



Higgs pair production at the LHC in the 2HDM

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Based on JHEP 1409 (2014) 124

HXSWG

HH-Subgroup meeting

24/2/15

Outline

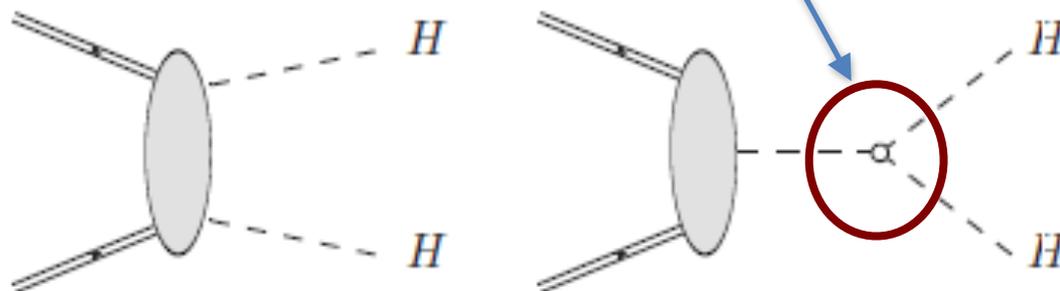
- ❖ Motivation
- ❖ HH in the 2HDM
- ❖ Calculation setup-Results
- ❖ Outlook

HH Motivation (1)

- ❖ **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 extensions:
2HDM

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

Fixed values
in the SM

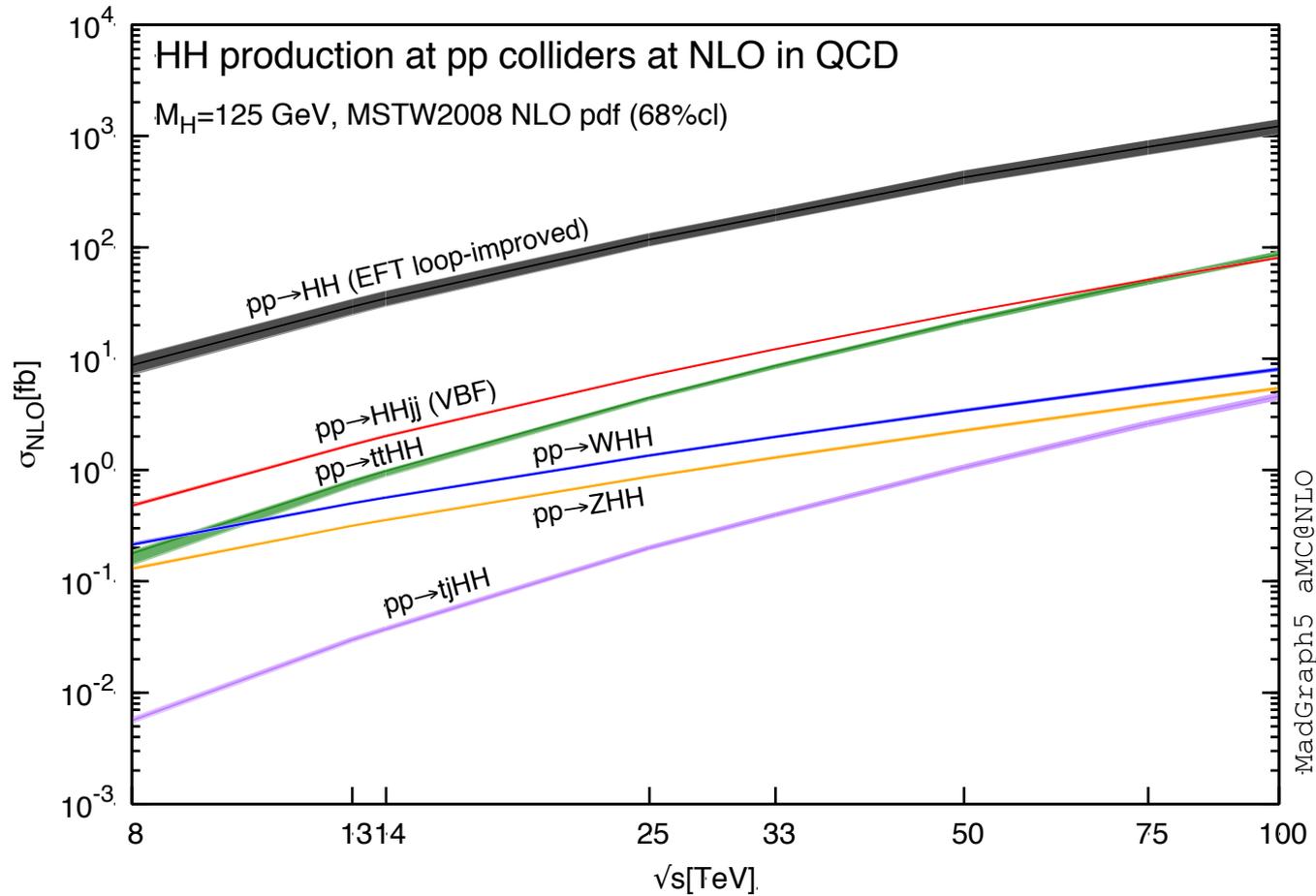
❖ *HH: a Beyond the SM physics window*

Specific models:
Additional particles
Resonances, loop contributions

Model independent:
EFT: Higher dimensional operators

- ❖ Non SM Yukawa couplings (1205.5444, 1206.6663)
- ❖ ttHH interactions (1205.5444)
- ❖ Resonances from extra dimensions (1303.6636)
- ❖ Vector-like quarks (1009.4670, 1206.6663)
- ❖ Light coloured scalars (1207.4496)
- ❖ Higher-dimension operators (hep-ph/0609049, arxiv: 1410.3471, arxiv:1502.00539)
- ❖ 2HDM (1403.1264, 1407.0281)

MadGraph5_aMC@NLO SM results

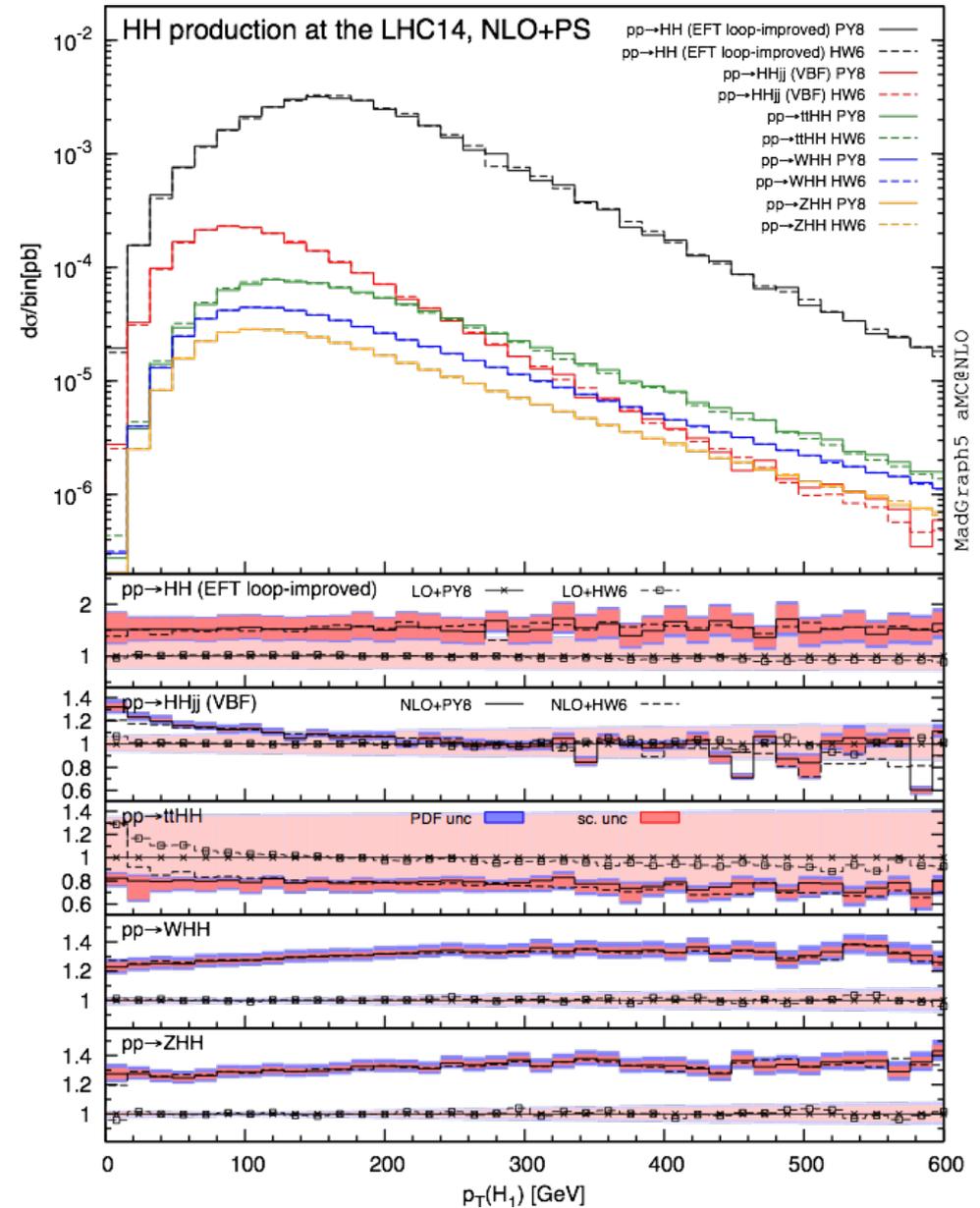
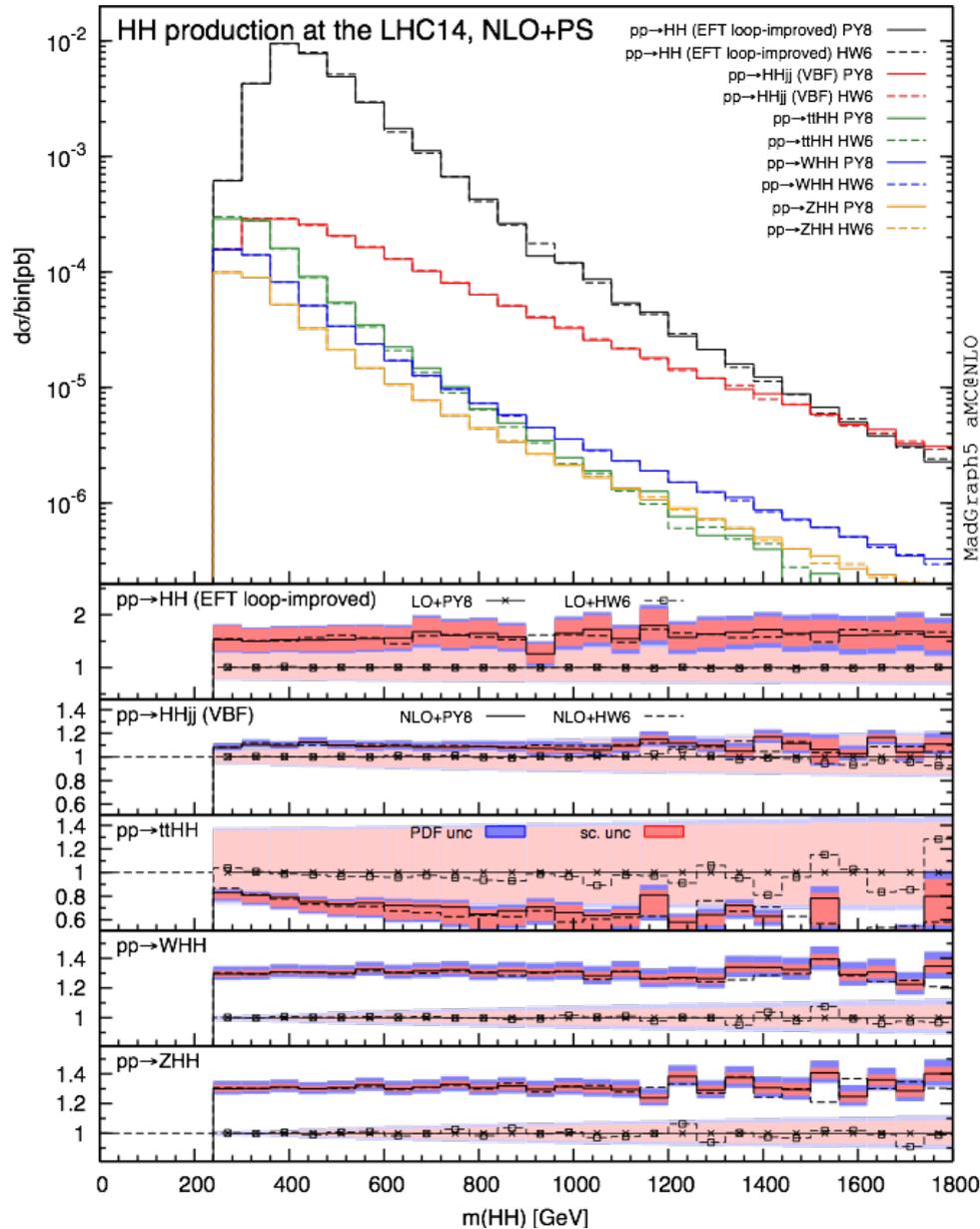


Frederix et al. arxiv:1401.7340

F. Maltoni, EV, M. Zaro arxiv:1408.6542



Differential distributions for the LHC



Higgs pair production in the 2HDM

2HDM: Additional Higgs doublet

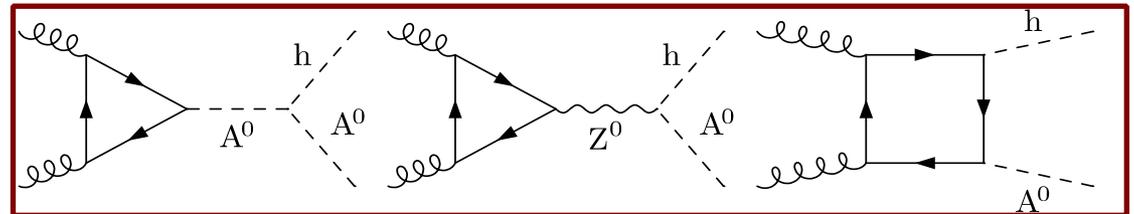
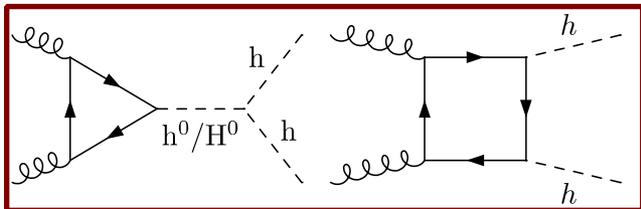
h light CP even
 H heavy CP even
 A CP odd
 $H^+ H^-$ charged

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

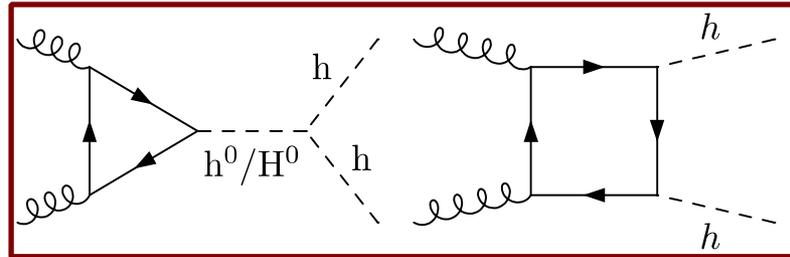
hh hH HH hA HA AA H^+H^-

Topologies:



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

Light Higgs pair production



Relevant couplings:

- Heavy quark Yukawas

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

	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

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

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

Calculation setup (1)

- ❖ Exact LO computation with the full top and bottom mass dependence
- ❖ Exact NLO computation requires:
 - ❖ Real emissions: Available
 - ❖ Virtual corrections: 2-loop multi-scale amplitudes: Not available
- ❖ Inclusion of the exact real emission matrix elements, HEFT virtuals rescaled by the exact born (as in SM computation in 1401.7340)
 - NLO HEFT event generation within MG5_aMC@NLO
 - Reweigh on an event by event basis using the results of the exact loop matrix elements
 - Loop matrix elements obtained by MadLoop for both Born and real emission amplitudes
- ❖ Exact real emission amplitudes provide a better description of hard emissions
- ❖ Matching to parton showers with the MC@NLO method

Calculation setup (2)

- Calculation of all seven gluon fusion combinations at LO and approximate NLO
- 2HDM calculation using the NLOCT package (Degrande arxiv: 1406.3030) within the MG5_aMC@NLO framework
- Codes available:
<https://cp3.irmp.ucl.ac.be/projects/madgraph/wiki/HiggsPairProduction>
- Codes can be used to produce LHE events for any 2HDM setup: fully differential computation
- Results obtained for a series of 2HDM benchmarks, in agreement with all up-to-date constraints (see next slide)
- Cross sections strongly depend on the 2HDM parameter input, but k-factors stay close to the SM values ~ 1.6
- Production of the heavy pairs heavily suppressed

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

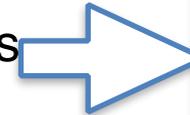
decoupling limit

$$\xi = \cos(\beta - \alpha) \ll 1$$

2HDM deviations still possible:

Non-resonant effects:

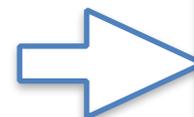
- enhanced, suppressed or sign-flipped Yukawa couplings
- modified trilinear Higgs couplings



enhancement/suppression/
interference patterns

Resonant effects:

- on-shell production of moderately heavy states



significantly enhanced
total rates-resonance
peaks

Constraints by interfacing public tools:

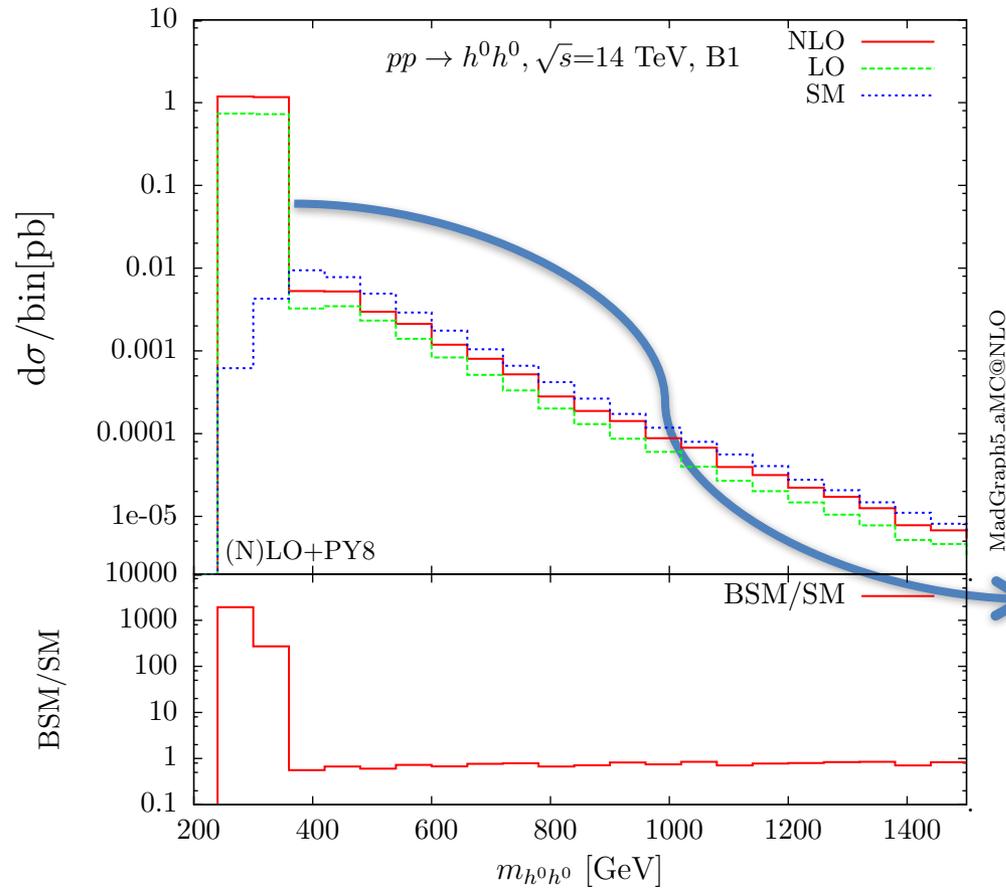
2HDMC, HIGGSBOUNDS, SUPERISO, HIGGSSIGNALS+own codes

Light Higgs pair production

Resonant 2HDM scenario: Light H

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 $H \rightarrow hh$
- ❖ Distinctive resonance peak
- ❖ Away from the resonance Yukawa coupling shifts give small deviations from the SM
- ❖ See also Baglio et al. arxiv: 1403.1264

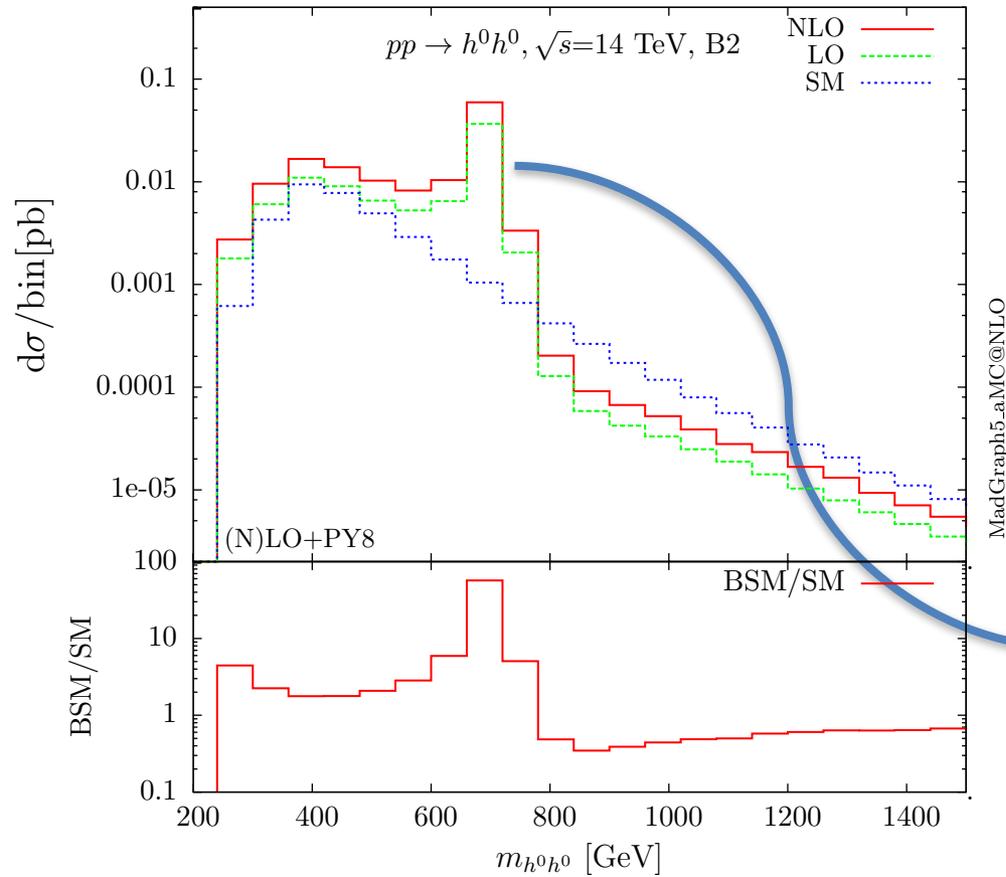
$\sigma_{hh} \sim 60$ times the SM prediction

Light Higgs pair production

Resonant 2HDM scenario: Heavy H

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



$\sigma_{hh} \sim 4$ times the SM prediction

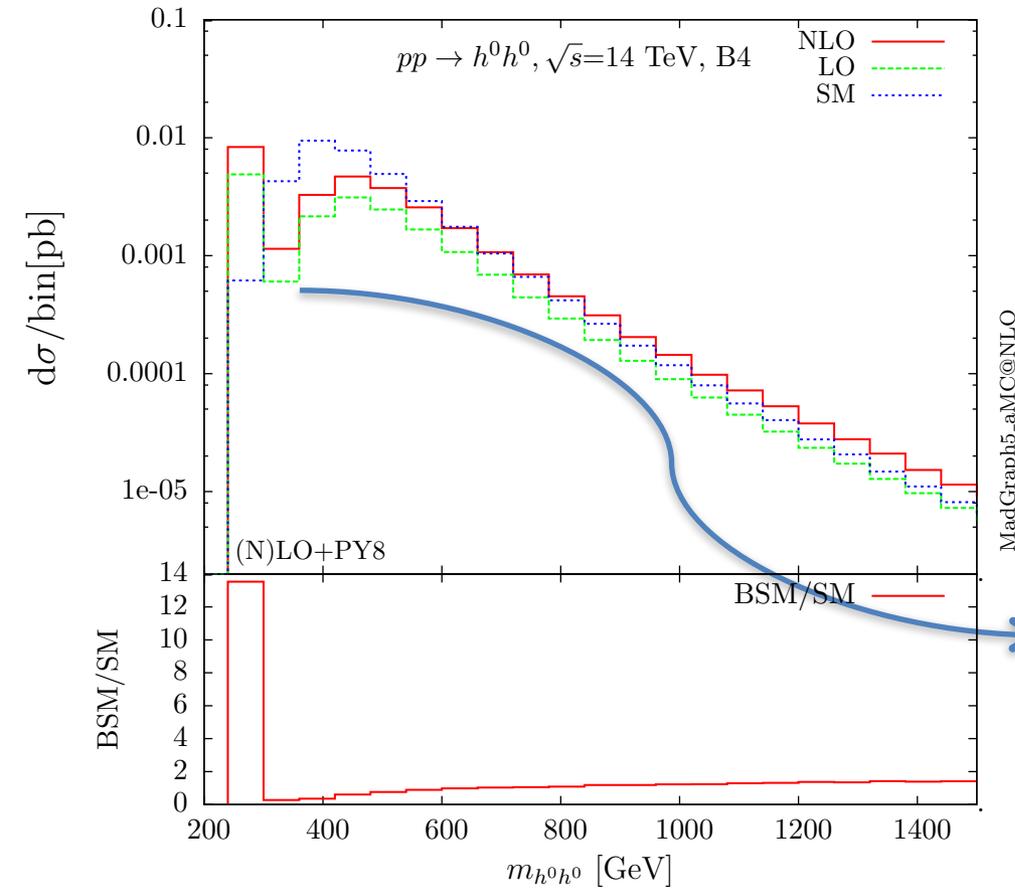
- ◆ Slightly reduced top Yukawa
- ◆ 40% reduction of the hhh coupling
- ◆ Enhanced Hhh coupling
- ❖ Significant resonant enhancement from $H \rightarrow hh$ now at 700 GeV
- ❖ Distinctive resonance peak
- ❖ Interference patterns before and after the peak

Light Higgs pair production

Non-resonant 2HDM scenario

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
- ◆ Enhanced 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

$\sigma_{hh} \sim 30\%$ reduction of the SM prediction

Conclusions-Outlook

- ❖ Higgs pair production key to the measurement of triple Higgs coupling, path to explore extended Higgs sectors
- ❖ 2HDM an attractive framework to study the process:
Computation for all pairs of Higgs bosons in gluon fusion
<https://cp3.irmp.ucl.ac.be/projects/madgraph/wiki/HiggsPairProduction>
- ❖ Codes available within the MG5_aMC@NLO framework, can be used for any 2HDM setup
- ❖ Light Higgs pair production can receive significant total rate enhancements but also changes in the distribution shapes: resonant and non-resonant
- ❖ Next step: further phenomenological studies including decays, acceptance cuts and detector effects to assess prospects at the LHC

Thanks for your attention...