Part III
Beyond the Standard Model (BSM)
From a bottom-up perspective it represents the scale up to which only SM fields propagate.
It parametrizes our ignorance of physics above $\Lambda$.

From a top-down perspective (where we assume a given BSM) it represents a typical mass scale (e.g. $m_{H^2}$ in 2 Higgs doublets models).
Some models have more scales...

Synonyms: UV scale, Cutoff, Microscopic scale,...
What did we learn from the Higgs Discovery/Mass about the Microcosm?

Mass $m_h=125$ GeV

(Later: what can be learned from couplings?)

Because of $m_h=125$ GeV, no more (WW) unitarity argument for new TeV physics

Now: $\Lambda=?$

Because of $m_h=125$ GeV, the SM up to $M_{pl}$ is (meta) stable
a BSM Higgs?

What did we learn from the Higgs Discovery/Mass about the Microcosm?

**Mass \( m_h = 125 \text{ GeV} \)**

(Later: what can be learned from couplings?)

Because of \( m_h = 125 \text{ GeV} \), the EW phase transition in the early universe is not first order.

(Sakharov (1967): to produce the baryon asymmetry we need an out-of-equilibrium situations, like in a 1st order phase transition.)

Need BSM!

...but there are models with \( \Lambda = 10^{15} \text{ GeV} \) that can produce the baryon asymmetry (leptogenesis)
The hierarchy problem (brief):

Number of degrees of freedom...

<table>
<thead>
<tr>
<th></th>
<th>( m = 0 )</th>
<th>( m \neq 0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fermions</td>
<td>( \psi_L )</td>
<td>( \psi_L, \psi_R )</td>
</tr>
<tr>
<td>Vectors</td>
<td>( \epsilon^\pm )</td>
<td>( \epsilon^\pm, \epsilon^0 )</td>
</tr>
<tr>
<td>Scalars</td>
<td>( \phi )</td>
<td>( \phi )</td>
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</table>

Discontinuity \(\Rightarrow\) quantum corrections cannot generate a mass...

Scalars have no discontinuity \(\Rightarrow\) generated mass of order cutoff \(\Lambda\)

Discontinuity computation would be used to calculate the temperature for a snowball in hell; you expect it to melt!

Rattazzi/Giudice
Number of degrees of freedom...

Fermions: \( \psi_L \) → \( \psi_L, \psi_R \)

Vectors: \( \epsilon^\pm \) → \( \epsilon^\pm, \epsilon^0 \)

Scalars: \( \phi \) → \( \phi \)

Discontinuity ➔ quantum corrections cannot generate a mass...

Scalars have no discontinuity ➔ generated mass of order cutoff \( \Lambda \)

Simplest known solution: Naturalness \( \Lambda \sim \text{TeV} \)
a BSM Higgs?

Summary so far: Physics BSM exists (DM, baryon asymmetry, ...) ...but we do not know its scale (and the Higgs didn't add much)

Only physical hypothesis that LHC is guaranteed to test: naturalness

(New states lurking around $\Lambda \approx \text{TeV}$)

New States at LHC!
- big (resonant) effects
- big model-dependence

No new States at LHC!
- small effects
- model-independent parametrization possible

Most general Lagrangian with SM gauge group and field content:

$$\mathcal{L} = \Lambda^4 + \text{loop} \Lambda^2 |H|^2 + \mathcal{L}_4 + \frac{\mathcal{L}_5}{\Lambda} + \frac{\mathcal{L}_6}{\Lambda^2} + \cdots$$

$$m_h = 125\text{GeV} \rightarrow \Lambda \approx 1\text{ TeV}$$

Might be observable!

Effective Field Theory:
**Effective Field Theory**

Write the most general Lagrangian with only light (SM) fields: it will automatically include all effects that can be generated at \( \Lambda \) and how they modify SM physics!

\[
\mathcal{L}_{\text{EFT}} = \mathcal{L}_{d \leq 4} + \frac{\mathcal{L}_5}{\Lambda} + \frac{\mathcal{L}_6}{\Lambda^2} + \cdots
\]

\( \mathcal{L}_n \) includes all field operators with dimension=\( n \), e.g for dim-6:

\[
|H^\dagger H|B_{\mu\nu}B^{\mu\nu}
\]

But this is non-renormalizable!

"Non-renormalizable theories are as renormalizable as renormalizable ones" - S. Weinberg

(meaning that infinities are still unobservable and the theory remains predictive - to a given \( O(E/\Lambda) \))

Where does it come from? (top-down perspective)

E.g. a theory with a heavy resonance of mass \( m_{Z'} = \Lambda \), would look at low energy exactly like this:

\[
\begin{align*}
\frac{1}{p^2 - \Lambda^2} & \quad \xrightarrow{p^2 \ll \Lambda^2} \\
\frac{g_*^2}{\Lambda^2} & \quad \xrightarrow{O\left(\frac{p^2}{\Lambda^2}\right)}
\end{align*}
\]

What does it do? (bottom-up perspective)

It deforms the relations implied by the SM \( \mathcal{L}_\text{SM} \equiv \mathcal{L}_{d \leq 4} \)

Exemple, the relation between Higgs couplings and particle masses:

\[
\mathcal{L}_\text{SM} + c_f \frac{|H|^2}{\Lambda^2} \bar{\psi}_L H \psi_R \quad \xrightarrow{\text{SM}} \quad -i \frac{m_f}{v} (1 + c_f \frac{v^2}{\Lambda^2})
\]
Effective Field Theory

\[ \mathcal{L}_{\text{EFT}} = \mathcal{L}_{d \leq 4} + \frac{\mathcal{L}_5}{\Lambda} + \frac{\mathcal{L}_6}{\Lambda^2} + \ldots \]

EFT for the Higgs, why?

- Practically: EFT is a **systematic** parametrization of deviations from the SM and carries a **physical meaning** → precision tests comparable with direct searches.
- Theoretically: If EWSB sector strongly coupled, bigger effects here.

Ok, but how many new parameters are we talking about?

- How many? Only one*...
  \[ \frac{\left(\bar{L} \tilde{H}^*\right)\left(L \tilde{H}^+\right)}{\Lambda} \]
  \[ \tilde{H} = i \sigma_2 H \]

- What BSM generates it? Heavy RH neutrinos with \( m = \frac{\Lambda}{\sqrt{2}} \)

- What does it do to the SM? Gives mass to neutrinos \( m_\nu \propto \frac{v^2}{\Lambda} \)

(*= for simplicity I’ll consider a universal flavor structure and no CPV - See Gori’s Lecture)
EFT for Higgs Physics

Has many terms, but only 17 affect Higgs physics (modifying the SM predictions)

| $O_r$ | $|H|^2(D_\mu H)\dagger(D^\mu H)$ |
|-------|----------------------------------|
| $O_{yd}$ | $y_d|H|^2\bar{Q}_L H d_R$ |
| $O_{ye}$ | $y_e|H|^2\bar{L}_L H e_R$ |
| $O_{yu}$ | $y_u|H|^2\bar{Q}_L \tilde{H} u_R$ |
| $O_{GG}$ | $\frac{g_2^2}{4}|H|^2 G^A_{\mu\nu} G^{A\mu\nu}$ |
| $O_{BB}$ | $\frac{g_2^2}{4}|H|^2 B_\mu B^{\mu}$ |
| $O_{WW}$ | $\frac{g_2}{4}|H|^2 W^{a}_{\mu\nu} W^{a\mu\nu}$ |
| $O_6$ | $\lambda |H|^6$ |

| $O_{WB}$ | $\frac{g_2^4}{4}(H^\dagger \sigma^a H)W^{a}_{\mu\nu} B^{\mu\nu}$ |
| $O_T$ | $\frac{1}{2} (H^\dagger \tilde{D}_\mu H)^2$ |
| $O_R^u$ | $(iH^\dagger \tilde{D}_\mu H)(\bar{u}_R \gamma^\mu u_R)$ |
| $O_R^d$ | $(iH^\dagger \tilde{D}_\mu H)(\bar{d}_R \gamma^\mu d_R)$ |
| $O_R^e$ | $(iH^\dagger \tilde{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$ |
| $O_L^q$ | $(iH^\dagger \tilde{D}_\mu H)(\bar{Q}_L \gamma^\mu Q_L)$ |
| $O_L^{(3)}q$ | $(iH^\dagger \sigma^a \tilde{D}_\mu H)(\bar{Q}_L \sigma^a \gamma^\mu Q_L)$ |

| $O_L$ | $(iH^\dagger \tilde{D}_\mu H)(\bar{L}_L \gamma^\mu L_L)$ |
| $O_L^{(3)}$ | $(iH^\dagger \sigma^a \tilde{D}_\mu H)(\bar{L}_L \sigma^a \gamma^\mu L_L)$ |

Actually a small number: if #terms < #observables → relations
What do they do to the SM? Are they already constrained? Can we see them at LHC?

In the vacuum $\langle h \rangle = v$, operators $|H|^2 \times \mathcal{L}_{SM}$ only redefine SM parameters! Observable only in Higgs physics!

$$\frac{1}{g_s^2} G_{\mu\nu} G^{\mu\nu} + \frac{|H|^2}{\Lambda^2} G_{\mu\nu} G^{\mu\nu} = \left( \frac{1}{g_s^2} + \frac{v^2}{\Lambda^2} \right) G_{\mu\nu} G^{\mu\nu} + \frac{2v}{\Lambda^2} G_{\mu\nu} G^{\mu\nu} + \ldots$$
EFT for Higgs Physics

What do they do to the SM?
Are they already constrained?
Can we see them at LHC?

Higgs Physics Only

 Measurements couplings are motivated by this framework

$\kappa$ parameters are actually testing the SM $\kappa = 1$ versus the EFT $\kappa \neq 1$
### Higgs Physics Only

<table>
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</tr>
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<tr>
<td>$O_{WW}$</td>
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<tr>
<td>$O_6$</td>
<td>$\lambda</td>
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### Higgs and EW

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EFT for Higgs Physics

In the vacuum \( \langle h \rangle = v \), these operators can be measured!

7 of these operators modify:

- \( Z \bar{u}u_L \)  
- \( Z \bar{e}_L e_L \)  
- \( Z \bar{e}_R e_R \)  
- \( Z \bar{d}_L d_L \)  
- \( Z \bar{d}_R d_R \)

All tightly constrained by LEP <0.001

\[
\begin{align*}
\mathcal{O}_{WB} &= \frac{g_s}{4} (H^\dagger \sigma^a H) W^a_{\mu \nu} B^{\mu \nu} \\
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\mathcal{O}_L^q &= (iH^\dagger D_\mu H) (\bar{Q}_L \gamma^\mu Q_L) \\
\mathcal{O}_L^{(3)} &= (iH^\dagger \sigma^a D_\mu H) (\bar{Q}_L \sigma^a \gamma^\mu Q_L) \\
\mathcal{O}_L &= (iH^\dagger D_\mu H) (\bar{L}_L \gamma^\mu L_L) \\
\mathcal{O}_L^{(3)} &= (iH^\dagger \sigma^a D_\mu H) (\bar{L}_L \sigma^a \gamma^\mu L_L)
\end{align*}
\]

(Gupta), Pomarol, FR’13–14; Falkowski, FR’14
EFT for Higgs Physics

In the vacuum $\langle h \rangle = v$, these operators can be measured!

7 of these operators modify:

$Z \bar{\nu} \nu$ $Z \bar{\ell} \ell$
$Z \bar{u}_L u_L$ $Z \bar{d}_L d_L$ $Z \bar{d}_R d_R$

All tightly constrained by LEP < 0.001

Impact of these operators in H-physics is irrelevant

Falkowski, FR '14

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<tr>
<td>$O^{(4)}_L$</td>
<td>$(i H^\dagger \sigma^a \bar{D}_\mu H)(\bar{L}_L \gamma^\mu L_L)$</td>
</tr>
<tr>
<td>$O^{(5)}_L$</td>
<td>$(i H^\dagger \sigma^a \bar{D}_\mu H)(\bar{L}_L \sigma^a \gamma^\mu L_L)$</td>
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EFT for Higgs Physics

In the vacuum \( \langle h \rangle = v \), these operators can be measured!

2 of these operators modify (wrt SM):

\[
\frac{\delta g_1^Z}{\kappa_\gamma} \quad \text{and} \quad \frac{\delta g_2^Z}{\kappa_\gamma}
\]

Again, LEP:

\[
\delta g_1^Z, \kappa_\gamma \lesssim 0.05
\]

Impact of these operators in H-physics is small.
Might as well use these as parameters, to keep relations between observables manifest!

“BSM Primaries”

Gupta, Pomarol, FR’14
Can we see them at LHC?

Deviations in different distributions of $h \rightarrow Zff$ or $h \rightarrow Wff$

Related with Triple Gauge Coupling

Related with $h \rightarrow Z\gamma\gamma$

Related with $Zff$ couplings

Related with $h \rightarrow VV$

This is the sensitivity we are aiming to make H-physics competitive!
Custodial Symmetry in $h$ decays $h \rightarrow VV^*$

- **Off-Shell $V$**
- $m_Z \neq m_W$

Integrated Decay Width already sensitive to $p$-dependence of $hVV$ coupling!

$$\lambda_{WZ}^2 - 1 \approx 0.6 \delta g_1^Z - 0.5 \delta \kappa_{\gamma} - 1.6 \kappa_{Z\gamma}$$

This is the sensitivity we are aiming to make H-physics competitive!
Summary of Part 3 - BSM

- EFT: systematic and self-consistent framework that motivates precision tests of the SM in terms of a physical quantity $\Lambda$
  - Naturalness is the only principle suggesting this is small, and its effects visible at LHC...

- Leading expected BSM effects, parametrized by dim-6 Lagrangian:
  17 New interactions that modify the predictions of the SM

- Given constraints from LEP: LHC is genuinely probing only the 8 “Higgs-Only” operators with $|H|^2$
  - Measurements of $h^3$ and $h \rightarrow Z\gamma$ can still hide $O(1)$ deviations from SM
  - Deviations in distributions expected much smaller
The Standard Model of particle physics

Years from concept to discovery

- Electron
- Photon
- Muon
- Electron neutrino
- Muon neutrino
- Down
- Strange
- Up
- Charm
- Tau
- Bottom
- Gluon
- W boson
- Z boson
- Top
- Tau neutrino
- HIGGS BOSON
- **BSM**

**Years from Th. Proposal to Exp. Discovery**