A3b Precision Predictions of Higgs Boson Properties as a Probe of New Physics

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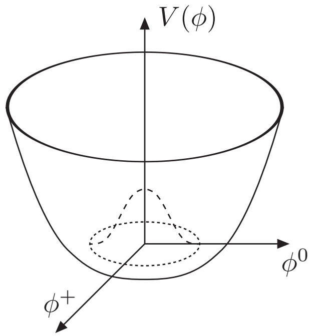
$\mathcal{I}$ntroduction

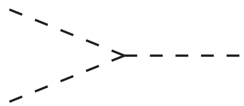
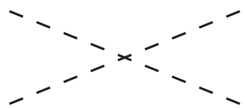
$\mathcal{H}$iggs $\mathcal{P}$otential

- **Parameters of the Higgs Potential:**
  - Higgs boson mass and Higgs self-couplings
  - Their interplay is extremely important for stability of the Higgs potential

- **SM Higgs Potential:**

$$V(H) = \frac{1}{2!}\lambda_{HH} H^2 + \frac{1}{3!}\lambda_{HHH} H^3 + \frac{1}{4!}\lambda_{HHHH} H^4$$



$\mathcal{T}$rilinear coupling	$\lambda_{HHH} = 3\frac{M_H^2}{v}$	
$\mathcal{Q}$uartic coupling	$\lambda_{HHHH} = 3\frac{M_H^2}{v^2}$	

- **Beyond-the-SM Potentials:**
  - Relation between masses and self-couplings more complicated
  - Masses and self-couplings can be independent of each other ($\leftarrow$ underlying symmetry)

The Role of the Higgs Boson Mass

- **Present accuracy:** [ATLAS, CMS, Phys Rev Lett 114 (2015) 191803]

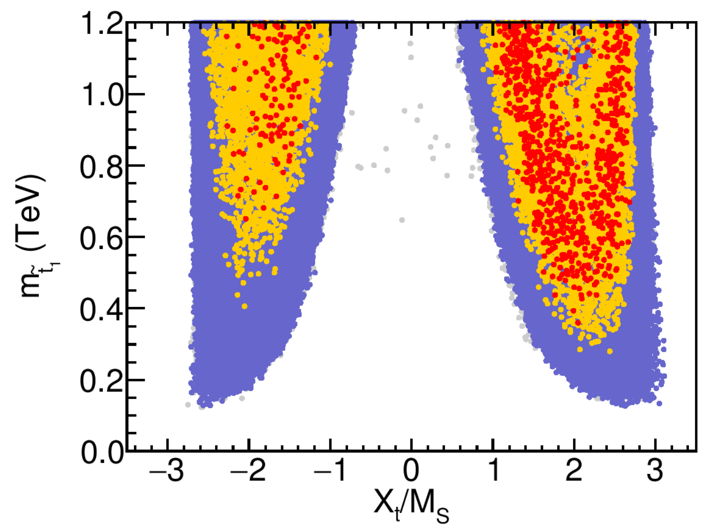
$$M_H = 125.09 \pm 0.21 \text{ (stat)} \pm 0.11 \text{ (syst) GeV}$$

- **Higgs boson mass:**
  - ∗ SM: fundamental parameter, not given by theory
  - ∗ Supersymmetry: calculable from input parameters - loop corrections Δm_h^2 are important!

MSSM: $m_H^2 \approx M_Z^2 \cos^2 2\beta \quad + \Delta m_H^2 \leftarrow (85 \text{ GeV})^2$!

NMSSM: $m_H^2 \approx M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta \quad + \Delta m_H^2 \leftarrow (55 \text{ GeV})^2$

MSSM: see e.g. [Bechtle,Haber,Heinemeyer Stal,Stefaniak,Weiglein,Zeune '16]



$\mathcal{T}$he $\mathcal{R}$ole of the $\mathcal{H}$iggs $\mathcal{B}$oson $\mathcal{M}$ass

- **Why precision?**
  - $*$ Self-consistency test of SM at quantum level (*e.g.:* Higgs loop corrections to W boson mass)
  - $*$ $M_H \leftrightarrow$ stability of the electroweak vacuum [Degrassi eal;Bednyakov eal]
  - $*$ Higgs mass uncertainty feeds back in uncertainty on Higgs observables
  - $*$ Test parameter relations in beyond-SM theories

    $\rightsquigarrow$ indirect constraint of viable Beyond-SM (BSM) parameter space!

$\rightarrow$ Link to project A3a

$\mathcal{T}$he $\mathcal{R}$ole of the $\mathcal{H}$iggs $\mathcal{S}$elf-$\mathcal{I}$nteraction

- **The EWSB potential:**

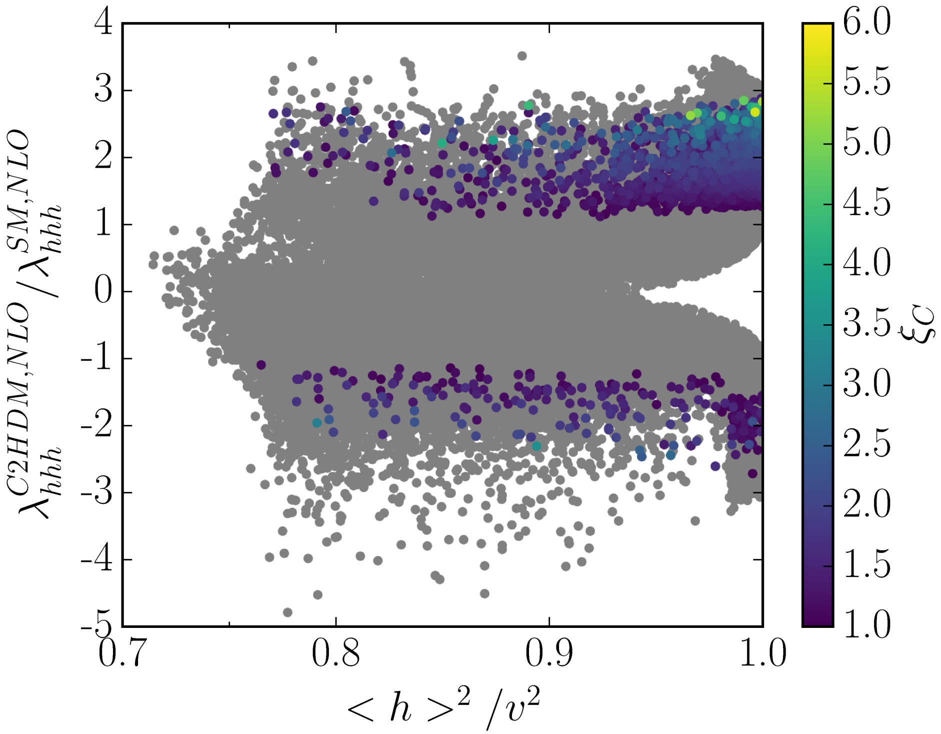
$$V(H) = \frac{1}{2!}\lambda_{HH} H^2 + \frac{1}{3!}\lambda_{HHH} H^3 + \frac{1}{4!}\lambda_{HHHH} H^4$$

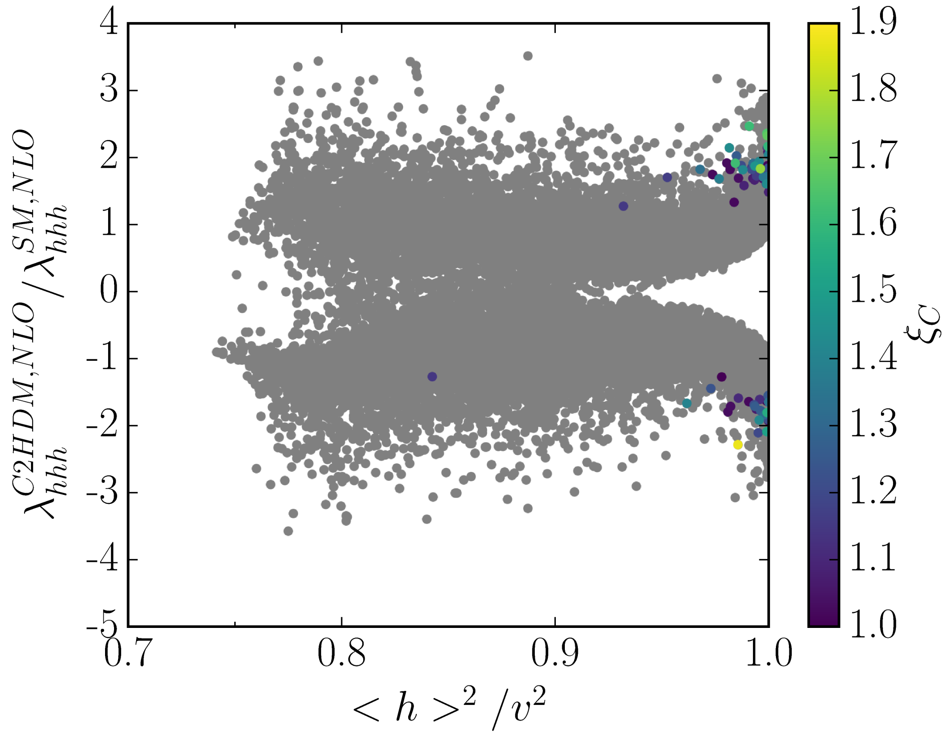
$\mathcal{M}$easurement of the scalar boson self-couplings and $\mathcal{R}$econstruction of the EWSB potential	} $\mathcal{E}$xperimental verification $\mathcal{O}$f the scalar sector of the $\mathcal{E}$WSB mechanism

- **The Role of the Higgs Self-Coupling:**
  - ∗ Measurement crucial for our understanding of the mechanism behind EWSB
  - ∗ Size important for successful baryogenesis $\rightarrow$ T
  - ∗ Despite very SM-like Higgs couplings, self-interaction can still deviate substantially from SM value

$\mathcal{E}$ffects on the $\mathcal{T}$rilinear $\mathcal{H}$iggs $\mathcal{S}$elf-$\mathcal{C}$oupling - $\mathcal{C}$2HDM

Type I, $H_1 = h$ - right plot: only CP-violating points [Basler,MM,Wittbrodt '17; Basler,MMM BSMPT '18]





* Grey: exp+theor constraints, colour $\xi_c \geq 1$
* $1.1 \lesssim \left| \frac{\lambda_{hhh}^{\text{C2HDM,NLO}}}{\lambda_{hhh}^{\text{SM,NLO}}} \right| \lesssim 2.9$
* CP-odd part of $h \lesssim 24\% \xrightarrow{\text{EWPT}} \sim 2.5\%$

$\mathcal{A}$ccess to the $\mathcal{H}$iggs $\mathcal{S}$elf-$\mathcal{I}$nteraction

- **How large can λ_{3H} be?** $\lambda_{3H} = \kappa_\lambda \lambda_{3H}^{\text{SM}}$
  - $|\kappa_\lambda| \leq 6$ [Di Luzio, Grober, Spannowsky, 1704.02311]
  - $|\kappa_\lambda| \leq 6$ [Di Vita, Grojean, Panico, Riembau, Vantalon, 1704.01953]
  - $\kappa_\lambda \leq 5/3$ [Kurup, Perelstein, 1704.03381]
  - $|\kappa_\lambda| \leq 10$ [Falkowski, Rattazzi]

- **Determination of the scalar boson self-couplings at colliders:**

  $\boldsymbol{\lambda_{HHH}}$ via Higgs-to-Higgs decays ($\leftarrow$ BSM)

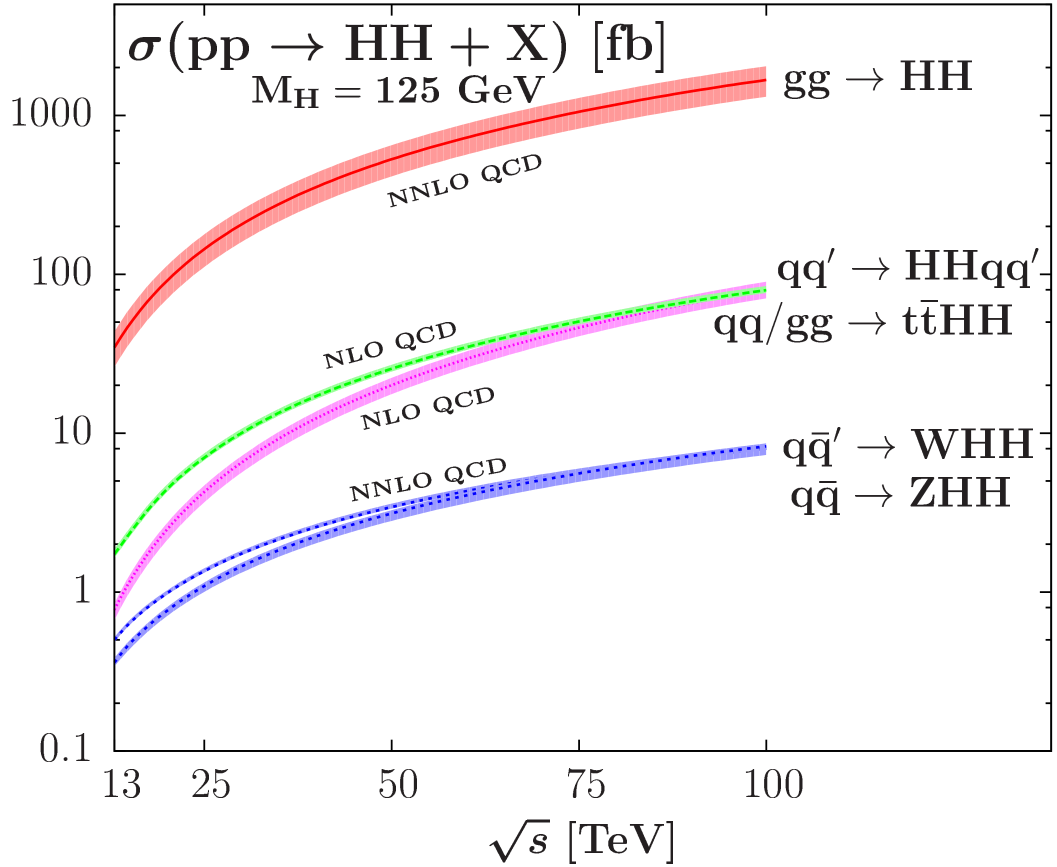
  $\boldsymbol{\lambda_{HHH}}$ pair production

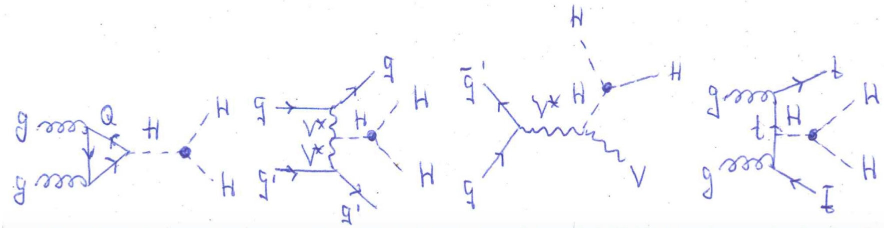
  $\boldsymbol{\lambda_{HHHH}}$ triple production

  radiation off W/Z, WW/ZZ fusion, assoc. prod. w/ $t\bar{t}$, gg fusion

$\mathcal{D}$ouble $\mathcal{H}$iggs $\mathcal{P}$roduction $\mathcal{P}$rocesses

Baglio,Djouadi,Quevillon





$\mathcal{G}$oals of $\mathcal{P}$roject $\mathcal{A}$3b

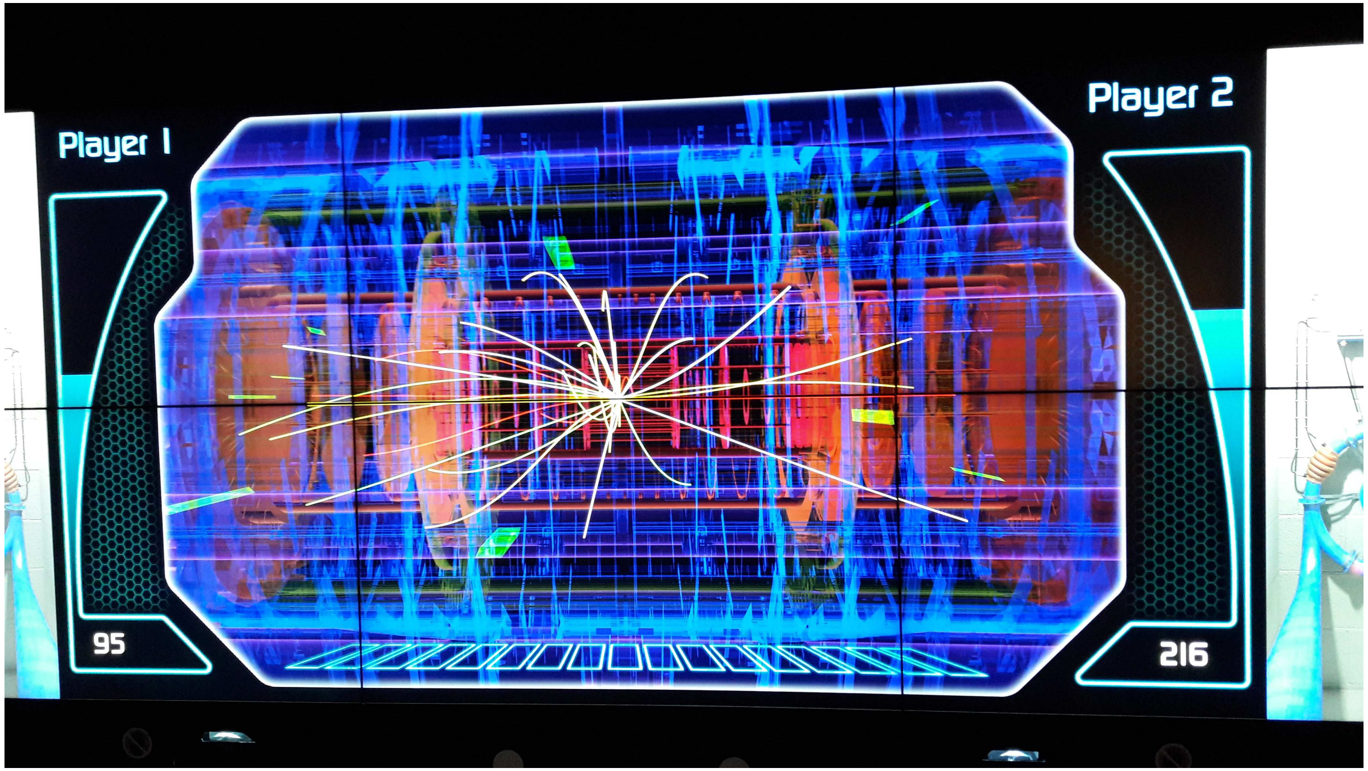
- **Project Goal:** Provide precise predictions for Higgs potential parameters and related observables

- **Increase Precision in $gg \to HH$:**
  - ◇ NLO QCD corrections including the full mass dependence in SM and MSSM
  - ◇ Improve approximate results at NNLO
  - ◇ N^3LO in SM in large top-mass expansion

- **Increase Precision in Higgs-to-Higgs Decays:**
  - ◇ NLO corrections for C2HDM, N2HDM, NMSSM $\leftarrow$ possibility of decays chains with subsequent Higgs-to-Higgs decays, possibility of Higgs pair with different Higgs bosons in the final state

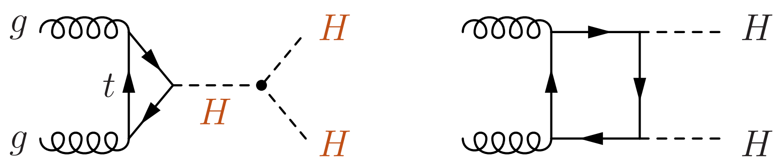
- **Computation of HO Corrections to Higgs Boson Masses:**
  - ◇ MSSM: three-loop corrections enhanced by Yukawa couplings
  - ◇ NMSSM: relevant two-loop corrections
  - ◇ Implementation in computer codes

Higgs Pair Production



$\mathcal{D}$ominant $\mathcal{H}$H $\mathcal{P}$rocess at the $\mathcal{L}$HC

- **Gluon fusion - dominant process**



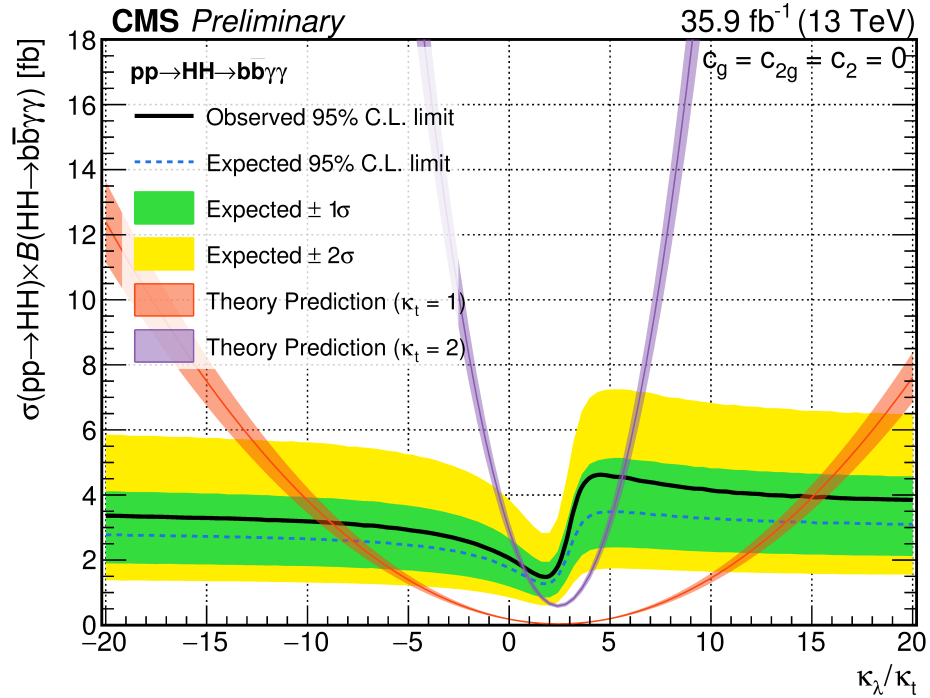
- **SM HH cross section small:**

$$\sigma^{\text{NLO}}_{gg\to HH} = 32.91^{+13.6\%}_{-12.6\%}\ \text{fb @14 TeV}$$ [Borowka eal '16]

$\mathcal{C}$hallenge $\mathcal{D}$i-$\mathcal{H}$iggs $\mathcal{P}$roduction

- **Small signal + large QCD background $\rightsquigarrow$ Experimental challenge!**
  $\mathcal{O}(\pm(15-20)\lambda_{HHH}^{SM})$ [ATLAS,CMS]

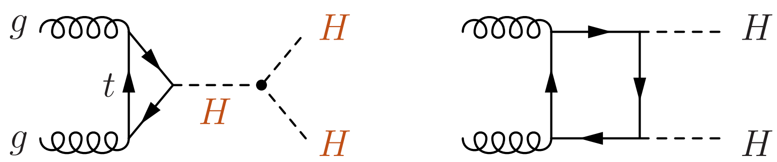
[CMS-PAS-HIG-17-008]



- **Prospects in $b\bar{b}\gamma\gamma$ final state:** $-0.8 < \lambda_{hhh}/\lambda_{hhh}^{SM} < 7.7$ [ATL-PHYS-PUB-2017-001]

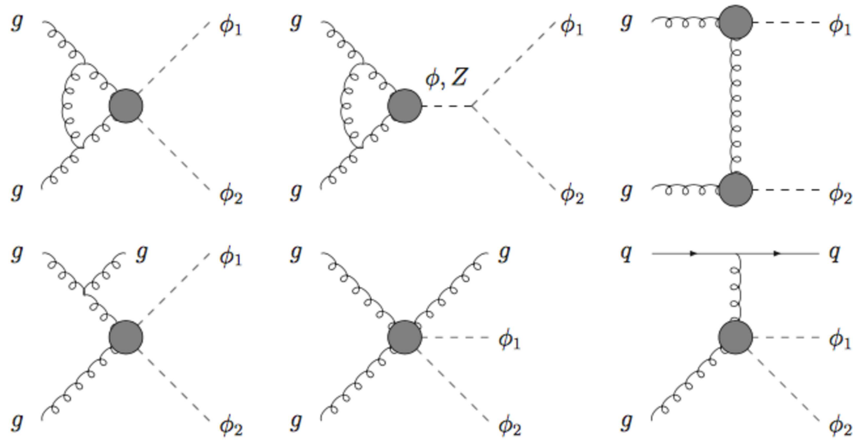
$\mathcal{G}$luon $\mathcal{F}$usion into $\mathcal{H}$iggs $\mathcal{P}$airs

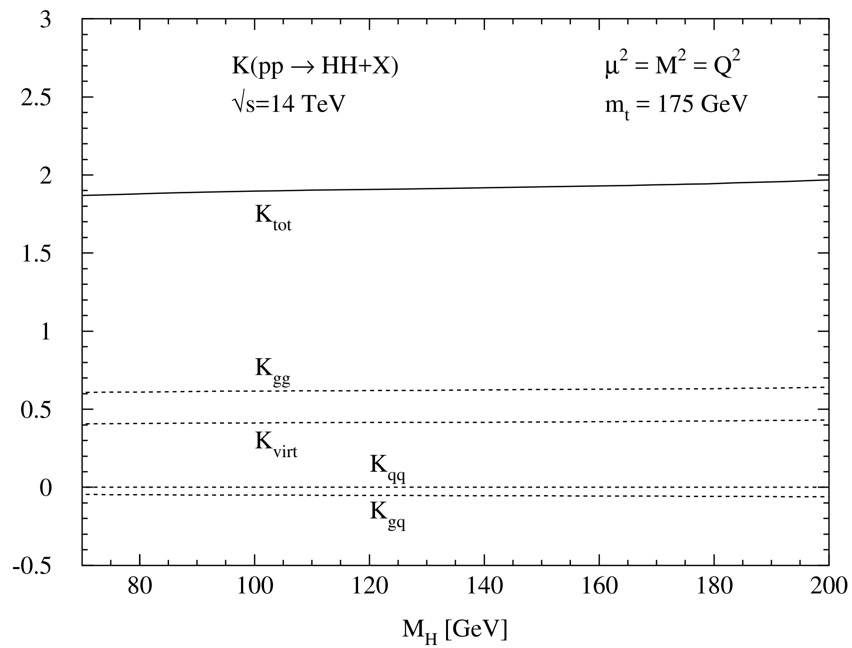
- **Gluon fusion:** loop induced, third generation dominant $\rightsquigarrow t, b$



- **NLO QCD corrections (HTL):** $\sim 90 - 100\%$ $[M_H^2 \ll 4m_t^2, \mu = M_{HH}]$

[Dawson,Dittmaier,Spira]





Status Higher Order Corrections

• 2-loop QCD corrections	large top mass expansion, $\pm 10\%$	Grigo,Hoff,Melnikov,Steinhauser
• NLO mass effects @ NLO in real corrections	$\sim -10\%$	Frederix,Frixione,Hirschi,Maltoni, Mattelaer,Torrielli,Vryonidou,Zaro
• NNLO QCD corrections	$M_H^2 \ll 4m_t^2$, $\sim$20%	de Florian,Mazzitelli; Grigo,Melnikov,Steinhauser
• Soft gluon resummation	$M_H^2 \ll 4m_t^2$, $\sim$10%	Shao,Li,Li,Wang; de Florian, Mazzitelli
• NLO: high energy	$Q^2 \gg m_t^2$	Davies,Mishima, Steinhauser,Wellmann
• NNLO differential		deFlorian,Grazzini,Hanga,Kallweit, Lindert,Maierhöfer,Mazzitelli,Rathlev
• NNLO Monte Carlo	full top-mass effects @ NLO, $+10$ to $+20\%$ in distributions	Grazzini,Heinrich,Jones, Kallweit,Kerner,Lindert,Mazzitelli
• At NLO	matching to parton showers	Heinrich,Jones,Kerner, Luisoni,Vryonidou

$\mathcal{F}$ull $\mathcal{N}$LO $\mathcal{C}$alculation

- **Full NLO calculation:** top only

Borowka,Greiner,Heinrich,Jones, Kerner,Schlenk,Schubert,Zirke

numerical integration, sector decomposition, tensor reduction, contour deformation

14TeV: $(m_t = 173\text{GeV})$ $\quad \sigma_{\text{NLO}} = 32.91(10)^{+13.8\%}_{-12.8\%}$ fb

$\sigma^{\text{HTL}}_{\text{NLO}} = 38.75^{+18\%}_{-15\%}$ fb $\quad (\leftarrow$ HPAIR)

$\Rightarrow$ -15% mass effects on top of LO $\quad \rightarrow$ T

- **New expansion/extrapolation methods:**

(i) $1/m_t^2$ expansion + conformal mapping + Padé aprroximants — Gröber,Maier,Rauh

(ii) p_T^2 expansion — Bonciani,Degrassi,Giardino,Gröber

- **Full NLO calculation:** top only first independent cross-check

Baglio,Campanario,Glaus MM,Spira,Streicher

numerical integration, IR subtraction, no tensor reduction, Richardson extrapolation

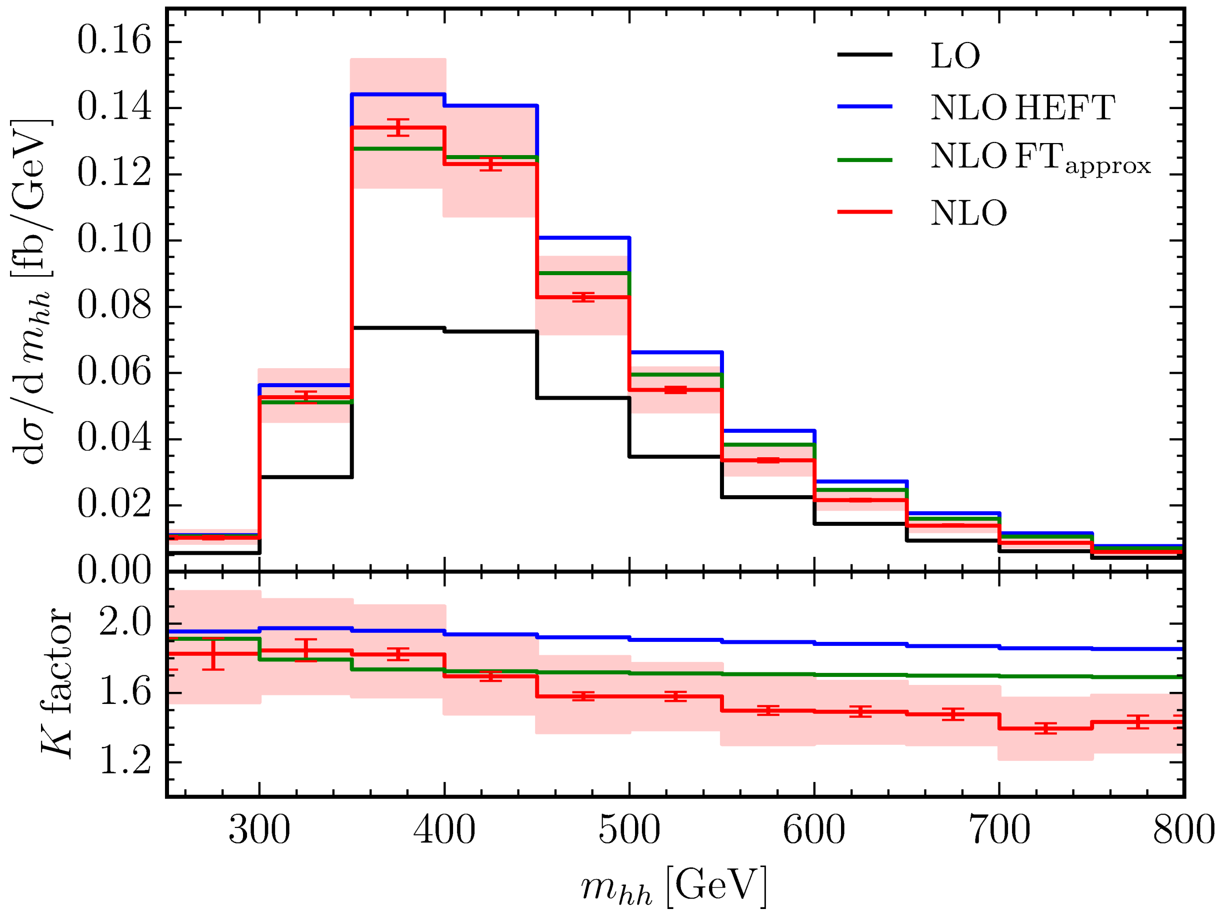
14TeV: $(m_t = 172.5\text{GeV})$ $\quad \sigma_{\text{NLO}} = 32.78(7)^{+13.5\%}_{-12.5\%}$ fb

$\sigma^{\text{HTL}}_{\text{NLO}} = 38.66^{+18\%}_{-15\%}$ fb $\quad (\leftarrow$ HPAIR)

$\Rightarrow$ -15% mass effects on top of LO

NLO $gg \to HH$ with $\mathcal{F}$ull $\mathcal{M}$ass $\mathcal{D}$ependence

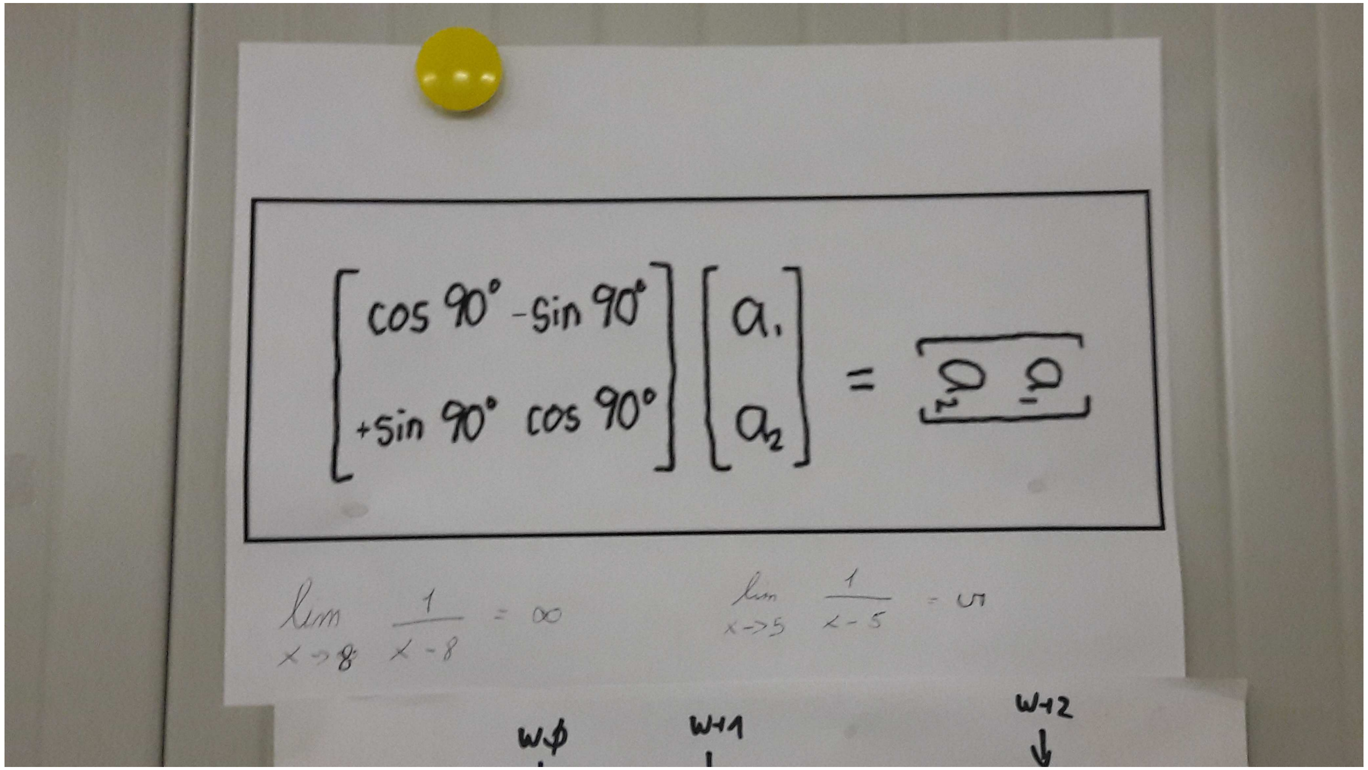
Borowka,Greiner,Heinrich,Jones,Kerner,Schlenk,Schubert,Zirke, Phys.Rev.Lett. 117 (2016) 1



Red: full result w/ mass dependence; blue/green approximations; scale variation: $\mu = (0.5...2)m_{hh}/2$

See also [Borowka eal, JHEP 1610(2016)107]

Project Part: Approximations



$gg \to HH$ $\mathcal{A}$pproximations for $\mathcal{N}$LO

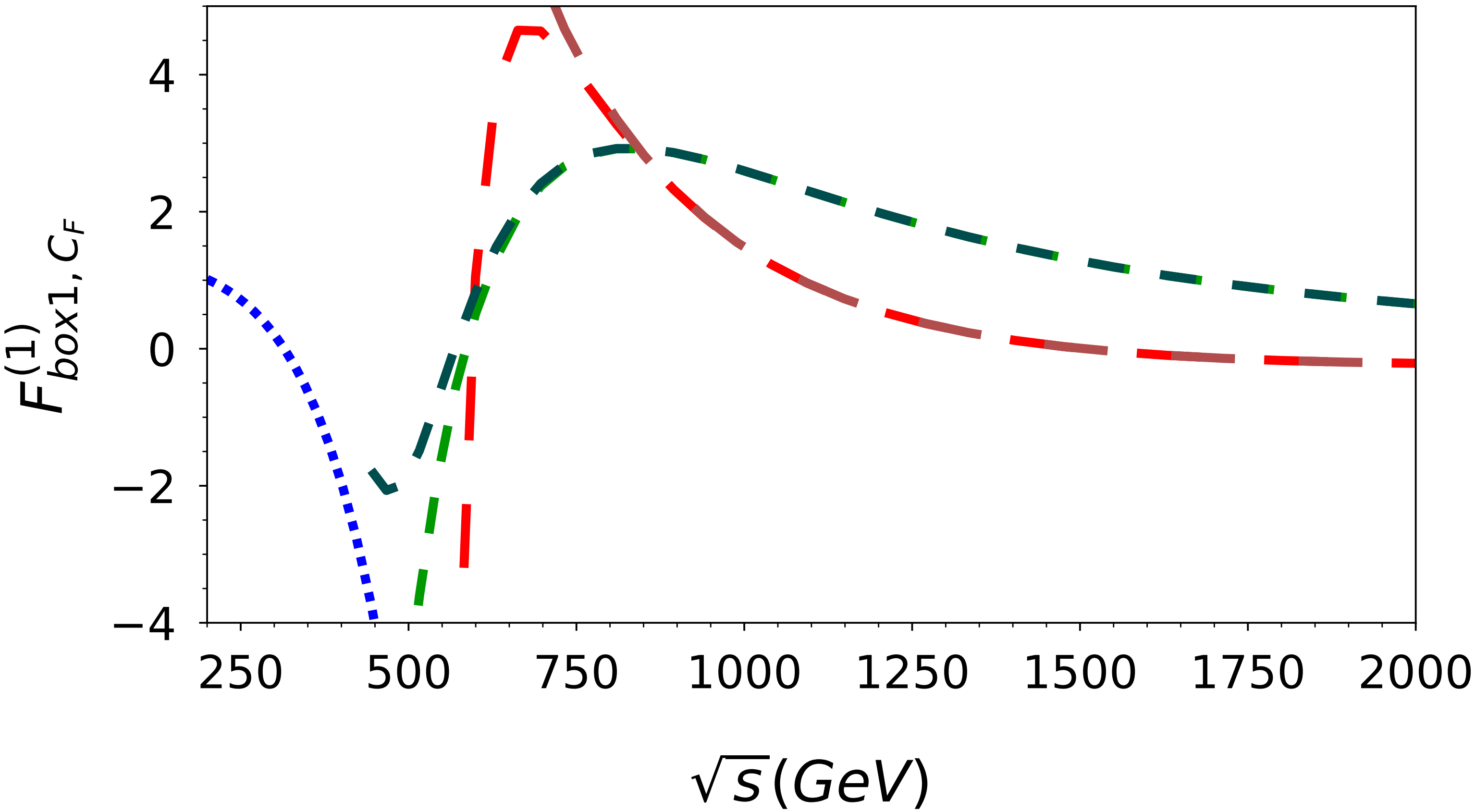
* exact NLO: very CPU-time expensive [Borowka,Greiner,Heinrich,Jones,Kerner,Schlenk,Zicke'16; Baglio,Campanario,Glaus,Mühlleitner,Spira,Streicher'18]

* idea: construct approximations
  - ◇ cross-check for exact result
  - ◇ combine different kinematic regions and construct fast and precise approximation

* large m_t [Grigo,Hoff,Melnikov,Steinhauser'13; Degrassi,Giardine,Gröber'16]
  threshold [Gröber,Maier,Rauh'17]
  small-p_T [Bonciani,Degrassi,Giardino,Gröber'18]
  high-energy [Davies,Mishima,Steinhauser,Wellmann'18'19]

$gg \to HH$ $\mathcal{A}$pproximations for $\mathcal{N}$LO - $\mathcal{R}$esults

F_{tri}, F_{box1}, F_{box2}



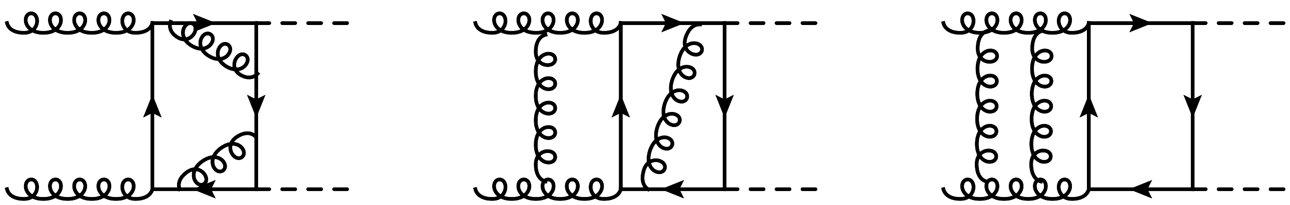
real and imaginary part; m_t^{14} and m_t^{16} terms [Davies,Mishima,Steinhauser,Wellmann'18]

$1/m_t^{12}$ terms from [Grigo,Hoff,Steinhauser'15]

$gg \to HH$: $\mathcal{V}$irtual $\mathcal{C}$orrections at $\mathcal{N}$NLO for $\mathcal{L}$arge m_t

* Aim:
  - ◇ use Padé approach [Gröber,Maier,Rauh'17] and construct approximation
  - ◇ improve approximations as [Grazzini,Heinrich,Jones,Kallweit,Kerner,Lindert,Mazzitelli'18]

- Needed: "many" expansion terms for large m_t for the form factors $F_{\rm tri}$, $F_{\rm box1}$, $F_{\rm box2}$
- [Grigo,Hoff,Steinhauser'15]: 3 terms for $\mathrm{d}\sigma/\mathrm{d}s$
- extension to 5 terms non-trivial . . . work in progress [Davies,Steinhauser]
- information about threshold from [Gröber,Maier,Rauh'17]

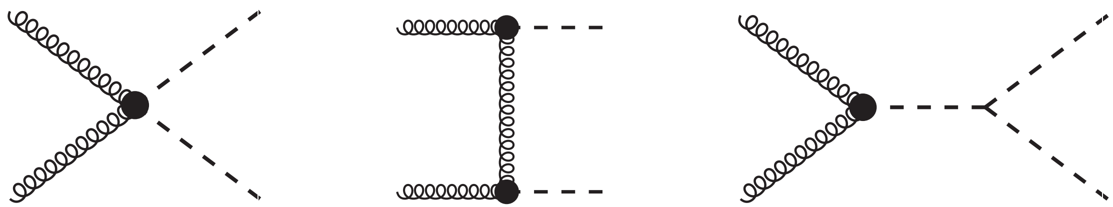


$gg \to HH$: N^{3}LO for $m_t \to \infty$

$$\mathcal{L}_{\rm eff} = -\frac{H}{v} C_H \mathcal{O}_1 + \frac{1}{2}\left(\frac{H}{v}\right)^2 C_{HH}\mathcal{O}_1 \qquad \mathcal{O}_1 = G^a_{\mu\nu}G^{\mu\nu,a}/4$$

Matching: [Gerlach,Herren,Steinhauser'18]

$$(C_{HH}Z_{\mathcal{O}_1} + C_H^2 Z_{11}^L)\mathcal{A}^{\rm eff}_{\rm LO,1PI} + C_H^2 Z^2_{\mathcal{O}_1}\mathcal{A}^{\rm eff}_{\rm LO,1PR,\lambda=0} + C_H Z_{\mathcal{O}_1}\mathcal{A}^{\rm eff}_{\rm LO,1PR,\lambda\neq 0}$$
$$= \frac{1}{\zeta_3^0}\left(\mathcal{A}^h_{\rm 1PI} + \mathcal{A}^h_{\rm 1PR,\lambda=0} + \mathcal{A}^h_{\rm 1PR,\lambda\neq 0}\right) + \mathcal{O}(1/m_t)$$



Z_{11}^L: new at 4 loops; renormalization of product of two operators $\mathcal{O}_1$ [Zoller'16]

- direct calculation of C_H to 4 loops
  agreement with LET [Schröder,Steinhauser'06; Chetyrkin,Kühn,Sturm'06]
- direct calculation of C_{HH} to 4 loops agreement with LET [Spira'16]

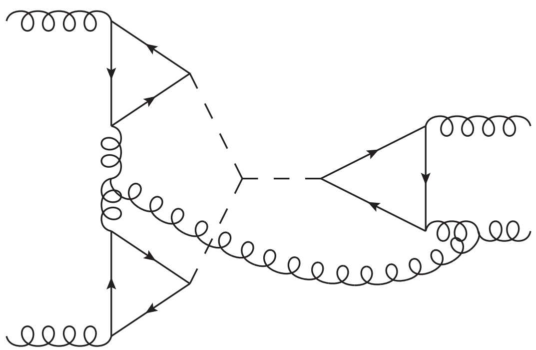
$gg \to HH$: $\mathcal{N}$NLO $\mathcal{R}$eal $\mathcal{R}$adiation for $\mathcal{L}$arge m_t

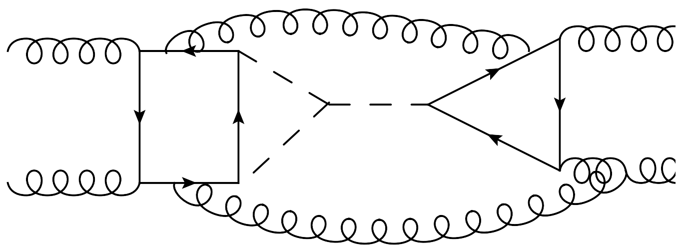
* $m_t \to \infty$: [de Florian, Mazzitelli'13]

* $+1/m_t^2, 1/m_t^4$: only soft-virtual approximation [Grigo,Hoff,Steinhauser'15]

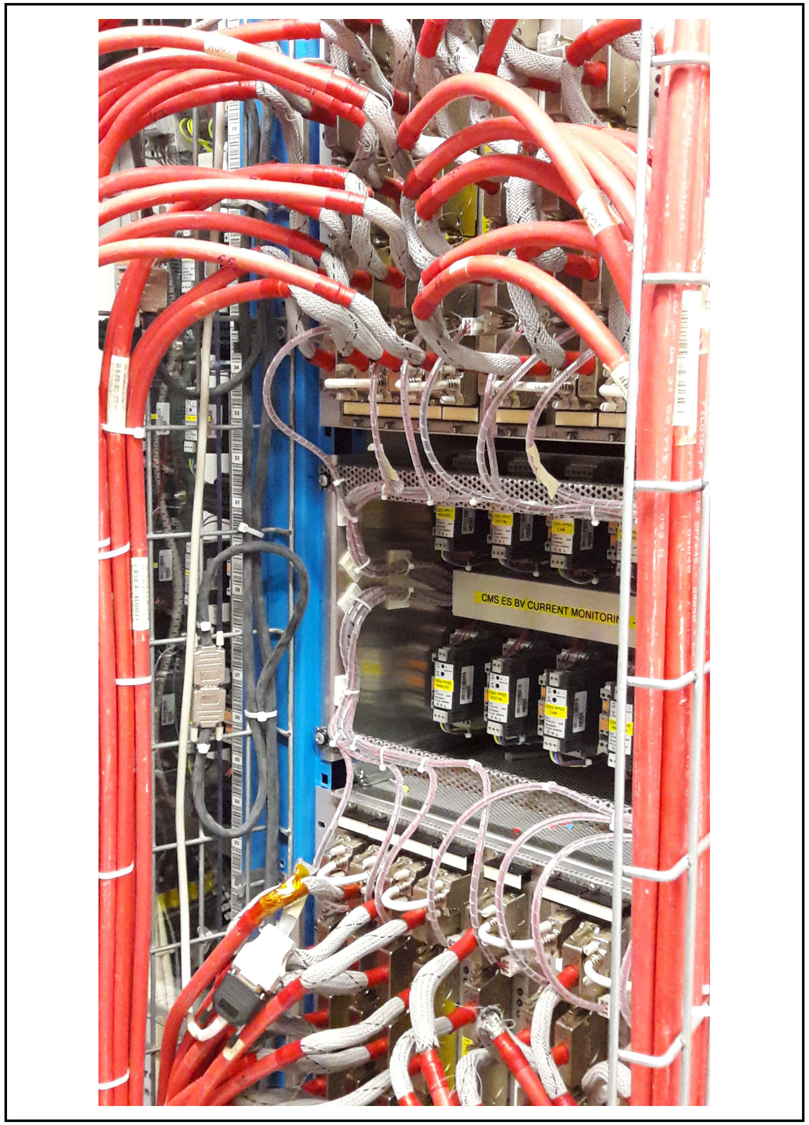
* Aim: real radiation for $m_t^2 \gg s, t$

work in progress [Davies,Herren,Mishima,Steinhauser]



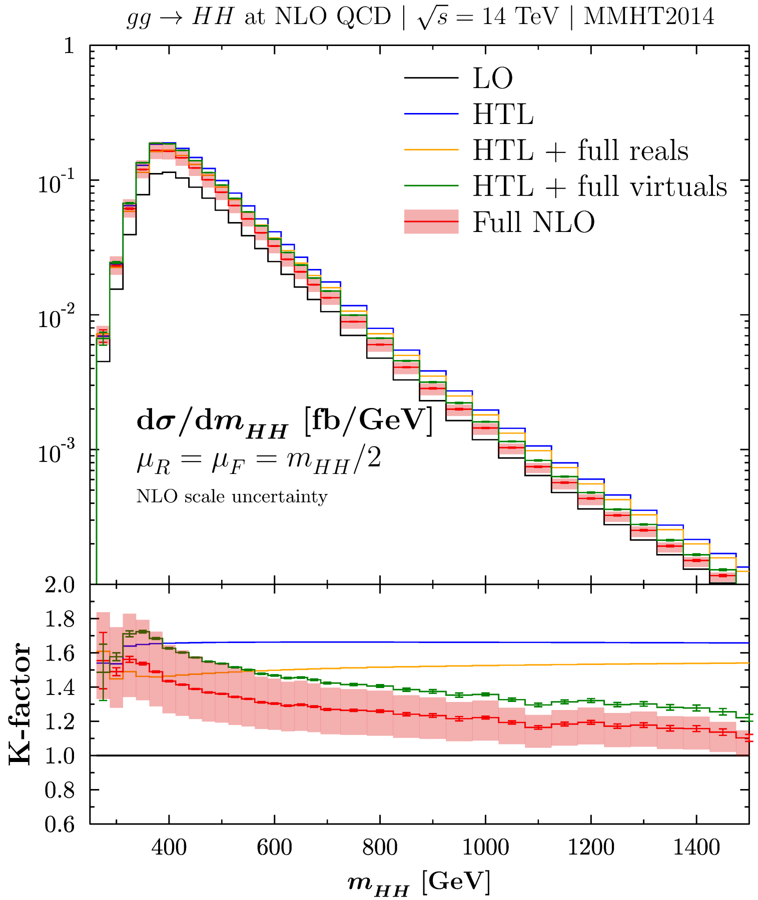


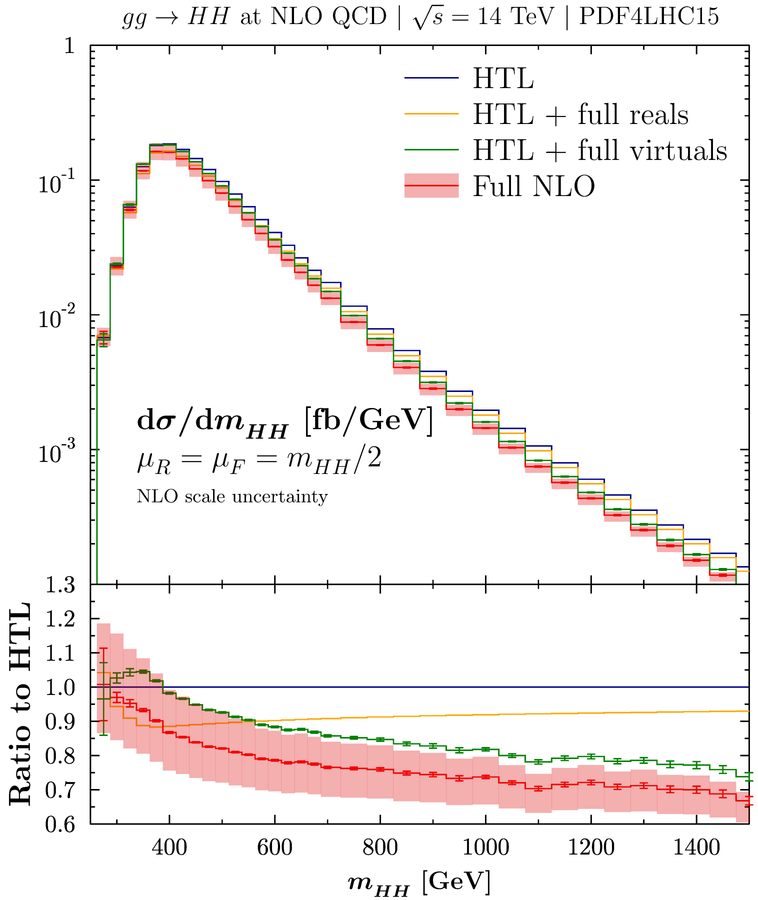
Project Part: Exact Calculation at NLO



NLO $gg \to HH$ with $\mathcal{F}$ull $\mathcal{M}$ass $\mathcal{D}$ependence

Baglio,Campanario.Glauss,MM,Streicher,Spira '18





- independent cross-check of [Borowka eal]; completely different methods; no fixed masses
- first untertainty estimate due to scheme and scale choice of top-quark mass

NLO $\mathcal{W}$ith $\mathcal{I}$nclusion of $\mathcal{M}$ass $\mathcal{E}$ffects

- **NLO Result w/ Mass Dependence:**
  - $*$ Mass effects significant, in particular in distributions $\leftarrow$ New Physics effects
  - $*$ Also important to check validity of approximations

NLO $\mathcal{W}$ith $\mathcal{I}$nclusion of $\mathcal{M}$ass $\mathcal{E}$ffects

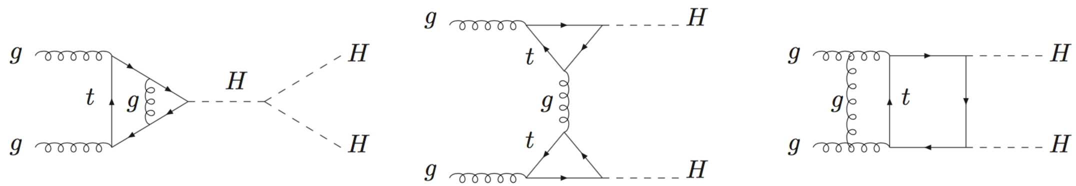
- **Projects:**
  - ∗ Extend SM calculation to inclusion of effective dimension-6 operators to generically consider New Physics effects
  - ∗ NLO QCD corrections to MSSM Higgs pair production including full mass effects
- **Features of Calculation in the MSSM:**
  - ∗ Application of techniques developped in SM → T
  - ∗ $gg \to hh, HH, hH, AA, hA, HA$ new: → T
    - ◇ bottom quark loops can become important ← large $\tan\beta$
    - ◇ Squark loops, genuine SUSY-QCD correections
    - ◇ heavy, light Higgs exchanges in triangle diagram
    - ◇ $gg \to AA, hA, HA$ requires proper treatmen of γ_5
    - ◇ $gg \to hA, HA$ mediated by A, Z exchange, new tensor structures → beyond current CRC

Beyond current CRC: extend results to other well-motivated BSM models, e.g. NMSSM, C2HDM

SM $\mathcal{C}$alculation: $\mathcal{V}$irtual $\mathcal{C}$orrections

- **Virtual corrections**

  47 generic box diagrams, 8 triangle diagrams ($\leftarrow$ single Higgs), 1PR ($\leftarrow H \to Z\gamma$)



  $*$ full diagram w/o tensor reduction $\to$ 6-dim. Feynman integral

  $*$ UV singularities: end-point subtractions

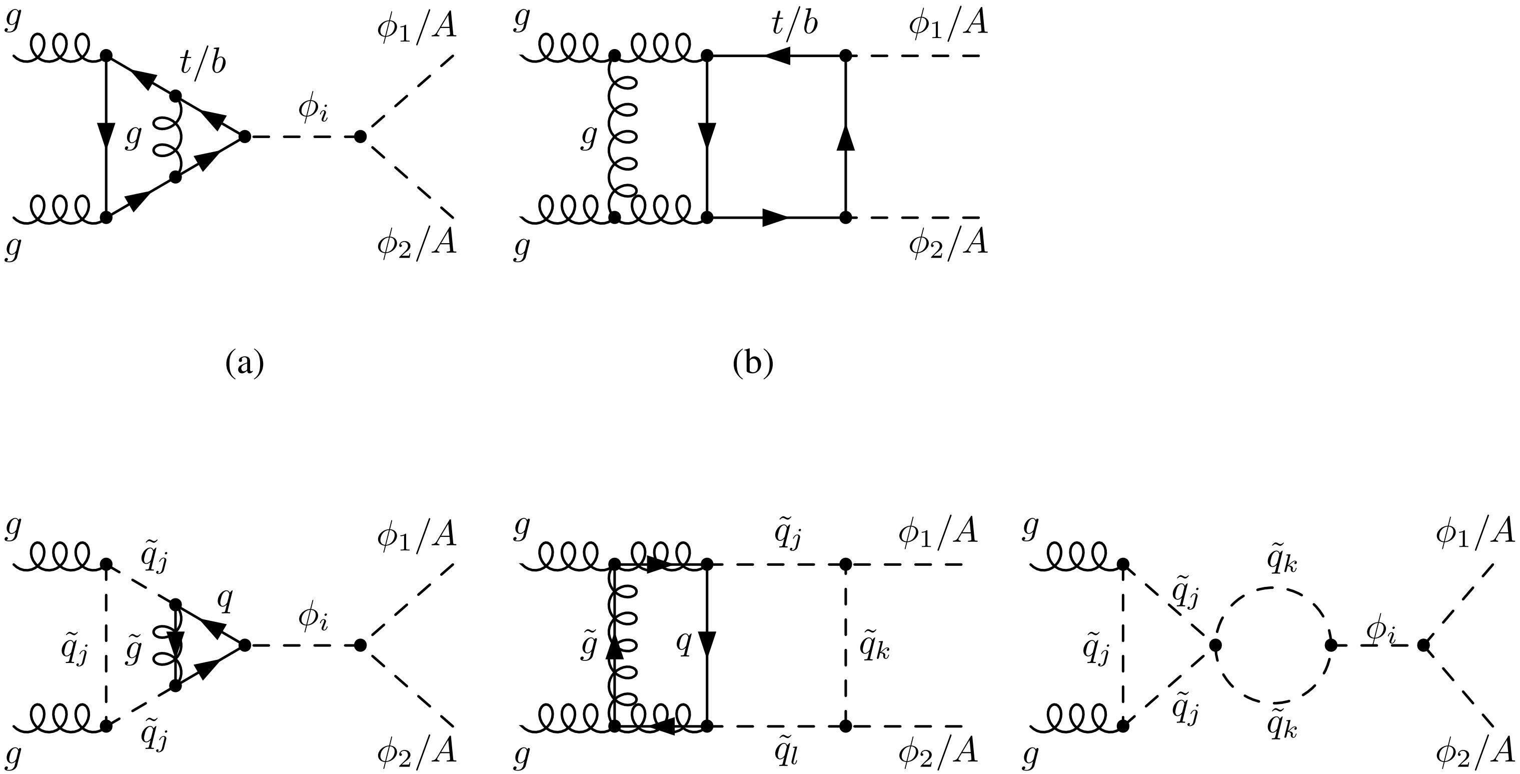
$$\int_0^1 dx \frac{f(x)}{(1-x)^{1-\epsilon}} = \int_0^1 dx \frac{f(1)}{(1-x)^{1-\epsilon}} + \int_0^1 dx \frac{f(x)-f(1)}{(1-x)^{1-\epsilon}} = \frac{f(1)}{\epsilon} + \int_0^1 dx \frac{f(x)-f(1)}{1-x} + \mathcal{O}(\epsilon)$$

  $*$ IR singularities: IR subtraction (based on struc. of integrand and relative to HTL)

  $*$ thresholds: $Q^2 \geq 0, 4m_t^2 \rightsquigarrow$ IBP $\rightsquigarrow$ reduction of power of denominator
  $[m_t^2 \to m_t^2(1-ih)]$

$$\int_0^1 dx \frac{f(x)}{(a+bx)^3} = \frac{f(0)}{2a^2 b} - \frac{f(1)}{2b(a+b)^2} + \int_0^1 dx \frac{f'(x)}{2b(a+bx)^2}$$

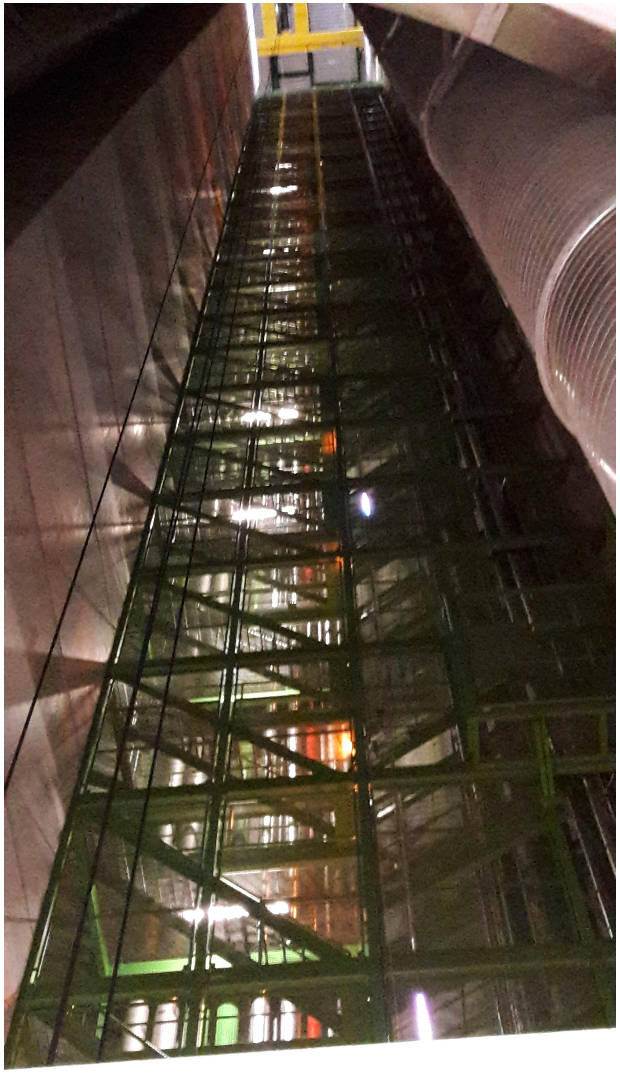
NLO $\mathcal{MSSM}$ $\mathcal{G}$luon $\mathcal{F}$usion to $\mathcal{H}$iggs $\mathcal{P}$airs - $\mathcal{D}$iagrams



(a) (b) (c) (d) (e)

$\phi_{1,2} \in \{h, H\}$

Higgs-To-Higgs Decays



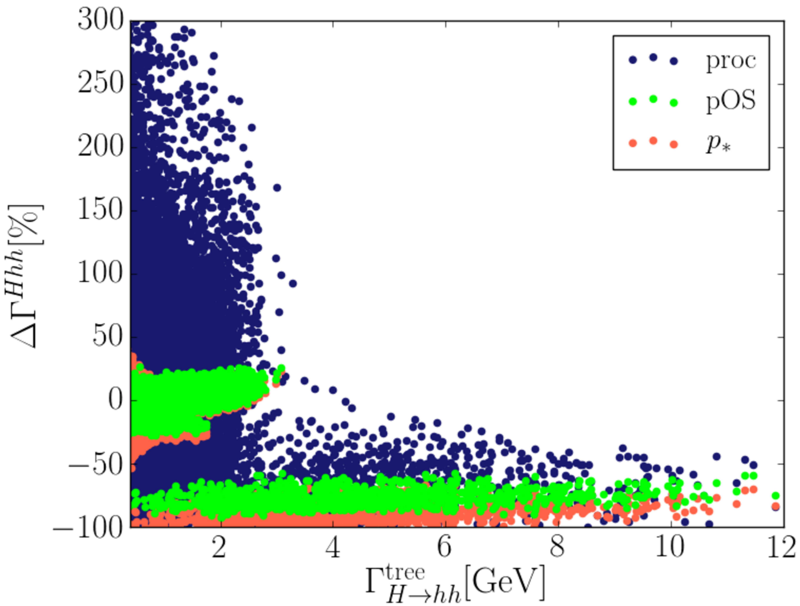
$\mathcal{B}$SM $\mathcal{H}$iggs-to-$\mathcal{H}$iggs $\mathcal{D}$ecays

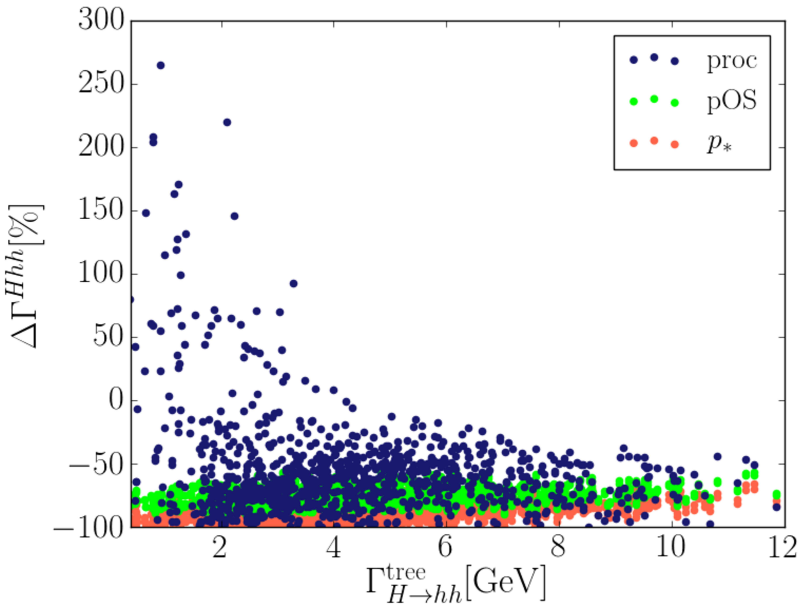
- **Higgs Sector Extensions** by singlet and doublet fields $\leftarrow$ no unreasonable amount of finetuning
  - $*$ Two-Higgs Doublet Model (2HDM) and Next-to-2HDM (N2HDM) as benchmark models for MSSM and NMSSM
  - $*$ More freedom, richer phenomenology $\leftarrow$ no underlying supersymmetry
  - $*$ Enlarged Higgs sector allows for Higgs-to-Higgs (cascade) decays $\rightsquigarrow$ exotic signatures

- **Higher-Order Corrections:**
  - ◇ Electroweak corrections can become substantial due to large Higgs self-couplings or light particles in the loop $\rightarrow$ T
    [Kanemura eal; Krause,MMM,Santos,Ziesche; Krause,Lopez-Val,MMM,Santos]
  - ◇ Corrections to MSSM Higgs neutral self-couplings can become substantial: at one-loop a factor 2, at $\mathcal{O}(\alpha_t\alpha_s)$ few percent [Hollik,Penaranda; Dobado eal; Brucherseifer,Gavin,Spira]
  - ◇ Effective one-loop-corrected NMSSM couplings have substantial impact on Higgs-to-Higgs decays [Nhung,MMM,Streicher,Walz] $\rightarrow$ T
    relative two-loop $\mathcal{O}(\alpha_t\alpha_s)$ corrections are of $\mathcal{O}(5-10\%)$ [MMM,Nhung,Ziesche]

2$\mathcal{H}$DM $\mathcal{H}$igher-$\mathcal{O}$rder $\mathcal{H}$iggs-to$\mathcal{H}$iggs $\mathcal{D}$ecays

[Krause,MMM,Santos,Ziesche,'16]





- ◇ Points pass theoretical and experimental constraints
- ◇ Three different renormalization schemes: two pinched, one process-dependent scheme
- ◇ Right: Only strong-coupling regime

$\mathcal{P}$roject $\mathcal{B}$SM $\mathcal{H}$iggs-to-$\mathcal{H}$iggs $\mathcal{D}$ecays

- **Increase Precision in Higgs-to-Higgs Decays:**
  - ∗ NLO corrections for C2HDM, N2HDM, NMSSM
    - ⋄ possibility of decays chains with consecutive Higgs-to-Higgs decays
    - ⋄ possibility of Higgs pair with different Higgs bosons in the final state
    - ⋄ models differ in underlying symmetries ← differently affected by constraints ⇝ variations in their signatures → link to A3a

- **Investigations:**
  - ⋄ Estimate theory uncertainty (different renormalization schemes implemented)
  - ⋄ Compare with effective coupling results
  - ⋄ Implementation in computer codes
  - ⋄ Comparative analysis including all constraints → link to A3a

Higher-Order Corrections to Higgs Boson Masses

$\mathcal{S}$upersymmetric $\mathcal{H}$iggs $\mathcal{M}$ass $\mathcal{C}$omputations

- **MSSM and NMSSM Masses no free parameters:** Predictive power of the MSSM, NMSSM and other extensions $\rightsquigarrow$ important experimental test to be passed $\rightarrow$ link to A3a
- **Status of MSSM and NMSSM Higher-Order Corrections:**
  - $*$ Precise predictions
    - $m_{h,\text{MSSM}}$: up to 2-loop and dominant 3-loop (real+complex MSSM)
      [Okada eal;Ellis eal; Brignole eal;Haber,Hempfling;Chankowski eal;Dabelstein;Pierce eal;Barbieri eal;Espinosa,Quiros;Casas eal;Carena eal;Heinemeyer eal;Zhang;Degrassi eal;Dedes eal;Martin; Borowka eal;Draper,Lee;Harlander eal;Kant eal;Staub,Porod;Goodsell eal;Bahl,Hollik;Bagnaschi eal;Kunz eal;Mihaila,Zerf; ...]
    - $m_{h,\text{NMSSM}}$: up to 2-loop (real+complex) NMSSM
      [Ellwanger eal; Elliott eal; Pandita; Degrassi,Slavich;Staub eal;King eal;Graf eal;Ender eal;Drechsel eal;MM eal;Goodsell eal;Ham eal;Funakubo eal;Cheung eal; ...]
  - $*$ Estimate of uncertainty
    - MSSM: ± 3 GeV [Degrassi eal; Allanach eal]
    - NMSSM: comparison of $\overline{\text{DR}}$ calculations [Staub eal];
      comparison of OS calculations [Drechsel eal]

$\mathcal{S}$upersymmetric $\mathcal{H}$iggs $\mathcal{M}$ass $\mathcal{C}$omputations $\mathcal{C}$ontinued

- **Numerous Program Packages for Higgs Mass Computations:** `FeynHiggs`, `FlexibleSUSY`, `H3m`, `Himalaya`, `NMSSMCALC`, `NMSSMTools`, `SARAH`, `SoftSUSY`, `SPheno`, ...

- **Recent and ongoing activities:**
  * Lightest MSSM Higgs mass at three loop [Reyes,Fazio,'19], second calculation after [Harlander,Kant,Mihaila,Steinhauser,'10]
  * light CP-even Higgs mass resummed to 4th logarithmic order (heavy SUSY spectrum); three-loop matching coefficient to $\mathcal{O}(\alpha_t^2\alpha_s^2)$ implemented in `Himalaya` [Harlander,Klappert,Franco,Voigt,'18]
  * Finalization of $\mathcal{O}(\alpha_t^2)$ corrections to CP-violating NMSSM Higgs masses [Gröber,Krause,MMM,Nhung,Rzehak]

$\mathcal{MSSM}$ $\mathcal{M}$ass $\mathcal{P}$rojects

- **LHC Higgs Mass Determination:** $\mathcal{O}$(100 MeV); however in large parts of SUSY parameter space three-loop corrections to lightest Higgs mass from strong sector of MSSM are of $\mathcal{O}$(few GeV) $\rightsquigarrow$

- **Planned Projects:**

  * Complement three-loop $\mathcal{O}(\alpha_t \alpha_s^2)$ corrections [Kant,Harlander,Mihaila,Steinhauser,'10] by $\mathcal{O}(\alpha_b \alpha_s^2)$, $\mathcal{O}(\alpha_{t,b}^2 \alpha_s)$, $\mathcal{O}(\alpha_{t,b}^3)$ corrections at vanishing external momentum

  * Implementation of the corrections in `H3m`, provide also stand-alone C++ code similar to `Himalaya` $\rightsquigarrow$ link to other programs possible $\rightarrow$ close collaboration w/ Aachen

  * leading three-loop corrections of $\mathcal{O}$(1 GeV) $\rightsquigarrow$ obtain information about four-loop term (depending on project progress) $\rightarrow$ future beyond current CRC

$\mathcal{N}$MSSM $\mathcal{M}$ass $\mathcal{P}$rojects

- **NMSSM Mass Theory Predictions:** Higher-order corrections to NMSSM Higgs masses need to catch up with MSSM mass predictions, with experimental accuracy $\rightsquigarrow$

- **Ongoing:** [Gröber,Krause,MMM,Nhung,Rzehak]

  * $\mathcal{O}(\alpha_t^2)$ corrections in the gaugeless limit at vanishing external momentum
  * based on mixed OS-$\overline{\text{DR}}$ renormalization scheme $\leftarrow$ other NMSSM codes at this loop level in $\overline{\text{DR}}$ scheme
  * possibility to choose between OS and $\overline{\text{DR}}$ renormalization

possibility to estimate theoretical uncertainty due to missing higher-order corrections
based on renormalization scheme change

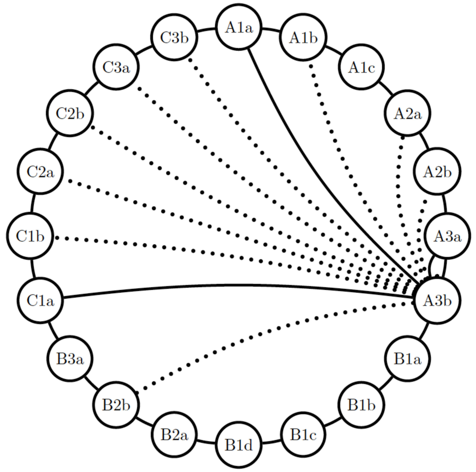
$\mathcal{N}$MSSM $\mathcal{M}$ass $\mathcal{P}$rojects

- **Planned Projects:**
  - Complement $\mathcal{O}(\alpha_t\alpha_s + \alpha_t^2)$ corrections [Gröber eal; NMSSMCALC] by $\mathcal{O}(\alpha_t\alpha_\lambda)$, $\mathcal{O}(\alpha_\lambda^2)$ corrections
  - implementation in `NMSSMCALC`
  - challenge treatment of massless Goldstones in self-energies w/ vanishing external momentum (possible soluations [Brucherseifer eal; Kumar,Martin; Goodsell,Staub])
  - $\mathcal{O}(\alpha_t\alpha_\kappa)$, $\mathcal{O}(\alpha_\lambda\alpha_\kappa)$, $\mathcal{O}(\alpha_\kappa^2)$ corrections if time permits $\rightarrow$ future beyond current CRC
  - future: $\mathcal{O}(\alpha_t\alpha_b)$, $\mathcal{O}(\alpha_b^2)$

Link MSSM and NMSSM results and codes to get most precise prediction for NMSSM masses in MSSM limit $\rightarrow$ close collaboration ITP, TTP at KIT and Aachen

$\alpha_{\lambda/\kappa} \equiv \lambda^2/(4\pi)$, $\kappa^2/(4\pi)$

$\mathcal{L}$inks to $\mathcal{O}$ther $\mathcal{P}$rojects

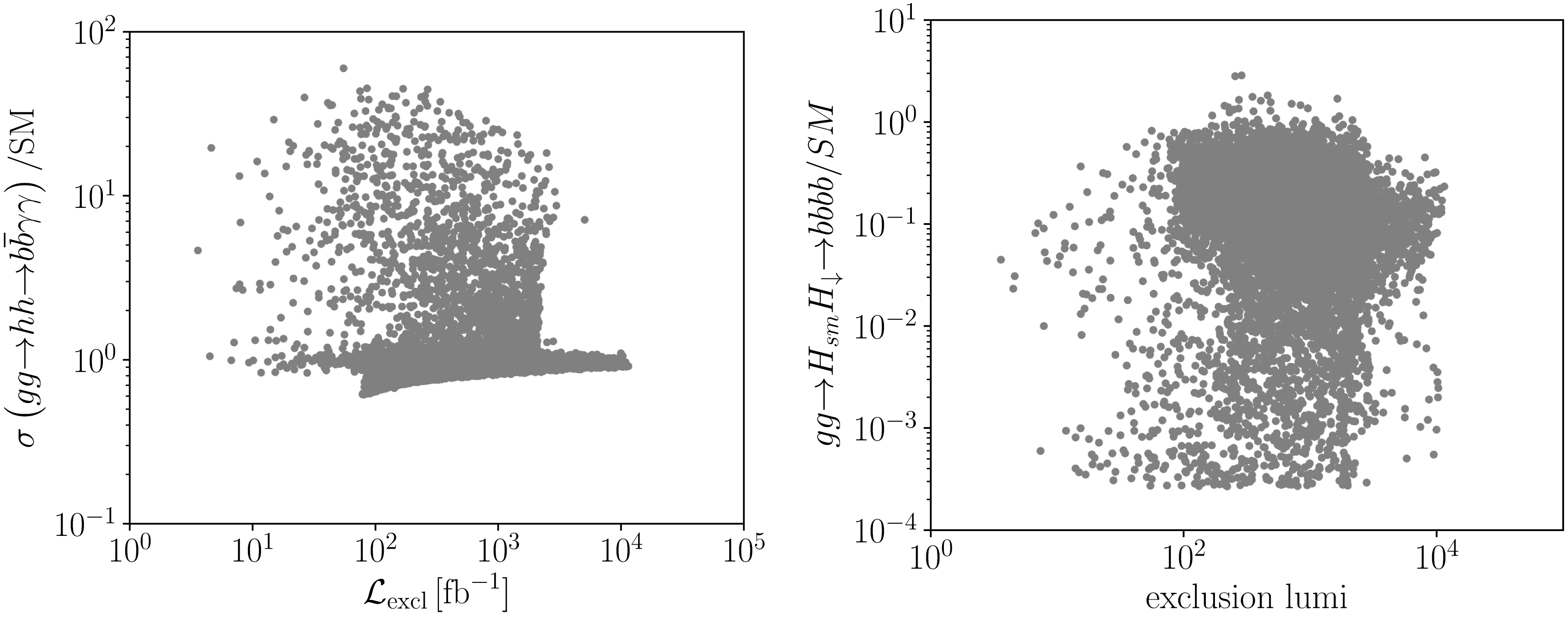


- ⋄ EFT analyses of A2a, A2b can be mapped onto complete models of A3b
- ⋄ insights gained in A3a feed back into A3b and vice versa
- ⋄ insights gained on NP in the top sector and heavy top partners in B2b, C3a feed back into higher-order corrections to BSM Higgs observables
- ⋄ dito for information gained on flavour and CP observables from C
- ⋄ overlap on technical questions with A1a, C1a, C1b

Thank You For Your Attention!

$\mathcal{S}$catter $\mathcal{P}$lots $\mathcal{C}$2HDM

[Basler,Dawson,Englert,MM '18]

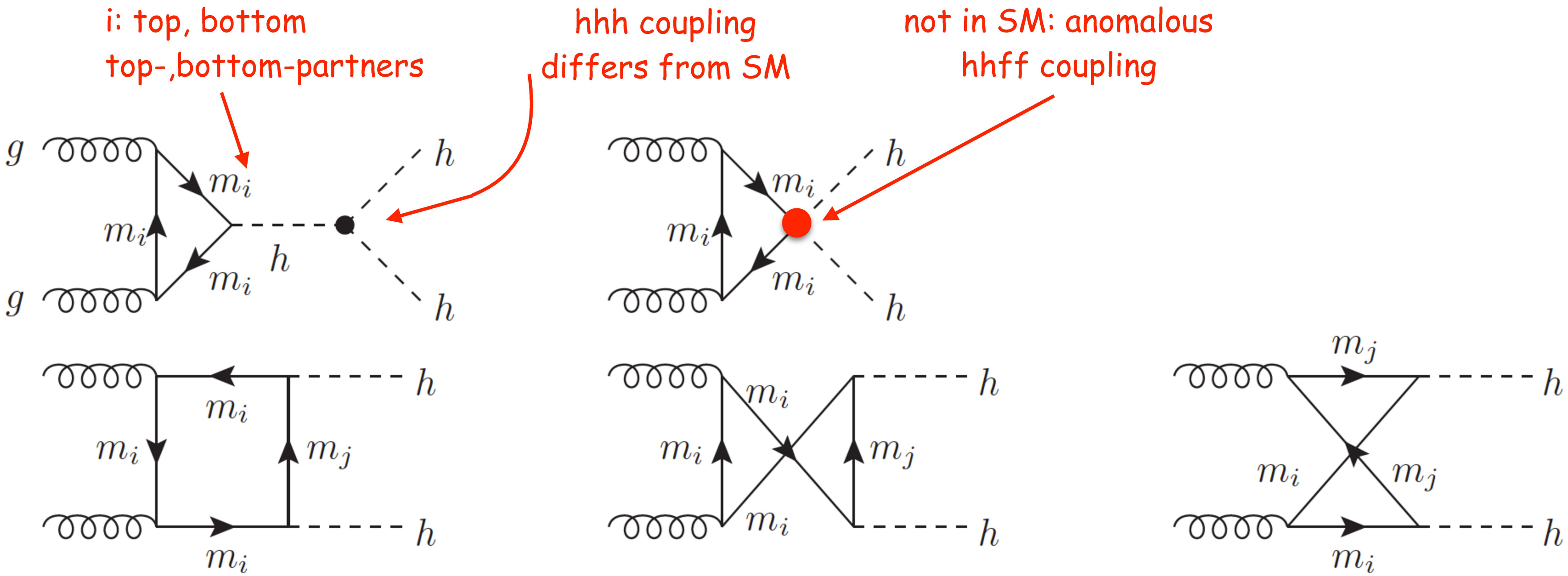


- Left: C2HDM T1 $hh \to 2b2\gamma$; large $t\bar{t}$ rates responsible for exclusion beyond HiggsBounds
- Right: C2HDM T1 $hH_{\downarrow} \to 4b$ enhanced by about a factor of 3

$\mathcal{D}$i-$\mathcal{H}$iggs $\mathcal{P}$roduction $\mathcal{B}$eyond the $\mathcal{S}$M

- **Beyond SM HH production:** Cross sections can be considerably larger: ex.: composite Higgs

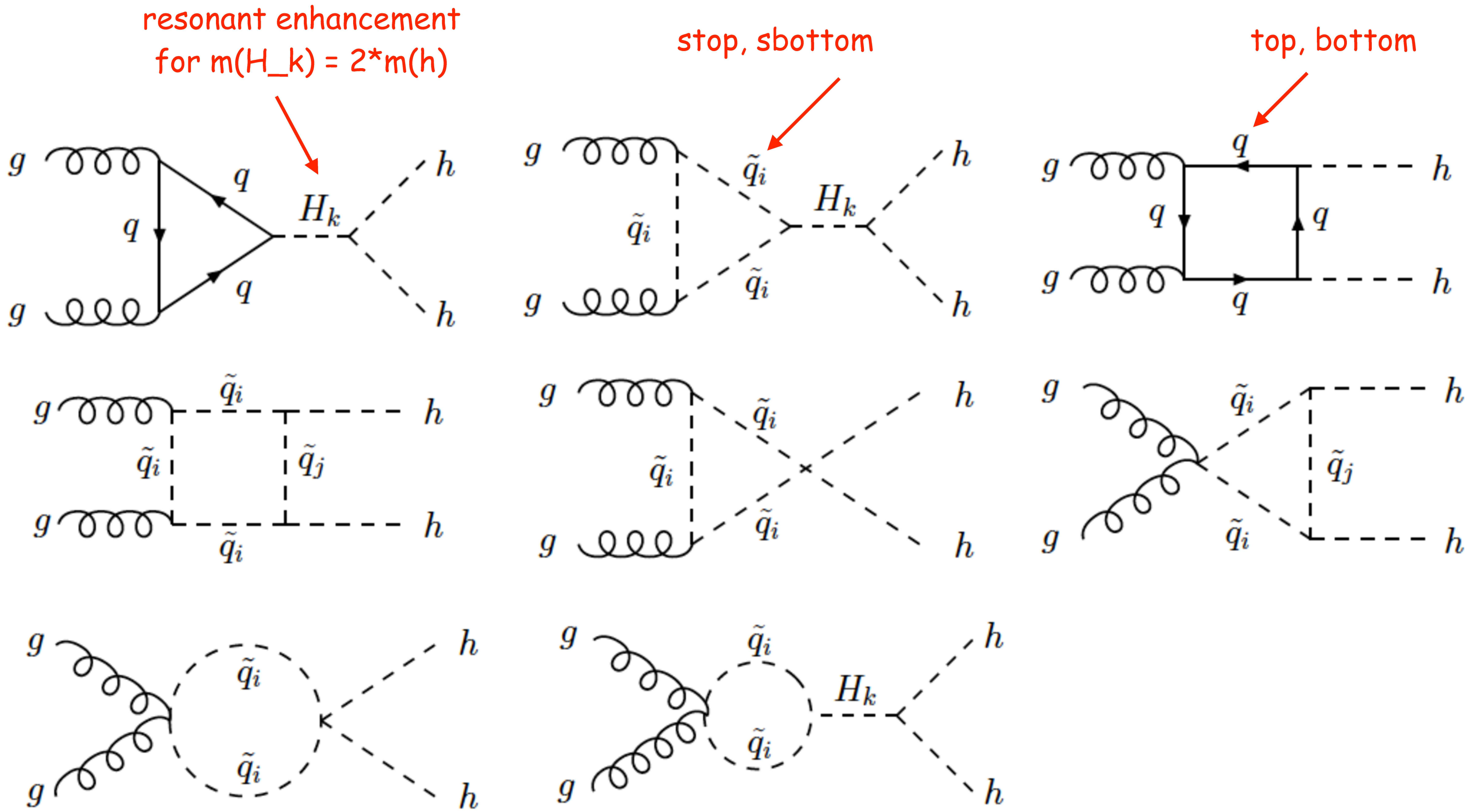
  $*$ different λ_{3H}; $*$ novel couplings; $*$ novel particles in the loop; $*$ resonant enhancement



$\mathcal{D}$i-$\mathcal{H}$iggs $\mathcal{P}$roduction $\mathcal{B}$eyond the $\mathcal{S}$M

- **Beyond SM HH production:** Cross sections can be considerably larger: ex.: NMSSM

  $*$ different λ_{3H}; $*$ novel couplings; $*$ novel particles in the loop; $*$ resonant enhancement



$\mathcal{D}$i-$\mathcal{H}$iggs $\mathcal{P}$roduction $\mathcal{B}$eyond the $\mathcal{S}$M

- **How large can λ_{3H} be?** $\lambda_{3H} = \kappa_\lambda \lambda_{3H}^{\text{SM}}$

- **Expect the unexpected:**

$\ast$ Higgs-to-Higgs cascade decays in non-minimal Higgs sectors $\rightsquigarrow$
Exotic multi-fermion and/or multi-photon final states

- **Higher-order corrections to σ_{hh}:**
  - available in large loop particle mass limit
  - K-factor typically of $\mathcal{O}(1.5-2)$
  - new physics effects on K-factors in general small
  - new physics effects on absolute cross section large
  - for higher-order corrections for BSM Higgs pair production, see
    [Dawson,Dittmaier,Spira; Agostini,Degrassi,Gröber,Slavich; Dawson,Lewis;
    Gröber,MM,Spira,Streicher; Gröber,MM,Spira; Hespel,Lopez-Val,Vryonidou; Moyoti eal; ...]

SM $\mathcal{C}$alculation

$$\sigma_{\rm NLO} = \sigma_{\rm LO} + \Delta\sigma_{\rm virt} + \Delta\sigma_{gg} + \Delta\sigma_{qg} + \Delta\sigma_{q\bar{q}},$$

with

$$\sigma_{\rm LO} = \int_{\tau_0}^{1} d\tau \frac{d\mathcal{L}^{gg}}{d\tau} \hat{\sigma}_{\rm LO}\left(Q^2 = \tau s\right),$$

$$\Delta\sigma_{\rm virt} = \frac{\alpha_s\left(\mu_R^2\right)}{\pi} \int_{\tau_0}^{1} d\tau \frac{d\mathcal{L}^{gg}}{d\tau} \hat{\sigma}_{\rm LO}\left(Q^2 = \tau s\right) C_{\rm virt}\left(Q^2\right),$$

$$\Delta\sigma_{ij} = \frac{\alpha_s\left(\mu_R^2\right)}{\pi} \int_{\tau_0}^{1} d\tau \frac{d\mathcal{L}^{ij}}{d\tau} \int_{\frac{\tau_0}{\tau}}^{1} \frac{dz}{z}\, \hat{\sigma}_{\rm LO}\left(Q^2 = z\tau s\right) C_{ij}(z)$$

where

$$C_{gg} = -zP_{gg}(z)\log\frac{\mu_F^2}{\tau s} + d_{gg}(z) + 6[1 + z^4 + (1-z)^4]\left(\frac{\log(1-z)}{1-z}\right)_+,$$

$$C_{gq} = -\frac{z}{2}P_{gq}(z)\log\frac{\mu_F^2}{\tau s(1-z)^2} + d_{gq}(z),$$

$$C_{q\bar{q}} = d_{q\bar{q}}(z)$$

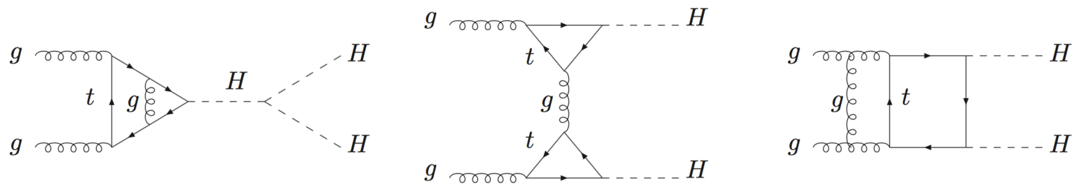
SM $\mathcal{C}$alculation $\mathcal{C}$ontinued

In the heavy top limit (HTL)

$$
\begin{aligned}
C_{\rm virt} &\to \pi^2 + \frac{11}{2} + C_{\triangle\triangle} \\
d_{gg} &\to -\frac{11}{2}(1-z)^3 \\
d_{gq} &\to= \frac{2}{3}z^2 - (1-z)^2, \\
d_{q\bar{q}} &\to \frac{32}{27}(1-z)^3
\end{aligned}
$$

- **Virtual corrections**

  47 generic box diagrams, 8 triangle diagrams ($\leftarrow$ single Higgs), 1PR ($\leftarrow H \to Z\gamma$)



  * full diagram w/o tensor reduction $\to$ 6-dim. Feynman integral
  * UV singularities: end-point subtractions

$$\int_0^1 dx \frac{f(x)}{(1-x)^{1-\epsilon}} = \int_0^1 dx \frac{f(1)}{(1-x)^{1-\epsilon}} + \int_0^1 dx \frac{f(x)-f(1)}{(1-x)^{1-\epsilon}} = \frac{f(1)}{\epsilon} + \int_0^1 dx \frac{f(x)-f(1)}{1-x} + \mathcal{O}(\epsilon)$$

  * IR singularities: IR subtraction (based on struc. of integrand and relative to HTL)
  * thresholds: $Q^2 \geq 0, 4m_t^2 \rightsquigarrow$ IBP $\rightsquigarrow$ reduction of power of denominator
    $[m_t^2 \to m_t^2(1-ih)]$

$$\int_0^1 dx \frac{f(x)}{(a+bx)^3} = \frac{f(0)}{2a^2b} - \frac{f(1)}{2b(a+b)^2} + \int_0^1 dx \frac{f'(x)}{2b(a+bx)^2}$$

SM $\mathcal{C}$alculation: $\mathcal{V}$irtual and $\mathcal{R}$eal $\mathcal{C}$orrections

- **Virtual corrections continued:**

$\ast$ **Renormalization:** α_s: $\overline{\text{MS}}$, 5 flavours, m_t: on-shell

$\ast$ **Phase space integration:** 7-dim. integrals for $d\sigma/dQ^2$

$\ast$ **Infrared mass effects:** after subtraction of HTL [adding back HTL results obtained with `HPAIR`]

$\ast$ **Richardson extrapolation:** extraction to narrow-width approximation $(h \to 0)$

- **Real Corrections:**

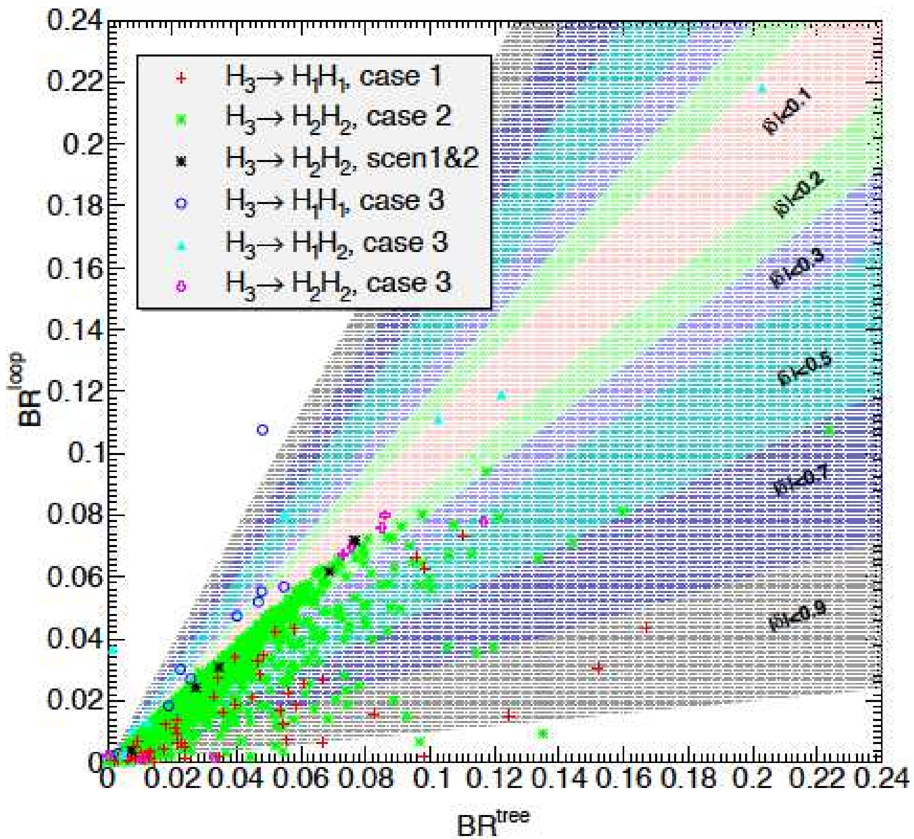
  - full matrix elements generated with `FeynArts` and `FormCalc`
  - matrix elements in HTL involving full LO sub-matrix elements subtracted $\rightsquigarrow$ IR-, COLL-finite [adding back HTL results obtained from `HPAIR`]

$\mathcal{L}$oop $\mathcal{C}$orrected $\mathcal{T}$rilinear $\mathcal{H}$iggs $\mathcal{S}$elf-$\mathcal{C}$oupling

- **Higgs mass and self-couplings:** determined from Higgs potential $\leadsto$ consistent description of Higgs sector at higher order requires loop corrections to masses and self-couplings

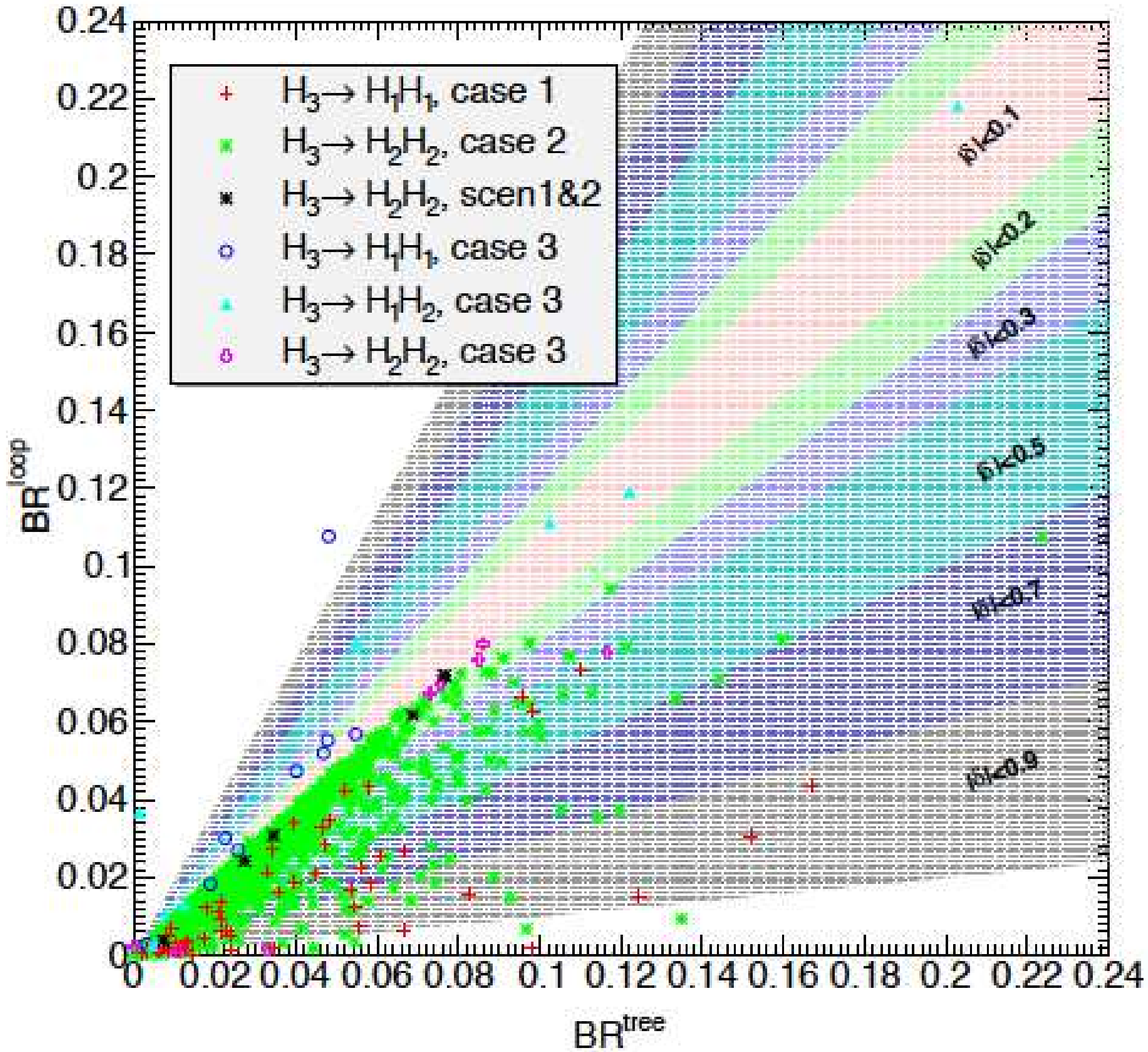
$\Rightarrow$ determination of higher order corrections to trilinear Higgs self-couplings

Dao,MMM,Streicher,Walz '13



$$\delta \equiv \frac{\mathrm{BR}^{\mathrm{loop}} - \mathrm{BR}^{\mathrm{tree}}}{\mathrm{BR}^{\mathrm{tree}}}$$

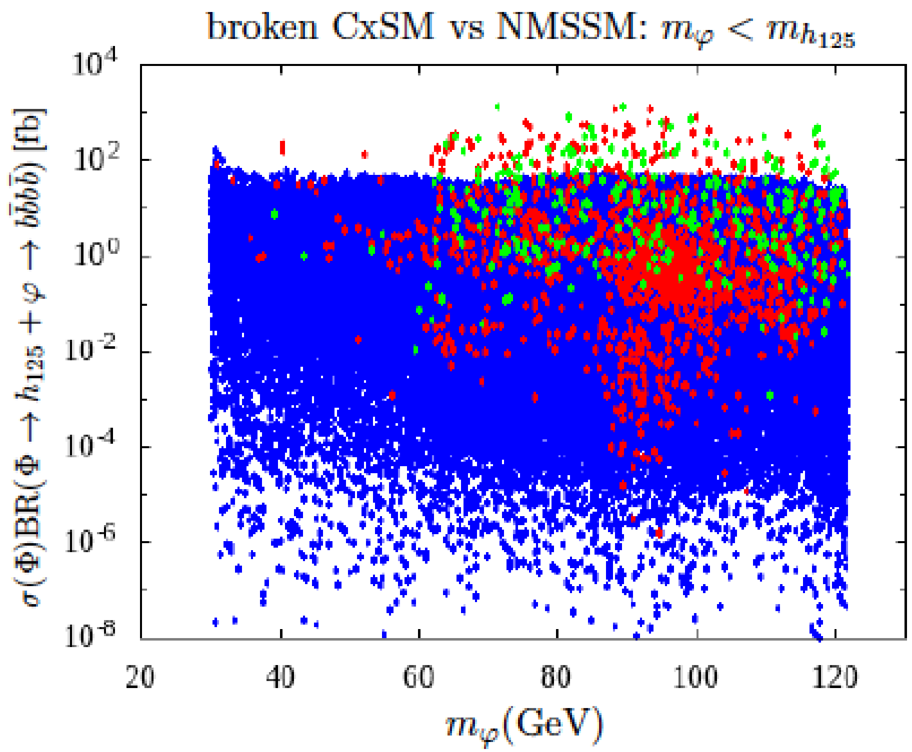
Dao,MMM,Streicher,Walz '13

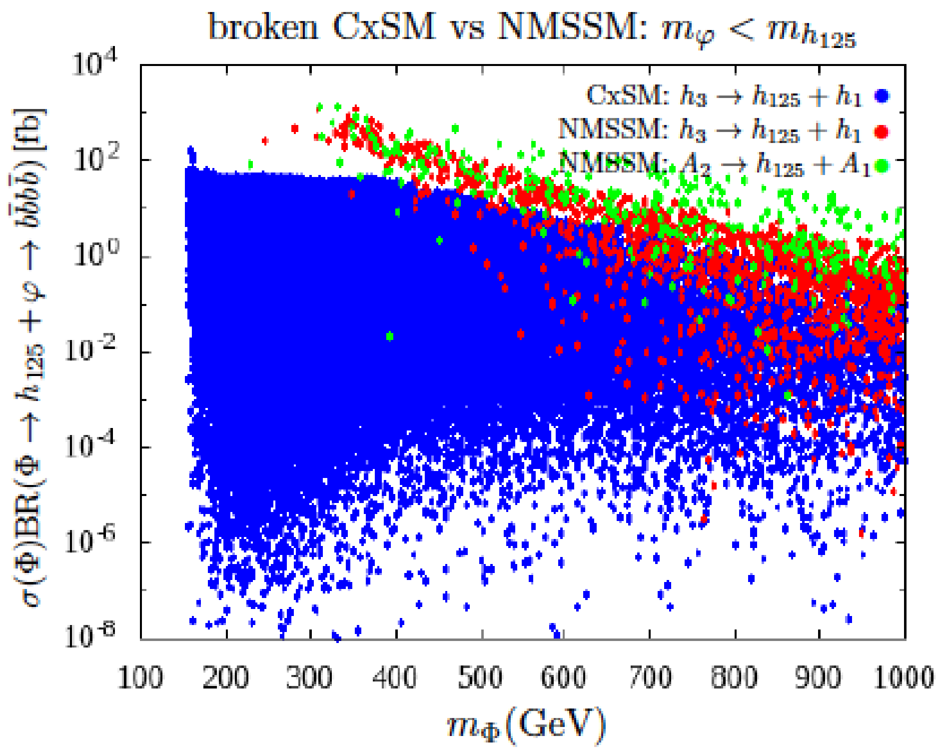


$$\delta \equiv \frac{BR^{loop} - BR^{tree}}{BR^{tree}}$$

$\mathcal{D}$istinction of $\mathcal{C}$xSM and $\mathcal{N}$MSSM

[Costa,MM,Sampaio,Santos '16]



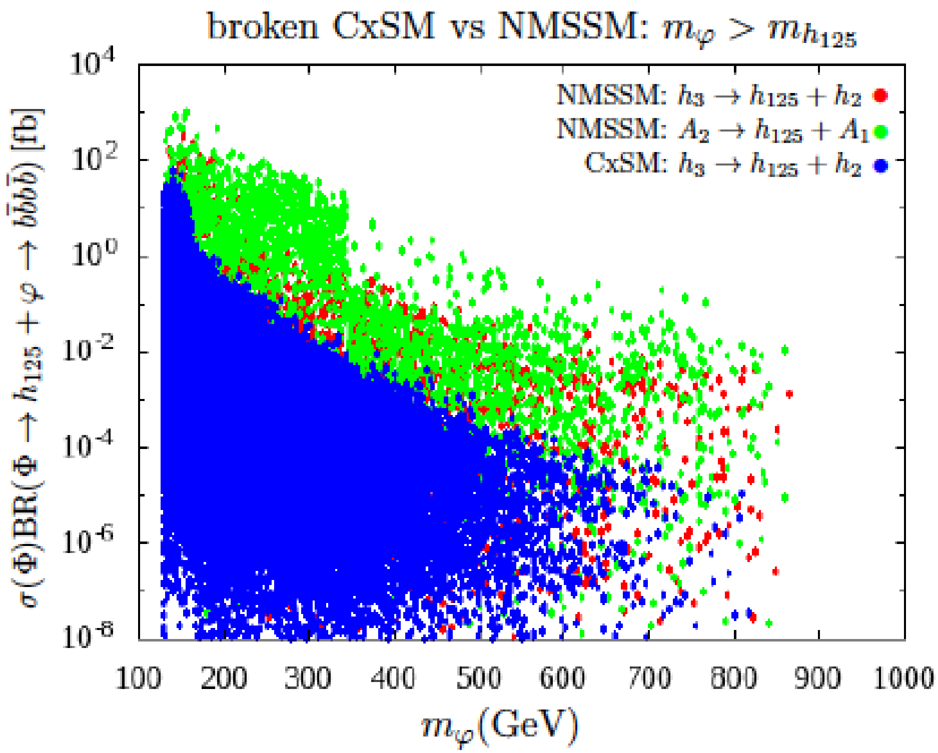


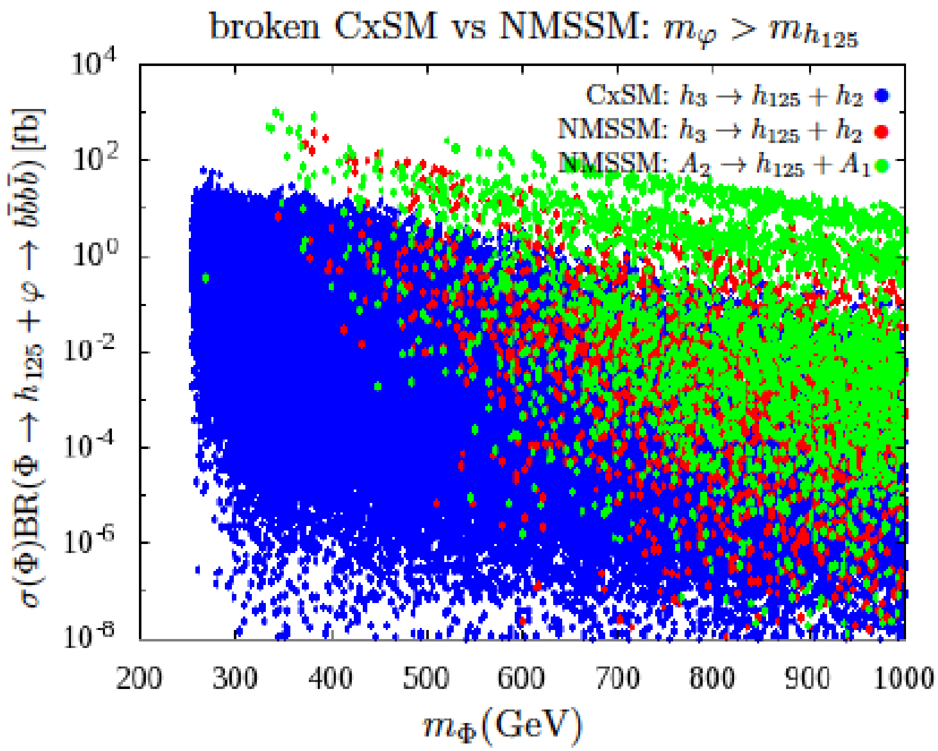
Red: NMSSM: $\Phi \equiv h_3$, $h_{125} \equiv h_2$ and $\varphi \equiv h_1$

Green: NMSSM: $\Phi \equiv A_2$, $h_{125} \equiv h_{1,2}$ and $\varphi \equiv A_1$

$\mathcal{D}$istinction of $\mathcal{C}$xSM and $\mathcal{N}$MSSM

[Costa,MM,Sampaio,Santos '16]



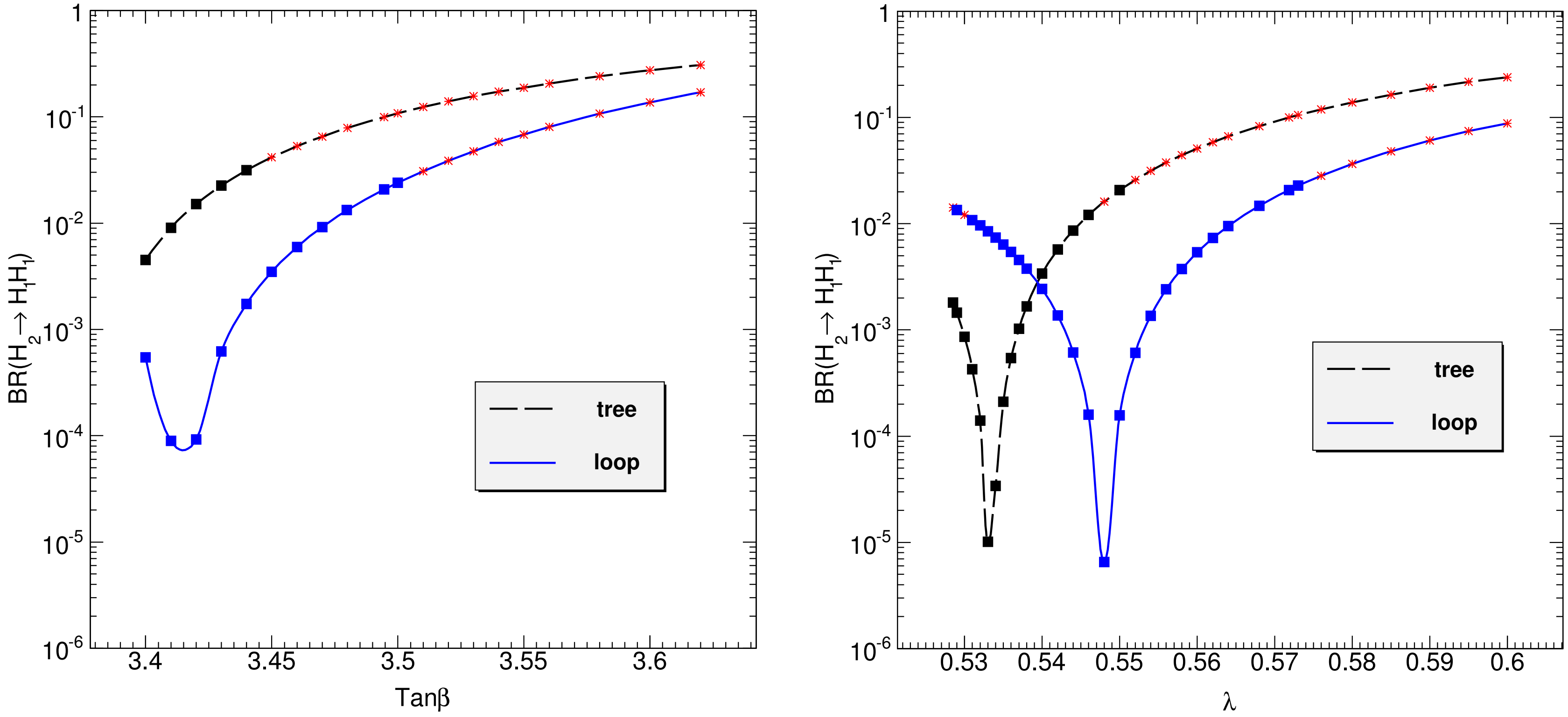


Red: NMSSM: $\Phi \equiv h_3$, $h_{125} \equiv h_1$ and $\varphi \equiv h_2$

Green: NMSSM: $\Phi \equiv A_2$, $h_{125} \equiv h_{1,2}$ and $\varphi \equiv A_1$

$\mathcal{I}$mpact of $\mathcal{L}$oop-$\mathcal{C}$orrected $\mathcal{S}$elf-$\mathcal{C}$oupling on ($\mathcal{N}$on-)$\mathcal{E}$xclusion

[Dao,MMM,Streicher,Walz]



$H_2 \equiv 125$ GeV Higgs; dashed - tree-level; full - loop-corrected; red - excluded