Electroweak corrections in the Singlet Extension of the Standard Model

David López-Val

based on work together with
♭**F. Bojarski**, **G. Chalons** (LPSC U. Grenoble-Alpes) & **T. Robens** (IKTP, TU Dresden.)

arXiv:1406.1043 [hep-ph] & **arXiv:1511.08120 [hep-ph]**

CP3 - Université catholique de Louvain

IST Lisboa **MULTI-HIGGS WORKSHOP** **September 7th 2016**

Outline

Outline

1. Foreword
2. About the model
3. Electroweak precision: Δr and m_W
4. Renormalization
5. Heavy-to-light Higgs decays
6. Take–home ideas

Foreword

We are building on an evidence . . .

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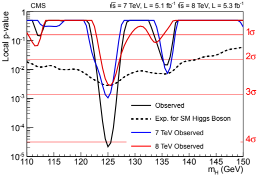

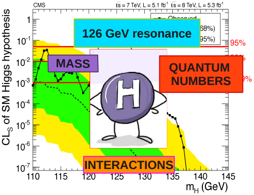

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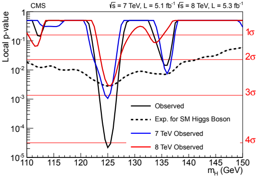

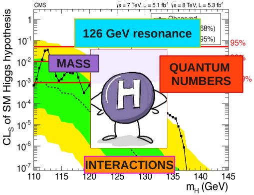

Is it THE (SM) ONE or instead a SIGNAL FROM BEYOND?

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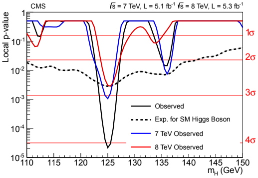

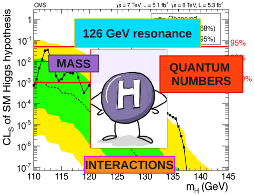

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Some key questions

- **Fundamental** or **composite**?
- **Single** or **multiple**? Or even **overlapped**?
- **Natural**? **Weakly** or **strongly** coupled?
- **Stable**? Up to an arbitrary UV scale? During inflation?
- **Linked** to flavor, neutrinos?

Outline

The singlet-extended SM

Lagrangian & field content

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \partial^\mu S \partial_\mu S - \mu_s^2 S^2 - \lambda_2 S^4 - \lambda_3 \Phi^\dagger \Phi S^2$$

$$\Phi = \begin{pmatrix} G^+ \\ \frac{v + \phi_h + iG^0}{\sqrt{2}} \end{pmatrix}$$

$$S = \frac{v_s + \phi_s}{\sqrt{2}}$$

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♠ **Parameters**

$$m_h,\, m_H,\, \sin\alpha,\, v,\, \tan\beta \equiv \frac{v_s}{v}$$

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Interactions

$$g_{xxy} = g_{xxy}^{\text{SM}} (1 + \Delta_{xy}) \qquad \text{with} \qquad 1 + \Delta_{xy} = \begin{cases} \cos\alpha & y = h \\ \sin\alpha & y = H \end{cases}$$

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Simplified model $\rightarrow \mathcal{L}_{\text{UV}}$

EW baryogenesis

Proxy for Heavy scalar LHC searches

Outline

Δr and m_W in the singlet model

$m_V - G_F - \tau_\mu$: a golden probe of quantum effects

- $\flat$ **SM:** Djouadi ['83]; Hollik [''88]; Kniehl ['91]; Freitas ['00]; Awramik ['02]; . . . Boughezal, Chetykrin ['06]
- $\flat$ **MSSM:** Van der Bij ['83]; . . . Garcia, Chankowski ['93]; . . . Heinemeyer ['13]]
- $\flat$ **2HDM:** Frère ['86]; Bertolini ['88] . . . DLV, Solà ['12], Hessenberger, Hollik ['16]
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♣ Matching the μ-lifetime prediction in the Fermi theory onto the SM result:

$$m^2_{W^\pm}\left(1-\frac{m^2_{W^\pm}}{m^2_Z}\right)=\frac{\pi\,\alpha_{\text{em}}}{\sqrt{2}G_F}\,(1+\Delta r)$$

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$$\Delta\,r=\Pi_\gamma(0)-\frac{c^2_w}{s^2_w}\left(\frac{\delta\,m^2_Z}{m^2_Z}-\frac{\delta\,m^2_{W^\pm}}{m^2_{W^\pm}}\right)+\frac{\Sigma_{W^\pm}(0)-\delta\,m^2_{W^\pm}}{m^2_{W^\pm}}+2\,\frac{c_w}{s_w}\,\frac{\Sigma_{\gamma Z}(0)}{m^2_Z}+\Delta\,r^{[\text{vert},\text{box}]}$$

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$$m^2_{W^\pm}\left(1-\frac{m^2_{W^\pm}}{m^2_Z}\right) = \frac{\pi\,\alpha_{\text{em}}}{\sqrt{2}G_F}\,(1+\Delta r)$$

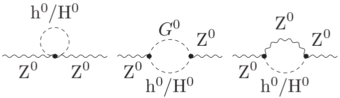
$$\Delta\, r = \Pi_\gamma(0) - \frac{c^2_w}{s^2_w}\left(\frac{\delta\, m^2_Z}{m^2_Z} - \frac{\delta\, m^2_{W^\pm}}{m^2_{W^\pm}}\right) + \frac{\Sigma_{W^\pm}(0) - \delta\, m^2_{W^\pm}}{m^2_{W^\pm}} + 2\,\frac{c_w}{s_w}\,\frac{\Sigma_{\gamma Z}(0)}{m^2_Z} + \Delta\, r^{[\text{vert},\text{box}]}$$

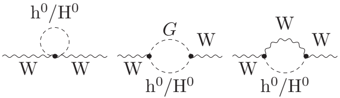
♠ $$\Delta r = \Delta\alpha - \frac{c^2_w}{s^2_w}\,\delta\rho + \Delta r_{\text{rem}}$$

♠ $$\delta(\Delta r_{\text{sing}}) \equiv \Delta r^{[\text{H}]}_{\text{sing}} - \Delta r^{[\text{H}]}_{\text{SM}} \quad \text{where} \quad \Delta r^{[\text{H}]}_{\text{SM}} = \Delta r^{[\text{H}]}_{\text{sing}}\Big|_{\sin\alpha=0}$$

Δr and m_W in the 2HDM

- **Oblique corrections to the gauge boson self–energies**





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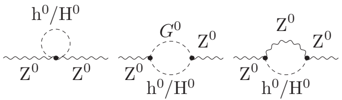

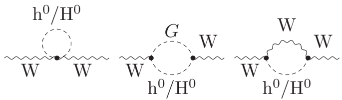

♠ Static contributions only: $\delta\rho$

$$\Delta(\delta\rho_{\text{sing}}) \equiv \delta\rho^{[\text{H}]}_{\text{sing}} - \delta\rho^{[\text{H}]}_{\text{SM}}$$

$$\frac{G_F\ \sin^2\alpha}{2\sqrt{2}\pi^2}\left\{ m_Z^2\ \left[\log\left(\frac{m_h^2}{m_H^2}\right) + \frac{m_Z^2}{m_h^2 - m_Z^2}\log\left(\frac{m_h^2}{m_Z^2}\right) - \frac{m_Z^2}{m_H^2 - m_Z^2}\log\left(\frac{m_H^2}{m_Z^2}\right)\right.\right.$$

$$\left. + \frac{m_H^2}{4(m_H^2 - m_Z^2)}\log\left(\frac{m_H^2}{m_Z^2}\right) - \frac{m_h^2}{4(m_h^2 - m_Z^2)}\log\left(\frac{m_h^2}{m_Z^2}\right)\right]$$

$$- m_W^2\ \left[\log\left(\frac{m_h^2}{m_H^2}\right) + \frac{m_W^2}{m_h^2 - m_W^2}\log\left(\frac{m_h^2}{m_W^2}\right) - \frac{m_W^2}{m_H^2 - m_W^2}\log\left(\frac{m_H^2}{m_W^2}\right)\right.$$

$$\left.\left. + \frac{m_H^2}{4(m_H^2 - m_W^2)}\log\left(\frac{m_H^2}{m_W^2}\right) - \frac{m_h^2}{4(m_h^2 - m_W^2)}\log\left(\frac{m_h^2}{m_W^2}\right)\right]\right\}$$

Δr and m_W in the 2HDM

♠ Predicting the W–boson mass:

$$m_{W^\pm}^{\text{th}\,2} = \frac{1}{2}\,m_Z^2\left[1+\sqrt{1-\frac{4\,\pi\,\alpha_{\text{em}}}{\sqrt{2}\,G_F\,m_Z^2}\left[1+\Delta\,r(m_{W^\pm}^2)\right]}\,\right] \Rightarrow$$

$$\Delta m_{W^\pm} \simeq -\frac{1}{2}\,m_{W^\pm}\,\frac{s_w^2}{c_w^2-s_w^2}\,\delta(\Delta r)$$

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$m^{\text{SM}}_W = 80.360$ GeV

$|m^{\text{exp}}_W - m^{\text{SM}}_W| \simeq$ **20 MeV**

$m^{\text{exp}}_W = 80.385 \pm 0.015$ GeV

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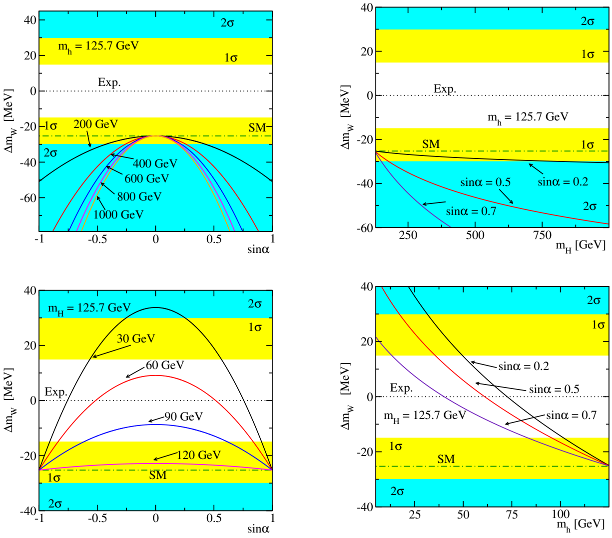
$m_W^{\text{SM}} = 80.360$ GeV | $|m_W^{\text{exp}} - m_W^{\text{SM}}| \simeq$ **20 MeV** | $m_W^{\text{exp}} = 80.385 \pm 0.015$ GeV

♣ State–of–the–art theory prediction Awramik et al. [hep-ph/0311148]:

$$M^{\text{SM}}_{W^\pm} = M^0_{W^\pm} - d_1\,\text{dH} - d_2\,\text{dH}^2 + d_3\,\text{dH}^4 + d_4\,(dh - 1) - d_5\,\text{d}\alpha + d_6\,\text{dt} - d_7\,\text{dt}^2$$
$$- d_8\,\text{dH}\,\text{dt} + d_9\,dh\,dt - d_{10}\,\text{d}\alpha_s + d_{11}\,\text{dZ}$$

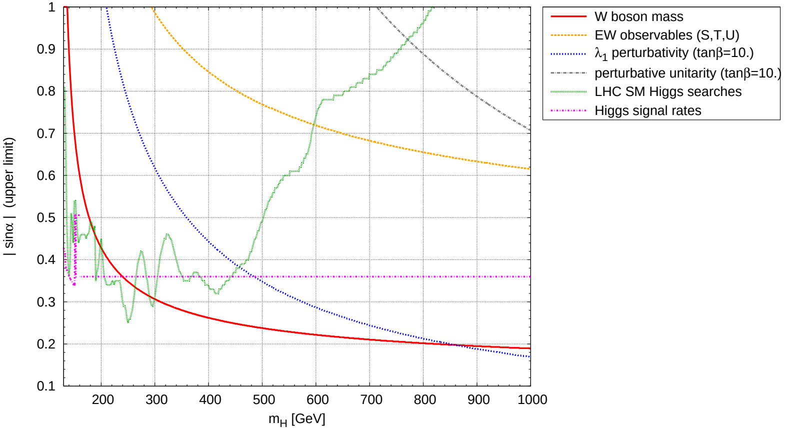
$$
\begin{array}{lll lll}
M^0_{W^\pm} & = & 80.3800\,\text{GeV}; & d_6 & = & 0.5270\,\text{GeV}; \\
d_1 & = & 0.05253\,\text{GeV}; & d_7 & = & 0.0698\,\text{GeV}; \\
d_2 & = & 0.010345\,\text{GeV}; & d_8 & = & 0.004055\,\text{GeV}, \\
d_3 & = & 0.001021\,\text{GeV}, & d_9 & = & 0.000110\,\text{GeV}, \\
d_4 & = & -0.0000070\,\text{GeV}, & d_{10} & = & 0.0716\,\text{GeV}, \\
d_5 & = & 1.077\,\text{GeV}, & d_{11} & = & 115.0\,\text{GeV}; \\
\text{dH} & = & \ln\left(\frac{M_{\text{H}}}{100\,\text{GeV}}\right); & \text{dt} & = & \left(\frac{m_t}{174.3\,\text{GeV}}\right)^2 - 1; \\
\text{d}\alpha & = & \frac{\Delta\alpha}{0.05907} - 1; & \text{d}\alpha_s & = & \frac{\alpha_s(M_Z)}{0.119} - 1; \\
\text{dZ} & = & M_Z/(91.1875\,\text{GeV}) - 1; & \text{dh} & = & \left(\frac{M_{\text{H}}}{100\,\text{GeV}}\right)^2;
\end{array}
$$

Δr and m_W in the singlet model



DLV, Robens [arXiv:1406.1043]

Parameter space constraints



Robens, Stefaniak [arXiv:1501.02234] - *updated in arXiv:1511.08120*

Intermezzo: a two-slide EFT perspective

$$\mathcal{L}_{\text{eff}}(\phi, m) = \mathcal{L}_{\text{SM}} + \sum_{d=5}^{\infty} \sum_{a_d} \frac{C_{a_d}^{(d)}}{\Lambda^{d-4}}(\{g_{\text{UV}}\}, M)\, \mathcal{O}_{a_d}^{(d)}(\phi)$$

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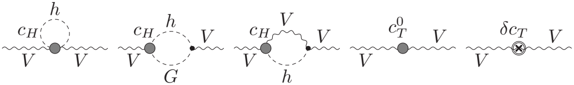

$$\Pi_{WW}(0) = \frac{\alpha_{\text{em}}\, \overline{c}_H}{16\pi s_w^2} \left\{ 3m_W^2 \Delta_\epsilon - 4m_W^2 \log\frac{m_h^2}{\mu^2} + \frac{5m_W^2 - m_h^2}{2} + \right.$$
$$\left. + m_W^2 \log\frac{m_W^2}{\mu^2} - \frac{m_W^2}{m_h^2 - m_W^2}\left(4m_W^2 - m_h^2\right) \log\frac{m_h^2}{m_W^2} \right\} + \Xi[\delta Z_{c_{W,B,T}}]$$

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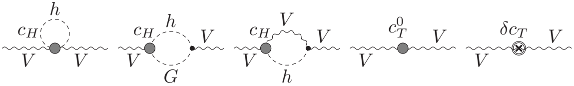

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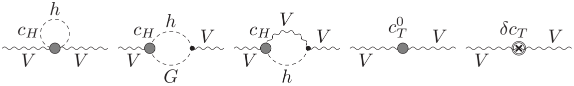

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$$\gamma_{\text{TH}} \equiv \gamma_{\text{H}\to\text{T}} = \frac{3}{2}\frac{e^2}{c_w^2}$$

$$\frac{v^2}{\Lambda^2} c_T(m_Z) = -\frac{3\alpha_{\text{ew}}\, \tan^2\theta_W}{(4\pi)^2}\left(\frac{\lambda_3^2\, v^2}{2\lambda_2\,(2\lambda_2 v_s^2)}\right)\log\left(\frac{2\lambda_2\, v_s^2}{m_Z^2}\right)$$

Intermezzo: a two-slide EFT perspective

Potential Hazards: ♠ Multiple M_{heavy}'s ♠ v-induced scales ♠ Eigenmass splittings

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Implications Freitas, DLV, Plehn arXiv:1607.08614

- Λ choice and/or truncation not always univoque
- Additional v-induced scales $\sim M_{\text{heavy}} \pm gv$ $\Rightarrow$ spoilt scale separation & sizable mass splittings
- Large $d > 6$ contributions $\mathcal{O}^d \propto \mathcal{O}^{d=6}\,(\Phi^\dagger\Phi)^{d-6}$ $\Rightarrow$ *v-improvement*

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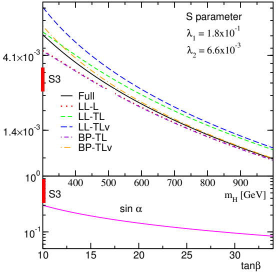
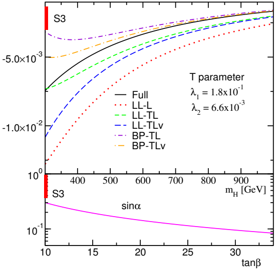
$$\alpha_{\text{em}} S = \frac{4\pi m_W^2}{\Lambda^2}\,(c_W + c_B)$$

$$\alpha_{\text{em}} T = c_T\,\frac{v^2}{\Lambda^2}$$





Outline

Higgs sector

EW vacuum

- **Tadpoles:** $\hat{T}_h = T_h + \delta T_h = 0;$ $\hat{T}_H = T_H + \delta T_H = 0$
- **Doublet vev:** $v = \frac{2\, m_W\, s_W}{e} \rightarrow \frac{\delta v}{v} = \frac{1}{2}\frac{\delta m_W^2}{m_W^2} + \frac{\delta s_W}{s_W} - \frac{\delta Z_e}{e}$
- **Singlet vev:** $\phi_s + v_s \rightarrow Z_S^{1/2}(\phi_s + v_s + \delta\bar{v}_s)$

- $\delta\bar{v}_s^{\text{div}} = 0$ Sperling, Stöckinger, Voigt ['13]
- $\delta\bar{v}_s^{\text{fin}} \equiv 0$ $\Rightarrow$ $\tan\beta \equiv \tan\beta\Big|^{\text{phys}}$

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- **Doublet vev:** $v = \frac{2\, m_W\, s_W}{e} \quad \rightarrow \quad \frac{\delta v}{v} = \frac{1}{2}\frac{\delta m_W^2}{m_W^2} + \frac{\delta s_W}{s_W} - \frac{\delta Z_e}{e}$
- **Singlet vev:** $\phi_s + v_s \rightarrow Z_S^{1/2}(\phi_s + v_s + \delta\bar{v}_s)$

• $\delta\bar{v}_s^{\text{div}} = 0$ Sperling, Stöckinger, Voigt ['13] • $\delta\bar{v}_s^{\text{fin}} \equiv 0$ $\Rightarrow$ $\tan\beta \equiv \tan\beta\Big|^{\text{phys}}$

Higgs masses

- **OS physical masses**

$\text{Re}\hat{\Sigma}_\phi(m_\phi^2) = 0$ $\text{Re}\hat{\Sigma}_\phi(p^2) = \text{Re}\,\Sigma_\phi(p^2) + \delta Z_\phi(p^2 - m_\phi^2) - \delta m_\phi^2, \qquad [\phi = h, H]$

Higgs sector

EW vacuum

- **Tadpoles:** $\hat{T}_h = T_h + \delta T_h = 0;$ $\hat{T}_H = T_H + \delta T_H = 0$

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... *But loops are there!* $\Rightarrow$

$$\text{Re}\hat{\Sigma}_{hH}(p^2) = \text{Re}\,\Sigma_{hH}(p^2) + \frac{1}{2}\delta Z_{hH}(p^2 - m_h^2) + \frac{1}{2}\delta Z_{Hh}(p^2 - m_H^2) - \delta m_{hH}^2$$

Higgs sector

Higgs fields

♣ **All-order mixing angle**

$$\begin{pmatrix} h \\ H \end{pmatrix}^0 = U(\alpha) \begin{pmatrix} \phi_h \\ \phi_s \end{pmatrix}^0 \quad \Rightarrow \quad \begin{pmatrix} h \\ H \end{pmatrix} = U(\alpha) \begin{pmatrix} \phi_h \\ \phi_s \end{pmatrix}.$$

♣ **Higgs wave-function renormalization**

$$\begin{pmatrix} h \\ H \end{pmatrix}^0 \to \begin{pmatrix} 1 + \frac{1}{2}\delta Z_h & \frac{1}{2}\delta Z_{hH} \\ \frac{1}{2}\delta Z_{Hh} & 1 + \frac{1}{2}\delta Z_H \end{pmatrix} \begin{pmatrix} h \\ H \end{pmatrix} + \mathcal{O}(\alpha_{ew}^2)$$

♠ Diagonal parts:

$$\text{Re}\hat{\Sigma}'_{\phi\phi}(m_\phi^2) = 0 \quad \Rightarrow \quad \delta Z_{\phi\phi} = -\text{Re}\Sigma'_\phi(m_{\phi\phi}^2) \qquad [\phi = h, H]$$

Higgs sector

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Summarizing . . .

- tadpoles: $\delta T_h, \delta T_H$
- Higgs masses: $\delta m_h^2, \delta m_H^2$
- vev: $\delta v, \delta v_s$
- fields: $\delta Z_h, \delta Z_H, \delta Z_{hH}, \delta Z_{Hh}$
- mixing: δm_{hH}^2

Higgs sector

Mixing

	$\delta Z_{hH,Hh}$	δm^2_{hH}
Minimal field	$\delta Z_{hH} = \frac{1}{2} s_{2\alpha}\,[\delta Z_h + \delta Z_H]$ $\delta Z_{Hh} = \delta Z_{hH}$	$\text{Re}\,\Sigma_{hH}(\mu^2_R) + \left[\mu^2_R - \frac{m^2_h + m^2_H}{2}\right]$
OS	$\delta Z_{hH} = \frac{\text{Re}\,\Sigma_{hH}(m^2_H) - \text{Re}\,\Sigma_{hH}(m^2_h)}{m^2_h - m^2_H}$ $\delta Z_{Hh} = \delta Z_{hH}$	$\frac{\text{Re}\,\Sigma_{hH}(m^2_h) + \text{Re}\,\Sigma_{hH}(m^2_H)}{2}$
Mixed $\overline{MS}$/OS	$\delta Z_{hH} = \frac{2}{m^2_h - m^2_H}\left[\text{Re}\,\Sigma_{hH}(m^2_H) - \delta m^2_{hH}\right]$ $\delta Z_{Hh} = \frac{2}{m^2_H - m^2_h}\left[\text{Re}\,\Sigma_{hH}(m^2_h) - \delta m^2_{hH}\right]$	through $\delta\lambda_2^{\overline{MS}} = \frac{-1}{16\pi^2}\left[\lambda_3^2 + 9\lambda_2^2\right]\Delta_\epsilon$
Improved OS	$\delta Z_{hH} = \frac{2}{m^2_h - m^2_H}\left[\text{Re}\,\Sigma_{hH}(m^2_H) - \delta m^2_{hH}\right]$ $\delta Z_{Hh} = \frac{2}{m^2_H - m^2_h}\left[\text{Re}\,\Sigma_{hH}(m^2_h) - \delta m^2_{hH}\right]$	$\text{Re}\,\Sigma_{hH}(p^2_*), \quad p^2_* = \frac{m^2_h + m^2_H}{2}$

Higgs sector

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A hidden threat

Gauge parameter independence

Outline

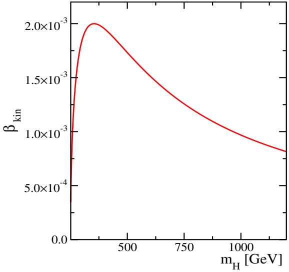
$H \to hh$: leading-order features

$$\Gamma^{\text{LO}}_{H\to hh} = \frac{\lambda^2_{Hhh}}{32\,\pi\,m_H}\sqrt{1-\frac{4m_h^2}{m_H^2}}$$

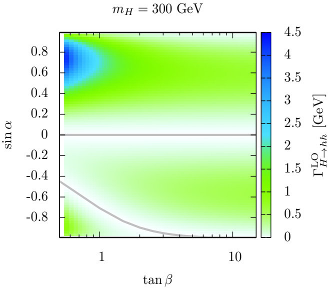
LO width

$$\lambda_{Hhh} = -\frac{is_{2\alpha}}{v}\left[m_h^2+\frac{m_H^2}{2}\right](c_\alpha + s_\alpha\, t_\beta^{-1})\;.$$

Heavy-light trilinear



Kinematics



Parameter space

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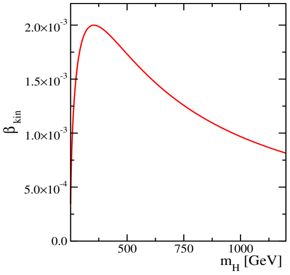
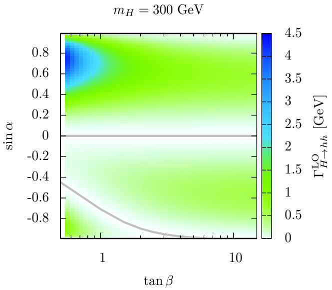


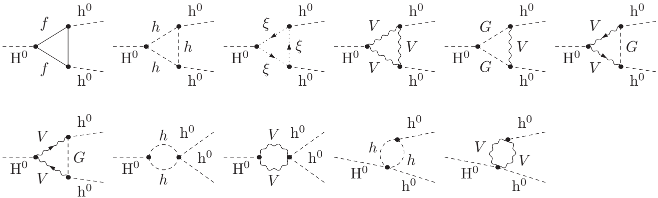


Kinematics

Parameter space

$$\text{BR}_{H\to\phi\phi}\,(m_H) = \frac{s_\alpha^2\,\Gamma^{\text{SM}}_{H\,\to\,\phi\phi}\,(m_H)}{s_\alpha^2\,\Gamma^{\text{SM}}_{H\text{tot}}\,(m_H)+\Gamma_{H\to hh}\,(m_H)}$$

$H \to hh$: Electroweak corrections



$$\Gamma^{\text{NLO}}_{H\to hh} = \frac{1}{32\pi\, m_H}\sqrt{1-\frac{4m_h^2}{m_H^2}}\left[\lambda^2_{Hhh} + 2\,\text{Re}\,\lambda_{Hhh}\,\left(\delta\Gamma^{\triangle}_{Hhh} + \delta\Gamma^{\text{WF}}_{Hhh} + \delta\lambda_{Hhh}\right)\right]$$

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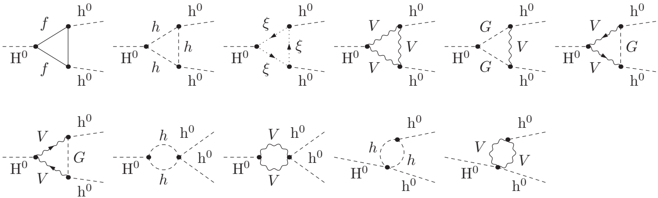

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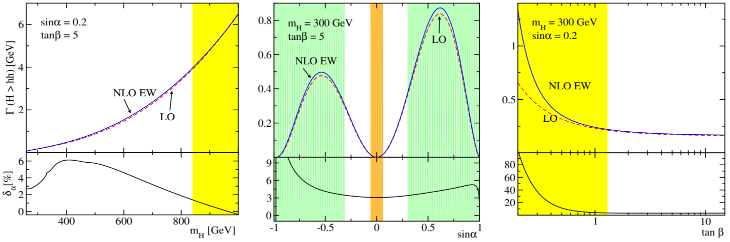
$$\delta_\alpha \equiv \frac{\Delta\Gamma^{\text{1-loop}}_\alpha}{\Gamma^{\text{LO}}_\alpha} = \frac{\Gamma^{\text{NLO}}_\alpha - \Gamma^{\text{LO}}_\alpha}{\Gamma^{\text{LO}}_\alpha}$$

$H \to hh$ @ NLO

♠ High mass region $m_H > m_h$ $\quad h(125)$



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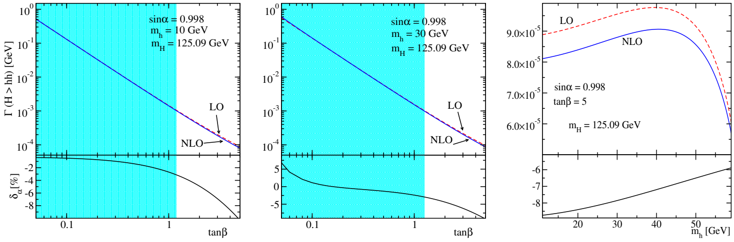

Outline

To take home

- Δr & m_W available to 1(resp. 2) loop accuracy in the BSM(SM).
- Shifts up to $\boxed{\Delta r \sim \mathcal{O}(10\%)}$ & $\boxed{m_W \sim \mathcal{O}(50)\ \text{MeV}}$ yield **leading constraints** in some regions
- Complete **Renormalization** of the singlet-extended Higgs sector, including scheme comparisons and gauge-parameter independence
- Applied to $H \to hh$ @ NLO EW
  - $\boxed{\delta_r \sim +\mathcal{O}(1)\% \text{ for } m_H > m_h \quad [h(125)]}$
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  - mild scheme & scale dependences $\Rightarrow$ small TH uncertainty
- EFT as a tool for BSM Higgs physics *including quantum effects and precision observables:*
  - **Robust** for **weakly-coupled** theories & **well-separated** scales
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Backup slides

BACKUP SLIDES

$H \to hh$: Maximal BR scenarios

♣ **Maximal BR benchmarks** Robens, Stefaniak ['16]

	high mass region				low mass region			
	m_H	$\lvert\sin\alpha\rvert_{\text{max}}$	BR_{max}	$\tan\beta$	m_h	$\lvert\sin\alpha\rvert_{\text{min}}$	BR_{max}	$\tan\beta$
BHM1	300	0.31	0.34	3.71	60	0.9997	0.26	0.29
BHM3	500	0.24	0.27	2.17	40	0.9998	0.26	0.32
BHM6	800	0.21	0.23	4.00	10	0.9998	0.26	0.30

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♣ High mass region

	$\Gamma^{\text{LO}}_{H\to hh}$	$\Gamma^{\text{NLO}}_{H\to hh}$	δ_α [%]	$b\bar{b}$	$t\bar{t}$	WW	ZZ	gg	hh
BM1	0.399	0.413	3.411	0.04	< 0.01	46.35	20.56	0.04	33.02
BM3	1.383	1.463	5.803	0.01	14.19	40.36	19.29	0.04	26.09
BM6	3.798	3.867	1.826	< 0.01	8.57	46.29	23.07	0.02	22.07

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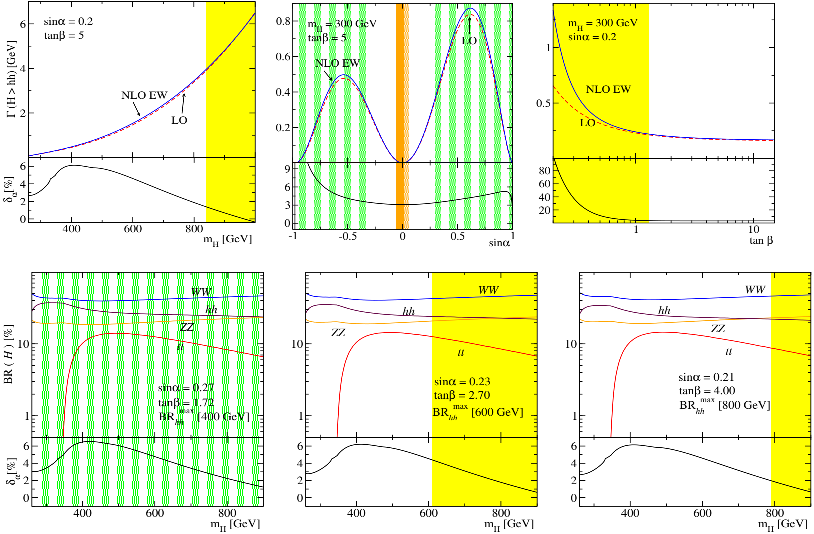
	$\Gamma^{\text{LO}}_{H\to hh}$	$\Gamma^{\text{NLO}}_{H\to hh}$	δ_α [%]	$b\bar{b}$	$\gamma\gamma$	WW	ZZ	gg	hh
BM1	1.426	1.536	7.765	42.65	0.17	16.04	1.97	6.34	25.90
BM3	1.423	1.432	0.586	42.67	0.17	16.05	1.97	6.35	25.86
BM6	1.427	1.421	-0.438	42.64	0.17	16.04	1.97	6.34	25.91

$H \to hh$ @ NLO - High mass region

♠ **High mass region** $m_H > m_h$ $h(125)$



$H \to hh$ @ NLO - Low mass region

♠ **Low mass region $m_h < m_H$ $H(125)$**