Review on Higgs Calculators

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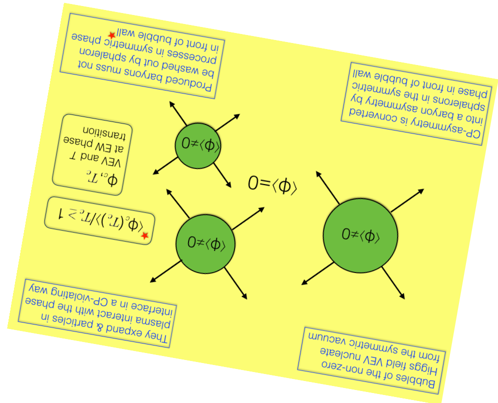
IP2I Lyon

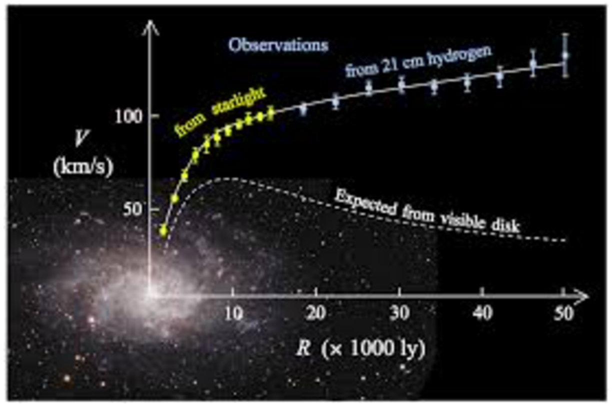
Tools 2020

Tools for High Energy Physics and Cosmology

(BSM) Precision Codes around the Higgs Boson

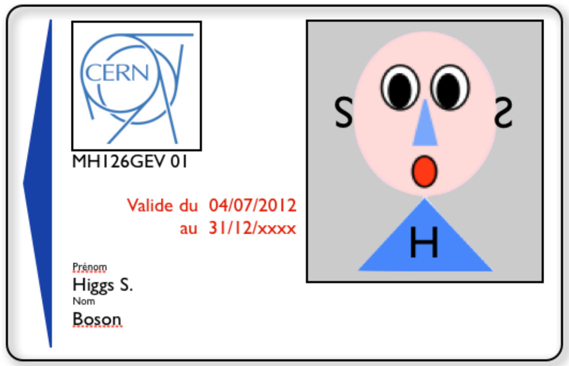
✦ Need of beyond-the-SM (BSM) Higgs physics:
Unsolved puzzles in the SM call
for Higgs sector extensions





✦ Extended Higgs sectors: provide Dark Matter (DM) candidates, additional sources of CP violation, enable successful baryogenesis, alleviate metastability

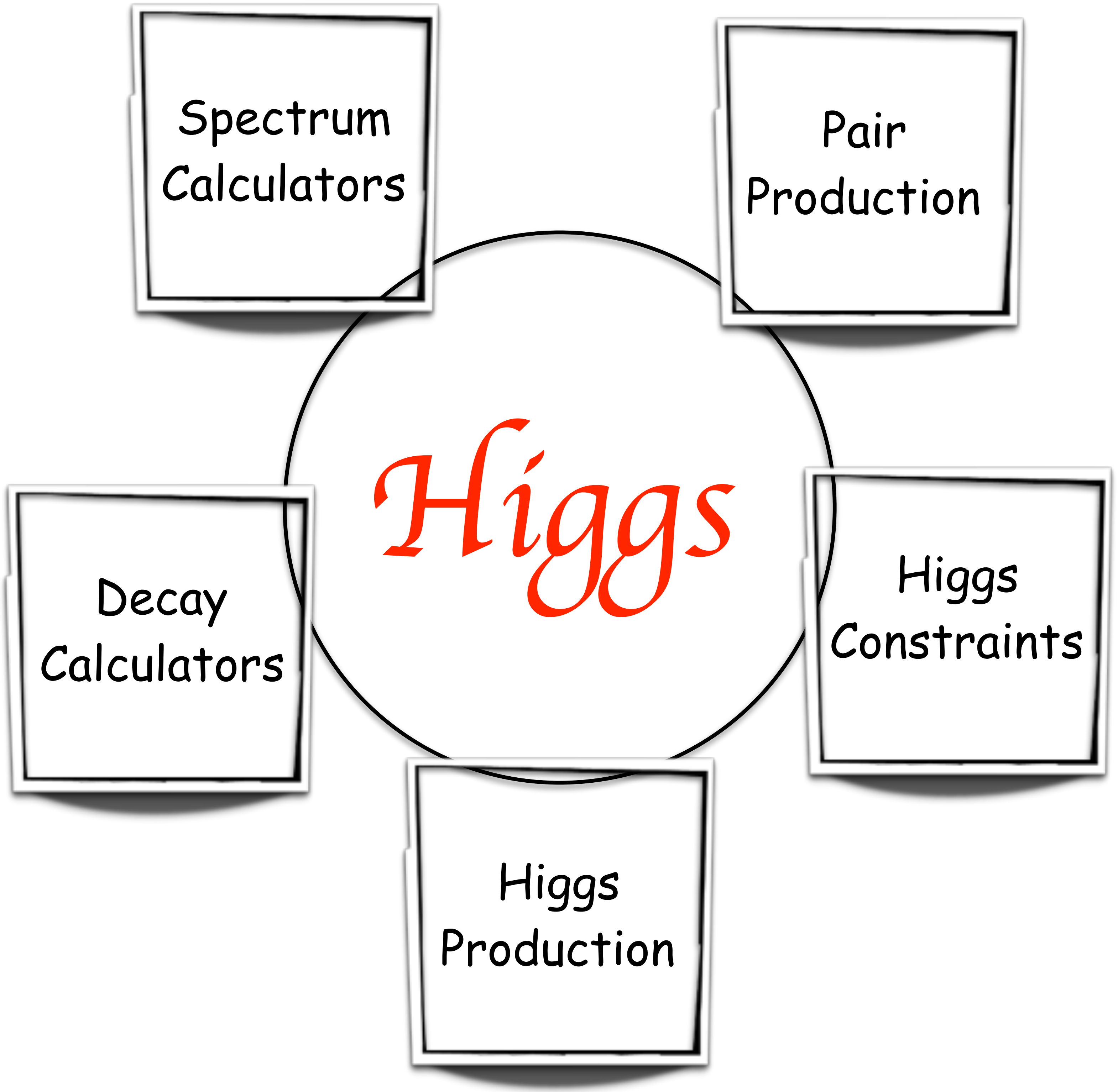
✦ Why precision calculations?



- No direct sign of new physics yet, but we have the Higgs boson
  -> indirect search for new physics in the Higgs sector
- Higgs boson behaves very SM-like -> new physics effects are small
- different new physics models lead to similar effects
- We have to check if our models are still valid <- theoretical and experimental constraints
  How are they affected by higher-order corrections?

✦ How select our models?
- effective field theory (EFT) valid for new physics scales much larger than electroweak scale
- investigate specific UV complete models to be sensitive to light resonances

Topics


Spectrum Calculators
Pair Production
Higgs
Decay Calculators
Higgs Constraints
Higgs Production

Disclaimer

The codes presented in the following are necessarily only a selection

There are many more codes on the market

A good overview of Higgs codes can be obtained from the Higgs Cross Section Working Group reports

My sincere apologies to all those codes not mentioned here


Spectrum
Calculators

The Role of the Higgs Boson Mass

✦ Higgs mass accuracy: [ATLAS,CMS, Phys.Rev.Lett.114(2015)191803]

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

✦ Why precision?

* Self-consistency of SM at quantum level (e.g. Higgs loop corrections to W boson mass)

* M_H <-> stability of electroweak vacuum [Degrassi eal;Bednyakov eal]

* Higgs mass uncertainty feeds back in uncertainty on Higgs observables

* Test parameter relations in beyond-the-SM theories
  -> indirect constraints of beyond-SM (BSM) parameters space

✦ MSSM and NMSSM computed from input parameters: predictive power of the MSSM, NMSSM and other extensions -> important experimental test to be passed

SUSY Higgs Masses

- **Supersymmetry:** requires at least 2 complex Higgs doublets

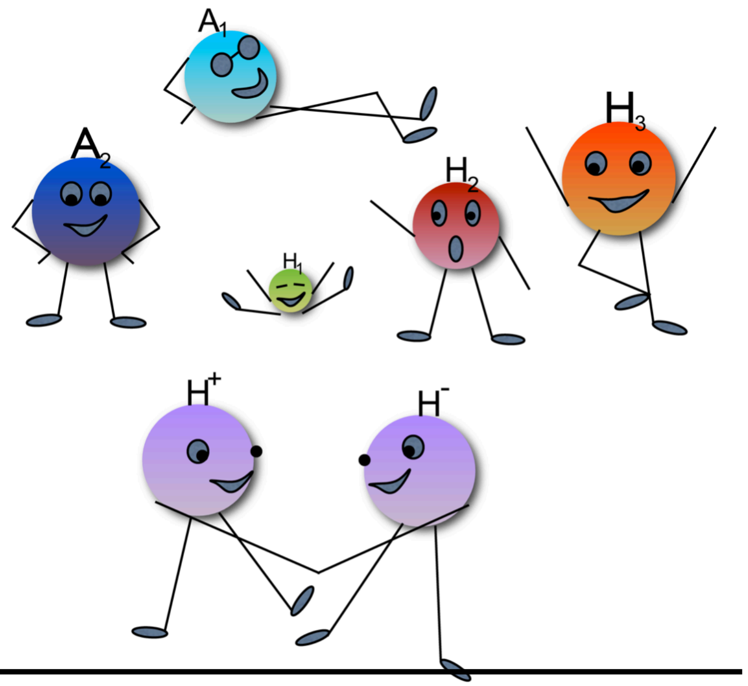
- **Minimal Supersymmetric extension (MSSM):** 2 complex Higgs doublets

5 Higgs bosons:	*h, H, A, H*$^+$*, H*$^-$
4 neutralinos:	$\tilde{\chi}_i^0$ $(i = 1, ..., 4)$

- **Next-to-MSSM (NMSSM):** 2 complex Higgs doublets plus complex singlet field

- **Enlarged Higgs and neutralino sector:**

7 Higgs bosons:	$H_1, H_2, H_3, A_1, A_2, H^+, H^-$
5 neutralinos:	$\tilde{\chi}_i^0$ $(i = 1, ..., 5)$



Spectrum Calculations

❖ Methods for Higgs mass calculations: fixed-order (FO) - effective field theory (EFT) - hybrid

- FO: full (N)MSSM perturb. series truncated at fixed order reliable for not too heavy SUSY masses
- EFT: some very heavy SUSY masses: large logarithms require resummation
- hybrid: combines virtues of fixed order and EFT calculation

❖ Status MSSM spectrum calculations:

FO: up to 2-loop in on-shell (OS) and DR scheme, partial 3-loop in DR scheme

EFT: up to N^2LL (included in calculators), N^3LL (recently [Harlander eal,'18])

❖ Status NMSSM spectrum calculations:

up to 2-loop in mixed OS-DR scheme and in DR-scheme

MSSM Spectrum Calculators

FO - fixed order; LL - leading log; NLL - next-to-leading log; ...; RPV - R-parity violating; CPV - CP-violating, NMFV - -non-minimal flavour violation

- Himalaya [Harlander,Kant,Mihaila,Steinhauser]: FO full 1L, 2L $O((\alpha_t+\alpha_b)^2+(\alpha_t+\alpha_b)\alpha_s+\alpha_\tau\alpha_b+\alpha_\tau^2)$, 3L up to $O((\alpha_t+\alpha_b)\alpha_s^2)$, N^3LL resummation coefficient for EFT approach, link to FlexibleSUSY
- FeynHiggs [Bahl,Hahn,Heinemeyer,Hollik,Paßehr,Rzehak,Sobolev,Weiglein]: CP-conserving FO: full 1L, up to 2L $O(\alpha_t\alpha_s,\alpha_b\alpha_s,\alpha_t^2,\alpha_t\alpha_b,\alpha_b^2)$ in mixed OS-DR scheme, CP-violating FO: full 1L, 2L $O(\alpha_t\alpha_s,\alpha_t^2)$, NMFV at 1L, EFT (2HDM) full LL & NLL resummation, $O(\alpha_t,\alpha_s)$ NNLL resummation, hybrid approach, overview updates in [1811.09073], estimate of mass uncertainty in [1912.04199]; link to Himalaya and EFT w/ complex phases implemented and to be released soon
- FlexibleSUSY [Athron,Bach,Harries,Kotlarski,Kwasnitza,Park,Stöckinger,Voigt,Ziebell]: MSSM& non-minimal versions, FO: up to 3L via Himalaya, pure EFT: $N^3LO + N^3LL$, hybrid: full NLO + NNLO $O(\alpha_t\alpha_s,\alpha_t^2)$ and full NLL + NNLL $O(\alpha_t\alpha_s,\alpha_t^2)$; split SUSY - pure EFT: 3L RGEs, 2L matching, 3L self-energy; best result, see [2003.04639]

*** For details and further new developments, see talk by W. Kotlarski ***

- CPsuperH [Lee,Pilaftsis,Carena,Choi,Drees,Ellis,Wagner]: CPV MSSM, FO 2L RG-improved

MSSM Spectrum Calculators

- SOFTSUSY [Allanach,Athron,Bednyiakov,Bernhardt,Cridge,Grellscheid,Hanussek,Kom,Martin,Robertson,RuizdeAustri,Slavich, Tunstall,Voigt,Williams]: MSSM and RPV MSSM, FO DR: full 1-loop at $p^2 \neq 0$ for all Higgses, 2-loop up to $O(\alpha_t^2)$, $O(\alpha_b\alpha_\tau)$, $O(\alpha_b^2)$, $O(\alpha_t\alpha_s)$, $O(\alpha_b\alpha_s)$, $O(\alpha_t\alpha_b)$, $O(\alpha_\tau^2)$ at $p^2=0$ for m_h, m_H, m_A [courtesy of P.Slavich], link to Himalaya for $O((\alpha_t+\alpha_b)\alpha_s^2)$, estimate of mass uncertainty
- SPheno [Porod,Staub]: several MSSM variants (mSUGRA/CMSSM, AMSB, GMSB, NUHM1,NUHM2, seesaw, RPV,...), FO: full 1-loop, 2-loop effective potential $O((\alpha_t+\alpha_b)\alpha_s)$, $O(\alpha_t^2)$, $O(\alpha_b^2)$, $O(\alpha_\tau^2)$
- SuSpect [Djouadi,Kneur,Moultaka,Ughetto,Zerwas]: general MSSM, mSUGRA, GMSB, AMSB, FO exact 1L, dominant 2L in DR, C++ version since SuSpect3
- SARAH [Goodsell,Porod,Staub]: any renormalisable model, CPV included, FO: full 1L w/ momentum dependence+complete 2L tadpoles/masses in generalised effective potential limit at fixed momentum, also pole matching
- MhEFT [Draper,Lee,Wagner]: hybrid calculation, complete 1L & partial 2L threshold corrections at M_S, m_A and (2HDM type II, SM) RGEs at (2L, 3L)
- SUSYHD [Vega,Villadoro]: EFT; full NLL and gaugeless NNLL calculation in MSSM w/ all SUSY particles and heavy Higgs doublets integrated out at same scale; NLL calculation in original split-SUSY scenario w/ only one light Higgs doublet; DR and OS scheme; estimate of mass uncertainty

Generic Models

- FlexibleSUSY via FlexibleEFTHiggs [Athron,Bach,Harries,Kotlarski,Kwasnitza,Park,Stöckinger,Voigt,Ziebell]: hybrid:
  full 1L + 2L $\log^2$ plus 2L log plus NLL resummation at higher orders
  Remark: avoids double counting problem
- SPheno/SARAH [Goodsell,Porod,Staub] arbitrary particle content

MSSM: M_h to N^3LO+N^3LL

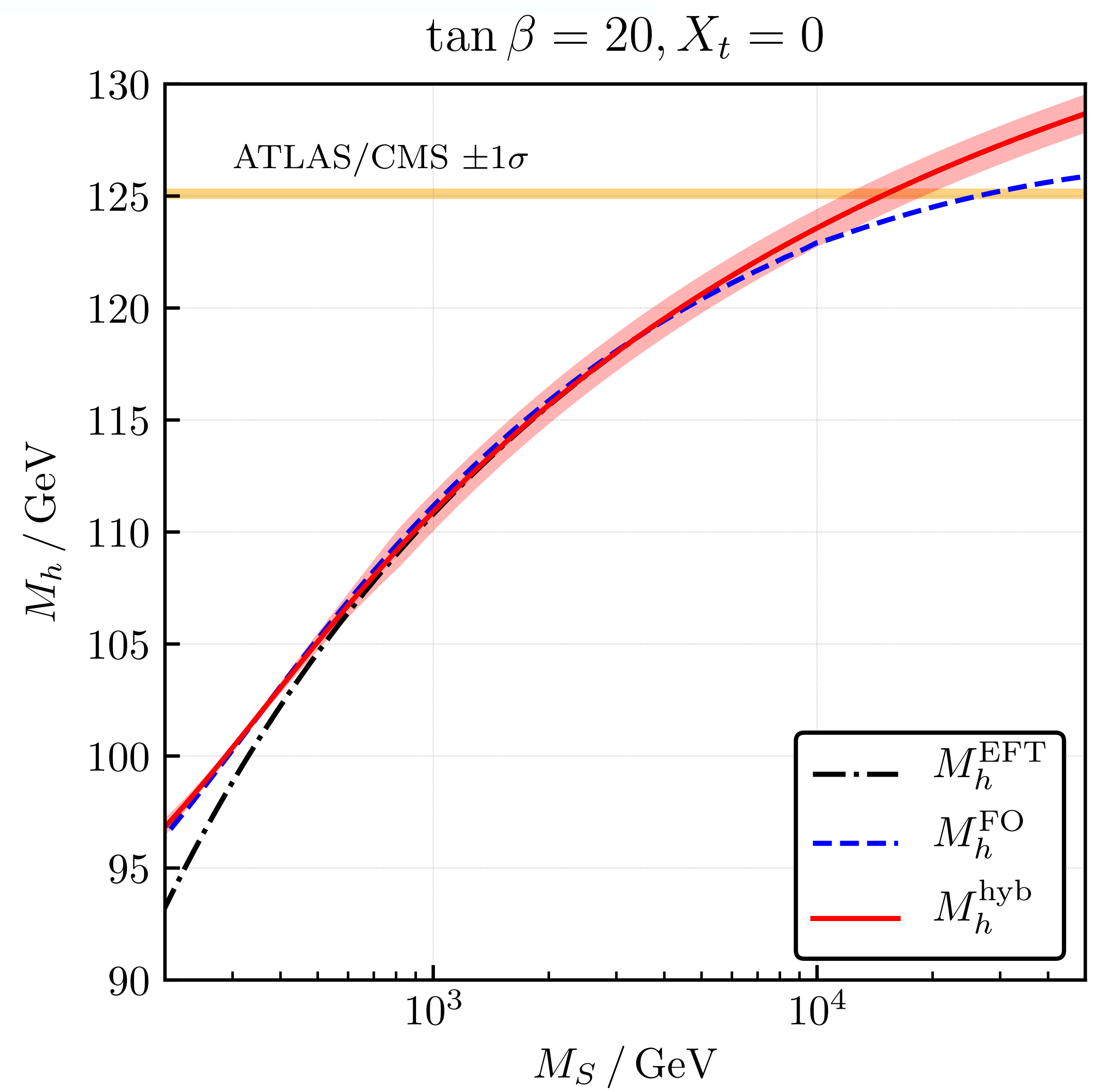
[Harlander,Klappert,Voigt,Eur.Phys.J.C80(2020)3]

Combination:

FlexibleSUSY+ Himalaya	HSSUSY+ Himalaya	FlexibleEFTHiggs
1-, 2-loop w/ O(v/Ms) 3-loop w/o O(v/Ms) w/o resummation	1-, 2-loop w/o O(v/Ms) 3-loop w/o O(v/Ms) w/ resummation	1-loop w/ O(v/Ms) w/ resummation

add O(v/Ms)

- hybrid FO+EFT result in DRbar scheme
- includes
  - tree-level + LL resummation
  - full 1-loop + NLL resummation
  - full $\alpha_t\alpha_s + \alpha_t^2$ + NNLL resummation
  - $\alpha_t\alpha_s^2$ w/o O(v/Ms) + N³LL resummation
- missing higher orders sizable at low Ms
- EFT sufficient above 1-2 TeV



NMSSM Spectrum Calculators

- FlexibleSUSY [Athron,Bach,Harries,Kotlarski,Kwasnitza,Park,Stöckinger,Voigt,Ziebell]: DR, FO & hybrid, through FlexibleEFTHiggs
- NMSSMCALC [Baglio,Dao,Gröber,MM,Rzehak,Spira,Streicher,Walz]: FO, real & complex NMSSM, DR and mixed OS-DR
- NMSSMTools [Ellwanger,Gunion,Hugonie]: FO, DR scheme
- SOFTSUSY [Allanach,Athron,Bednyakov,Tunstall,Voig,RuizdeAustri,Williams]: FO, DR scheme
- SPheno [Porod,Staub]: FO, DR scheme

<u>Remarks:</u>

- comparison of codes in DR scheme: [Staub,Athron,Ellwanger,Gröber,MM,Slavich,Voigt,'15] FlexibleSUSY,NMSSMCALC,NMSSMTools, SOFTSUSY,SPheno
- comparison of codes in mixed OS-DR scheme: [Drechsel,Gröber,Heinemeyer,MM,Rzehak,Weiglein,'16] FeynHiggs, NMSSMCALC
- solution of Goldstone boson catastrophe [Braathen,Goodsell,´16], [Braathen,Goodsell,Staub,'17]
- advances in FeynHiggs: [Drechsel,Galeta,Heinemeyer,Hollik,Liebler,Moortgat-Pick,Paßehr,Weiglein] real&complex NMSSM, GNMSSM: 1-loop in, 2-loop&resummation of HO log-effects only in MSSM limit, no public code yet
- OS masses CP-violating NMSSM, consistent description production/decay [Domingo,Drechsel,Paßehr]

taken from [Staub,Athron, Ellwanger,Gröber, MM,Slavich, Voigt,'15]

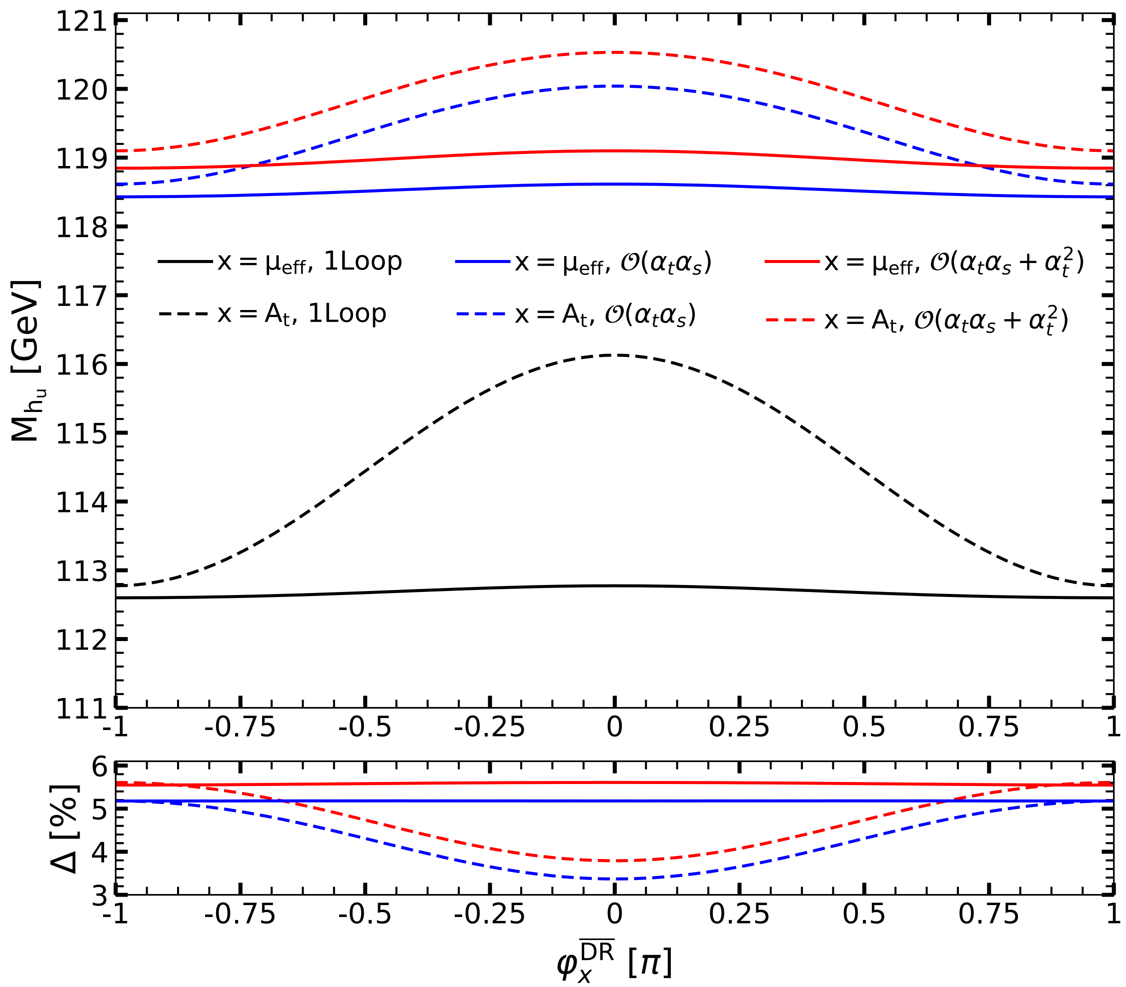
red: new since ´15

	FlexibleSUSY	NMSSMCALC	NMSSMTools	SOFTSUSY	SPheno
Code					
type	using SARAH	stand alone	stand alone	stand alone	using SARAH
language	C++	Fortran 77 and 90	Fortran 77	C++	Fortran 90
Models					
No $\mathbb{Z}_3$	✓	✗	✓	✓	✓
GUT model	✓	✗	✓	✓	✓
CPV	(✓)	✓	✓ (red, new)	✗	✓ (red, new)
Thresholds					
scale(s)	M_Z	$M_t\,, M_{SUSY}$	$M_t\,, M_{SUSY}$	M_Z	M_Z
EW parameters	full one-loop	OS definitions	full one-loop	full one-loop	full one-loop
Yukawas	full one-loop; two-loop QCD	one-loop (S)QCD; two-loop QCD	one-loop (S)QCD+Yukawa; two-loop QCD	full one-loop; two-loop QCD; optionally two-loop SQCD	full one-loop two-loop QCD
strong gauge	one-loop top+SUSY	—	—	one-loop top+SUSY	one-loop top+SUSY
Higgs mass calculation					
scheme	$\overline{\text{DR}}$	OS, $\overline{\text{DR}}$	$\overline{\text{DR}}$	$\overline{\text{DR}}$	$\overline{\text{DR}}$
one-loop	full	full	full	full	full
two-loop	$\alpha_s(\alpha_b+\alpha_t)$ + MSSM	$\alpha_s\alpha_t$ α_t^2 (red, new)	$\alpha_s(\alpha_b+\alpha_t)$ + MSSM	$\alpha_s(\alpha_b+\alpha_t)$ + MSSM	$\alpha_s\alpha_i+\alpha_i\alpha_j$.
SUSY masses					
one-loop	✓	✗	✓	✓	✓
momentum effects	✓	✗	✓ ($\alpha_s, \alpha_t, \alpha_b$ only)	✓	✓
Other observables					
decays	✗	✓	via NMHDECAY	via NMHDECAY	✓
flavour, $g-2$	✗	✗	✓	✗	✓

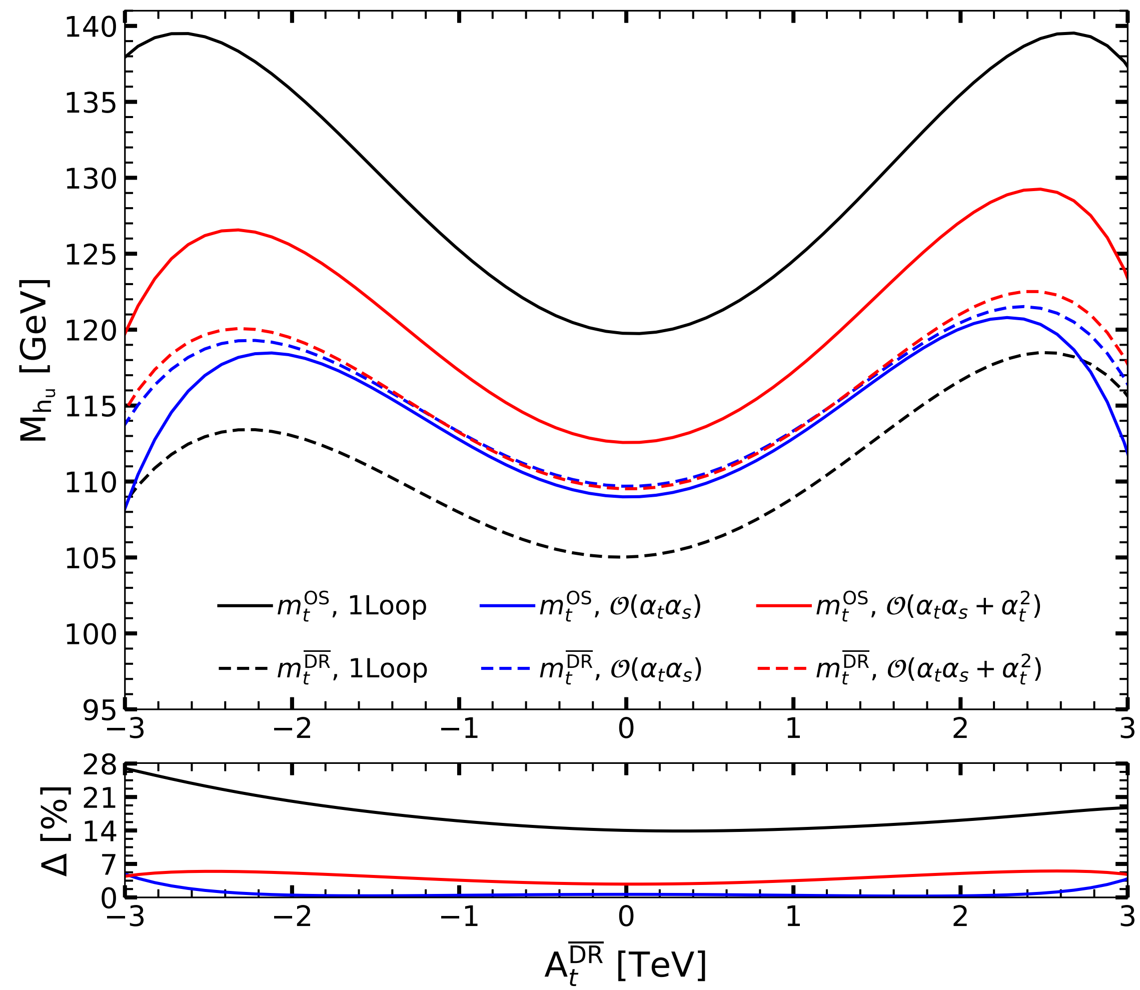
Results for $O(\alpha_t^2)$ Corrections

[Dao,Gröber,Krause,MM,Rzehak, JHEP08 (2019) 114]

Size of relative corrections



Renormalization scheme dependence



* tree-level CP-violating phase kept zero
* $\Delta = \frac{|M_{h_u}^{(2,x)} - M_{h_u}^{(1)}|}{M_{h_u}^{(1)}}$ and $x = \mathcal{O}(\alpha_t\alpha_s),\ \mathcal{O}(\alpha_t\alpha_s + \alpha_t^2)$

* $\Delta = \frac{|M_{h_u}^{m_t(\overline{DR})} - M_{h_u}^{m_t(OS)}|}{M_{h_u}^{m_t(\overline{DR})}}$

Decay Calculators

HDECAY and Variants

- HDECAY [Djouadi,Kalinowski,Spira,´97;,Djouadi,Kalinowski,MM,Spira,´18]:
  SM, MSSM, 2HDM decay widths and branching ratios

  * state-of-the-art HO QCD corrections in qq decays; full NLO mass effects & NNLO in heavy-top-limit to gluonic decays; full NLO mass effects in photonic decays; SUSY-QCD to decays into squarks; resummed SUSY-QCD & SUSY-EW corrections through Δ_b,, Δ_s, Δ_τ effects, also in H^+ decays; off-shell effects in decays into heavy quarks & WW/ZZ; SM: approximated EW to H->W*W*/Z*Z*->4f (within 1% of [Bredenstein,Denner,Dittmaier,Weber] ,[Boselli eal]), full EW to gluonic decay through grid [Actis,Passarino,Sturm,Uccirati];
  * for details on 2HDM decays, see [Harlander,MM,Rathsman,Spira,Stal'13]
  * Link to FeynHiggsFast [Heinemeyer,Hollik,Weiglein]
  * Links to SuSpect [Djouadi,Kneur,Moultaka,Ughetto,Zerwas] and SDECAY [MM,Djouadi,Mambrini] => SUSY-HIT [Djouadi,MM,Spira] to also calculate MSSM SUSY particle decays

Non-SUSY HDECAY Variants

Extensions of HDECAY to BSM Higgs sectors - QCD corrections can be transferred:

- sHDECAY [Costa,MM,Sampaio,Santos,'15]: real and complex singlet extension of the SM (RxSM, CxSM), both in dark matter and broken phase
- C2HDM_HDECAY [Fontes,MM,Romao,Santos,Silva,Wittbrodt] complex 2-Higgs-Doublet Model
- 2HDECAY [Krause,MM,Spira,1810.00768] EW corrections to 2HDM decays including state-of-the-art QCD corrections in different (gauge-independent) renormalization schemes [Krause,Lorenz,MM,Santos,Ziesche,1605.04853] including those of [Altenkamp,Dittmaier,Rzehak,1704.02645;Denner,Dittmaier,Lang,1808.03466]
- N2HDECAY [MM,Sampaio,Santos,Wittbrodt],N2HDM decays (doublet+singlet extension), in different phases (broken, dark singlet, dark doublet, dark singlet+doublet) [Engeln,MM,Wittbrodt]
- ewN2HDECAY [MM,Krause] EW corrections to 2HDM decays including state-of-the-art QCD corrections in different (gauge-independent) renormalization schemes [Krause,Lopez-Val,MM,Santos,1708.01578]
- eHDECAY [Contino,Ghezzi,Grojean,MM,Spira] EFT in linear and non-linear realization, composite Higgs (MCHM4, MCHM5), inclusion of QCD corrections, EW corrections to SM part only
- anyHDECAY [Wittbrodt] modern C++ interface to the HDECAY variants for scalar extensions

EW Corrections 2HDM and N2HDM

Impact of EW corrections on SM Higgs branching ratios $\Delta \mathrm{BR} = \dfrac{\mathrm{BR}^{\mathrm{QCD\&EW}} - \mathrm{BR}^{\mathrm{QCD}}}{\mathrm{BR}^{\mathrm{QCD}}}$ [HDECAY]

ΔBR	$b\bar{b}$	$\tau^+\tau^-$	$\mu^+\mu^-$	$s\bar{s}$	$c\bar{c}$	gg	$\gamma\gamma$	$Z\gamma$	W^+W^-	ZZ
	-1.76%	-1.59%	-3.52%	2.24%	-3.81%	4.34%	-2.29%	-0.71%	3.68%	1.61%

Example: Impact of EW corrections on branching ratios of SM-like 2HDM Higgs boson [Krause,MMM,JHEP04(2020)083]

Type	$\Delta\mathrm{BR}^{S_1}_{hb\bar{b}}$	$\Delta\mathrm{BR}^{S_2}_{hb\bar{b}}$	$\Delta\mathrm{BR}^{S_3}_{hb\bar{b}}$	$\Delta\mathrm{BR}^{\mathrm{OS2}}_{hb\bar{b}}$	$\Delta\mathrm{BR}^{\overline{\mathrm{MS}}}_{hb\bar{b}}$
I	$\lesssim 2.5\,\%$ (96 %)	$\lesssim 5.0\,\%$ (98 %)	$\lesssim 2.5\,\%$ (90 %)	$\lesssim 2.5\,\%$ (94 %)	$\lesssim 10.0\,\%$ (50 %)
	$\lesssim 5.0\,\%$ (100 %)	$\lesssim 7.5\,\%$ (99 %)	$\lesssim 5.0\,\%$ (99 %)	$\lesssim 5.0\,\%$ (99 %)	$\gtrsim 100.0\,\%$ (12 %)
II	$\lesssim 2.5\,\%$ (99 %)	$\lesssim 2.5\,\%$ (54 %)	$\lesssim 2.5\,\%$ (98 %)	$\lesssim 2.5\,\%$ (81 %)	$\lesssim 40.0\,\%$ (50 %)
	$\lesssim 5.0\,\%$ (100 %)	$\lesssim 7.5\,\%$ (96 %)	$\lesssim 5.0\,\%$ (99 %)	$\lesssim 5.0\,\%$ (99 %)	$\gtrsim 100.0\,\%$ (36 %)
LS	$\lesssim 2.5\,\%$ (96 %)	$\lesssim 2.5\,\%$ (54 %)	$\lesssim 2.5\,\%$ (75 %)	$\lesssim 2.5\,\%$ (94 %)	$\lesssim 17.5\,\%$ (50 %)
	$\lesssim 5.0\,\%$ (99 %)	$\lesssim 5.0\,\%$ (97 %)	$\lesssim 5.0\,\%$ (99 %)	$\lesssim 5.0\,\%$ (99 %)	$\gtrsim 100.0\,\%$ (14 %)
FL	$\lesssim 2.5\,\%$ (96 %)	$\lesssim 2.5\,\%$ (54 %)	$\lesssim 2.5\,\%$ (75 %)	$\lesssim 2.5\,\%$ (94 %)	$\lesssim 17.5\,\%$ (50 %)
	$\lesssim 5.0\,\%$ (99 %)	$\lesssim 5.0\,\%$ (97 %)	$\lesssim 5.0\,\%$ (99 %)	$\lesssim 5.0\,\%$ (99 %)	$\gtrsim 100.0\,\%$ (12 %)

Type	$\Delta\mathrm{BR}^{S_1}_{h\gamma\gamma/hZZ}$	$\Delta\mathrm{BR}^{S_2}_{h\gamma\gamma/hZZ}$	$\Delta\mathrm{BR}^{S_3}_{h\gamma\gamma/hZZ}$	$\Delta\mathrm{BR}^{\mathrm{OS2}}_{h\gamma\gamma/hZZ}$	$\Delta\mathrm{BR}^{\overline{\mathrm{MS}}}_{h\gamma\gamma/hZZ}$
I	$\lesssim 5.0\,\%$ (97 %)	$\lesssim 5.0\,\%$ (90 %)	$\lesssim 5.0\,\%$ (90 %)	$\lesssim 5.0\,\%$ (94 %)	$\lesssim 20.0\,\%$ (50 %)
	$\lesssim 7.5\,\%$ (99 %)	$\lesssim 10.0\,\%$ (98 %)	$\lesssim 7.5\,\%$ (99 %)	$\lesssim 7.5\,\%$ (99 %)	$\gtrsim 100.0\,\%$ (21 %)
II	$\lesssim 5.0\,\%$ (99 %)	$\lesssim 5.0\,\%$ (60 %)	$\lesssim 2.5\,\%$ (96 %)	$\lesssim 5.0\,\%$ (82 %)	$\lesssim 62.0\,\%$ (50 %)
	$\lesssim 7.5\,\%$ (99 %)	$\lesssim 12.5\,\%$ (96 %)	$\lesssim 5.0\,\%$ (99 %)	$\lesssim 7.5\,\%$ (97 %)	$\gtrsim 100.0\,\%$ (47 %)
LS	$\lesssim 5.0\,\%$ (97 %)	$\lesssim 5.0\,\%$ (75 %)	$\lesssim 2.5\,\%$ (88 %)	$\lesssim 5.0\,\%$ (95 %)	$\lesssim 12.5\,\%$ (50 %)
	$\lesssim 7.5\,\%$ (99 %)	$\lesssim 10.0\,\%$ (99 %)	$\lesssim 5.0\,\%$ (99 %)	$\lesssim 7.5\,\%$ (99 %)	$\gtrsim 100.0\,\%$ (13 %)
FL	$\lesssim 5.0\,\%$ (97 %)	$\lesssim 5.0\,\%$ (75 %)	$\lesssim 2.5\,\%$ (88 %)	$\lesssim 5.0\,\%$ (95 %)	$\lesssim 15.0\,\%$ (50 %)
	$\lesssim 7.5\,\%$ (99 %)	$\lesssim 10.0\,\%$ (99 %)	$\lesssim 5.0\,\%$ (99 %)	$\lesssim 7.5\,\%$ (99 %)	$\gtrsim 100.0\,\%$ (11 %)

Type	$\Delta\mathrm{BR}^{S_1}_{h\tau^+\tau^-}$	$\Delta\mathrm{BR}^{S_2}_{h\tau^+\tau^-}$	$\Delta\mathrm{BR}^{S_3}_{h\tau^+\tau^-}$	$\Delta\mathrm{BR}^{\mathrm{OS2}}_{h\tau^+\tau^-}$	$\Delta\mathrm{BR}^{\overline{\mathrm{MS}}}_{h\tau^+\tau^-}$
I	$\lesssim 2.5\,\%$ (98 %)	$\lesssim 2.5\,\%$ (88 %)	$\lesssim 2.5\,\%$ (97 %)	$\lesssim 2.5\,\%$ (98 %)	$\lesssim 7.5\,\%$ (50 %)
	$\lesssim 5.0\,\%$ (99 %)	$\lesssim 5.0\,\%$ (99 %)	$\lesssim 5.0\,\%$ (99 %)	$\lesssim 5.0\,\%$ (99 %)	$\gtrsim 100.0\,\%$ (12 %)

EW Corrections 2HDM and N2HDM

Impact of EW corrections on SM Higgs branching ratios $\Delta\text{BR} = \frac{\text{BR}^{\text{QCD\&EW}} - \text{BR}^{\text{QCD}}}{\text{BR}^{\text{QCD}}}$ [HDECAY]

ΔBR	$b\bar{b}$	$\tau^+\tau^-$	$\mu^+\mu^-$	$s\bar{s}$	$c\bar{c}$	gg	$\gamma\gamma$	$Z\gamma$	W^+W^-	ZZ
	-1.76%	-1.59%	-3.52%	2.24%	-3.81%	4.34%	-2.29%	-0.71%	3.68%	1.61%

Example: Impact of EW corrections on branching ratios of non-SM-like 2HDM Higgs boson

[Krause,MMM,JHEP04(2020)083]

Type	$\Delta\text{BR}^{S_1}_{H\tau^+\tau^-}$	$\Delta\text{BR}^{S_2}_{H\tau^+\tau^-}$	$\Delta\text{BR}^{S_3}_{H\tau^+\tau^-}$	$\Delta\text{BR}^{S_4}_{H\tau^+\tau^-}$	$\Delta\text{BR}^{\overline{\text{MS}}}_{H\tau^+\tau^-}$
I	$\lesssim$ 15.0 % (49 %)	$\lesssim$ 15.0 % (51 %)	$\lesssim$ 15.0 % (48 %)	$\lesssim$ 15.0 % (55 %)	$\lesssim$ 60.0 % (50 %)
	$\lesssim$ 35.0 % (88 %)	$\lesssim$ 35.0 % (88 %)	$\lesssim$ 35.0 % (77 %)	$\lesssim$ 35.0 % (88 %)	$\gtrsim$ 100.0 % (40 %)
II	$\lesssim$ 15.0 % (54 %)	$\lesssim$ 20.0 % (53 %)	$\lesssim$ 10.0 % (51 %)	$\lesssim$ 25.0 % (47 %)	$\lesssim$ 85.0 % (14 %)
	$\lesssim$ 25.0 % (91 %)	$\lesssim$ 30.0 % (90 %)	$\lesssim$ 35.0 % (90 %)	$\lesssim$ 40.0 % (86 %)	$\gtrsim$ 100.0 % (84 %)
LS	$\lesssim$ 15.0 % (54 %)	$\lesssim$ 17.5 % (48 %)	$\lesssim$ 7.5 % (46 %)	$\lesssim$ 25.0 % (46 %)	$\lesssim$ 77.5 % (15 %)
	$\lesssim$ 27.5 % (90 %)	$\lesssim$ 30.0 % (88 %)	$\lesssim$ 30.0 % (88 %)	$\lesssim$ 40.0 % (85 %)	$\gtrsim$ 100.0 % (81 %)
FL	$\lesssim$ 15.0 % (55 %)	$\lesssim$ 17.5 % (48 %)	$\lesssim$ 7.5 % (46 %)	$\lesssim$ 25.0 % (46 %)	$\lesssim$ 77.5 % (15 %)
	$\lesssim$ 27.5 % (90 %)	$\lesssim$ 30.0 % (88 %)	$\lesssim$ 30.0 % (88 %)	$\lesssim$ 40.0 % (85 %)	$\gtrsim$ 100.0 % (81 %)

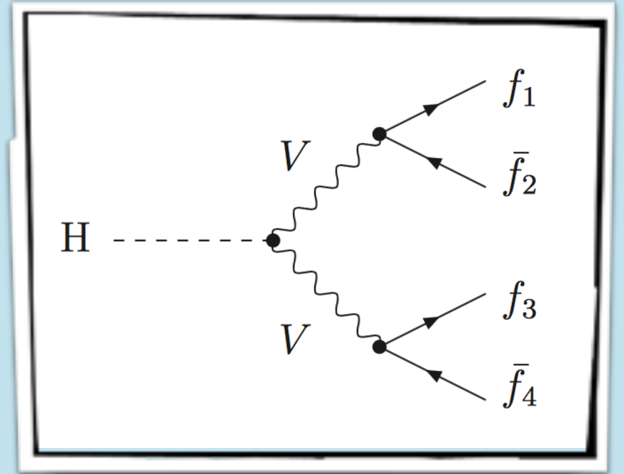
Type	$\Delta\text{BR}^{S_1}_{HZA}$	$\Delta\text{BR}^{S_2}_{HZA}$	$\Delta\text{BR}^{S_3}_{HZA}$	$\Delta\text{BR}^{S_4}_{HZA}$	$\Delta\text{BR}^{\overline{\text{MS}}}_{HZA}$
I	$\lesssim$ 5.0 % (51 %)	$\lesssim$ 5.0 % (51 %)	$\lesssim$ 10.0 % (46 %)	$\lesssim$ 10.0 % (53 %)	$\lesssim$ 80.0 % (26 %)
	$\lesssim$ 15.0 % (80 %)	$\lesssim$ 15.0 % (80 %)	$\lesssim$ 30.0 % (80 %)	$\lesssim$ 22.5 % (83 %)	$\gtrsim$ 100.0 % (52 %)
II	$\lesssim$ 5.0 % (68 %)	$\lesssim$ 5.0 % (69 %)	$\lesssim$ 10.0 % (50 %)	$\lesssim$ 7.5 % (73 %)	$\lesssim$ 85.0 % (20 %)
	$\lesssim$ 10.0 % (91 %)	$\lesssim$ 12.5 % (94 %)	$\lesssim$ 25.0 % (81 %)	$\lesssim$ 10.0 % (90 %)	$\gtrsim$ 100.0 % (56 %)
LS	$\lesssim$ 5.0 % (65 %)	$\lesssim$ 5.0 % (65 %)	$\lesssim$ 10.0 % (48 %)	$\lesssim$ 7.5 % (41 %)	$\lesssim$ 85.0 % (29 %)
	$\lesssim$ 10.0 % (86 %)	$\lesssim$ 10.0 % (86 %)	$\lesssim$ 27.5 % (80 %)	$\lesssim$ 15.0 % (90 %)	$\gtrsim$ 100.0 % (44 %)
FL	$\lesssim$ 5.0 % (65 %)	$\lesssim$ 5.0 % (63 %)	$\lesssim$ 10.0 % (53 %)	$\lesssim$ 7.5 % (51 %)	$\lesssim$ 82.5 % (20 %)
	$\lesssim$ 10.0 % (88 %)	$\lesssim$ 10.0 % (88 %)	$\lesssim$ 15.0 % (83 %)	$\lesssim$ 10.0 % (84 %)	$\gtrsim$ 100.0 % (30 %)

Type	$\Delta\text{BR}^{S_1}_{HW^\pm H^\mp}$	$\Delta\text{BR}^{S_2}_{HW^\pm H^\mp}$	$\Delta\text{BR}^{S_3}_{HW^\pm H^\mp}$	$\Delta\text{BR}^{S_4}_{HW^\pm H^\mp}$	$\Delta\text{BR}^{\overline{\text{MS}}}_{HW^\pm H^\mp}$
I	$\lesssim$ 5.0 % (56 %)	$\lesssim$ 5.0 % (55 %)	$\lesssim$ 10.0 % (49 %)	$\lesssim$ 10.0 % (57 %)	$\lesssim$ 70.0 % (25 %)
	$\lesssim$ 17.5 % (81 %)	$\lesssim$ 17.5 % (81 %)	$\lesssim$ 30.0 % (78 %)	$\lesssim$ 25.0 % (82 %)	$\gtrsim$ 100.0 % (52 %)

Further non-SUSY Decay Calculators

- PROPHECY 4F [Denner,Dittmaier,Mück]: based on Bredenstein ea´07;Altenkamp,Dittmaier, Rzehak,'17;Altenkamp,Boggia,Dittmaier,'18;Denner,Dittmaier,Lang,´18]

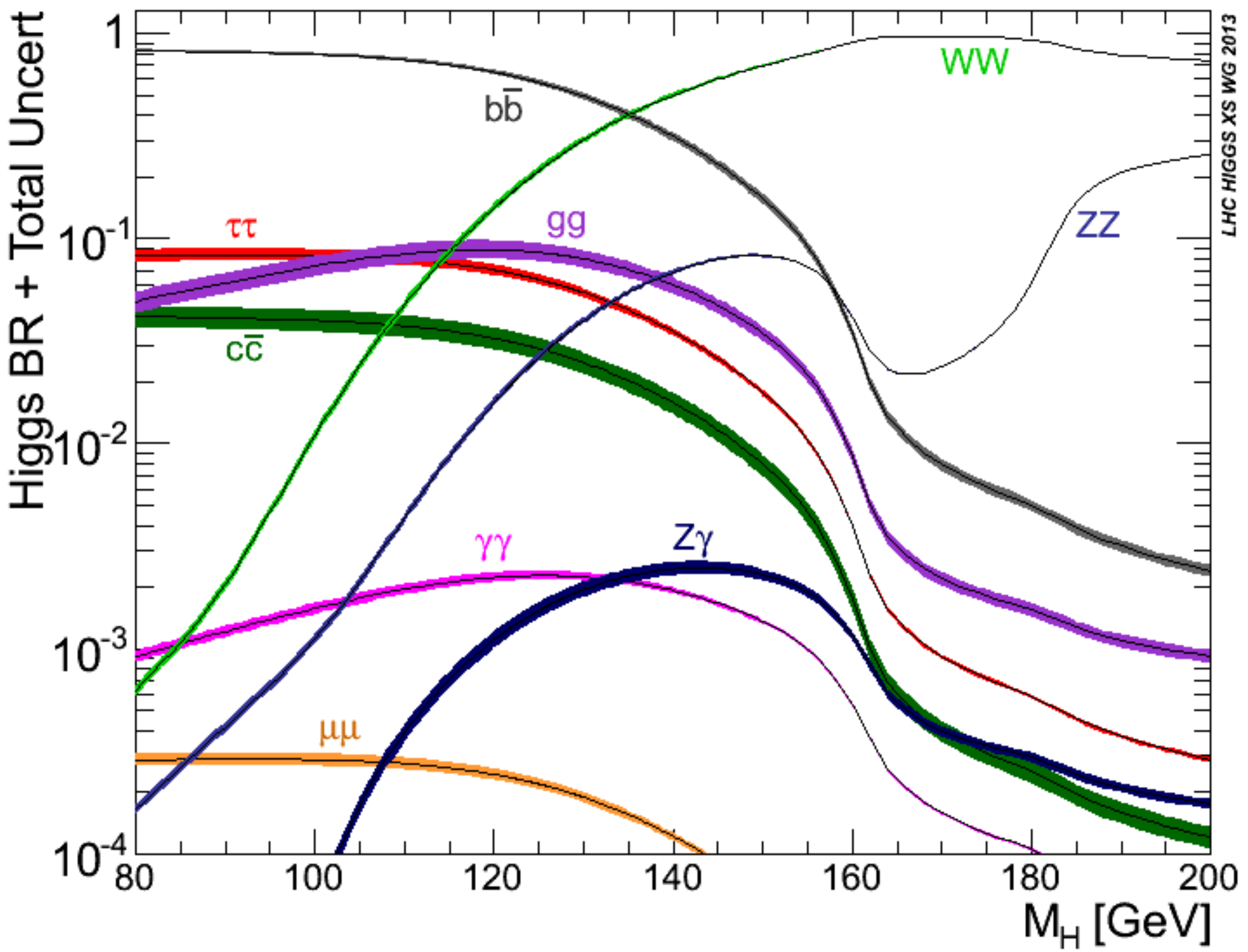
  Monte Carlo generator for H->W*W*/Z*Z*->4f with the SM, SESM, SM w/ 4th generation, 2HDM, including NLO EW and QCD corrections; fully differential predictions; supports many different renormalisation schemes; uses integral library COLLIER [Denner,Dittmaier,Hofer,´16];



- Recola [Denner,Lang,Uccirati] automated generation and numerical computation of tree and one-loop amplitudes at NLO (EW, QCD) in the SM and BSM - (hence not only decays!)

- Hto4l [Boselli,Carloni Calame,Montagna,Nicrosini,Piccinini] SM H->Z*Z*->4 charged leptons w/ NLO EW matched to QED parton shower

SM Higgs Branching Ratios



Further non-SUSY Decay Calculators

- 2HDMC [Rathsman,Stal] 2HDM decay widths w/ NLO QCD to fermionic, gluonic decays; different 2HDM parametrizations, flexible Yukawa sector

- HCOUP [Kanemura,Kikuchi,Mawatari,Sakurai,Yagyu] singlet model, 2HDM, inert doublet model; at NNLO QCD and NLO EW

Further SUSY(& Generic) Decay Calculators

- FeynHiggs [Bahl,Hahn,Heinemeyer,Hollik,Paßehr,Rzehak,Sobolev,Weiglein]: MSSM; including state-of-the-art HO QCD corrections; into VV: Prophecy4f rescaled; external Higgs bosons set OS
- SoftSUSY [Allanach,Athron,Bednyakov,Tunstall,Voig,RuizdeAustri,Williams]: MSSM & NMSSM; 1->2 tree-level Higgs into {Higgs/sparticles/SM} particles and Sparticles into {Higgs}, h -> Vff at tree level, MSSM/NMSSM Higgs -> gg,qq at NLO QCD, MSSM -> γγ,Zγ at NLO QCD
- SPheno [Porod,Staub]: MSSM Higgs decays; includes als 2- and 3-body decays of SUSY particles; QCD corrections to decays into qq [Drees eal,´90] and gg,γγ [Spira eal,´95]
- SARAH/SPheno [Goodsell,Liebler,Staub]: fully generic implementation of 2-body decay widths of fermions and scalars at full 1L, see [1703.09237] for details
- NMSSMTools [Ellwanger,Hugonie]: NMSSM; HO QCD corrections à la HDECAY, but no 3-body decays, new: updated QCD corrections to H->gg from HDECAY [1801.09506]; constraints on reduced Higgs couplings in κ framework from ATLAS [1909.02845] CMS [1809.10733]; checks for DM relic density and regularly updated constraints on DM direct detection using MicrOmegas; computes also sparticle decays through generalization of SDECAY (MSSM) to NMSSM
- SloopS [Baro,Boudjema,Semenov]: MSSM, NMSSM w/ complete one-loop corrections; renormalisation in non-linear gauge fixing; different renormalisation schemes; different tanβ definitions

SUSY Decay Calculators - Continued

- NMSSMCALC [Baglio,Gröber,MM,Nhung,Rzehak,Spira,Streicher,Walz]: CP-conserving and CP-violating NMSSM

  state-of-the-art HO QCD corrections from latest HDECAY version, Δ_b,,Δ_s,Δ_τ corrections b,τ,s final states, all relevant off-shell into WW/ZZ,ZH_i,WH^+,H_iH_j,tt; also effective couplings output

- NMSSMCALCEW [Baglio,Dao,MM]: EW, SUSY-QCD & SUSY-EW to CP-conserving and CP-violating NMSSM Higgs decays; consistently combined w/ QCD and Δb; 1L to EWino, stop, sbottom masses in OS and DR scheme

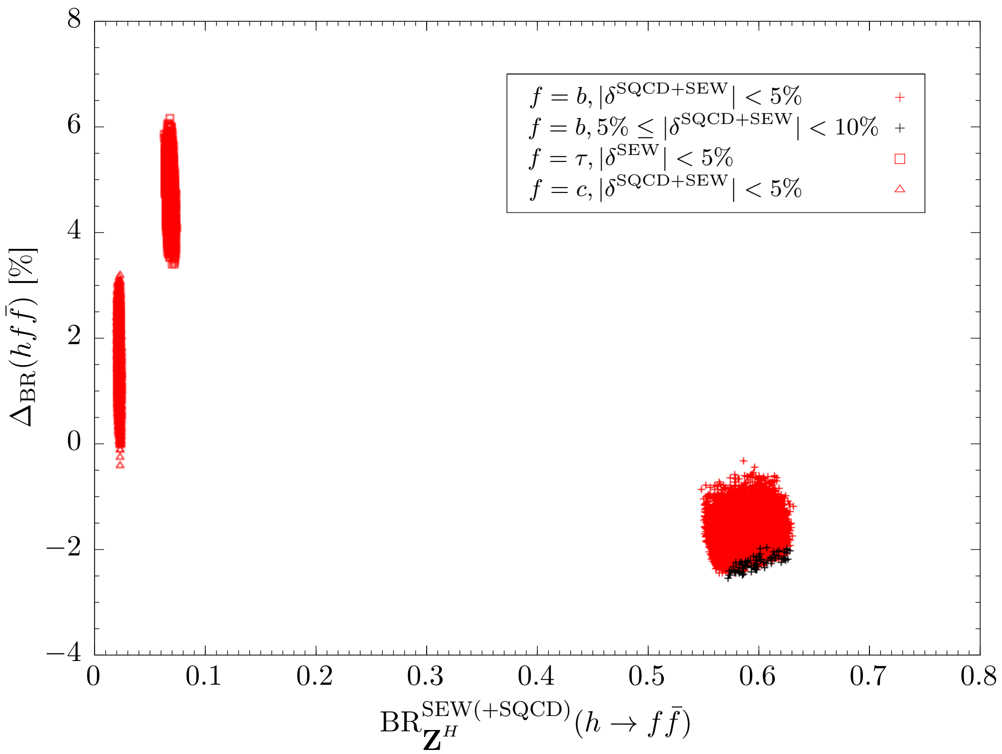
<u>Remarks:</u>

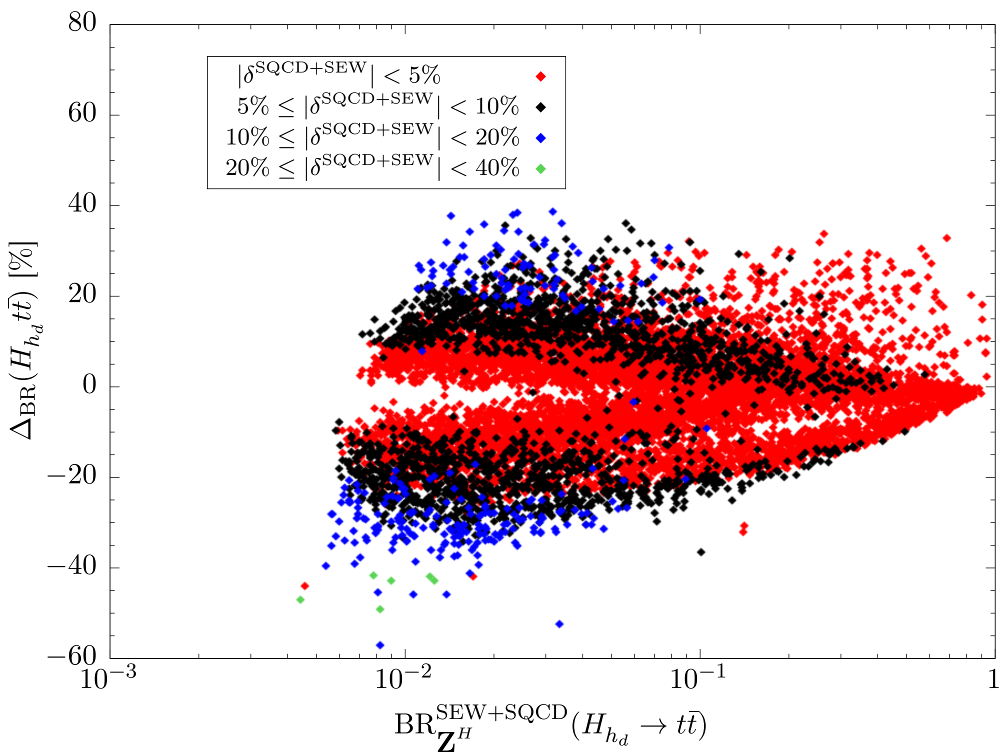
- Full 1L to NMSSM Higgs decays in fermions and gauge bosons [Domingo,Paßehr,Weiglein,´18]
- EW corrections - effects on heavy NMSSM Higgs fermionic decays [Domingo,Paßehr,´19]
- Gauge dependence in 1L to H^+->W^+H_i in NMSSM [Dao,Fritz,Krause,MM,Patel,´19]
- Restoring gauge invariance in Higgs decays w/ (N)MSSM Higgs mixing effects [Domingo Paßehr,´20]

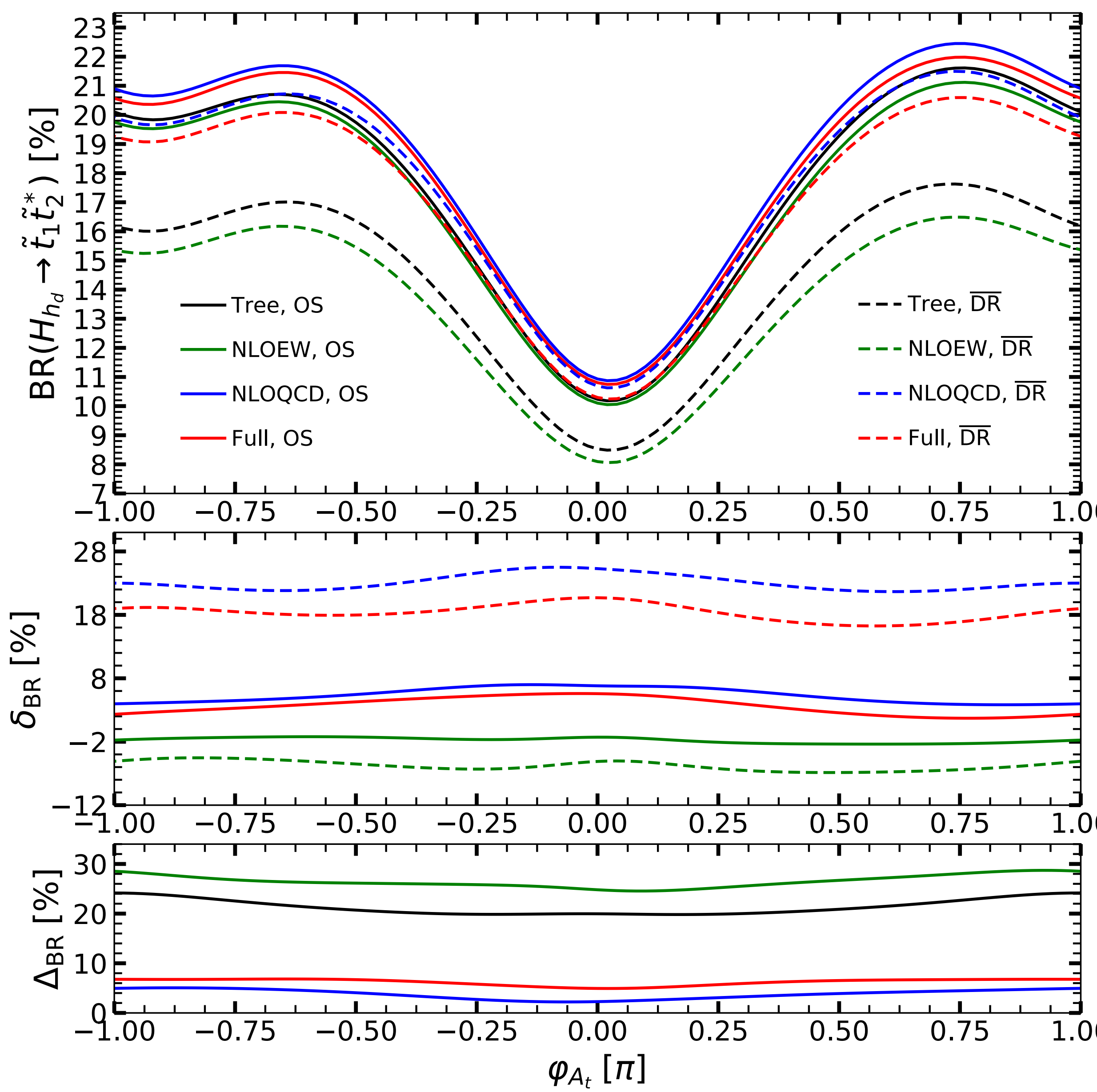
NMSSMCALCEW [Baglio,Dao,MM,EPJC 80(2020) 10,960]

$$\Delta_{\rm BR}(H_i X_j X_k) = \frac{{\rm BR}^{\rm SEW(+SQCD)}_{\mathbf{Z}^H}(H_i \to X_j X_k) - {\rm BR}^{\rm tree}_{\mathcal{R}^l}(H_i \to X_j X_k)}{\max({\rm BR}^{\rm SEW(+SQCD)}_{\mathbf{Z}^H}(H_i \to X_j X_k), {\rm BR}^{\rm tree}_{\mathcal{R}^l}(H_i \to X_j X_k))}$$

$$\delta_{\rm BR} = \frac{{\rm BR}^{\rm EW/QCD/EW+QCD}_{\mathbf{Z}^H} - {\rm BR}^{\rm tree}_{\mathbf{Z}^H}}{{\rm BR}^{\rm Tree}_{\mathbf{Z}^H}}$$








Single Higgs Production

Very small Selection - Single Higgs Production

- SusHi [Harlander,Liebler,Mantler] SM; *total gluon fusion cross section* at N^3LO QCD, EW NLO, mixed EW/QCD assuming factorization of the corrections, $1/m_{top}$ effects at NNLO; *qq->H* at NNLO QCD; 2HDM at N3LO QCD; MSSM NLO+approx N^3LO; NMSSM NLO+approx N^3LO; cMSSM at NLO; point-like at N^3LO; link to FeynHiggs, 2HDMC, HiggsBounds, HiggsSignals

- vh@NNLO [Brein,Harlander,Zirke v1], [Harlander,Klappert,Lieblier,Simon v2], SM,2HDM,MSSM; *total Higgs-strahlung cxn* at NNLO QCD, NLO EW; in gg channel: MSSM, vector-like quarks, effective operators; link to 2HDMC, FeynHiggs

Remark: Both codes work also for pseudoscalar Higgs bosons

- Higlu [Spira] SM,MSSM ggF at full NLO QCD (top+bottom+charm), NNLO QCD (heavy top-limit), dim-6 and non-linear EFT at NNLO QCD, link to HDECAY

- FeynHiggs [Bahl,Hahn,Heinemeyer eal] SM ggF LHCHXSWG SM-prediction w/ effective coupling approx., MSSM LO ggF plus NLO/NNLL SM corrections, tb->H^+ best 2HDM prediction w/ Δ_b corr.

Very small Selection - Single Higgs Production

- HAWK [Denner,Dittmaier,Kallweit,Mück] SM; Monte Carlo program for hadronic Higgs production in vector-boson fusion and Higgs-strahlung; fully differential predictions including the full QCD and EW NLO corrections; both integrated cross sections and binned distributions for important hadron-collider observables

- MCFM [Campbell,Ellis,Williams], MC program for various processes at hadron colliders; also e.g. H+2j w/ finite top-quark mass (LO and virtual matrix elements) and H+jet w/ finite top-mass effects (NLO)


Constraints

Role of Constraints

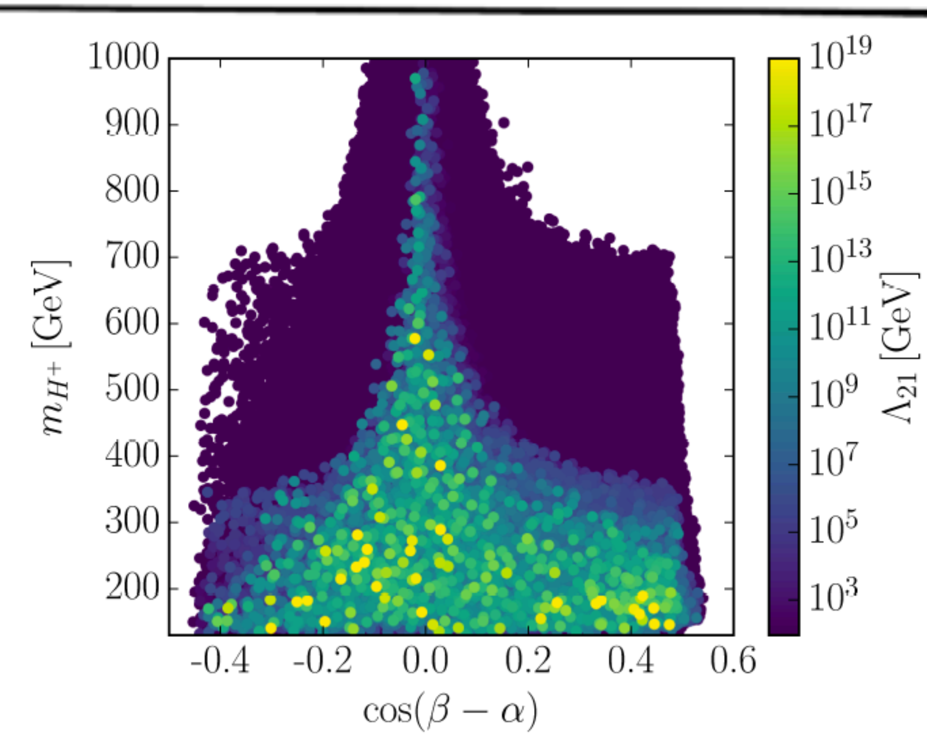
- **Validity of Model:** check for compatibility with theoretical and experimental constraints
- **Theoretical Constraints:** Higgs potential bounded from below, EW minimum = global minimum, tree-level perturbative unitarity
- **Experimental Constraints:** compatibility w/ EW precision data, Higgs data and Higgs exclusion limits, low-energy physics, B-physics, EDMs (models w/ CP violation), DM constraints (models w/ DM candidate), exclusion limits on new particles (models w/ additional particle content, e.g. SUSY)
- **Importance of check:** extract viable parameter space of the model; make reliable predictions for experimental signatures; identify observables w/ sensitivity to model parameter space

[Basler,Ferreira,MM,Santos,´17]

impact of theoretical and experimental constraints on 2HDM type 1

Alignment for $m_{H^+} \gtrsim 500$ GeV and validity up to the Planck scale

generated with ScannerS



HiggsBounds

by Philip Bechtle, Sven Heinemeyer, Tobias Klingl, Tim Stefaniak, Georg Weiglein, and Jonas Wittbrodt

HiggsBounds `https://gitlab.com/higgsbounds/higgsbounds`

Test scalar sectors against exclusion bounds from LEP, the Tevatron, and the LHC.

- includes limits from over 200 experimental analyses
- new HiggsBounds-5 manual released in July [Bechtle et al. 2006.06007]

HiggsSignals `https://gitlab.com/higgsbounds/higgssignals`

Compare scalar sectors to the latest measurements of the h_{125}.

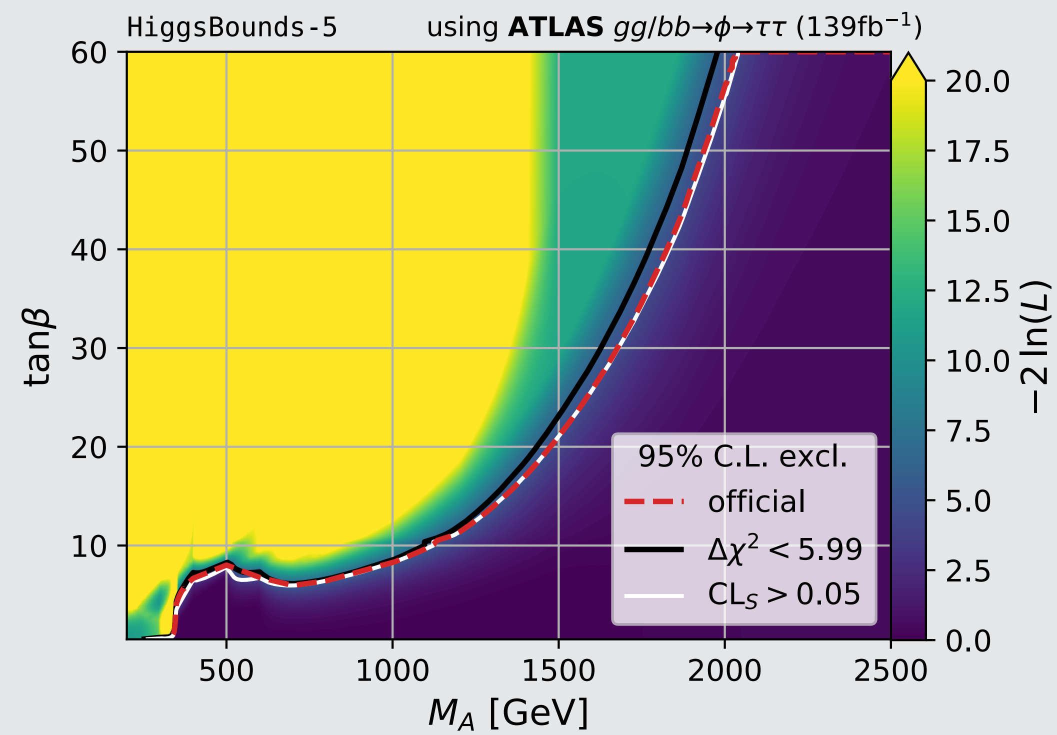
- many measurements using the full LHC Run-2 dataset
- new HiggsSignals-2 manual to be released before Christmas

Both codes are continuously updated with the latest results.

Improved limit setting for exclusion likelihoods

- reconstruct CL_s from provided likelihood profiles
- set model specific limits with the same method used by ATLAS/CMS

⇒ e.g. for [ATLAS 2002.12223] in the M_h^{125} scenario [Bagnaschi et al. 1808.07542]



Extended effective coupling input

Easy-to-use parametrized cross section predictions for:

- $gg/qq \to VH$ sub-channels including CP-violation
  - important for STXS measurements in HiggsSignals
- $pp \to \phi^{\pm}tb$, important charged Higgs search channel

See the new manual for more details. [Bechtle et al. 2006.06007]

Simplified Template Cross Sections (STXS) in HiggsSignals

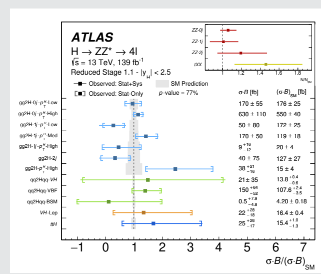
Used by the experimental collaborations to present Run-2 measurements.

- allow testing h_{125} candidates with non-SM-like kinematics

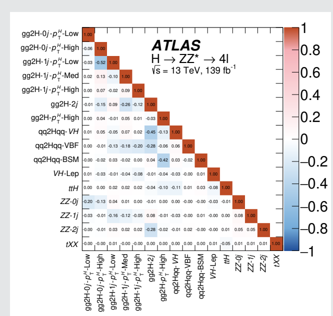
Latest LHC Run-2 measurements — Example: ATLAS $H \to 4\ell$ [ATLAS 2004.03447]

HiggsSignals implementation

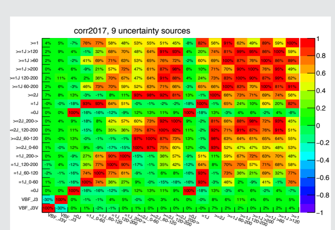
- measurements (12-bin STXS)



- experimental correlations

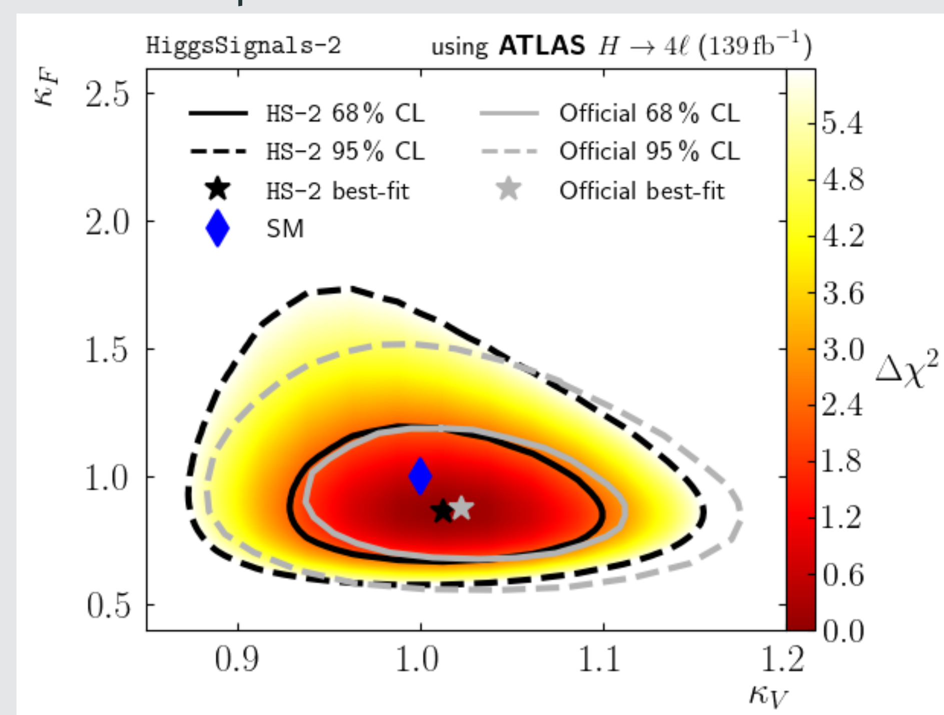


- theory correlations [2017 Scheme]



Performance of HiggsSignals

compared to official κ-fit.



Upcoming manual with detailed performance studies and in-depth statistical discussion of HiggsSignals χ^2 interpretation.

ScannerS

ScannerS [Coimbra,Sampaio,Santos,´13],[MM,Sampaio,Santos,Wittbrodt,´20]

Automatisation of scans of the parameter space of arbitrary scalar potentials beyond the SM from user defined analysis,
includes singlet extensions, (CP-violating) 2HDM, different phases of the N2HDM, ...

- computes single Higgs production and decay channels
- checks theoretical constraints (tree-level perturbative unitarity, boundedness from below, if available absolute stability)
- check experimental constraints (compatibility w/ Higgs data - through HiggsBounds & HiggsSignals), STU precision data, B-physics (if applicable), DM (if applicable), EDMs (if applicable)
- points kept or discarded according to user input

Recent developments: improvement of performance; simplified installation with automatic dependency management

Remarks

- Check for minima of extended Higgs sector potentials:

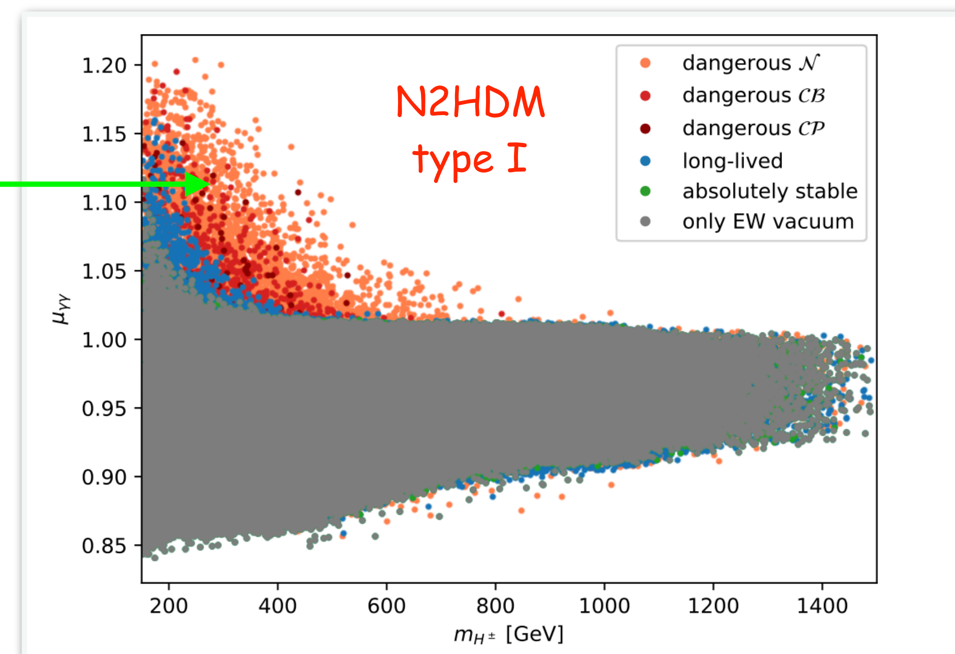
  * BSMPT [Basler,MM,Müller] 2HDM, C2HDM, N2HDM, CxSM; computation of EWPT, BAU; new models can easily be implemented
  * EVADE [Hollik,Weiglein,Wittbrodt] fast and efficient method for vacuum (meta)stability studies at tree level in multi-Higgs models
  * PhaseTracer [Athron,Balazs,Fowlie,Zhang] cosmological phase transitions; potentials obtained e.g. from FlexibleSUSY
  * CosmoTransitions [Wainwright] cosmological phase transitions
  * Vevacious [Camargo-Molina, O´Leary,Porod,Staub] global minima at NLO of extended Higgs sectors

[Ferreira,Santos,MMM,Weiglein,Wittbrodt,´19]

Not allowed

models can be excluded based on vacuum study

$$\mu_{\gamma\gamma} = \frac{\sigma(pp \to h_{125})\mathrm{BR}(h_{125} \to \gamma\gamma)}{\sigma(pp \to h_{\mathrm{SM}})\mathrm{BR}(h_{\mathrm{SM}} \to \gamma\gamma)}$$



Remarks

- Various observables/constraints also calculated/checked by spectrum and decay calculators:
  * FeynHiggs (EWPO: $\Delta\rho$,Δr,M_W,$\sin\theta_W^{eff,lept}$,$(g-2)_\mu$,EDMS (Th,n,Hg), $B\to X_s\gamma$,ΔM_s,$B_s\to\mu^+\mu^-$)
  * SPheno (EDMs, leptonic anomalous magnetic moments, LFV decays of muon,tau,Z, B meson mixing, B decays)
  * SARAH generated versions (through Flavorkit numerous flavour observables; S,T,U parameters,...; interfaces to CalcHEP, MicrOmegas, WHIZARD; generation of UFO files-> combination w/ Herwig, MadGrapha,...; WCxf standards -> link to Flavio, SMEFT programs)
  * NMSSMCALC (EDMs; output of effective couplings)
  * NMSSMTools (Higgs, particle exclusion limits check; Higgs couplings checks; B and K physics constraints; muon anomalous magnetic moment; DM constraints through MicrOmegas)
  * HCOUP (tree-level unitarity, triviality & vacuum stability bound (tree level and improved by RGEs); true vacuum condition, experimental constraint EW S, T) ...

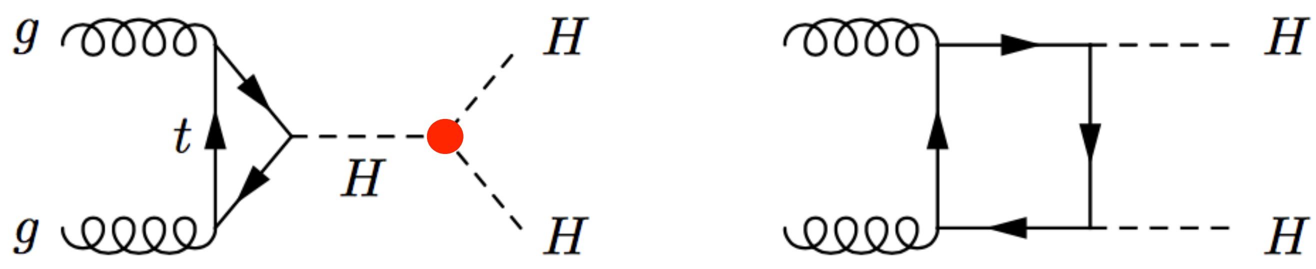
- For Higgs data check, see also e.g. Lilith [Bernon,Dao,Duc,Dumont,Kraml,Loc] (details in talk by Sabine Kraml)

- Not in this talk Fitting Tools (another vast field):
  * GAMBIT [The Gambit Community]
  * Fittino [Bechtle,Desch,Wienemann]
  * SFitter [Rauch,Lafaye,Plehn,Zerwas] ...


Double Higgs Production

Higgs Pair Production - Ultimate Test of the Higgs Mechanism

✦SM Higgs pair production at the LHC- dominant process: Gluon fusion



* ⁎ mediated by top and bottom loops
* ⁎ SM: destructive interference triangle and box diagrams

✦Cross section: $\sqrt{s} = 13\ \text{TeV}: \quad \sigma_{tot} \quad = \quad 31.05^{+6\%}_{-23\%}\ \text{fb}$

[Grazzini eal'19;]
for extensive list of refs.
see [di Micco eal'19]

at FT_{approx}: full NNLO QCD in the heavy-top-limit with full LO and NLO mass effects and full mass dependence in the one-loop double real corrections at NNLO

✦Challenge: small cross sections and large QCD backgrounds

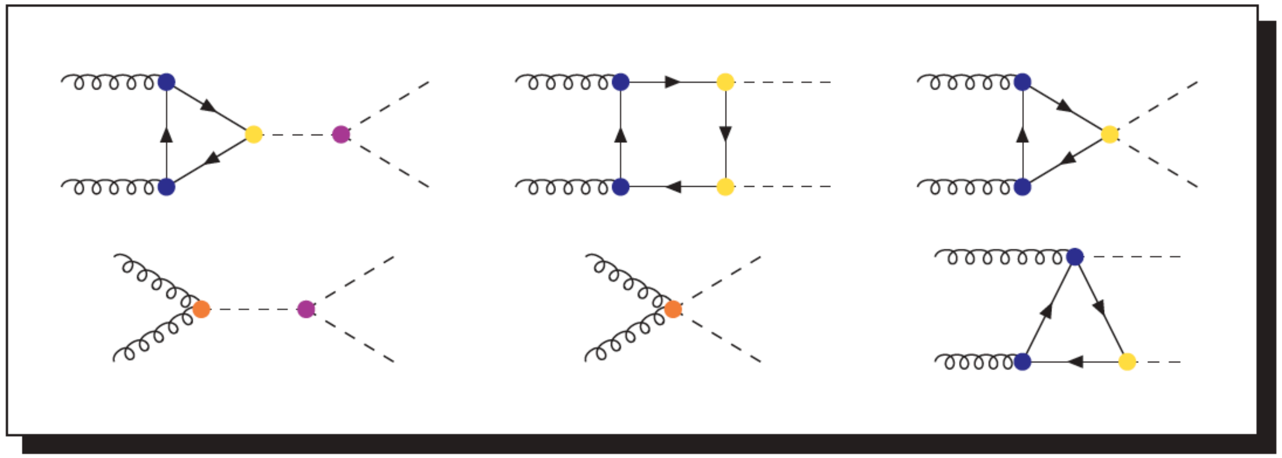
ggHH

by [Heinrich,Jones,Kerner,Luisoni,Vryonidou], [Heinrich,Jones,Kerner,Luisoni,Scyboz],[Heinrich,Jones,Kerner,Scyboz]

Precision tools for experimentalists

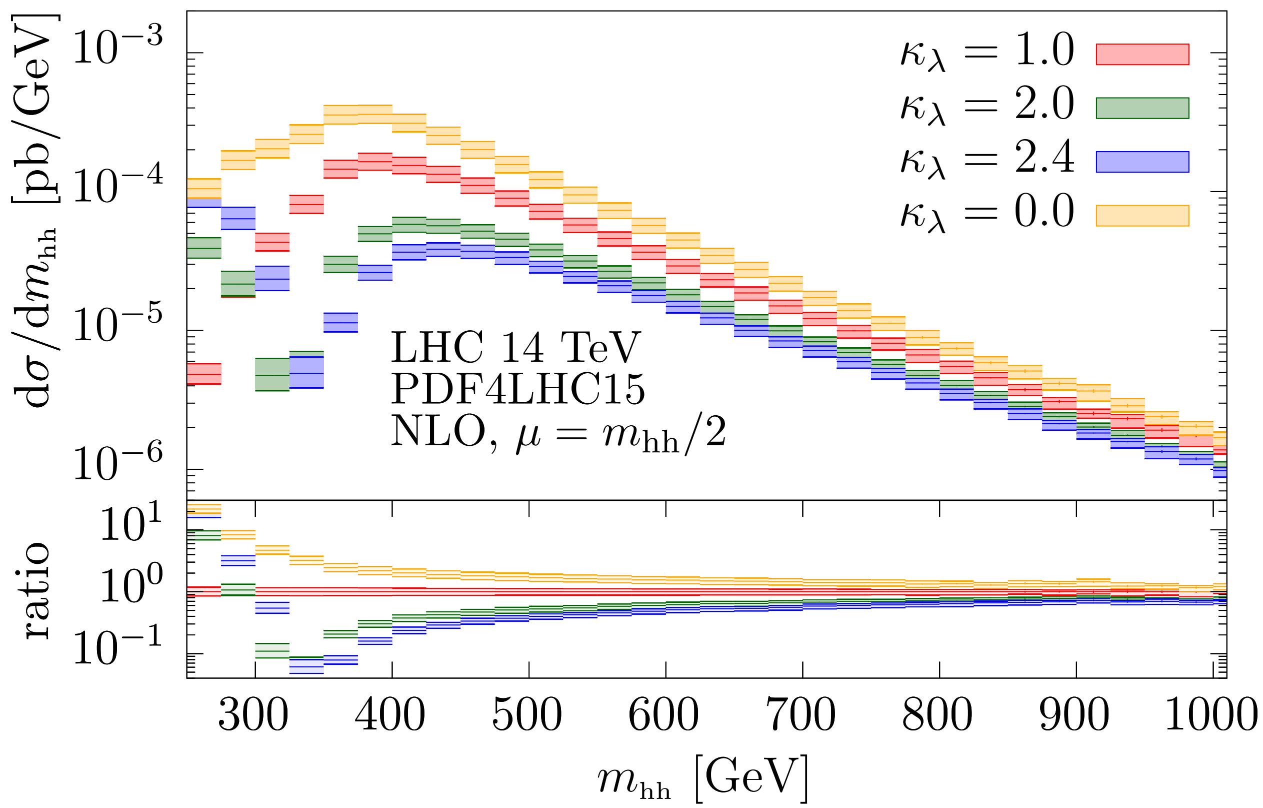
http://powhegbox.mib.infn.it/User-Process-V2/ggHH

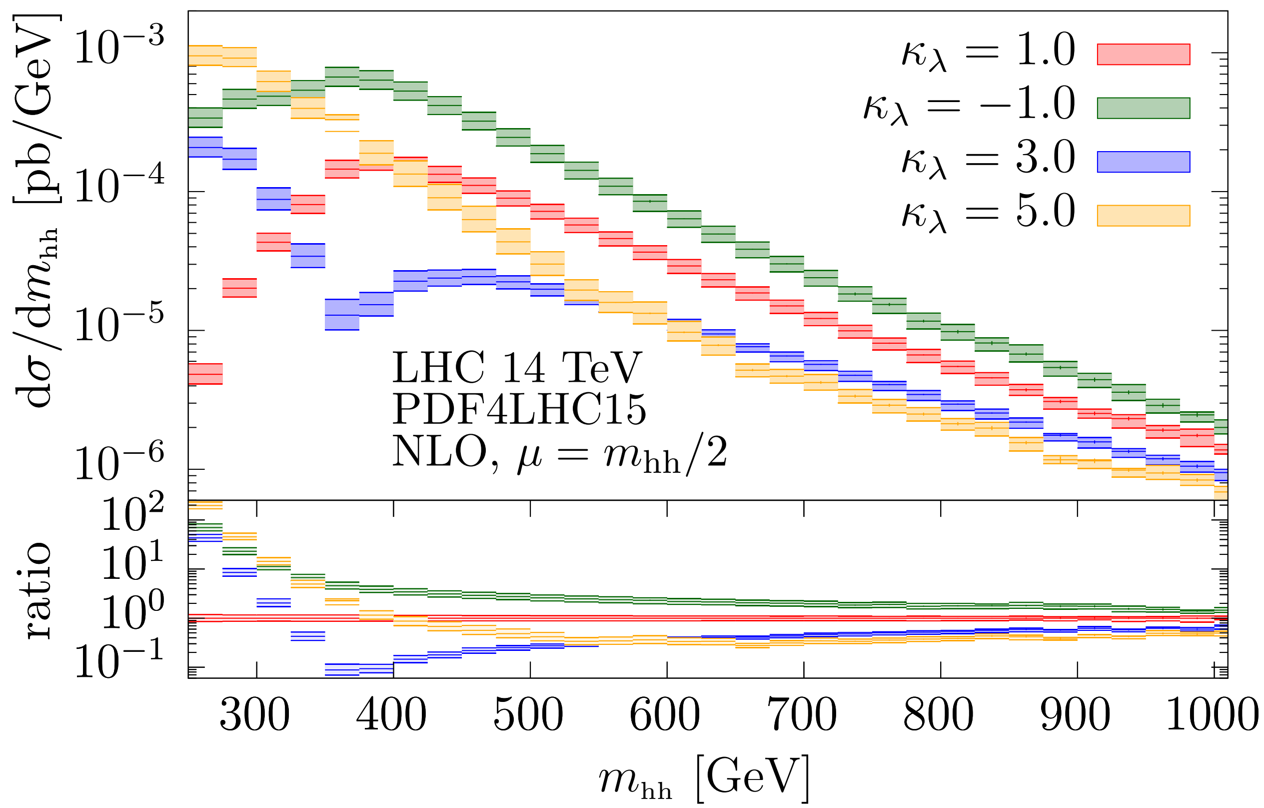
- Monte Carlo program for HH:
  full NLO results for Higgs pair production in gluon fusion
- interface to Pythia and two different Herwig parton showers
- option to vary 5 anomalous couplings: c_{hhh}, c_t, c_{tt}, c_{ggh}, c_{gghh}
- recent developments: benchmark points for characteristic shapes of m_{HH} distributions based on full NLO calculation and shape analysis with machine learning tools [Capozi,Heinrich]

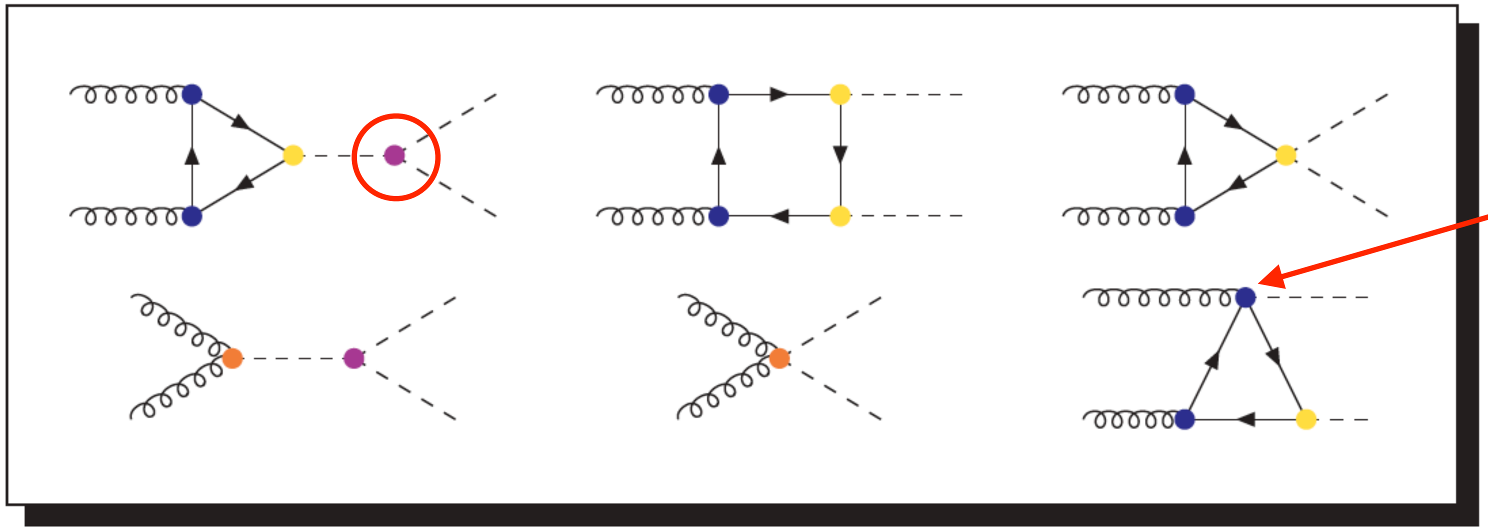


Variation of κλ

[Heinrich,Jones,Kerner,Luisoni,Scyboz]







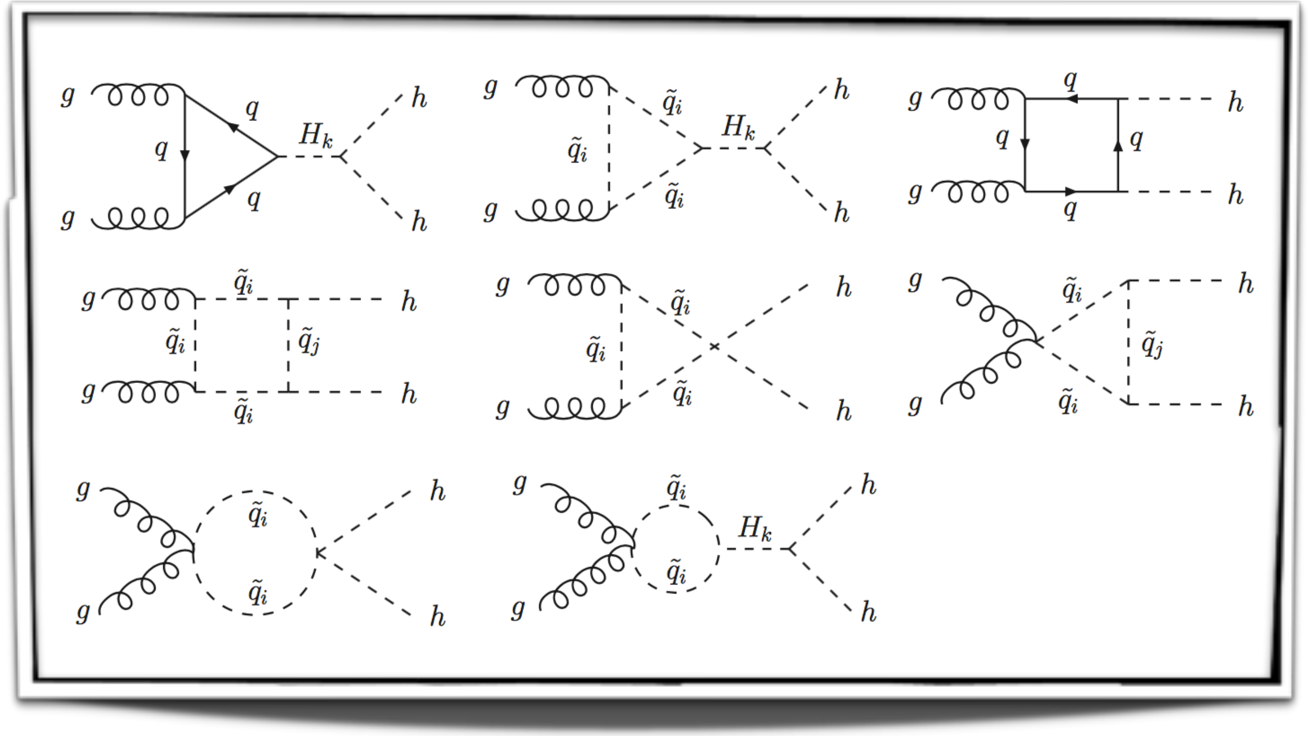
not included in code as suppressed

HPAIR

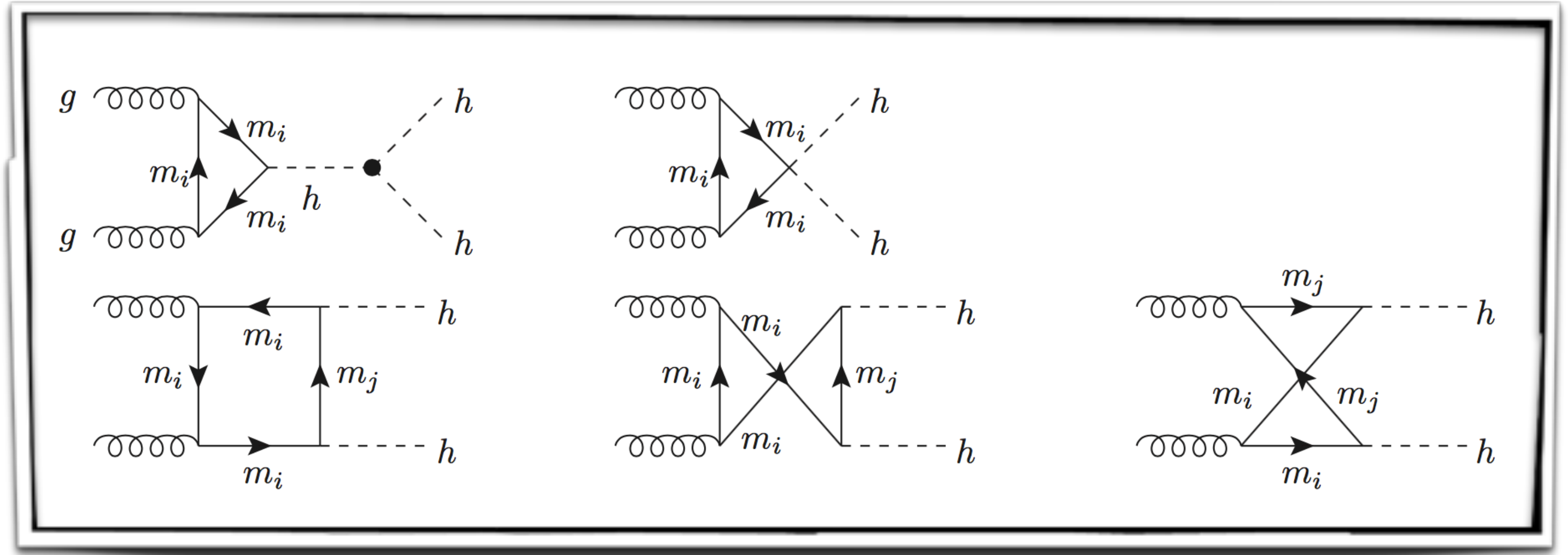
gg->HH: SM, MSSM (hh,HH,AA,hA,HA) [Spira],
dim-6 and non-linear EFT [Gröber,MM,Spira,Streicher,´15]
at NLO Born-improved HTL

Private versions:

* NMSSM [Dao,MM,Streicher,Walz,´13]
* C2HDM [Gröber,MM,Spira,´17]
* 2HDM [MM]
* N2HDM [MM]



NMSSM



Composite Higgs

CP-Violating 2HDM (C2HDM)

R.Gröber, MM, M.Spira, Nucl.Phys.B.925 (2017) 1

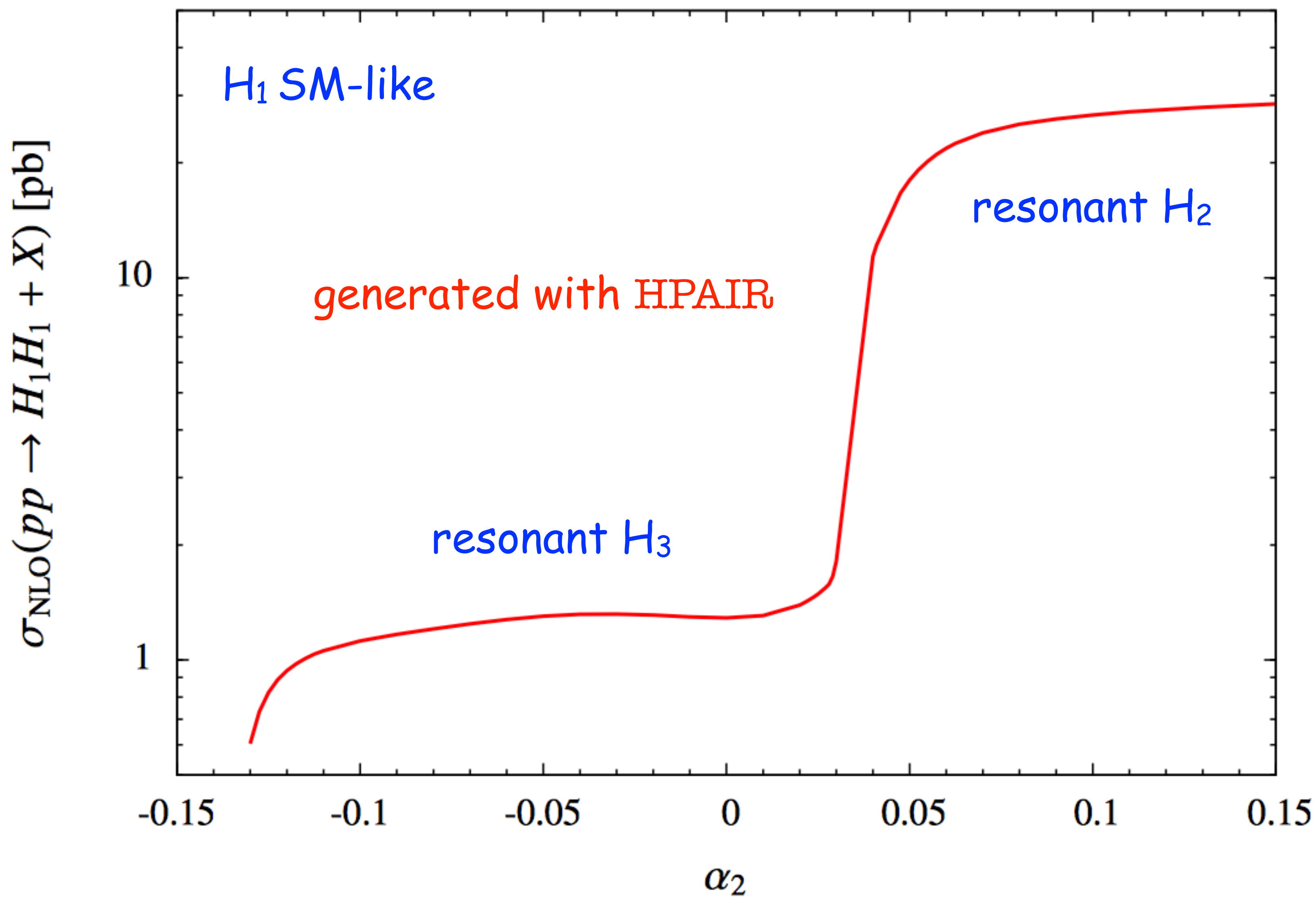
$$V = m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + h.c.) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2$$
$$+\lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}[(\Phi_1^\dagger\Phi_2)^2 + h.c.] \,.$$

complex

$$\begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix} = R \begin{pmatrix} \rho_1 \\ \rho_2 \\ \rho_3 \end{pmatrix}$$

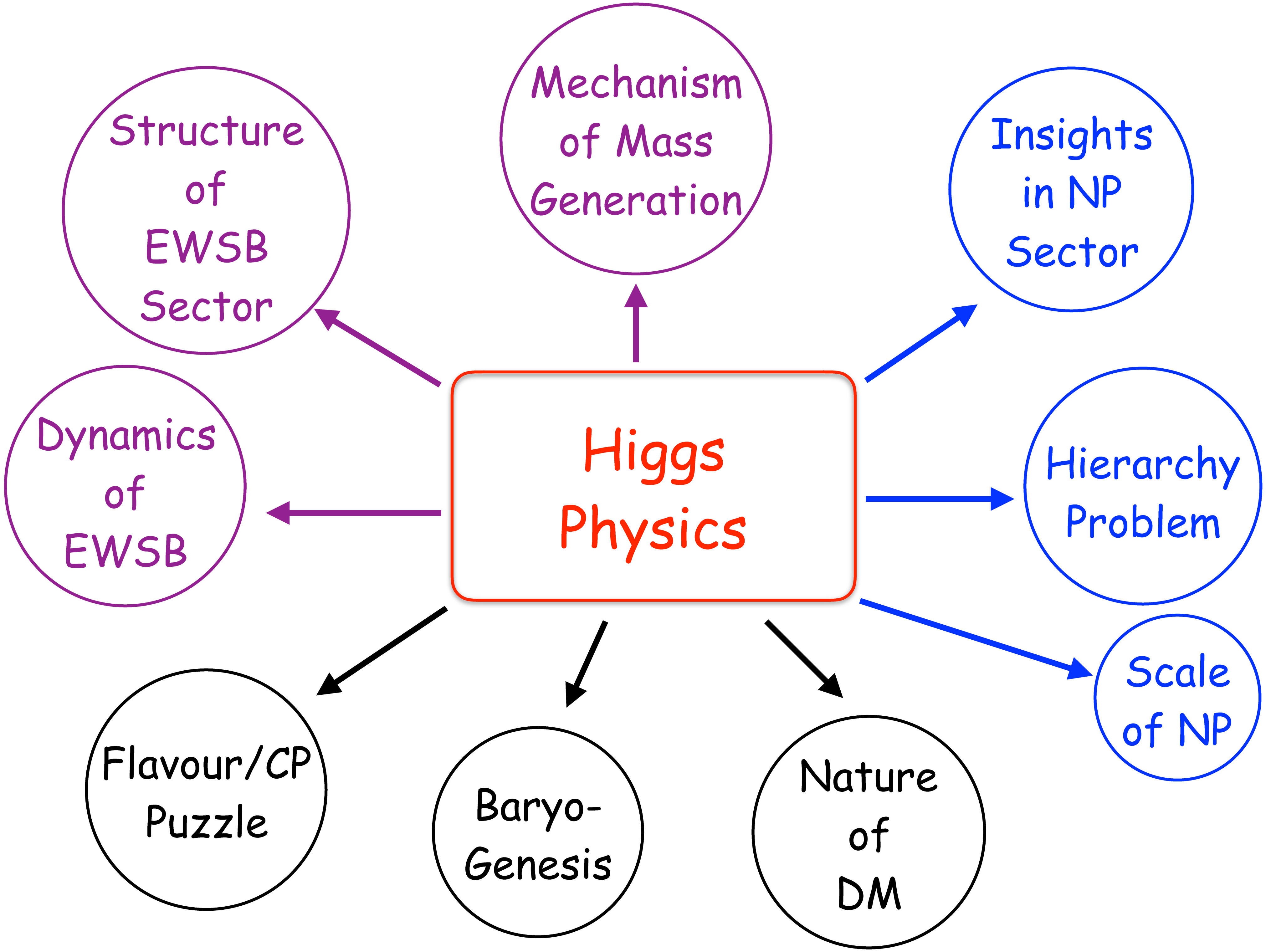
3 neutral CP-mixing Higgs bosons

Cxn at NLO QCD



$$377.6 \text{ GeV} \geq M_{H_2} \geq 277.0 \text{ GeV} \quad \text{and} \quad 1398.2 \text{ GeV} \geq M_{H_3} \geq 377.6 \text{ GeV}$$

Summary



Higgs Physics
Structure of EWSB Sector
Mechanism of Mass Generation
Insights in NP Sector
Dynamics of EWSB
Hierarchy Problem
Scale of NP
Flavour/CP Puzzle
Baryo-Genesis
Nature of DM

Summary

HIGGS BOSON
the answer to
live, the Universe
and everything?

requires clever ideas, good theories,
precise theoretical calculations,
excellent experimental techniques and
TOOLS TOOLS TOOLS

Prepartion of talk: thanks to

Ben Allanach, Duarte Azevedo, Peter Athron, Henning Bahl, Ulrich Ellwanger,
Mark Goodsell, Robert Harlander, Gudrun Heinrich, Jean-Loic Kneur, Werner Porod,
Rui Santos, Michael Spira, Dominik Stöckinger, Jonas Wittbrodt, Dirk Zerwas

Thank you for your attention