Higgs boson electroweak symmetry breaking and searching for BSM physics in ATLAS

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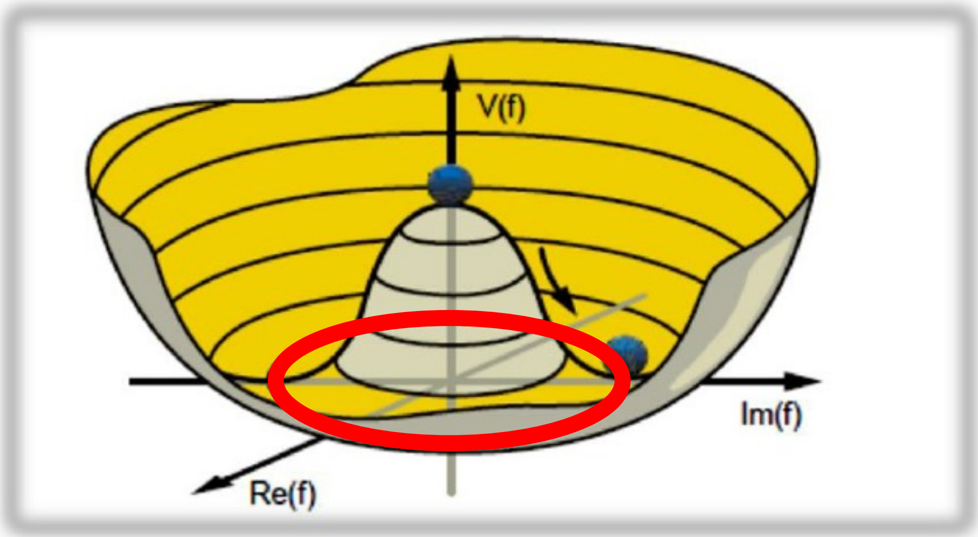
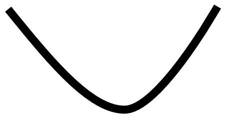
- In the 1950s theory of electroweak interactions was largely complete, based on quantum field theory description
- Only “a few” puzzles left to solve:
- At high energies, the weak and electromagnetic forces merge into a single electroweak force. Yet at low energies, electromagnetic waves (such as light) 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.

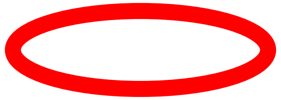
- Several ideas of a mechanism of spontaneuous breaking of SU(2)xU(1) symmetry were proposed over the years
- Analogy with Anderson’s model of a plasmon explaining superconductivity
- Works by Hagen, Kibble, Goldstone, Nambu, Salam, … already included crucial steps in understanding symmetry breaking in gauge theories.
- The discovery of the mechanism of electroweak symmetry breaking is eventually attributed to Peter Higgs, Robert Brout and François Englert

The Higgs mechanism in the SM (1964)

- The mechanism postulates a new scalar SU(2) field, with a non-trivial vacuum structure added in the electroweak theory.
- Through the boson couplings to electroweak gauge bosons bosons fields:
  - electroweak fields gain mass
  - absorb some degrees of freedom and gain longitudinal polarisations



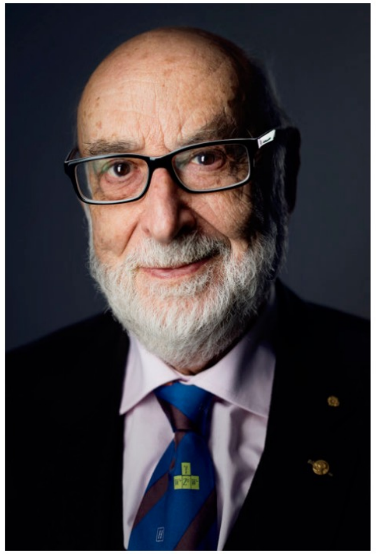
 massive real boson

 3 massless Goldstone bosons

Higgs vacuum expectation value v = 246 GeV

Higgs boson discovery 2012

- Discovery by ATLAS and CMS experiments at the LHC Phys.Lett. B716 (2012) 1-29
- using Higgs boson decays into $H \to ZZ^* \to 4\ell$, $H \to \gamma\gamma$ and $H \to WW \to \mu\upsilon e\upsilon$
- Resulted in a Nobel Prize in Physics 2013



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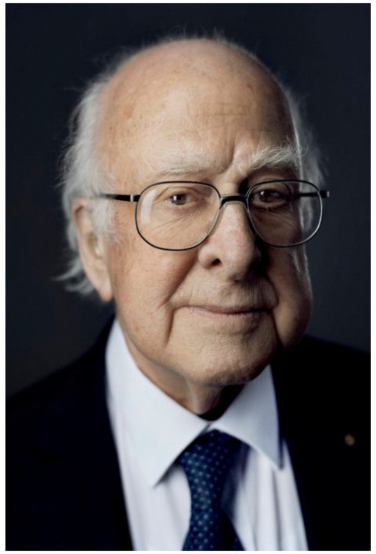
François Englert

Prize share: 1/2



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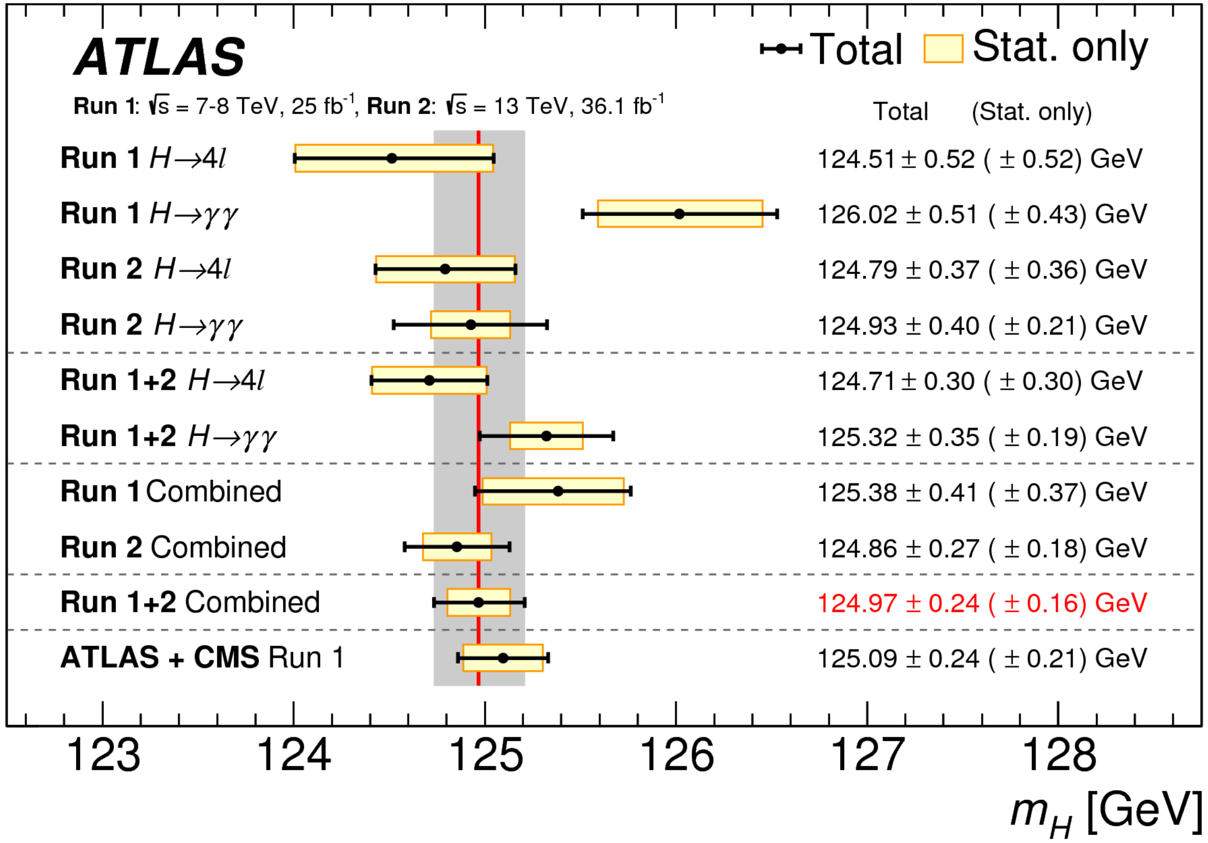
Peter W. Higgs

Prize share: 1/2

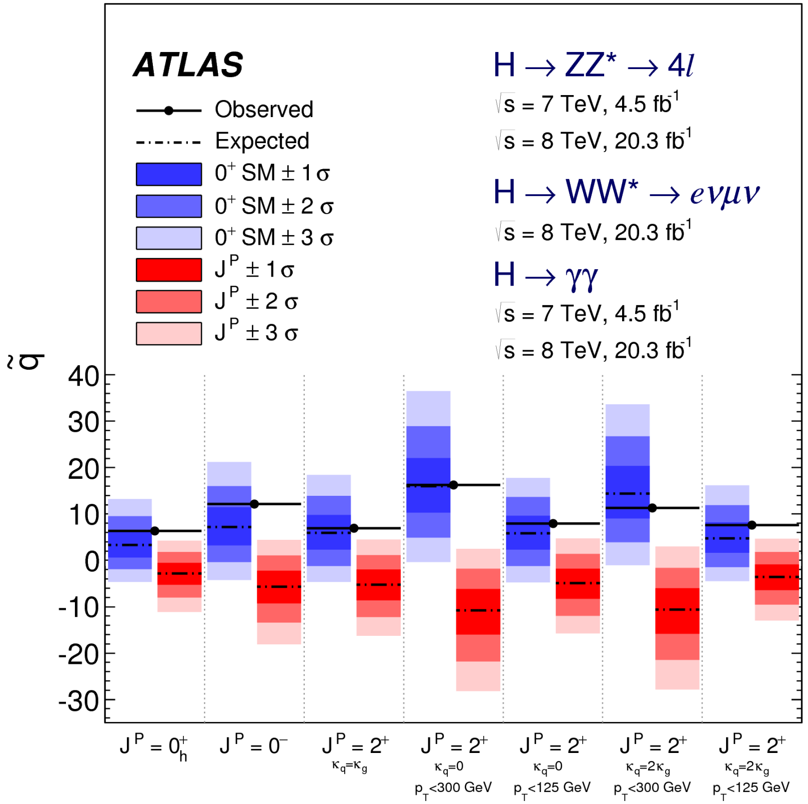
Mass measurements

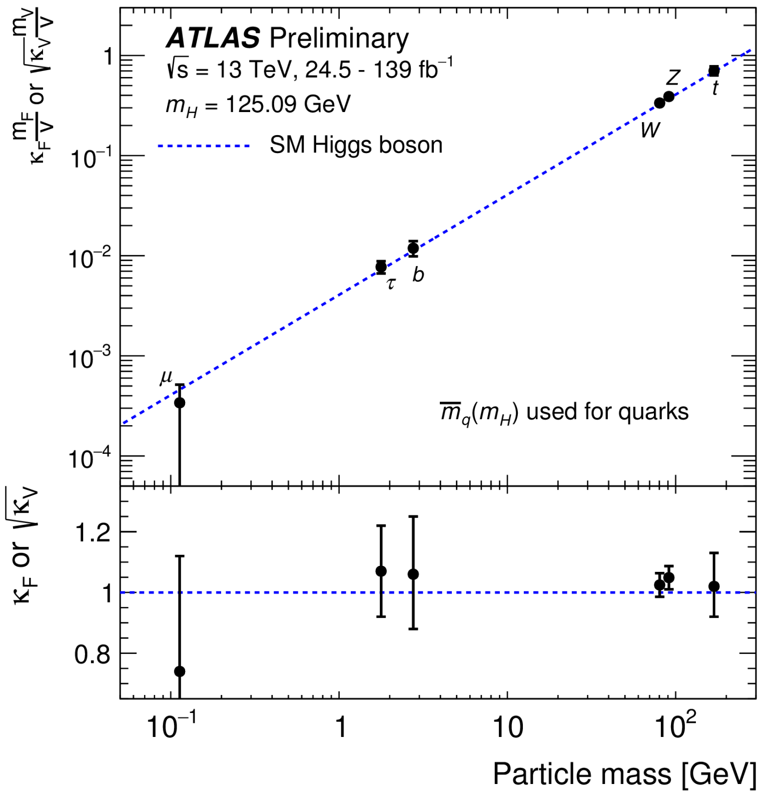


Higgs boson mass m_h = 125.09 GeV

spin and CP

Yukawa couplings





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

Couplings consistent with SM predictions.

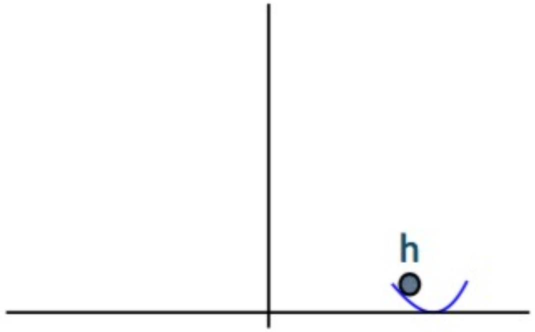
All measurements so far confirm the SM nature of the Higgs boson.

But what do we know about the Higgs mechanism?

Have we measured the Higgs potential?

The shape of the Higgs potential

- By measuring its couplings to bosons and fermions we can access properties of the Higgs potential close to the vacuum.



- But... the global shape of the potential can be different from the SM!

picture from 1511.06495

How to probe the Higgs potential?

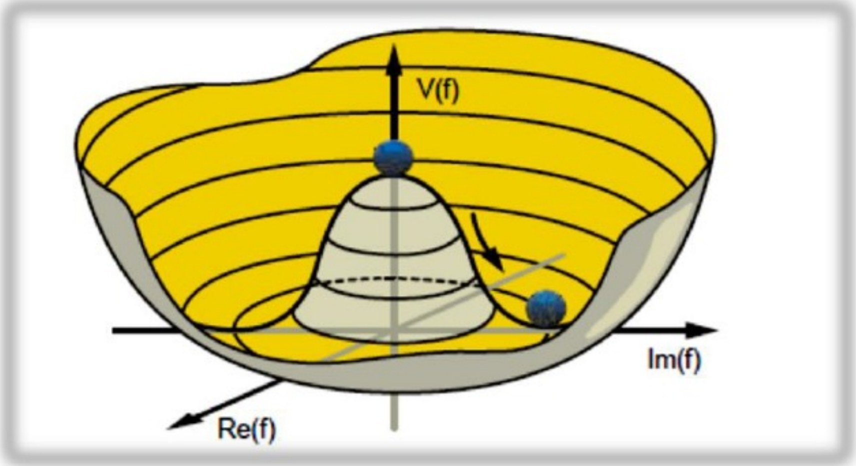
$$V = -\mu H^2 + \lambda H^4$$

Electroweak Symmetry Breaking

$$V = \frac{m_h^2}{2}h^2 + \lambda_3 v h^3 + \frac{\lambda_4}{4}h^4$$

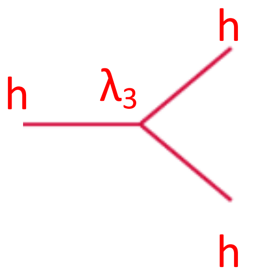
$$\lambda_3 = \lambda_4 = m_h^2/(2v^2)$$

Higgs potential in the SM is parametrised with v and λ.



Probing the Higgs potential could be achieved by measuring:

Higgs trilinear self-coupling

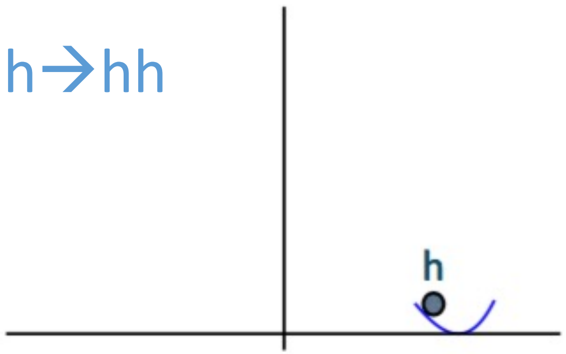


Absorbed Goldstone modes

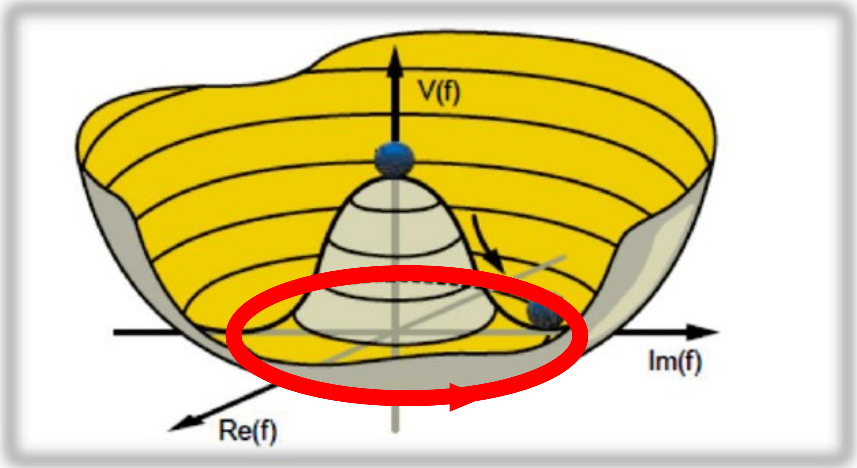
Content of this talk

- Two types of Higgs interactions investigated:

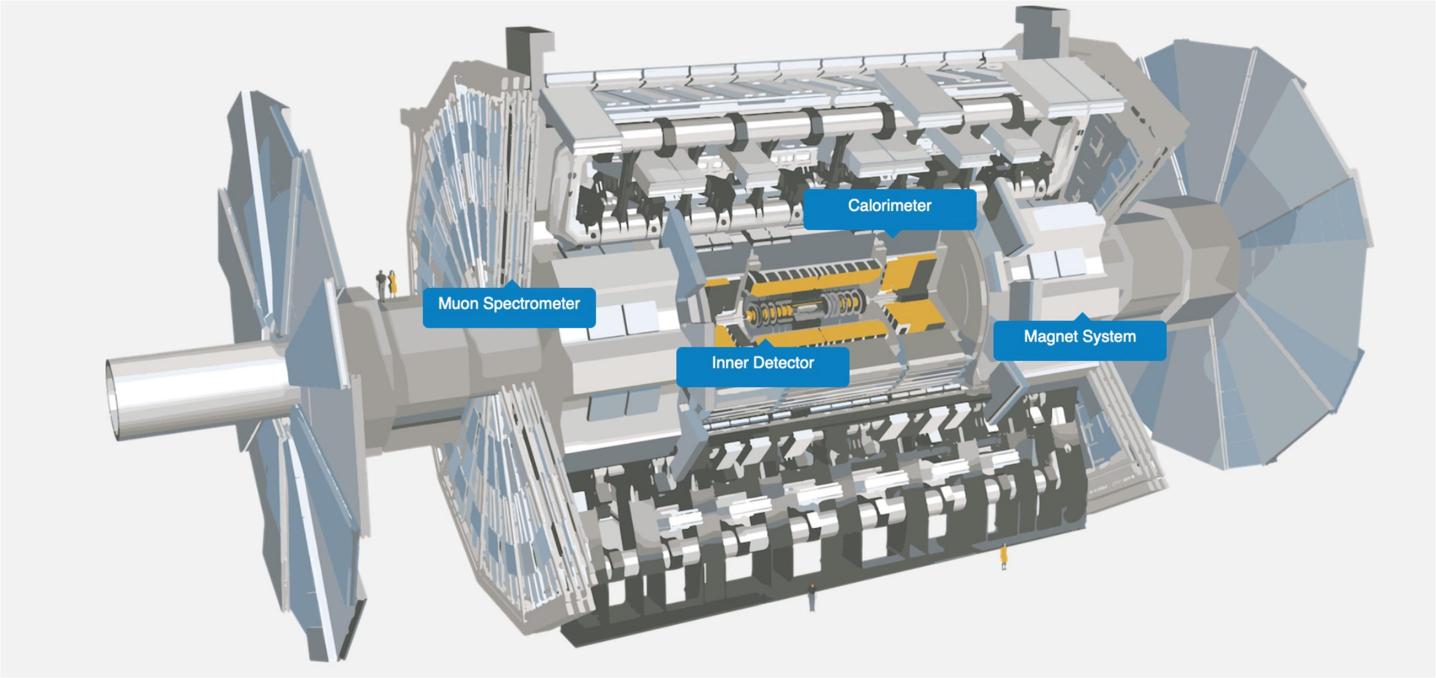
  - Higgs boson self-interactions h→hh



  - Higgs boson interactions with longitudinally polarised electroweak bosons using h→ WW^* decays



Data collected by the ATLAS detector at the Large Hadron Collider (LHC)



The ATLAS detector

LHC, CERN, Geneva

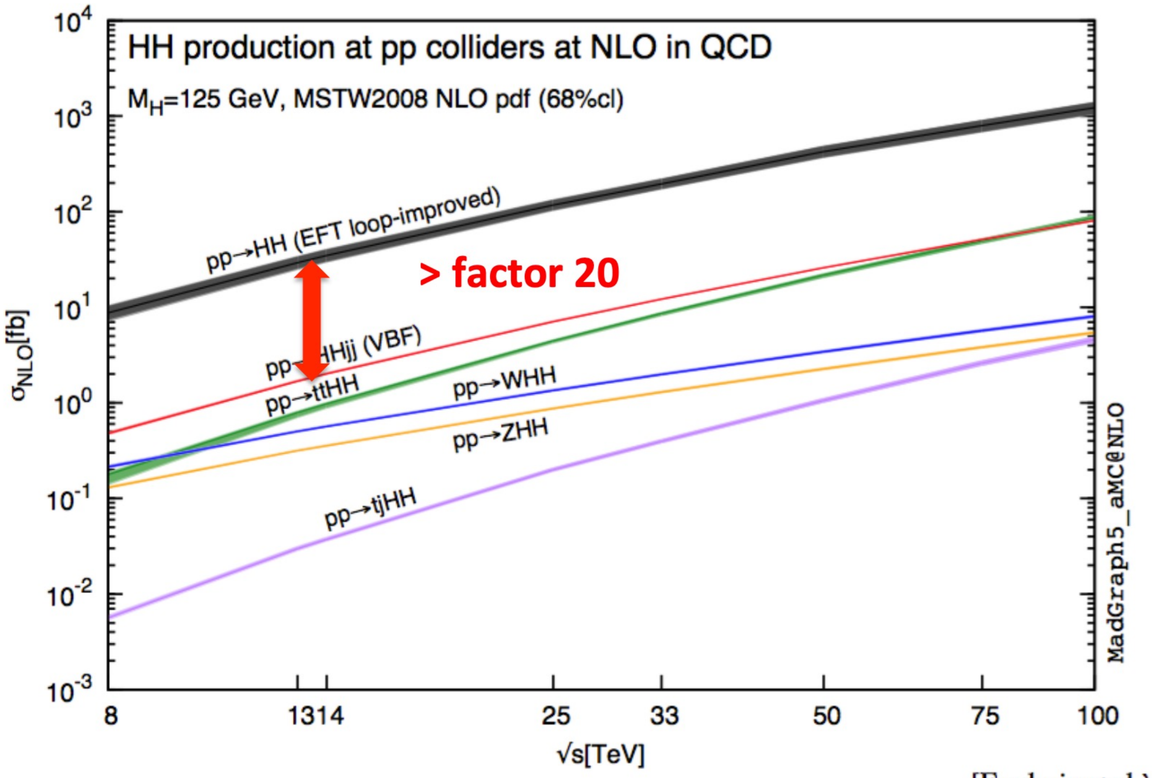
Content of this talk

- Two types of Higgs interactions investigated:
  - Higgs boson self-interactions $H \rightarrow HH$
  - Higgs boson interactions with longitudinally polarised electroweak bosons using $H \rightarrow WW^{*}$ decays
- Datasets: proton-proton collisions at the LHC
  - Run 1 data (2009–2013): E_{CM} = 7 and 8 TeV
  - early Run 2 data (2015-2018): E_{CM} = 13TeV, luminosities: 20.3 fb^{-1}, 40 fb^{-1},
  - projections towards High Luminosity-LHC (HL-LHC) (2029-2039): E_{CM} =14 TeV, 3000 fb^{-1},

h→ hh

Higgs pair production at proton-proton colliders

Double Higgs production has a cross-section ~ 1-10 fb.
This is ~1000 times smaller than single Higgs production!
We consider the largest production mechanism for Higgs pairs…



[Frederix et al ` 14]

gluon fusion

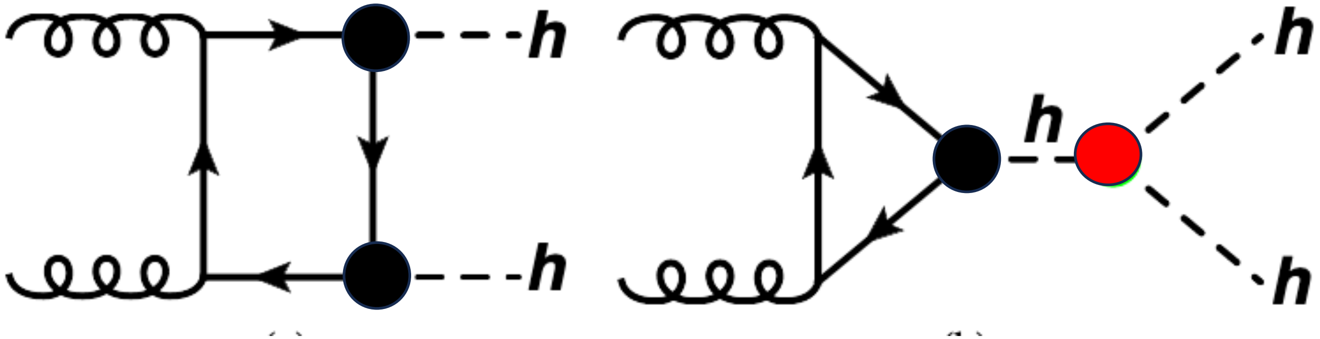
vector boson fusion

associated with top quark pairs

associated with W and Z bosons

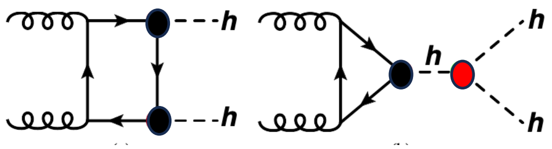
associated with a single top quark

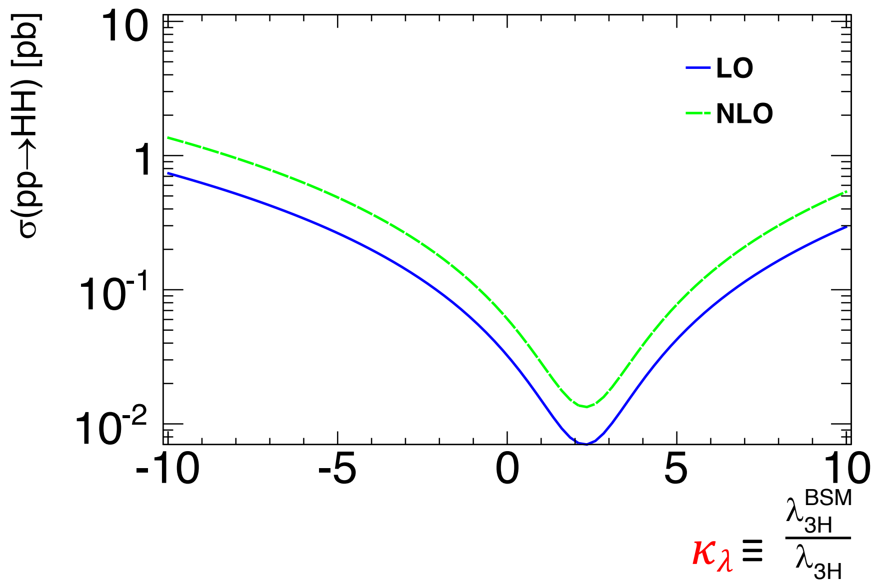
Predictions for Higgs pairs production through gluon fusion



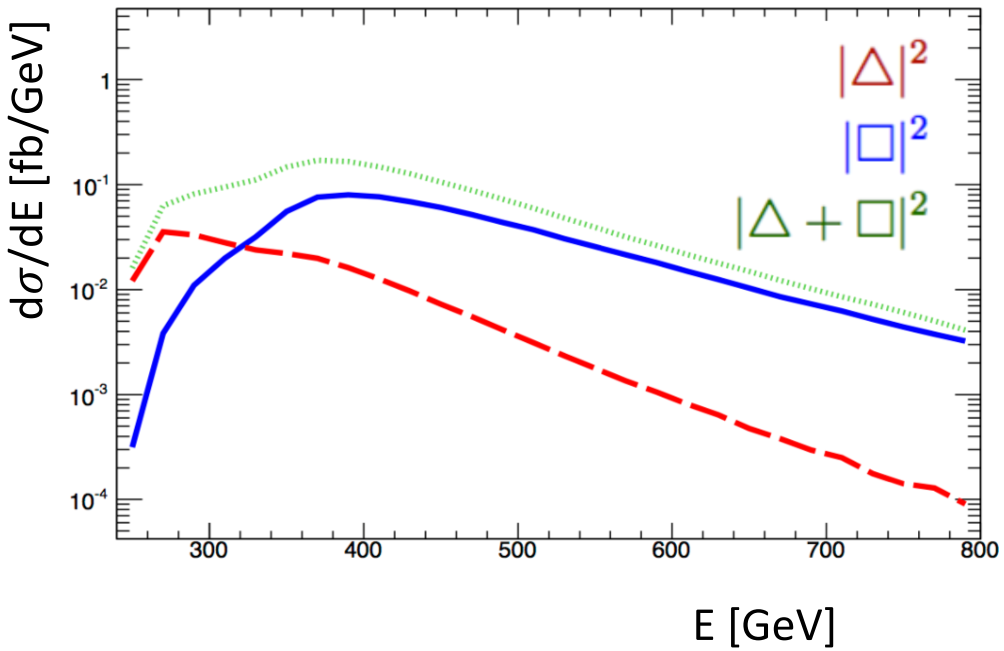
arXiv:1408.5010.

Sensitivity to trilinear coupling





Cross-section dependence on coupling modification κ_λ



Sensitivity to κ_λ largest at the hh threshold

Decays of Higgs boson pairs

one Higgs decays to →

the other Higgs decays to ↓

	bb	WW^*	$\tau\tau$	$\gamma\gamma$
bb	34%			
WW^*	25%	5%		
$\tau\tau$	7%	3%	0,4%	
$\gamma\gamma$	0,26%	0,10%	0,01%	0,001%

Branching fractions probabilities

Feasibility studies for measuring h→ hh at the HL-LHC

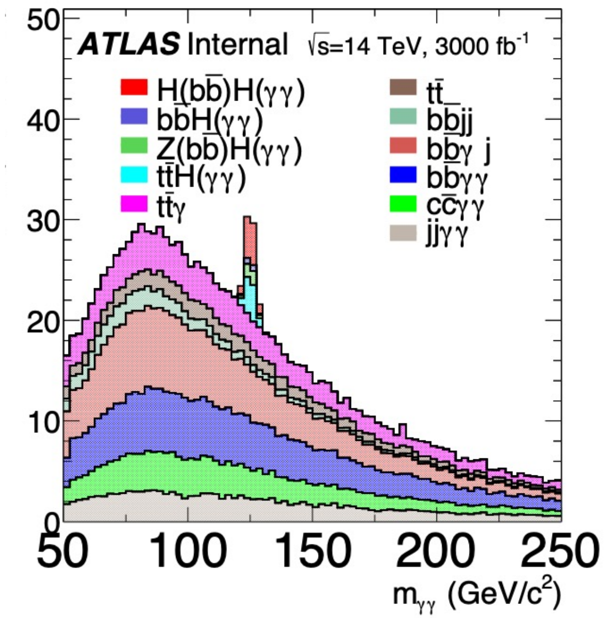
E_{CM} = 14 TeV, Luminosity 3000 fb^{-1}

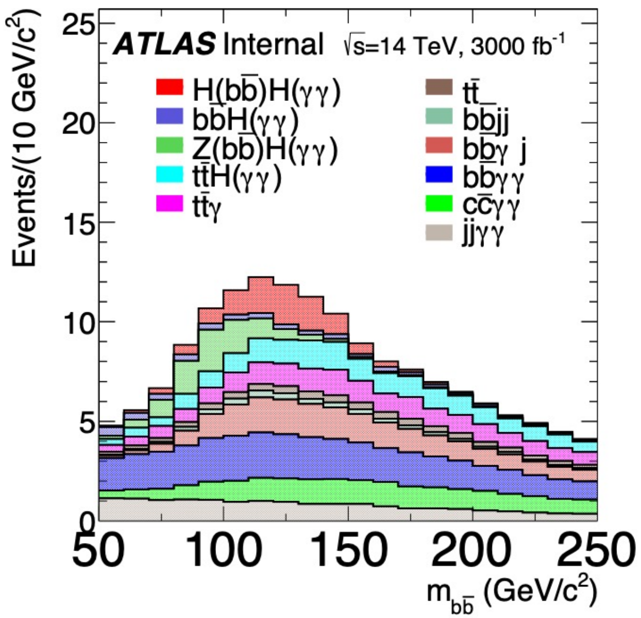
Final state with one h→ bb, the other h→ $\gamma\gamma$

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 phonon.





HL-LHC conditions

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

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

Does not realistically describe pile-up conditions (optimistic)

Energy scale correction for jets applied with 100% accuracy

Feasibility studies for the HL-LHC

- After event selection, expected event yields in total (barrel, end-cap):
- background events:

  47± 3.5 (29 ±2.7, 18 ±2.3)
- SM signal events:

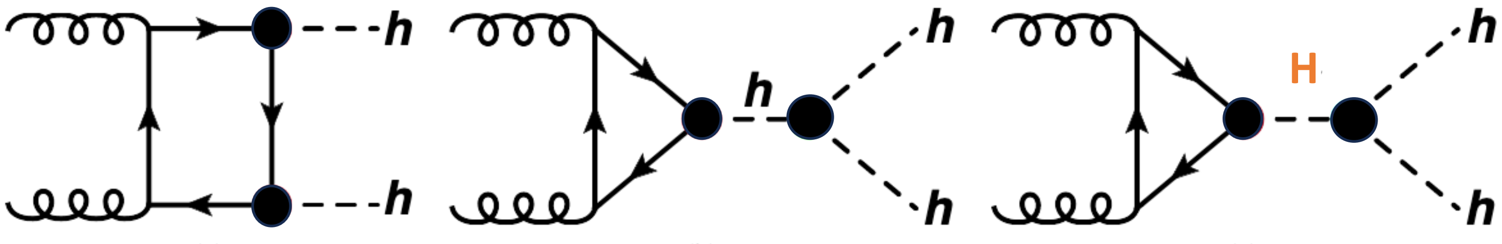
  8.4 ±0.1 (6.7 ±0.1, 1.8 ± 0.1)

- Sensitivity to the SM Higgs pair production is ~1.4σ
- 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...

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

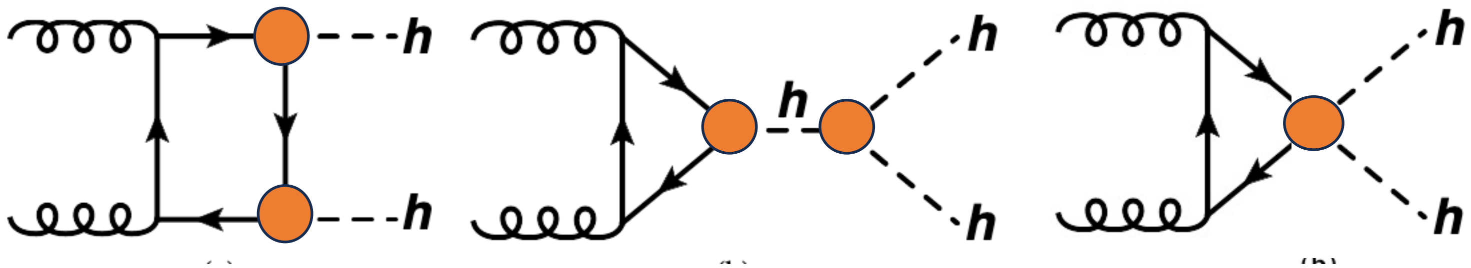


(a) (b) (c)

Heavy H can be a part of:

- Higgs singlet model,
- Minimal Supersymmetric Standard Model,
- Two Higgs Doublet Model,
- a spin-2 Kaluza-Klein graviton,
- …

Enhancement through non-resonant modification of Higgs and di-Higgs couplings



Heavy unobservable particles, whose effects at low energies can be parametrised by effective theories, such as:

- Higgs compositeness models (SILH)
- Non-explicit models parametrised with Effective Field Theory Operators

Phys. Rev. D 92 (2015) 092004

Combination of Run1 measurements

- E_{CM} = 8 TeV
- Luminosity 20.3 fb^{-1}
- 4 channels combined: $hh \rightarrow bb\tau\tau, \gamma\gamma WW^*, \gamma\gamma bb, bbbb$

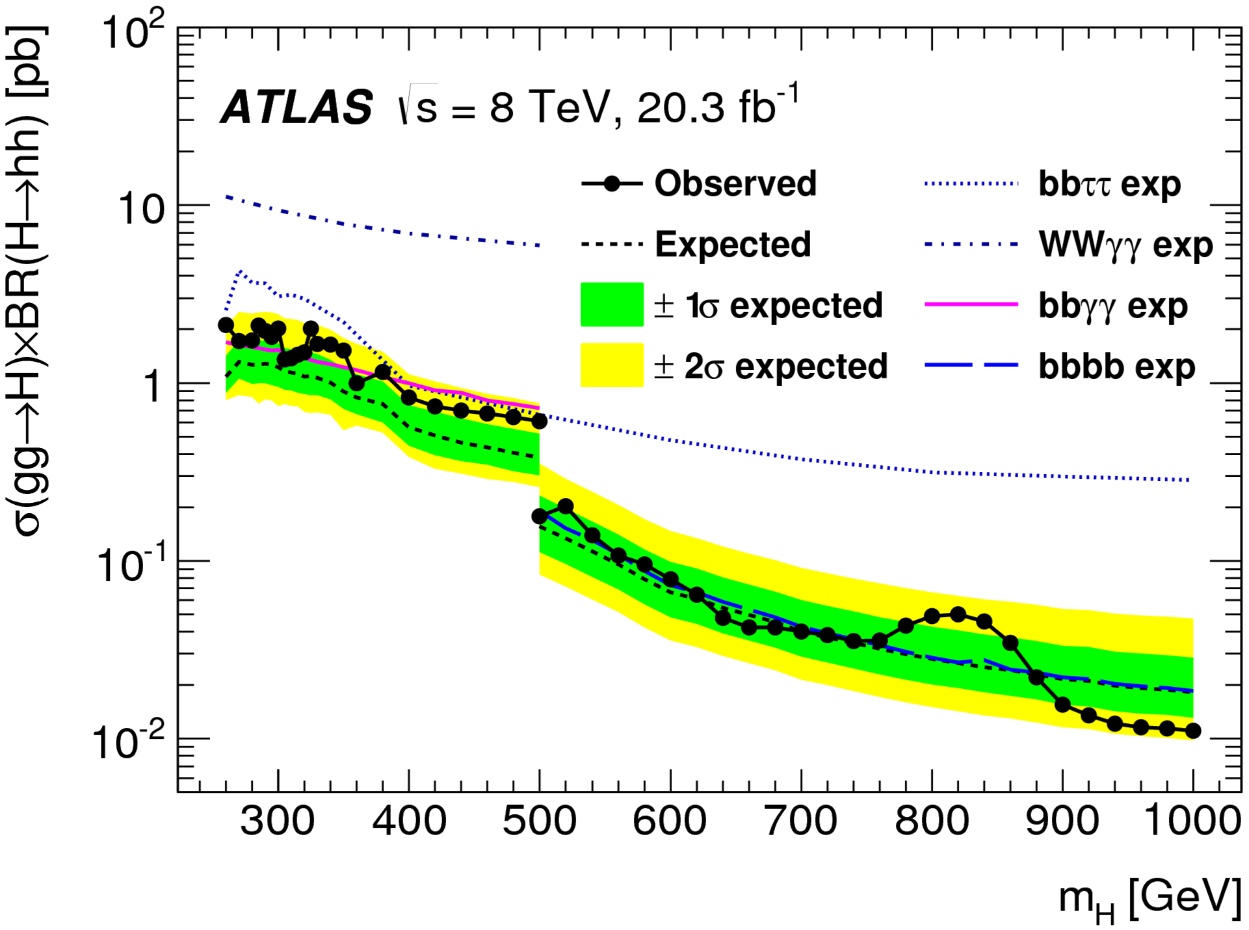
hh final state	Nonresonant search Categories	Nonresonant search Discriminant	Resonant search Categories	Resonant search Discriminant	m_H [GeV]
$\gamma\gamma bb$	1	$m_{\gamma\gamma}$	1	event yields	260–500
$\gamma\gamma WW^*$	1	event yields	1	event yields	260–500
$b\bar{b}\tau\tau$	4	$m_{\tau\tau}$	4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

- Expected limits on the cross-section $10^2 \times$ SM

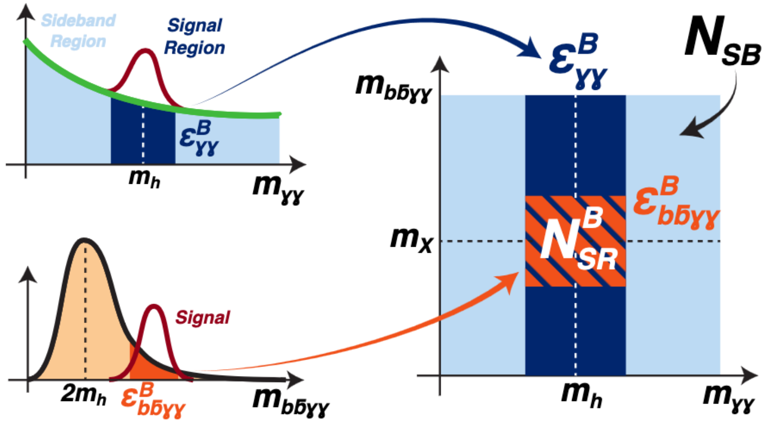
Results of resonant searches

- *hh→bbττ*, and, *hh→ γγbb* most sensitive at small masses of the BSM scalar
- *hh→ bbbb* most sensitive at large resonance masses
- The largest excess of events is at m_X=300GeV and has local significance of 2.5σ. This is due to an excess observed in *hh→ γγbb*.

Observed and expected upper limits on the cross-section



Searching for Higgs pairs production in early Run 2 data, H→ bb, H→ γγ



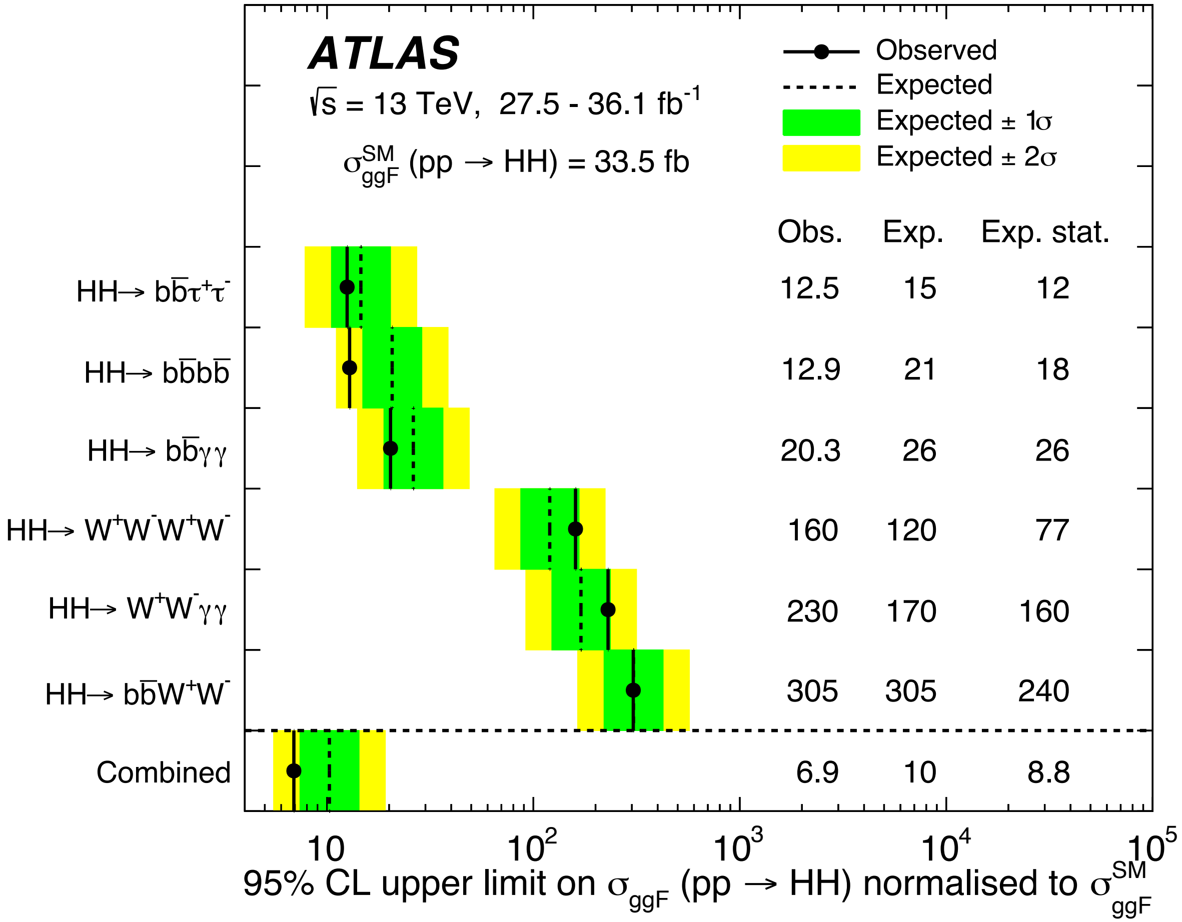
- Luminosity 3.2 fb^{-1}
- E_{CM} = 13 TeV
- Signal selection using invariant masses
  - 105 < $m_{\gamma\gamma}$ < 160 GeV and
  - 95 < m_{bb} < 135 GeV.
    - 2 b-tagged jets and 2 photons
- Background estimated from sideband fits to $m_{\gamma\gamma}$ and $m_{bb\gamma\gamma}$

Process	0-tag	2-tag
Continuum background	35.8 ± 2.1	1.63 ± 0.30
SM single-Higgs	1.8 ± 1.5	0.14 ± 0.05
SM di-Higgs	<0.001	0.027 ± 0.006
Observed	27	0

- An upper limit of 3.9 pb ((5.4 pb) on the cross-section for non-resonant production is observed (expected) at the 95% confidence level
- In the search for a narrow X→hh resonance, m_X in range 275–400 GeV the observed limit ranges between 7.0 pb and 4.0 pb (the expected limit varies between 7.5 pb and 4.4 pb)
- NO excess of events in this dataset

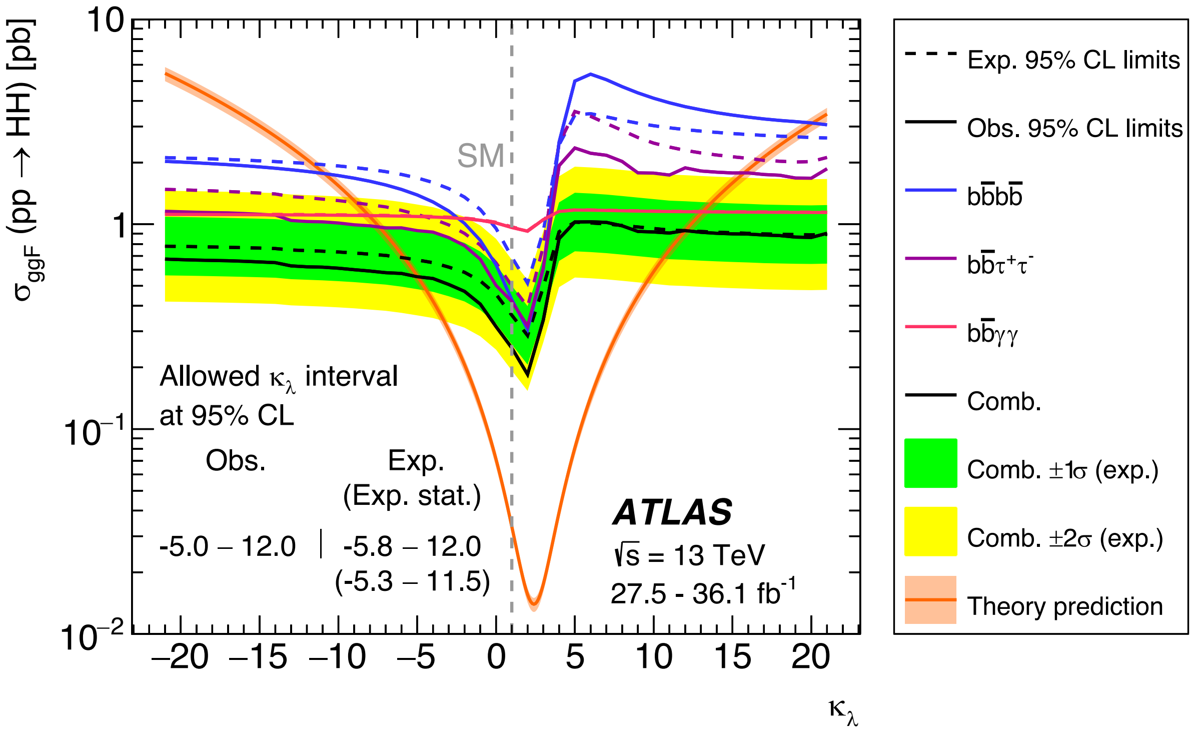
Run 2 searches of Higgs pair production

- Increase in expected event yields due to luminosity increase of cross-section with energy
- Six final state investigated
- Search for SM, and BSM non-resonant and resonant di-Higgs production



Physics Letters B 800 (2020) 135103

Run 2 limits on κ_λ



Exclusion for κ_λ already similar to HL-LHC prospects!

- Three most sensitive channels selected for κ_λ studies: $hh \rightarrow bb\tau\tau$, $\gamma\gamma bb$, $bbbb$
- Sensitivity to κ_λ comes from shapes of discriminating variables and signal acceptance
- Allowed κ_λ interval at 95% CL from the combination:

[-5.0, +12.1] (expected) and

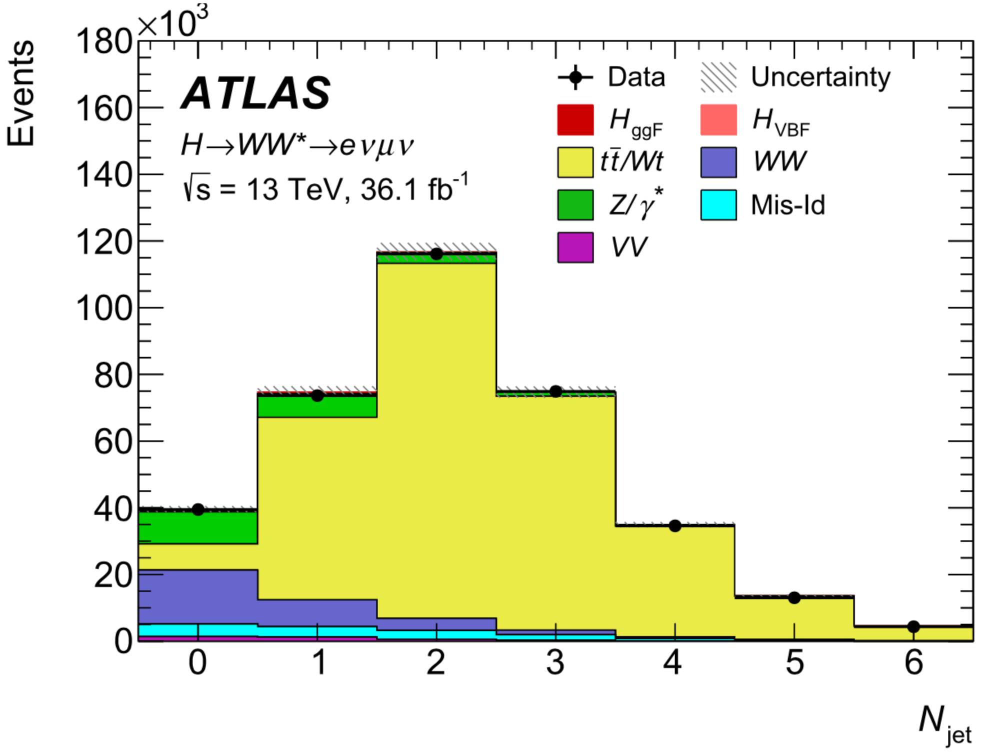
[-5.8, 12.0] (observed)

$h \rightarrow WW^*$

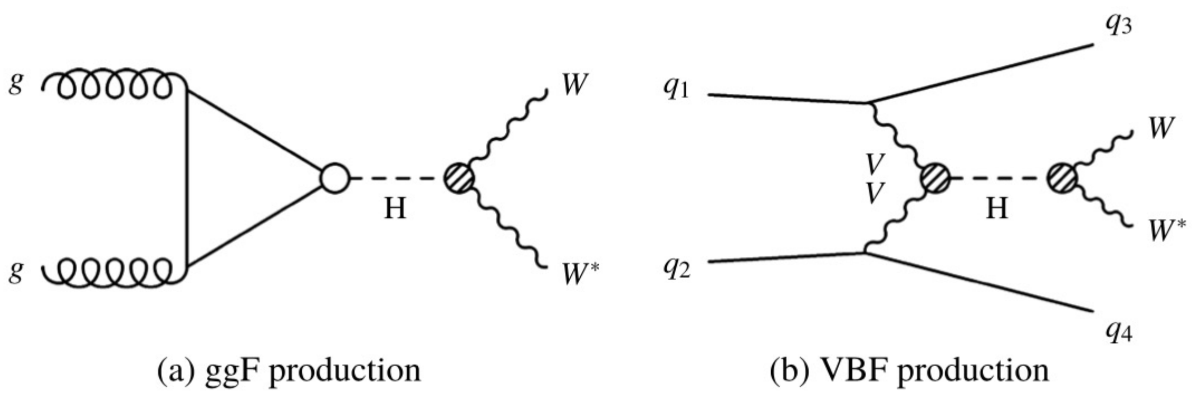
Physics Letters B 789 (2019) 508–529

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)
  - vector boson fusion Higgs production (VBF)



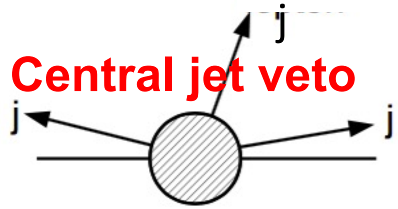
QCD versus electroweak Higgs production



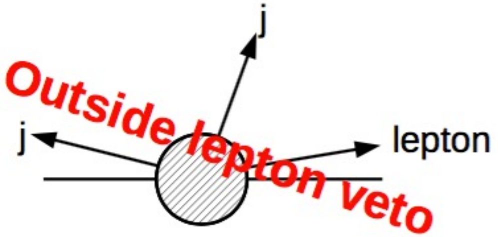
(a) ggF production (b) VBF production

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)

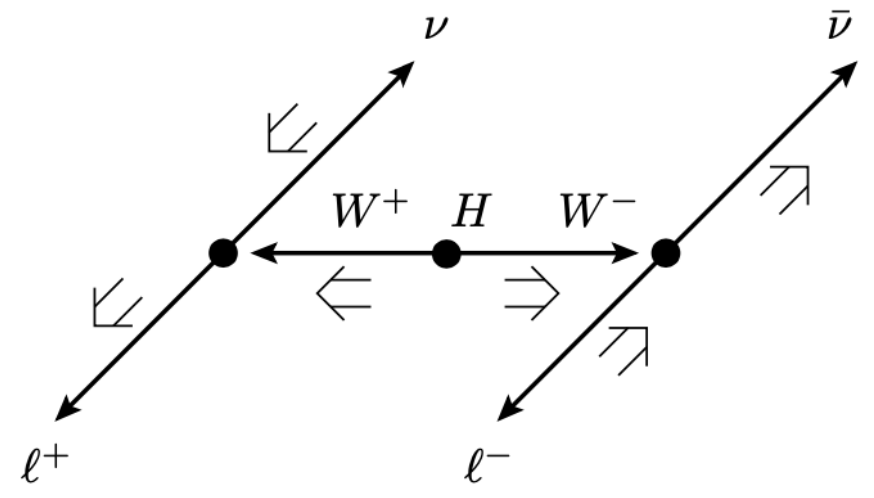


h→ WW* → eν $\mu\nu$ final state

- 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

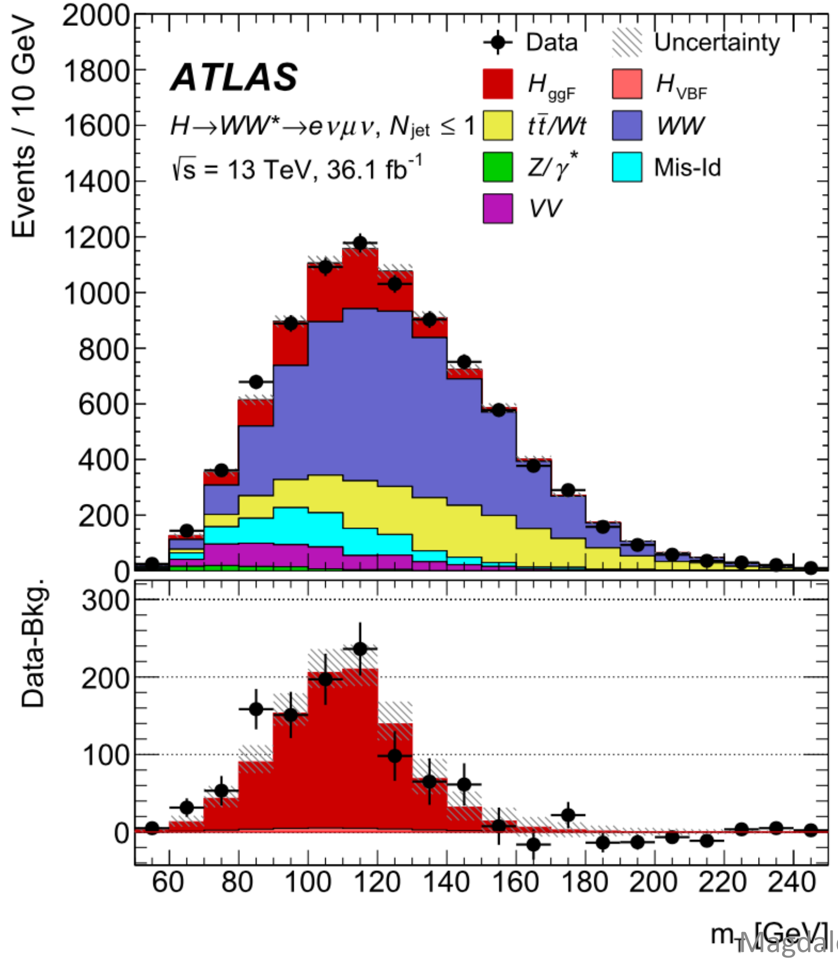
$$m_{\mathrm{T}} = \sqrt{\left(E_{\mathrm{T}}^{\ell\ell} + E_{\mathrm{T}}^{\mathrm{miss}}\right)^2 - \left|\mathbf{p}_{\mathrm{T}}^{\ell\ell} + \boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}\right|^2}$$



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

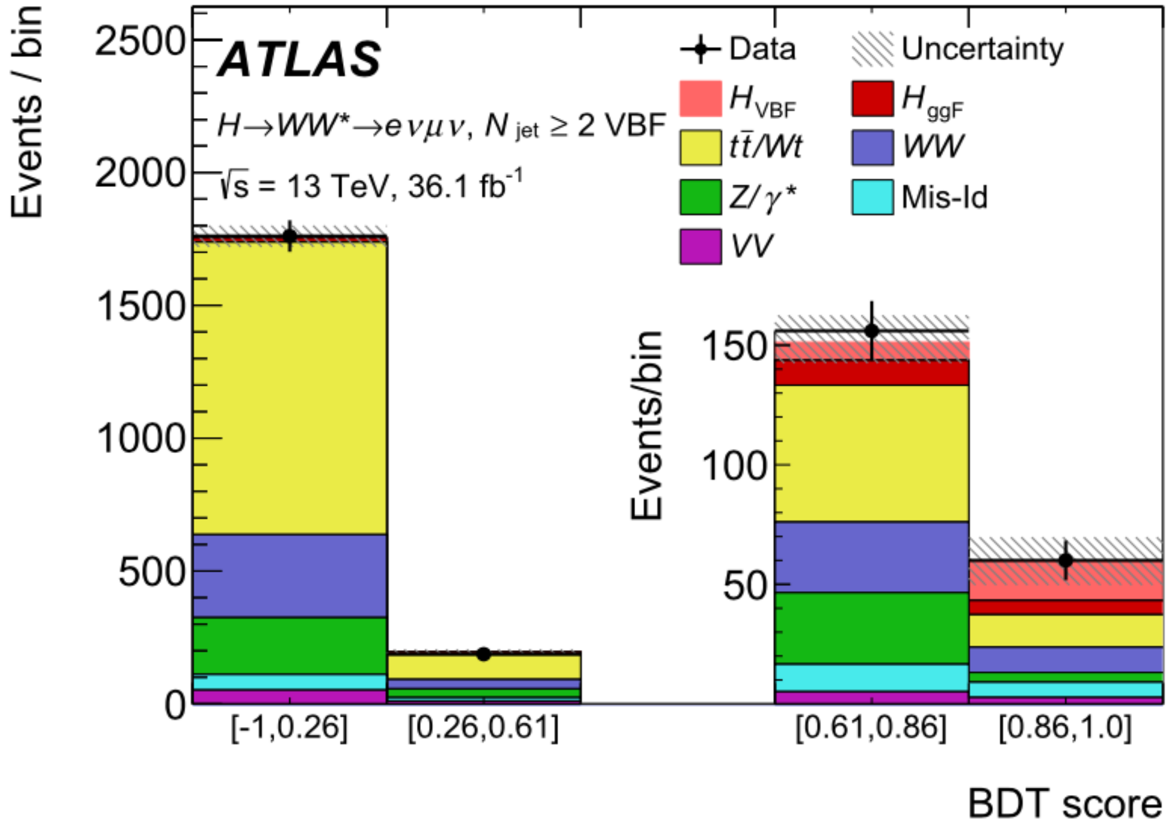
m_T distribution in ggf and ggf+1j

Events with up to 1 jet combined in one signal region



Machine Learning techniques adopted in VBF

Four signal regions ranked by sensitivity to signal

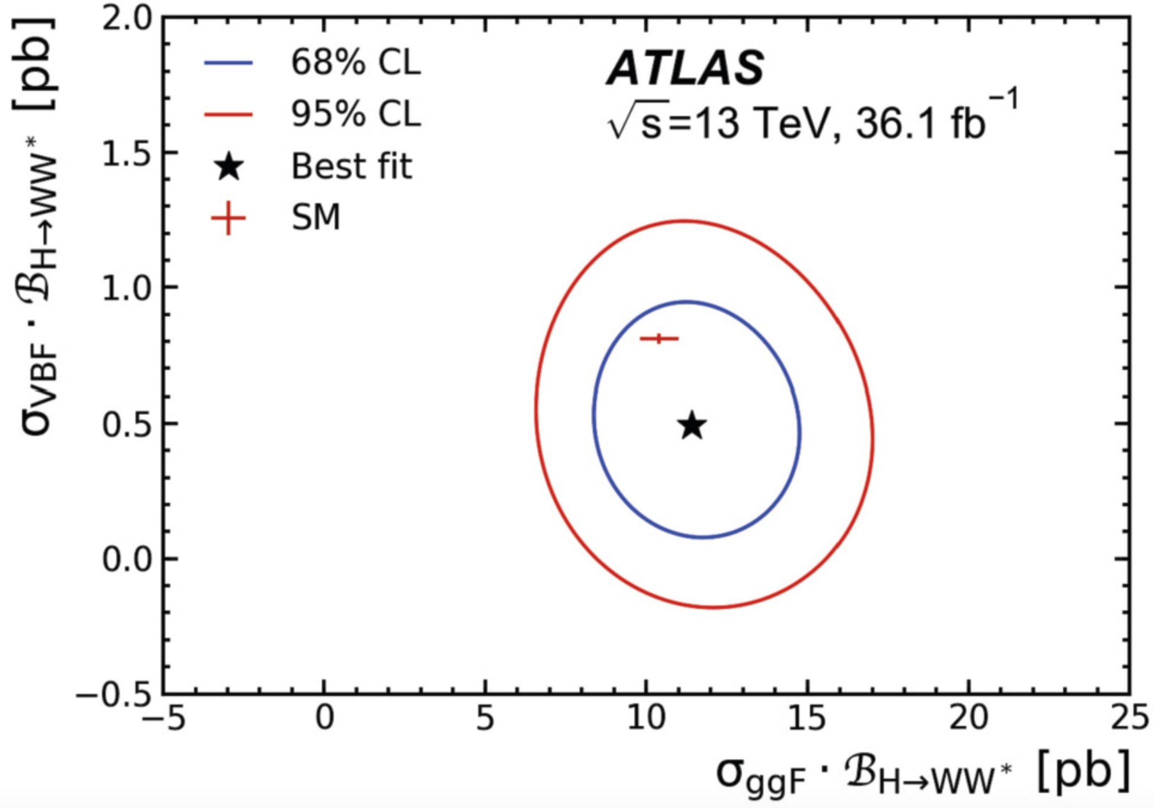


Cross-sections measurements

- Measured cross-section times branching fractions are:

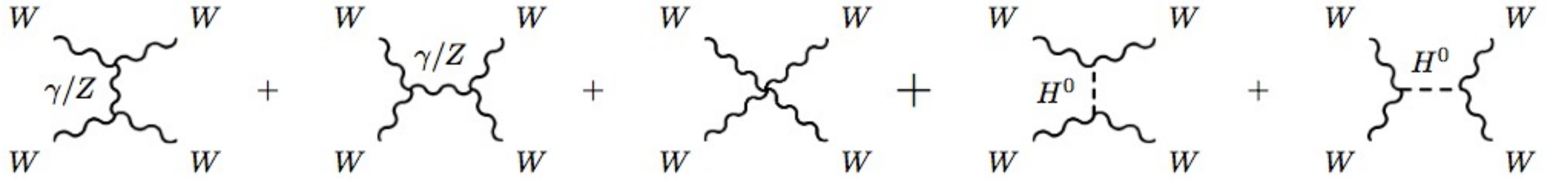
$$\sigma_{\text{ggF}} \cdot \mathcal{B}_{H\to WW^*}$$
$$= 11.4^{+1.2}_{-1.1}(\text{stat.})^{+1.2}_{-1.1}(\text{theo syst.})^{+1.4}_{-1.3}(\text{exp syst.})\ \text{pb}$$
$$= 11.4^{+2.2}_{-2.1}\ \text{pb}$$

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



- Measured values are consistent with SM predictions.

VBF H→ WW* is a part of $W_L W_L$ scattering

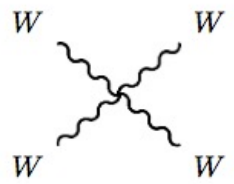


It can test unitarity of the SM elektroweak symmetry breaking

- The Higgs mechanism introduces masses of gauge bosons and their longitudinal polarisations

$$e^{\mu}_{\pm} = \frac{1}{\sqrt{2}}(0, 1, \pm i, 0), \quad e^{\mu}_{L} = \frac{\sqrt{s}}{2M_W}(\beta, 0, 0, 1)$$

- As a consequence $W_L W_L$ scattering amplitude diverges with center of mass energy $O(s^2)$



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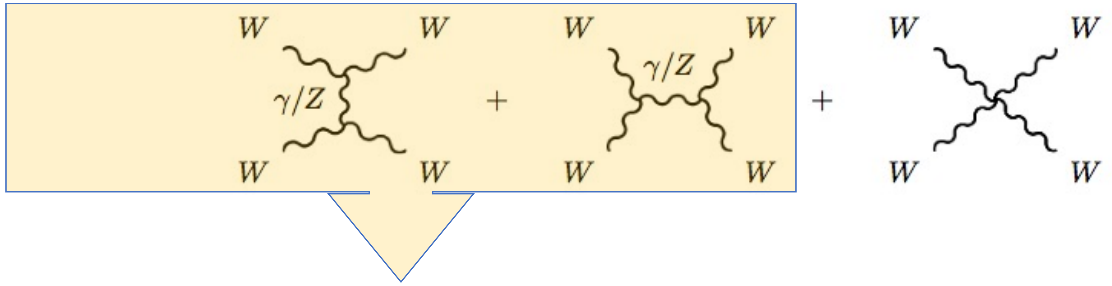

- The addition of diagrams with other gauge bosons

  leaves O(s) divergence

- The Higgs mechanism introduces masses of gauge bosons and their longitudinal polarisations

$$e^\mu_\pm = \frac{1}{\sqrt{2}}(0,1,\pm i,0), \quad e^\mu_L = \frac{\sqrt{s}}{2M_W}(\beta,0,0,1)$$

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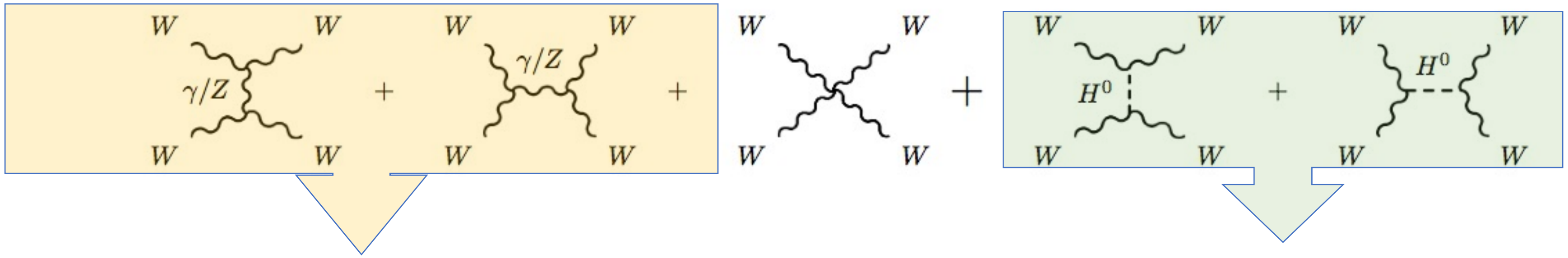
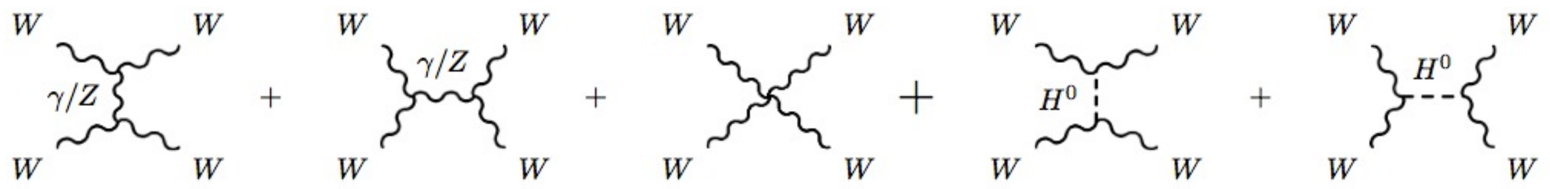


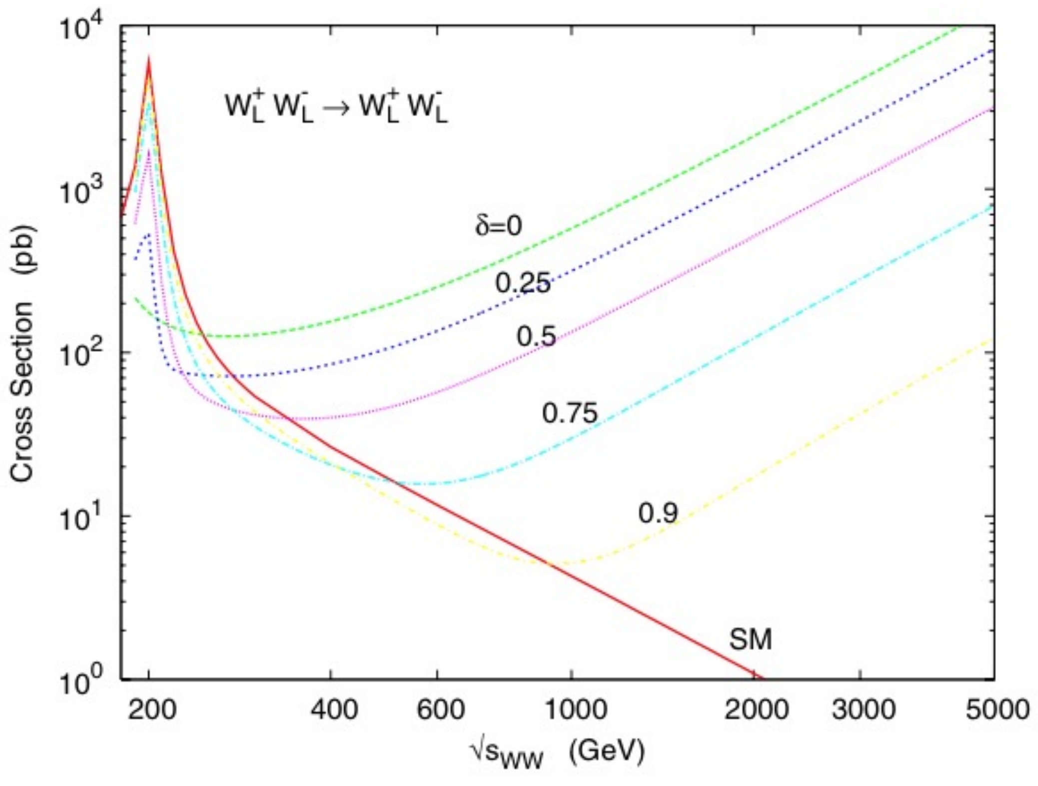
- The addition of other gauge diagrams leaves O(s) divergence,

subtracted by Higgs diagrams if $g_{HVV}=g_V\ m_{VV}$ (gauge invariance requirement)

VBF H→ WW* is a part of $W_L W_L$ scattering

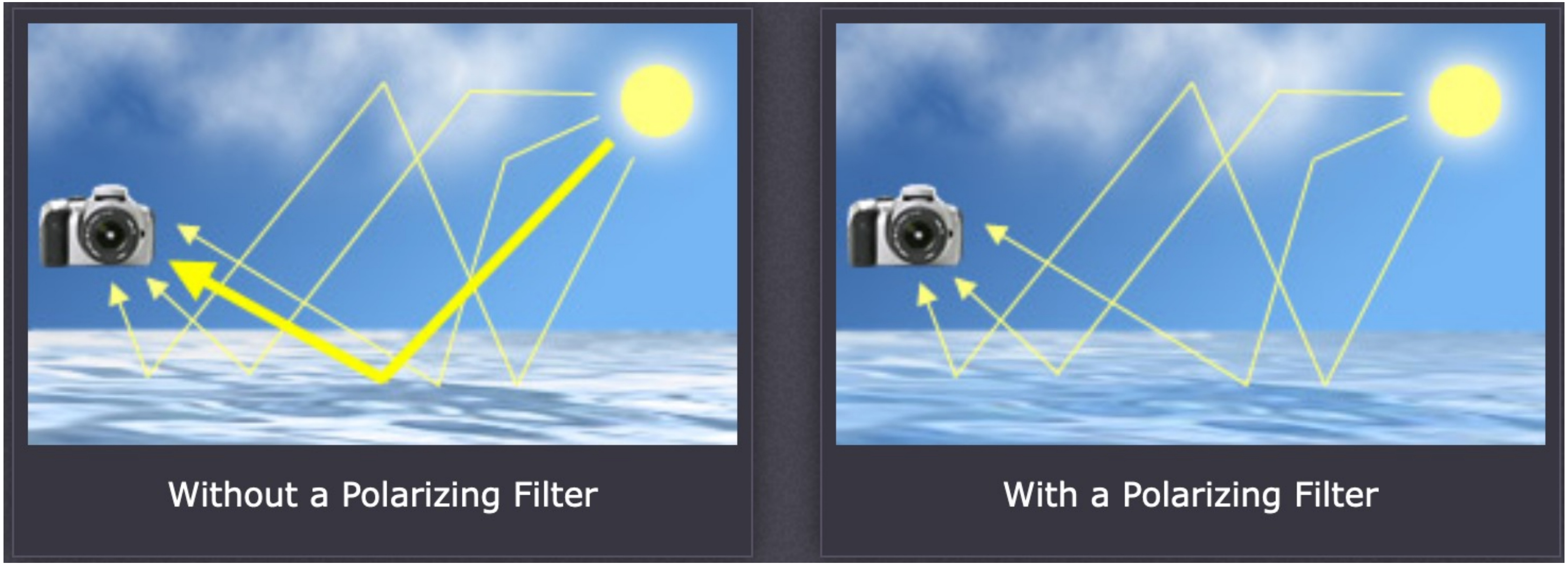


Deviation of $g_{HVV}=g_V\, m_{VV}$ results in non-unitarity of the SM:
At large energies cross-section is infinite!



PHYS.REV.D 78, 051701(R) (2008)

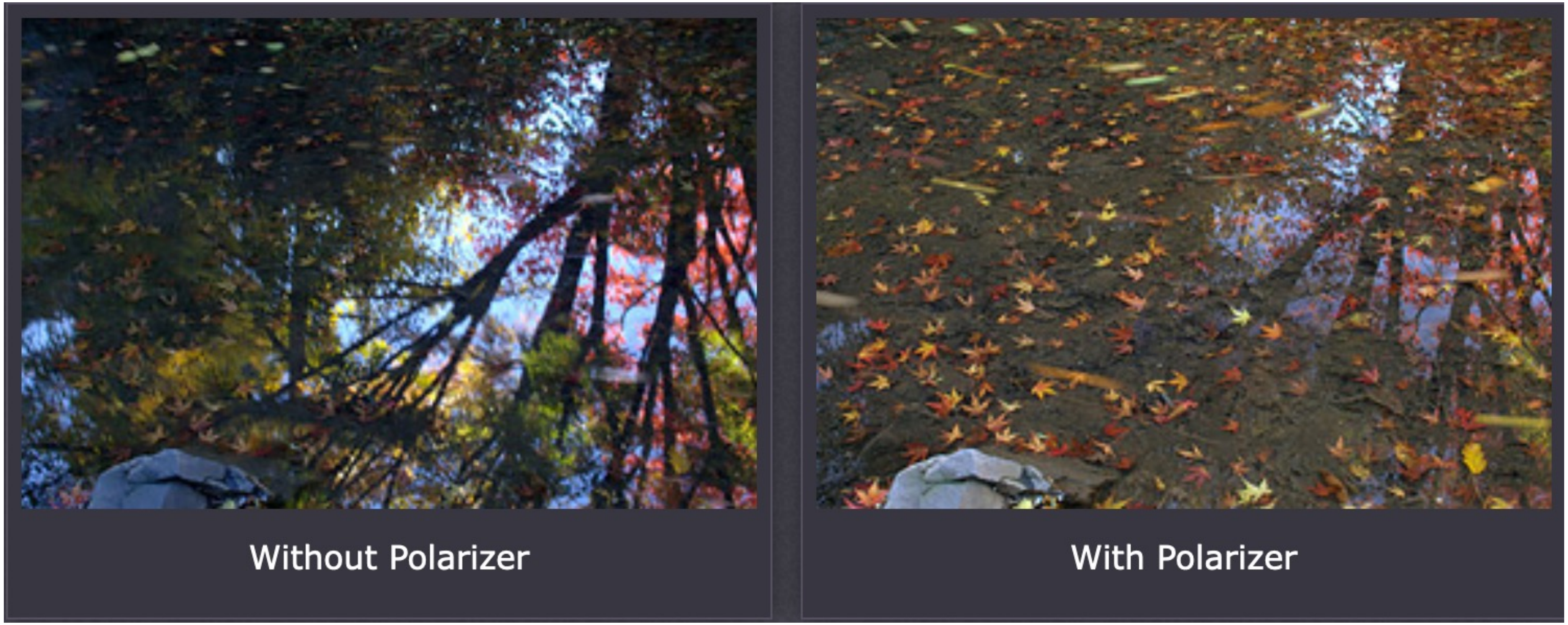
How to probe $W_L W_L$ scattering at smaller energies?



https://www.cambridgeincolour.com/tutorials/polarizing-filters.htm

- See also public briefing: https://atlas.cern/updates/briefing/refining-picture-higgs-boson

How to probe $W_L W_L$ scattering at smaller energies?



https://www.cambridgeincolour.com/tutorials/polarizing-filters.htm

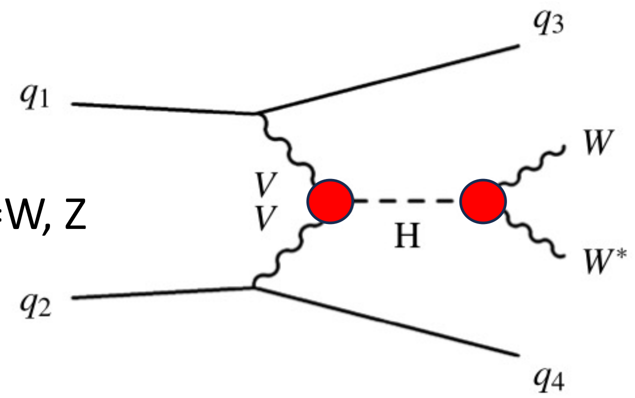
- See also public briefing: https://atlas.cern/updates/briefing/refining-picture-higgs-boson

BSM parametrisation

Anomalous couplings parametrised with

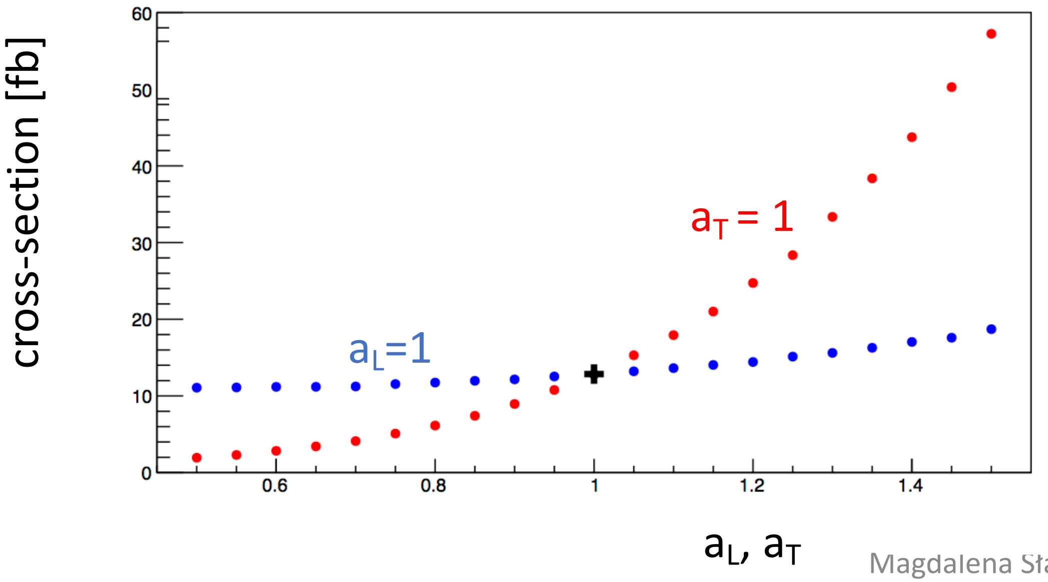
$a_L = g_{HVLVL}/g_{HVV}$ and $a_T = g_{HVTVT}/g_{HVV}$

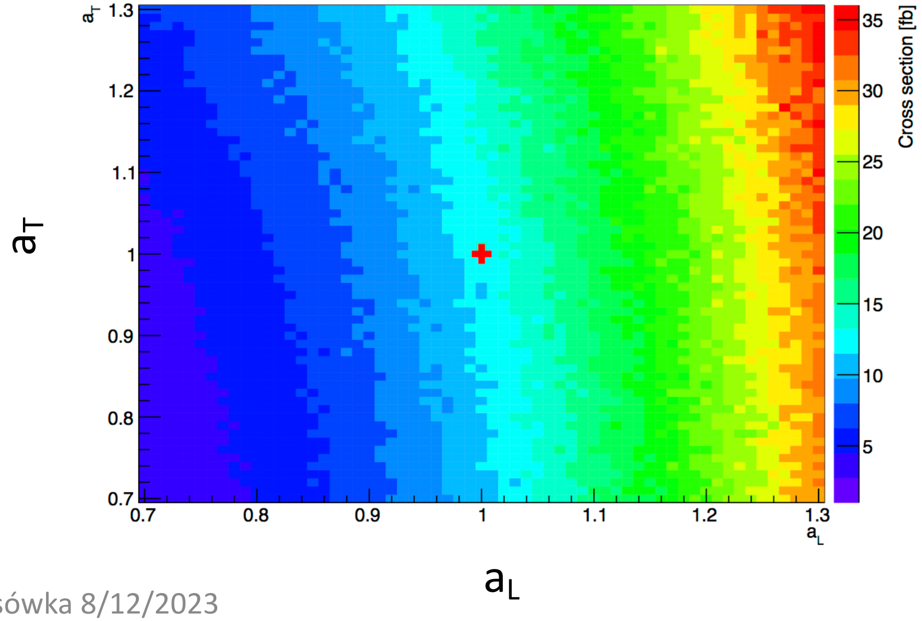
V=W, Z



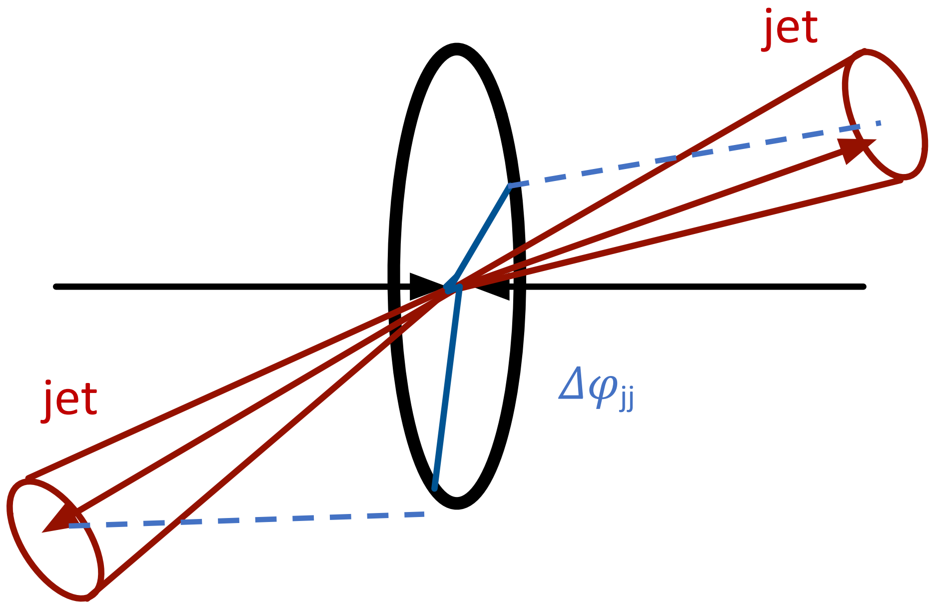
and defined in the Higgs rest frame so that only HV_LV_L and HV_TV_T are present. In the SM $a_L = a_T = 1$.

following Phys.Rev. D90 (5) (2014) 054023 (2014),arXiv:1404.5951



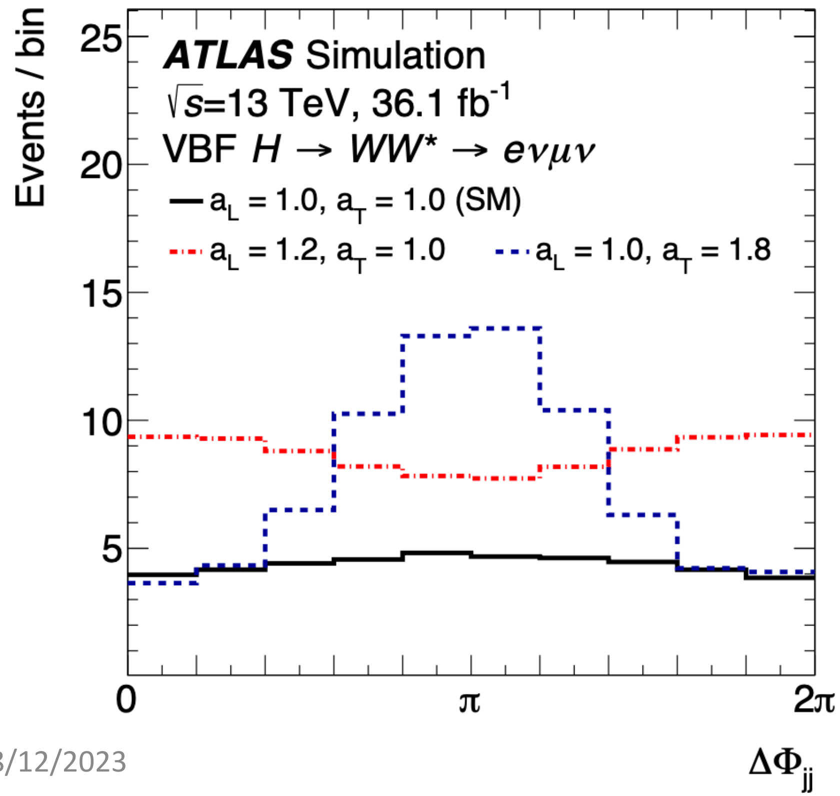


Kinematical effects of coupling modifications



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

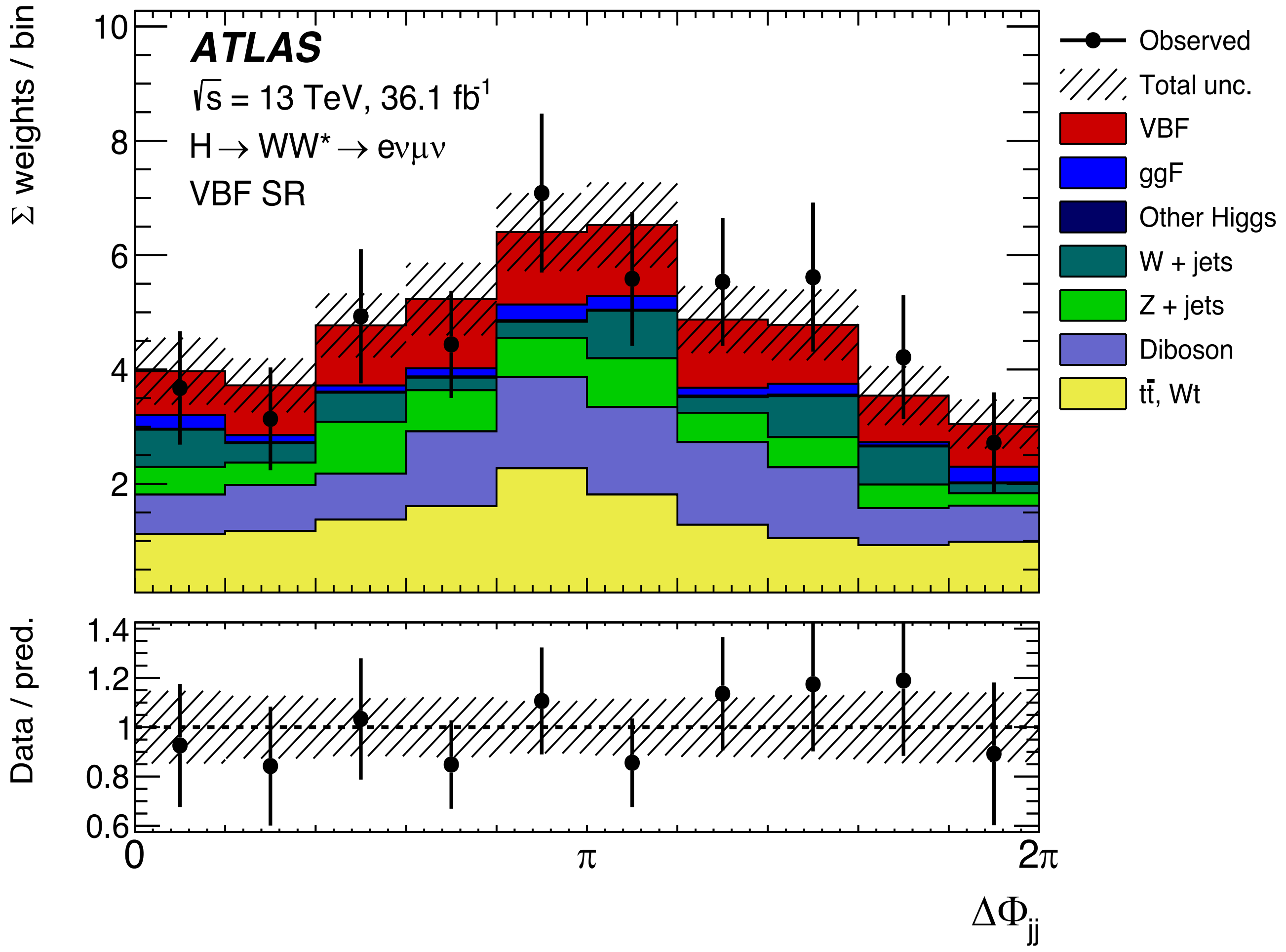
$\Delta\varphi_{jj} = \varphi_{j1} - \varphi_{j2}$ if $\eta_{j1} > \eta_{j2}$, and $\varphi_{jj} = \varphi_{j2} - \varphi_{j1}$ otherwise



- Total rates σ_{VBF} x Br(h->WW sensitive to a_L because VBF is dominated by longitudinal W scattering at high energies.
- Signed $\Delta\varphi_{jj}$ is sensitive to (a_L - a_L).

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.

Conclusions and outlook

- Discovery of the Higgs boson opened up new direction to study th mechanism of electroweak symmetry breaking
- Challenging measurement of Higgs self coupling is being improved
- First measurements of Higgs couplings to longitudinally and transversally polarised electroweak bosons complete.
- Combinations of various final states as well as Higgs and electroweak processes are vital in maximising research potential of the LHC experiments and future colliders.

Publication list

Published papers:

1. ATLAS Collaboration, **"Constraints on Higgs boson properties using $WW^*(\to e\nu\mu\nu)jj$ production in 36.1 fb^{-1} at $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector"**
   Eur. Phys. J. C 82 (2022), no. 7 622,
   arXiv:2212.0583 [hep-ex].

2. **"Measurements of gluon-gluon fusion and vector-boson fusion Higgs boson production cross-sections in the $H \to WW^* \to e\nu\mu\nu$ decay channel in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector"**
   M. Aaboud *et al.* [ATLAS Collaboration].
   Phys. Lett. B 789 (2019) 50829,
   arXiv:1808.09054 [hep-ex]
   DOI:10.1016/j.physletb.2018.11.064
   Phys. Lett. B **789**, 508 (2019)
   CERN-EP-2018-212

3. ATLAS Collaboration, **"Search for Higgs boson pair production in the $\gamma\gamma b\bar{b}$ final stat**
   13 TeV pp collision data collected by the ATLAS experiment"
   arXiv:1807.04873 [hep-ex]
   DOI:10.1007/JHEP11(2018)040
   JHEP **1811**, 040 (2018)
   CERN-EP-2018-130

4. M. Slawinska, **"High-luminosity LHC prospects with the upgraded ATLAS detector"**
   arXiv:1609.08434 [hep-ex]
   DOI:10.22323/1.265.0266
   PoS DIS **2016**, 266 (2016)
   ATL-PHYS-PROC-2016-152

5. ATLAS Collaboration, **"Searches for Higgs boson pair production in the $hh \to bb\tau\tau, \gamma\gamma W$**
   channels with the ATLAS detector"
   arXiv:1509.04670 [hep-ex]
   DOI:10.1103/PhysRevD.92.092004
   Phys. Rev. D **92**, 092004 (2015)
   CERN-PH-EP-2015-225

Preprints and internal notes of the ATLAS Collaboration:

1. **"Combination of searches for Higgs boson pairs in pp collisions at 13 TeV with the ATLAS experiment."**
   ATLAS-CONF-2018-043, September 2018,

2. **"Search for Higgs boson pair production in the $b\bar{b}\gamma\gamma$ final state using pp collision data at $\sqrt{s} = 13$ TeV with the ATLAS detector"**
   The ATLAS Collaboration ,
   ATLAS-CONF-2016-004, March 2016,

3. **"Prospects for measuring Higgs pair production in the channel $H(\to \gamma\gamma)H(\to b\bar{b})$ using the ATLAS detector at the HL-LHC"**
   The ATLAS Collaboration,
   ATL-PHYS-PUB-2014-019, October 2014, ,

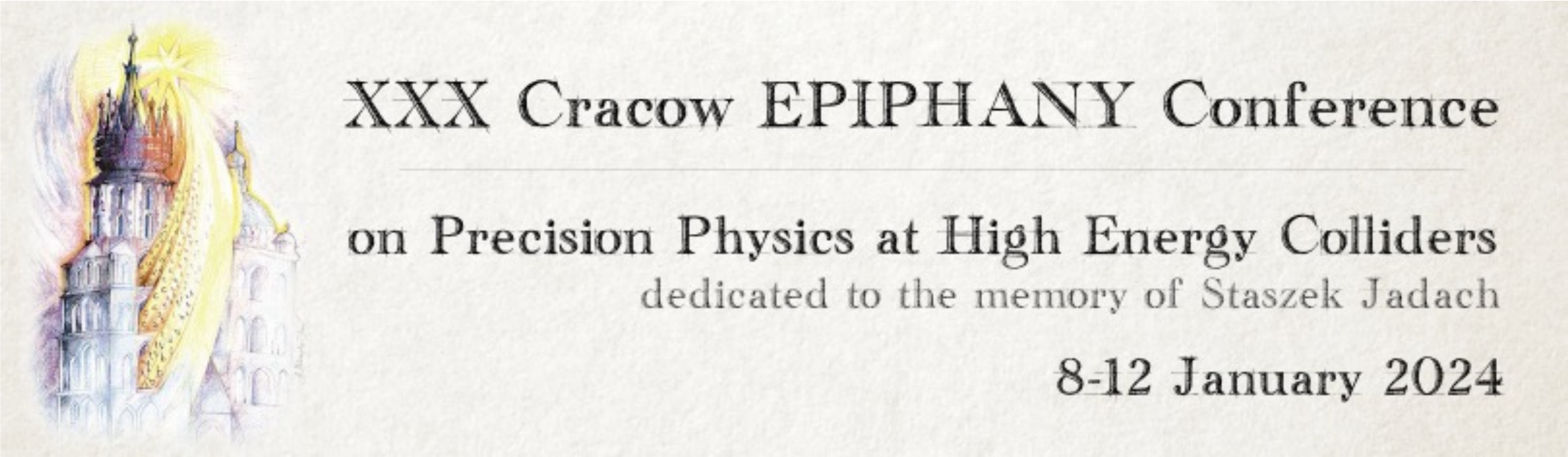
4. **"Phenomenology of the trilinear Higgs coupling at proton-proton colliders"**
   M. Slawinska, W. van den Wollenberg, B. van Eijk and S. Bentvelsen.
   arXiv:1408.5010 [hep-ph]
   NIKHEF-2014-029

Monographs:

1. **"VBSCan Thessaloniki 2018 Workshop Summary"**
   R. Bellan *et al.*.
   arXiv:1906.11332 [hep-ph]
   VBSCAN-PUB-05-19, DESY-19-108, Nikhef/2019-025, UWThPh 2019-20

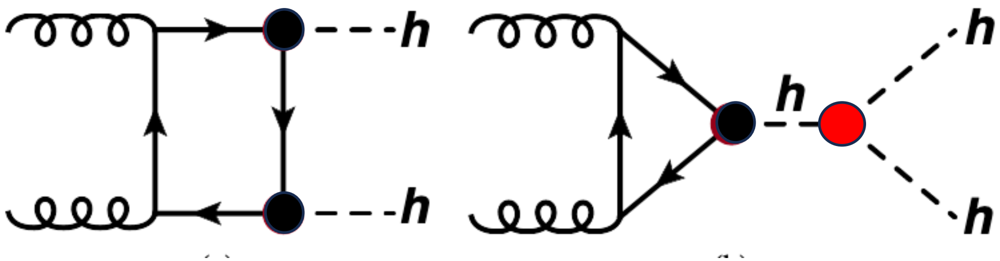
2. **"Vector boson scattering: Recent experimental and theory developments"**
   C. F. Anders *et al.*.
   arXiv:1801.04203 [hep-ph]
   DOI:10.1016/j.revip.2018.11.001
   Rev. Phys. **3**, 44 (2018)
   VBSCAN-PUB-01-17, FERMILAB-CONF-18-021-PPD, VBSCan-PUB-01-17 [?]

3. **"Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector"**
   D. de Florian *et al.* [LHC Higgs Cross Section Working Group].
   arXiv:1610.07922 [hep-ph]
   DOI:10.2172/1345634, 10.23731/CYRM-2017-002
   FERMILAB-FN-1025-T, CERN-2017-002-M


XXX Cracow EPIPHANY Conference
on Precision Physics at High Energy Colliders
dedicated to the memory of Staszek Jadach
8-12 January 2024

Backup

Predictions for Higgs pairs production through gluon fusion



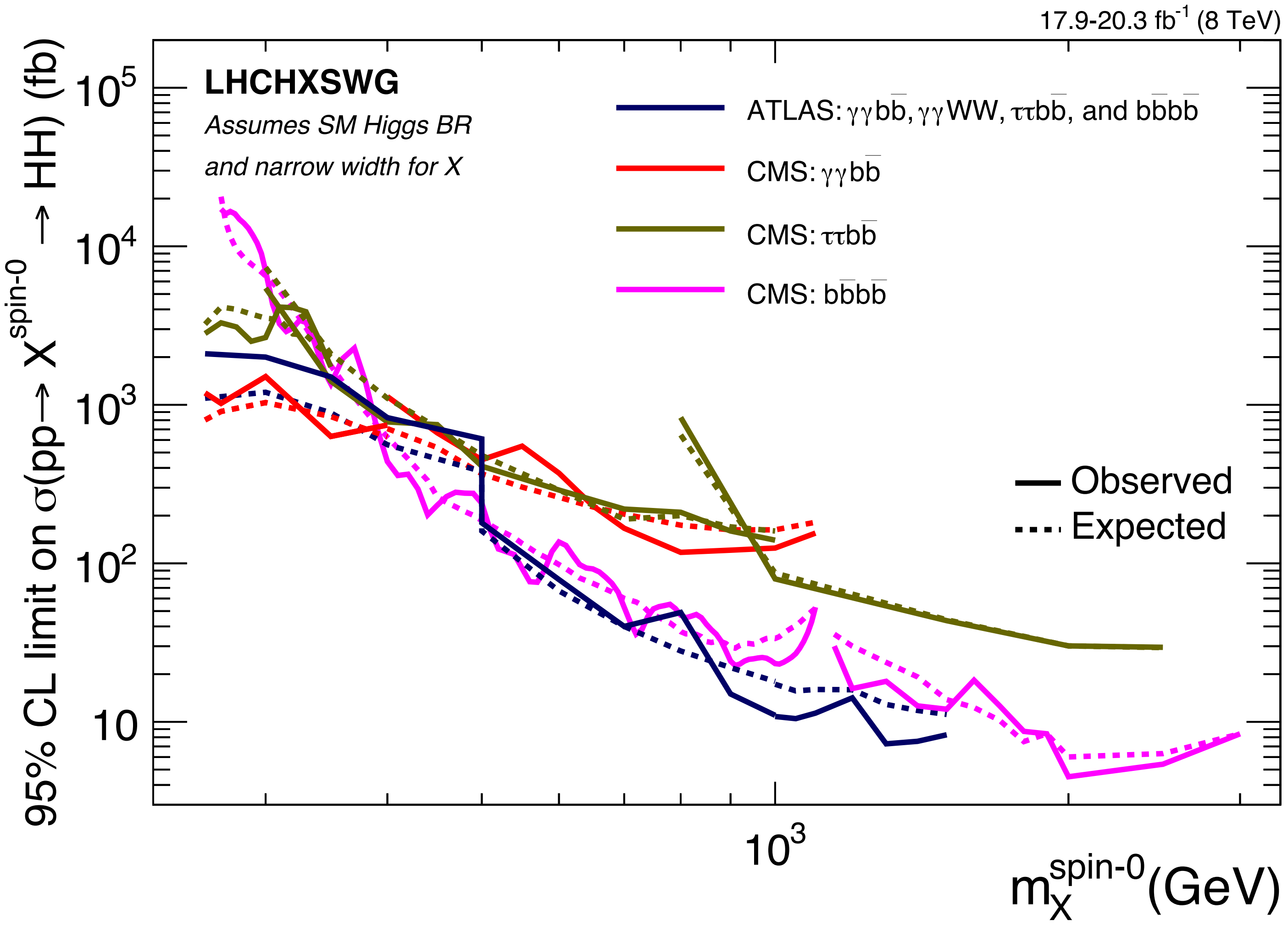
x4

x3

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

LHCHXSWG YR4, arXiv:1610.07922v2,
based on: arXiv:1505.07122, arXiv:1604.06447

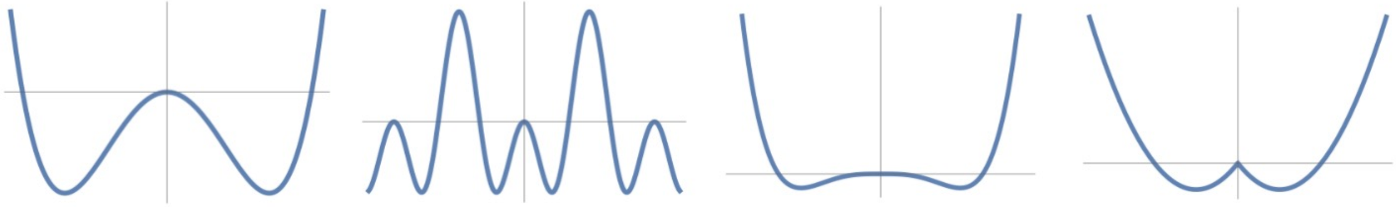
Run 1 summary: ATLAS and CMS



Slawinska et al, *Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector*

Phys. Rev. D 101, 075023 (2020)

SM as an effective field theory



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

SM+SMEFT

(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.

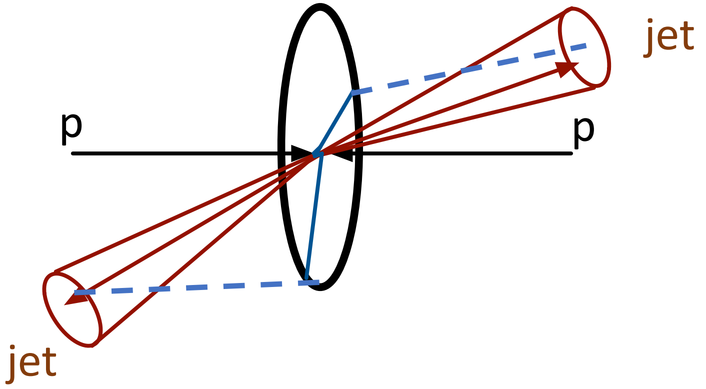
(c) describes Coleman-Weinberg Higgs boson, with EWSB resulting from renormalization group running effects

(d) a tadpole-induced Higgs and its mass parameter is positive.

Methodology

- **Signal signature:** two (forward) jets, two different flavor opposite sign leptons, no b-quarks
- **Main backgrounds**:
  - double and single top,
  - Z+2jets,
  - WW
  - other dibosons
- **Signal optimisation:** several signal categories, separately for each analysis, using BDTs

- Signal modifications sensitive to the distribution of signed $\Delta\varphi_{jj}$ between jets in the plane perpendicular to the beam axis



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

Coupling modifiers and dim-6 EFT operators

$$\mathcal{L}_{SM} = (\mathbf{D}_\mu \phi)^\dagger \mathbf{D}^\mu \phi$$

$$\mathcal{L}_{\phi W} = -\frac{g^2 F_{\phi W}}{4} \left(\phi^\dagger \phi - \frac{v^2}{2} \right) \mathrm{tr}\left[\mathbf{W}_{\mu\nu} \mathbf{W}^{\mu\nu} \right] ,$$

$$\mathcal{L}_\phi = F_{HD} \left(\phi^\dagger \phi - \frac{v^2}{2} \right) \left((\mathbf{D}_\mu \phi)^\dagger \mathbf{D}^\mu \phi \right) .$$

$$a_T = 1 + \frac{v^2 F_\phi}{2} + F_{\phi W} q_1 \cdot q_2 ,$$

$$a_L = 1 + \frac{v^2 F_\phi}{2} + F_{\phi W} \frac{q_1^2 q_2^2}{q_1 \cdot q_2} .$$

Mapping between (a_L and a_T) and EFT operators momentum dependent. EFT kinematics can be reproduced fitting a_L and a_T (see 1404.5951)
Independent variations in (a_L and a_T) not possible in the dimension-6 set of EFT operators

Mapping to Pseudo-Observables

Eur. Phys. J. C 75 (2015) 128, arXiv:1412.6038 [hep-ph]

Signal paraletrised using (a_L, a_T) couplings scale factors is not Lorentz invariant.

Approximate(*) mapping to Pseudo Observables:

$$\boxed{\begin{gathered} a_L = \kappa_{VV} + \Delta_L(q_1, q_2)\epsilon_{VV}, \quad a_T = \kappa_{VV} + \Delta_T(q_1, q_2)\epsilon_{VV}. \\ \kappa_{VV} = a_\mathrm{L} - \Delta_\mathrm{L}(q_1, q_2)\varepsilon_{VV}, \quad \varepsilon_{VV} = \frac{a_\mathrm{T} - a_\mathrm{L}}{\Delta_\mathrm{T}(q_1, q_2) - \Delta_\mathrm{L}(q_1, q_2)} \end{gathered}}$$

where
$$\Delta_\mathrm{L} = \frac{m_H^2}{2m_W^2}\frac{4q_1^2 q_2^2}{m_H^2(m_H^2 - q_1^2 - q_2^2)}, \quad \Delta_\mathrm{T} = \frac{m_H^2}{2m_W^2}\frac{m_H^2 - q_1^2 - q_2^2}{m_H^2}.$$

From MG5 simulation the mean values of formfactors for incoming bosons (generator level cuts) are:

$\Delta_L(q_1, q_2) = 0$ and $\Delta_T(q_1, q_2) = 2\,\frac{{m_h}^2}{2{m_V}^2}$

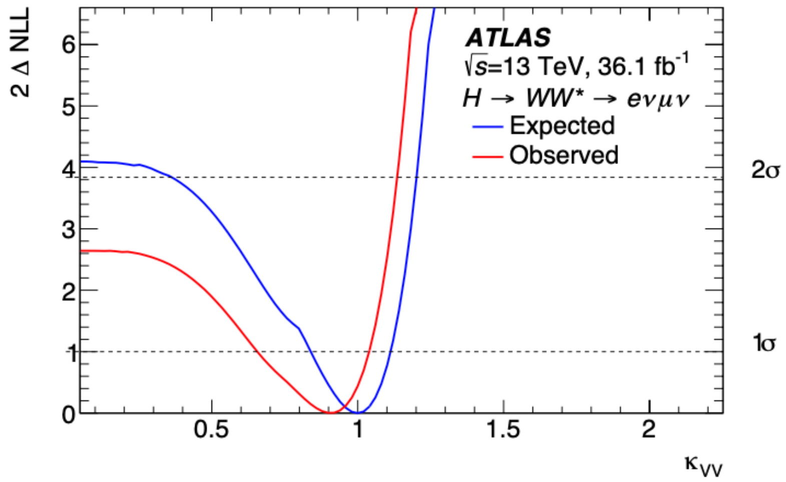
$$\boxed{\kappa_{VV} = a_L, \qquad \varepsilon_{VV} = 0.5\,(a_T - a_L),}$$

In the SM: on-shell coupling $\kappa_{VV} = 1$, off-shell coupling $\varepsilon_{VV} = 0$

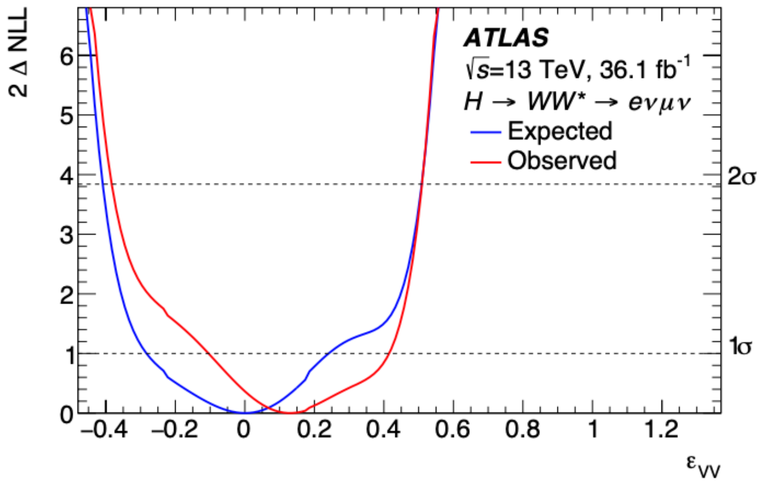
(*) assuming custodial symmetry, no new physics in the boson–fermion couplings Wff and Zff , and a CP-even Higgs boson with CP-conserving HVV interactions.

Results

Type	Expected	Observed
ε_{VV} shape-only fit ($\kappa_{VV}=1$)	$0.00^{+0.23}_{-0.25}\text{(stat.)}^{+0.14}_{-0.17}\text{(syst.)}$	$0.14^{+0.39}_{-0.22}\text{(stat.)}^{+0.16}_{-0.12}\text{(syst.)}$
κ_{VV} shape + rate fit ($\varepsilon_{VV}=0$)	$1.00^{+0.08}_{-0.10}\text{(stat.)}^{+0.08}_{-0.13}\text{(syst.)}$	$0.91^{+0.09}_{-0.12}\text{(stat.)}^{+0.09}_{-0.18}\text{(syst.)}$
ε_{VV} shape + rate fit ($\kappa_{VV}=1$)	$0.00^{+0.18}_{-0.24}\text{(stat.)}^{+0.08}_{-0.13}\text{(syst.)}$	$0.09^{+0.13}_{-0.16}\text{(stat.)}^{+0.06}_{-0.07}\text{(syst.)}$
κ_{VV} shape + rate fit (ε_{VV} profiled)	$1.00^{+0.08}_{-0.10}\text{(stat.)}^{+0.08}_{-0.13}\text{(syst.)}$	$0.91^{+0.10}_{-0.18}\text{(stat.)}^{+0.09}_{-0.17}\text{(syst.)}$
ε_{VV} shape + rate fit (κ_{VV} profiled)	$0.00^{+0.22}_{-0.24}\text{(stat.)}^{+0.11}_{-0.15}\text{(syst.)}$	$0.13^{+0.28}_{-0.20}\text{(stat.)}^{+0.08}_{-0.10}\text{(syst.)}$



(a) κ_{VV} shape+rate fit with profiled ε_{VV}



(b) ε_{VV} shape+rate fit with profiled κ_{VV}