Higgs in Future Colliders

Israeli Input: European Strategy for Particle Physics

Town hall meeting, 5 December 2018

Yossi Nir

Motivation (SPC)

The Higgs program is a guaranteed program for the LHC and all proposed future colliders

The Higgs program touches many of the fundamental open questions in particle physics and in cosmology

When comparing various proposals for future experiments, their capabilities in measuring Higgs properties is one of the most significant aspects

There is a variety of ways in which one can assess the capabilities in measuring Higgs properties (λ_{hhh}, $\sigma(e^+e^- \to hZ)$, EFT…)

I proposed to make the comparison via the potential of making progress on the open questions

What we know now

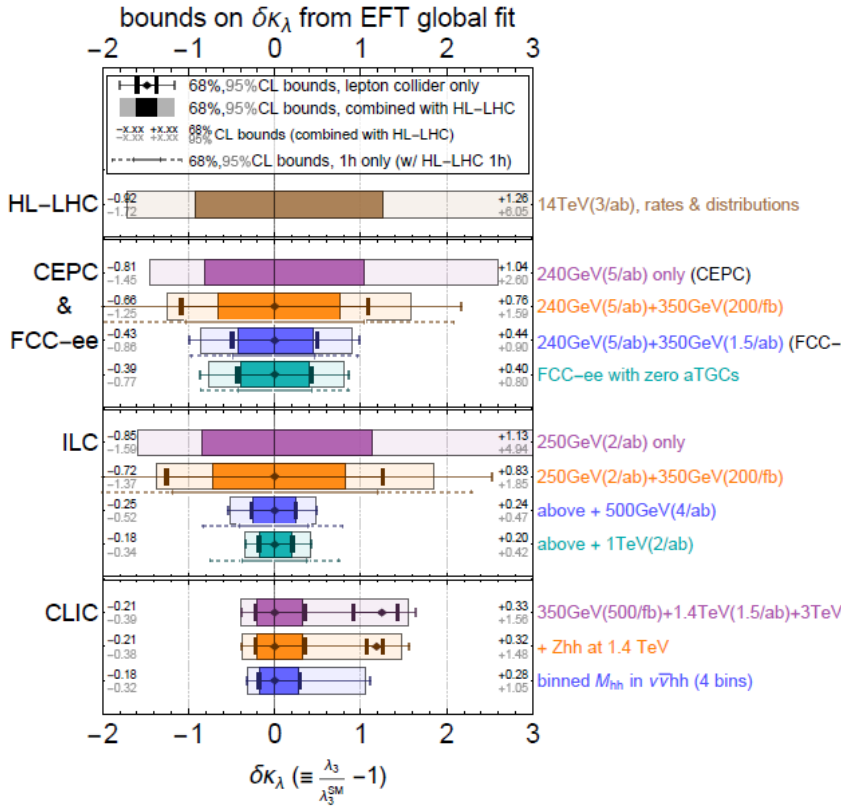
$\mu_{\gamma\gamma}$	1.14 ± 0.14
μ_{ZZ^*}	1.17 ± 0.23
μ_{WW^*}	0.99 ± 0.15
$\mu_{b\bar{b}}$	0.98 ± 0.20
$\mu_{\tau\tau}$	1.09 ± 0.23
$\mu_{c\bar{c}}$	< 104
$\mu_{\mu\mu}$	< 2.8
μ_{ee}	$< 4 \times 10^5$

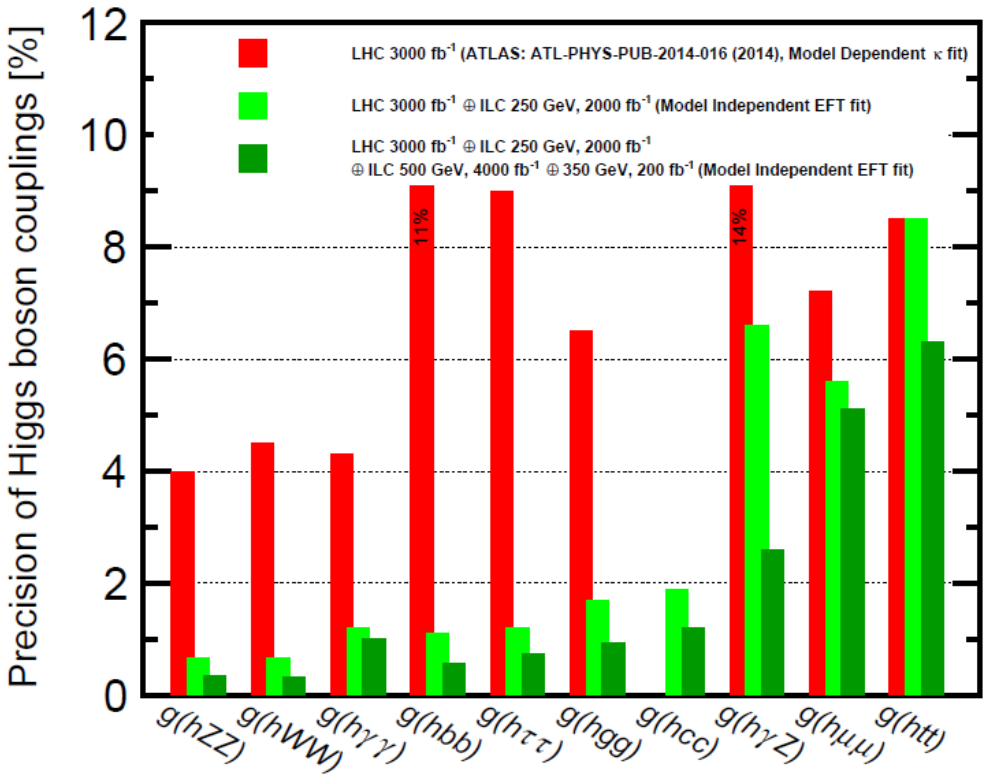
$\mathrm{BR}(t \to ch)$	$\leq 2.2 \times 10^{-3}$
$\mathrm{BR}(t \to uh)$	$\leq 2.4 \times 10^{-3}$
$\mathrm{BR}(h \to \tau\mu)$	$\leq 2.5 \times 10^{-3}$
$\mathrm{BR}(h \to \tau e)$	$\leq 6.1 \times 10^{-3}$
$\mathrm{BR}(h \to \mu e)$	$\leq 3.4 \times 10^{-4}$

$\mu_{gg\mathrm{F}}$	1.03 ± 0.14
μ_{VBF}	1.18 ± 0.23
μ_{Wh}	0.89 ± 0.38
μ_{Zh}	0.79 ± 0.36
$\mu_{t\bar{t}h}$	1.56 ± 0.42

$\mathrm{BR}(h \to \mathrm{inv})$	≤ 0.28
$\mathrm{BR}(h \to \mathrm{untagged})$	≤ 0.34

$\lambda_{hhh}, \sigma_{hZ}$, EFT





1711.03978

1710.07621

Questions to h

- Is h alone? ($\phi^0 = \frac{1}{\sqrt{2}}(v + h)$?)
- Is h elementary?
- What keeps $m_h^2 \ll m_{\mathrm{Pl}}^2$?
- Was the EWPT (strongly) 1st order?
- Did CPV h interactions generate the baryon asymmetry?
- Are there light SM-singlet degrees of freedom?
- What is the solution of the flavor puzzle(s)?

$1.\ \phi = \left(0, \frac{1}{\sqrt{2}}(v+h)\right)^T$?

- If
  - h is purely an SU(2)-doublet,
  - h is in the direction of v,
- Then
  - $\kappa_V = 1$

2. Is h elementary?

- Composite Higgs:
- In the $SILH$ framework

  $\Delta g_{hxx}/g_{hxx} \propto g_\rho^2 v^2/m_\rho^2$ $(m_\rho > 3\ TeV, g_\rho \leq 4\pi)$:

  - $\Delta g_{hVV}/g_{hVV} \leq 8\ \%$
  - $\Delta g_{hf\bar{f}}/g_{hf\bar{f}} \leq 10's\ of\ \%$
  - $\Delta g_{hgg}/g_{hgg} \leq 10's\ of\ \%$

❖ 0703164(SILH), 1206.3560, 1710.07621

3. Why $m_h^2 \ll m_{\mathrm{Pl}}^2$?

- Composite Higgs
- Supersymmetry
  - $\kappa_V = s_{\beta-\alpha};\ \kappa_t = c_\alpha/s_\beta;\ \kappa_{b,\tau} = -s_\alpha/c_\beta$
    - $\frac{\Delta g_{hVV}}{g_{hVV}}, \frac{\Delta g_{ht\bar{t}}}{g_{ht\bar{t}}}, \frac{\Delta g_{hb\bar{b}}}{g_{hb\bar{b}}} \leq 0.01, 0.03, 0.1 - 1$
- Relaxion
  - $h \to RR$
    - $h \to$ invisible, $h \to$ untagged, $h \to 4\mu$

4. Strongly 1st order EWPT?

- New scalar S: $m_S < 400\ GeV$; $\kappa|S|^2|\phi|^2$ with $\kappa = O(1)$
  - If S colored – enhanced hgg coupling
  - If S EM charged – enhanced $h\gamma\gamma$ coupling
- Gauge-singlet scalar
  - If $m_S < m_h/2$: $h \rightarrow$ invisible
  - $\sigma_{hZ} \equiv \sigma(e^+e^- \rightarrow hZ)$ modified
- Dimension-six terms $\left(\frac{c_6}{\Lambda^2}\right)\left(\phi^\dagger\phi\right)^3$
  - $O(1)$ modification of $\lambda_{hhh} \Longrightarrow$ modified di-Higgs production

5. The CPV of baryogenesis?

- $y_t \overline{Q_3} \phi t_R + (z_t/\Lambda^2)(\phi^\dagger \phi)\overline{Q_3} \phi t_R$
  - CPV in htt: $(\sqrt{2}\, m_t/v)\kappa_t h\bar{t}(c_\alpha + i s_\alpha \gamma_5)t$
  - CPV observables in $gg \to htj, hjj, t\bar{t}h$
- $y_\tau \overline{L_3} \phi \tau_R + (z_\tau/\Lambda^2)(\phi^\dagger \phi)\overline{L_3} \phi \tau_R$
  - CPV in $h\tau\tau$: $(\sqrt{2}\, m_\tau/v)\kappa_\tau h\tau^-(c_\alpha + i s_\alpha \gamma_5)\tau^+$
  - CPV observables in

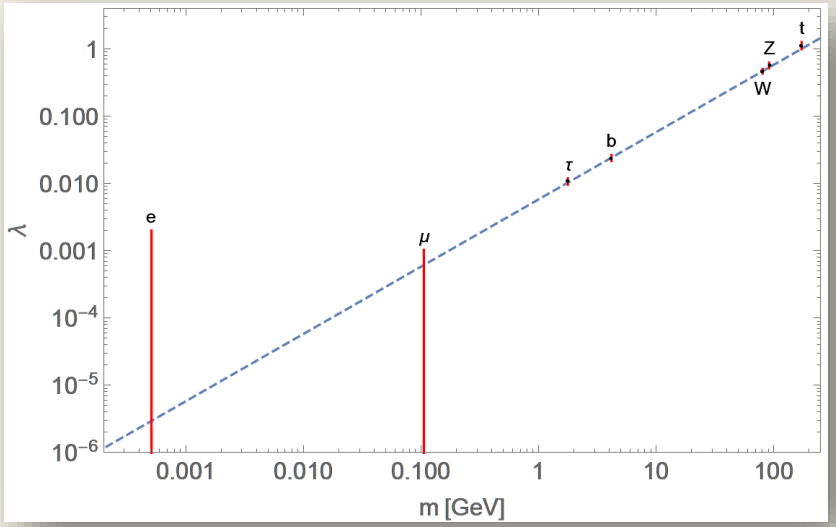
$$h \to \tau^+\tau^- \to (\pi^+\pi^0)_\rho \bar{\nu} (\pi^-\pi^0)_\rho \nu$$

6. Light SM singlets via h-portal?

- Theory:
  - $hs^2, h^2s^2, h\nu N$
  - $(\phi^\dagger\phi)(\bar{\chi}\chi), (\phi^\dagger\phi)(\bar{\chi}\gamma_5\chi)$
- Experiment:
  - $h \to \text{invisible}, h \to f\bar{f}E_{Tmiss}$
  - $h \to aa \to 4\tau, 2\tau 2b, 2\mu 2b, 2\mu 2\tau, 2\gamma 2j$

7. Solving flavor puzzles?

- $Y_F = (\sqrt{2}/v)M_F$:
  - Proportionality
    - $y_i/y_j = m_i/m_j$
  - Factor of proportionality
    - $y_i/m_i = \sqrt{2}/v$
  - Diagonality
    - $Y_{ij} = 0$ for $i \neq j$



- We can test various solutions
  - NFC, MFV, FN, GL…

Summary: Questions to h

	μ_{VV}	μ_{33}	μ_{ggF}	$\mu_{\gamma\gamma}$	λ_{hhh}	σ_{hZ}	BR_{inv}	BR_{unt}	μ_{ll}	$BR_{\tau\mu}$
Alone?	+	+			+	+				
Elementary?		+	+	+						
$m_h^2 \ll m_{pl}^2$	+	+					+	+		
EWPT			+	+	+	+	+			
BG		+(CPV)								
Singlets							+	+	+	
Flavor									+	+

The Higgs program is relevant to many fundamental open questions

All measurements are relevant and helpful