Fellowship at the INFN, CMS group of Bari
"Double Higgs (H) production at Run2-LHC"

III International Workshop on recent LHC Physics results and related topics in Tirana

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- The Brout-Englert-Higgs mechanism (I, II)
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The Brout-Englert-Higgs mechanism I

• Proposed in 1964 independently by Englert and Brout, Higgs , and also by Guralnik, Hagen, and Kibble as a solution to generate the gauge boson masses and explain the fermion masses.
• The mechanism is based on the concept of spontaneous symmetry breaking, a phenomenon observed in Nature, whenever individual ground states of a system do not satisfy the symmetries of the system itself.

• Spontaneous symmetry breaking is realized through the introduction of a complex scalar doublet of fields: $\Phi = \begin{pmatrix} \phi_+ \\ \phi_0 \end{pmatrix}$

- The field must be scalar to satisfy space isotropy
- The VEV v would be frame-independent and constant to satisfy space homogeneity
- The hypercharge of the field is $Y_\Phi = 1$
- Its covariant derivative is: $D_\mu = \partial_\mu - igW^i_\mu \frac{\sigma}{2} - \frac{1}{2} ig' B_\mu$

$$\mathcal{L}_{BEH} = (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi^\dagger \Phi)$$

$$V(\Phi^\dagger \Phi) = -\mu \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2 \quad \text{where} \quad \mu, \lambda > 0$$

• All the doublets that satisfy the condition: $\mid \Phi \mid^2 = \frac{\mu^2}{2\lambda} \equiv \frac{v^2}{2}$ are minima of these potential, and are connected through gauge transformations that change the phase of the field Φ but not its modulus.
• If the symmetry is spontaneously broken to the ground state parallel to the ϕ_0 component of the doublet, than, this specific ground state is still invariant under the $U(1)_{em}$ symmetry group. As a consequence, the field expansion around this minimum is written as:

$$\Phi(x) = \frac{1}{\sqrt{2}} exp \left[\frac{i\sigma_i \theta^i(x)}{v} \right] \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$$

• This corresponds to the presence of a scalar real massive field H and of three massless fields $\theta^i(x)$. The latter are expected as consequence of the Goldstone theorem.
• Such massless bosons are not observed in Nature. They can be removed with an $SU(2)_L$ transformation that consists in the choice of a specific gauge called unitary gauge:

$$\Phi(x) \rightarrow \Phi'(x) = exp \left[-\frac{i\sigma_i \theta^i(x)}{v} \right] \Phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$$

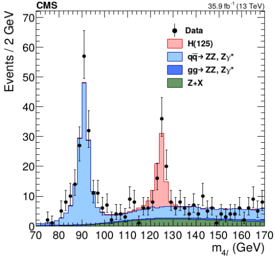
The Brout-Englert-Higgs mechanism II

- After the transformation, only the real scalar field $H(x)$ remains and its quanta corre- spond to a new physical massive particle, the Higgs boson (H).

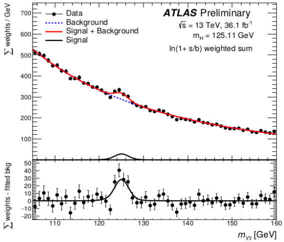
$$\mathcal{L}_{BEH} = \frac{1}{2}\partial_\mu H \partial^\mu H - \frac{1}{2}\left(2\lambda v^2\right) H^2 \quad \Rightarrow \text{ evolution of the Higgs scalar field}$$

$$+ \left[\left(\frac{gv}{2}\right)^2 W^{\mu +} W^-_\mu + \frac{1}{2}\frac{\left(g^2 + g'^2\right) v^2}{4} Z^\mu Z_\mu\right]\left(1 + \frac{H}{v}\right)^2 \quad \Rightarrow \text{ the mass terms of the weak bosons}$$

$$+\lambda v H^3 + \frac{\lambda}{4} - \frac{\lambda}{4} v^4 \quad \Rightarrow \text{ prediction of cubic and quartic self-interactions of the Higgs boson}$$



(a) H $\to ZZ^* \to \ell^+\ell^-\ell'^+\ell'^-$ chan- nel (CMS)



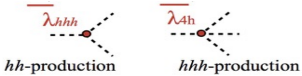
(b) H $\to \gamma\gamma$ channel (ATLAS)

Four-lepton invariant mass (a) and photon pair invariant mass (b) distributions in events collected at $\sqrt{s} = 13$TeV

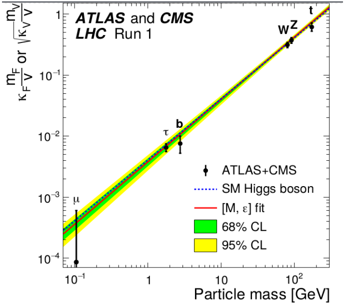
Higgs potential and Higgs self-coupling constant λ_{HHH}

- The BEH potential can be rewritten in terms of a trilinear and a quadrilinear coupling as:

$$V = \frac{1}{2} m_H^2 H^2 + \lambda_{HHH} v H^3 + \frac{1}{4} \lambda_{HHHH} H^4 - \frac{\lambda}{4 v^4}, \quad \lambda_{HHH} = \lambda_{HHHH} = \frac{m_H^2}{2v^2} \approx 0.13$$



Normalized Higgs boson coupling constant as a function of the boson or fermion mass:

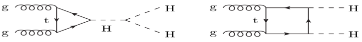


- Directly related to the parameters of the scalar potential
- Entirely determined from the Higgs boson mass, VEV.
- Their measurement thus represents a test of the validity and coherence of the SM.
- In contrast to the weak boson self-interactions, that have a gauge nature, the Higgs boson self-interactions are purely related to the scalar sector of the theory
- Responsible for the mass of the Higgs boson itself
- Their experimental determination is thus crucial to reconstruct the Higgs boson potential and explore the nature of the EWSB.
- Experimentally measuring of λ_{HHH} (HH-boson production), λ_{HHHH} is crucial for the mechanism of electroweak symmetry breaking.

The SM HH production

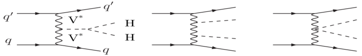
Main Higgs pair production mechanisms predicted from the SM, listed below in decreasing oder of their cross sections:

1)gluon fusion production $gg \to HH$**:**



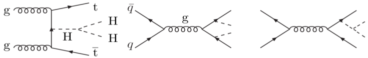
$\sigma_{13\,TeV}[fb] = 33.49^{+4.1\%}_{-5.7\%}(scale) \pm 3.1\%(PDF) \pm 2.6\%(\alpha_s) \pm 5.0\%(top)$

2)vector boson fusion (VBF) production $qq^{'} \to jjHH$**:**



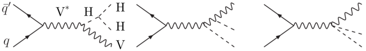
$\sigma_{13\,TeV}[fb] = 1.62^{+2.3\%}_{-2.7\%}(scale) \pm 2.3\%(PDF + \alpha_s)$

3)top quark pair associated production $qq^{'}/gg \to t\bar{t}HH$**:**



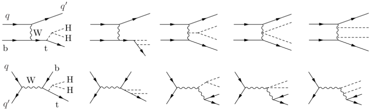
$\sigma_{13\,TeV}[fb] = 0.772^{+1.7\%}_{-4.5\%}(scale) \pm 3.2\%(PDF + \alpha_s)$

4)vector boson associated production $qq^{'} \to VHH$**,** $V = W^{\pm}, Z$**:**



$\sigma_{13\,TeV}[fb] = (\sigma_{W+}, \sigma_{W-}) = 0.329(0.173)^{+0.32\%(1.2)}_{-0.41\%(-1.3)}(scale) \pm 2.2\%(2.8)(PDF + \alpha_s)$

5)single top quark associated production $qq^{'} \to tjHH$**:**



$\sigma_{13\,TeV}[fb] = 0.0281^{+5.2\%}_{-3.2\%}(scale) \pm 4.2\%(PDF + \alpha_s)$

Double Higgs (HH) productions in term of BSM phenomenology

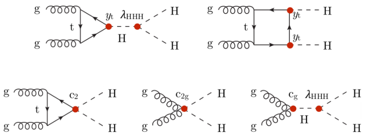
- Gluon fusion $gg \to hh$ is the dominant Higgs (H) pair production mode.
- BSM contribution in order to enhance the HH cross section;

COMBINATION OF DECAY CHANNELS ENSURES OPTIMAL COVERAGE OF BSM TOPOLOGIES

NON-RESONANT HH production:

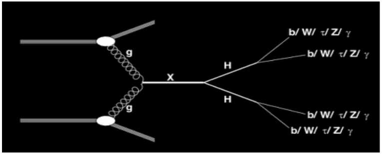
- Extension of the SM Lagrangian with dimension 4 and 6 operators is one of the BSM implementation in order to enhance the HH cross section, which allows and requires anomalous Higgs (H) couplings constants:

$$\mathcal{L}_{HH} = \frac{1}{2}\partial_\mu \partial^{mu} h - \frac{1}{2} m_h^2 h^2 - k_\lambda \lambda_{SM} v h^3 - \frac{m_t}{v}\left(v + k_t h + \frac{c_2}{v} hh\right)(\bar{t}_L t_R + h.c.) + \frac{\alpha_s}{12}\left(c_{1g} h - \frac{c_{2g}}{2v} hh\right) G^A_{\mu\nu} G^{A\mu\nu}$$



RESONANT HH production:

- Looking for a narrow resonance X with a mass m_X using the invariant mass spectrum m_{HH}
- Cross section is significantly enhanced on resonances (up to pb)



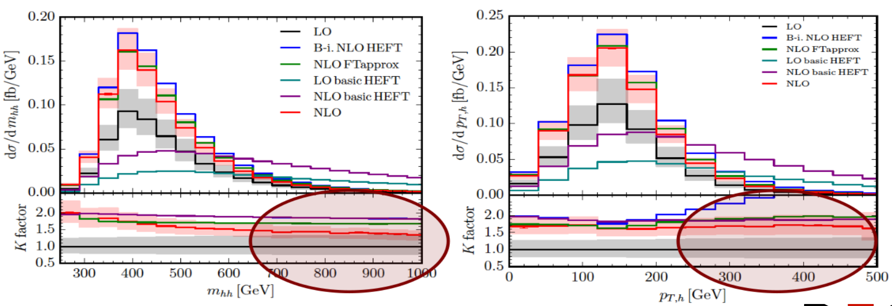
Well-motivated signatures according to several scenarios:

- Broad class of models predicting new scalars that can decay to HH and broad mass range to explore (MSSM: $250 \leq m_X \leq 350$GeV, 2HDM: $250 \leq m_X \leq 1000$GeV)
- Randall-Sundrum warped extra dimension (up to 3TeV!) $\Rightarrow$ spin-0 radion or spin-2 KK graviton

Analysis techniques

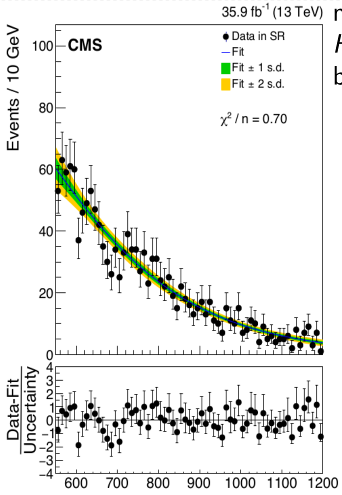
The usaged pf MC-frameworks helpfull for BSM phenomenology, calculation of cross sections and more:

- `MadGraph5_aMC@NLO` generates collision events. Processes can be simulated to LO accuracy for any user-defined Lagrangian and NLO accuracy in the case of QCD corrections to SM processes
- `POHWEG-Box` is able to produce *HH* production at NLO accuracy, too
- Parton showering and hadronization with `Pythia-8.2.3.5`
- `Delphes-3.4.1` performs fast multipurpose detector response simulations, especially on LHC detectors. Meanwhile `Geant4-10` is useful for full detector simulation analysis.
- Existence of theoretical models for NNLO accuracy range.

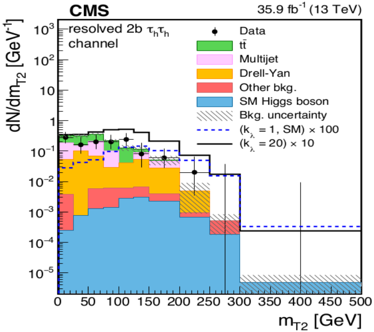


(Credits: Eleni Vryonidou "Monte Carlo Modelling of HH" at HH workshop Fermilab, Borowka et al arXiv:1604.06447 and 1608.04798)

Recent results (Part I)



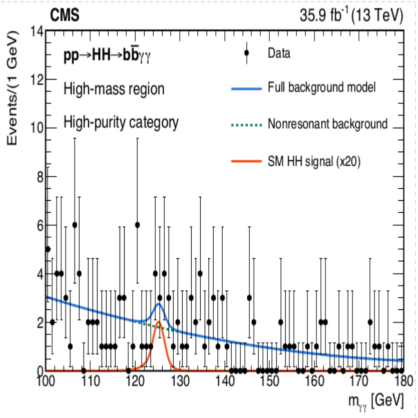
- Analyses for different resonance mass ranges for $HH \to 4b$ have been done:
  - Resolved: $4b$ jets used to reconstruct the $HH \to 4b$
  - Fully-merged: 2 large-area jets each identifying a boosted $H \to bb$
  - Semi-resolved: 1 large-area jet and $2b$ jets



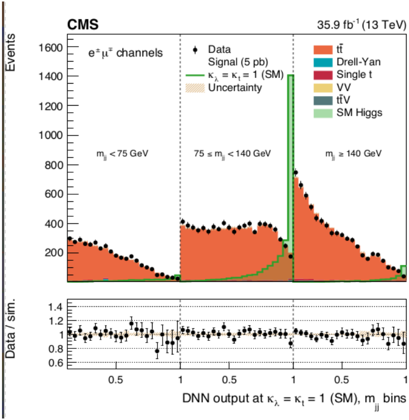
- Analyses for both resonant and non-resonant in 3 categories for $HH \to bb\tau\tau$ have been done:
  - Resolved: resolved 1 b-tag, 2 b-tag and boosted

Recent results (Part II)

$HH \to bb\gamma\gamma$



$HH \to bbll\nu\nu$

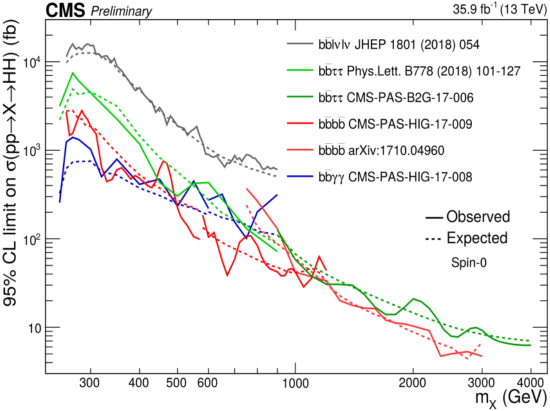


- Single CMS analysis for resonant and nonresonant production
- Signal extraction on $m_{bb}/m_{\gamma\gamma}$

- Single analysis for resonant and nonresonant production
- Based on MVA methods for signal extraction

Recent results (Part III):

Combinations of resonant *HH*-decay channels:



New search channels

- New search channels are being investigated, which are less sensitive and more challenging:

$$(1) \quad HH \rightarrow \tau\tau\tau\tau$$

$$(2) \quad HH \rightarrow bbZZ$$

where three channels are available:

$$(2.1) \quad HH \rightarrow bbl^+l^-\nu\nu$$

$$(2.2) \quad HH \rightarrow bbl^+l^-l^+l^-$$

$$(2.3) \quad HH \rightarrow bbl^+l^-qq$$

The interest of our research group is based especially on the following production HH: $HH \rightarrow bbZZ$ **and respective decay channel, where we would like to contribute on future** HH **production research:**

$$\boxed{HH \rightarrow bbZZ\,(l^+l^-l^+l^-)}$$

Conclusions

- CMS has conducted extensive searches for the *HH* production for all sensitive channels, in large mass ranges and for both resonant and non-resonant modes
- All results consistent with SM backgrounds so far
- Combined observed (expected) limit$\sim$ 22(13)xSM
- New search channels are being investigated
- We are now switching toward processing rest of *Run*2 data (2017, 2018)
- Combination of HH analyses is necessary to improve the CMS sensitivity to HH production:
    - similar sensitivity to SM signal from many analyses
    - complementary coverage of BSM parameter space
- Checks of the phase space overlap and proper treatment of systematic uncertainties are a necessary step for a reliable combined result
- The combined limit is to date the most sensitive result to SM *HH* production:
    - combined limits on resonant production
    - combined limits on anomalous (trilinear) coupling
    - EFT parameter space explored using shape benchmark signals
- The combined results are statistically limited and expected to improve with larger datasets $\Rightarrow$ a future goal for HL-LHC and FCC

$\Rightarrow$ **The future topic of my PhD research together with my research team at the INFN, will be the following event** *HH*: $HH \rightarrow bbZZ$ **and the respective decay channel, where we would like to contribute on future** *HH* **production:**

$$HH \rightarrow bbZZ\left(l^+l^-l^+l^-\right)$$

Backup slides

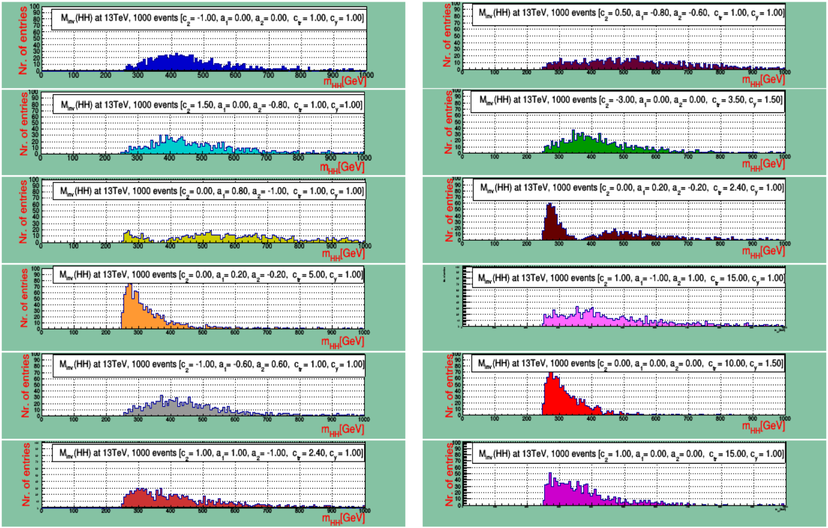
MC generations: benchmarks shapes (I)

Benchmark nr.	k_λ	k_t	c_2	c_g	c_{2g}
1	7.5	1.0	-1.0	0.0	0.0
2	1.0	1.0	0.5	-0.8	0.6
3	1.0	1.0	-1.5	0.0	-0.8
4	-3.5	1.5	-3.0	0.0	0.0
5	1.0	1.0	0.0	0.8	-1.0
6	2.4	1.0	0.0	0.2	-0.2
7	5.0	1.0	0.0	0.2	-0.2
8	15.0	1.0	0.0	-1.0	1.0
9	1.0	1.0	1.0	-0.6	0.6
10	10.0	1.5	-1.0	0.0	0.0
11	2.4	1.0	0.0	1.0	-1.0
12	15.0	1.0	1.0	0.0	0.0
SM	1.0	1.0	0.0	0.0	0.0

- Each benchmark shape corresponds to a specific choice of the 5 EFT couplings
- The choice does not have a special physical meaning: it is only meant to represent a shape, not a special point in the EFT parameter space

MC generations: benchmark signal shapes (II)

Below I reproduced the benchmark signal shapes, generating several distributions (1000 events each) of double Higgs boson invariant mass $M_{inv}(HH)$, in LO accuracy using as MC generator MadGraph5_aMC@NLO (MG5_aMC_v2.6.3.2), combining the values of the coupling coeficients from the SM extended Langrangian in the framework of the EFT:



NLO and NNLO implementations

(Credits: J. Baglio "Full NLO-QCD corrections to $gg \to HH$", HH Production at Colliders Workshop, 9/5/2018)

- **LO QCD (1-loop):** Dominated by top-quark loops [Eboli, Marques, Novaes, Natale, PLB 197 (1987) 269; Glover, van der Bij, NPB 309 (1988) 282; Dicus, Kao, Willenbrock, PLB 203 (1988) 457]
- **NLO QCD HTL (1-loop):** $+93\%$ correction [Dawson, Dittmaier, Spira, PRD 58 (1998) 115012]
- **Toward full NLO QCD (2-loop):**
  $\rightarrow$ NLOFT$_{\text{approx}}$, m_t-effects in real radiation: -10%
  [Maltoni, Vryonidou, Zaro, JHEP 1411 (2014) 079]
  $\rightarrow$ $\mathcal{O}(1/m_t^{12})$ terms in virtual amplitudes: $\pm 10\%$
  [see e.g. Grigo, Hoff, Steinhauser, NPB 900 (2015) 412]
- **NNLO QCD HTL (2-loop):** $+20\%$ on total cross section [De Florian, Mazzitelli, PLB 724 (2013) 306; PRL 111 (2013) 201801]
- **Latest NNLO QCD:** full NLO QCD + NNLO HTL + NNLO exact reals $\Rightarrow$ $+10\%$ to $+20\%$ in distributions
  [Grazzini, Heinrich, Jones, Kallweit, Kerner, Lindert, Mazzitelli, JHEP 1805 (2018) 059]

References

- The CMS Collaboration "Search for non-resonant Higgs pair-production in the $b\bar{b}b\bar{b}$ final state with the CMS detector" (2018/07/04)
- The CMS Collaboration "Search for resonant pair-production of Higgs bosons decaying to botoom quanrk-antiquark pairs in proton-proton collisions at 13 TeV" (2011/11/07)
- The CMS Collaboration "Search for Higgs pair-production in the final state containing two photonss and two bottom quarks in proton-proton collisions at $\sqrt{s} = 13$ TeV" (2017/07/06)
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- The CMS Collaboration "Search for resonant and non-resonant Higgs pair-production in the $b\bar{b}l\nu l\nu$ final state using 2016 data" (2017/03/26)
- The CMS Collaboration "Search for non-resonant Higgs pair-production in the $b\bar{b}\tau^+\tau^-$ final state using 2016 data" (2016/08/04)
- The CMS Collaboration "Search for resonant Higgs pair-production in the $b\bar{b}\tau^+\tau^-$ final state using 2016 data" (2016/08/04)