Higgs pair production at the LHC within the 2HDM

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LAL Orsay

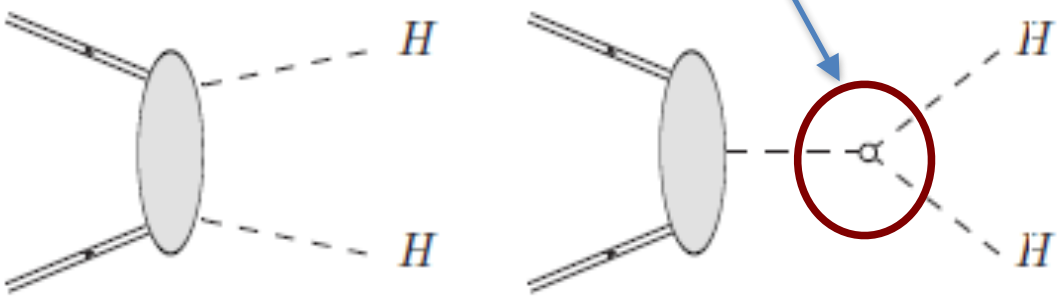
Outline

- Brief SM overview
- HH in the 2HDM
- HH other BSM scenarios
- Outlook

HH Motivation

- ***Higgs self couplings***
  - SM Higgs potential:

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



SM and similarly in BSM extensions

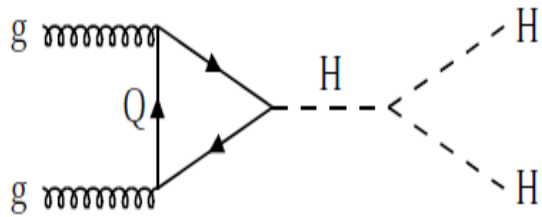
$$\lambda_{HHH} = \lambda_{HHHH} = \frac{M_H^2}{2v^2}$$

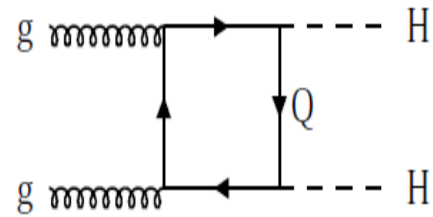
Fixed values in the SM

HH in the SM

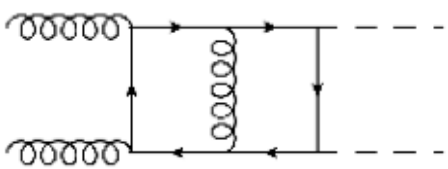
Gluon Fusion is the dominant production channel:

At LO:





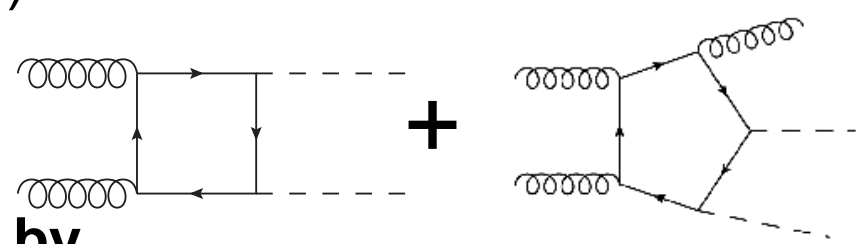
- Exact NLO computation requires:
  - Real emissions: HHj one loop
  - Virtual corrections: Include 2-loop amplitudes



Not available

- NLO results in the HEFT (hep-ph/9805244)

Within MG5_aMC@NLO
Exact real emission matrix elements



Virtual corrections in the HEFT-rescaled by the exact born (arxiv:1401.7340 and 1408.6542)

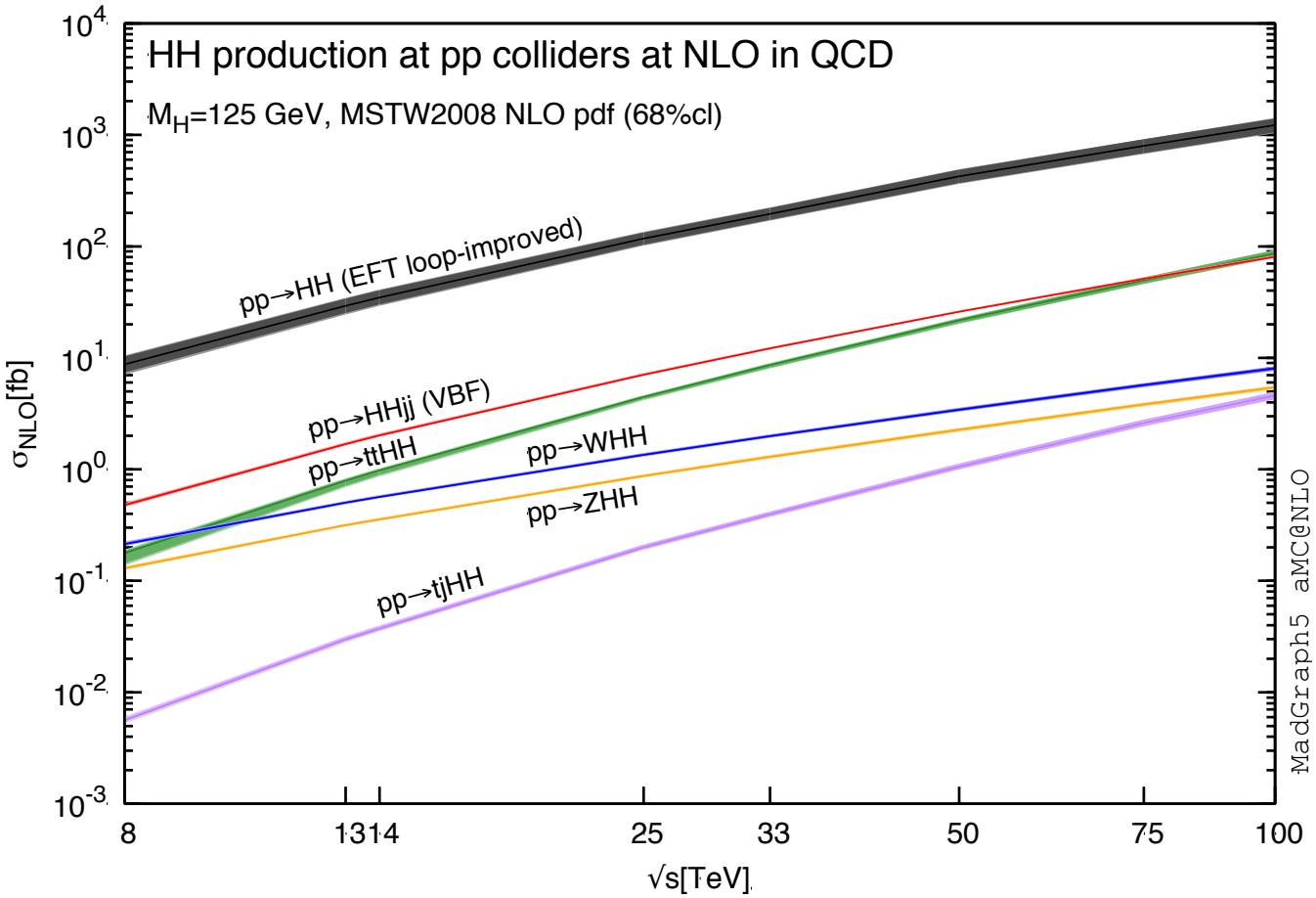
Status of SM computation

Gluon fusion results:

- NNLO+NNLL results in the EFT (rescaled by exact born): arxiv:1309.6594 & arXiv:1505.07122. Completed by the computation of the 3-loop matching coefficient: arxiv:1408.2422.
- Top mass effects at NLO in 1/mt expansion arXiv:1508.00909 & arxiv: 1305.7340
- Exact real corrections + EFT virtuals: arxiv:1401.7340 and 1408.6542 better description of the distribution tails (MG5_aMC@NLO framework).
- Merged samples (LO accuracy): Li, Yan, Zhao arXiv:1312.3830
  Maierhofer, Papaefstathiou arXiv:1401.0007
  Exact one-loop born and 1-jet matrix elements

13TeV cross-section:
NNLO+NNLL (Exact Born):
+5.1 − 6.0% scale
36.8fb
+10% top mass uncertainty
+4.0 − 4.3% PDF
de Florian and Mazzitelli

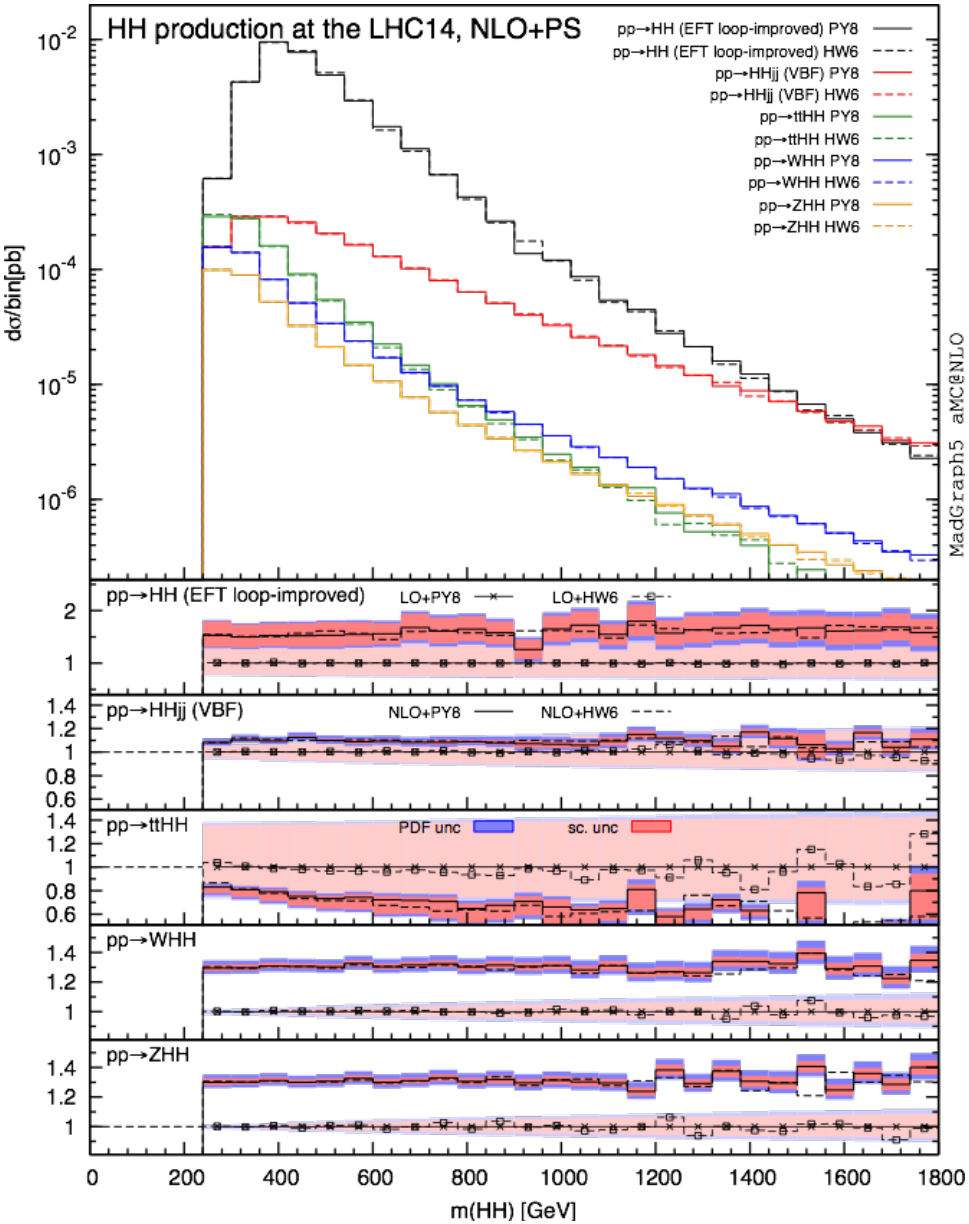
SM results for all channels

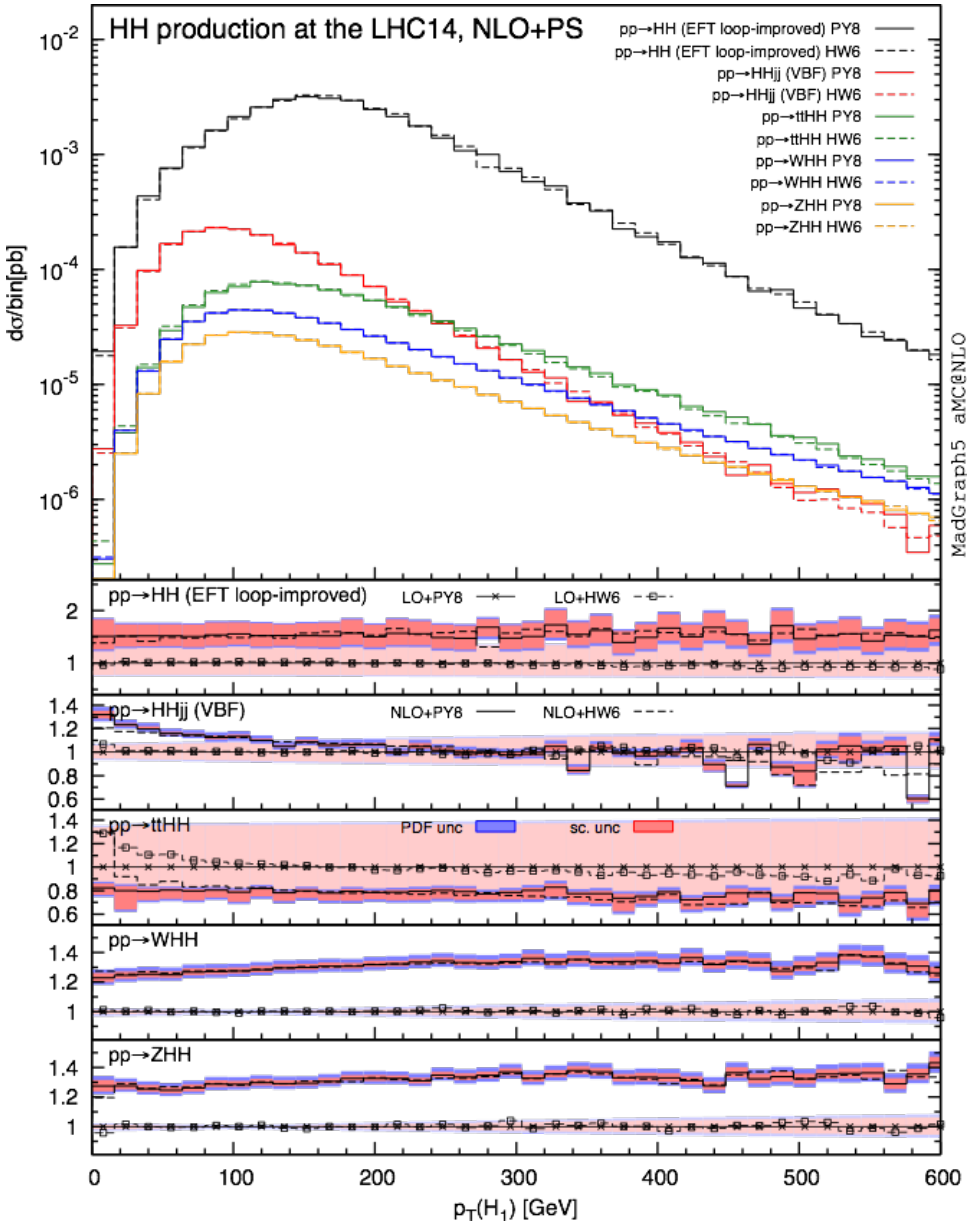


Small SM cross-sections
Gluon fusion dominant
Other channels at least one order of magnitude smaller

arxiv:1401.7340

Differential distributions for the LHC





MG5_aMC@NLO arxiv: 1401.7340

SM phenomenology

- Top mass effects are important: ~10% uncertainty due to missing effects
  Need for the exact NLO calculation for gluon fusion
- Next step:
  Phenomenology with a ~40fb (gluon fusion) cross-section: Not easy
- Which are the promising decay channels to observe the process?
  Recent progress with boosted techniques
  - bbγγ (1212.5581)
  - bbττ (1206.5001, 1212.5581)
  - bbWW (1209.1489, 1212.5581)
  - bbbb (1404.7139)
- Prospects for the measurement of the trilinear Higgs coupling?
  - Optimistic estimate of 20-30% accuracy with 3000 fb^{-1} at 14 TeV (arxiv: 1404.7139)
- Prospects in other channels? ttHH arxiv:1409.8074, VBF: 1506.08008

HH in BSM

HH: a Beyond the SM physics window

Specific models:
Additional particles
Resonances, loop contributions

Model independent:
EFT: Higher dimensional operators

- Non SM Yukawa couplings (1205.5444, 1206.6663)
- Resonances from extra dimensions (1303.6636)
- Vector-like quarks (1009.4670, 1206.6663)
- Light coloured scalars (1207.4496,1504.05596)
- **Dimension-6 operators (hep-ph/0609049, 1410.3471, 1502.00539, 1504.06577, 1205.5444)**
- **Higgs Singlet Model (1508.05397)**
- **2HDM (1403.1264, 1407.0281)**

Higgs pair production in the 2HDM

2HDM: Additional Higgs doublet

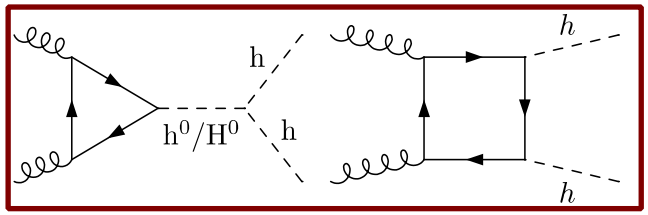
h light CP even
H heavy CP even
A CP odd
H^+ H^- charged

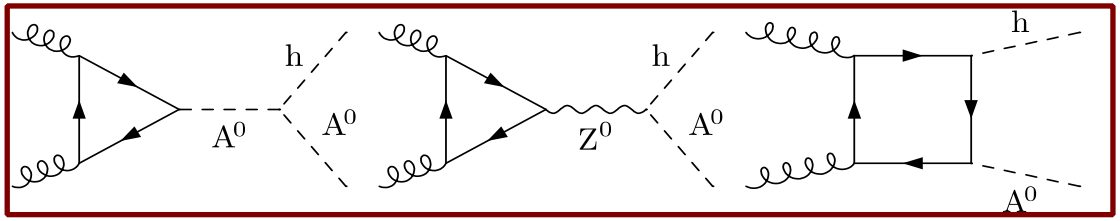
Type-I and Type-II setups
2HDM input:
$\tan\beta$, $\sin\alpha$, m_h, m_H, m_A, m_{H+}, m_{12}^2

Pair production in gluon fusion

hh hH HH hA HA AA H^+H^-

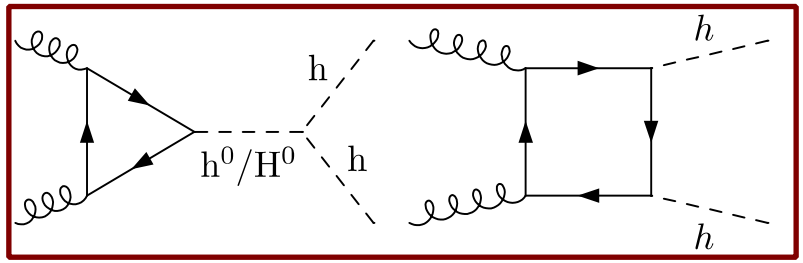
Topologies:





also tree-level qq for hA, HA, H^+H^-

Light Higgs pair production



Relevant couplings:

- Heavy quark Yukawas

$$g_{hxx} \equiv g_x^h = \left(1 + \Delta_x^h\right) \; g_x^{\mathrm{SM}}$$

	Type I	Type II
$1+\Delta_t^{h^0}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$
$1+\Delta_b^{h^0}$	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$
$1+\Delta_t^{H^0}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$
$1+\Delta_b^{H^0}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$

- Trilinear Higgs couplings

$$\lambda_{h^0h^0h^0}: \quad -\frac{3}{\sin 2\beta}\left[\frac{4\cos(\alpha+\beta)\cos^2(\beta-\alpha)\,m_{12}^2}{\sin 2\beta} - m_{h^0}^2\left(2\cos(\alpha+\beta) + \sin 2\alpha\,\sin(\beta-\alpha)\right)\right]$$

$$\lambda_{h^0h^0H^0}: \quad \frac{\cos(\beta-\alpha)}{\sin 2\beta}\left[\sin 2\alpha\,(2m_{h^0}^2 + m_{H^0}^2) - \frac{2m_{12}^2}{\sin 2\beta}(3\sin 2\alpha - \sin 2\beta)\right]$$

2HDM Benchmark selection

Constraints on the 2HDM parameter space:

- Theoretical: Unitarity
  Perturbativity
  Vacuum stability
- Experimental: Electroweak precision tests
  LHC Higgs measurements
  LHC searches for heavy neutral and charged Higgses

decoupling limit $\boxed{\xi = \cos(\beta - \alpha) \ll 1}$

2HDM deviations still possible:

Non-resonant effects:

- enhanced, suppressed or sign-flipped Yukawa couplings
- modified trilinear Higgs couplings

→ enhancement/suppression/ interference patterns

Resonant effects:

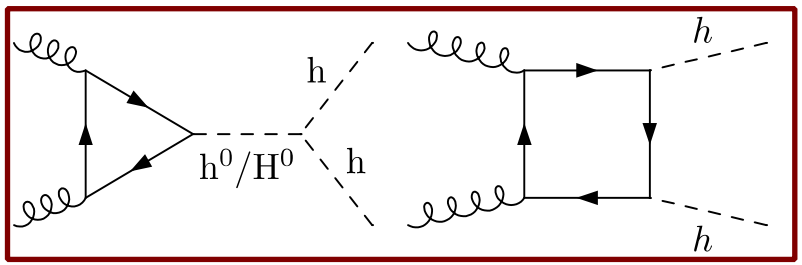
- on-shell production of moderately heavy states

→ significantly enhanced total rates-resonance peaks

Constraints by interfacing public tools:
2HDMC, HIGGSBOUNDS, SUPERISO, HIGGSSIGNALS

Calculation setup (1)

- 2HDM calculation using the NLOCT package (Degrande arxiv: 1406.3030) within the MG5_aMC@NLO framework
- Model available in Feynrules database
- http://feynrules.irmp.ucl.ac.be/wiki/NLOModels
- Exact LO computation with the full top and bottom mass dependence
- MG5_aMC@NLO version > 2.3 (loop-induced event generation)
  - import model 2HDM_NLO
  - generate g g > h1 h1 [QCD]
  - output gghh
- This includes the SM-like diagrams + heavy Higgs diagrams + interference



Calculation setup (2)

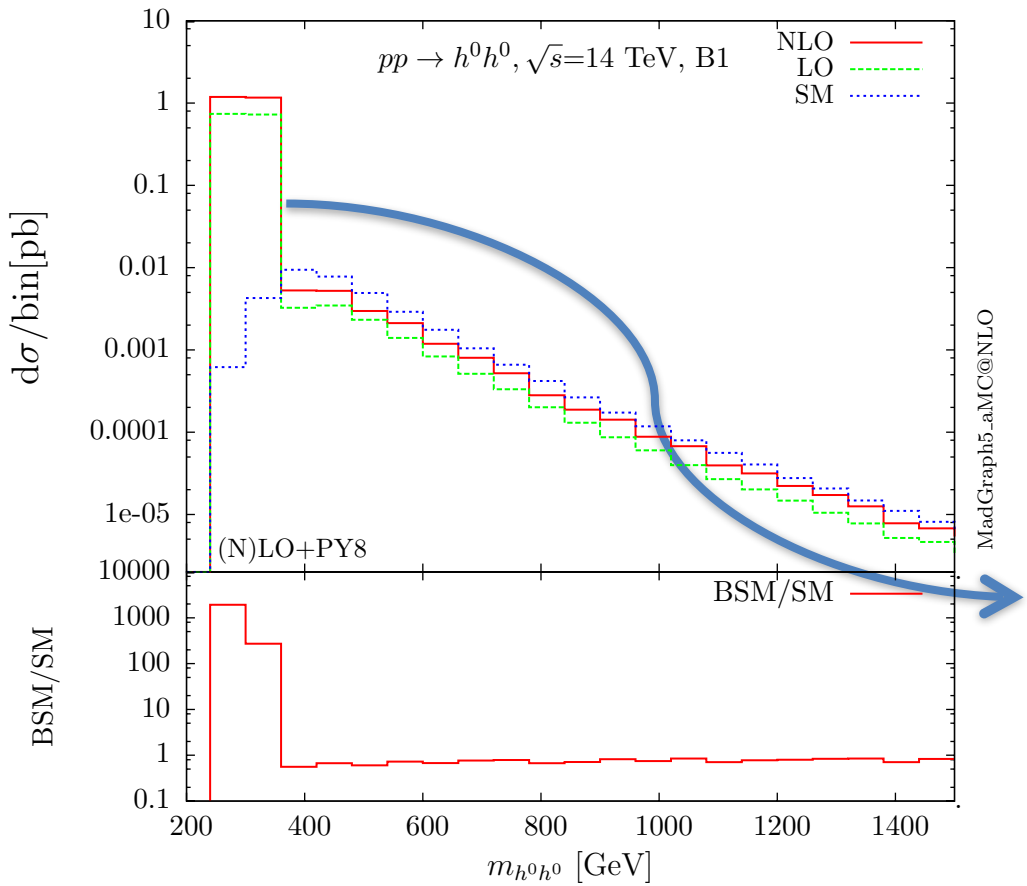
- NLO: Inclusion of the exact real emission matrix elements, HEFT virtuals rescaled by the exact born (as in SM computation in 1401.7340)
- Exact real emission amplitudes provide a better description of hard emissions
- Matching to parton showers with the MC@NLO method
- Codes can be used to produce LHE events for any 2HDM setup: fully differential computation
- Codes available on request-More information:
- https://cp3.irmp.ucl.ac.be/projects/madgraph/wiki/HiggsPairProduction
- NLO codes are slower, but the NLO computation gives a better description of the process, smaller theoretical uncertainties and more accurate distribution shapes (not all observables have flat k-factors)

Calculation setup (3)

- Parameter input can be obtained through the 2HDMC generator arxiv:0902.0851
- Starting from $\tan\beta$, $\sin\alpha$, m_h, m_H, m_A, m_{H+}, m_{12}^2
- 2HDM Lagrangian implemented in the most general way i.e. without flavour and CP conservation constraints in arxiv:1406.3030
- Heavy Higgs width also computed by 2HDMC
- Within MG5_aMC@NLO a fixed width propagator is used - as input in parameter card

Light Higgs pair production

Resonant 2HDM scenario: Light H



σ_{hh}~ 60 times the SM prediction

2HDM input: Type-II

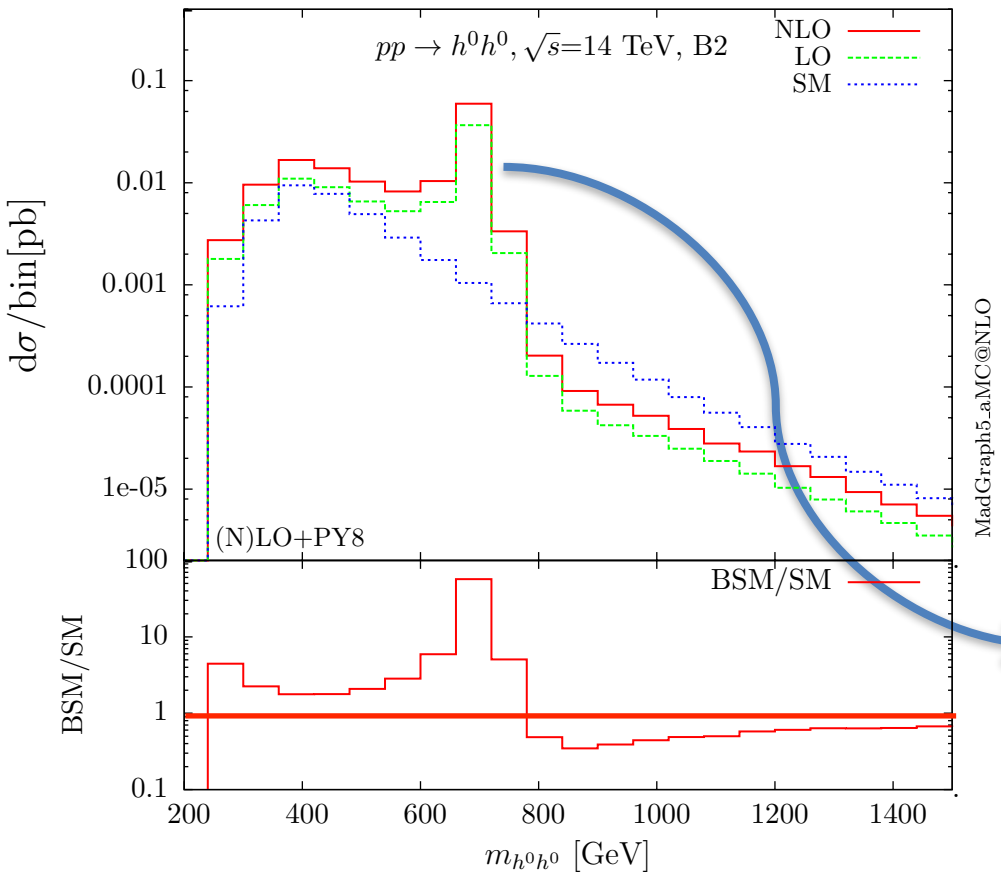
	$\tan\beta$	α/π	m_{H^0}	m_{A^0}	$m_{H^\pm}$	m_{12}^2
B1	1.75	-0.1872	300	441	442	38300

- **Slightly reduced top Yukawa**
- **SM-like hhh coupling**
- **Reduced Hhh coupling**

- Low mass resonant enhancement from H➔hh
- Distinctive resonance peak
- Away from the resonance Yukawa coupling shifts give small deviations from the SM
- See also Baglio et al. arxiv: 1403.1264

Light Higgs pair production

Resonant 2HDM scenario: Heavy H



σ_{hh}~ 4 times the SM prediction

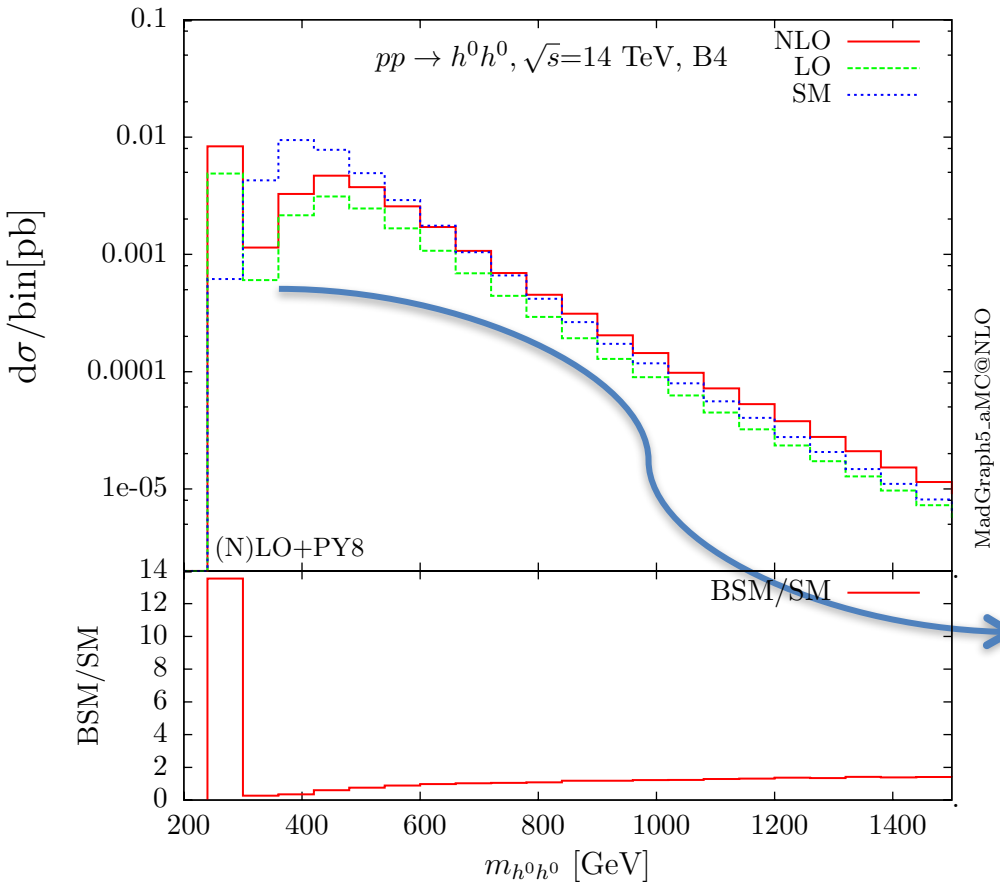
2HDM input: Type-II

	$\tan\beta$	α/π	m_{H^0}	m_{A^0}	$m_{H^\pm}$	m_{12}^2
B2	1.50	-0.2162	700	701	670	180000

- **Slightly reduced top Yukawa**
- **40% reduction of the hhh coupling**
- **Enhanced Hhh coupling**

- Significant resonant enhancement from H➔hh now at 700 GeV
- Distinctive resonance peak
- Interference patterns before and after the peak

Light Higgs pair production
Non-resonant 2HDM scenario



σ_{hh}~ 30% reduction of the SM prediction

2HDM input: Type-I

	$\tan\beta$	α/π	m_{H^0}	m_{A^0}	$m_{H^\pm}$	m_{12}^2
B4	1.20	-0.1760	200	500	500	-60000

- **Slightly enhanced top Yukawa**
- **Enhaced hhh coupling**
- **Enhanced Hhh coupling**

- Heavy Higgs mass below the hh threshold: No resonant enhancement
- Interference between different contributions leads to a different shape compared to the SM
- Important to study the distributions, not just total rates

HH in the Higgs singlet model

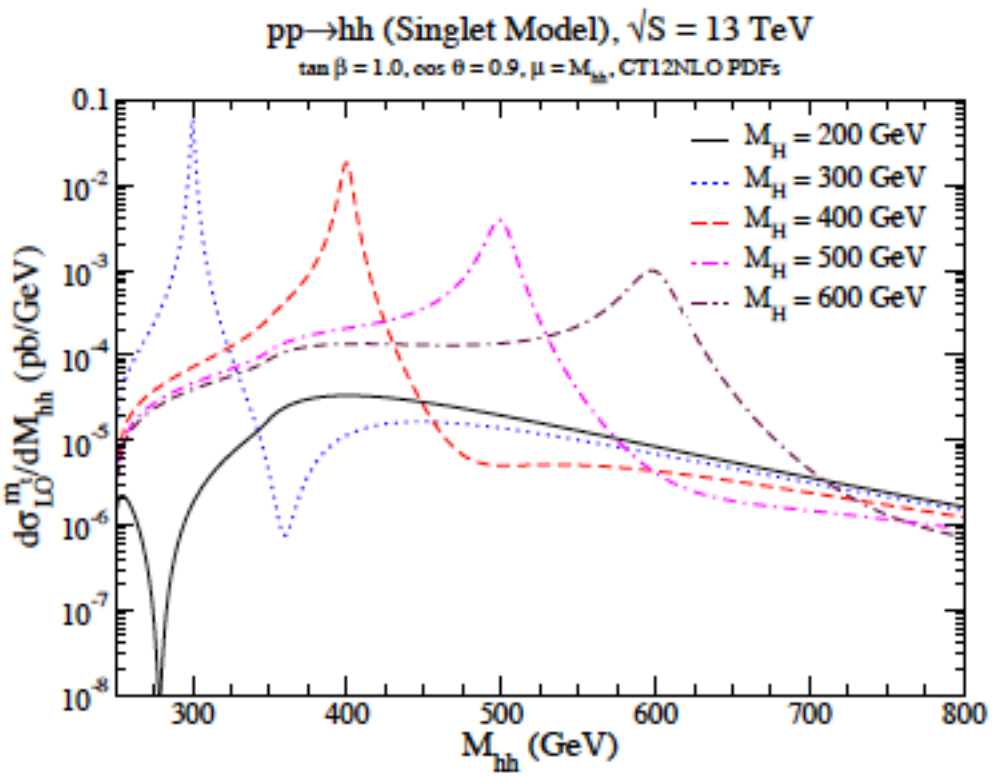
arxiv:1508.05397

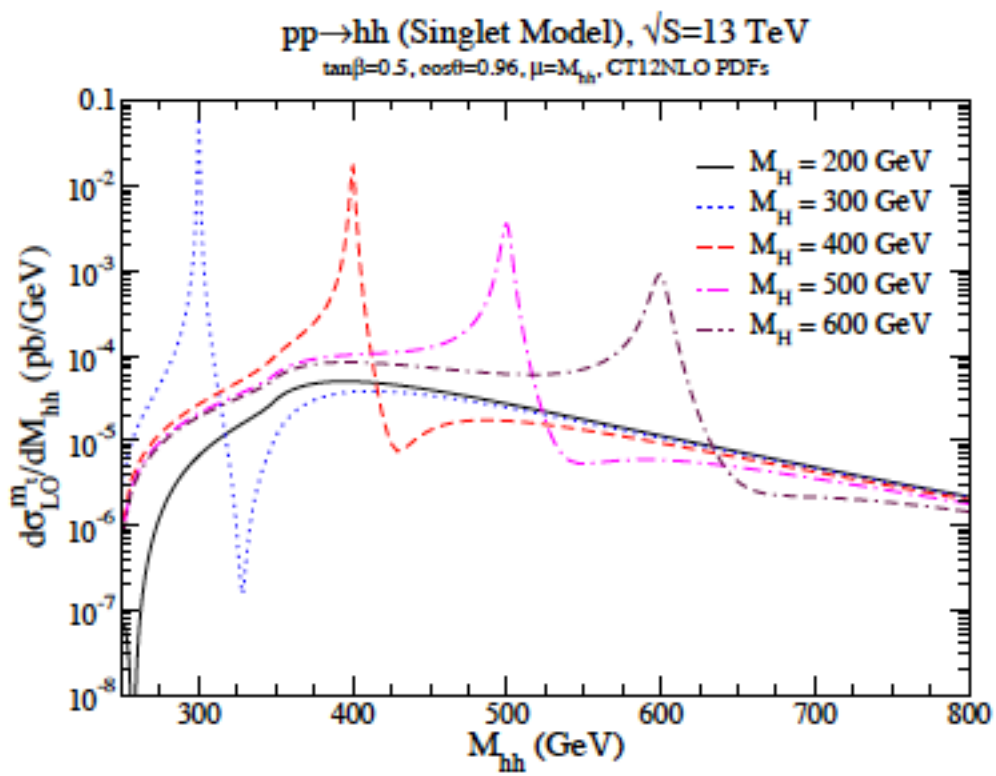
$$V = -\mu^2 \Phi^\dagger\Phi - m^2 S^2 + \lambda(\Phi^\dagger\Phi)^2 + \frac{a_2}{2}\Phi^\dagger\Phi\, S^2 + \frac{b_4}{4}S^4$$

Additional real singlet S

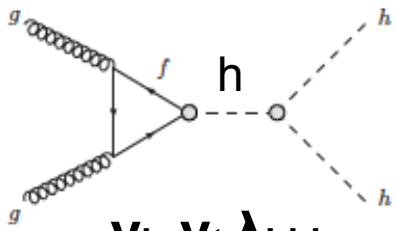
$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \phi_0 - v \\ s \end{pmatrix}$$

$$m_h = 125\ GeV, M_H, v = 246\ GeV, \tan\beta, \cos\theta$$

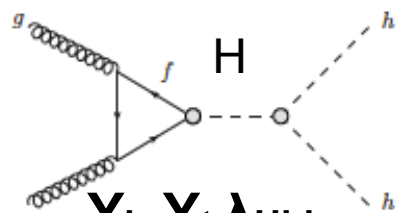




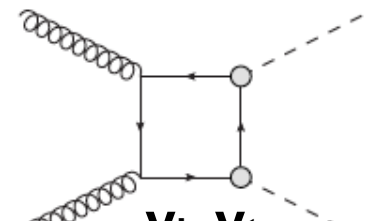
General comments on parameter space for models with extra scalars



y_b, y_t, λ_{hhh}



Y_b, Y_t, λ_{Hhh}



y_b, y_t

In models with extra scalars:

- Parameters of interest for HH production:
  - Light and Heavy Higgs Yukawas
  - Trilinear Hhh coupling
  - Trilinear hhh coupling

For a pronounced resonance:

Enhanced Heavy Higgs top Yukawa
+ Large trilinear Hhh coupling
+ Relatively Low Mass Heavy Higgs

- For Heavy Higgs above 1TeV significant off-shell contribution expected due to PDF suppression at high energies
- For the 2HDM and singlet models: heavy Higgs couplings constrained by light Higgs measurements

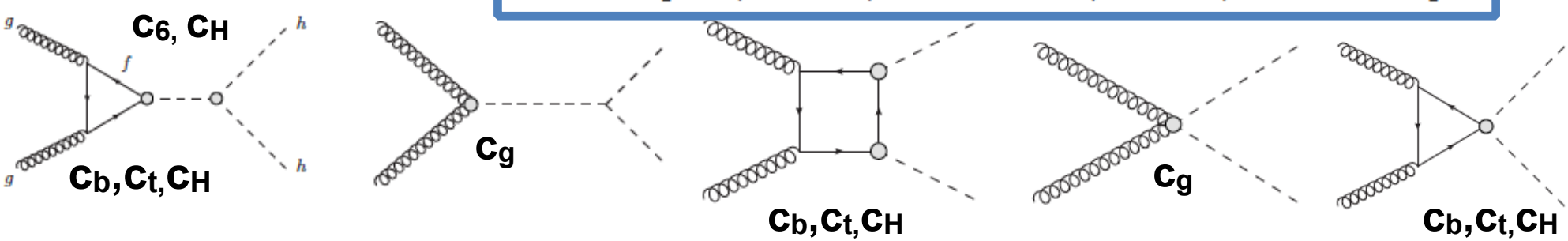
HH production in the EFT

EFT approach: No additional states
Dimension-6 operators suppressed by scale Λ

$$\mathcal{L}_{h^n} = -\mu^2|H|^2 - \lambda|H|^4 - (y_t\bar{Q}_L H^c t_R + y_b\bar{Q}_L H b_R + \text{h.c.}) + \frac{c_H}{2\Lambda^2}(\partial^\mu|H|^2)^2 - \frac{c_6}{\Lambda^2}\lambda|H|^6 + \frac{\alpha_s c_g}{4\pi\Lambda^2}|H|^2 G^a_{\mu\nu}G^{\mu\nu}_a - \left(\frac{c_t}{\Lambda^2}y_t|H|^2\bar{Q}_L H^c t_R + \frac{c_b}{\Lambda^2}y_b|H|^2\bar{Q}_L H b_R + \text{h.c.}\right),$$

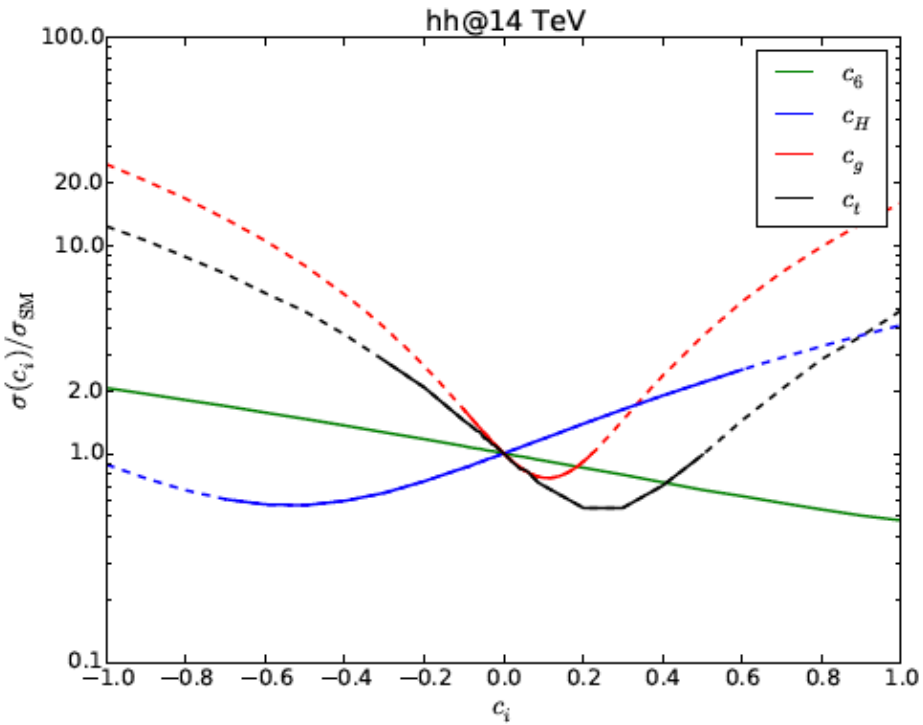
arxiv: 1410.3471

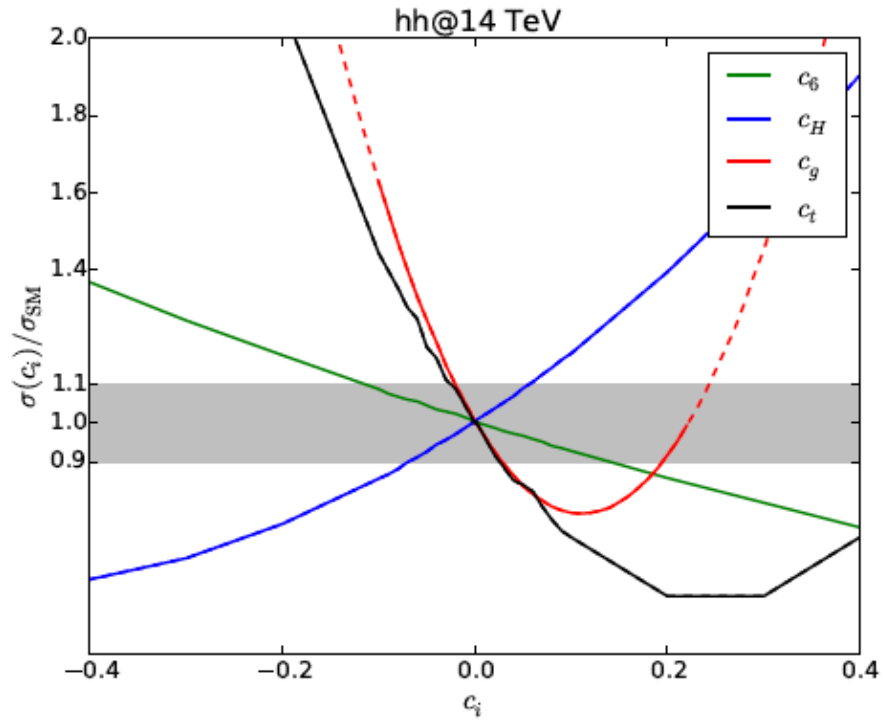
$$\mathcal{L}_{hh} = -\frac{m_h^2}{2v}\left(1 - \frac{3}{2}c_H + c_6\right)h^3 - \frac{m_h^2}{8v^2}\left(1 - \frac{25}{3}c_H + 6c_6\right)h^4 + \frac{\alpha_s c_g}{4\pi}\left(\frac{h}{v} + \frac{h^2}{2v^2}\right)G^a_{\mu\nu}G^{\mu\nu}_a - \left[\frac{m_t}{v}\left(1 - \frac{c_H}{2} + c_t\right)\bar{t}_L t_R h + \frac{m_b}{v}\left(1 - \frac{c_H}{2} + c_b\right)\bar{b}_L b_R h + \text{h.c.}\right] - \left[\frac{m_t}{v^2}\left(\frac{3c_t}{2} - \frac{c_H}{2}\right)\bar{t}_L t_R h^2 + \frac{m_b}{v^2}\left(\frac{3c_b}{2} - \frac{c_H}{2}\right)\bar{b}_L b_R h^2 + \text{h.c.}\right],$$



5 parameters: c_6, c_H, c_b,c_t,c_H

HH cross-section in the EFT





arxiv:1410.3471

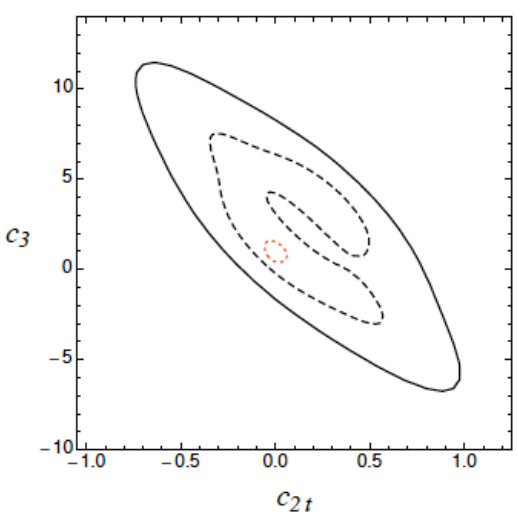
Dashed lines already constrained by single Higgs measurements
c_6 only accessible through HH production

EFT analyses

Focussing on the bbττ decay channel arxiv:1410.3471

model	$L = 600\ \mathrm{fb}^{-1}$	$L = 3000\ \mathrm{fb}^{-1}$
c_6-only	$c_6 \in (-0.5, 0.8)$	$c_6 \in (-0.4, 0.4)$
full	$c_6 \gtrsim -1.3$	$c_6 \gtrsim -1.2$
$c_6 - c_t - c_\tau - c_b$	$c_6 \gtrsim -2.0$	$c_6 \in (-1.8, 2.3)$

Focussing on the bbγγ decay arxiv:1502.00359



$$\mathcal{L}_{non-lin} \supset -m_t \bar{t}t \left(c_t \frac{h}{v} + c_{2t} \frac{h^2}{v^2} \right) - c_3 \frac{m_h^2}{2v} h^3 + \frac{g_s^2}{4\pi^2} \left(c_g \frac{h}{v} + c_{2g} \frac{h^2}{2v^2} \right) G^a_{\mu\nu} G^{a\,\mu\nu}$$

Prospects for HH measurement:

	LHC_{14}	HL-LHC	FCC_{100}
68% interval on μ	$[-0.41, 3.0]$	$[0.50, 1.6]$	$[0.92, 1.1]$
$\mu = \sigma/\sigma_{SM}$	$300\ \mathrm{fb}^{-1}$	$3\ \mathrm{ab}^{-1}$	$3\ \mathrm{ab}^{-1}$

Conclusions-Outlook

- Higgs pair production key to the measurement of triple Higgs coupling, path to explore beyond the SM physics
- BSM possibilities include models with new states and models with new interactions (EFT)
- 2HDM an attractive framework to study the process
- Higgs pair production in the 2HDM can receive significant total rate enhancements but also changes in the distribution shapes: resonant and non-resonant
- HH within the EFT can also give significant modifications compared to the SM prediction, but generally constrained from single Higgs data

Thanks for your attention...