THE OHIO STATE UNIVERSITY

ATLAS EXPERIMENT

Exploring electroweak symmetry breaking and scalar sector with $bbWW$ final state

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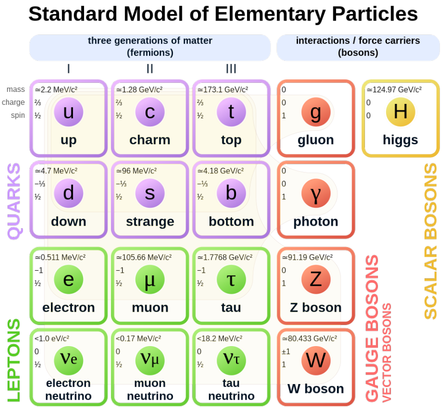
Standard Model (SM) of Particle Physics

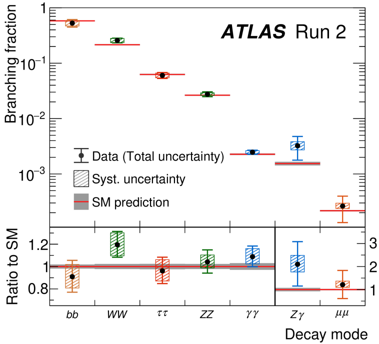
- The SM is $SU(3)_C \times SU(2)_L \times U(1)_Y$ local gauge theory.
- Describes matter particles and their interactions (except gravity).
- Matter particles (quarks and leptons): spin-$1/2$
- Force mediators: spin-1 (bosons).
- Strong force mediated by massless gluons, weak force mediated by massive W and Z bosons, and electromagnetism mediated by massless photons.

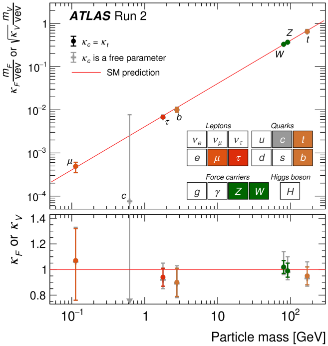


- Predicts existence of a scalar particle called Higgs boson. It provides evidence for electroweak symmetry breaking that results in generation of gauge boson masses.

Measured couplings of Higgs boson

- ATLAS and CMS experiments at CERN discovered SM-like Higgs boson in 2012. Since then several of the properties of Higgs boson have been studied and have been found to be consistent with the SM predictions.
- One of the important properties yet to be measured: Higgs self-coupling.





Figures from Nature 607, 52–59 (2022).

Standard Model Higgs potential

- In the SM, the Higgs potential is given by

$$V(\Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

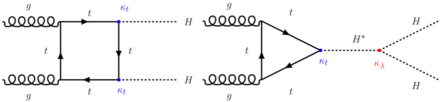
- Expanding around the minimum after the symmetry breaking, it becomes

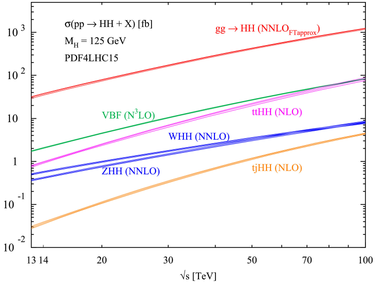
$$V(h) = \lambda v^2 h^2 + \lambda v h^3 + \frac{\lambda}{4} h^4 = \underset{\text{mass term}}{\boxed{\frac{1}{2} m_h^2 h^2}} + \underset{\substack{\text{tri-linear} \\ \text{self-coupling}}}{\boxed{\lambda v h^3}} + \underset{\substack{\text{quartic} \\ \text{self-coupling}}}{\boxed{\frac{\lambda}{4} h^4}}$$

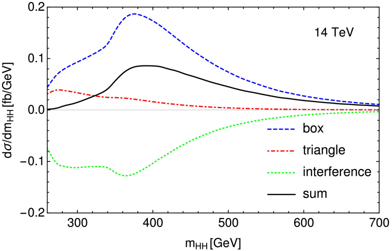
- λ: dimensionless coupling constant. In the SM, $\lambda = \frac{m_h^2}{2v^2}$ → exact prediction.
- Measurement of λ needed to reconstruct Higgs potential.
- If $\lambda \neq \lambda_{\text{SM}}$ it means the SM prediction needs correction! Quantified by $\kappa_\lambda = \frac{\lambda}{\lambda_{\text{SM}}}$.
- Tri-linear self-coupling can be directly probed only by Higgs boson pair (di-Higgs) production, which might be reachable with High Luminosity (HL)-LHC; quartic self-coupling is beyond the reach of the HL-LHC.

Higgs boson pair production at the LHC

- The most dominant production mode is gluon-gluon fusion (ggF).
- In ggF mode, there are two leading order Feynman diagrams-box and triangle (sensitive to κ_λ).
- Destructive interference between the two diagrams leads to small production cross-section (≈ 31 fb at $\sqrt{s} = 13$ TeV, ≈ 36.69 fb at $\sqrt{s} = 14$ TeV).



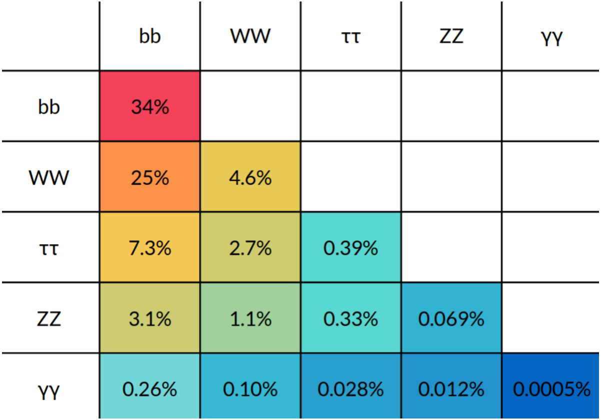




arXiv:1910.00012v4

di-Higgs decay channels

- Many possible decay channels since Higgs boson directly couples with most of the fermions and bosons.
- The decay channels with higher branching ratio (BR) are those that have at least one of the Higgs bosons decaying to b-quark pair.



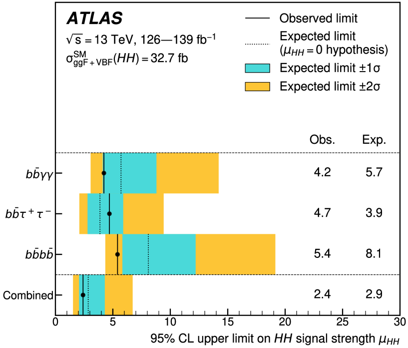
	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

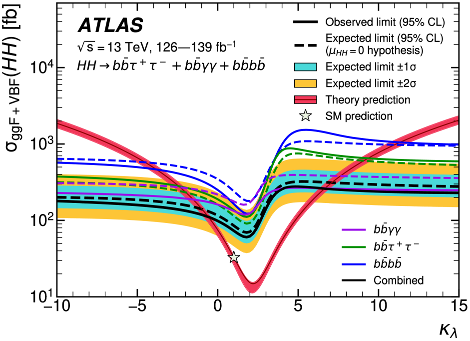
di-Higgs searches at the LHC

- No single golden channel for di-Higgs.
- General trend is to use the final states which either have large BRs (eg: $HH \rightarrow 4b$) or have cleaner signatures (eg: $HH \rightarrow bb\gamma\gamma$) or some compromise between the two (eg: $HH \rightarrow bb\tau\tau$).
- To get sizeable BR, searches are often performed in final states with at least one $H \rightarrow bb$ decay.
- While they have large BRs, all-hadronic final states tend to suffer from large multijet background whereas all leptonic states have lower BRs.
- Need to combine multiple channels in order to observe di-Higgs at the LHC.

Current limits

- The current best upper limits on signal strength, $\mu = \frac{\sigma_{\mathrm{HH}}}{\sigma_{\mathrm{HH}}^{\mathrm{SM}}}$, come from $4b$, $bb\gamma\gamma$, $bb\tau\tau$, and $bb\ell\ell+$ MET channels.
- For $bb\ell\ell+$ MET channel, the observed (expected) upper limit on the cross-section is 9.7(16.2) times the SM prediction.





ATLAS-CONF-2022-050

$HH \to bbWW^*$ channel

- Has the second highest BR. One of the W bosons is off-shell.
- Depending on W decay modes ($W \to \ell\nu$ or hadrons), final state can contain 0, 1, or 2 leptons.
- Large irreducible background from $t\bar{t} \to bWbW$.
- Sensitivity depends on the ability to reduce backgrounds in the signal region and systematic uncertainties.
- Can significantly reduce backgrounds by using multivariate methods. Reducing systematics is challenging - data driven background estimation may help with background modeling systematics. Example:

Expected upper limit on μ (1-lepton analysis)		
	Statistical Unc. only	Including systematics
Partial Run 2 ($\mathcal{L} = 36.1\text{fb}^{-1}$)	190	300
Full Run 2 ($\mathcal{L} = 140.1\text{fb}^{-1}$)	16.2	27.3

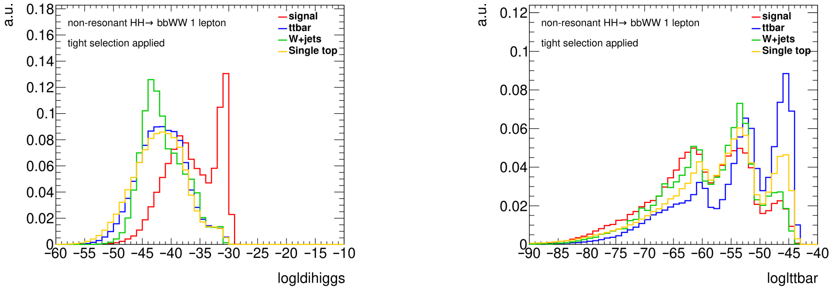
  - A factor of 2 improvement from increased dataset.
  - A factor of 5 improvement from analysis optimization using Deep Neural Network.

Previous work on $HH \rightarrow bbWW^*$

- We have worked on kinematic fitting, derivation of missing transverse energy (MET) trigger scale factors, and analysis preservation for resolved 1-lepton analysis.
- Kinematic fit is a method to exploit kinematic constraints (in both signal and background) based on an assumed decay topology.
- Example: in a top quark decay to $bW \rightarrow bqq'$ we can ask the invariant mass of b, q and q' pair to be consistent with the mass of the top quark.
- We used a tool called KLFitter which does the kinematic fitting based on likelihood constructed by the user. The likelihood is a product of various constraints based on assumed decay topology. $\Longrightarrow$ github repo
- The likelihood is then calculated for the various permutations of final state particles. The permutation with the highest likelihood is taken to give the correct assignment of final particles to parent particle.
- Example: if we had three light jets in our final state in above example, we take the two light jets that give the highest likelihood to be originating from W decay.

Kinematic fit in $HH \rightarrow bbWW$

- In 1-lepton resolved channel we use the highest loglikelihood distribution as input to DNN classifier since it improves $S/\sqrt{B}$.
- $t\bar{t}$ likelihood was used as it is from KLFitter whereas di-higgs likelihood was constructed by the analysis team.



(Left) Log likelihood under the signal HH hypothesis based on the highest likelihood obtained from kinematic fit. (Right) Log likelihood under the top-quark hypothesis based on the highest likelihood obtained from kinematic fit.

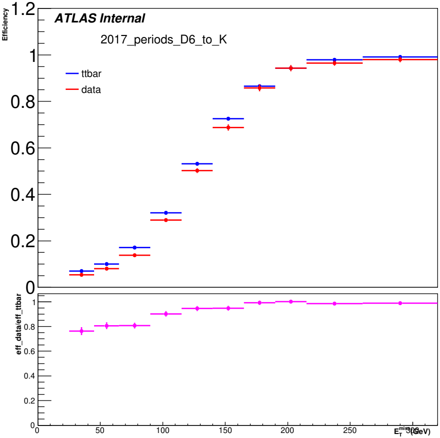
MET trigger scale factors

- Triggers are used to select interesting events in the proton-proton collisions.
- 1-lepton analysis uses events selected by single lepton triggers and MET triggers. MET triggers were added as they increase signal efficiency on top of single lepton triggers.
- We need correction factors (scale factors, aka SFs) if there is a difference between data and monte carlo simulation.
- For analyses operating in region that is not well above MET trigger thresholds, we need to compute SFs (central SFs not provided).
- MET trigger efficiency is calculated in dedicated control regions defined by various selections and a selection on log of likelihood of ttbar from kinematic fit.

$$\text{Efficiency} = \frac{\text{No. of events passing selection \& trigger}}{\text{No. of events passing selection}}$$

$$\text{SF} = \frac{\text{Efficiency of data}}{\text{Efficiency of MC}}$$

MET trigger scale factor plot



GW-2HDM model

- Despite its success, most theorists think the SM is not complete. For instance it cannot explain small Higgs boson mass.
- With observed Higgs boson having nearly SM couplings (see slide 2), is there possibility for extended Higgs sector?
- There are some models that try to answer why the known couplings of the observed Higgs are so SM-like (alignment). One of them is Gildener-Weinberg (GW) 2HDM model [Phys. Rev. D 13, 3333, 1976]. Bonus: small Higgs boson mass occurs naturally in this model!
- Two Higgs doublets instead of one as in the SM → 5 Higgs bosons $(A, H, H', H^{\pm})$.
- No quadratic term in scalar field Φ in the Higgs potential of GW-2HDM → classically scale-invariant.
- Imposes type-I Z_2 symmetry:

$$\Phi_1 \to -\Phi_1, \Phi_2 \to \Phi_2, \psi_L \to -\psi_L, \psi_{uR} \to \psi_{uR}, \psi_{dR} \to \psi_{dR}$$

  Means all fermions couple to Φ_1 only (no Flavour-changing neutral currents, aka FCNCs, induced by Higgs exchange at tree-level)

GW-2HDM model (continued)

$$\begin{aligned} V_0(\Phi_1,\Phi_2) =& \lambda_1(\Phi_1^\dagger\Phi_1)^2 + \lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \\ & \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}\lambda_5((\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_1)^2) \end{aligned}$$

where

$$\Phi_k = \frac{1}{\sqrt{2}}\begin{pmatrix} \sqrt{2}\phi_k^+ \\ \rho_k + ia_k \end{pmatrix}, k = 1,2$$

- V_0 not only has a trivial minimum ($\Phi = 0$), but also has non-trivial minimum along the ray

$$\Phi_{1\beta} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ \phi\cos\beta \end{pmatrix}, \Phi_{2\beta} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ \phi\sin\beta \end{pmatrix}$$

which spontaneously breaks scale-invariance. $\phi > 0$ is a real mass scale, β is angle to be determined.

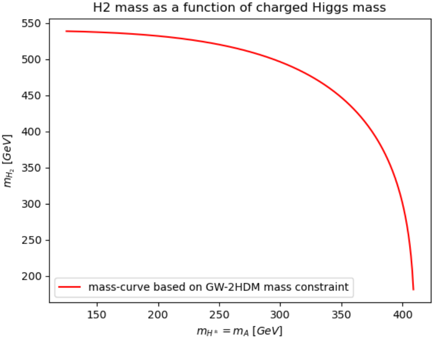
GW-2HDM model (continued)

- Can perform same linear transformation of the CP-odd, charged, and CP-even scalar pairs to get mass eigenvectors $(z, A), (w^{\pm}, H^{\pm}), (H, H')$. At tree level the lightest CP-even scalar, H, is massless! $z, w^{\pm}$ are longitudinal components of the EW gauge bosons.
- But experimentally, we have have 125 GeV Higgs boson! **Enter one-loop corrections**.
- Including one-loop effective potential V_1, and extremizing it along the ray $\Phi_{i\beta}$ leads to a deeper minimum where $V_0 + V_1 < 0$, picking out particular value v of ϕ (explicit symmetry breaking).
- Vacuum expectation values of Φ_1 and Φ_2 are $v_1 = v\cos\beta$, $v_2 = v\sin\beta$ so that $\tan\beta = v_2/v_1$.
- Using the one-loop effective potential one can find new mass matrices which result in new eigenvalues and eigenvectors. The lightest neutral Higgs is no longer massless!
- Mass of H:

$$M_H^2 = \frac{1}{8\pi^2 v^2}(6M_W^4 + 3M_Z^4 + M_{H'}^4 + M_A^4 + 2M_{H^{\pm}}^4 - 12M_t^4)$$

GW-2HDM model (continued)

- Can find sum rule by fixing $M_H = 125$ GeV. Results in $(M_{H'}^4 + M_A^4 + 2M_{H^\pm}^4)^{1/4} = 540$ GeV $\rightarrow$ Higgs masses highly constrained!



- Requiring $M_A = M_{H^\pm}$, Eichten and Lane [arXiv:2209.06632v2] find, at two loops,

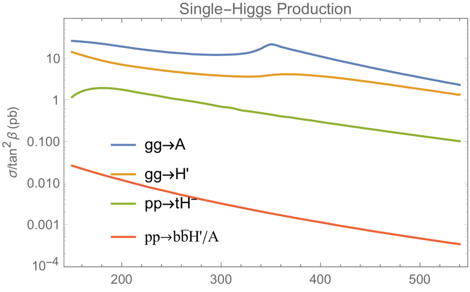
$$180 \text{ GeV} \leq M_{A,H^\pm} \leq 380\text{−}425 \text{ GeV and } 550\text{−}700 \text{ GeV} \geq M_{H_2} \geq 125 \text{ GeV}$$

GW-2HDM model decay modes

- For the mass-ranges in previous slide, the most important BSM decay modes are:

$$H^+ \to t\bar{b}$$
$$A \to b\bar{b}, \tau^+\tau^-, t\bar{t}$$
$$H_2 \to b\bar{b}, \tau^+\tau^-, t\bar{t}$$

- Consequence of alignment of H is that $H', A \to W^+W^-, ZZ, HZ$ and $H^\pm \to W^\pm Z, W^\pm H$ are highly suppressed.
- $H^+ \to t\bar{b}$ provides the tightest constraints on $\tan\beta$ for this model.

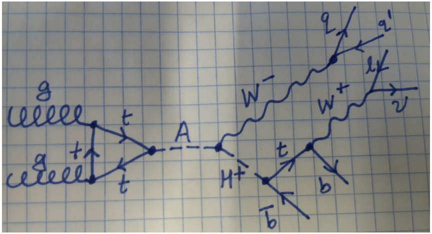


Some BSM Higgs searches

- There have been multiple searches in the mass range relevant to GW-2HDM model.
- $gg \to H^{\pm}\bar{t}b \to t\bar{t}b\bar{b}$: Searches done by ATLAS and CMS. Best limit set by 8 TeV search by CMS [JHEP 11 (2015) 018] - $\tan\beta \leq 0.5$ for $180 \text{ GeV} < M_{H^{\pm}} \leq 500 \text{ GeV}$. The searches at 13 TeV have not improved on this limit → large $t\bar{t}$ background at low masses.
- $gg \to t\bar{t} \to t\bar{t}A/H_2 \to 4t$: Searches done by ATLAS and CMS with full run2 dataset. Searches for resonant $t\bar{t}$ excess in the four-top quark data. Has weaker constraint on $\tan\beta$. Example: for ATLAS search [ATLAS-CONF-2022-008] $\tan\beta < 0.9$ for $m_{H_2} = 600$ GeV.

Neutral Higgs search in *bbWW* channel

- Eichten and Lane [arXiv:2209.06632v2] proposed a search for the heavier Higgs' using the process $gg \to H_2 \to W^{\pm}H^{\mp}$. (never done before)
- It has same final state $bbWW$ as $t\bar{t}$. But since this is a resonant production, the hope is to be able to use kinematic constraints to reduce the background.
- Most of the mass-range allowed in GW-2HDM model has not been excluded yet → chance to set limit on the mass-range!
- The ATLAS search in this channel is in early phase and is being carried out by OSU, UIUC, and Warwick.



Neutral Higgs search in bbWW channel

- The initial focus of the search is on 1-lepton channel and using Run 2 data.
- The analysis team is working on multiple things:
  - Regression of A and H^+ masses using multivariate approaches (BDT).
  - Kinematic fitting for signal and $t\bar{t}$. There are many mass constraints available- m_A, m_{H^+}, m_t, m_W.
- We are also thinking about data-driven estimation of $t\bar{t}$ background. There are some analyses that have done it, so it is natural to try one of their methods first [examples: JHEP10(2020)061, JHEP10(2019)125].

Concluding remarks

- One could argue that the most important measurement to make is Higgs self-coupling if we are to understand the nature of electroweak symmetry breaking.
- Since the production cross-section of di-Higgs is low, it is important to improve the sensitivity in multiple channels if we hope to observe di-Higgs at HL-LHC.
- One way to have new beyond the standard model particles while accomodating alignment of standard model like Higgs is via something like GW scheme.
- Heavier neutral Higgs decay in final state $bbWW$ could be used to either verify or falsify the GW-2HDM model.
- Searches in $bbWW$ final state are important, but also challenging due to large $t\bar{t}$ background.
- Many processes have $t\bar{t}$ as a background, so developing new techniques to either reduce the background (such as kinematic fit), or reduce the systematic uncertainties from top modeling is crucial.

BACKUP SLIDES

Likelihoods for $bbWW^*$ 1-lepton channel

- $t\bar{t}$ likelihood:

$$L_{t\bar{t}} = BW(m_{q_1q_2q_3}|m_t\Gamma_t) \cdot BW(m_{q_1q_2}|m_W\Gamma_W) \cdot BW(m_{q_4\ell\nu}|m_t\Gamma_t) \cdot BW(m_{\ell\nu}|m_W\Gamma_W)$$

$$\prod_{i=1}^{4} W_{jet}(E_i^{meas}|E_i) \cdot W_\ell(E_\ell^{meas}|E_\ell) \cdot W_{miss}(E_x^{miss}|p_x^\nu) \cdot W_{miss}(E_y^{miss}|p_y^\nu).$$

- di-Higgs likelihood

$$L_{HH} = BW(m_{q_1q_2}|m_H\Gamma_H) \cdot BW(m_{q_3q_4\ell\nu}|m_H\Gamma_H)$$

$$\prod_{i=1}^{4} W_{jet}(E_i^{meas}|E_i) \cdot W_\ell(E_\ell^{meas}|E_\ell) \cdot W_{miss}(E_x^{miss}|p_x^\nu) \cdot W_{miss}(E_y^{miss}|p_y^\nu),$$

- log of relativistic Breit-Wigner function:

$$\log BW(m_{bb}|M_H\Gamma_H) = -\log[(m_{bb}^2 - M_H^2)^2 + \Gamma_H^2 M_H^2]$$

Transfer functions in KLFitter

- General form given by a double Gaussian

$$W(\Delta E) = \frac{1}{\sqrt{2\pi}(p_2 + p_3 p_5)}[e^{-\frac{(\Delta E - p_1)^2}{2p_2^2}} + p_3\, e^{-\frac{(\Delta E - p_4)^2}{2p_5^2}}],$$

- $\Delta E = \frac{E_{truth} - E_{reco}}{E_{truth}}$, and the quantities p_i's are functions of E_{truth}.
- In case of light jets and b-jets, the p_i's are

$$p_1 = Parameter[0] + \frac{Parameter[1]}{E_{truth}}$$
$$p_2 = Parameter[2] + \frac{Parameter[3]}{\sqrt{E_{truth}}}$$
$$p_3 = Parameter[4] + \frac{Parameter[5]}{E_{truth}}$$
$$p_4 = Parameter[6] + \frac{Parameter[7]}{\sqrt{E_{truth}}}$$
$$p_5 = Parameter[8] + Parameter[9] \cdot E_{truth}$$

- Parameter's obtained from global fit to ΔE of a particle (separate fits for different types of particles and for different eta regions).