Before, Behind and Beyond the Standard Model

Andrea Wulzer
Plan of the lecture

• **Before the SM**
  • No-Lose Theorems
  • Why the Higgs is Revolutionary

• **Behind the SM**
  • The “SM-only” option
  • The Naturalness Argument
  • “Microscopic” Naturalness (and the LHC)
  • What if Un-Natural?

• **Beyond the SM**
  • What could be there …
  • … that we can probe
No-Lose Theorems

A number of \textit{guaranteed} discoveries in the history of HEP
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Beyond the Fermi Theory:

\[ G_F E^2 \lesssim E^2 / v^2 < 16\pi^2 \]

\[ m_W < 4\pi v \]
Beyond the Fermi Theory:

\[ G_F E^2 \approx E^2 / v^2 < 16\pi^2 \]

\[ m_W < 4\pi v \]

Fermi was aware of the Fermi Theory No-Lose Theorem!

**Fermi’s Ultimate Accelerator:**

\[ E_B = 5000 \text{ TeV} \]

\[ \sqrt{s} = \sqrt{2 m_P E_B} = 3 \text{ TeV} \]

Fermi could not predict 2-beams collisions, nor improved magnets
No-Lose Theorems

A number of **guaranteed** discoveries in the history of HEP

Beyond the Fermi Theory:

\[ f f \rightarrow f f \sim G_F E^2 \sim E^2/v^2 < 16\pi^2 \rightarrow m_W < 4\pi v \]

Beyond the Bottom Quark:

\[ b \gamma/Z W_L \rightarrow \bar{b} W_L \sim g_W^2 E^2/m_W^2 < 16\pi^2 \rightarrow m_t < 4\pi v \]
A number of **guaranteed** discoveries in the history of HEP

**Beyond the Fermi Theory:**
\[
\sim G_F E^2 \sim E^2/v^2 < 16\pi^2 \quad \Rightarrow \quad m_W < 4\pi v
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**Beyond the Bottom Quark:**
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\sim g_W^2 E^2/m_W^2 < 16\pi^2 \quad \Rightarrow \quad m_t < 4\pi v
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**Beyond the (Higgsless) EW Theory:**
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\sim g_W^2 E^2/m_W^2 < 16\pi^2 \quad \Rightarrow \quad m_H < 4\pi v
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\]

Each secretly due to d=6 non-renormalizable operators, signalling nearby new physics.
Each time we exploit one No-Lose Theorem, we get rid of one $d=6$ operator ...

e.g.
No-Lose Theorems

Each time we exploit one No-Lose Theorem, we get rid of one $d=6$ operator …

* e.g.

\[
\begin{align*}
\frac{1}{G_N} \sqrt{g R} & \quad \text{grav.} \\
\end{align*}
\]

\[
\begin{align*}
\sim \frac{G_N E^2}{M_P^2} \lesssim 16\pi^2 \\
\Lambda_{\text{SM}} \lesssim M_P
\end{align*}
\]

… and only one is left after Higgs discovery …

\[
\begin{align*}
\end{align*}
\]
No-Lose Theorems

Each time we exploit one No-Lose Theorem, we get rid of one $d=6$ operator …

\[
\frac{1}{G_N} \sqrt{gR} \quad \text{grav.} \quad \times \quad \text{grav.} \quad \sim G_N E^2 \lesssim E^2 / M_P^2 < 16\pi^2 \quad \Lambda_{\text{SM}} \lesssim M_P
\]

… and only one is left after Higgs discovery …

… the last, impractical, No-Lose Theorem is Q.G. at $M_P$!
The statement survives quantum corrections:

- No relevant Landau Pole

\[ m_H = 125.7 \text{ GeV} \]
The statement survives quantum corrections:

- No relevant Landau Pole
- **Instability scale** $\sim 10^9$ GeV

But no need of N.P.
No-Lose Theorems

The statement survives quantum corrections:

- No relevant Landau Pole
- Instability scale $\sim 10^9$ GeV

But no need of N.P.

Non trivial result. Depends on Higgs and Top mass:
Why the Higgs is Revolutionary

The SM can be extrapolated up the Planck scale.
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**Why the Higgs is Revolutionary**

**HEP before the Higgs**

- Higgs
- SUSY, etc.
- Top
- W boson

**HEP after the Higgs**

- ?
- ?
- ?

Particle physics is not **validation** anymore, rather it is **exploration of unknown territories**
Behind the SM

Physics is the continuous effort towards a deeper understanding of the laws of Nature.
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The SM is the state-of-the-art of our knowledge of Fundamental Interactions.
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**BSM** aims to unveil the microscopic origin of the SM, of its fields, Lagrangian and parameters.
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BSM ≠ Beyond the SM
(goal is not “new physics” per se)
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The SM is the state-of-the-art of our knowledge of Fundamental Interactions.

**BSM** aims to unveil the microscopic origin of the SM, of its fields, Lagrangian and parameters.

BSM ≠ Beyond the SM
(goal is not “new physics” per se)

BSM ≡ Behind the SM
(goal is explain SM mysteries)
The “SM-only” Option

Strings, GUT, ...
The “SM-only” Option

Strings, GUT, ...

Above here, unspecified fundamental theory.
The “SM-only” Option

Below here, SM particles only.

Below $\Lambda_{SM}$, fundamental theory reduces to SM fields and SM (Lorentz+gauge) symmetries.
The “SM-only” Option

Below $\Lambda_{\text{SM}}$, fundamental theory reduces to SM fields and SM (Lorentz+gauge) symmetries.

One day, effective SM Lagrangian and parameters will be derived from the fundamental theory.

Fermi theory analogy:

$$G_F \sim \frac{g_W^2}{4\sqrt{2}m_W^2}$$
The “SM-only” Option

Below $\Lambda_{SM}$, fundamental theory reduces to SM fields and SM (Lorentz+gauge) symmetries.

One day, effective SM Lagrangian and parameters will be derived from the fundamental theory.

Fermi theory analogy: $G_F \sim \frac{g_W^2}{4\sqrt{2}m_W^2}$
The “SM-only” Option

\[ L = \text{sum of op.s made of SM fields and compatible with SM symm.} \]

\[ = L^{(d=4)} + \frac{1}{\Lambda_{SM}} L^{(d=5)} + \frac{1}{\Lambda_{SM}^2} L^{(d=6)} + \ldots \]

**dimensional analysis** for coefficients

\[ L^{(d=4)} : \text{the CERN T-shirt Lagrangian (almost)} \]
The “SM-only” Option

\[ \mathcal{L} = \text{“sum of op.s made of SM fields and compatible with SM symm.”} \]

\[ = \mathcal{L}^{(d=4)} + \frac{1}{\Lambda_{\text{SM}}} \mathcal{L}^{(d=5)} + \frac{1}{\Lambda_{\text{SM}}^2} \mathcal{L}^{(d=6)} + \ldots \]

**dimensional analysis** for coefficients

\[ \mathcal{L}^{(d=4)} : \text{describes all what we see (almost)} \ldots \]

Strings, GUT, ...

\[ E \]

\[ M_P \]

\[ M_{\text{GUT}} \]

\[ \Lambda_{\text{SM}} \]

\[ \text{EW} \]
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\[ \mathcal{L}^{(d=4)} : \text{describes all what we see (almost) … … and what we don’t see.} \]

\[ (\Gamma_{\text{proton}}/m_{\text{proton}})_{\text{exp.}} < 10^{-64}!! \iff (\Gamma_{\text{proton}}/m_{\text{proton}})_{(d=4)} = 0 \]

accidental Baryon num. symm.

\[ \text{BR}(\mu \to e\gamma)_{\text{exp.}} < 10^{-12}!! \iff \text{BR}(\mu \to e\gamma)_{(d=4)} = 0 \]

accidental Lepton family symm.
The “SM-only” Option

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**dimensional analysis** for coefficients

- \( \mathcal{L}^{(d=4)} \): describes all what *we* see (almost) …
  … and what *we* don’t see.

- \( \mathcal{L}^{(d=5)} \): can describe what *we* see small

\[ \mathcal{L}^{(d=5)} = (\bar{L}_L H^c)(L_L^c H^c) \]

*unique* (Weinberg) operator
The “SM-only” Option

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**unique** (Weinberg) operator

\[ m_\nu \sim \frac{v^2}{\Lambda_{SM}} \]

Majorana neutrino mass-matrix
The “SM-only” Option

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**dimensional analysis** for coefficients

\( \mathcal{L}^{(d=4)} \): describes all what **we see** (almost) … … and what **we don’t see**.

\( \mathcal{L}^{(d=5)} \): can describe what **we see small** right v mass size if \( \Lambda_{SM} \sim 10^{14} \text{GeV} \sim M_{\text{GUT}} \)!!

\[ \mathcal{L}^{(d=5)} = (\overline{L}_L H^c)(L_L^c H^c) \]

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dimensional analysis for coefficients

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\[ \mathcal{L}^{(d=5)} : \text{can describe what \textbf{we see small right \nu mass size if } } \Lambda_{\text{SM}} \sim 10^{14} \text{GeV} \sim M_{\text{GUT}}!! \]

\[ \mathcal{L}^{(d=6)} : \text{not yet seen. } \Lambda_{\text{SM}} \gtrsim 10^{15} \text{GeV from proton decay.} \]
The “SM-only” Option

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**dimensional analysis** for coefficients

- \( \mathcal{L}^{(d=4)} \): describes all what **we see** (almost) …
  … and what **we don’t see**.

- \( \mathcal{L}^{(d=5)} \): can describe what **we see small** right v mass size if \( \Lambda_{\text{SM}} \sim 10^{14} \text{GeV} \sim M_{\text{GUT}} \)!!

- \( \mathcal{L}^{(d=6)} \): not yet seen. \( \Lambda_{\text{SM}} \gtrsim 10^{15} \text{GeV} \) from proton decay. Majorana v’s and p-decay would be indications of SM-only
The “SM-only” Option

The Lagrangian \( \mathcal{L} \) can be written as the sum of operators made of SM fields and compatible with SM symmetries:

\[
\mathcal{L} = \mathcal{L}^{(d=4)} + \frac{1}{\Lambda_{SM}} \mathcal{L}^{(d=5)} + \frac{1}{\Lambda_{SM}^2} \mathcal{L}^{(d=6)} + \ldots
\]

But we forgot one operator. Using dimensional analysis for coefficients:

\[
\mathcal{L}^{(d=2)} = H^\dagger H
\]

But we forgot one operator.

\[
\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \gamma^\mu \psi \partial_\mu + X_i Y_i X_i \phi + h.c. + |D\phi|^2 - V(\phi)
\]
The “SM-only” Option

\[ \mathcal{L} = \text{“sum of op.s made of SM fields and compatible with SM symm.”} \]
\[ = \mathcal{L}^{(d=4)} + \frac{1}{\Lambda_{\text{SM}}} \mathcal{L}^{(d=5)} + \frac{1}{\Lambda_{\text{SM}}^2} \mathcal{L}^{(d=6)} + \ldots \]

\text{dimensional analysis for coefficients}

But we forgot one operator. Using again \textbf{dim. analysis}:

\[ \mathcal{L}_{H\text{-mass}} = \Lambda_{\text{SM}}^2 \mathcal{L}^{(d=2)} = \Lambda_{\text{SM}}^2 H^\dagger H \]

Instead, \[ \mathcal{L}_{H\text{-mass}} = \frac{m_H^2}{2} H^\dagger H \]
The “SM-only” Option

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\textbf{The Naturalness Problem: Why } m_H \ll \Lambda_{\text{SM}}? \\
(or, why dim. analysis works for } d>4 \text{ and not for } d<4?)
To understand Naturalness, think to the “Final Theory” formula that predicts $m_H$. It will look like this:

$$m_H^2 = \int_0^{\infty} dE \frac{dm_H^2}{dE} (E; p_{\text{FT}})$$
The Naturalness Argument
(not a Theorem)

To understand Naturalness, think to the “Final Theory” formula that predicts $m_H$. It will look like this:

$$m_H^2 = \int_0^\infty dE \frac{d m_H^2}{dE}(E; p_{FT})$$

$$= \int_0^{\Lambda_{SM}} dE(\ldots) + \int_{\Lambda_{SM}}^\infty dE(\ldots)$$
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$\delta_{BSM} m_H^2 = c \Lambda_{SM}^2$
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**SM Contribution**
$$\delta_{SM} m_H^2 = \frac{3y_t^2}{8\pi^2} \Lambda_{SM}^2$$

(NOT a quadratic divergence calculation!!)

**UV (BSM) Contribution**
$$\delta_{BSM} m_H^2 = c\Lambda_{SM}^2$$
To understand Naturalness, think to the “Final Theory” formula that predicts $m_H$. It will look like this:

$$m_H^2 = \int_0^\infty dE \frac{dm_H^2}{dE} (E; p_{FT})$$

$$= \int_0^{\Lambda_{SM}} dE (...) + \int_{\Lambda_{SM}}^\infty dE (...)$$

$$= \delta_{SM} m_H^2 + \delta_{BSM} m_H^2$$

Since the result must be $(125 \text{ GeV})^2$, two terms must be $\sim$ equal and opposite and cancel, by an amount

$$\Delta \geq \frac{\delta m_H^2}{m_H^2} \sim \left( \frac{125 \text{ GeV}}{m_H} \right)^2 \left( \frac{\Lambda_{SM}}{500 \text{ GeV}} \right)^2$$
The Naturalness Argument
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To understand Naturalness, think to the “Final Theory” formula that predicts \( m_H \). It will look like this:

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\]

**Fine-tuning:** quantifies the “degree of Un-Naturalness”
The Naturalness Argument
(not a Theorem)

“Is $m_H$ Natural?” $\equiv$ “Is $m_H$ Predictable?”
The Naturalness Argument
(not a Theorem)

“Is $m_H$ Natural?” $\equiv$ “Is $m_H$ Predictable?”

What to do with that?
The Naturalness Argument
(not a Theorem)

“Is $m_H$ Natural?”  $=$  “Is $m_H$ Predictable?”

What to do with that?

Measure what is measurable,
and make measurable what is not so.

G. Galilei
The Naturalness Argument
(not a Theorem)

“Is $m_H$ Natural?”  $==$  “Is $m_H$ Predictable?”

What to do with that?

Measure what is measurable,
and make measurable what is not so.

G. Galilei

We must search for “Natural” new physics at the TeV.
• If we find it, go out and celebrate!
 (than come back and measure it better)
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$$\Delta \geq \frac{\delta m_H^2}{m_H^2} \sim \left( \frac{125 \text{ GeV}}{m_H} \right)^2 \left( \frac{\Lambda_{\text{SM}}}{500 \text{ GeV}} \right)^2$$
The Naturalness Argument
(not a Theorem)

“Is $m_H$ Natural?” == “Is $m_H$ Predictable?”

What to do with that?

Measure what is measurable,
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G. Galilei

We must search for “Natural” new physics at the TeV.

• If we find it, go out and celebrate!
  (than come back and measure it better)
• If we don’t, measure Un-Naturalness

Where to stop?

$\Delta \sim 10$ definitely OK
$\Delta \sim 1000$ probably not OK
Half a century of thoughts led to only two mechanisms that provide a Natural microscopic origin for Higgs mass.

Compositeness          Supersymmetry
Half a century of thoughts led to only two mechanisms that provide a Natural microscopic origin for Higgs mass.

**Compositeness**

\[ \text{Higgs} = l_H = \frac{1}{m_*} \]

Higgs is **transparent** to HE modes.

**Supersymmetry**

\[ \frac{d m_H^2}{d E} \]

\( m_H \) generation **localised** at \( m_* \)
Half a century of thoughts led to only two mechanisms that provide a Natural microscopic origin for Higgs mass.

**Compositeness**

Higgs = \( \frac{1}{m_*} \)

Higgs is transparent to HE modes

\[ \frac{d m_H^2}{dE} \]

\( m_H \) generation localised at \( m_* \)

**Supersymmetry**

Higgs protected by fermionic superpartner chiral symmetry.

With soft breaking, produces famous top/stop cancellation:

\[ \delta_{IR} m_H^2 \simeq \frac{3}{8\pi^2} \Lambda^2 [y_t^2 - y_1^2] + \frac{3y_t^2}{8\pi^2} M_t^2 \log(\Lambda/M_{EW}) \]
The Composite Higgs Picture

Composite Sector

Elementary Sector

SM gauge fields: $W_\mu^\alpha, B_\mu$

SM fermions: $\{t_L, b_L\}, t_R, \ldots$
The Composite Higgs Picture

**Composite Sector**

$m_* = \text{Resonances}$

$\text{Higgs}$

**Elementary Sector**

**SM gauge fields:** $W_\mu^\alpha, B_\mu$.

**SM fermions:** $\{t_L, b_L\}, t_R, \ldots$

Higgs must be a **Nambu-Goldstone Boson**.
This ensures a mass-gap with other hadrons (resonances).
And allows SM-like couplings though vacuum misalignment.
The Composite Higgs Picture

**Composite Sector**

"Exact" symmetry $SO(5)$.

Spontaneously broken to $SO(4)$.

$m^* = \text{Resonances}$

$\text{Higgs} = \text{pNGB}$

**Elementary Sector**

SM gauge fields: $W^\alpha, B_\mu$.

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Higgs must be a **Nambu-Goldstone Boson**.

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"Minimal" breaking: $SO(5) \rightarrow SO(4)$

Delivers one Higgs doublet only in the spectrum
The Composite Higgs Picture

**Composite Sector**
- “Exact” symmetry $SO(5)$.
- Spontaneously broken to $SO(4)$.
- $m_\ast \equiv \text{Resonances}$
- Higgs = pNGB

**Elementary Sector**
- SM gauge fields: $W_\mu^\alpha$, $B_\mu$.
- Coupled by gauging.
- SM fermions: $\{t_L, b_L\}$, $t_R$, ...

$\mathcal{L}_\text{int}^g = gV \cdot J$

SM vectors couple by **gauging** (linear int. with current)
The Composite Higgs Picture

**Composite Sector**

"Exact" symmetry $SO(5)$.

Spontaneously broken to $SO(4)$.

$\mathbf{m}_* \equiv \text{Resonances}$

$\text{Higgs} = p\text{NGB}$

**Elementary Sector**

SM gauge fields: $W^\alpha_\mu, B_\mu$.

Coupled by *gauging*.

SM fermions: $\{t_L, b_L\}, t_R, \ldots$

Linearly coupled to CS

i.e., Partial Compositeness

---

SM vectors couple by **gauging** (linear int. with current)

Fermions also couple **linearly** (partial ferm. compositeness)

The alternative, bilinear coupling, was excluded for the top with **bootstrap**.

Potentially viable for light fermions.
The Composite Higgs Picture

**Composite Sector**

- “Exact” symmetry $SO(5)$.
- Spontaneously broken to $SO(4)$.
- $m^*_\star$: Resonances
- $\text{Higgs} = \text{pNGB}$

**Elementary Sector**

- SM gauge fields: $W^\alpha_\mu, B_\mu$.
- Coupled by gauging.
- SM fermions: $\{t_L, b_L\}, t_R, \ldots$
- Linearly coupled to CS
  - i.e., Partial Compositeness

$\mathcal{L}^g_{\text{int}} = g V \cdot J$

$\mathcal{L}^f_{\text{int}} = \lambda \bar{f} \mathcal{O}$

SM vectors couple by **gauging** (linear int. with current)

Fermions also couple **linearly** (partial ferm. compositeness)

- The alternative, bilinear coupling, was excluded for the top with **bootstrap**.
- Potentially viable for light fermions.

Also notice that:

- Scaling dimension $\sim 5/2$ required for top Operator. UV-feasible or not?
- Phenomenology built on assumed symmetry patterns and dim. analysis.
- UV model believed unnecessary for LHC viability assessment of the scenario.
**Composite Higgs Signatures**

**Higgs couplings:** robustly predicted by Goldstone symm. Departures from SM $\sim \xi = v^2/f^2$, and $1/\xi$ is irreducible source of fine-tuning.

Current bound is $\xi \lesssim 0.15$.
**Composite Higgs Signatures**

**Higgs couplings:** robustly predicted by Goldstone symm. Departures from SM $\sim \xi = v^2/f^2$, and $1/\xi$ is irreducible source of fine-tuning. More will come from future LHC precision program in Higgs and EW sector.

Current bound is $\xi \lesssim 0.15$
Composite Higgs Signatures

**Fermionic top partners:** must be light, or cost extra tuning, given $m_H$.

Current bounds at $\sim 1.2$ TeV. Final LHC reach of $\sim 1.5$ or 2 (model-dependent)
**Composite Higgs Signatures**

**Heavy Vectors:** the most robust direct signature

![Graph showing mass vs. coupling for heavy vectors with various collider limits.](image)

- **Figure 3.2:** Comparison of direct and indirect searches in the \( (m_\rho, g_\rho) \) plane. Left panel: region up to \( m_\rho = 10 \text{ TeV} \) showing the relevance of LHC direct searches at 8 TeV with 20 fb \(^{-1}\) (LHC8), 14 TeV with 300 fb \(^{-1}\) (LHC) and 3 ab \(^{-1}\) (HL-LHC); right plot: region up to \( m_\rho = 40 \text{ TeV} \) showing the comparison between the LHC and FCC reach with 1 and 10 ab \(^{-1}\).

The global message which emerges from these pictures is rather simple and expected. An increase of the collider energy improves the mass reach dramatically, and in particular only the 100 TeV FCC can access the multi–TeV region. An increase in luminosity, instead, has a marginal effect on the mass reach but considerably extends the sensitivity in the large \( g_\rho \) (i.e., small rate) direction. In particular we see that the impact of the high luminosity extension of the LHC is considerable given that largish values of the \( g_\rho \) coupling are perfectly plausible in the CH scenario (see the Conclusions for a more detailed discussion).

Let us now turn to the indirect constraints from the measurement of the Higgs coupling to vector bosons. The \( 1 \sigma \) (68% CL) error on \( \rho \) (i.e., twice the one on \( k_\rho' \)) obtainable for different collider options, as extracted from currently available literature, are summarised in table 3.1. Twice those values, which in the assumption of gaussian statistics corresponds to the 95% CL limits on \( \rho \), are reported in figures 3.2 and 3.3 as black dashed curves, with the excluded region sitting above the lines. In the \( (m_\rho, \rho) \) plane, the limits simply corresponds to horizontal lines and translate into straight lines with varying inclination in the \( (m_\rho, g_\rho) \) plane.
Composite Higgs Signatures

The LHC can robustly **exclude** CH up to one-digit tuning

Very limited **discovery** (and characterisation) prospects
In 89, **any sensible physicist** would have believed in SUSY.

- Natural theory
- Truly minimal viable model (MSSM)
- Dark Matter Candidate
- Easily comes from string theory
In 89, any sensible physicist would have believed in SUSY. However …

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• Truly minimal viable model (MSSM)?
  Higgs heavier than $Z$ needs exponentially heavy stops
  Natural SUSY requires non-minimality, less sharply defined framework

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  Direct Detection excludes WIMP in “Natural” energy range

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Supersymmetry: A Tale from the 80’

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- Easily comes from string theory?
  As “easy” as any other model in Landscape!
In 89, any sensible physicist would have believed in SUSY. However …

- Natural theory?
  LHC is telling us

- Truly minimal viable model (MSSM)?
  **Higgs heavier than Z** needs exponentially heavy stops
  Natural SUSY requires non-minimality, less sharply defined framework

- Dark Matter Candidate?
  Direct Detection excludes **WIMP** in “Natural” energy range

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  As “easy” as any other model in Landscape!
LHC SUSY Searches

Quantitative illustration

ATLAS SUSY Searches - 95% CL Lower Limits

Qualitative illustration

Naturalness

from arXiv:1309.0528
Higgs couplings also relevant in non-minimal scenarios
Higgs couplings also relevant in non-minimal scenarios
Like CH, 1-digit tuning or more generically unavoidable
(Un-)Naturalness \textit{discovery} has \textbf{profound implications} \textbf{Crucial} to make our best with LHC phenomenology and model building. Any \textit{loophole}? [Twin Higgs, Folded SUSY, compressed spectra …]
(Un-)Naturalness discovery has profound implications. Crucial to make our best with LHC phenomenology and model building. Any loophole? [Twin Higgs, Folded SUSY, compressed spectra …]

If Un-Natural, $m_H$ has no microscopic origin (e.g. $\neq G_F$).

It could:
- be a fundamental input par. of the Final Theory
- have environmental anthropic origin
- have dynamical (set by time evolution) origin
Environmental is a parameter whose value is dictated by external conditions.
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Set by Earth mass and radius. Different on other planets.
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Set by Earth mass and radius. Different on other planets.

Higgs mass depends on the vacuum where we live.

Not quite like $g$. Vacua are causally disconnected. Cannot go there and check.

Landscape of vacua
What if Un-Natural?

Environmental is a parameter whose value is dictated by external conditions. Environment in itself not a solution: why $m_H \ll \Lambda_{SM}$?
What if Un-Natural?

**Environmental** is a parameter whose value is dictated by **external conditions**

Environment in itself **not a solution**: why $m_H \ll \Lambda_{SM}$?

Becomes solution only with **anthropic selection**: E.g., why 15°C is the average temperature of earth?

Landscape of vacua
Environmental is a parameter whose value is dictated by external conditions

Environment in itself not a solution: why $m_H \ll \Lambda_{SM}$?

Becomes solution only with anthropic selection:
E.g., why $15^\circ C$ is the average temperature of earth?

We live where we can. There might be upper bound on $m_H$ for us to exist.

Landscape distribution peaks at $\Lambda_{SM}$, but has a tail. Likely to live close to the upper bound.
Environmental is a parameter whose value is dictated by external conditions

Environment in itself not a solution: why $m_H \ll \Lambda_{SM}$?

Becomes solution only with anthropic selection:
E.g., why 15°C is the average temperature of earth?

Successful Weinberg prediction of the Cosmological Constant:

For galaxies to form, it must be:
$$\Lambda_{c.c.} \lesssim (\text{few} \cdot 10^{-3}\text{eV})^4 \sim 10^{-120} M_P^4$$

Observed value:
$$\Lambda_{c.c.} \simeq (2 \cdot 10^{-3}\text{eV})^4$$
Dynamical is a parameter whose value is set by time evolution.
**What if Un-Natural?**

**Dynamical** is a parameter whose value is set by time evolution.

Recent proposal: **Relaxion**

Field-dependent Higgs mass

\[ (-M^2 + g\phi)|h|^2 + (gM^2\phi + g^2\phi^2 + \cdots) + \Lambda^4 \cos(\phi/f) \]

Proportional to Higgs VEV

Field rolls during Inflation.

Stops right after \( m_H^2 < 0 \).

Because of the cos term.
Dynamical is a parameter whose value is set by time evolution.

Recent proposal: Relaxion

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Proportional to Higgs VEV

Field rolls during Inflation.

 Stops right after \( m_H^2 < 0 \).

Because of the cos term.

Viability of large field excursion requires ad hoc mechanism like Clockwork

[Graham, Kaplan, Rajendran, 2015]

[Kaplan, Rattazzi & Choi, Kim, Yun]
What if Un-Natural?

One can like/believe these radical speculations or not.

One can argue that they involve too much complexity to produce a concrete BSM scenario.

One can hope in UV physics “obeying different rules”, nullifying Naturalness problem, but concretely what?

All this shows the **dramatic impact** Un-Naturalness discovery is having on our field.
Beyond the SM

What could be there …

- Light DM
- Very Light DM
- Axions
- Portals ($v_R, \gamma_D, ..$)

The Coupling Frontier
[not as easy to characterise as the Energy one]

- DM as primordial Black Holes? [direct GW probe?]
- What to do with LIGO/Virgo? [on top of g/\gamma speed?]
Beyond the SM

... that we can probe

- Light DM
- Very Light DM
- Axions
- Portals \( (\nu_R, \gamma_D, ..) \)

Direct Detection
DM-e scattering/absorption, on SC, graphene ...
conversion in \( \gamma \) [e.g. ADMX], or
induced currents [e.g. ABRACADABRA]
Beyond the SM

... that we can probe

- Light DM
- Very Light DM
- Axions
- Portals ($\nu_R, \gamma_D, ..$)

Direct Detection
DM-e scattering/absorption, on SC, graphene ...
conversion in $\gamma$ [e.g. ADMX], or
induced currents [e.g. ABRACADABRA]

Lab Production

**Dedicated:**
beam dump [e.g. SHIP]
missing momentum [e.g. LDMX]
detection [e.g. BDX]

**Parasitical:**
e.g. Mathusla/CODEX-b
Summary

After the Higgs, no \textbf{discovery guarantee} in HEP, nor in other areas of fundamental interactions physics.

LHC entering a mature stage is opportunity for great phenomenology. Conclusive TeV-scale exploration?

Exploring new ideas on “Un-Naturalness” implications.

Physics \textbf{Besides} (≠Beyond) Colliders is a flourishing field. Interesting interplay with experimental/technological developments in other fields.
Learn from yesterday, live for today, hope for tomorrow.

The important thing is not to stop questioning.

– Albert Einstein