Understanding the emptiness: the Higgs field and beyond

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July 27, 2021

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Johns Hopkins University QuarkNet Physics Workshop
FCC (CERN) vision of the next 70 years

LHC program (funded)

- 2021: present LHC
- 2026: High Luminosity - LHC

Future Circular Collider
- pp 100 TeV (in R&D now)
- 2038: FCC-$e^+e^-$
- 2063: FCC-hh

"backup:" High Energy - LHC (27 TeV)

Timeline:
- Present LHC
- 2021: LHC run 3
- 2022: LS 3
- 2024: LHC run 4
- 2026: LS 4
- 2028: LHC run 5
- 2030: LS 5
- 2034: LHC run 6

10 years:
- 2026: LHC run 4
- 2038: FCC-$e^+e^-$

15 years operation:
- 2026: LHC run 4
- 2038: FCC-$e^+e^-$

~ 25 years operation:
- 2026: LHC run 4
- 2038: FCC-$e^+e^-$
- 2063: FCC-hh

Project preparation & administrative processes
Funding & governance strategy

Geological investigations, infrastructure detailed design and tendering preparation

Tunnel, site and technical infrastructure construction

FCC-ee accelerator R&D and technical design

FCC-ee accelerator construction, installation, commissioning

Detector R&D and concept development

FCC-ee detector technical design, collaborations

FCC-ee detector construction, installation, commissioning

Superconducting wire and high-field magnet R&D

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The Next Microscope (Collider Proposals)

Future $e^+e^-$ Higgs Factory
linear or circular, in Europe or Asia…

$e^+ e^-$: ~ 125 GeV

$Z(\gamma)$: Precision EFT studies

$H$: CP-violation

arXiv:1309.4819
The Future of Particle Physics: “Snowmass” planning

Decadal community planning process

1982 — concept of SSC…
...
2001 — flavor physics and future facilities (LHC)
2013 — Higgs discovery and the next steps (see P5 below)
2022 — starting now…

US strategic planning (P5), advise NSF and DOE through HEPAP
(P5 = Particle Physics Project Prioritization Panel)

Use the Higgs boson as a new tool for discovery
• Pursue the physics associated with neutrino mass
• Identify the new physics of dark matter
• Understand cosmic acceleration: dark energy and inflation
• Explore the unknown: new particles, interactions, and physical principles

focus today
Higgs Potential and Stability of the Vacuum

\[ V(\phi) = \mu^2 \phi^{\dagger} \phi + \lambda^2 (\phi^{\dagger} \phi)^2 \]

- Quantum corrections \( \Rightarrow \) metastable vacuum
  - assume SM up to very large \( M \)

1. Universe cools down
2. Symmetry spontaneously breaks
3. Tunnel away?

- First steps to test Higgs potential \( V(\phi) \)
  - \( \mu \)
  - \( g \)
  - \( H \)

- test \( HHHH(H) \) interaction

- need more data, new facilities…

(or in virtual EFT effects)
We learn that there are fields…

Gravity

Electricity

Magnetism
Quantum Field Theory =
Quantum Mechanics (very small)
+ Special Relativity (very fast)
The Unified Vision: the Standard Model (SM)

Cosmology (SM)

General Relativity

Gravity

Origin of Space-Time (?)

Unified Theory (?)

The Ultimate Theory (?)

Quantum Gravity

Dark Matter? +

Inflation?

Dark Energy?

Higgs

Electro-Weak

Particle Physics (SM)

Weak

E&M

Strong

Electricity

Magnetism

ν

matter

vacuum
The Unified Vision: the Standard Model (SM)

The Ultimate Theory (?)
Quantum Gravity

Origin of Space-Time (?)
Unified Theory (?)

Cosmology (SM)

Particle Physics (SM)

Problems:
- Understanding the matter
- Understanding the vacuum

- Dark matter?
- Baryogenesis? (matter over antimatter)
  baryon number violation (p decay?)
  CP violation? non-equilibrium?
- Are neutrinos special? …
- Higgs field and masses (hierarchy problems)
  (vacuum stability)
- Dark energy?
- Inflation?

Crisis of Standard Models of Particles Physics & Cosmology
Understanding the Vacuum

\[ R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R - \Lambda g_{\mu\nu} = -8\pi G T_{\mu\nu} \]

energy density of the vacuum = $\Lambda/8\pi G$

many orders away from the Higgs field expectation

\[ H^0(125) \] has quantum numbers of the vacuum $J^{PC} = 0^{++}$

scalar field(s) may be at the core of solutions, Higgs field is the first “studied”

- $H^0(125)$ boson is an excitation of the Higgs field
  completely new state of matter-energy
Approach the Problems: Astrophysics

- Origin of Space-Time (?)
- Cosmology (SM)
- General Relativity
- Dark Energy?
- Dark Matter? +
- Particle Physics (SM)
- Gravity

Telescope
Approach the Problems: Particle Physics

Microscope

Large Hadron Collider

CMS (ATLAS) detector

Unified Theory (?)

Particle Physics (SM)

Higgs

Electro-Weak

Weak

E&M

Strong

Electricity

Magnetism

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Scales in Particle Physics

Energy = \frac{hc}{\text{Distance}}

"new physics" \quad M = ?

unknown gap

\nu \sim 246 \text{ GeV}
\sim 5 \times 10^{-15} \text{ m}

\sim 1 \text{ GeV}
\sim 10^{-12} \text{ m}

visible light \sim \text{ eV}
\sim \mu \text{ m}

⇒ High-Energy Physics

Unified Theory (?)

Higgs \quad \text{Electro-Weak} \quad \text{top quark}

Strong

Electricity \quad Magnetism
“Optimistic” Scale in Particle Physics

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Energy

$M = ? \sim \text{TeV}$

$v \sim 246 \text{ GeV}$

LHC simulation at 13 TeV

We did find this “bump” but none appeared so far…

Find new physics “bump”

Higgs | Electro-Weak | top quark

JHUGen

Beyond SM
"Pessimistic" Scale in Particle Physics

$M \gg v$

$v \sim 246 \text{ GeV}$

Particle Physics (SM) is an Effective Field Theory (EFT)

precise up to $\sim \left( \frac{v}{M} \right)^2$

Energy

$\begin{array}{|c|}
\hline
\text{Higgs} & \text{Electro-Weak} & \text{top quark} \\
\hline
\end{array}$

Unified Theory (?)
Effective Field Theory

- Effective Field Theory (EFT)
  - describes energies (of interest) below $M$ (underlying dynamics)
  - no “new physics” up to $M \gg m_H$

\[ m_H c^2 = 125 \text{ GeV} \]

\[ \Delta E = m_x c^2 \gg m_H c^2 \]

point-like interaction

Heisenberg's uncertainty principle

\[ \Delta E \Delta t \sim \hbar \]

- Look for deviations $\sim \left( \frac{v}{M} \right)^2$ parameterized in EFT
Table-Top, “Low-Energy,” LHC experiments

- Electric Dipole Moment (EDM) of electron
  \[ d_e < 1.1 \times 10^{-29} \text{ e cm} \]
  \[ d_e^{SM} \sim 10^{-38} \text{ e cm} \]
  \[ d_n < 3.0 \times 10^{-26} \text{ e cm} \]

  hypothetical
  CP violation

\[ \gamma, g \]
\[ \ell, q \]
\[ H \]

- Heavy-Quark meson decays:
  hypothetical
  CP violation

\[ W, W \]
\[ \bar{b}, q \]

SU(2)xU(1)

complementary to LHC in EFT

25 year old...

Colloquium 2007
Heavy-Quark (“Low-Energy”) Experiments

$(e^+e^-)$ CLEO, BABAR, BELLE(II),
$(p\bar{p}, pp)$ CDF/D0, LHCb,…

\[ \frac{1}{2} M_B \sim 5 \text{ GeV} \]
Quark and Neutrino “Flavor” Physics: CP Violation

- The only known source of CP violation (difference matter-antimatter)
  - in the Quark sector (completion of the Standard Model in this sector)
  - the Lepton (neutrino $\nu$) sector in active development (Nobel Prize 2015: $\nu$ mass)

The Nobel Prize in Physics 2008

The Nobel Prize in Physics 2008 was divided, one half awarded to Yoichiro Nambu “for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics”, the other half jointly to Makoto Kobayashi and Toshihide Maskawa “for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature”.

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quantum numbers and anomalous couplings of the parton shower and detector calculations. We extend the matrix element approach by incorporating the machine learning procedure to account for. This approach relies on the MC simulation, reweighting tools, and optimal observables constructed from matrix element approach to accommodate both challenges, while keeping the approach generic enough for further extensions. This likelihood description of a single process with the increasing number of parameters of interest. We present a practical is the fast growth of both the number of observable dimensions and the number of contributing components in the provide the multi-parameter results in both the EFT and the generic approaches. The main challenge in this analysis to excite the vacuum (Higgs field $\Phi$).

$g \rightarrow H \rightarrow Z Z^{(*)}$, $m_{H} = 125 \text{GeV}$, $m_{Z^{(*)}} < 35 \text{GeV}$, $m_{Z} = 91 \text{GeV}$, $\sim 62.5 \text{GeV}$, $\sim 7000 \text{GeV}$.
The Nobel Prize in Physics
2013

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider."

$m_H \sim 125$ GeV
The Higgs boson eight years later…

- Couples to matter-energy rates as \( \sim \) expected.
- **Mass**: quantum corrections
- **Lifetime**: faster decay to new states? to dark matter?…
- **Quantum numbers**?
  - expect \( J^{PC} = 0^{++} \) as vacuum
- **New source of \( CP \) violation**?
- **Any hints of EFT effects** \( \sim \left( \frac{V}{M} \right)^2 \) ?…
- **Higgs field(s) and potential**?

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The Higgs boson eight years later…

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- Lifetime: faster decay to new states? to dark matter?…
- Quantum numbers? expect $J^{PC} = 0^{++}$ as vacuum
- New source of $CP$ violation?
- Any hints of EFT effects $\sim \left( \frac{v}{M} \right)^2$?…
- Higgs field(s) and potential?

\[ \mathcal{L} = \text{Gauge boson interaction} \]
\[ \quad \begin{align*}
\quad + |D_\mu \varphi|^2 & \\
\quad + \Psi_i \gamma_{ij} \Psi_j \varphi & + \text{h.c.} \\
\quad - V(\varphi) & \\
\end{align*} \]

\[ \text{Interaction with matter} \]
\[ \text{Higgs potential} \]
\[ \text{Higgs field} \]
Summary

- Crisis of Standard Models of **Particles Physics & Cosmology**
- Use the **Higgs boson** as a new tool for discovery
  - may reach to new **particles, interactions (EFT)**
  - may be our window to **dark matter**
  - may relate to **baryogenesis (CP)**
  - **Higgs field** responsible for stability of the vacuum
  - interplay with **inflation and dark energy**: scalar fields in vacuum
- Active research program of **Higgs physics**
  - from **discovery** to detailed **properties**
  - **Run-3** of LHC, to **High-Luminosity LHC**
  - **Higgs Factory** on the horizon…
  - synergy with **table-top, dark-matter, low-energy** experiments