Seung J. Lee (KAIST)

Have we really discovered a SM-like Higgs boson?

1. Study of SM Higgs boson partial widths and branching fractions

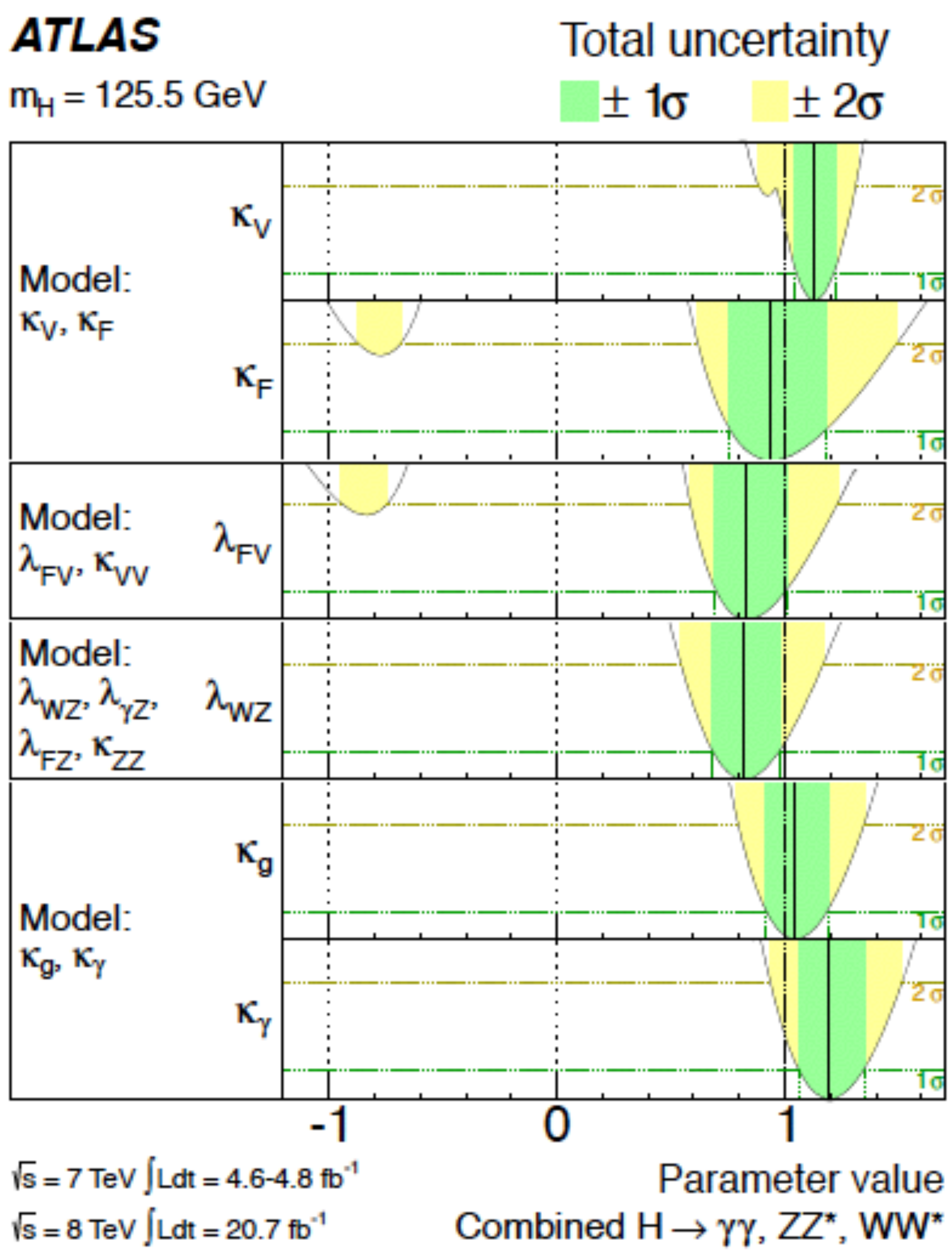
2. Higgs potentials and more: Higgs from a quantum phase transition

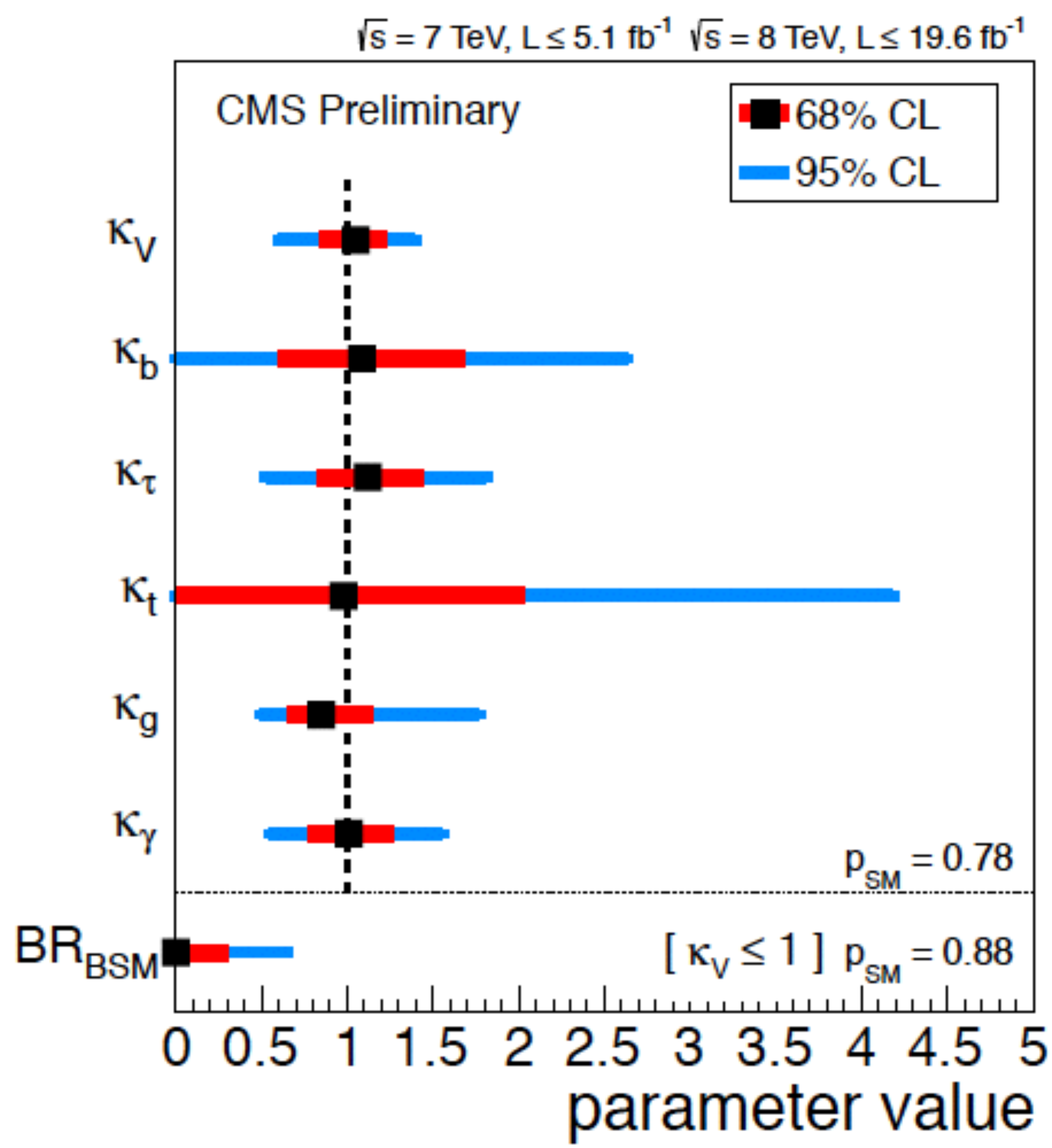
1. L. Almeida, S.L., S. Porkorski, J. Wells
arXiv:1311.6721v3 (Phys.Rev. D89 (2014) 033006)

2. B. Bellazzini, C. Csaki, J. Hubisz, S.L., J. Serra, J. Terning
work in progress (to appear)

Nothing but Higgs, with ~10-20% Precision for Higgs couplings so far

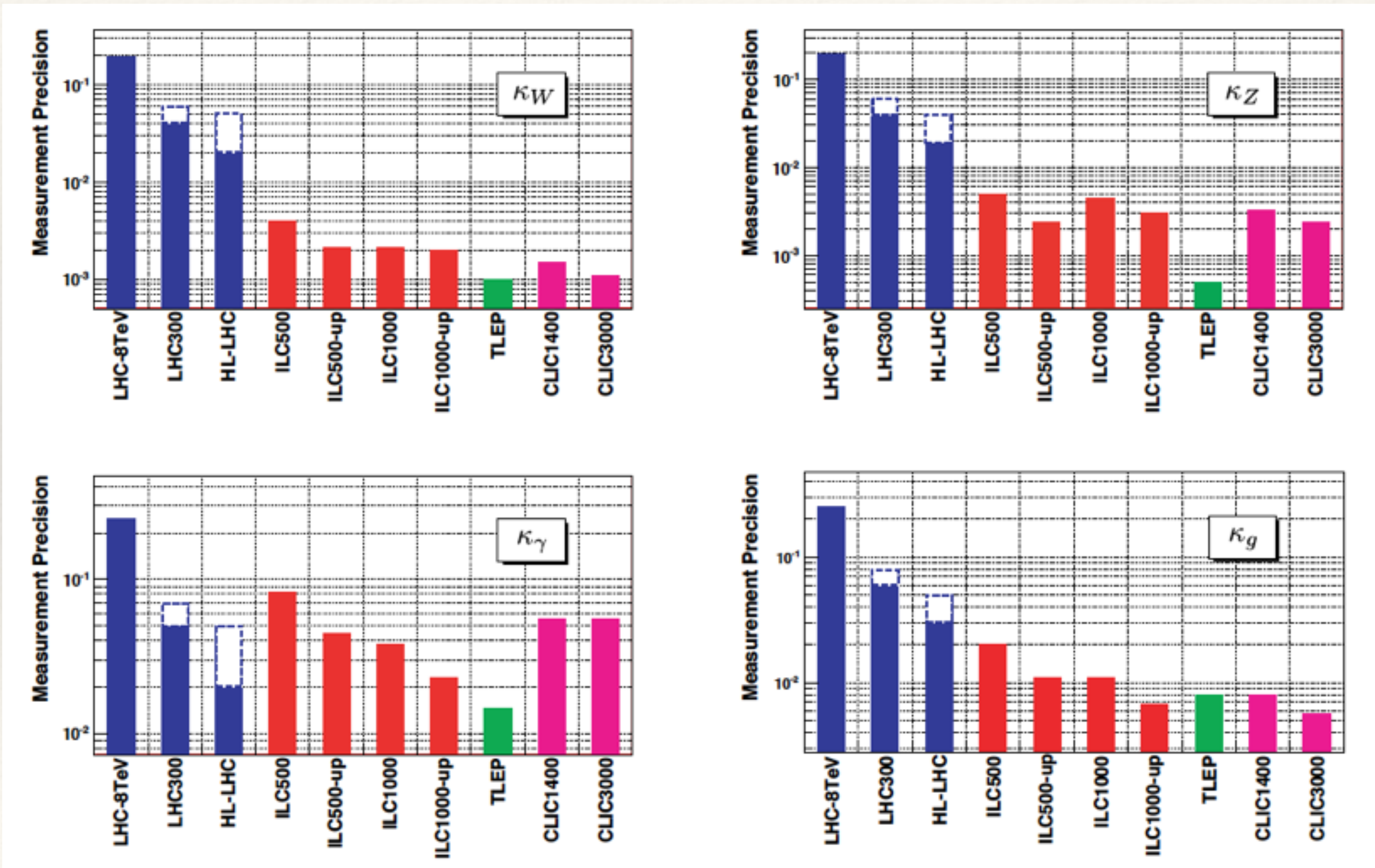
coupling scaling factors (from Snowmass Higgs working group report)





New era of precision studies of the Higgs sector

(from Snowmass Higgs working group report): Higgs precision will approach that of EWP



Part I: **Precision Higgs Analysis:** expansion formalism of the Higgs boson partial widths and branching fractions

L. Almeida, S.L., S. Porkorski, J. Wells

arXiv:1311.6721v3 (Phys.Rev. D89 (2014) 033006)

- The sub-percent-level determination of the Higgs boson mass now enables a complete set of input observables whereby any perturbative high-energy observable involving the Higgs boson can be predicted.
  - careful exposition of the decay partial widths and branching fractions of a SM Higgs boson with mass near 126 GeV.
  - state-of-the-art formulas that can be used in any precision electroweak analysis to investigate compatibility of the data with the SM predictions in these most fundamental and sensitive observables

What's new in our expansion formalism?

- Other calculations exist in the literature, mostly notably from the computer program HDECAY; however, we wish to provide an independent calculation that includes the latest advances and allows us to vary the renormalization scale in all parts of the computations. This flexibility will be useful in discussions regarding **uncertainties**
- We also aim to detail the errors that each input into the computation propagates to the final answer for each observable

Our Expansion Formalism of Partial Widths and Uncertainties

Taylor expand the full expressions for partial width around the input observables. This expansion is made possible by the fact that with the discovery of the Higgs boson, and knowledge of its mass, all input observables are now known to good enough accuracy to render an expansion of this nature useful and accurate.

We represent the partial width expansion by

$$\Gamma_{H\to X} = \Gamma_X^{(\mathrm{ref})}\left(1 + \sum_i a_{\tau_i,X}\overline{\delta\tau_i}\right) \quad (7)$$

where

$$\overline{\delta\tau_i} = \frac{\tau_i - \tau_{i,ref}}{\tau_{i,ref}}, \quad (8)$$

and τ_i are the input observables (Eq. 1) for the calculation. The total width is the sum of all the partial widths and for convenience we present dedicated expansion parameters for that as well:

$$\Gamma_{\mathrm{tot}} = \sum_X \Gamma_{H\to X} = \Gamma_{\mathrm{tot}}^{(\mathrm{ref})}\left(1 + \sum_i a_{\tau_i,\mathrm{tot}}\overline{\delta\tau_i}\right). \quad (9)$$

Our Expansion Formalism of Partial Widths and Uncertainties

Taylor expand the full expressions for partial width around the input observables. This expansion is made possible by the fact that with the discovery of the Higgs boson, and knowledge of its mass, all input observables are now known to good enough accuracy to render an expansion of this nature useful and accurate.

We represent the partial width expansion by

$$\Gamma_{H\to X} = \Gamma_X^{(\mathrm{ref})}\left(1 + \sum_i a_{\tau_i,X}\overline{\delta\tau_i}\right) \tag{7}$$

where

$$\overline{\delta\tau_i} = \frac{\tau_i - \tau_{i,ref}}{\tau_{i,ref}}, \tag{8}$$

and τ_i are the input observables (Eq. 1) for the calculation. The total width is the sum of all the partial widths and for convenience we present dedicated expansion parameters for that as well:

$$\Gamma_{\mathrm{tot}} = \sum_X \Gamma_{H\to X} = \Gamma_{\mathrm{tot}}^{(\mathrm{ref})}\left(1 + \sum_i a_{\tau_i,\mathrm{tot}}\overline{\delta\tau_i}\right). \tag{9}$$

Our Expansion Formalism of Partial Widths and Uncertainties

Taylor expand the full expressions for partial width around the input observables. This expansion is made possible by the fact that with the discovery of the Higgs boson, and knowledge of its mass, all input observables are now known to good enough accuracy to render an expansion of this nature useful and accurate.

We represent the partial width expansion by

$$\Gamma_{H\to X} = \Gamma_X^{(\mathrm{ref})}\left(1 + \sum_i a_{\mathcal{T}_i,X}\overline{\delta\mathcal{T}_i}\right) \tag{7}$$

where

$$\overline{\delta\mathcal{T}_i} = \frac{\mathcal{T}_i - \mathcal{T}_{i,ref}}{\mathcal{T}_{i,ref}}, \tag{8}$$

and $\mathcal{T}_i$ are the input observables (Eq. 1) for the calculation. The total width is the sum of all the partial widths and for convenience we present dedicated expansion parameters for that as well:

$$\Gamma_{\mathrm{tot}} = \sum_X \Gamma_{H\to X} = \Gamma_{\mathrm{tot}}^{(\mathrm{ref})}\left(1 + \sum_i a_{\mathcal{T}_i,\mathrm{tot}}\overline{\delta\mathcal{T}_i}\right). \tag{9}$$

Our Expansion Formalism of Partial Widths and Uncertainties

Taylor expand the full expressions for partial width around the input observables. This expansion is made possible by the fact that with the discovery of the Higgs boson, and knowledge of its mass, all input observables are now known to good enough accuracy to render an expansion of this nature useful and accurate.

We represent the partial width expansion by

$$\Gamma_{H\to X} = \Gamma_X^{(\mathrm{ref})}\left(1+\sum_i a_{\mathcal{T}_i,X}\overline{\delta\mathcal{T}_i}\right) \tag{7}$$

where

$$\overline{\delta\mathcal{T}_i} = \frac{\mathcal{T}_i - \mathcal{T}_{i,ref}}{\mathcal{T}_{i,ref}}, \tag{8}$$

	$\Gamma_X^{(\mathrm{Ref})}$/GeV	$a_{m_t,X}$	$a_{m_H,X}$	$a_{\alpha(M_Z),X}$	$a_{\alpha_S(M_Z),X}$	$a_{m_b,X}$	$a_{M_Z,X}$	$a_{m_c,X}$	$a_{m_\tau,X}$	$a_{G_F,X}$
total	4.17×10^{-3}	-3.3×10^{-2}	4.34	8.35×10^{-1}	-5.05×10^{-1}	1.32	-3.21	7.80×10^{-2}	1.24×10^{-1}	8.49×10^{-1}
gg	3.61×10^{-4}	-1.62×10^{-1}	2.89	0.	2.48	-6.51×10^{-2}	3.76×10^{-1}	0.	0.	1.00
$\gamma\gamma$	1.08×10^{-5}	-2.69×10^{-2}	4.32	2.56	1.80×10^{-2}	8.29×10^{-3}	-1.86	0.	0.	7.24×10^{-1}
$b\bar{b}$	2.35×10^{-3}	8.07×10^{-3}	8.09×10^{-1}	3.76×10^{-2}	-1.12	2.36	-2.72×10^{-1}	0.	0.	9.53×10^{-1}
$c\bar{c}$	1.22×10^{-4}	-4.52×10^{-2}	7.99×10^{-1}	1.02×10^{-2}	-3.10	0.	-4.89×10^{-1}	2.67	0.	9.70×10^{-1}
$\tau^+\tau^-$	2.58×10^{-4}	4.71×10^{-2}	9.95×10^{-1}	-2.09×10^{-2}	-2.14×10^{-3}	0.	-1.61×10^{-2}	0.	2.01	1.02
WW^*	9.43×10^{-4}	-1.13×10^{-1}	1.37×10^{1}	3.66	9.04×10^{-3}	0.	-1.21×10^{1}	0.	0.	2.49×10^{-1}
ZZ^*	1.17×10^{-4}	2.27×10^{-2}	1.53×10^{1}	-7.37×10^{-1}	-1.82×10^{-3}	0.	-1.12×10^{1}	0.	0.	2.53
$Z\gamma$	6.89×10^{-6}	-1.52×10^{-2}	1.11×10^{1}	8.45×10^{-1}	0.	-7.93×10^{-3}	-4.82	0.	0.	2.62
$\mu^+\mu^-$	8.93×10^{-7}	4.82×10^{-2}	9.92×10^{-1}	-4.31×10^{-2}	-2.19×10^{-3}	0.	-1.62×10^{-2}	0.	0.	1.02

Input Parameters for our expansion

- $$\text{Inputs}: \left\{ m_H, M_Z, \Delta\alpha^{(5)}_{had}, \alpha_S(M_Z), m_f \right\}, \qquad (1)$$

- Now that we have established our convention that M_W is an output observable, when the W mass appears in formulas below, we should view it as a short-hand notation for the full computation of the W mass within the theory in terms of our agreed-upon inputs. In the SM this substitution is

$$M_W \xrightarrow{SM} (80.368\,\text{GeV})\,(1 + 1.42\,\delta M_Z + 0.21\,\delta G_F - 0.43\,\delta\alpha + 0.013\,\delta M_t - 0.0011\,\delta\alpha_S - 0.00075\,\delta M_H)\,. \quad (3)$$

$$\delta\tau \equiv (\tau - \tau_{ref})/\tau_{ref}$$

-

m_H	125.7(4)	pole mass m_t	173.07(89)
$\overline{\text{MS}}$ mass m_c	1.275(25)	$\overline{\text{MS}}$ mass m_b	4.18(3)
pole mass m_τ	1.77682(16)	$\alpha_S(M_Z)$	0.1184(7)
$\alpha(M_Z)$	1/128.96(2)	$\Delta\alpha^{(5)}_{had}$	0.0275(1)

Expansion of BR and ratio of BRs

$$\mathrm{B}(H \to \mathrm{X}) = \mathrm{B}(\mathrm{X})^{(\mathrm{ref})} \left(1 + \sum_{\mathrm{i}} \mathrm{b}_{\tau_{\mathrm{i}},\mathrm{X}} \overline{\delta\tau_{\mathrm{i}}}\right), \tag{12}$$

where τ_i represents the same parameters as Eq. (1). Expansion parameters $b_{\tau_i,X}$ are related to $a_{\tau_i,X}$ by

$$b_{\tau_i,X} = a_{\tau_i,X} - a_{\tau_i,tot}. \tag{13}$$

$$\frac{\mathrm{B}(H \to \mathrm{X})}{\mathrm{B}(H \to \mathrm{Y})} = \frac{\mathrm{B}(\mathrm{X})^{(\mathrm{ref})}}{\mathrm{B}(\mathrm{Y})^{(\mathrm{ref})}} \left(1 + \sum_i r_{\tau_i,X,Y} \overline{\delta\tau_i}\right),$$

where τ_i represent the same parameters as Eq. (1). The expansion parameters $r_{\tau_i,X,Y}$ is related to $a_{\tau_i,X}$ by

$$r_{\tau_i,X,Y} = a_{\tau_i,X} - a_{\tau_i,Y}. \tag{17}$$

Expansion of BR and ratio of BRs

$$\mathrm{B}(H \to \mathrm{X}) = \mathrm{B}(\mathrm{X})^{(\mathrm{ref})} \left(1 + \sum_{\mathrm{i}} \mathrm{b}_{\tau_{\mathrm{i}},\mathrm{X}} \overline{\delta \tau_{\mathrm{i}}} \right), \qquad (12)$$

The table of expansion coefficients enables us to compute the uncertainty in a final state branching ratio due to each input parameter. The percent uncertainty Δ_i^X on branching fraction $B(X)$ due to input parameter τ_i is

$$\Delta_i^X = (100\%) \times |b_{\tau_i,X}| \frac{\Delta \tau_i}{\tau_i^{ref}} \qquad (14)$$

where $\Delta \tau_i$ are the current experimental uncertainties in input parameter τ_i. For example, the percentage uncertainty in the $H \to gg$ branching fraction is

$$\Delta_b^{gg} = (100\%)(1.389) \frac{0.03\,\mathrm{GeV}}{4.18\,\mathrm{GeV}} = 1.00\%. \qquad (15)$$

Expansion of BR and ratio of BRs

$$\mathrm{B}(H \to \mathrm{X}) = \mathrm{B}(\mathrm{X})^{(\mathrm{ref})} \left(1 + \sum_{\mathrm{i}} \mathrm{b}_{\tau_\mathrm{i},\mathrm{X}} \overline{\delta\tau_\mathrm{i}}\right), \qquad (12)$$

The table of
the uncertainty
input paramete
fraction $B(X)$

where $\Delta\tau_i$ are t
parameter τ_i. F
$H \to gg$ bran

the uncertainty in the b-quark mass input observable constitutes the largest uncertainty in the branching ratio computations.

The large uncertainty of the charm quark mass is the decisive contributor to H ->cc uncertainty as well

$$\Delta_b^{gg} = (100\%)(1.389)\frac{0.03\,\mathrm{GeV}}{4.18\,\mathrm{GeV}} = 1.00\%. \qquad (15)$$

How well can we predict SM observables?

Percent relative uncertainty, P_Q: $Q = Q_0\,(1 + 0.01\,P_Q)$.

	$P_\Gamma^\pm$(par.add.)	$P_\Gamma^\pm$(par.quad.)	$(P_\Gamma^+, P_\Gamma^-)(\mu)$
total	2.82 (1.79)	1.71 (1.07)	(0.08,0.10)
gg	2.52 (1.83)	1.74 (1.49)	(0.05,0.03)
$\gamma\gamma$	1.45 (0.42)	1.38 (0.35)	(1.31,0.60)
$b\bar{b}$	2.62 (2.43)	1.84 (1.82)	(0.29,0.01)
$c\bar{c}$	7.34 (7.15)	5.55 (5.54)	(0.45,0.35)
$\tau^+\tau^-$	0.36 (0.12)	0.32 (0.08)	(0.01,0.01)
WW^*	4.41 (1.17)	4.97 (1.25)	(0.25,0.31)
ZZ^*	4.90 (1.25)	4.42 (1.11)	(0.,0.)
$Z\gamma$	3.56 (0.92)	3.52 (0.88)	(0.56,0.23)
$\mu^+\mu^-$	0.34 (0.11)	0.32 (0.08)	(0.03,0.03)

The meaning of "$P_\Gamma^\pm$(par.add.)" is that all input parameters have been allowed to range over their 1σ errors and the maximum percent relative errors are recorded. The meaning of "$P_\Gamma^\pm$(par.quad.)" is that the uncertainties of each parameter are added in Gaussian quadrature. In other words, $P_{\Gamma_i}^\pm(\text{par.quad.}) = 100\,\Delta\Gamma_i/\Gamma_i$, where

$$(\Delta\Gamma_i)^2 = \left(\frac{\partial\Gamma_i}{\partial m_t}\right)^2 (\Delta m_t)^2 + \left(\frac{\partial\Gamma_i}{\partial\alpha_s}\right)^2 (\Delta\alpha_s)^2 + \cdots . \quad (11)$$

The uncertainties in varying the scale parameter μ in the calculation, attempts to capture the uncertainty in not knowing higher order corrections. A full calculation at all orders would give a result that does not depend on μ but a finite-order calculation does, and the uncertainty of dropping the higher order calculations are assumed to be approximated reasonably well by noting how much the result changes by varying μ by a factor of two upward and downward: $m_H/2 < \mu < 2m_H$. The meaning of "$P_\Gamma^\pm(\mu)$" in Table 4 concerns the relative percent uncertainties associated with this scale dependence algorithm.

How well can we predict SM observables?

Percent relative uncertainty, P_Q: $Q = Q_0\,(1 + 0.01\,P_Q).$

	$P_\Gamma^\pm$(par.add.)	$P_\Gamma^\pm$(par.quad.)	$(P_\Gamma^+, P_\Gamma^-)(\mu)$
total	2.82 (1.79)	1.71 (1.07)	(0.08,0.10)
gg	2.52 (1.83)	1.74 (1.49)	(0.05,0.03)
$\gamma\gamma$	1.45 (0.42)	1.38 (0.35)	(1.31,0.60)
$b\bar{b}$	2.62 (2.43)	1.84 (1.82)	(0.29,0.01)
$c\bar{c}$	7.34 (7.15)	5.55 (5.54)	(0.45,0.35)
$\tau^+\tau^-$	0.36 (0.12)	0.32 (0.08)	(0.01,0.01)
WW^*	4.41 (1.17)	4.97 (1.25)	(0.25,0.31)
ZZ^*	4.90 (1.25)	4.42 (1.11)	(0.,0.)
$Z\gamma$	3.56 (0.92)	3.52 (0.88)	(0.56,0.23)
$\mu^+\mu^-$	0.34 (0.11)	0.32 (0.08)	(0.03,0.03)

The meaning of "$P_\Gamma^\pm$(par.add.)" is that all input parameters have been allowed to range over their 1σ errors and the maximum percent relative errors are recorded. The meaning of "$P_\Gamma^\pm$(par.quad.)" is that the uncertainties of each parameter are added in Gaussian quadrature. In other words, $P_{\Gamma_i}^\pm(\text{par.quad.}) = 100\,\Delta\Gamma_i/\Gamma_i$, where

$$(\Delta\Gamma_i)^2 = \left(\frac{\partial\Gamma_i}{\partial m_t}\right)^2 (\Delta m_t)^2 + \left(\frac{\partial\Gamma_i}{\partial\alpha_s}\right)^2 (\Delta\alpha_s)^2 + \cdots . \quad (11)$$

The uncertainties in varying the scale parameter μ in the calculation, attempts to capture the uncertainty in not knowing higher order corrections. A full calculation at all orders would give a result that does not depend on μ but a finite-order calculation does, and the uncertainty of dropping the higher order calculations are assumed to be approximated reasonably well by noting how much the result changes by varying μ by a factor of two upward and downward: $m_H/2 < \mu < 2m_H$. The meaning of "$P_\Gamma^\pm(\mu)$" in Table 4 concerns the relative percent uncertainties associated with this scale dependence algorithm.

How well can we predict SM observables?

Percent relative uncertainty, P_Q: $Q = Q_0\,(1 + 0.01\,P_Q)$.

	$P_\Gamma^\pm$(par.add.)	$P_\Gamma^\pm$(par.quad.)	$(P_\Gamma^+, P_\Gamma^-)(\mu)$
total	2.82 (1.79)	1.71 (1.07)	(0.08,0.10)
gg	2.52 (1.83)	1.74 (1.49)	(0.05,0.03)
$\gamma\gamma$	1.45 (0.42)	1.38 (0.35)	(1.31,0.60)
$b\bar{b}$	2.62 (2.43)	1.84 (1.82)	(0.29,0.01)
$c\bar{c}$	7.34 (7.15)	5.55 (5.54)	(0.45,0.35)
$\tau^+\tau^-$	0.36 (0.12)	0.32 (0.08)	(0.01,0.01)
WW^*	4.41 (1.17)	4.97 (1.25)	(0.25,0.31)
ZZ^*	4.90 (1.25)	4.42 (1.11)	(0.,0.)
$Z\gamma$	3.56 (0.92)	3.52 (0.88)	(0.56,0.23)
$\mu^+\mu^-$	0.34 (0.11)	0.32 (0.08)	(0.03,0.03)

quark	at $\mu = m_H$ $(m_H/2,\, 2m_H)$	$P_m(\Delta m)$
$m_c(\mu)$	0.638 (0.675, 0.603) GeV	2.62%
$m_b(\mu)$	2.79 (2.96, 2.64) GeV	0.85%
$m_t(\mu)$	166.5 (176.8,157.8) GeV	0.56%

The meaning of "$P_\Gamma^\pm$(par.add.)" is that all input parameters have been allowed to range over their 1σ errors and the maximum percent relative errors are recorded. The meaning of "$P_\Gamma^\pm$(par.quad.)" is that the uncertainties of each parameter are added in Gaussian quadrature. In other words, $P_{\Gamma_i}^\pm(\text{par.quad.}) = 100\,\Delta\Gamma_i/\Gamma_i$, where

$$(\Delta\Gamma_i)^2 = \left(\frac{\partial\Gamma_i}{\partial m_t}\right)^2 (\Delta m_t)^2 + \left(\frac{\partial\Gamma_i}{\partial\alpha_s}\right)^2 (\Delta\alpha_s)^2 + \cdots. \quad (11)$$

The uncertainties in varying the scale parameter μ in the calculation, attempts to capture the uncertainty in not knowing higher order corrections. A full calculation at all orders would give a result that does not depend on μ but a finite-order calculation does, and the uncertainty of dropping the higher order calculations are assumed to be approximated reasonably well by noting how much the result changes by varying μ by a factor of two upward and downward: $m_H/2 < \mu < 2m_H$. The meaning of "$P_\Gamma^\pm(\mu)$" in Table 4 concerns the relative percent uncertainties associated with this scale dependence algorithm.

SM vs. New Physics? Uncertainties in BRs

	Δ_{m_t}	Δ_{m_H}	$\Delta_{\alpha(M_Z)}$	$\Delta_{\alpha_S(M_Z)}$	Δ_{m_b}	Δ_{M_Z}	Δ_{m_c}	Δ_{m_τ}	Δ_{G_F}
gg	0.07	0.46 (0.12)	0.01	1.77	1.00	0.01	0.15	-	-
$\gamma\gamma$	-	0.01 (-)	0.03	0.31	0.94	-	0.15	-	-
$b\bar{b}$	0.02	1.13 (0.28)	0.01	0.36	0.74	0.01	0.15	-	-
$c\bar{c}$	0.01	1.13 (0.28)	0.01	1.53	0.95	0.01	5.08	-	-
$\tau^+\tau^-$	0.04	1.07 (0.27)	0.01	0.30	0.95	0.01	0.15	0.02	-
WW^*	0.04	2.97 (0.74)	0.04	0.30	0.95	0.02	0.15	-	-
ZZ^*	0.03	3.48 (0.87)	0.02	0.30	0.95	0.02	0.15	-	-
$Z\gamma$	0.01	2.14 (0.53)	-	0.30	0.96	-	0.15	-	-
$\mu^+\mu^-$	0.04	1.07 (0.27)	0.01	0.30	0.95	0.01	0.15	-	-

$$\Delta_i^X = (100\%) \times |b_{\tau_i,X}| \frac{\Delta\tau_i}{\tau_i^{ref}}$$

	$P^{\pm}_{\mathrm{BR}}$(par.-add.)	$P^{\pm}_{\mathrm{BR}}$(par.-quad.)	$(P^{+}_{\mathrm{BR}},\ P^{-}_{\mathrm{BR}})(\mu)$
gg	3.47 (3.12)	2.09 (2.04)	(0.03,1.38)
$\gamma\gamma$	1.45 (1.44)	1.01 (1.01)	(1.81,1.83)
$b\bar{b}$	2.43 (1.58)	1.41 (0.89)	(0.21,0.)
$c\bar{c}$	8.72 (7.87)	5.51 (5.40)	(0.54,0.44)
$\tau^+\tau^-$	2.55 (1.75)	1.47 (1.04)	(0.09,0.07)
WW^*	4.48 (2.26)	3.13 (1.25)	(0.10,0.08)
ZZ^*	4.96 (2.34)	3.63 (1.33)	(0.10,0.08)
$Z\gamma$	3.56 (1.96)	2.36 (1.15)	(0.83,0.80)
$\mu^+\mu^-$	2.53 (1.73)	1.47 (1.04)	(0.07,0.06)

() => if the Higgs mass uncertainty were 0.1 GeV (instead of 0.4 GeV)

SM vs. New Physics? Uncertainties in BRs

	Δ_{m_t}	Δ_{m_H}	$\Delta_{\alpha(M_Z)}$	$\Delta_{\alpha_S(M_Z)}$	Δ_{m_b}	Δ_{M_Z}	Δ_{m_c}	Δ_{m_τ}	Δ_{G_F}
gg	0.07	0.46 (0.12)	0.01	1.77	1.00	0.01	0.15	-	-
$\gamma\gamma$	-	0.01 (-)	0.03	0.31	0.94	-	0.15	-	-
$b\bar{b}$	0.02	1.13 (0.28)	0.01	0.36	0.74	0.01	0.15	-	-
$c\bar{c}$	0.01	1.13 (0.28)	0.01	1.53	0.95	0.01	5.08	-	-
$\tau^+\tau^-$	0.04	1.07 (0.27)	0.01	0.30	0.95	0.01	0.15	0.02	-
WW^*	0.04	2.97 (0.74)	0.04	0.30	0.95	0.02	0.15	-	-
ZZ^*	0.03	3.48 (0.87)	0.02	0.30	0.95	0.02	0.15	-	-
$Z\gamma$	0.01	2.14 (0.53)	-	0.30	0.96	-	0.15	-	-
$\mu^+\mu^-$	0.04	1.07 (0.27)	0.01	0.30	0.95	0.01	0.15	-	-

$$\Delta_i^X = (100\%) \times |b_{\tau_i,X}| \frac{\Delta\tau_i}{\tau_i^{ref}}$$

For example, if the data at a later stage of the LHC, or ILC, or CLIC suggests that the branching fraction into b quarks can be determined to better than 1%, this does not mean that we are sensitive to new physics contributions of 1% to $H \to b\bar{b}$. The reason can be seen from Tables 6 and 7 that the SM uncertainty in computing $B(H \to b\bar{b})$ is presently 2.4% (sum of absolute values of all errors) and expected to not get better than 1.6%, with most of that coming from uncertainty of the bottom Yukawa coupling determination stemming from the uncertainty of the measured bottom quark $\overline{\mathrm{MS}}$ mass

	$P^{\pm}_{\mathrm{BR}}$(par.-add.)	$P^{\pm}_{\mathrm{BR}}$(par.-quad.)	$(P^{+}_{\mathrm{BR}}, P^{-}_{\mathrm{BR}})(\mu)$
gg	3.47 (3.12)	2.09 (2.04)	(0.03,1.38)
$\gamma\gamma$	1.45 (1.44)	1.01 (1.01)	(1.81,1.83)
$b\bar{b}$	2.43 (1.58)	1.41 (0.89)	(0.21,0.)
$c\bar{c}$	8.72 (7.87)	5.51 (5.40)	(0.54,0.44)
$\tau^+\tau^-$	2.55 (1.75)	1.47 (1.04)	(0.09,0.07)
WW^*	4.48 (2.26)	3.13 (1.25)	(0.10,0.08)
ZZ^*	4.96 (2.34)	3.63 (1.33)	(0.10,0.08)
$Z\gamma$	3.56 (1.96)	2.36 (1.15)	(0.83,0.80)
$\mu^+\mu^-$	2.53 (1.73)	1.47 (1.04)	(0.07,0.06)

() => if the Higgs mass uncertainty were 0.1 GeV (instead of 0.4 GeV)

SM vs. New Physics: Uncertainties in BRs

	Δ_{m_t}	
gg	0.07	0.4
$\gamma\gamma$	-	0.0
$b\bar{b}$	0.02	1.1
$c\bar{c}$	0.01	1.1
$\tau^+\tau^-$	0.04	1.0
WW^*	0.04	2.9
ZZ^*	0.03	3.4
$Z\gamma$	0.01	2.1
$\mu^+\mu^-$	0.04	1.0

Thus, without reducing this error, any new physics contribution to the bb branching fraction that is not at least a factor of three or four larger than 1% cannot be discerned from SM. Thus, a deviation of at least 3% is required of detectable new physics.

However, the lattice QCD calculation could improve it to match the experimental improvement on time. (arXiv:1404.0319v1, Lepege, Mechenzie, Peskin)

For example, if the data at a later stage of the ILC, or CLIC suggests that the branching fraction into ks can be determined to better than 1%, this does not m hat we are sensitive to new physics contributions of 1% t $I \to b\bar{b}$. The reason can be seen from Tables 6 and 7 tha the SM uncertainty in computing $B(H \to b\bar{b})$ is presently 2.4% (sum of absolute values of all errors) and expected to not get better than 1.6%, with most of that coming from uncertainty of the bottom Yukawa coupling determination stemming from the uncertainty of the measured bottom quark $\overline{\mathrm{MS}}$ mass

	$P^{\pm}_{\mathrm{BR}}$(par.-add.)	$P^{\pm}_{\mathrm{BR}}$(par.-quad.)	$(P^{+}_{\mathrm{BR}}, P^{-}_{\mathrm{BR}})(\mu)$
gg	3.47 (3.12)	2.09 (2.04)	(0.03,1.38)
$\gamma\gamma$	1.45 (1.44)	1.01 (1.01)	(1.81,1.83)
$b\bar{b}$	2.43 (1.58)	1.41 (0.89)	(0.21,0.)
$c\bar{c}$	8.72 (7.87)	5.51 (5.40)	(0.54,0.44)
$\tau^+\tau^-$	2.55 (1.75)	1.47 (1.04)	(0.09,0.07)
WW^*	4.48 (2.26)	3.13 (1.25)	(0.10,0.08)
ZZ^*	4.96 (2.34)	3.63 (1.33)	(0.10,0.08)
$Z\gamma$	3.56 (1.96)	2.36 (1.15)	(0.83,0.80)
$\mu^+\mu^-$	2.53 (1.73)	1.47 (1.04)	(0.07,0.06)

() => if the Higgs mass uncertainty were 0.1 GeV (instead of 0.4 GeV)

Summary I

- Higgs Precision will be soon reaching at the level of EWP.
- With improved theoretical tools (e.g. expansion formalism), SM will be tested at per mille level
- SM Higgs vs. BSM Higgs will be coming out.

Part II: New model of generalizing higgs sector

B. Bellazzini, C. Csaki, J. Hubisz, S.L., J. Serra, J. Terning
work in progress (to appear)

- With the observation of a scalar with properties close to the SM Higgs, we are now confident that the interactions of the Higgs boson with gauge bosons and fermions are mainly dictated by its kinetic term and Yukawa coupling $$\mathcal{L}_H = |D_\mu H|^2 - \bar{\psi}^\alpha H \psi^\beta$$

- Higher-dimensional operators predict relations between the mass of a given particle and its coupling to the Higgs that deviate O(1) from the ones derived from the above Lagrangian. $$|D_\mu H|^2 |H|^2,\ F_{\mu\nu}^2 |H|^2,\ \text{or}\ \bar{\psi} H \psi |H|^2$$

- The observation at the LHC of Higgs couplings consistent with the above Lagrangian implies that such higher-dimensional operators must be treated as small perturbations.

- The situation is however different in what regards the last part of the SM Lagrangian, the Higgs potential, $$V(H) = -\mu^2 |H|^2 + \lambda |H|^4$$

$\mu \sim 88$ GeV $\qquad \lambda \sim 0.13$

Higgs Potential: a toy example

- Let's consider the following potential

$$\tilde{V}(H) = -\lambda |H|^4 + c_6 |H|^6$$

$$c_6 \sim \Lambda^{-2}$$

Higgs Potential: a toy example

- Let's consider the following potential

$$\tilde{V}(H) = -\lambda|H|^4 + c_6|H|^6 \qquad c_6 \sim \Lambda^{-2}$$

- With this potential the VEV and mass of the Higgs are given by,

$$v^2 = \frac{4}{3}\frac{\lambda}{c_6}\,, \qquad \frac{m_h^2}{v^2} = 2\lambda \xrightarrow{\text{experimentally}} \lambda \approx 0.13$$

Higgs Potential: a toy example

- Let's consider the following potential

$$\tilde{V}(H) = -\lambda |H|^4 + c_6 |H|^6$$

$$c_6 \sim \Lambda^{-2}$$

- With this potential the VEV and mass of the Higgs are given by,

$$v^2 = \frac{4}{3}\frac{\lambda}{c_6}\,, \qquad \frac{m_h^2}{v^2} = 2\lambda$$

experimentally

$$\lambda \approx 0.13$$

- defining $c_6 = 1/f^2$, we find f ~ 600 GeV, so new physics effects from such scale might have escaped detection with $\Lambda \sim 4\pi f$

Higgs Potential: a toy example

- Let's consider the following potential

$$\tilde{V}(H) = -\lambda|H|^4 + c_6|H|^6$$

$$c_6 \sim \Lambda^{-2}$$

- With this potential the VEV and mass of the Higgs are given by,

$$v^2 = \frac{4}{3}\frac{\lambda}{c_6}\,, \qquad \frac{m_h^2}{v^2} = 2\lambda$$

experimentally

$$\lambda \approx 0.13$$

- defining $c_6 = 1/f^2$, we find f ~ 600 GeV, so new physics effects from such scale might have escaped detection with $\Lambda \sim 4\pi f$

This is just one simple example that shows that the form of the Higgs potential is completely undetermined

Higgs Potential: a toy example

- However, future measurements at the LHC can potentially distinguish between the two possibilities just presented.

- In particular, via double Higgs production, the triple Higgs coupling can be probed: i.e.

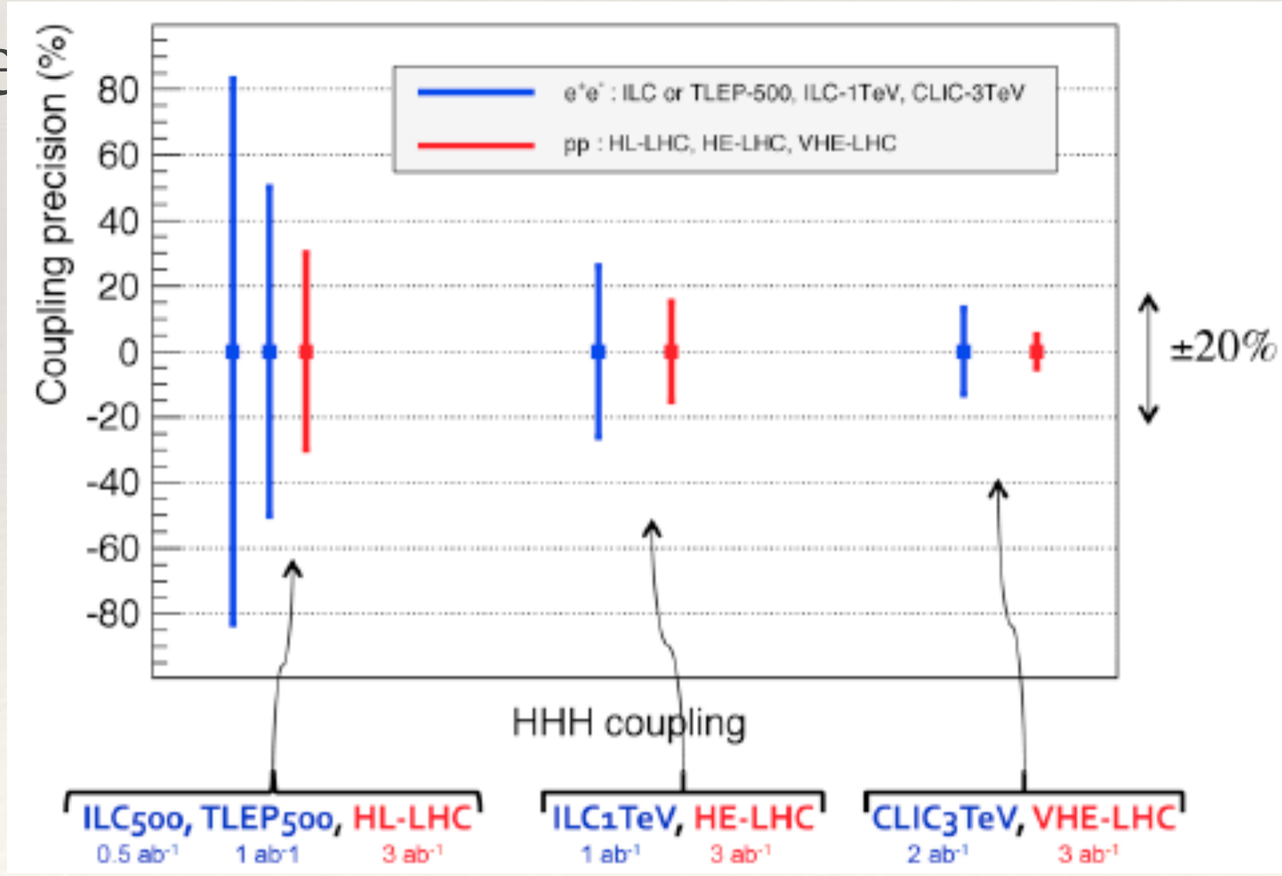
$$\lambda_{hhh} = 3\frac{m_h^2}{v} \longleftrightarrow \tilde{\lambda}_{hhh} = 7\frac{m_h^2}{v}$$

Higgs Potential: a toy example

- However, future measurements at the LHC can potentially distinguish between the two possibilities just presented.

- In particular, via double Higgs production, the triple Higgs coupling can be probe

$$\lambda_{hhh} = 3\frac{m_h^2}{v}$$



SM vs. Our Suggestion for Generalizing the Higgs sector

- Encouraged by the lack of current information on the Higgs potential, we are going to generalize all the terms in the SM Lagrangian that involve the Higgs:
    - we are going to parametrize with unknown coefficients the dimensions of the operators and of the Higgs field itself, and not merely include extra operators beyond those of dimension equal or lower than four.

SM vs. Our Suggestion for Generalizing the Higgs sector

- Encouraged by the lack of current information on the Higgs potential, we are going to generalize all the terms in the SM Lagrangian that involve the Higgs:
  - we are going to parametrize with unknown coefficients the dimensions of the operators and of the Higgs field itself, and not merely include extra operators beyond those of dimension equal or lower than four.

$$\mathcal{L}_H = -H^\dagger (D_\mu D^\mu + \mu^2)^{2-\Delta} H \left(1 + c_g \frac{|H|^{2\Delta_g}}{\Lambda^{2\Delta_g \Delta}}\right) - y_t \bar{q}_L \frac{H}{\Lambda^{\Delta-1}} t_R \left(1 + c_t \frac{|H|^{2\Delta_t}}{\Lambda^{2\Delta_t \Delta}}\right) \; ,$$

$$V_H = \frac{\Lambda^4}{(4\pi)^2} \sum_i c_i \frac{|H|^{2\Delta_i}}{\Lambda^{2\Delta_i \Delta}} \; ,$$

Physics behind of it: general Lagrangian describing a Higgs field near a second order Quantum Phase Transition

- The appearance of a light scalar degree of freedom (~125 GeVB Higgs) is quite unusual both in particle physics and in condensed matter systems.
- While there is no previous particle physics precedent, condensed matter systems can produce a light scalar by tuning the parameters such that one ends up close to a second order phase transition.
- Phase transitions happening at zero temperature are usually referred to as quantum phase transitions (QPT's). It is thus natural to use a condensed matter analogy and describe the Higgs in terms of a second order QPT. At the second order QPT all masses vanish and the theory is scale invariant, characterized by the scaling dimensions of the field

Physics behind of it: general Lagrangian describing a Higgs field near a second order Quantum Phase Transition

- The assumption that the theory is close to a QPT implies that the Higgs field should be characterized by its scaling dimension Δ, where $1 < \Delta < 2$. The simplest scale invariant kinetic term would be given by

$$\mathcal{L}_{kin} = H^{\dagger} \left[-\partial^2\right]^{2-\Delta} H$$

Physics behind of it: general Lagrangian describing a Higgs field near a second order Quantum Phase Transition

- The assumption that the theory is close to a QPT implies that the Higgs field should be characterized by its scaling dimension Δ, where $1 < \Delta < 2$. The simplest scale invariant kinetic term would be given by

$$\mathcal{L}_{kin} = H^\dagger \left[-\partial^2\right]^{2-\Delta} H$$

- The above Lagrangian corresponds to continuum of particles, which manifests itself in cut in the propagator with a branch point at zero (but no pole).

- One can move the cut away from the origin by shifting the kinetic term by μ:

$$\mathcal{L}_{kin} = H^\dagger \left[-\partial^2 + \mu^2\right]^{2-\Delta} H$$

Physics behind of it: general Lagrangian describing a Higgs field near a second order Quantum Phase Transition

- The assumption that the theory is close to a QPT implies that the Higgs field should be characterized by its scaling dimension Δ, where $1 < \Delta < 2$. The simplest scale invariant kinetic term would be given by

$$\mathcal{L}_{kin} = H^\dagger \left[-\partial^2\right]^{2-\Delta} H$$

- The above Lagrangian corresponds to continuum of particles, which manifests itself in cut in the propagator with a branch point at zero (but no pole).

- One can move the cut away from the origin by shifting the kinetic term by μ:

$$\mathcal{L}_{kin} = H^\dagger \left[-\partial^2 + \mu^2\right]^{2-\Delta} H$$

- This however gives a large contribution to the potential in the p ➔ 0 limit, removing all light degrees of freedom. A light pole can be reintroduced (while leaving the cut starting at μ) by subtracting the mass term:

$$\mathcal{L}_{kin} = H^\dagger \left[-\partial^2 + \mu^2\right]^{2-\Delta} H - \mu^{4-2\Delta} H^\dagger H$$

Physics behind of it: general Lagrangian describing a Higgs field near a second order Quantum Phase Transition

- The assumption that the theory is close to a QPT implies that the Higgs field should be characterized by its scaling dimension Δ, where 1 < Δ < 2. The simplest scale invariant kinetic term would be given by

$$\mathcal{L}_{kin} = H^\dagger \left[-\partial^2\right]^{2-\Delta} H$$

- The above Lagrangian corresponds to continuum of particles, which manifests itself in cut in the propagator with a branch point at zero (but no pole).

- One can move the cut

- This however gives a la
removing all light degr
leaving the cut starting at μ) by subtrac ng the mass term:

$$\mathcal{L}_{kin} = H^\dagger \left[-\partial^2 + \mu^2\right]^{2-\Delta} H - \mu^{4-2\Delta} H^\dagger H$$

Higgs is mixing with the states of the conformal matter corresponding to the physics of the quantum phase transition

Summary: Have we really discovered a SM-like Higgs boson?

- With improved theoretical tools, SM will be tested at per mille level.
- Meanwhile we are quite ignorant about the form of Higgs potential, or even kinetic term.
- Higgs from a QPT: a new way of parametrizing Higgs physics motivated by condensed matter physics.