Electroweak corrections in the Two-Higgs-Doublet Model and Singlet Extensions of the Standard Model

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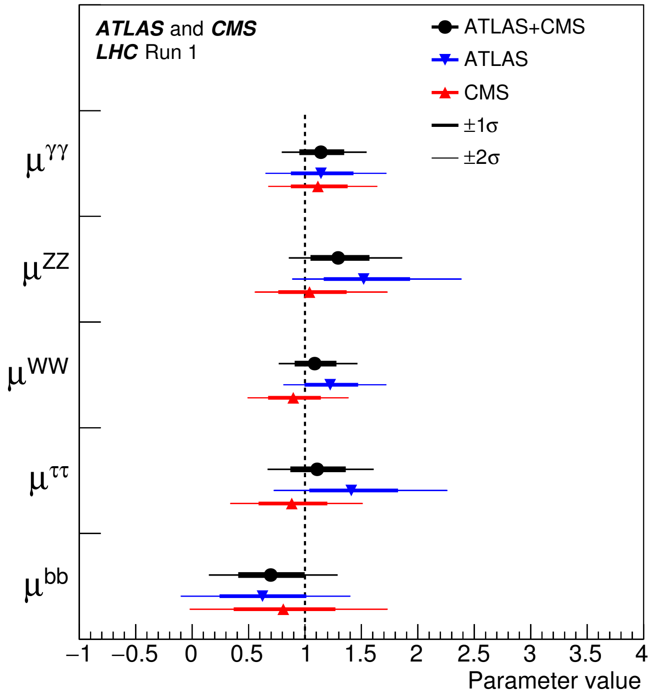
(in collaboration with L.Altenkamp, M.Boggia and H.Rzehak;
see arXiv:1704.02645, arXiv:1710.07598 and arXiv:1801.07291)

Contents

Introduction

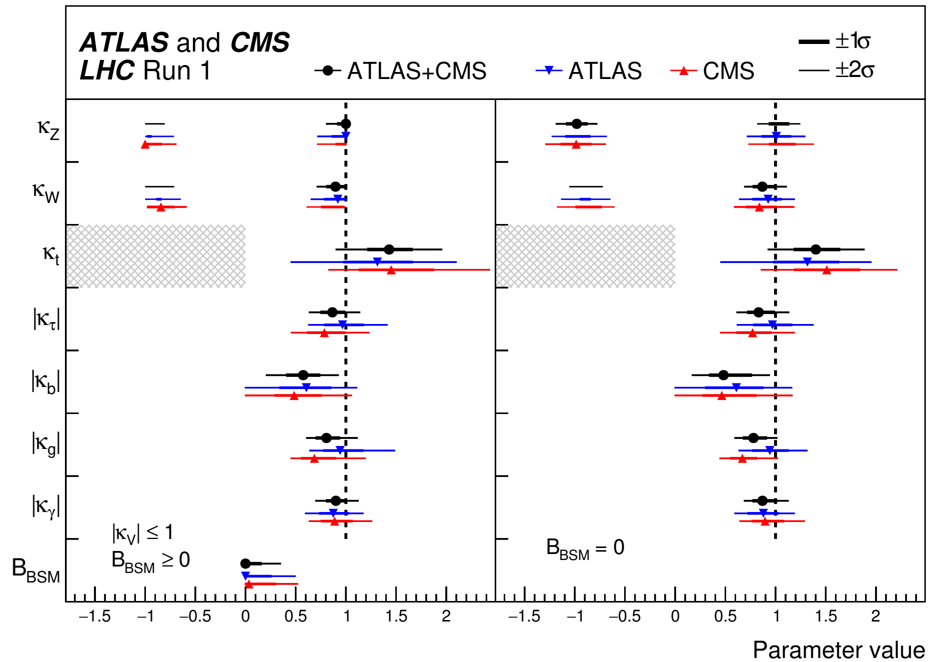
Some central LHC results from profiling the Higgs boson

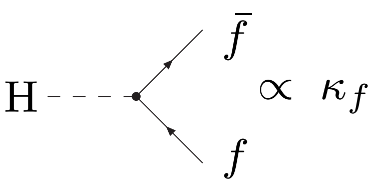
Decay signal strength:

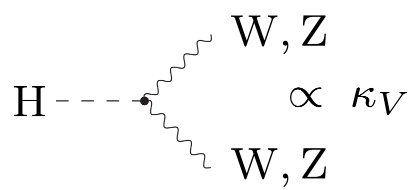


$$\mu = \frac{\Gamma_{\mathrm{exp}}}{\Gamma_{\mathrm{SM}}}$$

Fit of coupling modifiers:







Compatibility with Standard Model

Reveal BSM effects with higher precision ?

$\Rightarrow$ Precision calculations in BSM models necessary

$\rightarrow$ THDM considered in this talk

Renormalization of the THDM

THDM Lagrangian and Higgs fields

Lagrangian: restriction to CP-conserving case!

$$\mathcal{L}_{\mathrm{Higgs}} = (D_\mu \Phi_1)^\dagger (D^\mu \Phi_1) + (D_\mu \Phi_2)^\dagger (D^\mu \Phi_2) - V(\Phi_1, \Phi_2),$$

$$D_\mu = \partial_\mu - \mathrm{i} g_2 I^a_{\mathrm{W}} W^a_\mu + \mathrm{i} g_1 \frac{Y_{\mathrm{W}}}{2} B_\mu$$

Higgs potential:

$$\begin{aligned} V = {} & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1) \\ & + \tfrac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \tfrac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) \\ & + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \tfrac{1}{2}\lambda_5 \left[(\Phi_1^\dagger \Phi_2)^2 + (\Phi_2^\dagger \Phi_1)^2 \right] \end{aligned}$$

Two complex scalar SU(2) doublets: $v_{1,2} =$ vevs

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(\eta_1 + i\chi_1 + v_1) \end{pmatrix}, \qquad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(\eta_2 + i\chi_2 + v_2) \end{pmatrix}, \qquad Y_{\mathrm{W}}(\Phi_{1,2}) = 1$$

Transition to the "mass basis":

CP-even neutral fields: $\begin{pmatrix} \eta_1 \\ \eta_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}$

CP-odd neutral fields: $\begin{pmatrix} \chi_1 \\ \chi_2 \end{pmatrix} = \begin{pmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} G_0 \\ A_0 \end{pmatrix}, \qquad \tan\beta = \frac{v_2}{v_1}$

charged fields: $\begin{pmatrix} \phi_1^\pm \\ \phi_2^\pm \end{pmatrix} = \begin{pmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix}$

Higgs potential after diagonalization:

$$V = \underbrace{-t_\mathrm{h} h - t_\mathrm{H} H}_{\text{tadpoles} \to 0} + \frac{1}{2} M_\mathrm{h}^2 h^2 + \frac{1}{2} M_\mathrm{H}^2 H^2 + \frac{1}{2} M_{\mathrm{A}_0}^2 A_0^2 + M_{\mathrm{H}^+}^2 H^+ H^- + \dots$$

Transformation of input parameters:

original set: $\{\lambda_1, \dots, \lambda_5, m_{11}^2, m_{22}^2, m_{12}^2, v_1, v_2, g_1, g_2\}$

$\downarrow$

mass basis: $\{\underbrace{M_\mathrm{H}, M_\mathrm{h}, M_{\mathrm{A}_0}, M_{\mathrm{H}^+}, M_\mathrm{W}, M_\mathrm{Z}, e}_{\text{renormalized on-shell}}, \underbrace{\lambda_5, \alpha, \beta}_{\overline{\mathrm{MS}}}, \underbrace{t_\mathrm{H}, t_\mathrm{h}}_{\text{2 ren. variants}}\}$

Renormalization (see also Santos/Barroso '97; Kanemura et al. '04; Lopez-Val/Sola '09; Degrande '14)

$\hookrightarrow$ follow on-shell renormalization as far as possible/reasonable

related work by Krause et al. '16; Denner et al. '16

On-shell renormalization:

- all particle masses: $M_{\mathrm{W}}, M_{\mathrm{Z}}, M_{\mathrm{h}}, M_{\mathrm{H}}, \dots$
- matrix-valued renormalization for all fields:

$$\begin{pmatrix} H_0 \\ h_0 \end{pmatrix} = \begin{pmatrix} 1+\frac{1}{2}\delta Z_{\mathrm{H}} & \frac{1}{2}\delta Z_{\mathrm{Hh}} \\ \frac{1}{2}\delta Z_{\mathrm{hH}} & 1+\frac{1}{2}\delta Z_{\mathrm{h}} \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}, \qquad \text{etc.}$$

  $\hookrightarrow$ no mixing of external (on-shell) states
- elmg. coupling α_{em} in the Thomson limit

$\overline{\mathrm{MS}}$ renormalization:

- mixing angles α, β

  $\hookrightarrow$ e.g. determined by Higgs mixing self-energies
- Higgs self-coupling λ_5

  $\hookrightarrow$ e.g. determined by $\mathrm{HA_0A_0}$ vertex correction

$\Rightarrow$ Renormalization-scale-dependent parameters $\alpha(\mu_{\mathrm{r}}), \beta(\mu_{\mathrm{r}}), \lambda_5(\mu_{\mathrm{r}})$

Tadpole renormalization:

Note: No physical effect (just bookkeeping)
if all parameters are fixed by "physical renormalization conditions"!

But: $\overline{\mathrm{MS}}$ parameters in general depend on tadpole renormalization!

Two commonly used variants:

a) Vanishing renormalized tadpoles t_S: $t_{S,0} = t_S + \delta t_S = 0 + \delta t_S$

- (explicit tadpole loops Γ^S) $+ \delta t_S = 0 \quad \Rightarrow$ explicit tadpoles can be ignored
- (implicit) tadpole contributions δt_S in counterterms
- drawback: $t_{S,0} = \delta t_S$ enters relation between bare basic input parameters
  $\hookrightarrow$ potentially gauge-dependent terms $\propto \delta t_S$ enter relations
  between renormalized parameters and predicted observables

b) Vanishing bare tadpoles $t_{S,0}$: $t_{S,0} = 0$ Fleischer/Jegerlehner '80; Actis et al. '06

- explicit tadpole loops Γ^S have to included everywhere,
  technical variant: remove Γ^S from 2-point functions by shift $v_S \to v_S + \Delta v_s$
- advantage: no gauge-dep. δt_S terms in relations between bare parameters
  $\hookrightarrow$ relation between ren. parameters and observables gauge independent

Different schemes employed in NLO calculation for $\mathrm{h} \to 4f$:

- $\overline{\mathrm{MS}}(\alpha)$: see also by Krause et al. '16; Denner et al. '16
  - input: β, λ_5, α
  - tadpole treatment a): $t_S = 0$
  - gauge dependent: results tied to 't Hooft–Feynman gauge
- $\mathrm{FJ}(\alpha)$: see also by Krause et al. '16; Denner et al. '16
  - input: β, λ_5, α
  - FJ tadpole treatment b): $t_{S,0} = 0$
  - gauge independent
- $\overline{\mathrm{MS}}(\lambda_3)$:
  - as $\overline{\mathrm{MS}}(\alpha)$, but α replaced by coupling λ_3 as input
  - gauge independent only in R_ξ gauges at NLO
- $\mathrm{FJ}(\lambda_3)$:
  - as FJ(α), but α replaced by coupling λ_3 as input
  - gauge independent

$\hookrightarrow$ Study renormalization scheme and renormalization scale dependence of results

Running of $\overline{\text{MS}}$ parameters: (numerical solution of ren. group eqs.)

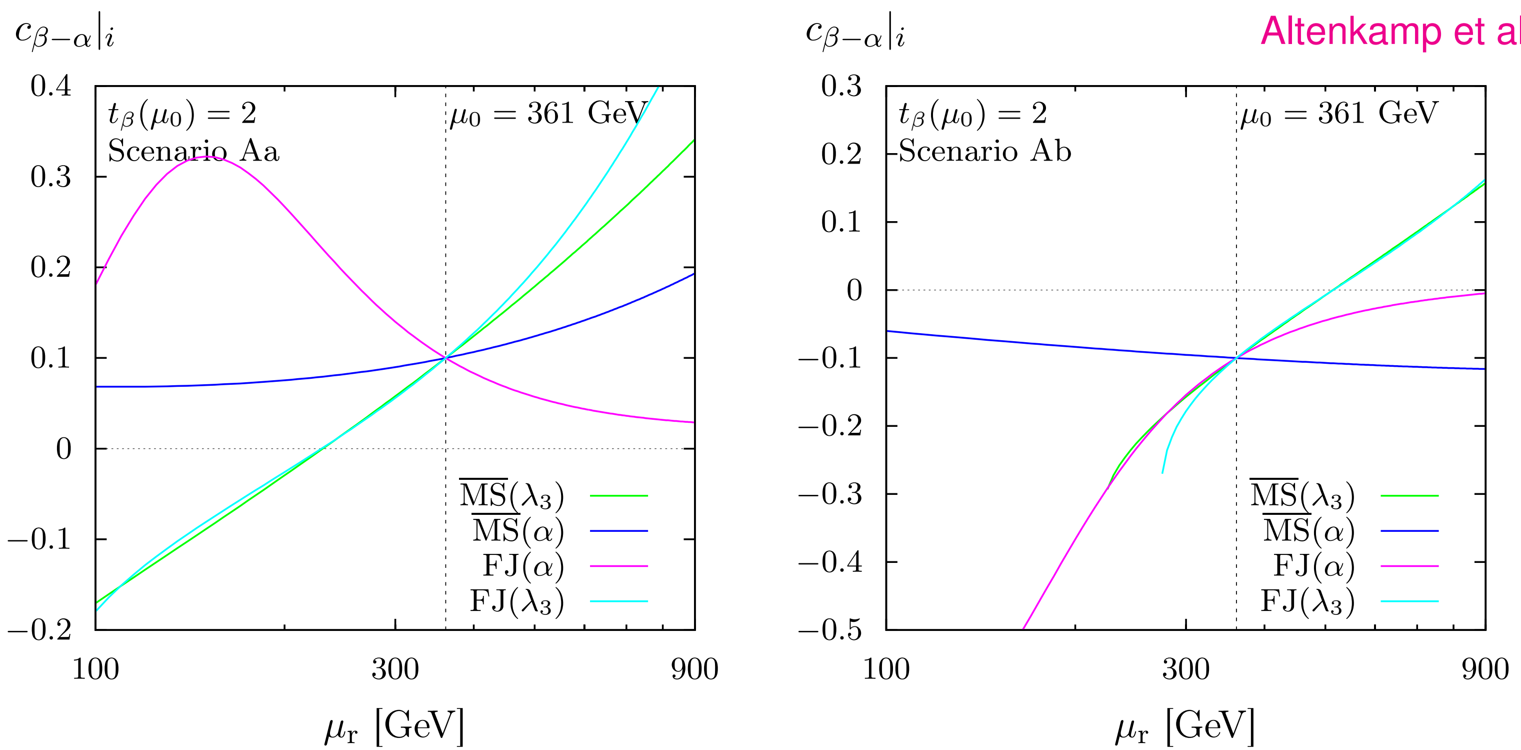
Example: $c_{\beta-\alpha}$ in a THDM low-mass scenario of Type I

Scenario A: $M_\mathrm{h} = 125\,\mathrm{GeV}, \quad c_{\beta-\alpha} = +0.1$ (Aa) or $c_{\beta-\alpha} = -0.1$ (Ab)

$$M_\mathrm{H} = 300\,\mathrm{GeV}, \quad M_{\mathrm{A}_0} = M_{\mathrm{H}+} = 460\,\mathrm{GeV}, \quad \lambda_5 = -1.9, \quad \tan\beta = 2$$

default scale: $\mu_0 = \frac{1}{5}(M_\mathrm{h} + M_\mathrm{H} + M_{\mathrm{A}_0} + 2M_{\mathrm{H}+}) = 361\,\mathrm{GeV}$

Altenkamp et al. '17



Strong dependence of running on renormalization scheme

Conversion between renormalization schemes:

Note: Values of ren. parameters of a model scenario depend on the ren. scheme!

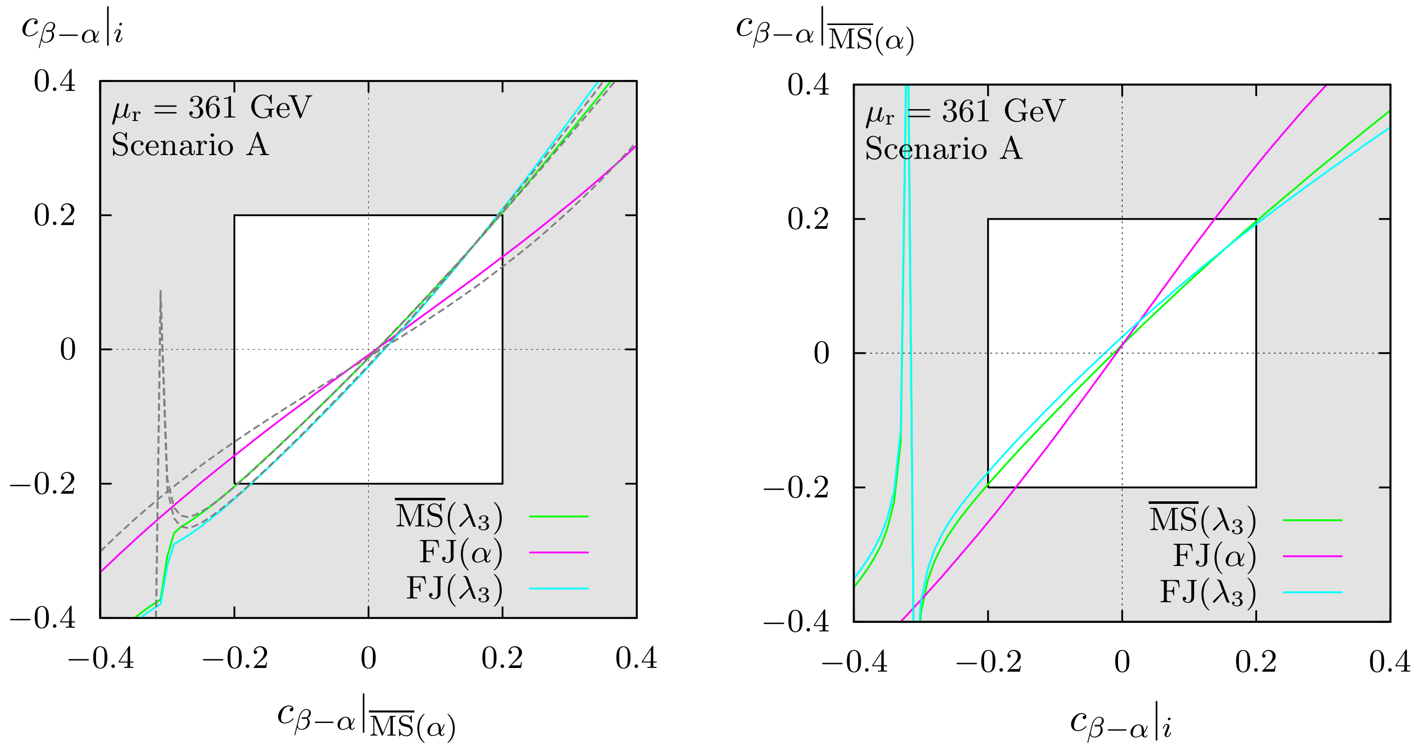
Conversion between schemes (1) and (2) via equality of bare parameters:

$$p_0 = p^{(1)} + \delta p^{(1)}(p^{(1)}) \;=\; p^{(2)} + \delta p^{(2)}(p^{(2)})$$

$$\Rightarrow\; p^{(2)} = p^{(1)} + \delta p^{(1)}(p^{(1)}) - \delta p^{(2)}(p^{(2)}) \overset{\text{NLO}}{=} p^{(1)} + \delta p^{(1)}(p^{(1)}) - \delta p^{(2)}(p^{(1)}) + \dots$$

Example: $c_{\beta-\alpha}$ in low-mass scenario A

Altenkamp et al. '17



Sizeable conversion effects!

Renormalization of the SESM

SESM Lagrangian and Higgs fields

Lagrangian: restriction to real, $\mathbb{Z}_2$-symmetric case!

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

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

Complex scalar SU(2) doublet & real scalar singlet: $v_{1,2} =$ vevs

$$\Phi = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}(\eta_2 + i\chi + v_2) \end{pmatrix}, \qquad \sigma = v_1 + \eta_1, \qquad Y_{\text{W}}(\Phi) = 1$$

$\hookrightarrow$ "mass basis" h, H of Higgs fields: $\begin{pmatrix} \eta_1 \\ \eta_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}$

Transformation and renormalization of input parameters:

original set: $\{\lambda_1, \lambda_2, \lambda_{12}, m_1^2, m_2^2, v_1, v_2, g_1, g_2\}$

$\downarrow$

mass basis: $\{\underbrace{M_{\text{H}}, M_{\text{h}}, M_{\text{W}}, M_{\text{Z}}, e}_{\text{renormalized on-shell}}, \underbrace{\lambda_{12}, \alpha}_{\overline{\text{MS}}}, \underbrace{t_{\text{H}}, t_{\text{h}}}_{\overline{\text{MS}}/\text{FJ variants}}\}$

$\Rightarrow$ running parameters $\alpha(\mu_{\text{r}}), \lambda_{12}(\mu_{\text{r}})$

related work:
Bojarski et al. ,15;
Kanemura et al. '15,'17;
Denner et al. '17

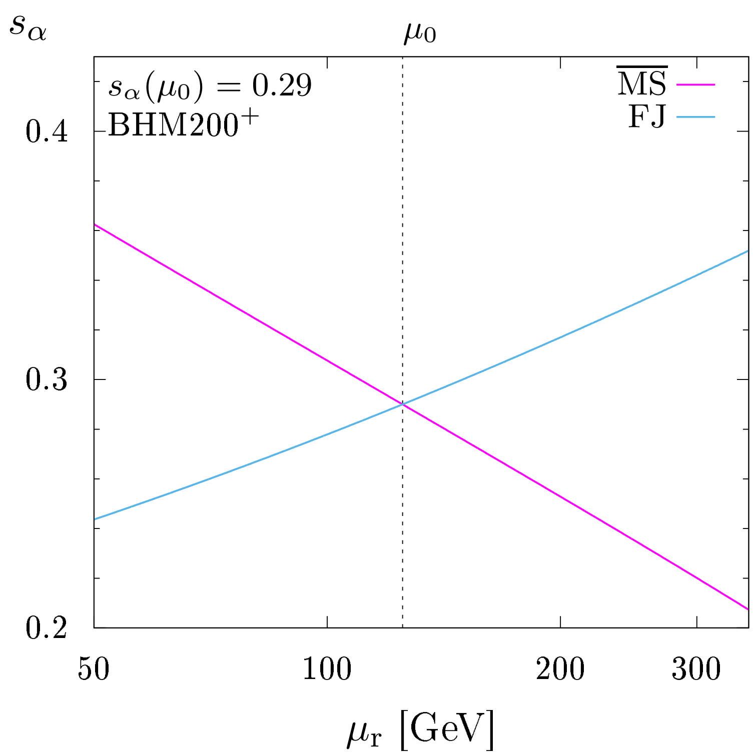
Running of $\overline{\text{MS}}$ parameters and scheme conversion:

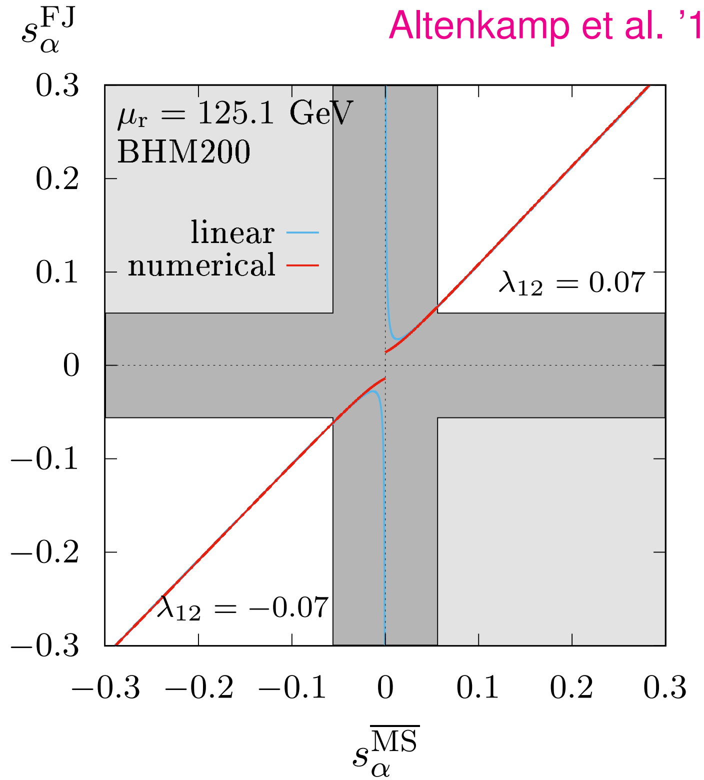
Example: s_α in a SESM low-mass scenario

Scenario BHM200$^\pm$: $M_\text{h} = 125.1\,\text{GeV}, \quad M_\text{H} = 200\,\text{GeV},$

$s_\alpha = \pm 0.29 \quad \lambda_{12} = \pm 0.07,$ default scale: $\mu_0 = M_\text{h}$

Altenkamp et al. ’18





strong dependence of running on ren. scheme

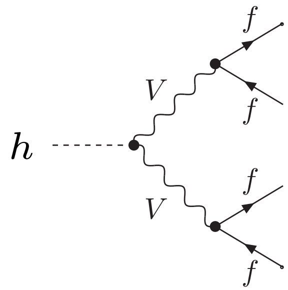
moderate conversion effects

(shaded areas non-perturbative or theoretically impossible)

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

Survey of Feynman diagrams for NLO corrections to $\mathrm{h} \to \mathrm{WW/ZZ} \to 4f$

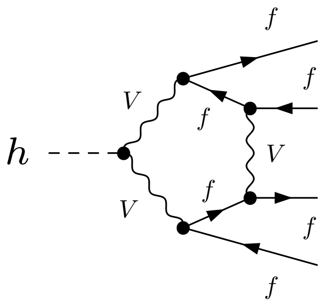
Lowest order:



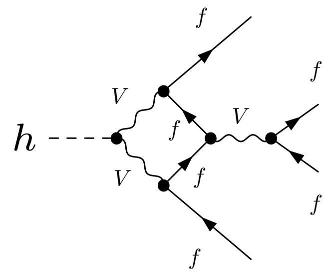
$$= \sin(\beta - \alpha)\, \mathcal{M}_{\mathrm{SM,LO}}$$

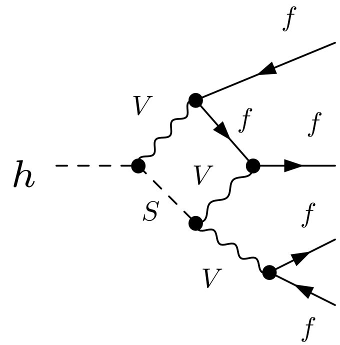
Typical one-loop diagrams: # diagrams = $\mathcal{O}(200\text{–}400)$

pentagons

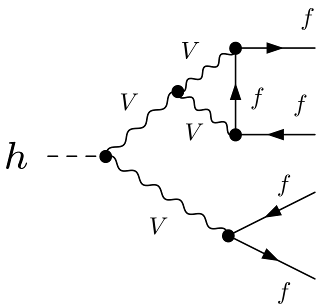


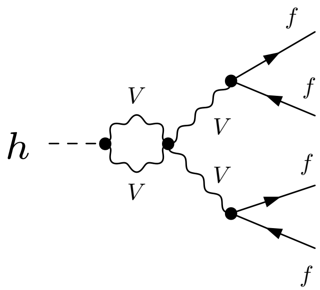
boxes



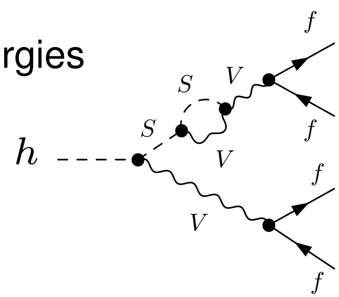


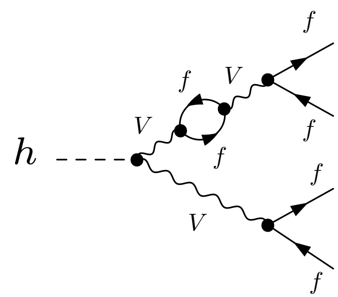
vertices





self-energies





$+$ counterterms

$+$ tree graphs with real gluon or photons

Details of the NLO calculation

Virtual corrections

- model file generation with FeynRules
- diagram generation with FeynArts
- amplitude reduction with inhouse Mathematica routines or FormCalc
- W/Z resonances treated in the *complex-mass scheme* Denner, S.D., Roth, Wieders '05
- loop integrals evaluated with Collier

Real corrections and Monte Carlo integration

- all amplitudes from SM calculation via rescaling with factor $s_{\beta-\alpha}$
- IR singularities treated with dipole subtraction Catani, Seymour '96; S.D. '99; S.D. et al. '08
- multi-channel Monte Carlo integration within Prophecy4f

Two independent calculations of all ingredients

Details of

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- loop ir

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- IR sin '99; S.D. et al. '08
- multi-c

Two indep

Collier – Hepforge http://collier.hepforge.org/private/index.html

Collier is hosted by Hepforge, IPPP Durham

COLLIER

A Complex One-Loop LIbrary with Extended Regularizations

Released in April 2016!

Authors

Ansgar Denner	*Universität Würzburg, Germany*
Stefan Dittmaier	*Universität Freiburg, Germany*
Lars Hofer	*Universitat de Barcelona, Spain*

Features of the library

COLLIER is a fortran library for the numerical evaluation of one-loop scalar and tensor integrals appearing in perturbative relativistic quantum field theory with the following features:

- scalar and tensor integrals for high particle multiplicities
- dimensional regularization for ultraviolet divergences
- dimensional regularization for soft infrared divergences (mass regularization for abelian soft divergences is supported as well)
- dimensional regularization or mass regularization for collinear mass singularities
- complex internal masses (for unstable particles) fully supported (external momenta and virtualities are expected to be real)
- numerically dangerous regions (small Gram or other kinematical determinants) cured by dedicated expansions
- two independent implementations of all basic building blocks allow for internal cross-checks
- cache system to speed up calculations

If you use Collier for a publication, please cite all the references listed here!

Details of the NLO calculation

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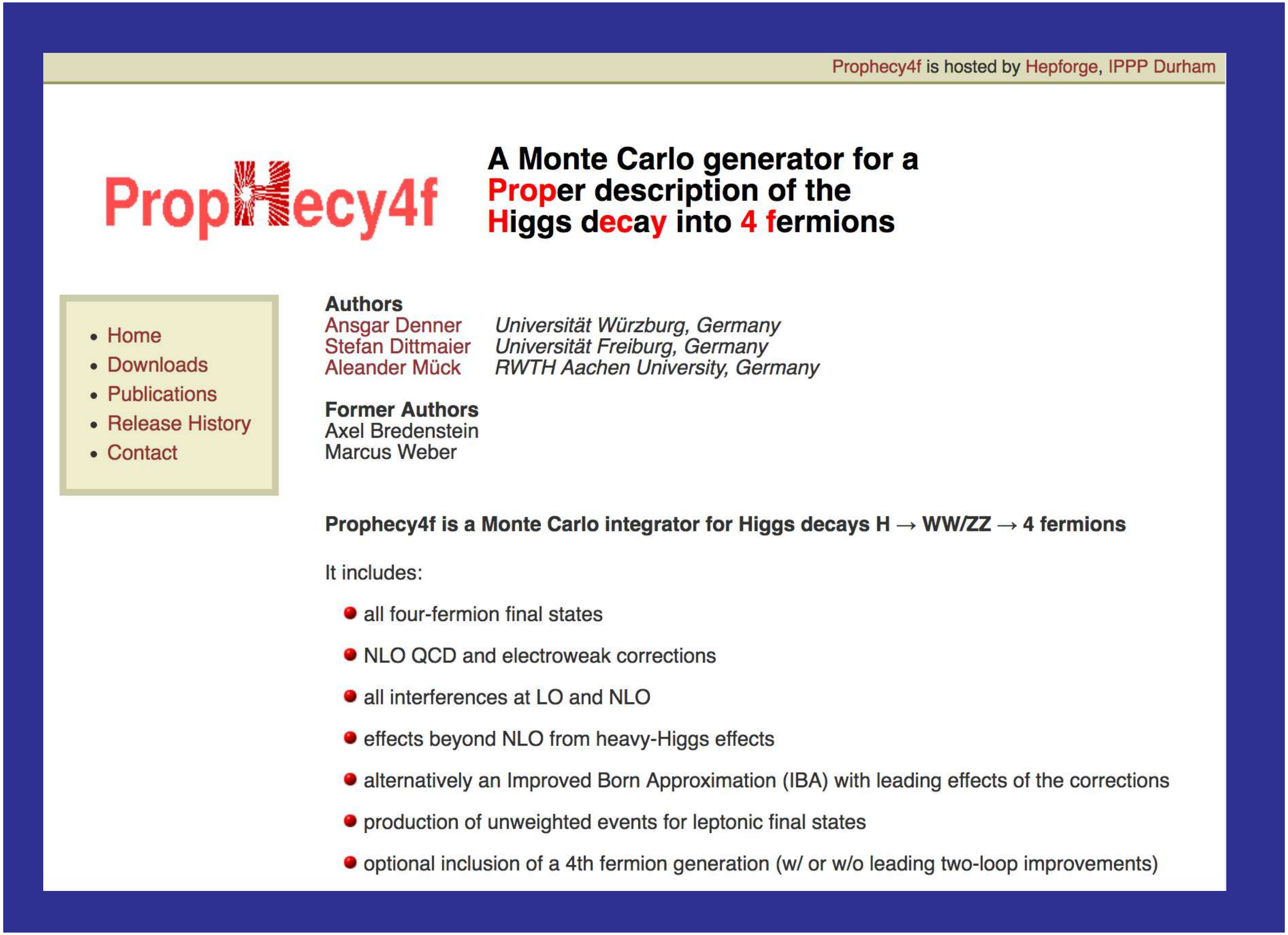
Two independent calculations of all ingredients

NLO corrections to $\mathrm{h} \to 4f$ in the THDM implemented in ...



Prophecy4f is hosted by Hepforge, IPPP Durham

PropHecy4f

A Monte Carlo generator for a Proper description of the Higgs decay into 4 fermions

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Prophecy4f is a Monte Carlo integrator for Higgs decays H → WW/ZZ → 4 fermions

It includes:

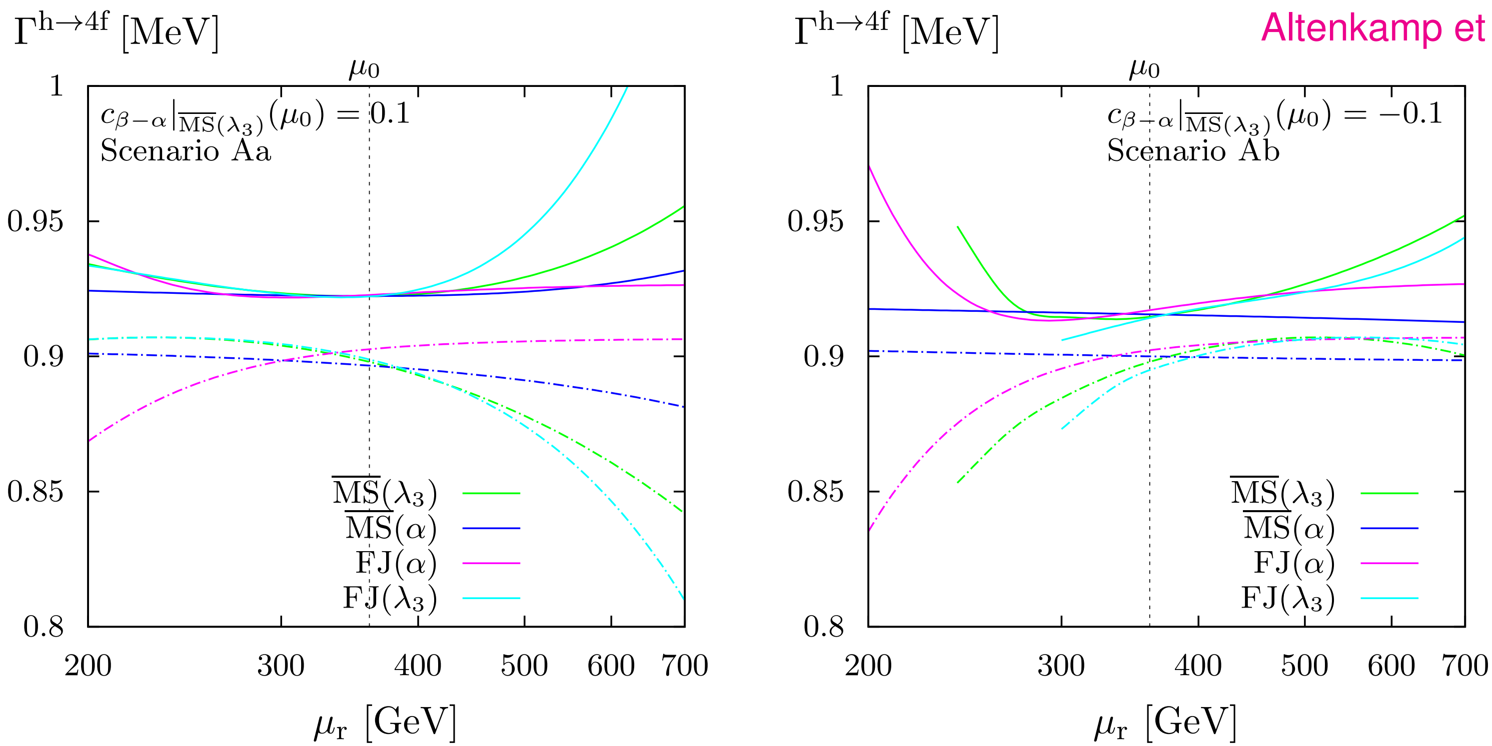
- all four-fermion final states
- NLO QCD and electroweak corrections
- all interferences at LO and NLO
- effects beyond NLO from heavy-Higgs effects
- alternatively an Improved Born Approximation (IBA) with leading effects of the corrections
- production of unweighted events for leptonic final states
- optional inclusion of a 4th fermion generation (w/ or w/o leading two-loop improvements)

$\hookrightarrow$ New PROPHECY4F version available on request (on hepforge soon)

Numerical results for the THDM

Scale depencence of the $h \to 4f$ width in scenario A:

Altenkamp et al. ’17

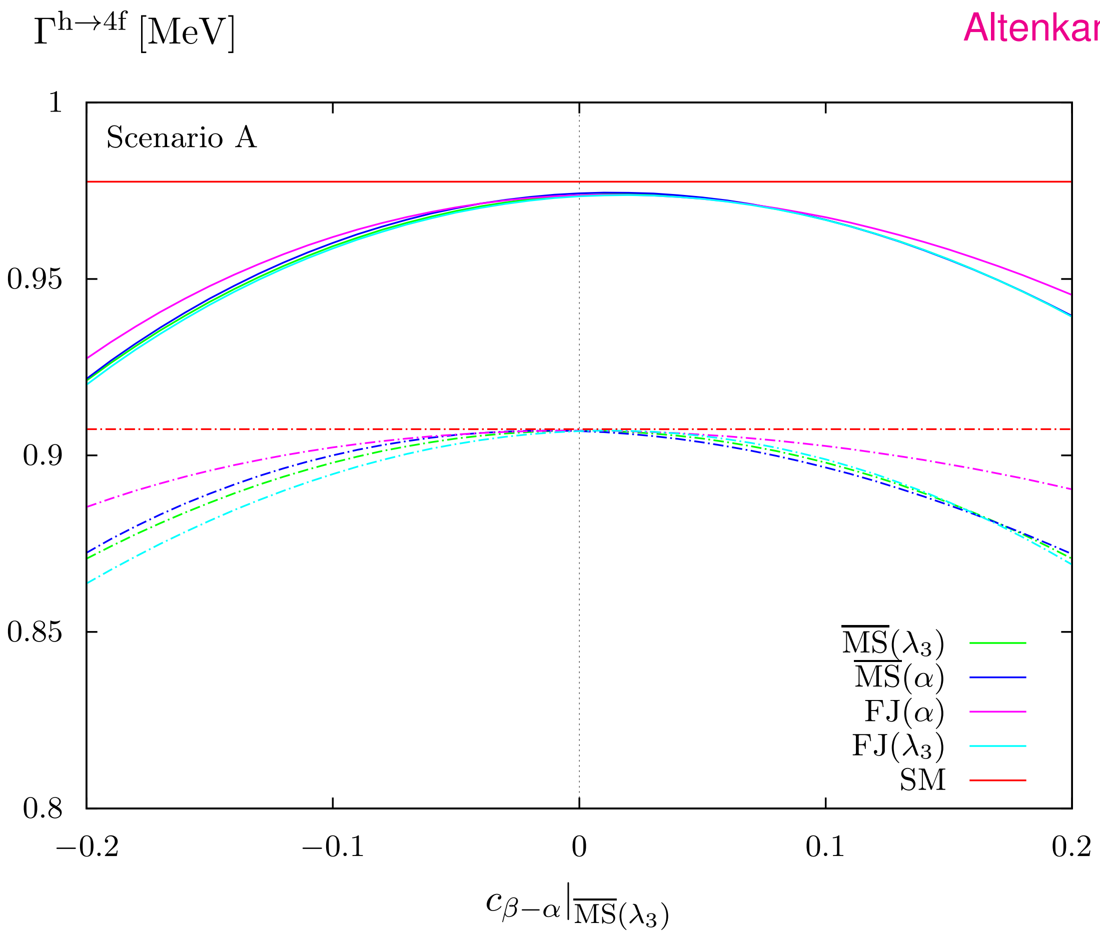


LO: dashed curves
NLO: solid curves

- Ren. scale dependence: reduction from LO $\to$ NLO in all schemes
  Note: scale $\mu_r = M_h$ inappropriate
- Ren. scheme dependence: reduction from LO $\to$ NLO
  Note: consistent parameter conversion mandatory!

$c_{\beta-\alpha}$ dependence of $\mathrm{h}\to 4f$ width in scenario A:

Altenkamp et al. '17



LO: dashed curves
NLO: solid curves

- $\overline{\mathrm{MS}}(\lambda_3)$ scheme used $\Rightarrow$ $\Gamma^{\mathrm{h}\to 4f}_{\mathrm{THDM,LO}}\Big|_{\overline{\mathrm{MS}}(\lambda_3)} = s^2_{\beta-\alpha}\,\Gamma^{\mathrm{h}\to 4f}_{\mathrm{SM,LO}}$
- relative difference to SM: $\Delta_{\mathrm{SM}} \lesssim 2\%\,(6\%)$ for $|c_{\beta-\alpha}| < 0.1\,(0.2)$

Partial $\mathrm{h}\to 4f$ widths in scenario Aa

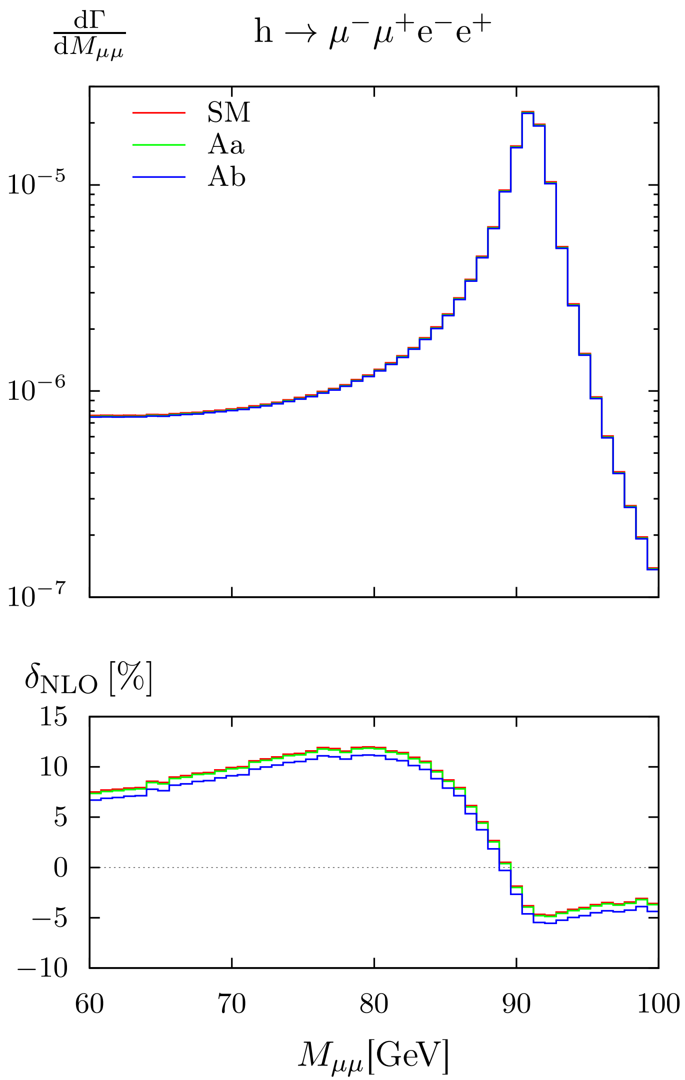
Altenkamp et al. '17

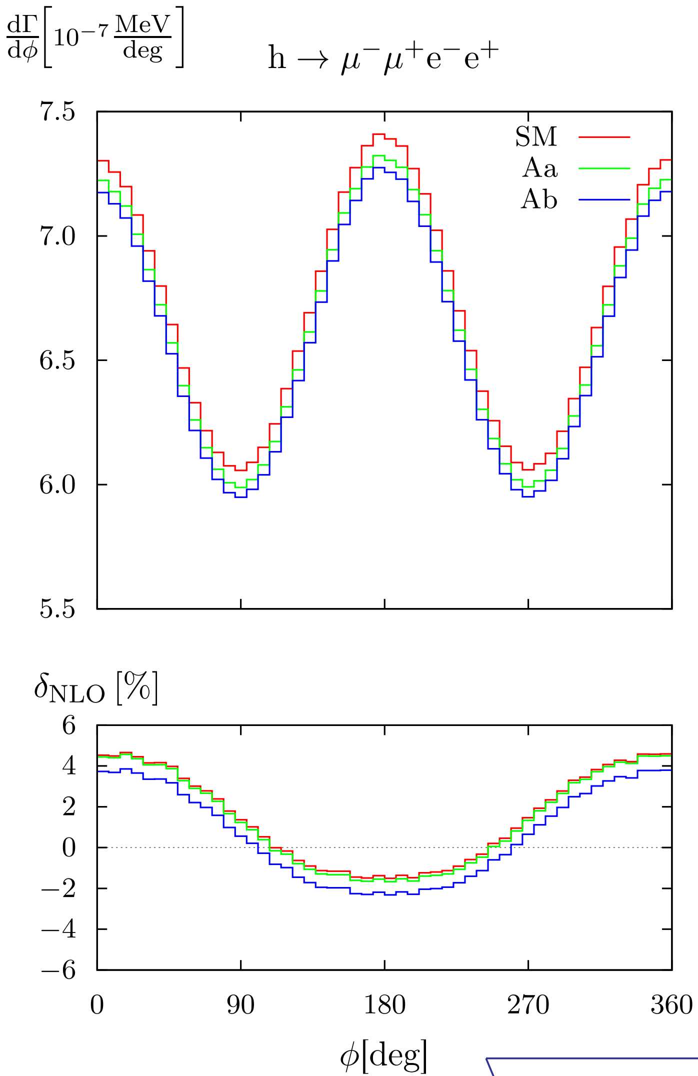
$\overline{\mathrm{MS}}(\lambda_3)$

Final state	$\Gamma^{\mathrm{h}\to 4f}_{\mathrm{NLO}}$ [MeV]	δ_{EW} [%]	δ_{QCD} [%]	$\Delta^{\mathrm{NLO}}_{\mathrm{SM}}$ [%]	$\Delta^{\mathrm{LO}}_{\mathrm{SM}}$ [%]
inclusive $\mathrm{h}\to 4f$	0.96730(7)	2.71(0)	4.96(1)	−1.05(1)	−1.00(1)
ZZ	0.106126(6)	0.34(0)	4.88(0)	−1.13(1)	−1.00(0)
WW	0.86630(8)	3.00(0)	5.01(1)	−1.04(1)	−1.00(1)
WW/ZZ int.	−0.00513(5)	1.3(2)	12.0(8)	−1(1)	−1(1)
$\nu_e e^+ \mu^- \bar{\nu}_\mu$	0.010201(1)	3.03(0)	0.00	−1.04(1)	−1.00(1)
$\nu_e e^+ u\bar{d}$	0.031719(4)	3.02(0)	3.76(1)	−1.04(2)	−1.00(1)
$u\bar{d}s\bar{c}$	0.09847(2)	2.97(0)	7.52(1)	−1.04(2)	−1.00(1)
$\nu_e e^+ e^- \bar{\nu}_e$	0.010197(1)	3.12(0)	0.00	−1.04(1)	−1.00(1)
$u\bar{d}d\bar{u}$	0.10048(2)	2.85(0)	7.35(2)	−1.06(3)	−1.00(1)
$\nu_e\bar{\nu}_e\nu_\mu\bar{\nu}_\mu$	0.000949(0)	3.01(0)	0.00	−1.14(1)	−1.00(1)
$e^- e^+ \mu^- \mu^+$	0.000239(0)	1.30(1)	0.00	−1.13(2)	−1.00(1)
$\nu_e\bar{\nu}_e\mu^-\mu^+$	0.000477(0)	2.45(1)	0.00	−1.13(2)	−1.00(1)
$\nu_e\bar{\nu}_e\nu_e\bar{\nu}_e$	0.000569(0)	2.90(0)	0.00	−1.14(2)	−1.00(1)
$e^- e^+ e^- e^+$	0.000132(0)	1.12(1)	0.00	−1.12(2)	−1.00(1)
$\nu_e\bar{\nu}_e u\bar{u}$	0.001679(0)	0.60(1)	3.76(1)	−1.12(2)	−1.00(1)
$\nu_e\bar{\nu}_e d\bar{d}$	0.002177(1)	1.69(0)	3.76(1)	−1.12(2)	−1.00(1)
$e^- e^+ u\bar{u}$	0.000845(0)	0.11(1)	3.76(1)	−1.12(2)	−1.00(1)
$e^- e^+ d\bar{d}$	0.001088(0)	0.47(1)	3.76(1)	−1.12(2)	−1.00(1)
$u\bar{u}c\bar{c}$	0.002971(0)	−1.80(1)	7.51(1)	−1.11(2)	−1.00(1)
$d\bar{d}d\bar{d}$	0.002556(1)	−0.38(0)	4.38(2)	−1.21(3)	−1.00(1)
$d\bar{d}s\bar{s}$	0.004956(1)	−0.36(0)	7.51(1)	−1.12(2)	−1.00(1)
$u\bar{u}s\bar{s}$	0.003852(1)	−0.66(1)	7.51(1)	−1.11(2)	−1.00(1)
$u\bar{u}u\bar{u}$	0.001506(0)	−1.92(1)	4.06(3)	−1.24(4)	−1.00(1)

NLO corrections to leptonic distributions in scenario A

Altenkamp et al. '17

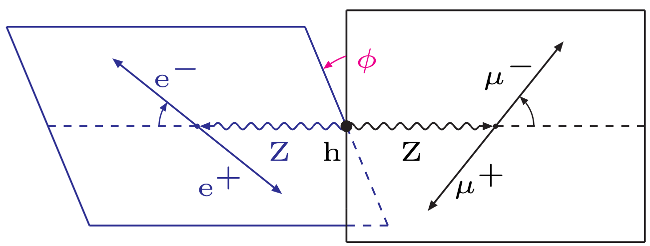




$\overline{\mathrm{MS}}(\lambda_3)$

correction $\delta_{\mathrm{THDM}} \approx \delta_{\mathrm{SM}} + \mathrm{const.}$

mainly due to external hH mixing



Numerical results for the SESM

Scale and scheme depencence of the $h \to 4f$ width in scenario BHM200$^+$:

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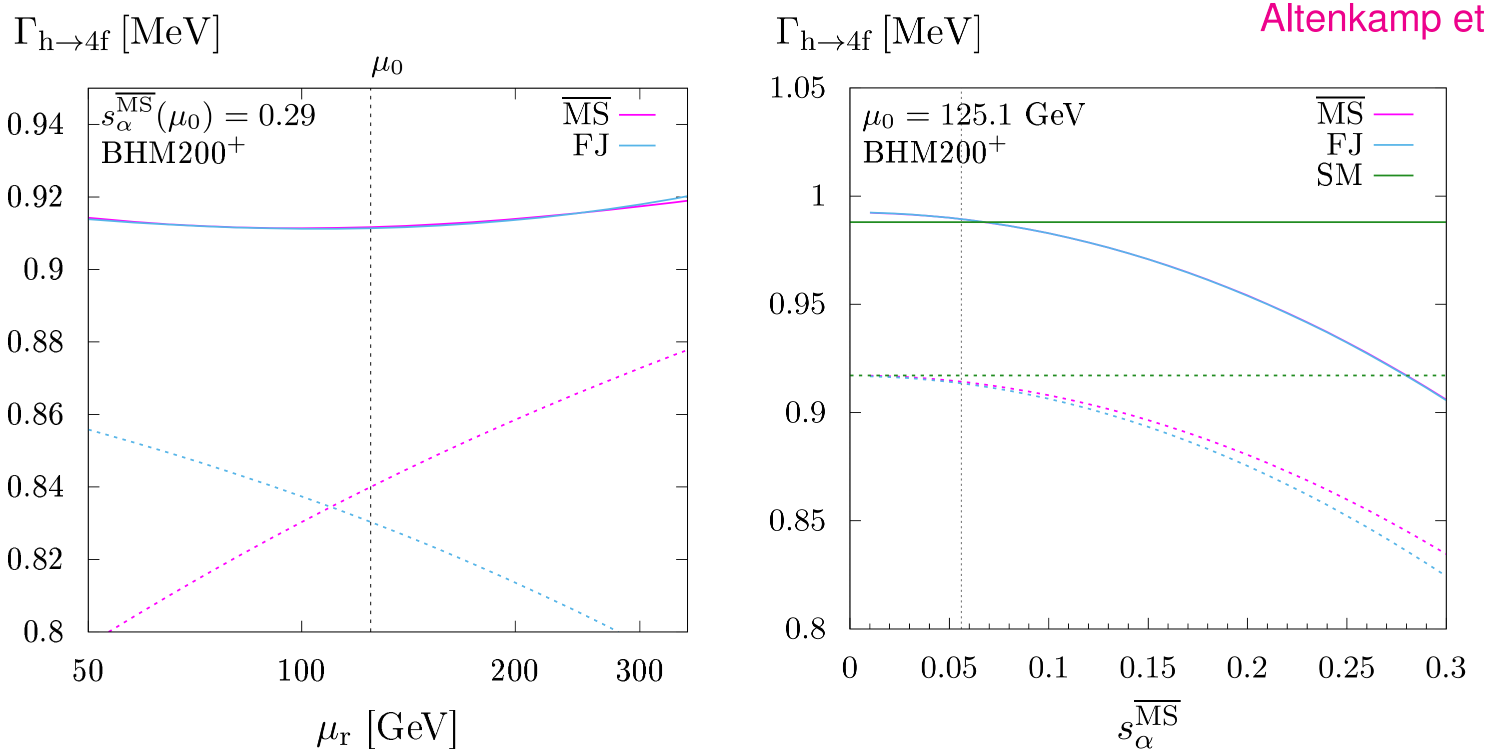

LO: dashed curves
NLO: solid curves

Observations in all considered scenarios (also with high M_H):

- Ren. scale dependence: ($\mu_r = M_h$ is good choice)
  reduction from $\lesssim 3$–4% @ LO $\to$ $\lesssim 0.5\%$ @ NLO in all schemes
- Ren. scheme dependence: negligible @ NLO
  but: consistent parameter conversion mandatory!
- Distributions: no distortion by BSM effects

NLO corrections to leptonic distributions

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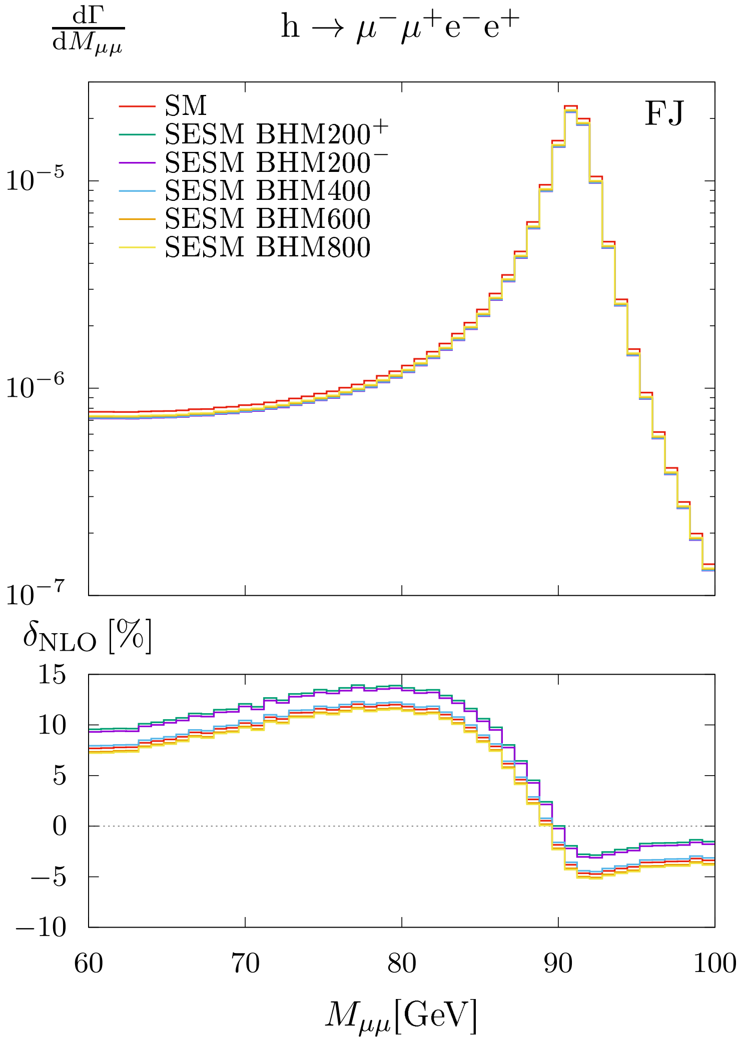
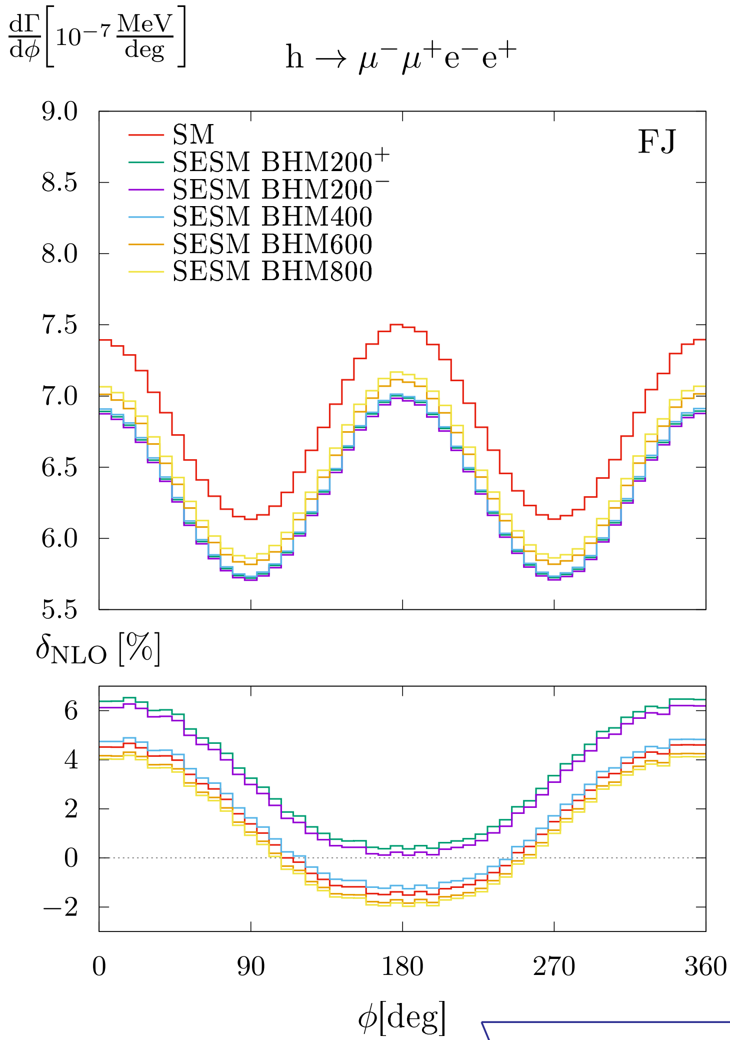
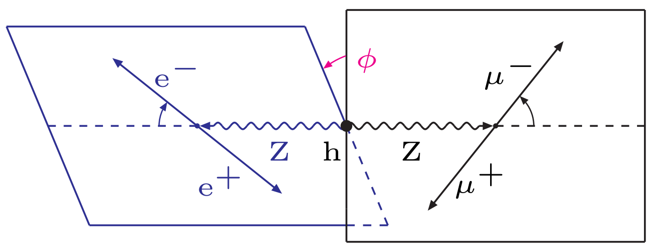




FJ scheme

correction $\delta_{SESM} \approx \delta_{SM} + \text{const.}$

mainly due to external hH mixing

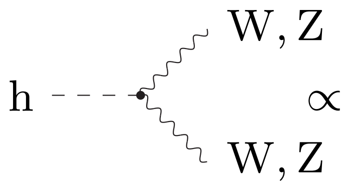


Outlook and conclusions

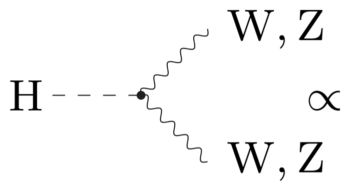
Outlook: generalizations, extensions, issues

Heavy Higgs decays $\mathrm{H} \to \mathrm{WW/ZZ} \to 4f$

- technical machinery works as for light Higgs boson h, but ...
- LO prediction suppressed by small mixing factors:



$\propto \cos\gamma \gtrsim 0.9(0.95)$



$\propto \sin\gamma \lesssim 0.4(0.3)$

LHC result: $\mu = \left.\frac{\Gamma_{\mathrm{exp}}}{\Gamma_{\mathrm{SM}}}\right|_{\mathrm{Higgs}\to\mathrm{WW/ZZ}} = 1 \pm 20\%(10\%) \sim \cos^2\gamma$

$\Rightarrow$ Potentially large corrections to $\mathrm{H} \to \mathrm{WW/ZZ}$

Perturbatively stable renormalization schemes particularly important!

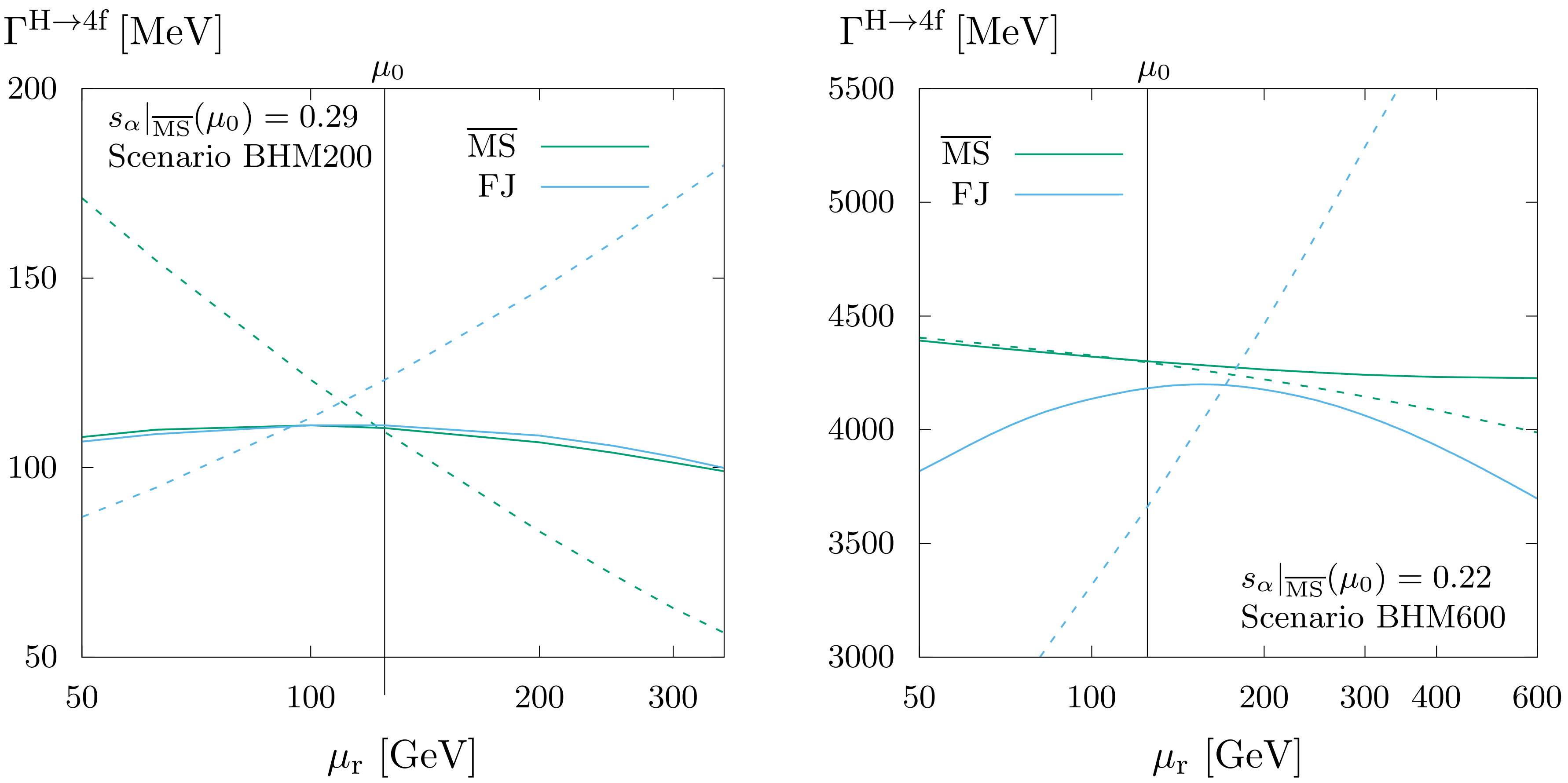
Issue of mass degeneracy

Typical for $\overline{\mathrm{MS}}$-ren. mixing angle: $\delta(\mu_{\mathrm{r}}) = A + \frac{B\ln(\mu_{\mathrm{r}}/\mu_0) + C}{M_{\mathrm{h}}^2 - M_{\mathrm{H}}^2}$

$\Rightarrow$ Perturbative instability for $M_{\mathrm{H}} \to M_{\mathrm{h}}$ (narrow or no plateaus in μ_{r})

Alternative schemes desirable!

Outlook: first results on $\mathrm{H} \to \mathrm{WW/ZZ} \to 4f$ in the SESM



- Significant reduction of ren. scale and scheme dependence @ NLO (though with larger uncertainties than for h)
- THDM: situation much more delicate ... (severe instabilities in some scenarios)

NLO corrections in the THDM and SESM

in principle straightforward, but involve issues:

- choice of input parameters, which ones in $\overline{\mathrm{MS}}$?
- gauge dependences, perturbative stability, etc.

$\hookrightarrow$ various renormalization schemes discussed in recent literature

This talk: several schemes proposed and applied to $\mathrm{h} \to \mathrm{WW/ZZ} \to 4f$ at NLO

- THDM & SESM:
  - ◇ on-shell masses, $\overline{\mathrm{MS}}$ mixing angles, $\overline{\mathrm{MS}}$ scalar self-couplings
  - ◇ conversion between schemes, analysis of NLO scale & scheme dependence
  - ◇ $\mathrm{h} \to 4f$: no distortions of distributions by BSM effects
- THDM:
  - ◇ no sensitivity of $\mathrm{h} \to 4f$ to the type of THDM
  - ◇ moderate scenarios (alignment region, moderate heavy Higgs masses, non-degeneracy)
    $\hookrightarrow$ perturbatively stable NLO results
  - ◇ issues in extreme scenarios, in particular for H decays
- SESM:
  - ◇ very robust NLO results for $\mathrm{h}, \mathrm{H} \to \mathrm{WW/ZZ} \to 4f$

In progress: construction of “universally well-behaved” ren. schemes

Backup slides

THDM Yukawa couplings:

Avoid FCNC at tree level!

$\hookrightarrow$ Couple each fermion flavour only to one Φ_n ($\mathbb{Z}_2$ symmetry)

$$\mathcal{L}_{\text{Yukawa}} = -\bar{L}'^{\text{L}} Y^l l'^{\text{R}} \Phi_{n_1} - \bar{Q}'^{\text{L}} Y^u u'^{\text{R}} \tilde{\Phi}_{n_2} - \bar{Q}'^{\text{L}} Y^d d'^{\text{R}} \Phi_{n_3} + h.c.$$

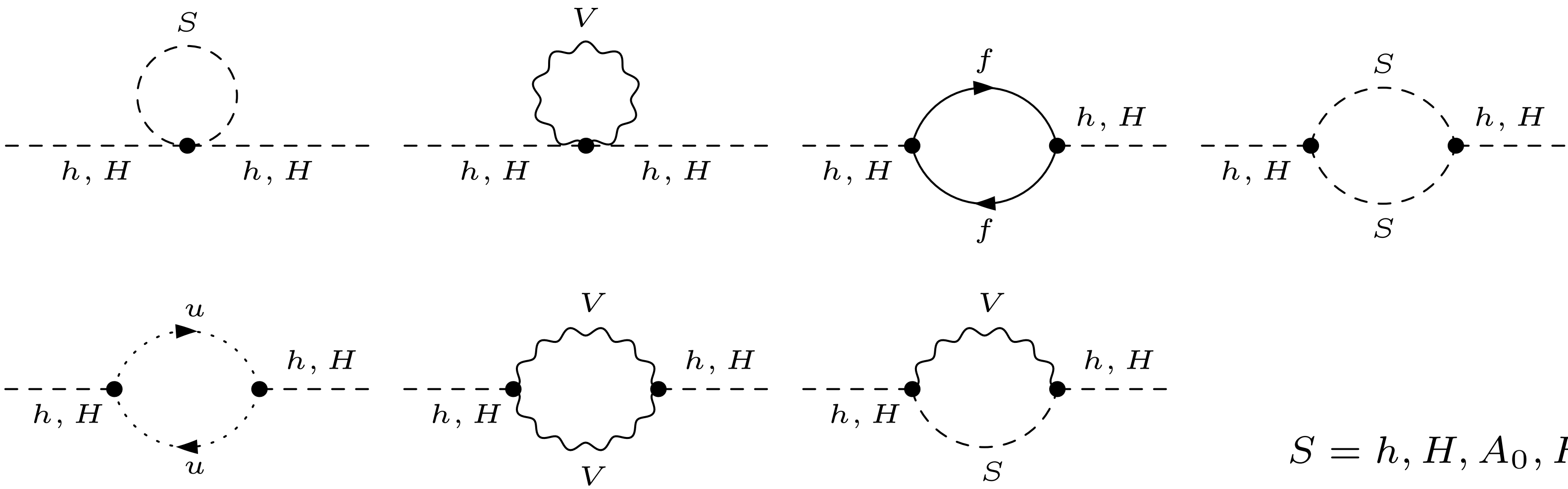
THDM type	u_i	d_i	e_i	$\mathbb{Z}_2$ symmetry
Type I	Φ_2	Φ_2	Φ_2	$\Phi_1 \to -\Phi_1$
Type II	Φ_2	Φ_1	Φ_1	$(\Phi_1, d_i, e_i) \to -(\Phi_1, d_i, e_i)$
Lepton-specific	Φ_2	Φ_2	Φ_1	$(\Phi_1, e_i) \to -(\Phi_1, e_i)$
Flipped	Φ_2	Φ_1	Φ_2	$(\Phi_1, d_i) \to -(\Phi_1, d_i)$

Yukawa couplings modified by THDM factors $\xi^f_{\text{H,h,A}_0}$:

	Type I	Type II	Lepton-specific	Flipped
ξ^l_{H}	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$
ξ^u_{H}	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
ξ^d_{H}	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
ξ^l_{h}	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$
ξ^u_{h}	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
ξ^d_{h}	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
$\xi^l_{\text{A}_0}$	$\cot\beta$	$-\tan\beta$	$-\tan\beta$	$\cot\beta$
$\xi^u_{\text{A}_0}$	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
$\xi^d_{\text{A}_0}$	$\cot\beta$	$-\tan\beta$	$\cot\beta$	$-\tan\beta$

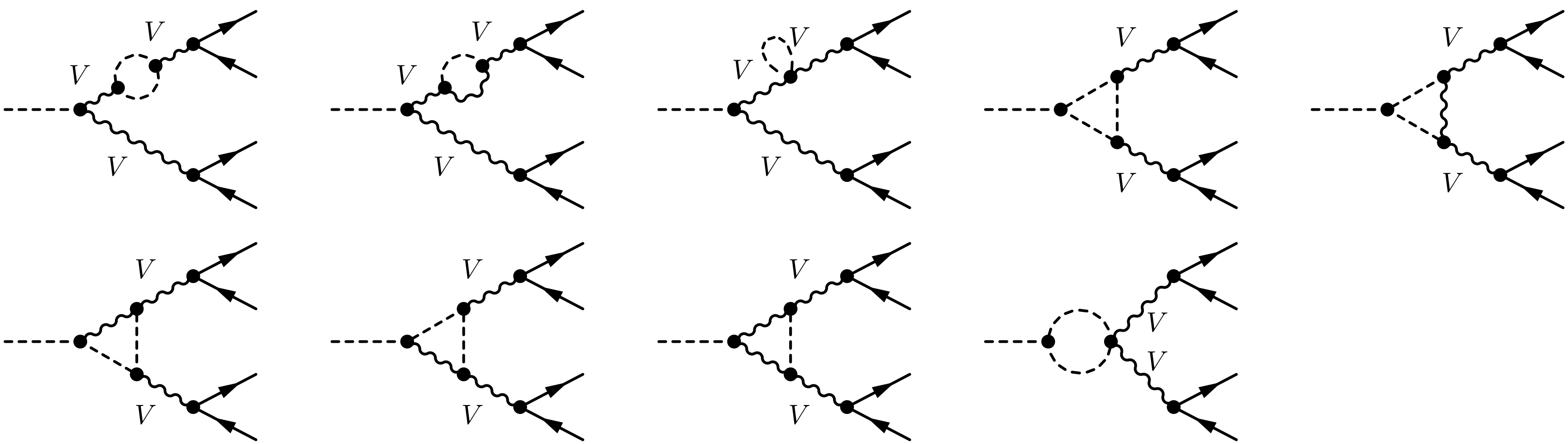
Generic diagrams for hh, hH, HH self-energies

$\hookrightarrow$ external wave-function renormalization + hH mixing



$S = h, H, A_0, H^{\pm}, G_0, G^{\pm}$

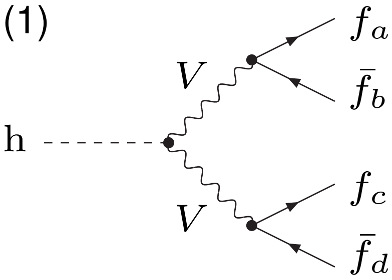
Generic diagrams with internal heavy Higgs bosons H, $\mathrm{A_0}$, $\mathrm{H^{\pm}}$



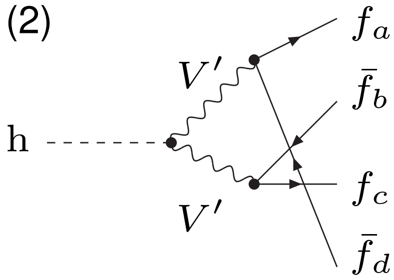
Classification of QCD corrections

Possible Born diagrams:

(1)



(2)



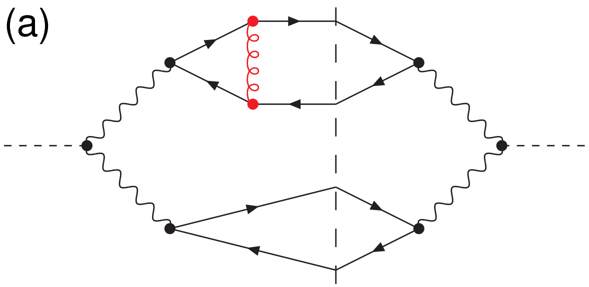
diagrams (2) only for

$f\bar{f}f\bar{f}$ and $f\bar{f}f'\bar{f}'$ channels

(f' = weak-isospin partner of f)

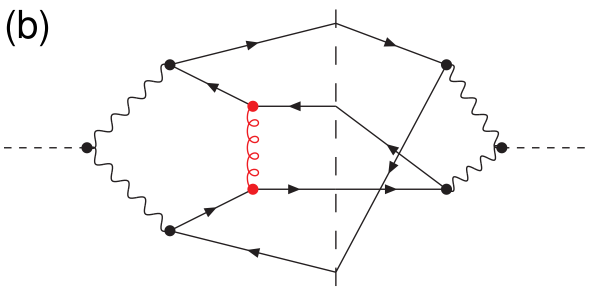
Classification of QCD corrections into four categories: (typical diagrams shown)

(a)

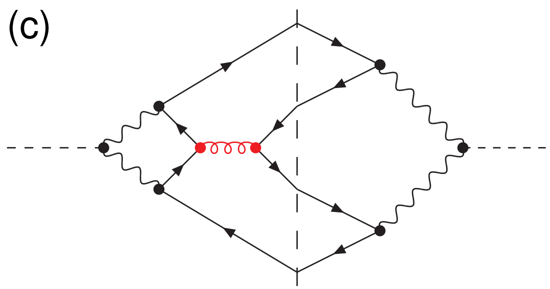


(d) only QCD correction without universal scaling $\propto s_{\beta-\alpha}$ from $\mathcal{M}_{\rm SM}$

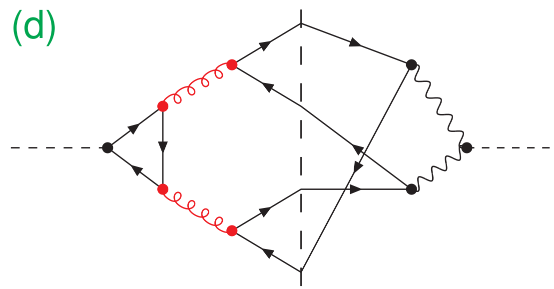
(b)



(c)



(d)



(b,c,d) = corrections to interferences (only for $q\bar{q}q\bar{q}$ and $q\bar{q}q'\bar{q}'$ channels)

Partial $h \to 4f$ widths in THDM scenario Ab

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$\overline{\mathrm{MS}}(\lambda_3)$

Final state	$\Gamma^{h\to 4f}_{NLO}$ [MeV]	δ_{EW} [%]	δ_{QCD} [%]	Δ^{NLO}_{SM} [%]	Δ^{LO}_{SM} [%]
inclusive $h \to 4f$	0.95980(7)	1.87(0)	4.97(1)	−1.82(1)	−1.00(1)
ZZ	0.105464(5)	−0.34(0)	4.90(0)	−1.75(1)	−1.00(0)
WW	0.85938(8)	2.14(0)	5.01(1)	−1.83(1)	−1.00(1)
WW/ZZ int.	−0.00504(5)	0.5(1)	10.7(8)	−2(1)	−1(1)
$\nu_e e^+ \mu^- \bar\nu_\mu$	0.010116(1)	2.17(1)	0.00	−1.87(1)	−1.00(1)
$\nu_e e^+ u \bar d$	0.031463(4)	2.16(0)	3.76(1)	−1.84(2)	−1.00(1)
$u \bar d s \bar c$	0.09770(2)	2.11(0)	7.52(1)	−1.81(2)	−1.00(1)
$\nu_e e^+ e^- \bar\nu_e$	0.010112(1)	2.27(1)	0.00	−1.87(1)	−1.00(1)
$u \bar d d \bar u$	0.09972(2)	1.99(0)	7.38(2)	−1.80(2)	−1.00(1)
$\nu_e \bar\nu_e \nu_\mu \bar\nu_\mu$	0.000943(0)	2.34(0)	0.00	−1.78(1)	−1.00(1)
$e^- e^+ \mu^- \mu^+$	0.000237(0)	0.62(1)	0.00	−1.79(2)	−1.00(1)
$\nu_e \bar\nu_e \mu^- \mu^+$	0.000474(0)	1.78(1)	0.00	−1.78(2)	−1.00(1)
$\nu_e \bar\nu_e \nu_e \bar\nu_e$	0.000565(0)	2.23(0)	0.00	−1.79(2)	−1.00(1)
$e^- e^+ e^- e^+$	0.000131(0)	0.45(1)	0.00	−1.78(2)	−1.00(1)
$\nu_e \bar\nu_e u \bar u$	0.001668(0)	−0.08(1)	3.76(1)	−1.76(2)	−1.00(1)
$\nu_e \bar\nu_e d \bar d$	0.002163(0)	1.02(0)	3.76(1)	−1.76(2)	−1.00(1)
$e^- e^+ u \bar u$	0.000840(0)	−0.57(1)	3.76(1)	−1.77(2)	−1.00(1)
$e^- e^+ d \bar d$	0.001081(0)	−0.21(1)	3.76(1)	−1.76(2)	−1.00(1)
$u \bar u c \bar c$	0.002952(0)	−2.48(1)	7.51(1)	−1.75(2)	−1.00(1)
$d \bar d d \bar d$	0.002545(1)	−1.06(0)	4.57(2)	−1.67(3)	−1.00(1)
$d \bar d s \bar s$	0.004925(1)	−1.04(0)	7.51(1)	−1.74(2)	−1.00(1)
$u \bar u s \bar s$	0.003828(1)	−1.35(1)	7.51(1)	−1.74(2)	−1.00(1)
$u \bar u u \bar u$	0.001500(0)	−2.60(1)	4.31(2)	−1.65(3)	−1.00(1)

NLO corrections to leptonic distributions in THDM scenario A

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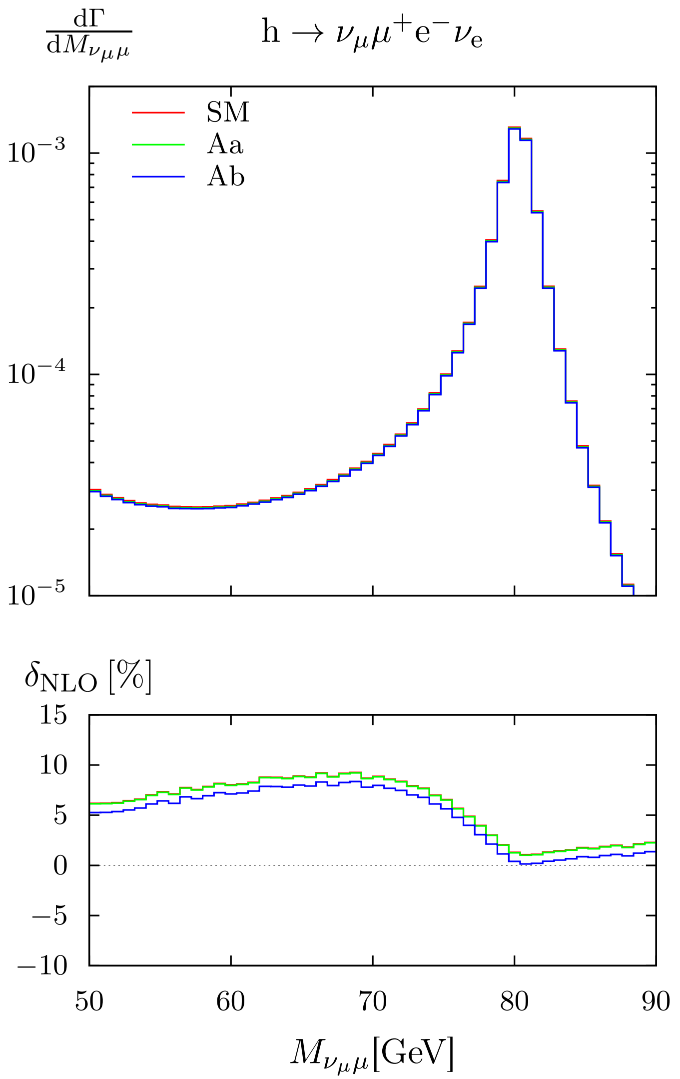

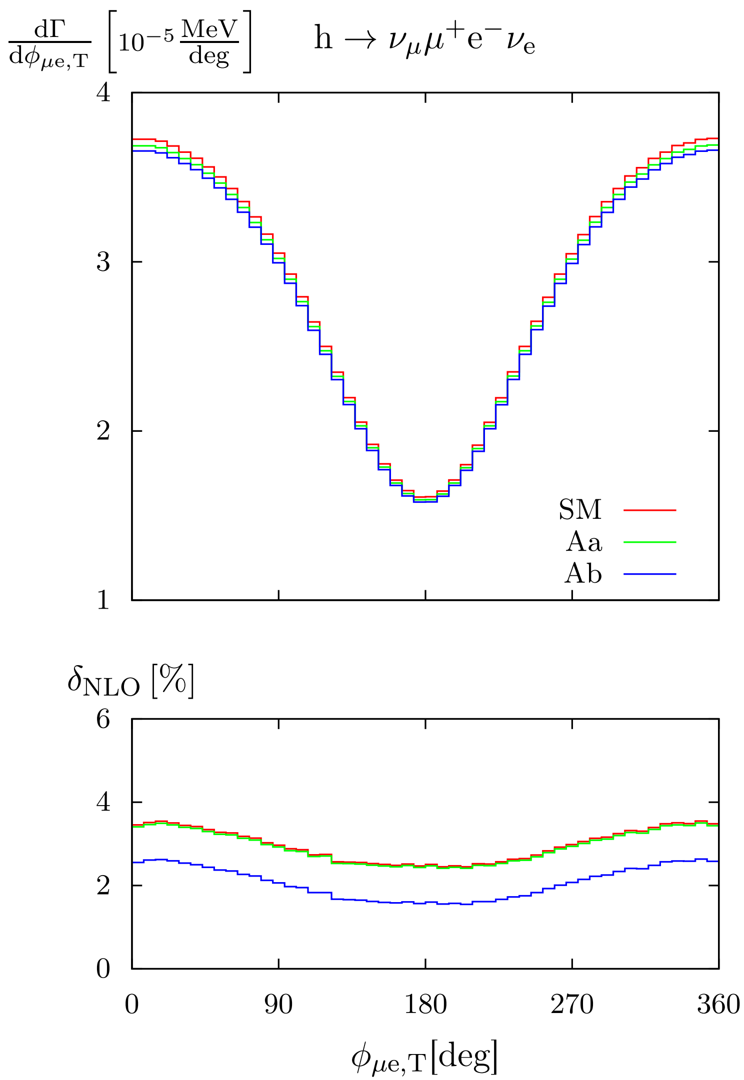

$\overline{\text{MS}}(\lambda_3)$

correction $\delta_{THDM} \approx \delta_{SM} + \text{const.}$

mainly due to external hH mixing

$\phi_{T,\mu e} = \angle(\mu, e)$ in a fixed plane $\approx$ (plane $\perp$ beams)

NLO corrections to semileptonic distributions in THDM scenario A

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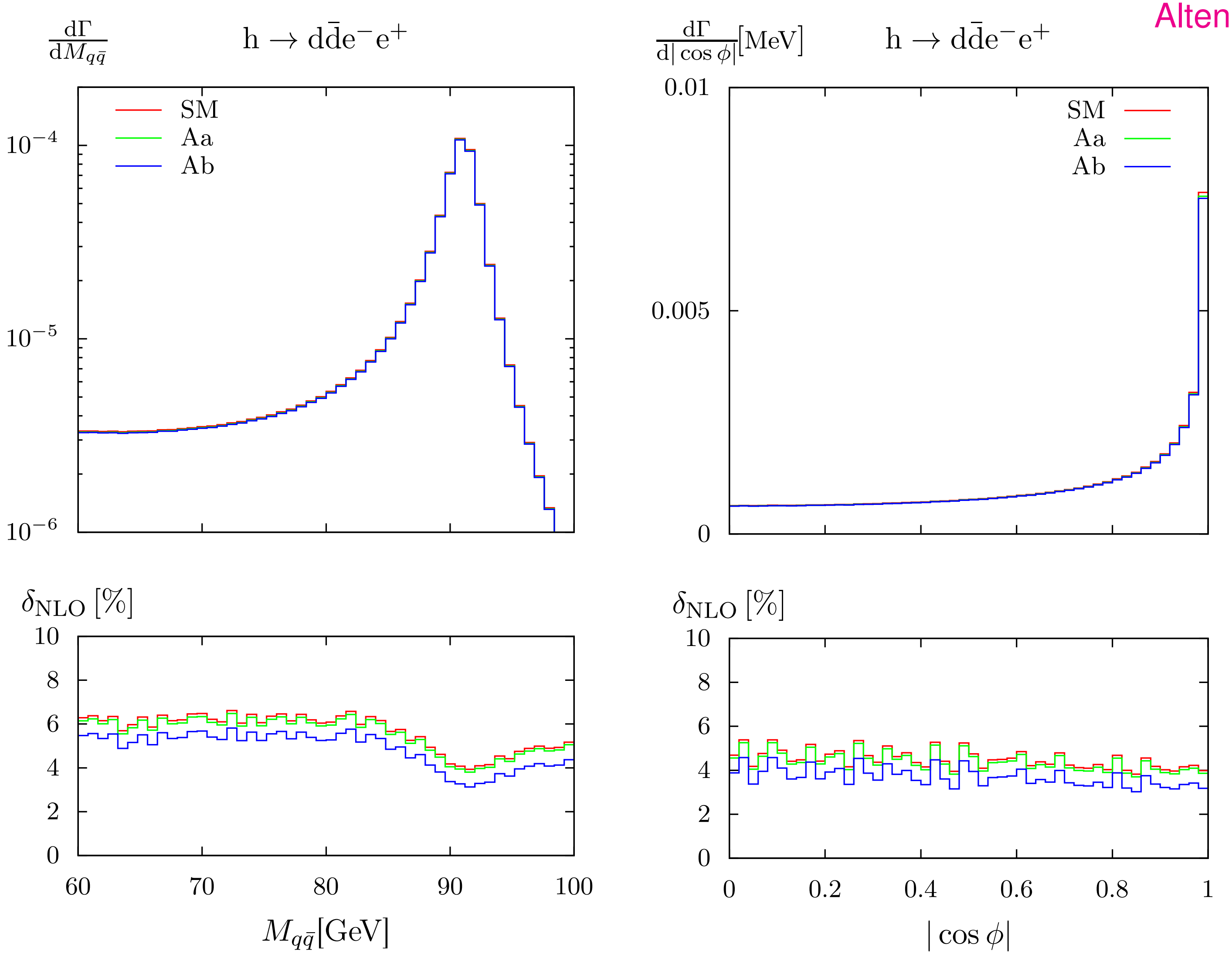

$\overline{\mathrm{MS}}(\lambda_3)$

NLO corrections to semileptonic distributions in THDM scenario A

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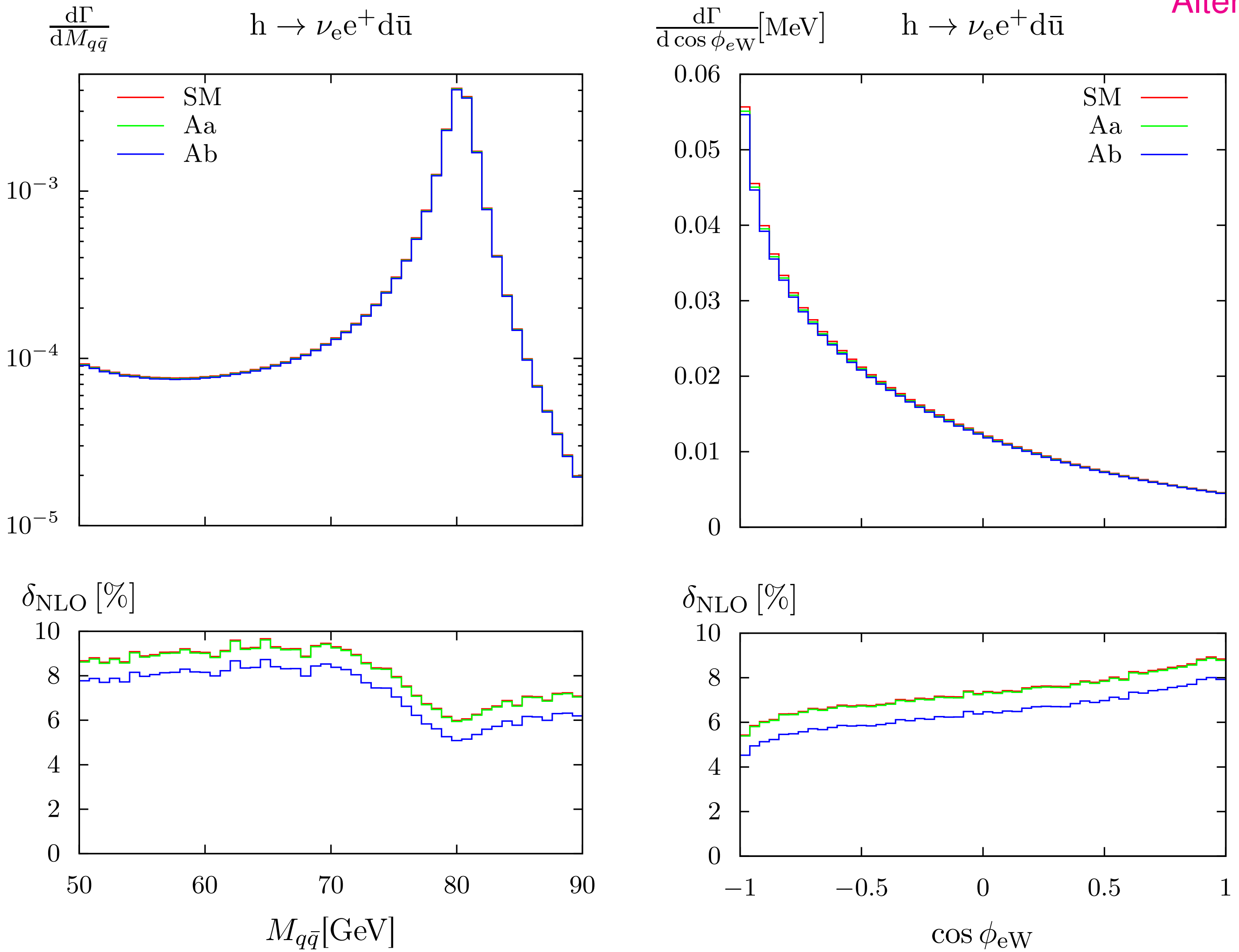
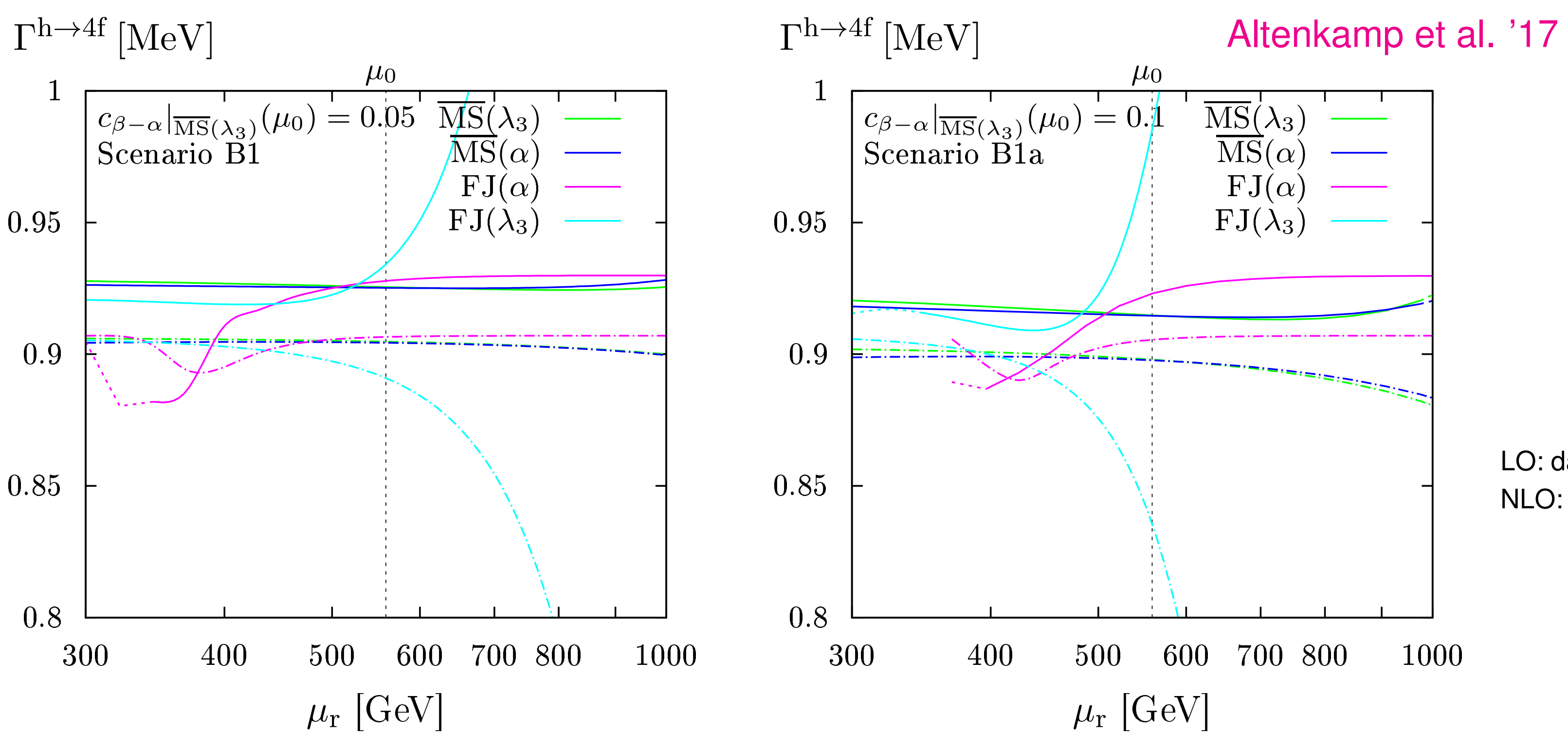


$\overline{\text{MS}}(\lambda_3)$

Scale depencence of the $h \to 4f$ width in large-mass THDM scenario B1:

$M_H = 600\,\text{GeV}, \quad M_{A_0} = M_{H^+} = 690\,\text{GeV}, \quad \lambda_5 = -1.9, \quad \tan\beta = 4.5$



LO: dashed curves
NLO: solid curves

Ren. scale and scheme dependence in LO $\to$ NLO:

- stabilization degrades when $\cos(\beta - \alpha)$ increases
  (getting away from the decoupling limit)
- good stability for $\overline{MS}(\alpha)$ and $\overline{MS}(\lambda_3)$ schemes
- FJ schemes degrade earlier due to large tadpole terms