Higgs self-couplings: Di-Higgs $\rightarrow bb\ell\ell$

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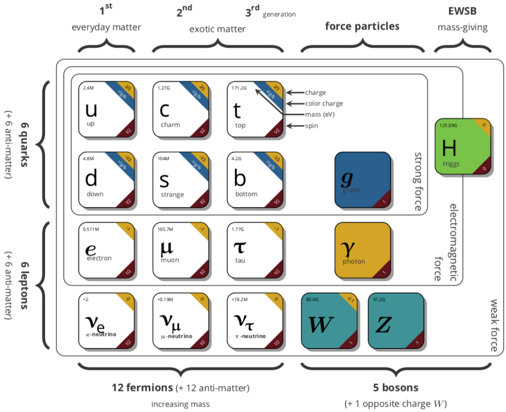
SM & Higgs

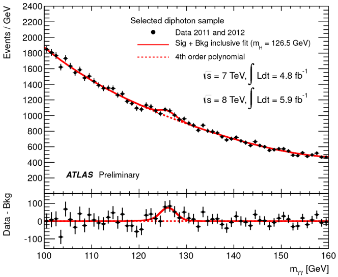


Higgs stands out for a few notable properties:

- Only fundamental scalar particle
- Only boson not mediating fundamental interactions
- No electric, color charge
- It gives mass to other fundamental particles

Higgs couplings

- Higgs mass measured with high precision: $m_H = 124.97 \pm 0.24$ GeV



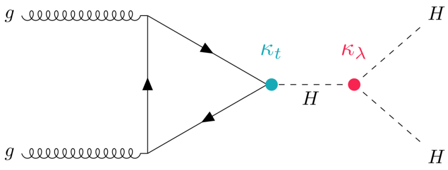
- $\rightarrow$ Higgs couplings measurements next hot topic in Higgs physics
  - Higgs couplings predicted by SM (EWSB)
  - Higgs trilinear and quadrilinear couplings: $\mathcal{L}_{Higgs} \ni -\frac{1}{2}M_H^2H^2 - \lambda_3 vH^3 - \frac{1}{4}\lambda_4 H^4$
    - ★ $\lambda_3 = \frac{M_H^2}{2v^2}$
    - ★ $v = \sqrt{\frac{|\mu^2|}{\lambda}} = (\sqrt{2}G_F)^{-\frac{1}{2}} \approx 246$ GeV [1]
  - Measuring λ_3:
    - ★ Need to find Di-Higgs events
    - ★ Never been done before
    - ★ Test of EWSM, a long tern goal of LHC
    - ★ Possible hints at BSM physics

[1] vev can be determined independently from Higgs physics, e.g. from muon lifetime

ggF production modes

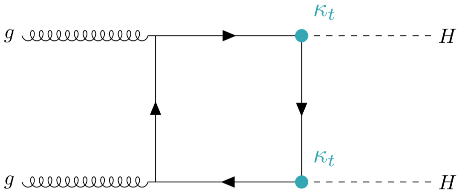
- Trilinear-diagram and box-diagram interfere destructively
- $\rightarrow$ small di-Higgs cross-section: σ_{ggF} =31.05 fb

Trilinear-diagram



- Sensitive to κ_τ, κ_λ $\rightarrow$ Higgs trilinear self-coupling

Box-diagram

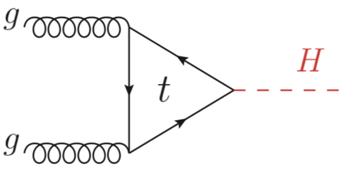


- Sensitive to κ_τ
- Causing negative interference

Production modes

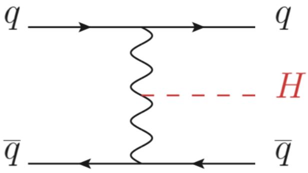
Let's consider 2nd largest production mode

gluon-gluon Fusion (ggF)



- Fraction of total cross-section: $(88.4 \pm 4)\%$
- This process happens mainly through a loop of heavy quarks
- Contribution from lighter virtual quarks are suppressed as $\frac{m_q^2}{m_t^2}$

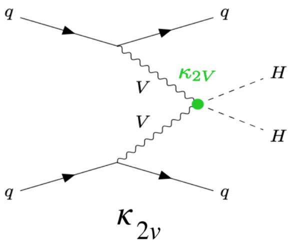
Vector Boson Fusion (VBF)



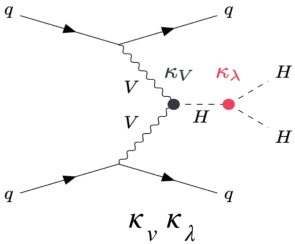
- Fraction of total cross-section: $(6.9 \pm 0.1)\%$
- Two W or Z bosons, radiated by quarks, fuse to create an Higgs boson

VBF production modes

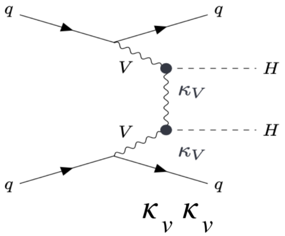
Different di-Higgs production modes are sensitive to different Higgs couplings



- Sensitive to $\kappa_{2\nu}/cvv$



- Sensitive to κ_ν/cv, κ_λ/l
- Only mode sensitive to trilinear Higgs coupling

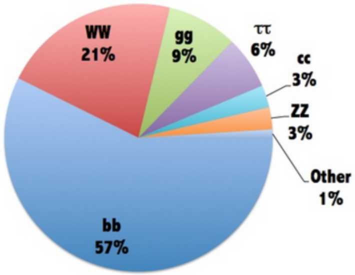


- Sensitive to κ_ν/cv

- Tagging jets: key to identify VBF

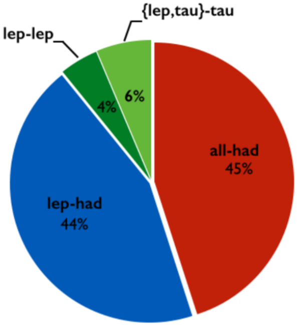
Decay channels

BRs of the SM Higgs boson



- $b\bar{b}$ most common decay channel for Higgs
- WW, ZZ and $\tau\tau$ sum up to 30%

BRs of a WW system

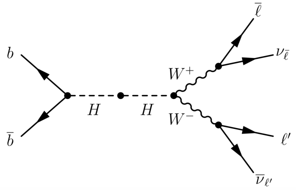


- Fully leptonic decay for WW system is rare
- By requiring that both W bosons decay leptonically, branching ratio decreases to around 1%
- Advantage: leptons easy to identify, better resolution

The HH $\rightarrow bb\ell\ell + E_T^{miss}$ channel

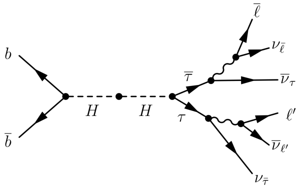
- Luckily, multiple HH decay channels contribute to $bb\ell\ell$ + MET final state (l = e, μ)
- Decay topologies of HH$\rightarrow bb\ell\ell$ decays:

bbWW



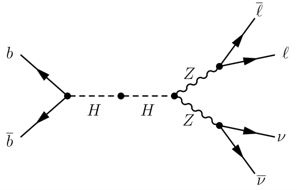
- BR = 1.62%
- W -pair has spin correlation
- small $m\ell\ell$ and $\Delta\phi\ell\ell$

bb$\tau\tau$



- BR = 0.91%
- light leptons are collinear to τ-lepton $\Rightarrow m_{\tau\tau}^{coll}$

bbZZ



- BR = 0.095%
- $m\ell\ell$ close to Z peak or small for offshell Z
- only same flavour leptons

Low cross-section but relatively clean signal

Background

- main background: $t\bar{t}$

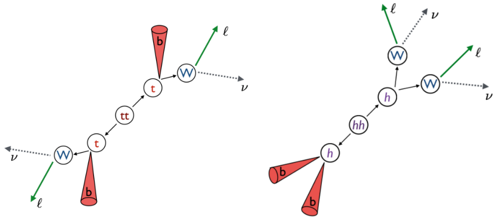


Figure: $t\bar{t}$ and diHiggs processes sharing the same $WWb\bar{b}$ final state

- single-top Wt

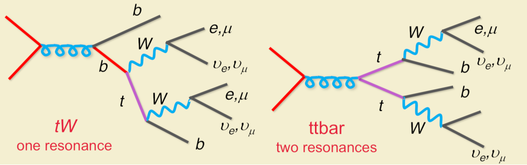
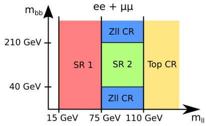


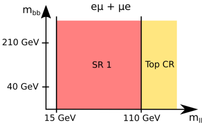
Figure: $t\bar{t}$ and diHiggs processes sharing the same $WWb\bar{b}$ final state

Analysis strategy

ggF

- preselection
  - single and dilepton triggers
  - exactly two light leptons of opposite charge ($p_T > 9$ GeV)
  - one or two b-tagged jets ($p_T > 20$ GeV , DL1r, 77%)
- split further into signal and control regions
- data in the CRs is used to constrain the MC cross-section, overall normalization of the MC is 'semi-data-driven'
- shape taken from MC in the SR

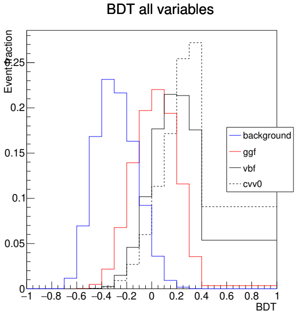




  - SR1: target $bbWW$, $bb\tau\tau$, and low $m_{\ell\ell}$ part of $bbZZ$
  - SR2: target high $m_{\ell\ell}$ part of bbZZ
  - Zll CR: also used in $bb\tau\tau$ analysis
- NN trained on MC samples

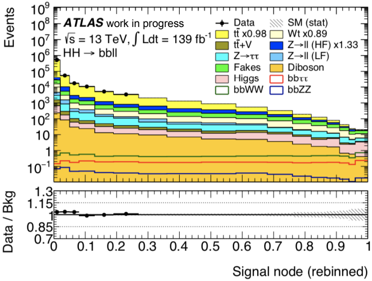
VBF

- first time implementation
- event selection applied on top of ggF selection
  - at least 2 extra non b-tagged jets with $p_T >$ 30 GeV
  - $\max(\Delta\eta_{jj}) > 4$ where $j =$ non b-tagged jet
  - $\max(m_{jj}) >$600 GeV
- BDT trained on MC samples



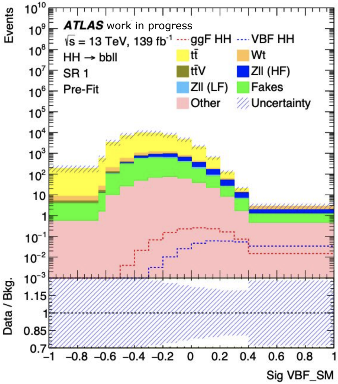
Distributions

ggF



- NN distributions

VBF



- BDT distributions

Preliminary results

First look at signal strenght $\mu = \sigma_{HH}/\sigma_{HH_{SM}}$, set 95% CLs limit on

- VBF: $\mu_{VBF}(HH)$ very competitive compared with other channels

channel	-2 σ	-1 σ	median	1 σ	2 σ
$bbbb$	287.3	385.8	535.4	745.1	998.9
$bb\gamma\gamma$	60.4	89.4	142.0	233.5	373.0
$bb\ell\ell$	50.1	69.8	101.9	150.8	216.8

- ggF + VBF: improvement compared to ggF only
  - if only ggF sample is used: $\mu_{ggF}(HH)$
  - if ggF and VBF sample is used: $\mu_{ggF+VBF}(HH)$

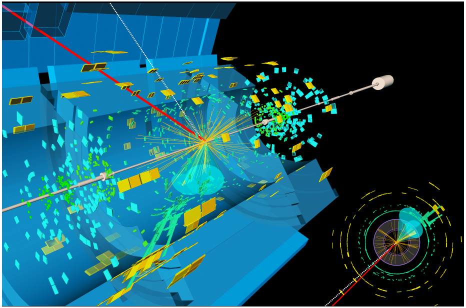
samples	signal regions	-2 σ	-1 σ	median	1 σ	2 σ
ggF	SR1 ggF	4.0	5.38	7.46	10.54	14.48
ggF + VBF	SR1 ggF	3.98	5.34	7.41	10.47	14.38
ggF + VBF	SR1 ggF + SR1VBF	3.92	5.26	7.31	10.31	14.16

- Current combined limit on other di-Higgs channels $\sim 3 \rightarrow$ we can get even closer to 1 when including $bb\ell\ell$ channel

Conclusions

Take-home message:

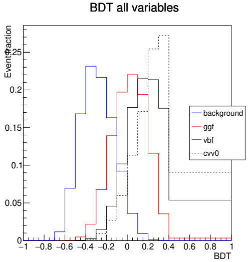
- VBF $bb\ell\ell$ channel is competitive for Di-Higgs searches
- VBF can improve Di-Higgs results once included in ggF analysis, combinations
- Precision measurements in the pre-Hi-Lumi era are already possible!



Outline

BDT

BDT trained on SM VBF vs ggF + background



	Limit			
BDT training sample	SM	cvv0	kl0	kl10
SM	101.917	125 %	105 %	152 %
cvv0	129%	1.74602	110 %	123 %
kl0	110 %	112 %	51.9474	122 %
kl10	155 %	101 %	113 %	3.30675