The trilinear Higgs coupling and new physics

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India-JINR workshop on elementary particle and nuclear physics, and condensed matter research

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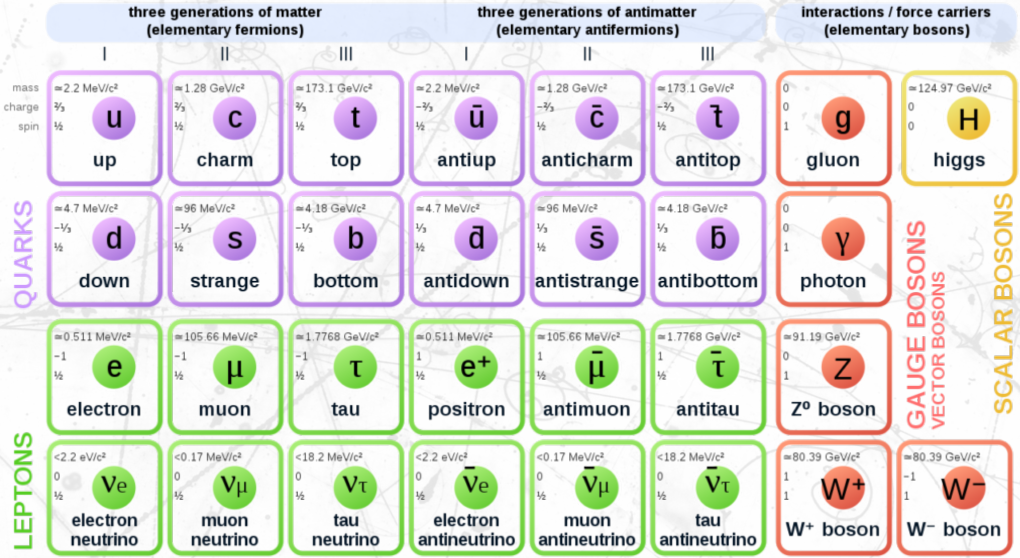
Standard Model of Elementary Particles

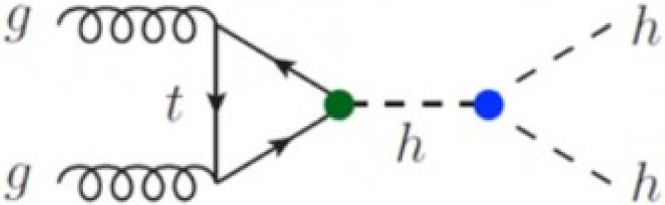


Developed in the early 1970s, the Standard Model (SM) has established itself as a well-proven physics theory over time and through numerous experiments, and many of its input parameters experimentally matched.

Five mysteries of the universe the Standard Model can't explain:

1. Why do neutrinos have mass?
2. What is dark matter?
3. Why is there so much matter in the universe?
4. Why is the expansion of the universe accelerating?
5. Is there a particle associated with the force of gravity?

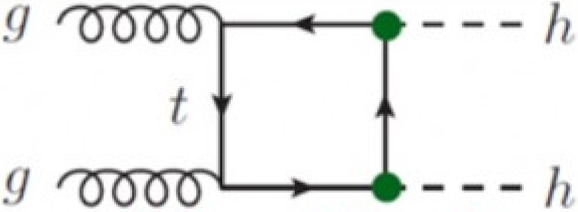
That is why you require New Physics, often known as Beyond the Standard Model (BSM).



$\lambda_{SM} = m^2_H/(2v^2)$

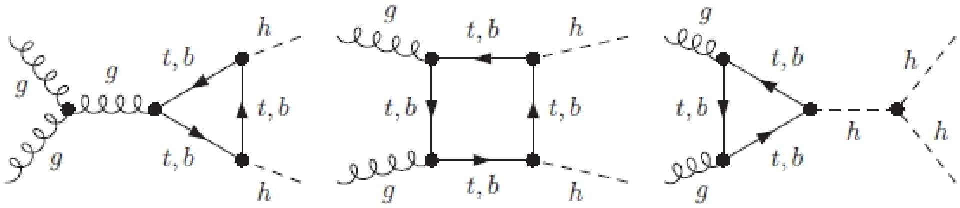
$= 0.129$

Tri-linear coupling λ_{HHH}



SM processes

Yukawa interaction y_T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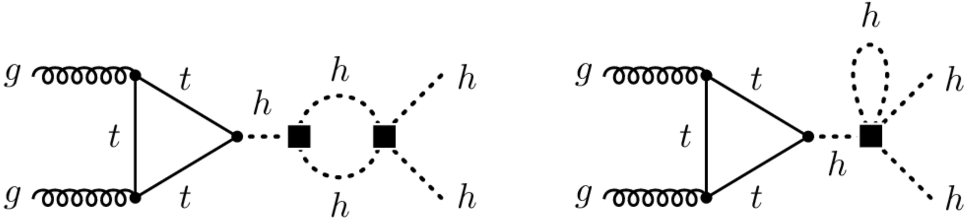
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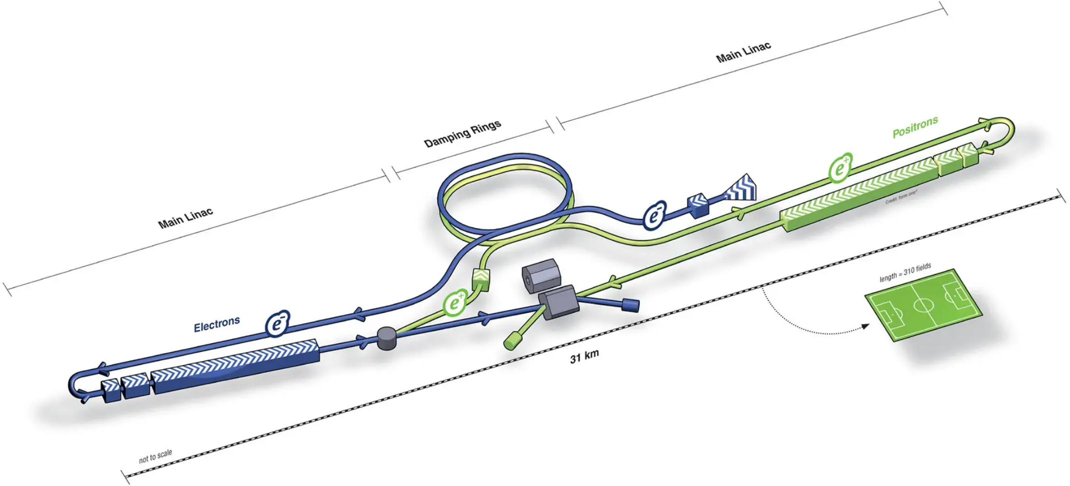
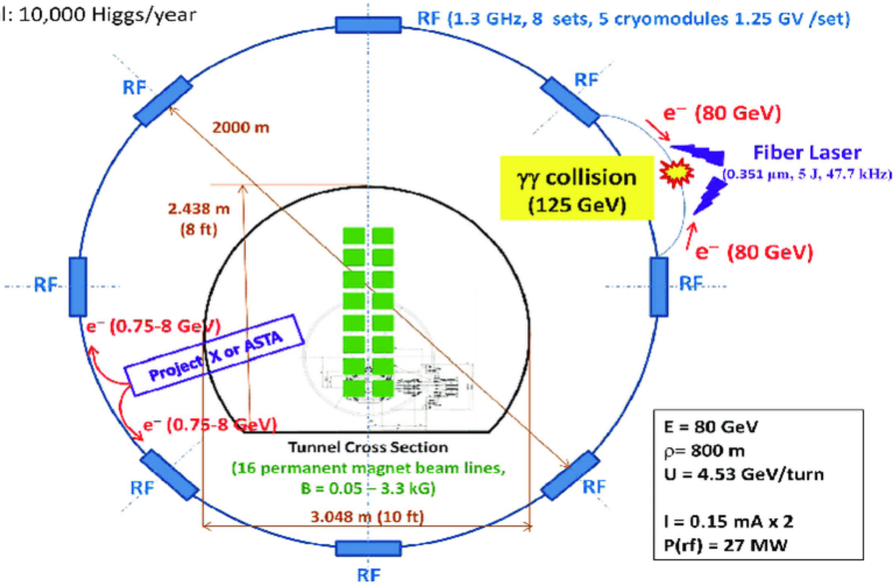


ILC Scheme | © www.form-one.de

HFiTT – Higgs Factory in Tevatron Tunnel

Goal: 10,000 Higgs/year



E = 80 GeV
ρ= 800 m
U = 4.53 GeV/turn

I = 0.15 mA x 2
P(rf) = 27 MW


LINEAR COLLIDER
CIRCULAR COLLIDER
GAMMA COLLIDER
MUON COLLIDER

Preliminaries

- Undoubtedly, one of the most crucial jobs at the LHC and next colliders is the measurement of the trilinear Higgs self-coupling.
- It is the first step toward the direct experimental verification of the Higgs mechanism *sui generis* and the experimental reconstruction of the Higgs potential.
- In the Standard Model (SM), it is accessible through the challenging measurement of Higgs pair production at colliders.
- The Higgs self-couplings are also implicated in Higgs-to-Higgs decays in models with extended Higgs sectors.
- The trilinear Higgs self-coupling is connected to the Higgs boson mass via the Higgs potential.
- While the Higgs mass in the Standard Model (SM) is an arbitrary input parameter, in certain (supersymmetric) theories it is derived from the model's parameters.

Preliminaries

- We must carefully examine the 125 GeV Higgs boson's properties in order to determine whether it is, in fact, the SM Higgs boson. The Higgs sector in the SM is entirely governed by the following Lagrangian:

$$
\begin{aligned}
\mathscr{L}_{\text{Higgs}} &= |D_\mu \Phi|^2 - \sum_f y_f \bar{L}_f \Phi R_f - V(\Phi) \\
\text{where,}\ \ \Phi^\dagger &= (\phi^- \phi^0) \\
D_\mu &\equiv \partial_\mu - i g_2 W_\mu^a T^a - i g_1 B_\mu \\
V(\Phi) &= -\mu^2 (\Phi^\dagger \Phi) + \lambda (\Phi^\dagger \Phi)^2 .
\end{aligned}
$$

- Due to electroweak symmetry breaking (EWSB), the first term results in the couplings of the Higgs with gauge bosons. The second term results in the couplings of the Higgs with fermions, and the third term results in the trilinear and quartic Higgs self-couplings of the Higgs boson. At the LHC, the SM couplings of the Higgs boson to gauge fermions and bosons are known with a precision of 10–20%. The Higgs self-couplings in the LHC, however, are essentially unconstrained.

Preliminaries

- Correction to SM triple Higgs coupling:
  According to PDG the largest possible experimental value for λ_{HHH} is 12 times the SM prediction, from Run 2 data for the $b\bar{b}\gamma\gamma$ channel alone.
  (https://pdg.lbl.gov/2023/reviews/rpp2022-rev-higgs-boson.pdf, page 29–30, chapter 11, Section 3.4.2 and page 66, chapter 11, Section 6.2.5.)

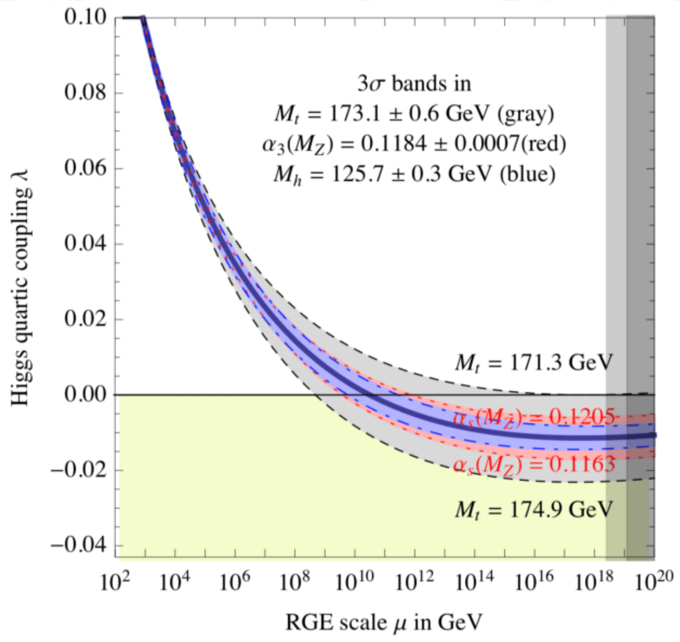
Important

- A key component of electroweak symmetry breaking, the trilinear self-coupling constant of the Higgs boson, will be precisely measured as part of the physics program of future colliders.

Review of Particle Physics (2023), Workman et al. (Particle Data Group)
Prog. Theor. Exp. Phys. **2022**, *083C01 (2022) and 2023 update.*

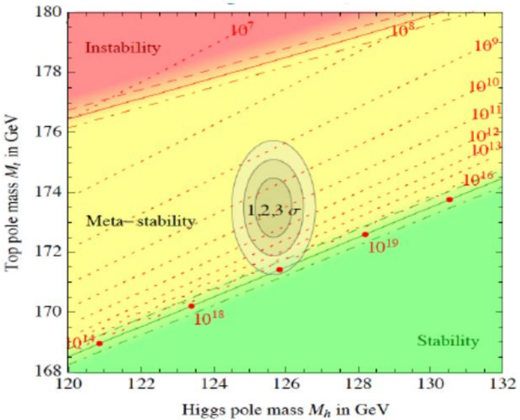
Introduction

- After the discovery of the Standard Model (SM) Higgs boson, every elementary particle of the SM has been confirmed to exist.
- Even though the past forty years have been a spectacular triumph for the SM, the mass of the Higgs boson ($m_H = 125.25 \pm 0.17$ GeV) poses a serious problem for the SM.
- It is well-known that the SM Higgs potential is metastable, as the sign of the quartic coupling, λ_H, turns negative at instability scale $\Lambda_{\mathrm{IS}} \sim 10^{11}$ GeV.
- The largest uncertainties in SM vacuum stability are driven by top quark pole mass and the mass of the SM Higgs boson.
- The current data are in significant tension with the stability hypothesis, making it more likely that the universe is in a false vacuum state.
- The expected lifetime of vacuum decay to a true vacuum is extraordinarily long, and it is unlikely to affect the evolution of the universe.



3σ bands in
M_t = 173.1 ± 0.6 GeV (gray)
$\alpha_3(M_Z)$ = 0.1184 ± 0.0007(red)
M_h = 125.7 ± 0.3 GeV (blue)
M_t = 171.3 GeV
$\alpha_s(M_Z)$ = 0.1205
$\alpha_s(M_Z)$ = 0.1163
M_t = 174.9 GeV
Higgs quartic coupling λ
RGE scale μ in GeV
0.10
0.08
0.06
0.04
0.02
0.00
−0.02
−0.04
10^2 10^4 10^6 10^8 10^{10} 10^{12} 10^{14} 10^{16} 10^{18} 10^{20}

Stability and Higgs Mass



To understand stability, in absence of any new physics, requires very precise determination of top quark and Higgs mass.

Introduction

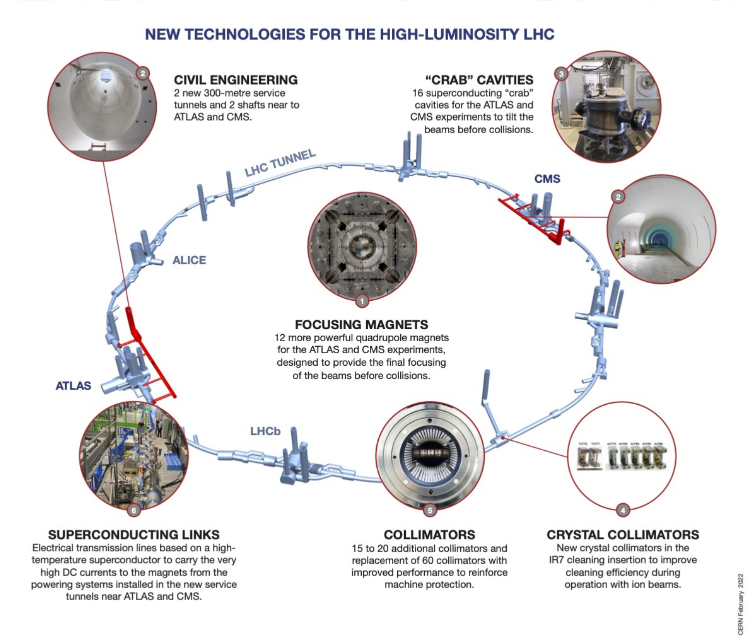
- However, it is unclear why the vacuum state entered into a false vacuum to begin with during the early universe.
- In this post-SM era, the emergence of vacuum stability problems (among many others) forces the particle theorists to expand the SM in such a way that the λ_H will stay positive during the run all the way up to the Planck scale.
- It is possible that at or below the instability scale, heavy degrees of freedom originating from a theory beyond the SM start to alter the running of the SM parameters of renormalization group equations (RGE).
- It has been shown that incorporating the Type-I seesaw mechanism will have a large destabilizing effect if the neutrino Yukawa couplings are large, and an insignificantly small effect if they are small.
- Thus, to solve the vacuum stability problem simultaneously with neutrino mass, a larger theory extension is required.

Introduction

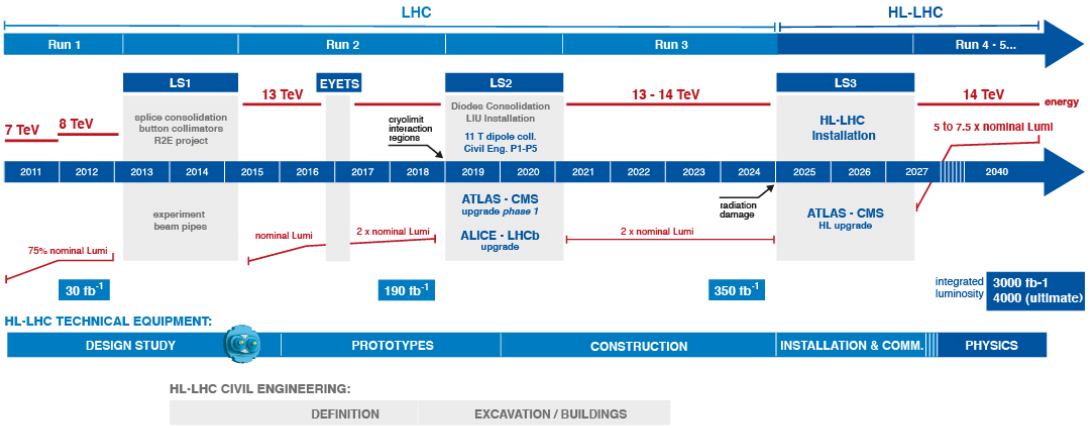
- Embedding the invisible axion model together with the Type-I seesaw was considered previously.
- The axion appears as a phase of a complex singlet scalar field.
- This approach aims to solve the vacuum stability problem by proving that the universe is currently in a true vacuum.
- The scalar sector of such a theory may stabilize the vacuum with a threshold mechanism.
- The effective SM Higgs coupling gains a positive correction $\delta \equiv \lambda_{H\sigma}^2/\lambda_\sigma$ at m_ρ, where $\lambda_{H\sigma}$ is the Higgs doublet-singlet portal coupling and λ_σ is the quartic coupling of the new scalar.
- Corrections altering λ_H in such a model would also induce corrections to the triple Higgs coupling, $\lambda_{HHH}^{\text{tree}} = 3m_H^2/v$, where $v = 246.22$ GeV is the SM Higgs vacuum expectation value (VEV).

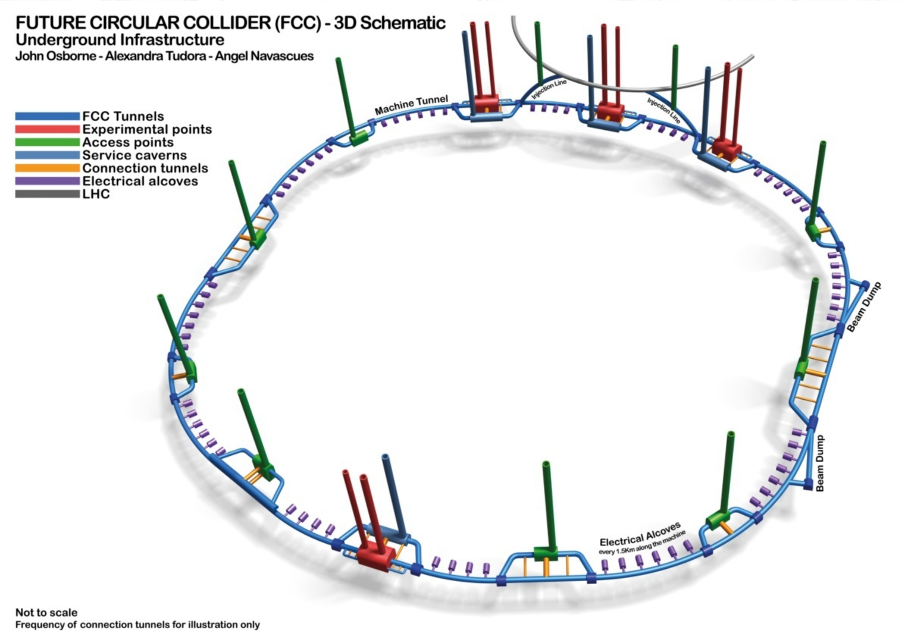
Future prospects

- Future prospects of measuring a deviation of triple Higgs coupling by the high-luminosity upgrade of the LHC (HL-LHC) or by a planned next-generation Future Circular Collider (FCC) give us hints of the structure of the scalar sector of a beyond-the-SM theory.

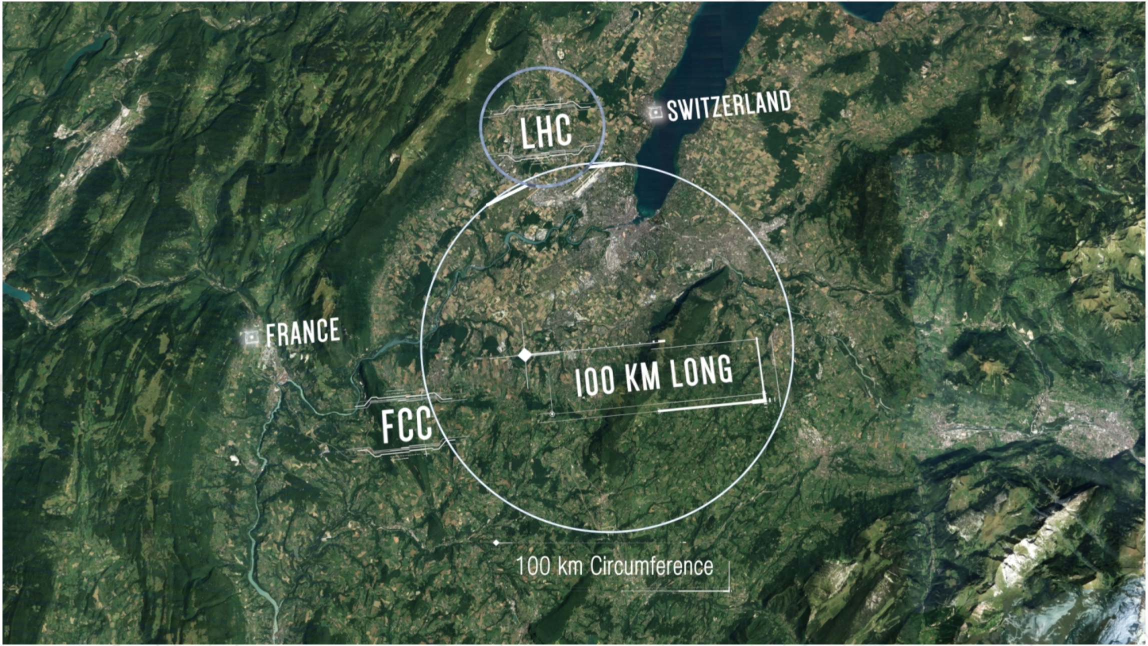

NEW TECHNOLOGIES FOR THE HIGH-LUMINOSITY LHC
CIVIL ENGINEERING
2 new 300-metre service tunnels and 2 shafts near to ATLAS and CMS.
"CRAB" CAVITIES
16 superconducting "crab" cavities for the ATLAS and CMS experiments to tilt the beams before collisions.
LHC TUNNEL
CMS
ALICE
FOCUSING MAGNETS
12 more powerful quadrupole magnets for the ATLAS and CMS experiments, designed to provide the final focusing of the beams before collisions.
ATLAS
LHCb
SUPERCONDUCTING LINKS
Electrical transmission lines based on a high-temperature superconductor to carry the very high DC currents to the magnets from the powering systems installed in the new service tunnels near ATLAS and CMS.
COLLIMATORS
15 to 20 additional collimators and replacement of 60 collimators with improved performance to reinforce machine protection.
CRYSTAL COLLIMATORS
New crystal collimators in the IR7 cleaning insertion to improve cleaning efficiency during operation with ion beams.
CERN February 2022

LHC / HL-LHC Plan





FUTURE CIRCULAR COLLIDER (FCC) - 3D Schematic
Underground Infrastructure
John Osborne - Alexandra Tudora - Angel Navascues
FCC Tunnels
Experimental points
Access points
Service caverns
Connection tunnels
Electrical alcoves
LHC
Machine Tunnel
Injection Line
Injection Line
Beam Dump
Beam Dump
Electrical Alcoves
every 1.5Km along the machine
Not to scale
Frequency of connection tunnels for illustration only


LHC
SWITZERLAND
FRANCE
FCC
100 KM LONG
100 km Circumference

SM-Axion-Seesaw-Higgs Portal Inflation (SMASH) Model

- The complex singlet scalar, and consequently, the corresponding threshold mechanism, is embedded in a recent SMASH theory, which utilizes it at $\lambda_{H\sigma} \sim -10^{-6}$ and $\lambda_\sigma \sim 10^{-10}$.
- The mechanism turns out to be dominant unless the new Yukawa couplings of SMASH are $\mathcal{O}(1)$.
- In addition to its simple scalar sector extension, SMASH includes electroweak singlet quarks Q and $\overline{Q}$ and three heavy right-handed Majorana neutrinos N_1, N_2 and N_3 to generate masses for neutrinos.

Theory

The SMASH framework expands the scalar sector of the SM by introducing a complex singlet field

$$\sigma = \frac{1}{\sqrt{2}} (v_\sigma + \rho) \, e^{iA/v_\sigma}, \tag{1}$$

where ρ and A (the axion) are real scalar fields, and $v_\sigma \gg v$ is the VEV of the complex singlet. The scalar potential of SMASH is then

$$\begin{aligned} V(H,\sigma) &= \lambda_H \left(H^\dagger H - \frac{v^2}{2}\right)^2 + \lambda_\sigma \left(|\sigma|^2 - \frac{v_\sigma^2}{2}\right)^2 \\ &\quad + 2\lambda_{H\sigma} \left(H^\dagger H - \frac{v^2}{2}\right) \left(|\sigma|^2 - \frac{v_\sigma^2}{2}\right). \end{aligned} \tag{2}$$

Theory

Defining $\phi_1 = H$ and $\phi_2 = \sigma$, in basis (H, σ), the scalar mass matrix of this potential is

$$(M_{ij})_{\text{scalar}} = \frac{1}{2}\frac{\partial^2 V}{\partial\phi_i\partial\phi_j}\bigg|_{\substack{H=v/\sqrt{2},\\ \sigma=v_\sigma/\sqrt{2}}} = \begin{pmatrix} 2\lambda_H v^2 & 2\lambda_{H\sigma} v v_\sigma \\ 2\lambda_{H\sigma} v v_\sigma & 2\lambda_\sigma v_\sigma^2 \end{pmatrix}, \tag{3}$$

which has eigenvalues

$$m_H^2 = v^2\lambda_H + v_\sigma^2\lambda_\sigma - \sqrt{v^4\lambda_H^2 + 4v^2v_\sigma^2\lambda_{H\sigma}^2 - 2v^2v_\sigma^2\lambda_H\lambda_\sigma + v_\sigma^4\lambda_\sigma^2}, \tag{4}$$

and

$$m_\rho^2 = v^2\lambda_H + v_\sigma^2\lambda_\sigma + \sqrt{v^4\lambda_H^2 + 4v^2v_\sigma^2\lambda_{H\sigma}^2 - 2v^2v_\sigma^2\lambda_H\lambda_\sigma + v_\sigma^4\lambda_\sigma^2}. \tag{5}$$

Theory

At the heavy singlet limit $\lambda_\sigma v_\sigma^2 \gg \lambda_H v^2$

$$m_H^2 = 2v^2 \left(\lambda_H - \frac{\lambda_{H\sigma}^2}{\lambda_\sigma} \right) + \mathcal{O}\left(\frac{v^2}{v_\sigma^2} \right) , \tag{6}$$

and

$$m_\rho^2 = 2v_\sigma^2 \lambda_\sigma - 2v^2 \frac{\lambda_{H\sigma}^2}{\lambda_\sigma} + \mathcal{O}\left(\frac{v^4}{v_\sigma^2} \right) . \tag{7}$$

Defining threshold correction $\delta \equiv \lambda_{H\sigma}^2 / \lambda_\sigma$ in Equation (12),

$$m_H^2 \approx 2v^2(\lambda_H - \delta) \equiv 2v^2 \lambda_H^{\mathrm{SM}} , \tag{8}$$

and

$$m_\rho^2 \approx 2v_\sigma^2 \lambda_\sigma - 2v^2 \delta . \tag{9}$$

The first term in the Equation (9) is the leading component.

Threshold correction

Consider an energy scale below $m_\rho < \Lambda_{\mathrm{IS}}$, where the heavy scalar ρ is integrated out. The low-energy Higgs potential should match the SM Higgs potential

$$V(H) = \lambda_H^{\mathrm{SM}} \left(H^\dagger H - \frac{v^2}{2} \right)^2 . \tag{10}$$

It turns out that the quartic coupling we measure has an additional term

$$\lambda_H^{\mathrm{SM}} = \lambda_H - \frac{\lambda_{H\sigma}^2}{\lambda_\sigma} . \tag{11}$$

Threshold correction

Since the SM Higgs quartic coupling will be approximately $\lambda_H(M_{Pl}) \approx -0.02$, the threshold correction

$$\delta \equiv \frac{\lambda_{H\sigma}^2}{\lambda_\sigma} \tag{12}$$

should have a minimum value close to $|\lambda_H(M_{Pl})|$ or slightly larger to push the high-energy counterpart λ_H to positive value all the way up to M_{Pl}. A too-large correction will, however, increase λ_H too rapidly, exceeding the perturbativity limit $\sqrt{4\pi}$. Similar to λ_H, the SM Higgs quadratic parameter μ_H gains a threshold correction

$$\left(\mu_H^{\mathrm{SM}}\right)^2 = \mu_H^2 - \frac{\lambda_{H\sigma}}{\lambda_\sigma}\mu_\sigma^2. \tag{13}$$

Correction to triple Higgs coupling

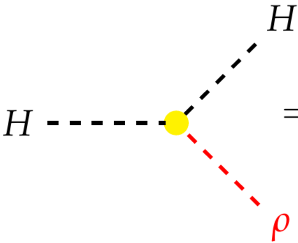
$$
\begin{aligned}
\Delta\lambda_{HHH} \quad = \quad & \left(2^2 \cdot \lambda_{HHH}\lambda_{H\sigma}^2 v_\sigma^2 I(m_H, m_H, m_\rho; p, q) + 2\,\mathrm{permutations}\right) \\
& + \left(2^3 \cdot \lambda_{H\sigma}^3 v v_\sigma^2 I(m_H, m_\rho, m_\rho; p, q) + 2\,\mathrm{permutations}\right) \\
& + 2^3 \cdot \lambda_{H\sigma}^3 v^3 I(m_\rho, m_\rho, m_\rho; p, q).
\end{aligned} \tag{14}
$$

Here, p and q are the external momenta and the loop integral is defined as

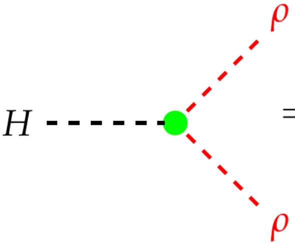
$$
I(m_A, m_B, m_C; p, q) =
$$

$$
\int \frac{d^4k}{(2\pi)^4} \frac{1}{(k^2 - m_A^2)((k-p)^2 - m_B^2)((k+q)^2 - m_C^2)}. \tag{15}
$$

Tree-level correction to triple Higgs coupling



$$= -i2\lambda_{H\sigma} v_{\sigma},$$



$$= -i2\lambda_{H\sigma} v$$

Figure 1. Vertex factors on trilinear vertices involving the SM Higgs boson as well as a real singlet ρ. They can be derived from Equation (2). We denote ρ and its propagator by red color.

One-loop correction to triple Higgs coupling

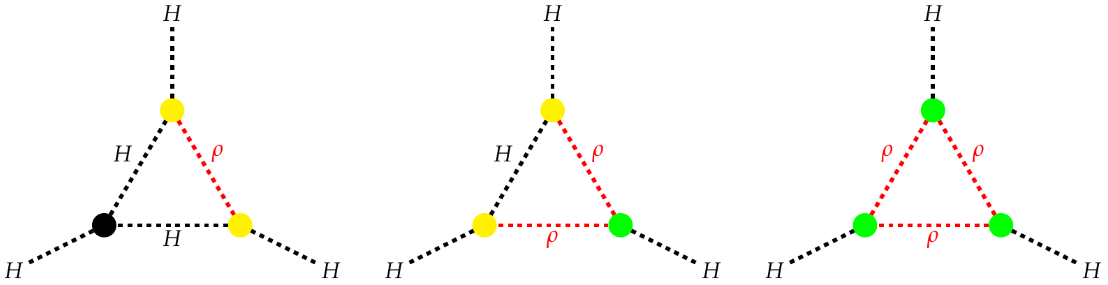


Figure 2. One-loop corrections to SM triple Higgs coupling induced by the existence of an extra scalar singlet. In Equation (15), the correction $\Delta\lambda_{HHH}$ is derived.

One-loop correction to triple Higgs coupling

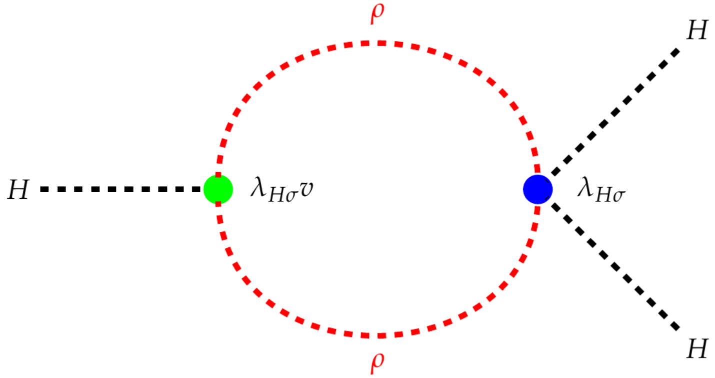


Figure 3. One-loop SM triple Higgs coupling correction diagram with a cubic vertex and a quartic vertex.

The contribution from diagram Figure 3 is subleading, since it is proportional to $\lambda_{H\sigma}^2 v \Rightarrow \delta\lambda_\sigma v \ll \lambda_{HHH}$.

Correction to triple Higgs coupling

We calculate the finite part of it using dimensional regularization and obtain

$$\begin{aligned} \Delta\lambda_{HHH} &= -4\lambda_{HHH}\left(\frac{v_\sigma}{m_\rho}\right)^2\left(\frac{\lambda_{H\sigma}^2}{16\pi^2}\right)\left(2+\ln\frac{\mu^2}{m_H^2}-z\ln\frac{z+1}{z-1}\right) \\ &\simeq -2\lambda_{HHH}\left(\frac{\delta}{16\pi^2}\right)\left(2+\ln\frac{\mu^2}{m_H^2}-z\ln\frac{z+1}{z-1}\right), \end{aligned} \tag{16}$$

where $z \equiv \sqrt{1+(4m_H^2/q^2)}$ and $\mu = m_\rho$ is the regularization scale. We have used the modified minimal subtraction scheme ($\overline{\mathrm{MS}}$).

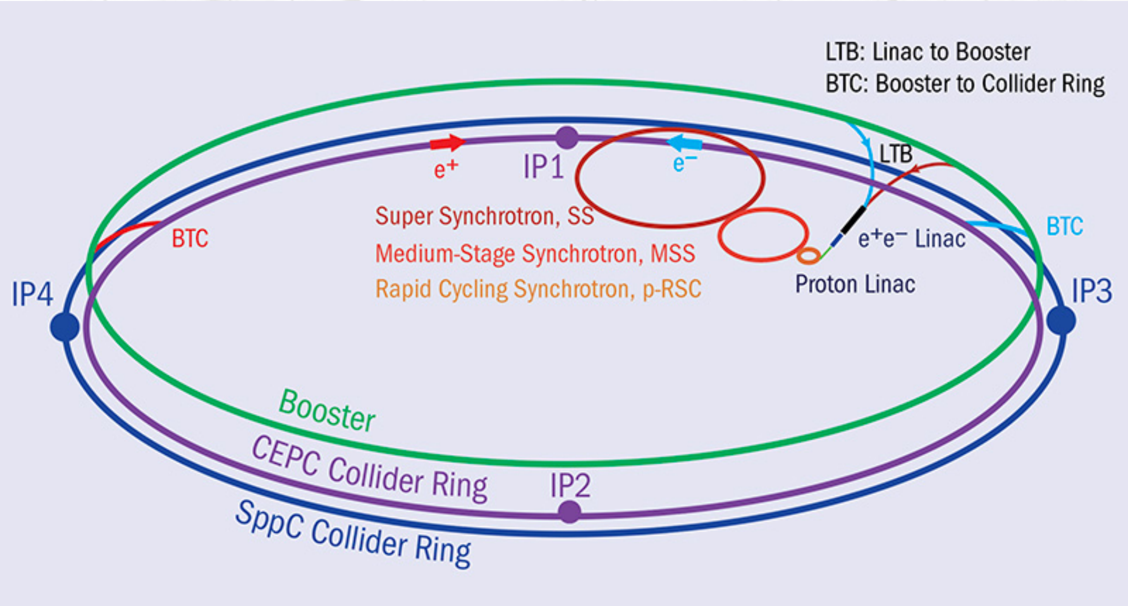
Benchmarks

Our aim is to find suitable benchmark points, which:

- Allow the quartic and Yukawa couplings of the theory to remain positive and perturbative up to the Planck scale;
- Utilize a threshold correction mechanism to λ_H via $\delta \simeq 0.1$;
- Avoid the overproduction of dark radiation via the cosmic axion background (requiring $\lambda_{H\sigma} < 0$);
- Produce a significant contribution matter–antimatter asymmetry via leptogenesis (requiring hierarchy between the heavy neutrinos);
- We have plotted how the running of the SM quartic coupling, λ_H changes with each benchmark points and found the stability of vacuum.

Only produce a $\sim$5% correction to Standard Model triple Higgs coupling λ_{HHH}.

To establish new physics, we need a lot more experimental statistics.


LTB: Linac to Booster
BTC: Booster to Collider Ring
e+
IP1
e−
LTB
Super Synchrotron, SS
BTC
Medium-Stage Synchrotron, MSS
e+e− Linac
BTC
Rapid Cycling Synchrotron, p-RSC
Proton Linac
IP4
IP3
Booster
CEPC Collider Ring
IP2
SppC Collider Ring