Resonant di-Higgs production in extended scalar sectors
Summary of HH subgroup meeting (28th September)

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(https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHWGHH)

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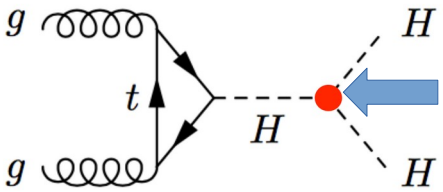
26th Deutsche Physikerinnentagung 22 – Karlsruhe
German Conference of Women in Physics

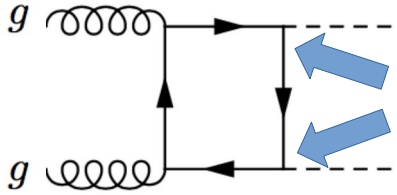
- Over 250 participants
- Vast physics program and career seminars/workshops over 4 days
- https://indico.scc.kit.edu/event/2604/

SM Di-Higgs production

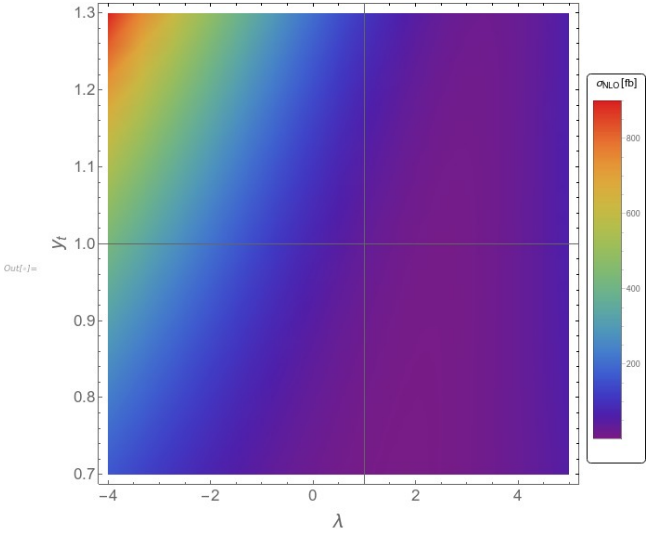
At LO



Trilinear
λ_{HHH}



Top Yukawa
y_t



$$\sigma_{hh}^{LO}[\text{fb}] = 5.22\lambda^2 y_t^2 - 25.1\lambda y_t^3 + 37.3 y_t^4 + \mathcal{O}(y_b y_t^2) \approx 17.42 fb$$
$$\sigma_{hh}^{NLO}[\text{fb}] = 9.66\lambda^2 y_t^2 - 49.9\lambda y_t^3 + 70.1 y_t^4 + \mathcal{O}(y_b y_t^2) \approx 29.86 fb$$

(Internal note, NLO heavy top mass limit)

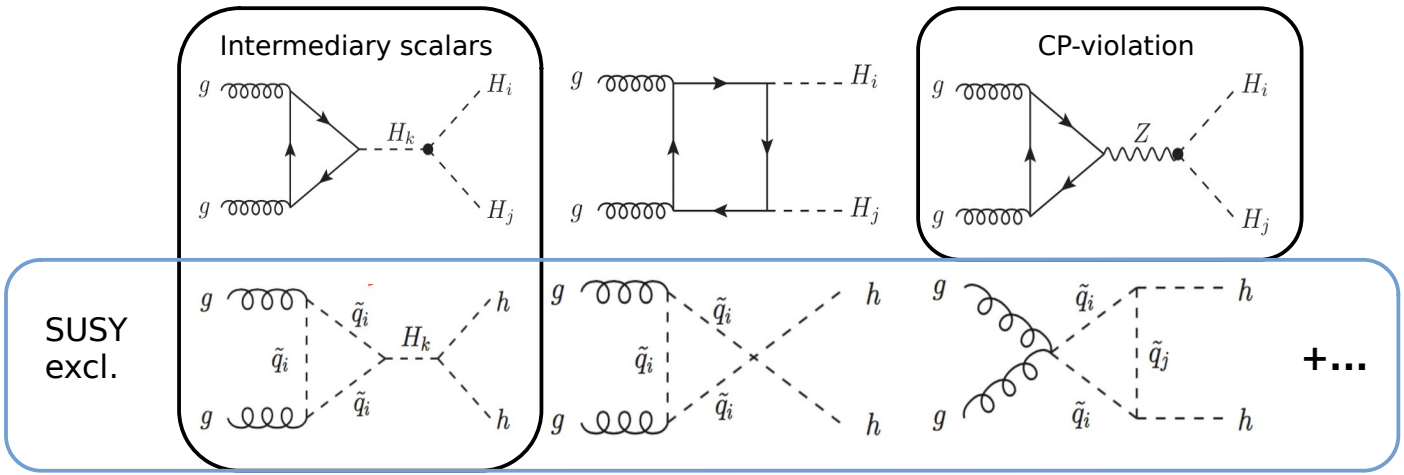
√s	7 TeV	8 TeV	13 TeV	14 TeV	27 TeV	100 TeV
$\sigma_{\text{NNLO FTapprox}}$ [fb]	6.572	9.441	31.05	36.69	139.9	1224

LHCXSWG

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

BSM Di-Higgs production

- Deviations from the SM trilinear coupling and top Yukawa.
- New particles:



- Several new Yukawa coup., masses, widths, trilinear couplings. R2HDM: 6 parameters [SM tril./yuk + BSM tril/yuk/mass/width]
- In CP-violating scenarios, last diagram is expected to be small.

Defined tasks from HH subgroup meeting

- **Interest to extend resonant searches to include large width/interference effects [motivated from several BSM models]**
- **Interferences in a model independent** way → dependence with trilinear, yukawas, masses, widths…**

Tasks:

1) Get the allowed maximum res. prod. XS (pp → H → h_SM h_SM) for mass values of the resonance, and ranges of pertinent parameters around these maxima
2) What is the differential distributions dependence on these parameters [(R2HDM Katerina's talk)]
3) Implement models for MC generators to simulate these signals

Models/definitions

Models:

- R2HDM – One possible heavy resonance (H_1, H_2, A)
- N2HDM – Two possible heavy resonance (H_1, H_2, H_3, A)
- Generally, models include res., non-res. and interference parts.

Random parameter scans [ScannerS]:

- Single Higgs: SusHi@NNLO
- Double Higgs: HPAIR@LO [K-factor 2]
- Relevant theoretical constraints
- STU/Single Higgs constraints
- Res. HH contraints applied to NWA points [w/m<5%] [assumes no interf. and SM-like non. res contribution]
- Non. res. HH constraints applied to points where res. contribution is less than 10% the full XS

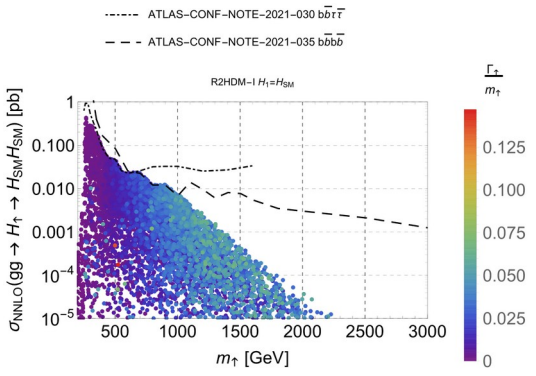
Allowed resonant production

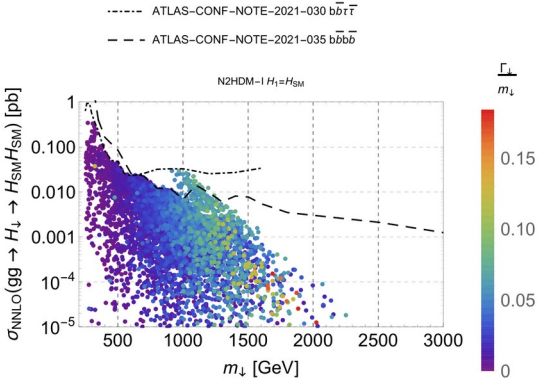
R2HDM

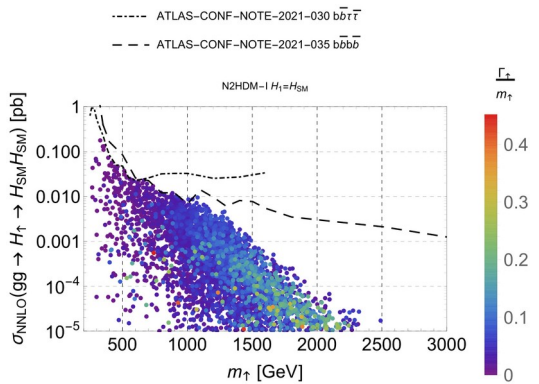
N2HDM

N2HDM

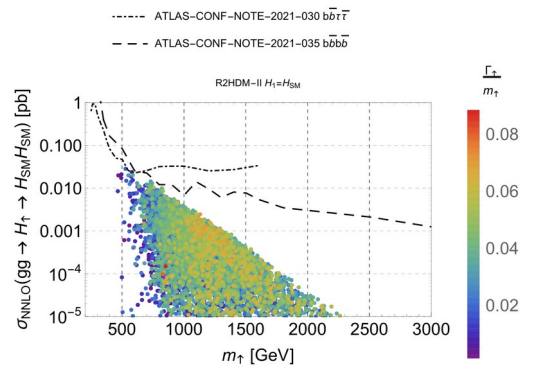
Type - I

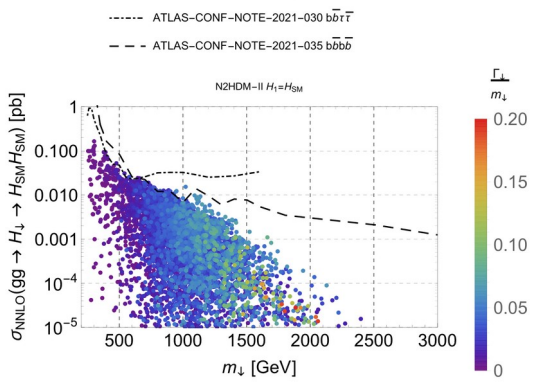




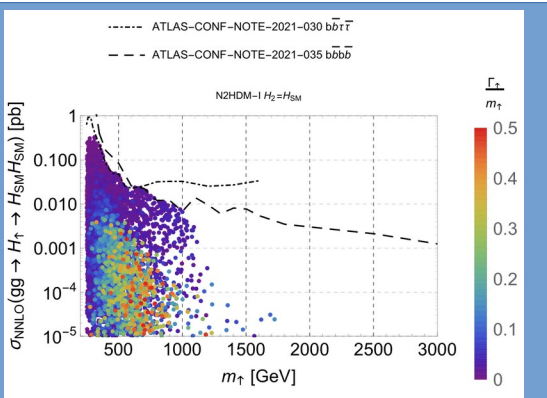


Type - II

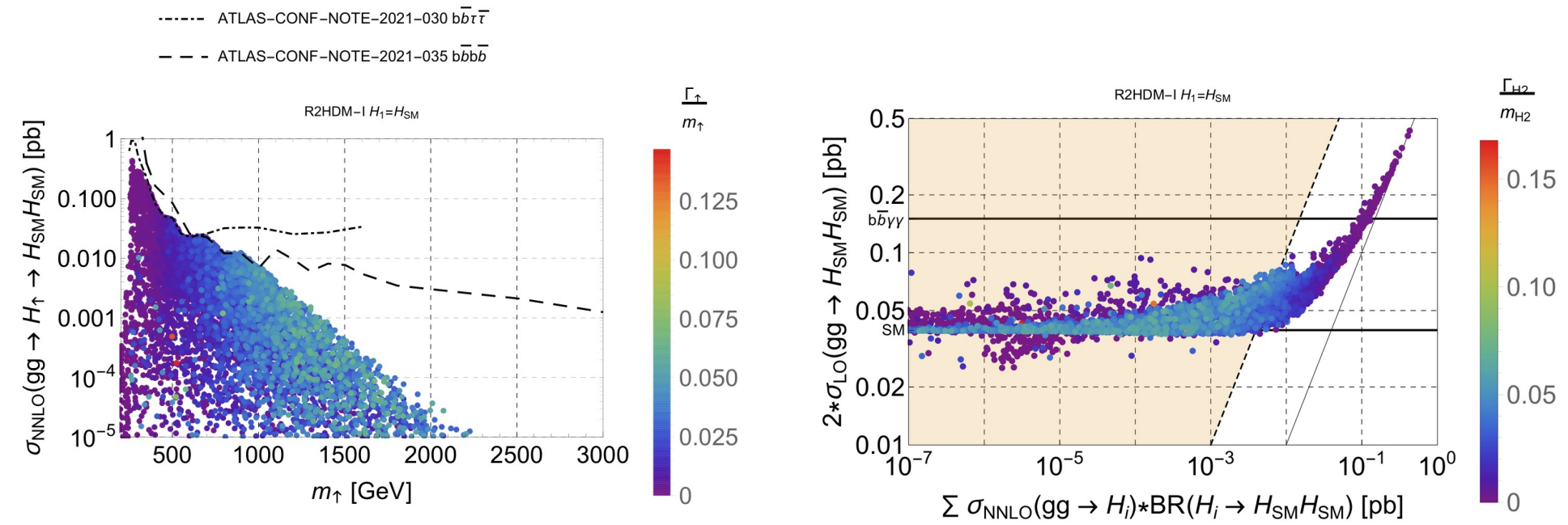




N2HDM-I H2 is SM-like



Allowed resonant production
R2HDM-I



- Left: XS*BR [assumes NWA], Right: Full XS vs. Res. Contribution [NWA]
- Approximation is valid for high XS
- Full discussion of exp. limits on these models: 2112.12515

First task – preliminary results

- Reference mass values: 260, 500, 1000, 1500, 2000, 2500, 3000 GeV (+/- 5 GeV)
- Look at maximum res. XS: Draw -10% window [not possible due to sample size]

  → Draw – O(10^-1) window

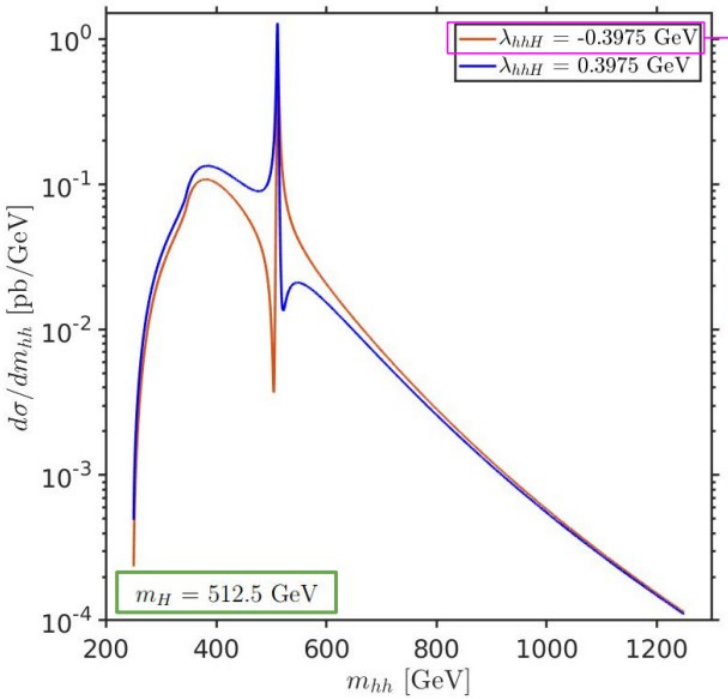
	mH2 [GeV]	max_ggH2_H1H1 [pb]	max_ggH1H1 [pb]	min_klambda	max_klambda	min_lam112 [GeV]	max_lam112 [GeV]	min_wH2/mH2	max_wH2/mH2
0	260	5.984307e-01	0.572147	0.663050	1.200975	2.011274	202.506147	0.000002	0.014659
1	500	4.740896e-02	0.101435	0.258465	1.172680	27.261492	311.515046	0.000179	0.031930
2	1000	8.161890e-03	0.083294	0.202194	0.972100	169.418554	588.779709	0.001595	0.061028
3	1500	5.436489e-04	0.058290	0.620417	0.974586	245.989449	824.928686	0.001529	0.069883
4	2000	4.775569e-05	0.049413	0.783884	0.981825	278.655419	901.378721	0.001087	0.066461
5	2500	5.894216e-06	0.045645	0.851887	0.986336	300.835876	969.375566	0.000828	0.064384
6	3000	7.954098e-07	0.043811	0.903199	0.990328	297.168288	958.810287	0.000563	0.062201

- κ_λ and λ_{112} have the same sign

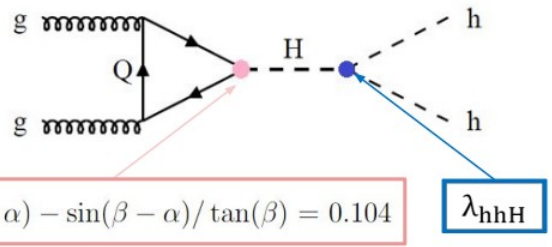
Trilinear sign effects
Taken from: Katerina Radchenko [LHC-HH Subgroup meeting 28 Sep. 22]

3. Effect of the couplings

➢ What is the effect of the couplings on the invariant mass distributions ?



physical value



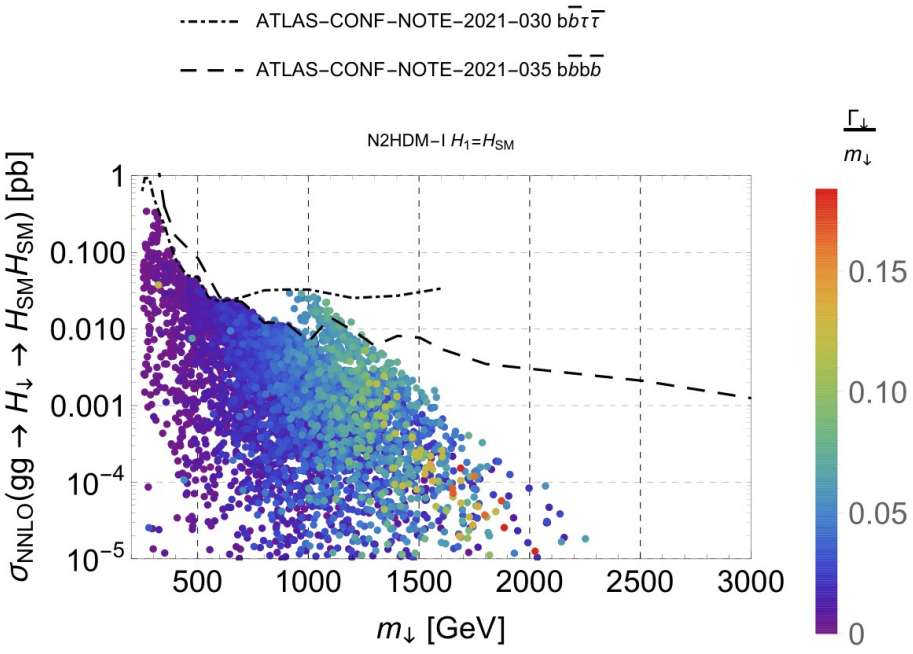
$\xi_H^t = \cos(\beta-\alpha) - \sin(\beta-\alpha)/\tan(\beta) = 0.104$

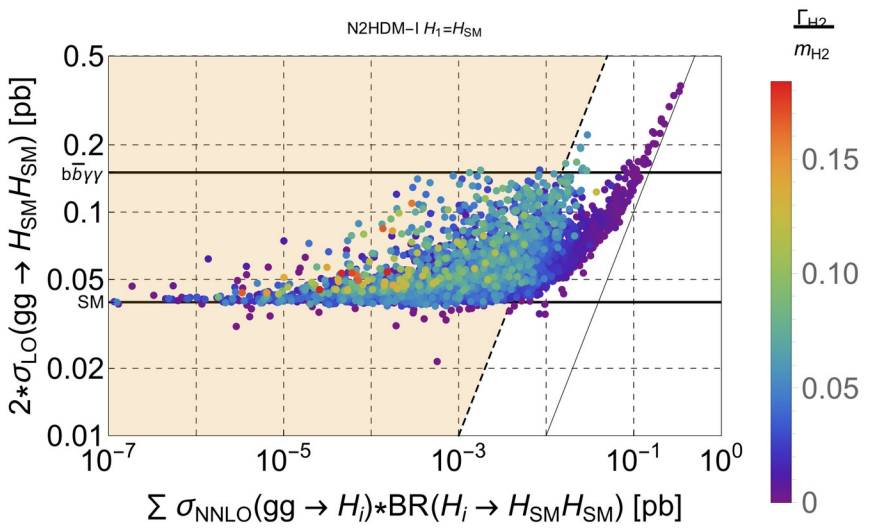
λ_{hhH}

The **relative sign** of the top Yukawa and the BSM coupling to the heavy Higgs gives a **structure** to the resonance:

sign $(\lambda_{hhH} \cdot \xi_H^t)$	structure
+	peak-dip
-	dip-peak

Allowed resonant production N2HDM-I





- Larger widths allowed → NWA not valid anymore

First task – preliminary results

N2HDM-I (H2 as res. of interest):

	mH2 [GeV]	max_ggH2_H1H1 [pb]	max_ggH3_H1H1 [pb]	max_ggH1H1 [pb]	min_klambda	max_klambda	min_lam112 [GeV]	max_lam112 [GeV]	min_wH2/mH2	max_wH2/mH2
0	260	0.677723	0.194092	0.692520	-0.865330	0.998518	-181.844443	374.263122	0.000001	0.082465
1	500	0.047687	0.039810	0.134563	-1.189243	0.996701	-302.660704	588.105417	0.000372	0.077238
2	1000	0.031336	0.006275	0.241003	0.011330	1.805244	342.039096	1938.246190	0.005833	0.086758
3	1500	0.002797	0.000408	0.152712	0.000074	1.193269	578.683146	3049.620909	0.007911	0.167155
4	2000	0.000236	0.000034	0.149369	0.003549	1.091706	641.205453	4924.857333	0.007941	0.274927
5	2500	0.000020	0.000002	0.067509	0.305984	0.957961	570.130128	2454.286271	0.003424	0.061114

- Larger widths allowed → NWA not valid anymore
- κ_λ can be 0

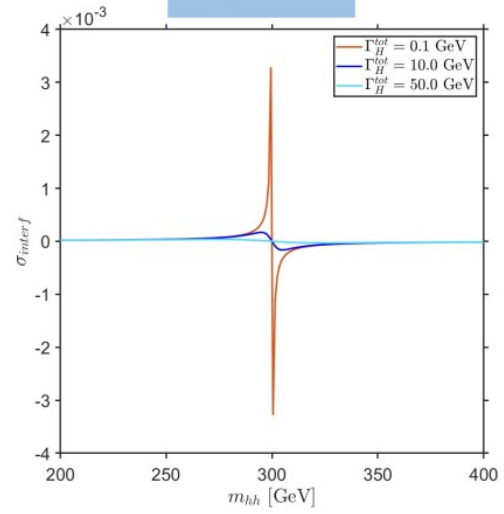
Width effects of the Heavy Higgs

Taken from: Katerina Radchenko [LHC-HH Subgroup meeting 28 Sep. 22]

2. Effect of the total decay width

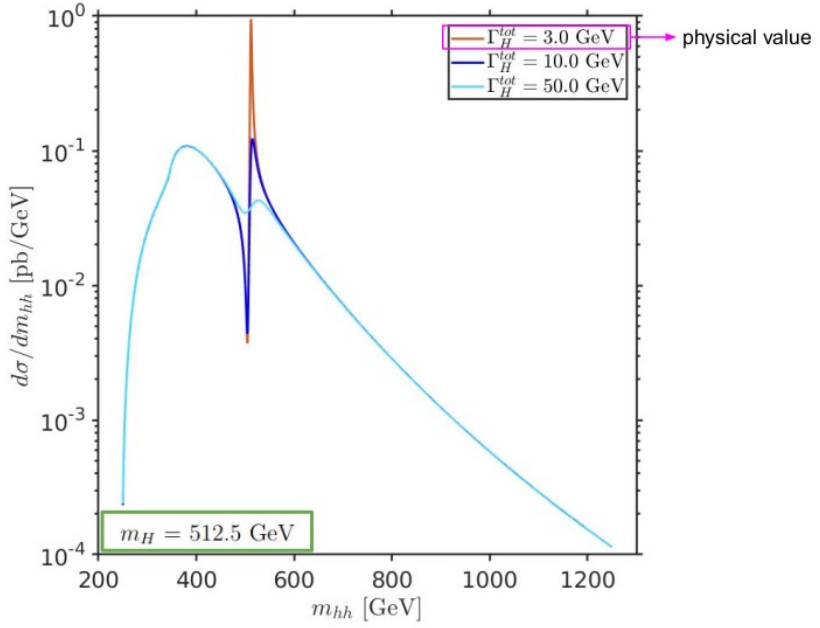
$$\frac{1}{Q^2 - M_{h/H}^2 + i\Gamma_{h/H} M_{h/H}}$$

Toy model



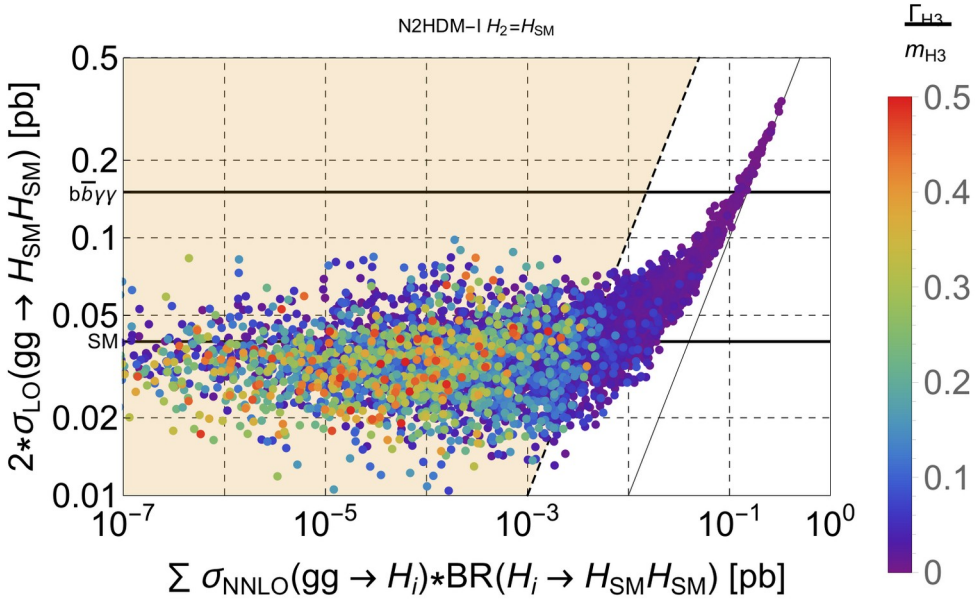
$$\sigma_{\text{interf}} \propto \frac{Q^2 - m_H^2}{(Q^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}$$

➢ For the green point of the previous benchmark plane we artificially change the total decay width of the heavy Higgs H:



For larger **total decay widths** the **height** of the resonance changes but the width where the effect can be seen does not change.

Allowed resonant production
N2HDM-I



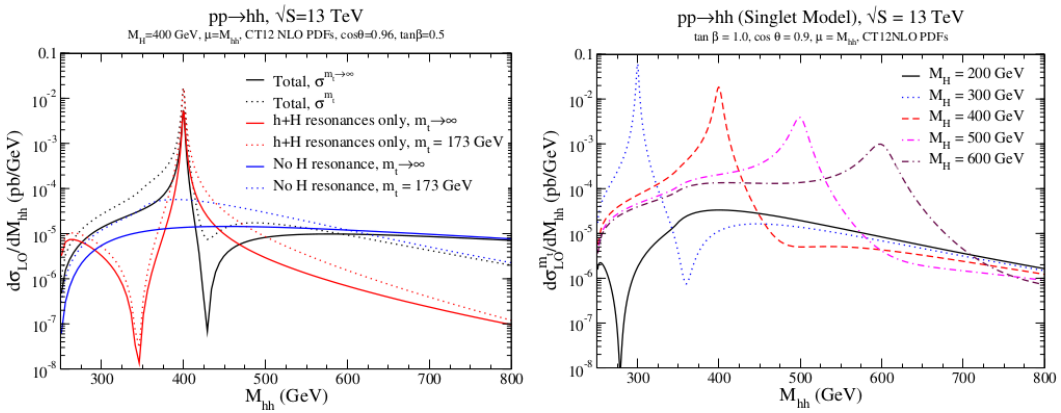
- H_2 is SM-like
- Very large destructive interferences

Approximation effects to differential distributions

Taken from: Tania Robens [LHC-HH Subgroup meeting 28 Sep. 22]

Extra singlet, di-Higgs final states

[S. Dawson, I. Lewis, Phys.Rev.D 92 (2015) 9, 094023]



left plot: continuum, via h and H, all

right plot: total contribution for various masses m_H

Conclusions [arXiv:2112.12515]

- BSM models allow for more complex phenomenology than SM
  - Resonances (maybe more than one)
  - Large widths
  - Interferences
  - Currently exp. analysis consider one resonance, NWA and SM-like HH non. resonant background
- First task: establish a common ground for comparison between BSM models
  - Dedicated scans are needed to focus on specific parameter space regions
- Second task: differential distributions dependence with parameters
  - Sign of the trilinears affects interference structure
  - Large widths/detector smearing flattens the distributions
  - Interplay of several resonances (to be done)
- Third task: Implementing a MC generator [implemented by F. Egle]