NLO corrections to $h \to WW/ZZ \to 4$ fermions in a Singlet Extension of the Standard Model

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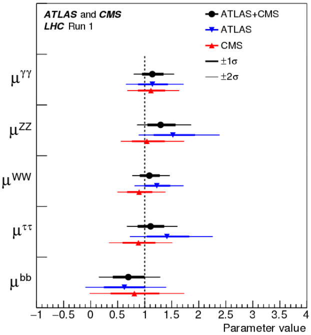
Overview

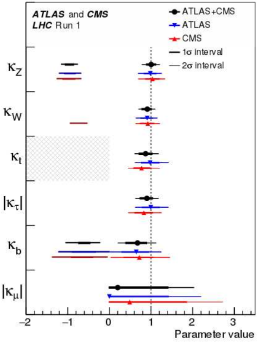
1. Introduction
2. SESM basics
3. Renormalization of SESM
4. The decay $h \to WW/ZZ \to 4$ fermions
5. Numerical analysis

Introduction

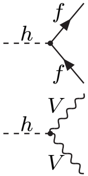
Intro

Higgs measurements are compatible with SM predictions





$$\mu = \frac{\Gamma_{\text{exp}}}{\Gamma_{\text{SM}}}$$



$\propto \kappa_f$

$\propto \kappa_V$

but

- baryon asymmetry
- dark matter
- neutrino masses
- ...

$\Rightarrow$ SM cannot be the ultimate theory
BSM precise predictions are required

Intro

the SM Higgs sector is working well, we consider

$$\mathcal{L}_{\text{Higgs}} = \mathcal{L}^{\text{SM}}_{\text{Higgs}} + \text{real singlet}$$

used in the literature for

- dark matter

  extra symmetry
  vanishing singlet VEV

  [Silveira, Zee, 1985] [McDonald, 1994]
  [Burgess et al., 2001] [Davoudiasl et al., 2005]
  [Barger et al., 2008] [Fischer, Van der Bij, 2014]

- hidden sector SB

  extra symmetry
  non-vanishing VEVs

  [Datta, Raychaudhuri, 1997] [Patt, Wilczek, 2008]
  [Pruna, Robens, 2013]

- baryon asymmetry

  [Profumo et al., 2007] [Barger et al., 2007]

SESM in a nutshell

recipe:

- most general $\mathbb{Z}_2$- and gauge-invariant scalar Lagrangian

$$\mathcal{L}_{\text{Higgs}} = (D_\mu \Phi)^\dagger (D^\mu \Phi) + \frac{1}{2}(\partial_\mu \sigma)(\partial^\mu \sigma) - V(\Phi, \sigma)$$

$$V(\Phi, \sigma) = -\mu_2^2 \Phi^\dagger \Phi + \frac{\lambda_2}{4}(\Phi^\dagger \Phi)^2 + \lambda_{12}\sigma^2 \Phi^\dagger \Phi - \mu_1^2 \sigma^2 + \lambda_1 \sigma^4$$

- EWSB on both scalar fields

$$\Phi = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}[v_2 + h_2 + \mathrm{i}\phi^0] \end{pmatrix}, \quad \sigma = v_1 + h_1$$

- covariant derivative

$$D_\mu = \partial_\mu - \mathrm{i} g_2 I_w^a W_\mu^a + \mathrm{i} g_1 \frac{Y_w}{2} B_\mu$$

SESM in a nutshell

after EWSB

$$V = -t_2 h_2 - t_1 h_1 + \frac{1}{2} \left(h_2, h_1\right) \mathcal{M}_{\text{Higgs}} \begin{pmatrix} h_2 \\ h_1 \end{pmatrix} + \ldots$$

with non-diagonal mass matrix $\mathcal{M}_{\text{Higgs}}$

$$\mathcal{M}_{\text{Higgs}} = \begin{pmatrix} v_1^2\lambda_{12} + \frac{3v_2^2\lambda_2}{4} - \mu_2^2 & 2v_1v_2\lambda_{12} \\ 2v_1v_2\lambda_{12} & v_2^2\lambda_{12} + 12v_1^2\lambda_1 - 2\mu_1^2 \end{pmatrix}$$

- rotation about an angle α to get "mass-basis" h, H

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h_2 \\ h_1 \end{pmatrix}$$

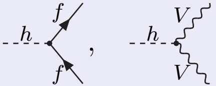
- diagonal Higgs propagators required

$$h \,\text{- - - - -}\, h = \frac{\mathrm{i}}{k^2 - M_h^2}, \qquad H \,\text{- - - - -}\, H = \frac{\mathrm{i}}{k^2 - M_H^2}, \qquad h \,\text{- - - - -}\, H = 0$$

SESM in a nutshell

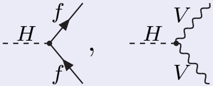
gauge- and fermion-scalar interactions

light Higgs



$\propto c_\alpha$

heavy Higgs



$\propto s_\alpha$

multi-scalar interactions

$$
\begin{aligned}
V \supset\; & c_{hhh}h^3 + c_{hhH}h^2H + c_{hHH}hH^2 + c_{HHH}H^3 + c_{\phi\phi\phi\phi}\left(2\phi^+\phi^- + \left(\phi^0\right)^2\right)^2 \\
& + c_{hhhh}h^4 + c_{hhhH}h^3H + c_{hhHH}h^2H^2 + c_{hHHH}hH^3 + c_{HHHH}H^4 \\
& + \left[c_{h\phi\phi}h + c_{H\phi\phi}H + c_{hh\phi\phi}h^2 + c_{hH\phi\phi}hH + c_{HH\phi\phi}H^2\right]\left(2\phi^+\phi^- + \left(\phi^0\right)^2\right)
\end{aligned}
$$

SESM parameters

$$\{M_h, M_H, M_W, M_Z, e, \lambda_{12}, \alpha, m_f, t_h, t_H\}$$

Renormalization of SESM

Renormalization

bare parameters do not have physical meaning

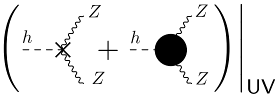
- as far as possible, make use of OS renormalization conditions

  M_h, M_H, M_W, M_Z, m_f
  are the physical (OS) masses

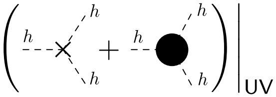
- OS renormalization not always possible!

  no natural choice for
  α, λ_{12}

our choice $\Rightarrow$ $\overline{\text{MS}}$ conditions for α and λ_{12}



$\stackrel{!}{=} 0$



$\stackrel{!}{=} 0$

Tadpole renormalization

two schemes considered

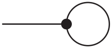
renorm. tadpoles $t_h = t_H = 0$

- ignore explicit tadpoles 
- gauge-dependent $\delta t_h, \delta t_H$ in counterterms
- bare parameters potentially gauge-dependent

gauge-dependent contributions cancel in OS scheme

bare tadpoles $t_{h,0} = t_{H,0} = 0$

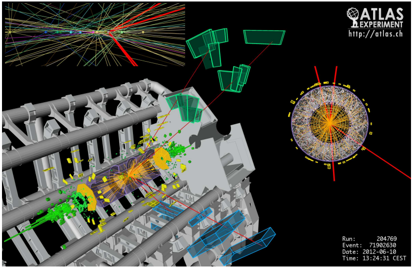
[Fleischer, Jegerlehner, 1980] [Actis et al., 2006]

- include everywhere 
- technical variants can be used (e.g. shift VEVs)

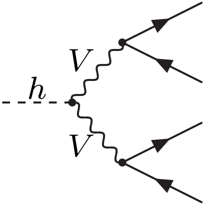
$\Rightarrow$ gauge-independent relations between ren. parameters and observables

$h \to WW/ZZ \to 4$ fermions

$h \to WW/ZZ \to 4$ fermions



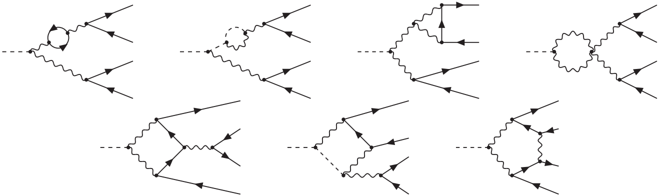
leading contribution



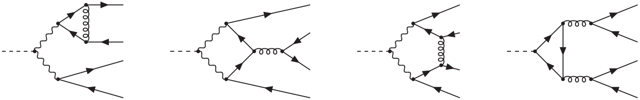
- most promising channel for precise Higgs measurements @LHC
- implemented in Prophecy4f — A Monte Carlo generator for a Proper description of the Higgs decay into 4 fermions
  - SM [Bredenstein et al., 2006]
  - THDM [Altenkamp et al., 2017] $\to$ see talk by S. Dittmaier
  - object of this talk $\to$ SESM

NLO corrections

EW



QCD

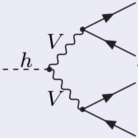


- $|\mathcal{M}_{\text{LO}}|^2$, QCD and real emission rescaled by c_α^2 wrt SM
- singlet changes EW loops
- CTs are consistently taken into account

Automation

- loop corrections

$\mathcal{L}^{\text{SESM}} \xrightarrow{\text{FeynRules}}$ `SESM.gen` `SESM.mod` $\xrightarrow{\text{FeynArts}}$



$\longrightarrow$ FormCalc

$+$ complex mass scheme for vector bosons [Denner et al., 2005]

- real corrections
  - dipole subtraction for IR singularities
    [Catani, Seymour, 1996] [Dittmaier, 1999] [Dittmaier et al., 2008]
- multi-channel MC integration within Prophecy4f

Numerical analysis

Input parameters

$$\{M_h, M_H, M_W, M_Z, e, \lambda_{12}, \alpha, m_i\}$$

SM parameters

- [ATLAS, CMS, 2015] $\rightarrow M_h$
- [HXSWG, 2016] $\rightarrow M_W^{\mathrm{OS}}, M_Z^{\mathrm{OS}}, \Gamma_W^{\mathrm{OS}}, \Gamma_Z^{\mathrm{OS}}, m_f, G_\mu, \alpha_{\mathrm{s}}$

BSM parameters restricted by

- perturbativity

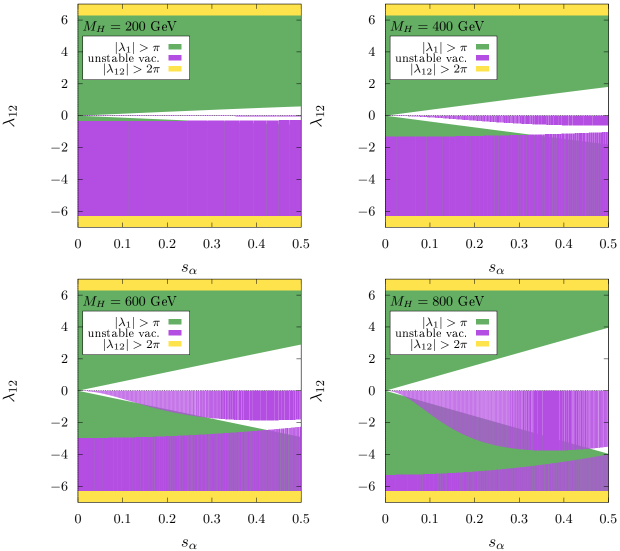
$$4\,|\lambda_1| \lesssim 4\pi, \qquad \frac{|\lambda_2|}{4} \lesssim 4\pi, \qquad 2\,|\lambda_{12}| \lesssim 4\pi$$

- vacuum stability $\mu_2^2, \mu_1^2 > 0$

$$-\frac{c_\alpha^2 M_H^2 + M_h^2 s_\alpha^2}{2v_2^2} < \lambda_{12} < -\frac{c_\alpha^2 s_\alpha^2 (M_H^2 - M_h^2)^2}{2v_2^2 (c_\alpha^2 M_h^2 + M_H^2 s_\alpha^2)} \quad \text{or} \quad \lambda_{12} > 0$$

Input parameters

Perturbativity and vacuum stability constraints



perturbativity matters for small M_H

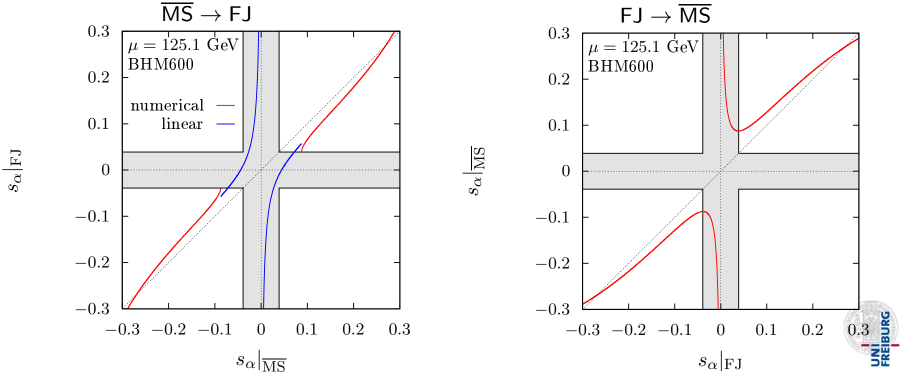
vacuum stab. important for higher M_H

$\lambda_{12} < 0$ mostly excluded

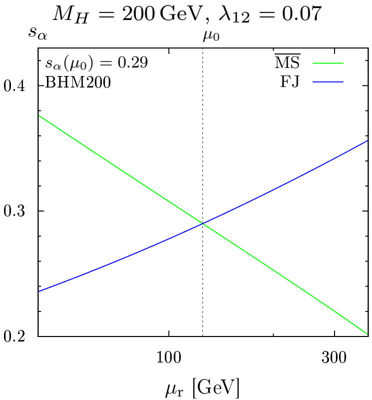
considered 4 scenarios from [HXSWG, 2016] [Robens, Stefaniak 2016] in order to compare results in different renormalization schemes

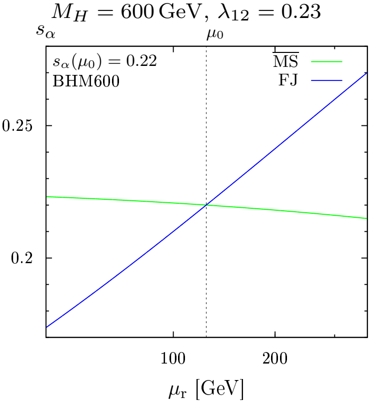
$$p_0 = p^{\overline{\mathsf{MS}}} + \delta p^{\overline{\mathsf{MS}}}(p^{\overline{\mathsf{MS}}}) = p^{\mathsf{FJ}} + \delta p^{\mathsf{FJ}}(p^{\mathsf{FJ}})$$

example for $M_H = 600\,\mathrm{GeV}$, $\lambda_{12} = 0.23$



Running of s_α

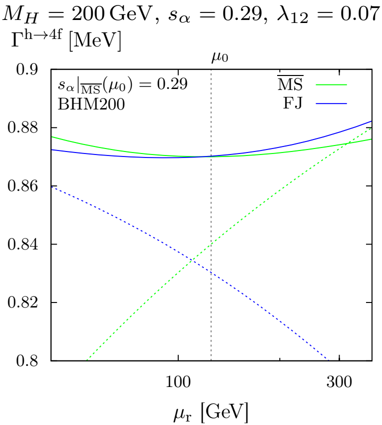


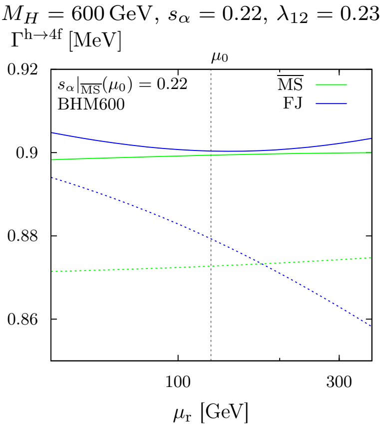


- explains LO behavior of $\Gamma^{h\to 4f}$ scale dependence
- for consistency, running of λ_{12} taken into account

Scale dependence of $\Gamma^{h\to 4f}$

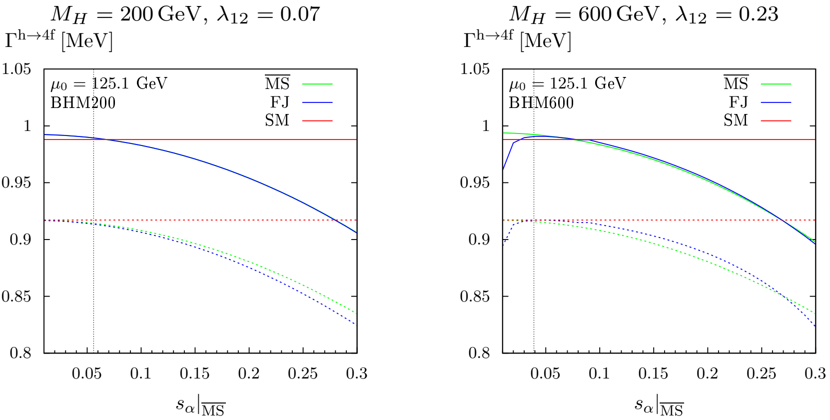
LO (dashed) vs. NLO (solid)





- more pronounced scale and scheme dependence at LO
- $\mu_r = M_h$ appropriate renormalization scale

Mixing angle dependence of $\Gamma^{h\to 4f}$
LO (dashed) vs. NLO (solid)



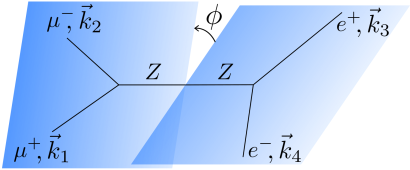
- behavior mostly driven by c_α^2 factor
- Δ_{SM} typically reduced by NLO contributions
- $\Delta_{\mathsf{SM}} \lesssim 5\%(10\%)$ for $s_\alpha < 0.2(0.3)$

* spurious effects in LO driven by NLO parameter conversion

Differential distributions

possible generation of distributions for

- invariant masses
- angles

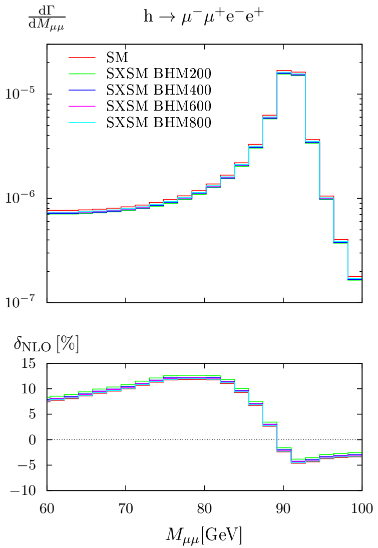


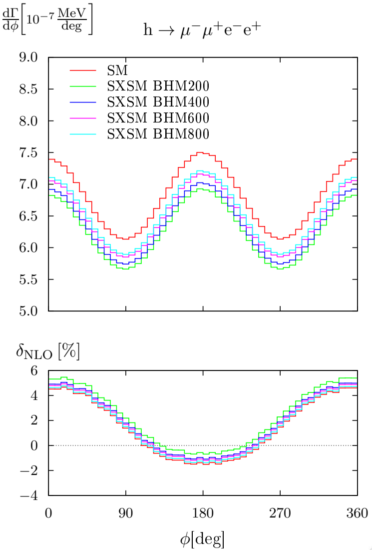
$$\cos\theta_{Z\mu} = \frac{\vec{k}_{2,Z} \cdot \left(\vec{k}_{3,Z} + \vec{k}_{4,Z}\right)}{\left|\vec{k}_{2,Z}\right| \left|\vec{k}_{3,Z} + \vec{k}_{4,Z}\right|}$$

$$\cos\phi_{\mu e,T} = \frac{\vec{k}_{2,T} \cdot \vec{k}_{3,T}}{\left|\vec{k}_{2,T}\right| \left|\vec{k}_{3,T}\right|}$$

for all four-light-fermion final states

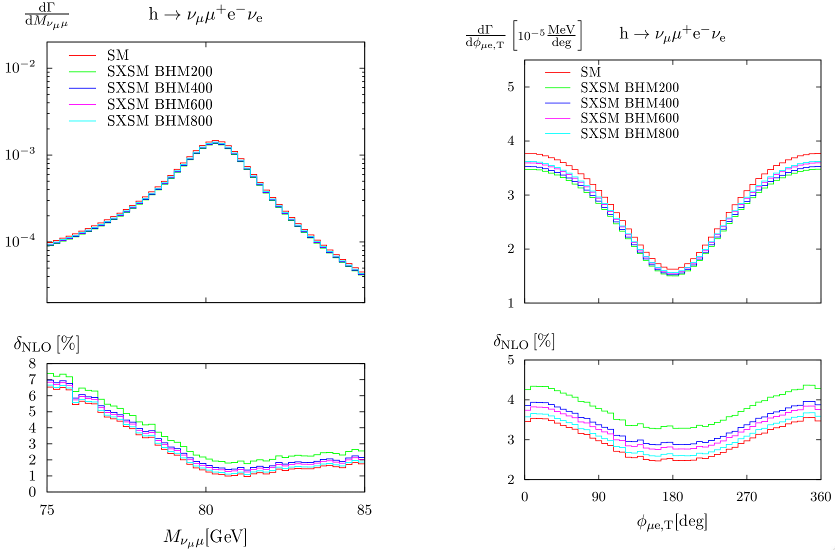
NLO leptonic distributions





- constant offset in δ_{NLO} wrt SM distributions
- similar behavior and magnitude in the FJ scheme

NLO leptonic distributions



- constant offset in δ_{NLO} wrt SM distributions
- similar behavior and magnitude in the FJ scheme

Conclusions

SESM

- renormalization performed treating tadpoles within two schemes
- FeynArts model file for one-loop calculations produced
- computed matrix elements for the decay $h \to WW/ZZ \to 4f$

$h \to WW/ZZ \to 4f$ results

- scheme conversion: sizable effects, become larger approaching non-perturbative regions
- renormalization group equations solved for $\overline{\text{MS}}$ parameters
- scale and scheme dependence reduced in NLO results
- $\Delta_{\text{SM}} \lesssim 10\%$ for the decay width in the proposed scenarios
- no further distortion wrt SM in differential distributions

coming soon

- Prophecy4f version including SESM implementation
- paper in preparation

Backup

SESM in a nutshell

after EWSB

$$V = -t_2 h_2 - t_1 h_1 + \frac{1}{2}\left(h_2, h_1\right)\mathcal{M}_{\text{Higgs}}\begin{pmatrix} h_2 \\ h_1 \end{pmatrix} + \dots$$

with non-diagonal mass matrix $\mathcal{M}_{\text{Higgs}}$

$$\mathcal{M}_{\text{Higgs}} = \begin{pmatrix} v_1^2\lambda_{12} + \frac{3v_2^2\lambda_2}{4} - \mu_2^2 & 2v_1v_2\lambda_{12} \\ 2v_1v_2\lambda_{12} & v_2^2\lambda_{12} + 12v_1^2\lambda_1 - 2\mu_1^2 \end{pmatrix}$$

$\Rightarrow h_2, h_1$ have non-diagonal propagators!

$$h_2 \text{-------} h_2 = \frac{\mathrm{i}}{k^2 - M_{22}^2}, \qquad h_1 \text{-------} h_1 = \frac{\mathrm{i}}{k^2 - M_{11}^2}, \qquad h_2 \text{-------} h_1 \neq 0$$

rotate about an angle α to get "mass-basis" h, H

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix}\begin{pmatrix} h_2 \\ h_1 \end{pmatrix}$$

SESM in a nutshell

requiring diagonal Higgs propagators

$$\overset{h}{\bullet}\text{-------}\overset{h}{\bullet} = \frac{\mathrm{i}}{k^2 - M_h^2}, \qquad \overset{H}{\bullet}\text{-------}\overset{H}{\bullet} = \frac{\mathrm{i}}{k^2 - M_H^2}, \qquad \overset{h}{\bullet}\text{-------}\overset{H}{\bullet} = 0$$

$\Rightarrow$ inversion relations

$$\mu_2^2 = \frac{1}{2v_2}\left[3c_\alpha t_h + 3t_H s_\alpha + c_\alpha M_h^2 \left(v_2 c_\alpha - v_1 s_\alpha\right) + M_H^2 s_\alpha \left(v_1 c_\alpha + v_2 s_\alpha\right)\right]$$

$$\mu_1^2 = \frac{1}{4v_1}\left[M_h^2 s_\alpha \left(v_1 s_\alpha - v_2 c_\alpha\right) + c_\alpha M_H^2 \left(v_1 c_\alpha + v_2 s_\alpha\right) + 3c_\alpha t_H - 3t_h s_\alpha\right]$$

$$\lambda_2 = \frac{2}{v_2^3}\left[v_2 \left(c_\alpha^2 M_h^2 + M_H^2 s_\alpha^2\right) + c_\alpha t_h + t_H s_\alpha\right]$$

$$\lambda_1 = \frac{1}{8v_1^3}\left[v_1 \left(c_\alpha^2 M_H^2 + M_h^2 s_\alpha^2\right) + c_\alpha t_H - t_h s_\alpha\right]$$

$$v_1 = \frac{c_\alpha s_\alpha}{2\lambda_{12} v_2}\left(M_H^2 - M_h^2\right)$$

SESM in a nutshell

requiring diagonal Higgs propagators

$$h\text{ - - - - - - }h = \frac{\mathrm{i}}{k^2 - M_h^2}, \qquad H\text{ - - - - - - }H = \frac{\mathrm{i}}{k^2 - M_H^2}, \qquad h\text{ - - - - - - }H = 0$$

$\Rightarrow$ mass terms

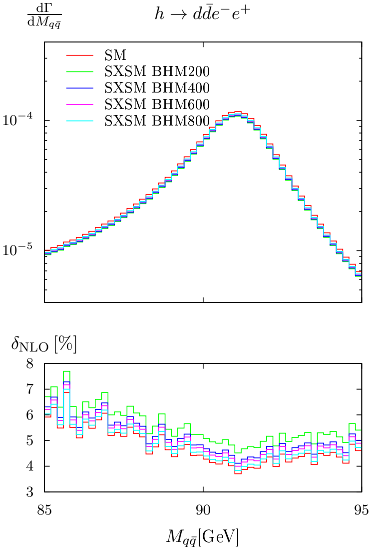
$$M_h^2 = \frac{1}{4}v_2^2\lambda_2 + 4v_1^2\lambda_1 \pm \sqrt{\left(2v_1v_2\lambda_{12}\right)^2 + \frac{1}{16}\left(16v_1^2\lambda_1 - v_2^2\lambda_2\right)^2}$$

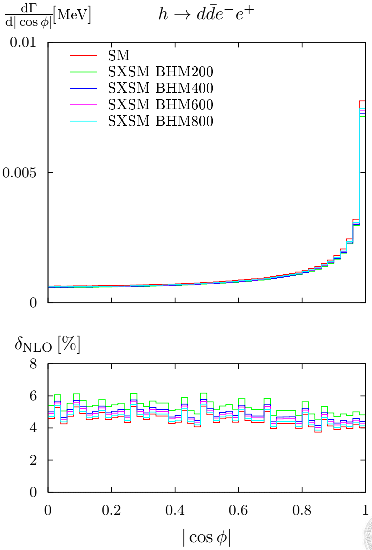
$$M_H^2 = \frac{1}{4}v_2^2\lambda_2 + 4v_1^2\lambda_1 \mp \sqrt{\left(2v_1v_2\lambda_{12}\right)^2 + \frac{1}{16}\left(16v_1^2\lambda_1 - v_2^2\lambda_2\right)^2}$$

sign choice such that

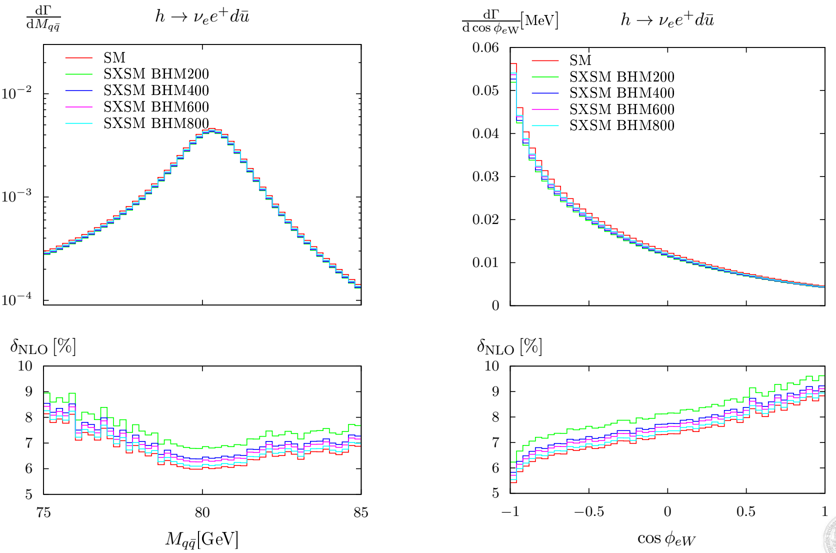
$$M_H^2 > M_h^2$$

NLO semileptonic distributions





NLO semileptonic distributions



Input parameters

SM parameters

- [ATLAS, CMS, 2015]

$$M_h = 125.09 \pm 0.21\,(\text{stat.}) \pm 0.11\,(\text{syst.})\,\text{GeV} \approx 125.1\,\text{GeV}$$

- [HXSWG, 2016]

$$M_W^{\text{OS}} = 80.385\,\text{GeV} \qquad \Gamma_W^{\text{OS}} = 2.085\,\text{GeV}$$

$$M_Z^{\text{OS}} = 91.1876\,\text{GeV} \qquad \Gamma_Z^{\text{OS}} = 2.4952\,\text{GeV}$$

$$m_e = 0.510998928\,\text{MeV} \qquad m_\mu = 105.6583715\,\text{MeV} \qquad m_\tau = 1776.82\,\text{MeV}$$

$$m_u = 0.1\,\text{GeV} \qquad m_c = 1.51\,\text{GeV} \qquad m_t = 172.5\,\text{GeV}$$

$$m_d = 0.1\,\text{GeV} \qquad m_s = 0.1\,\text{GeV} \qquad m_b = 4.92\,\text{GeV}$$

$$G_\mu = 1.1663787 \cdot 10^{-5}\,\text{GeV}^{-2} \qquad \alpha_s = 0.118$$

Input parameters

internally

- pole masses from

$$M_V = \frac{M_V^{\mathsf{OS}}}{\sqrt{1 + \left(\Gamma_V^{\mathsf{OS}} / M_V^{\mathsf{OS}}\right)^2}}$$

- pole decay widths Γ_W and Γ_Z calculated from the experimental input, taking into account $\mathcal{O}(\alpha_{\mathsf{em}})$ corrections and using real masses
- G_μ-scheme (large corrections shifted to lowest order)

$$\alpha_{\mathsf{em}} = \frac{\sqrt{2} G_\mu M_W^2}{\pi} \left(1 - \frac{M_W^2}{M_Z^2}\right)$$

scenarios taken from [HXSWG, 2016] [Robens, Stefaniak 2016]

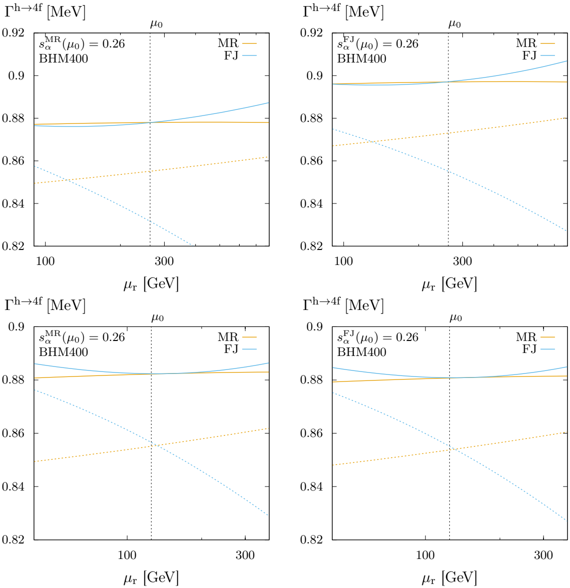
Scenario	$M_H\,[\mathrm{GeV}]$	$\sin\alpha$	λ_{12}
BHM200	200	0.29	0.07
BHM400	400	0.26	0.17
BHM600	600	0.22	0.23
BHM800	800	0.2	0.26

three basic ingredients

- CP violation
- baryon number violation
- departure from thermal equilibrium (otherwise CPT would assure compensation between processes increasing and decreasing baryon number)

	SM	SESM
CP violation	✓	✓
B violation[1]	✓	✓
first order EWPT		✓

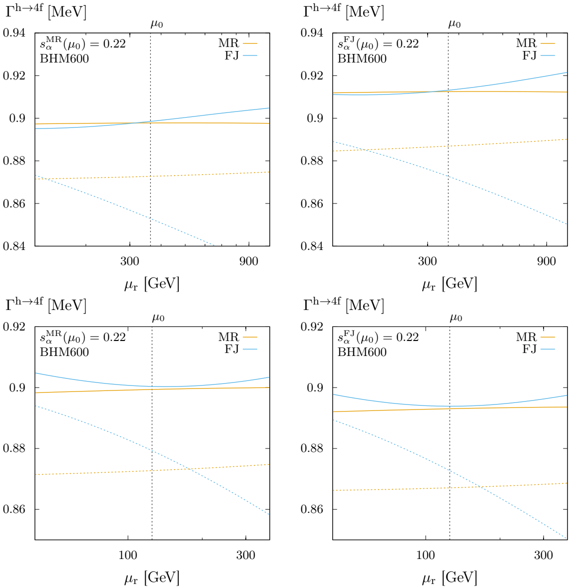
[1] non-perturbative effect



$$\mu_0 = \frac{M_h + M_H}{2}$$

$$\mu_0 = M_h$$

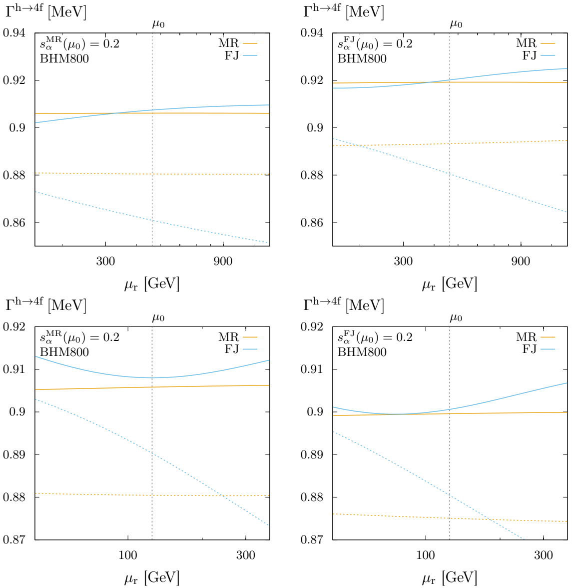
Scale choice
BHM600



$$\mu_0 = \frac{M_h + M_H}{2}$$

$$\mu_0 = M_h$$

Scale choice
BHM800



$$\mu_0 = \frac{M_h + M_H}{2}$$

$$\mu_0 = M_h$$