Advanced Course on Higgs Physics

1st Graduate Week of the Quantum Universe Research School

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Hamburg, Germany | 5-8 February 2024
Accessing the fundamental laws of Nature

➢ Particle Physics aims to understand the fundamental building blocks of Nature (elementary particles) and the interactions between them

➢ High-energy particle colliders like Large Hadron Collider at CERN (or HERA at DESY!)

➢ But not only! There is a multitude of experiments aiming for short distances and/or early times, like precision (low-energy) measurements, or cosmological observations of early-Universe relics

➢ Probe higher energies and infinitesimally short distances → probe the early Universe

Known particles as of 2012

Artist view of space-based interferometer LISA that will search for primordial gravitational waves
Higgs discovery in 2012: a milestone for Particle Physics

➢ 4th July 2012: discovery of a Higgs boson of mass 125 GeV by ATLAS and CMS collaborations at CERN Large Hadron Collider was a major milestone for Particle Physics
→ discovery channels: $h \to \gamma\gamma$ and $h \to ZZ^* \to 4\ell$

➢ 2013 Nobel Prize for F. Englert and P. Higgs
Higgs discovery in 2012: a milestone for Particle Physics

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→ Brout-Englert-Higgs mechanism confirmed as origin of masses of elementary particles

➢ Particle content of Standard Model of Particle Physics (SM) is “complete” → is this the end of the story?
Higgs discovery in 2012: a milestone for Particle Physics

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- Particle content of Standard Model of Particle Physics (SM) is “complete” → is this the end of the story?
The motivation for New Physics

➢ In spite of the Higgs discovery, many questions remain unsolved, e.g.
  ➢ Form and origin of Higgs potential (i.e. *why* do particles get masses, not just *how*)
  ➢ Gauge hierarchy problem, i.e. why is gravity so much weaker than the other forces (or why is the Planck scale so much higher than the electroweak scale)
  ➢ Reason for three fermion families and origin of flavour
  ➢ Origin of matter-antimatter asymmetry of the Universe
  ➢ Dark Matter
  ➢ Structure of Higgs sector (no good guiding principle!)
    Etc.

➢ Not addressed by our current best description of Particle Physics, the Standard Model (SM)
  → *New Physics must exist beyond-the-Standard-Model (BSM)!*

➢ Many open problems relate to Higgs sector
  → the 125-GeV Higgs boson will certainly play a *key role in understanding the nature of BSM Physics*
  → BSM models often feature *additional Higgs bosons/scalars*
Goal of this lecture series: explain the central role of the Higgs boson to probe New Physics

- Thermal History of Universe
- Origin of EWSB?
- Higgs Portal to Hidden Sectors?
- Stability of Universe
- CPV and Baryogenesis
- Origin of masses?
- Origin of Flavor?
- Is it unique?
- Naturalness
- Fundamental or Composite?
Goal of this lecture series: explain the central role of the Higgs boson to probe New Physics

Disclaimer:

There is no chance I could give justice, in 3 lectures, to the immense breadth of active research topics related to Higgs Physics

→ in the following, I will try to be thorough in what I mention, but I will only explain in detail a selection of topics (related to my past and current interests and/or those represented at DESY)
Outline of the lectures

- Part 1: Why a Higgs boson is needed
- Part 2: Connections between Higgs Physics and unanswered questions of Particle Physics (and possible solutions to them)
- Part 3: What can be learnt from the Higgs boson at high-energy colliders – an overview
- Part 4: The Higgs boson mass as a precision observable – calculations and interpretations
- Part 5: The Higgs boson potential, its trilinear coupling, and relations with early-Universe evolution
Part 1: The need for a Higgs boson
Masses of elementary particles

➢ Strong, weak and electromagnetic fundamental interactions described as **gauge theories**
  - Quantum Chromodynamics (QCD) → SU(3)_c
  - Electroweak (EW) interactions → SU(2)_L × U(1)_Y

➢ Underlying gauge theories is the principle of **gauge invariance**, which strongly constrains allowed terms in the Lagrangian.

  For instance, under a finite local transformation V(x) of a gauge group G, a gauge field A_μ transforms as

  \[ A_\mu \xrightarrow{V} V A V^{-1} + \frac{i}{g} V (\partial_\mu V^\dagger) \]

  thus a mass term \[ m_A^2 A_\mu A^\mu \] is **forbidden by gauge invariance**

➢ Additionally, the currently-known fermions are **chiral**, i.e. weak interactions treat left-handed and right-handed fermions differently → **mass terms for chiral fermions are also forbidden by gauge invariance**

  e.g.

  \[ m_e \bar{e}_L e_R + h.c. \]

  \( Y=+1 \) & part of SU(2)_L doublet

  \( Y=-2 \) & part of SU(2)_L singlet

➢ How can we explain the **observed masses** of EW gauge bosons and fermions?

  → **Brout-Englert-Higgs mechanism**
Brout-Englert-Higgs mechanism

➢ **Idea** (in its minimal realisation): introduce a scalar* $\Phi$ – the **Higgs field** – doublet under SU(2)$_L$ and with hypercharge $Y=+1$, and with potential

\[ V(\Phi) = \mu^2 |\Phi|^2 + \lambda |\Phi|^4 \]

* Why a scalar? → so that it can get a vacuum expectation value without breaking Lorentz symmetry

➢ The potential $V(\Phi)$ itself (and thus also the Lagrangian of the theory) obeys the fundamental SU(2)$_L \times U(1)_Y$ gauge symmetry but the **vacuum does not**

➢ In other words, the Higgs field acquires a non-zero **vacuum expectation value** $v$ that triggers the **spontaneous breaking of the EW symmetry (EWSB)**

\[ \Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \rightarrow \langle \Phi \rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} \]

➢ Vacuum remains symmetric under $U(1)_{QED}$ gauge group (otherwise there would be charge breaking with strong phenomenological consequences!)

\[ SU(2)_L \times U(1)_Y \xrightarrow{\text{EWSB}} U(1)_{QED} \]
Brout-Englert-Higgs mechanism and particle masses

\[ V(\Phi) = \mu^2|\Phi|^2 + \lambda|\Phi|^4 \quad \lambda > 0 \quad \mu^2 < 0 \]

\[ SU(2)_L \times U(1)_Y \xrightarrow{\text{EWSB}} U(1)_{\text{QED}} \]

➢ Masses of gauge bosons via **scalar kinetic term**, with covariant derivative

\[ D_\mu \Phi = \partial_\mu \Phi - \frac{1}{2} i \left( \frac{g_2 W^3_\mu + g_Y B_\mu}{\sqrt{2g_2 W^-_\mu}} \quad \frac{\sqrt{2g_2} W^+_\mu}{g_2 W_\mu} - gW^3_\mu + g_Y B_\mu \right) \Phi \]

with \[ \Phi = \left( \frac{G^+}{\sqrt{2}(v+h+iG^0)} \right)^h: \text{Higgs boson} \]

\[ G^0, G^\pm: \text{Goldstone bosons} \]

and \[ W^\pm = \frac{1}{\sqrt{2}}(W^1_\mu \mp iW^2_\mu) \]

which gives

\[ |D_\mu \Phi|^2 \supset \frac{1}{4} g_2^2 v^2 W^+_\mu W^-_\mu + \frac{1}{4} (g_2^2 + g_Y^2) v^2 Z_\mu Z^\mu \]

(▲)

where \[ Z_\mu = \frac{g_2 W^3_\mu - g_Y B_\mu}{\sqrt{g_2^2 + g_Y^2}} \]

➢ Before EWSB:

\[ \Phi \rightarrow 4 \text{ degrees of freedom (d.o.f.)} + 4 \text{ massless gauge bosons of SU}(2)_L \times U(1)_Y (W_1, W_2, W_3, B) \rightarrow 4 \times 2 = 8 \text{ d.o.f.} \]

➢ After EWSB: would-be Goldstone bosons are “eaten” by gauge bosons which become massive

\[ h \rightarrow 1 \text{ d.o.f} + 3 \text{ massive gauge bosons } W^\pm, Z \rightarrow 3 \times 3 = 9 \text{ d.o.f} + 1 \text{ massless photon } A \rightarrow 2 \text{ d.o.f.} \]

**Exercise:** rederive equation (▲) + find the expression of the photon A in terms of \( W_3 \) and B
Brout-Englert-Higgs mechanism and particle masses

\[ V(\Phi) = \mu^2 |\Phi|^2 + \lambda |\Phi|^4 \quad \lambda > 0 \quad \mu^2 < 0 \]

\[ SU(2)_L \times U(1)_Y \xrightarrow{\text{EWSB}} U(1)_{\text{QED}} \]

➢ Masses of gauge bosons via scalar kinetic term, with covariant derivative

\[ D_\mu \Phi = \partial_\mu \Phi - \frac{1}{2} i \left( g_2 W^3_\mu + g_Y B_\mu \right) \left( \frac{\sqrt{2} g_2 W^+_\mu}{\sqrt{g_2^2 + g_Y^2}} - g W^3_\mu + g_Y B_\mu \right) \Phi \]

with \( \Phi = \left( \begin{array}{c} G^+ \\ \frac{1}{\sqrt{2}} (v + h + iG^0) \end{array} \right) \)

\( h: \) Higgs boson
\( G^0, G^\pm: \) Goldstone bosons

and \( W^\pm = \frac{1}{\sqrt{2}} (W^1_\mu \mp iW^2_\mu) \)

which gives

\[ |D_\mu \Phi|^2 \supset \frac{1}{4} g_2^2 v^2 W^+_\mu W^-_\mu + \frac{1}{4} (g_2^2 + g_Y^2) v^2 Z_\mu Z^\mu \quad (\uparrow) \]

where \( Z_\mu = \frac{g_2 W^3_\mu - g_Y B_\mu}{\sqrt{g_2^2 + g_Y^2}} \)

➢ Masses of fermions (e.g. electron) via Yukawa-interaction term

\[ \mathcal{L} \supset -y_e \bar{L}_L \Phi e_R + \text{h.c.} \xrightarrow{\text{EWSB}} - \frac{y_e}{\sqrt{2}} v \bar{e}_L e_R + \text{h.c.} \]

\( Y = +1 \)
\( \text{conjugate of } \) \( \text{SU}(2)_L \) doublet

\( Y = +1 \)
\( \text{SU}(2)_L \) doublet

\( Y = -2 \)
\( \text{SU}(2)_L \) singlet
Where to find “the” Higgs boson? A unitarity argument

➢ Higgs-less alternatives to BEH mechanism were also devised (e.g. technicolor)
   → How to test the BEH mechanism? At what scale can the Higgs boson be found?

➢ Consider a massive $W$ boson $W_\mu$ with momentum $k_\mu = (E,0,0,k)$
   → 3 possible polarisations such that $k_\mu \cdot \varepsilon^\mu = 0$ and $\varepsilon_\mu \cdot \varepsilon^\mu = -1$
   → 2 transverse polarisations $\varepsilon_{T1}^\mu = (0,1,0,0)$, $\varepsilon_{T2}^\mu = (0,0,1,0)$
   + 1 longitudinal polarisation $\varepsilon_L^\mu = (k/M_W,0,0,E/M_W) \sim k_\mu/M_W$ for $E \gg M_W$

➢ Consider the $2\rightarrow2$ scattering of longitudinally polarised $W$ bosons $W_L W_L \rightarrow W_L W_L$
   → without a Higgs boson, only gauge-boson diagrams like

\[
A \sim g_2^2 \frac{E^2}{M_W^2}
\]

→ adding a Higgs boson in the theory:

\[
A_h \sim -g_2^2 \frac{E^2}{M_W^2}
\]

\[
\Rightarrow A_{\text{tot}} \sim g_2^2 \frac{M_h^2}{M_W^2}
\]

A Higgs boson unitarises the theory if its mass < $\sim 1$ TeV.

Loss of unitarity for large $E$ (from $\sim M_W/g_2$)!
Where to find “the” Higgs boson? A unitarity argument

- Higgs-less alternatives to BEH mechanism were also devised (e.g. technicolor)
  - How to test the BEH mechanism? At what scale can the Higgs boson be found?
- Consider a massive $W$ boson $W_\mu$ with momentum $k^\mu = (E,0,0,k)$
  - 3 possible polarisations
  - 2 transverse polarisations $\varepsilon^{T1}_\mu = (0,1,0,0)$, $\varepsilon^{T2}_\mu = (0,0,1,0)$
  - 1 longitudinal polarisation $\varepsilon^L_\mu = (k/M_W,0,0,E/M_W)$ for $E >> M_W$

- Consider the $2\rightarrow 2$ scattering of longitudinally polarised $W$ bosons $W_L W_L \rightarrow W_L W_L$
  - without a Higgs boson

- Adding a Higgs boson in the theory:

  \[ A_h \sim -g_2^2 \frac{E^2}{M_W^2} \]

  \[ \Rightarrow A_{\text{tot}} \sim g_2^2 \frac{M_h^2}{M_W^2} \]

  A Higgs boson unitarises the theory if its mass $< \sim 1$ TeV

No lose theorem (for LHC)

- either a Higgs boson exists below/around the TeV scale, to unitarise gauge boson scattering in EW gauge theory
- some new strong dynamics would appear at $\sim$ TeV scale

In other words, theory guaranteed that the LHC would see something!
Part 2: Probing New Physics with the Higgs boson
Goal of this lecture series: explain the central role of the Higgs boson to probe New Physics
Hierarchy problems in Higgs Physics

\[ \mathcal{L} \supset -\frac{1}{4} F_{\mu\nu}^{\alpha} F^{\alpha,\mu\nu} + \bar{\psi}_i \gamma_\mu D^\mu_{ij} \psi_j \]

\rightarrow \text{entirely constrained by gauge symmetry, tested to high precision (e.g. LEP)}

\[ \mathcal{L} \supset -y_{ij} \bar{\psi}_i \Phi \psi_j + \mu^2 |\Phi|^2 + \lambda |\Phi|^4 - V_0 \]

**Yukawa couplings:** Hierarchy of fermion masses and flavour

**Higgs mass term:** Gauge hierarchy problem

**Vacuum energy:** Cosmological constant problem

**Quartic Higgs coupling:** UV behaviour and vacuum stability *(more later)*
Naturalness and the gauge hierarchy problem

➢ The EW scale is around $m_{EW} \sim 100$ GeV ($v=246$ GeV) while the Planck scale, at which effects of quantum gravity must manifest themselves is $M_{Pl} \sim 10^{19}$ GeV → why are there 17 orders of magnitude between $m_{EW}$ and $M_{Pl}$? → (gauge) hierarchy problem

➢ At a more concrete level, the Higgs mass also poses a theoretical problem, as it is not protected from large (quadratic) corrections – unlike for fermions and gauge bosons, nothing forbids scalar mass terms

➢ Let’s consider the effect of a heavy BSM fermion $\psi$, of mass $M \sim M_{pl}$ with a Lagrangian

$$\mathcal{L} \supset \bar{\psi}(i\gamma^\mu \partial_\mu - M)\psi - y_\psi \bar{\psi}\psi h$$

and let’s compute the leading corrections to the Higgs mass in this toy model

$$\Delta^{(1)} m_h^2 = -(-iy_\psi)^2 \int \frac{d^dk}{i(2\pi)^2} \text{tr} \left[ \frac{i(k + M)}{k^2 - M^2} \frac{i((\psi - k) + M)}{(p - k)^2 - M^2} \right]$$

$$\approx -\frac{y_\psi^2}{4\pi^2} M_{Pl}^2 \quad \text{with} \quad p^2 \ll M^2 \quad \& \quad Q = M \approx M_{Pl}$$

➢ Getting the Higgs mass right at 125 GeV would imply a tuning between tree-level mass and loop corrections to 32 digits!!! → technical hierarchy problem
Solutions to the gauge hierarchy problem: Supersymmetry

- **Supersymmetry (SUSY):** [Wess, Zumino ’74] and many more
  - Extend space-time symmetry (Poincaré group) by introducing **new symmetry between fermions and bosons** (SUSY is only option to circumvent Coleman-Mandula theorem [Coleman, Mandula ’67], see [Haag, Lopuszanski, Sohnius ’75])
  - Each fermion (boson) has a bosonic (fermionic) superpartner, with same mass and related couplings, e.g. for toy model of previous slide, $\psi$ has a superpartner $\tilde{\psi}$, with interaction terms
    \[ \mathcal{L} \supset -y_\psi \bar{\psi} \psi h - y_\psi^2 \bar{\tilde{\psi}} * \tilde{\psi} h^2 \]
    
    such that

    \[ \frac{y_\psi^2}{4\pi^2} M_{Pl}^2 \]

- **NB:** SUSY must be broken, otherwise selectron would have mass 511 keV and would have had to be seen already
- But SUSY can be broken *(super)*softly, i.e. **without reintroducing quadratic divergences in $m_h$**
- Numerous phenomenological models, such as Minimal Supersymmetric Standard Model (MSSM), Next-to-MSSM (NMSSM), Dirac gaugino models, etc., however so far no sign of SUSY at the LHC...
Solutions to the gauge hierarchy problem: Compositeness

➢ Compositeness: see e.g. [Agashe, Contino, Pomarol ’04], [Giudice, Grojean, Pomarol, Rattazzi ’07] + refs therein

Light scalars already known in Nature, e.g. pions, but these are not fundamental, rather bound – or in other words composite – states

→ Introduce a new strongly coupled sector, with a global symmetry group G, spontaneous broken down to H at a scale f

\[ G \xrightarrow{SSB} H \supset SU(2)_L \times U(1)_Y \]

→ Higgs boson appears as a pseudo-Goldstone boson → naturally light

Minimal model (1 Higgs doublet):

→ G = SO(5) (10d); H = SO(4) (6d)

Composite Two-Higgs-Doublet Model:

→ G = SO(6) (15d); H = SO(4) x SO(2) (7d)

➢ Ratio v/f determined by misalignment between directions of G/H and SU(2)_L x U(1)_Y / U(1)_QED breakings

➢ Partial compositeness to explain quark mass patterns

![Diagram showing QCD and Composite Higgs models](Image)
Other solutions to the gauge hierarchy problem

➢ **Large Extra-dimensions:** [Arkani-Hamed, Dimopoulos, Dvali ‘98]
(see e.g. Randall-Sundrum models, [Randall, Sundrum ‘99])
Add at least one more dimension of space-time, which is compactified → tower of excited states + effective Planck scale in 4d is lowered

➢ **Gauge-Higgs unification:** [Manton ‘79], [Fairlie ‘79], [Hosotani ‘83], etc.
*Hosotani mechanism:* In 5d, a gauge boson contains 5 components → 4 components of a 4d gauge boson + 1 component to 4d Higgs boson (which triggers EWSB) → Higgs mass is then again protected by gauge symmetry in 5d

➢ **Cosmological relaxation:**
see e.g. [Graham, Kaplan, Rajendran ‘15], [Espinosa et al. ‘15]
Promote the Higgs mass term $\mu^2$ to a dynamical field, the relaxion, and give this field a potential and interactions with the Higgs boson (and VEV) such that it selects the appropriate value of $\mu^2$

➢ and many more...
The Yukawa hierarchy problem and flavour

- Fermion mass patterns completely unexplained why is $m_t \sim 3 \times 10^5 m_e$? (not to mention neutrinos…)

- Fermion masses in SM → entirely determined by Yukawa couplings between fermions and Higgs boson
  → why does the Higgs treat the three fermion families (identical w.r.t gauge symmetries) so differently?

- No guiding principle in Yukawa interactions in SM

- Gauge symmetries act on all three fermion families in the same way → something must treat the families differently → for instance a “horizontal symmetry”?

Figure adapted from [Darme ‘24]
The cosmological constant and its fine-tuning problem

➢ Cosmological observations → Universe expanding at accelerating pace

➢ Explained in ΛCDM model by cosmological constant, corresponding to a vacuum energy:

\[ \rho_{\text{vac}} \sim 2.5 \times 10^{-47} \text{ GeV}^4 \]

➢ Value of Higgs potential at EW minimum not fixed by theoretical arguments, nor constrained by colliders

\[
V(\Phi) = \mu^2 |\Phi|^2 + \lambda |\Phi|^4 + V_0
\]

\[ \rightarrow V_{\text{min}} = \frac{1}{2} \mu^2 v^2 + \frac{1}{4} \lambda v^4 + V_0 = -1.2 \times 10^8 \text{ GeV}^4 + V_0 = \rho_{\text{vac}} \sim 2.5 \times 10^{-47} \text{ GeV}^4 \]

➢ Cancellation/fine-tuning of \textit{~55 digits} needed in \(V_0\) to reproduce the measured vacuum energy!

→ cosmological constant problem

➢ Possible solutions involve anthropic principle (multiverse), modifications of GR/ΛCDM, or of QFT, etc.
Form of the Higgs potential and trilinear Higgs coupling

- Brout-Englert-Higgs mechanism = origin of electroweak symmetry breaking ...
  … but very little known about the Higgs potential causing the phase transition
Form of the Higgs potential and trilinear Higgs coupling

- Brout-Englert-Higgs mechanism = origin of **electroweak symmetry breaking** ...
  … but very little known about the Higgs potential causing the phase transition

- Shape of the potential determined by **trilinear Higgs coupling** $\lambda_{hhh}$
Form of the Higgs potential and trilinear Higgs coupling

- Brout-Englert-Higgs mechanism = origin of electroweak symmetry breaking ...
  ... but very little known about the Higgs potential causing the phase transition

- Shape of the potential determined by trilinear Higgs coupling $\lambda_{hhh}$

\[
\text{In the SM: } V_{SM}^{(0)} = \frac{1}{2} m_h^2 h^2 + \frac{1}{3!} \left( \frac{3 m_h^2}{v} \right) h^3 + \frac{1}{4!} \left( \frac{3 m_h^2}{v^2} \right) h^4 + \ldots \\
\equiv (\lambda_{hhh}^{(0)})_{SM}^{(0)}
\]

\[
\text{In general: } V^{(0)} = \frac{1}{2} m_h^2 h^2 + \frac{1}{3!} \kappa_\lambda \left( \frac{3 m_h^2}{v} \right) h^3 + \frac{1}{4!} \kappa_4 \left( \frac{3 m_h^2}{v^2} \right) h^4 + \ldots \\
\text{with } \kappa_\lambda \equiv \lambda_{hhh} / (\lambda_{hhh}^{(0)})_{SM}^{(0)} \text{ and } \kappa_4 \equiv \lambda_{hhh} / (\lambda_{hhh}^{(0)})_{SM}^{(0)}
\]

$V = \phi$ 

$[\phi = v + h]$

\[m_h^2 = (125 \text{ GeV})^2\]

Vacuum expectation value $v = 246$ GeV
Form of the Higgs potential and baryon asymmetry

➢ Brout-Englert-Higgs mechanism = origin of electroweak symmetry breaking ... … but very little known about the Higgs potential causing the phase transition

➢ Shape of the potential determined by trilinear Higgs coupling $\lambda_{hhh}$

➢ Among Sakharov conditions necessary to explain baryon asymmetry via electroweak phase transition (EWPT):
  ➢ **Strong first-order EWPT**
    → barrier in Higgs potential
    → typically significant deviation in $\lambda_{hhh}$ from SM
Baryogenesis

- **Observed Baryon Asymmetry of the Universe (BAU)**

  \[ \eta \equiv \frac{n_b - n_{\bar{b}}}{n_\gamma} \simeq 6.1 \times 10^{-10} \quad \text{[Planck '18]} \]

- **Sakharov conditions** [Sakharov '67] for a theory to explain BAU:
  1. Baryon number violation
  2. C and CP violation
  3. Loss of thermal equilibrium

\( n_b \): baryon no. density
\( n_{\bar{b}} \): antibaryon no. density
\( n_\gamma \): photon no. density
Baryogenesis

➢ Observed Baryon Asymmetry of the Universe (BAU)

\[ \eta \equiv \frac{n_b - n_{\bar{b}}}{n_\gamma} \simeq 6.1 \times 10^{-10} \]  

[Planck '18]

➢ Sakharov conditions [Sakharov '67] for a theory to explain BAU:

1) Baryon number violation

2) C and CP violation

3) Loss of thermal equilibrium

→ Sphaleron transitions (break B+L)

→ C violation (SM is chiral), but not enough CP violation

→ No loss of th. eq. → in SM, the EWPT is a crossover

➢ SM cannot reproduce the BAU → BSM physics needed!
Electroweak Baryogenesis

- Many scenarios proposed, including:
  - Grand Unified Theories
  - Leptogenesis
  - Electroweak Baryogenesis (EWBG) [Kuzmin, Rubakov, Shaposhnikov, ‘85], [Cohen, Kaplan, Nelson ‘93]

- Sakharov conditions in EWBG
  1) Baryon number violation → Sphaleron transitions (break B+L)
  2) C and CP violation → C violation + CP violation in extended Higgs sector
  3) Loss of thermal equilibrium → Loss of th. eq. via a strong 1st order EWPT
The Higgs potential and the Electroweak Phase Transition

Possible thermal history of the Higgs potential:

- VEV is discrete \( \rightarrow 1^{st} \) order PT
- VEV is continuous \( \rightarrow 2^{nd} \) order PT

\( \lambda_{hhh} \) determines the nature of the EWPT!

\( \Rightarrow \) deviation of \( \lambda_{hhh} \) from its SM prediction typically needed to have a strongly first-order EWPT

[Grojean, Servant, Wells ’04], [Kanemura, Okada, Senaha ’04]
Electroweak Baryogenesis – a brief sketch

- **Sakharov conditions** in EWBG
  1) Baryon number violation
  2) C and CP violation
  3) Loss of thermal equilibrium

→ Sphaleron transitions (break B+L)
→ C violation + CP violation in extended Higgs sector
→ Loss of th. eq. via a strong 1\textsuperscript{st} order EWPT

EWBG only involves phenomena around the EW scale → **testable in the foreseeable future**
via $\lambda_{hhh}$, collider searches, gravitational waves or primordial black holes (sourced by 1\textsuperscript{st} order EWPT)
Higgs portal to dark sectors

➢ Dark matter (DM)
  · Non-relativistic matter (→ can’t be neutrinos)
  · Only/mostly gravitational interactions → several types of astrophysical evidence (e.g. galaxy rotation curves, etc.)
  · Collisionless (c.f. Bullet cluster) & pressureless
  · Needed to seed large-structure formation
    → No SM particle can fit this!

➢ $|\Phi|^2$ is a gauge singlet → Higgs field provides a perfect way to write a portal term in the Lagrangian, e.g. simplest example = add to SM a singlet $S$, charged under a global $Z_2$ symmetry to stabilise DM

$$\mathcal{L}_{Z_2SSM} = \mathcal{L}_{SM} - \lambda_{\text{portal}} S^2 |\Phi|^2 - \lambda_{\text{dark}} S^4$$

$\lambda_{\text{portal}}$: controls DM relic density & detection

➢ Plethora of models: inert singlets, doublets, triplets; Next-to-Two-Higgs-Doublet Model (N2HDM), S2HDM, etc.
Cosmic inflation

Anisotropies in the Cosmic Microwave Background (CMB)

$\frac{\delta T}{T} \sim 10^{-5}$

[Planck '18]
Cosmic inflation

Anisotropies in the Cosmic Microwave Background (CMB)

\[ \frac{\delta T}{T} \sim 10^{-5} \]

[Planck '18]
The Higgs boson as the inflaton

- Phase of exponential growth driven by scalar field – **inflaton** – with very flat potential \( \rightarrow \text{slow-roll inflation} \)

- What if the Higgs boson plays the role of the inflaton? 
  [Bezrukov, Shaposhnikov '07]
  \( \rightarrow \text{Higgs inflation} \)
  \( \rightarrow \) Higgs coupled **non-minimally** to gravity

\[
\mathcal{L} = \mathcal{L}_{\text{SM}} - \frac{1}{2} M_{\text{Pl}}^2 R - \xi |\Phi|^2 R
\]
(in Jordan frame)

- Change from **Jordan frame** (in which Lagrangian is written) to **Einstein frame** (with canonical coupling to gravity)

\[
g_{\mu
u}^E = \Omega^2(h) g_{\mu
u}^J, \quad \text{with} \quad \Omega^2(h) = 1 + \frac{\xi h^2}{M_{\text{Pl}}^2}
\]

\[
\Rightarrow \mathcal{L}^E \supset -\frac{1}{2} M_{\text{Pl}}^2 R^E + \frac{1}{2} (\partial_\mu \chi)^2 - \frac{\lambda}{4 \Omega^4(h(\chi))} (h(\chi)^2 - v^2)^2
\]

\(\chi: \text{Higgs field in Einstein frame}\)

- Numerous developments (non-minimal Higgs sectors, different couplings, etc.)

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Figure adapted from Bezrukov, Shaposhnikov, '07
The Higgs boson as the inflaton

➢ Phase of exponential growth driven by scalar field – **inflaton** – with very flat potential → **slow-roll inflation**

➢ What if the Higgs boson plays the role of the inflaton?

[Bezrukov, Shaposhnikov '07]

→ **Higgs inflation**

→ Higgs coupled **non-minimally** to gravity

\[ \mathcal{L} = \mathcal{L}_{SM} - \frac{1}{2} M_{P1}^2 R - \xi |\Phi|^2 R \]

(in Jordan frame)

➢ Change from **Jordan frame** (in which Lagrangian is written) to **Einstein frame** (with canonical coupling to gravity)

\[ g^E_{\mu\nu} = \Omega^2(h) g^J_{\mu\nu}, \quad \text{with} \quad \Omega^2(h) = 1 + \frac{\xi h^2}{M_{P1}^2} \]

\[ \Rightarrow \mathcal{L}^E = -\frac{1}{2} M_{P1}^2 R^E + \frac{1}{2} (\partial_\mu \chi)^2 - \frac{\lambda}{4\Omega^4(h(\chi))} (h(\chi)^2 - v^2)^2 \]

\[ = U(\chi) \]

\( \chi \): Higgs field in Einstein frame

➢ Numerous developments (non-minimal Higgs sectors, different couplings, etc.)

Figure adapted from [Bezrukov, Shaposhnikov, '07]
The Higgs boson as the inflaton

- Phase of exponential growth driven by scalar field – **inflaton** – with very flat potential → **slow-roll inflation**

- What if the Higgs boson plays the role of the inflaton?  
  [Bezrukov, Shaposhnikov ’07]  
  → **Higgs inflation**  
  → Higgs coupled **non-minimally to gravity**

\[ \mathcal{L} = \mathcal{L}_{\text{SM}} - \frac{1}{2} M_{\text{Pl}}^2 R - \xi |\Phi|^2 R \]  
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- Change from **Jordan frame** (in which Lagrangian is written) to **Einstein frame** (with canonical coupling to gravity)

\[ g^{\mu\nu}_E = \Omega^2(h) g^{\mu\nu}_J, \quad \text{with } \Omega^2(h) = 1 + \frac{\xi h^2}{M_{\text{Pl}}^2} \]

\[ \Rightarrow \mathcal{L}^{\text{E}} = -\frac{1}{2} M_{\text{Pl}}^2 R^{\text{E}} + \frac{1}{2} (\partial_\mu \chi)^2 - \frac{\lambda}{4 \Omega^4(h(\chi))} (h(\chi)^2 - v^2)^2 \]

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\[ \chi: \text{Higgs field in Einstein frame} \]

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![Usual picture of slow-roll inflation](image-url)
Neutrino masses and Higgs boson(s)

➢ SM contains no right-handed neutrinos → no neutrino masses

➢ However, since 1960’s early signs of neutrino oscillations (“solar neutrino deficit”), eventually confirmed ~25 years ago
→ atmospheric neutrino oscillations in 1998
→ solar neutrino oscillations in 2001
→ 2015 Nobel Prize for Kajita and McDonald
→ neutrinos do have masses → extension of SM needed!

➢ Most common solutions rely on variants of seesaw mechanism (types I, II, III)
→ basic idea (type I): introduce, heavy, right-handed Majorana neutrinos (RHN) \( N_R \)

\[
\mathcal{L}_{1-fam.} \ni (\bar{\nu}_L \, \bar{N}_R^c) \begin{pmatrix} 0 & y_{\nu} v / \sqrt{2} \\ y_{\nu} v / \sqrt{2} & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N_R \end{pmatrix}
\] with \( M_R \gg v \)

⇒ \( m_{\nu_L} \sim \frac{y_{\nu}^2 v^2}{M_R} \)

However, this usually introduces a new hierarchy problem + is difficult to test experimentally

➢ Other possibility: generate tiny neutrino masses via radiative effects from extended scalar sectors
→ [Zee ‘80], [Babu ‘88], [Aoki, Kanemura, Seto ‘08], etc.
→ no longer need for very heavy RHN

An example of radiative neutrino mass generation: the Aoki-Kanemura-Seto model

Figure from [Aoki, Enomoto, Kanemura ‘22]
Thank you very much for your attention!

Contact

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