Effective Field Theories Across the Universe

The Standard Model Effective Field Theory

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Outline

Introduction to EFT in particle physics

- Main ideas.
- Main strategies.
- Some examples: from Fermi theory to the SM to the SMEFT.

Constructing the SMEFT

- The SM: brief review, strengths and weaknesses.
- Adding SMEFT interactions, how and why.

The SMEFT hands on

- SMEFT effects on SM parameters and SM interactions.
- Calculating observables in the SMEFT.

Constraining SMEFT interactions

- Global fits of collider observables (EW, Higgs, top), flavor observables, low energy observables.
- Matching to UV models.

Introduction to EFT in particle physics

- Main ideas.
- Main strategies.
- Some examples: from Fermi theory to the SM to the SMEFT.

EFT - Main idea

- During this workshop you will be exposed to several EFT, in very different domains, all reflecting the **fundamental idea** that **the dynamics of a system at low energy (long distance) does not depend *on the details* of the dynamics at the physics at high energy (short distance)**.
- **EFT ideal for physics problems involving multiple scales** over a broad range.
- **EFT are full-fledged QFT**, with a **limited range of validity** (in energy, distance, kinematic configurations, etc.). Hence, they benefit of the formal properties of QFT and in their range of validity offer a complete description of physical phenomena and a systematic approach to explore the UV regime.
- EFT are therefore **predictive**, the uncertainty of their predictions is quantifiable, and their prediction can be directly compared to experiments.
- It is a **fundamental approach to the study of physical systems**.

Can you think of some examples?

Formally, in a nutshell

"Integrate out the heavy fields" =
averaging over ϕ_H configurations

$$
\begin{tikzcd}
\Lambda_H \arrow[r, dash] & \mathcal{L}(\phi_H, \phi_L) \arrow[d, "\cancel{\phi_H}"] \\
\Lambda_L \arrow[r, dash] & \mathcal{L}_{EFT}(\phi_L)
\end{tikzcd}
$$

$$
\begin{aligned}
Z(J_L) &= \int D\phi_H D\phi_L \exp\left[\int d^4x(\mathcal{L}(\phi_H, \phi_L) + \phi_L J_L)\right] \\
&= \int D\phi_L \exp\left[\int d^4x(\mathcal{L}_{EFT}(\phi_L) + \phi_L J_L)\right]
\end{aligned}
$$

$$
\mathcal{L}_{EFT}(\phi_L) = \mathcal{L}_{d\leq 4} + \sum_{d=5}^{\infty} \frac{1}{\Lambda_H^{d-4}} \sum_{i=1}^{n_d} C_i^{(d)} Q_i^{(d)}(\phi_L)
$$

Coefficients (a.k.a. ***Wilson coefficients***),
depends on $M \sim \Lambda_H$ and couplings of UV theory:
RGE-evolved from $\Lambda_H \rightarrow \Lambda_L$

Towers of higher-dimension ($d > 4$) operators =
contact interactions expressed in terms of ϕ_L and suppressed by powers of Λ_H.
Systematic expansion, **predictive power**

Wilson, K G (1983), "The renormalization group and critical phenomena," Rev. Mod. Phys. 55, 583–600

Formally, in a nutshell

Λ_H ——— $\mathcal{L}(\phi_H, \phi_L)$ **Matching at Λ_H**

$\cancel{\phi}_H$ **RGE running $\Lambda_H \to \Lambda_L$**

Λ_L ——— $\mathcal{L}_{EFT}(\phi_L)$ **Predictions for observables, measured at Λ_L**

$$\mathcal{L}_{EFT} = \mathcal{L}_{d\leq 4} + \sum_{d=5}^{\infty} \frac{1}{\Lambda_H^{d-4}} \sum_{i=1}^{n_d} C_i^{(d)} Q_i^{(d)}$$

EFT are order by order (in Λ_H) renormalizable and s.t. the $C_i^{(d)}$ satisfy RGE (they are couplings)

$$\mu \frac{d}{d\mu}\mathcal{A} = 0 = \mu \frac{d}{d\mu}\left(C_i(\mu)\langle Q_i(\mu)\rangle\right) = \mu \frac{d}{d\mu} C_i(\mu)\langle Q_i(\mu)\rangle + C_i(\mu)\mu\frac{d}{d\mu}\langle Q_i(\mu)\rangle$$

$$\mu \frac{d}{d\mu} Q_i = -\gamma_{ij} Q_j \longrightarrow \mu \frac{d}{d\mu} C_i(\mu) = \gamma_{ij} C_j(\mu)$$

$$\left\{ \begin{array}{l} \gamma = \mathbf{Z}^{-1} \dfrac{d\mathbf{Z}}{d\ln\mu} \\ Q_{i,0} = \mathbf{Z}_{ij} Q_j \end{array} \right.$$

anomalous dimension

renormalization constant

Same as for any interaction in a renormalizable Lagrangian and its associated coupling

EFT - Main strategies

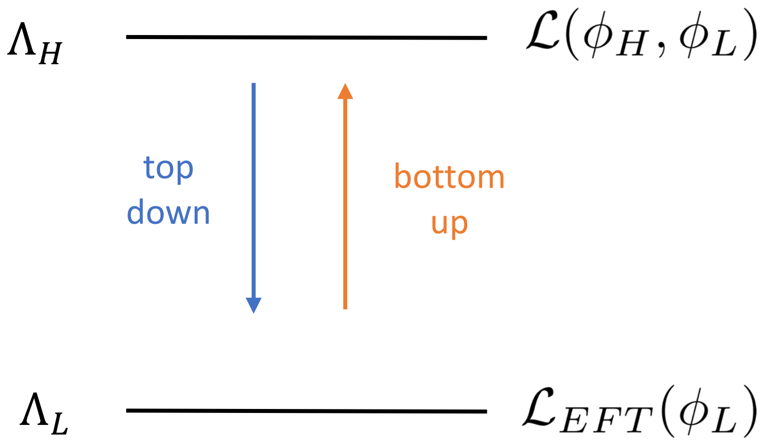
- The best use of EFT depends on how much is known of the UV theory
  - **Bottom-up** vs **Top-down**

- <u>**Some examples**</u>
  - *"eV world"* → QED
  - Fermi theory → Standard Model (SM) (**and back**!)
  - SM → SMEFT
  - SM → Flavor
  - …

Bottom-up

Top-down

Bottom-up vs Top-down



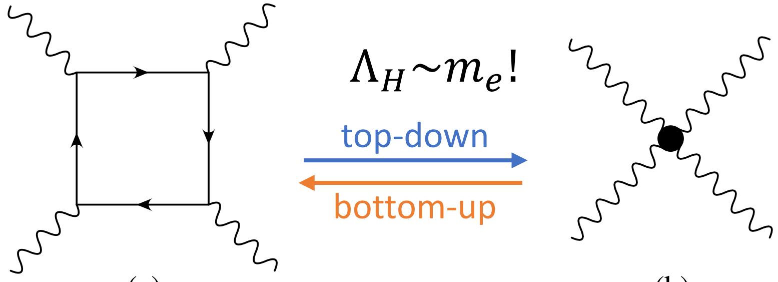
$$\mathcal{L}_{EFT} = \mathcal{L}_{d\leq 4} + \sum_{d=5}^{\infty} \frac{1}{\Lambda_H^{d-4}} \sum_{i=1}^{n_d} C_i^{(d)} Q_i^{(d)}$$

Bottom-up: most common in exploring unknown physics. Use the phenomenological knowledge of the Λ_L scale (local and global symmetries) to constrain the form of $\mathcal{L}_{EFT}$.

Top-down: preserves only relevant interactions plus improves accuracy through RGE evolution of Wilson coefficients. Crucial for theories involving multiple scales with large scale gaps.

Let's illustrate it with a few examples geared towards introducing the SM and the SM EFT

Example 1: photon-photon scattering



(a) (b)

$E \geq m_e$ (e, γ)

$E \ll m_e$ (γ)

Top-down:
convenient to calculate $\gamma\gamma \to \gamma\gamma$ at very low energy

$$\mathcal{L}_{QED} = \bar{\psi}(i\gamma^\mu D_\mu - m_e)\psi - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}$$

$$D_\mu = \partial_\mu + ieA^\mu$$
$$F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu$$

$$\mathcal{L}_{EFT} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{\alpha^2}{m_e^4}\left[c_1(F^{\mu\nu}F_{\mu\nu})^2 + c_2(F^{\mu\nu}\tilde{F}_{\mu\nu})^2\right]$$

(phase space)

$$\sigma_1 \sim \left(\frac{\alpha^2 E_\gamma^4}{m_e^4}\right)^2 \frac{1}{2E_\gamma^2} \sim \frac{\alpha^4 E_\gamma^6}{m_e^8} + O\left(\frac{E_\gamma^8}{m_e^{10}}\right)$$

Bottom-up:
living in a world with only photons!

Quite different conclusion if one assume $U(1)_{QED}$ or not

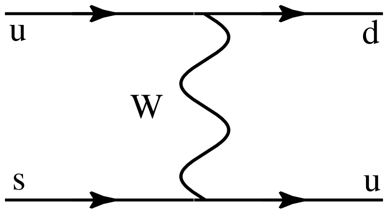
$$\mathcal{L}_{EFT} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \alpha^2(A^\mu A_\mu)^2$$

$$\sigma_2 \sim \alpha^4 \frac{1}{E_\gamma^2}$$

$$\frac{\sigma_1}{\sigma_2} \sim \left(\frac{E_\gamma}{m_e}\right)^8 \sim 10^{-48} \text{ (!!)}$$

$(E_\gamma \sim 1 \text{ eV}, m_e \sim 0.5 \text{ MeV})$

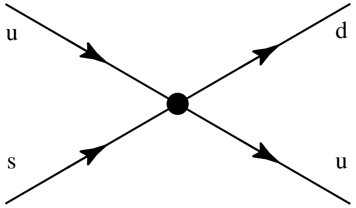
Example 2: Fermi theory → SM (and back!)



$\Lambda_H \sim M_W$

bottom-up

top-down



Top-down:

Low-Energy Effective Theory – Flavor physics

$$\mathcal{L}_{SM} = \ldots - \frac{ig}{\sqrt{2}} V_{ij} \bar{q}_i \gamma_\mu (1-\gamma_5) q_j W^\mu + \ldots$$

$$\frac{1}{p^2 - M_W^2} = -\frac{1}{M_W^2}\left(1 + \frac{p^2}{M_W^2} + \cdots\right)$$

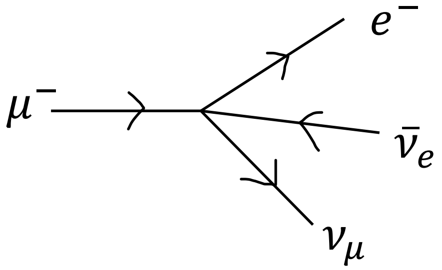
$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}$$

$$\mathcal{L}_{EFT} = -\underbrace{\frac{4G_F}{\sqrt{2}}}_{C_1} V_{us} V_{ud}^* \underbrace{[\bar{u}\gamma^\mu(1-\gamma_5)s][\bar{d}\gamma_\mu(1-\gamma_5)u]}_{Q_1} + O\left(\frac{1}{M_W^4}\right)$$

$\boxed{\text{+ QCD+QED evolution} \rightarrow C_1(\mu) \text{ entering meson decays}}$

Botton-up:

Fermi Theory (muon decay)



$$\mathcal{L}_{EFT} = -\frac{4G_F}{\sqrt{2}} [\bar{\nu}_\mu \gamma^\mu (1-\gamma_5)\mu][\bar{e}\gamma_\mu(1-\gamma_5)\bar{\nu}_e]$$

Purely phenomenological representation of weak charged currents → Found its UV completion in the SM

Example 3: SM → SMEFT

The SM as an effective low-energy realization of some UV completion.

Since the UV completion is unknown it is necessarily **bottom-up**,
although it can be very instructive to **try top-down exercises with template models**

$$\mathcal{L}_{SMEFT}(\psi, H, A) = \mathcal{L}_{SM}(\psi, H, A) + \sum_{d=5}^{\infty} \sum_{i=1}^{n_d} \frac{C_i^{(d)}}{\Lambda^{(d-4)}} Q_i^{(d)}(\psi, H, A)$$

ψ → fermions
H → scalars
A → gauge bosons

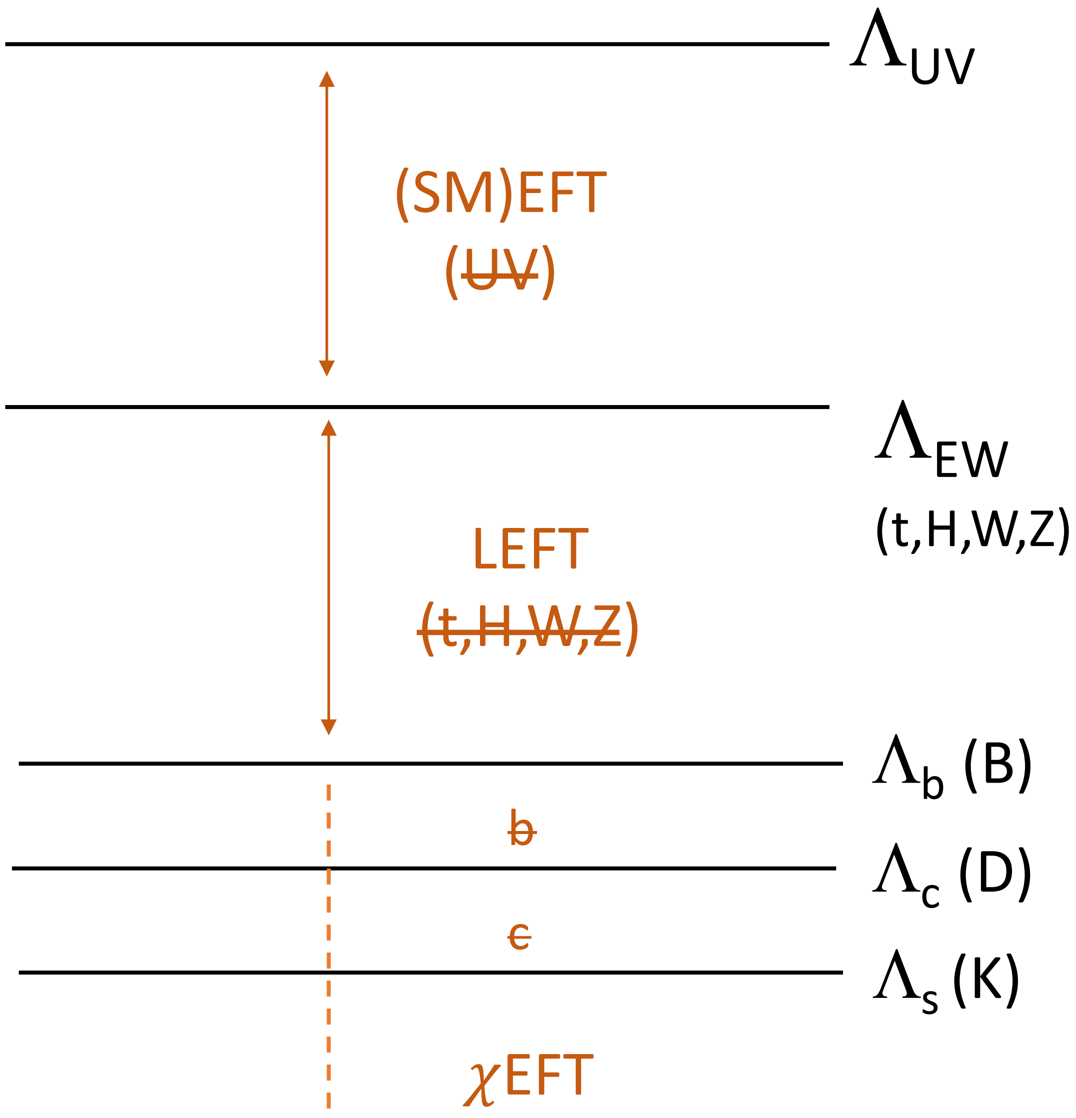
where the $Q_i^{(d)}$ are functions of the fields of the SM (ψ, H, A) and respect

- Lorentz invariance
- $SU(3)_c \times SU(2)_L \times U(1)_Y$ SM gauge symmetry
- Global symmetry such as lepton (L) and barion (B) number conservation

We will analyze in detail the case of dim=6 operators, and discuss the validity of such approximation

The full picture

Connecting far apart scales (from BSM to flavor) naturally lends itself to the EFT framework



Heavy physics decouples and leaves effective contact interactions of dim > 4

RGE

EFT operators in terms of SM fields

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{i,d} \frac{C_{i,d}^{\text{SMEFT}}}{\Lambda^2} \mathcal{O}_{i,d}^{\text{SMEFT}}$$

RGE

WC depend on m_t, M_W, M_Z, M_H, ...M_X

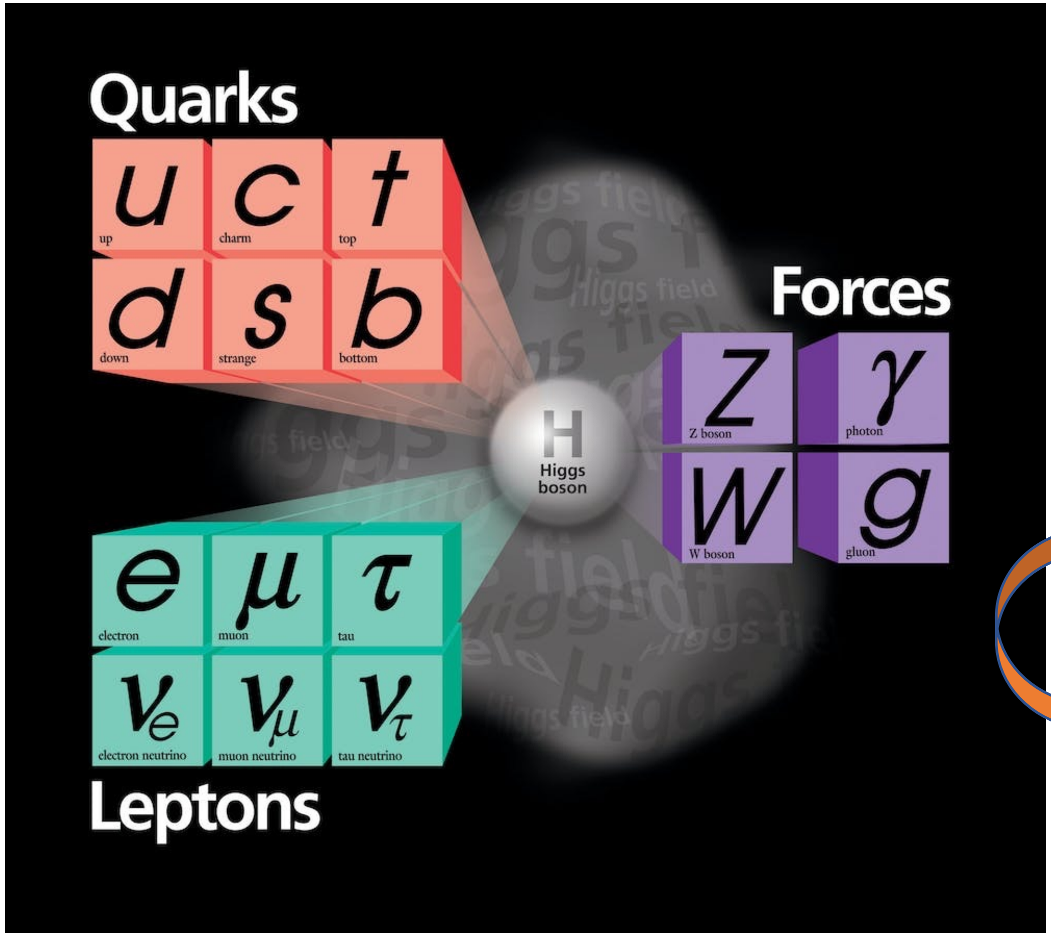
$$\mathcal{L}_{\text{LEFT}} = \mathcal{L}_{\text{QCD+QED}} + \sum_{i,d} \frac{C_{i,d}^{\text{LEFT}}}{v^2} \mathcal{O}_{i,d}^{\text{LEFT}}$$

Calculate physical processes at each scale and derive constraints on the UV theory

Constructing the SMEFT

- The SM: brief review, strengths and weaknesses.
- Adding dim=6 SMEFT interactions.

The SM – main framework, strengths and weaknesses



A very minimal quantum field theory describing strong, weak, and electromagnetic interactions, based on a local (gauge) symmetry

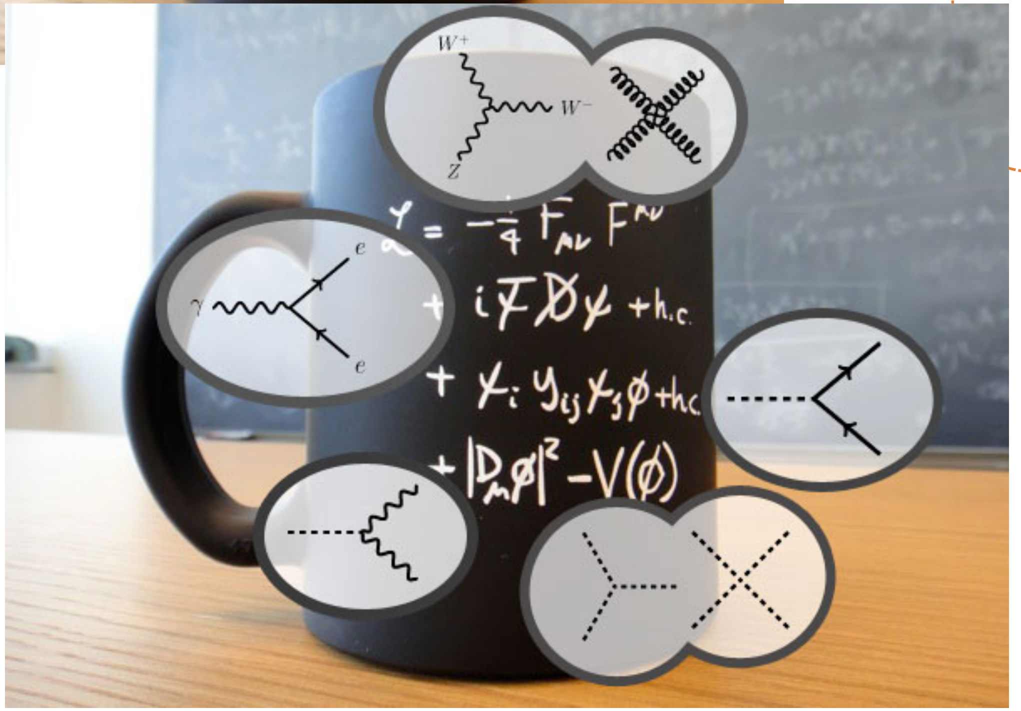
$$SU(3)_c \times SU(2)_L \times U(1)_Y \to SU(3)_c \times U(1)_Q$$

Strong interactions: gluons → $m_g = 0$
Electromagnetic interactions: photon → $m_\gamma = 0$
Weak interactions: $W^\pm$ and Z → $M_W, M_Z \neq 0$

Due to the presence of a scalar field whose potential spontaneously breaks the gauge symmetry of electroweak interactions and gives origin to massive gauge bosons (W,Z)

The Higgs boson (H) is the physical particle associated with such field

SM on a mug ...



$$\mathcal{L}_{SM}^{(4)} = -\frac{1}{4} G_{\mu\nu}^{A} G^{A,\mu\nu} - \frac{1}{4} W_{\mu\nu}^{I} W^{I,\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}$$

SSB, origin of W/Z masses

$$+ (D_\mu \varphi)^\dagger (D^\mu \varphi) + m^2 \varphi^\dagger \varphi - \frac{1}{2} \lambda (\varphi^\dagger \varphi)^2$$

$$+ i \left(\bar{l'}_L \not{D} l'_L + \bar{e'}_R \not{D} e'_R + \bar{q'}_L \not{D} q'_L + \bar{d'}_R \not{D} d'_R \right)$$

$\mathcal{L}_{Yukawa}$, origin of fermion masses

$$- \left(\bar{l'}_L \Gamma_e e'_R \varphi + \bar{q'}_L \Gamma_u u'_R \tilde{\varphi} + \bar{q'}_L \Gamma_d d'_R \varphi \right) + h.c.$$

with covariant derivative:

$$D_\mu = \partial_\mu + i g_s G_\mu^A \mathcal{T}^A + i g_W W_\mu^I T^I + i g_1 B_\mu Y$$

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

$$\left\{ \begin{array}{rcl} G_{\mu\nu}^{A} & = & \partial_\mu G_\nu^A - \partial_\nu G_\mu^A + g_3 f^{ABC} G_\mu^B G^C{}_\nu \\ W_{\mu\nu}^{I} & = & \partial_\mu W_\nu^I - \partial_\nu W_\mu^I + g_2 \epsilon^{IJK} W_\mu^J W^K{}_\nu \\ B_{\mu\nu} & = & \partial_\mu B_\nu - \partial_\nu B_\mu \end{array} \right.$$

SM Higgs mechanism: a very constrained pattern

$$\{g_s\}$$

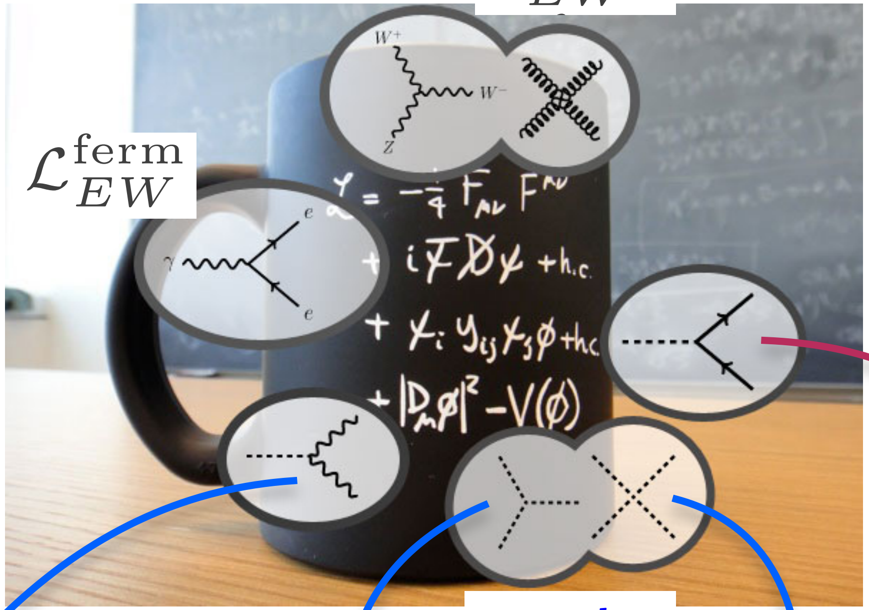
$$\mathcal{L}_{SM} = \mathcal{L}_{QCD} + \mathcal{L}_{EW}$$

$$\{g_1, g_2, \underline{\mu, \lambda}\} + \{\underline{y_f, V_{CKM}}\}$$

$$\mathcal{L}_{EW} = \mathcal{L}_{EW}^{\rm gauge} + \mathcal{L}_{EW}^{\rm ferm} + \mathcal{L}_{EW}^{Yukawa} + \mathcal{L}_{EW}^{scalar}$$

$$\mathcal{L}_{EW}^{\rm gauge}$$

$$\mathcal{L}_{EW}^{\rm ferm}$$



$$\mathcal{L}_{EW}^{Yukawa}$$

$$-i\frac{m_f}{v} = iy_f$$

$$\mathcal{L}_{EW}^{scalar}$$

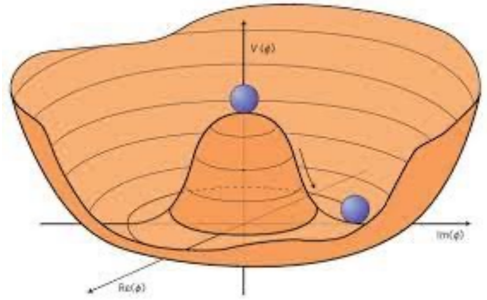
$$-2i\frac{M_V^2}{v} g^{\mu\nu} \qquad -3i\frac{M_H^2}{v} = -6iv\lambda \qquad -3i\frac{M_H^2}{v^2} = -6i\lambda$$

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$

$$\langle \phi \rangle = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \xrightarrow{\text{SSB}} \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ H + v \end{pmatrix}$$

$$(\mu^2 < 0)$$

$$v = (-\mu^2/\lambda)^{1/2}$$



Higgs interactions

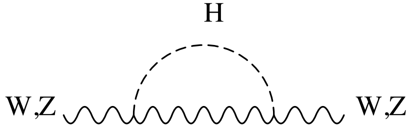
particle masses

SM: unique pattern of Higgs couplings and particle masses

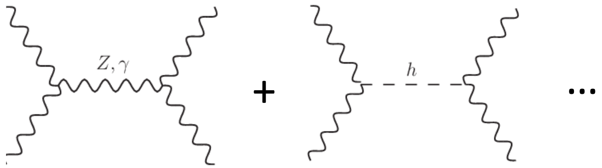
But the origin of such pattern escapes the SM

The Higgs is necessary to the consistency of the SM as a quantum theory,
W and Z have longitudinal components that can be problematic without a Higgs:

- Loop corrections are not finite without a Higgs



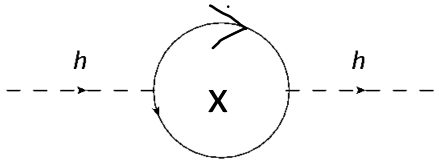
- Scattering amplitudes grows with energy: unitarity violation



But the origin of SSB and ultimately of the EW scale is unexplained by the SM

- Why the **Higgs potential**? Why $\mu^2<0$?
  - Dynamical origin? What induces it?

- Why M_H=125 GeV? → **Hierarchy problem** - **Naturalness**
  - Mass of scalar not protected by symmetry, receives large quantum corrections



$$\Delta M_H^2 \propto \pm \frac{\lambda_X}{16\pi^2} M_X^2$$

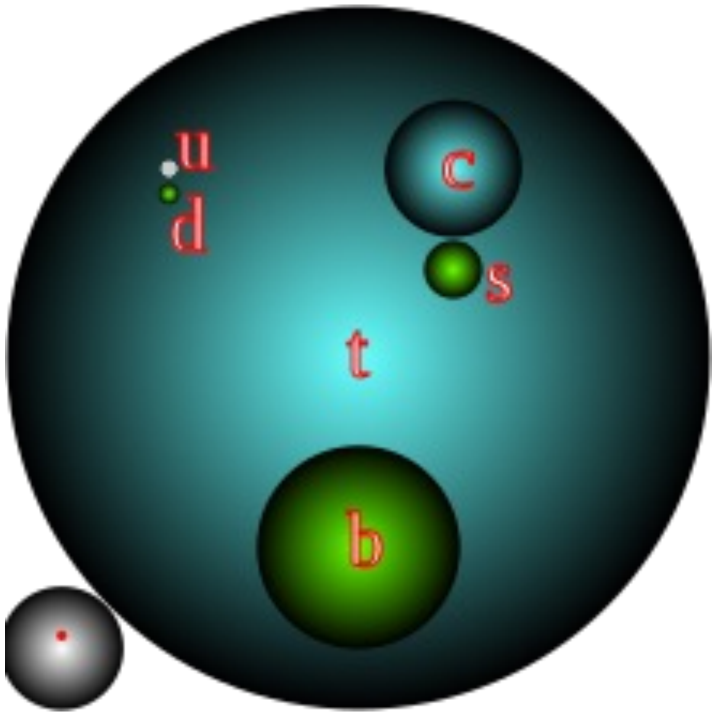
Yukawa couplings to fermions: an even deeper mystery

$$L_{Yuk} = y_{ij}\bar{\psi}_L^i \phi \psi_R^j + h.c.$$

$$\phi \to H + v$$

Yukawa couplings

fermion masses



- Why the hierarchy of fermion masses?
- Why the hierarchy of Yukawa couplings?
  (arbitrary in the SM)

- Why flavor-diagonal scalar couplings? ↔ Why one Higgs?
  (With more than one Higgs mass and current eigenstates can be different)

$$y_{ij} \to \frac{m_f}{v}\,\delta_{ij} = y_f$$

- Intimately related to flavor dynamics

- **Is this a new force all together??**

SM – weaknesses and strengths

Apart from not explaining nor including

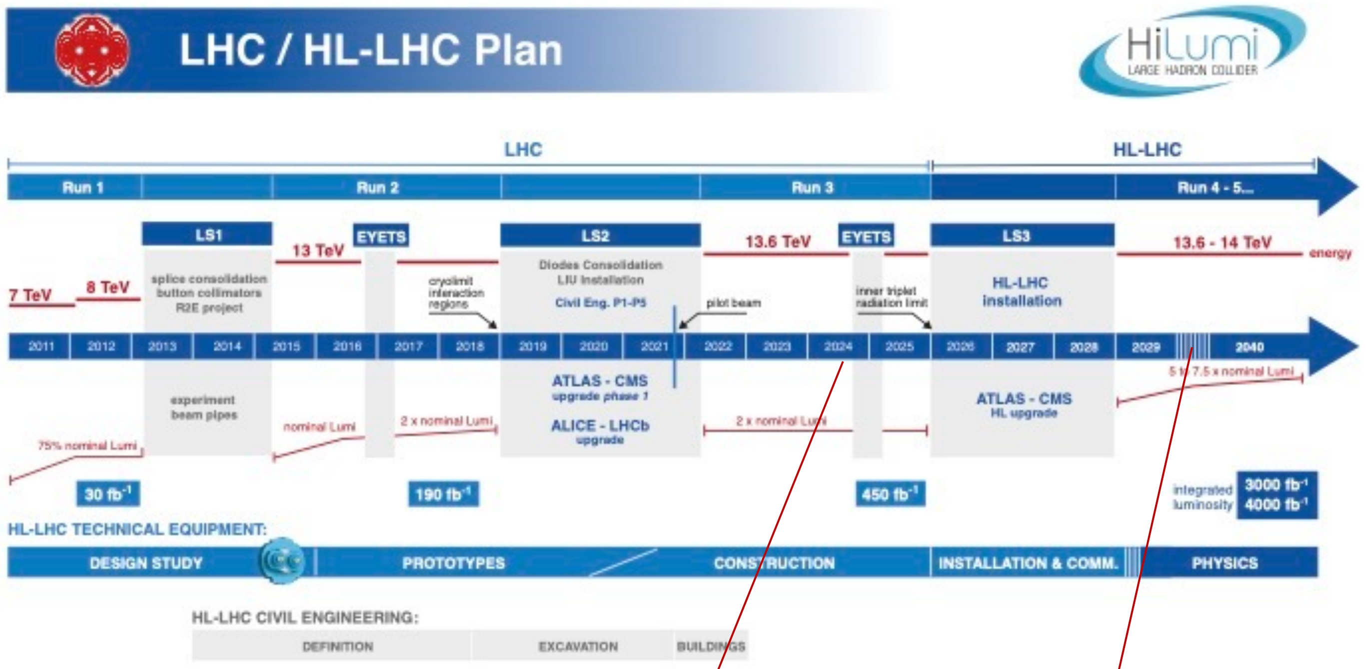
- The nature of dark matter and dark energy
- The origin of the baryon asymmetry of the universe
- Gravity as a quantum theory

The scalar sector of the SM leaves lots of questions unexplained and mainly fails to explain the origin of the EW scale itself.

This could also be the strength of the SM:

The incredible success of the SM theory in describing the EW scale phenomenology, all the way to the discovery of the Higgs and the measurement of its properties, is giving us a **unique handle on physics beyond the SM (BSM) if we can identify and interpret its signals.**

The LHC era: exploring the TeV scale



We are only here

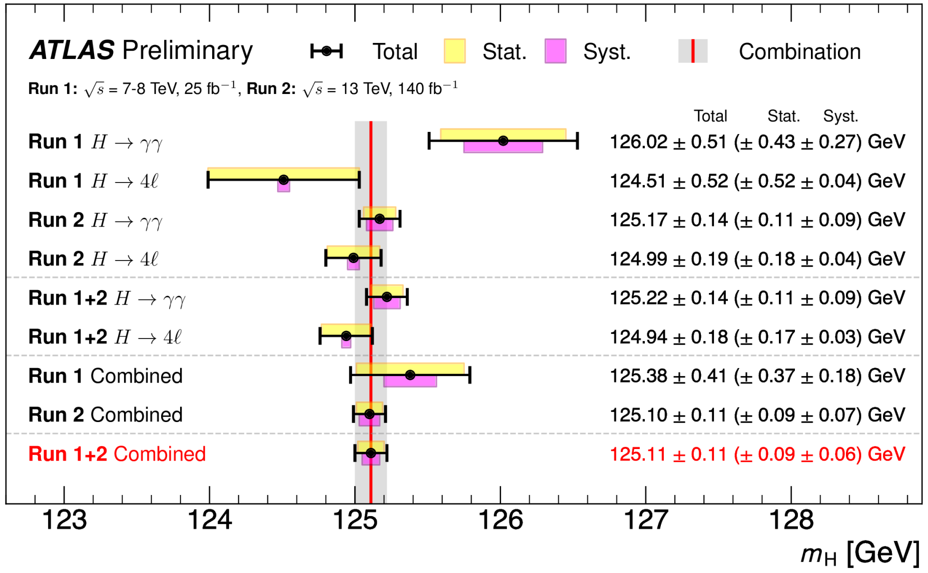
Many years of HL running ahead of us

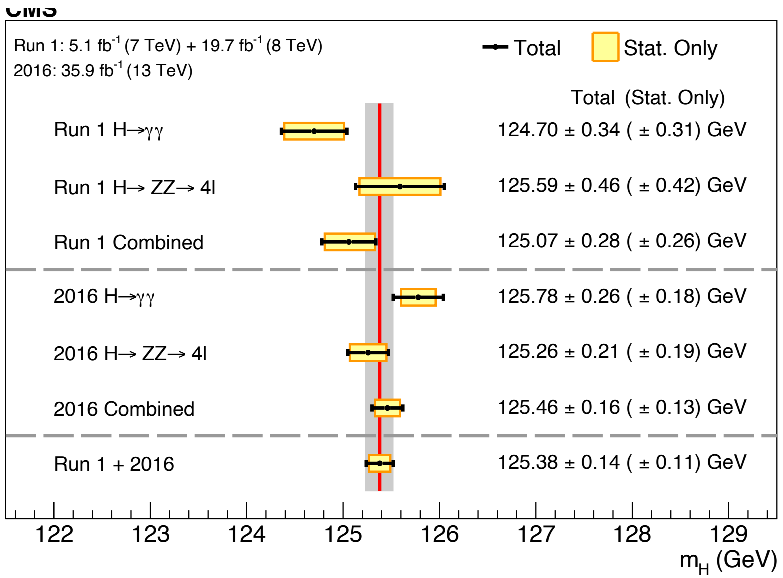
- Run 2+3 delivery for Higgs couplings outperformed expectations
- State-of-the-art precision measurements of SM parameters
- LHC will define top physics till the next high-energy collider
  - e^+e^- > 500 GeV
  - pp@100 TeV
  - $\mu^+\mu^-$ > 10 TeV

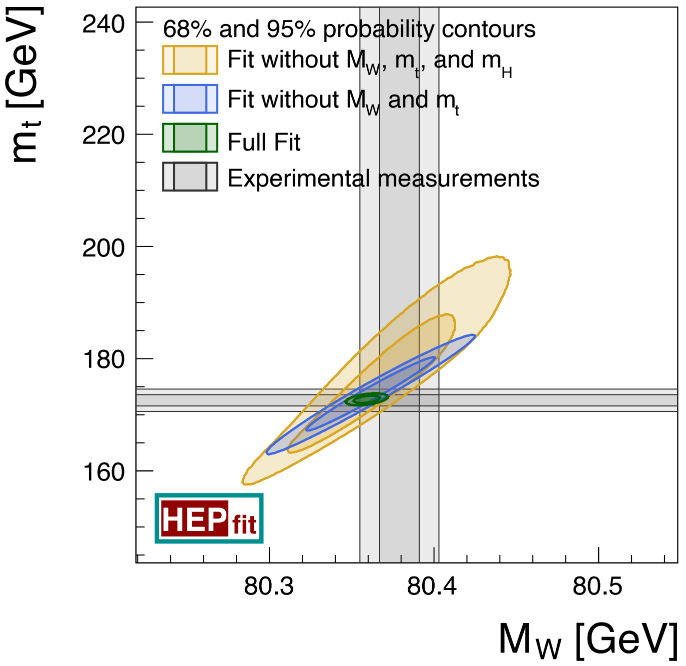
→ 2-fold increase in statistics by the end of Run 3
→ 20-fold increase in statistics by the end of HL-LHC!

Run 1+2

From discovery to precision physics



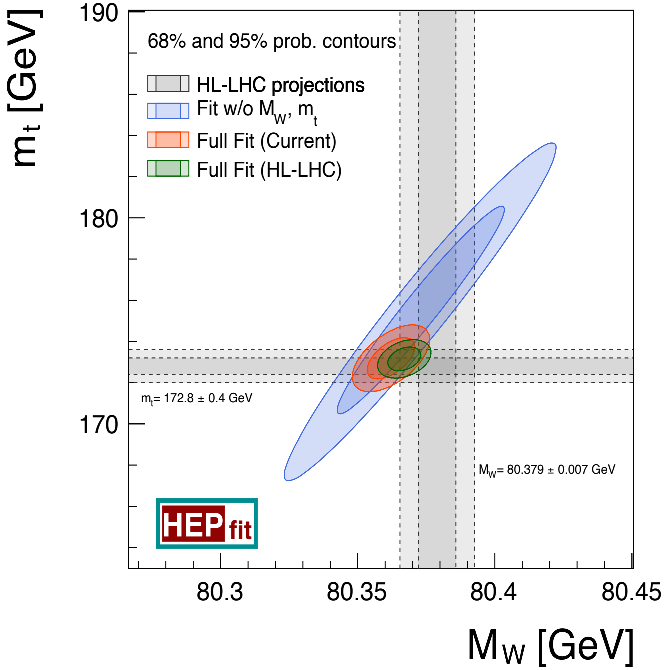




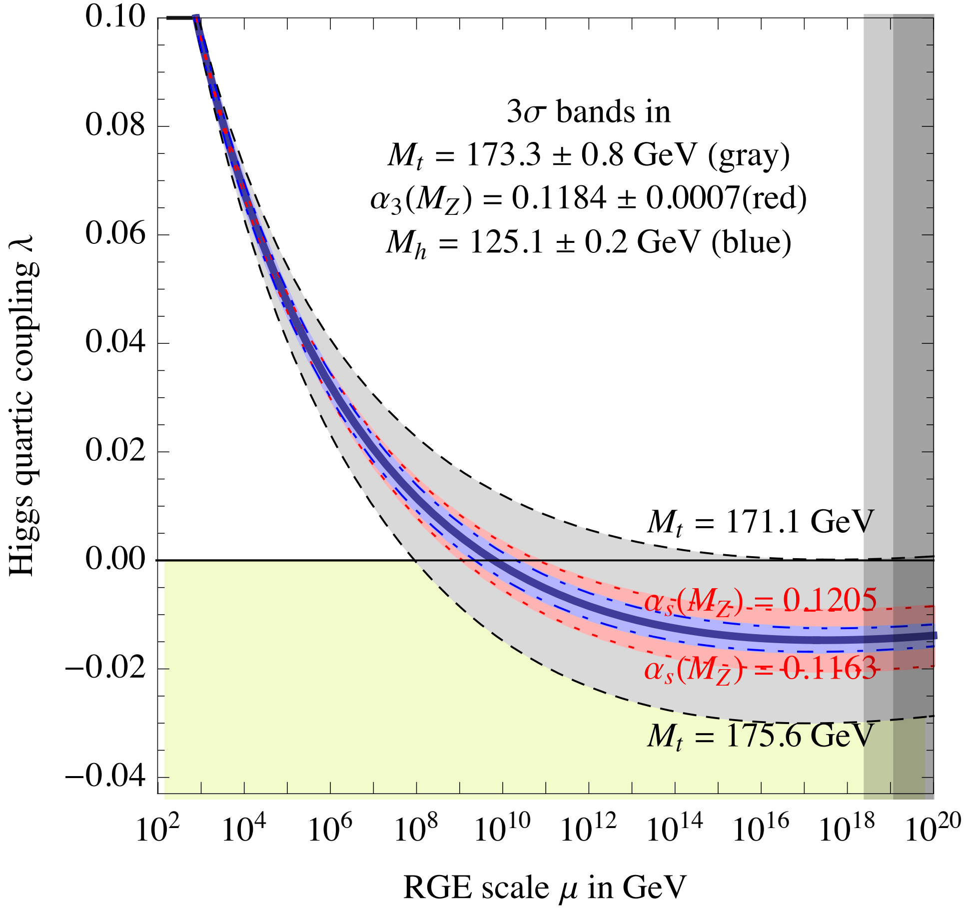
De Blas et al. [2204.04204] (HEPfit collaboration)

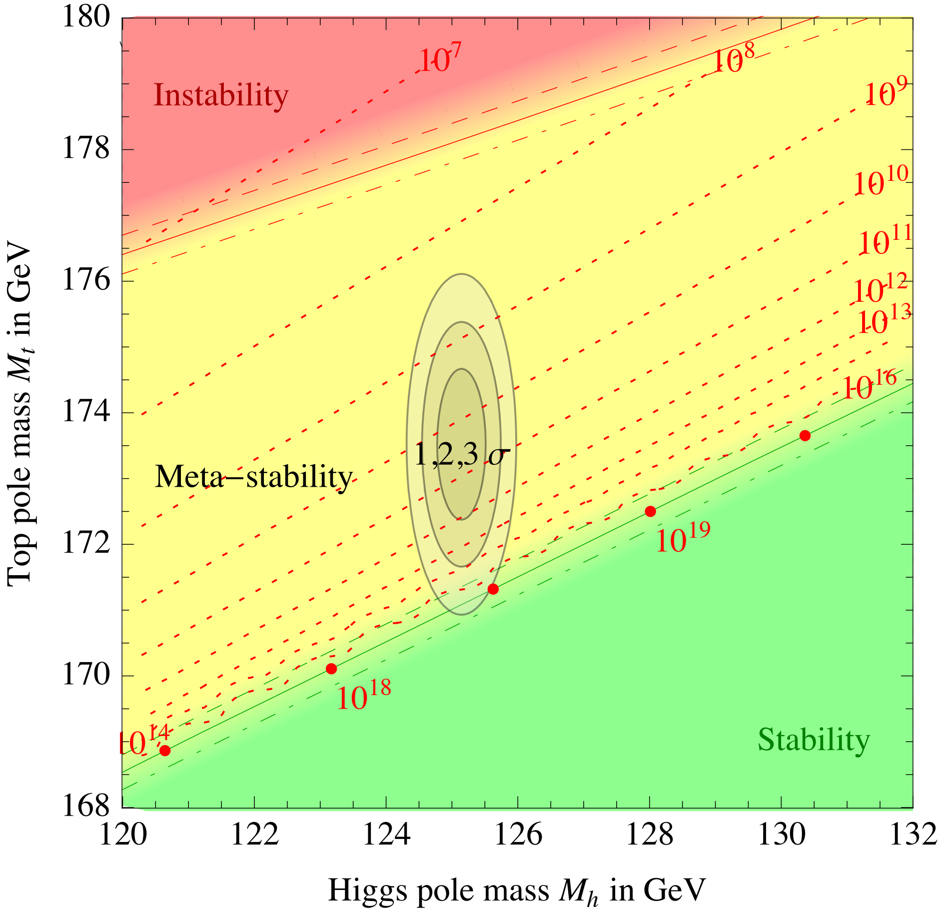
De Blas et al. HL/HE-LHC Report [1902.04070]

M_H promoted to EW precision observable



$M_t \leftrightarrow M_H$, the EW phase transition, and the history of the universe





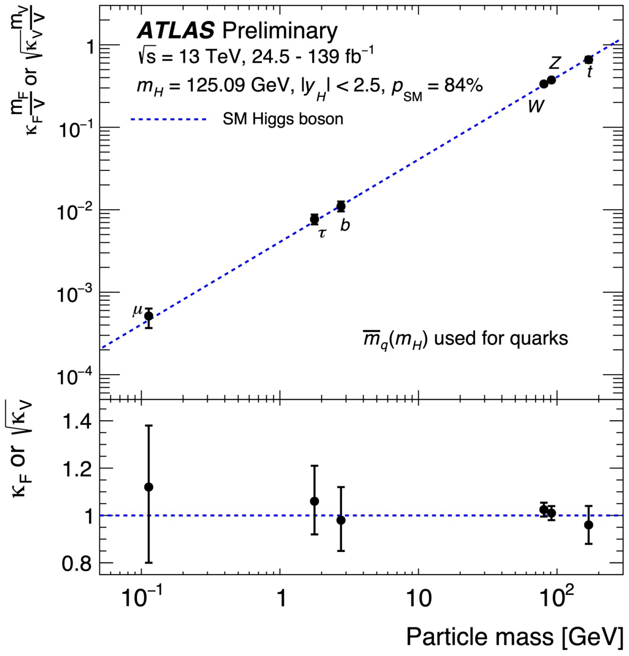
Buttazzo et al., arXiv:1307.3536

Criticality (**λ → 0**) condition reached for $\Lambda \approx 10^{10}$–10^{12} GeV.

Is this a signal of NP below the Planck scale?

Run 2+3 Zooming in on couplings to probe the TeV scale

CMS, arXiv:2207.00043

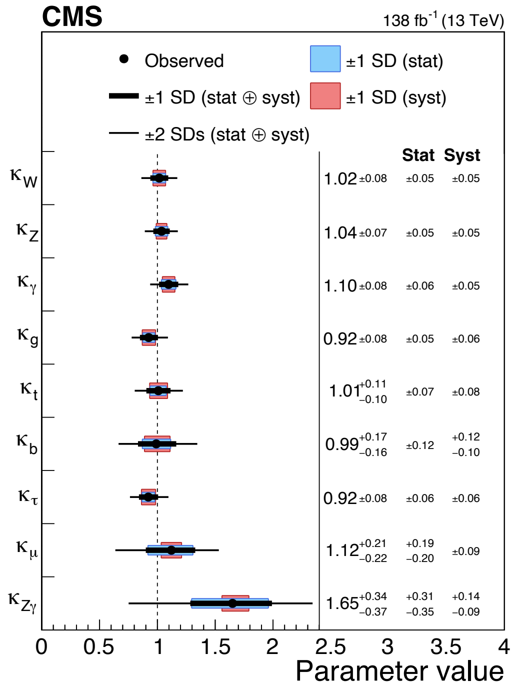


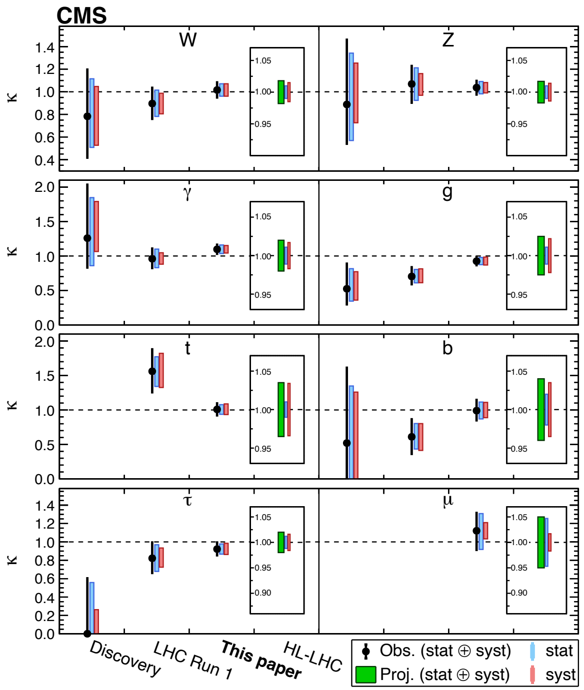
$\kappa = g_X/g_X^{SM} = 1 + \Delta\kappa$

$\Delta\kappa \propto v^2/\Lambda_{BSM}^2$

Precision on $\Delta\kappa$

reach for Λ_{BSM}





- Couplings to **W/Z at 5-10 %**
- Couplings to **3rd generation to 10-20%**
- **First measurements of 2nd generation** couplings

- **HL-LHC projections** from **partial Run 2** data (YR):
  - **2-5 % on most couplings**
  - **< 50% on Higgs self-coupling.**
- **Full Run2** results **drastically improve partial Run 2 results:** better projections expected

Run 3 and beyond

Beyond SM-coupling rescaling

Extend SM Lagrangian by effective interactions (ex. SM EFT)

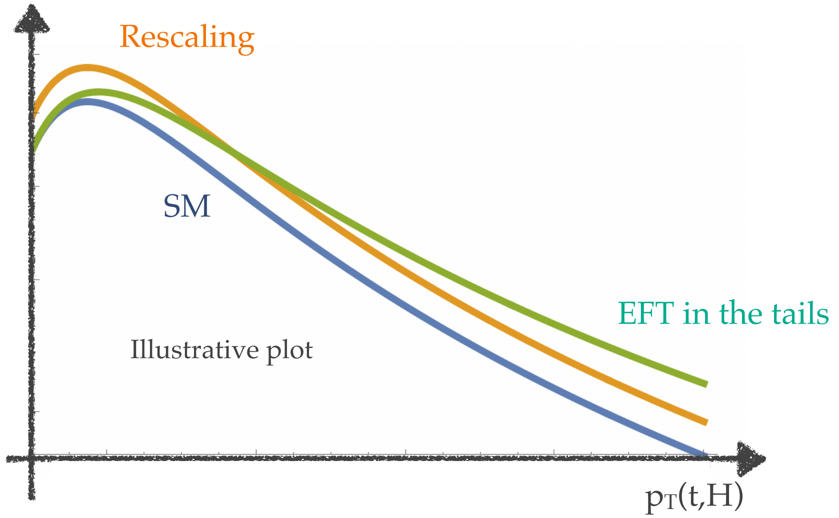
$$\mathcal{L}_{\rm SM}^{\rm eff} = \mathcal{L}_{\rm SM} + \sum_{d>4} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

$$\mathcal{L}_d = \sum_i C_i^{(d)} \mathcal{O}_i^{(d)}, \quad \left[\mathcal{O}_i^{(d)}\right] = d$$

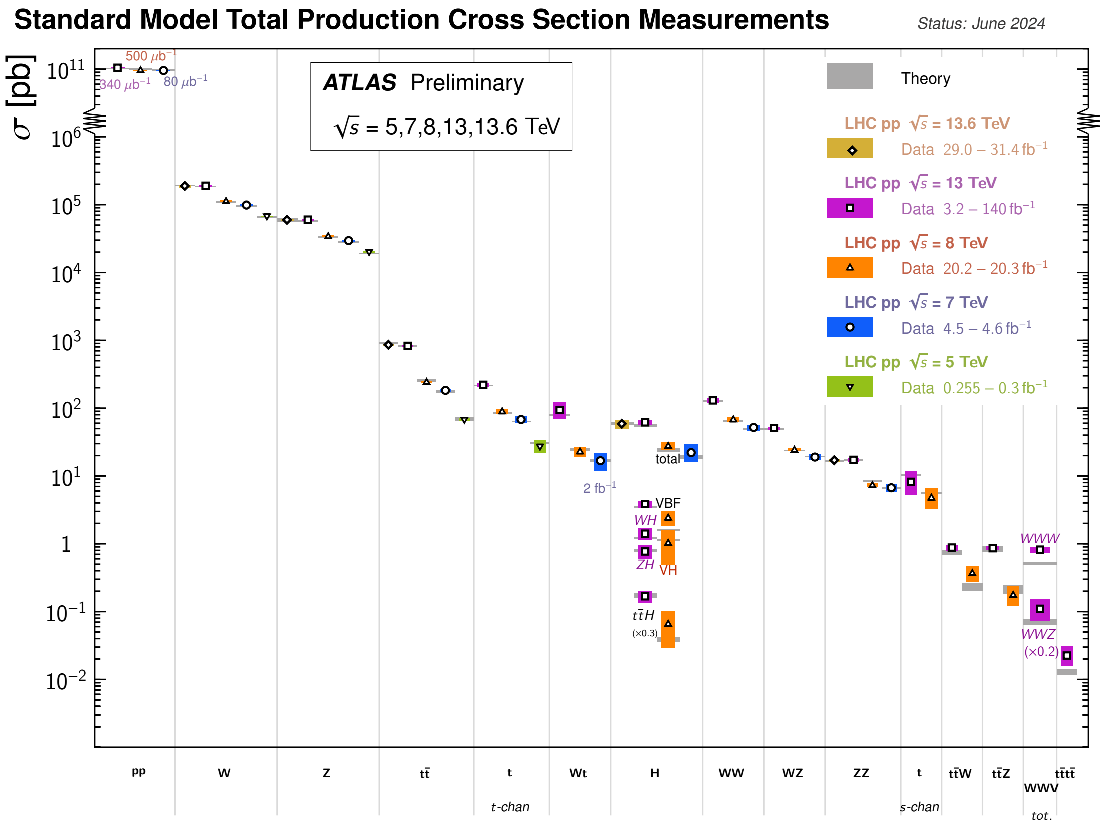
Under the assumption that new physics leaves at scales $\Lambda > \sqrt{s}$

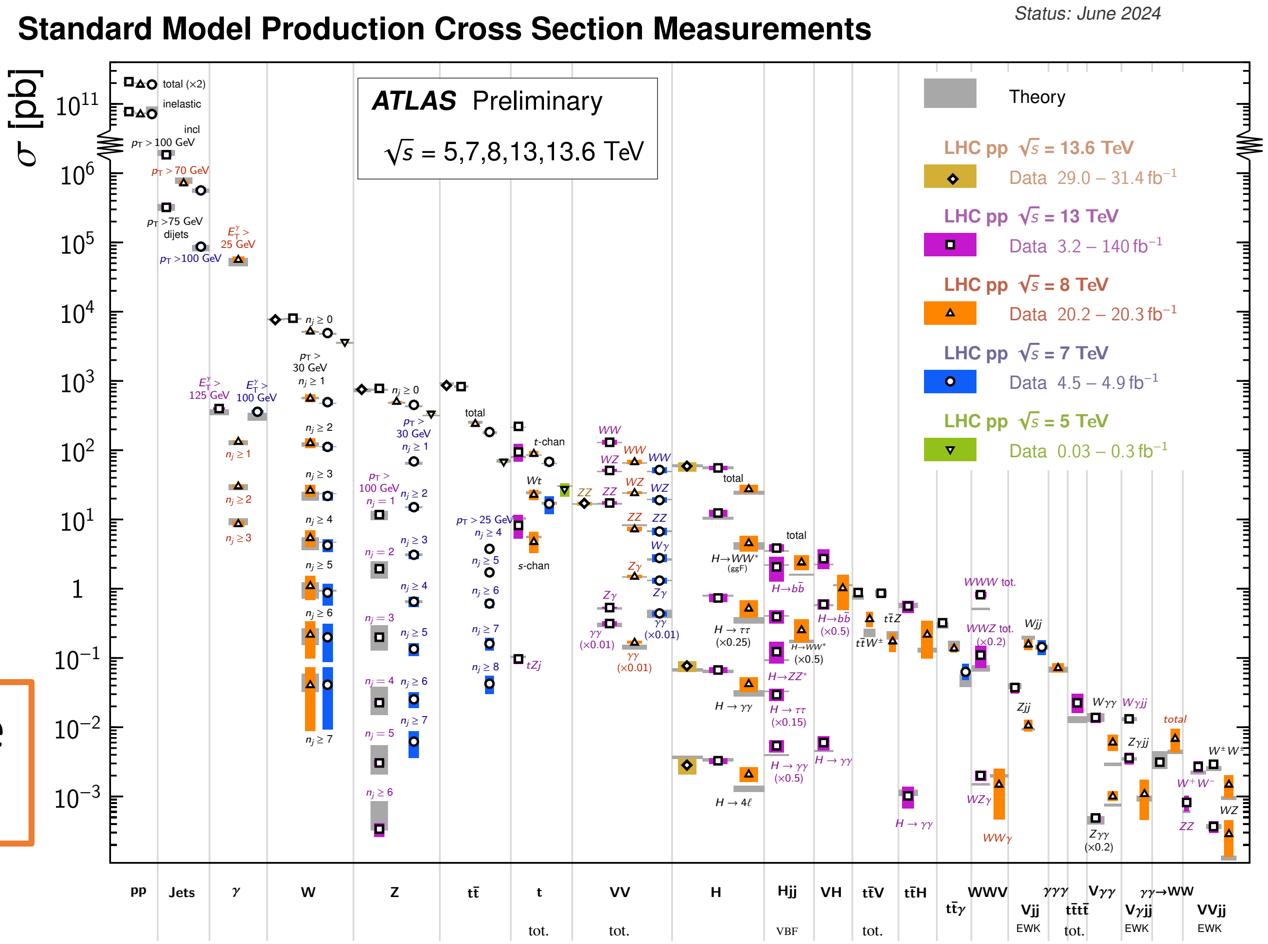
Expansion in $(v, E)/\Lambda$: **affects all SM observables** at both low and high energy

- **SM masses and couplings** → **rescaling**
- **Shapes of distributions** → more visible in **tails of distributions**



The breadth of LHC measurements





Literally hundreds of *observables* that all have to agree on the same new physics pattern!

Ideally suited for EFT approach

The SM EFT framework

Grzadkowski, Iskrzynski, Misiak, Rosiek, 1008.4884

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM}^{(4)} + \sum_i \frac{C_i}{\Lambda^2} Q_i + \dots$$

"Warsaw" basis

$$\mathcal{L}_{SM}^{(4)} = -\frac{1}{4}G^A_{\mu\nu}G^{A,\mu\nu} - \frac{1}{4}W^I_{\mu\nu}W^{I,\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + (D_\mu\varphi)^\dagger(D^\mu\varphi) + m^2\varphi^\dagger\varphi - \frac{1}{2}\lambda(\varphi^\dagger\varphi)^2 + i\left(\bar{l}'_L \not{D} l'_L + \bar{e}'_R \not{D} e'_R + \bar{q}'_L \not{D} q'_L + \bar{d}'_R \not{D} d'_R\right) - \left(\bar{l}'_L \Gamma_e e'_R \varphi + \bar{q}'_L \Gamma_u u'_R \tilde{\varphi} + \bar{q}'_L \Gamma_d d'_R \varphi\right) + h.c.$$

with covariant derivative:

$$D_\mu = \partial_\mu + i g_s G^A_\mu T^A + i g_W W^I_\mu T^I + i g_1 B_\mu Y$$

Higgs field and Mh

Yukawa couplings

Vff, HFF

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
$\mathcal{O}_G$	$f^{ABC}G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$	$\mathcal{O}_\varphi$	$(\varphi^\dagger\varphi)^3$	$\mathcal{O}_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p\varphi e_r)$
$\mathcal{O}_W$	$\varepsilon^{IJK}W^{I\nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho$	$\mathcal{O}_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$\mathcal{O}_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p\tilde{\varphi}u_r)$
		$\mathcal{O}_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star\left(\varphi^\dagger D_\mu\varphi\right)$	$\mathcal{O}_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p\varphi d_r)$
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$\mathcal{O}_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu}G^{A\mu\nu}$	$\mathcal{O}_{eW}$	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I\varphi W^I_{\mu\nu}$	$\mathcal{O}^{(1)}_{\varphi l}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{l}_p\gamma^\mu l_r)$
$\mathcal{O}_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu}W^{I\mu\nu}$	$\mathcal{O}_{eB}$	$(\bar{l}_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$\mathcal{O}^{(3)}_{\varphi l}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$\mathcal{O}_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{uG}$	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\tilde{\varphi}\, G^A_{\mu\nu}$	$\mathcal{O}_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{e}_p\gamma^\mu e_r)$
$\mathcal{O}_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{uW}$	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\tilde{\varphi}\, W^I_{\mu\nu}$	$\mathcal{O}^{(1)}_{\varphi q}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_p\gamma^\mu q_r)$
		$\mathcal{O}_{uB}$	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tilde{\varphi}\, B_{\mu\nu}$	$\mathcal{O}^{(3)}_{\varphi q}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
		$\mathcal{O}_{dG}$	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)\varphi\, G^A_{\mu\nu}$	$\mathcal{O}_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_p\gamma^\mu u_r)$
		$\mathcal{O}_{dW}$	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W^I_{\mu\nu}$	$\mathcal{O}_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{d}_p\gamma^\mu d_r)$
		$\mathcal{O}_{dB}$	$(\bar{q}_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$\mathcal{O}_{\varphi ud}$	$(\tilde{\varphi}^\dagger iD_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

gauge fields and masses, HVV, VVV

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

4-fermion interactions: tt, ttH, DY

- Obeying SM symmetries, CP even
- One Higgs doublet of $SU(2)_L$, SSB linearly realized.
- Assuming various flavor symmetries.