Probing the Higgs Potential at the Large Hadron Collider

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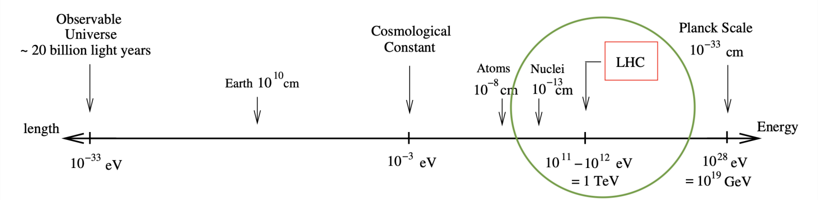
Outline

- Significance of the Higgs boson in electroweak theory
- Stability of the Standard Model vacuum
- Probing the Higgs potential (beyond the SM)

Basics



David Tong lecture notes, 2007

Building blocks → Elementary particles (quarks and leptons)

Interactions → Forces (strong, weak, EM, gravity)

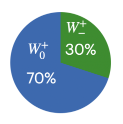
Rules → Relativity + QM

We do have a quantum theory for strong, weak, and EM interactions

Theory with massive vector bosons

Consider a decay process, $t \to bW^+$ ($W^+_\pm$: *Transverse* , W^+_0 : *Longitudinal*)

Decay rate, $\Gamma(t \to bW^+)$ $\longrightarrow$ [



]

Q. What is origin of the enhancement?

$$\Gamma(t \to bW^+_0) \sim \alpha_W m_t \frac{m_t^2}{2m_W^2}$$

Are these enhancements real or spurious?

Consider a complex scalar field,

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\phi^+ \\ v + h + i\xi^0 \end{pmatrix}, \quad v \to vev$$

- Yukawa Lagrangian:

$$\mathcal{L}_Y = -y_t\, \bar{Q}_L \cdot \phi_c \cdot t_R + h.c. \qquad (\phi_c = i\sigma_2\phi^*)$$

Decay rate, $\quad \Gamma(t \to b\phi^+) \propto m_t\, y_t^2 \to m_t \frac{g^2}{2}\frac{m_t^2}{m_W^2}$

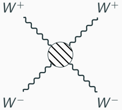
Higgs boson

Q. What is the significance of the Higgs boson?

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\phi^+ \\ v + h + i\xi^0 \end{pmatrix}$$

Does WW scattering make sense?

- Without a Higgs boson



$$\mathcal{M} \sim -g_W^2 \frac{E^2}{4m_W^2}$$

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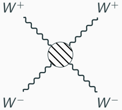

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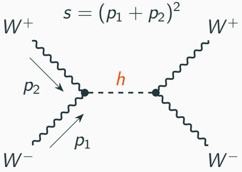


$$\mathcal{M} \sim g_{hWW}^2 \left(\frac{E^2}{4m_W^4} - \frac{m_h^2}{2m_W^4} \right)$$

for $\sqrt{s} \gg m_h, m_W$

$$\boxed{g_{hWW} = g_W m_W}$$

Prior to the Higgs discovery

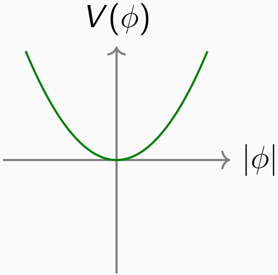
$$\boxed{\text{Standard Model :} \quad m_h \;\rightarrow\; \text{free parameter}}$$

Theoretical considerations were used to place bound on the Higgs mass

... such as perturbative unitarity bounds

Higgs potential

$$\boxed{V(\phi) = -\mu'^2|\phi|^2 + \lambda|\phi|^4}$$



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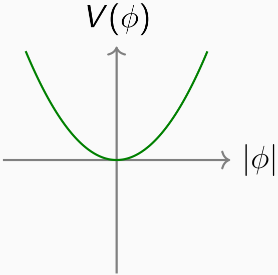

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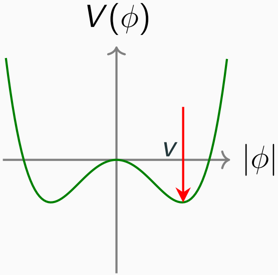

$\mu'^2 > 0, \quad \lambda > 0$

This is a potential at tree-level

Bounds on Higgs Mass

Higgs mass : $\quad m_h = \sqrt{2\lambda}\, v$

Unitarity bounds on the partial-wave amplitudes ($2 \to 2$ bosonic scatterings) implies

$$\boxed{m_h \lesssim 1 \text{ TeV}}$$

B.W. Lee, C. Quigg, H.B. Thacker, PRL 38 (1977)

Stability of the SM vacuum

$$V(\phi) = -\mu'^2|\phi|^2 + \lambda|\phi|^4$$

Parameters evolve with energy – running couplings

SM Higgs mass, $\boxed{m_h \approx 125 \text{ GeV}}$

$$\Rightarrow \quad \boxed{\lambda(\Lambda) < 0} \quad \text{for} \quad \Lambda \sim 10^{11} \text{ GeV}$$

metastable or unstable?

G. Hiller, T. Höhne, D. F. Litim, T. Steudtner, 2401.08811 [hep-ph]

Hint for beyond the SM

- *Metastability (or instability?) is a high energy effect*
  - its remedy may arise from new physics around TeV scale

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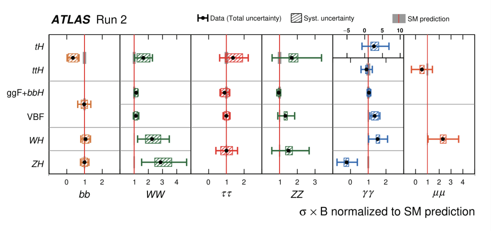
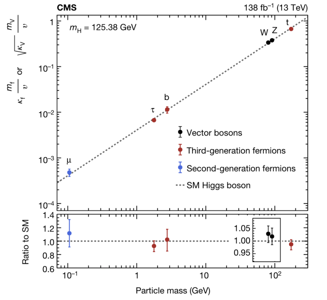
Do the LHC data preclude the existence of additional multiplets in the scalar sector of the SM?

LHC era



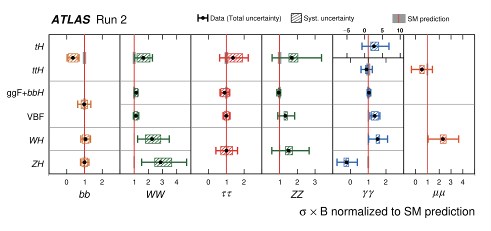
ATLAS Collaboration, Nature 607 (2022)



CMS Collaboration, Nature 607 (2022)

$$\mu_i^f = \frac{\sigma_i \times B^f}{(\sigma_i \times B^f)_{\mathrm{SM}}}, \qquad \kappa_f = \frac{g_{hff}}{g_{hff}^{\mathrm{SM}}}, \quad \kappa_V = \frac{g_{hVV}}{g_{hVV}^{\mathrm{SM}}}$$

LHC era



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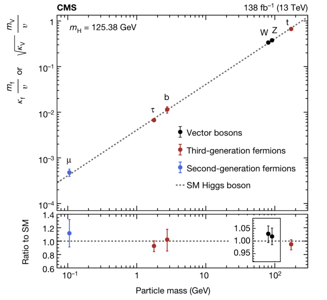

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Any deviation from unity suggesting that the SM needs to be extended

Explore the extended scalar sector

SM Higgs boson might be an admixture of other exotic Higgs bosons – come from the additional multiplets

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- SM + additional doublet

$$\{h, H, A, H^+\} \quad \Rightarrow \quad \kappa_V < 1 \quad (h: \text{SM-like Higgs})$$

Explore the extended scalar sector

SM Higgs boson might be an admixture of other exotic Higgs bosons – come from the additional multiplets

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$$\{h,\ H,\ A,\ H^+\} \quad \Rightarrow \quad \kappa_V < 1 \quad (h:\ \text{SM-like Higgs})$$

- SM + additional triplets

$$\{h,\ H, F, A, H^+, ..., F^{++}\} \quad \Rightarrow \quad \boxed{\kappa_V < 1 \ \text{ and } \ \kappa_V > 1}$$

SM + additional triplets

Observable : $\rho = \frac{m_W^2}{m_Z^2 \cos^2 \theta_W}$ ($= 1$, at tree-level)

consequence of custodial symmetry

θ_W : weak-mixing angle

$$\boxed{\rho = 1.00038 \pm 0.00020}$$ *(PDG, 2022)*

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In 1985, first proposed by Georgi and Machacek :

$$\boxed{\text{SM} + \text{real triplet } (Y = 0) + \text{complex triplet } (Y = 1)}$$

Georgi-Machacek Model (Y : hypercharge)

H. Georgi and M. Machacek, NPB 262 (1985)

Higgs potential with triplets

SM Higgs doublet (ϕ, $Y = 1/2$) + real triplet (ξ, $Y = 0$) +
complex triplet (χ, $Y = 1$)

$$
\begin{aligned}
V = & -m_\phi^2\left(\phi^\dagger\phi\right) - m_\xi^2\left(\xi^\dagger\xi\right) - m_\chi^2\left(\chi^\dagger\chi\right) + \mu_1\left(\chi^\dagger t_a\chi\right)\xi_a + \mu_2\left(\phi^\dagger\tau_a\phi\right)\xi_a \\
& + \mu_3\left[\left(\phi^T\epsilon\tau_a\phi\right)\tilde{\chi}_a + \text{h.c.}\right] + \lambda_\phi\left(\phi^\dagger\phi\right)^2 + \lambda_\xi\left(\xi^\dagger\xi\right)^2 + \lambda_\chi\left(\chi^\dagger\chi\right)^2 \\
& + \tilde{\lambda}_\chi\left|\tilde{\chi}^\dagger\chi\right|^2 + \lambda_{\phi\xi}\left(\phi^\dagger\phi\right)\left(\xi^\dagger\xi\right) + \lambda_{\phi\chi}\left(\phi^\dagger\phi\right)\left(\chi^\dagger\chi\right) + \lambda_{\chi\xi}\left(\chi^\dagger\chi\right)\left(\xi^\dagger\xi\right) \\
& + \kappa_1\left|\xi^\dagger\chi\right|^2 + \kappa_2\left(\phi^\dagger\tau_a\phi\right)\left(\chi^\dagger t_a\chi\right) + \kappa_3\left[\left(\phi^T\epsilon\tau_a\phi\right)\left(\chi^\dagger t_a\xi\right) + \text{h.c.}\right]
\end{aligned}
$$

A. Kundu, P. Mondal, P.B. Pal, PRD 105 (2022)

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A. Kundu, P. Mondal, P.B. Pal, PRD 105 (2022)

$$
\langle\phi\rangle = v_\phi\,,\quad \langle\xi\rangle = v_\xi\,,\quad \langle\chi\rangle = v_\chi
$$

$$
\rho = \frac{v_\phi^2 + 4\left(v_\xi^2 + v_\chi^2\right)}{v_\phi^2 + 8v_\chi^2} \quad \Rightarrow \quad \rho = 1 \quad \text{requires} \quad \boxed{v_\chi = v_\xi}
$$

State-of-the-art theoretical constraints

- Higgs potential must be bounded from below
- Unitarity bounds on the partial-wave amplitudes

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- Higgs potential must be bounded from below
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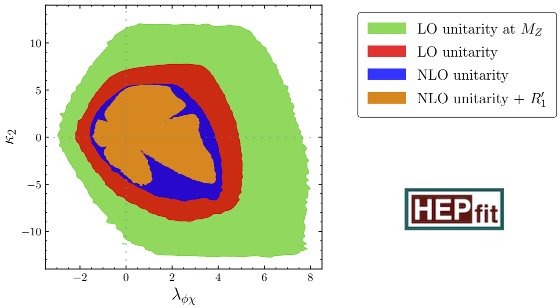
These are used to put bound on the potential parameters or exotic Higgs masses

D. Chowdhury, P. Mondal, ***SS****, 2404.18996 [hep-ph]*

Parameter space

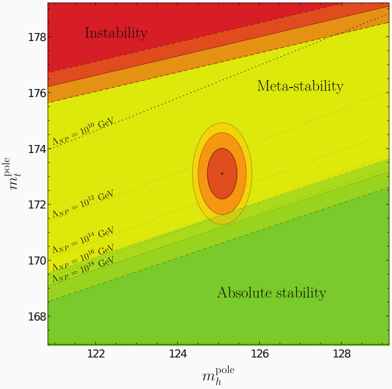
Partial-wave amplitude $\rightarrow$ a_0 , $\boxed{R_1' = \frac{|a_0^{\rm NLO}|}{|a_0^{\rm LO}|} < 1}$



D. Chowdhury, P. Mondal, ***SS****, 2404.18996 [hep-ph]*

Questions?

Backup slide



A. Andreassen, W. Frost, M. D. Schwartz, PRD 97 (2018)