Beyond the Standard Model

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Lectures Plan

1. Motivation: shortcomings of the SM

2. The BSM toolbox
   - Effective Field Theories: physics across scales
   - symmetries
   - naturalness
   - unitarity bounds

3. Concrete examples
   - BSM for neutrino masses: seeesaw models
   - BSM for the Hierarchy Problem (basics)

4. Direct and indirect phenomenological probes (mostly LHC / colliders)

1. Motivation

The Standard Model of particle physics

$$\mathscr{L}_{SM} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}W^i_{\mu\nu}W^{i\mu\nu} - \frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu}$$
$$+ D_\mu H^\dagger D^\mu H - V(H^\dagger H)$$
$$+ \bar{q}i\not{D}q + \bar{u}i\not{D}u + \bar{d}i\not{D}d + \bar{\ell}i\not{D}\ell + \bar{e}i\not{D}e$$
$$- \left[\bar{q}Y_d H d + \bar{q}Y_u\tilde{H}u + \bar{\ell}Y_e H e + \mathrm{hc}\right]$$

$$V(H^\dagger H) = -\frac{m^2}{2}H^\dagger H + \lambda(H^\dagger H)^2$$

The Standard Model of particle physics

$$
\begin{aligned}
\mathscr{L}_{SM} = & -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}W^i_{\mu\nu}W^{i\mu\nu} - \frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu} \\
& + D_\mu H^\dagger D^\mu H - V(H^\dagger H) \\
& + \bar{q}i\not{D}q + \bar{u}i\not{D}u + \bar{d}i\not{D}d + \bar{\ell}i\not{D}\ell + \bar{e}i\not{D}e \\
& - \left[\bar{q}Y_d H d + \bar{q}Y_u \tilde{H}u + \bar{\ell}Y_e H e + \mathrm{hc}\right]
\end{aligned}
$$

$$
V(H^\dagger H) = -\frac{m^2}{2}H^\dagger H + \lambda(H^\dagger H)^2
$$

$$
D_\mu q = \left[\partial_\mu + ig_s G^a_\mu \frac{\lambda^a}{2} + igW^i_\mu \frac{\sigma^i}{2} + ig' B_\mu \mathbf{y}_q\right] q
$$

$$
W^i_{\mu\nu} = \partial_\mu W^i_\nu - \partial_\nu W^i_\mu - g\varepsilon^{ijk}W^j_\mu W^k_\nu
$$

	q	u	d	ℓ	e	H
$SU(3)_c$	**3**	**3**	**3**	**1**	**1**	**1**
$SU(2)_c$	**2**	**1**	**1**	**2**	**1**	**2**
$U(1)_Y$	$1/6$	$2/3$	$-1/3$	$-1/2$	-1	$1/2$

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$$-\left[\bar{q}Y_d H d + \bar{q}Y_u \tilde{H} u + \bar{\ell}Y_e H e + \mathrm{hc}\right]$$

$$V(H^\dagger H) = -\frac{m^2}{2}H^\dagger H + \lambda(H^\dagger H)^2$$

spin $SU(2)_L$ flavor

$$i\bar{q}_{rI\alpha}\,\delta_{\alpha\beta}\,\gamma^\mu_{rs}\,[D_\mu]_{IJ}\,q_{sJ\beta}$$

$$-\bar{q}_{rI\alpha}\,(Y_d)_{\alpha\beta}\,\delta_{rs}\,H_I\,d_{s\beta}$$

$$D_\mu q = \left[\partial_\mu + ig_s G^a_\mu \frac{\lambda^a}{2} + igW^i_\mu \frac{\sigma^i}{2} + ig' B_\mu \mathbf{y}_q\right] q$$

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	q	u	d	ℓ	e	H
$SU(3)_c$	**3**	**3**	**3**	**1**	**1**	**1**
$SU(2)_c$	**2**	**1**	**1**	**2**	**1**	**2**
$U(1)_Y$	1/6	2/3	−1/3	−1/2	−1	1/2

What the SM does for us

- explains all particle interactions via simple fundamental modeling assumptions:
  gauge principle + charges

- **Higgs mechanism** : predicts relations between masses and Higgs couplings, predicts $m_Z^2/m_W^2 \simeq (g^2+g'^2)/g^2$, relation between weak and electromagnetic interactions ...

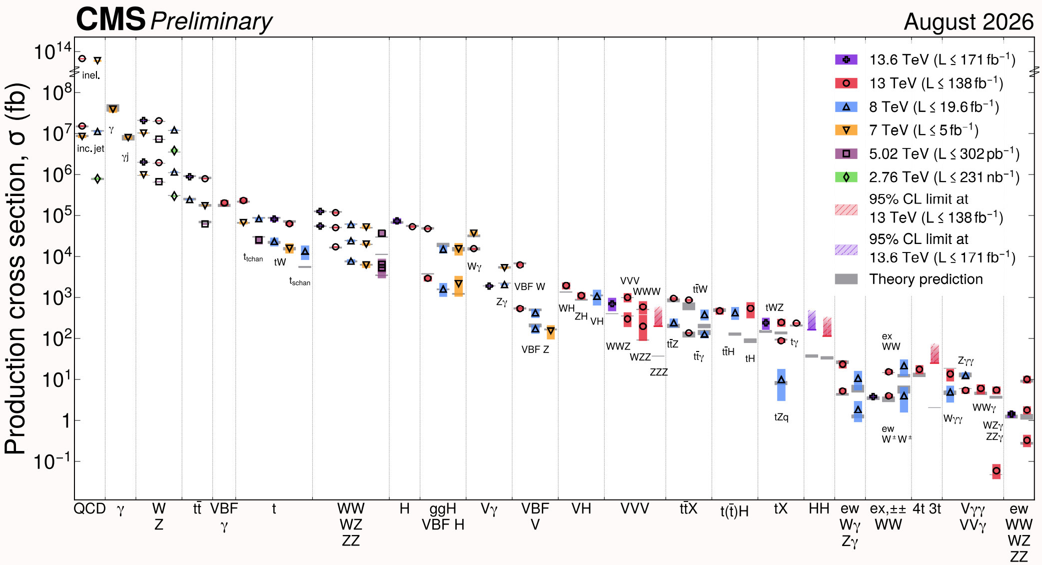
- predict that the 3 quark generations should mix, and CP should be violated in charged currents

- predicts precisely many (∞) physical quantities (cross sections, branching ratios...) starting from a few input measurements

  ☞ **18** free parameters* $(g_s, g, g', m^2, \lambda, \theta_{12}, \theta_{23}, \theta_{13}, \delta, 9\times m_f)$

$^* + \bar\theta$

One of the most precisely tested theories ever



What the SM does *not* do for us

a things the SM does not contain / cannot explain

- gravitational interactions + Dark Energy

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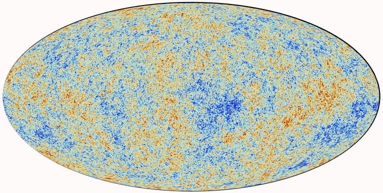
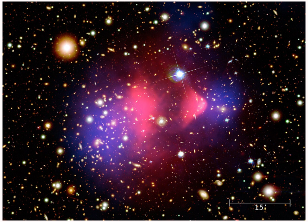
a things the SM does not contain / cannot explain

- gravitational interactions + Dark Energy
- Dark Matter ☞ observation requires a particle that is stable, cold ($M \gg T_{eq}$), neutral under QCD + QED, produced with correct Ω_{DM} → no SM candidates

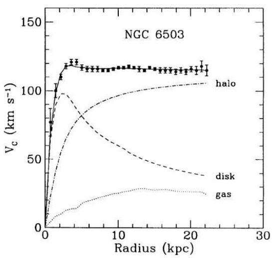
$\Omega_{DM} \simeq 0.27$



Planck



Chandra X-Ray Observatory



ned.ipac.caltech.edu/level5/Sept17/Freese/Freese2.html

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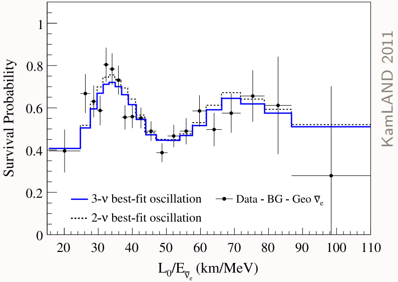
a things the SM does not contain / cannot explain

- gravitational interactions + Dark Energy
- Dark Matter
- neutrino masses and mixings



☞ neutrino oscillations indicate that at least 2 ν are massive
the PMNS has large mixing angles, perhaps large δ

the SM does not contain ν_R $\rightarrow$ predicts $m_\nu \equiv 0$

[will spell this problem out more precisely later]

What the SM does *not* do for us

a things the SM does not contain / cannot explain

- gravitational interactions + Dark Energy
- Dark Matter
- neutrino masses and mixings
- baryon/anti-baryon asymmetry

☞ our universe (planets, stars, galaxies, clusters…) is made of matter, not antimatter

the matter imbalance is quantified by $\eta_B = \dfrac{n_B - n_{\bar{B}}}{n_\gamma} \simeq 6.1 \times 10^{-10}$ Planck 2018 (CMB) + BBN

Baryogenesis

to achieve $\eta_B \neq 0$ cosmologically, nature must fulfill the three **Sakharov conditions**:

1. baryon number (B) must be violated (it is not an exact symmetry)
2. both C and CP must be violated
3. there must be a phase in which the B violating processes occur out of thermal equilibrium

They are **not** satisfactorily realized in the SM:

1. B is violated at quantum level via the $B+L$ anomaly ✔
   $\rightarrow$ B violation happens via **sphalerons**, which are only present at $T \gtrsim 130\,\mathrm{GeV}$, where EW symmetry is unbroken
2. C and CP are violated by the EW interactions due to chiral nature + CKM phase.
   however, the amount of CP violation in the SM is insufficient ✘ Gavela+ 9312215
3. out-of-equilibrium $\cancel{B}$ transitions are only achieved via a first-order EW phase transition (EWPT)
   $\rightarrow$ coexistence of phases with and without sphalerons (bubbles of unbroken / broken EW sym)
   however, the EWPT is not first order in the SM with $m_h = 125\,\mathrm{GeV}$ ✘ Kajantie+ 9605288
   $\rightarrow$ the minima corresponding to broken and unbroken sym are not separated by a potential barrier

$\rightarrow$ BSM required

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b things that are in the SM, but unexplained / theoretically unsatisfactory

- why 3 copies of (u, d, ν_e, e^-), with those hierarchical masses and mixings

flavor puzzle

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- why that gauge structure
  why only LH $SU(2)$, why g, g', g_s have those values, why those charges:
  $\rightarrow$ 2 $\mathbf{y}_f$ remain free after requiring gauge anomaly cancellation

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- why does QCD conserve CP — strong CP problem

The strong CP problem

In principle the QCD Lagrangian contains a term that **violates CP**

$$\mathscr{L}_{QCD} \supset \boxed{\theta} \frac{g_s^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu} \qquad\qquad \tilde{G}^{a\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\rho\sigma} G^a_{\rho\sigma}$$

where θ is a free parameter.

this interaction is unphysical on perturbative configurations of the gluon field.
however, it gives nonvanishing effects on non-perturbative configurations (**instantons**)

via the chiral anomaly, it can be equivalently recast into an imaginary part of the quark Yukawas, e.g.:

$$\boxed{\theta} \frac{g_s^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu} \quad \longrightarrow \quad -\bar{q}(Y_d e^{i\theta/6}) H d - \bar{q}(Y_u e^{i\theta/6}) \tilde{H} u + \mathrm{h.c.}$$

from here, one can see that the physical quantity is $\boxed{\bar{\theta} = \theta + \arg\det(Y_u Y_d)}$ and that it contributes to the **electric dipole moment (EDM) of the neutron**.

$$d_n \approx \frac{1}{8\pi^2} \frac{m_q}{m_n} \frac{\bar{\theta} e}{m_n} \approx 10^{-4}\, \bar{\theta} e \ \mathrm{GeV}^{-1} \quad \longrightarrow \quad d_n \text{ measurements imply } \boxed{|\bar{\theta}| \lesssim 10^{-10}}$$

Extending the SM

- the shortcomings listed so far can be addressed by adding **new particles and interactions** to the SM

+ no particular reason why the SM should be the ultimate theory of everything

the expectation is that the SM should be replaced by a new theory. two directions:

- adding new **light** particles/interactions ($M \lesssim 100\,\mathrm{GeV}$) that we might have missed so far
- formulate a theory that describes physics at energies above the EW scale (**heavy**)

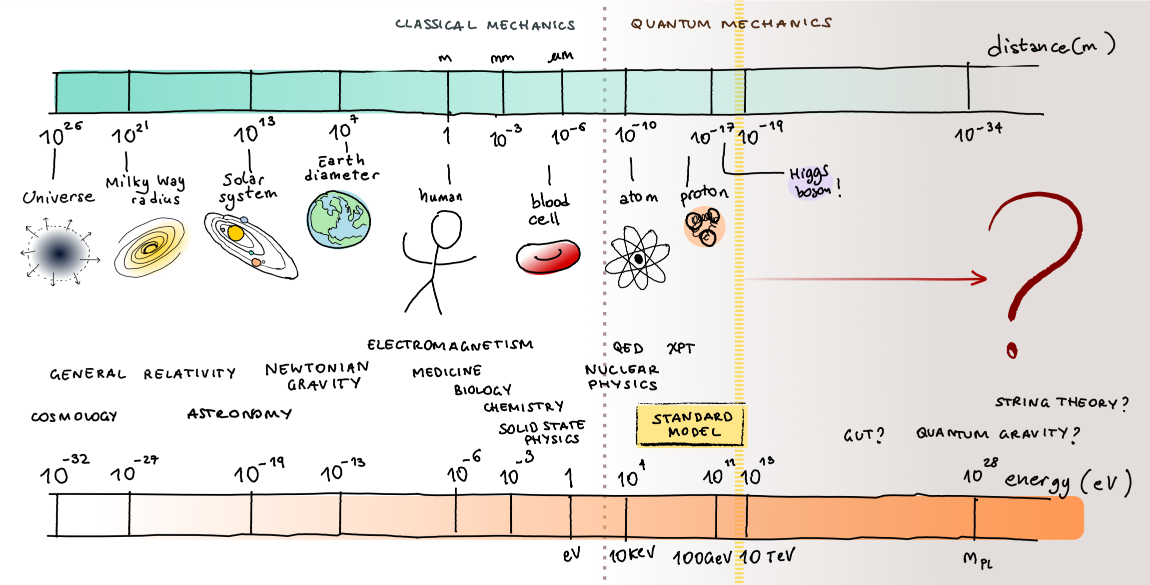
a number of theory and pheno tools should be used to devise a *viable* BSM theory

- a huge number of BSM hypotheses/mechanisms/theories has been devised in the literature, intractable in a 4h course!

goal: provide general toolbox & explore a few relevant examples

2. The BSM toolbox

Energy scales



Extending the SM: at what scale?

at what scale would we expect new physics to appear (naively)?

gravity → Planck scale $\simeq 10^{19}\,\mathrm{GeV}$

neutrino masses → eV (Dirac) – $10^{16}\,\mathrm{GeV}$ (Majorana)

Dark Matter → $10^{-22}\,\mathrm{eV}$ (fuzzy) – $10^{16}\,\mathrm{GeV}$ (WIMPzillas)

baryon asymmetry → TeV (EW), $10^{9} - 10^{16}\,\mathrm{GeV}$ (leptogenesis)

flavor → TeV (MFV) – $10^{5}\,\mathrm{TeV}$ (anarchic)

charges / couplings origin → $10^{16} - 10^{19}\,\mathrm{GeV}$ ("GUT" scale)

hierarchy problem → $1 - 10\,\mathrm{TeV}$

strong CP problem → $\lesssim \Lambda_{QCD} = 300\,\mathrm{MeV}$ (axion) + $\gtrsim 10^{9}\,\mathrm{GeV}$ (UV completion)

⚠ highly dependent on modeling specifics, possible to stretch by a few orders of magnitude

☞ most problems require physics $\gg \mathrm{TeV}$ + potentially new (feebly interacting) light particles

2.1 Effective Field Theories

Effective Field Theories

M

$$\mathscr{L}_{UV} = \frac{1}{2}\partial_\mu\Phi\partial^\mu\Phi + \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{M^2}{2}\Phi^2 - \frac{m^2}{2}\phi^2 - V_{UV}(\Phi,\phi)$$

$m \ll M$ **large scale separation**

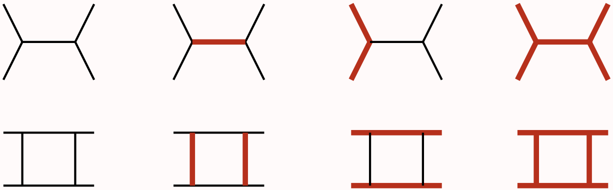
m

$$\mathscr{L}_{IR} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{m^2}{2}\phi^2 - V_{IR}(\phi) + \dots$$

at energies $E \sim m$ we can work with a theory that does not contain Φ

$\Phi : M$ $\qquad\qquad$ $\varphi : m$

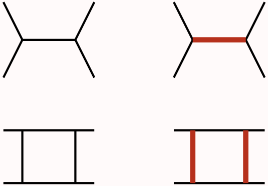
$E \simeq M$



Effective Field Theories

$\Phi : M$ $\qquad\qquad$ $\varphi : m$

$E \simeq m \ll M$

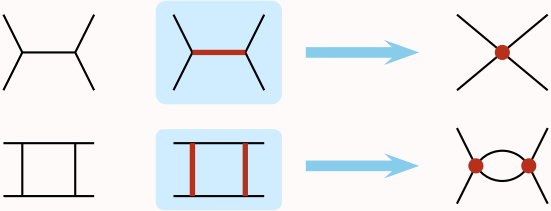


Φ can never be produced on-shell $\to$ never external state

Effective Field Theories

$\Phi : M$ $\qquad\qquad$ $\varphi : m$

$E \simeq m \ll M$



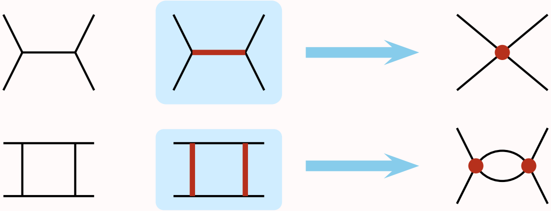
$\sim \dfrac{1}{M^2}$

$\sim \dfrac{1}{M^4}$

$$\Phi \text{ propagator: } \frac{i}{p^2 - M^2 + i\varepsilon} \xrightarrow{p \ll M} \frac{i}{M^2}$$

$\Phi : M$ $\qquad$ $\varphi : m$

$E \simeq m \ll M$



$\sim \dfrac{1}{M^2}$

$\sim \dfrac{1}{M^4}$

The effects of Φ at $E \ll M$ are described by

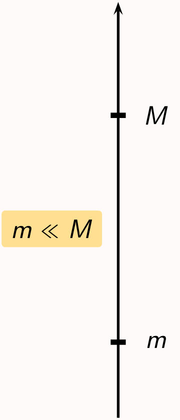
local, analytic operators $\propto \dfrac{1}{M^n}$

uncertainty principle

internal lines never on-shell

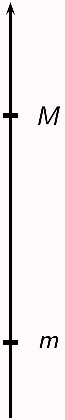
Decoupling Theorem Appelquist, Carrazzone PRD11 (1975) 2856

Effective Field Theories



$$\mathscr{L}_{UV} = \frac{1}{2}\partial_\mu \Phi \partial^\mu \Phi + \frac{1}{2}\partial_\mu \phi \partial^\mu \phi - \frac{M^2}{2}\Phi^2 - \frac{m^2}{2}\phi^2 - \frac{\lambda_{UV} M}{2}\phi^2 \Phi + \dots$$

$$\mathscr{L}_{EFT} = \frac{1}{2}\partial_\mu \phi \partial^\mu \phi - \frac{m^2}{2}\phi^2 - \frac{\lambda_4}{4!}\phi^4 + \\ + \frac{c_6}{6!}\frac{\phi^6}{M^2} + \frac{c_8}{8!}\frac{\phi^8}{M^4} + \frac{c_8'}{4}\frac{(\partial_\mu \partial_\nu \phi)^2 \phi^2}{M^4} + \dots$$



$m \ll M$

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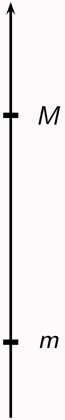
$$\mathscr{L}_{EFT} = \frac{1}{2}\partial_\mu \phi \partial^\mu \phi - \frac{m^2}{2}\phi^2 - \frac{\lambda_4}{4!}\phi^4 + \\ + \sum_{d=5}^{\infty} \sum_i \frac{c_i^{(d)}}{M^{d-4}} \mathcal{O}_i^{(d)}$$

effective operators encode IR physics

Wilson coefficients: encode UV physics

Effective Field Theories



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the EFT gives predictions order by order
in a series expansion in $1/M$

Effective Field Theories: matching

M

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$m \ll M$

m

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Effective Field Theories: matching

automated tools: `Matchete` Fuentes-Martin+ 2012.08506, 2212.04510 `matchmakerEFT` Carmona+ 2112.10787

M

$$\mathscr{L}_{UV} = \frac{1}{2}\partial_\mu\Phi\partial^\mu\Phi + \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{M^2}{2}\Phi^2 - \frac{m^2}{2}\phi^2 - \frac{\lambda_{UV} M}{2}\phi^2\Phi + \dots$$

$m \ll M$

impose that **all** (L-loop) **amplitudes** computed with $\mathscr{L}_{UV}$ and $\mathscr{L}_{EFT}$ are **equal** up to some order in M at a scale $\longrightarrow C_i(\lambda_{UV})$

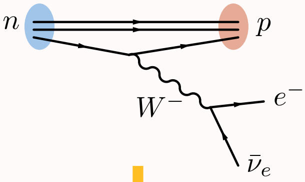
m

$$\mathscr{L}_{EFT} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{m^2}{2}\phi^2 - \frac{\lambda_4}{4!}\phi^4 + \frac{c_6}{6!}\frac{\phi^6}{M^2} + \dots$$

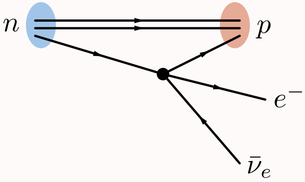
☞ tree: $\lambda_4 = -\lambda_{UV}^2\left(3 + 4\frac{m^2}{M^2}\right)$ $\qquad \frac{c_6}{M^2} = -\frac{60\lambda_{UV}^4}{M^2}$

EFTs: the Fermi theory example

"Top-down"



$q^2 < m_N^2 \ll m_W^2$



E

M

Full theory: SM

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

matching

m

EFT: Fermi theory

$$\mathscr{L} = \mathscr{L}_4 - 2\sqrt{2}\,\boxed{G_F}\,(\bar{u}\gamma^\mu P_L d)(\bar{\nu}\gamma^\mu P_L e) + \ldots$$

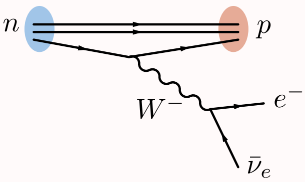
$$\boxed{G_F} = \frac{g^2}{4\sqrt{2}m_W^2} = \frac{1}{\sqrt{2}v^2}$$

EFTs: the Fermi theory example

"Bottom-up"

E

M



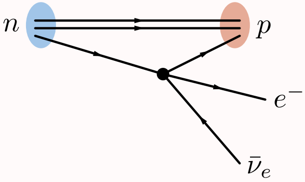
Full theory: SM

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

Fermi th. was formulated in the 1930s w/o SM knowledge.

- it makes precise predictions
- it reveals: universality, P violation, EW scale $\sim G_F^{-1/2}$

m

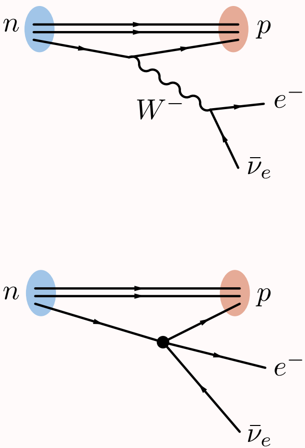


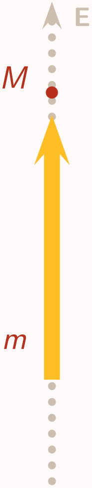
EFT: Fermi theory

$$\mathscr{L} = \mathscr{L}_4 - 2\sqrt{2}\, G_F\, (\bar{u}\gamma^\mu P_L d)(\bar{\nu}\gamma^\mu P_L e) + \ldots$$

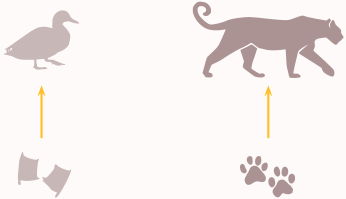
$$G_F = \frac{g^2}{4\sqrt{2}m_W^2} = \frac{1}{\sqrt{2}v^2}$$

EFTs: bottom up





measuring EFT parameters **reveals properties** of full theory

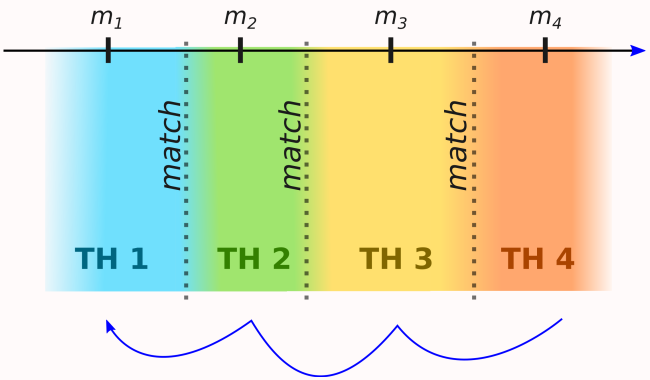


→ no reference to underlying model:
$\mathcal{O}_i^{(d)}$ are all possible (independent) dim-d interactions that can be built with light fields and symmetries

→ **totalitarian principle**:
anything not forbidden is compulsory

→ $C_i^{(d)}/M^{d-4}$ are free couplings that can be measured

Reductionism



moving *down* in E

- each theory gives way to another, which is its EFT
- the impact of very heavy physics becomes more and more irrelevant → decoupling

moving *up* in E: each theory is an EFT, one would like to find a viable UV completion

The Standard Model Effective Field Theory – SMEFT

promoting the Standard Model to an EFT $\equiv$ add **higher-dimensional** terms made of SM **fields** and respecting the SM **symmetries**

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \frac{1}{\Lambda^3}\mathcal{L}_7 + \frac{1}{\Lambda^4}\mathcal{L}_8 + \dots$$

$$\mathcal{L}_d = \sum_i C_i \mathcal{O}_i^{(d)}$$

at each d, $\mathcal{O}_i^{(d)}$ form a basis

- any BSM with particles much heavier than $v = 246\,\mathrm{GeV}$ must reduce to SMEFT for $E/\Lambda \ll 1$
- $d \geqslant 5$ operators modify SM predictions $\rightarrow$ new phenomena, distributions... **small** effects!
- SMEFT gives **the complete catalogue** of potential signatures, sorted by expected relevance
- some C_i are already very constrained $\rightarrow$ BSM matching must give suppressed values

SMEFT at $d = 6$: the Warsaw basis

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	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}{}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}{}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

Grzadkowski,Iskrzynski,Misiak,Rosiek 1008.4884

SMEFT at $d=6$: the Warsaw basis

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
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}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$		

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2.2 Symmetries

Symmetries

the Standard Model ($d \leqslant 4$) respects a few **(approximate) symmetries** (classically)

$\updownarrow$

fully / nearly forbidden processes, confirmed experimentally

- baryon number (B) $\leftrightarrow$ ✖ $p \to e^+\pi^0$
- total lepton number (L) $\leftrightarrow$ ✖ $p \to e^+\pi^0$, neutrinoless double β decay
- individual lepton numbers (L_i) $\leftrightarrow$ ✖ $\mu \to e\gamma$
- custodial symmetry $\leftrightarrow$ W/Z masses and couplings in fixed relations
- $U(3)^5$ flavor $\leftrightarrow$ ✖ FCNC, non-universal gauge interactions, small flavor violation (CKM $\approx \mathbb{1}$)
- CP $\leftrightarrow$ small EDMs, $J \simeq 3 \times 10^{-5}$

☞ to fulfill experimental bounds, BSM cannot introduce large breakings of these symmetries

Exact (classical) symmetries: B, L_i

baryon and lepton number are **accidental** symmetries of $\mathscr{L}_{SM}$: preserved but never *imposed*

$\equiv$ all possible $d = 4$ interactions involving SM fields happen to be B, L_i preserving.

going to $d \geqslant 5$ we **can** construct interactions that violate B, L_i ☞ all odd-d operators violate them!

Kobach 1604.05726

Weinberg PRL43(1979)1566

$$\mathcal{L}_5 = \frac{C_{5,\alpha\beta}}{\Lambda}\left(\ell_\alpha^T \tilde{H}^*\right)\mathcal{C}\left(\tilde{H}^\dagger \ell_\beta\right) + \text{h.c.}$$

$\downarrow$ EWSB

$$= \frac{C_{5,\alpha\beta}}{\Lambda}\,\frac{(v+h)^2}{2}\,\nu_{L,\alpha}^T\,\mathcal{C}\,\nu_{L,\beta} + \text{h.c.}$$

$\Delta L = 2$

☞ **Majorana mass for neutrinos** $m_{\nu,\alpha\beta} = \dfrac{C_{5,\alpha\beta} v^2}{\Lambda} \quad \Rightarrow \quad C_5/\Lambda \simeq 10^{-16} - 10^{-14}\,\mathrm{GeV}^{-1}$

☞ the only operator for which we have evidence of $C \neq 0$ (not a bound!)

Exact (classical) symmetries: B, L_i

baryon and lepton number are **accidental** symmetries of $\mathscr{L}_{SM}$: preserved but never *imposed*

$\equiv$ all possible $d = 4$ interactions involving SM fields happen to be B, L_i preserving.

going to $d \geqslant 5$ we **can** construct interactions that violate B, L_i ☞ all odd-d operators violate them!

Kobach 1604.05726

Weinberg PRL43(1979)1566

$$\mathcal{L}_6 \supset \frac{C_{duu,\alpha\beta\gamma\delta}}{\Lambda^2} f^{abc} \left(d_\alpha^{aT} \mathcal{C} u_\beta^b\right) \left(u_\gamma^{cT} \mathcal{C} e_\delta\right) + \text{h.c.} \qquad \Delta B = 1,\ \Delta L = 1$$

☞ $p \to e^+ \pi^0 \quad \Rightarrow \quad C_{duu,1111}/\Lambda^2 \simeq 10^{-30}\,\mathrm{GeV}^{-2}$ Bas i Beneito+ 2312.13361

☞ other B/L violating operators are constrained similarly
☞ strongest constraints on the scale come from lowest dimension
☞ can consider the bound as applying to the B/L violating BSM scale.
not necessarily the same entering B/L conserving operators!

The problem with neutrino masses

we said the SM does not contain m_ν. why don't we just introduce ν_R and a Yukawa term?

☞ because we are not sure whether neutrinos are **Dirac or Majorana** particles

equivalently: we are not sure **whether L is violated in the SMEFT**, by the $\mathscr{L}_5$ operator

	L violated	L conserved
no ν_R	Majorana ν	✖
ν_R	Majorana ν + new (sterile) ν	Dirac ν

having L violated is a more attractive scenario:

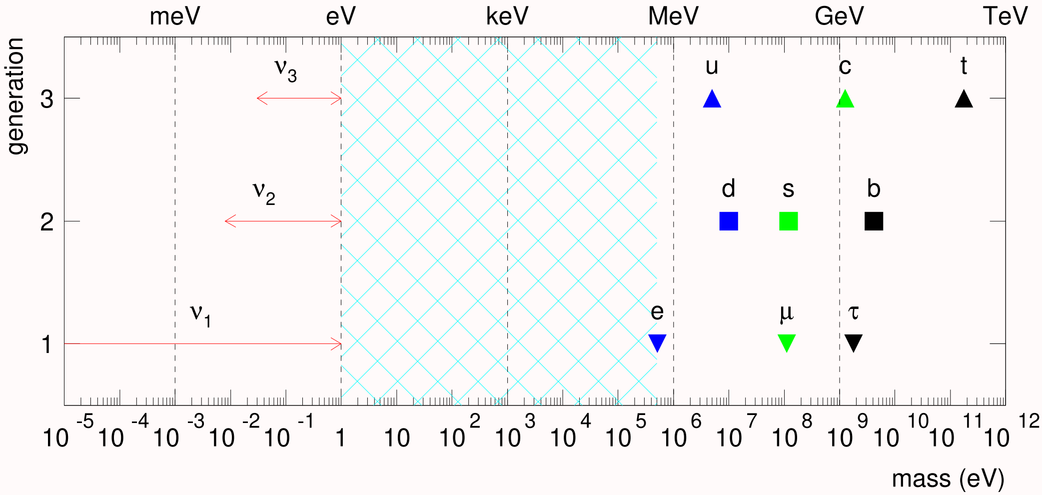
→ smallness of m_ν explained by dim-5 vs dim-4, rather than $y_\nu \ll y_e$

→ gives an additional way to achieve baryon asymmetry: leptogenesis

→ more minimal: ν are 2-component spinors

→ directly implies new physics

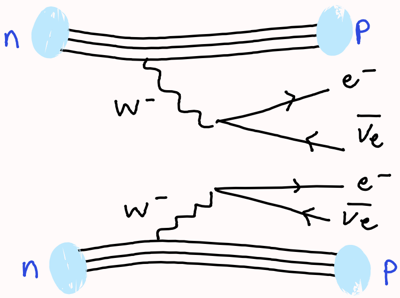
Neutrino vs other fermion masses



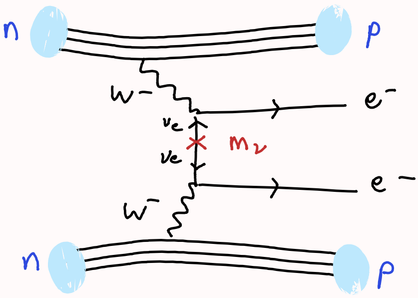
A. de Gouvêa 0411274

Neutrinoless double-β decay

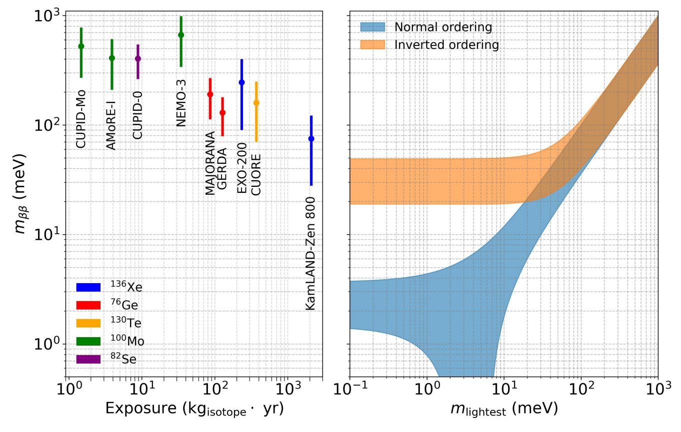
normal double-β decay



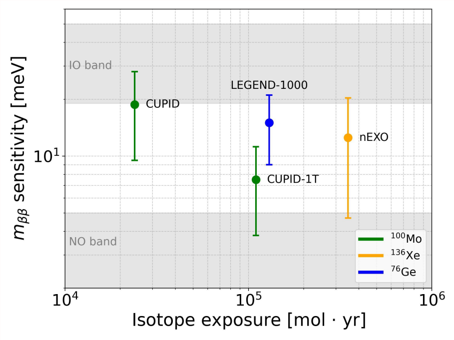
neutrinoless double-β decay



Neutrinoless double-β decay



(2030s - 2040s)



Giuliani 2604.13696

Approximate symmetries

some symmetries are broken in the SM by the presence of non-zero but **small parameters**
$\Rightarrow$ their violation is small, and only occurs proportionally to those parameters
☞ symmetry violations larger than the SM ones are strongly constrained experimentally

- **CP** is only broken by $\delta_{CKM} \neq 0$.
  $\rightarrow$ any process that violates CP is proportional to the Jarlskog invariant
  $J = s_{12}s_{23}s_{13}c_{12}c_{23}c_{13}^2 \sin\delta_{CKM} \simeq 3 \times 10^{-5}$

- the **flavor** structure of the SM has an approximate $U(3)^5$ symmetry, broken down to B, L_i by the Yukawa couplings
  $\rightarrow$ FCNC are absent at tree level, GIM-suppressed at loop level
  $\rightarrow$ quark flavor violation is suppressed:
  e.g. $K^0 - \bar{K}^0$ mixing ($\Delta S = 2$) is $\sim (G_F^2 m_W^2/16\pi^2) \sum_u (V_{us}^* V_{ud})^2 \, F(m_u^2/m_W^2)$

- the **custodial symmetry** is broken by $g' \neq 0 \leftrightarrow \sin\theta_W \neq 0$
  $\rightarrow m_W/m_Z \simeq \cos\theta_W$
  $\rightarrow W, Z$ couplings to fermions and bosons satisfy precise relations

The custodial symmetry

the custodial symmetry is the **global** $SU(2)_C$ that exchanges the three SM Goldstones

$$H = \frac{v+h}{\sqrt{2}}\mathbf{U}\begin{pmatrix}0\\1\end{pmatrix} = \frac{v+h}{\sqrt{2}}\exp\left(i\frac{\pi_i\sigma^i}{v}\right)\begin{pmatrix}0\\1\end{pmatrix}$$

$$\mathbf{U} \mapsto \Omega_C\mathbf{U}\Omega_C^\dagger \qquad\qquad \Omega_C \in SU(2)_C$$

→ it is preserved by the Higgs potential: $H^\dagger H = (v+h)^2/2 \mapsto H^\dagger H$

→ it can be identified with the diagonal $SU(2)_C \equiv SU(2)_V = SU(2)_{L+R}$ where

$$\mathbf{U} \mapsto \Omega_L\mathbf{U}\Omega_R^\dagger \qquad\qquad \Omega_L \in SU(2)_L \quad \Omega_R \in SU(2)_R$$

→ the gauged $SU(2)_L$ coincides with the global one → $g \neq 0$ preserves custodial
$U(1)_Y$ coincides with the group generated by T^3_R → $g' \neq 0$ breaks $SU(2)_R, SU(2)_C$

☞ if $SU(2)_C$ was exact ($g'=0$), we'd have $m_Z = m_W$ and $s_\theta = 0, c_\theta = 1 \Rightarrow$ same coupl. for W/Z

Approximate symmetries in SMEFT

when moving to SMEFT, we find (many!) operators that break the approx symmetries

- $(H^\dagger D_\mu H)(D^\mu H^\dagger H)$ breaks custodial $\rightarrow$ corrects m_Z but not m_W
- $(\bar{d}_1 \gamma^\mu d_2)(H^\dagger i \overleftrightarrow{D}_\mu H)$ breaks the flavor $U(3)_d$ $\rightarrow$ introduces FCNC $Z\bar{d}s$
- $\mathbf{i}\,(\bar{q}_1 H d_1)(H^\dagger H)$ breaks CP $\rightarrow$ introduces CP-odd $H\bar{d}d$ coupling

☞ their Wilson coeff. are more experimentally constrained than those of symmetry-preserving operators

one way to have a version of SMEFT that preserves the approximate symmetries of the SM, with the same breaking patterns, is to actively impose this condition

☞ assume that BSM is such that the way these symmetries are broken in $d \geqslant 5$ operators is **the same** as for the $d \leqslant 4$ operators

Example: Minimal Flavor Violation

$$U(3)^5 = U(3)_q \times U(3)_u \times U(3)_d \times U(3)_\ell \times U(3)_e$$

$U(3)_q$: $q_\alpha \mapsto (\Omega_q)_{\alpha\beta} q_\beta, \quad \Omega_q \in U(3)_q$

an exact symmetry of the kinetic term: $\bar{q} i \not{D} q \mapsto \bar{q} \Omega_q^\dagger i \not{D} \Omega_q q = \bar{q} i \not{D} q$

broken by Yukawas $\bar{q} H Y_d d \mapsto \bar{q} H \Omega_q^\dagger Y_d \Omega_d d$

☞ promote Y_ψ to **spurions**: $Y_d \mapsto \Omega_q Y_d \Omega_d^\dagger$, $Y_u \mapsto \Omega_q Y_u \Omega_u^\dagger$, $Y_e \mapsto \Omega_\ell Y_e \Omega_e^\dagger$ D'Ambrosio+ 0207036

makes the Yukawas formally invariant → every time there is a $\bar{q} d$ current, we *must* insert Y_d, etc.

in SMEFT

w/o MFV	with MFV
$C_{dH,\alpha\beta}(\bar{q}_\alpha H d_\beta)(H^\dagger H)$	$C_{dH}(\bar{q}_\alpha H Y_{d,\alpha\beta} d_\beta)(H^\dagger H)$
free flavor structure	same flavor structure as SM
$h \to \bar{d} s \quad \sim C_{dH,12}$	$h \to \bar{d} s$ forbidden

Example: Minimal Flavor Violation

$$U(3)^5 = U(3)_q \times U(3)_u \times U(3)_d \times U(3)_\ell \times U(3)_e$$

$U(3)_q$: $q_\alpha \mapsto (\Omega_q)_{\alpha\beta} q_\beta, \quad \Omega_q \in U(3)_q$

an exact symmetry of the kinetic term: $\bar{q} i \not{D} q \mapsto \bar{q} \Omega_q^\dagger i \not{D} \Omega_q q = \bar{q} i \not{D} q$

broken by Yukawas $\bar{q} H Y_d d \mapsto \bar{q} H \Omega_q^\dagger Y_d \Omega_d\, d$

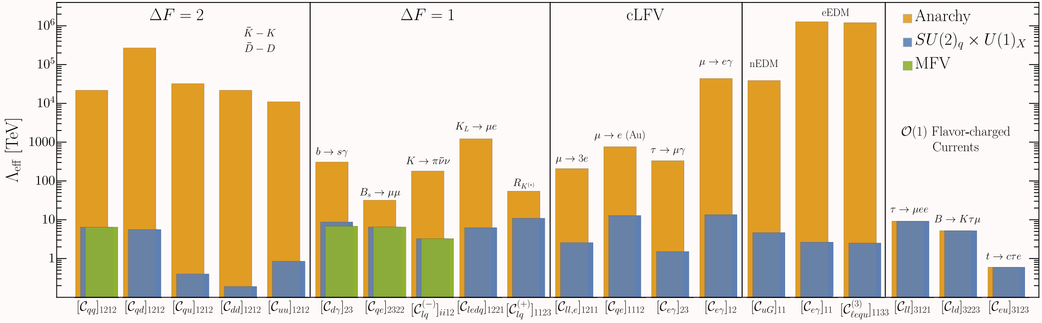
☞ promote Y_ψ to **spurions**: $Y_d \mapsto \Omega_q Y_d \Omega_d^\dagger,\ Y_u \mapsto \Omega_q Y_u \Omega_u^\dagger,\ Y_e \mapsto \Omega_\ell Y_e \Omega_e^\dagger$ D'Ambrosio+ 0207036

makes the Yukawas formally invariant → every time there is a $\bar{q}d$ current, we *must* insert Y_d, etc.

in SMEFT

w/o MFV	with MFV
$(\bar{q}_\alpha \gamma^\mu q_\beta)(\bar{q}_\gamma \gamma_\mu q_\delta)$	$(\bar{q}_\alpha \gamma^\mu q_\alpha)(\bar{q}_\beta \gamma_\mu q_\beta)$
free flavor structure	same flavor structure as SM
$K - \bar{K} \quad \sim C_{1212}$ (tree)	$K - \bar{K}$ forbidden (tree)

Example: Minimal Flavor Violation



Greljo+ 2512.04159

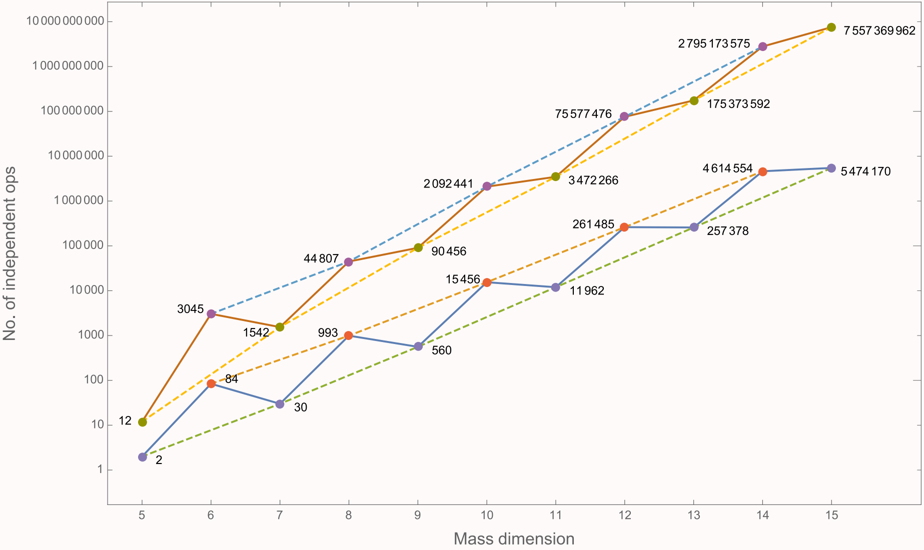
in general, BSM effects can carry (dimensional / scale) × (symmetry) suppressions

increasing one allows to relax the other

☞ symmetry-protected BSM is less constrained ≡ allowed to exist at a lower scale

SMEFT: number of independent parameters

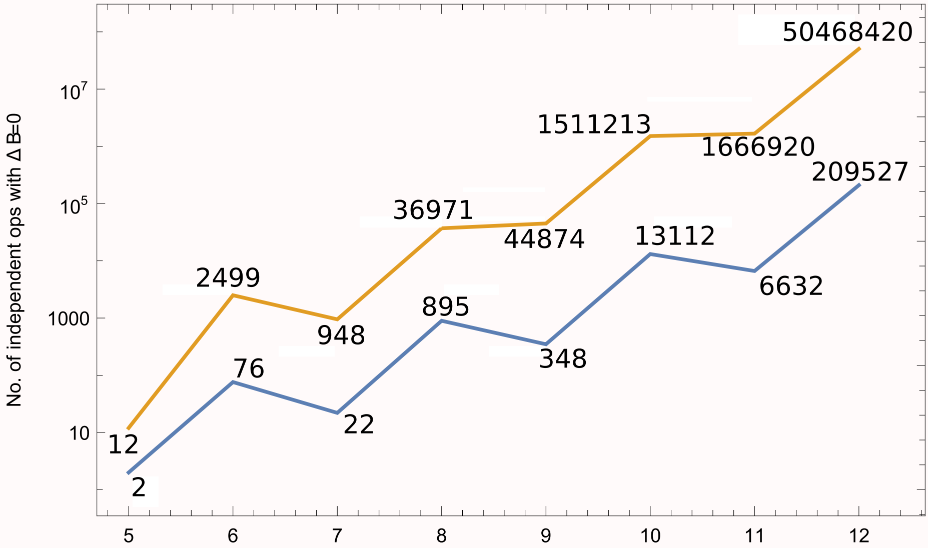
Henning, Lu, Melia, Murayama 1512.03433



SMEFT: number of independent parameters

imposing $\Delta B = 0$

Henning,Lu,Melia,Murayama 1512.03433



Flavorful SMEFT parameters

Classification within Warsaw basis

Grzadkowski,Iskrzynski,Misiak,Rosiek 1008.4884

Class	CP	$\not{CP}$	Total
X^3	2	2	4
$\varphi^6 + \varphi^4 D^2$	3	-	3
$\varphi^2 X^2$	4	4	8
$\varphi^2\psi^2$	27	27	54
$\varphi X\psi^2$	72	72	144
$\varphi^2 D\psi^2$	51	30	81
$(\bar{L}L)(\bar{L}L)$	171	126	297
$(\bar{R}R)(\bar{R}R)$	255	195	450
$(\bar{L}L)(\bar{R}R)$	360	288	648
$(\bar{L}R)(\bar{R}L)$	81	81	162
$(\bar{L}R)(\bar{L}R)$	324	324	648

- most parameters from **fermionic** terms
- **flavor** has dramatic impact on counting

Examples:

$B_{\mu\nu}(\bar{q}_i\sigma^{\mu\nu}d_j)\varphi$	$9+9$
$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_i\gamma^\mu u_j)$	$6+3$
$(\bar{l}_i\gamma_\mu l_j)(\bar{l}_k\gamma^\mu l_l)$	$27+18$
$(\bar{e}_i\gamma_\mu e_j)(\bar{u}_k\gamma^\mu u_l)$	$45+36$
$(\bar{l}_i^j e_j)(\bar{d}_k q_l^j)$	$81+81$

Fewer SMEFT parameters with flavor symmetries

Example operator	fl. general	$\mathbf{U(3)^5}$	$\mathbf{U(2)^3 \times U(3)^2}$
$B_{\mu\nu}(\bar{q}_i\sigma^{\mu\nu}d_j)\varphi$	$9+9$	$1+1\ (y)$	$2+2\ (y{,}1)$
$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_i\gamma^\mu u_j)$	$6+3$	1	2
$(\bar{l}_i\gamma_\mu l_j)(\bar{l}_k\gamma^\mu l_l)$	$27+18$	2	2
$(\bar{e}_i\gamma_\mu e_j)(\bar{u}_k\gamma^\mu u_l)$	$45+36$	1	2
$(\bar{l}_i^I e_j)(\bar{d}_k q_l^I)$	$81+81$	$1+1\ (y^2)$	$2+2\ (y^2, y)$

$$U(3)^5 = U(3)_q \times U(3)_u \times U(3)_d \times U(3)_l \times U(3)_e$$

$$U(2)^3 \times U(3)^2 = U(2)_q \times U(2)_u \times U(2)_d \times U(3)_l \times U(3)_e \qquad V_{CKM} = \mathbb{1}$$

2.3 Naturalness

Naturalness

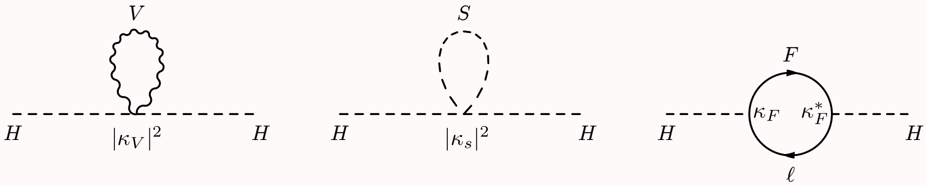
technical naturalness 't Hooft 1980

> *at any energy scale μ, a set of physical parameters $\alpha_i(\mu)$ is allowed to be very small* *only if the replacement $\alpha_i(\mu) = 0$ would increase the symmetry of the system.*

☞ if a symmetry is only broken by a certain $\alpha \neq 0$,
higher-order corrections to α can only be proportional to powers of α itself
$\rightarrow$ the condition of having a small α is stable, and therefore "natural"

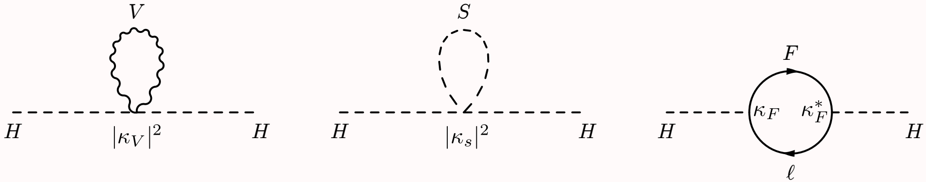
- small Yukawa couplings are technically natural: for $Y_u, Y_d, Y_e \rightarrow 0$ we recover $U(3)^5$
- small Majorana neutrino masses are technically natural: for $m_\nu \rightarrow 0$ we recover L
- small $\delta_{CKM}, \bar{\theta}$ are technically natural: for $\delta_{CKM}, \bar{\theta} \rightarrow 0$ we recover CP
- ...
- a small Higgs mass (compared to a large UV scale) is **not** technically natural

in EFT language: heavy new physics can give loop corrections to $(H^\dagger H)$



The hierarchy problem

in EFT language: heavy new physics can give loop corrections to $(H^\dagger H)$



$\downarrow$ integrating it out

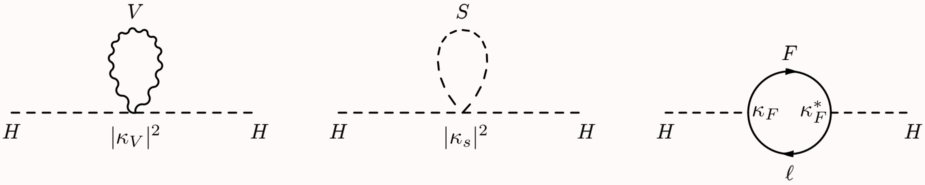
threshold matching contributions at $E < m_i$

[loops in DR+$\overline{MS}$ in the lim $v/m_i \to 0$]

$$\Delta V(H^\dagger H) \simeq H^\dagger H \left(\frac{3|\kappa_v|^2\, M_v^2\, N_v}{16\,\pi^2} + \frac{|\kappa_s|^2\, M_s^2\, N_s}{16\,\pi^2} - \frac{|\kappa_F|^2\, M_F^2\, N_F}{16\,\pi^2} \right) + \dots$$

The hierarchy problem

in EFT language: heavy new physics can give loop corrections to $(H^\dagger H)$



$\downarrow$ integrating it out

threshold matching contributions at $E < m_i$

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$$\Delta V(H^\dagger H) \simeq H^\dagger H \left(\frac{3|\kappa_v|^2 M_v^2 N_v}{16\,\pi^2} + \frac{|\kappa_s|^2 M_s^2 N_s}{16\,\pi^2} - \frac{|\kappa_F|^2 M_F^2 N_F}{16\,\pi^2} \right) + \dots$$

these corrections are always proportional to the heavy mass $M_X \gg m_h$

The hierarchy problem

$$\Delta V(H^\dagger H) \simeq H^\dagger H \left(\frac{3|\kappa_v|^2 M_v^2 N_v}{16\,\pi^2} + \frac{|\kappa_s|^2 M_s^2 N_s}{16\,\pi^2} - \frac{|\kappa_F|^2 M_F^2 N_F}{16\,\pi^2} \right) + \ldots$$

- the quantity in front of $H^\dagger H$ in $\mathscr{L}_{SM}$ $(m_h^2/2)$ is **not protected** by any symmetry
- it being small compared to the theory scale $(m_h^2 \ll M_X^2)$ is **not natural**: radiative corrections bring it closer to M_X^2
- if a "tree-level" parameter m_{h0}^2 was originally present in $\mathscr{L}_{SM}$, the physical Higgs mass is

$$m_h^2 = m_{h0}^2 + \frac{3|\kappa_V|^2}{8\pi^2} M_V^2 N_V + \frac{|\kappa_S|^2}{8\pi^2} M_S^2 N_S - \frac{|\kappa_F|^2}{8\pi^2} M_F^2 N_F$$

to have $m_h^2 \ll M_X^2$, the thresholds must cancel against m_{h0}^2 to leave a small number $\rightarrow$ **fine tuning**

when is this a problem?

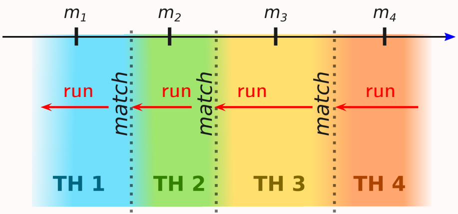
if $\exists$ new physics, coupling to the Higgs, for which $M_X^2 \gg m_h^2 \times (16\pi^2/N_X\kappa_X^2)$

easily $10^2 - 10^4$ $\rightarrow$ $M_X \gg 1 - 10$ TeV

2.4 RG evolution

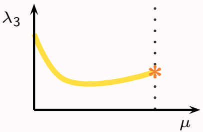
Running across scales

due to renormalization, the parameters of each theory undergo RG evolution



parameters run according to the RGEs of their theory TH X

the matching relations from TH $(X+1)$ set boundary conditions

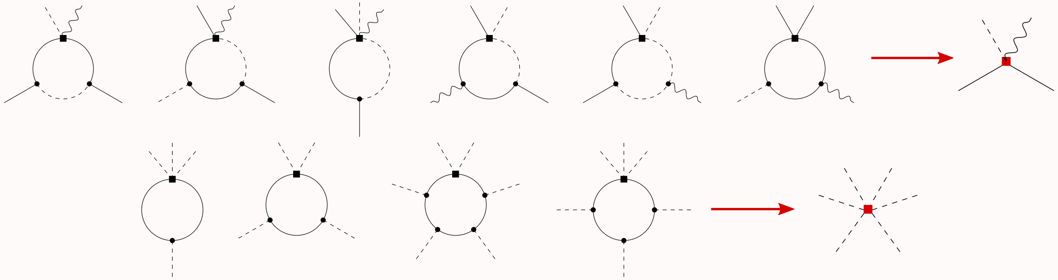


- symmetries are preserved by running
- parameters can change value dramatically, they remain small if natural

Renormalization Group evolution in SMEFT

when going to 1-loop divergences appear, reabsorbed by counterterms of the same dimension

→ SMEFT operators **run and mix** with each other, order by order in Λ



fully computed at 1 loop for dim-6, automated in `DsixTools`, `wilson`

Alonso,Jenkins,Manohar,Trott 1308.2627,1310.4838,1312.2014
Celis,Fuentes-Martin,Ruiz-Femenia,Vicente,Virto 1704.04504,2010.16341, Aebischer,Kumar,Straub 1804.05033

dim6-2loops and partial results for dim8-1loop

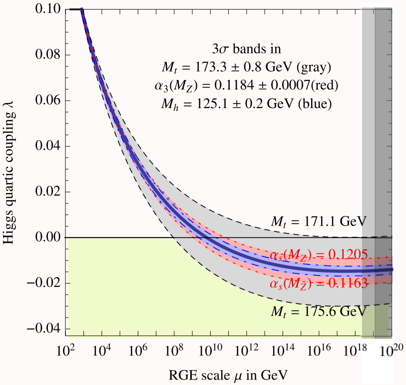
Elias-Miro' et al 2005.06983,2112.12131, Bern,Parra-Martinez 2005.12917, Jin,Ren,Yang 2011.02494, Fuentes-Martin,Palavric,Thomsen 2311.13630, Bresciani,Levati,Mastrolia,Paradisi 2312.05026, Chala et al 2106.05291,2205.03301,2309.16611, Born,Fuentes-Martin,Thomsen 2601.19974. . .

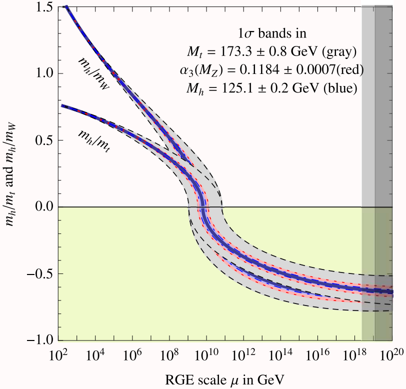
Vacuum stability

if the SM was valid up to the Planck scale, what values would its couplings take there?

important: how would the Higgs potential's shape change? would the EW vacuum remain stable?

Elias-Miro+ 1112.3022, Degrassi+ 1205.6497, Espinosa+ 1505.04825





Buttazzo+ 1307.3536

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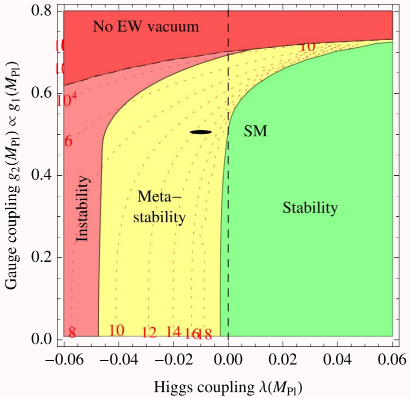

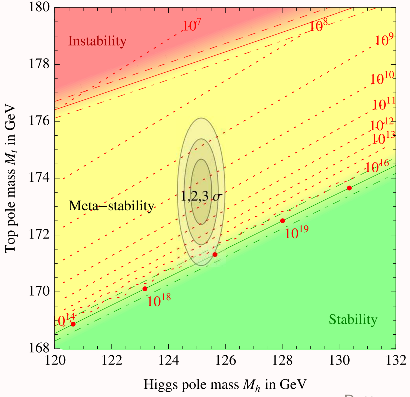

Buttazzo+ 1307.3536

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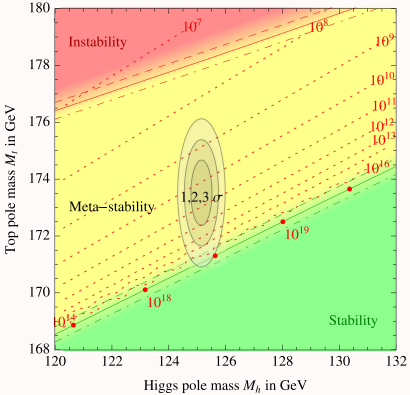
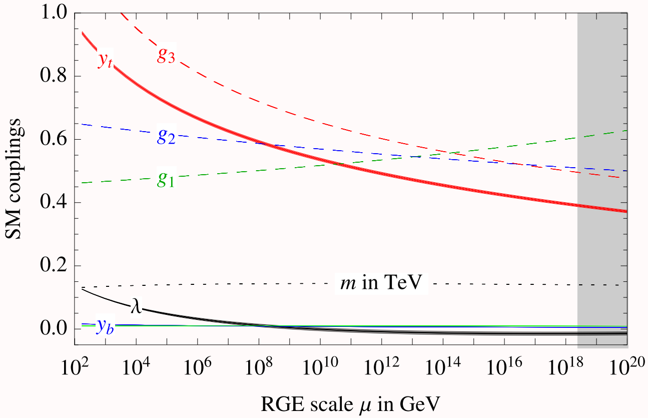
Elias-Miro+ 1112.3022, Degrassi+ 1205.6497, Espinosa+ 1505.04825

- if no other particles until M_{Pl}, the EW vacuum is metastable, with lifetime $> 10^{100}$ yr
- no BSM needed here
- if there is BSM, one needs to check that vacuum stability is not spoiled!



Buttazzo+ 1307.3536

Unification?



Buttazzo+ 1307.3536

2.5 Unitarity

Unitarity of the S matrix

conservation of probability in QM implies **unitarity of the S-matrix**
from this requirement, one derives the (generalized) **optical theorem** for scattering amplitudes

$$|\Psi, t\rangle = S|\Psi, 0\rangle$$

$$S = \mathbb{1} + iT \qquad \text{such that} \qquad \langle f|T|i\rangle = (2\pi)^4\delta^4(p_i - p_f)\mathcal{A}(i \to f)$$

$$\langle\Psi, t|\Psi, t\rangle = 1 \quad \Rightarrow \quad S^\dagger S = \mathbb{1} \quad \Rightarrow \quad \boxed{2Im\mathcal{A}(i \to f) = \sum_X d\Pi_X (2\pi)^4\delta^4(p_i - p_X)\mathcal{A}(i \to X)\mathcal{A}^*(X \to f)}$$

applying the optical theorem to forward elastic $2 \to 2$ scattering ($f = i$, $\theta = 0$)
and taking the limit $m_i^2/s \to 0$ one finds the **partial wave unitarity bounds**

$$\boxed{Im\, a_J(s) \geqslant |a_J(s)|^2}$$

where a_J are the coefficients of the partial-wave decomposition of the amplitude

$$\mathcal{A}(s, \theta) = 16\pi \sum_{J=0}^{\infty} a_J(s)(2J+1)P_J(\cos\theta), \qquad P_J(\cos\theta) = \text{ Legendre polys}$$

Partial wave unitarity bounds

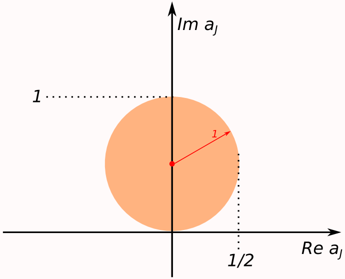
for a given elastic $2 \to 2$ scattering process, one can compute a_J as

$$a_J(s) = \frac{1}{32\pi}\int_{-1}^{1} d\cos\theta P_J(\cos\theta)\mathcal{A}(s,\theta)$$

and then check whether the unitarity condition $Im\, a_J \geqslant |a_J|^2$ is satisfied for all J.

minimal requirements:

$Im\, a_J \in [0,1]$
$|Re\, a_J| \leqslant 1/2$
$|a_J| \leqslant 1$



☞ violation of partial wave unitarity ⇒ unphysical scattering amplitude

Unitarity bounds on BSM

why are unitarity bounds relevant for BSM?

- **EFT.** amplitudes containing $d > 4$ interactions violate unitarity in the large-E limit:

$$\mathcal{A} \overset{s \gg m_i^2}{\sim} a \frac{s^n}{\Lambda^{2n}} \qquad \Rightarrow \qquad \text{theory only valid for} \quad \sqrt{s} \leqslant \frac{\Lambda}{(2a)^{1/2n}}$$

☞ can be used to identify which values of C/Λ^n are sensible at a certain s

- **(B)SM.** unitarity is preserved up to arbitrarily large s in the SM only under some conditions. most notably:

  (a) the Higgs couplings are exactly the SM ones (from doublet structure), with no deviations

  (b) the Higgs mass is below a certain max

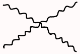
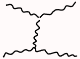
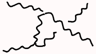
☞ deviations from SM Higgs couplings $\Rightarrow$ BSM + upper limit on Λ from unitarity

The LHC “no-lose theorem”

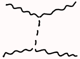
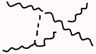
consider the scattering of longitudinal vector bosons in the SM: $W_L^+ W_L^+ \to W_L^+ W_L^+$

allow the Higgs couplings to deviate from their SM values ($a = b = 1$):

$$\mathscr{L} \supset m_W^2 W_\mu^+ W^{-\mu} \left(1 + 2\mathbf{a}\frac{h}{v} + \mathbf{b}\frac{h^2}{v^2}\right)$$

gauge only:  +  +  $\to \quad a_0 = -a_1 = \dfrac{s}{16\pi v^2} + \mathcal{O}(s^0)$

unitarity is lost at $\sqrt{s} \leqslant \sqrt{8\pi} v \simeq 1.2\,\mathrm{TeV}$ **something** else must appear before then!

if it’s the Higgs:  +  $\to \quad a_0 = -a_1 = -a^2 \dfrac{s}{16\pi v^2} + \mathcal{O}(s^0)$

$a = 1$ ($=$ doublet) needed for s terms to cancel exactly $=$ unitarity at **all** s

Unitarity bounds on the Higgs

repeating the same exercise e.g. for $W_L^+ W_L^- \to hh$ one finds

Contino 1005.4269

$$\to \quad a_0 \sim (b - a^2)s$$

- $b = a^2 = 1$ required to unitarize this amplitude.

  the Higgs coupling to fermion pairs is fixed similarly by demanding unitarity of $W_L^+ W_L^- \to \bar{\psi}\psi$

- the main reason to introduce the Higgs **doublet** in the SM is that it unitarizes all scattering amplitudes in the theory up to arbitrarily large energies.

---

going back to $W_L^+ W_L^+ \to W_L^+ W_L^+$ in the SM with the Higgs: one has

$$\lim_{s\to\infty} a_0 = -\frac{m_h^2}{8\pi v^2}$$

- to satisfy unitarity, it must be $m_h \leqslant \sqrt{4\pi} v \simeq 870\,\mathrm{GeV}$ **Lee-Quigg-Thacker bound** L-Q-T 1977

3. Example: neutrinos

Neutrino masses from the bottom up

for our first example we will consider the case of neutrino masses,
in a scenario where L is violated and ν_R are absent

we said that in this case m_ν comes from the unique $d = 5$ operator:

$$\mathscr{L}_5 = \frac{C_{5,\alpha\beta}}{\Lambda}\left(\ell_\alpha^T \tilde{H}^*\right)\mathcal{C}\left(\tilde{H}^\dagger \ell_\beta\right) + \text{h.c.}$$

$$\xrightarrow{\text{EWSB}} \frac{C_{5,\alpha\beta}}{\Lambda}\frac{(v+h)^2}{2}\,\nu_\alpha^T \mathcal{C}\nu_\beta + \text{h.c.} = -\frac{m_{\nu,\alpha\beta}}{2}\nu_\alpha^T\mathcal{C}\nu_\beta\left(1+\frac{h}{v}\right)^2 + \text{h.c.}$$

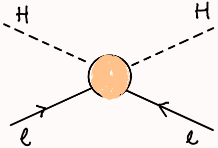
☞ by definition $\boxed{m_{\nu,\alpha\beta} = -\frac{v^2 C_{5,\alpha\beta}}{\Lambda}}$. $h\nu\nu$, $h^2\nu\nu$ couplings are also produced

we will address

- what BSM models can lead to this operators?
- how can use symmetry tools to lower the BSM scale
- does this BSM help other SM problems too?

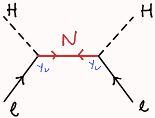
Tree-level UV completions of the Weinberg operator

$$\mathscr{L}_5 = \frac{C_{5,\alpha\beta}}{\Lambda}\left(\ell_\alpha^T \tilde{H}^*\right) \mathcal{C} \left(\tilde{H}^\dagger \ell_\beta\right) + \text{h.c.}$$



only 3 options

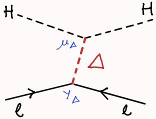
N = heavy fermion **singlet**



type-I seesaw

Minkowski 1977
Yanagida+ Gell-Mann+ Schechter+ 1980

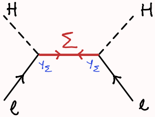
Δ^0 = heavy **scalar** $SU(2)$ triplet



type-II seesaw

Schechter, Valle 1980
Mohapatra, Senjanović 1980

Σ^0 = heavy **fermion** $SU(2)$ triplet



type-III seesaw

Foot+ 1989

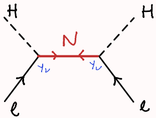
3.1 Neutrino mass models

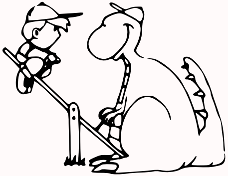
Type I seesaw model

Extend the SM with **heavy Majorana neutrinos N** $\rightarrow$ Heavy Neutral Leptons (HNL)

$$\mathcal{L}_{\mathrm{UV,\,leptons}} = \bar{\ell} i \not{D} \ell + \bar{N} i \not{\partial} N + \bar{e}_R i \not{D} e_R - \left[\bar{e}_R Y_e H^\dagger \ell + \bar{N}\, Y_\nu \tilde{H}^\dagger \ell + \text{h.c.}\right] - \frac{1}{2} \bar{N} M N$$

- adds a **full** Majorana $N = N^c$, not just N_R $(N = N_R + N_R^c)$
- assuming $M \gg v$, we can expand in M^{-1}





Integrating out N gives

$$\mathcal{L}_{\mathrm{SM}} + \frac{1}{2} (\bar{\ell}^c \tilde{H}^*)\, Y_\nu^T M^{-1} Y_\nu\, (\tilde{H}^\dagger \ell) + \mathcal{O}(M^{-2}) \qquad \rightarrow \qquad \boxed{\frac{C_{5,\alpha\beta}}{\Lambda} = \frac{1}{2} \left(Y_\nu^T M^{-1} Y_\nu\right)_{\alpha\beta} = -\frac{m_{\nu,\alpha\beta}}{v^2}}$$

"Seesaw": the heavier M, the lighter m_ν $\quad \rightarrow$ for $Y_\nu = 1$, we need $M \simeq 10^{14} - 10^{16}\,\mathrm{GeV}$

Type II seesaw model

Instead of a Majorana fermion singlet, introduce a **scalar** $SU(2)$ **triplet** with hypercharge $Y = 1$:

$$\Delta = \frac{\Delta^I \sigma^I}{\sqrt{2}} = \frac{1}{\sqrt{2}} \begin{pmatrix} \Delta_3 & \Delta_1 - i\Delta_2 \\ \Delta_1 + i\Delta_2 & -\Delta_3 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \Delta^+ & \sqrt{2}\Delta^{++} \\ \sqrt{2}\Delta^0 & -\Delta^+ \end{pmatrix}$$

The UV Lagrangian is:

$$\mathcal{L} = \mathrm{Tr}\big(D_\mu \Delta^\dagger D^\mu \Delta\big) - M^2\,\mathrm{Tr}(\Delta^\dagger \Delta) + \Big(-\bar{\ell}^c \varepsilon\, Y_\Delta\, \Delta\, \ell + \mu_\Delta\, \tilde{H}^\dagger \Delta H + \text{h.c.} \Big) + \dots$$

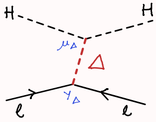
- Y_Δ: 3×3 matrix, gives L violation. $\mu_\Delta \in \mathbb{C}$ has dimension of mass
- all physical Δ fields have the same mass M
- potential terms at least quadratic in Δ are not needed for matching at $d = 5$

Type II: EFT result and Wilson coefficient

Integrating out Δ gives

$$\mathcal{L}_{\rm EFT} = \underbrace{2\frac{|\mu_\Delta|^2}{M^2}(H^\dagger H)^2}_{d4:\ \text{correction to Higgs potential}} \underbrace{-\frac{2}{M^2}\left(\mu_\Delta\,\bar\ell^c\tilde H^* Y_\Delta \tilde H^+\ell + \text{h.c.}\right)}_{d5} + \underbrace{\frac{2}{M^2}\left(\bar\ell_j Y_\Delta^\dagger(\varepsilon\ell^c)_i\right)\left((\bar\ell^c\varepsilon)_i Y_\Delta \ell_j\right)}_{d6} + \dots$$

$$\Rightarrow \quad \boxed{\frac{C_{5,\alpha\beta}}{\Lambda} = -\frac{2\mu_\Delta}{M^2}Y_{\Delta,\alpha\beta}}$$



☞ more parameters to play with!

- m_ν is **linear** in Y_Δ and μ_Δ
- for $Y_\Delta \sim 1$ we need $M^2/\mu_\Delta \sim 10^{14} - 10^{16}$ GeV: M can be $\sim$ light, as long as $\mu_\Delta \ll M$
- many more $d \geqslant 6$ effects: Δ is a scalar $\to$ impacts Higgs physics and EW sector

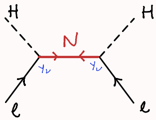
Type III seesaw model

introduce a Majorana **fermion triplet** with $Y = 0$

$$\Sigma = \Sigma^I \sigma^I = \begin{pmatrix} \Sigma^3 & \Sigma^1 - i\Sigma^2 \\ \Sigma^1 + i\Sigma^2 & -\Sigma^3 \end{pmatrix} = \begin{pmatrix} \Sigma^0 & \sqrt{2}\Sigma^+ \\ \sqrt{2}\Sigma^- & -\Sigma^0 \end{pmatrix}, \qquad \bar{\Sigma} = \begin{pmatrix} \bar{\Sigma}^0 & \sqrt{2}\bar{\Sigma}^- \\ \sqrt{2}\bar{\Sigma}^+ & -\bar{\Sigma}^0 \end{pmatrix}$$

the UV Lagrangian is

$$\mathcal{L} = \frac{1}{2}\mathrm{Tr}\big(\bar{\Sigma} i \not{D} \Sigma\big) - \frac{1}{2}\mathrm{Tr}\big(\bar{\Sigma} M \Sigma\big) - \big(\tilde{H}^\dagger \Sigma\, Y_\Sigma\, \ell_L + \text{h.c.}\big)$$



integrating out Σ gives

$$\mathcal{L}_{\rm EFT} = \frac{1}{2}\bar{\ell}^c \tilde{H}^* \, Y_\Sigma^T M^{-1} Y_\Sigma \, H^+ \ell_L + \text{h.c.} \quad \Rightarrow \quad \boxed{\frac{C_{\alpha\beta}}{\Lambda} = \frac{1}{2}\big(Y_\Sigma^T M^{-1} Y_\Sigma\big)_{\alpha\beta}}$$

analogous to type-I seesaw!

☞ going to $d = 6$ more operators are produced, affecting both neutrino and **charged lepton** couplings

Low-scale / Inverse / Double seesaw

Mohapatra, Valle 1986

the standard seesaw models point to very heavy BSM particles → hard to discover

☞ one can lower the seesaw scale by introducing an explicit symmetry suppression

Majorana singlets of two kinds N S with N_R carrying lepton number $+1$ and S_R carrying -1

$$\mathcal{L}_{\rm UV} \supset -\bar{N} Y_\nu \tilde{H}^\dagger \ell_L - \bar{N} M S - \frac{\mu}{2} \bar{S}^c S + \text{h.c.} \; = \; -\frac{1}{2} \bar{n}_L^c \mathcal{M}\, n_L + \text{h.c.}$$

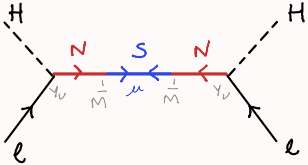
$$n_L = \begin{pmatrix} \nu_L \\ N_R^c \\ S_R^c \end{pmatrix}, \qquad \mathcal{M} = \begin{pmatrix} 0 & Y_\nu^T \tilde{H}^* & 0 \\ Y_\nu \tilde{H}^+ & 0 & M \\ 0 & M^T & \mu \end{pmatrix}$$

☞ $\mu \neq 0$ explicitly breaks lepton number. M, Y_ν do not → **$\mu \ll 1$ is technically natural**

Inverse seesaw: matching and scales

Integrating out N, S

$$\frac{C_{\alpha\beta}}{\Lambda} = \frac{1}{2}\left(Y_\nu^T M^{T-1} \mu\, M^{-1} Y_\nu\right)_{\alpha\beta}$$



☞ with this setup it's possible to have $M \sim$ TeV

we want $\dfrac{M^2}{\mu Y_\nu^2} \sim 10^{14} - 10^{16}\mathrm{GeV}$

if $M \sim 10^3$ GeV $\quad \Rightarrow \quad \mu Y_\nu^2 \sim 10^{-10} - 10^{-8}$ GeV $\sim 0.1 - 10$ eV

Radiative ν mass models

another way to lower the BSM scale of neutrino masses is via models that only generate C_5 at **1-loop**

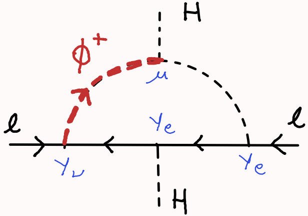
$\rightarrow$ some of the required suppression would come from the loop, so the BSM scale can be lighter

Zee model (Zee 1980)

add a scalar singlet ϕ^+ with $Y = Q = +1$, carrying lepton number $L = 2$ $\rightarrow$ ⚠ L broken by $\mu \neq 0$

$$\mathcal{L}_{\rm UV} \supset -\ell_i^T\, Y_\nu\, \mathcal{C}\varepsilon\, \ell_i\, \phi^+ + \mu\, H^\dagger \tilde{H}\, \phi^+ + \text{h.c.}$$

$$m_\nu \sim \underbrace{\frac{\mu}{16\pi^2}}_{\text{loop} + \cancel{L}\text{ suppr.}} \quad \underbrace{Y_\nu Y_e Y_e^\dagger}_{\substack{\text{Yukawa suppr.} \\ (Y_\tau\ \text{dominates})}} \quad \underbrace{\frac{v^2}{M_\phi^2} \log \frac{m_H^2}{M_\phi^2}}_{\text{EFT suppr.}}$$



UV completions for Dirac masses?

- main challenge: explain $\boxed{y_\nu \ll y_e}$
- the main setup employed is **extra dimensions**, motivated e.g. in string theory

Bulk/brane setup

Arkani-Hamed, Dimopoulos, Dvali, March-Russell 9811448

Assume the 4D space where our gauge invariance holds is a **brane** inside a larger-D space

- ν_R is taken to live in the **bulk** of the space
- ν_L lives only on **our brane** (free, while ν_L subject to gauge invariance)
- the mass term is present where brane and bulk **intersect**: proportional to $\dfrac{\text{(brane volume)}}{\text{(bulk volume)}} \ll 1$

3.2 Neutrino masses and...

Neutrino masses and... baryon-asymmetry

type-I seesaw

L violation $\xrightarrow{B+L \text{ anomaly}}$ B violation ✔

CP violation from Y_ν phases ✔

N freeze-out at $T < M$ $\rightarrow$ out-of-equilibrium ✔

Thermal Leptogenesis

Fukugita,Yanagida 1986

$$\eta_B \sim \epsilon_1 \, \kappa_{\rm washout} \, c_{\rm sph}$$

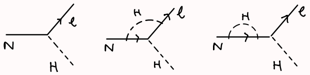
$$\epsilon_1 = \frac{\Gamma(N_1 \to \ell H^\dagger) - \Gamma(N_1 \to \bar\ell H)}{\Gamma(N_1 \to \ell H^\dagger) + \Gamma(N_1 \to \bar\ell H)}$$

$$\sim Im(Y_\nu Y_\nu^\dagger)^2_{1j} \frac{M_1}{M_j}$$

CPV needs 1-loop
assumes $M_1 \ll M_{2,3}$

efficiency of competing inverse processes before freeze-out

$L \to B$ asym conversion through **sphalerons** (at $T > 130$ GeV)



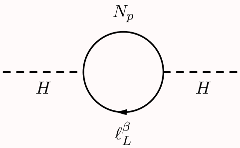
Davidson-Ibarra bound for hierarchical N: $\epsilon_1 \leqslant \dfrac{3M_1}{16\pi v^2}(\Delta m^2_{atm})^{1/2} \Rightarrow M_1 \gtrsim 10^8 - 10^9 \,\mathrm{GeV}$

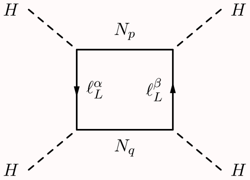
Davidson,Ibarra 0202239

Neutrino masses and... hierarchy problem

heavy Majorana neutrinos give 1-loop threshold corrections to the Higgs potential (hierarchy pb!)

Vissani 9709409, Casas+ 9904295
see also IB,Trott 1703.10924, 1809.03450





$$\Delta m_H^2 \simeq M^2 \frac{|Y_\nu|^2}{8\,\pi^2} \simeq \frac{M^3}{v^2}\frac{m_\nu}{8\pi^2} \qquad \Delta\lambda \simeq -\frac{5}{32\pi^2}|Y_\nu|^4 \ll 1$$

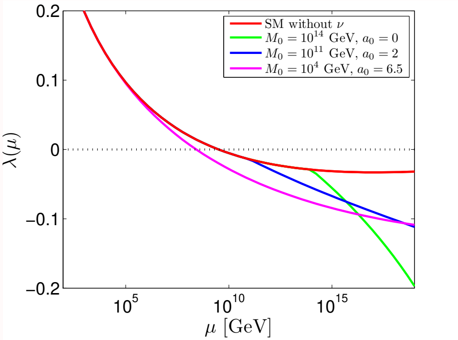
☞ $\Delta m_H^2 \leqslant (1\,\mathrm{TeV})^2 \quad \Rightarrow \quad M \lesssim \left(\frac{8\pi^2 v^2}{m_\nu}\mathrm{TeV}^2\right)^{1/3} = 1.7\times 10^7\,\mathrm{TeV}\times\left(\frac{\mathrm{eV}}{m_\nu}\right)^{1/3}$ **Vissani bound**

Neutrino masses and. . . EW vacuum stability

at $\mu \geqslant M$, the same diagrams contribute to the evolution of the potential

fermions $\Rightarrow$ $\beta_\lambda < 0$ EW vacuum more unstable

Rodejohann,Zhang 1203.3825
Ng,de la Puente 1510.00742



☞ one can constrain the parameter space by requiring the instability scale to be above some value

4. Example: Hierarchy Problem

Solutions to the hierarchy problem

- **ignore it**: "m_h cannot be predicted in a theory, just take it for what it is."
- theories that recover **scale invariance** → $M_{\rm Planck}$ does not play a role, corrections to m_h vanish (e.g. "agravity" Salvio,Strumia 1403.4226)
- **many vacua**: multiverse / anthropics / mechanisms selecting our universe out of many
- **extra dimensional** models (e.g. Randall-Sundrum, ADD Randall,Sundrum 9905221 Arkan-Hamed,Dimopoulos,Dvali 9803315)
- postulate **BSM physics that softens the HP**:
  - enforce cancellations among m_h^2 corrections → **Supersymmetry**
  - suppress m_h^2 corrections → **Composite Higgs** / Higgs as a pseudo-Goldstone boson

4.1 Composite Higgs

Inspiration: pion masses

pions $\pi^\pm, \pi^0$ are known to be the lightest mesons: $\dfrac{m_\pi}{m_K} \sim \dfrac{1}{3.5}, \quad \dfrac{m_\pi}{m_D} \sim \dfrac{1}{14}, \quad \dfrac{m_\pi}{m_B} \sim \dfrac{1}{37}$

☞ much lighter than the others because they are – in a better approx – **pseudo-Goldstone bosons**

---

in the limit $m_q = 0$ QCD with N flavors has a global $SU(N)_L \times SU(N)_R$ = **chiral symmetry**

the formation of quark condensates $\langle \bar\psi_i \psi_i \rangle \simeq \Lambda_{QCD}$ breaks it spontaneously to $SU(N)_{L+R}$

$\Rightarrow \quad (N^2 - 1)$ Goldstone bosons

for $N = 2\,(u, d) \to 3$ GB $= \pi^0, \pi^\pm$

☞ exact GBs are **massless** pseudo-scalars,
with a **shift symmetry** $\phi \mapsto \phi + c$ that only allows derivative interactions: ✔ $\partial_\mu \phi$ ✖ ϕ^n

for $m_q \neq 0$ the chiral sym. is explicitly broken $\Rightarrow$ the pions are **pseudo**-GBs, with $m_\pi \sim m_q \neq 0$

☞ the approximate chiral sym protects m_π because it requires $m_\pi \sim m_q$

☞ the pGB approximation is very good for π because $m_u, m_d \ll \Lambda_{QCD}$

The Higgs as a pseudo-Goldstone boson

apply the same idea to the Higgs: composite pGB from some BSM symmetry breaking

Generic setup

$\mathcal{G} \supset SU(2)_L \times U(1)_Y$ **approx global** symmetry

spontaneous break.

$\mathcal{H} \subset \mathcal{G}$

where $\mathcal{H} \supset SU(2)_L \times U(1)_Y$

(dim$\mathcal{G}-$ dim$\mathcal{H}$) composite GBs
must contain 4 with right quantum nrs to form Higgs doublet H

radiative corrections give a potential to H

EWSB

$U(1)_{em}$

☞ m_h at the EW scale is protected. at higher E the Higgs *dissolves* into its components
$\rightarrow$ HP solved at all scales

Example: modified Higgs couplings from MCHM

the Minimal Composite Higgs Model (MCHM) adopts $\mathcal{G}/\mathcal{H} = SO(5)/SO(4)$ Agashe,Contino,Pomarol 0412089

at LO, the kinetic term of the scalar Lagrangian gives

$$\mathscr{L}_\phi = \frac{1}{2}\partial_\mu h\, \partial^\mu h + g^2 f^2 \sin^2\left(\frac{\langle H\rangle + h}{2f}\right)\left(W^+_\mu W^{-\mu} + \frac{Z_\mu Z^\mu}{2c_\theta^2}\right) + \dots$$

$$= \frac{1}{2}\partial_\mu h \partial^\mu h + \frac{g^2 v^2}{4}\left(W^+_\mu W^{-\mu} + \frac{Z^2_\mu}{2c^2_\theta}\right)\left[1 + 2\sqrt{1-\frac{\xi}{4}}\,\frac{h}{v} + \left(1-\frac{\xi}{2}\right)\frac{h^2}{v^2} - \dots\right] + \dots$$

where $\boxed{\xi = \frac{v^2}{f^2} = 4\sin^2\frac{\langle H\rangle}{2f}}$

☞ hZZ/hWW and h^2ZZ/h^2WW interactions are modified in a correlated way

for $\xi \to 0$ one recovers the SM. depending on ξ, deviations can be large

Higgs potential from the MCHM

the scalar potential for H is generated in the presence of **explicit breakings** of $\mathcal{G}$

- one source of breaking is the **gauging** of the subgroup $SU(2)_L \times U(1)_Y \subset \mathcal{G}$
- another one is the fermionic sector (more later). dominantly: **top quark + partners**

Panico,Wulzer 1506.01961

$$V(H) \simeq -\alpha f^2 \sin^2 \frac{H}{2f} + \beta f^2 \sin^4 \frac{H}{2f}$$

minimized for $$4 \sin^2 \frac{\langle H \rangle}{2f} = \frac{v^2}{f^2} = \xi = \frac{2\alpha}{\beta}$$

expanding for $H = \dfrac{\langle H \rangle + h}{\sqrt{2}}$ one finds

$$V(h) = \frac{\beta\xi(4-\xi)}{16} h^2 + \frac{\beta}{16f}(2-\xi)\sqrt{\xi(4-\xi)}\, h^3 + \frac{\beta}{192 f^2}(12 - 28\xi + 7\xi^2)\, h^4 + \dots$$

☞ ξ constrained from hVV interactions $\quad\rightarrow\quad 2\alpha/\beta \lesssim 0.1 \quad\rightarrow$ some tuning needed

Composite Higgs in a nutshell

Low-energy signatures

- it predicts deviations from SM in Higgs interactions hVV, $hhVV$, $h^3\dots$
  following a specific pattern (e.g. fixed signs) as a function of $\xi = v^2/f^2$
- BSM corrections affect only h-dependence. $\left(W^2 + Z^2/2c_\theta^2\right)$ structure is preserved
  $\longrightarrow$ due to MCHM preserving custodial
- the EFT contains interactions with arbitrarily many h insertions from expanding trig functions
  $\longrightarrow$ remnant of pGB nature
- heavy composite resonances ($\sim$ mesons) expected at $\Lambda_{\mathcal{G}}$. by NDA, it satisfies $\Lambda_{\mathcal{G}} \leqslant 4\pi f$
  $\longrightarrow$ scale separation from misalignment $v^2/f^2 = \xi \ll 1$ allows decoupling! resonances can be heavy

Challenges

- some tuning needed to achieve $\alpha \ll \beta$ in scalar potential $\rightsquigarrow$ **little Higgs models** ($\alpha/\beta \sim g^2/16\pi^2$)
- some issues with flavor and fermion masses

Partial compositeness

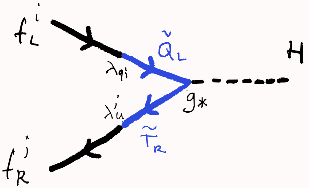
where do Yukawa couplings come from in a composite Higgs model?

standard paradigm: mixing between elementary fermions and composite resonances D. B. Kaplan 1991

$$|t_R\rangle = \cos\theta_{R,t}|t_{\text{elem},L}\rangle + \sin\theta_{R,t}|T_R\rangle \quad \rightarrow \text{ SM RH top quark}$$
$$|\tilde{T}_R\rangle = -\sin\theta_{R,t}|t_{\text{elem},R}\rangle + \cos\theta_{R,t}|T_R\rangle \quad \rightarrow \text{ RH top partner}$$

similar to **seesaw**! larger $\cos\theta \leftrightarrow$ lighter partner, heavier SM state

Yukawa operators emerge when integrating out heavy resonances



$$Y_{u,\alpha\beta} = g^* \sin\theta_{L,\alpha}\sin\theta_{R,\beta}$$

Anomalous Higgs couplings

we have seen that in composite Higgs models the Higgs couplings to other SM particles (incl. itself) get modified compared to the SM

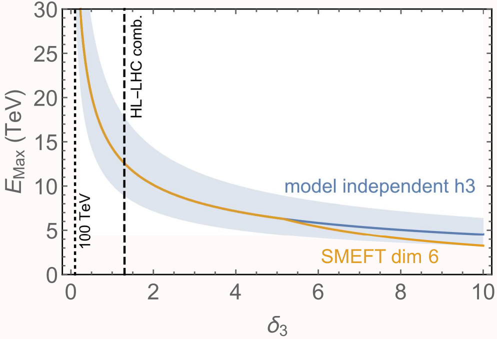
☞ this is **a general feature** of BSM extensions addressing the Hierarchy Problem!

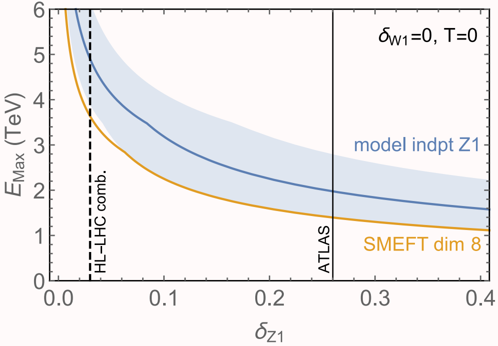
→ each BSM model predicts a different h coupling modification pattern

→ breaks SM unitarity! restored at high E by BSM resonances

☞ a particularly interesting one is the h^3 interaction: pure Higgs / EWSB sector

BSM scales from Higgs coupling modifications



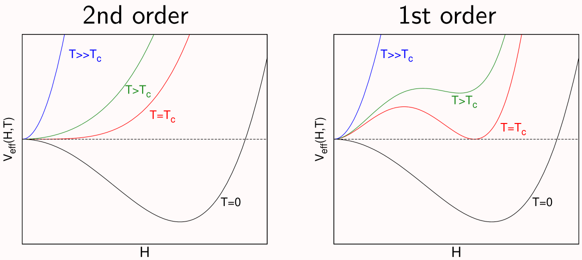


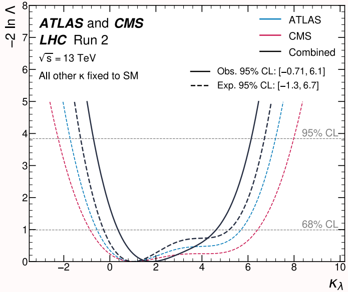
Abu-Ajamieh, Chang, Chen, Luty 2009.11293

Electroweak baryogenesis

why η_B cannot be achieved in the SM:
- not enough $\cancel{CP}$
- no first order EW phase transition

☞ an anomalous h^3 coupling can solve the non-equilibrium issue: needs $\kappa_\lambda \simeq 1.2 - 1.5$





Chen+ 2011.04265

ATLAS+CMS 2602.23991

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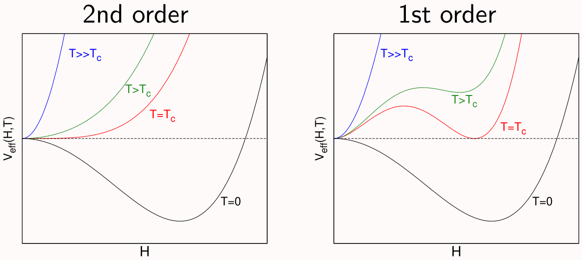
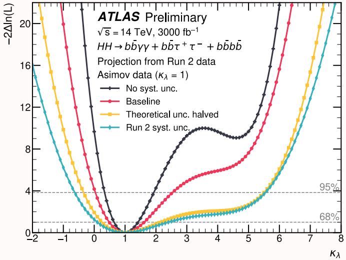


Chen+ 2011.04265



ATL-PHYS-PUB-2022-053

5. Phenomenological probes

Direct and indirect searches

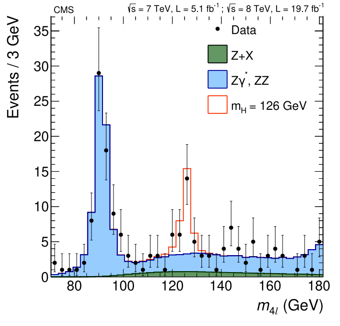
Direct signals

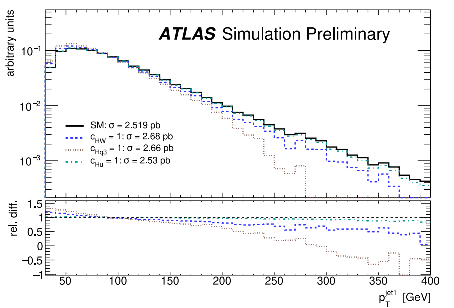
- target specific particle
- allow discovery

Indirect signals

- more model independent
- target EFT effects
- indirect indications

CMS-HIG-13-002





ATL-PHYS-PUB-2019-042

Direct and indirect searches

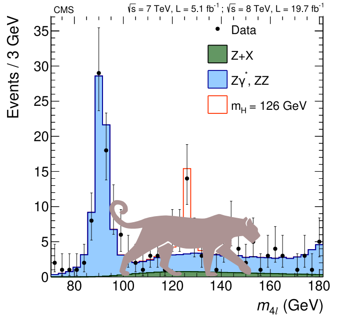
Direct signals

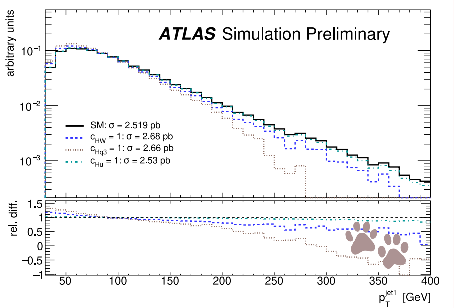
- target specific particle
- allow discovery

Indirect signals

- more model independent
- target EFT effects
- indirect indications

CMS-HIG-13-002





ATL-PHYS-PUB-2019-042

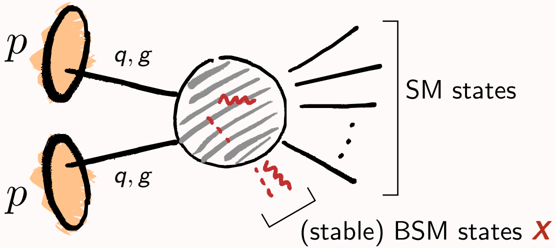
5.1 Direct searches at the LHC

Characterization of a BSM state

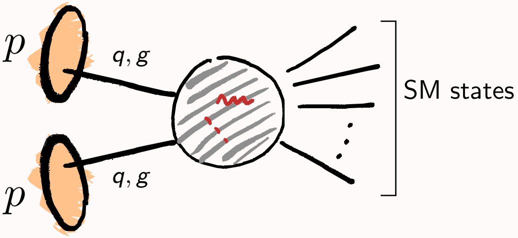
- mass M
  $\rightsquigarrow$ can it be produced on-shell?
- total decay width Γ
  $\rightsquigarrow$ is it stable, unstable, long-lived? broad, narrow?
- partial decay widths / branching ratios Γ_f Br_f
  $\rightsquigarrow$ what does it decay into, most often? at what distance?
- charges Q_i
  $\rightsquigarrow$ does it leave traces in the detector? what kind?
- couplings g_i
  $\rightsquigarrow$ what are the main production and decay channels?

model-dependent relations exist among these quantities

BSM states in LHC processes

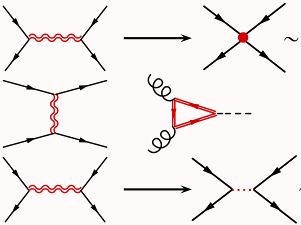


BSM states in LHC processes



A. *X* CANNOT be on-shell in the process considered, because:

- too heavy
- only appears in loop or t-channel
- too light



$\sim 1/M^2$ – more later

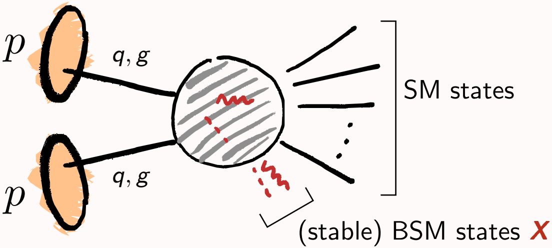
$\sim 1/s$ – more later

non-resonant signals:

(small) corrections to SM kinematic distr. and form factors

☞ $\sim$independent of Γ

BSM states in LHC processes



B. *X* CAN be on-shell

signals depend on lifetime, partial widths, decay channel(s), charges...

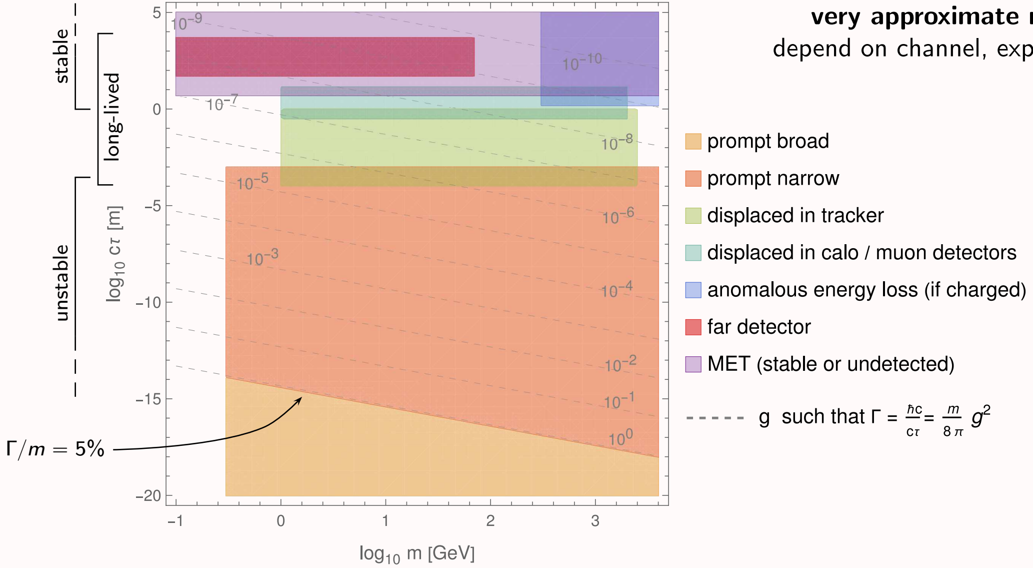
mainly: stable and neutral, or stable and light → $\not{E}_T$

stable, heavy and charged (HSCP) → **slow-moving, highly-ionizing objects in detector**

long-lived → **displaced and delayed signals**

unstable → **resonant decays**

On-shell BSM signals



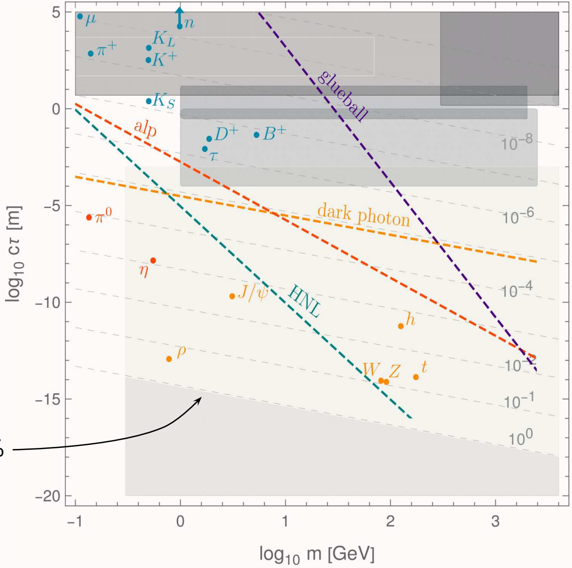
very approximate ranges!

depend on channel, experiment...

On-shell BSM signals

very approximate ranges!

depend on channel, experiment...



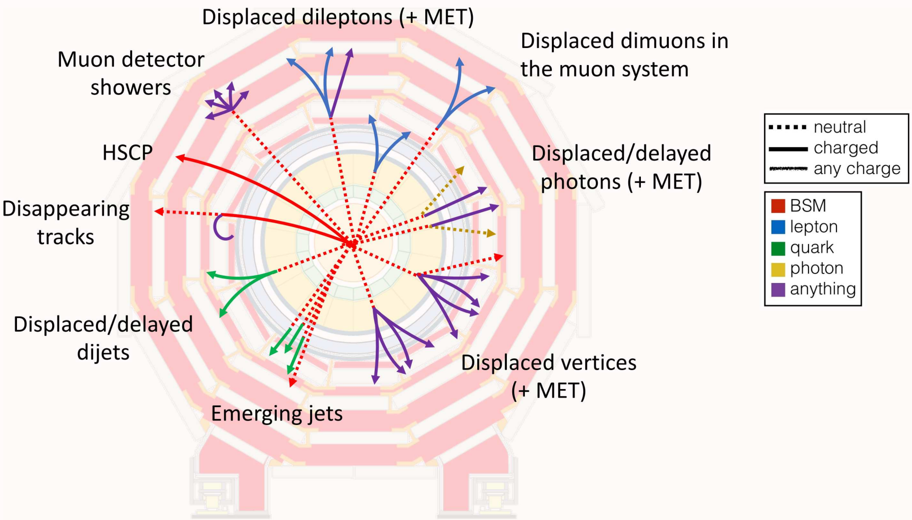
$\Gamma/m = 5\%$

- prompt broad
- prompt narrow
- displaced in tracker
- displaced in calo / muon detectors
- anomalous energy loss (if charged)
- far detector
- MET (stable or undetected)

----- g such that $\Gamma = \frac{\hbar c}{c\tau} = \frac{m}{8\pi} g^2$

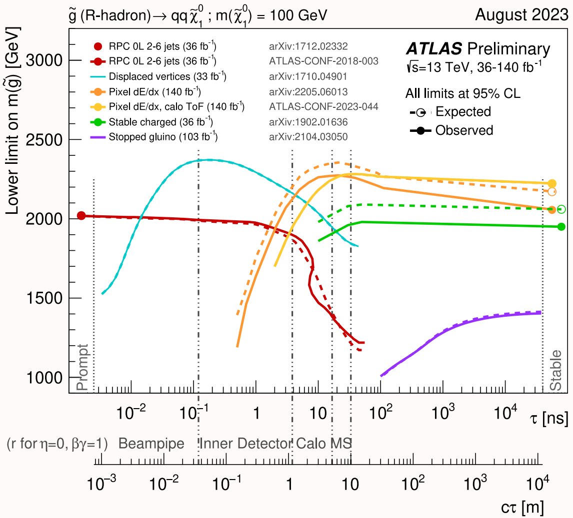
Knapen,Lowette 2212.03883

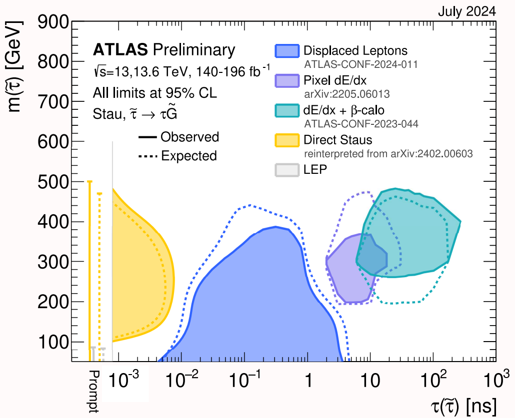
Long-lived particle signals



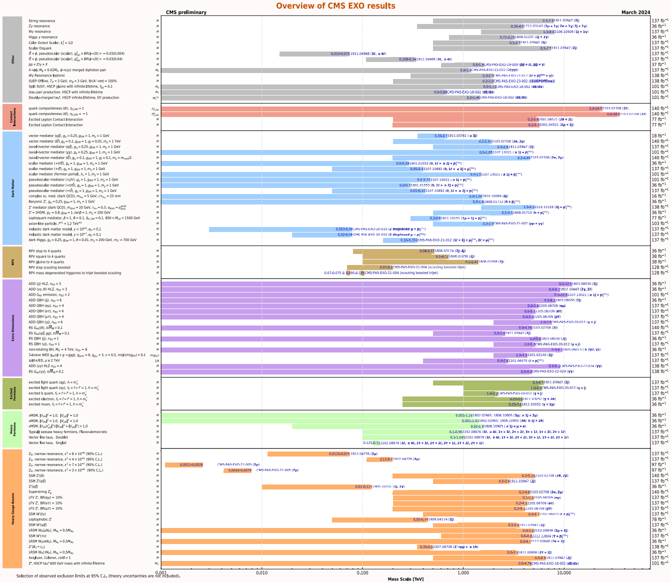
A Frankenthal (CMS) LLP2024

Complementarity between measurements (LLP examples)





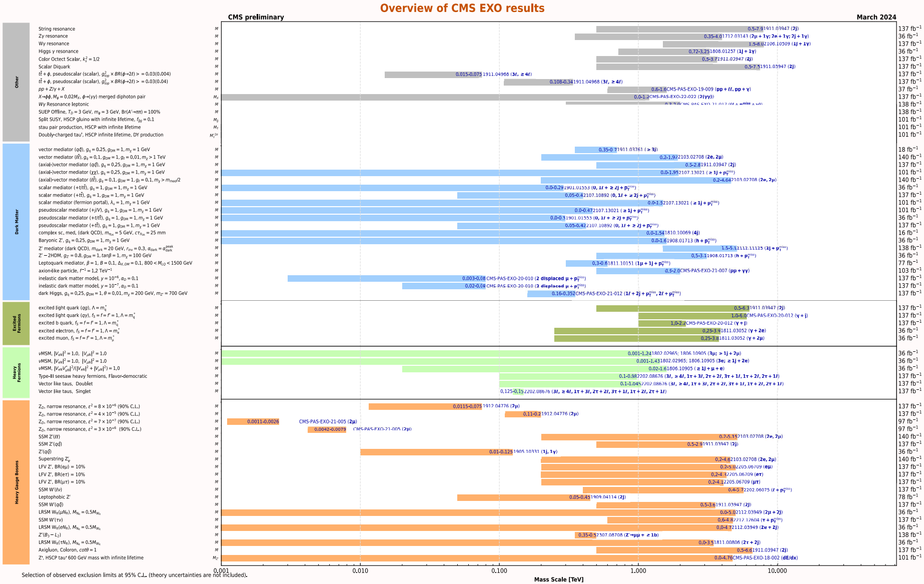
Direct BSM searches overview



⚠ much hidden complexity!

specific assumptions made in most cases, about resonance width, BR, couplings. . .

Direct BSM searches overview



5.2 Indirect searches

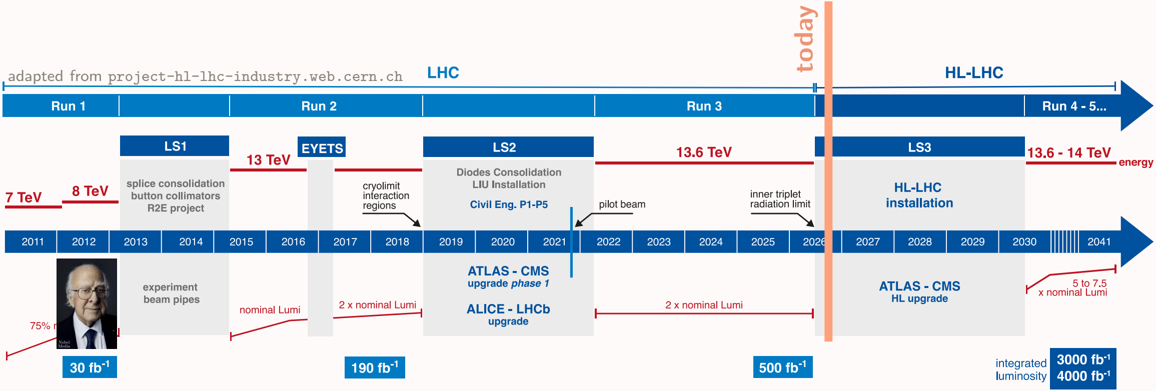
Indirect tests of new physics

indirect signatures can include
- modifications of SM rates
- modifications of SM kinematics
- appearance of (nearly) forbidden processes

Most relevant indirect measurements/searches

- EWPO and Higgs coupling measurements → custodial, unitarity
- flavor-changing processes: $\mu \to e\gamma$, K, B oscillations, semilept. decays...
  → (approx) flavor symmetries
- EDMs → test CP violation
- proton decay, $0\nu\beta\beta$ decays → B, L tests
- neutrino oscillation measurements → C_5/Λ parameters, L, CP
- ...

Historical context

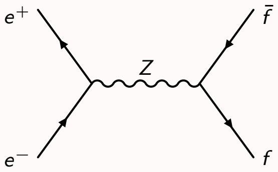


indirect searches have become increasingly popular in the past 15 yrs

- lack of discoveries and of clear indications favoring specific BSM
- prospective increase in precision
- potentially even more relevant if FCC-ee is next

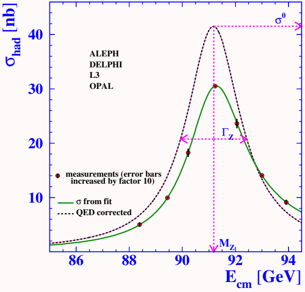
further in future
FCC
(maybe)

Z-pole Pseudo-Observables



$$\sigma(e^+e^- \to Z \to \bar{f}f) = \sigma_f^0 \frac{s^2 {\Gamma_Z}^2}{(s - {m_Z}^2)^2 + (s\Gamma_Z/m_Z)^2}$$

$$\sigma_f^0 = 12\pi \frac{\Gamma_{ee}\Gamma_{ff}}{\Gamma_Z^2 m_Z^2}$$



ALEPH,DELPHI,L3,OPAL,SLD 0509008

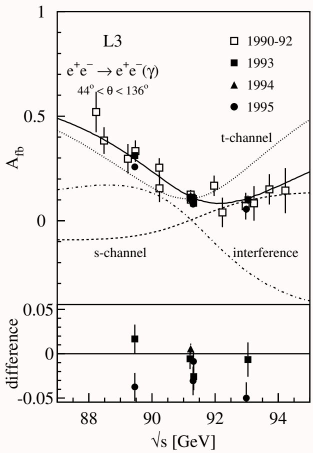
pseudo-observables: defined after deconvoluting QED radiation, acceptance, and subtracting non-resonant contributions

σ_f^0, Γ_Z, m_Z extracted from lineshape fit

↳ in global fit: $\sigma^0_{\rm had}$, $R^0_\ell = \dfrac{\Gamma_{\rm had}}{\Gamma_{\ell\ell}}$, $\ell = e, \mu, \tau$

$+$ indep. measurements of $R^0_q = \dfrac{\Gamma_{qq}}{\Gamma_{\rm had}}$, $q = c, b$

Z-pole Pseudo-Observables



$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} \qquad \sigma_{\substack{F\\B}} = \sigma\left(\cos\theta \gtrless 0\right)$$

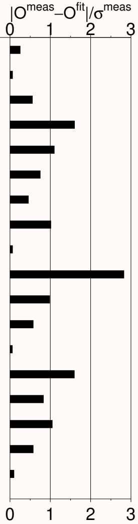
at LO in the SM:

$$A_{FB}^{0,f} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_f \qquad \mathcal{A}_f = \frac{g_{fR}^2 - g_{fL}^2}{g_{fR}^2 + g_{fL}^2}$$

ALEPH,DELPHI,L3,OPAL,SLD 0509008

Electroweak Precision Observables (EWPO)

	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4965
σ^0_{had} [nb]	41.540 ± 0.037	41.481
R_l	20.767 ± 0.025	20.739
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01642
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21562
R_c	0.1721 ± 0.0030	0.1723
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1037
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.425 ± 0.034	80.389
Γ_W [GeV]	2.133 ± 0.069	2.093
m_t [GeV]	178.0 ± 4.3	178.5



% precision or better
→ tree-level constraints on Zff couplings
→ loop-level constraints on m_h, m_t

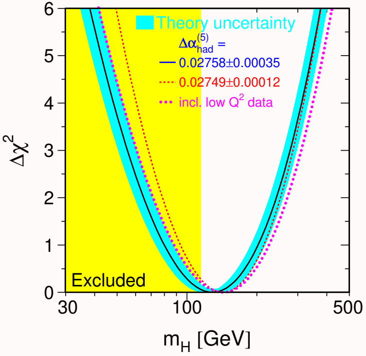
additional (pre-LHC) precision measurements

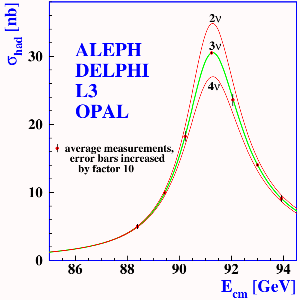
- m_W, Γ_W CDF,D0 1204.0042, LEP 041201
- m_t CDF, D0 0404010
- $e^+e^- \to W^+W^-$ diff. ALEPH EPJC(2004)147 LEP2 1302.3415
- $e^+e^- \to e^+e^-$ diff. LEP2 1302.3415

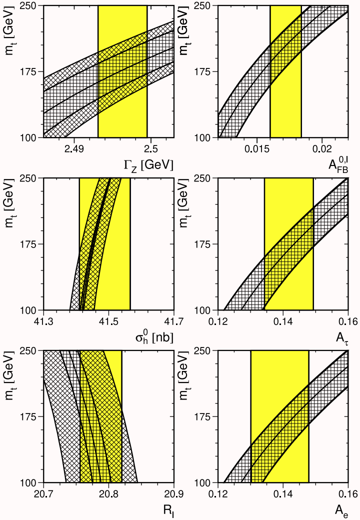
Predictions from EWPO

not just BSM constraints!

EWPO measurements were fundamental in predicting yet unmeasured quantities







LEP 0509008

LEP CERN-PPE/95-172 (1995)

Oblique parameters

Peskin, Takeuchi 1991

$$\alpha\mathbf{S} = s^2_{2\theta}\left(\Pi'_{ZZ}(0) - \frac{2}{t_{2\theta}}\Pi'_{Z\gamma}(0) - \Pi'_{\gamma\gamma}(0)\right) \quad \leftrightarrow \quad B_{\mu\nu}H^\dagger W^{\mu\nu}H$$

$$\alpha\mathbf{T} = \frac{\Pi_{WW}(0)}{m_W^2} - \frac{\Pi_{ZZ}(0)}{m_Z^2} \quad \leftrightarrow \quad (D_\mu H^\dagger H)(D^\mu H^\dagger H)$$

breaks cust.

$$\alpha\mathbf{U} = 4s^2_\theta\left(\Pi'_{WW}(0) - c^2_\theta\Pi'_{ZZ}(0) - s_{2\theta}\Pi'_{Z\gamma}(0) - s^2_\theta\Pi'_{\gamma\gamma}(0)\right) \quad \leftrightarrow \quad (H^\dagger W^{\mu\nu}H)^2$$

where Π_{AB} are vacuum polarizations:

$$\Pi^{\mu\nu}(q^2) = i\eta^{\mu\nu}\Pi_{AB}(q^2) + (q^\mu q^\nu \text{ terms})$$

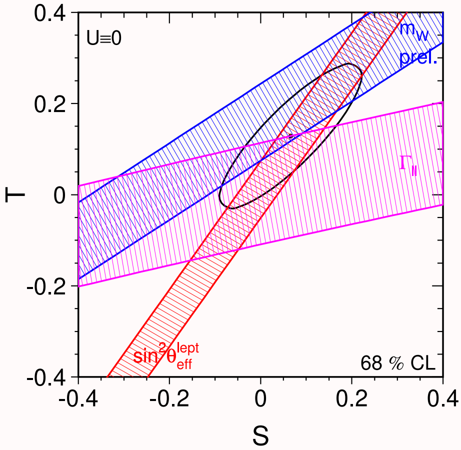
$$\Pi_{AB}(q^2) = \Pi_{AB}(0) + q^2\Pi'_{AB}(0)$$

- alternative BSM parameterization for EWPO
- **oblique / universal** : only sensitive to BSM affecting EW bosons (e.g. scalars), not $Z\bar{f}f$

Oblique parameters

U is more suppressed than S, T in the SM + $d = 8$ effect in SMEFT

$\rightarrow$ fit to EWPO with only 2 free parameters



LEP 0509008

Higgs couplings measurements: κ formalism

HXSWG 1209.0040, YR4 1307.1347

assming a **narrow** Higgs: $\sigma(gg \to h \to \gamma\gamma) = \sigma(gg \to h)\, \mathrm{Br}_{h\to\gamma\gamma} = \dfrac{\sigma(gg \to h)\Gamma(h \to \gamma\gamma)}{\Gamma_h}$

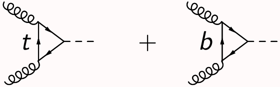
assuming **SM-like** Higgs couplings (rescalings only):

$$\frac{\sigma_{HW}}{\sigma_{HW}^{SM}} = \kappa_W^2 \quad \frac{\sigma_{HZ}}{\sigma_{HZ}^{SM}} = \kappa_Z^2 \quad \frac{\sigma_{VBF}}{\sigma_{VBF}^{SM}} = \kappa_{VBF}^2 \quad \frac{\sigma_{ggH}}{\sigma_{ggH}^{SM}} = \kappa_g^2 \quad \frac{\sigma_{ttH}}{\sigma_{ttH}^{SM}} = \kappa_t^2$$

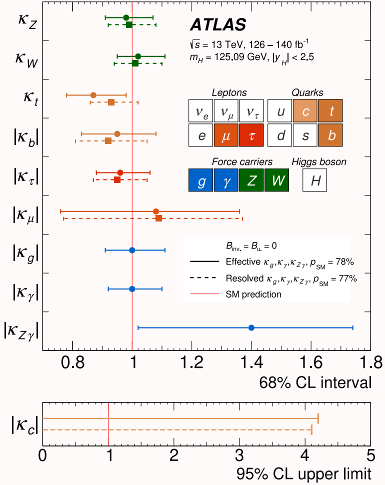
$$\frac{\Gamma_{WW}}{\Gamma_{WW}^{SM}} = \kappa_W^2 \quad \frac{\Gamma_{ZZ}}{\Gamma_{ZZ}^{SM}} = \kappa_Z^2 \quad \frac{\Gamma_{ff}}{\Gamma_{ff}^{SM}} = \kappa_f^2 \quad \frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{SM}} = \kappa_\gamma^2 \quad \frac{\Gamma_{Z\gamma}}{\Gamma_{Z\gamma}^{SM}} = \kappa_{Z\gamma}^2 \quad \frac{\Gamma_h}{\Gamma_h^{SM}} = \kappa_H^2 \quad \ldots$$

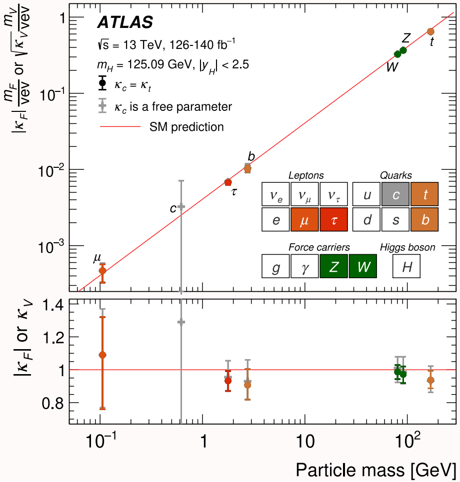
depending on desired accuracy and modeling assumptions, some κ's can be resolved, e.g.

$$\kappa_g = \frac{\kappa_t^2 \sigma_{ggH}^{tt} + \kappa_b^2 \sigma_{ggH}^{bb} + \kappa_t \kappa_b \sigma_{ggH}^{tb}}{\sigma_{ggH}^{tt} + \sigma_{ggH}^{bb} + \sigma_{ggH}^{tb}}$$



κ measurements





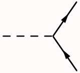
ATLAS 2608.07332

From anomalous couplings to SMEFT

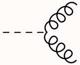
anomalous couplings
- typically limited to SM-like Lorentz structures
- not manifestly gauge-invariant → not properly loop-improvable
- without a power counting rationale

☞ a more rigorous parameterization is obtained with **SMEFT** truncated at $d = 6$ (8)

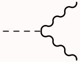
in many cases there exists a mapping, but in others SMEFT is genuinely different. examples: ($\bar{C} = \frac{v^2 C}{\Lambda^2}$)



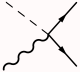
$$\frac{g_{eR}}{g_{eR}^{SM}} = 1 - \bar{C}_{Hl}^{(3)} + \frac{1}{2}\bar{C}'_{ll} - \frac{c_\theta^2}{2}\bar{C}_{HD} - s_\theta c_\theta \bar{C}_{HWB} - \frac{1}{2}\bar{C}_{He}$$



$$\kappa_g = 1 + \frac{48\pi^2}{g_s^2}\bar{C}_{HG}$$



$$\kappa_W = 1 + \bar{C}_{H\square} - \frac{1}{4}\bar{C}_{HD} - \bar{C}_{Hl}^{(3)} + \frac{1}{2}\bar{C}_{ll} \qquad + \frac{\mathbf{4i}(\mathbf{p}_+^\nu \mathbf{p}_-^\mu - \mathbf{p}_+ \cdot \mathbf{p}_- \eta^{\mu\nu})}{\mathbf{v}}\bar{\mathbf{C}}_{\mathbf{HW}}$$



$$\cancel{\kappa} \qquad \frac{\mathbf{ig}}{\mathbf{v c_\theta}}\gamma^\mu \mathbf{P_R}\,\bar{\mathbf{C}}_{\mathbf{He}}$$

☞ new kinematic structures and vertices
☞ correlations among EFT vertices

From anomalous couplings to SMEFT

anomalous couplings
- typically limited to SM-like Lorentz structures
- not manifestly gauge-invariant → not properly loop-improvable
- without a power counting rationale

☞ a more rigorous parameterization is obtained with **SMEFT** truncated at $d = 6$ (8)

in many cases there exists a mapping, but in others SMEFT is genuinely different. examples: ($\bar{C} = \frac{v^2 C}{\Lambda^2}$)

predictions in SMEFT

$$\mathcal{A}_{SMEFT} = \mathcal{A}_{SM} + \sum_i \frac{C_i}{\Lambda^2}\mathcal{A}_i\,, \qquad \mathcal{A}_i = \text{ amplitude with 1 insertion of operator } \mathcal{O}_i$$

$$\sigma_{SMEFT} = \sigma_{SM,best}\left[1 + \frac{1}{\Lambda^2}\sum_i \frac{2Re(C_i\,\mathcal{A}_i\mathcal{A}^\dagger_{SM})}{|\mathcal{A}_{SM}|^2} + \frac{1}{\Lambda^4}\sum_i \frac{|C_i\,\mathcal{A}_i|^2}{|\mathcal{A}_{SM}|^2} + \frac{1}{\Lambda^4}\sum_{i>j}\frac{2Re(C_iC_j^*\,\mathcal{A}_i\mathcal{A}_j^\dagger)}{|\mathcal{A}_{SM}|^2}\right]$$

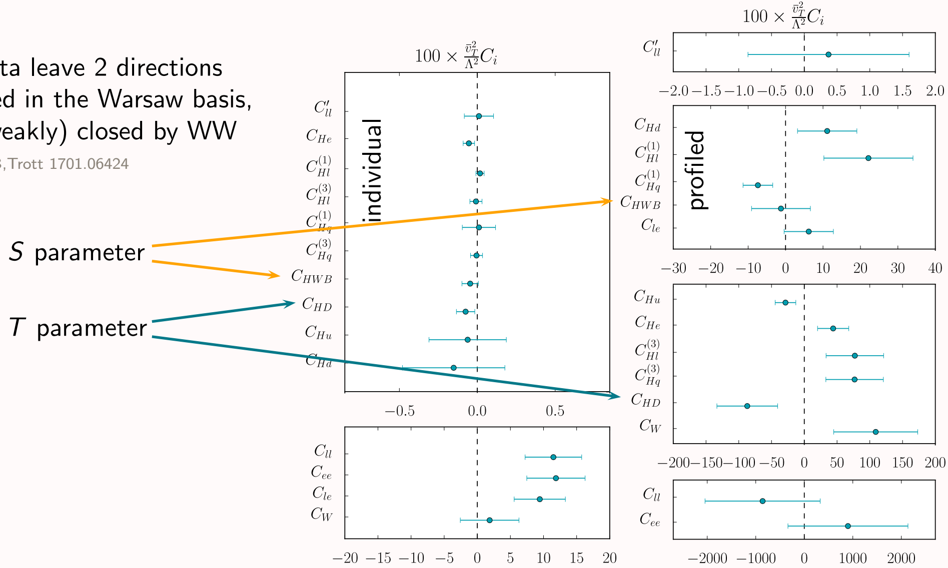
linear quadratics

automation: Monte Carlo IB 2012.11343 Degrande+ 2008.11743

EWPOs in SMEFT at $d = 6$

Z-pole data leave 2 directions unconstrained in the Warsaw basis, that are (weakly) closed by WW

IB, Trott 1701.06424



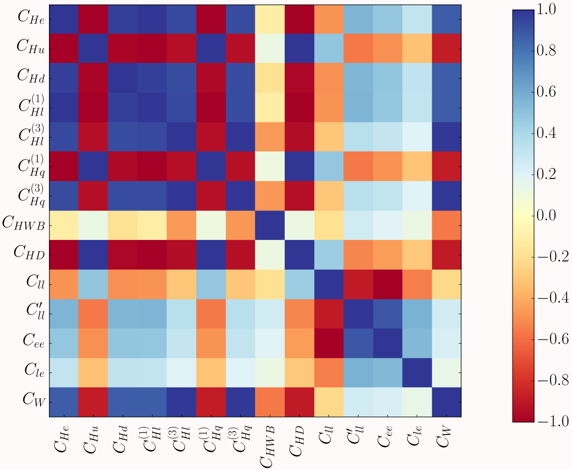
EWPOs in SMEFT at $d = 6$

Z-pole data leave 2 directions unconstrained in the Warsaw basis, that are (weakly) closed by WW

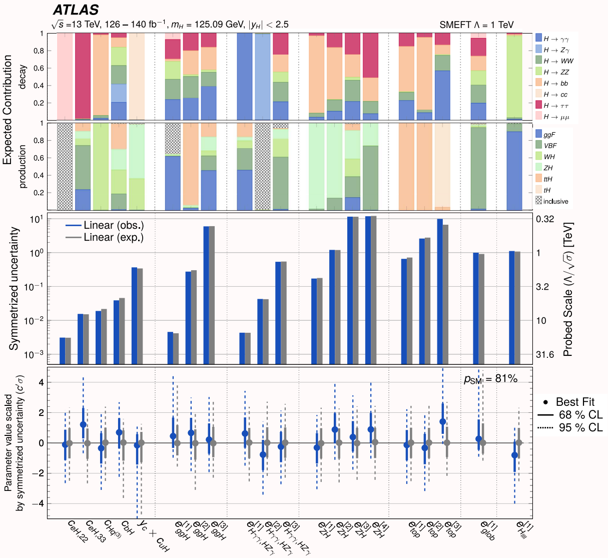
IB, Trott 1701.06424

$\downarrow$

results in strong residual correlations and large differences between individual and profiled bounds

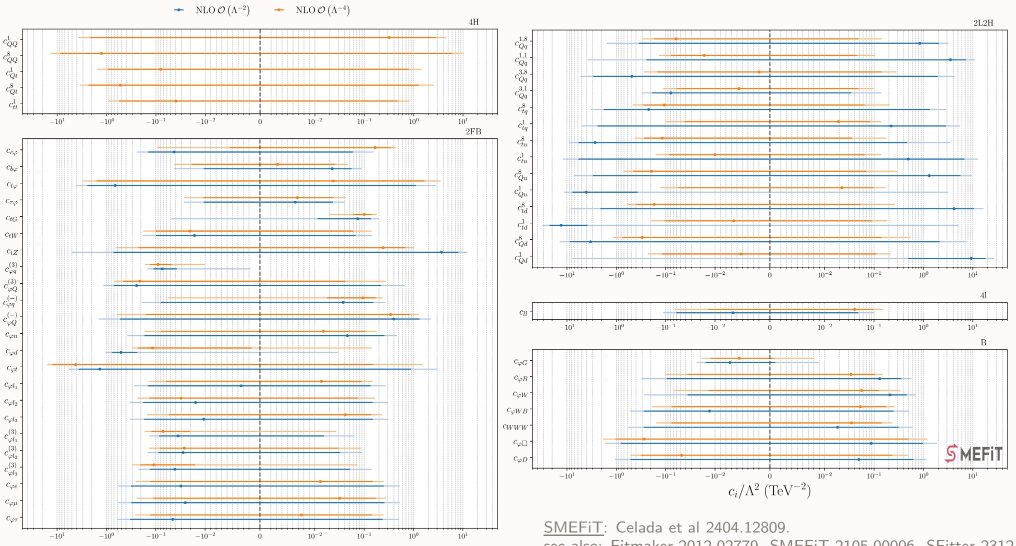


Higgs measurements in SMEFT at $d = 6$



ATLAS 2608.07332

EWPO + Higgs + top combinations

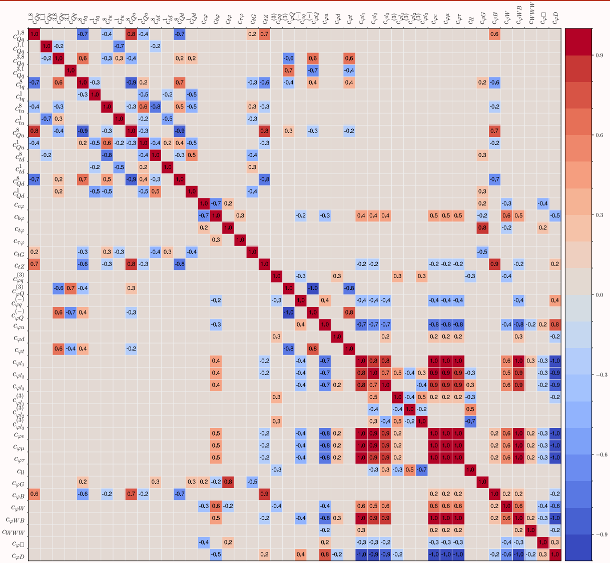


SMEFiT: Celada et al 2404.12809.
see also: Fitmaker 2012.02779, SMEFiT 2105.00006, SFitter 2312.12502

Correlation matrices

SMEFiT: Celada et al 2404.12809

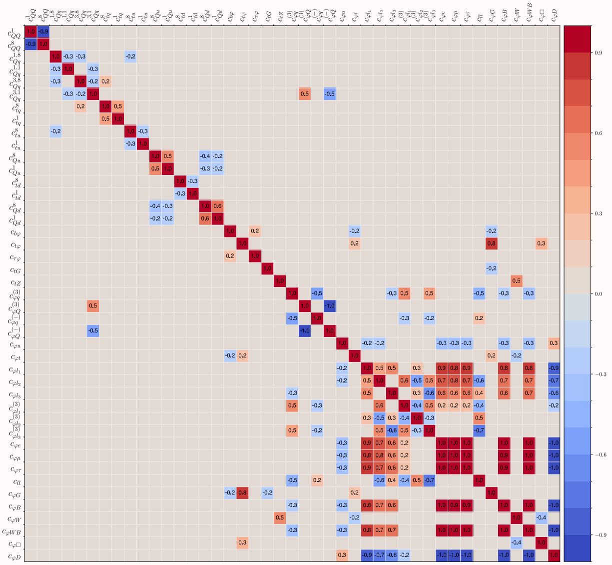
Linear fit



Correlation: NLO $\mathcal{O}\left(\Lambda^{-2}\right)$

SMEFiT: Celada et al 2404.12809

Quadratic fit

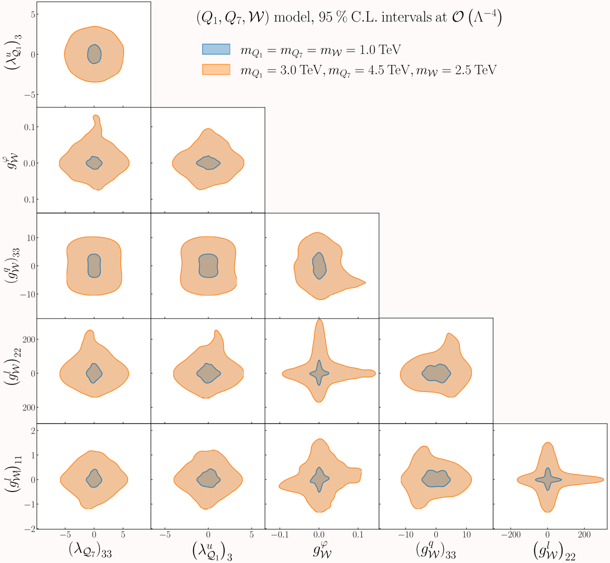


Correlation: NLO $\mathcal{O}(\Lambda^{-4})$

From SMEFT to BSM models

$$
\begin{aligned}
\mathscr{L}_{BSM} =& \frac{1}{2} D_\mu \mathcal{W}^a_\nu D^\nu \mathcal{W}^{a\mu} - \frac{1}{2} D_\mu \mathcal{W}^a_\nu D^\mu \mathcal{W}^{a\nu} \\
&+ \frac{M^2}{2} \mathcal{W}^a_\mu \mathcal{W}^{a\mu} \\
&- \frac{(g^\psi_\mathcal{W})_{ij}}{2} \mathcal{W}^{a\mu} \bar{\psi}_i \sigma^a \gamma_\mu \psi_j \\
&- \frac{g^\varphi_\mathcal{W}}{2} \mathcal{W}^{a\mu} H^\dagger \sigma^a i D_\mu H \\
&+ i \bar{\mathcal{Q}}_1 \not{D} \mathcal{Q}_1 + i \bar{\mathcal{Q}}_7 \not{D} \mathcal{Q}_7 \\
&+ M_{\mathcal{Q}_7} \bar{\mathcal{Q}}_7 \mathcal{Q}_7 + M_{\mathcal{Q}_1} \bar{\mathcal{Q}}_1 \mathcal{Q}_1 \\
&- (\lambda_{\mathcal{Q}_1})_{ij} \bar{\mathcal{Q}}_1 \tilde{H} t_R + (\lambda_{\mathcal{Q}_7})_{ij} \bar{\mathcal{Q}}_7 H t_R \\
&+ \text{h.c.}
\end{aligned}
$$

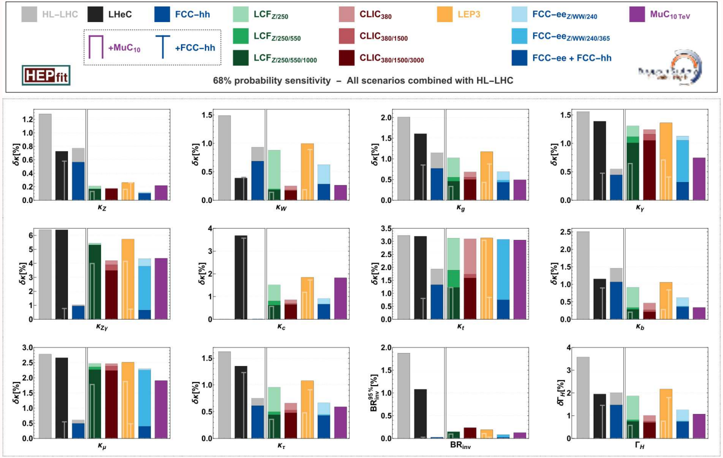
HXSWG 2009.01249



ter Hoeve, Magni, Rojo, Rossia, Vryonidou 2309.04523

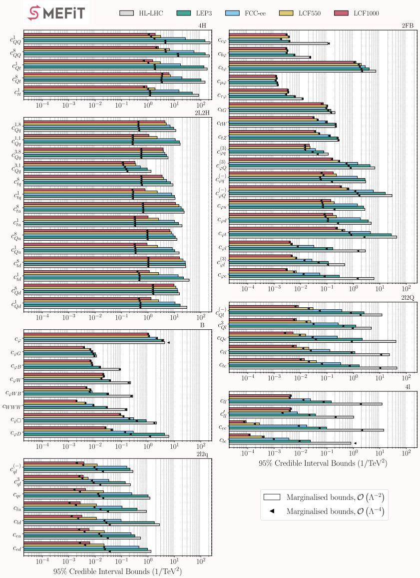
5.3 Looking ahead

Anomalous couplings at future colliders

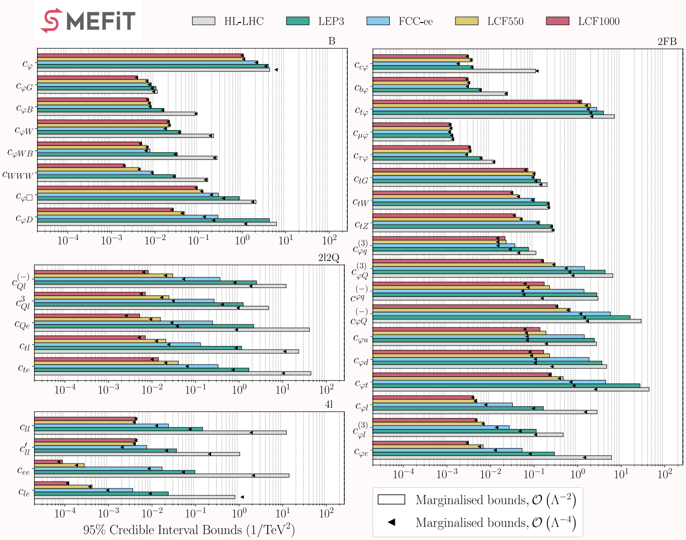


ESPP briefing book 2511.03883

SMEFT at future colliders

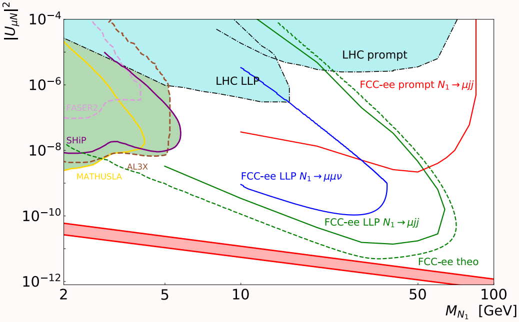


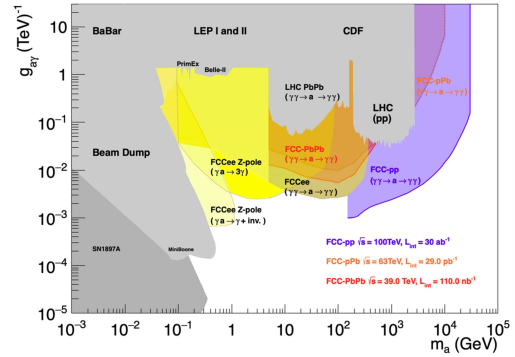
SMEFT at future colliders



Armadillo+ 2604.16596

FCC searches for light BSM





FCC feasibility study 2505.00272

Backup slides

Neutrino mixing parameters from oscillation exp

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.1$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
$\sin^2\theta_{23}$	$0.573^{+0.016}_{-0.020}$	$0.415 \to 0.616$	$0.575^{+0.016}_{-0.019}$	$0.419 \to 0.617$
$\theta_{23}/^\circ$	$49.2^{+0.9}_{-1.2}$	$40.1 \to 51.7$	$49.3^{+0.9}_{-1.1}$	$40.3 \to 51.8$
$\sin^2\theta_{13}$	$0.02219^{+0.00062}_{-0.00063}$	$0.02032 \to 0.02410$	$0.02238^{+0.00063}_{-0.00062}$	$0.02052 \to 0.02428$
$\theta_{13}/^\circ$	$8.57^{+0.12}_{-0.12}$	$8.20 \to 8.93$	$8.60^{+0.12}_{-0.12}$	$8.24 \to 8.96$
$\delta_{\mathrm{CP}}/^\circ$	197^{+27}_{-24}	$120 \to 369$	282^{+26}_{-30}	$193 \to 352$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.517^{+0.026}_{-0.028}$	$+2.435 \to +2.598$	$-2.498^{+0.028}_{-0.028}$	$-2.581 \to -2.414$

NuFit collaboration. Esteban et al 2007.14792

Particle content after EWSB

Scalars

- 3 neutral scalars: H^0, h^0, A^0
- 2 charged scalars: $H^\pm$

Fermions

- 4 neutral fermions $\tilde{\chi}^0_{1,2,3,4}$ — mixtures of $\tilde{H}^0_u, \tilde{H}^0_d, \tilde{B}^0, \tilde{W}^0$
- 4 charged fermions $\tilde{\chi}^\pm_1, \tilde{\chi}^\pm_2$ — mixtures of $\tilde{H}^+_u, \tilde{H}^-_d, \tilde{W}^\pm$

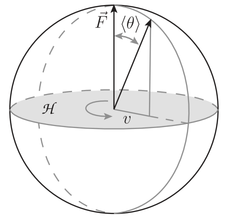
plus fields from SM fermion content.

- All neutral fermions are automatically Majorana → **neutralinos**; charged ones → **charginos**.
- The lightest R-odd state (LSP) is stable. If also neutral (a neutralino) → DM candidate.
- Gauginos draw the running of the gauge couplings to smaller values, leading to unification at 10^{16} GeV.

Vacuum misalignment

a key feature of composite Higgs is the **2-stages** symmetry breaking

- in the modeling, it is achieved via "vacuum misalignment"
- it makes it possible to have **small corrections to the Higgs couplings**



Panico,Wulzer 1506.01961

$\vec{F}$ = vev that breaks $\mathcal{G} \to \mathcal{H}$ $\qquad$ $SO(3)/SO(2)$

θ_1, θ_2 = Goldstone bosons from $\mathcal{G} \to \mathcal{H}$

$\langle\theta\rangle \neq 0$ produced via loops due to explicit $\mathcal{G}$ breaking
= misalignment

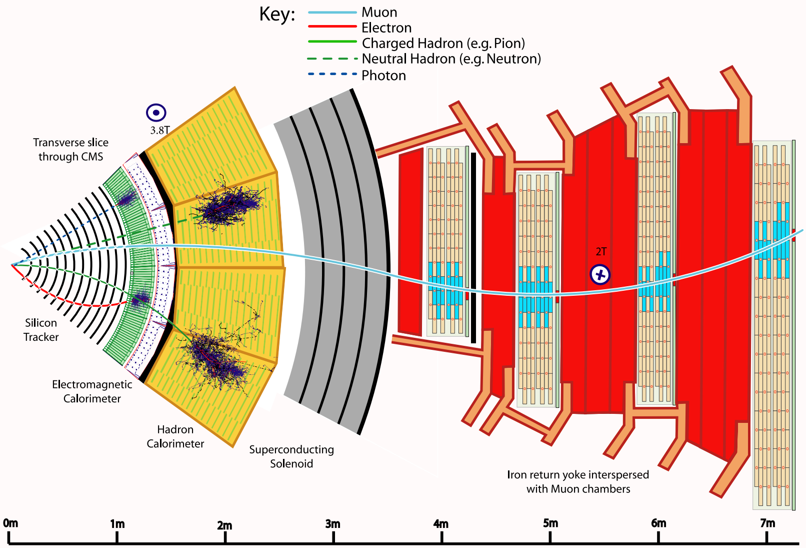
$\downarrow$

$v = |\vec{F}| \sin\langle\theta\rangle$

define $\boxed{\xi = \dfrac{v^2}{|\vec{F}|^2}} = \sin^2\langle\theta\rangle \in [0, 1]$

$\xi \to 1$ maximal misalignment $v = |\vec{F}|$
$\xi \to 0$ decoupling

A LHC detector



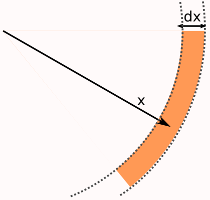
Long-lived particles

mean distance covered by a particle

$$\boxed{d(p)} = \beta c\, \gamma\tau = \sqrt{\gamma^2-1}\, c\tau = \boxed{\sqrt{\gamma^2-1}\,\frac{\hbar c}{\Gamma}} \qquad\qquad \gamma = E/mc^2$$

the decay law for a decay channel f is $\dfrac{dN}{dx} = -\dfrac{\mathrm{Br}_f}{d(p)} N(x)$

$\Rightarrow$ # particles per unit length that **decay** to f after traveling a distance x:



$$\boxed{\frac{dN_{events}(x)}{dx} \simeq \int d^4p\; f_{PDF}(p)\; \mathcal{M}(p) \;\times\; \frac{\mathrm{BR}_f}{d(p)}\; e^{-x/d(p)}}$$

- the mean distance depends only on **total width and 4-momentum**
- some challenges in modeling detector acceptances. formulas simplify taking approximations

☞ LLP searches developed **relatively recently**. dynamic field, many new ideas still emerging.