Renormalization of the THDM and NLO corrections to h → WW/ZZ → 4fermions

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(in collaboration with L.Altenkamp and H.Rzehak; see arXiv:1704.02645 + paper in preparation)

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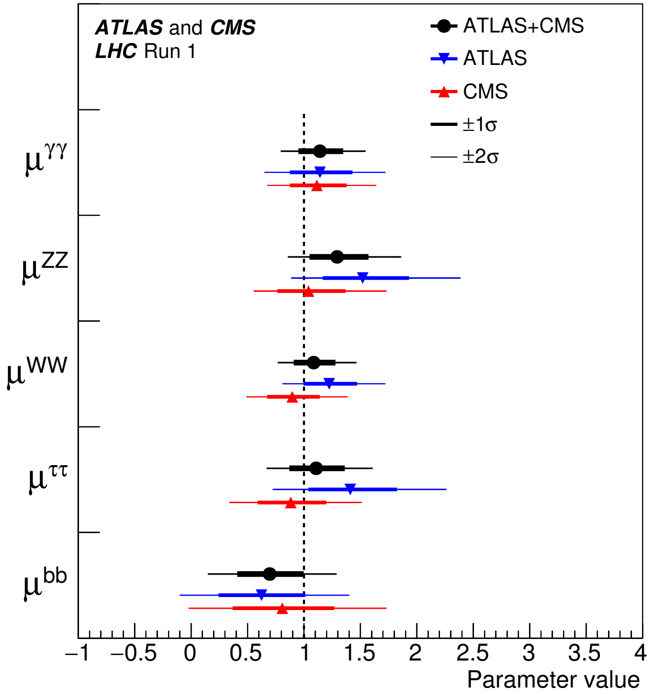
Introduction

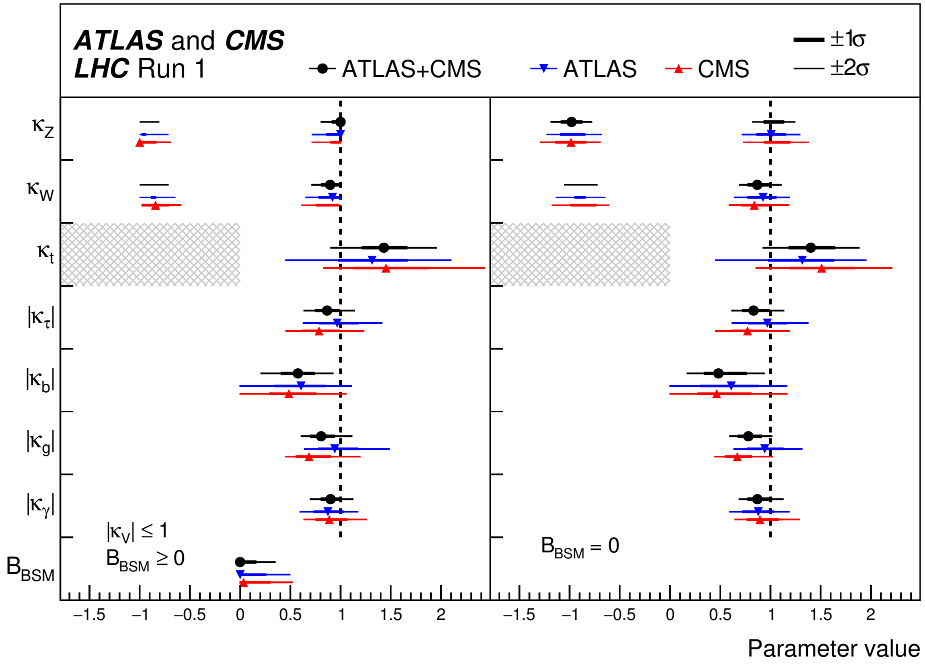
Some central LHC results from profiling the Higgs boson

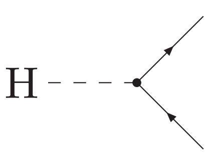
Decay signal strength:



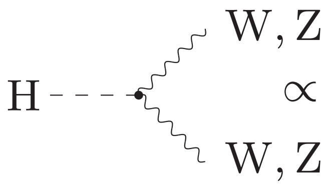
$$\mu = \frac{\Gamma_{\rm exp}}{\Gamma_{\rm SM}}$$

Fit of coupling modifiers:





$\propto \kappa_f$



$\propto \kappa_V$

Compatibility with Standard Model

Reveal BSM effects with higher precision ?

⇒ Precision calculations in BSM models necessary

→ 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:

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

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

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}	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
$\xi^l_{\text{A}_0}$	$\cot\beta$	$-\tan\beta$	$-\tan\beta$	$\cot\beta$
$\xi^u_{\text{A}_0}$	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
$\xi^d_{\text{A}_0}$	$\cot\beta$	$-\tan\beta$	$\cot\beta$	$-\tan\beta$

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) $+ \delta t_S = 0$ $\Rightarrow$ 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

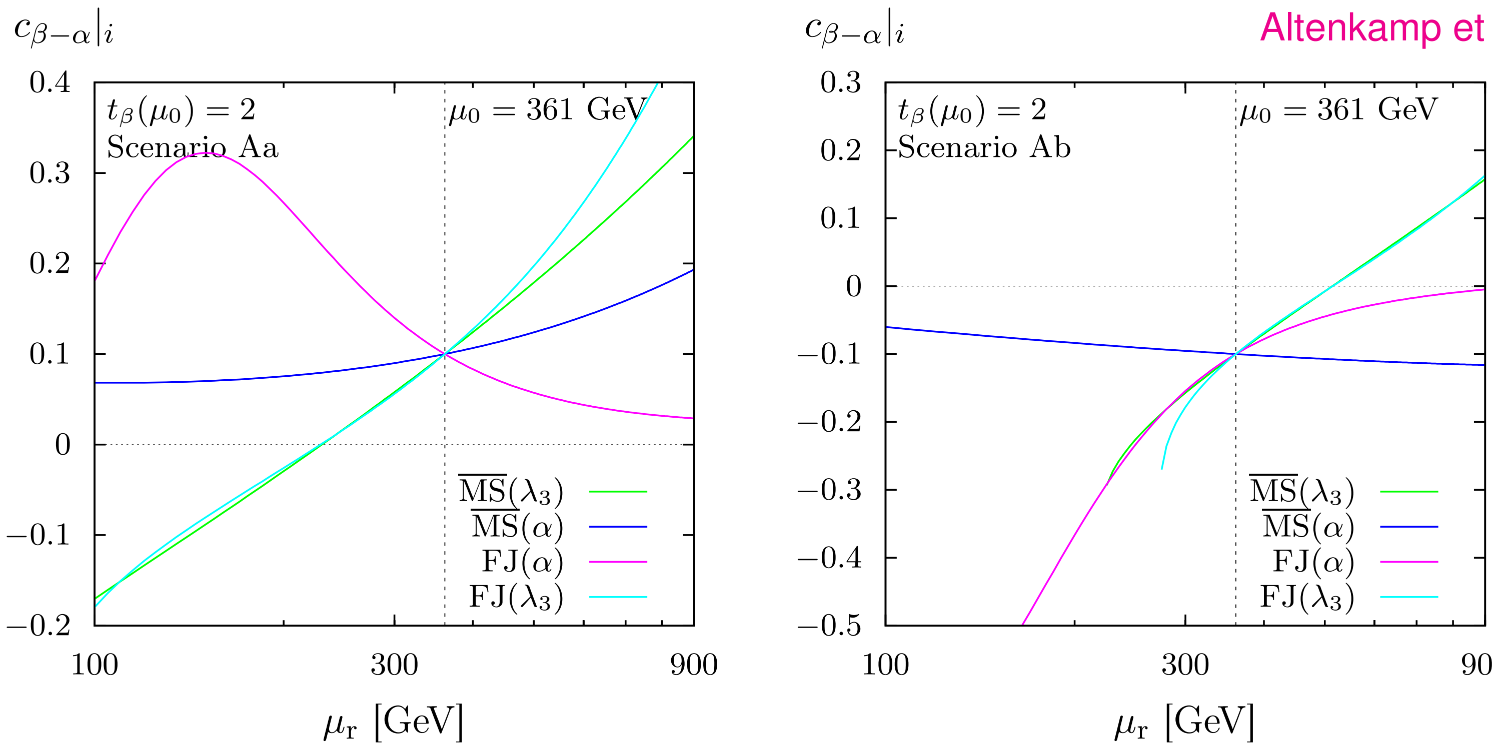
Running of $\overline{\mathrm{MS}}$ parameters: (numerical solution of ren. group eqs.)

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

Scenario A: $M_\mathrm{h} = 125\,\mathrm{GeV}$, $c_{\beta-\alpha} = +0.1$ (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!

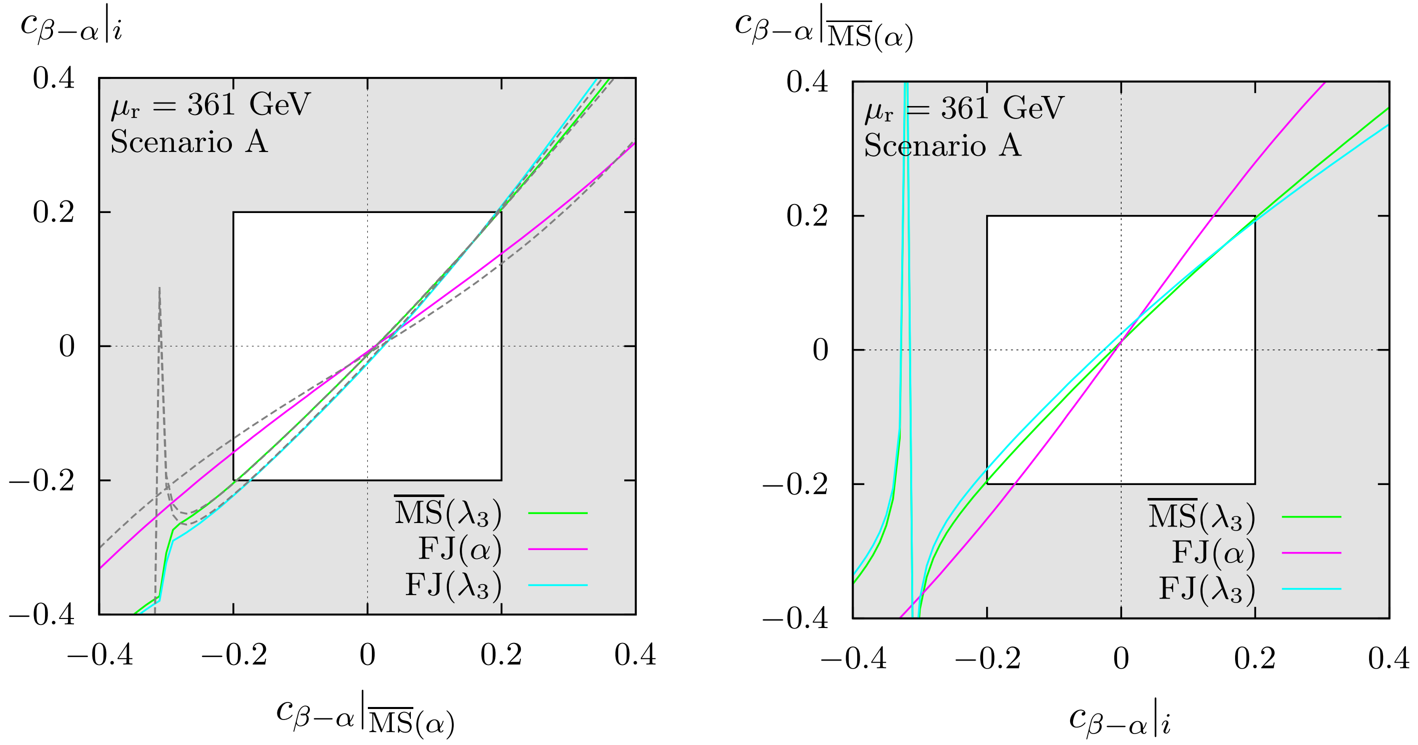
Conversion between schemes (1) and (2) via equality of bare parameters:

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

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

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

Altenkamp et al. ’17

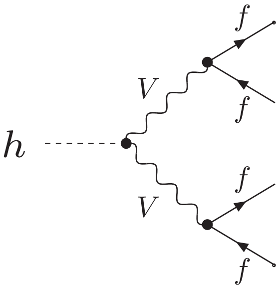


Sizeable conversion effects!

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

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

Lowest order:

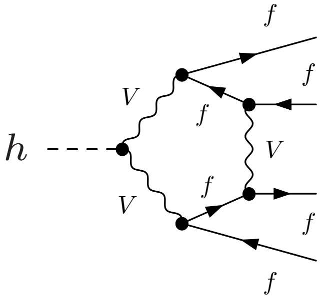


$$= \sin(\beta - \alpha)\, \mathcal{M}_{\mathrm{SM,LO}}$$

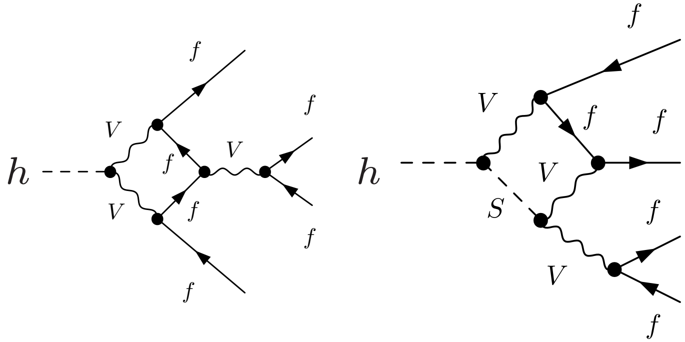
Typical one-loop diagrams:

diagrams = $\mathcal{O}(200\text{–}400)$

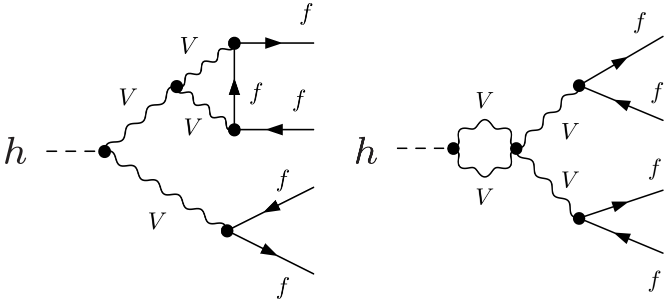
pentagons



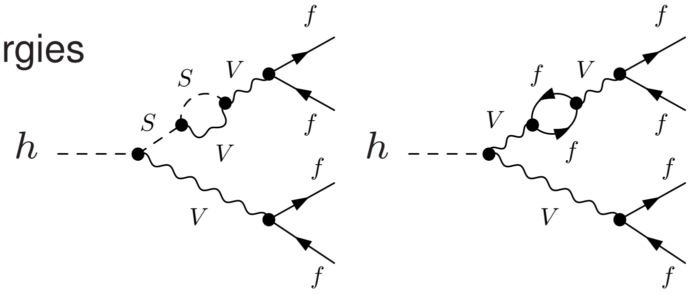
boxes



vertices



self-energies

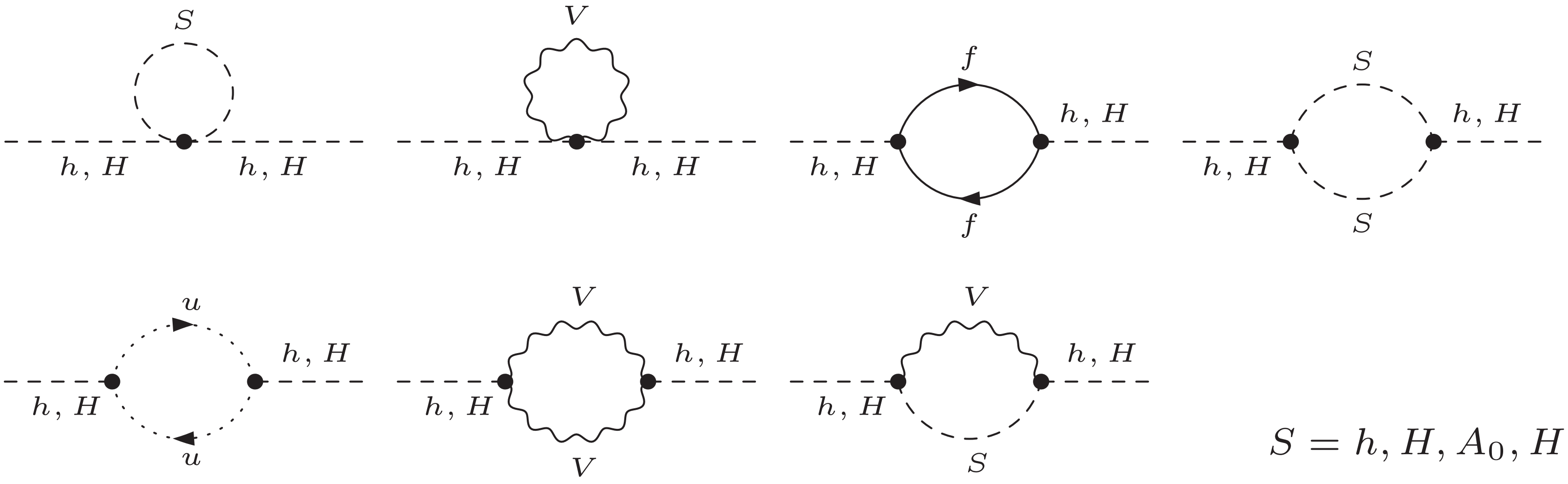


+ counterterms

+ tree graphs with real gluon or photons

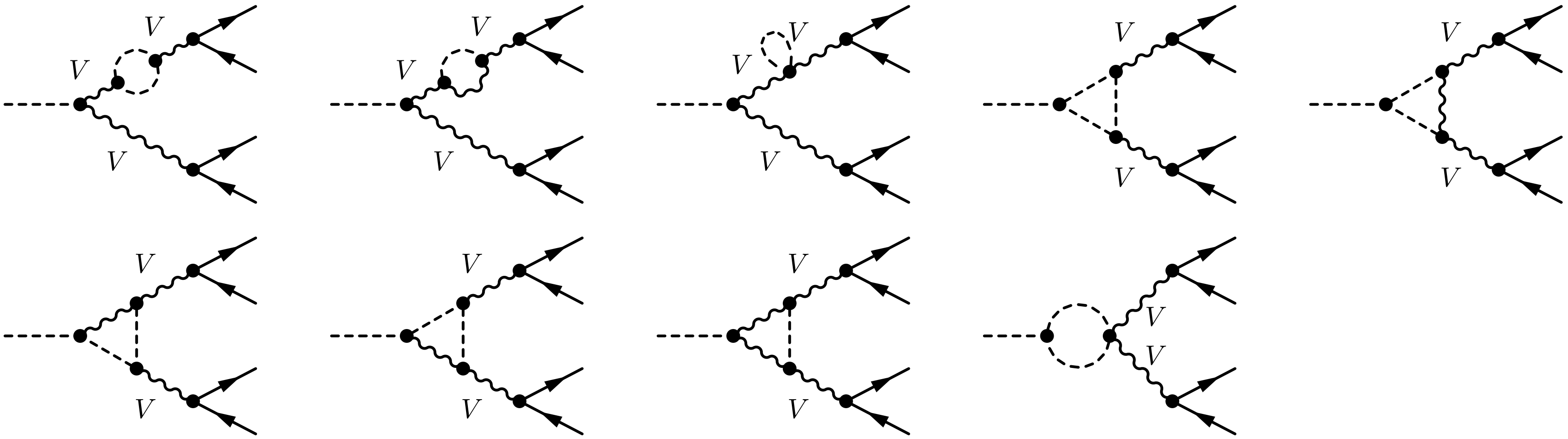
Generic diagrams for hh, hH, HH self-energies

↪ external wave-function renormalization + hH mixing



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

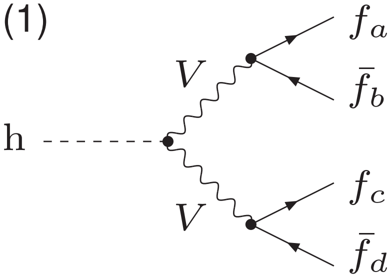
Generic diagrams with internal heavy Higgs bosons H, $\mathrm{A_0}$, $\mathrm{H^{\pm}}$



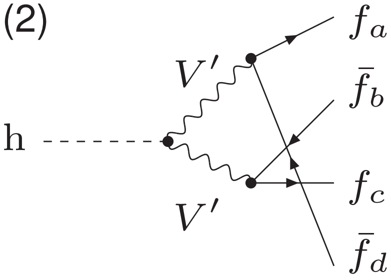
Classification of QCD corrections

Possible Born diagrams:

(1)



(2)

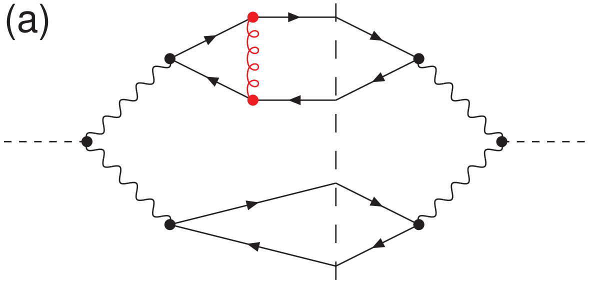


diagrams (2) only for $f\bar{f}f\bar{f}$ and $f\bar{f}f'\bar{f}'$ channels

(f' = weak-isospin partner of f)

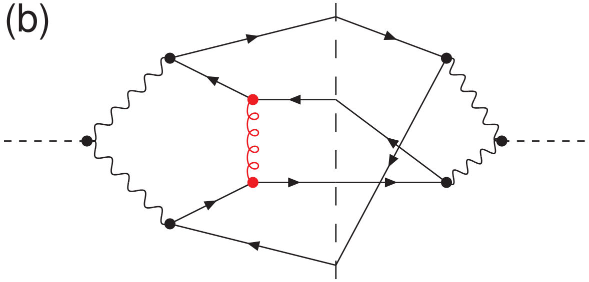
Classification of QCD corrections into four categories: (typical diagrams shown)

(a)

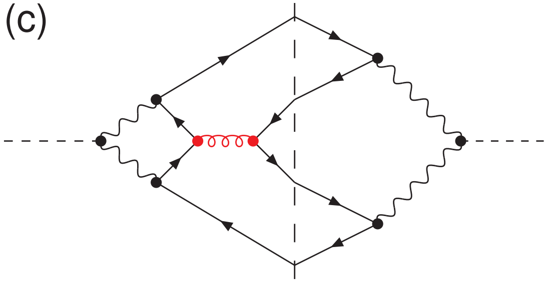


(d) only QCD correction without universal scaling $\propto s_{\beta-\alpha}$ from $\mathcal{M}_{\mathrm{SM}}$

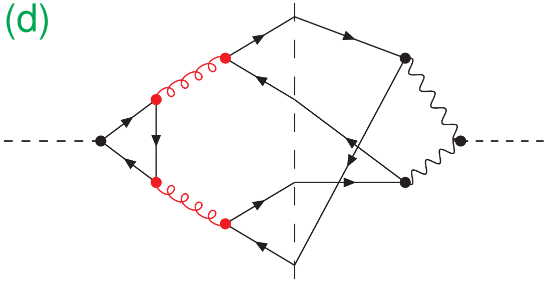
(b)



(c)



(d)



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

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

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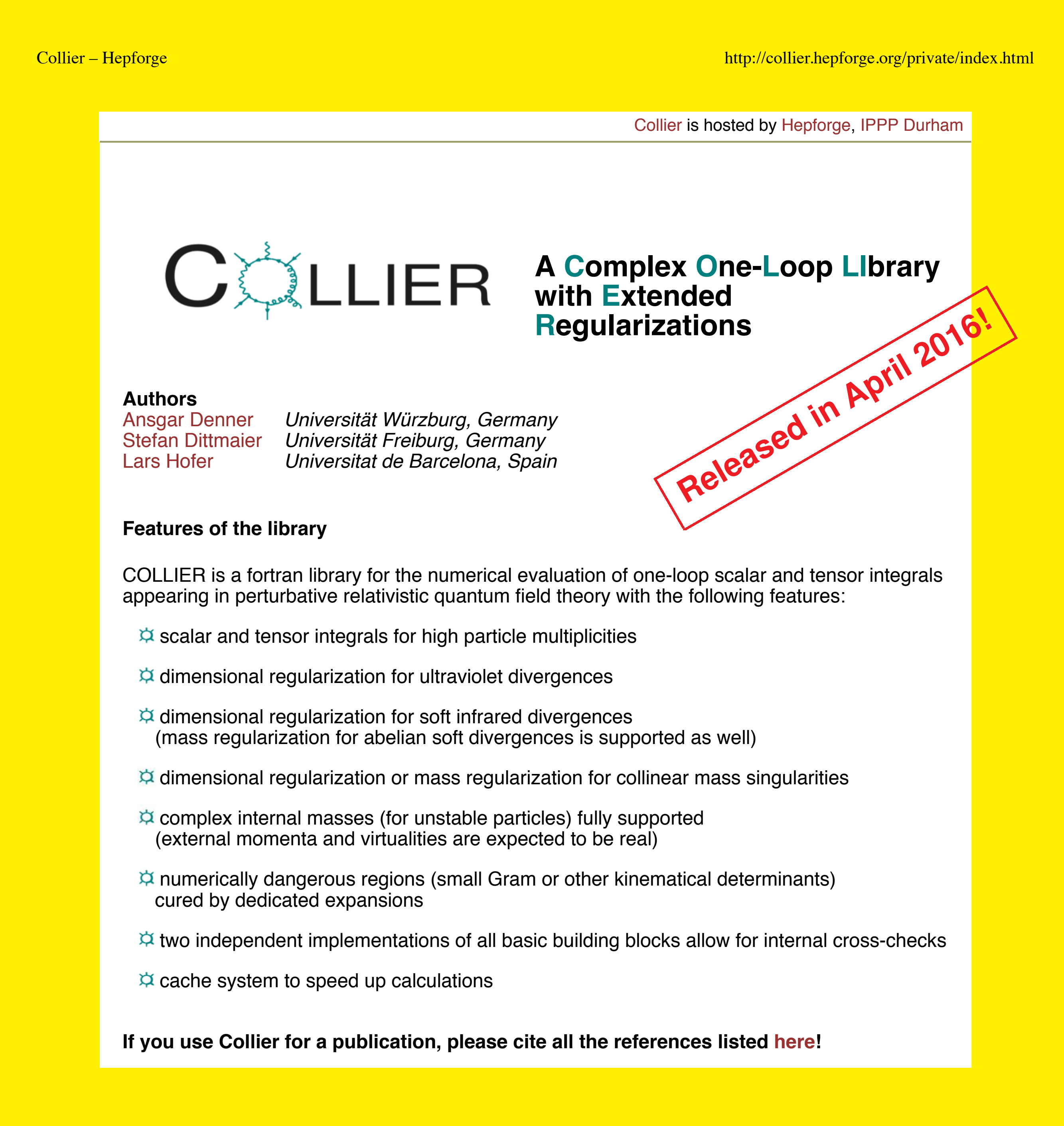

Collier – Hepforge

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!

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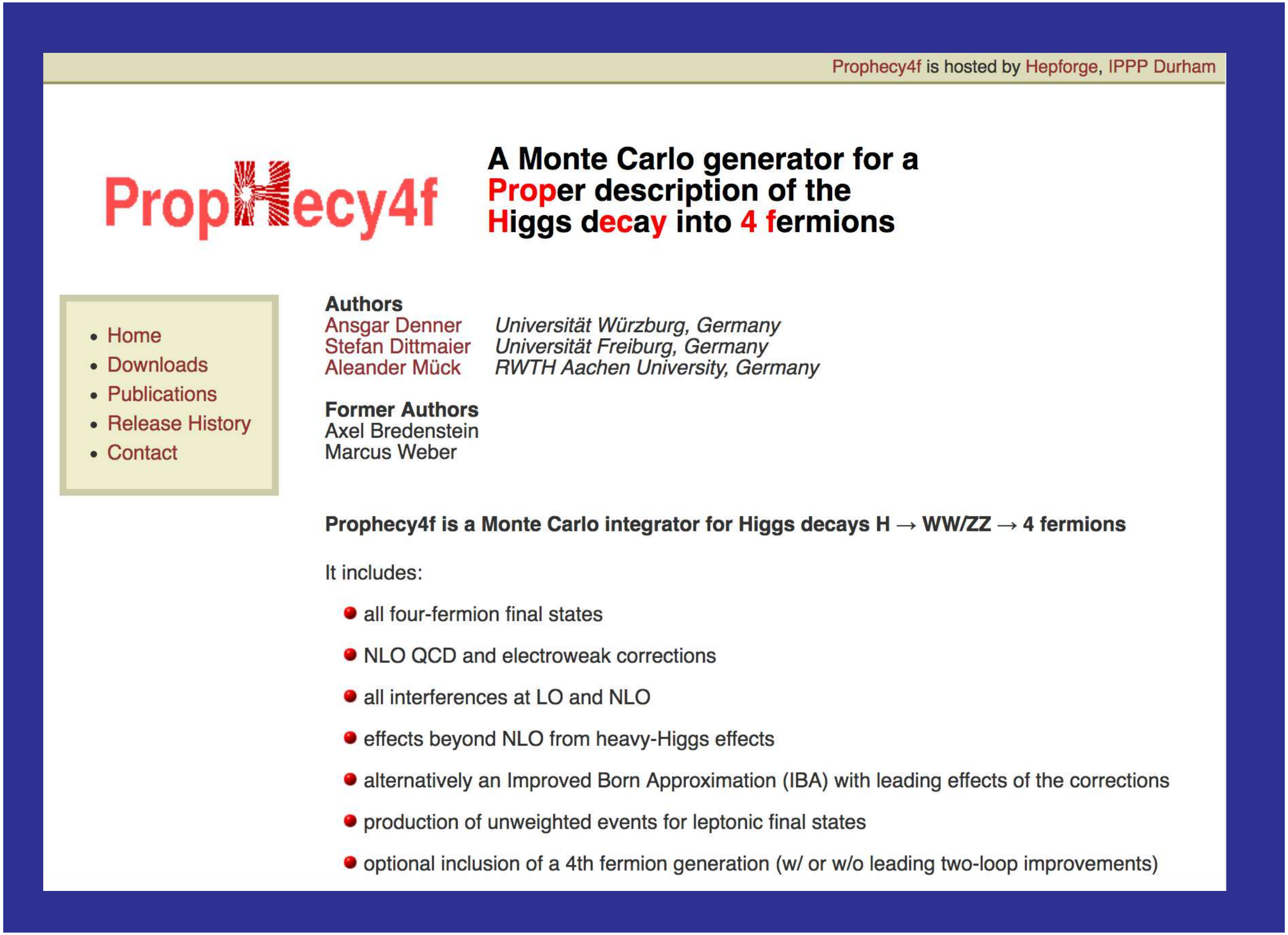
Two independent calculations of all ingredients

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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- Release History
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Marcus Weber

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

It includes:

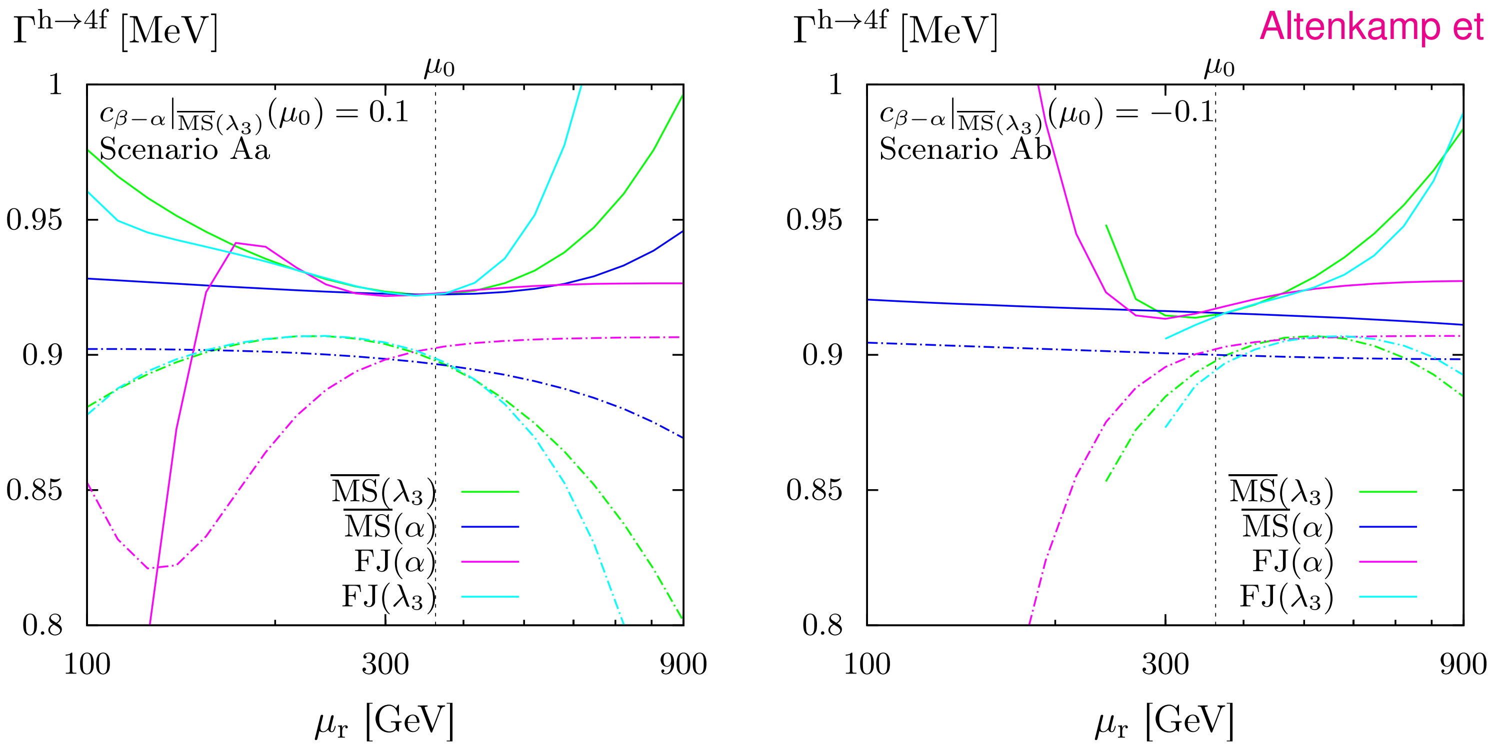
- all four-fermion final states
- NLO QCD and electroweak corrections
- all interferences at LO and NLO
- effects beyond NLO from heavy-Higgs effects
- alternatively an Improved Born Approximation (IBA) with leading effects of the corrections
- production of unweighted events for leptonic final states
- 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

Scale depencence of the $\mathrm{h}\to 4f$ 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

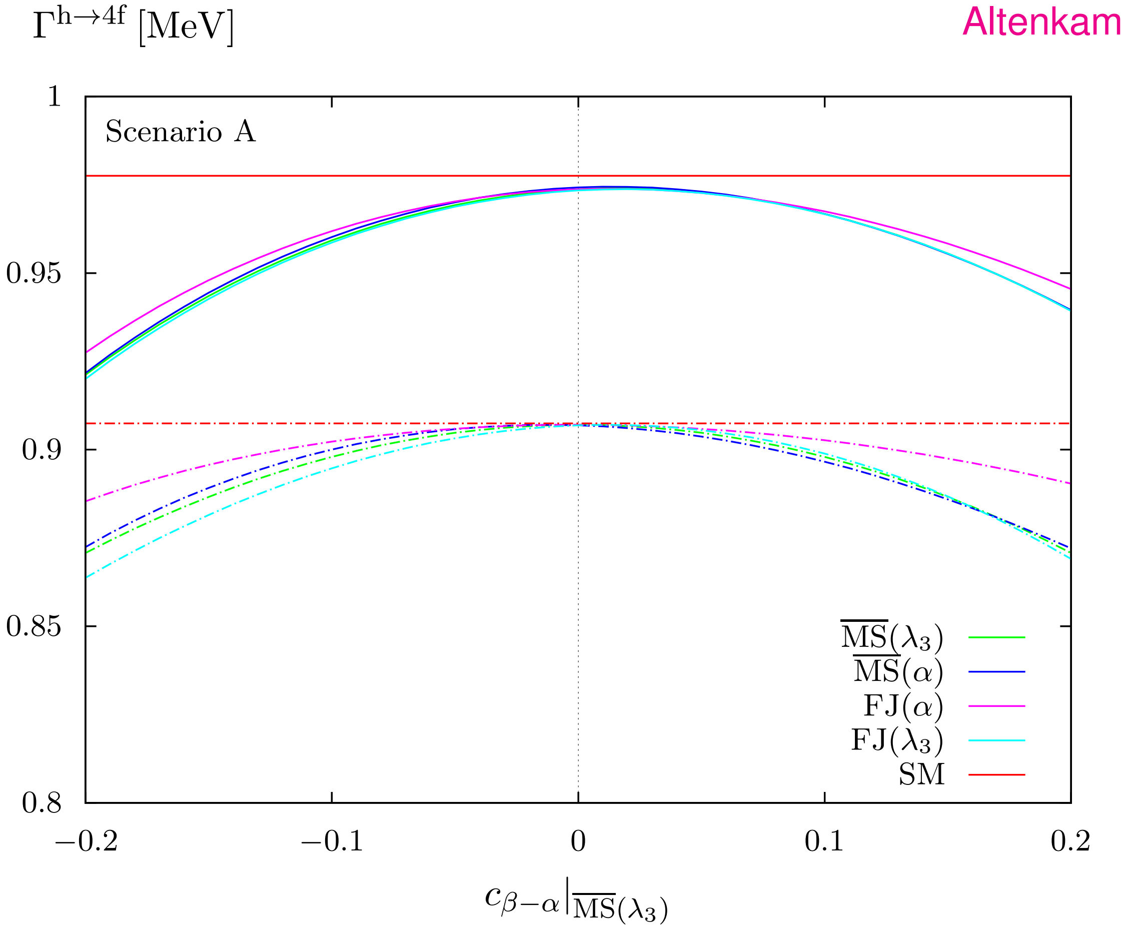
  Note: scale $\mu_\mathrm{r} = M_\mathrm{h}$ inappropriate

- 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

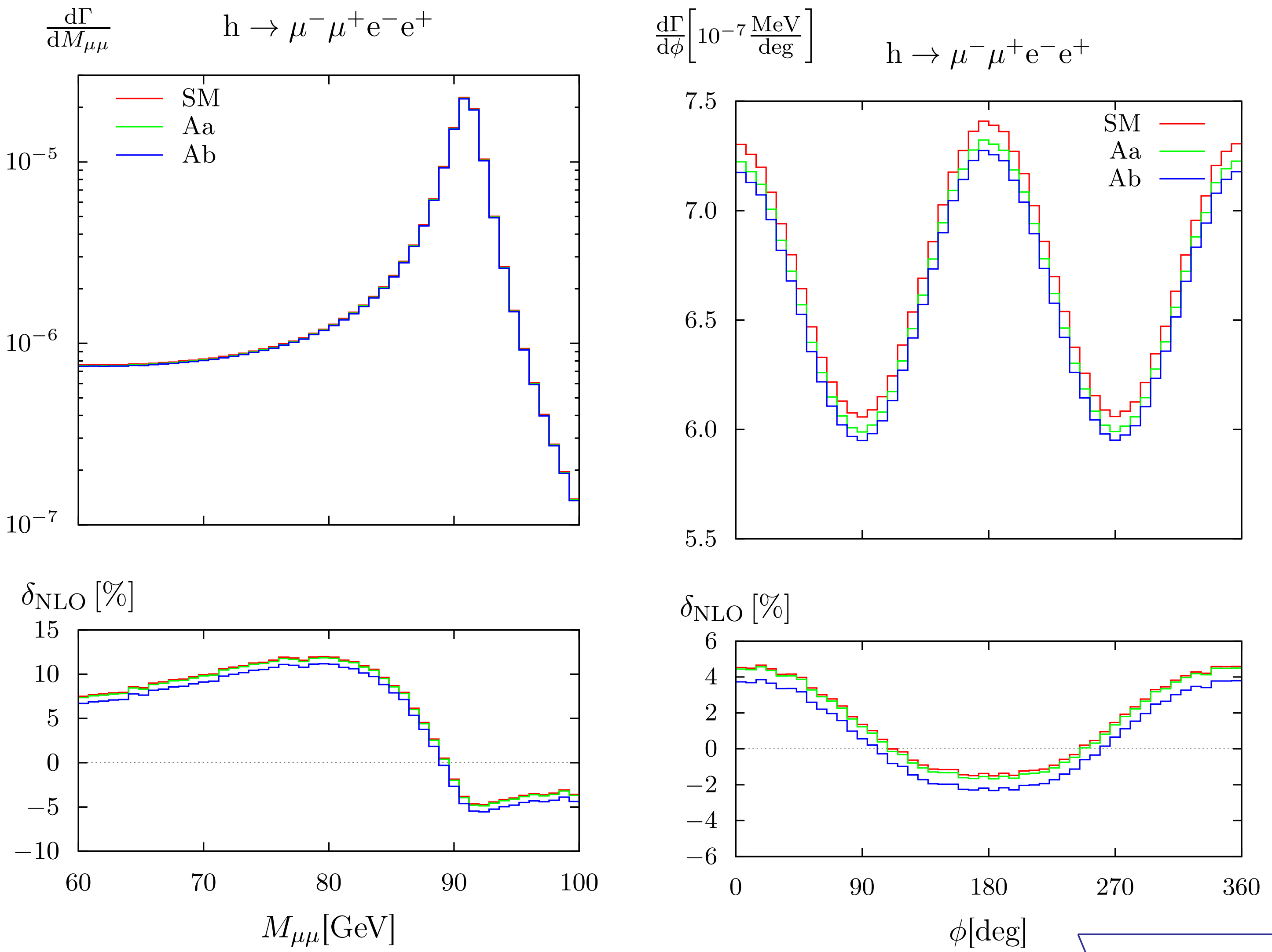
Altenkamp et al. ’17

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

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 $\mathrm{h}\to 4f$	0.967297	2.71	4.96	−1.05	−1.00
ZZ	0.106126	0.34	4.88	−1.13	−1.00
WW	0.866304	3.00	5.01	−1.04	−1.00
WW/ZZ int.	−0.005134	1.28	11.99	−0.51	−1.00
$\nu_{\mathrm{e}}\mathrm{e}^+\mu^-\bar{\nu}_\mu$	0.010201	3.03	0.00	−1.04	−1.00
$\nu_{\mathrm{e}}\mathrm{e}^+\mathrm{u}\bar{\mathrm{d}}$	0.031719	3.02	3.76	−1.04	−1.00
$\mathrm{u}\bar{\mathrm{d}}\mathrm{s}\bar{\mathrm{c}}$	0.098465	2.97	7.52	−1.04	−1.00
$\nu_{\mathrm{e}}\mathrm{e}^+\mathrm{e}^-\bar{\nu}_{\mathrm{e}}$	0.010197	3.12	0.00	−1.04	−1.00
$\mathrm{u}\bar{\mathrm{d}}\mathrm{d}\bar{\mathrm{u}}$	0.100473	2.85	7.35	−1.06	−1.00
$\nu_{\mathrm{e}}\bar{\nu}_{\mathrm{e}}\nu_\mu\bar{\nu}_\mu$	0.000949	3.01	0.00	−1.14	−1.00
$\mathrm{e}^-\mathrm{e}^+\mu^-\mu^+$	0.000239	1.30	0.00	−1.13	−1.00
$\nu_{\mathrm{e}}\bar{\nu}_{\mathrm{e}}\mu^-\mu^+$	0.000477	2.45	0.00	−1.13	−1.00
$\nu_{\mathrm{e}}\bar{\nu}_{\mathrm{e}}\nu_{\mathrm{e}}\bar{\nu}_{\mathrm{e}}$	0.000569	2.90	0.00	−1.14	−1.00
$\mathrm{e}^-\mathrm{e}^+\mathrm{e}^-\mathrm{e}^+$	0.000132	1.12	0.00	−1.12	−1.00
$\nu_{\mathrm{e}}\bar{\nu}_{\mathrm{e}}\mathrm{u}\bar{\mathrm{u}}$	0.001679	0.60	3.76	−1.12	−1.00
$\nu_{\mathrm{e}}\bar{\nu}_{\mathrm{e}}\mathrm{d}\bar{\mathrm{d}}$	0.002177	1.69	3.76	−1.12	−1.00
$\mathrm{e}^-\mathrm{e}^+\mathrm{u}\bar{\mathrm{u}}$	0.000845	0.11	3.76	−1.12	−1.00
$\mathrm{e}^-\mathrm{e}^+\mathrm{d}\bar{\mathrm{d}}$	0.001088	0.47	3.76	−1.12	−1.00
$\mathrm{u}\bar{\mathrm{u}}\mathrm{c}\bar{\mathrm{c}}$	0.002971	−1.80	7.51	−1.11	−1.00
$\mathrm{d}\bar{\mathrm{d}}\mathrm{d}\bar{\mathrm{d}}$	0.002556	−0.38	4.38	−1.21	−1.00
$\mathrm{d}\bar{\mathrm{d}}\mathrm{s}\bar{\mathrm{s}}$	0.004956	−0.36	7.51	−1.12	−1.00
$\mathrm{u}\bar{\mathrm{u}}\mathrm{s}\bar{\mathrm{s}}$	0.003852	−0.66	7.51	−1.11	−1.00
$\mathrm{u}\bar{\mathrm{u}}\mathrm{u}\bar{\mathrm{u}}$	0.001506	−1.92	4.06	−1.24	−1.00

NLO corrections to leptonic distributions in scenario A

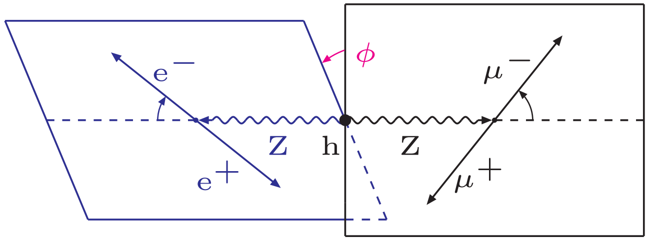
Altenkamp et al. ’17



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

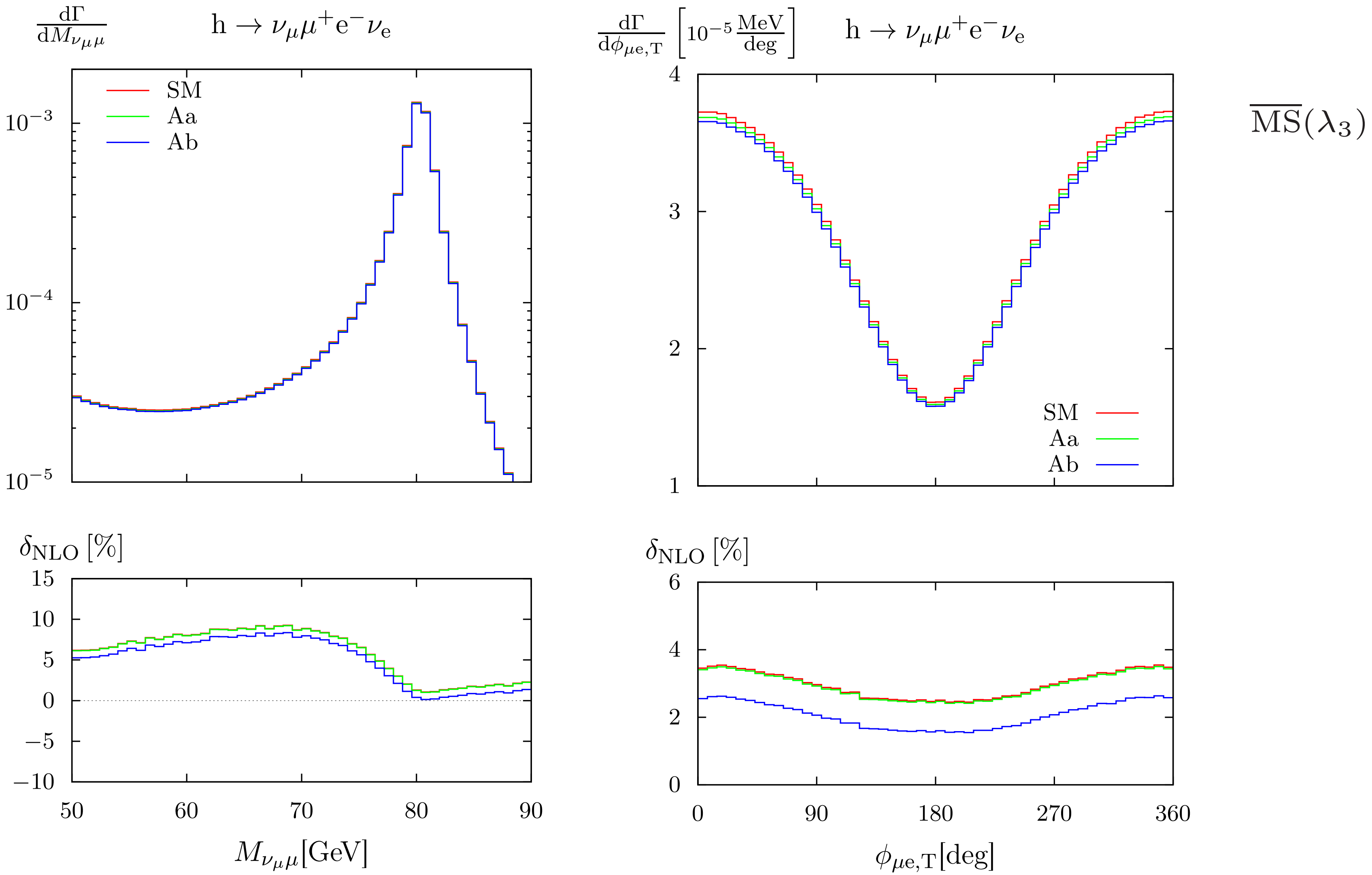
correction $\delta_{\text{THDM}} \approx \delta_{\text{SM}} + \text{const.}$

mainly due to external hH mixing



NLO corrections to leptonic distributions in scenario A

Altenkamp et al. ’17



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

mainly due to external hH mixing

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

Conclusions

NLO corrections in the THDM

- in principle straightforward with techniques used in the SM
- renormalization involves some issues
  - ◇ choice of input parameters, which ones in $\overline{\mathrm{MS}}$?
  - ◇ gauge dependences, perturbative stability, etc.

↪ several schemes proposed and applied in recent literature

$\mathrm{h} \to \mathrm{WW/ZZ} \to 4f$ at NLO in the THDM

- results presented for a low-mass scenario $(M_{\mathrm{H,A_0,H^+}} \sim 300{-}460\,\mathrm{GeV})$
  - ◇ $|\mathrm{THDM} - \mathrm{SM}| \lesssim 5\%$ for viable THDM parameters $c_{\beta-\alpha}$
  - ◇ significant reduction in ren. scale and scheme dependence for LO → NLO
  - ◇ no further distortion of distributions in SM → THDM at NLO
  - ◇ no sensitivity of $\mathrm{h} \to 4f$ to the type of THDM
- results for large $M_{\mathrm{H,A_0,H^+}}$ in preparation
  - ◇ results generically similar
  - ◇ but: pathologies for scenarios near exp. exclusion and theoretical bounds

Outlook: similar studies for SM singlet extensions

↪ work in progress within HiggsTools with Michele Boggia (ESR in Freiburg)

Backup slides

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

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

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 $\mathrm{h}\to 4f$	0.959800	1.87	4.97	−1.82	−1.00
ZZ	0.105464	−0.34	4.90	−1.75	−1.00
WW	0.859376	2.14	5.01	−1.83	−1.00
WW/ZZ int.	−0.005040	0.51	10.70	−2.32	−1.00
$\nu_\mathrm{e}\mathrm{e}^+\mu^-\bar{\nu}_\mu$	0.010116	2.17	0.00	−1.87	−1.00
$\nu_\mathrm{e}\mathrm{e}^+\mathrm{u}\bar{\mathrm{d}}$	0.031463	2.16	3.76	−1.84	−1.00
$\mathrm{u}\bar{\mathrm{d}}\mathrm{s}\bar{\mathrm{c}}$	0.097695	2.11	7.52	−1.81	−1.00
$\nu_\mathrm{e}\mathrm{e}^+\mathrm{e}^-\bar{\nu}_\mathrm{e}$	0.010112	2.27	0.00	−1.87	−1.00
$\mathrm{u}\bar{\mathrm{d}}\mathrm{d}\bar{\mathrm{u}}$	0.099720	1.99	7.38	−1.80	−1.00
$\nu_\mathrm{e}\bar{\nu}_\mathrm{e}\nu_\mu\bar{\nu}_\mu$	0.000943	2.34	0.00	−1.78	−1.00
$\mathrm{e}^-\mathrm{e}^+\mu^-\mu^+$	0.000237	0.62	0.00	−1.79	−1.00
$\nu_\mathrm{e}\bar{\nu}_\mathrm{e}\mu^-\mu^+$	0.000474	1.78	0.00	−1.78	−1.00
$\nu_\mathrm{e}\bar{\nu}_\mathrm{e}\nu_\mathrm{e}\bar{\nu}_\mathrm{e}$	0.000565	2.23	0.00	−1.79	−1.00
$\mathrm{e}^-\mathrm{e}^+\mathrm{e}^-\mathrm{e}^+$	0.000131	0.45	0.00	−1.78	−1.00
$\nu_\mathrm{e}\bar{\nu}_\mathrm{e}\mathrm{u}\bar{\mathrm{u}}$	0.001668	−0.08	3.76	−1.76	−1.00
$\nu_\mathrm{e}\bar{\nu}_\mathrm{e}\mathrm{d}\bar{\mathrm{d}}$	0.002163	1.02	3.76	−1.76	−1.00
$\mathrm{e}^-\mathrm{e}^+\mathrm{u}\bar{\mathrm{u}}$	0.000840	−0.57	3.76	−1.77	−1.00
$\mathrm{e}^-\mathrm{e}^+\mathrm{d}\bar{\mathrm{d}}$	0.001081	−0.21	3.76	−1.76	−1.00
$\mathrm{u}\bar{\mathrm{u}}\mathrm{c}\bar{\mathrm{c}}$	0.002952	−2.48	7.51	−1.75	−1.00
$\mathrm{d}\bar{\mathrm{d}}\mathrm{d}\bar{\mathrm{d}}$	0.002545	−1.06	4.57	−1.67	−1.00
$\mathrm{d}\bar{\mathrm{d}}\mathrm{s}\bar{\mathrm{s}}$	0.004925	−1.04	7.51	−1.74	−1.00
$\mathrm{u}\bar{\mathrm{u}}\mathrm{s}\bar{\mathrm{s}}$	0.003828	−1.35	7.51	−1.74	−1.00
$\mathrm{u}\bar{\mathrm{u}}\mathrm{u}\bar{\mathrm{u}}$	0.001500	−2.60	4.31	−1.65	−1.00

NLO corrections to semileptonic distributions in scenario A

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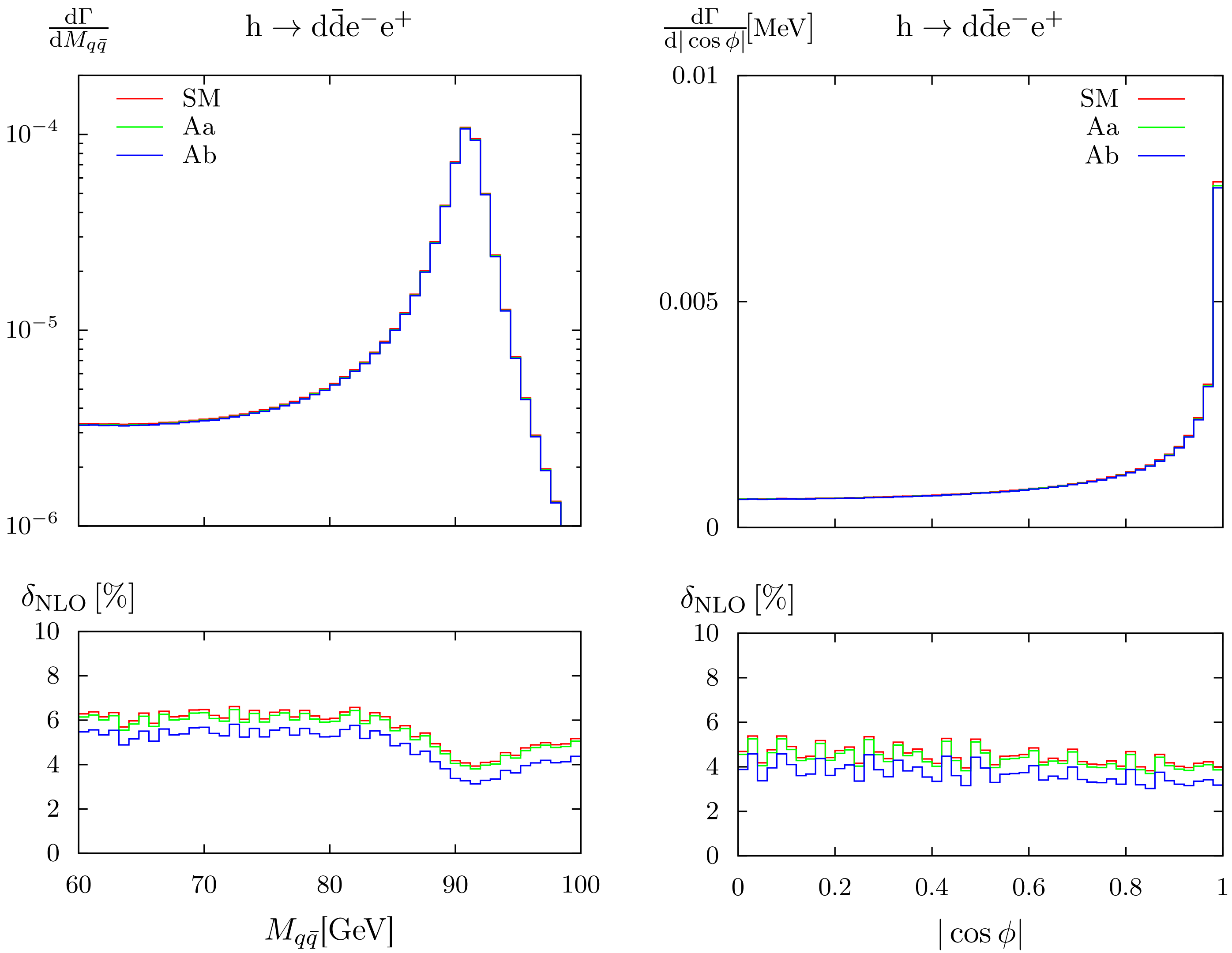

$\overline{\mathrm{MS}}(\lambda_3)$

NLO corrections to semileptonic distributions in scenario A

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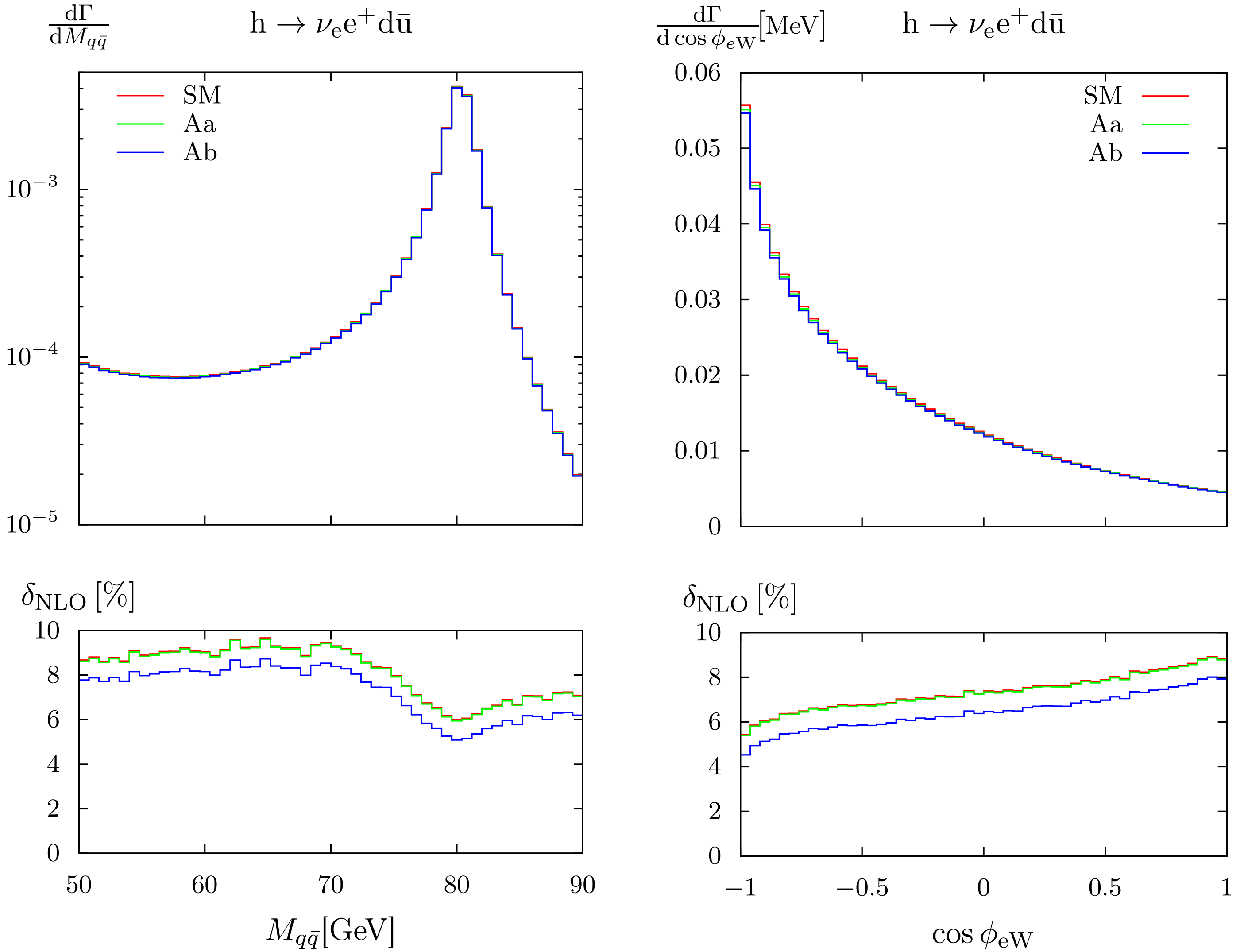

$\overline{\text{MS}}(\lambda_3)$