Higgs Physics

Antonio Pich
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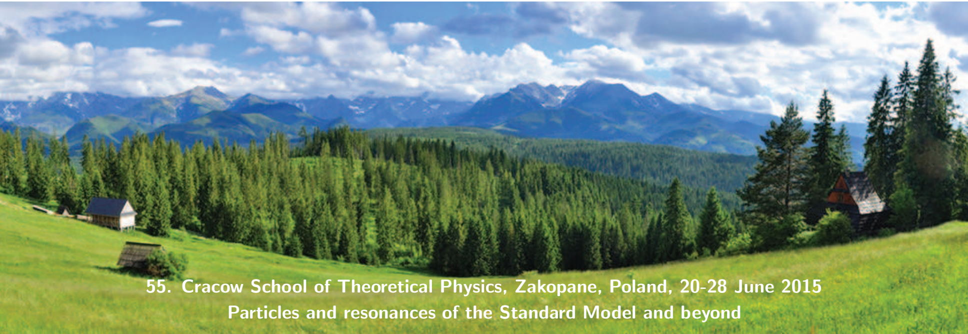


55. Cracow School of Theoretical Physics, Zakopane, Poland, 20-28 June 2015
Particles and resonances of the Standard Model and beyond

Outline

1) The Higgs Boson

- Higgs Mechanism
- Standard Model Higgs
- LHC data
- Higgs-singlet extension

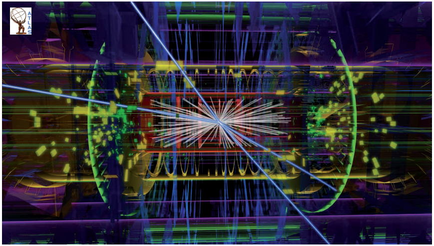
2) Aspects of EWSB

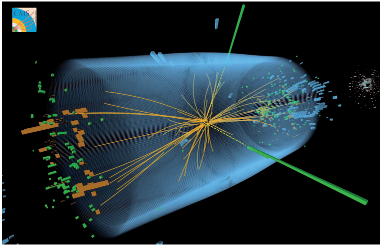
- Naturalness
- Vacuum stability
- Custodial Symmetry
- Unitarity

3) Two Higgs Doublets

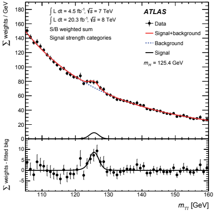
- FCNCs
- Flavour alignment
- Flavour bounds
- LHC constraints
- EDMs
- Rare decays

A New Higgs-Like Boson

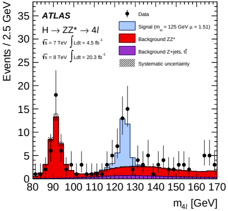




$H \to \gamma\gamma$



$H \to ZZ^* \to 4\ell$



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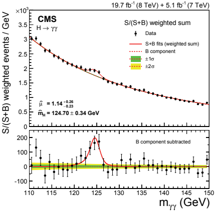

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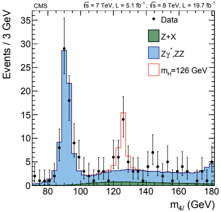
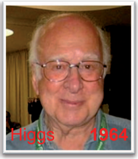
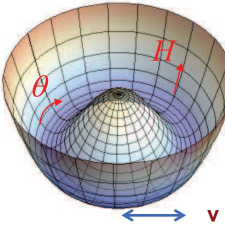


$$M_H = (125.09 \pm 0.21 \pm 0.11)\ \text{GeV}$$

Great success of the Standard Model

BEGHHK (≡ Higgs) Mechanism





$SU(2)_L \otimes U(1)_Y$ v = 246 GeV

Fundación
Príncipe de Asturias

$$M_Z \cos\theta_W = M_W = \frac{1}{2} \mathrm{v}\, g$$

Beautiful Discovery

Boson, $\boldsymbol{J = 0}$

Fermions = Matter ; Bosons = Forces

- **Fundamental Boson:** **New interaction which is not gauge**
- **Composite Boson:** **New underlying dynamics**

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If New Physics exists at $\Lambda_{\rm NP}$

$$\delta M_H^2 \sim \frac{g^2}{(4\pi)^2}\, \Lambda_{\rm NP}^2\, \log\left(\frac{\Lambda_{\rm NP}^2}{M_H^2}\right)$$

Which symmetry keeps M_H away from $\Lambda_{\rm NP}$?

- Fermions: Chiral Symmetry
- Gauge Bosons: Gauge Symmetry
- Scalar Bosons: Supersymmetry, Scale/Conformal Symmetry . . . ?

Possible Scenarios of EWSB

❶ **SM Higgs:** Favoured by EW precision tests

❷ **Alternative perturbative EWSB:**

Scalar Doublets and singlets $\rho_{\text{tree}} = \frac{M_W^2}{M_Z^2 c_W^2} = \frac{\sum_i v_i^2 [T_i(T_i+1) - Y_i^2]}{2\sum_i v_i^2 Y_i^2}$

❸ **Dynamical (non-perturbative) EWSB:**

Pseudo-Goldstone Higgs

Scalar Resonance

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Scalar Resonance

Higgs Mechanism:

Gauge invariance

Massless $W^\pm$, Z (spin 1)

3×2 polarizations $= 6$

Higgs Mechanism: 3 additional degrees of freedom $\varphi_i(x)$

Gauge invariance

Massless $W^\pm$, Z (spin 1)

3×2 polarizations $= 6$

$+$

3 Goldstones $\varphi_i(x)$

SSB ⬇

Massive $W^\pm$, Z

3×3 polarizations $= 9$

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SSB ↓

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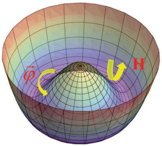
Spontaneous Symmetry Breaking

$$\mathcal{L}_\Phi = (D_\mu \Phi)^\dagger D^\mu \Phi - \mu^2 \Phi^\dagger \Phi - \lambda \left(\Phi^\dagger \Phi\right)^2$$



$\mu^2 < 0$

$$\Phi(x) = \exp\left\{ i\, \vec{\sigma} \cdot \frac{\vec{\varphi}(x)}{v} \right\} \frac{1}{\sqrt{2}} \begin{bmatrix} 0 \\ v + H(x) \end{bmatrix}$$

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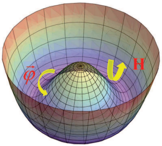

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$$D_\mu \Phi = (\partial_\mu + \tfrac{i}{2} \, g \, \vec{\sigma} \cdot \vec{W}_\mu + \tfrac{i}{2} \, g' \, B_\mu) \, \Phi \quad ; \quad v^2 = -\mu^2 / \lambda$$

$$(D_\mu \Phi)^\dagger D^\mu \Phi \;\to\; M_W^2 \, W_\mu^\dagger W^\mu + \frac{M_Z^2}{2} \, Z_\mu Z^\mu$$

$$\mathbf{M_W} = \mathbf{M_Z} \cos\theta_\mathbf{W} = \tfrac{1}{2} \, \mathbf{g} \, \mathbf{v}$$

Higgs Mechanism: 3 additional degrees of freedom $\varphi_i(x)$

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SSB ↓

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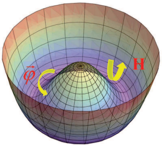

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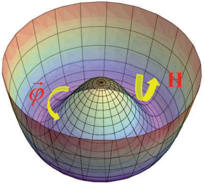
$$(D_\mu\Phi)^\dagger D^\mu\Phi \;\to\; M_W^2\,W_\mu^\dagger W^\mu + \frac{M_Z^2}{2}\,Z_\mu Z^\mu \times\left(1 + \frac{H}{v}\right)^2$$

$$\mathbf{M_W = M_Z\cos\theta_W = \tfrac{1}{2}\,g\,v}$$

SM Higgs Potential



$$\Phi(x) \;=\; \exp\left\{\frac{i}{v}\,\vec{\sigma}\,\vec{\varphi}(x)\right\}\;\frac{1}{\sqrt{2}}\;\begin{bmatrix} 0 \\ v + H(x) \end{bmatrix}$$

$$V(\Phi) + \frac{\lambda}{4}\,v^4 \;=\; \lambda\,\left(|\Phi|^2 - \frac{v^2}{2}\right)^2 \;=\; \frac{1}{2}\,M_H^2\,H^2 \;+\; \frac{M_H^2}{2v}\,H^3 \;+\; \frac{M_H^2}{8v^2}\,H^4$$

$$v \;=\; \frac{2M_W}{g} \;=\; \left(\sqrt{2}\,G_F\right)^{-1/2} \;=\; 246\ \mathrm{GeV}$$

$$M_H = (125.09 \pm 0.24)\ \mathrm{GeV} \quad \longrightarrow \quad \lambda \;=\; \frac{M_H^2}{2v^2} \;=\; 0.13$$

Standard Model Yukawas (1 family)

$$\Phi = \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix} \qquad , \qquad \langle 0|\Phi|0\rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix} \qquad , \qquad \tilde{\Phi} \equiv i\tau_2\, \Phi^*$$

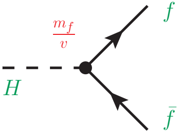
$$\mathcal{L}_Y = -\, c_1\, (\bar{u}_L, \bar{d}_L)\, \Phi\, d_R - c_2\, (\bar{u}_L, \bar{d}_L)\, \tilde{\Phi}\, u_R - c_3\, (\bar{\nu}_L, \bar{e}_L)\, \Phi\, e_R + \text{h.c.}$$

SSB

$$\mathcal{L}_Y = -\left(1 + \frac{H}{v}\right) \left\{ m_d\, \bar{d}d + m_u\, \bar{u}u + m_e\, \bar{e}e \right\}$$

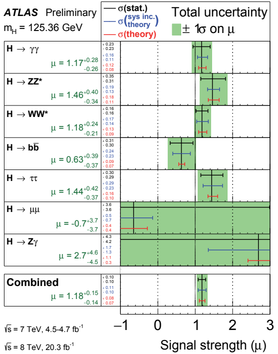
$$m_d = c_1\, \frac{v}{\sqrt{2}} \qquad , \qquad m_u = c_2\, \frac{v}{\sqrt{2}} \qquad , \qquad m_e = c_3\, \frac{v}{\sqrt{2}}$$

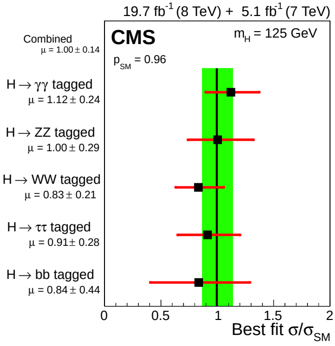
Couplings proportional to masses



Signal Strengths

$$\mu \equiv \sigma \cdot \mathrm{Br} / (\sigma \cdot \mathrm{Br})_{\mathrm{SM}}$$



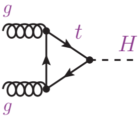


$$\langle \mu \rangle = 1.09 \pm 0.10$$

Decay Mode	ATLAS ($M_H = 125.36$ GeV)	CMS ($M_H = 125.0$ GeV)
$H \to bb$	$0.63\,^{+\,0.39}_{-\,0.37}$	0.84 ± 0.44
$H \to \tau\tau$	$1.44\,^{+\,0.42}_{-\,0.37}$	0.91 ± 0.28
$H \to \gamma\gamma$	$1.17\,^{+\,0.28}_{-\,0.26}$	1.12 ± 0.24
$H \to WW^*$	$1.18\,^{+\,0.24}_{-\,0.21}$	0.83 ± 0.21
$H \to ZZ^*$	$1.46\,^{+\,0.40}_{-\,0.34}$	1.00 ± 0.29
Combined	$\mathbf{1.18\,^{+\,0.15}_{-\,0.14}}$	$\mathbf{1.00 \pm 0.14}$

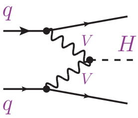
Production Channels

Gluon Fusion

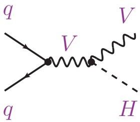


Vector Boson Fusion

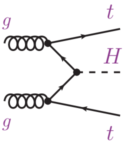
$(V = W^{\pm}, Z)$

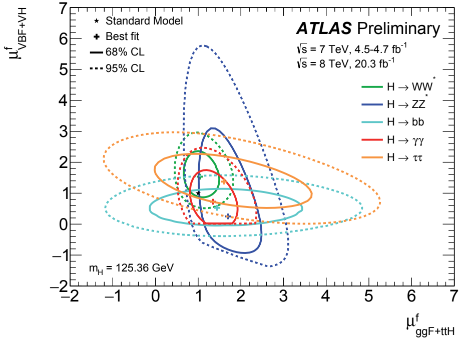


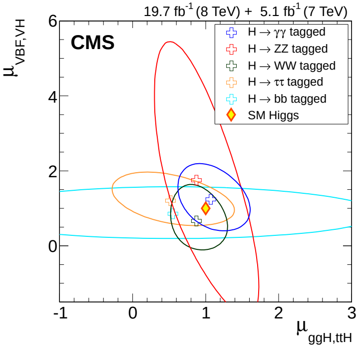
Ass. *VH* Production



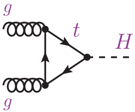
Ass. $t\bar{t}H$ Production



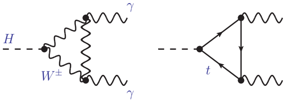




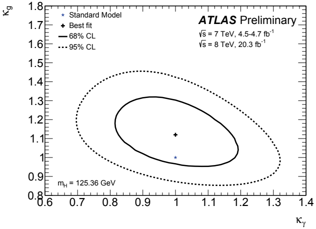
Strong (indirect) evidence for Higgs coupling to t

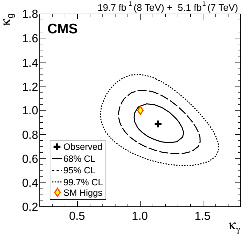


Dominant Production Mechanism



$\Gamma \sim |1 - 0.21|^2$

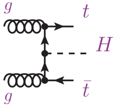




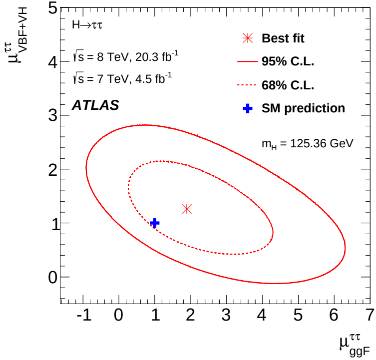
$\kappa_i \equiv g_i / g_i^{\mathrm{SM}}$

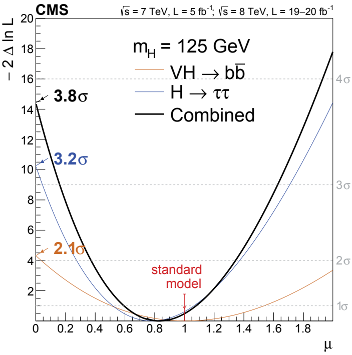
$H \to \gamma\gamma$	Signal Strength
ATLAS	$1.17\ {}^{+\,0.28}_{-\,0.26}$
CMS	1.12 ± 0.24

Direct (tree-level) sensitivity through $t\bar{t}H$



Strong evidence for Higgs coupling to τ and b





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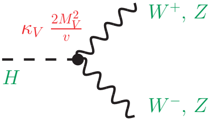
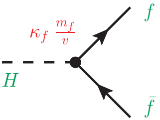
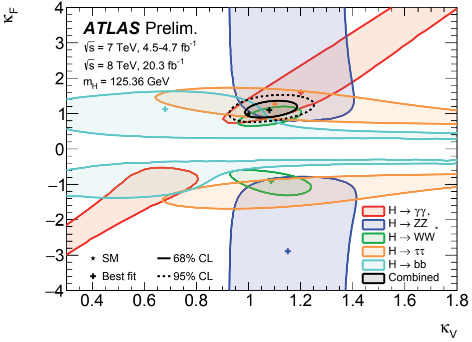
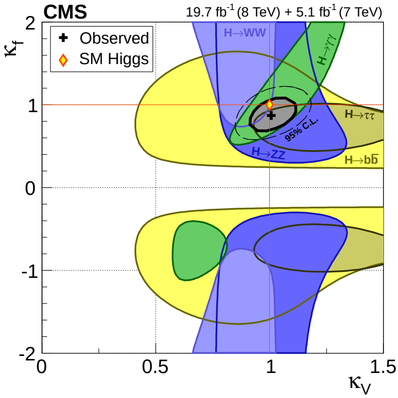
Effective Couplings





$$\kappa_i \equiv g_i / g_i^{\mathrm{SM}}$$

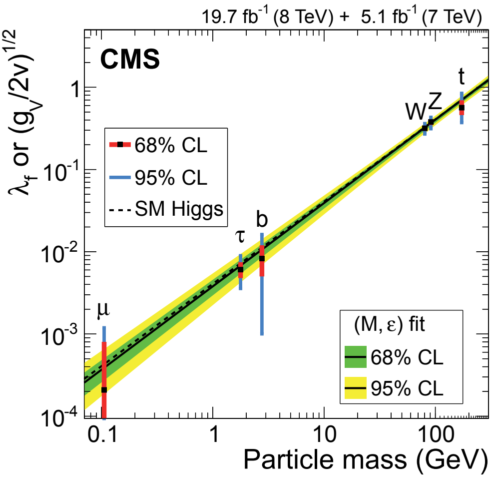




$$\sigma(i \to H) \cdot \mathrm{Br}(H \to f) \;=\; \sigma(i \to H) \cdot \Gamma(H \to f)/\Gamma_H \;\sim\; (\kappa_i \kappa_f / \kappa_H)^2$$

It is a Higgs Boson

$\lambda_f = (m_f/M)^{1+\epsilon}$, $(g_V/2v)^{1/2} = (M_V/M)^{1+\epsilon}$ Ellis-You, 1303.3879



SM: $\epsilon = 0$, $M = v = 246$ GeV

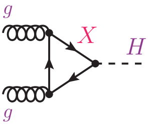
CMS: (95% CL)

$\epsilon \in [-0.054, 0.100]$

$M \in [217, 279]$ GeV

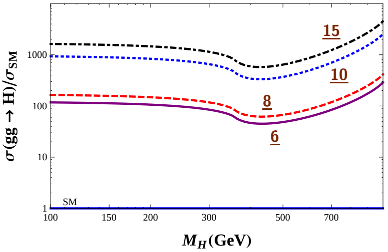
QCD Exotics

$X \in SU(3)_C$ representation $\underline{\mathrm{R}}$



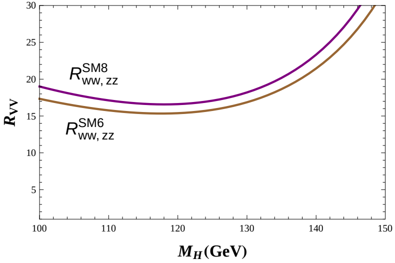
$$\sim \sum_{a=1}^{d_A} \mathrm{Tr}\left[t_R^a t_R^a\right] = C_R d_R$$

V. Ilisie - AP, 1202.3430



Non decoupling: $\mathcal{L} = -\frac{M_X}{v}\,(\bar{X}X)\,H$

$R_{VV} = \mu_{VV}$



Exotic fermions in higher-colour representations could only exist provided their masses are not generated by the SM Higgs

(or fine-tuned cancelations with scalar loops)

Higgs-Singlet Extension of the SM

$$V(\Phi, S) = \lambda \left(|\Phi|^2 - \frac{v^2}{2}\right)^2 + \left(a_\Phi\, S + b_\Phi\, S^2\right) \left(|\Phi|^2 - \frac{v^2}{2}\right) + \frac{1}{2}\, M_S^2\, S^2 + a_S\, S^3 + \lambda_S\, S^4$$

- Real singlet and neutral field: $S = S^\dagger$

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- Real singlet and neutral field: $S = S^\dagger$
- Minima: $\langle S \rangle = 0 \quad , \quad \langle \phi^{(0)} \rangle = \frac{v}{\sqrt{2}}$ $\qquad \phi^{(0)} = \frac{1}{\sqrt{2}}\,(v + \varphi)$

  $M_S^2 > a_\Phi^2/(4\lambda) > 0$

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  $M_S^2 > a_\Phi^2 / (4\lambda) > 0$

- Positive growing at large field values: $\lambda, \lambda_S, b_\Phi > 0$

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$$V(\Phi, S) \,=\, \lambda\, \left(|\Phi|^2 - \frac{v^2}{2}\right)^2 + \left(a_\Phi\, S + b_\Phi\, S^2\right) \left(|\Phi|^2 - \frac{v^2}{2}\right) + \frac{1}{2}\, M_S^2\, S^2 + a_S\, S^3 + \lambda_S\, S^4$$

- Real singlet and neutral field: $S = S^\dagger$
- Minima: $\langle S \rangle = 0 \quad , \quad \langle \phi^{(0)} \rangle = \frac{v}{\sqrt{2}}$ $\qquad \phi^{(0)} = \frac{1}{\sqrt{2}}\,(v + \varphi)$

  $M_S^2 > a_\Phi^2/(4\lambda) > 0$
- Positive growing at large field values: $\lambda, \lambda_S, b_\Phi > 0$
- Mass eigenstates **(mixing)**:

Higgs-Singlet Extension of the SM

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- Positive growing at large field values: $\lambda, \lambda_S, b_\Phi > 0$
- Mass eigenstates **(mixing)**: $(-\frac{\pi}{2} \le \alpha \le \frac{\pi}{2})$

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{bmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{bmatrix} \begin{pmatrix} \varphi \\ S \end{pmatrix} \qquad , \qquad \tan 2\alpha = \frac{2 a_\Phi\, v}{2v^2\lambda - M_S^2}$$

$$M_h^2 = \frac{1}{2}\,(\Sigma - \Delta) \qquad < \qquad M_H^2 = \frac{1}{2}\,(\Sigma + \Delta)$$

$$\Sigma = 2v^2\lambda + M_S^2 \qquad , \qquad \Delta = \sqrt{(2v^2\lambda - M_S^2)^2 + 4a_\phi^2 v^2}$$

The singlet scalar does not couple to fermions and gauge bosons

$$\kappa_V \equiv g_{hVV}/g_{hVV}^{\rm SM} = \cos\alpha \qquad , \qquad \kappa_f \equiv y_{hff}\,/y_{hff}^{\rm SM} = \cos\alpha$$

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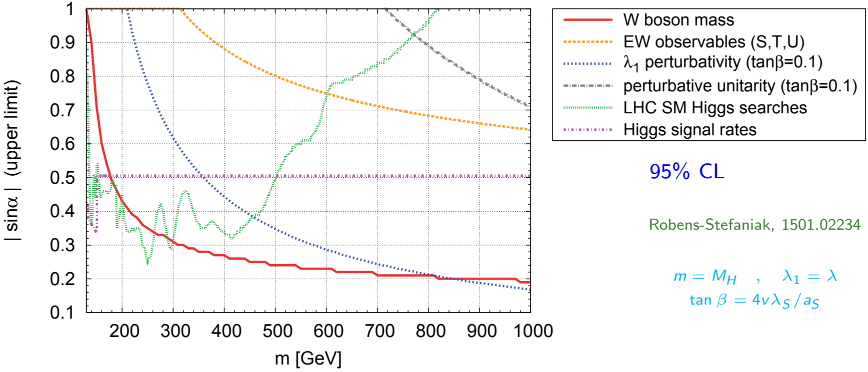


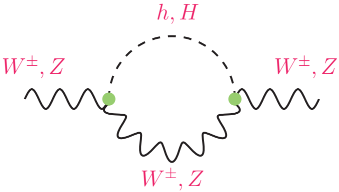
95% CL

Robens-Stefaniak, 1501.02234

$m = M_H \quad , \quad \lambda_1 = \lambda$

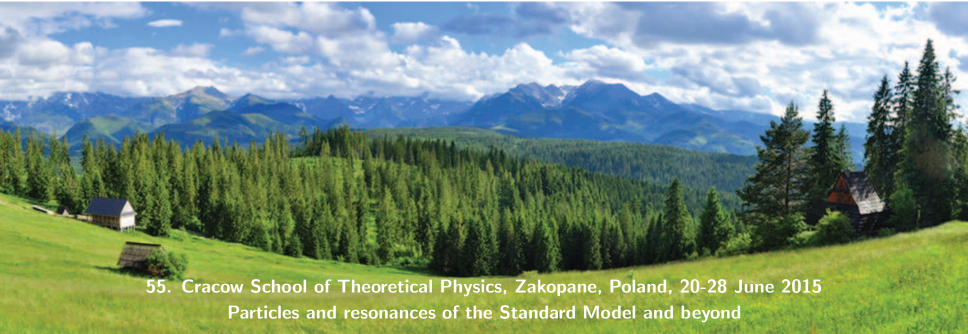
$\tan\beta = 4v\lambda_S/a_S$

$$M_W^2 \left(1 - \frac{M_W^2}{M_Z^2}\right) \; = \; \frac{\pi\alpha}{\sqrt{2}} \, (1 + \Delta r)$$



$$\delta(\Delta r) \; = \; \underbrace{\Delta r^H}_{\sin^2\alpha} + \underbrace{\Delta r^h - \Delta r^{\mathrm{SM}}}_{\cos^2\alpha - 1} \; \propto \; \sin^2\alpha$$

Backup Slides



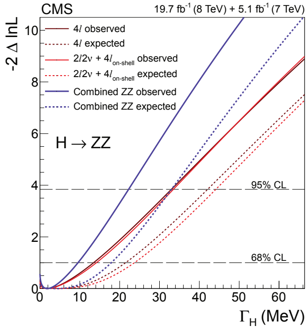
55. Cracow School of Theoretical Physics, Zakopane, Poland, 20-28 June 2015
Particles and resonances of the Standard Model and beyond

Higgs Width

Sensitivity to Γ_H off-shell:

Caola-Melnikov, Kauer-Passarino, Campbell et al

$$\frac{d\sigma_{gg\to H\to ZZ}}{dm^2_{ZZ}} \sim \frac{g^2_{ggH}\, g^2_{hZZ}}{(m^2_{ZZ}-M^2_H)^2 + M^2_H\Gamma^2_H} \quad , \qquad \sigma_{gg\to H\to ZZ} \sim \begin{cases} \dfrac{g^2_{ggH}\, g^2_{hZZ}}{M_H\Gamma_H} & \text{(on-shell)} \\ \dfrac{g^2_{ggH}\, g^2_{hZZ}}{4M^2_Z} & (m_{ZZ} > 2M_Z) \end{cases}$$



CMS, 1405.3455

$$\Gamma_H < 5.4\, \Gamma_H^{\rm SM} = 22 \text{ MeV} \quad (95\% \text{ CL})$$

ATLAS-CONF-2014-042: $\Gamma_H < 5.7\, \Gamma_H^{\rm SM}$

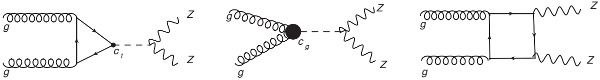
Assumes constant couplings unrelated to $\Delta\Gamma_H$

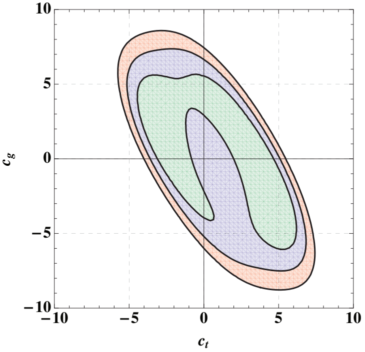
Englert-Spannowsky, 1405.0285

Alternative analysis:

Azatov et al, 1406.6338

$$\mathcal{L} = -c_t \frac{m_t}{v} \bar{t} t H + \frac{g_s^2}{48\pi^2 v^2} c_g G_{\mu\nu} G^{\mu\nu} H$$





$\sigma \sim |c_t + c_g|^2$ (on-shell)

$\mathcal{M}_{c_g} \sim c_g \hat{s}$ $(\hat{s} \gg m_t^2)$

Invisible Higgs Width