



# One Higgs is not enough. Studies of the Higgs potential with the ATLAS experiment at the LHC

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# Introduction

- In the 1950s theory of electroweak interactions was largely complete, based on quantum field theory description and local gauge invariance
- Only “a few” puzzles left to solve:
- At high energies, the weak and electromagnetic forces merge into a single electroweak force. Yet at low energies, electromagnetic waves (such as light) can travel an infinite distance, while weak interactions have a finite range.
- This means electroweak bosons should be massive.
- No theory how to give masses to bosons.
- How to break electroweak symmetry?

# Solution: add a new field!

- Complex scalar field – four degrees of freedom

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}$$

- Corresponding terms in the Lagrangian

$$\mathcal{L}_{\text{Higgs}} = \underbrace{|\mathcal{D}_\mu \Phi|^2}_{\text{Higgs kinetic term}} - \underbrace{V(\Phi)}_{\text{Higgs potential leading to electroweak symmetry breaking}} + \underbrace{\mathcal{L}_{\text{Yukawa}}}_{\text{Interactions between Higgs and fermions}}$$

Higgs kinetic term  
Responsible for masses  
of electroweak bosons

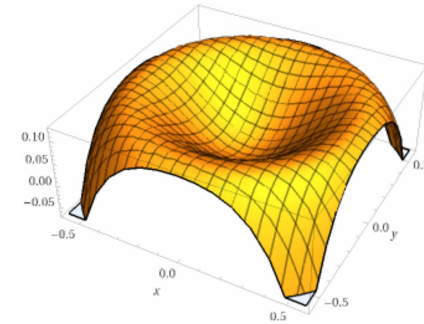
Higgs potential leading to  
electroweak symmetry breaking

Interactions between Higgs  
and fermions

# Solution: the Higgs potential

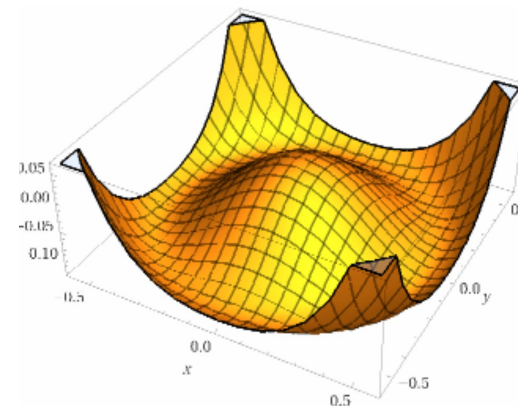
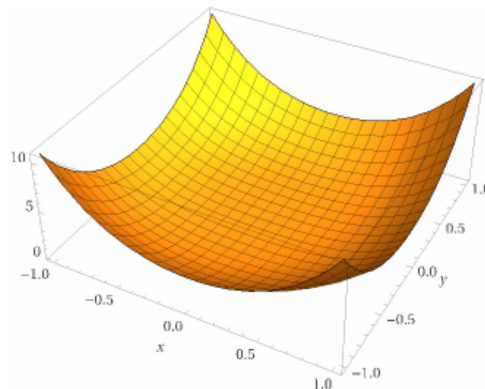
$$V(|\phi|^2) = \mu^2|\phi|^2 + \lambda|\phi|^4$$

- $\lambda < 0$ : potential unbounded from below,
- no stable vacuum

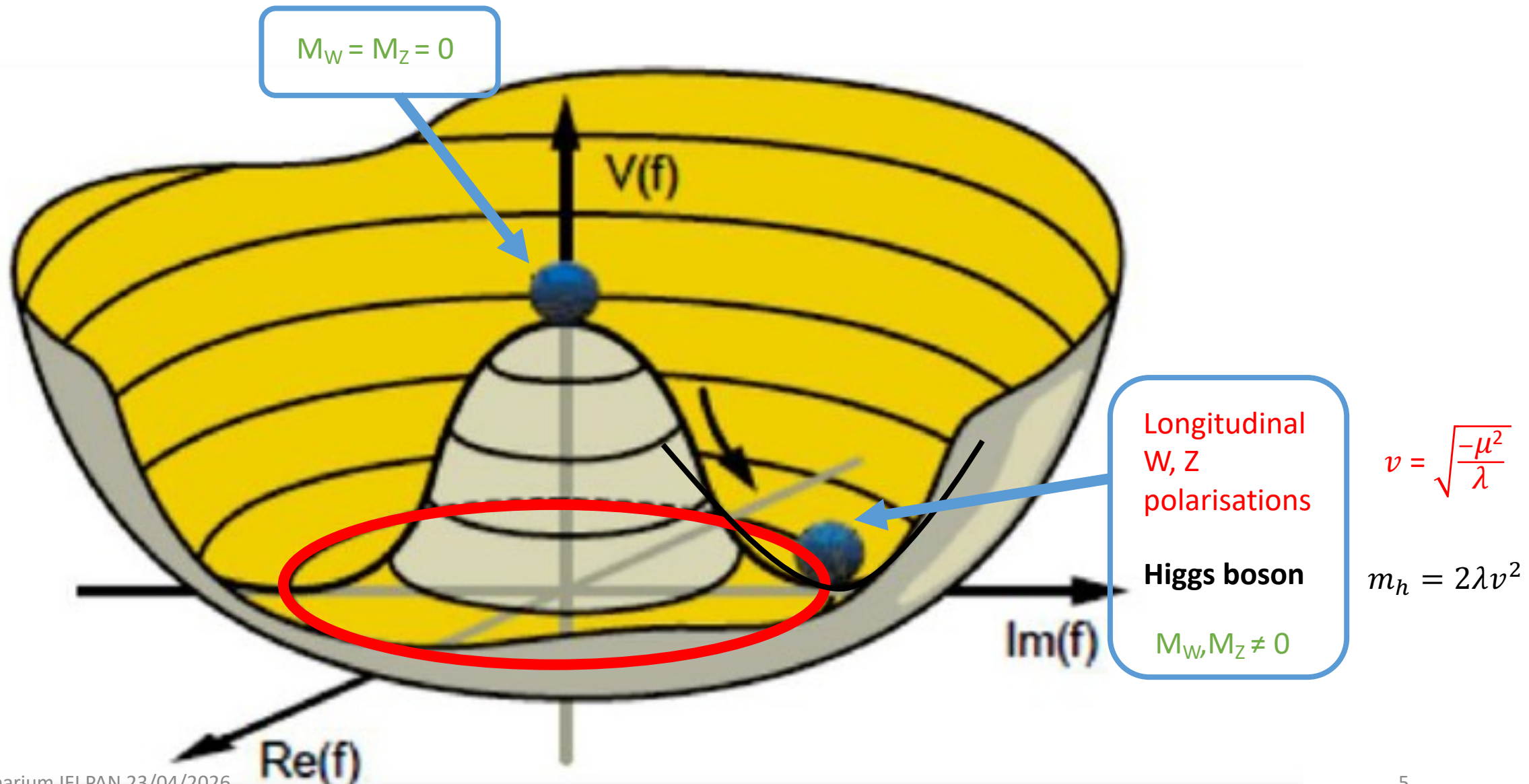


- $\lambda > 0$ : potential depends on the sign of  $\mu^2$ :

- $\mu^2 > 0$                        $\mu^2 < 0$



# Electroweak symmetry breaking



# The Higgs boson

- Discovered by ATLAS and CMS experiments at the LHC, 2012
- Resulted in a Nobel Prize in Physics 2013 for Peter Higgs and François Englert



© Nobel Media AB. Photo: A. Mahmoud  
François Englert  
Prize share: 1/2



© Nobel Media AB. Photo: A. Mahmoud  
Peter W. Higgs  
Prize share: 1/2

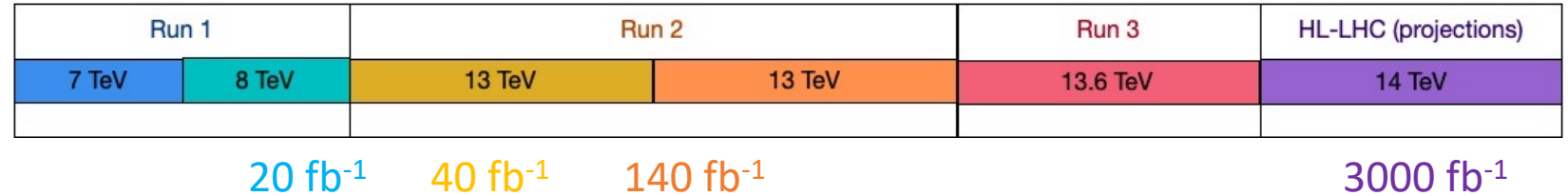
- Higgs mass measured at the LHC  $\rightarrow m_h = 125.09 \text{ GeV}$
- Higgs vacuum expectation value determined indirectly from electroweak observables  $\rightarrow v = 246,22 \text{ GeV}$
- Can we measure parameters of the Higgs potential independently?

# This talk is based on:

- My habilitation monograph
- ATLAS publications:

Magdalena Sławińska, “New Physics searches via the Higgs boson couplings to di-bosons”, 2025, DOI: <https://doi.org/10.48733/978-83-63542-45-0>

Using data from  
CM energy  
Int. luminosity



ATLAS Collaboration, M. Slawinska et al., *Searches for Higgs boson pair production in the  $hh \rightarrow bb\tau\tau, \gamma\gamma WW^*, \gamma\gamma bb, bbbb$  channels with the ATLAS detector*, *Phys. Rev.* **D92** (2015) 092004, [[arXiv:1509.04670](https://arxiv.org/abs/1509.04670)].

ATLAS Collaboration, M. Slawinska et al., *Measurements of gluon fusion and vector-boson fusion Higgs boson production cross-sections in the  $H \rightarrow WW^* \rightarrow e\nu\mu\nu$  decay channel in  $pp$  collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector*, *Phys. Lett.* **B 789** (2019) 508, [[arXiv: 1808.09054](https://arxiv.org/abs/1808.09054)]

ATLAS Collaboration, M. Slawinska et al., *Combination of searches for Higgs boson pairs in  $pp$  collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector*, *Phys.Lett.* **B 800** (2020) 135103, [[arXiv: 1906.02025](https://arxiv.org/abs/1906.02025)]

ATLAS Collaboration, M. Slawinska et al., *Constraints on Higgs boson properties using  $WW^*(\rightarrow e\nu\mu\nu)jj$  production in  $36.1$  fb<sup>-1</sup> at  $\sqrt{s} = 13$  TeV  $pp$  collisions with the ATLAS detector*, *The European Physical Journal C* **82** (2022), no. 7 622, [[arXiv:2109.13808](https://arxiv.org/abs/2109.13808)]

ATLAS Collaboration, M. Slawinska et al., *Measurements of the production cross-sections of a Higgs boson in association with a vector boson and decaying into  $WW^*$  with the ATLAS detector at  $\sqrt{s} = 13$  TeV*, *JHEP* 08 (2025) 034

ATLAS Collaboration, M. Slawinska et al., *Prospects for measuring Higgs pair production in the channel  $H(\rightarrow \gamma\gamma)H(\rightarrow b\bar{b})$  using the ATLAS detector at the HL-LHC*, ATL-PHYS-PUB-2014-019, CERN, Geneva, Oct, 2014.

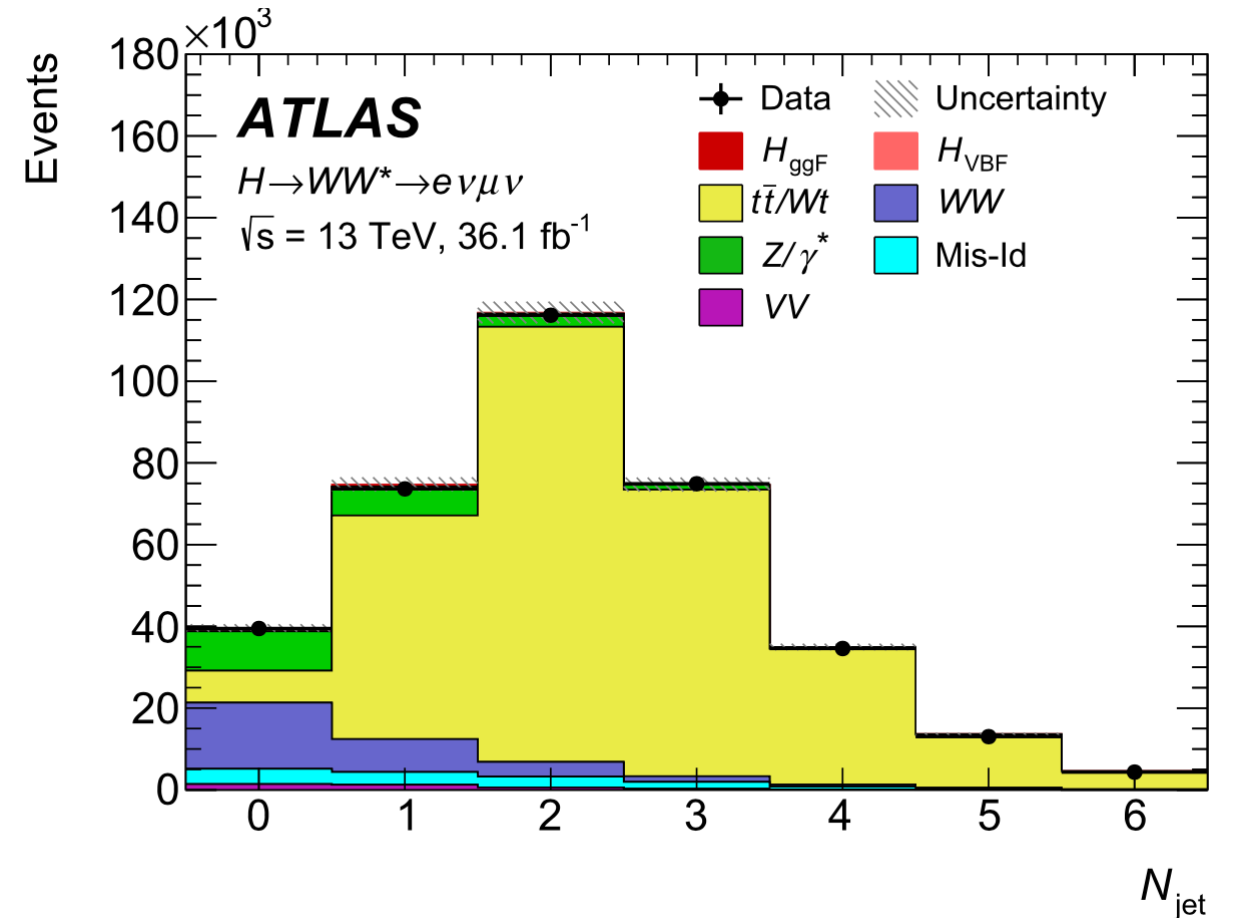
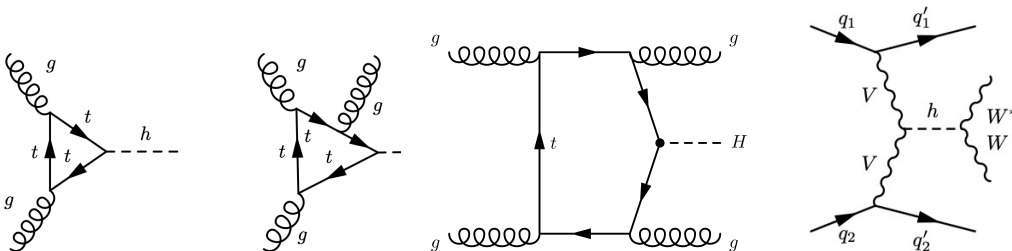
$h \rightarrow WW$

Higgs interactions with bosons depend on Higgs vacuum expectation value  $v$

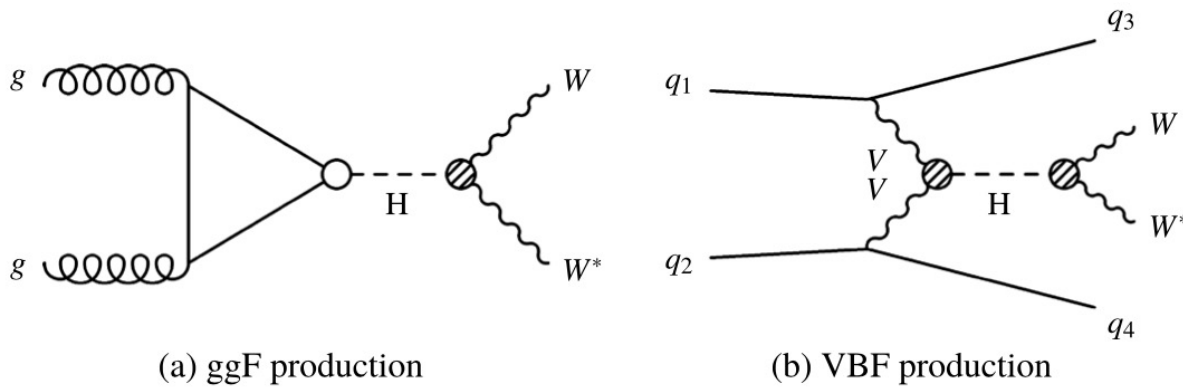
# Measurements of gluon fusion and vector-boson fusion Higgs boson production cross-sections

Events are classified into one of three processes based on the number of jets:

- gluon fusion Higgs production (ggf)
- gluon fusion with additional jet (ggf+1j)
- gluon fusion with two jets (ggf+2j)
- vector boson fusion Higgs production (VBF) – 2 jets



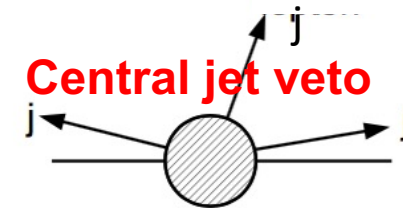
# QCD versus electroweak Higgs production



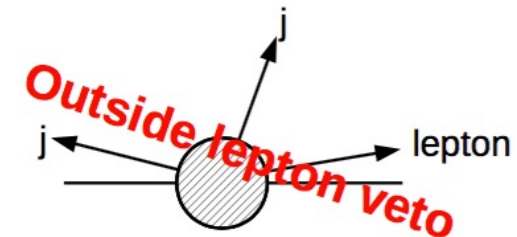
VBF: In the leading order no color flow between the forward jets

ggf: Beyond LO, ggf+1j, ggf+2j with jets emitted also in the central region

- VBF features energetic in a forward region in the detector but in opposite directions
  - large rapidity separation  $\Delta\eta_{jj}$
  - large invariant di-jet mass  $m_{jj}$
- little hadronic activity in the rapidity region between them – central jet veto (CJV)



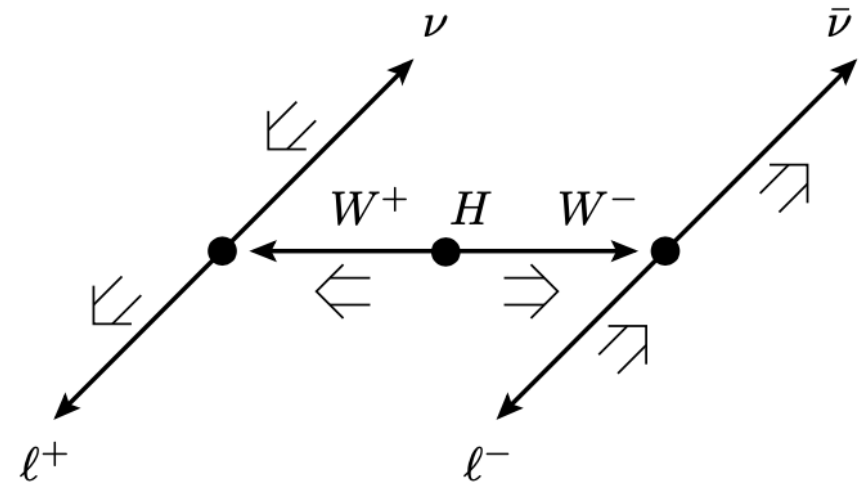
- leptons have intermediate rapidities – outside lepton veto (OLV)



# Kinematical properties of the $h \rightarrow WW^* \rightarrow e\nu \mu\nu$ final state

- The Higgs boson mass cannot be reconstructed due to undetectable neutrinos
- We reconstruct transverse mass instead, using energy and momentum of the lepton pair as well as momentum imbalance in the plane transverse to the beam axis

$$m_T = \sqrt{(E_T^{\ell\ell} + E_T^{\text{miss}})^2 - |\mathbf{p}_T^{\ell\ell} + \mathbf{E}_T^{\text{miss}}|^2}$$

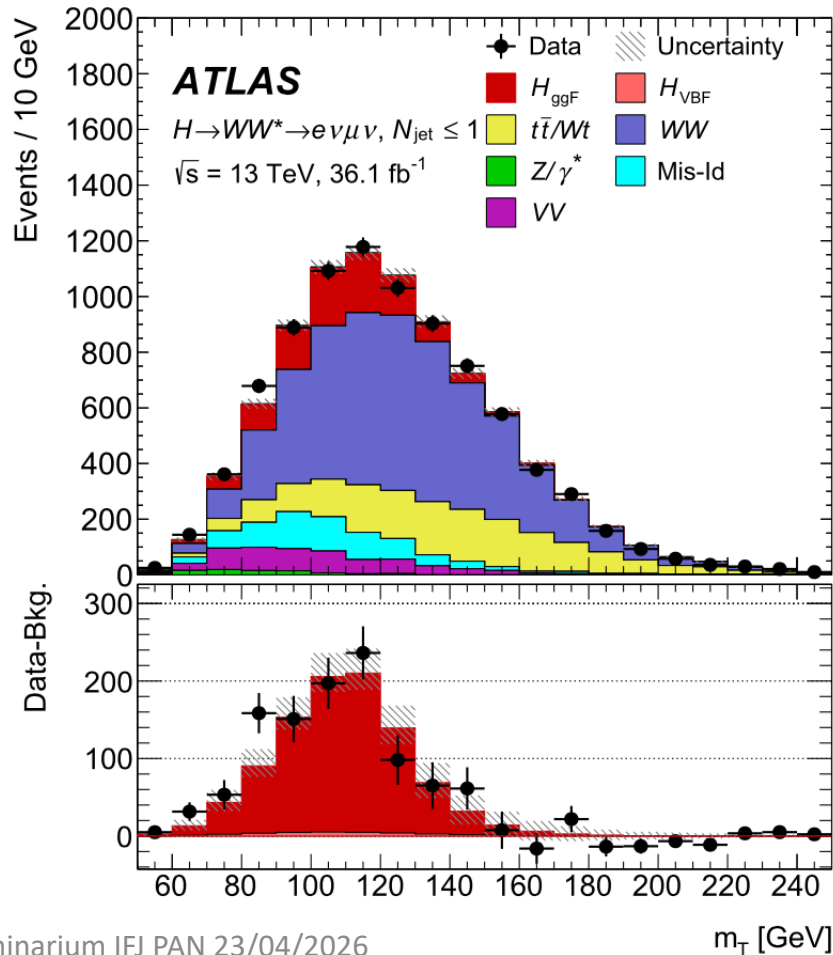


- Spin correlations between leptons and neutrinos due to massless neutrinos and spin-0 Higgs boson

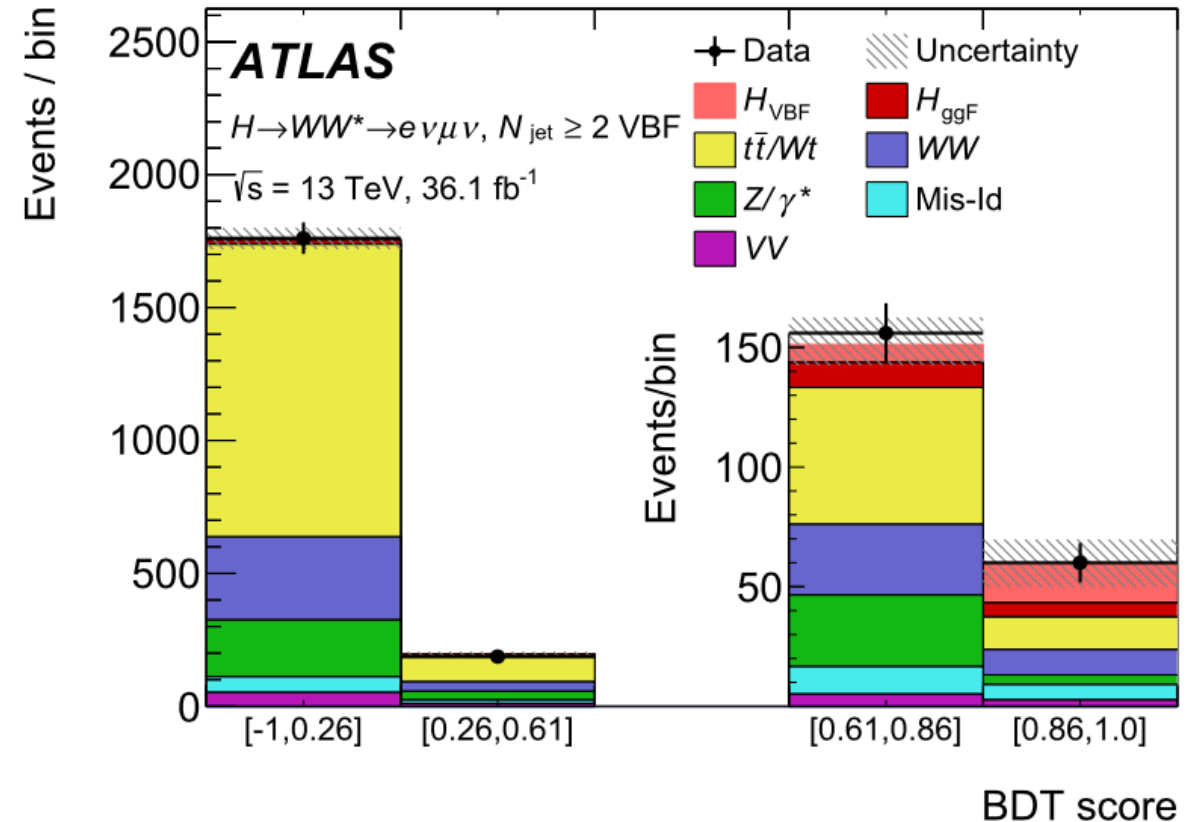
# $m_T$ distribution in ggf and ggf+1j

# Machine Learning techniques adopted in VBF

Events with up to 1 jet combined in one signal region



Signal regions grouped in 4 BDT bins  
ranked by sensitivity to signal



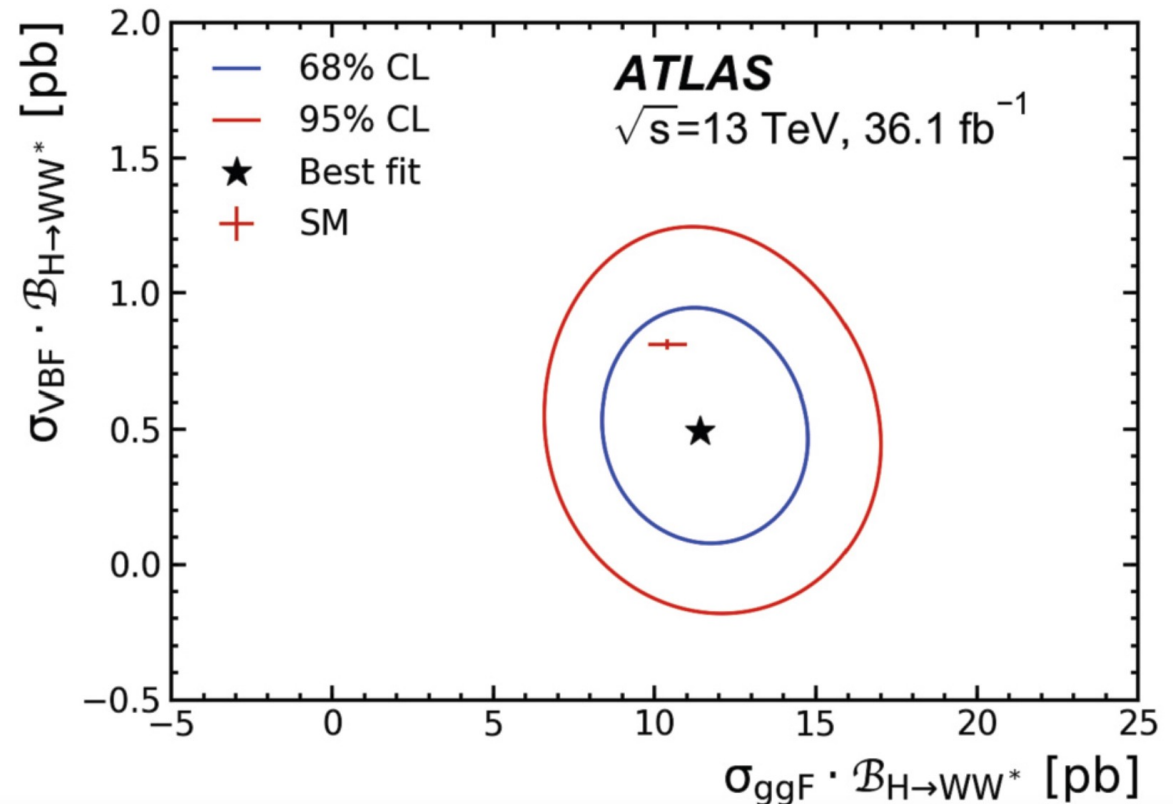
# Cross-sections measurements

- Measured cross-section times branching fractions are:

$$\begin{aligned}\sigma_{\text{ggF}} \cdot \mathcal{B}_{H \rightarrow WW^*} \\ &= 11.4_{-1.1}^{+1.2}(\text{stat.})_{-1.1}^{+1.2}(\text{theo syst.})_{-1.3}^{+1.4}(\text{exp syst.}) \text{ pb} \\ &= 11.4_{-2.1}^{+2.2} \text{ pb}\end{aligned}$$

$$\begin{aligned}\sigma_{\text{VBF}} \cdot \mathcal{B}_{H \rightarrow WW^*} \\ &= 0.50_{-0.22}^{+0.24}(\text{stat.}) \pm 0.10(\text{theo syst.})_{-0.13}^{+0.12}(\text{exp syst.}) \text{ pb} \\ &= 0.50_{-0.28}^{+0.29} \text{ pb}.\end{aligned}$$

- Measured values are consistent with SM predictions.



# What else could we learn from HWW interactions?

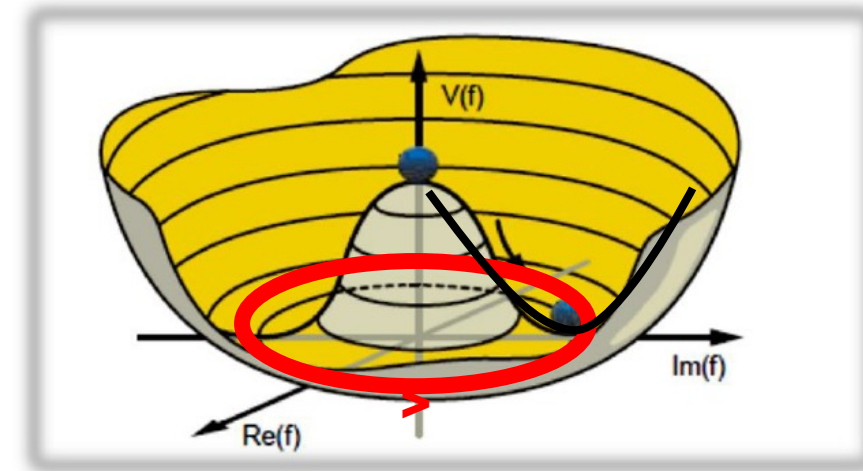
Higgs boson properties are (being) characterized.

Can we measure other degrees of freedom of the Higgs field?

At infinitely large momenta the transversely polarized parts of electroweak bosons correspond to the “proper” gauge bosons. Their longitudinally polarised parts arise from the “eaten” degrees of freedom of the Higgs field.

In the SM there is no distinction between coupling strengths of  $HV_L V_L$  and  $HV_T V_T$  interactions.

Unitarity bounds on  $HW_L W_L$  coupling, no unitarity constraints on  $HW_T W_T$  coupling.



- HVV couplings are sensitive to new physics, they can hint at
  - extended Higgs sectors,
  - Higgs as a composite pseudo-Goldstone boson (SILH, MCHM), ...
- Differences in  $HV_L V_L$  and  $HV_T V_T$  couplings could be a hint of W/Z compositeness

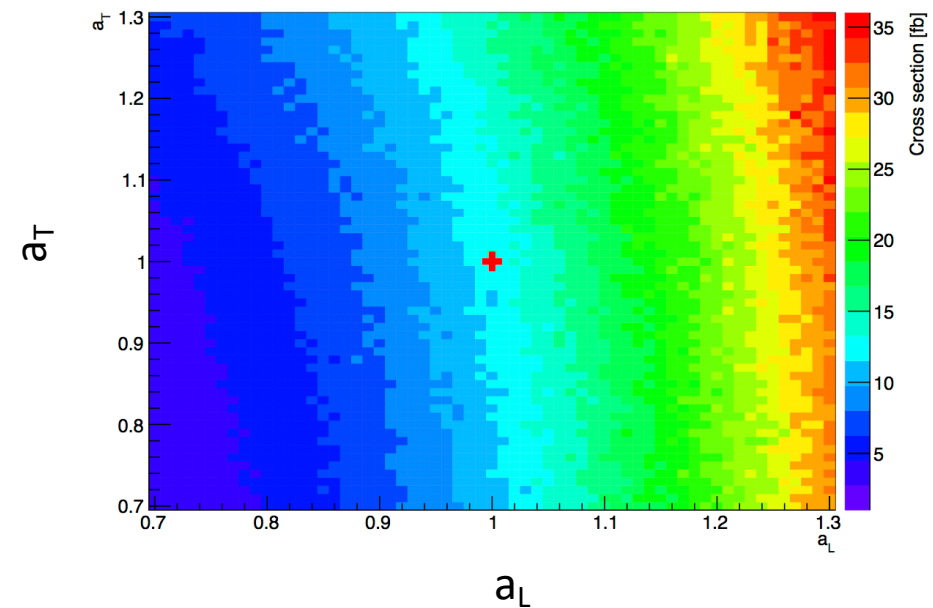
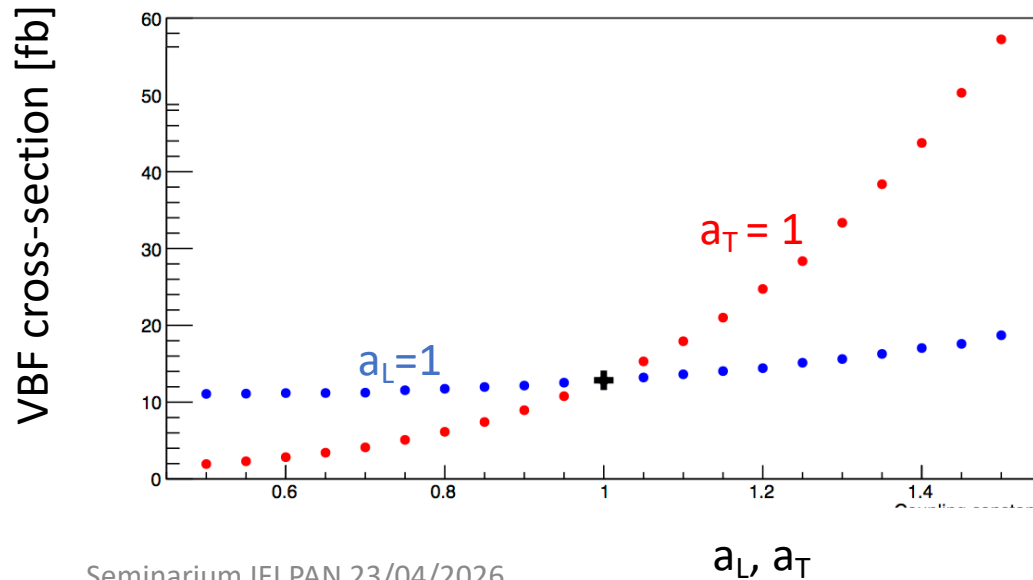
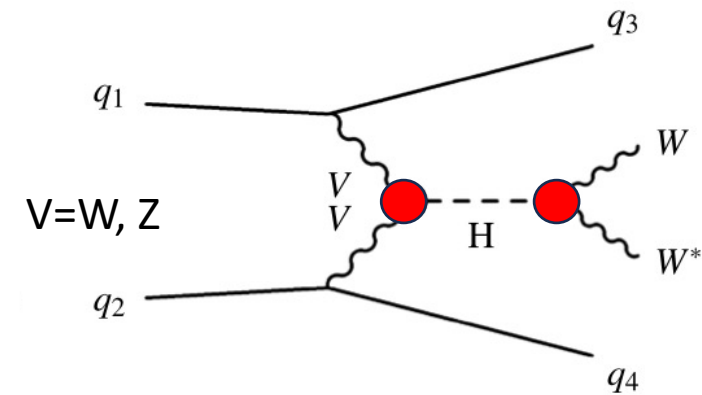
# Let us parametrise

$$a_L = g_{HVLVL}/g_{HVV} \quad \text{and} \quad a_T = g_{HVTVT}/g_{HVV}$$

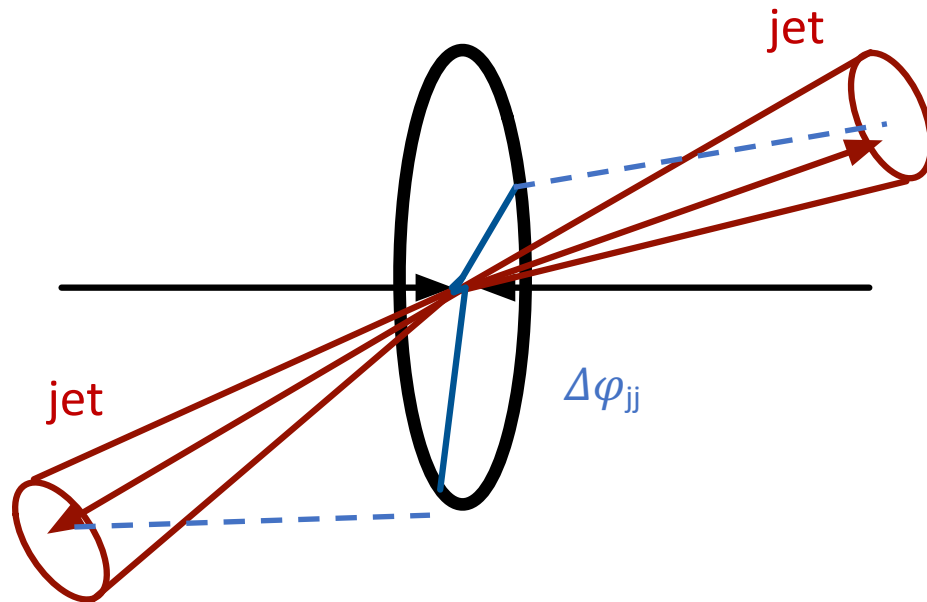
Where all the above couplings are defined in the Higgs rest frame so that only  $HV_LV_L$  and  $HV_TV_T$  are present. In the SM  $a_L = a_T = 1$ .

Let us simulate signals, in which these parameters can be varied independently.

We DO assume custodial symmetry.



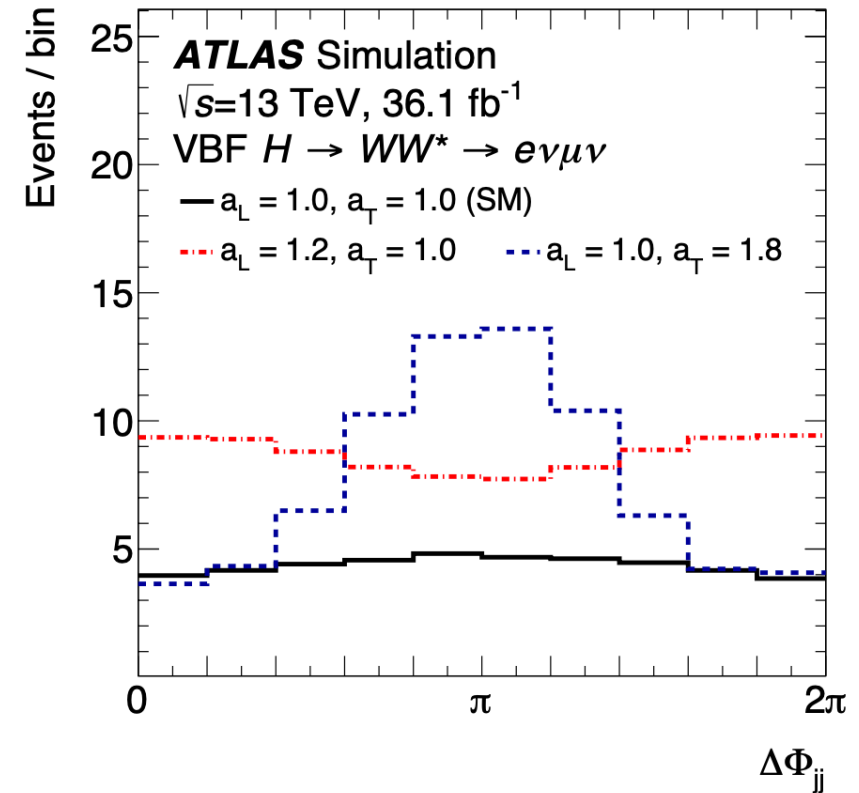
# Kinematical effects of coupling modifications



Distribution of signed  $\Delta\phi_{jj}$   
sensitive to coupling modifications

$$\Delta\phi_{jj} = \phi_{j1} - \phi_{j2} \text{ if } \eta_{j1} > \eta_{j2}, \text{ and } \phi_{jj} = \phi_{j2} - \phi_{j1} \text{ otherwise}$$

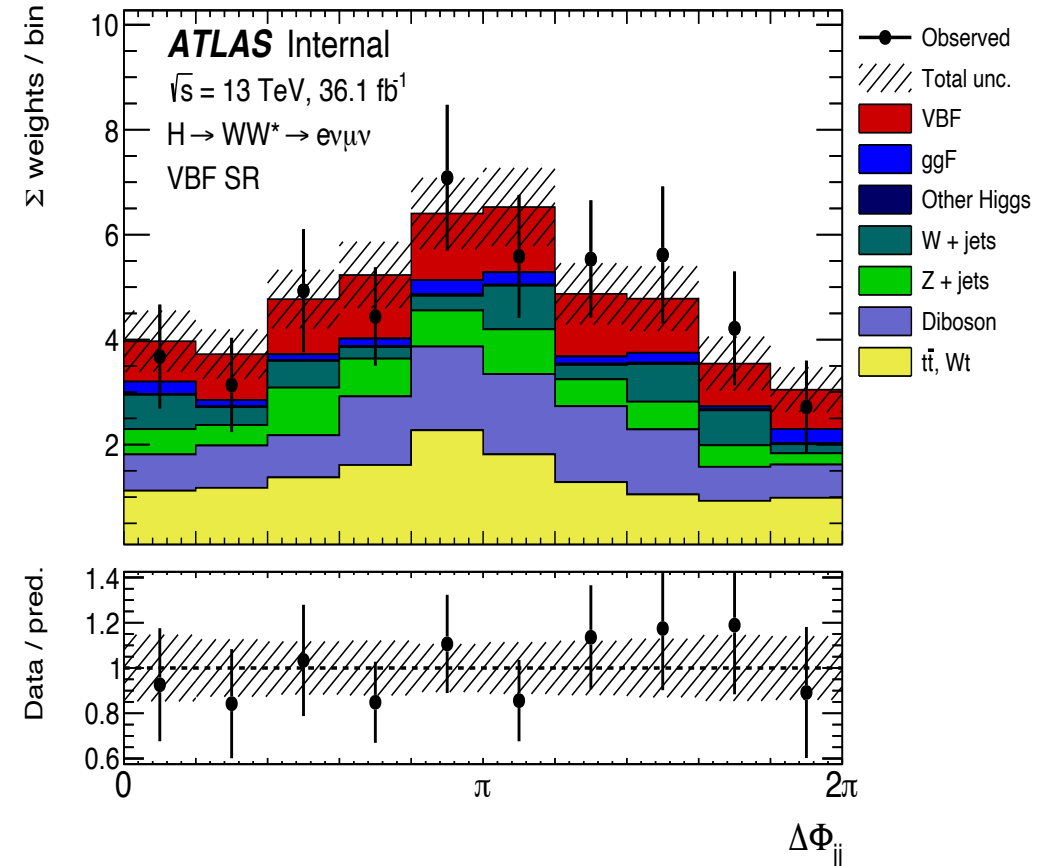
- Total rates  $\sigma_{\text{VBF}} \times \text{Br}(h \rightarrow WW)$  sensitive to  $a_L$  because VBF is dominated by longitudinal W scattering at high energies.
- Signed  $\Delta\phi_{jj}$  is sensitive to  $(a_L - a_T)$ .



# Results

Type	Expected	Observed
$a_T$ shape-only fit ( $a_L = 1$ )	$1.0 \pm 0.5(\text{stat.})^{+0.3}_{-0.4}(\text{syst.})$	$1.3^{+0.8}_{-0.4}(\text{stat.})^{+0.3}_{-0.2}(\text{syst.})$
$a_L$ shape + rate fit ( $a_T = 1$ )	$1.00^{+0.08}_{-0.10}(\text{stat.})^{+0.07}_{-0.13}(\text{syst.})$	$0.90^{+0.09}_{-0.13}(\text{stat.})^{+0.08}_{-0.18}(\text{syst.})$
$a_T$ shape + rate fit ( $a_L = 1$ )	$1.00^{+0.36}_{-0.49}(\text{stat.})^{+0.19}_{-0.27}(\text{syst.})$	$1.19^{+0.27}_{-0.32}(\text{stat.})^{+0.12}_{-0.14}(\text{syst.})$
$a_L$ shape + rate fit ( $a_T$ profiled)	$1.00^{+0.08}_{-0.10}(\text{stat.})^{+0.08}_{-0.13}(\text{syst.})$	$0.91^{+0.10}_{-0.18}(\text{stat.})^{+0.09}_{-0.17}(\text{syst.})$
$a_T$ shape + rate fit ( $a_L$ profiled)	$1.0^{+0.4}_{-0.5}(\text{stat.})^{+0.2}_{-0.4}(\text{syst.})$	$1.2 \pm 0.4(\text{stat.})^{+0.2}_{-0.3}(\text{syst.})$

Measured values of  $a_L$ ,  $a_T$  are consistent with SM

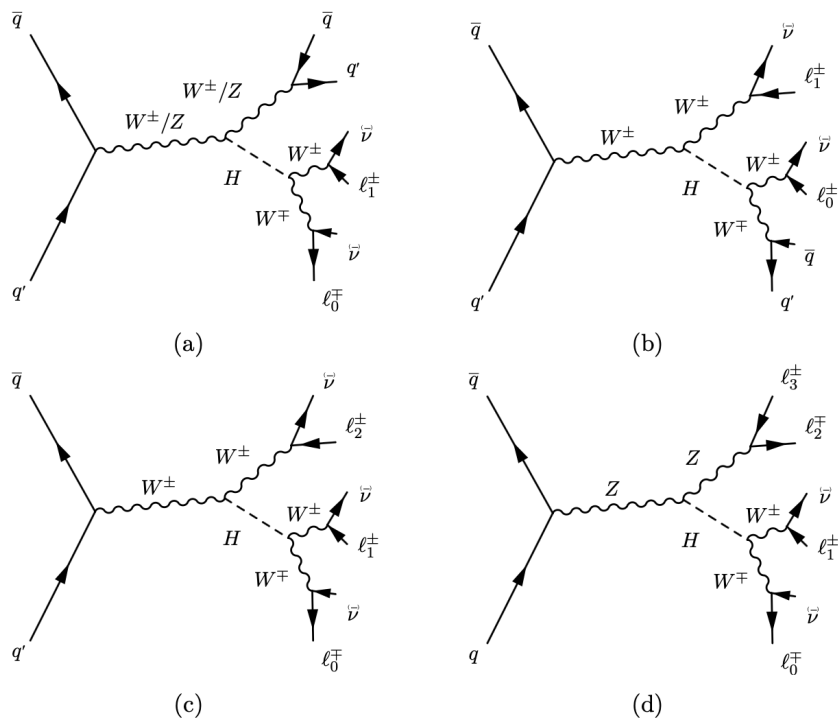


The weighted  $\Delta\Phi_{jj}$  distribution in the signal region, with signal and background yields fixed from the fits.

# Higgs boson production in association with a vector boson and decaying into WW\*

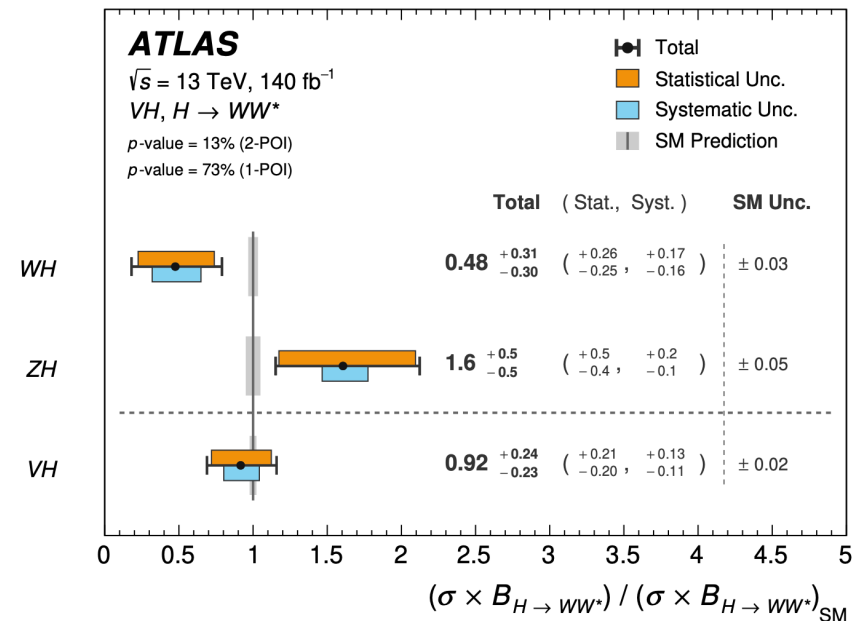
## Signal categories

the opposite-sign 2l channel      the same-sign 2l channel



the 3l channel

the 4l channel

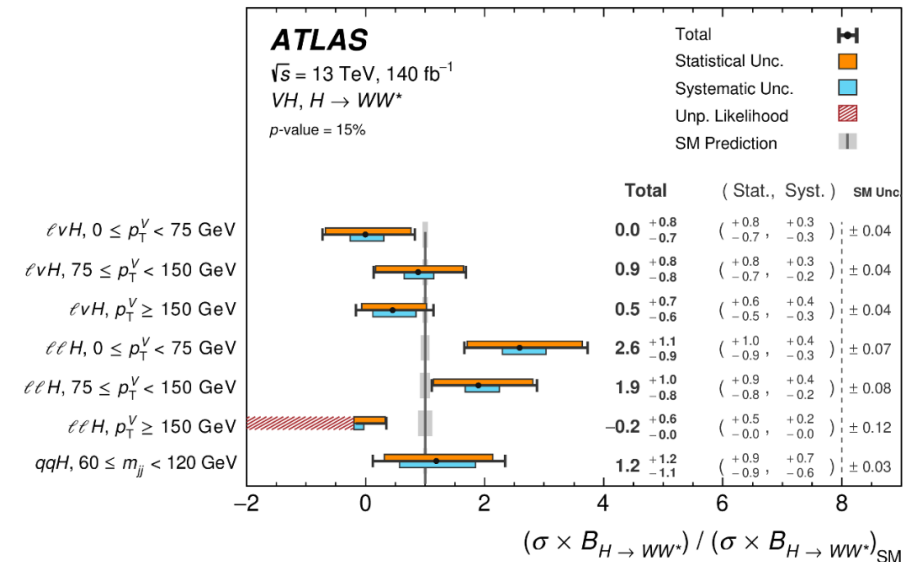


- WH cross-section smaller than expected due to deficit of events in signal regions of 3l and SS2l categories.
- ZH cross-section larger than predicted by the SM due to excess of events in 4l category

# Differential measurement using Simplified Template Cross-Sections

Differential measurement wrt boson transverse momentum

Channel	$p_T^V$ proxy	Reconstructed SR	Relevant $p_T^V$ range
Opposite-sign $2\ell$	Dijet transverse momentum, $p_T^{jj}$	$0 \leq p_T^{jj} < 160$ GeV $160 \leq p_T^{jj} < 260$ GeV $p_T^{jj} \geq 260$ GeV	$0 \leq p_T^V < 150$ GeV $150 \leq p_T^V < 250$ GeV $p_T^V \geq 250$ GeV
Same-sign $2\ell$	Scalar sum of lepton, jet, and missing transverse momenta, $\sum  p_T $	$0 \leq \sum  p_T  < 200$ GeV $200 \leq \sum  p_T  < 320$ GeV $320 \leq \sum  p_T  < 460$ GeV $\sum  p_T  \geq 460$ GeV	$0 \leq p_T^V < 75$ GeV $75 \leq p_T^V < 150$ GeV $150 \leq p_T^V < 250$ GeV $p_T^V \geq 250$ GeV
$3\ell$ Z-dominated	Regression ANN for $W$ transverse momentum, $p_T^R$	$0 \leq p_T^R < 90$ GeV $90 \leq p_T^R < 180$ GeV $p_T^R \geq 180$ GeV	$0 \leq p_T^V < 75$ GeV $75 \leq p_T^V < 150$ GeV $p_T^V \geq 150$ GeV
$3\ell$ Z-depleted	Regression ANN for $W$ transverse momentum, $p_T^R$	$0 \leq p_T^R < 90$ GeV $90 \leq p_T^R < 180$ GeV $180 \leq p_T^R < 270$ GeV $p_T^R \geq 270$ GeV	$0 \leq p_T^V < 75$ GeV $75 \leq p_T^V < 150$ GeV $150 \leq p_T^V < 250$ GeV $p_T^V \geq 250$ GeV
$4\ell$	Z boson transverse momentum, $p_T^Z$	$0 \leq p_T^Z < 75$ GeV $75 \leq p_T^Z < 150$ GeV $150 \leq p_T^Z < 250$ GeV $p_T^Z \geq 250$ GeV	$0 \leq p_T^V < 75$ GeV $75 \leq p_T^V < 150$ GeV $150 \leq p_T^V < 250$ GeV $p_T^V \geq 250$ GeV



First STXS measurement in HV production channels. Uncertainties dominated by statistical uncertainties.

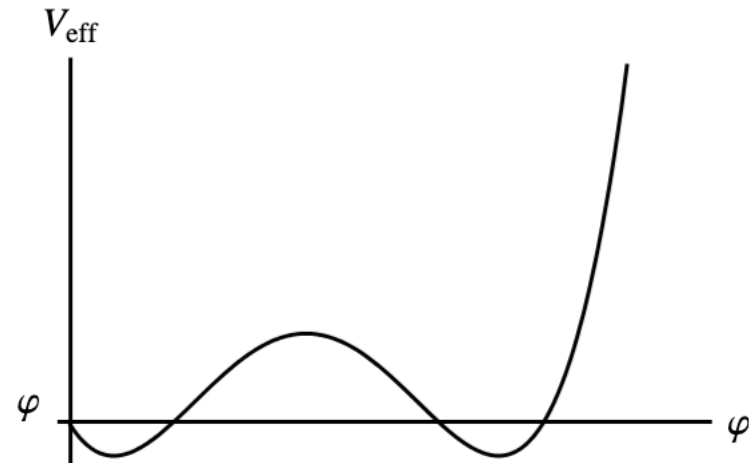
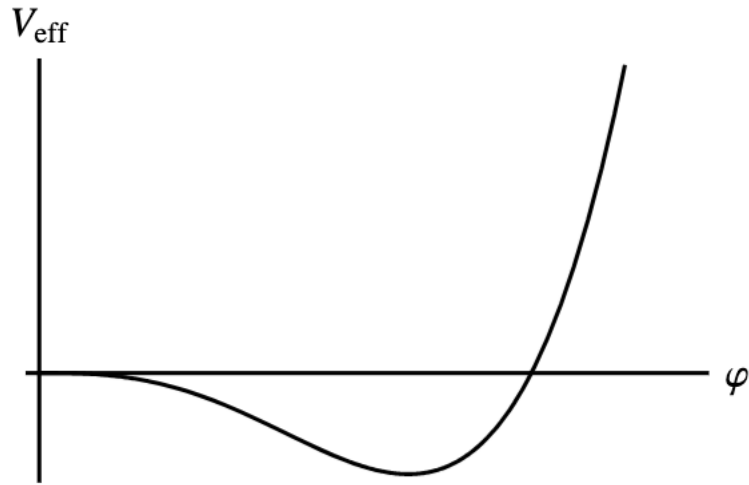
All measurements so far confirm the SM nature of the Higgs boson.

Can we measure the global shape of the Higgs potential?



picture from 1511.06495

The shape of the Higgs potential determines the dynamics of electroweak symmetry breaking

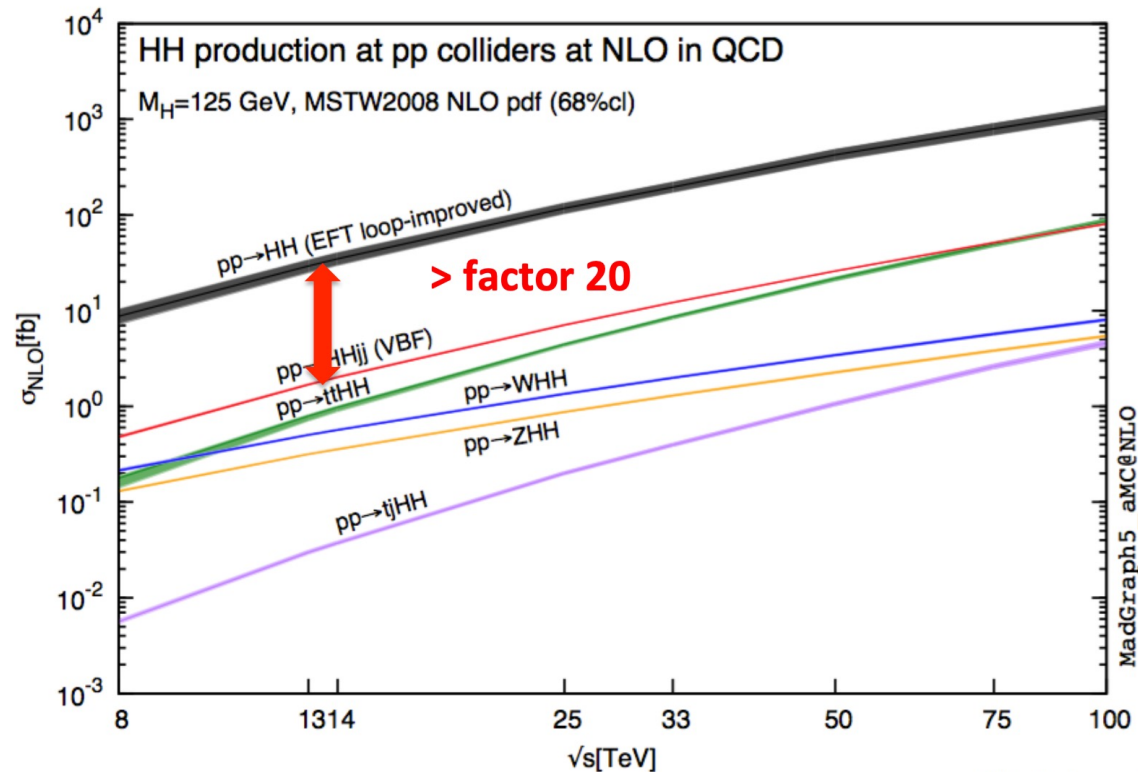


$h \rightarrow hh$

Due to electroweak symmetry breaking, Higgs boson acquires not only quartic, but also triple self interactions. Their strength is parametrised by  $\lambda$ .

# Higgs pair production at proton-proton colliders

Double Higgs production at the LHC energies has a cross-section  $\sim 1\text{-}10$  fb.  
This is  $\sim 1000$  times smaller than single Higgs production!  
We consider the largest production mechanism for Higgs pairs...



gluon fusion

vector boson fusion

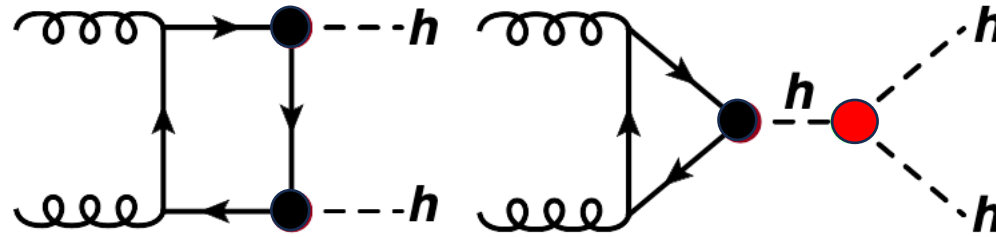
associated with top quark pairs

associated with W and Z bosons

associated with a single top quark

[Frederix et al ` 14]

# Higgs pairs production through gluon fusion

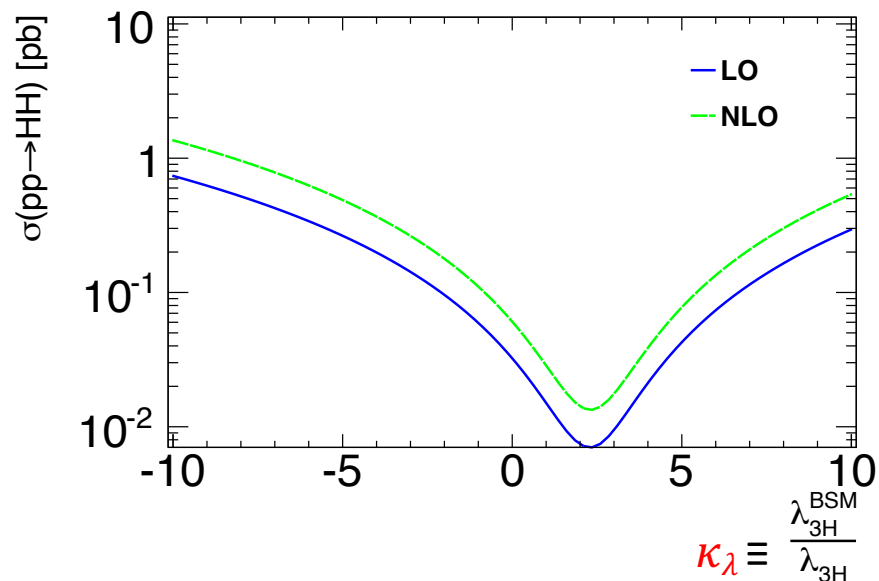
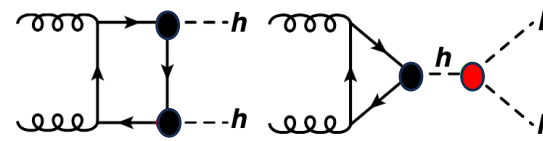


$$\kappa_\lambda = \lambda_{3h}^{\text{measured}} / \lambda_{3h}$$

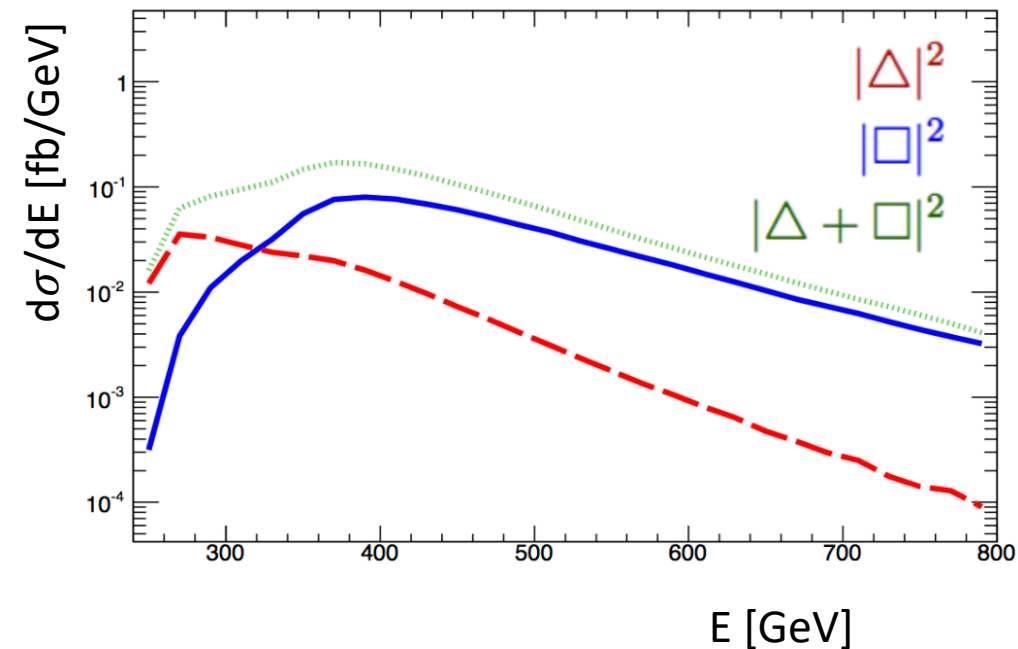
$m_h = 125 \text{ GeV}$	$\sigma'_{\text{NNLL}}(fb)$	Scale Unc. (%)	PDF Unc. (%)	$\alpha_s$ Unc. (%)
$\sqrt{s} = 7 \text{ TeV}$	7.078	+4.0 – 5.7	$\pm 3.4$	$\pm 2.8$
$\sqrt{s} = 8 \text{ TeV}$	10.16	+4.1 – 5.7	$\pm 3.1$	$\pm 2.6$
$\sqrt{s} = 13 \text{ TeV}$	33.53	+4.3 – 6.0	$\pm 2.1$	$\pm 2.3$
$\sqrt{s} = 14 \text{ TeV}$	39.64	+4.4 – 6.0	$\pm 2.1$	$\pm 2.2$

LHCHSWG YR4, [arXiv:1610.07922v2](https://arxiv.org/abs/1610.07922v2),  
 based on: [arXiv:1505.07122](https://arxiv.org/abs/1505.07122), [arXiv:1604.06447](https://arxiv.org/abs/1604.06447)

# Sensitivity to trilinear coupling



Cross-section dependence on coupling modification  $\kappa_\lambda$



Sensitivity to  $\kappa_\lambda$  largest at the hh threshold

# Feasibility studies for measuring $h \rightarrow hh$ at the HL-LHC

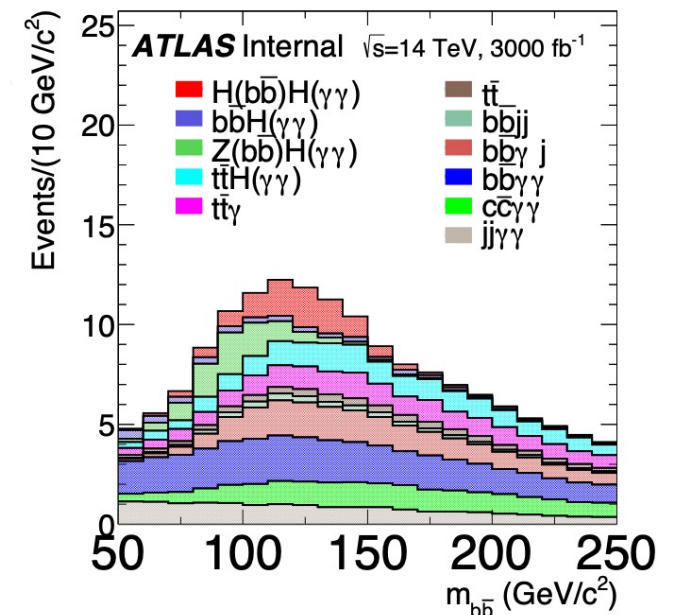
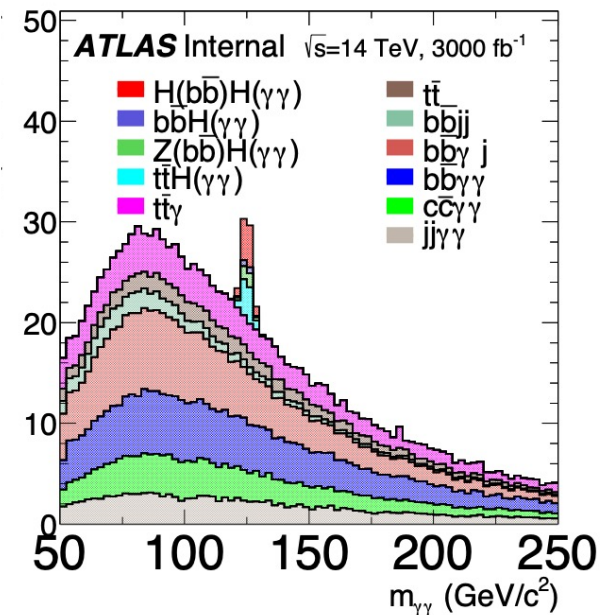
$E_{\text{CM}} = 14 \text{ TeV}$ , Luminosity  $3000 \text{ fb}^{-1}$

Final state with one  $h \rightarrow bb$ , the other  $h \rightarrow \gamma\gamma$

Dominant backgrounds originating from continuum  $bb\gamma\gamma$  production and misidentification of b-quarks

Invariant masses  $m_{\gamma\gamma}$  and  $m_{bb}$  are good signal discriminants

Isolation requirement between b-quarks and photons and between any of the b-quark and any of the photon.



## HL-LHC conditions

Analysis accounts for mis-tagging b-quark jets (conservative estimates)

Assumes different photon mistag probabilities in the barrel endcap and imperfect photon momentum reconstruction

Does not realistically describe pile-up conditions (optimistic)

Energy scale correction for jets applied with 100% accuracy

# Results and Conclusions from HL-LHC projections

- After event selection, expected event yields in total (barrel, end-cap):
- background events:  
 $47 \pm 3.5$  ( $29 \pm 2.7$ ,  $18 \pm 2.3$ )
- SM signal events:  
 $8.4 \pm 0.1$  ( $6.7 \pm 0.1$ ,  $1.8 \pm 0.1$ )

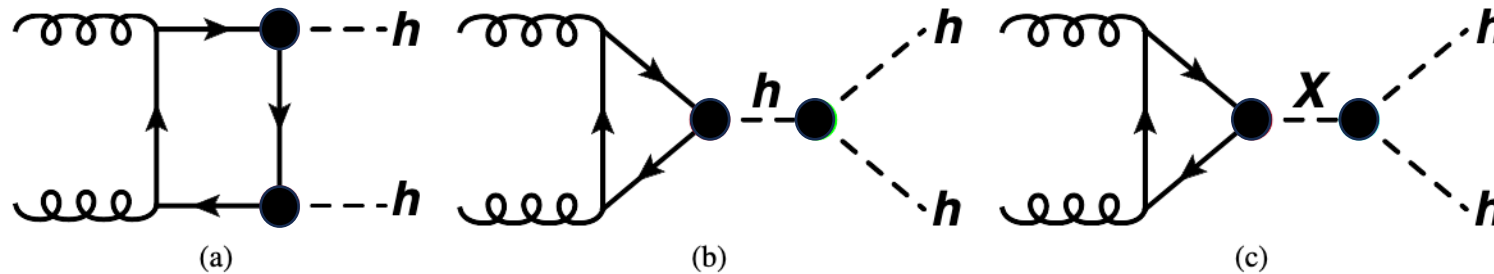
- Sensitivity to the SM Higgs pair production is  $\sim 1.4\sigma$
- Constraint on  $\kappa_\lambda \in [-1.3, 8]$  at 95% CL

It is unlikely to observe SM Higgs pair production currently at the LHC.

On the other hand, Higgs pair production cross-section can be enhanced by beyond SM (BSM) physics...

# Higgs pair production cross-section can be enhanced by BSM physics

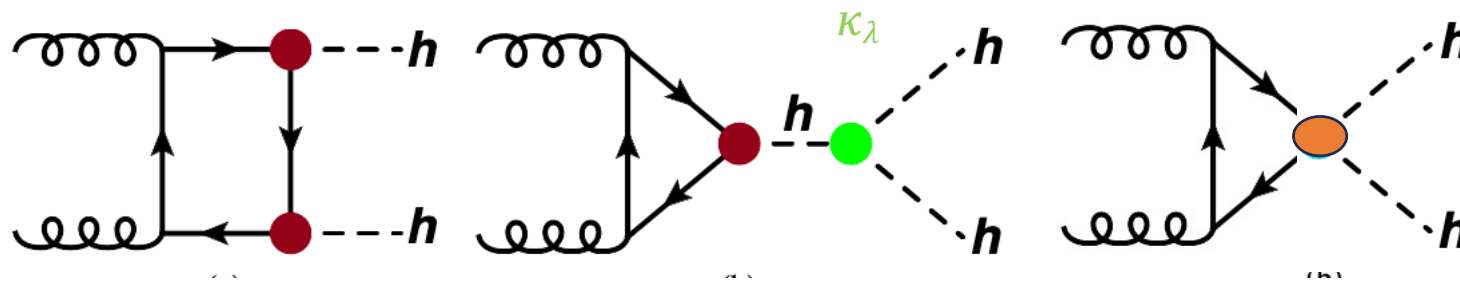
Through resonant production of an unknown heavy particle decaying into two Higgs bosons



- Higgs singlet model
- Kaluza-Klein gravitons
- Minimal Supersymmetric Standard Model
- Two Higgs Doublet Model

# Higgs pair production cross-section can be enhanced by BSM physics

Through modification of Higgs and di-Higgs couplings



Heavy unobservable particles, which effects at low energies lead to effective theories, such as:

Higgs compositeness models (SILH)

Non-explicit models parametrised with Effective Field Theory Operators (dim-6 operators): HEFT, SMEFT, ...

# Combination of Run1 measurements

- 4 channels combined:  $hh \rightarrow bb\tau\tau, \gamma\gamma WW^*, \gamma\gamma bb, bbbb$
- Event selection performed using kinematical cuts on invariant (di-)Higgs masses

$hh$ final state	Nonresonant search		Resonant search		
	Categories	Discriminant	Categories	Discriminant	$m_H$ [GeV]
$\gamma\gamma bb$	1	$m_{\gamma\gamma}$	1	event yields	260–500
$\gamma\gamma WW^*$	1	event yields	1	event yields	260–500
$b\bar{b}\tau\tau$	4	$m_{\tau\tau}$	4	$m_{bb\tau\tau}$	260–1000
$b\bar{b}b\bar{b}$	1	event yields	1	$m_{bbbb}$	500–1500

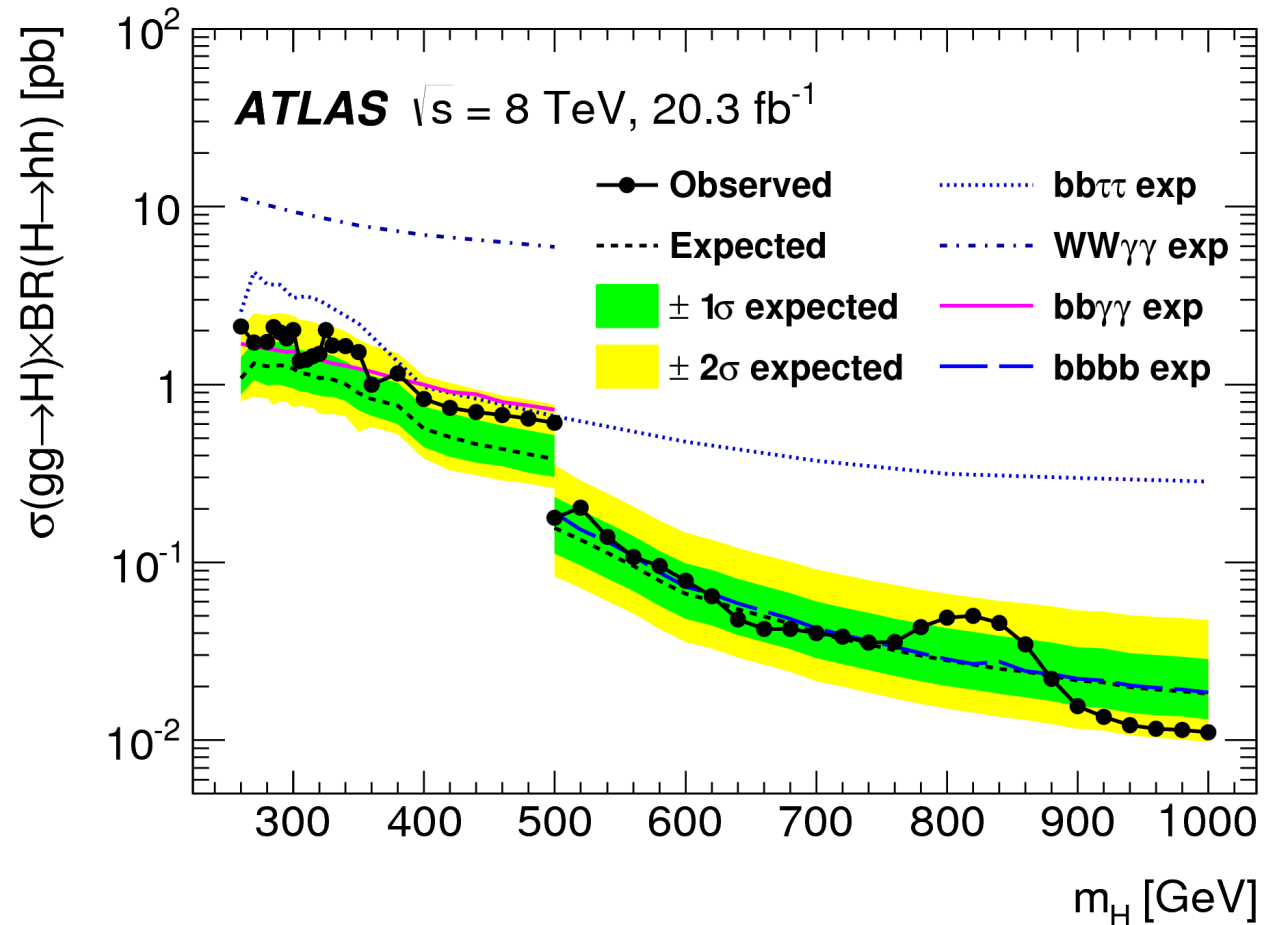
- Upper limits on the SM di-Higgs cross-section  $10^2 \times \text{SM}$

Analysis	$\gamma\gamma bb$	$\gamma\gamma WW^*$	$bb\tau\tau$	$bbbb$	Combined
Upper limit on the cross section [pb]					
Expected	1.0	6.7	1.3	0.62	0.47
Observed	2.2	11	1.6	0.62	0.69
Upper limit on the cross section relative to the SM prediction					
Expected	100	680	130	63	48
Observed	220	1150	160	63	70

# Results of resonant spin-0 searches

- $hh \rightarrow bb\tau\tau$ , and,  $hh \rightarrow \gamma\gamma bb$  most sensitive at small masses of the BSM scalar
- $hh \rightarrow bbbb$  most sensitive at large resonance masses
- The largest excess of events is at  $m_\chi = 300 \text{ GeV}$  and has local significance of  $2.5\sigma$ . This is due to an excess observed in  $hh \rightarrow \gamma\gamma bb$ .

Observed and expected upper limits on the cross-section

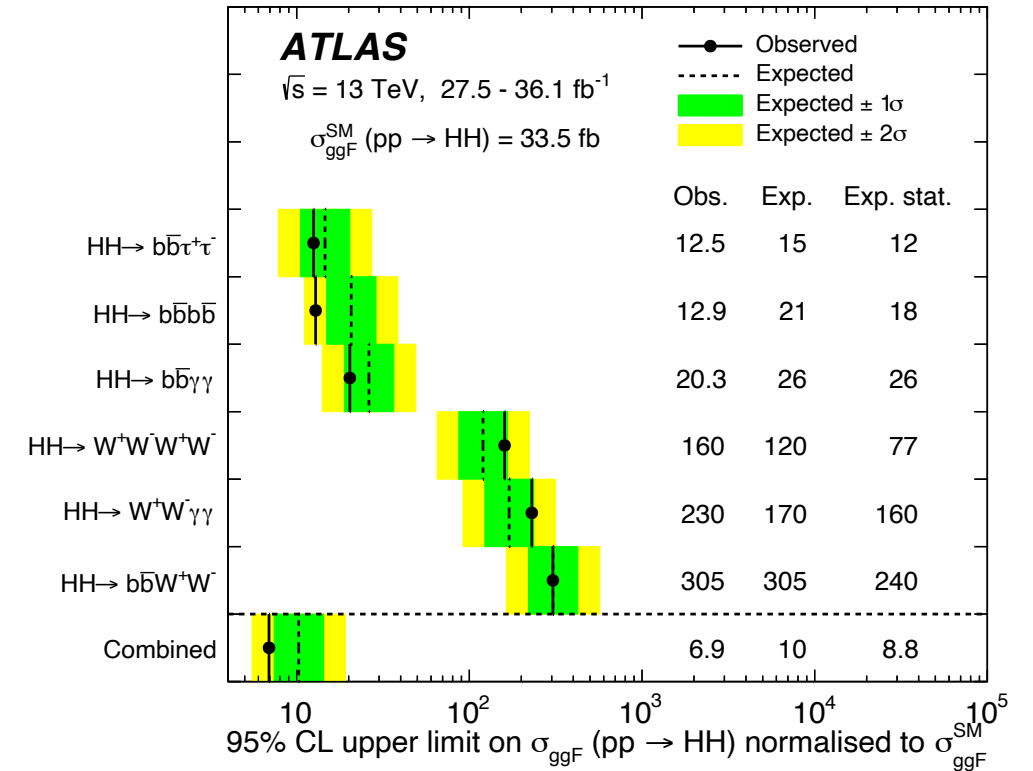


# Early Run 2 data combination

- Increase in expected event yields due to luminosity increase of cross-section with energy
- Six final state investigated

	$b\bar{b}b\bar{b}$	$b\bar{b}W^+W^-$	$b\bar{b}\tau^+\tau^-$	$W^+W^-W^+W^-$	$b\bar{b}\gamma\gamma$	$W^+W^-\gamma\gamma$
$\mathcal{B}(HH \rightarrow x\bar{x}y\bar{y})$	0.34	0.25	0.073	0.046	$2.6 \cdot 10^{-3}$	$1.0 \cdot 10^{-3}$
$\mathcal{L}_{\text{int}} [\text{fb}^{-1}]$	27.5 [36.1]	36.1	36.1	36.1	36.1	36.1
Categories	2 [2–5]	1 [1]	3 [2–3]	9 [9]	2 [2]	1 [1]
Discriminant	$m_{HH} [m_{HH}]$	c.e. [ $m_{HH}$ ]	BDT [BDT]	c.e. [c.e.]	$m_{\gamma\gamma} [m_{HH}]$	$m_{\gamma\gamma} [m_{\gamma\gamma}]$
Model	NR [S/G]	NR [S/G]	NR [S/G]	NR [S]	NR [S]	NR [S]
$m_{S/G} [\text{TeV}]$	[0.26–3.00]	[0.50–3.00]	[0.26–1.00]	[0.26–0.50]	[0.26–1.00]	[0.26–0.50]

- Search for SM, and BSM non-resonant and resonant di-Higgs production

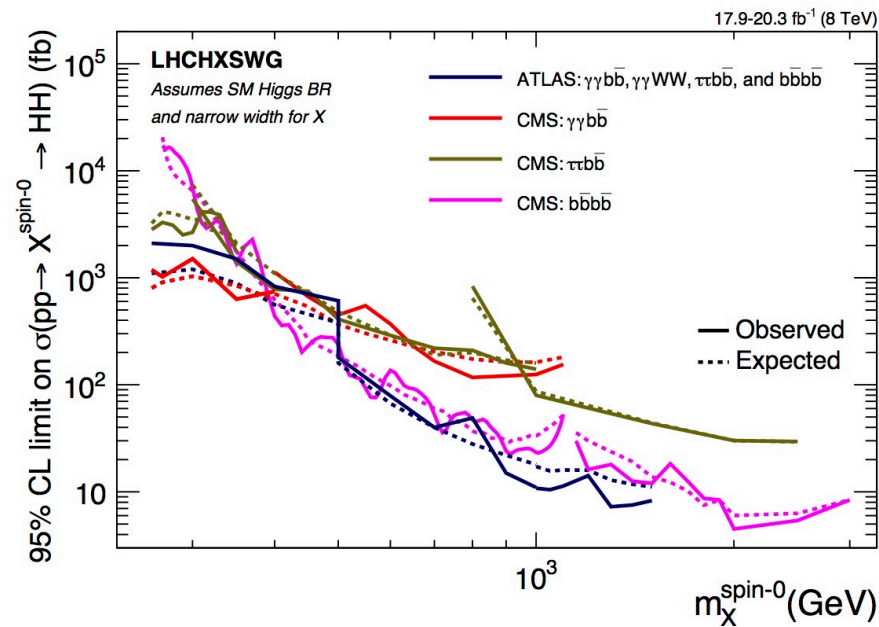




# Spin-0 heavy scalar cross-sections. Comparison of limits.

## Run 1:

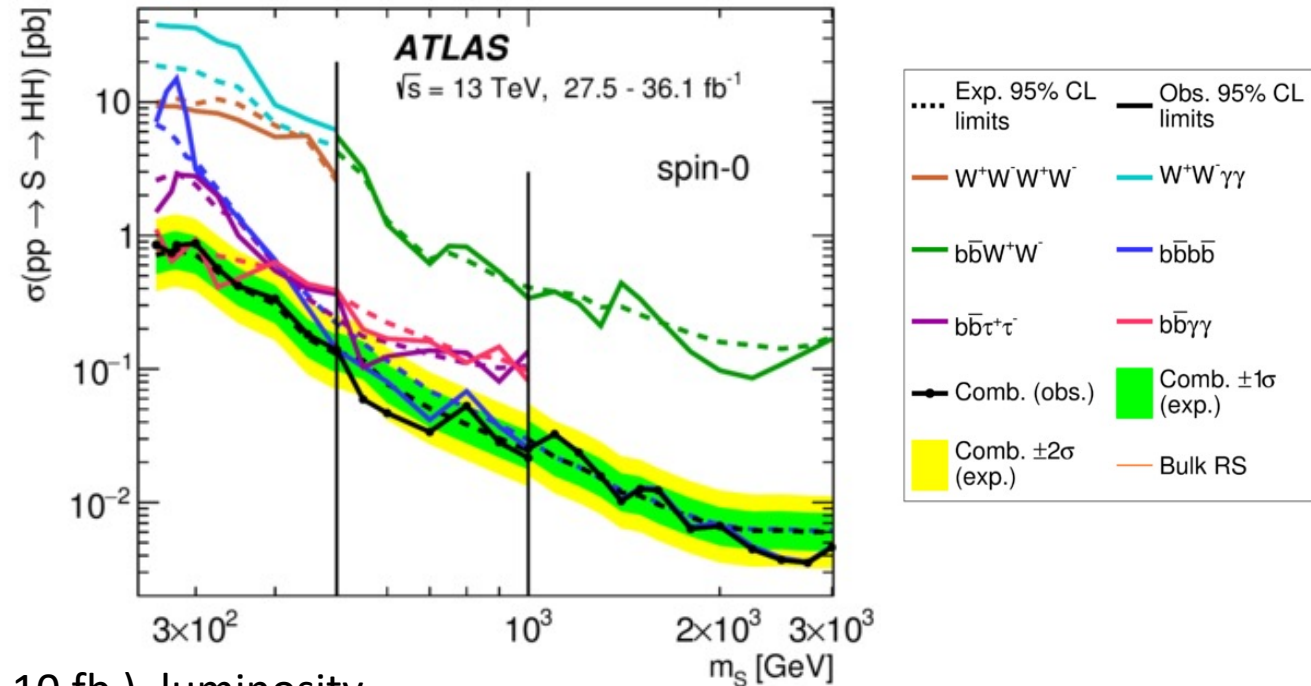
### CMS measurements & ATLAS combination



Improvements due to: larger cross-sections (31fb vs 10 fb ), luminosity (36.1/fb vs 17.9/fb) and experimental reconstruction

## Run 2:

### ATLAS combination

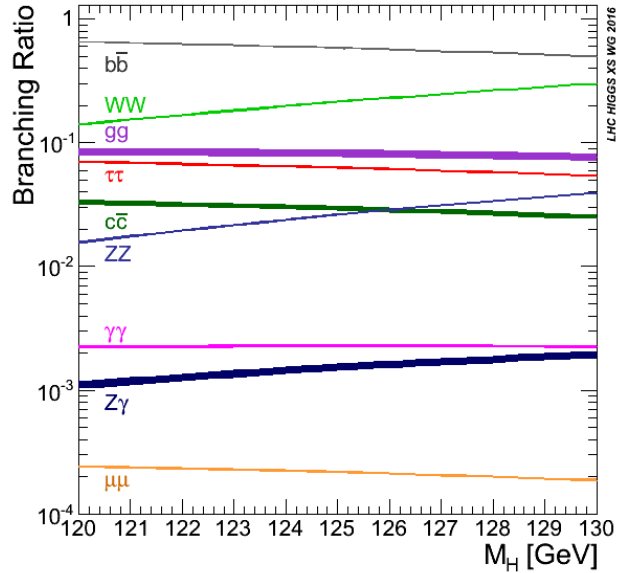
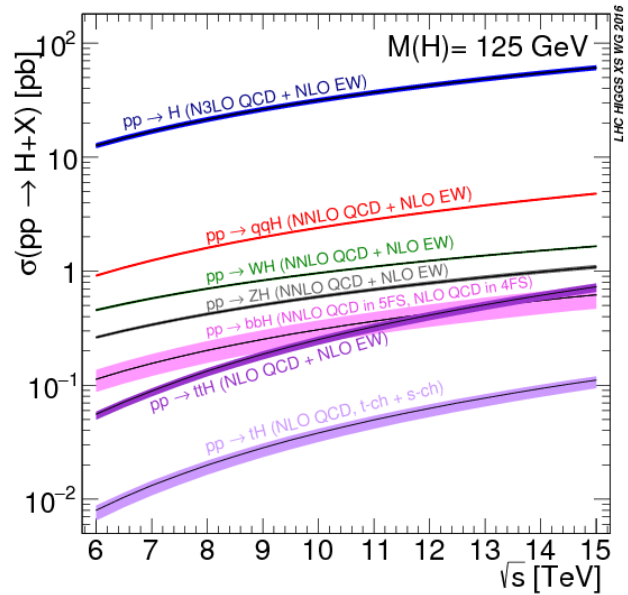


# Summary

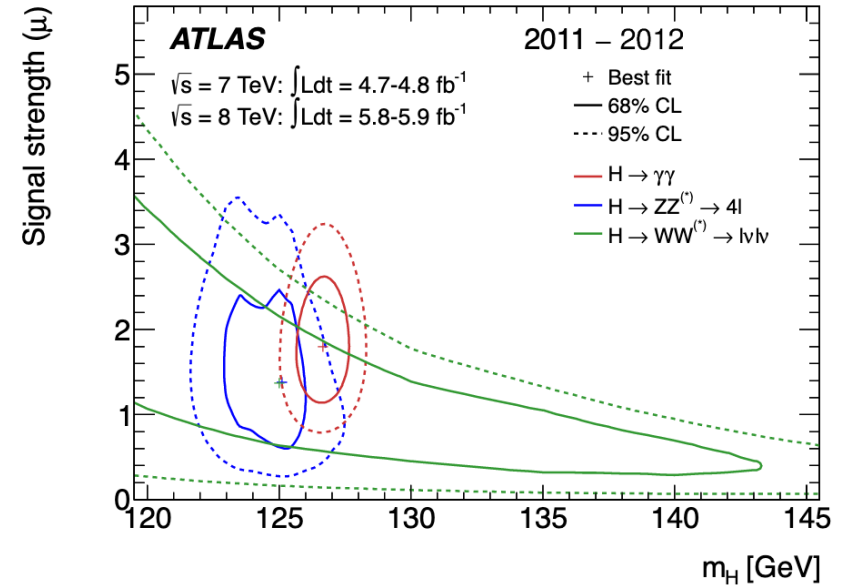
- Higgs boson couplings to electroweak bosons were crucial in establishing Higgs boson properties.
- Higgs decays to  $WW^*$  enabled measurements of Higgs production cross-sections in gluon fusion and electroweak channels. First measurements of Higgs couplings to longitudinally and transversally polarised electroweak bosons complete, confirming their SM nature.
- Observation of SM di-Higgs production is beyond the reach of the LHC. Challenging measurement of Higgs self coupling is being carried on and limits are being improved.
- Combinations of various final states as well as improvements in experimental techniques are vital in maximising research potential of the HL-LHC experiments and future colliders.

# Backup slides

# Higgs couplings to di-bosons – $WW^*$ , $ZZ^*$ , $\gamma\gamma$

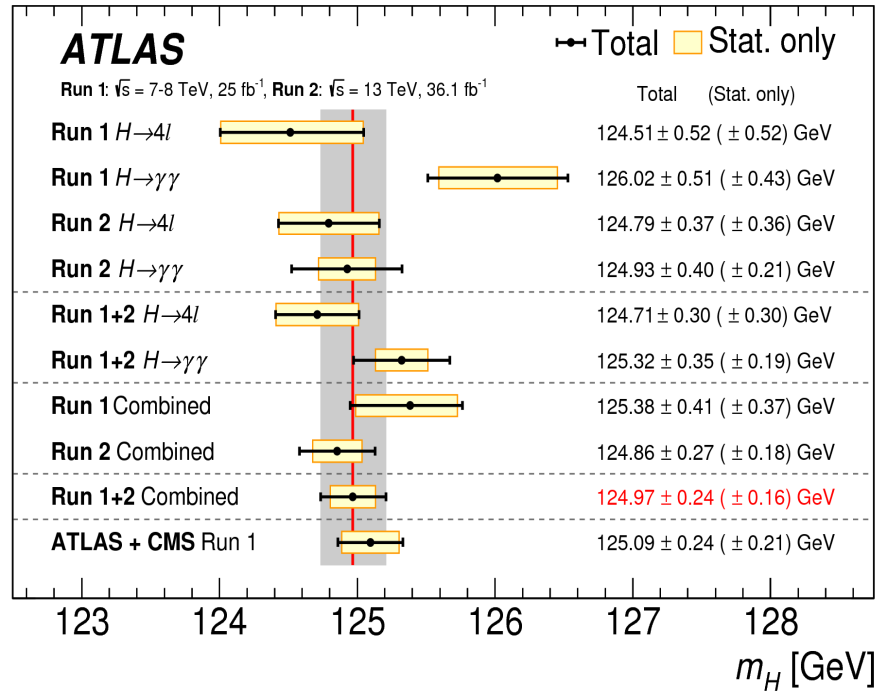


Production mechanisms and branching ratios offer large event yields



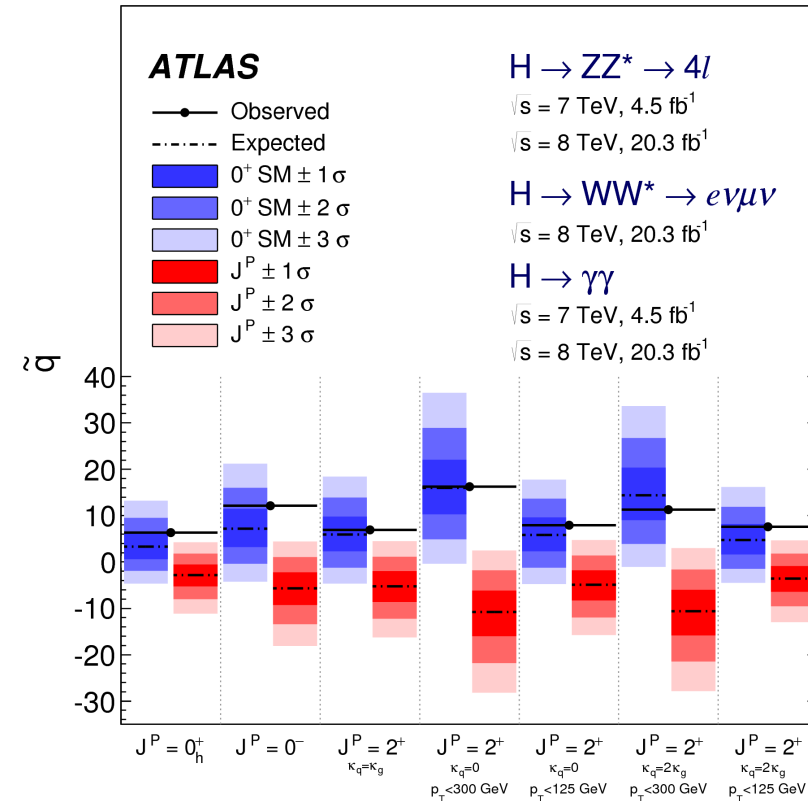
Higgs boson discovery using Higgs decays into  $H \rightarrow ZZ^* \rightarrow 4\ell$ ,  $H \rightarrow \gamma\gamma$  and  $H \rightarrow WW^* \rightarrow e\mu\nu e\nu$

# Mass measurements



Higgs boson mass  $m_h = 125.09$  GeV

# spin and CP



Spin-0, CP even –The Higgs boson is a scalar particle

# Higgs couplings to di-bosons - self-couplings

$$V_\phi = \mu^2 |\phi|^2 + \lambda |\phi|^4$$

Electroweak  
Symmetry

Breaking

$$\phi = (v + h^0)/\sqrt{2},$$

$$m_h^2 = -2\mu^2 = 2\lambda v^2$$

$$V(h^0) = 2\lambda v^2 \frac{(h^0)^2}{2} + 6\lambda v \frac{(h^0)^3}{3!} + 6\lambda \frac{(h^0)^4}{4!} - \frac{v^4 \lambda}{4}$$

$$\equiv m_h^2 \frac{(h^0)^2}{2} + \lambda_{3h} \frac{(h^0)^3}{3!} + \lambda_{4h} \frac{(h^0)^4}{4!} - \frac{v^4 \lambda}{4}$$

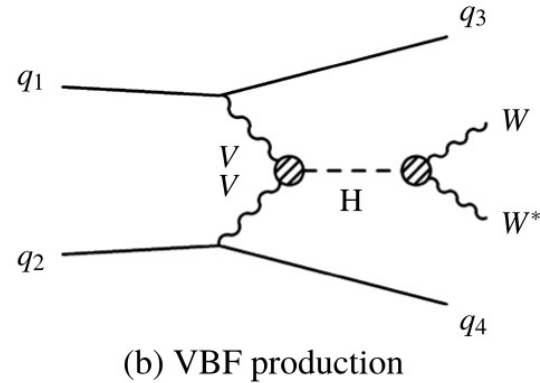
$$\lambda_{3h} = \frac{3m_h^2}{v}$$

$$\lambda_{4h} = \frac{3m_h^2}{v^2}$$

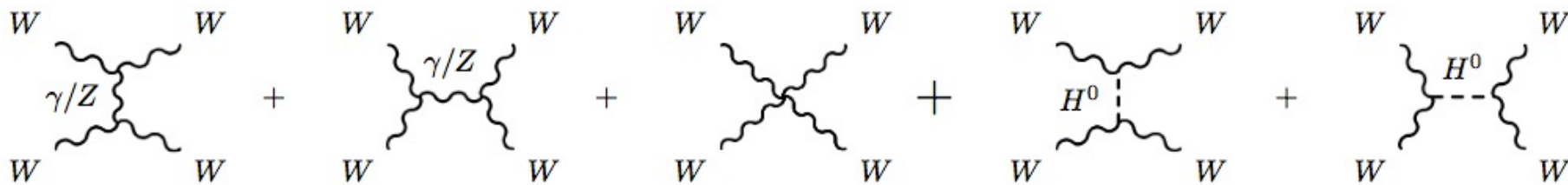
- Higgs self-coupling in the SM defined by its mass and VEV
- There is one self-coupling in the SM, in experiments we parametrise them separately to distinguish triple and quartic interactions
- Parametrisation of the trilinear coupling

$$\kappa_\lambda = \lambda_{3h}^{\text{measured}} / \lambda_{3h}$$

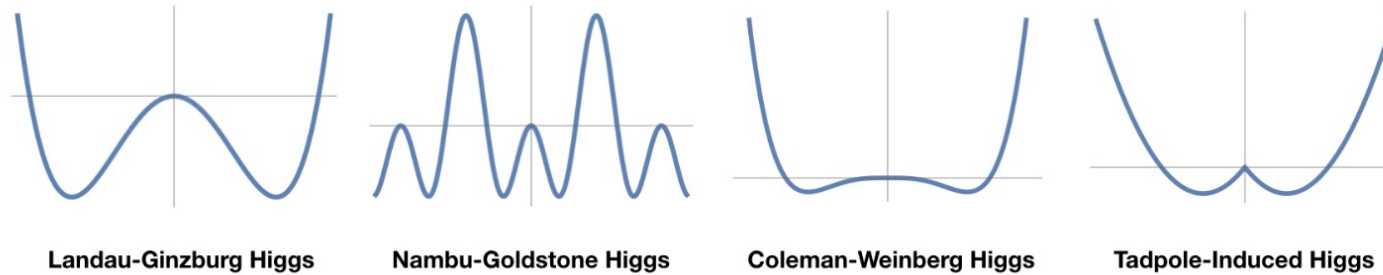
VBF  $H \rightarrow WW^*$  is a part of  $W_L W_L$  scattering



This process enables testing unitarity of the SM at the LHC



# SM as an effective field theory



$$V(H) \simeq \begin{cases} -m^2 H^\dagger H + \lambda (H^\dagger H)^2 + \frac{c_6 \lambda}{\Lambda^2} (H^\dagger H)^3, & \text{Elementary Higgs} \quad \text{SM+SMEFT} \\ -a \sin^2(\sqrt{H^\dagger H}/f) + b \sin^4(\sqrt{H^\dagger H}/f), & \text{Nambu-Goldstone Higgs} \\ \lambda (H^\dagger H)^2 + \epsilon (H^\dagger H)^2 \log \frac{H^\dagger H}{\mu^2}, & \text{Coleman-Weinberg Higgs} \\ -\kappa^3 \sqrt{H^\dagger H} + m^2 H^\dagger H, & \text{Tadpole-induced Higgs} \end{cases}$$

- (a) the potential of an elementary scalar Higgs boson, in which the Higgs boson, whose negative mass parameter thus triggers EWSB.
- (b) the potential of a pseudo-Nambu-Goldstone Higgs boson emerging from BSM strong dynamics at a high energy scale.
- (c) describes Coleman-Weinberg Higgs boson, with EWSB resulting from renormalization group running effects
- (d) a tadpole-induced Higgs and its mass parameter is positive.