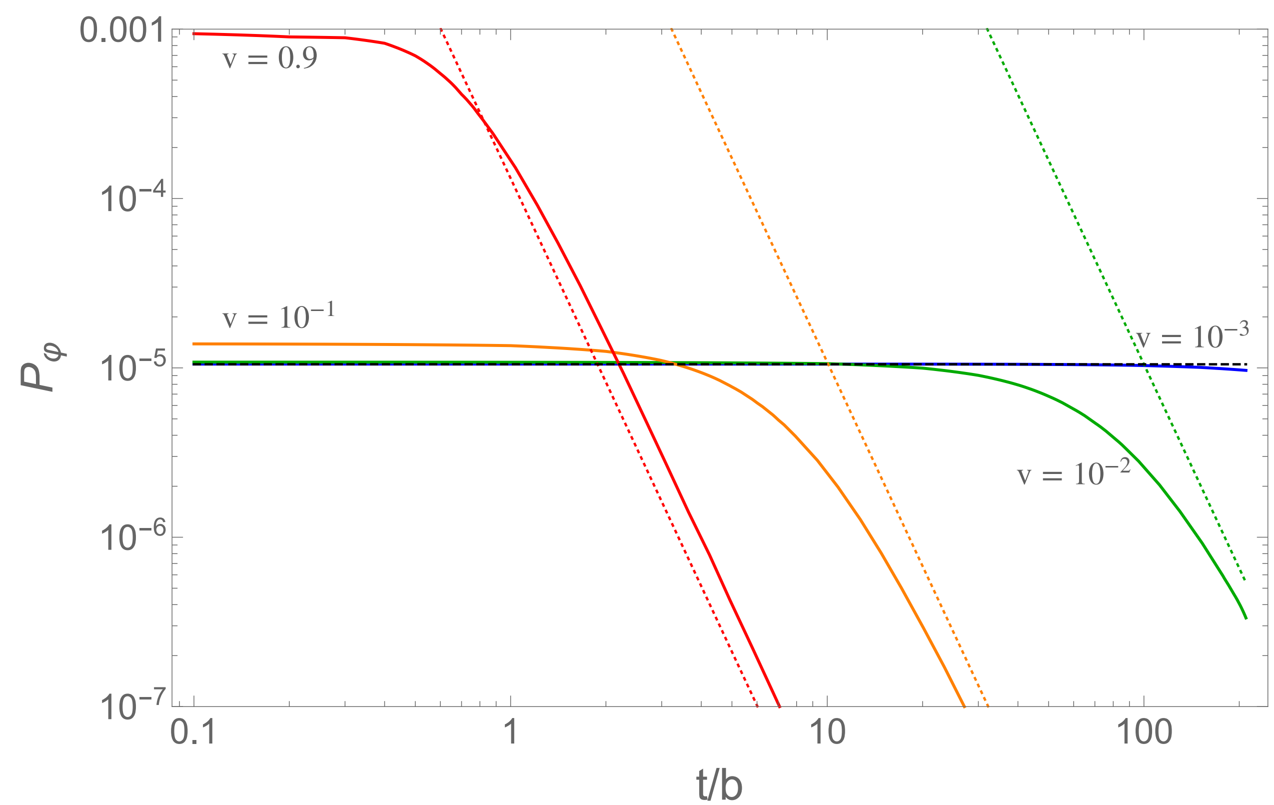
$$R^{\mu\nu\rho\sigma}R_{\mu\nu\rho\sigma} - 4R^{\mu\nu}R_{\mu\nu} + R^2 \qquad R^{\mu\nu\rho\sigma}\tilde{R}_{\mu\nu\rho\sigma}$$

Gauss Bonnet invariant

Chern Simons invariant

Emitted power

$$\frac{dP_\phi}{d\Omega} = (\partial_t W_\phi)^2$$



In units of $\dfrac{c_1^2 m_1^2 m_2^2}{b^4 M_{\rm Pl}^6}$

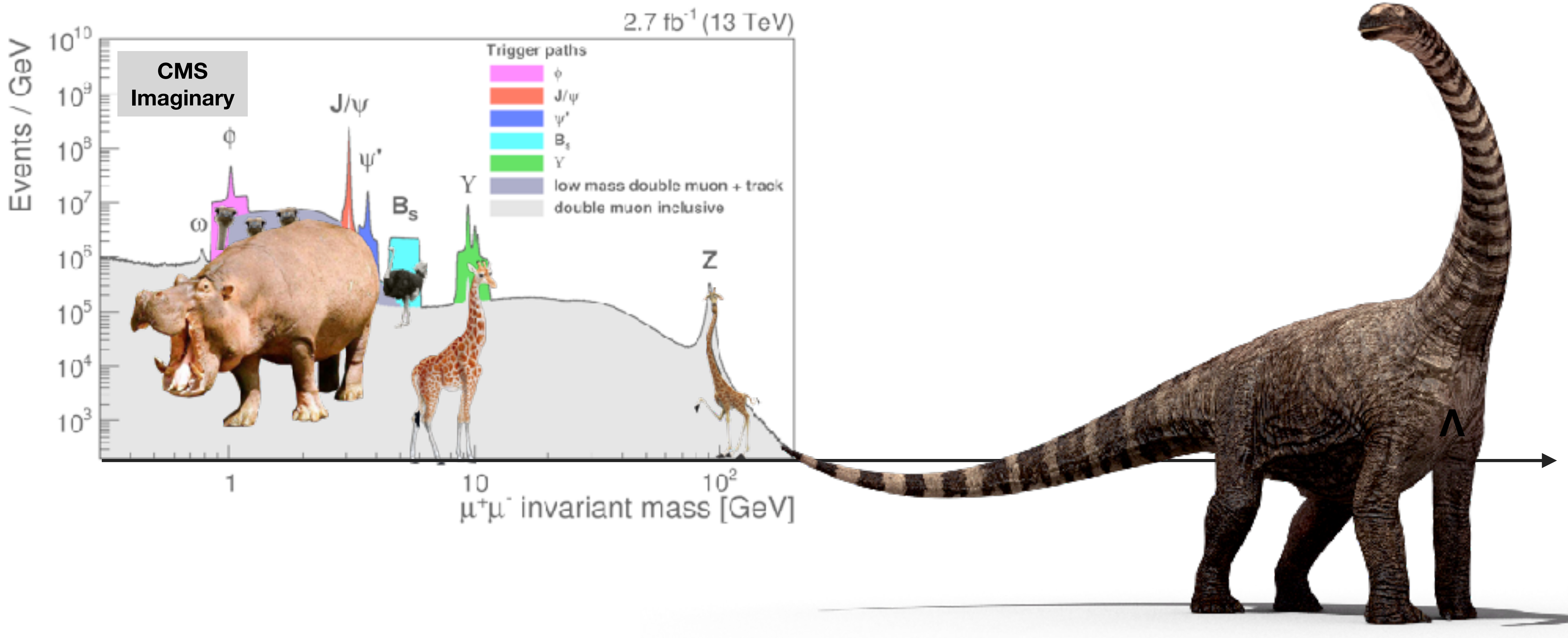
AA, Marinellis
2407.16457
2411.12909

Frontiers for GREFT

- **Higher-loop (post-Minkowskian) corrections to gravitational waves in classical limit**
  State of art is 5PM or 4 loops: 2403.07781
- **Higher-spin and tidal corrections to gravitational waves in classical limit**
  All-order spin corrections know at 2PM: 2304.13740
- **Scattering-to-bound dictionary**
  Much is known, but there remain open questions for waveforms: 2402.00124
- **Observables in the ringdown phase of black hole merger**
  Love numbers from amplitudes: 2503.13593
- **Positivity constraints in gravitational theories**
  Known UV completions in small islands 2103.12728
- **Soft theorems, memory, and asymptotic symmetries**

Surprising interconnections between all these: 1703.05448

Fantastic Beasts and Where To Find Them



THANK YOU