Interference effects in BSM discalar production

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di-Higgs meeting
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Disclaimer

- will not give a complete overview on status quo
- instead, **touch on (imho) open issues and trigger discussion**

Topic merits attention

Plan to discuss

⇒ input width in Monte Carlo generators (LO)

⇒ width and interference effects in BSM searches

⇒ open issues ??

Width from the theory prespective - a mini-introduction

[for more details, see e.g. standard textbooks on QFT, and/ or Phys.Rept. 864 (2020) 1-163]

Theoretically...

- calculation of S-matrix elements in perturbative QFT: relies on LSZ reduction (bringing asymptotically free states into interactions by relating $t = \pm\infty$ to t_{int}, S-matrix: residue of external particles propagator poles)

  only defined for stable particles !

  e.g. leptons, quarks, ...
- everything else is approximation, **in principle all unstable particles should only appear in form of propagators** $\sim \frac{1}{p^2 - M^2}$

Width from the theory prespective - a mini-introduction

Introduction of width

- **S-matrix: complex quantity;**
  at leading order, **poles can appear for $p^2 = M^2$**

  artefact of finite order calculation

- solution: **resummation of self-energy contributions near resonance** $\Rightarrow$ leads to modification $\frac{1}{p^2 - M^2 + \Sigma_R(p^2)}$
- **$\Sigma_R(M^2)$ related to total width Γ via optical theorem**

$$\text{Im}\Sigma_R = M\,\Gamma$$

  with $\Gamma = \sum_i \Gamma_i$, i denoting partial widths

- **leads to form** $\sim \frac{1}{p^2 - M^2 + i\,M\,\Gamma}$ [Breit-Wigner]

still many open issues, in particular gauge dependence $\Rightarrow$ several solutions exist, important for electroweak precision measurements

Narrow width approximation

[see e.g. also Nucl.Phys.B 814 (2009) 195-211; Diploma thesis C. Uhlemann, Wuerzburg, '07]

- in the limit $\Gamma \rightarrow 0$:

$$\frac{1}{|p^2 - M^2 + i\,M\,\Gamma|^2} \rightarrow \frac{\pi}{M\,\Gamma}\,\delta\left(p^2 - M^2\right)$$

$\Rightarrow$ leads to **factorized approach:**

$$\sigma_{ab\rightarrow c\rightarrow d\,e} \rightarrow \sigma_{ab\rightarrow c} \times \underbrace{\frac{\Gamma_{c\rightarrow d\,e}}{\Gamma}}_{\text{BR}_{c\rightarrow d\,e}}$$

- formal error: $\mathcal{O}\left(\frac{\Gamma}{M}\right)$

factorized approach

- even QM says: **should really consider**

$$\mathcal{M}_{ab\rightarrow de}$$

with all contributions, and interferences

Topic 1: Width in s-channel resonances in Monte Carlo [Trivia ?]

- sample process: $p\,p \to X \to Y\,Z$
- **factorized simulation:** $p\,p \to X,\, X \to Y\,Z$
  via $\sigma_{p\,p \to X} \times \text{BR}_{X \to Y\,Z}$

  relevant input: $\textbf{BR}_{X \to Y\,Z}$
- **full simulation** $p\,p \to Y\,Z$: **contains all intermediate states !**
  [more correct from a QM point of view]
- if dominantly via s-resonance:

  narrow width approximation realized in MC:

  $$\sigma_{p\,p \to X} \times \textbf{BR}_{X \to Y\,Z}$$

  but now $\textbf{BR}_{X \to Y\,Z} = \frac{\Gamma_{X \to Y\,Z}}{\Gamma_{X,\text{tot}}}$

  $\Gamma_{X \to Y\,Z}$ **from Monte Carlo (intrinsic),** $\Gamma_{X,\textbf{tot}}$ **input**

vary $\textbf{BR}_{X \to Y\,Z}$ via external input of $\Gamma_{X,\textbf{tot}}$

Topic 2: Current literature (incomplete)

extra singlet, di-boson final states (VV)

E. Maina, JHEP 06 (2015) 004; C. Englert, I. Low, M. Spannowsky, Phys.Rev.D 91 (2015) 7, 074029; N. Kauer, C. O'Brien, Eur.Phys.J.C 75 (2015) 374; A. Ballestrero, E. Maina, JHEP 01 (2016) 045; N. Kauer, C. O'Brien, E. Vryonidou, JHEP 10 (2015) 074; S. Martin, Phys.Rev.D 94 (2016) 3, 035003; A. Djouadi, J. Ellis, J. Quevillon, JHEP 07 (2016) 105; N. Kauer, A. Lind, P. Maierhoefer, W. Song, JHEP 07 (2019) 108

extensions, di-Higgs final states

S. Dawson, I. Lewis, Phys.Rev.D 92 (2015) 9, 094023; M. Carena, Z. Liu, M. Riembau, Phys.Rev.D 97 (2018) 9, 095032; A. Djouadi, J. Ellis, J. Quevillon, JHEP 07 (2016) 105; O. Atkinson, C. Englert, P. Stylianou, arXiv:2012.07424; B. Das, S. Moretti, S. Munir, P. Poulose, Eur.Phys.J.C 81 (2021) 4, 347

2HDM, di-boson final states (VV)

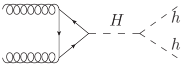
S. Jung, Y. W. Yoon, J. Song, Phys.Rev.D 93 (2016) 5, 055035; A. Djouadi, J. Ellis, J. Quevillon, JHEP 07 (2016) 105

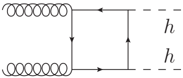
extensions, difermion final states

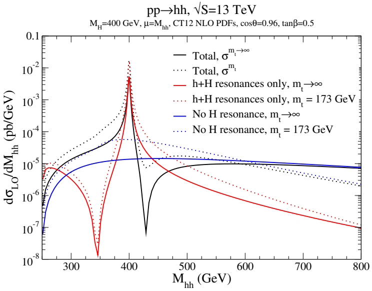
M. Carena, Z. Liu, JHEP 11 (2016) 159; A. Djouadi, J. Ellis, J. Quevillon, JHEP 07 (2016) 105; A. Djouadi, J. Ellis, A. Popov, J. Quevillon, JHEP 03 (2019) 119; N. Kauer, A. Lind, P. Maierhoefer, W. Song, JHEP 07 (2019) 108; P. Basler, S. Dawson, C. Englert, M. Muehlleitner, Phys.Rev.D 101 (2020) 1, 015019

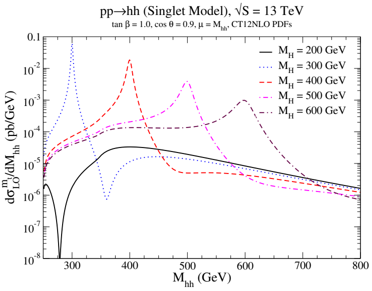
Extra singlet, di-Higgs final states

[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

From T. Lenz talk at Higgs Hunting

https://indico.ijclab.in2p3.fr/event/5923/contributions/19114/attachments/17023/22363/HHunting_bbtautau.pdf

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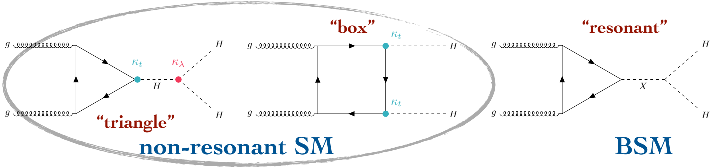
HH Production SM & BSM

- **HH production** → non-resonant and resonant



- **SM HH production** cross section 1000 times smaller than $pp \to H$
  - two diagrams with **destructive interference** = **31 fb @ 13 TeV**
- **BSM** can lead to enhancement in the HH production
  - **non-resonant** production due to modified λ, new vertices or new particles in the loop
  - **resonant** production modes: KK gravitons, H in 2HDM, new scalar singlets, cross sections up to O(pb)

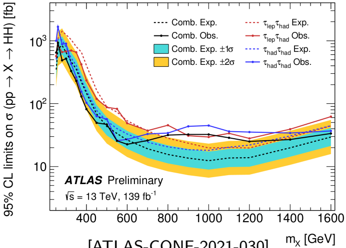
"Bump" at 1 TeV [ATLAS-CONF-2021-030]

- finite width effects

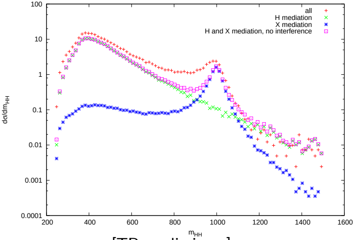
$\Longrightarrow$ width-dependence of results $\Longleftarrow$

$\Rightarrow$ exactly **what was used for DNN training ?**

[note this is only 1 variable...]



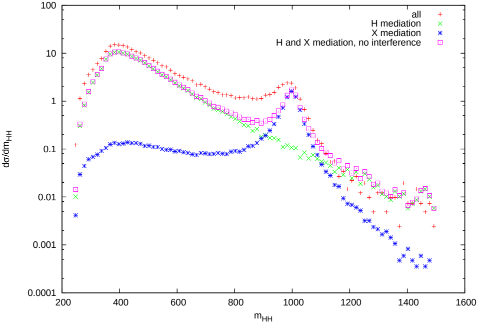
[ATLAS-CONF-2021-030]



[TR, preliminary]

Another comment on simulation and interference effects

setup: singlet extension,
heavy scalar with mass $1\,\mathrm{TeV},\ \Gamma_X \sim 50\,\mathrm{GeV}$



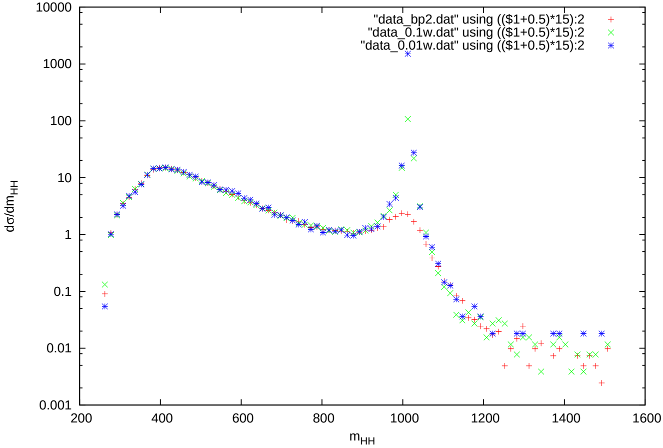
$\sigma_{\mathrm{tot}} \sim 24\,\mathrm{fb}$
$\sigma_{\mathrm{SM}} \sim 15\,\mathrm{fb}$
$\sigma_{\mathrm{BSM}} \sim 1.2\,\mathrm{fb}$
$\sigma_{\mathrm{SM}} + \sigma_{\mathrm{BSM}} \sim 16\,\mathrm{fb}$

discussion with ATLAS conveners: finite width/ interference not included

furthermore, widths set to $\sim 10\,\mathrm{MeV} \Rightarrow$ very difficult to realize in any realistic BSM model !! (as far as I know)

Effects of changing width to too small values

2 real singlet scenario, $M_x = 1\,\mathrm{TeV}$, $\Gamma_X \sim 80\,\mathrm{GeV}$



$\sigma = 24\,\mathrm{fb}$, $\sigma_{0.1} = 38\,\mathrm{fb}$, $\sigma_{0.01} = 181\mathrm{fb}$; $\sigma_X = 2.7\,\mathrm{fb}$, $\sigma_{SM} = 15\,\mathrm{fb}$

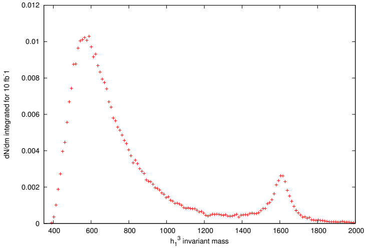
Topic 3: Importance of full simulation [TR, preliminary]

- sample process

$$p\,p \;\rightarrow\; h_3 \;\rightarrow\; h_1\,h_2 \;\rightarrow\; h_1\,h_1\,h_1$$

simulating full final state: $p\,p \;\rightarrow\; h_1\,h_1\,h_1$

- masses: $125\,\mathrm{GeV},\ 500\,\mathrm{GeV},\ 1600\,\mathrm{GeV}$



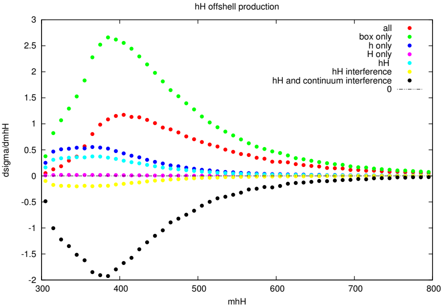
large contribution from offshell h_1

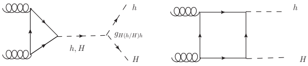
Topic 3: Importance of full simulation [TR, preliminary]

- sample process

$$p\,p \;\to\; h\,H$$

- masses: $125\,\mathrm{GeV},\ 166\,\mathrm{GeV}$ $\Rightarrow$ **non-resonant**



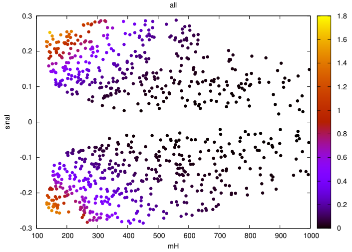


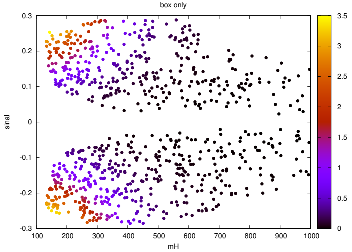
[implemented into Herwig7.2]

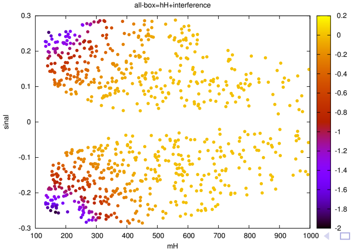
important interference effects (as in hh)

Hh cross sections at 13 TeV, in fb

[A. Papaefstathiou, TR, G. Tetlalmatzi-Xolocotzi, J. Zurita, in preparation]







(Personal) Summary

- **use most complete description possible !!**
- **do *not* forget there is a resonance at 125 GeV**
  $\Rightarrow$ **needs to be included in simulations** (preferably as part of "SM background")
- in my understanding, **several tools are already used now which include everything** $\Rightarrow$ **good !**

in general, interferences and finite width effects are important !

- **mainly discussed interference here**
  to do: **check what happens for varying widths**

Open issues ?

- **production K-factors ??**
- **which corrections should be included in widths** (NLO width in LO simulation ? etc)
- **factorization: "easy" inclusion of higher orders, full final states: include interference**

  $\Rightarrow$ **whats more important/ interesting** $\Leftarrow$

  (think about $h_{1,2}$ in an s-channel mediated process with interference effects)
- **alternative roads,** as e.g. usage of generalised narrow width approximation ? [E. Fuchs, S. Thewes, G. Weiglein, Eur.Phys.J.C 75 (2015) 254]
- ...

Appendix

Tools that can do it, I am aware of

which have been used in these publications

- gg2VV, https://gg2vv.hepforge.org/
- Mad-Graph5 aMC@NLO [with corresponding UFO file]
- Sherpa+OpenLoops
- Phantom
- JHU generator, http://spin.pha.jhu.edu/

some (e.g. gg2VV, JHU) already used in (some) experimental searches

from: E. Fuchs, "Interference effects in BSM searches", Extended Higgs Sector subgroup meeting, November 5, 2021

Interference of quasi degenerate resonances

- degeneracy: $\Delta M \leq \Gamma_i + \Gamma_j$
- mixing: so that $2\mathrm{Re}[\mathcal{M}_i \mathcal{M}_j^*] \neq 0$

Examples of quasi degenerate states in BSM

- Higgs bosons in extended Higgs sectors
- sfermions, higgsinos
- Extra dimensions: states at same Kaluza-Klein level

Interference term can be relevant → include in NWA!

Generalised NWA with interference term [EF, Thewes, Weiglein '15]

- matrix elements on-shell $\mathcal{P}_i(q^2 = M_i^2)$, $\mathcal{D}_i(q^2 = M_i^2)$
  - close to full result
  - evaluation of squared matrix elements
- 'interference weight factor' R: $\sigma \approx \sum_i \sigma_{P_i} \, \mathrm{BR}_i \cdot (1 + R_i)$
  - building blocks available as in sNWA: $\sigma_P, \Gamma_D, \Gamma^{\mathrm{tot}}, g_P, g_D$
  - **additional approximation** $M_i \approx M_j$