Constraints on the off-shell Higgs coupling and Non-SM Higgs interaction in EFT with Differential X-section

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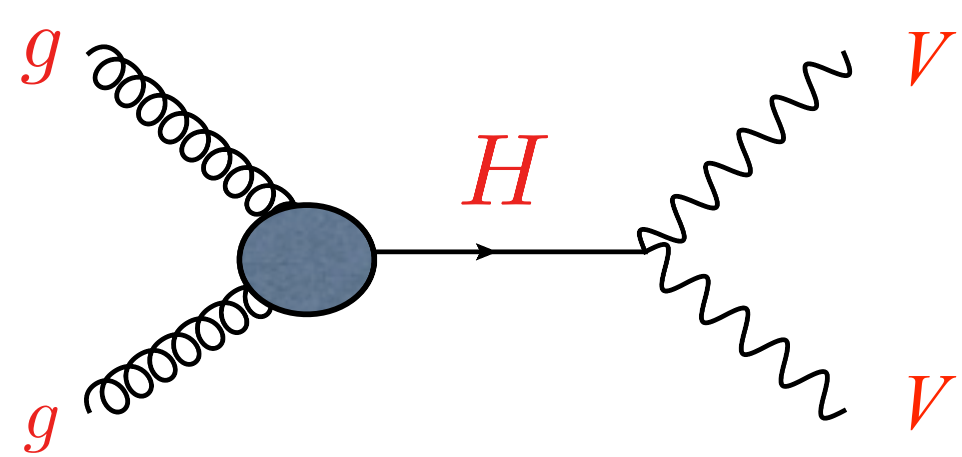
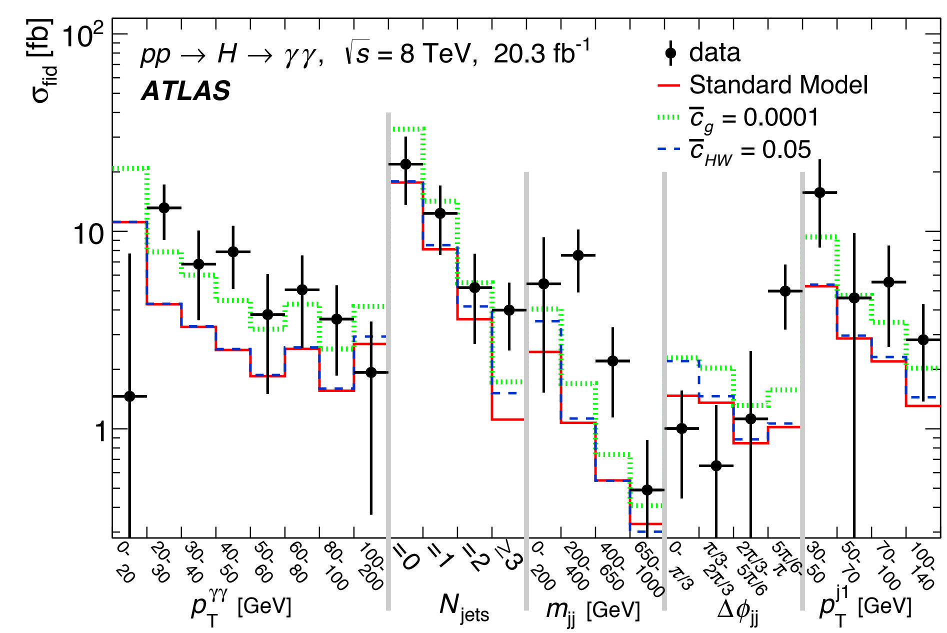


$$\sigma_H(m_{WW} > 160GeV) \approx 0.1\sigma_H$$



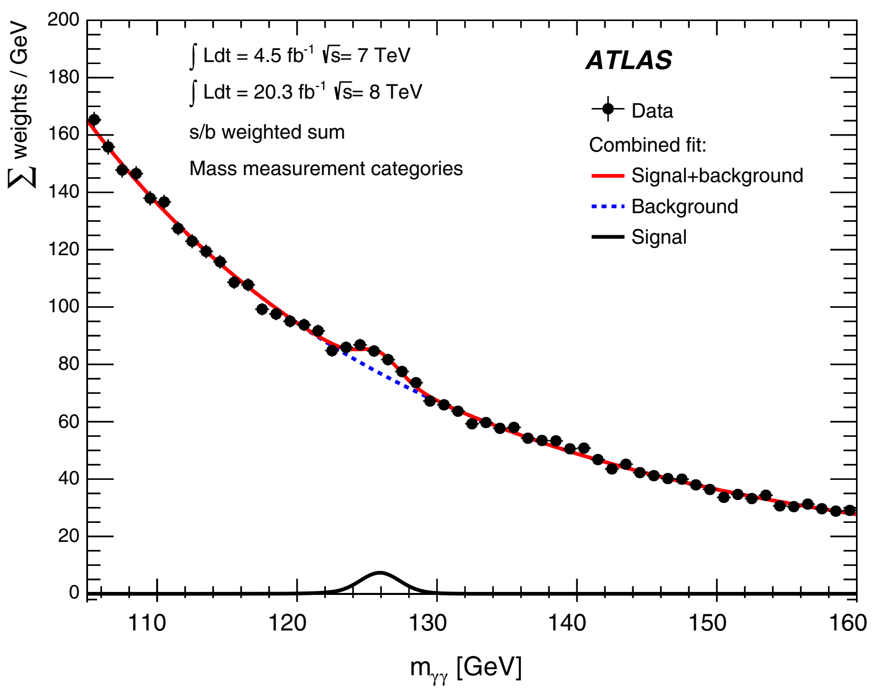
2016, 3. 14

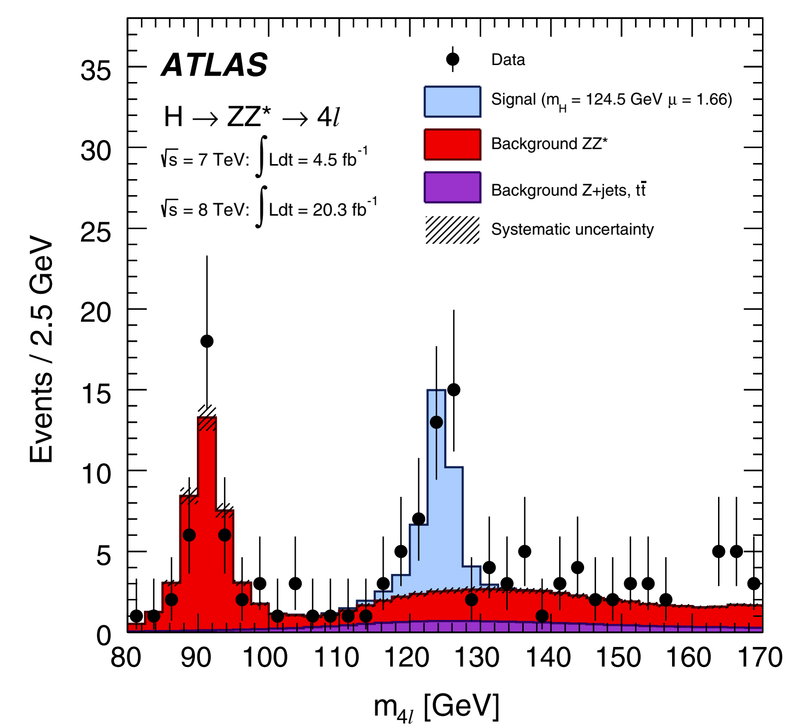
Introduction

- Higgs On-Shell property measurement: Coupling, Spin, width, cross section, etc.
- It is impossible to extract the coupling and Higgs width separately from on-shell property measurement $\rightarrow$ Importance of Γ_H measurement.

$$\sigma_{i\rightarrow H\rightarrow f}^{on-shell}(SM) \sim \frac{g_i^2 g_f^2}{\Gamma_H}$$

- LHC is insensitive to the direct Higgs width measurement (Γ_{SM}~4.2MeV)

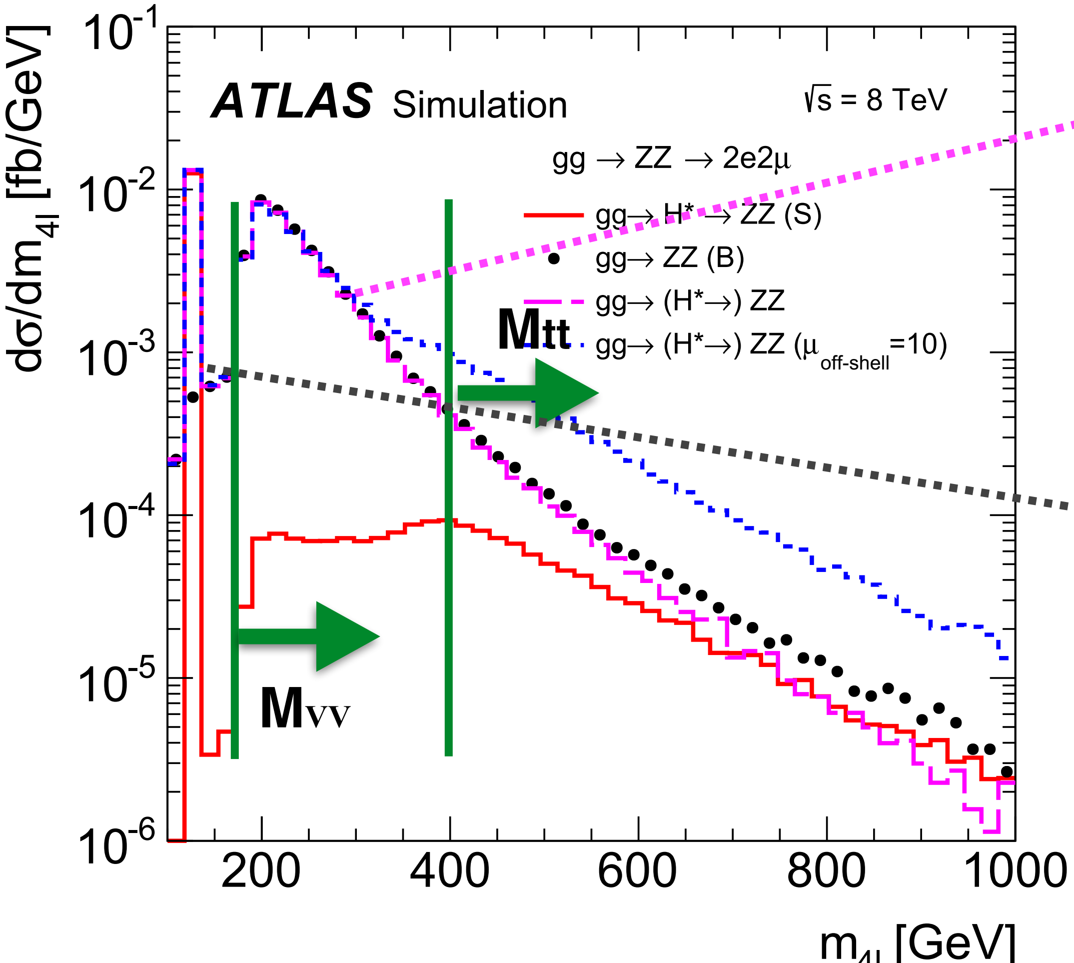




Γ: obs.(exp.)@ 95%	H→γγ	H→ZZ
ATLAS	5.0 (6.2) GeV	2.6 (6.2) GeV
CMS	2.4 (3.1) GeV	3.4 (2.8) GeV

3-order of magnitude larger w.r.t. SM width

Sizeable contribution in off-shell region



$$\mu_{\text{off-shell}}(\hat{s}) \equiv \frac{\sigma^{gg\to H^*\to VV}_{\text{off-shell}}(\hat{s})}{\sigma^{gg\to H^*\to VV}_{\text{off-shell, SM}}(\hat{s})} = \kappa^2_{g,\text{off-shell}}(\hat{s})\cdot\kappa^2_{V,\text{off-shell}}(\hat{s})$$

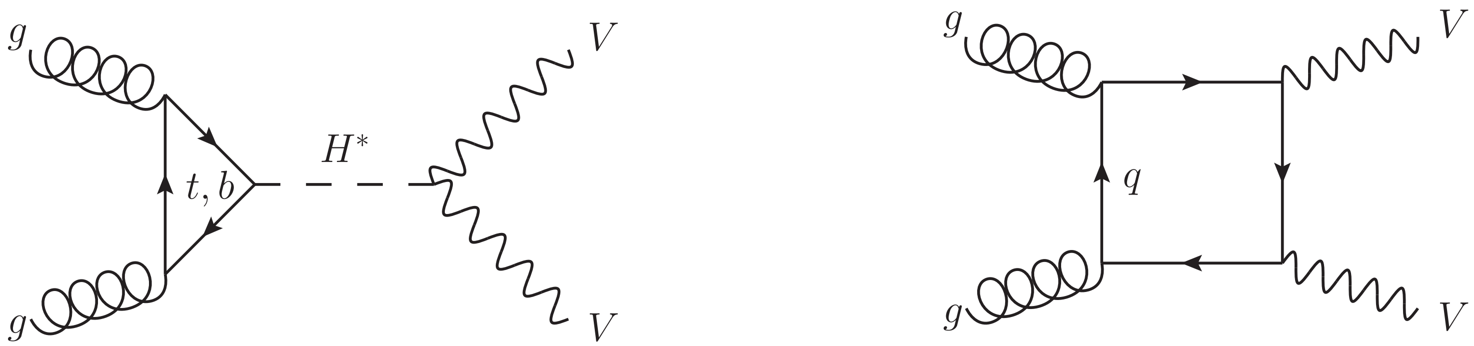
$$\mu_{\text{on-shell}} \equiv \frac{\sigma^{gg\to H\to VV}_{\text{on-shell}}}{\sigma^{gg\to H\to VV}_{\text{on-shell, SM}}} = \frac{\kappa^2_{g,\text{on-shell}}\cdot\kappa^2_{V,\text{on-shell}}}{\Gamma_H/\Gamma_H^{\text{SM}}}$$

$$\mu_{offshell} = \mu_{onshell}\times\Gamma_H/\Gamma_H(SM)$$

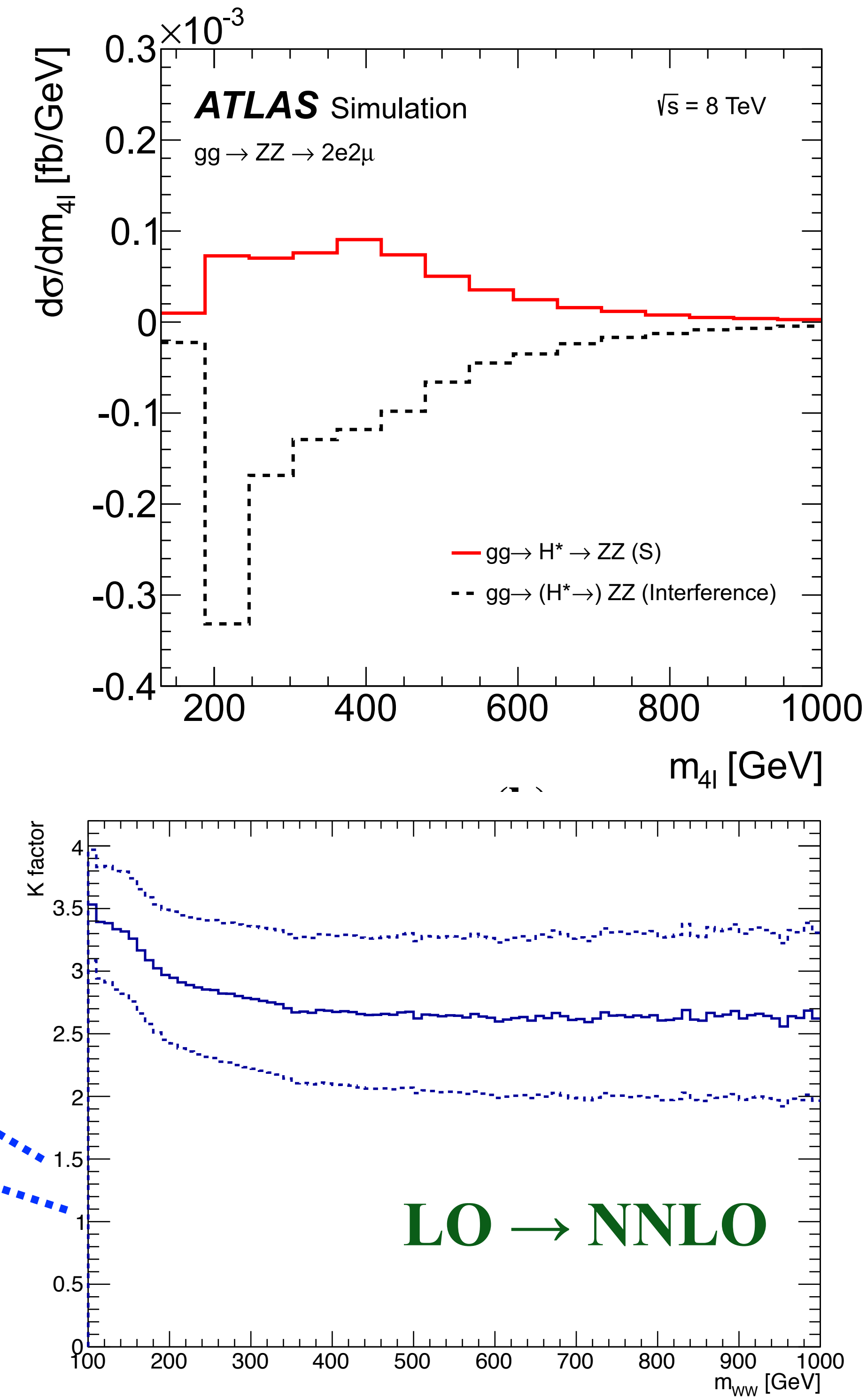
- **Measurement of the Higgs off-shell signal strength.**
- With the combination between on-shell and off-shell analysis:
  - Assuming the on-shell couplings are the same as the off-shell couplings, the coupling measurements can be reinterpreted as the **constraints on Γ_H**.
  - Assuming SM Higgs width, it can be reinterpreted as the **constraints on off-shell and on-shell coupling ratio**

MC simulation

Significant destructive signal-background interference



$$\sigma_{gg\to(H^*\to)VV}(\mu_{\text{off-shell}}) = \mathrm{K}^{H^*}(m_{VV})\cdot\mu_{\text{off-shell}}\cdot\sigma^{\text{SM}}_{gg\to H^*\to VV} + \sqrt{\mathrm{K}^{H^*}_{gg}(m_{VV})\cdot\mathrm{K}^{\text{B}}(m_{VV})\cdot\mu_{\text{off-shell}}}\cdot\sigma^{\text{SM}}_{gg\to VV,\,\text{Interference}} + \mathrm{K}^{\text{B}}(m_{VV})\cdot\sigma_{gg\to VV,\,\text{cont}}\cdot$$



- ✦ LO MCFM/gg2VV+Py8 is used for ggF:
  - Apply a M_{VV} dependence K-factor to NNLO prediction
  - Apply a p_{TVV} shape correction to Sherpa.
- gg→VV **only known to LO**, but believed related to signal rate:

$$R^{B}_{H^*} = \frac{\mathrm{K}(gg\to VV)}{\mathrm{K}(gg\to H^*\to VV)} = \frac{\mathrm{K}^{B}(m_{VV})}{\mathrm{K}^{H^*}_{gg}(m_{VV})}$$

varying between 0.5 and 2.0

- ✦ MG5 is used for VBF

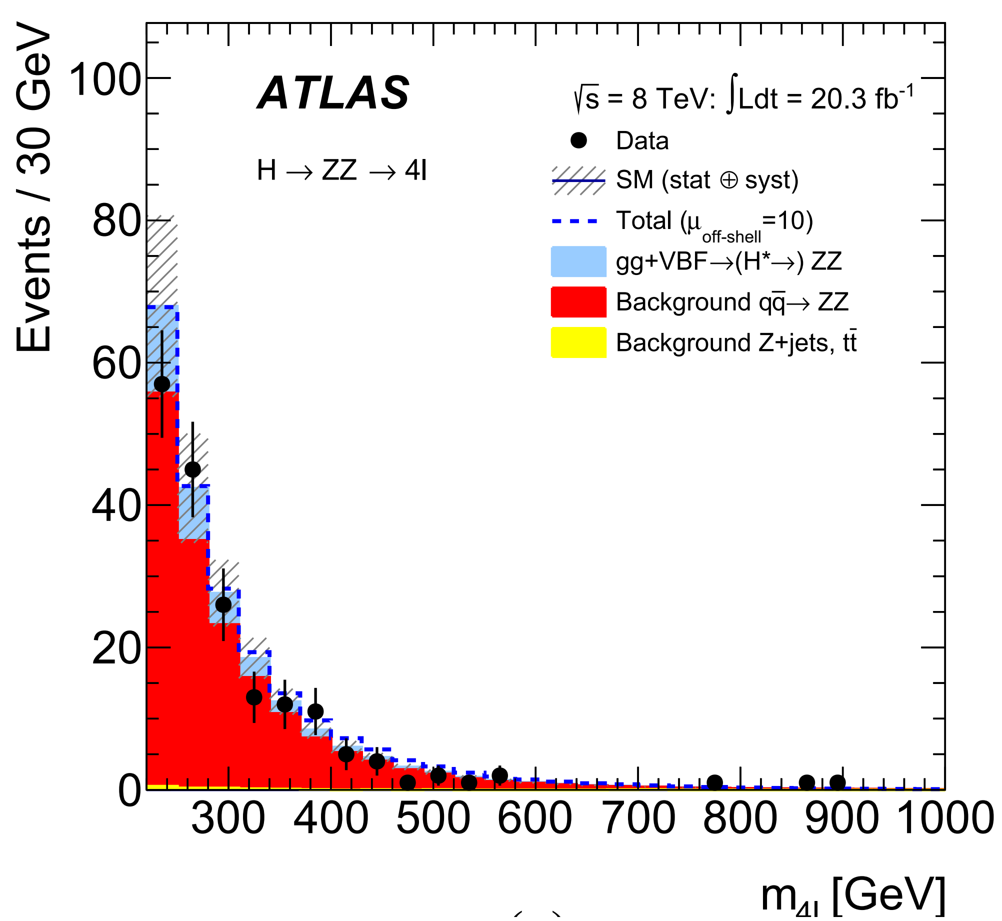
Analyses are performed inclusively in jet observables

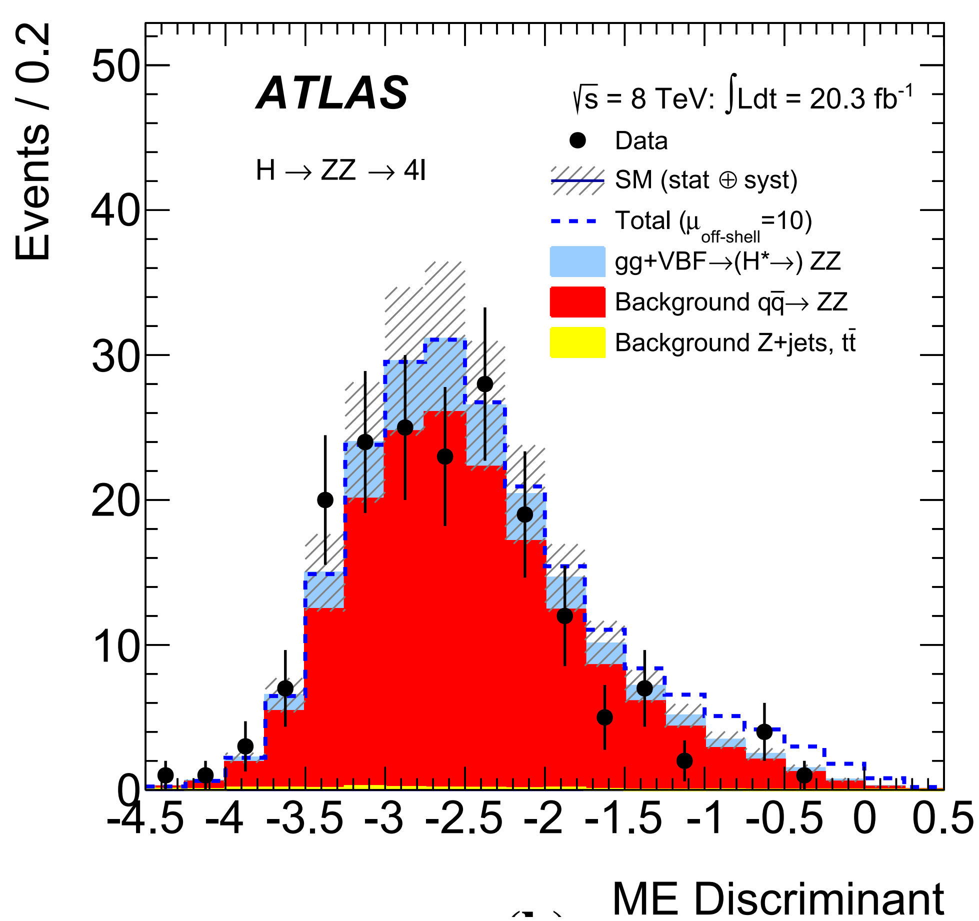
H*→ZZ→4l analysis

- Based on the on-shell H→ZZ*→4l analysis.
- **Binned ML fit observable**: Matrix element (ME) kinematic discriminant:

$$\mathrm{ME} = \log_{10}\left(\frac{P_H}{P_{gg} + c \cdot P_{q\bar{q}}}\right)$$

  - enhance separation among signal and backgrounds.
  - **m_{4l} range: 220 — 1000 GeV**



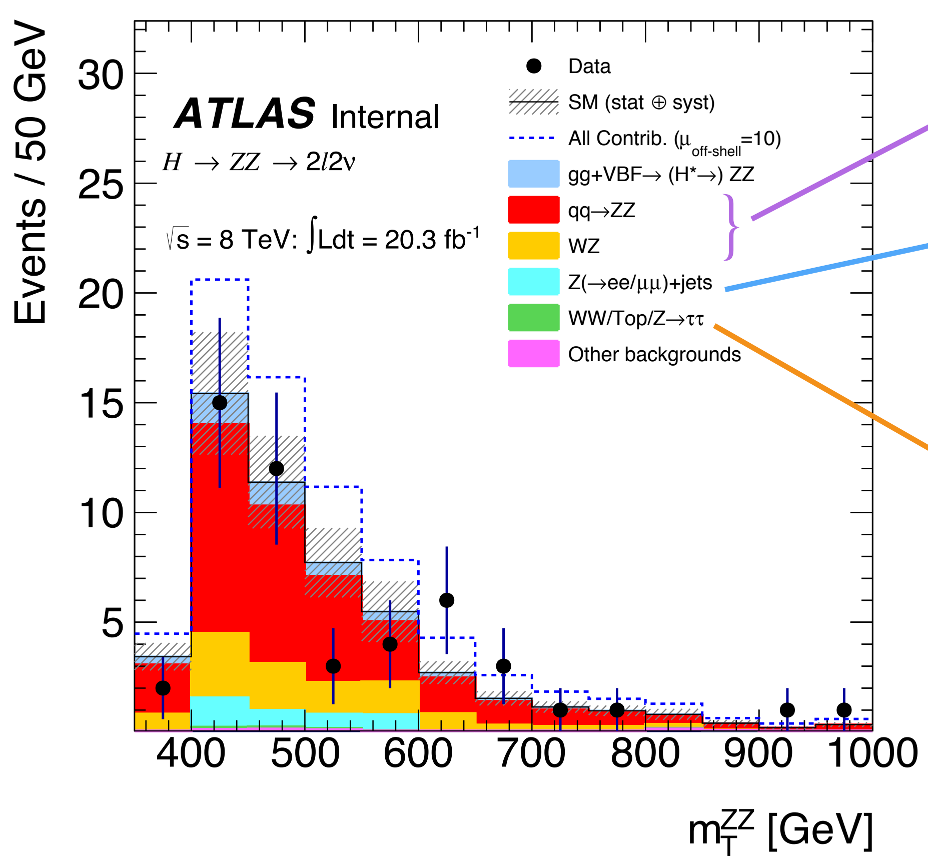


H*→ZZ→2l2ν analysis

- Based on ZH→ invisible analysis.
- **Binned ML fit observable**: transverse mass:

$$m_{\mathrm{T}}^{ZZ} \equiv \sqrt{\left(\sqrt{m_Z^2 + |\boldsymbol{p}_{\mathrm{T}}^{\ell\ell}|^2} + \sqrt{m_Z^2 + |\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}|^2}\right)^2 - |\boldsymbol{p}_{\mathrm{T}}^{\ell\ell} + \boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}|^2}$$

  - enhance sensitivity to gg→H*→ZZ signal
  - **m_T range: 380 — 1000 GeV**



Powheg simulation + NLO→NNLO Kfactor

fake-factor method

Lepton flavour symmetry in an eμ control region with date-driven method

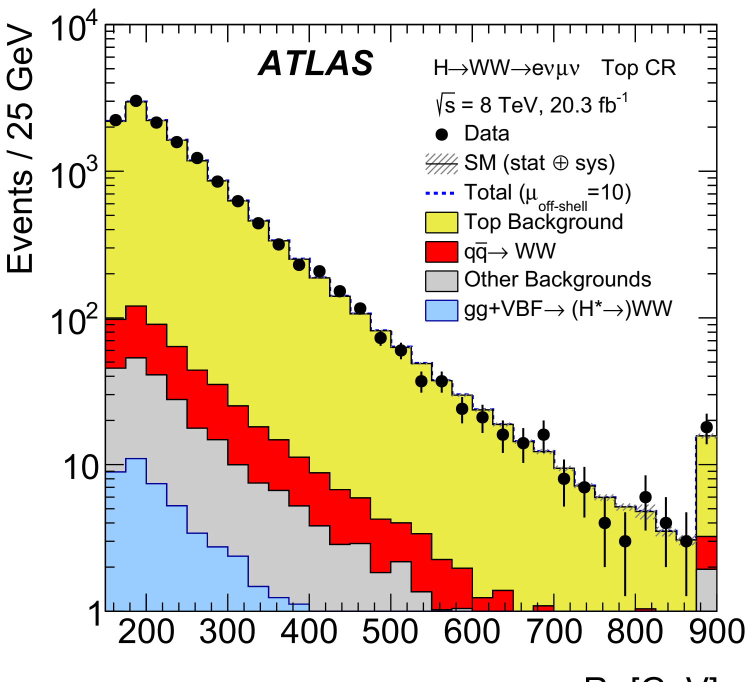
H*→WW→eνμν analysis

- Based on inclusive on-shell H→WW*→lνlν analysis.
- **One-bin ML fit observable: a new variable** Keep the inclusive-like shape

$$R_8 = \sqrt{m_{\ell\ell}^2 + \left(a \cdot m_{\mathrm{T}}^{WW}\right)^2}$$

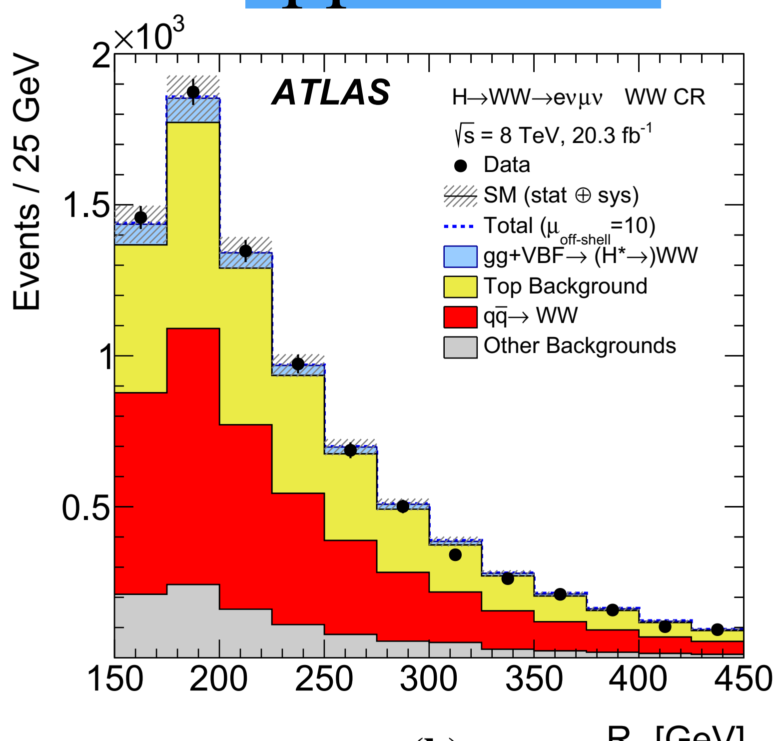
  - Signal region: R_8>450GeV, $\Delta\eta_{ll}$<1.2, b-veto
- Main qq→WW and top background normalised from control region.

Top CR



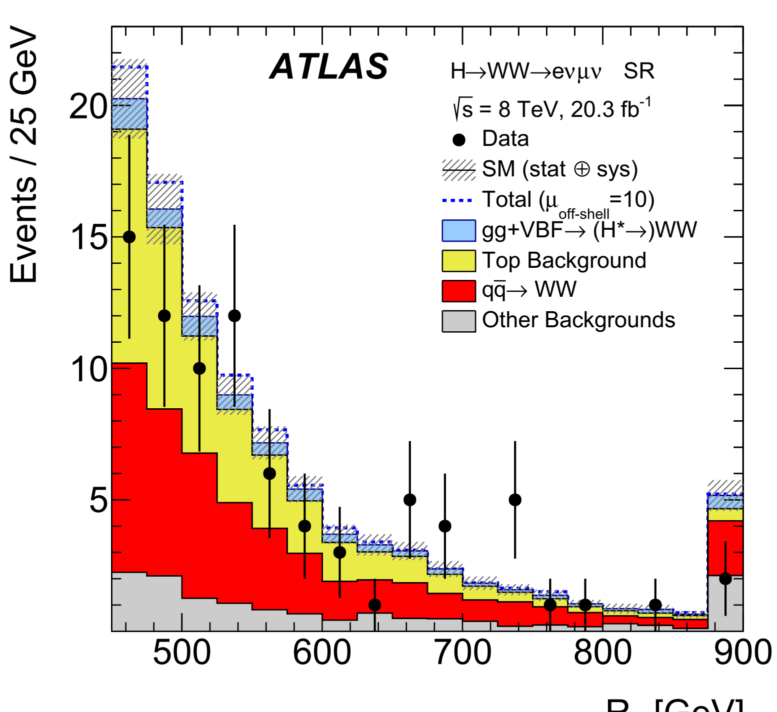
(a)

qqWW CR



(b)

SR

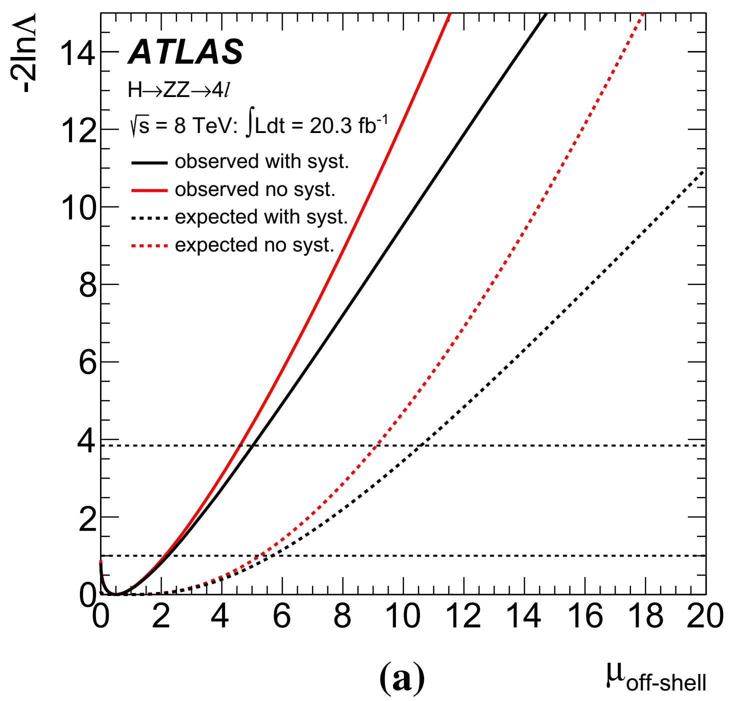


(c)

Results for the individual off-shell analysis — NLL scanning

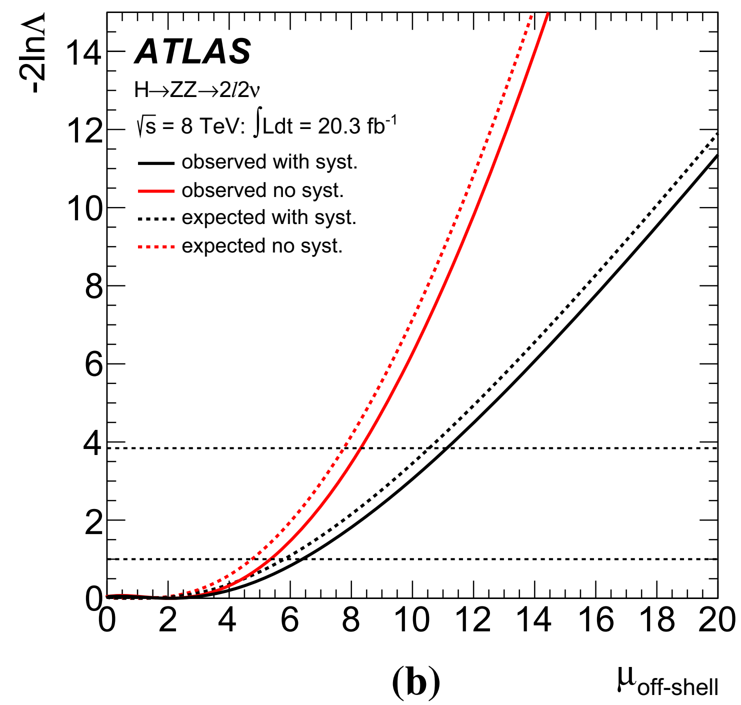
Negative log-likelihood, -2lnΛ, as a function of $\mu_{offshell}$:

H*→ZZ→4l



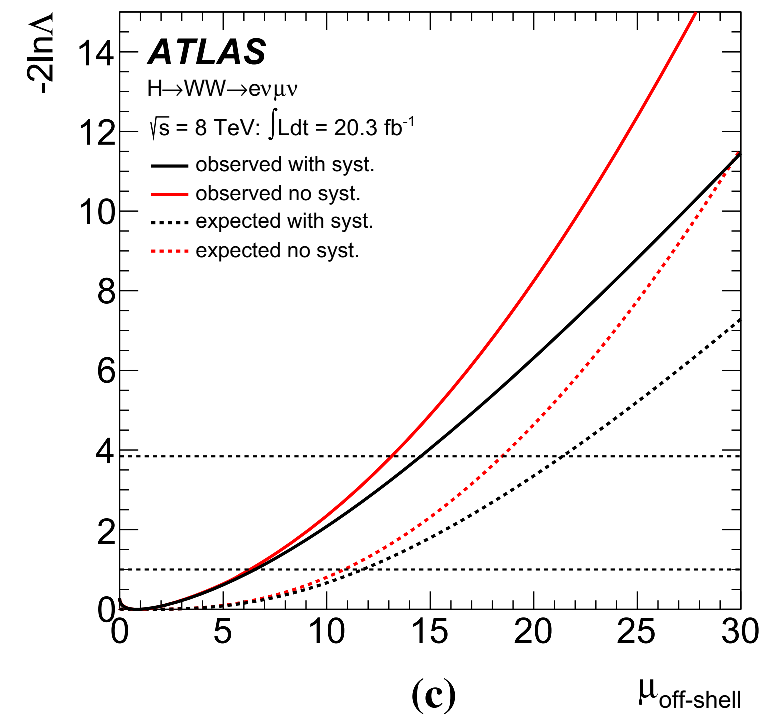
(a)

H*→ZZ→2l2ν



(b)

H*→WW→eνμν



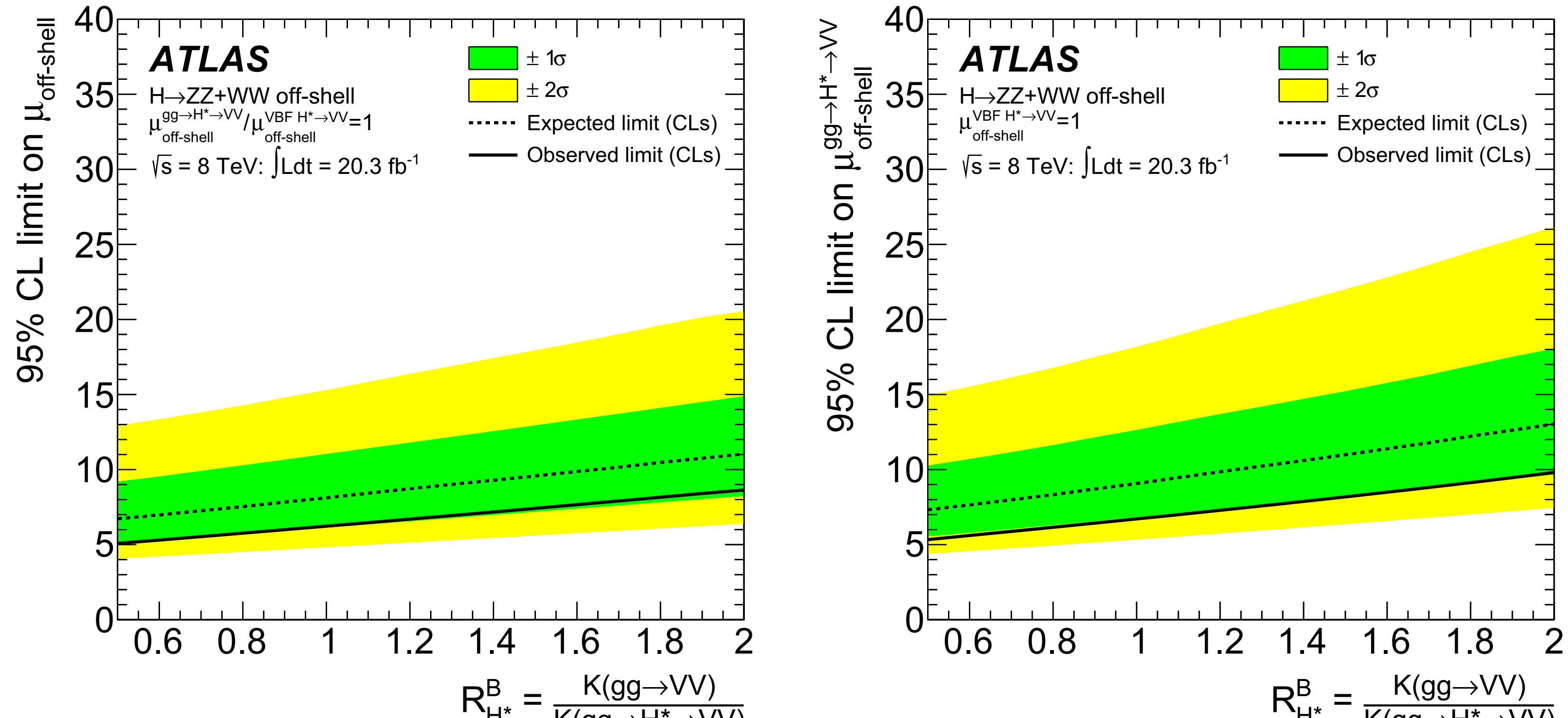
(c)

- ✦ **ZZ→4l and WW→eνμν channel is statistics dominate**
- ✦ **sensitivity in ZZ→2l2ν is significantly reduced by theory systematic uncertainty**

Combination of the off-shell ZZ and WW analysis

- Combine $ZZ\to 4l$, $ZZ\to 2l2\nu$ and $WW\to e\nu\mu\nu$ channels
  - Correlate the main theoretical uncertainty and related experimental uncertainty
- Two fitting assumptions:
  - Common $\mu_{\text{off-shell}}$, assuming ratio of ggF and VBF production modes as in SM.
  - Fit $\mu_{\text{off-shell}}$ for ggF and assume SM VBF couplings

$R^{B}_{H^*}$	Observed 0.5	Observed **1.0**	Observed 2.0	Median expected 0.5	Median expected **1.0**	Median expected 2.0	Assumption
$\mu_{\text{off-shell}}$	5.1	**6.2**	8.6	6.7	**8.1**	11.0	$\mu^{gg\to H^*}_{\text{off-shell}}/\mu^{VBF}_{\text{off-shell}}=1$
$\mu^{gg\to H^*\to VV}_{\text{off-shell}}$	5.3	**6.7**	9.8	7.3	**9.1**	13.0	$\mu^{\text{VBF } H^*\to VV}_{\text{off-shell}}=1$



(a) (b)

Breakdown of systematic uncertainties

Systematic uncertainty	95% CL_s up. lim. on $\mu_{\text{off-shell}}$
Interference $gg \to (H^* \to)VV$	7.2
QCD scale $\mathrm{K}^{H^*}(m_{VV})$ (correlated component)	7.1
PDF $q\bar{q} \to VV$ and $gg \to (H^* \to)VV$	6.7
QCD scale $q\bar{q} \to VV$	6.7
Luminosity	6.6
Drell–Yan background	6.6
QCD scale $\mathrm{K}_{gg}^{H^*}(m_{VV})$ (uncorrelated component)	6.5
Remaining systematic uncertainties	6.5
All systematic uncertainties	8.1
No systematic uncertainties	6.5

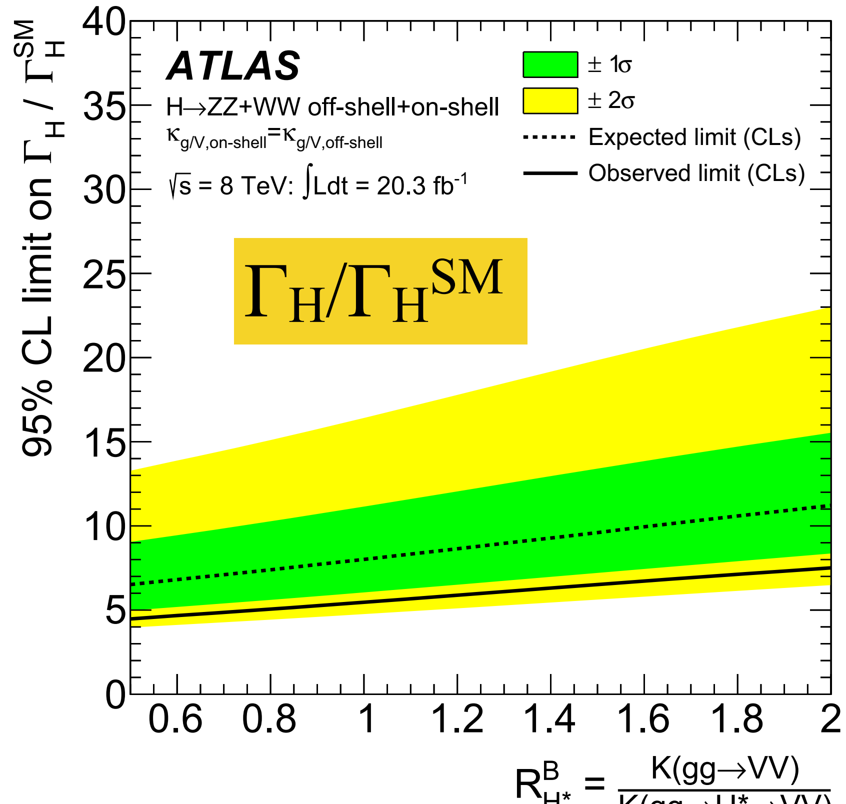
- fix all NP to the profit results, with the exception of the one under study.

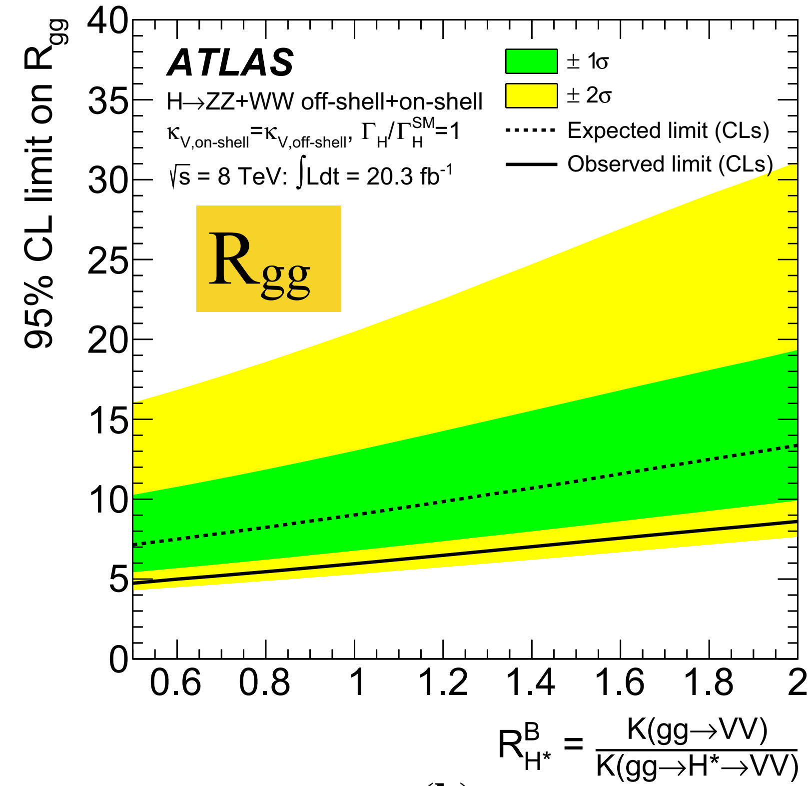
- Dominated by the statistical uncertainty and QCD theoretical uncertainty

Combination of the off-shell and on-shell ZZ and WW analysis

- Combine with 2012 on-shell ZZ and WW measurements.
- Interpretation:
  - Γ_H/Γ_H^{SM}, profiling κ_g and κ_V separately (assumes same on-shell and off-shell couplings)
  - $R_{gg} = \kappa^2_{g,\text{off-shell}}/\kappa^2_{g,\text{on-shell}}$, profiling κ_V(assumes Γ_H/Γ_H^{SM}=1)

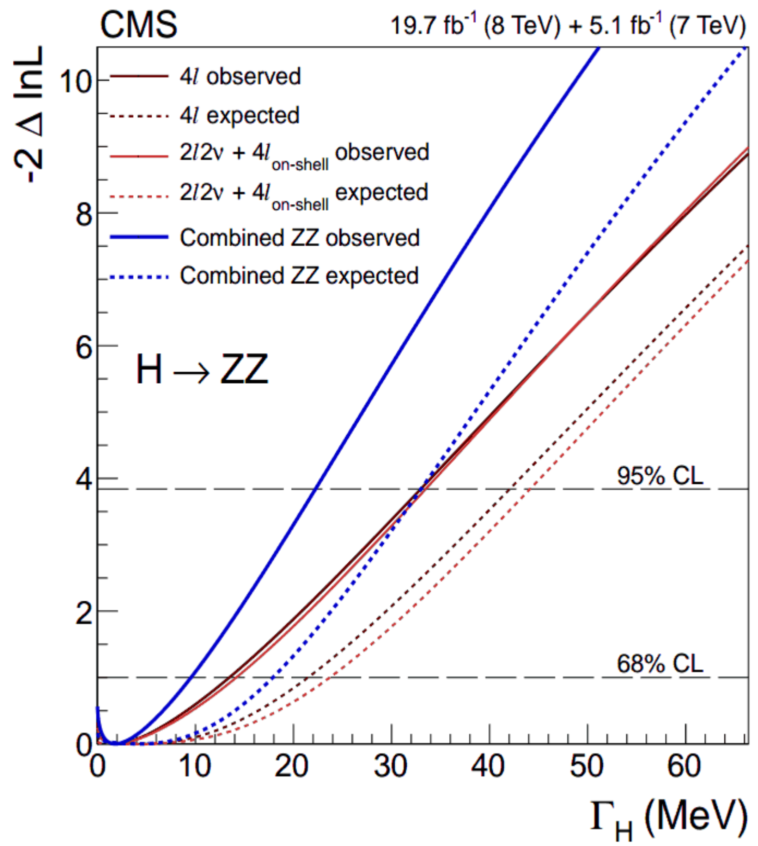
	Observed			Median expected			Assumption
$R^B_{H^*}$	0.5	**1.0**	2.0	0.5	**1.0**	2.0	
Γ_H/Γ_H^{SM}	4.5	**5.5**	7.5	6.5	**8.0**	11.2	$\kappa_{i,\text{on-shell}} = \kappa_{i,\text{off-shell}}$
$R_{gg} = \kappa^2_{g,\text{off-shell}}/\kappa^2_{g,\text{on-shell}}$	4.7	**6.0**	8.6	7.1	**9.0**	13.4	$\kappa_{V,\text{on-shell}} = \kappa_{V,\text{off-shell}}, \Gamma_H/\Gamma_H^{SM}=1$

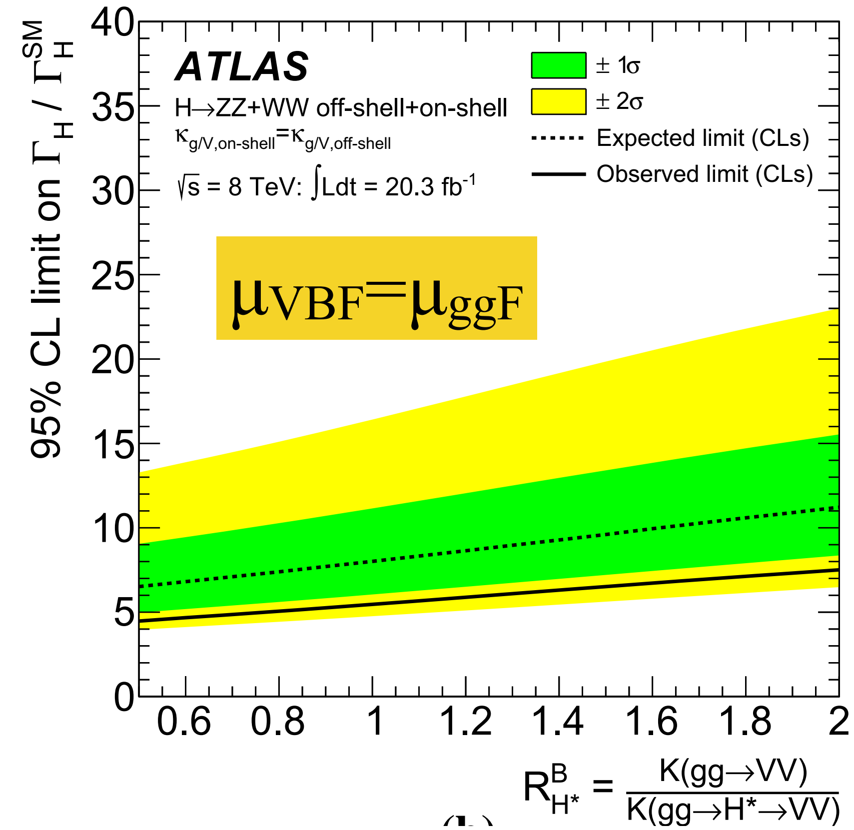




(b)

Comparison with CMS results





- **Different limit setting method.**
- **Treatment of ggZZ background k-factors:**
  - CMS uses 10% flat uncertainty
  - ATLAS: a results with a scan of the k-factors.
- **Treatment of the interference uncertainties:**
  - CMS: 10% (correlated with ggZZ bkg)
  - ATLAS: 30% uncorrelated with the rest

Γ/Γ_{SM} =obs.(exp.)	CMS	ATLAS
4l	8.0(10.1)	μ:7.3(10.6)
2l2ν	8.1(10.6)	μ:11.0(10.6)
lνlν		μ:17.2(21.3)
combined	5.4(8.0)	**5.5(8.0)**

Conclusion

- Using the results from five HSG2 and HSG3 analyses, can set 95% CL observed (expected) limits:
  - $\mu_{\text{off-shell}} < 5.1\text{–}8.6$ (6.7–11.0) for $R^{B}_{H*}=0.5\text{–}2.0$
  - $\Gamma_H/\Gamma_H^{SM} < 4.5\text{–}7.5$ (6.5–11.2) for $R^{B}_{H*}=0.5\text{–}2.0$
  - $\Gamma_H < 22.7$ (33.0) MeV for $R^{B}_{H*}=1$
  - $Rgg < 4.7\text{–}8.6$ (7.1–13.4) for $R^{B}_{H*}=0.5\text{–}2.0$
- It will be promising with high statistical sample and more precision theoretical precision.

Constraint on non-SM interaction in EFT

- The interactions of the Higgs boson have been probed using the κ-framework: Coupling strength is allowed to vary from SM, instead of Higgs kinematic properties.

- An alternative framework is in EFT approach:

  - New tensor structure for the interactions between Higgs and SM particle (kinematic shape can be changed)

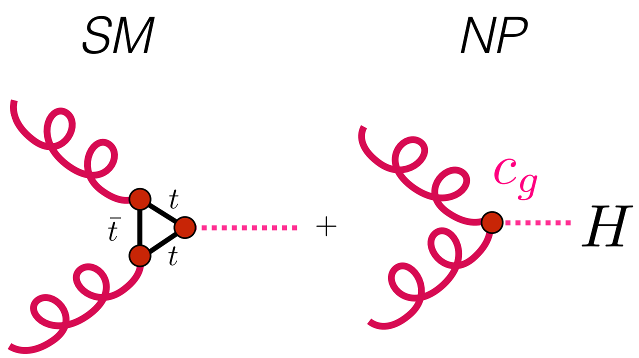
  - Probe the new physics that exists at larger energy scale

Analysis Overview

- **Aim:** setting limits on Wilson coefficients with the 6-dimension CP-even/odd operator with H→γγ differential cross sections.

$$\mathcal{L} = \bar{c}_\gamma O_\gamma + \bar{c}_g O_g + \bar{c}_{HW} O_{HW} + \bar{c}_{HB} O_{HB} + \tilde{c}_\gamma \tilde{O}_\gamma + \tilde{c}_g \tilde{O}_g + \tilde{c}_{HW} \tilde{O}_{HW} + \tilde{c}_{HB} \tilde{O}_{HB},$$

"Wilson coefficients" c_i specify the new interaction strength

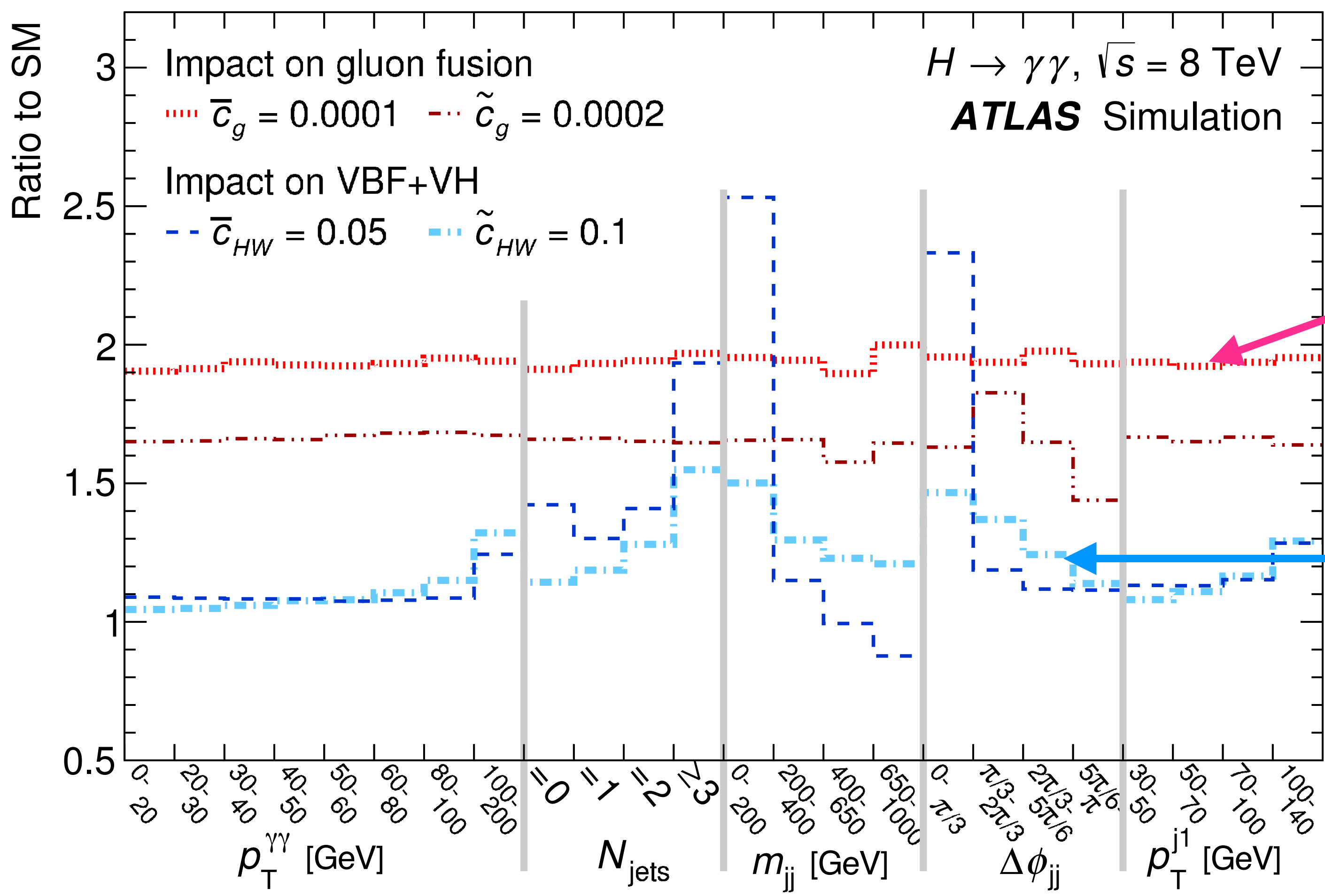


Wilson coefficient	Description
c_g	Eff. copuling of Higgs to gluons
$\tilde{c}_g$	Eff. copuling of Higgs to gluons
c_γ	Eff. copuling of Higgs to Photons
$\tilde{c}_\gamma$	Eff. copuling of Higgs to Photons
c_H	Eff. coupling of Higgs to itself
c_T	Higgs EoM term
c_B	Higgs EoM term & Z
c_W	Higgs EoM term & W
c_{HW}	Higgs EoM term & W
$\tilde{c}_{HW}$	Higgs EoM term & W
c_{HB}	Higgs EoM term & Z
$\tilde{c}_{HB}$	Higgs EoM term & Z

Theoretical prediction

- Take the high order SM prediction as the reference (MG5_aMC@NLO for ggF)
- Introduce the anomalous coupling effect by the correction scale factor (ratio of SM + AP case to the SM case).
- Sum over the different Higgs production mechanisms

$$\frac{d\sigma}{dX} = \sum_j \left(\frac{d\sigma_j}{dX}\right)^{\text{ref}} \cdot \left(\frac{d\sigma_j}{dX}\right)^{\text{MG5}}_{c_i} \Big/ \left(\frac{d\sigma_j}{dX}\right)^{\text{MG5}}_{c_i=0}$$



Large impact on the overall X-section normalisation

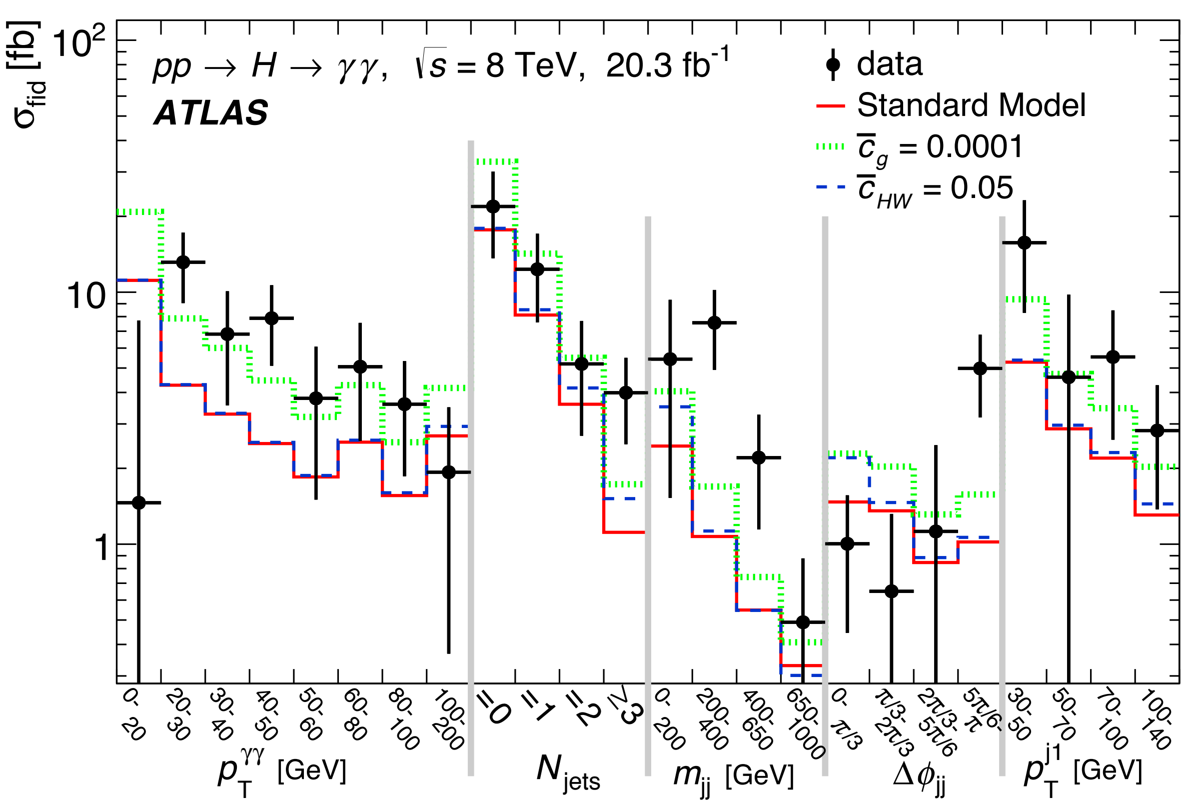
Sensitive to the shape of $\Delta\Phi_{jj}$ distribution

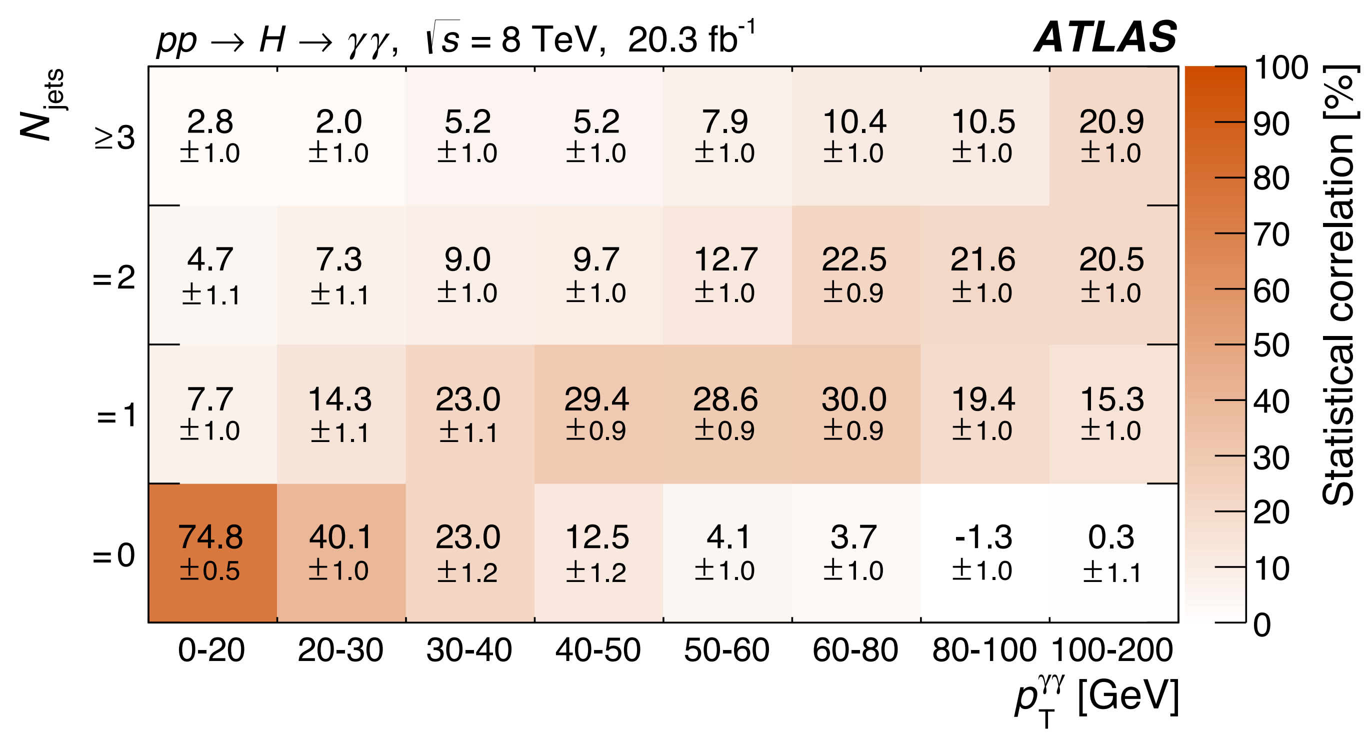
Statistics correlation between different distributions

- **Limits on the Wilson coefficients are set by constructing a $\chi 2$ function:**

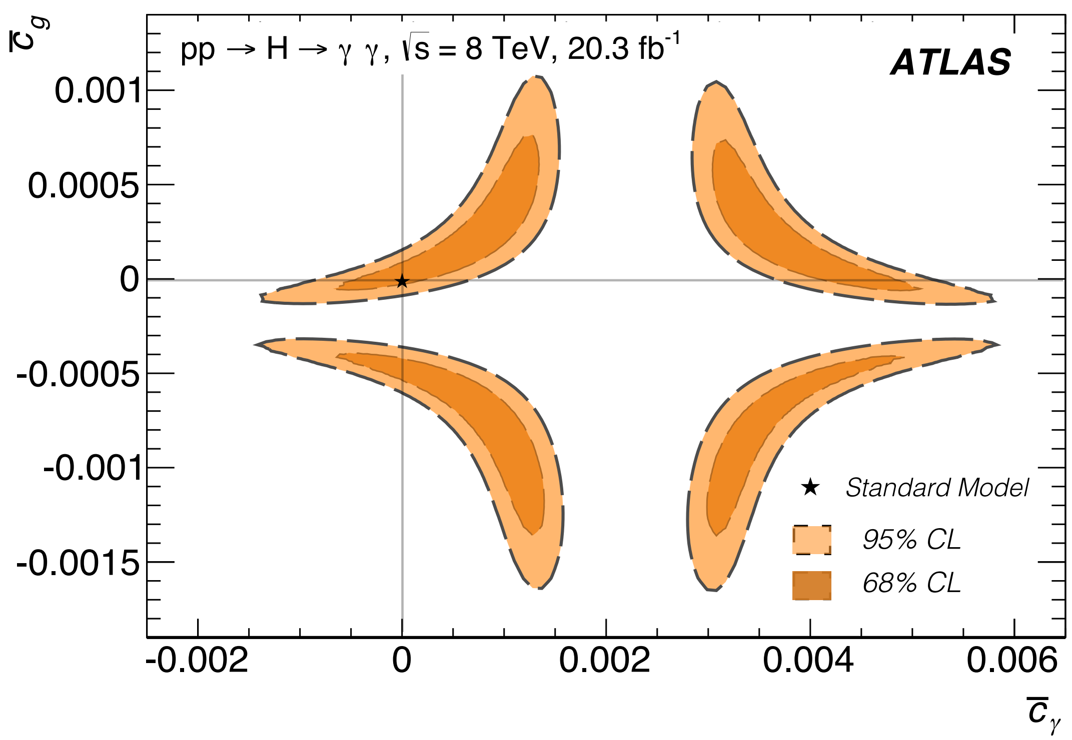
$$\chi^2 = \left(\vec{\sigma}_{\rm data} - \vec{\sigma}_{\rm pred}\right)^{\rm T} C^{-1} \left(\vec{\sigma}_{\rm data} - \vec{\sigma}_{\rm pred}\right)$$

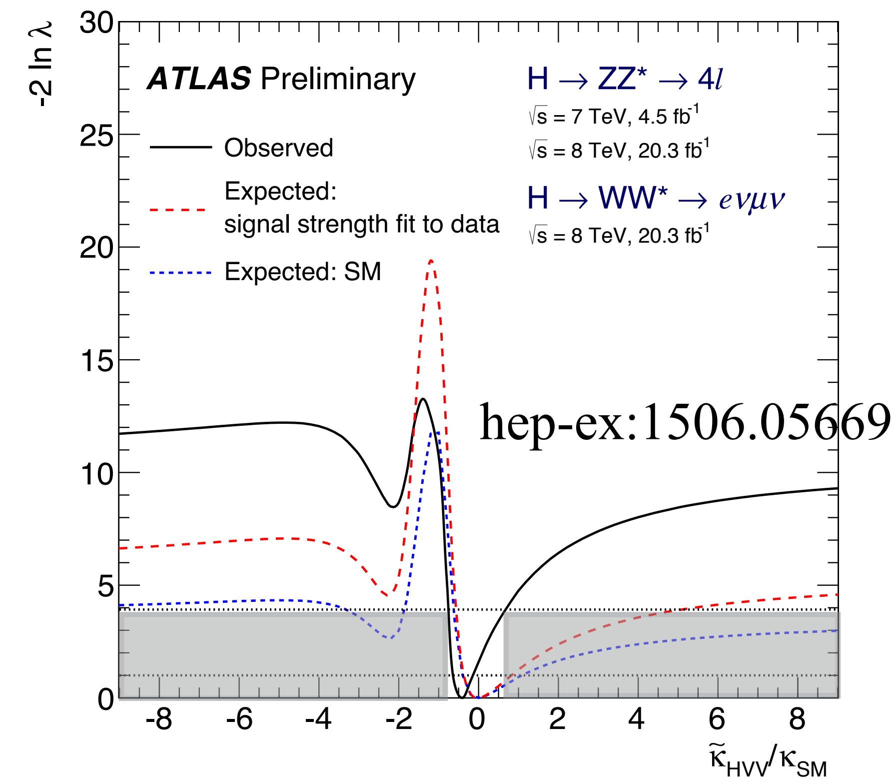
- Fit parameter of interest: **Wilson coefficients c_i**
- **Statistical correlations between differential distributions**
  - "Bootstrap" method is used: samples are constructed from the data by assigning each event a weight pulled from a Possion distribution with unit mean





Results





Coefficient	95% $1 - CL$ limit
$\bar{c}_\gamma$	[-7.4, 5.7]×10^{-4} ∪ [3.8, 5.1]×10^{-3}
$\tilde{c}_\gamma$	[-1.8, 1.8]×10^{-3}
$\bar{c}_g$	[-0.7, 1.3]×10^{-4} ∪ [-5.8, -3.8]×10^{-4}
$\tilde{c}_g$	[-2.4, 2.4]×10^{-4}
$\bar{c}_{HW}$	[-8.6, 9.2]×10^{-2}
$\tilde{c}_{HW}$	[-0.23, 0.23]

95%CL constraint	κ_{HVV}/κ_{SM}	$(\kappa_{AVV}/\kappa_{SM})\tan\alpha$
H→WW/ZZ	[-0.73, 0.63]	[-2.18, 0.83]
EFT in H→γγ	[-0.08, 0.09]	[-0.22, 0.22]

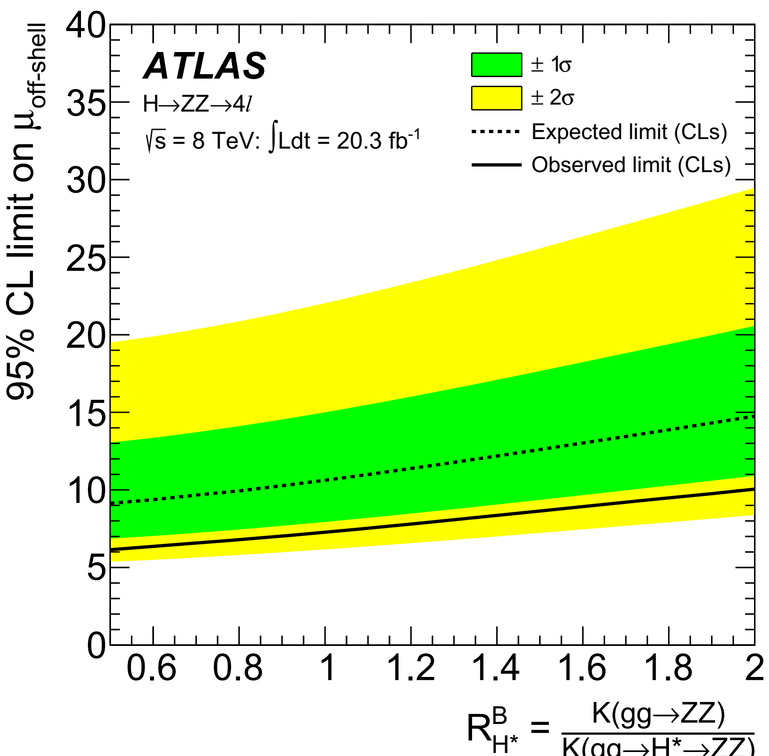
- No significant deviation from the SM are observed
- Provide more stringent constraint on the HVV Tensor structure w.r.t. the dedicated Spin and parity analysis in di-boson decays.

Results for the individual off-shell analysis — CLs limit setting

- CLs limit on $\mu_{offshell}$ as a function of unknown R^{B}_{H*} with alternative hypothesis of SM (**$\mu_{offshell}$=1**)

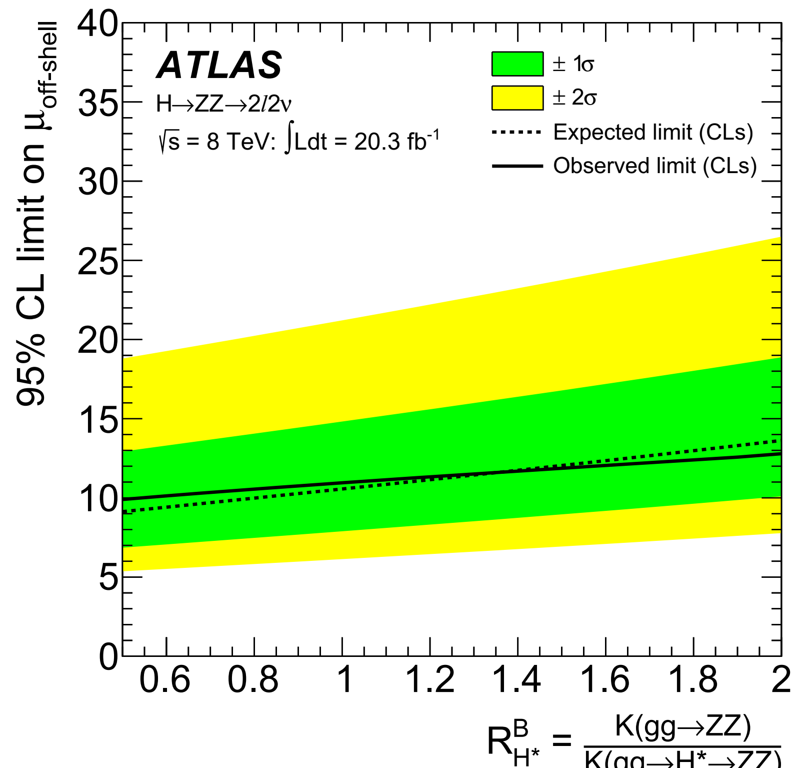
	Observed			Median expected		
$R^{B}_{H^*}$	0.5	**1.0**	2.0	0.5	**1.0**	2.0
$ZZ \to 4\ell$ analysis	6.1	**7.3**	10.0	9.1	**10.6**	14.8
$ZZ \to 2\ell 2\nu$ analysis	9.9	**11.0**	12.8	9.1	**10.6**	13.6
$WW \to e\nu\mu\nu$ analysis	15.6	**17.2**	20.3	19.6	**21.3**	24.7

H*→ZZ→4l



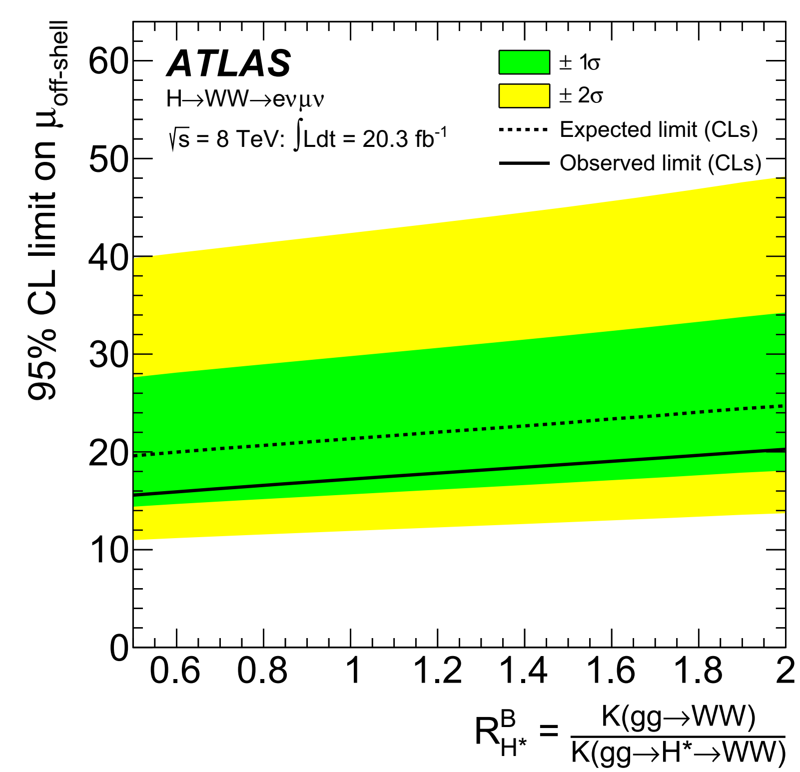
(a)

H*→ZZ→2l2ν



(b)

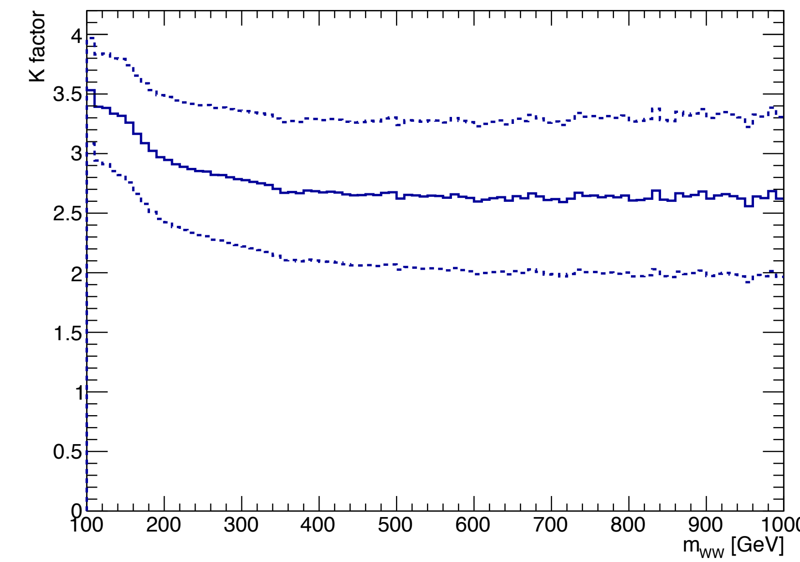
H*→WW→eνμν



(c)

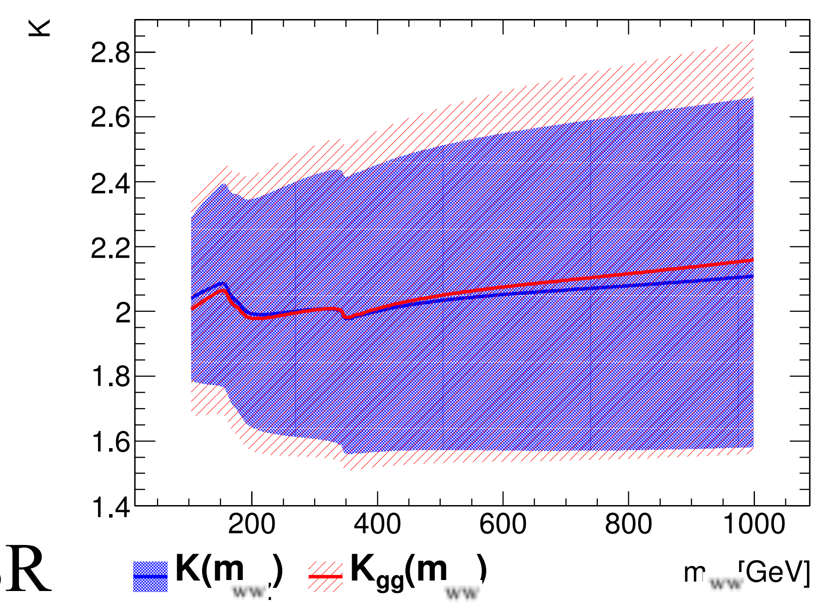
Theoretical uncertainty for ggF processes

- ggF processes include: gg→H*→WW(S), gg→WW(B) and gg(→H*)→WW(SBI)



- QCD scale Un. is variated by NNLO K-factor (20%)
- Extra QCD scale un. is assigned to take into account the uncertainty difference between K^{H^*} and $K^{H^*}_{gg}$ ($_{-11.8}^{+15.9}$%)
- QCD scale uncertainty on interference component: 30%
- PDF uncertainty is variated via:

$$w = 1 \pm 0.0066 \times \sqrt{m_{WW}/\mathrm{GeV} - 10}.$$ from yellow book



Taking into account the PDF acceptance Un., it is ~15% in SR

$$\begin{aligned} \mathrm{MC}_{gg\to(H^*\to)WW}(\mu_{\text{off-shell}}) = & \boxed{K^{H^*}(m_{WW})} \cdot \mu_{\text{off-shell}} \cdot \mathrm{MC}^{\mathrm{SM}}_{gg\to H^*\to WW} \\ & + K^{H^*}_{gg}(m_{WW}) \cdot \sqrt{\mathrm{R}^B_{H^*} \cdot \mu_{\text{off-shell}}} \cdot \mathrm{MC}^{\mathrm{Interference}}_{gg\to WW} \\ & + K^{H^*}_{gg}(m_{WW}) \cdot \mathrm{R}^B_{H^*} \cdot \mathrm{MC}^{\mathrm{cont}}_{gg\to WW} \end{aligned}$$

Anomalous coupling in Madgraph

- The anomalous Higgs interactions introduced using FeynRules:

$$
\begin{aligned}
\mathcal{L}_3 = & -\frac{m_H^2}{2v} g^{(1)}_{hhh} h^3 + \frac{1}{2} g^{(2)}_{hhh} h \partial_\mu h \partial^\mu h \\
& - \frac{1}{4} g_{hgg} G^a_{\mu\nu} G_a^{\mu\nu} h - \frac{1}{4} \tilde{g}_{hgg} G^a_{\mu\nu} \tilde{G}^{\mu\nu} h - \frac{1}{4} g_{h\gamma\gamma} F_{\mu\nu} F^{\mu\nu} h - \frac{1}{4} \tilde{g}_{h\gamma\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} h \\
& - \frac{1}{4} g^{(1)}_{hzz} Z_{\mu\nu} Z^{\mu\nu} h - g^{(2)}_{hzz} Z_\nu \partial_\mu Z^{\mu\nu} h + \frac{1}{2} g^{(3)}_{hzz} Z_\mu Z^\mu h - \frac{1}{4} \tilde{g}_{hzz} Z_{\mu\nu} \tilde{Z}^{\mu\nu} h \\
& - \frac{1}{2} g^{(1)}_{haz} Z_{\mu\nu} F^{\mu\nu} h - \frac{1}{2} \tilde{g}_{haz} Z_{\mu\nu} \tilde{F}^{\mu\nu} h - g^{(2)}_{haz} Z_\nu \partial_\mu F^{\mu\nu} h - \frac{1}{2} g^{(1)}_{hww} W^{\mu\nu} W^\dagger_{\mu\nu} h \\
& - \left[g^{(2)}_{hww} W^\nu \partial^\mu W^\dagger_{\mu\nu} h + \text{h.c.} \right] + g(1 - \frac{1}{2}\bar{c}_H) m_W W^\dagger_\mu W^\mu h - \frac{1}{2} \tilde{g}_{hww} W^{\mu\nu} \tilde{W}^\dagger_{\mu\nu} h \\
& - \left[\tilde{y}_u \frac{1}{\sqrt{2}} [\bar{u} P_R u] h + \tilde{y}_d \frac{1}{\sqrt{2}} [\bar{d} P_R d] h + \tilde{y}_\ell \frac{1}{\sqrt{2}} [\bar{\ell} P_R \ell] h + \text{h.c.} \right] ,
\end{aligned}
$$

g_{hgg}	$c_\alpha \kappa_{Hgg} g_{Hgg}$	$g_H - \frac{4\bar{c}_g g_s^2 v}{m_W^2}$
$\tilde{g}_{hgg}$	$s_\alpha \kappa_{Agg} g_{Agg}$	$-\frac{4\tilde{c}_g g_s^2 v}{m_W^2}$
$g_{h\gamma\gamma}$	$c_\alpha \kappa_{H\gamma\gamma} g_{H\gamma\gamma}$	$a_H - \frac{8g\bar{c}_\gamma s_W^2}{m_W}$
$\tilde{g}_{h\gamma\gamma}$	$s_\alpha \kappa_{A\gamma\gamma} g_{A\gamma\gamma}$	$-\frac{8g\tilde{c}_\gamma s_W^2}{m_W}$
$g^{(1)}_{hzz}$	$\frac{1}{\Lambda} c_\alpha \kappa_{HZZ}$	$\frac{2g}{c_W^2 m_W}\left[\bar{c}_{HB} s_W^2 - 4\bar{c}_\gamma s_W^4 + c_W^2 \bar{c}_{HW}\right]$
$\tilde{g}_{hzz}$	$\frac{1}{\Lambda} s_\alpha \kappa_{AZZ}$	$\frac{2g}{c_W^2 m_W}\left[\tilde{c}_{HB} s_W^2 - 4\tilde{c}_\gamma s_W^4 + c_W^2 \tilde{c}_{HW}\right]$
$g^{(2)}_{hzz}$	$\frac{1}{\Lambda} c_\alpha \kappa_{H\partial Z}$	$\frac{g}{c_W^2 m_W}\left[(\bar{c}_{HW} + \bar{c}_W) c_W^2 + (\bar{c}_B + \bar{c}_{HB}) s_W^2\right]$
$g^{(3)}_{hzz}$	$c_\alpha \kappa_{\text{SM}} g_{HZZ}$	$\frac{g m_W}{c_W^2}\left[1 - \frac{1}{2}\bar{c}_H - 2\bar{c}_T + 8\bar{c}_\gamma \frac{s_W^4}{c_W^2}\right]$
$g^{(1)}_{haz}$	$c_\alpha \kappa_{HZ\gamma} g_{HZ\gamma}$	$\frac{g s_W}{c_W m_W}\left[\bar{c}_{HW} - \bar{c}_{HB} + 8\bar{c}_\gamma s_W^2\right]$
$\tilde{g}_{haz}$	$s_\alpha \kappa_{AZ\gamma} g_{AZ\gamma}$	$\frac{g s_W}{c_W m_W}\left[\tilde{c}_{HW} - \tilde{c}_{HB} + 8\tilde{c}_\gamma s_W^2\right]$
$g^{(2)}_{haz}$	$\frac{1}{\Lambda} c_\alpha \kappa_{H\partial\gamma}$	$\frac{g s_W}{c_W m_W}\left[\bar{c}_{HW} - \bar{c}_{HB} - \bar{c}_B + \bar{c}_W\right]$
$g^{(1)}_{hww}$	$\frac{1}{\Lambda} c_\alpha \kappa_{HWW}$	$\frac{2g}{m_W}\bar{c}_{HW}$
$\tilde{g}_{hww}$	$\frac{1}{\Lambda} s_\alpha \kappa_{AWW}$	$\frac{2g}{m_W}\tilde{c}_{HW}$
$g^{(2)}_{hww}$	$\frac{1}{\Lambda} c_\alpha \kappa_{H\partial W}$	$\frac{g}{m_W}\left[\bar{c}_W + \bar{c}_{HW}\right]$

Different Lagrangian configurations are used in Madgraph and VBFNLO, the direct relation of the coefficients can be retrieved as:

$$c_{\mathrm{HW}} = \frac{m_W^2}{\Lambda^2} f_{\mathrm{WW}}$$

$$c_{\mathrm{HW}} + c_{\mathrm{W}} = -\frac{m_W^2}{2\,\Lambda^2} f_{\mathrm{W}}$$

$$c_{\mathrm{HB}} + c_{\mathrm{B}} = -\frac{m_W^2}{2\,\Lambda^2} f_{\mathrm{B}}$$

$$c_{\mathrm{HB}} + c_{\mathrm{HW}} = \frac{m_W^2}{\Lambda^2} f_{\mathrm{BW}}$$

$$c_{\mathrm{HB}} - 4c_\gamma = \frac{m_W^2}{\Lambda^2} f_{\mathrm{BB}}$$